ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK IN THE ANTAMINA MINE, PERU

by

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ABSTRACT

Cover systems have been included as a closure and long-term planning strategy for the estimated 1,539 Mt of waste rock at the Antamina Mine (Peru). A cover study was initiated to determine the most suitable type of cover system for the waste rock dumps at Antamina. The purpose of the four cover systems proposed in this study was to reduce net percolation to underlying waste rock via the combination of a low-permeability and a store-and-release cover, thereby limiting weathering and metal leaching from the waste rock. The low-permeability cover works as a barrier to percolation, whereas the store-and-release layer acts as a medium growth for vegetation, accumulates water during rain events and later releases most of it back to the environment through evapotranspiration.

Four field-scale cover systems were constructed of native, low permeability materials and topsoil at Antamina. Climate data, runoff and infiltration through the covers were continuously monitored for one year in the field. A numerical model was created with the purpose of predicting the covers systems' long term performance and the assessment of possible modification(s) to the design.

Results after the first year indicate that the proposed cover systems reduced net percolation to the underlying waste rock from 70% (for the control lysimeter with no cover installed) to 53%-63%. No runoff was generated from any of the lysimeters and evapotranspiration is the only mechanisms available to reduce net percolation throught the cover systems. Materials characteristics and construction methodology were recognized as the potential reasons for the observed performance of the cover systems. Recommendations were given to improve the performance of the cover systems by further reducing the permeability of low-permeability layers and/or decreasing the thickness of the store-and-release layers of the cover systems. The feasibility of these recommendations depends on Antamina's site specific conditions and remains to be evaluated. Finally, it was recognized that the data available to date is insufficient to draw major conclusions for the performance of each independent cover system. The Antamina cover study will continue over the following years and conclusions presented herein will be verified when new field data becomes available.

PREFACE

This research was conducted by the author under the supervision of Dr. G Ward Wilson, professor of the School of Mining and Petroleum Engineering, Department of Civil and Environmental Engineering, University of Alberta.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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To my family

CHAPTER 1. INTRODUCTION

1.1 Overview

Acid rock drainage (ARD) and metal leaching are two of the main concerns when dealing with the closure of facilities containing reactive waste rock or tailings. As a result, preventing oxidation (by minimizing oxygen and water availability), and limiting the contaminants transport (by minimizing water percolation and seepage), becomes critical. Remediation of the environmental liability left behind by orphan mines in North America, for example, is thought to approach the tens of billions of U.S. dollars (INAP, 2010). Facing this issue during the life of the mine and developing a sound ARD management plan can greatly help to reduce these costs.

A successful ARD management plan is highly site specific, as it depends on a number of variables such as site topography, geology, hydrology, hydrogeology, and climate conditions; along with the mine processing method, local environmental regulations and even the mine stakeholders. Nevertheless, any ARD management plan should, at least, consider the following components:

- Characterization of the geology and mineralogy of the waste rock, as well as the site climate, hydrology and hydrogeology. All of these will define the characteristics of the rock drainage and how it will be released to the environment.
- Prediction of the potential acidity of the rock drainage and its chemistry.
- Prevention and mitigation focused in delaying or even impeding the generation and/or transport of the rock drainage to the water receptor and the environment. The processes involved in this case are hydrological, physical, chemical and microbiological.
- ARD treatment, with different objectives such as recycling mine water within the operation, or improving its water quality to make it acceptable to be released to the environment.
- Monitoring the rock drainage and the environment, to ensure the proper ARD management plan is in place and improve or update it when it is required.

Compañia Minera Antamina S.A. (Antamina) is one of the largest zinc and copper producers in the world. The company recognized that an ARD management plan is an ongoing process and should be followed, revised and updated throughout the whole life of the mine. As part of this plan, Antamina, Teck and the University of British Columbia (UBC) initiated a research program in 2005 to assess the hydrological, geochemical and weathering characteristics of waste rock at the mine. This program includes the construction and monitoring of five 36 m x 36 m x 10 m experimental waste rock piles, 25 field kinetic cells, geochemical laboratory studies, and a detailed mineralogical characterization of the waste rock material. A cover study project consisting in the assessment of cover systems for waste rock at the Antamina mine, was developed in 2008 to help refine the closure plan for the 1,539 Mt waste rock dumps at Antamina. This thesis focuses in the first stage of the cover study component of the aforementioned research program.

The results of the cover study currently being conducted at Antamina will therefore enrich the mine's ARD management plan by assessing one of the prevention and mitigation alternatives available when dealing with potential acid rock drainage generation: the implementation of dry covers. Dry covers are unsaturated systems exposed to the atmosphere and the term includes a wide range of configurations. In this specific case, the dry covers selected for the Antamina cover study consist of two-layered systems constructed with earthen materials. The purpose of a dry cover on top of waste rock dumps containing potentially acid-generating material is to function as an oxygen and water barrier, thereby limiting weathering and metal leaching. The cover must also provide physical stability with respect to deformation, shear strength and erosion. The cover systems proposed in this study aim to reduce net percolation to underlying waste rock via the combination of a low-permeability and a store-and-release cover. The performance of the low-permeability cover will depend on its ability to work as a barrier to percolation and to limit oxygen entry, maintaining a high degree of saturation throughout the whole life of the cover system and also demonstrate a low hydraulic conductivity. The store-and-release cover, placed on top of the low-permeability barrier, acts as a growth medium for vegetation and reduces percolation by triggering evapotranspiration. The store-and-release cover also protects the low-permeability cover against erosion and desiccation. The cover study at Antamina is currently evaluating the performance of four different cover systems as well as a control system, by measuring the resulting water percolation and oxygen diffusion through the covers to the reactive waste rock below.

There are three complementary components included in the scope of this cover study, they are outlined in point form as follows.

1) The field experiment, comprised of the construction and monitoring of four fully instrumented cover lysimeters and one control, to mimic the conditions of the future platform for the covers on the waste rock dumps at Antamina. The lysimeters consist of 15 m x 15 m x 2.5 m excavations with 1.5:1 (H:V) sloped walls. Each lysimeter has two sets of pipes installed to collect run-off and percolation through the lysimeters. These pipes direct water to the tanks located downstream to the east of the five lysimeters, and then to the 10 tipping buckets installed next to the tanks to provide real-time flow measurements.
2) Predictive numerical modelling of the four tested cover systems, using the SoilCover model, with the specific purpose of predicting a system's long term performance at Antamina and the assessment of possible modification(s) to the covers design.
3) Laboratory testing to complete the characterization of the materials used to build the cover systems and determine input parameters for numerical models. The laboratory testing program includes:
   - Grain size analysis, to improve the understanding of the permeability and physical stability of the materials.
   - Atterberg limits, for a better understanding of the physical characteristics of the materials used.
   - Saturated hydraulic conductivity tests, to assist with the determination limiting percolation potential of the different cover systems.
   - Pressure plate tests using Tempe Cells, to obtain the soil-water characteristic curve of the soils acting as a water barrier.
   - Standard Proctor, to determine the compacted characteristics of the materials used for the construction of the cover systems.

These three components are integrated and evaluated to provide an assessment of the performance that can be expected from four cover systems that could be implemented for long-term closure.

1.2 Objective and Scope

The overall objective of the Assessment of Cover Systems for Waste Rock in the Antamina Mine is to determine a suitable cover system for the waste rock dumps at Antamina, and to provide the mine with a solid foundation to make the most efficient decision regarding the type of cover for the closure of their waste rock dumps. The assessment involved evaluating the field performance of four different cover systems and one control system constructed at Antamina. The performance of these systems was assessed by measuring the resulting water percolation through the covers to the reactive waste rock below.

The purpose of this thesis is to report the first stage of the Assessment of Cover Systems for Waste Rock as part of the Antamina research project, compare the performance of the different cover systems with the available data from the first rainy season, predict performances with the available data from the first rainy season, and calibrate models for the available data from the first rainy season. The scope of this thesis is to:

- Construct a field-scale experiment to mimic the conditions of the future platform for the covers on the waste rock dumps at Antamina. This experiment involves the construction of four field-scale cover lysimeters and one control lysimeter. The control lysimeter was designed to be filled with one of Antamina's most reactive waste rock types, while the remainder are only partially filled with the same kind of waste rock and have four different cover systems installed on the waste rock.
- Install the necessary instrumentation to measure the lysimeters water percolation and run off, matric suction in the cover profiles, oxygen diffusion through the covers and net radiation for evapotranspiration.
- Complete the first water balance of the system by measuring total precipitation, water percolation through the covers, runoff, and indirect measurements of evaporation on

each lysimeter and associated cover system. The data used to accomplish this is comprised of only one rainy season.

- Carry out laboratory testing to complete the characterization of the materials used to build the cover systems.
- Produce a numerical model with the purpose of predicting the performance of the four cover systems constructed at Antamina. The model being calibrated based on the data for the first rainy season.

It should be noted that assessing the performance of the cover systems as oxygen barriers was not included in the scope of this thesis and will be evaluated in the following stage(s) of the Assessment of Cover Systems for Waste Rock in the Antamina research project.

1.3 Thesis Outline

This thesis consists of seven chapters. Chapter 2 summarizes the literature review, including the review of a case study similar to the research conducted at Antamina: the evaluation of the performance of the cover system at the Equity Silver mine, in British Columbia, Canada. Chapter 3 includes a description of the field and construction works related to the Assessment of Cover Systems for Waste Rock in the Antamina research project, such as site characteristics, lysimeters and cover systems construction, materials and vegetation selection, and instruments installation. Field data and laboratory tests results are presented in Chapter 4 where comments on the field data collection and laboratory testing are also provided. Chapter 5 summarizes the steps followed for the generation of the predictive numerical models in SoilCover, including the calibration procedure and the numerical model results. A discussion and interpretation of results is provided in Chapter 6, where field, laboratory and predictive numerical model results are analyzed and compared. Finally, Chapter 7 presents the conclusions of this thesis and recommendations for further stages of the Assessment of Cover Systems for Waste Rock in the Antamina research project.

CHAPTER 2. LITERATURE REVIEW

This chapter summarizes the literature review carried out as part of this thesis. The literature review comprised the relevant sections of the Prevention and Control volume of the MEND Manual (MEND, 2001), along with concepts of flow of water through unsaturated soils. In addition, a brief description of the numerical model used for the predictive modelling of the research associated with this thesis is also included herein. Finally, a similar case study to the research conducted at Antamina is presented: the evaluation of the performance of the cover system at the Equity Silver mine, in British Columbia, Canada.

2.1 Soil Covers

The use of dry covers as a closure alternative is a wide spread technique in mine waste facilities around the world. The term dry cover encompass a wide range of configurations, from single to multilayer systems made of earthen materials (like the ones tested as part of this thesis), non-reactive waste, oxygen consuming materials and/or geosynthetics. They should also function as a medium for vegetation growth and should be resistant to water and wind erosion (MEND, 2001).

Dry covers are unsaturated systems exposed to the atmosphere, which means that not all of the pores in the dry cover are filled with water. This system, also known as the soil-atmosphere continuum, is comprised of the atmosphere, the vegetation on the cover surface, the soil cover itself, and the underlying waste material.

The main purpose of a dry cover is to minimize the influx of atmospheric oxygen and/or water percolation to the waste material below. Dry covers can be classified in five categories as shown in Table 2-1 (after MEND, 2001). The tri-linear plot presented in the GARD Guide (The International Network for Acid Prevention (INAP), 2009), which relates precipitation, evaporation, temperature and climate with cover types, provides an updated view of the different kinds of cover systems available for dealing with closure and reclamation of mine waste (Figure 2-1).

Table 2-1 Classification of Dry Covers (after MEND, 2001)

Dry Cover Classification	**Primary role of Cover in Inhibition of ARD**
Oxygen transport barriers	Act to retain moisture and hence provides a low diffusion barrier to atmospheric oxygen
Oxygen consumption barriers	Act as an oxygen consuming sink to provide low oxygen concentrations at the interface
Reaction inhibiting barriers	Act to inhibits reactions, neutralizes pH
Store and release percolation barriers	Act to minimize moisture flux by maximizing near surface storage of moisture with subsequent release by evapotranspiration
Low permeability barriers	Act to minimize moisture flux by generating ponding in the surface of the barrier due to its low hydraulic conductivity. Water can be then released in the form of runoff or evapotranspiration.

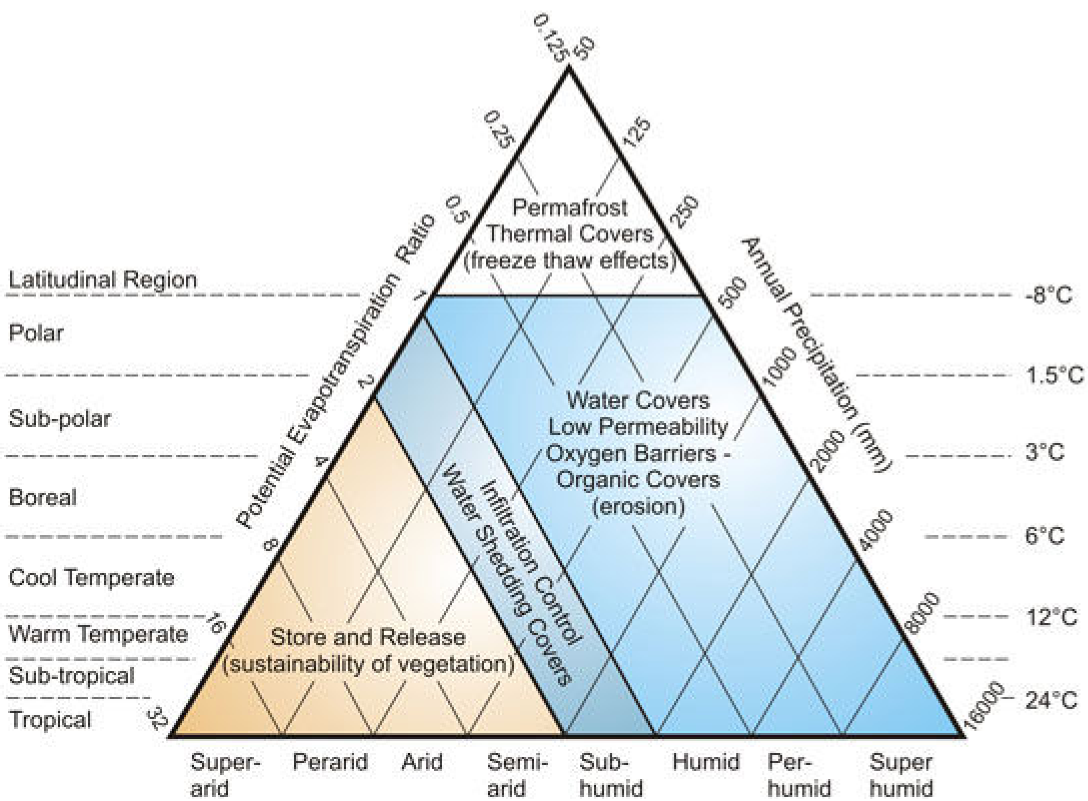

Figure 2-1 Covers and Climate Types (INAP, 2010)

Minimizing atmospheric oxygen influx can be achieved by maintaining a high degree of saturation in one or more layers of a dry cover. In a saturated material (i.e. voids in the soil are filled with water), oxygen will travel through the soil layer by diffusion through the water in the pores (Nicholson et al, 1989). As Figure 2-2 indicates, degrees of saturation between 0% and 50% have no significant effect in the oxygen diffusion coefficient, but higher degrees of saturation, above approximately 85%-90%, will make an effective oxygen-diffusion barrier (MEND, 2001). Materials with a high rate of oxygen consumption could also be used as covers aiming to reduce oxygen diffusion, but this option was not considered adequate for the waste dumps at Antamina due to availability of these materials at the mine site, and therefore was not incorporated in the scope of this research.

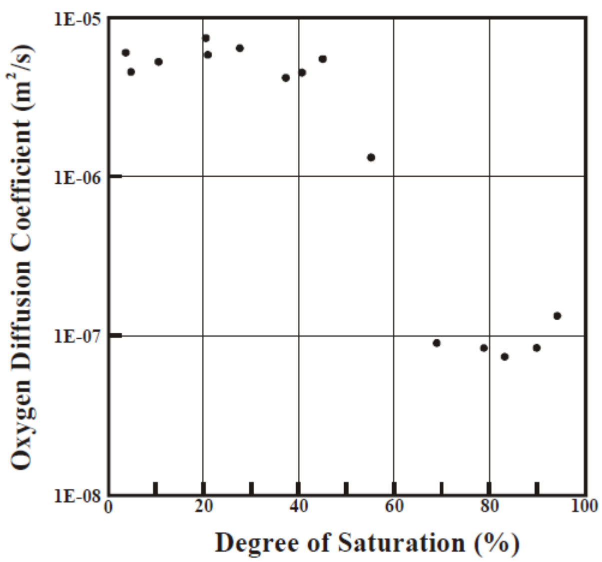

Figure 2-2 Effect of Degree of Saturation in the Oxygen Diffusion Coefficient (MEND, 2001)

Reducing oxygen entry is not always feasible, as keeping highly saturated covers all year round could be proven difficult in certain climates regimes (e.g. arid and semi-arid climates). Therefore, limiting net water percolation becomes a valid alternative when dealing with closure of reactive waste facilities, as it is partly responsible of ARD generation and also serves as a medium for contaminant transport. Net water percolation represents the difference between total precipitation and runoff, evaporation, evapotranspiration, and change in soil water content. As a result, net percolation is indirectly influenced by rainfall intensity, surface topography, vegetation, soil properties, and soil surface moisture conditions, as all these affect runoff and percolation rate; along with atmospheric conditions and soil properties that act on evaporation and evapotranspiration (MEND, 2001).

Based on the classification of dry cover presented in Table 2-1, two kinds of water percolation barriers could be combined to create a cover system: store and release covers and low permeability barriers. Store and release covers are covers that, as their name suggests, first accumulate water during rain events and later release most of it back to the environment through evapotranspiration. This kind of cover works best in arid and semi-arid climates. Low permeability barriers, on the other hand, rely on the low hydraulic conductivity characteristics of one or more soil layers in the cover to generate ponding and runoff, and therefore reduce net percolation. It should be noted that quality and quantity of runoff and seepage waters from the waste impoundment will have to be controlled to minimize their effect in local surface and groundwater systems. Figure 2-3 summarizes all the components interacting with this kind of covers, and exemplifies how runoff and actual evapotranspiration are the only two significant mechanisms for reducing percolation through the system. Storage will also affect percolation values, although to a lesser degree.

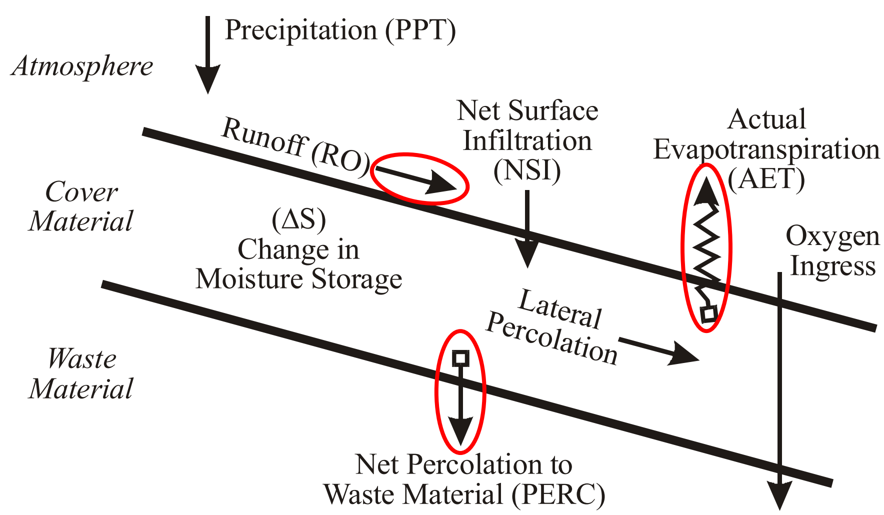

Figure 2-3 Schematic of the Components Affecting the Performance of a Cover (after MEND, 2001)

Vegetation plays an important role in the performance of a soil cover as it reduces the effects of water and wind erosion on the surface of the cover, improving its long-term performance. This will also help restore wildlife habitat in the area, and could be a key component of the cover performance by triggering evapotranspiration (MEND, 2001).

Finally, the MEND Manual provides a list of aspects that should be considered when designing a cover system (MEND, 2001). These aspects are intended to provide general guidelines, keeping in mind that the design of a cover system is highly site specific:

- Performance will be different between a horizontal and a sloped cover. These differences are associated with climate conditions, slope geometry, and the properties of the materials used to build the covers.
- All sources of water influx to the waste facility have to be taken into account. These include rainfall, basal flow from groundwater discharges, and slope flow from valley walls.
- Geochemical and hydraulic characteristics of the waste material are paramount when determining the most adequate cover system for a specific site.

2.2 Unsaturated Characteristics of Soils

Negative pore-water pressure, or suction, has a significant influence on the unsaturated characteristics of soils that are controlled by the soil-water characteristic curve (SWCC) and hydraulic conductivity function. The SWCC is a relationship used to understand the capability of a soil to store and release water by representing how the degree of saturation, or moisture content, is affected by suction (Figure 2-4a). As Figure 2-4a shows, the SWCC varies by soil type and depends on grain size distribution (MEND, 2001). The SWCC is developed through a laboratory pressure plate, whereby the volumetric water content of the soil is measured at different applied suctions. There are two points of special interest on the SWCC: the air entry value (AEV) and the residual water content, or residual degree of saturation. The AEV is defined as the negative pore-water pressure required before air can enter the soil, or alternatively, as the suction required for the largest pores to start draining water in a saturated soil. The residual water content, on the other hand, represents the moisture content at which an increase in suction does not significantly reduces the degree of saturation further (D. G. Fredlund & Rahardjo, 1993). Hydraulic conductivity, also referred as the coefficient of permeability, is a property of any porous medium (in this case a soil) used to describe the space available for water to flow through it, and is dependent on the fluid and soil properties.

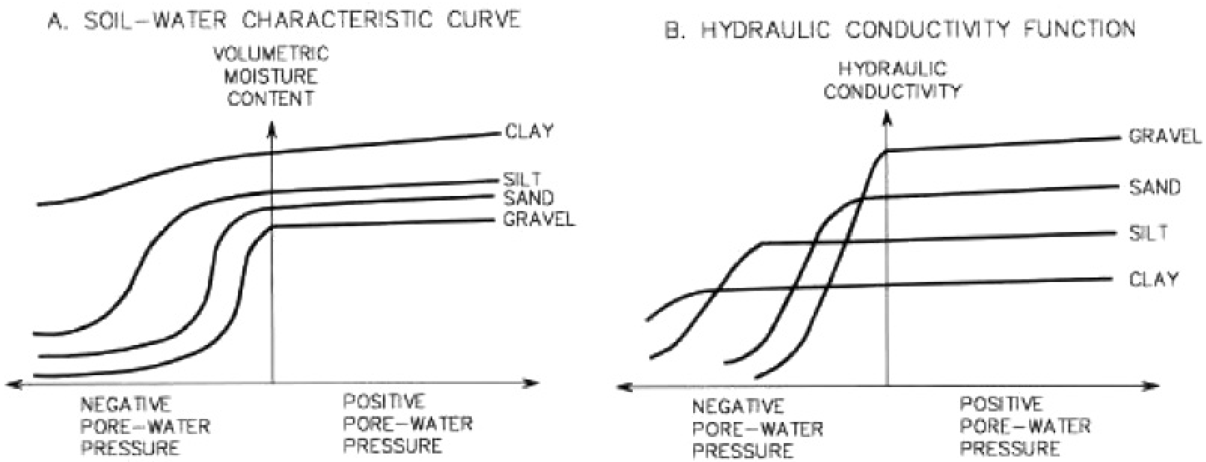

Figure 2-4 Soil-Water Characteristic Curves and Hydraulic Conductivity Functions for Different Soil Types (MEND, 2001)

The effect of suction on the unsaturated characteristics of soils can be used to design a particular kind of cover such as a cover with a capillary barrier effect (CCBE) (Dagenais, Aubertin, Bussière, & Martin, 2005). A capillary barrier is formed when coarse material underlies a layer of finer material. Water in the finer layer will be retained due to capillary forces, keeping the layer saturated, while water in the coarser layer will drain, effectively reducing the hydraulic conductivity of this layer. As seen in Figure 2-4b, hydraulic conductivity of coarser materials can become lower than hydraulic conductivity of finer materials at negative pore-water pressures. Saturation in the fine-grained layer will reduce oxygen percolation through the cover, and the low hydraulic conductivities of both the fine and coarse layers will minimize water percolation.

2.3 SoilCover Model

SoilCover is a one-dimensional soil-atmosphere computer model that predicts water percolation through soils by linking three components used to represent the soil-atmosphere continuum: the atmosphere above the soil, the near surface unsaturated zone and the deeper saturated zone (Unsaturated Soils Group, 2000).

Design of cover systems for mine waste facilities requires the prediction of the flow of water between the soil surface and the atmosphere, which is dependent on three factors as follows:

- The supply and demand of water set on the soil by atmospheric conditions, such as total precipitation, net radiation, wind speed, and air temperature;
- The soil capability of conducting water, which depends on the hydraulic conductivity and storage characteristics of the soil; and,
- The influence of vegetation, which is related to vegetation density and type, affecting evaporation through the consumption of water by root uptake, as well as runoff rates and surface retention.

The SoilCover model is a transient flow model that couples and integrates these components to compute net infiltration (or percolation) to the underlying waste rock. The theory behind SoilCover is based on both Darcy's and Fick's laws, used to describe the movement of liquid and vapour water; and Fourier's law, which describes heat flow in the soil. Evaporation from the soil to the atmosphere is addressed by a modified Penman formulation (Wilson, 1990). Coupling between the atmosphere and the soil in this model is achieved by estimating soil evaporation, using modified Penman formulation (Wilson, 1990):

$$E = \frac{\Gamma Q + \nu E_a}{\Gamma + \mathrm{A}\nu}$$

Where,

E = Vertical evaporative flux (mm/day)

Γ = Slope of the saturation vapour pressure vesus temperature curve at the mean temperature of the air,

Q = Net radiant energy available at the surface (mm/day),

ν = Psychrometric constant,

$E_a = f(u)P_a(B-A)$,

f(u) = Function dependent on wind speed, surface roughness, and eddy diffusion = $0.35(1+0.15U_a)$,

U_a = Wind speed (km/hr),

P_a = Vapour pressure in the air above the evaporating surface,

B = Inverse of the relative of the air = $1/h_A$, and

A = Inverse of the relative humidity at the soil surface = $1/h_r$

2.4 Case Study: Glacial Till Cover at Equity Silver Mine

The following case study was selected for its resemblance with the research program developed at Antamina. Climate conditions and materials availability for the construction of the cover systems at the Equity Silver mine are similar to Antamina's. The summary of the Equity Silver mine case study presented here was developed based on several papers listed in the References section of this thesis (O'Kane, Wilson, Barbour, & Swanson, 1995; O'Kane, Wilson, & Barbour, 1998; Swanson, Barbour, Wilson, & O'Kane, 2003; Weeks & Wilson, 2005; Wilson, Williams, & Rykaart, 2003).

The Equity Silver mine operated between 1980 and 1994, mining copper, silver and gold as an open pit operation. The mine is located in the central interior of British Columbia, approximately 575 km from Vancouver, at 1,300 meters above sea level (m.a.s.l). The site has a humid alpine climate with an annual total precipitation of 710 mm, approximately 60% of the total precipitation occurring as snow melting during the spring, and an annual potential evaporation of approximately 500 mm. Average monthly temperatures usually descend below 10°C from November to March. By the end of the life of the mine three waste dumps, comprising approximately 100 hectares (ha), had to be reclaimed: the Main dump, the Southern Tail dump, and the Bessemer dump.

Glacial till covers were installed on top of the Main, Southern Tail and Bessemer dumps between 1991 and 1994, to limit oxygen entry and water percolation to the waste rock. The cover systems consist of a 500 mm compacted glacial till layer underlying a

300 mm non-compacted layer of the same material. The lower till layer in the cover system was compacted to 95% of standard Proctor maximum dry density. A capillary barrier was generated between the waste rock and the compacted layer of the cover system, as a result of the coarse nature of the waste material. Grain size analysis of the waste rock at the Equity Silver mine shows that D_{80} (the particle size of which 80% of the soil by weight is finer) ranges between 127 mm and 128 mm, while D_{10} ranges from 3.5 mm to 0.45 mm (O'Kane et al., 1998). Table 2-2 and Table 2-3 summarize the properties of the glacial till and the covers as placed, respectively. These materials are very similar to the ones used at Antamina to construct the cover study field experiment.

Table 2-2 Equity Silver Till Properties (Weeks & Wilson, 2005)

Plastic limit (%)	17
Liquid limit (%)	40
Grain size	
Cobble and gravel (%)	23
Sand (%)	28
Silt (%)	40
Clay (%)	9

Table 2-3 Cover Layers Properties as Placed (Weeks & Wilson, 2005)

Parameter	Non-compacted upper layer	Compacted lower layer
Hydraulic conductivity (m/s)	$1x10^{-7}$	$1x10^{-10}$
Air entry value (kPa)	10	200
Porosity (%)	38	33
Saturated water content (%)	22	18

The Equity Silver Mines Ltd. laboratory and field instrumentation program was initiated in 1992 to assess the performance of the installed till covers and provide data for the predictive numerical model simulations. The objective of the field instrumentation program was to measure *in situ* matric suction, moisture content and temperature in the till covers. Lysimeters were installed at the base of the cover systems to measure water percolation. Matric suction and temperature were measured with Agwatronics thermal conductivity (TC) sensors, and moisture content was measured with CPN 503/503DR hydroprobes. Jet-fill tensiometers were used to confirm measurements from the TC sensors. A weather station was installed on site to measure climate conditions including daily precipitation, air temperature, relative humidity, wind speed and net radiation. Additionally, the laboratory characterisation program included tests such as grain size distribution, Atterberg limits, specific gravity, standard Proctor, consolidation – K_{sat} (void ratio vs. K_{sat} relationship), and the results used to develop the SWCC. Predictive numerical models were generated using the SoilCover model, employing the input from the laboratory and field instrumentation program (O'Kane et al., 1995).

Evaluation of the collected data between 1992 and 1995 showed that the degree of saturation of the compacted layer remained at 85% or higher through the annual cycle of wetting and drying (O'Kane et al., 1995). Near saturation of the lower compacted layer was seen as a sign that the cover system was working as an oxygen limiting barrier, which was one of its purposes. This was possible due to the low hydraulic conductivity of the compacted till layer, the capillary break and the even lower hydraulic conductivity of waste rock at its residual water content. On the other hand, moisture content of the non-compacted till layer was significantly influenced by atmospheric demands (degree of saturation ranged between 62% and 85%), and prevented a decrease in saturation of the lower compacted layer. The non-compacted layer provided a successful medium for vegetation growth, along with protection from erosion, freeze-thaw cycles and desiccation to the lower compacted layer. Finally, flow data from the lysimeters shows that percolation was reduced to approximately 5% of the total precipitation, complying with the objective of limiting water influx to the waste rock. All of these elements indicated that the cover system performed as designed (O'Kane et al., 1998).

Numerical models were calibrated and verified with input from the field investigation program with the purpose of predicting maximum water percolation and maximum oxygen entry through the cover. Maximum water percolation was estimated with climate data from an historical wet year, and maximum oxygen entry was estimated from an historical dry year (Swanson et al., 2003).

Two simulations were conducted over a 153 day period. For the first one, data from the instruments installed in the Main dump was used to compare the predicted and field measurements (i.e. surface runoff and water percolation through the cover). The second simulation considered the records from the Southern Tail dump instrumentation site for the comparison. Water balances of the systems were completed by including precipitation, and potential and actual evaporation. Predicted matric suction and temperature were compared with daily data from the field, while predicted moisture content profiles were contrasted with measurements from the hydroprobes taken on five occasions during the assessed period. The SWCC developed in the laboratory had to be normalized to the field data to better represent actual ambient conditions. Saturated hydraulic conductivities for the upper and lower layers were calibrated in virtue of their matric suction responses (Swanson et al., 2003).

Results from the predictive models are encouraging when compared to the early field response in the experiment, reported in (O'Kane et al., 1998); and indicate an adequate level of accuracy for predicting the long-term performance of the Equity Silver cover system. The Degree of saturation in the upper non-compacted layer of the cover was predicted to reduce down to approximately 50%, while the lower compacted layer was predicted to dry only to a degree of saturation of 80% (Swanson et al., 2003). In addition, percolation rates were predicted to reduce from 60% to 80% in the uncovered waste rock dumps, to values ranging from 2% to 4% in the covered dumps. Most of the percolation was expected to occur in the spring as a result of snowmelt. It should be noted that although early assessments of the performance of the cover system validated the results (e.g. early reported percolations 4.6% (O'Kane et al., 1998)), a subsequent evaluation carried out after an operational period of 10 years, showed different results regarding net percolation.

Long-term performance of the cover system at the Equity Silver mine was assessed again 10 years later, and results were published in the Canadian Geotechnical Journal (Weeks & Wilson, 2005). This evaluation involved the review of the moisture content profiles in the cover system at various locations, to determine if the cover remained nearly saturated year round over the assessed period. Data collected from the in-situ instrumentation showed that the cover performed as expected, maintaining a degree of saturation above 90% at all times in the lower compacted layer, and a degree of saturation between 50% and 85% in the upper non-compacted layer. The higher variability of moisture content in the upper non-compacted layer also showed that it continued to perform as a store and release cover, protecting the lower layer from desiccation. The upper layer also proved effective in resisting erosion, and no major signs of erosion were visible over the 10 year period. It was also noted that although seasonal changes in moisture content occurred in the cover system, the range in saturation in the compacted layer fluctuated by only 5%.

CHAPTER 3. FIELD EXPERIMENT

The field work undertaken to support this thesis included the construction of five lysimeters filled with waste rock and covered with four different soil cover systems (see the drawings in Appendix A). Each lysimeter was instrumented with tipping buckets, to measure runoff and percolation volumes; thermal conductivity sensors, to measure matric suction in the cover; oxygen sampling tubes, to measure oxygen diffusion through the cover, and a weather station, to record precipitation and net radiation data. The lysimeters and related structures were constructed at Punto B (approximately 4,380 m.a.s.l.), the UBC and Antamina designated research location at the Antamina Mine.

3.1 Site Characteristics

The Antamina mine, one of the largest zinc and copper producers in the world, is located at approximately 270 km north-east of Lima (9°32' south and 77°03' west), at an average altitude of 4,300 m.a.s.l., in the north-central Peruvian Andes.

The climate at Antamina is characterized by distinct wet and dry seasons, with high rainfall in the summer periods, between October and April; followed by low to negligible precipitation during the winter months, from May to September. Average annual precipitation is approximately 1,200 mm, with maximum daily precipitation of 36 mm. Temperature ranges between -4°C and 23°C, with a mean annual temperature of 6.0°C.

Surficial geology in the Antamina valley is comprised of glacial till deposited between 10 - 20 thousand years ago, and more recent local veneers of colluvium, alluvium and/or soils produced from other weathering processes (Klohn-Crippen, 1997). Four types of surficial soils were identified at the Antamina mine in the preliminary geotechnical assessment for the waste dumps and were analysed as potential cover material:

- Topsoil: Dark brown to black organic, highly plastic highly compressible clayey silt containing a trace of sand and some fibrous roots, which according to the Unified soil classification system (USCS) classifies as MH or OH. Fines content of the topsoil layer ranges from 92% to 100%. Topsoil layers thickness was estimated from 0.1 m and greater than 2.85 m (Piteau Associates Engineering Ltd., 1997).

- Colluvial soils: Brown, medium to high plastic, sandy, clayey silt, with varying amounts of gravel and other coarse angular material. Antamina colluvium is highly variable and its USCS classification depends on the organic and fines content, ranging from MH/OH to CH and CL. Colluvium fines content ranges between 10% and 90% (Piteau Associates Engineering Ltd., 1997).
- Fluvial soils and organics: Loose to compact silty sand to sandy silt of medium compressibility, generally located in local drainages and or swampy areas (Piteau Associates Engineering Ltd., 1997).
- Glacial tills: Grey to brown, compact to dense, clayey, silty sand and gravel with cobbles and occasional boulders up to about 400 mm in diameter. Fines content is variable, ranging from 4% to more than 50% (Piteau Associates Engineering Ltd., 1997). Thickness of the glacial till layer is variable across the mine site, ranging from a "thin blanket" in the areas of the tailings impoundment to greater than 30 m in the Quebrada Yanacancha (Klohn-Crippen, 1997). USCS classification of the material ranges from GC to CL. Glacial till is expected to be one of the most abundant soils at the mine site.

Two of these soil types have been incorporated into the cover systems profiles evaluated with the experiment described below, the topsoil and glacial till.

3.2 Lysimeters

Construction of the five lysimeters was carried out by an Antamina team between October and December 2008, following a design developed by Antamina and UBC. The lysimeters are inverted truncated pyramids of 15 m x 15 m x 2.5 m dimensions, with 1.5:1 (H:V) sloped walls (Figure 3-1 and Figure 3-2). The base of the lysimeters has a 5% slope to the center to direct water to a sump. Each lysimeter has two sets of pipes installed to collect precipitation runoff, close to the crown of the lysimeters, and percolation, in the sump at the bottom of each lysimeters.

Drainage from runoff and percolation piping is directed to separate 1 m^3 tanks, for a total of 10 tanks in this study (Figure 3-3). A tipping bucket is located at the outflow of each tank to record flow rate and volume. Tanks were included in the design to provide storage capacity and to regulate flow rate in case of a storm event, which could produce higher flows than what the tipping buckets sensors are able to register. Percolation collection pipes coming from each lysimeter have "U" shaped water traps just before the 1 m^3 tanks. These traps are always filled with water and prevent air from going into the lysimeters. Lysimeters #1, #2, #4 and #5 were covered with a 5.42 mm bituminous geomembrane (Coletanche NTP 4), while Lysimeter #3 was covered with two layers of a 2 mm HDPE geomembrane, due to shortage of the bituminous one. A third geomembrane sheet was installed in the lysimeters prior the placement of waste rock and covers. This third geomembrane was not welded and its only purpose is to protect the liner underneath it from any damage the waste rock may cause.

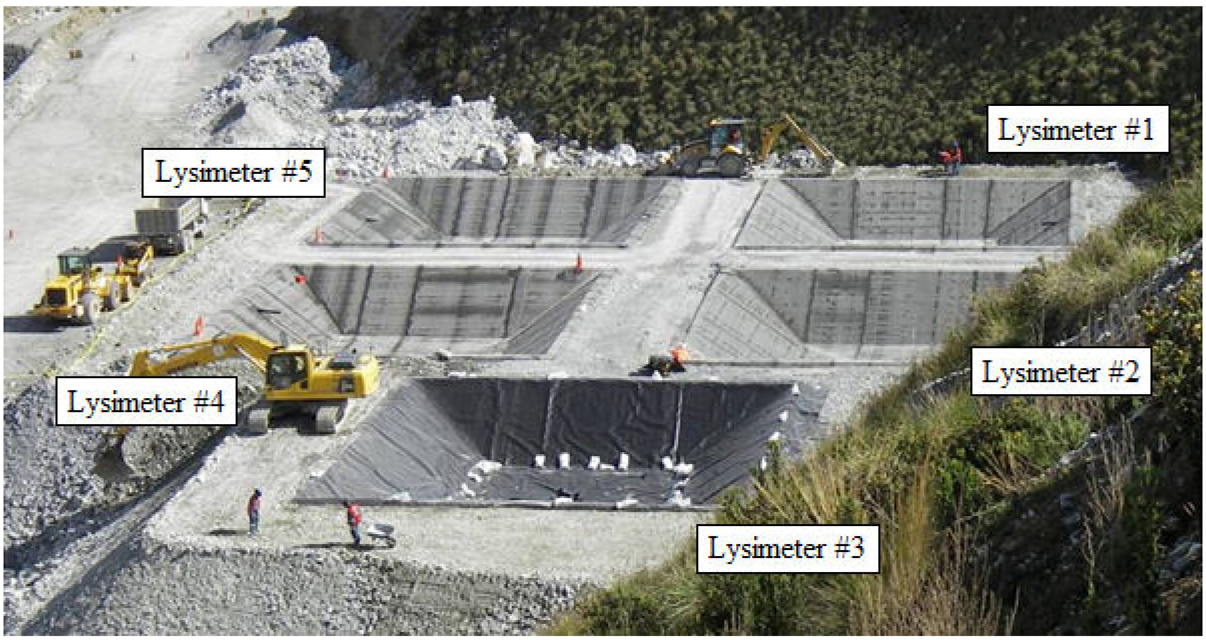

Figure 3-1 Lysimeters Layout

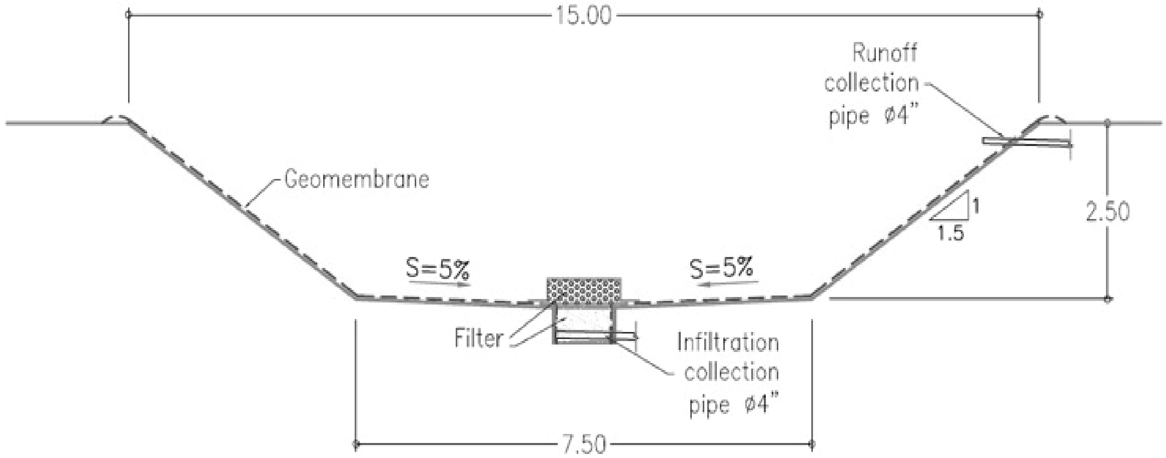

Figure 3-2 Lysimeter Schematic (dimensions in metres)

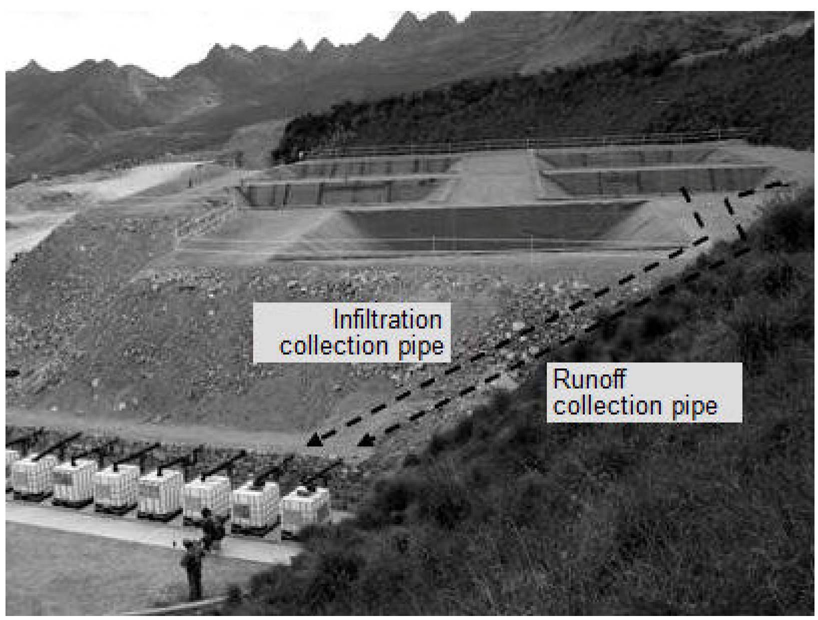

Figure 3-3 Schematic of Runoff and Percolation Collection Pipes

Each lysimeter has a 1 m x 1 m sump at the center of its base, where the percolation pipe is located. The sump is 0.5 m deep and is filled with crushed rock without fines. This sump was installed to act as a filter. A second filter was later placed on top of the sump, to provide further protection and avoid the clogging of the sump filter. The second filter comprised selected alluvium material with less than 5% fines, surrounded by a geotextile

(GEOTEXTIL PAVCO GTX 050M). Details of the first and second filter are presented in the drawings in Appendix A.

3.3 Materials

A material characterization laboratory program was undertaken to assess the physical properties of the native soils used in this study. Details of the laboratory tests conducted are described in Chapter 4 of this thesis. The material characterization program began with an assessment of the native materials to evaluate their potential suitability to function as covers. This assessment consisted of determining the permeability and grain size distribution of the native soils (i.e. suitability to function as the low-permeability barrier and store and release layers of the cover system). Of the four aforementioned native soils found at Antamina only two were used in this study, topsoil and glacial till. The colluviums, fluvial and organic soils were not tested given their scarce availability and poor suitability (i.e. high permeability) to function as covers. Topsoil was selected as the growth medium and one topsoil sample was tested. Two samples of till from different locations were tested. Results from these tests showed till heterogeneity in regards to composition and grain size distributions, coinciding with the till characterization described by Piteau (Piteau Associates Engineering Ltd., 1997). Glacial till was thus divided into two sub-types; a clayey, coarser glacial till; and a silty, finer glacial till. Results of these tests are presented in section 4.2 of this thesis.

Intrusive Class A (Bay, 2009) was the preferred type of waste rock for this experiment for two reasons. First it is classified as one of the most reactive or 'potentially acid-generating' materials at Antamina. Second, Class A waste rock will comprise the majority of the reactive waste dump composition, according to the Antamina mine plan. Native, surficial materials were preferred for the design and construction of the cover systems due to their suitability as barrier or store and release covers, and their relatively low cost of borrowing.

Once the suitability of the glacial till and topsoil to function as covers was confirmed based on their permeability and composition characteristics, these materials were borrowed and stockpiled at Punto B prior the construction of the cover systems. Glacial till was obtained from two different sites at Antamina. Clayey till was borrowed from the slopes of a site denominated “Punto F” (N: 8944906, E: 275893), while silty still was borrowed from slopes close to the Yanacancha weather station (N: 8942158, E: 277158). Topsoil was also borrowed from the same site as the clayey till, at “Punto F” (Figure 3-4).

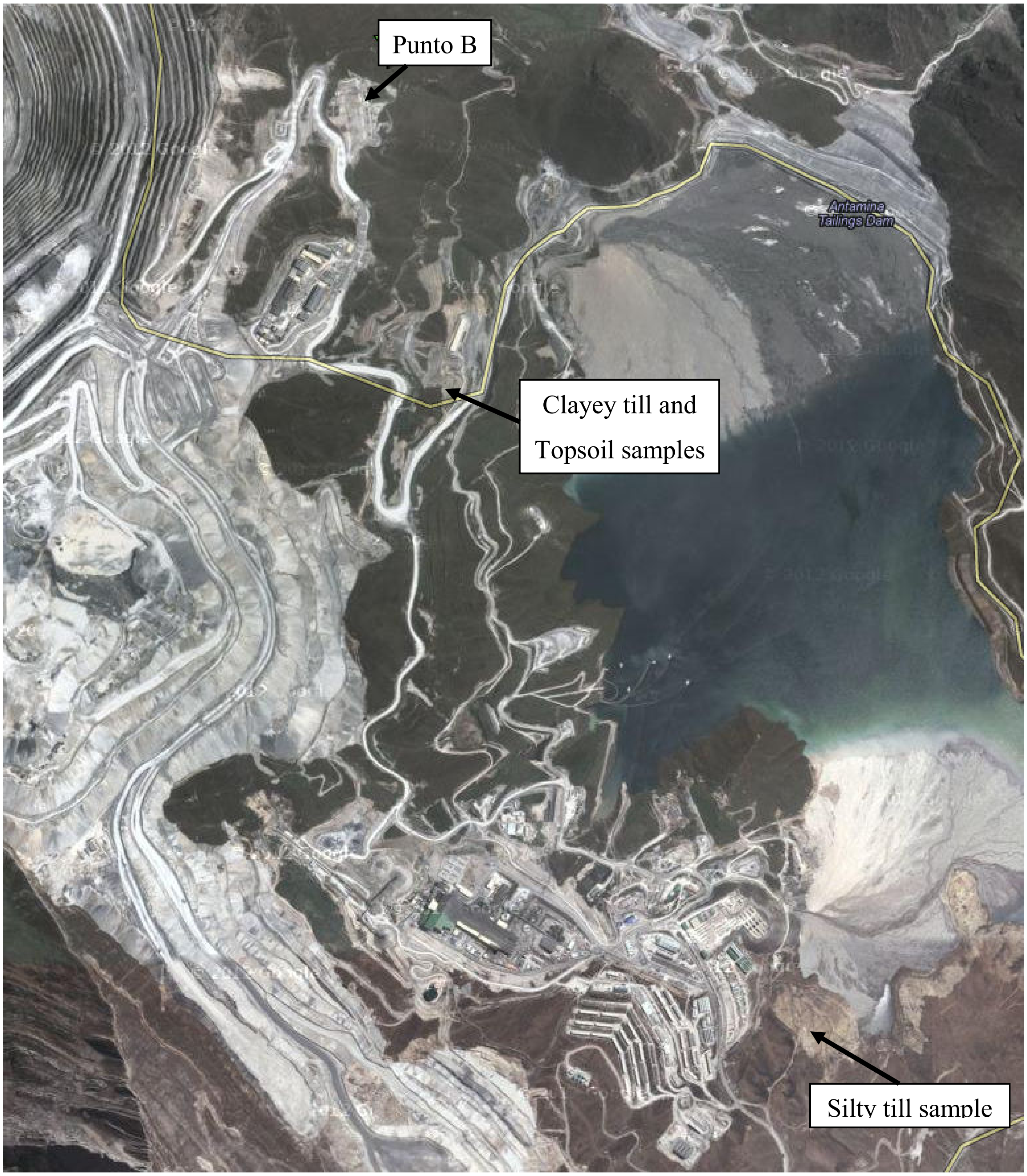

Figure 3-4 Glacial till and Topsoil Samples Location Map (Source: Imagery ©2012 DigitalGlobe, GeoEye, Map data ©2012 Google)

3.4 Cover Systems

Construction of the cover systems commenced in October 2009, when the lysimeters were filled with Class A Intrusive waste rock. Lysimeters #1, #2, #4 and #5 were partially filled with Intrusive Class A waste rock whereas the control lysimeter was completely filled with the same material. Waste rock was exposed to the environment for 11 months in the lysimeters (i.e. one rainy and almost one full dry season) before the cover systems were placed. The cover systems were exposed to the environment for 6 months (i.e. almost one full rainy season) before percolation and runoff measurements were recorded. Waste rock was placed and spread in the lysimeters using a crawler excavator (Komatsu PC220LC). Final slopes were achieved employing shovels and wheelbarrows. Slopes and elevations were controlled with an automatic level (see photos in Appendix B).

The focus of the cover study was modified in 2010 based on recommendations made by the Independent Geotechnical and Tailings Review Board (IGTRB) at Antamina. Thus some minor changes in slopes and elevations were performed on the already placed waste rock, prior the construction of the covers. Four 4" HDPE corrugated pipes were included in each lysimeter as part of the first design, allowing oxygen to reach waste rock once the covers were placed. Otherwise, waste rock would have been encapsulated by the geomembrane and the covers, thus not truly replicating actual conditions on the field. With the revised study focus, geochemistry was no longer a priority of the study and the 4" pipes were no longer required. As a result, the pipes were cut 200 mm below the already placed waste rock and covered with a geotextile cap. Waste rock was later re-placed up to their new design levels, effectively burying the pipes. Drawings in Appendix A show the final elevations and slopes of the waste rock in the lysimeters.

Four different cover systems were installed between August and September 2010 in lysimeters #1, #2, #4 and #5, after exposing the waste rock already placed in the lysimeters to one full rainy season. Covers design was based on previous experience in similar projects, along with the recommendations made by the IGTRB. The cover systems were designed to consist of a barrier component, which were meant to reduce water percolation and air diffusion through the cover; and a growth medium and store and release cover, which will help reducing percolation by triggering evapotranspiration. Barrier covers with a thickness of

600 mm and media growth covers with a thickness of 300 mm were considered suitable for the platforms of the waste dumps at Antamina and the scope of this study. Barrier covers of 600 mm thickness are practical to construct with large mine equipment and should be composed of two layers of 300 mm each, as a requisite to decrease the chance that segregation and variability in grain size distribution in a single layer affects the performance of the whole cover. 600 mm barrier covers will also prevent excessively thin zones due to waste rock unevenness. Thickness of the growth medium covers was defined following the recommendations of the Assessment of Revegetation Test Plots at the Antamina Mine, carried out by AMEC (AMEC Earth & Environmental, 2004).

The purpose of having four different cover systems in this experiment is to compare their performances regarding the materials used for their construction, and the compaction or non-compaction of their layers. Assessment of the effect of the cover layers thickness can be carried out by numerical modelling once the predictive models are calibrated with field results, thus layer thickness was kept as a constant in the field experiment.

Two feasibility studies carried out for Antamina in 1997, the Preliminary Geotechnical Assessment for the Waste Dumps by Piteau Associates Engineering, and the Tailings Feasibility Design by Klohn-Crippen, state that glacial till is one of the most abundant soils at the mine site. The tills at Antamina are typically clayey or silty gravel and sand, with cobbles and boulders. Fines content is variable, ranging from 4% to more than 50% (Klohn-Crippen, 1997; Piteau Associates Engineering Ltd., 1997). Considering that the purpose of covers is to limit water percolation and oxygen diffusion, low permeability soils will perform better as barrier covers, establishing glacial till as the perfect candidate. Table 3-1 shows the layout of each cover system and its assigned lysimeter.

Table 3-1 Cover Systems Layout

Lysimeter	Cover Material (1)	Thickness	Cover Material (2)	Thickness
1	Compacted clayey till	600 mm	Topsoil with vegetation	300 mm
2	Non-compacted clayey till	600 mm	Topsoil with vegetation	300 mm
3	None (Control)	-	-	-
4	None	-	Topsoil with vegetation	300 mm
5	Compacted silty till	600 mm	Topsoil with vegetation	300 mm

Construction of the cover systems was carried out by placing and spreading the cover materials in the lysimeters using a crawler excavator (Komatsu PC220LC), to the desired elevations exemplified by Figure 3-5. Final slopes were achieved by employing shovels and wheelbarrows, whereas slopes and elevations were controlled with an automatic level. Clayey till and silty till layers in Lysimeter 1 and 5 were compacted with an 800 kg vibrating roller (Wacker Neuson RD7), as shown in Figure 3-6. A vibrating plate compacted the corners and sides of the constructed layers. Slopes and elevations were controlled with an automatic level (see photos in Appendix B).

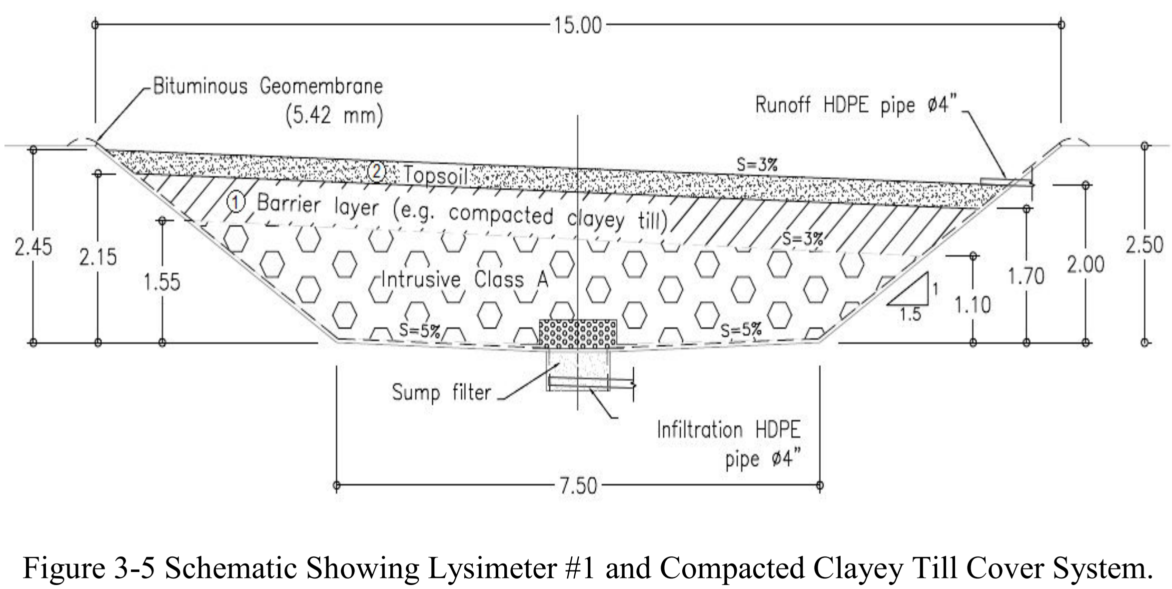

Figure 3-5 Schematic Showing Lysimeter #1 and Compacted Clayey Till Cover System.

The light weight and reduced compaction capacity of the 800 kg vibrating roller required modifications to the construction procedure of the cover systems. Compaction of glacial till layers was specified as at least 95% of the maximum density of the standard Proctor test, within ±2% moisture content from the optimum moisture content. These specifications were defined by the compaction platform tests conducted before the construction of the cover systems in the lysimeters. However, 300 mm thick layers could not be compacted to the required specification by the available equipment. Therefore, the barrier cover in Lysimeter #1 was composed of four 150 mm clayey till layers instead of two 300 mm layers, and the barrier cover in Lysimeter #5 was composed of three 200 mm silty till layers, instead of the ideal two 300 mm layers. Non-compacted soils presented no issues during installation. The clayey till cover in Lysimeter #2 was placed in two 300 mm layers, whereas the topsoil covers were placed as a single 300 mm layer in every lysimeter, replicating what will likely occur in the actual waste dump. When particles greater than 4 inches were found in any of the glacial till layers, they were removed manually.

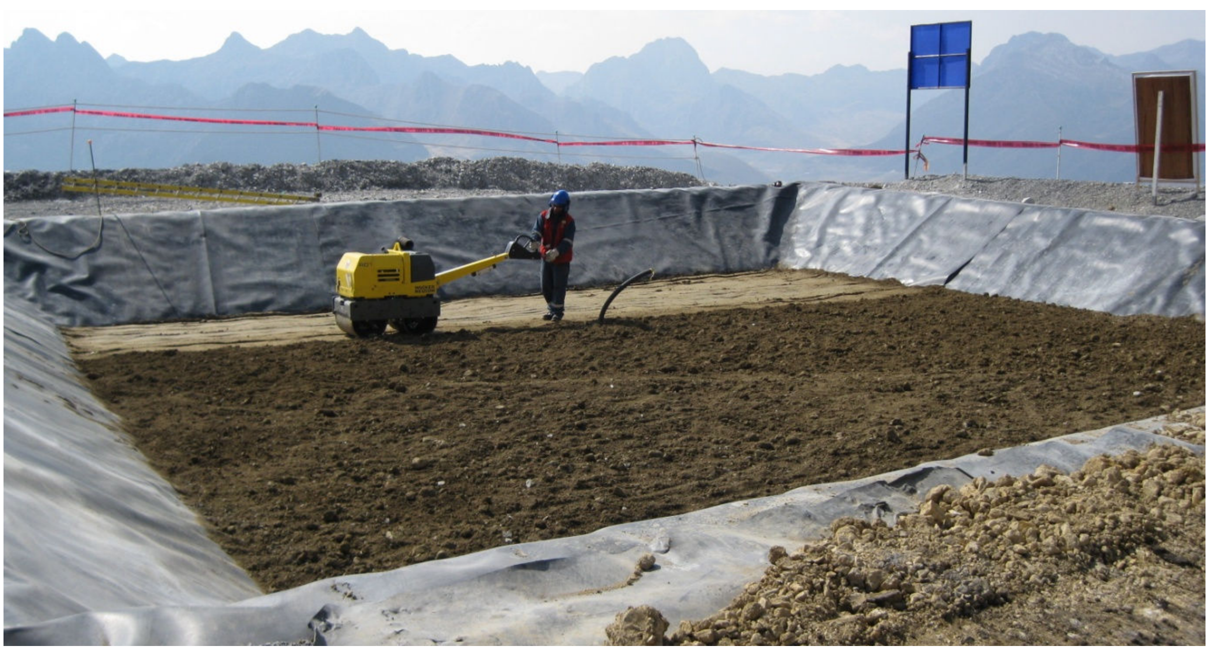

Figure 3-6 Compaction of the First Silty Till Layer in Lysimeter #5

Nuclear density tests were carried out as part of the construction quality control (QC) program by Golder Associates, following ASTM-2922. These tests were conducted with a Troxler 3440 Surface Moisture – Density Gauge. A number of compaction tests were conducted on four test platforms prior the compaction of the actual cover layers, in the same materials which later were used to build the covers. These tests were used to determine the effective compaction depth achievable by the available equipment, and the number of roller passes required for reaching the specified compaction requirement.

Unusually early rains in late August and early September (2010) affected the construction schedule and material handling. Strong intermittent rains were very common at the time of the construction. Stockpiled materials had to be covered by plastic sheets to avoid an increase in moisture contents. Clayey and silty till were 7% higher and 1.3% drier, respectively, than the optimum moisture content according to the initial standard Proctor tests performed. Rain intermittence also hindered the management of the clayey till, since it needed to be spread and dried by the sun to achieve the specified moisture content. The compacted layers in the lysimeters had to be subsequently protected by plastic sheets as well, to avoid their soaking and the effect this could have on the subsequent cover layers.

Clayey till in a large extent was excessively dried out in attempt to get close to the optimum water content. Delays in the construction of the cover systems due to laboratory and density gauge availability also affected the water content of the silty till, decreasing it further. Water was added manually prior to the compaction of the over-dried glacial till layers, once the material was already placed in the lysimeters. Wetted material was then blended to achieve uniform water content. Once water content was deemed satisfactory, the layer was compacted.

The soil mechanics laboratory at Antamina was not available during the construction of the cover systems, thus glacial till samples taken during construction had to be sent to Golder Associates laboratory in Lima for testing. In addition, the imminent start of the rainy season did not allow extending the construction schedule of the cover systems and waiting for the results of the standard Proctor tests conducted in Lima. Therefore, the degree of compaction of the glacial till layers in lysimeters #1 and #5 was controlled and approved based on data from the standard Proctor tests carried out for the compaction platforms. A second density assessment of the cover systems was calculated once results of the standard Proctor tests conducted on the actual construction materials became available. This assessment showed that glacial till layers in lysimeters #1 and #5 were not always compacted according to the specification (i.e. 95% of the maximum density and within ±2% from the optimum moisture content). Table 3-2 summarize the results of the compaction tests performed on the cover layers.

Table 3-2 Results of Compaction Tests

Lysimeter	Material	Layer	Standard Proctor test		Field results	
			Maximum Dry Density (g/cm^3)	Optimum Water Content (%)	(%) Proctor	WC (%)
L #1	Clayey till	1	1.903	14.00	94.3	15.10
L #1	Clayey till	1	1.903	14.00	93.7	14.80
L #1	Clayey till	2	1.884	14.10	94.4	13.90
L #1	Clayey till	2	1.884	14.10	96.2	14.70
L #1	Clayey till	3	1.827	16.30	98.2	12.10
L #1	Clayey till	3	1.827	16.30	97.8	13.80
L #1	Clayey till	3	1.827	16.30	96.9	14.20
L #1	Clayey till	4	1.794	16.60	98.6	15.30
L #1	Clayey till	4	1.794	16.60	100.4	15.60
L #1	Clayey till	4	1.794	16.60	98.5	15.20
L #1	Clayey till	4	1.794	16.60	104.4	14.80
L #5	Silty till	1	1.603	21.40	91.2	25.20
L #5	Silty till	1	1.603	21.40	92.3	23.30
L #5	Silty till	1	1.603	21.40	92.2	25.30
L #5	Silty till	1	1.603	21.40	91.6	21.90
L #5	Silty till	2	1.601	21.80	92.9	18.20
L #5	Silty till	2	1.601	21.80	93.1	19.00
L #5	Silty till	3	1.576	20.60	94.5	15.30
L #5	Silty till	3	1.576	20.60	97.3	11.70
L #5	Silty till	3	1.576	20.60	98.9	10.50

3.5 Vegetation

High elevation and climate regime of the Antamina mine affects the kind of vegetation applicable to the topsoil layer of the cover systems. Vegetation selected for these layers was native *Calamagrostis sp.* (locally known as i*chu*) and *Trifolium repens* (locally known as white clover). White clover is a foreign species but will grow faster than *ichu*, thus protecting the exposed layer of the cover system from erosion and triggering evapotranspiration in the early stages of the cover life. It is expected that *ichu* will eventually replace most of the white clover (AMEC Earth & Environmental, 2004). *Ichu* was transplanted from nearby natural slopes and was placed every 0.5 m in the topsoil layer of the covers. White clover was sown in a rate of 7.1 kg/ha (160 gr on each lysimeter). Vegetation was transplanted and sown in mid January, 2011. Selection of species and transplantation and planting procedures were based on the recommendations given by AMEC (AMEC Earth & Environmental, 2004). Figure 3-7 shows vegetation in the topsoil layers of the covers in its early stages of development. The slope next to the lysimeter is also covered by the same kind of vegetation. It is expected that vegetation in the cover system will grow to a similar density as the vegetation on the slope.

Figure 3-7 Vegetation Early Stages (Lysimeter #2)

Figure 3-8 Vegetation One and a Half Years after Transplanting (Lysimeter #1)

3.6 Instrument Installation

The cover study field experiment was instrumented with hydrological, geotechnical and weather instrumentation. These instruments are currently providing data for the development and calibration of predictive numerical models and for the completion of an accurate water balance of the system.

3.6.1 Tipping Buckets

Ten tipping buckets, each with a tank and collection pipe, were installed on a concrete platform, downstream and to the north of the lysimeters. Ten protection wooden huts were built around the tanks and tipping buckets to shield the instruments. At first, the tipping buckets were fixed to the huts by laths. With the first rains of the season, the wooden laths swelled causing the instruments to become unlevel. The tipping bucket bases were then replaced by an adjustable plastic system, attached to the concrete platform. This system allows the instruments to be levelled manually.

The tipping buckets and tanks were installed almost at the same elevation. A pipe coming from the bottom of the tanks directs water to the tipping buckets. Due to the pipe outflow configuration, a certain amount of water has to be stored in the tank before it can freely flow into the tipping buckets (Figure 3-9). Water must accumulate for the first time in the tanks, then it starts flowing to the tipping buckets and the instruments will register "new" flows coming into the tank. Water was stored in the percolation tanks before the covers and tipping buckets were installed, due to rain being collected by the percolation collection system in each lysimeter during the construction stage of the experiment. Therefore, percolation records registered by tipping buckets were not affected by water required to be stored in the tanks before reaching the free flowing level.

Tipping bucket data are collected with a Campbell Scientific CR1000 datalogger, and are uploaded via a telemetry system on a daily basis. The datalogger is powered by a 12-V rechargeable battery by a solar panel. Pictures of the boxes, bases and tipping buckets are included in Appendix B.

Tipping buckets were labelled after their assigned lysimeter in addition to an "R" or an "I", depending if they were meant to measure runoff or percolation, respectively. The following code was used: Lysimeter number – Percolation or Runoff (e.g. L4-I, for Lysimeter #4 – Percolation). Tipping buckets were ordered from the manufacturer in two sizes: 0.6 L per tip and 1.0 L per tip. It should be mentioned that the exact amount of water required to tip the instrument varies with flow rate. As a result, tipping buckets were calibrated for different flow rates at Antamina. They have been calibrated once every 6 months since their installation. Table 3-3 summarizes some information and the calibration equations of each tipping bucket, whereas Figure 3-10 shows the calibration plot of L1-I.

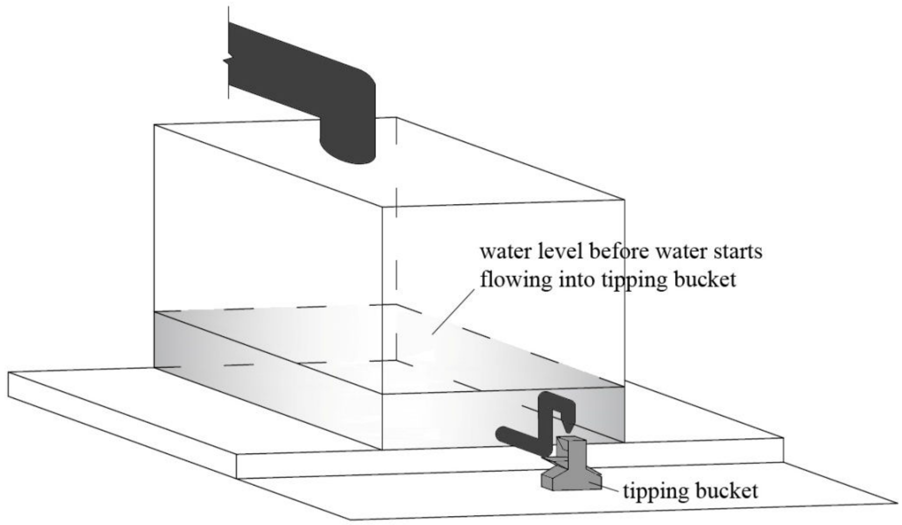

Figure 3-9 Schematic of a Tipping Bucket Installed Next to a Tank

Table 3-3 Tipping Buckets Information

Tipping Bucket	Serial No.	Approx mL/tip	Calibration equation*
L1-R	09-23	1.0	$y = 1129.2x^{-0.995}$
L1-I	09-27	0.6	$y = 723.03x^{-1.012}$
L2-R	09-24	1.0	$y = 1122.0x^{-1.013}$
L2-I	09-28	0.6	$y = 748.06x^{-1.024}$
L3-R	09-30	0.6	$y = 784.65x^{-1.036}$
L3-I	09-29	0.6	$y = 908.32x^{-1.104}$
L4-R	09-25	1.0	$y = 1243.3x^{-1.023}$
L4-I	09-31	0.6	$y = 731.52x^{-1.021}$
L5-R	09-26	1.0	$y = 1048.6x^{-0.991}$
L5-I	09-32	0.6	$y = 730.95x^{-1.028}$

* y = flow rate (mL/sec); x = tip rate (sec/tip)

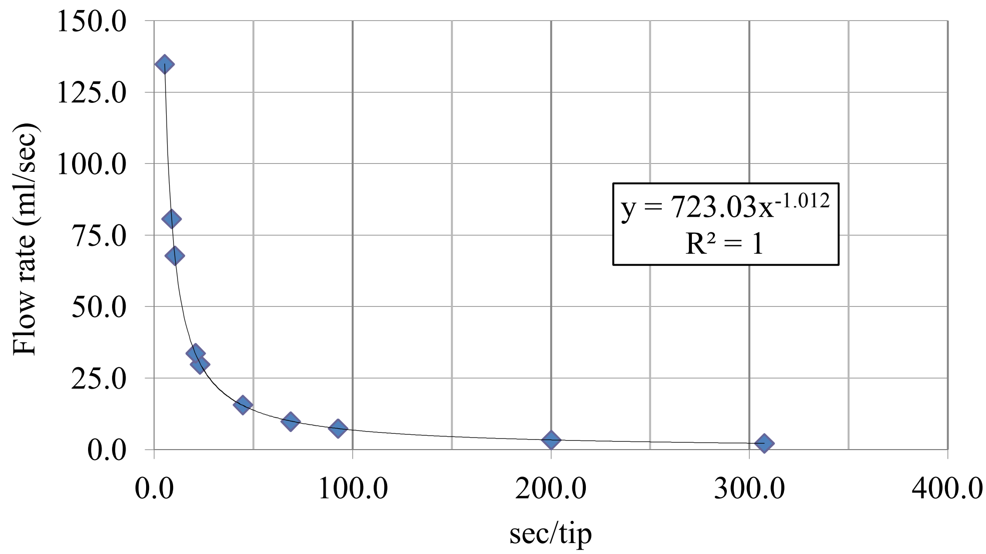

Figure 3-10 Calibration Plot and Equation for L1-I

One calibration plot was developed for each tipping bucket, and was used to estimate percolation or runoff flow rates and volumes of the corresponding lysimeter. Tipping buckets recorded tips every 30 minutes in this stage of the study. The number of tips recorded in that period of time was averaged to obtain a value in units of seconds per tip, which was used to estimate the corresponding flow rate based on the calibration equation from each plot. Finally, this flow rate was transformed into a volume over the assessed period of time, representing the percolation or runoff each tipping bucket recorded. The wiring diagram and program used for recording data from the tipping buckets are presented in Appendix C.

3.6.2 Thermal Conductivity Sensors

Ten Fredlund Conductivity Sensors (FTC-100), made by GCTS Testing Systems (GCTS), were installed in the covers to indirectly measure soil matric suction. Matric suction measurements describe the stress state of the soil, and are related to its degree of saturation. Soil matric suction is indirectly measured through the FTC-100 sensors by raising the temperature of a heating element inside a ceramic tip, with a standard quantity of heat. The temperature the ceramic tip will reach depends on its thermal conductivity, which is linked to the water content of the sensor. Finally, the water content of the sensor is directly related to the matric suction of the soil around it.

FTC-100 sensors are connected to a GCTS suction sensor controller unit with 16-channel multiplexer and a memory module. The controller is powered through a 12-V rechargeable battery by a solar panel (BP Solar, model SX320J). Data is scheduled to be downloaded every two weeks by Antamina staff. The software used for setting up, download and assessing the FTC-100 sensors readings is SuctionData v1.14, developed by GCTS. This program allows the display and plotting of the FTC-100 sensors data in a Windows interface. FTC-100 sensors were distributed in the cover systems as shown in Table 3-4. Figure 3-11 presents a schematic of the approximate location of each sensor in the cover systems.

Table 3-4 FTC-100 Sensors Used in the Experiment

Location	**Sensors Serial #**	**Depth**	**Material**	**Datalogger Channel**
Lysimeter #1	33-16	150 mm	Topsoil	#3
Lysimeter #1	33-12	480 mm	Compacted clayey till	#2
Lysimeter #1	33-17	750 mm	Compacted clayey till	#1
Lysimeter #2	33-13	150 mm	Topsoil	#10
Lysimeter #2	33-15	460 mm	Non-compacted clayey till	#9
Lysimeter #2	32-20	750 mm	Non-compacted clayey till	#8
Lysimeter #4	32-21	150 mm	Topsoil	#7
Lysimeter #5	30-22	150 mm	Topsoil	#6
Lysimeter #5	33-14	450 mm	Compacted silty till	#5
Lysimeter #5	33-11	650 mm	Compacted silty till	#4

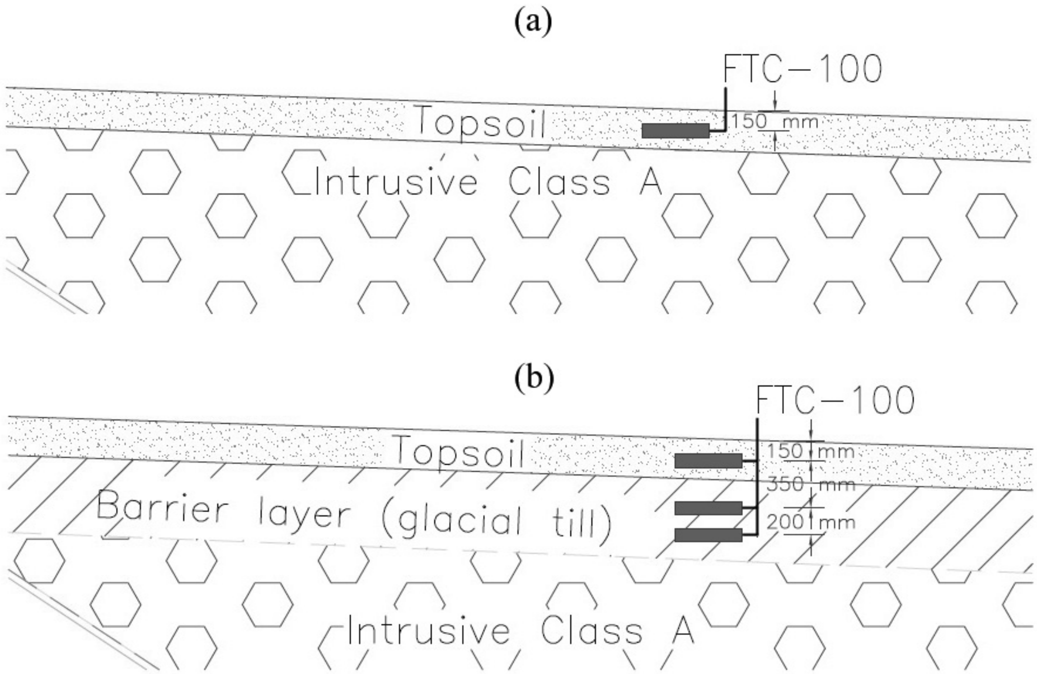

Figure 3-11 FTC Sensors Approximate Location in the Covers

Standard procedure for installing FTC-100 sensors in compacted soils involves digging a test pit and using a 28 mm diameter auger to drill a horizontal hole where the sensor will be installed (Marjerison, Richardson, Widger, Fredlund, & Berthelot, 2001). A new procedure for the installation of the FTC-100 sensors had to be developed at Antamina since it was not possible to get one of the aforementioned augers. This new procedure involved covering four ¾" (19.05 mm) diameter and 150 mm long PVC pipes by duct tape until an external diameter of 28.6 mm was obtained. These pipes were then tied to a nylon line and horizontally buried while the compacted covers were being built. The nylon line and a vertical PVC pipe were used to locate the buried duct taped pipes after the construction of the compacted covers was finished. A test pit was dug next to the standing PVC pipes using a shovel, and after locating the horizontal PVC pipes they were slowly pulled out of the compacted covers, taking care not to collapse the horizontal hole left by the PVC pipes. The end of the hole was compacted with an iron bar and the length of the hole was measured with a measuring tape, and then cleaned. TC sensors were then slowly pushed inside the hole until they reached the end of it. The remainder of the hole was partially filled with the finer fraction of the same material dug from the test pit, and was compacted with a piece of PVC pipe. The remaining portion of the hole was then sealed with expandable foam. As shown in

Table 3-4, two FTC-100 sensors were installed in each compacted cover following this procedure. The cables were brought up vertically and the test pit was filled with the same material taken from it. This material was then compacted in three layers with a vibrating plate. The degree of compaction was confirmed by nuclear density tests. Photos #63 to #73 in Appendix B show the sequence followed in the installation of the FTC-100 sensors in the compacted cover systems.

3.6.3 Oxygen Sampling Tubes

Prior to the construction of the four cover systems, five oxygen sampling tubes were installed in the waste rock exposed face of Lysimeters #1, #2, #4 and #5. The oxygen sampling tubes are made of PVC with a 3.18 mm (1/8”) inner diameter. Tubing for oxygen measurements where protected from damage by the waste rock located adjacent to the PVC and HDPE piping. Horizontal tubing was protected by the latter PVC piping and sealed with expandable foam to avoid air entry and disruption to oxygen measurements. Vertical portions of the oxygen sampling tubes were protected by 2” HDPE pipe, which was filled with sand and sealed with a bentonite cap. Figure 3-12 shows a schematic of the oxygen sampling tubes in the lysimeters, whereas Figure 3-13 show the oxygen sampling tubes coming out of the cover system through the 2” HDPE pipe. Any oxygen measurements can be conducted with a portable gas analyser. It should be noted that although oxygen sampling tubes were installed, oxygen sampling and data interpretation is not part of the scope of this thesis. Oxygen sampling will be conducted in the following years as part of the second stage of this research.

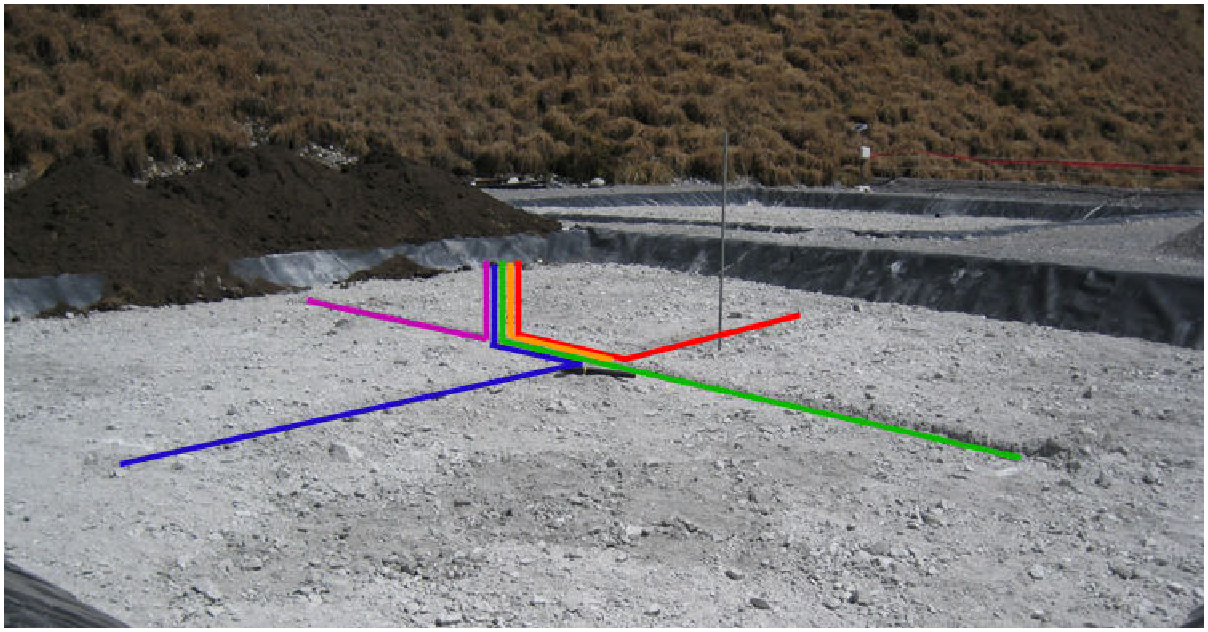

Figure 3-12 Oxygen Sampling Tubes Layout (red, orange, green, purple and blue lines represent the layout of the oxygen sampling pipes in the waste rock)

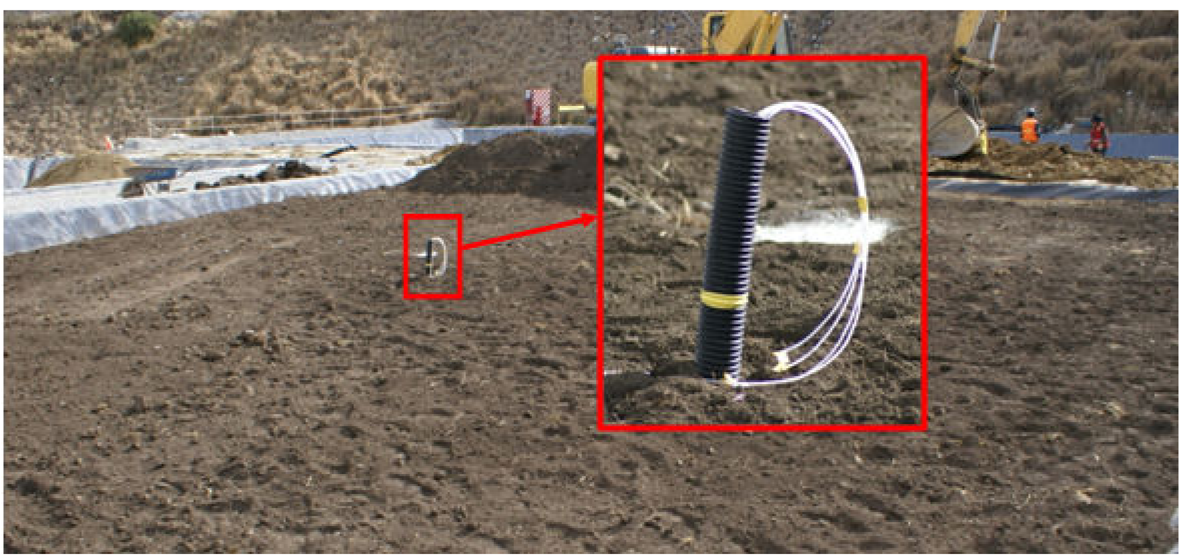

Figure 3-13 HDPE Pipe Coming Out of Topsoil Layer, with Oxygen Sampling Tubes Inside

3.6.4 Weather Station

Two rain gauges were already operating prior the construction of this experiment. They are located approximately 100 m away from the lysimeters, and are being used as the main source of precipitation data for the cover study. Precipitation data is collected with a Campbell Scientific CR1000 datalogger, and is uploaded via telemetry on a daily basis. One net radiometer (NR-Lite, manufactured by Campbell Scientific) was installed on top of Lysimeter #4 for estimation of evaportranspiration from the cover system. This net radiometer was installed on a galvanized iron tube approximately 1.8 m from the topsoil cover surface. Data from the Net Radiometer was not used in the predictive numerical models developed for this thesis. The reason was that data had not been recorded consistently throughout this stage of the experiment. The rain gauges and net radiometer were meant to provide precipitation and net radiation data for the completion of the numerical models and water balances of each lysimeter in the current and next stage of the experiment.

CHAPTER 4. FIELD AND LABORATORY DATA

This chapter presents data collected from the instruments installed within the field cover lysimeters. Included are the results of the laboratory material characterization program and the construction quality control program.

4.1 Field Data

Field data were collected intermittently, due to instrument performance and installation issues, between February 15, 2011 and February 14, 2012; for a period of 365 days. When climate data was not available, missing records were estimated based on data from Antamina's main weather station (i.e. the Yanacancha station), and by correlating reliable flow data from the waste dump test pile experiment, also located at Punto B. A similar procedure for using Yanacancha precipitation records to interpolate missing precipitation records at Punto B was previously undertaken, concluding that meteorological records from the Yanacancha station reasonably represent meteorological behavior at Punto B (Bay, 2009). A method for estimating precipitation records at Punto B based on Pile 4 outflow was recently developed. Flow in Pile 4 is characterized by preferential flows paths, which lead to a quick outflow response to rain events (Blackmore, 2012). A summary of both techniques for estimating lost data is presented in the following section.

The Yanacancha station is located approximately 3.5 km away from Punto B, at 4,189 m.a.s.l., approximately 190 meters below Punto B. Estimated data is shown on the figures used in the following discussion.

4.1.1 Precipitation

As noted previously, precipitation was primarily collected by a rain gauge installed at Punto B. Consistent precipitation records at Punto B are not available from August 17th, 2011 onwards, due to rain gauge datalogger malfunctioning. The missing data had to be estimated up to February 14th, 2012, to be able to complete the predictive numerical models and assessment of the covers systems herein. Precipitation records were available from the Yanacancha weather station, but due to the difference in elevation and location, the data patterns did not exactly match records from Punto B. Therefore, precipitation data was interpolated based on two techniques, by combining and correlating records from both the Yanacancha weather station and the two lysimeters installed at the base of one of the experimental test piles (Lysimeter A and Lysimeter D at Pile 4).

4.1.2 Estimation of Missing Precipitation

Precipitation at the Yanacancha station is measured by a rain gauge, whereas outflow from Pile 4 is captured by a set of lysimeters and is conveyed to tipping buckets, where the flow rate and volume are recorded. This difference was taken into consideration when developing the equations for the estimation of precipitation at Punto B, by accounting for the calibration and transforming Pile 4 outflow by dividing volumes by the lysimeter cross-sectional area. The best method for correlating precipitation between Yanacancha station and Punto B was through weekly values, given the poor relationship between the two sites due to a high variability in daily precipitation records (Bay, 2009). On the other hand, daily outflow records from Pile 4 showed a good correlation with precipitation at Punto B. Figure 4-1 and Figure 4-2 present the relationships between Yanacancha weather station, Pile 4 outflow and Punto B precipitation. The apparent weak correlation between the outflows for Pile 4 and Punto B precipitation shown in Figure 4-2 are probably due to wetting of the pile, since Pile 4 was built at the end of 2008 and not completed until early 2009.

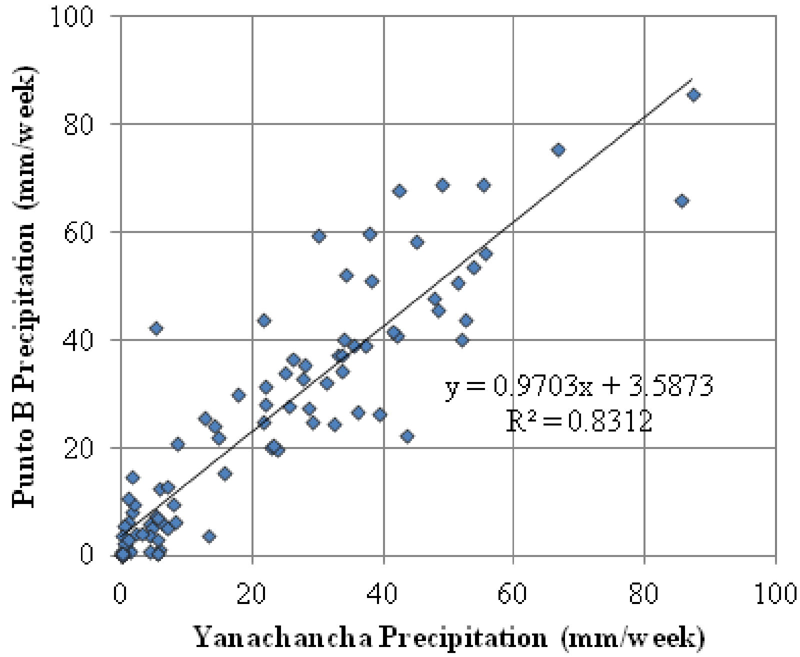

Figure 4-1 Correlation between Yanacancha and Punto B Precipitation, September 14th, 2009 to August 15th, 2012 (Blackmore, 2012)

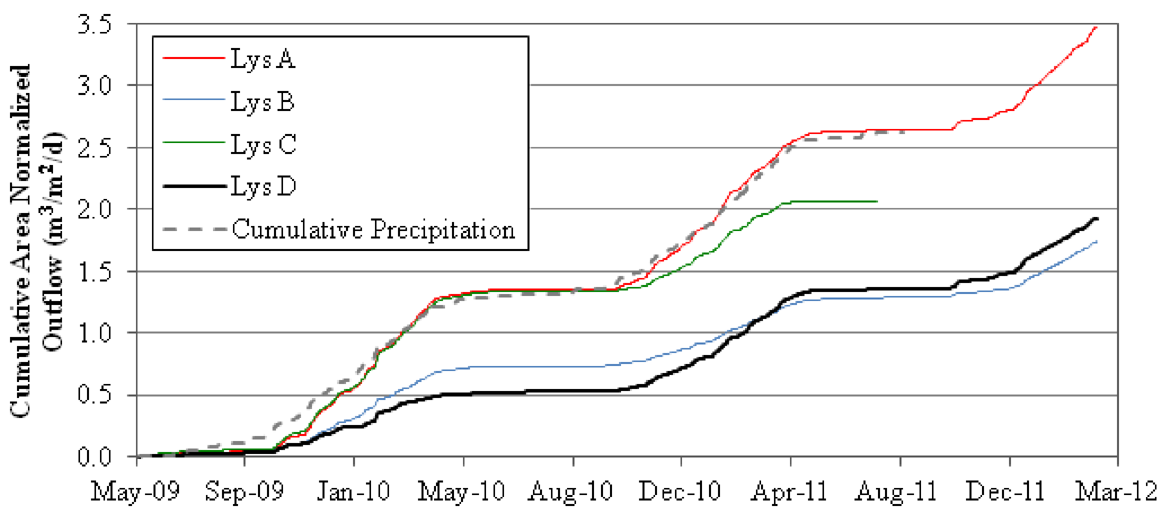

Figure 4-2 Area Normalized Outflow from Pile 4 Compared to Punto B Precipitation (Blackmore, 2012)

The degree of correlation shown in Figure 4-3 varies with the time and proxy assessed. After taking into consideration different factors, such as geographical location, location of the lysimeters within Pile 4, correlation variability, and preferential flow paths in

Pile 4 based on the tracer studies, the following conclusions were reached (Blackmore, 2012):

- Lysimeter D will be used for the estimation of missing precipitation data at Punto B for the start of the wet season (between October and December 2011). This was based on Lysimeter D having a shorter flow path (i.e. <10 m) than the rest of Pile 4 Lysimeters, therefore allowing a faster wetting up after the dry season; and also because of its geographical location (i.e. Pile 4 is located at Punto B).
- Lysimeter A will be used for the estimation of missing precipitation data at Punto B for the height of the wet season (between mid December 2011 and March 2012), based on the good and steady correlation between Lysimeter A and precipitation at Punto B, because it presents the largest component of preferential flow, and also because of its geographical location.
- The Yanacancha weather station will be used for estimating the missing precipitation data at Punto B to the end of the wet season 2012 and also during the dry season (between March and September 2012). This is based on the strong correlation between Yanacancha station an Punto B for the recommended period of time, and also because Lysimeters in Pile 4 will continue to flow in the dry season despite decreased precipitation events.

The aforementioned method was also used to estimate precipitation data whenever precipitation records from Putnto B were not available (i.e. due to malfunctioning of the rain gauges). Precipitation records used in this thesis correspond to the period where the tipping buckets were already functioning (i.e. between Februaty 15th 2011 and February 14th 2012); therefore, only Lysimeters D and A in Pile 4 were used to the estimate the missing precipitation records at Punto B. For further stages of this research, and until rain gauge at Punto B is fully operational again, precipitation records should consider using the relationship developed for the Yanacancha weather station following the recommendations given by Blackmore (Blackmore, 2012).

Figure 4-3 shows a comparison between the different proxies developed for the estimation of precipitation in Punto B, whereas Table 4-1 presents a summary of the relationships developed and time periods recommended for the use with each relationship.

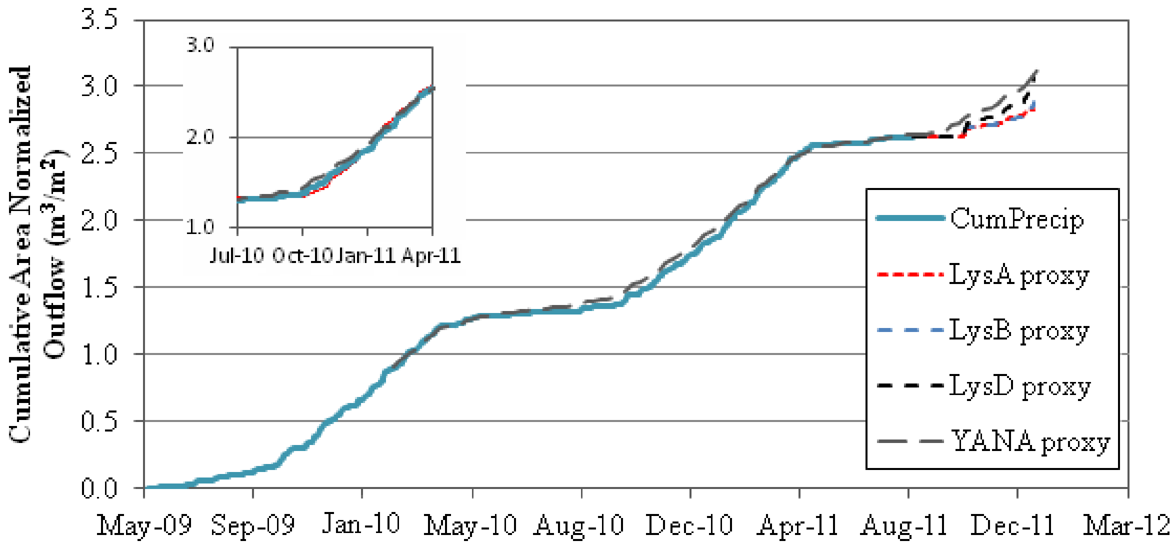

Figure 4-3 Comparison of Four Precipitation Proxies to Interpolate Missing Punto B Precipitation Values (Blackmore, 2012)

Table 4-1 Summary of Precipitation Estimation Techniques (Blackmore, 2012)

Data	Relationship	Confidence
Using Lysimeter D relationship	2.03*Lysimeter D outflow (as $m^3/m^2/d$)	Conservative estimate of start of wet season (October – December)
Using Lysimeter A relationship	1.0*Lysimeter A outflow (as $m^3/m^2/d$)	Height of wet season (December – February)
Using Yanacancha relationship	(Yana Precip.)*0.9703 + 3.5873	r^2 = 0.8312; best for the end of the wet season (March – September)

4.1.3 Precipitation Data Used in this Thesis

All missing precipitation data was estimated and incorporated to the measured records at Punto B according to the recommendations outlined in the previous section. Precipitation data from the Punto B rain gauges was recorded for a 1 m^2 area, therefore had to be scaled to the actual size of the catchment area of the lysimeters (i.e. 225 m^2 for comparison purposes). This is valid so long as rainfall is assumed as spatially uniform. Figure 4-4 and Figure 4-5 present daily and cumulative precipitation records, respectively, between February 15th 2011 and February 14th 2012. As Figure 4-4 and Figure 4-5 illustrate, the climate regime at Antamina is characterized by distinct wet and dry seasons; with a significant proportion of the annual rainfall occurring between October and April, followed by low to negligible precipitation from May to September. The total precipitation registered for the assessed period of time (i.e. 1 year) was 1,307 mm, equivalent to 294,195 L when scaled to the catching area of the lysimeters.

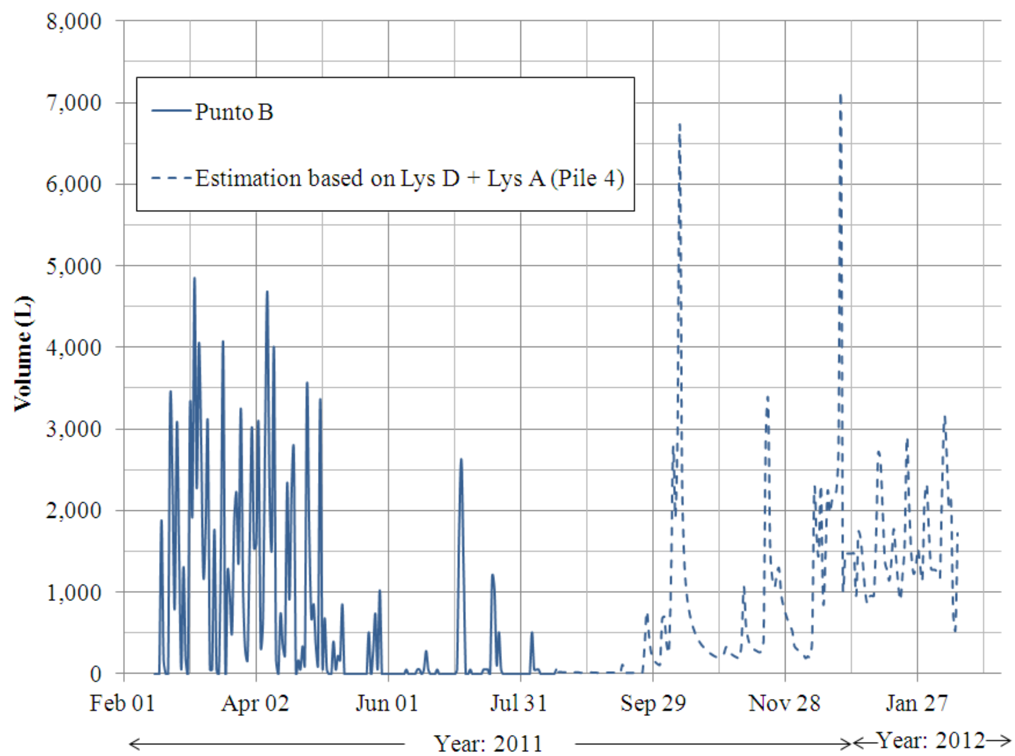

Figure 4-4 Daily Precipitation Records from Punto B

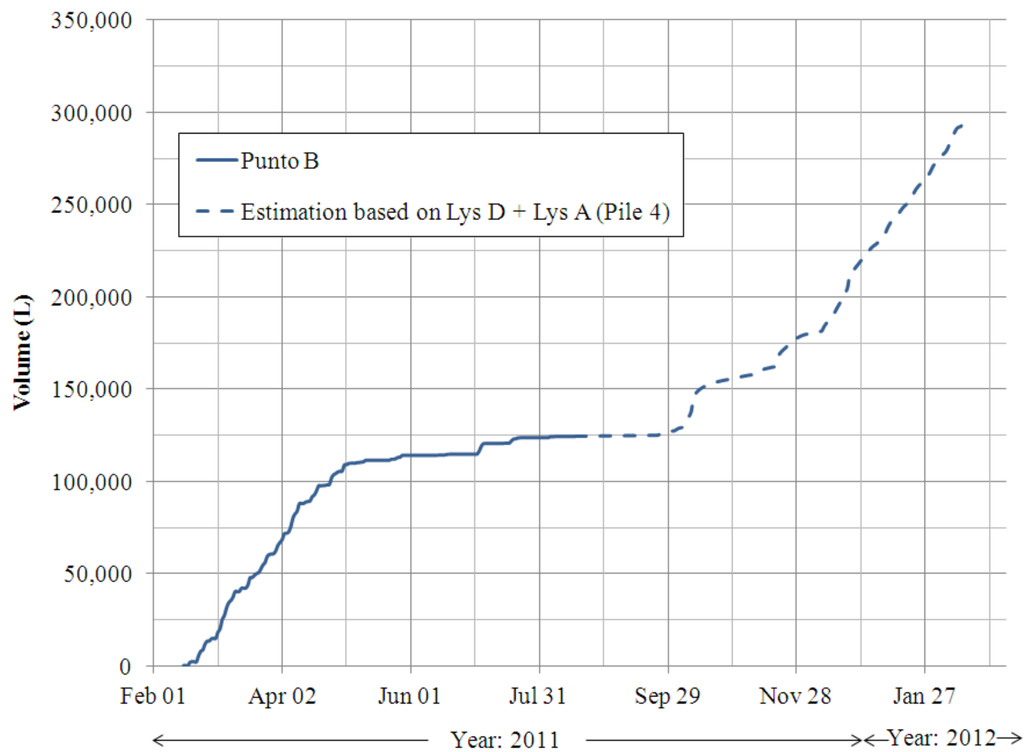

Figure 4-5 Cumulative Precipitation Records from Punto B

4.1.4 Net Percolation and Runoff

Net percolation was first recorded in February 2011, 6 months (i.e. almost one full rainy season) after the construction of the cover systems. Therefore, initial wetting up of the waste rock and cover systems is not considered to be affecting the net percolation and runoff measurements from the lysimeters. Consistent data uploading from all lysimeters was not achieved until late April due to installation problems. The recorded data from Lysimeter #1 is available starting on February 15, 2011 (Figure 4-6), whereas a consistent record is only available for Lysimeters #2, #4, and #5 starting on March 24, 2011 (Figure 4-7) and since April 20, 2011 for Lysimeter #3 (Figure 4-8). No runoff has been registered by any lysimeter at the time this thesis was written, and inspection of the 1 m^3 tanks revealed no water collection as of February 14, 2012. The absence of water in the runoff tanks indicates no runoff has occurred from any of the cover systems since installation in October, 2010.

Lysimeter #2 percolation tipping bucket stopped working in August, 2011, and was repaired in January, 2012. Nevertheless, the early trend presented in Figure 4-7 show that the performance of the cover system installed in Lysimeter #2 (non-compacted clayey till and topsoil) is very similar to the one installed in Lysimeter #1 (compacted clayey till and topsoil), and comparable to the other cover systems.

It should be noted that the tipping buckets used in this field experiment have an accuracy of ±2%, while measuring flow less than 25 litres/minute. Runoff and percolation flows never exceeded this value during the assessed period of time.

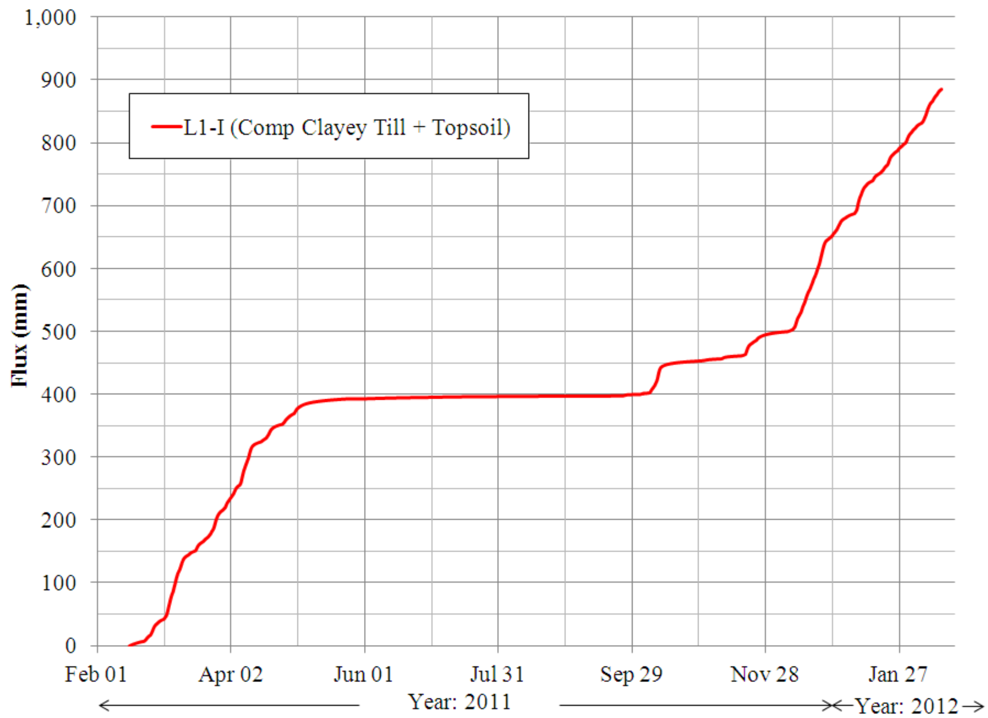

Figure 4-6 Cumulative Lysimeter #1 Net Percolation
(February 15, 2011 to February 14, 2012)

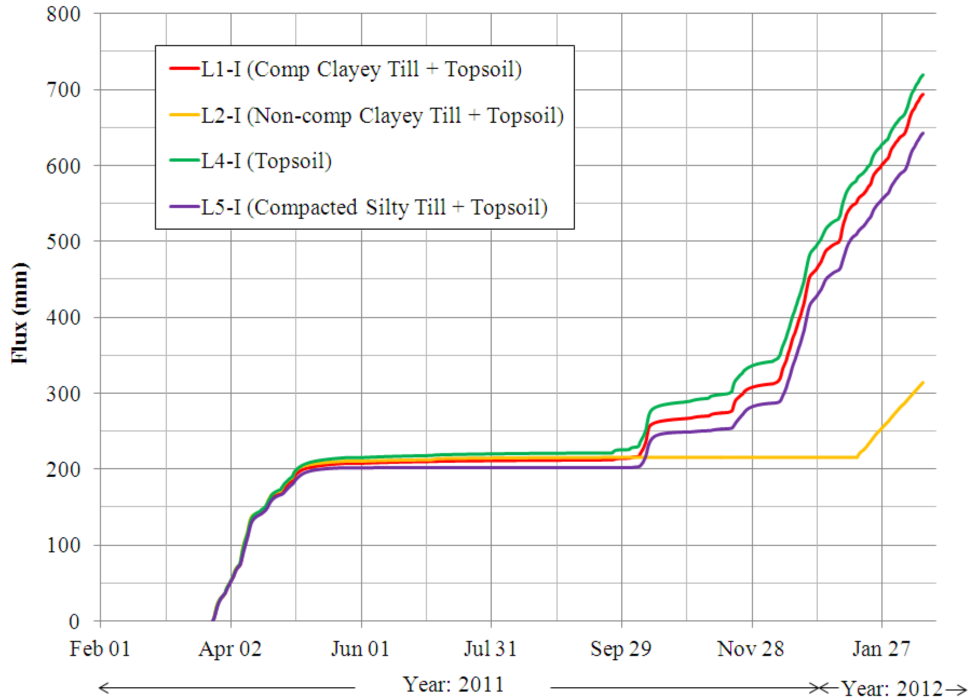

Figure 4-7 Cumulative Lysimeters #1, #2, #4 and #5 Net Percolation
(March 24, 2011 to February 14, 2012)

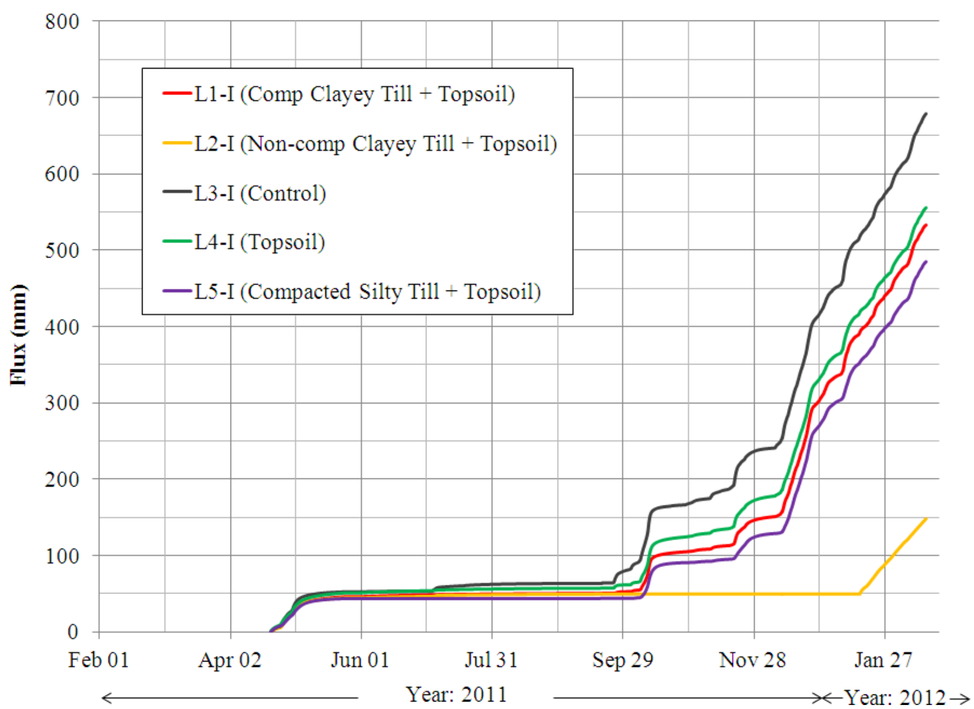

Figure 4-8 Cumulative Lysimeters #1, #2, #3, #4 and #5 Net Percolation
(April 20, 2011 to February 14, 2012)

4.1.5 Net Radiation

Net radiation is the balance of the incoming solar radiation (i.e. both short and long wave) and the radiation reflected by the ground surface. Evaporation and transpiration occurring at the soil surface is directly related to the amount of net radiation. Ground conditions, such as slope angle and relative location to the incoming solar radiation, determine the amount of net radiation. Net radiation was therefore used to estimate evapotranspiration from the assessed cover systems by using the net radiation in the modified Penman equation, defined in Section **Error! Reference source not found.** of this thesis.

The net radiometer installed at Punto B was not effectively functioning during the data collection period of this thesis. Therefore, net radiation records from the Yanacancha weather station were used instead. Hourly net radiation data from the Yanacancha station was available starting on April 16, 2011. Net radiation was estimated for the period of time between February 15 and April 16, 2011 for the predictive numerical models. Other gaps in data existed for the following dates: April 12 to 16, 2011; May 7 to May 18, 2011; and August 23 to September 20, 2011. In short, the estimation of missing net radiation data was carried out by averaging two weeks of recorded data before and after the gaps occurred. Figure 4-9 summarizes the daily net radiation data between February 15, 2011 and February 14, 2012, whereas Figure 4-10 presents the variation in net radiation for three typical days in the month of June during the dry season. Negative values of net radiation were observed during the night as expected, as can be seen in Figure 4-10.

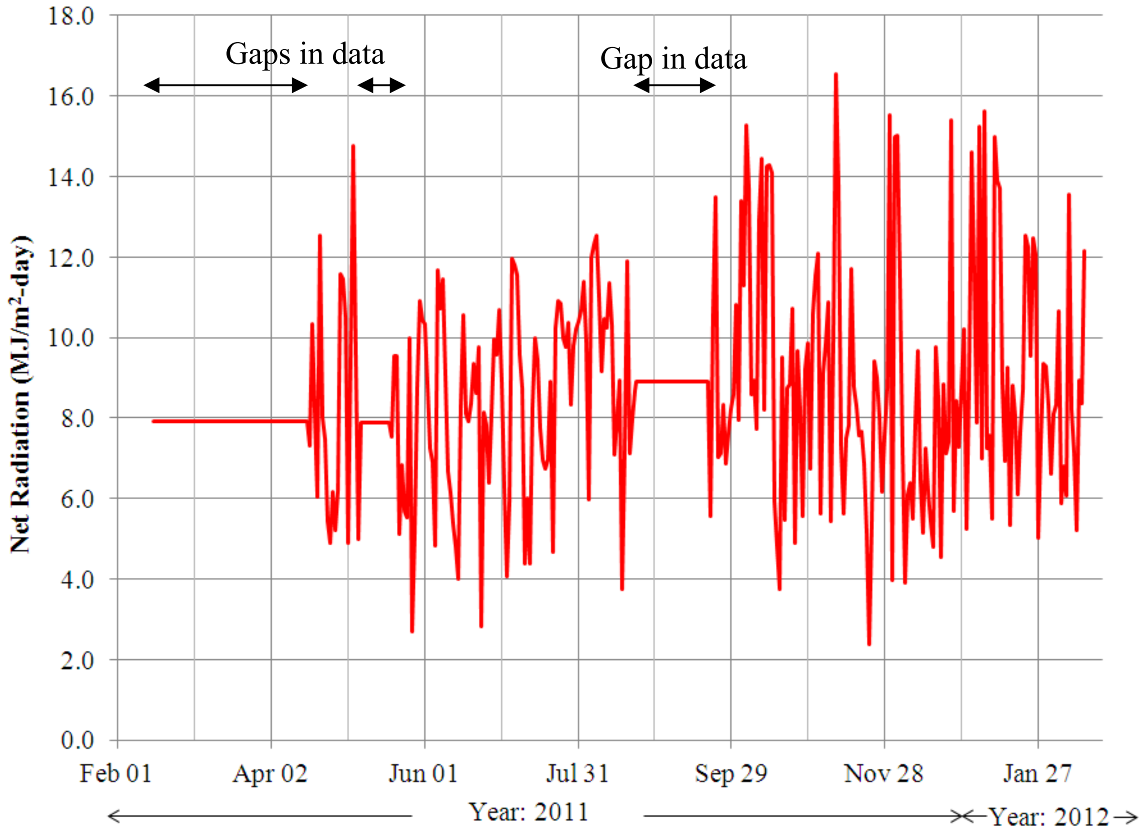

Figure 4-9 Daily Net Radiation from February 15, 2011 to February 14, 2012

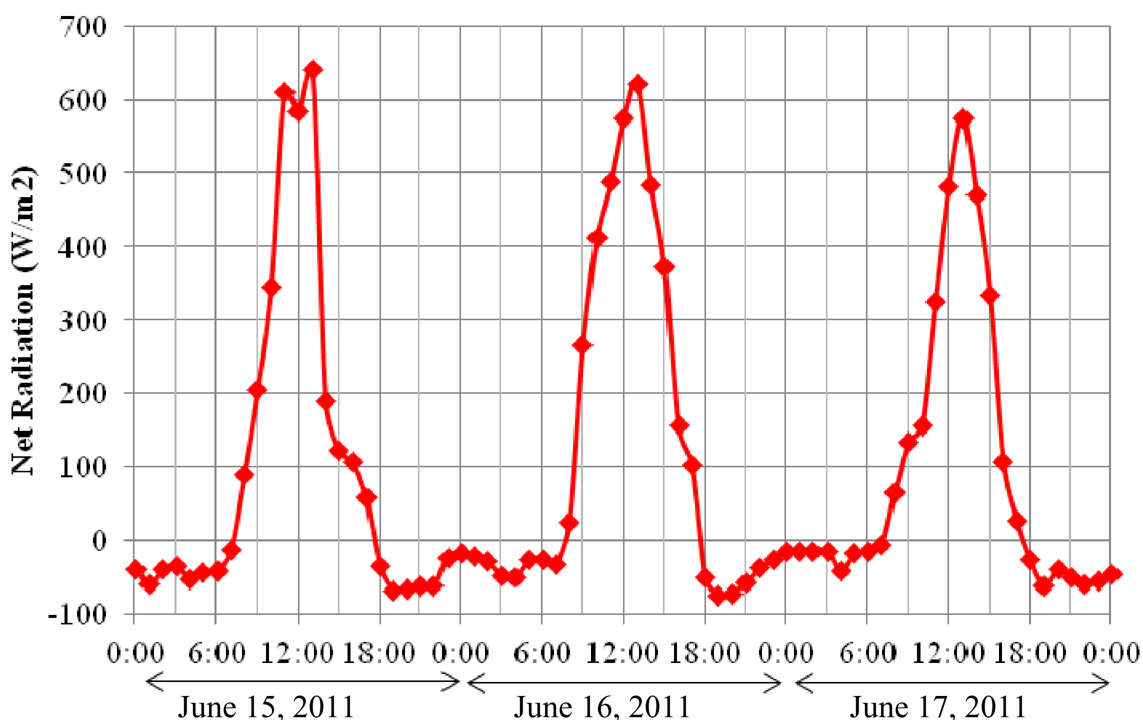

Figure 4-10 Variation in Net Radiation Over Three Typical Days of the Dry Season

4.1.6 Matric Suction

Matric suction was intended to be measured with FTC-100 sensors that had been installed during construction of the covers. However, a problem with the controller for the sensors prevented this during 2011. The controller was sent back to the manufacturer for repair after the instrument could not be accessed through the project laptop, and after different troubleshooting procedures recommended by the manufacturer of the sensors failed. The controller was re-installed again early in 2012. No data from 2011 could be recovered. The controller and FTC-100 sensors are currently functioning and recording data, which will be used in future stages of this research for the calibration of the predictive numerical models.

4.1.7 Air Temperature, Wind Speed and Relative Humidity

Air temperature, wind speed and relative humidity records from Yanacancha weather station were also input in the modified Penman equation for the estimation of evapotranspiration from the cover systems. Wherever gaps in the recorded data occurred, missing data was estimated using the same procedure as for the missing net radiation records. Gaps in data existed for the following dates: April 12 to 16, 2011; May 7 to May 18, 2011; and August 23 to September 20, 2011. Minimum air temperature recorded was deemed non-reliable from February 15 to March 8, 2011 due to unrealistic low values (e.g. between -12.92°C and -36.65°C). Therefore, temperatures for this period of time were estimated using the average of the first two weeks of reliable data, from March 9 to March 23, 2011. Figure 4-11 and Figure 4-12 present the recorded and estimated data.

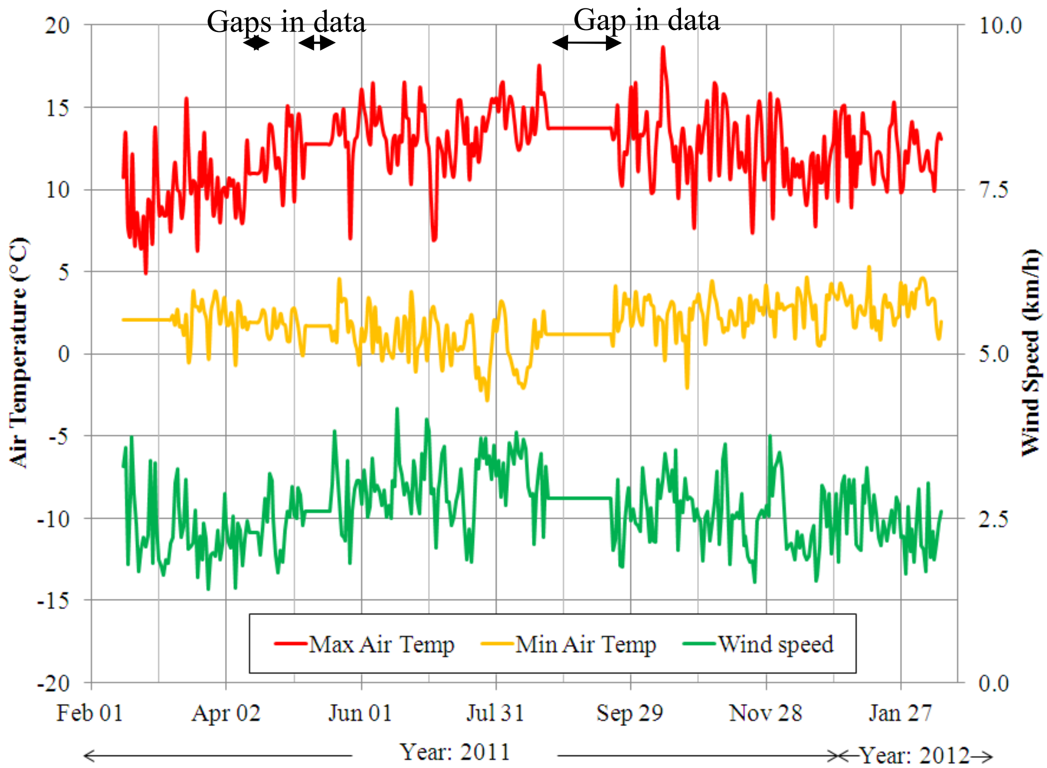

Figure 4-11 Air Temperature and Wind Speed Records from Yanacancha Station

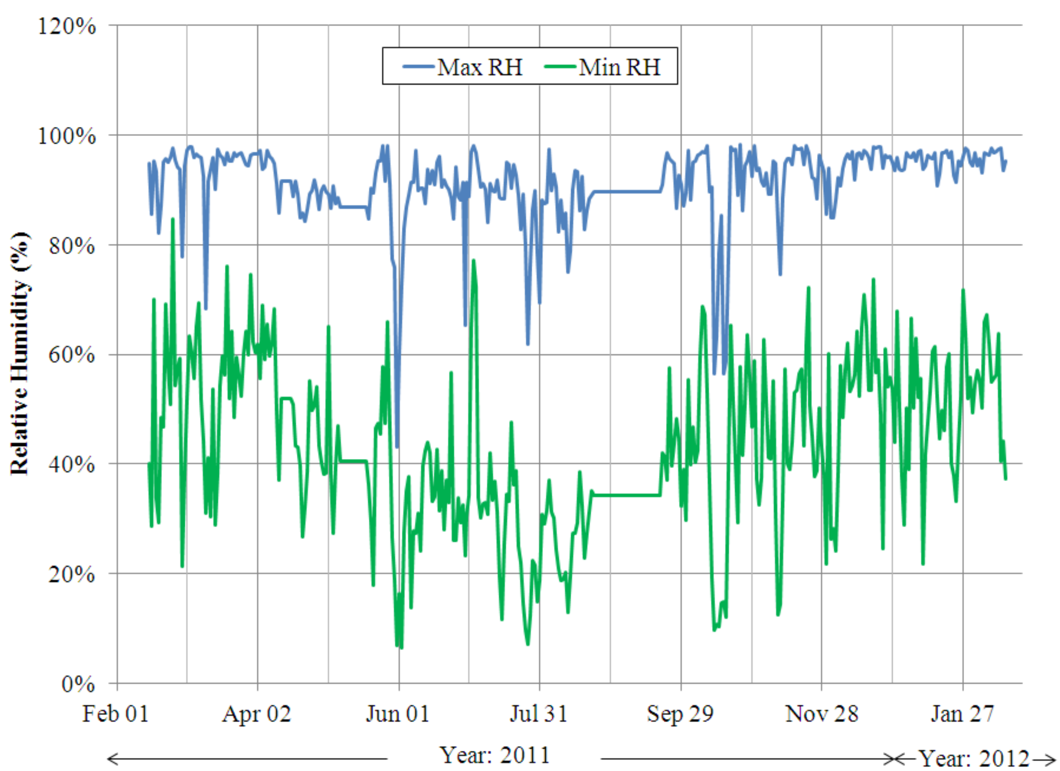

Figure 4-12 Maximum and Minimum Relative Humidity from Yanacancha Station

4.2 Laboratory Data

A number of laboratory tests were conducted as part of the materials characterization program and construction quality control (QC) for the present research. The following sections summarize the results of the aforementioned tests.

4.2.1 Assessment of Native Materials Potential to Function as Covers

Golder Associates, as requested by UBC and Antamina, conducted laboratory tests on select native Antamina soils to assess their physical properties. Results aided in evaluating their potential to function as cover materials. Specifically, these laboratory tests included: USCS classification, *in situ* moisture content, saturated hydraulic conductivity and standard Proctor compaction tests. No proctor test was carried out for the topsoil samples. It should be mentioned that hydraulic conductivity tests were conducted with an effective pressure of 8.85 kPa on the clayey till specimen, and 1 kPa on the silty till and topsoil specimens. A summary of the results of these tests is presented in Table 4-2.

Table 4-2 Summary of the Tests Results for the Assessment of Native Materials

Material	Gravel (%)	Sand (%)	Fines (%)	Liquid Limit (%)	Plasticity Index (%)	K_{sat}* (m/s)	MDD** (kg/cm^3)	W_{opt}*** (%)
Clayey till	45.6	28.9	25.5	31.5	11.9	$2.1x10^{-9}$	2.078	10.90
Silty till	0.0	4.3	95.7	50.3	16.1	$7.3x10^{-8}$	1.428	30.1
Topsoil	11.1	12.4	76.5	78.3	27.4	$4.6x10^{-6}$	-	-

*Clayey and silty till saturated hydraulic conductivities were tested on samples compacted at 95% of the maximum dry density of standard Proctor test.

**MMD = Maximum dry density from the standard Proctor test.

***Wopt = Optimum water content from the standard Proctor test

4.2.2 Materials Characterization Program and Construction Quality Control

Samples for the materials characterization program were obtained from the soils used in the construction of the cover systems. As mentioned in section 3.4, the covers were composed of layers ranging from 150 mm to 300 mm, depending on material type and compaction requirements. Four 20 L pails full of samples were collected from each layer in the barrier covers, ranging from 150 mm, 200 mm, to 300 mm thick (i.e. four pails of each of the four clayey till layers in lysimeter #1, four pails of each of the two clayey till layers in lysimeter #2, and four pails of each on the three silty till layers in lysimeter #5). These samples were labeled with the following code: Material code – lysimeter number – layer number (e.g. CT-L1-2, for clayey till – lysimeter #1 – 2nd layer) and were sent to Golder Associates laboratory in Lima to determine grain size distributions, Atterberg limits, specific gravities, and maximum dry densities and optimum water contents from standard Proctor tests. Additionally, a sample of approximately 2 m^3 was taken from each constructed layer, and was blended together with other 2 m^3 samples collected from each layer of the same cover and lysimeter. These stockpiles were later quartered 3 times and two 20 L pails of samples were taken from each of the barrier covers quartered stockpiles, whereas one 20 L pail sample was taken from each of the topsoil quartered stockpiles. The code used to label these samples was: Material code – lysimeter number – pail number (e.g. CT-L1-p2, for clayey till – lysimeter #1 – pail 2). These pails were sent to University of Alberta, where Atterberg limits, saturated hydraulic conductivity, and Tempe pressure cells tests were conducted. Figure 4-13, Figure 4-14, Figure 4-15, and Table 4-3 summarize the results of the tests conducted by Golder.

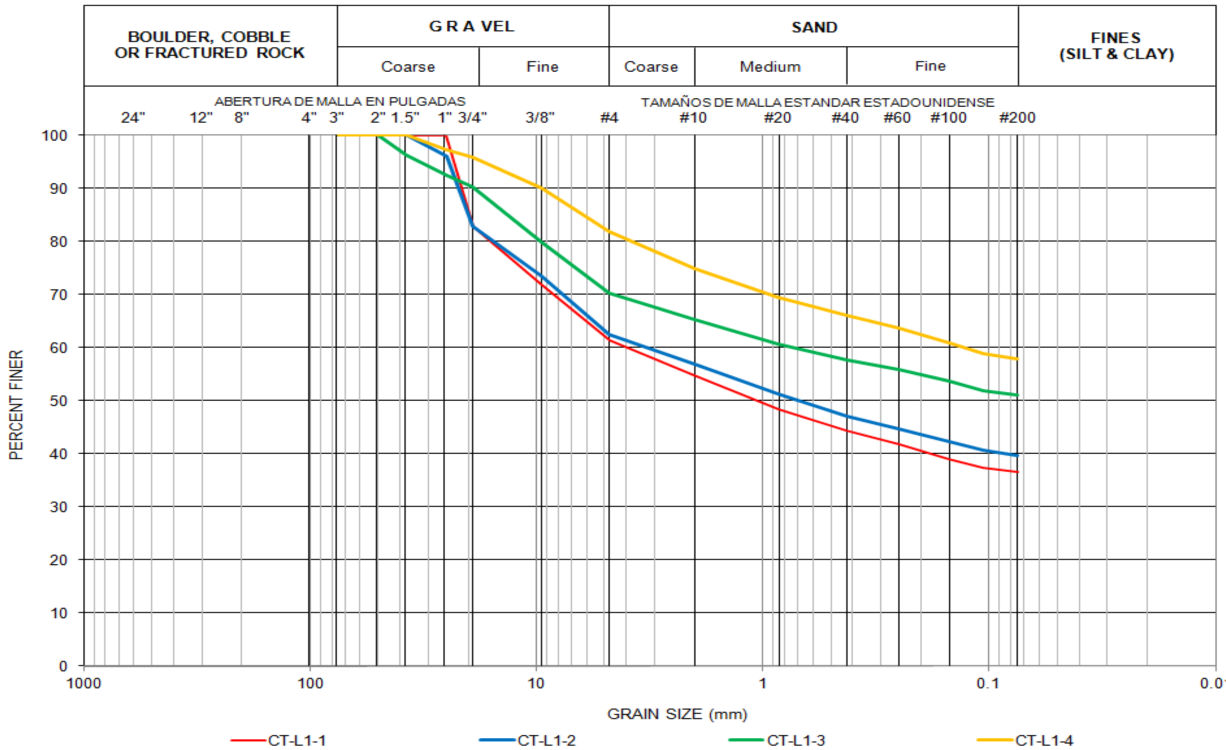

Figure 4-13 Clayey Till Grain Size Distributions of Samples Taken from Lysimeter #1

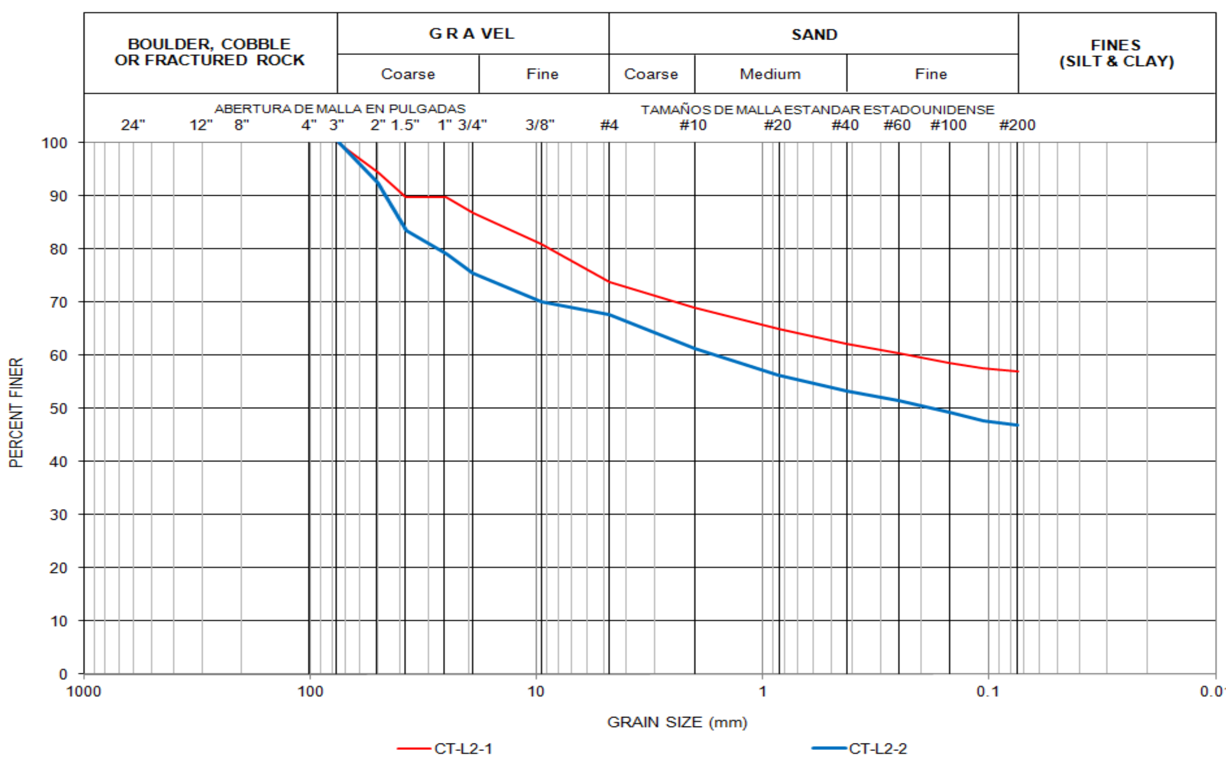

Figure 4-14 Clayey Till Grain Size Distributions of Samples Taken from Lysimeter #2

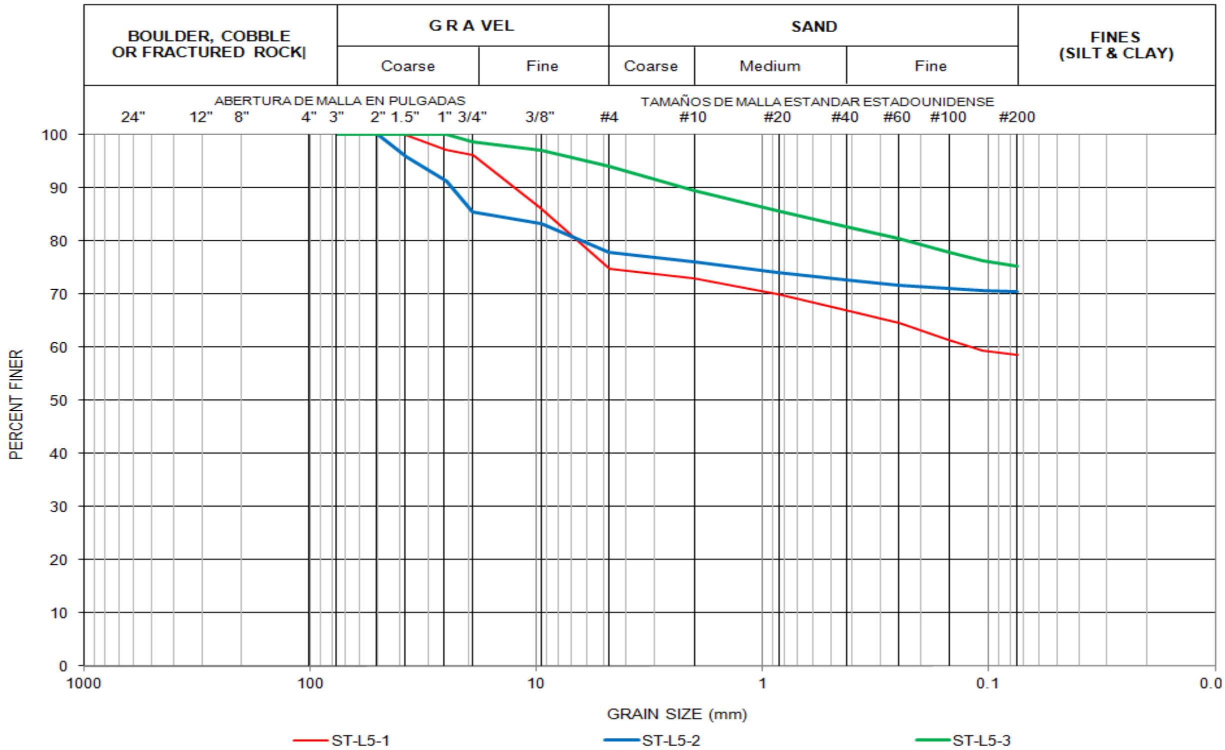

Figure 4-15 Silty Till Grain Size Distributions of Samples Taken from Lysimeter #5

Table 4-3 Cover Materials Laboratory Tests Results Conducted By Golder Associates

Material	Atterberg Limits		Standard Proctor Test		G_s (gr/cm^3)	USCS Classification	USCS Description
	Liquid Limit	Plasticity Index	Maximum dry density (kg/cm^3)	Optimum water content (%)			
Clayey till, Lysimeter #1	34 - 38	14 - 15	1794 - 1903	14.0 - 16.6	2.38 - 2.76	GC to CL	Clayey gravel with sand to sandy/gravelly low plasticity clay with gravel/sand.
Clayey till, Lysimeter #2	36	15 - 16	1800 - 1857	15.1 - 16.4	2.54 - 2.62	GC to CL	Clayey gravel with sand to gravelly low plasticity clay with sand.
Silty till, Lysimeter #5	50 - 54	20 - 24	1576 - 1603	20.6 - 21.8	2.69 - 2. 74	MH	Gravelly high plasticity silt with sand to sandy high plasticity silt.

4.2.3 Saturated Hydraulic Conductivity and SWCC

Saturated hydraulic conductivity (K_{sat}) tests were conducted at the University of Alberta (UofA) laboratory to confirm previous results obtained during the assessment of native materials potential to function as cover program. These tests also served to complete the characterization of the actual soils used to build the cover system for the experiment. Constant head saturated hydraulic conductivity tests were conducted in compacted and non-compacted clayey till (CGT), compacted silty till (SGT), and topsoil specimens passing #4 sieve (i.e. particle sizes smaller than 4.75 mm), at different consolidation pressures: self-weight, 10 kPa and 20 kPa. Compacted specimens were prepared by estimating the desired density based on the proctor curves corresponding to each material, and then compacting the required mass of soil in the cell that would used for the test. The results for these tests are summarized in Figure 4-16.

The hydraulic conductivity test conducted on the compacted silty till specimen is not considered representative of the actual silty till layer installed in Lysimeter #5. When the specimen was being saturated from the bottom up, prior the initiation of the test, the specimen was "pushed up", losing its compaction and becoming lose. This is shown in Figure 4-16, where the hydraulic conductivity of the silty till specimen suffers a significant drop when increasing the vertical effective stress to 10 kPa. As a consequence, the saturated hydraulic conductivity of the compacted clayey till K_{sat} was probably underestimated by this test. The clayey till specimen was apparently over compacted during placement in the cell where it was later tested, resulting in a lower K_{sat} value than what was likely achieved on the field experiment. Results from the Golder saturated hydraulic conductivity tests are also included in Figure 4-16 for comparison purposes.

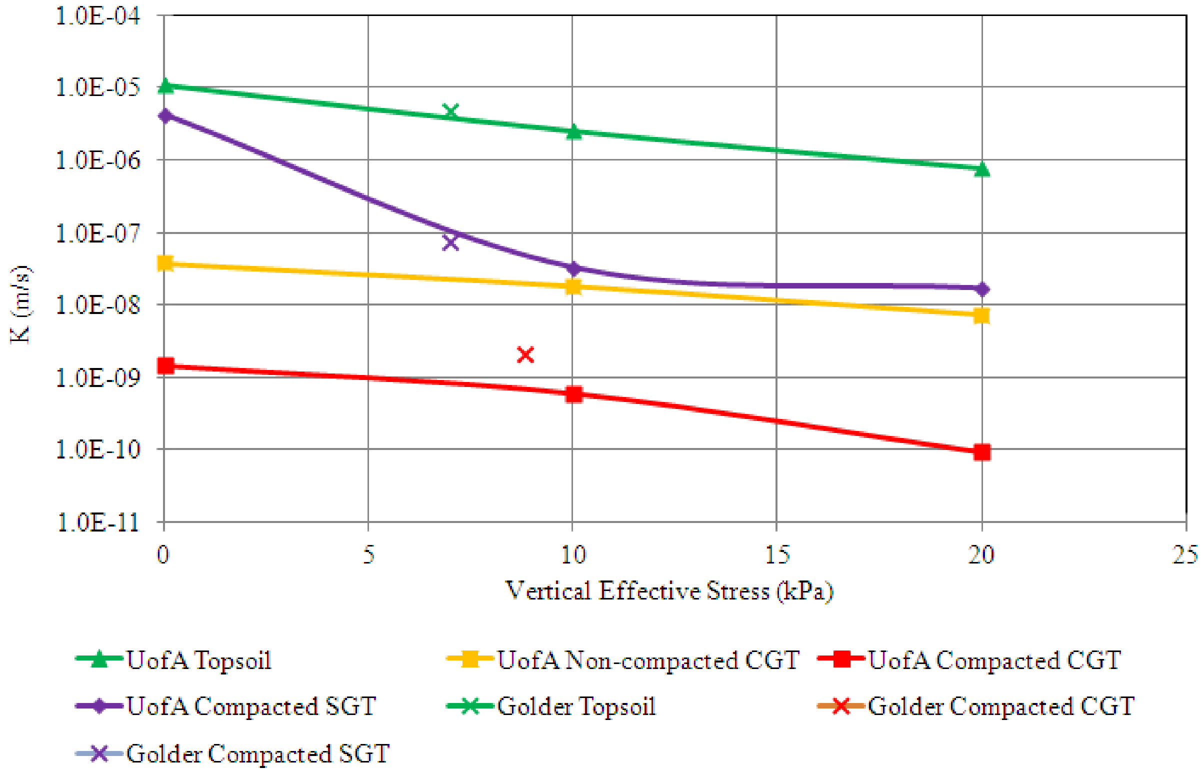

Figure 4-16 Hydraulic Conductivity vs Vertical Effective Stress Test Results

Laboratory tests for determining the soil water characteristic curves (SWCC) of the materials used to build the experimental covers were also carried out at University of Alberta. These tests were conducted in 69 mm (inside diameter) Tempe cells over a period of 20 to 27 days. Specimens consisted of compacted and non-compacted clayey till, compacted silty till, and topsoil passing #4 sieve (i.e. particle sizes smaller than 4-75 mm). Suction was applied in the Tempe cell and was incrementally increased from 0 kPa to approximately 100 kPa (for the topsoil and non-compacted clayey glacial till specimens) and 300 kPa (for the compacted clayey and silty till specimens). Figure 4-17 shows the equipment and tempe cells used to conduct the tests. Figure 4-18, Figure 4-19, Figure 4-20 and Figure 4-21 present the measured soil-water characteristic curves.

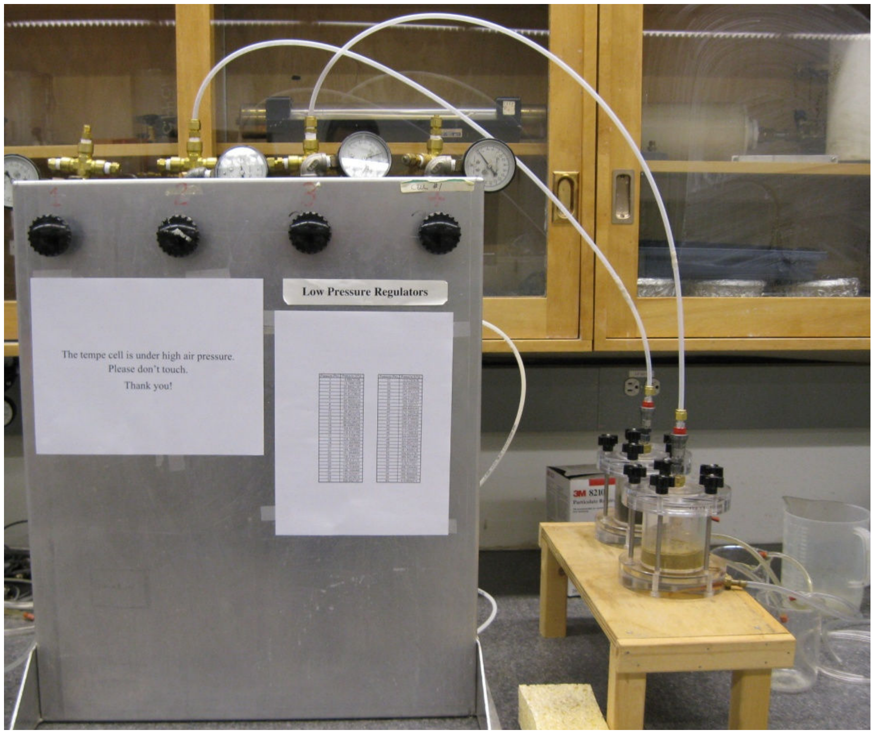

Figure 4-17 Tempe Cell Apparatus

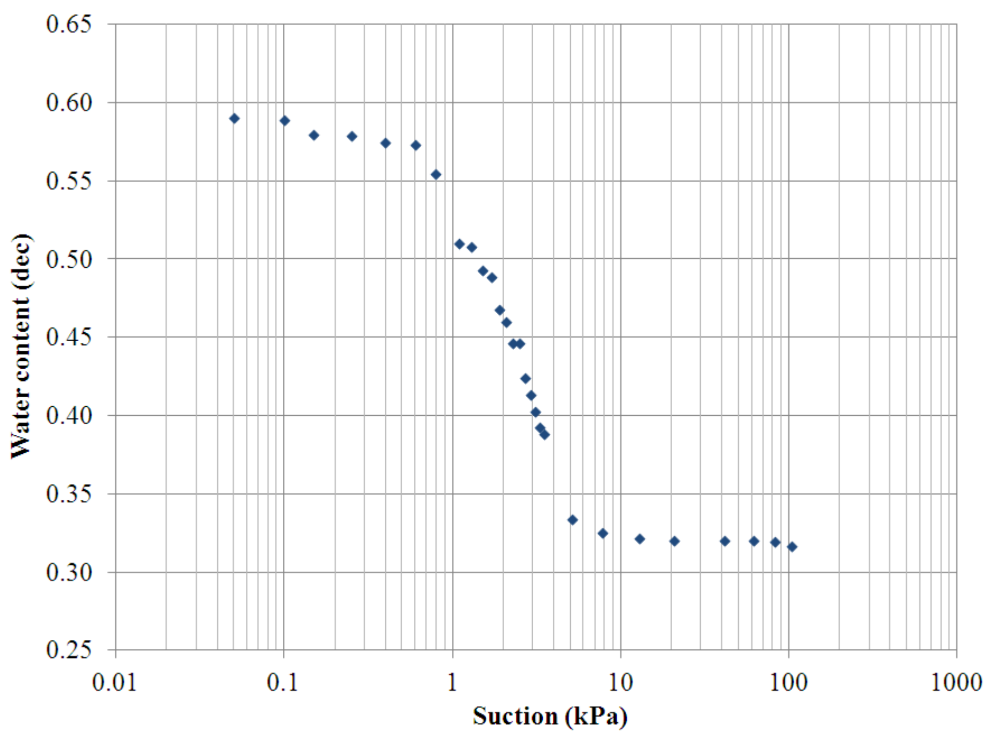

Figure 4-18 Soil Water Characteristic Curve of the Topsoil

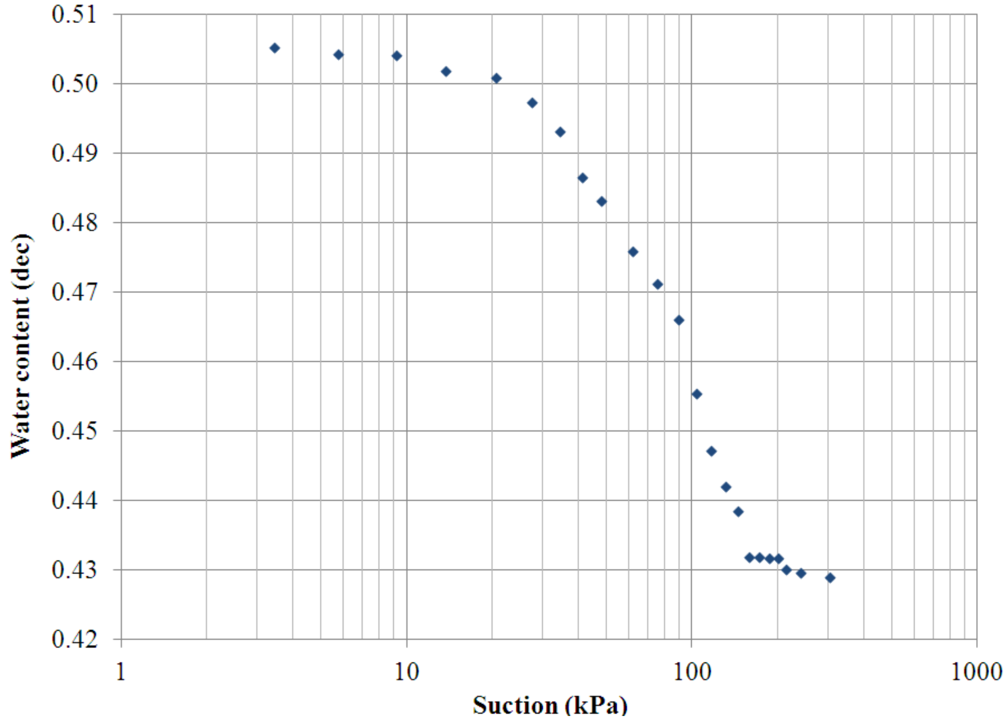

Figure 4-19 Soil Water Characteristic Curve for L1-CGT

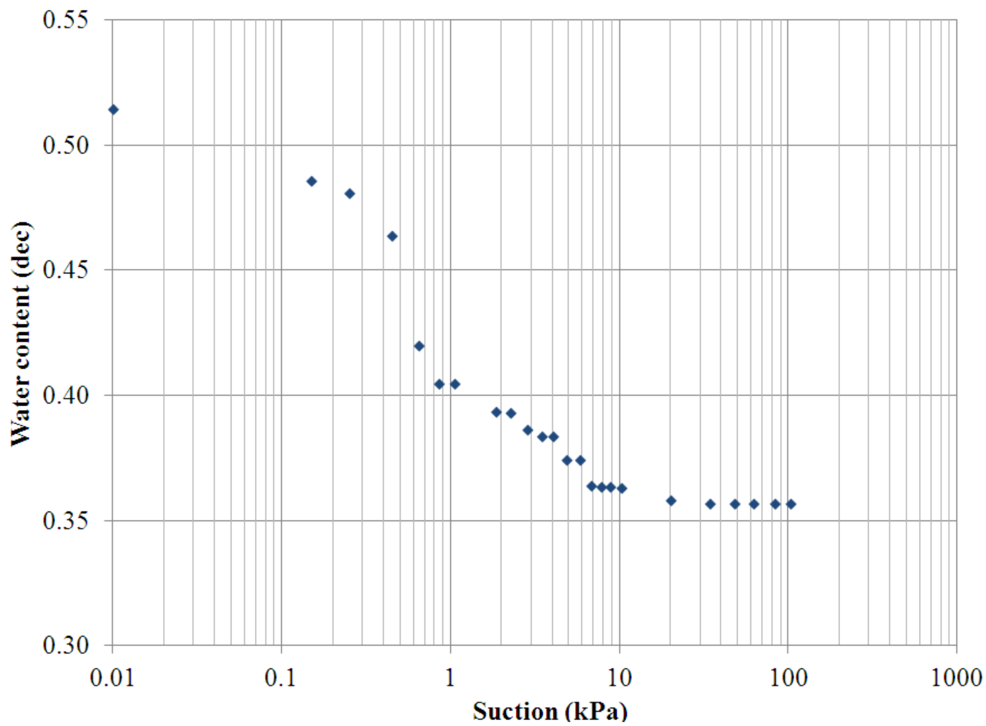

Figure 4-20 Soil Water Characteristic Curve for L2-CGT

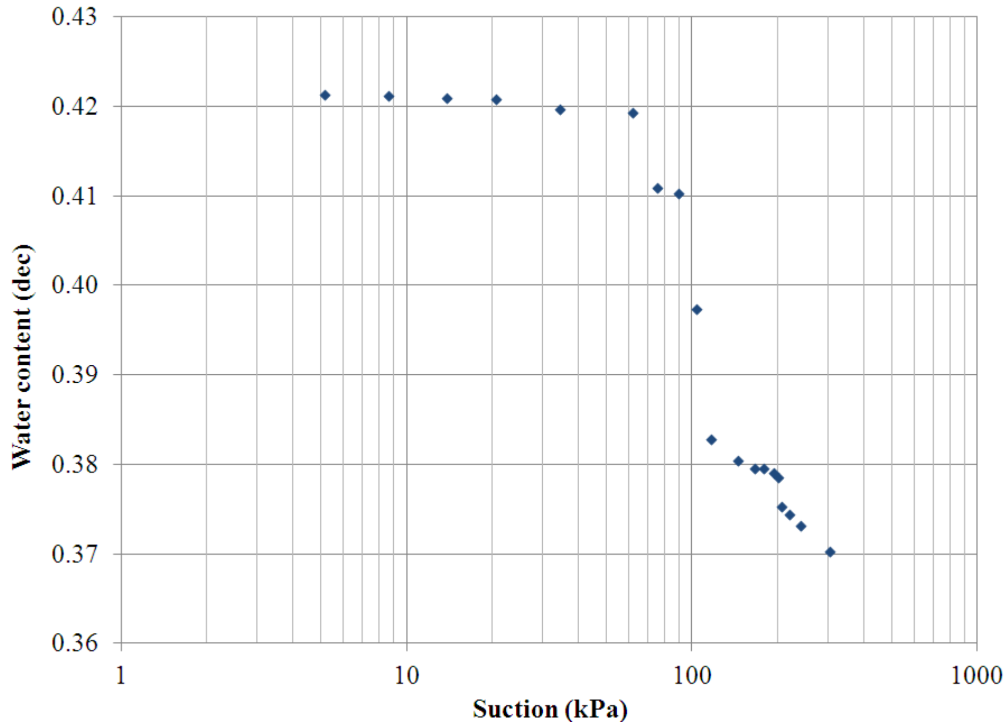

Figure 4-21 Soil Water Characteristic Curve for L5-SGT

4.3 Summary of Field and Laboratory Data

Field data including weather records, runoff and net percolation from the cover systems, were collected at Punto B. The data collected from Punto B was obtained intermittently over a one year due to acquisition problems. Missing precipitation records (between August 2011 and February 2012) were estimated based on data from the Yanacancha weather station and by correlating reliable flow data from the piles experiment, also located at Punto B. Net radiation, air temperature, wind speed and relative humidity were obtained from the Yanacancha weather station, 3.5 km away from Punto B. The cover system performance indicators, such as runoff and net percolation were measured by tipping buckets. No runoff has been registered by any lysimeter at the time this thesis was written.

Soil samples were collected at different stages of the study as part of the materials characterization and construction quality control programs. Laboratory tests, such as grain size analysis, Atterberg limits, Proctor compaction, specific gravity, constant head permeability and SWCC tests were conducted on selected samples to determine their properties.

CHAPTER 5. PREDICTIVE NUMERICAL MODELS

A base case predictive numerical model was created as part of this research to represent the one-dimensional movement of water in the covers and waste rock system. The base case model was created using SoilCover, a one-dimensional fully coupled soil-atmosphere model for predicting water percolation through soils. Soil type, climate and vegetation parameters, along with boundary conditions and initial conditions, were specified in SoilCover to model the field-scale experiment constructed at Antamina. The objectives of the numerical model were to facilitate the prediction of the performance of the cover systems and assess of modifications in the design of the covers. For this purpose, the numerical model was calibrated with results from the field-scale experiment component of this research by comparing percolation and runoff records, and adjusting parameters such as leaf are index and saturated hydraulic conductivities in the numerical model. A summary of the steps followed for the calibration is presented in section 5.1.5 of this thesis.

The predictive numerical models presented in this thesis represent the first stage in the numerical modelling component of the cover study conducted at Antamina and should provide a foundation for the future modelling conducted in this research. At the time of writing, only one year of percolation and runoff records from the field experiment were available. Vegetation in the cover systems was also relatively new during the assessed year having been transplanted and sown in mid January, 2011. More representative results of the transpiration potential of the cover systems will become available in the next few years once vegetation has fully grown and spread on the covers. Therefore, Lysimeter #1 was the only lysimeter modelled, since it offered the longest percolation records available. Further stages of this research will model the remainder of the lysimeters, once additional field data becomes available.

A series of sensitivity analyses were conducted to assess the effect of the saturated hydraulic conductivity of the barrier layer (i.e. compacted clayey till) and the Leaf Area Index (LAI) in the numerical model results. The following sections summarize the predictive numerical models setup and sensitivity analyses conducted.

5.1 Models Setup

The duration of the simulation period was 365 days, from February 15 2011 to February 14 2012. The starting date was selected based on the first percolation records available from the lysimeters experiment, for comparison and calibration purposes. The components of the predictive numerical model set up included:

- finite elements mesh,
- initial conditions,
- boundary conditions,
- soil properties, and
- calibration of the numerical models.

5.1.1 Finite Elements Mesh

The models were developed to represent the waste rock and cover system in Lysimeter #1, following the layout presented in Table 3-1 and Figure 3-5, in Chapter 3 (Field Experiment) of this thesis. Elevations at the center of the lysimeters were used as reference points for the modelled layers. Therefore, the model profile consisted of 132.5 cm of waste rock overlain by 60 cm of compacted clayey glacial till and 30 cm of topsoil (Figure 5-1). As shown in Figure 5-1, nodes spacing was gradually incremented in each layer, which resulted in a higher concentration of nodes in the upper and bottom sections of each layer. A higher concentration of nodes was preferred in the upper layers (i.e. topsoil and compacted clayey till layer) given that evapotranspiration and percolation through the low permeability layer are the key factors of the performance of the cover system. A 0.1 cm and 0.2 cm node spacing with an expansion factor of 1.2 and 1.5 were used for the topsoil and compacted clayey till layers, respectively. The maximum node spacing was 2 cm in both cases.

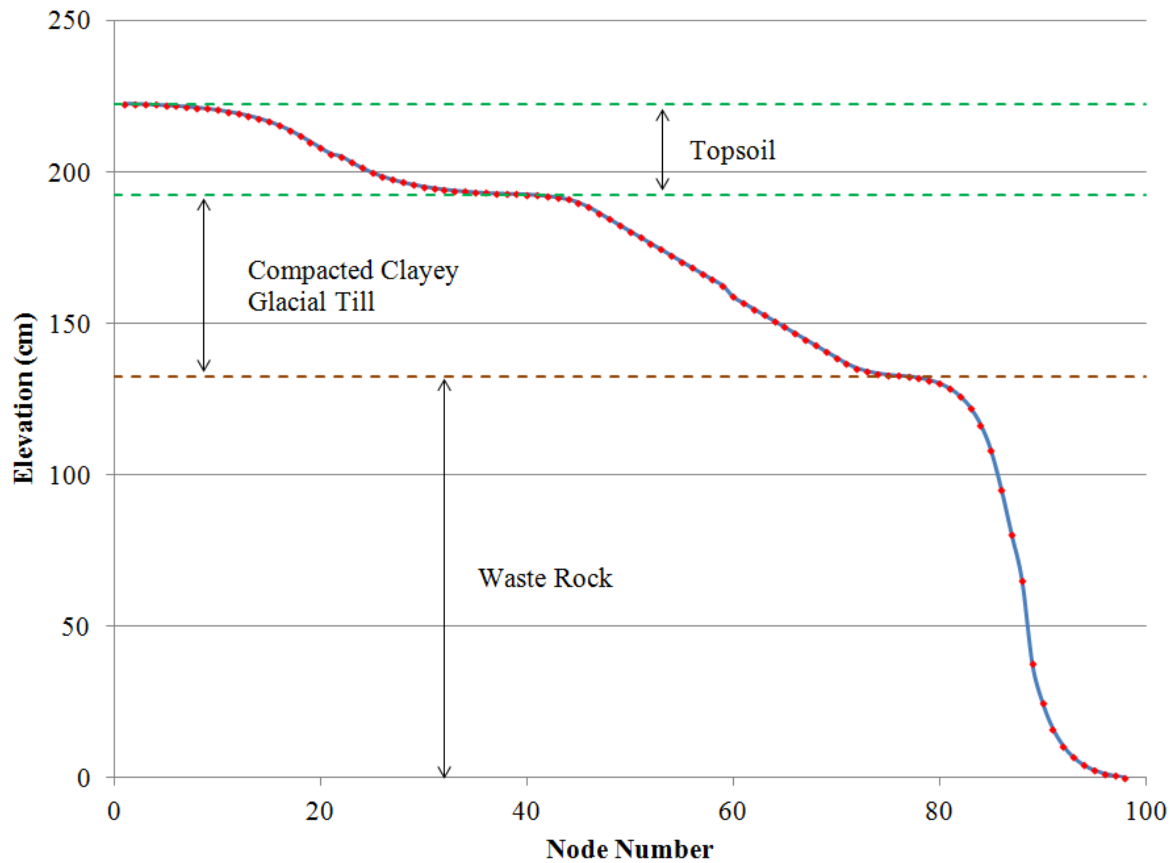

Figure 5-1 Nodal Distribution adopted for the Numerical Models

5.1.2 Initial Conditions

Initial suction and temperature conditions were required as top and bottom conditions for each layer. This data should have been obtained from the FTC-100 sensors installed in the cover systems, but the malfunctioning of the datalogger prevented the data from being recorded in 2011. Therefore, suction and temperature initial conditions were estimated for the first run and then adjusted based on the model results. An iterative process was followed until the initial conditions were consistent with results from the numerical model. Table 5-1 presents the suction and temperature input in the predictive numerical models.

Table 5-1 SoilCover Initial Conditions

	Top Suction (kPa)	Bottom Suction (kPa)	Top Temperature (°C)	Bottom Temperature (°C)
Topsoil	1	1	25	25
Compacted clayey till	1	4	25	25
Waste rock	4	0	25	25

5.1.3 Boundary Conditions

Daily records from the Yanacancha weather station and Punto B rain gauge were used as boundary conditions for the estimation of evapotranspiration and percolation through the modelled cover systems. These daily records included maximum and minimum air temperature, maximum and minimum relative humidity, wind speed, precipitation, and net radiation or pan evaporation. Records used in the modelling component of this thesis are the ones presented in Chapter 4 (Field and Laboratory Data) of this document.

Suction at the bottom of the lysimeter (i.e. bottom of the waste rock layer) was also specified, throughout the whole assessed year, as a boundary condition. The value assigned was 0 kPa, assuming there was no water table inside the lysimeters. This assumption was based on the coarse characteristics and therefore high hydraulic conductivity of the waste rock. Vegetation parameters were also included in the model in the form of Leaf Area Index (LAI). The Leaf Area Index is a representation of the amount of leaves on a given area (e.g. on the topsoil layer of the cover system) and it is directly related to the potential transpiration of that area. It is defined as the surface area of leaves per unit of ground surface area. For example, a LAI = 1 implies that the ground surface area is the same as the one-sided area of the leaves. LAI can be input as Poor (LAI = 1), Good (LAI = 2) or Excellent (LAI = 3) in SoilCover, representing the amount of vegetation on the cover surface. A higher LAI will increase the transpiration potential of the cover system (i.e. higher water demand from vegetation) and at the same time reduce the actual evaporation from the covers, by limiting the net radiation intercepted by the soil surface (i.e. additional shade). A poor LAI was selected for the base case model in this thesis, given the early stages of vegetation growth by the time field data was recorded. The vegetation roots depth also plays a key role in the potential transpiration from the covers. Roots were modeled to reach up to 300 mm depth based on Antamina experience with the vegetation species '*ichu*' used on the cover systems. Finally, the daily duration of the precipitation events had to be input as well. An average of 12 hours rain events per day was deemed appropriate for this case.

5.1.4 Soil Properties

Soil-water characteristic curves and saturated hydraulic conductivity values for the topsoil and compacted clayey till materials, presented in section 4.2 (Laboratory Data) of this thesis, were input into the SoilCover model. Given the impracticability of shipping waste rock samples from Peru to Canada, where the SWCC tests were conducted, the Soil-water characteristic curve and saturated hydraulic conductivity used to represent the waste rock at Antamina were based on tests conducted for Golden Sunlight waste rock and included in the SoilCover data base. Figure 5-2 shows the waste rock soil-water characteristic curve input in the predictive numerical models.

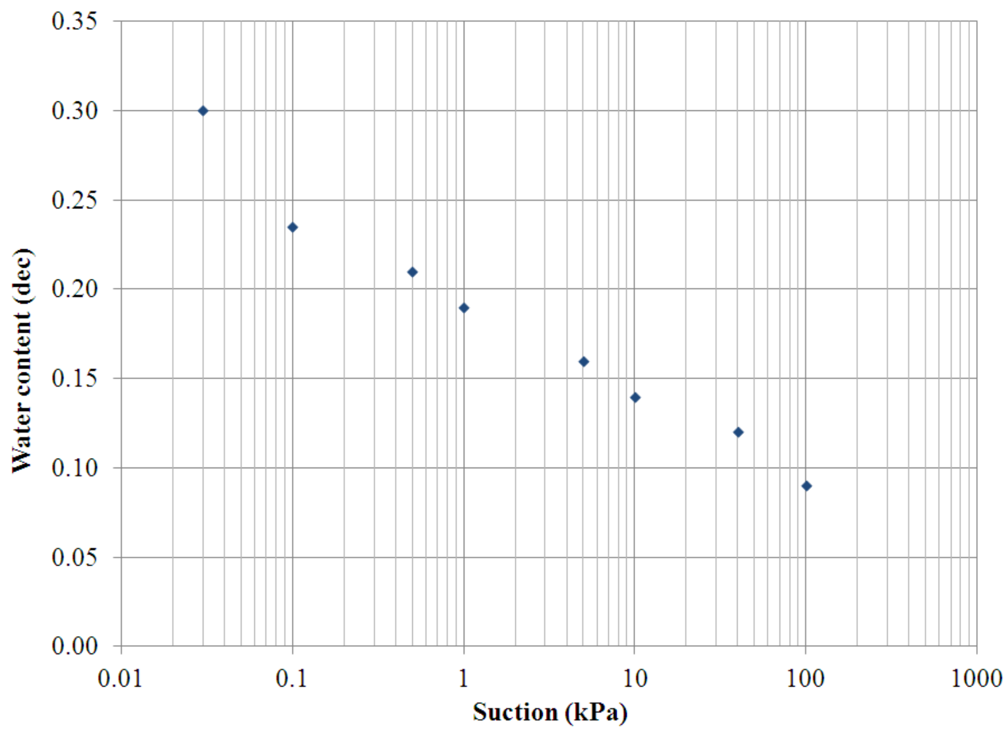

Figure 5-2 Waste Rock SWCC Adopted from SoilCover Data Base

5.1.5 Calibration of the Model

Calibration of the predictive numerical models was conducted by comparing percolation and runoff from the field experiment with results from the SoilCover model. The non-calibrated numerical model, based on the compacted clayey till hydraulic conductivity obtained from laboratory tests (i.e. 2 x10^{-9} m/s) showed approximately 470 mm of runoff by the end of the model year, in clear contradiction with lack of runoff recorded in the field experiment (Figure 5-3). As a consequence, the predicted net percolation through the system was lower than the values recorded by the tipping buckets in the field. The reason behind the existence of runoff in the numerical models was most likely due to the input of low saturated hydraulic conductivity values obtained for the compacted clayey till in the laboratory tests. In the numerical model, precipitation was shown to overwhelm the storage capacity of the topsoil layer because the underlying compacted clayey till was not allowing water to percolate downward fast enough. Even if generating runoff was the original objective of the glacial till layers in the cover systems, this was not what was actually occurring in the field. Therefore, the saturated hydraulic conductivity of the compacted clayey till layer was deemed to be higher in the field than the results obtained from laboratory testing. As a result, saturated hydraulic conductivity of the compacted clayey till layer was increased to the point where no runoff was generated, effectively increasing it from $2x10^{-9}$ m/s to $7x10^{-8}$ m/s. The adjusted saturated hydraulic conductivity of the compacted clayey till layer was obtained from field percolation records by averaging the precipitation rates recorded during the wettest months of the rainy season.

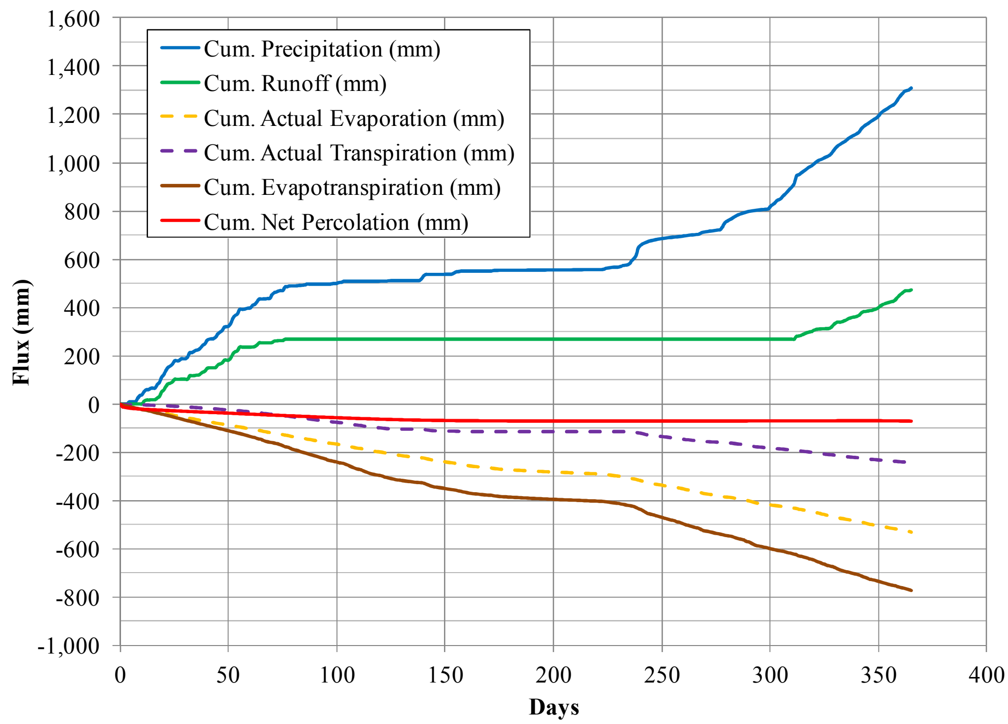

Figure 5-3 Numerical Model Results before Calibration

5.2 Sensitivity Analyses

A series of sensitivity analysis were conducted to assess the effect of the leaf area index (LAI), the saturated hydraulic conductivity (K_{sat}) of the compacted clayey till layer, and the thickness of the topsoil layer with respect to the performance of the cover systems.

5.2.1 Leaf Area Index

The leaf area index (LAI) is directly related to the evapotranspiration potential of the cover system, and therefore to net percolation. The LAI effect in the predictive numerical models was assessed by modifying the original leaf area index option in SoilCover from Poor

Grass to Good Grass and Excellent Grass. A fourth case was also analyzed without vegetation. While running the LAI sensitivity analyses, the other input parameters were kept constant as in the base case. Figure 5-4 shows the LAI options available in SoilCover.

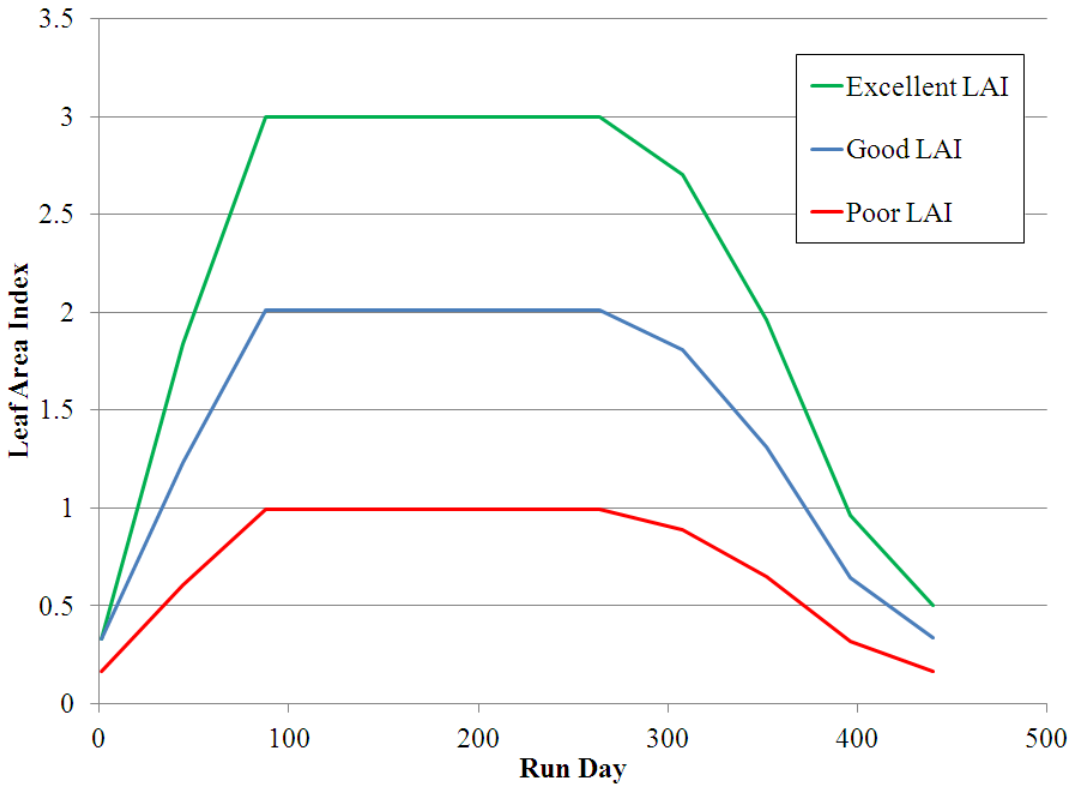

Figure 5-4 Leaf Area Index Options Available in the SoilCover Model

5.2.2 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of the compacted clayey till layer was adjusted in the predictive numerical models to assess the effect that more permeable or less permeable layer would have on the net percolation through the cover systems. These lower or higher hydraulic conductivities can be achieved by modifying the material type and/or compaction degree of the water barrier layer in the cover systems.

Five alternate values of saturated hydraulic conductivities were included in the sensitivity analysis, two higher and three lower compared to the base case as shown in Table 5-2. While running the saturated hydraulic conductivity sensitivity analyses, the other input parameters were kept constant as in the base case.

Table 5-2 Sensitivity Analyses Hydraulic Conductivities

	K_{sat} (m/s)	Comment
Base Case	$7x10^{-8}$ m/s	
Case 1	$2x10^{-7}$ m/s	Similar to the highest peak percolations recorded from Lysimeter #1.
Case 2	$7x10^{-7}$ m/s	Higher than case 1 and any percolation rate recorded. Selected as the upper bound k_{sat}.
Case 3	$2x10^{-8}$ m/s	Similar to non-compacted clayey till k_{sat} obtained from laboratory tests.
Case 4	$7x10^{-9}$ m/s	One order of magnitude less than base case, and intermediate point between cases 3 and 5.
Case 5	$2x10^{-9}$ m/s	Compacted clayey till k_{sat} obtained from laboratory tests.

5.2.1 Topsoil Layer Thickness

The thickness of the topsoil layer, along with its porosity, is related to the storage capacity of the store and release layer of the cover systems. The original 300 mm thick topsoil layer was reduced in the sensitivity analysis to 100 mm and 50 mm, in order to assess if such a reduction would influence the generation of runoff from the cover systems in the field. The maximum vegetation root depth was also modified in this sensitivity analysis from 300 mm to the reduced thicknesses of the topsoil layer (i.e. 100 mm and 50 mm), assuming that *ichu* roots will not penetrate the compacted clayey till layer.

CHAPTER 6. DISCUSSION AND ANALYSIS OF RESULTS

The following section presents and compares the results of the field experiment (based on data collected between February 15, 2011 and February 14, 2012) with the calibrated predictive numerical models. It should be noted that precipitation volumes used in the analysis for the performance of the cover systems, represent estimated values obtained from Punto B precipitation records applied to a 15 m by 15 m area (i.e. the area of the lysimeters). This assumes a uniform distribution of rain over the surface of the cover systems, which is not necessarily the case, but is deemed an acceptable simplification given the relatively small area of the lysimeters.

6.1 Field Experiment First Rainy Season Results

After analyzing 365 days of Lysimeter #1 data, consisting of precipitation and percolation records between February 15, 2011 and February 14, 2012, approximately 68% of the total precipitation received at the experimental cover system was reported as percolation. Lysimeters #4 and #5 reported percolations of 66% and 58%, respectively, during the assessed 328 days (between March 24, 2011 and February 14, 2012). Lysimeter #3 (i.e. the control) presented the highest percolation of all the lysimeters equal to 70% of the precipitation recorded over its assessed period of time (between April 20, 2011 and February 14, 2012). Finally, Lysimeter #2 was only functional during 179 days of the experiment (between March 24 and September 19, 2011, mostly during the dry season), and reported 67% percolation over that period of the time.

Figures 6-1 to 6-9 present daily and cumulative comparisons between precipitation and net percolation records, for all the five lysimeters constructed at Punto B. The cover system installed in Lysimeter #1 (compacted clayey till and topsoil) reported net percolation equivalent to the 88% of the net percolation produced by the control lysimeter. Similarly, Lysimeter #4 (topsoil) and Lysimeter #5 (compacted silty till and topsoil) reported net percolations of 90% and 76%, respectively, when compared to the control lysimeter. Net percolation values recorded from the five lysimeters are fairly similar and follow the same trend (Figure 6-9).

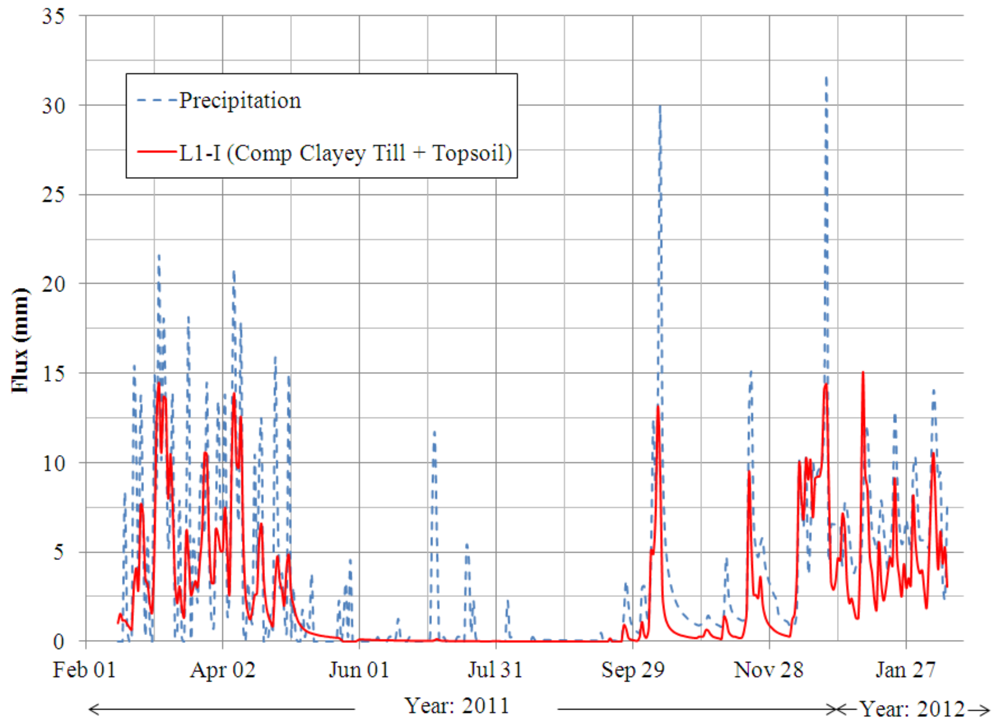

Figure 6-1 Daily Precipitation and Lysimeter #1 Net Percolation (Feb 15, 2011 to Feb 14, 2012)

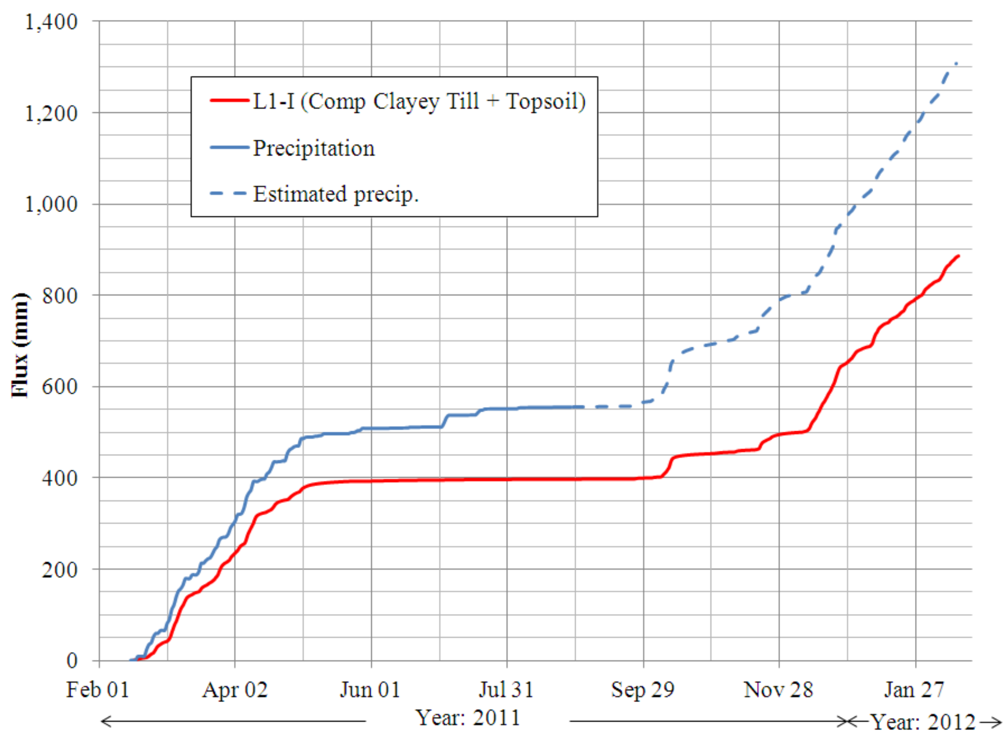

Figure 6-2 Cumulative Precipitation and Lysimeter #1 Net Percolation Records (Feb 15, 2011 to Feb 14, 2012)

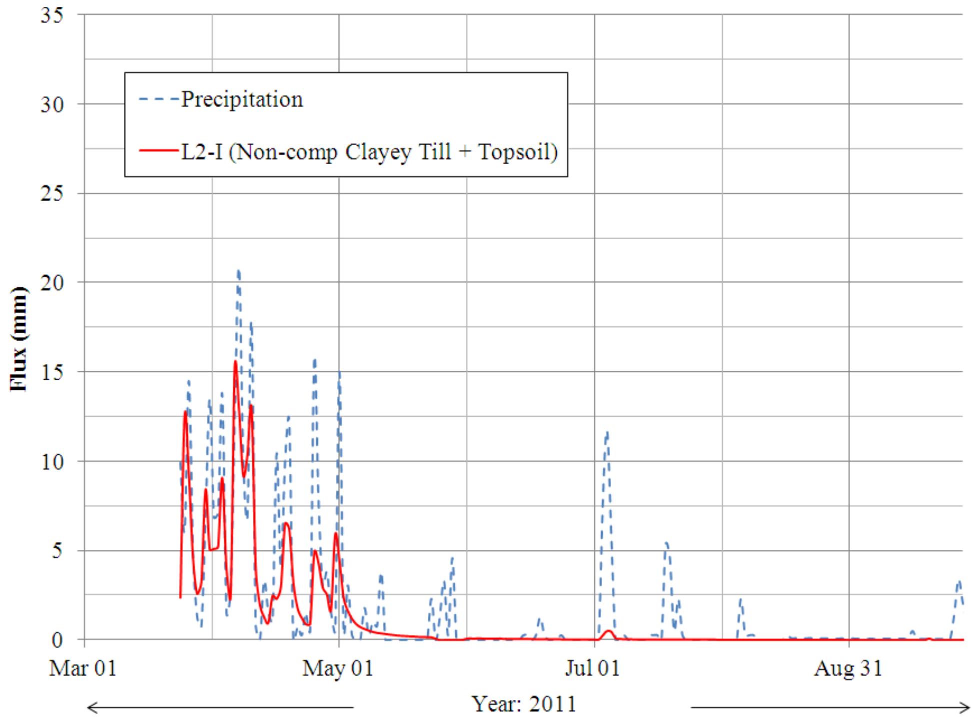

Figure 6-3 Daily Precipitation and Lysimeter #2 Net Percolation (Mar 24 to Set 19, 2011)

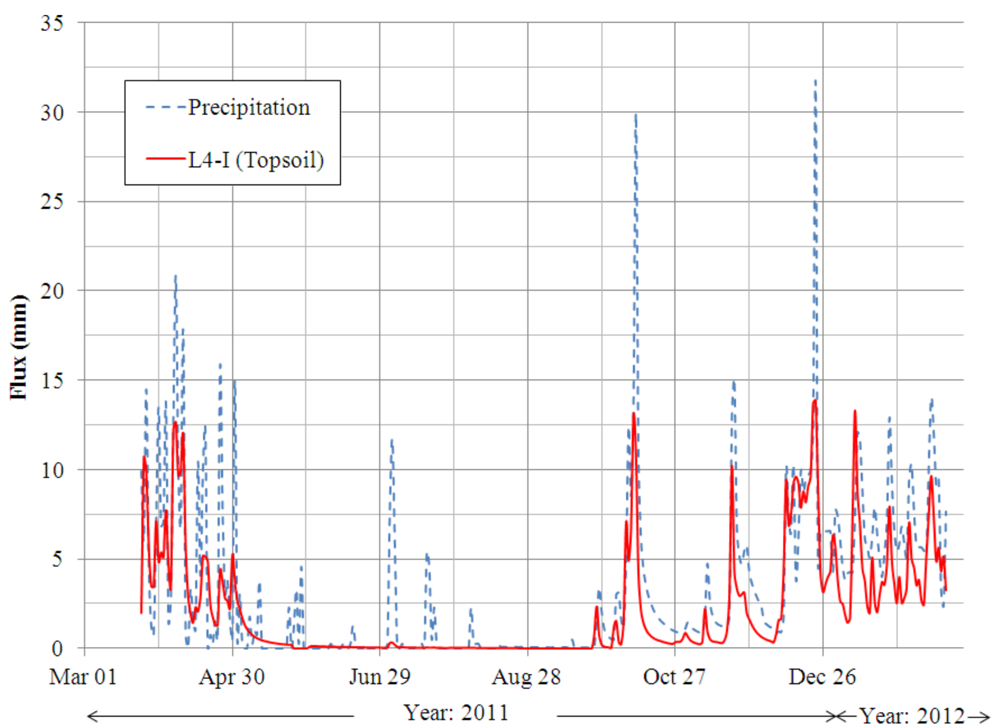

Figure 6-4 Daily Precipitation and Lysimeter #4 Net Percolation (Mar 24, 2011 to Feb 14, 2012)

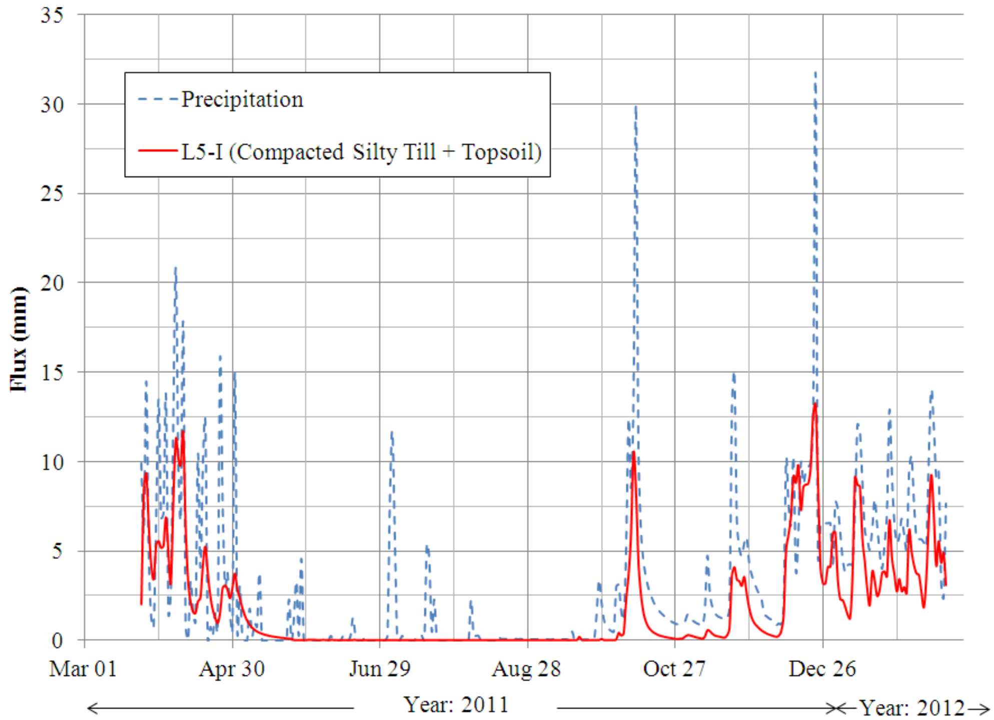

Figure 6-5 Daily Precipitation and Lysimeter #5 Net Percolation (Mar 24, 2011 to Feb 14, 2012)

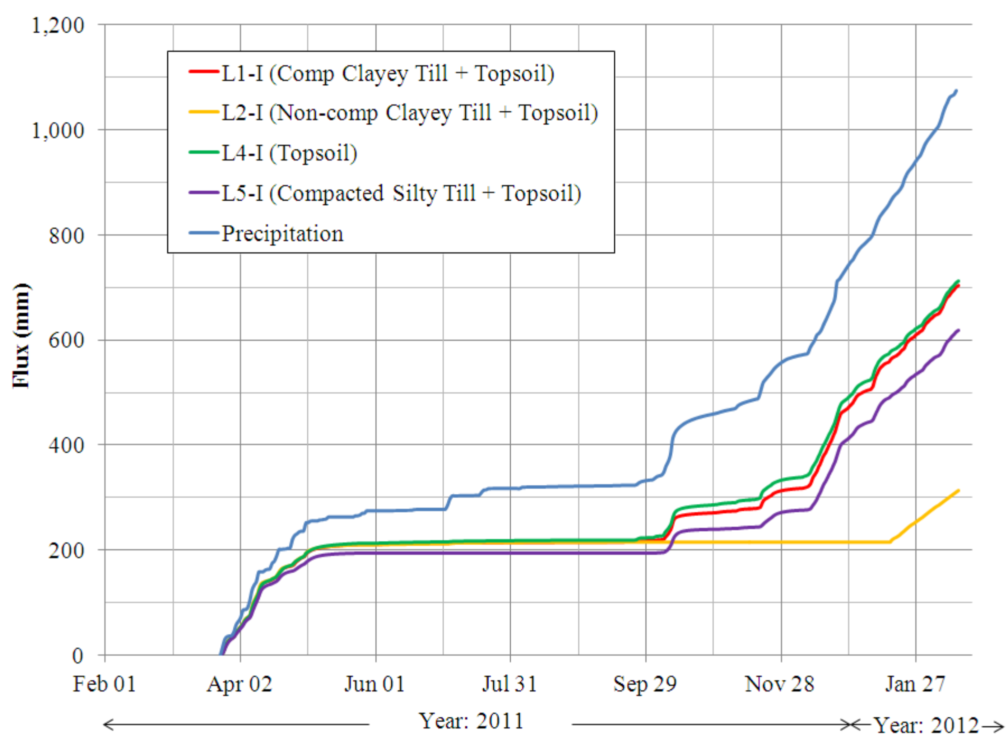

Figure 6-6 Cumulative Precipitation and Lysimeters #1, #2, #4, and #5 Net Percolation Records (Mar 24, 2011 to Feb 14, 2012)

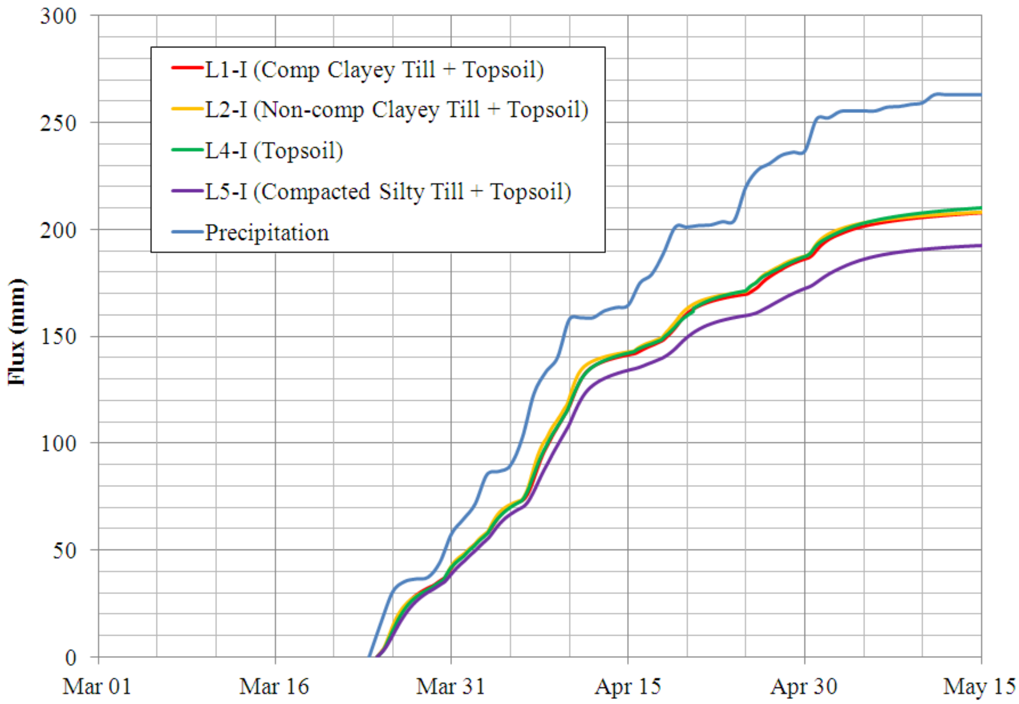

Figure 6-7 Cumulative Precipitation and Lysimeters #1, #2, #4, and #5 Net Percolation Records (Zoom-In between Apr 20 and May 15, 2011)

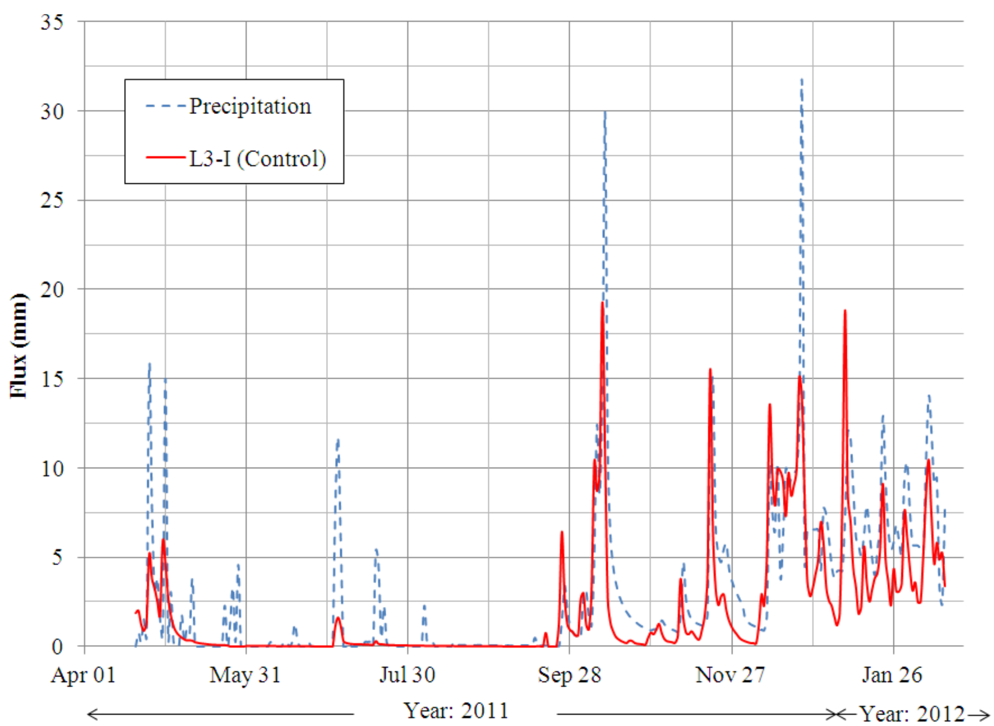

Figure 6-8 Daily Precipitation and Lysimeter #3 Net Percolation (Apr 20, 2011 to Feb 14, 2012)

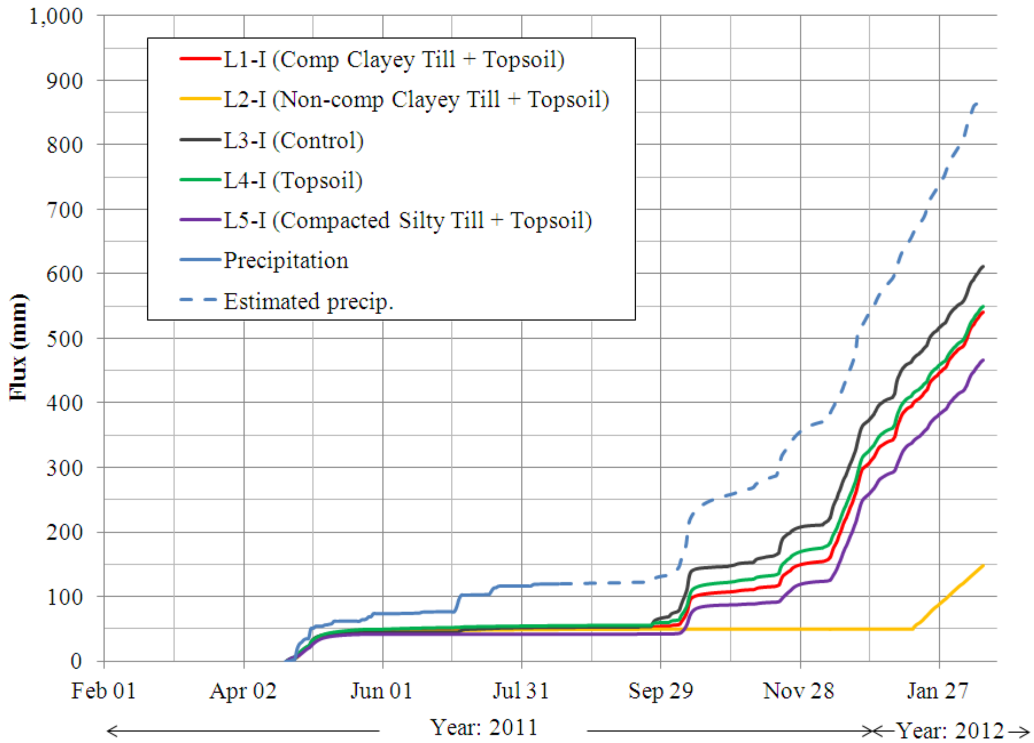

Figure 6-9 Cumulative Precipitation and Lysimeters #1, #2, #3, #4, and #5 Net Percolation Records (Apr 20, 2011 to Feb 14, 2012)

As the daily records illustrate (Figures 6-1, 6-3, 6-4, 6-5 and 6-8), net percolation does not always represent the same fraction of the correspondent daily precipitation value. This is due to the fact that daily net percolation recorded is dependent on the potential evaporation available on each specific date, as well as the degree of saturation/storage of the cover system and underlying waste rock at the time when percolation occurs. There is also a time lag between the occurrence of the precipitation event and the corresponding percolation of water reaching the tipping bucket. All this complicates the assessment of daily records and must be taken into consideration when drawing conclusion from the data. Daily records also demonstrate that there is a general agreement between the estimated precipitation records and the reported percolations.

The recorded precipitation data indicates that rainfall occurred at the cover study site with an average intensity of 6.8×10^{-8} m/s between February 15 and May 11, 2011. This value is higher than saturated hydraulic conductivity measured in the laboratory for the compacted clayey till specimen (2.1×10^{-9} m/s), and within the same order of magnitude for the saturated hydraulic conductivities obtained from the non-compacted clayey till ($3x10^{-8}$ m/s) and the compacted silty till ($7.3x10^{-8}$ m/s). When looking at the highest daily, weekly and 15-day rainfall records, precipitation rates are even higher. Table 6-1 summarizes the highest rainfall events based on the recorded data (February 15 to August 16, 2011) and the estimated data (August 17, 2011 to February 14, 2012). Table 6-2 presents the highest daily, weekly and 15-day percolation rates recorded for all five lysimeters. It should be noted that only three records are being reported from lysimeters #2 and #3 given the lack of available percolation records in late 2011 and early 2011, respectively.

Table 6-1 Highest Precipitation Events (Feb 15, 2011 – Feb 14, 2012)

Date	**Precip. (mm)**	**Precip. Rate (m/s)**	**Comment**
March 5, 2011	21.6	$2.5x10^{-7}$	Daily recorded precip.
December 23, 2011	31.7	$3.7x10^{-7}$	Daily estimated precip.
March 3-9, 2011	91.2	$1.5x10^{-7}$	Weekly recorded precip.
December 17-23, 2011	91.8	$1.5x10^{-7}$	Weekly estimated precip.
February 22 - March 8, 2011	142.5	$1.1x10^{-7}$	15-day recorded precip.
December 11-25, 2011	147.3	$1.1x10^{-7}$	15-day estimated precip.

Table 6-2 Percolation Rates Recorded (Feb 15, 2011 – Feb 14, 2012)

Lysimeter #1			
Date	**Percolation (mm)**	**Percolation Rate (m/s)**	**Comment**
March 5, 2011	14.5	$1.7x10^{-7}$	Daily, 2010-2011 rainy season
January 8, 2012	15.1	$1.7x10^{-7}$	Daily, 2011-2012 rainy season
March 4 – March 10, 2011	83.4	$1.4x10^{-7}$	Weekly, 2010-2011 rainy season
December 18 – December 24, 2011	75.1	$1.2x10^{-7}$	Weekly, 2011-2012 rainy season
February 25 – March 11, 2011	121.6	$9.4x10^{-8}$	15-day, 2010-2011 rainy season
December 10 – December 24, 2011	140.2	$1.1x10^{-7}$	15-day, 2011-2012 rainy season

Lysimeter #2			
Date	**Percolation (mm)**	**Percolation Rate (m/s)**	**Comment**
April 6, 2011	15.3	$1.8x10^{-7}$	Daily, 2010-2011 rainy season
April 5 – April 11, 2011	67.1	$1.1x10^{-7}$	Weekly, 2010-2011 rainy season
March 27 – April 10, 2011	110.4	$8.5x10^{-8}$	15-day, 2010-2011 rainy season
Lysimeter #3			
Date	**Percolation (mm)**	**Percolation Rate (m/s)**	**Comment**
October 10, 2011	19.3	$2.2x10^{-7}$	Daily, 2010-2011 rainy season
December 18 – December 24, 2011	74.5	$1.2x10^{-7}$	Weekly, 2010-2011 rainy season
December 10 – December 24, 2011	147.0	$1.1x10^{-7}$	15-day, 2010-2011 rainy season
Lysimeter #4			
Date	**Percolation (mm)**	**Percolation Rate (m/s)**	**Comment**
April 7, 2011	12.7	$1.5x10^{-7}$	Daily, 2010-2011 rainy season
December 23, 2011	13.9	$1.6x10^{-7}$	Daily, 2011-2012 rainy season
April 5 – April 11, 2011	65.8	$1.1x10^{-7}$	Weekly, 2010-2011 rainy season
December 18 – December 24, 2011	72.4	$1.2x10^{-7}$	Weekly, 2011-2012 rainy season
March 28 – April 11, 2011	107.7	$8.3x10^{-8}$	15-day, 2010-2011 rainy season
December 10 – December 24, 2011	136.4	$1.1x10^{-7}$	15-day, 2011-2012 rainy season
Lysimeter #5			
Date	**Percolation (mm)**	**Percolation Rate (m/s)**	**Comment**
April 10, 2011	11.6	$1.3x10^{-7}$	Daily, 2010-2011 rainy season
December 23, 2011	13.2	$1.5x10^{-7}$	Daily, 2011-2012 rainy season
April 6 – April 12, 2011	60.4	$1.0x10^{-7}$	Weekly, 2010-2011 rainy season
December 18 – December 24, 2011	70.3	$1.2x10^{-7}$	Weekly, 2011-2012 rainy season
March 27 – April 10, 2011	101.0	$7.8x10^{-8}$	15-day, 2010-2011 rainy season
December 10 – December 24, 2011	127.2	$9.8x10^{-8}$	15-day, 2011-2012 rainy season

As discussed previously in Chapter 2, the two principal mechanisms to reduce water percolation through the experimental cover systems are runoff generation and evapotranspiration, and to a lesser degree storage created by low permeable layers. Observed results obtained during the first rainy season of the experiment differ from initial research expectations, especially when comparing the performance of the different cover systems with each other. Lysimeters #1 and #5, the compacted clayey and silty till respectively, were expected to report lower percolations than Lysimeter #4 (topsoil only), for example. There are a number other factors that may be affecting the hydraulic conductivity and overall performance of the cover systems.

The results presented in Tables 6-1 and 6-2, along with the lack of runoff generated during the assessed period of time, suggest that net percolation has been most strongly dependent on rainfall intensity relative to the cover systems hydraulic conductivity. Rainfall intensities, as seen in the recorded period of this study are not high enough to generate runoff from the topsoil covers, since they do not exceed the infiltration or storage capacity of the topsoil layers. The observed results indicate that water is currently infiltrating the topsoil layer of the cover system and is being temporarily retained above the low permeability layers, until it drains down through to the underlying waste rock. If the rainfall intensities at Punto B were high enough to overwhelm the storage capacity of the topsoil layer, runoff would have been generated and the associated net percolation may have been reduced even further. As this is evidently not the case, the difference between rainfall and percolation is primarily attributed to evapotranspiration for all the lysimeters and to a lesser degree to storage.

No significant losses of water due to leakage of the piping system have been identified to date, and consistency between the different lysimeters percolation records rule out instruments malfunction as a source of error, except those already recognized in this thesis. However, construction of the compacted clayey till and compacted silty till covers in a sequence of 150 mm and 200 mm layers, respectively, may have had an adverse effect in reducing the permeability of the covers. The glacial till at Antamina is known to be highly variable and in some cases presented particles larger than 100 mm. During the construction of the compacted covers, particles greater than 100 mm were removed by hand from but it was very difficult to detect all of them, and the possibility that some particles larger than 100 mm remained in the cover. If this is the case, particles of this size in a 150 mm or even

200 mm layer may reduce the amount of fine material encapsulating the larger particles, thus creating areas with a higher permeability. The clayey till was considered to be coarser than the silty till, and therefore Lysimeter #1 has a highest probability of containing oversized particles in the low-permeability layer compared to Lysimeter #5.

Hydraulic conductivity varies depending on the water content of the material at the time of compaction. Clay soils tend to show a significantly higher hydraulic conductivity when compacted on the dry side of the Proctor test curve (i.e. water content below the optimum water content) compared to the same soils compacted wet of optimum (Daniel, 1981; Rogowski, 1990). As was described in Chapter 3, clayey till and silty till were compacted in a drier state than the optimum water content determined by the standard Proctor test for each material. Even if the glacial till used to build the cover systems at Antamina was not strictly a clay soil, the high content of coarse particles in the material and its drier than optimum state during compaction may have resulted in a higher hydraulic conductivity for the compacted covers.

Finally, it should be noted that hydraulic conductivities obtained from laboratory tests may differ from field values (Daniel, 1981); as they represent the hydraulic conductivity for a test specimen, at a given porosity and under different stress conditions compared to those encountered in the field. It is very difficult to obtain a truly undisturbed sample from the field and test it under the same conditions in the laboratory. Flow through macro-pores, such as the ones potentially present in the compacted layers of the cover systems due to the presence of bigger than expected particles (as discussed above), is unlikely to be represented by a conventional hydraulic conductivity test conducted in a laboratory. Nevertheless, laboratory tests are necessary and should ideally be compared with field permeability results to improve the understanding of the characteristics for the materials being assessed.

As mentioned in section 4.1.4 of this thesis, no runoff has been registered by any lysimeter to date. Horizontal flow may have been generated between the low permeability and topsoil layers of the cover systems, but this could not be captured and measured because of the location of the runoff pipes (i.e. at the surface of the cover systems). Nevertheless, this interlayer flow was not considered to have the potential to reduce net percolation, and thus a second "runoff" pipe located between the aforementioned layers was not deemed necessary.

Runoff and interlayer flows in the full-scale cover systems, for the actual waste rock dumps, will only travel a limited distance before infiltrating/percolating. Runoff on the full-scale cover systems may be captured by the surficial (e.g. erosion control) channels and diverted away from the facility, but once water infiltrates the topsoil layer it will inevitably percolate unless it is removed from the system by evapotranspiration.

6.2 Predictive Numerical Models Results

Figure 6-10 presents the water balance of the calibrated, base case model (Lysimeter #1, K_{sat} = 7x10^{-8} m/s). Positive values in the following graphs represent fluxes entering the model mesh (i.e. precipitation) or not entering the mesh (i.e. runoff), whereas negative values represent fluxes leaving the model mesh (i.e. evaporation, transpiration and net percolation). Net percolation is represented in the following graphs as "Cum. int flx (mm)". As expected, the model results predict no runoff occurs (due to the calibration of the saturated hydraulic conductivity of the low-permeability layer).

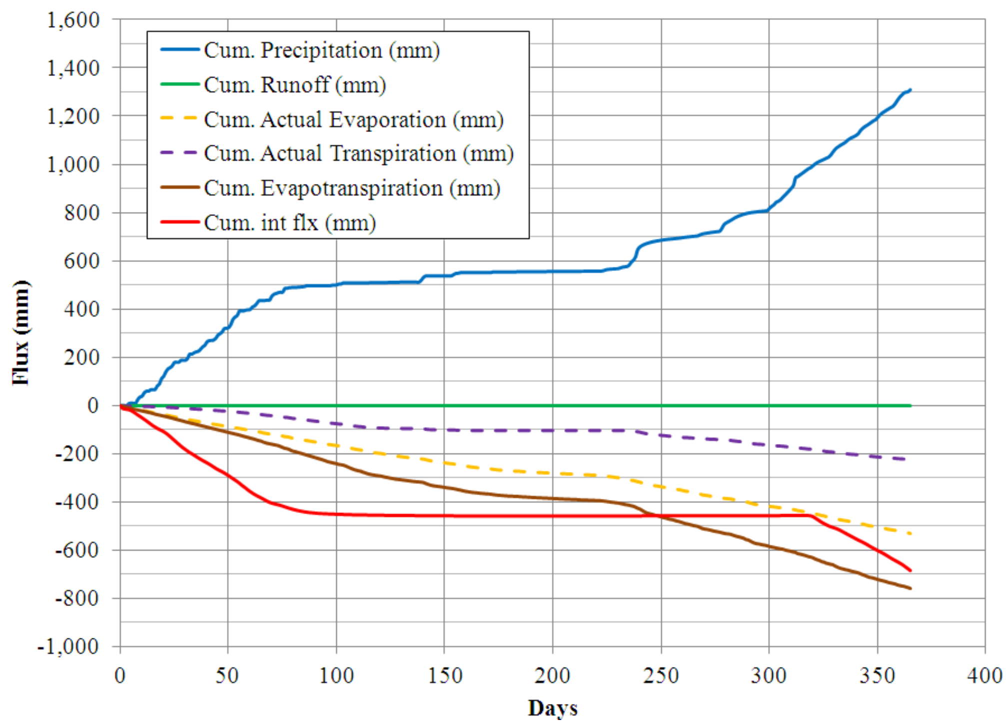

Figure 6-10 Base Case SoilCover Cumulative Water Balance

As Figure 6-10 shows, the computed evapotranspiration obtained from the base case numerical model is, after one year, higher than the quantities for precipitation less net percolation (i.e. Cum. int flx). In general, net percolation should be equal total precipitation less evapotranspiration and runoff (change in storage is negligible in this case). However, results in Figure 6-10 suggest that water is being evapotranspirated from the total precipitation and from the moisture initially stored in the pores of the material. This process continues during the dry season when precipitation is significantly reduced.

6.2.1 Sensitivity Analyses

Three sensitivity analyses were conducted with the predictive numerical models, one varying the saturated hydraulic conductivity of the low-permeability layer of the cover system, a second one varying the presence and quantity of vegetation on the topsoil cover, and a finally a third case varying the thickness of the topsoil layer. Figures 6-11 to 6-13 illustrates the results of the first analysis (i.e. varying K_{sat}), whereas figures 6-14 to 6-16 and figures 6-17 to 6-18 present the results of the second (i.e. varying LAI) and third (i.e. varying topsoil thickness) analyses, respectively.

As shown in Figure 6-11, net percolation is significantly reduced when decreasing the saturated hydraulic conductivity of the low-permeability layer. Lowering the saturated hydraulic conductivity of the compacted clayey till by one order of magnitude, for example, reduces net percolation by 75% compared to the base case predictive model, representing only 13% of the total precipitation of the first rainy season. This reduction in net percolation is primarily due to the generation of runoff, as Figure 6-12 illustrates. Alternatively, increasing the saturated hydraulic conductivity of the compacted clayey till layer does not significantly increase the amount of net percolation from the cover system (Figure 6-13). In this case it is the quantity of precipitation less evapotranspiration that is controlling the amount of water percolating the cover system.

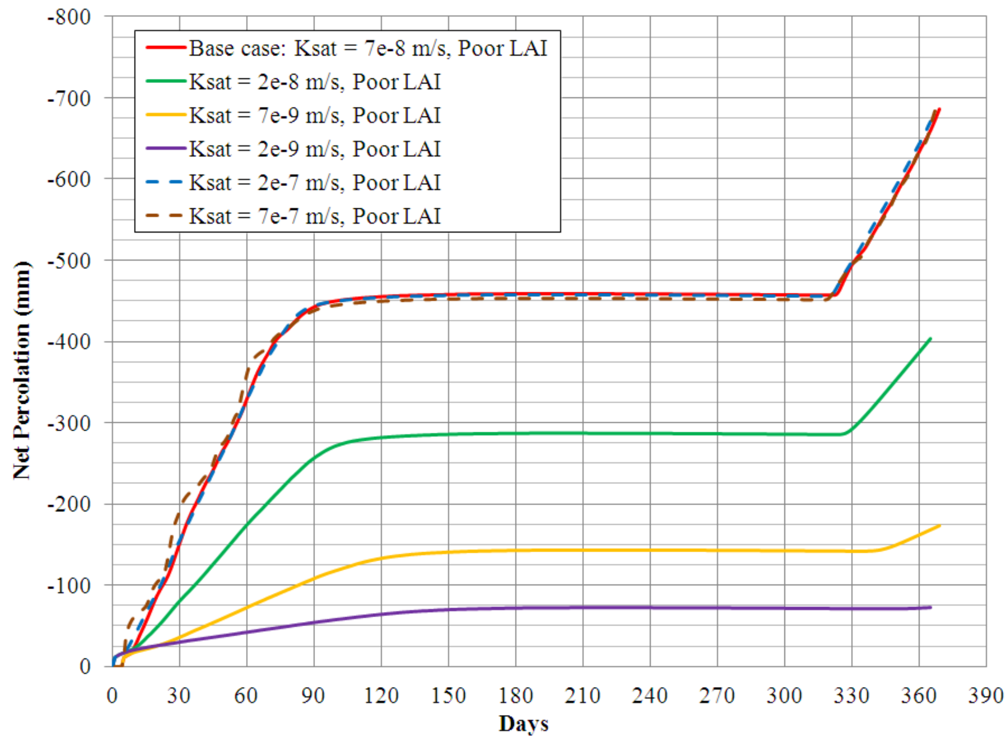

Figure 6-11 Net Percolation Results of All Sensitivity Analyses Varying Saturated Hydraulic Conductivity

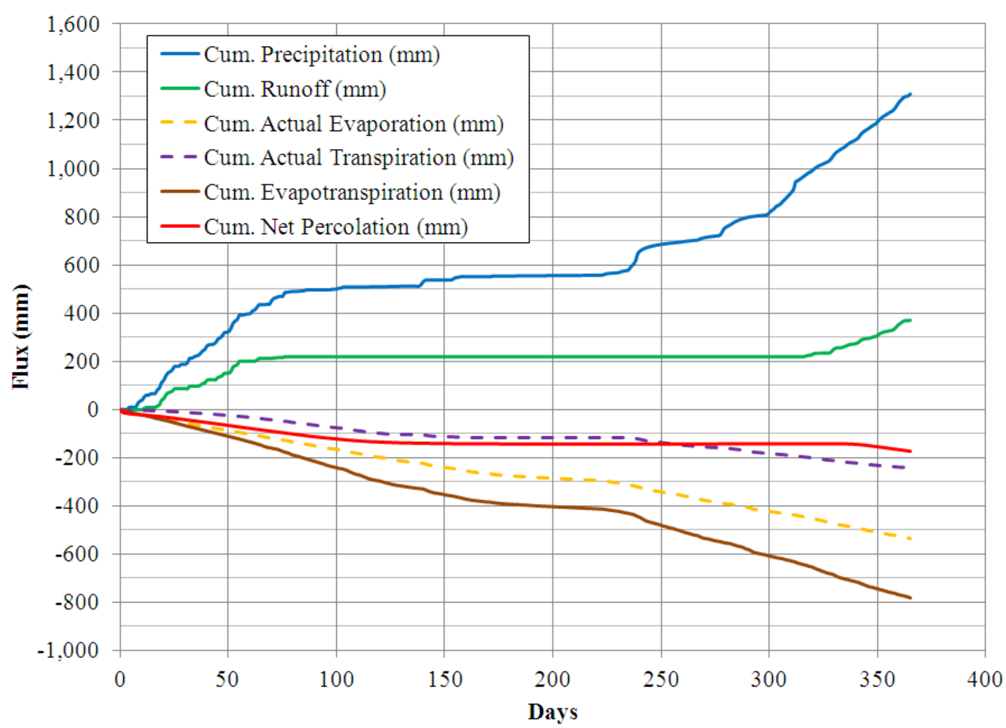

Figure 6-12 Flux Results from Sensitivity Analysis Varying K_{sat} ($K_{sat} = 7x10^{-9}$ m/s)

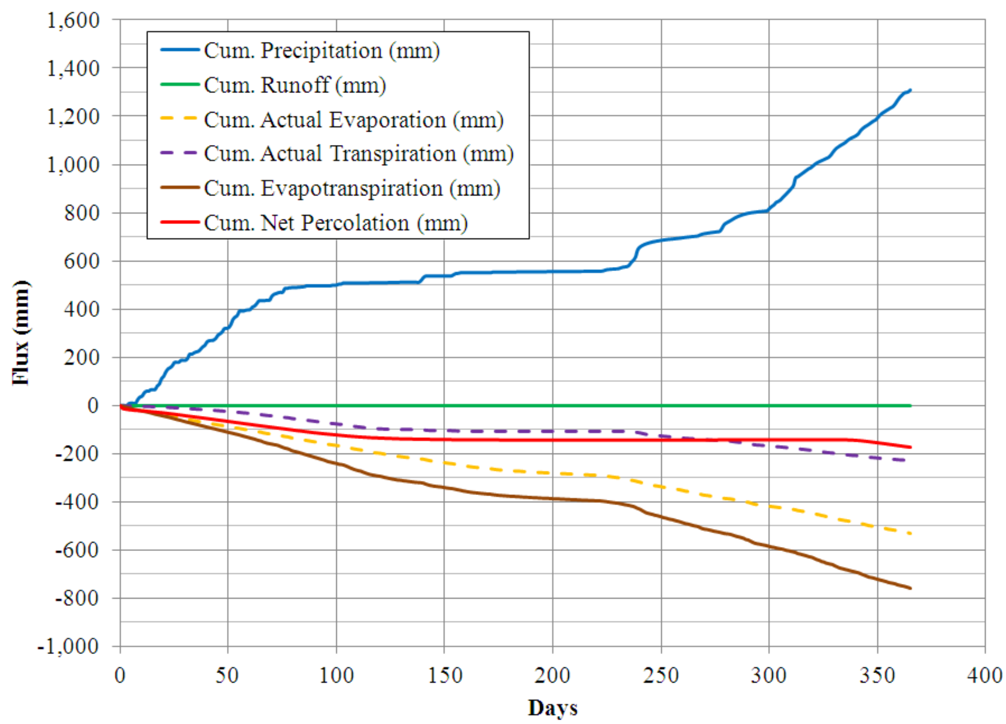

Figure 6-13 Flux Results from Sensitivity Analysis Varying K_{sat} ($K_{sat} = 7x10^{-7}$ m/s)

Results for the Leaf Area Index sensitivity analysis indicate that evapotranspiration will not be significantly increased by the development of vegetation on the cover systems. As figures 6-15 and 6-16 illustrate, potential transpiration from the numerical model varies when improving vegetation quality and quantity. However, both the actual transpiration and actual evaporation consume all the energy available to drive evapotranspiration thus reducing the influence of vegetation. In other words, even with poor vegetation, actual soil evaporation, based on the available potential evaporation energy at the site, remains high enough to compensate the lack of actual transpiration. Nevertheless, when the LAI is higher and the energy is used for transpiration, there is less available energy to maintain actual soil evaporation rates. It should be noted that the input used in the predictive numerical models for the estimation of evapotranspiration was obtained from the Yanacancha weather station. Using the same relevant parameters obtained from Punto B may offer different results, considering that actual evaporation and transpiration depend on the energy budget available at site, which in turn can significantly vary from one side of a mountain to another.

When comparing results from the poor, good and excellent LAI sensitivity analysis, percolation from the model with an excellent LAI reports a slightly higher percolation than the other two. This is probably due to the numerical features of the SoilCover model. Predicted percolation values from the three sensitivity analyses are fairly close (between 664 mm and 702 mm) and given the accuracy of the model, it is safe to assume percolation for all these three scenarios, given the current conditions, are practically the same.

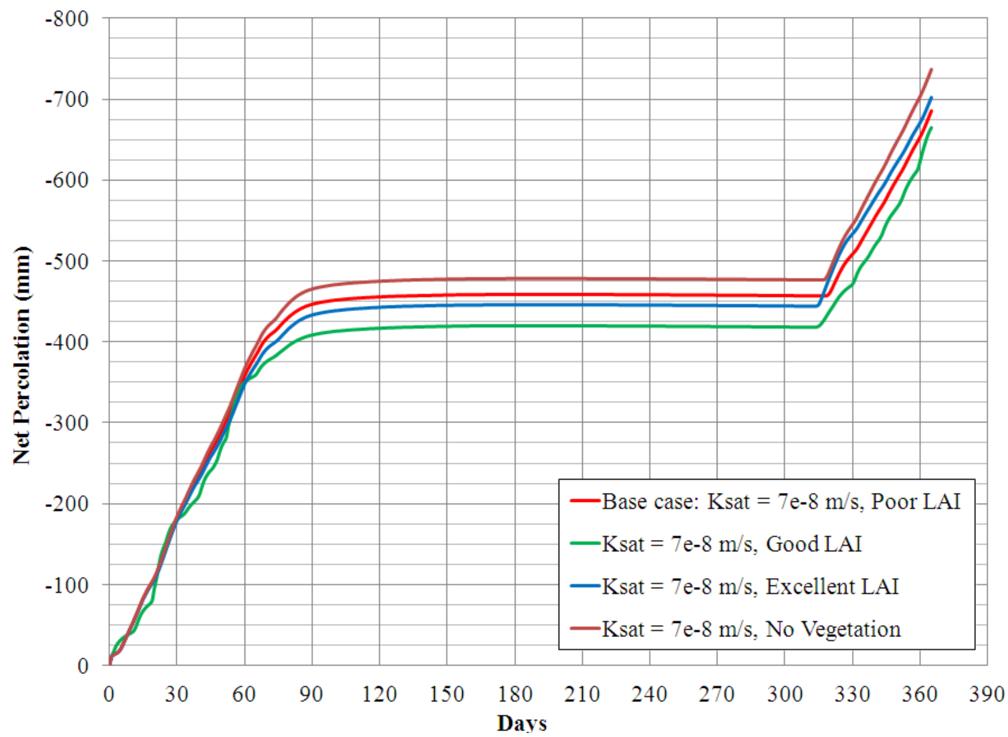

Figure 6-14 Net Percolation Results of Sensitivity Analyses Varying LAI

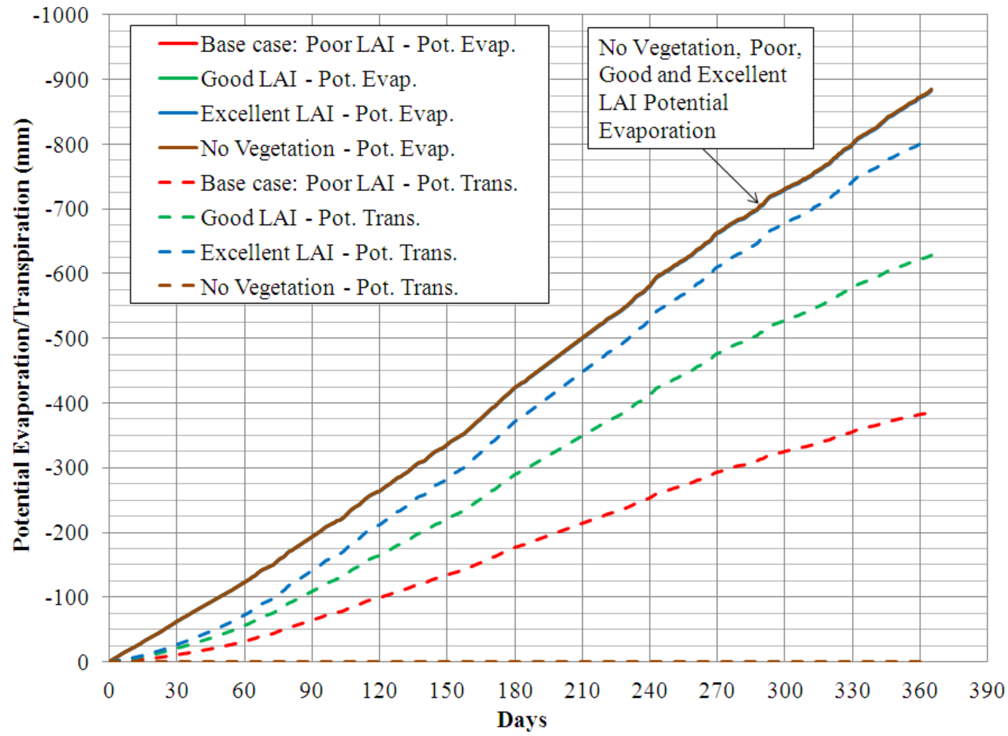

Figure 6-15 Potential Evaporation and Potential Transpiration from LAI Sensitivity Analysis

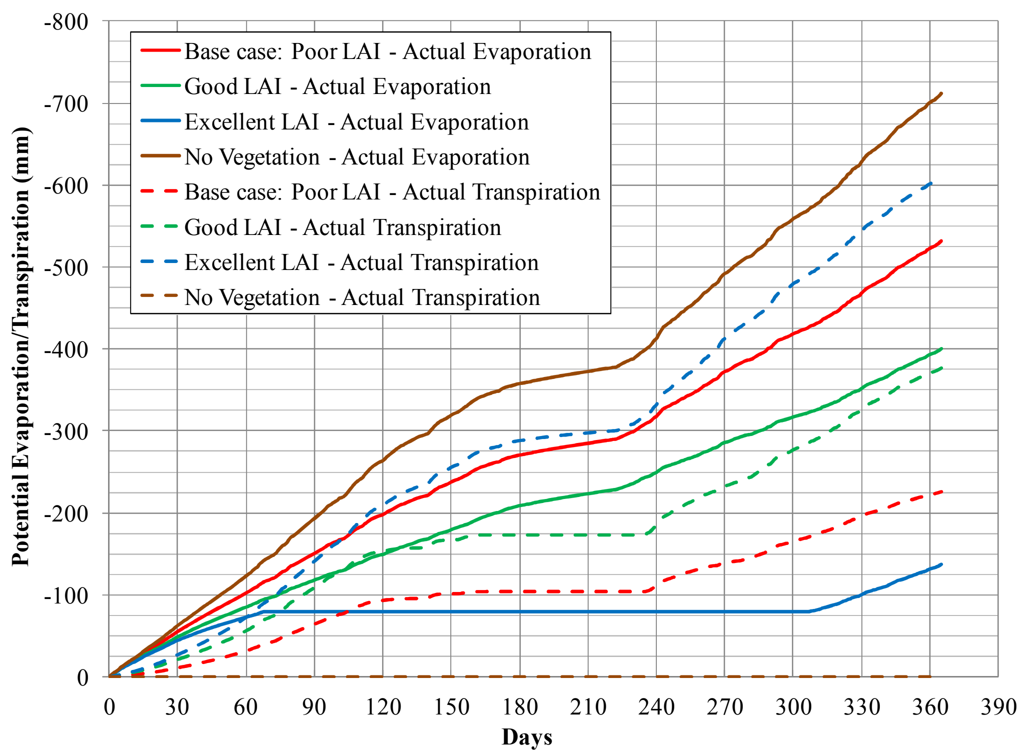

Figure 6-16 Actual Evaporation and Actual Transpiration from LAI Sensitivity Analysis

As Figure 6-17 shows, reduction of the topsoil layer thickness from 300 mm to 100 mm and 50 mm increases the generation of runoff from the cover system, although not significantly. Results of this sensitivity analysis indicate that net percolation was reduced from 686 mm (base case) to 627 mm (100 mm topsoil layer) and 570 mm (50 mm topsoil layer), largely due to runoff generation. Runoff generated was in the order of 37 mm (Figure 6-18, for the 100 mm topsoil sensitivity analysis) and 85 mm (for the 50 mm topsoil sensitivity analysis), representing approximately 3% and 7%, respectively of the total precipitation reported at Punto B. It should be noted that constructing soil cover layers thinner than 100 mm in the field, using conventional mine equipment, will prove challenging and maybe not be practical.

The assumption for vegetation roots not penetrating the compacted clayey till layer underlying the topsoil should be revised once/if field evidence becomes available. Roots penetrating the compacted clayey till may increase the hydraulic conductivity of the low permeability layer, complicating the prediction of net percolation and potentially hindering the cover systems performance.

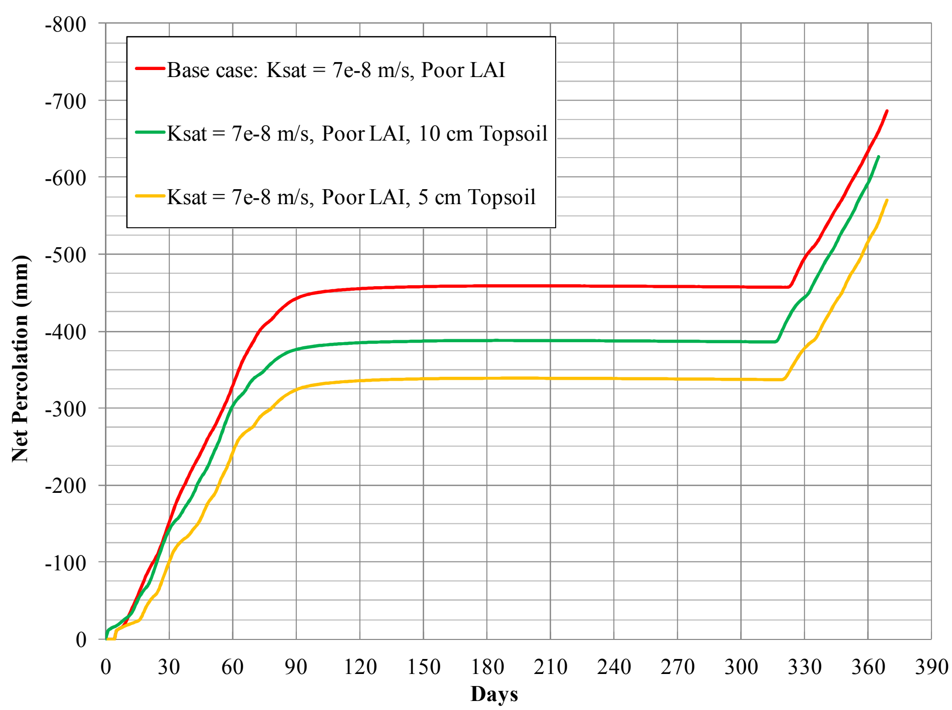

Figure 6-17 Net Percolation Results for a Topsoil Layer Thickness Sensitivity Analysis

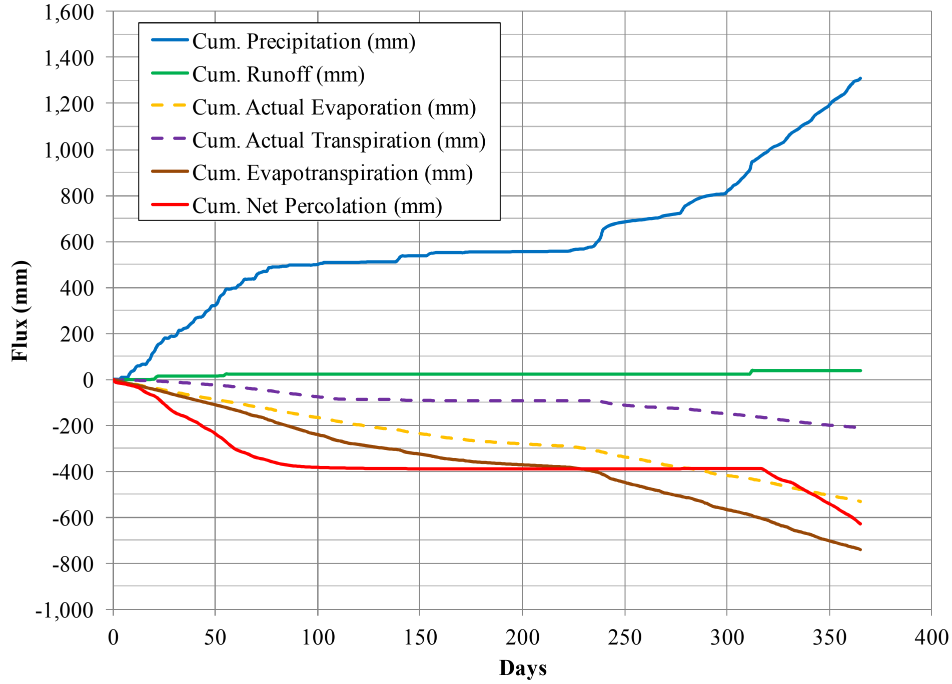

Figure 6-18 Water Balance Results for a 100 mm Topsoil Layer Sensitivity Analysis

6.3 Field and Model Results Comparison

The base case predictive numerical model results presented high evapotranspiration, higher than what was observed in the field. This may be attributed to the net radiation, air temperature, wind speed and relative humidity inputs used in the SoilCover model. These inputs were obtained from the Yanacancha weather station and are highly dependent on local parameters. Sun exposure and wind speed can vary significantly from Punto B to Yanacancha station, affecting these parameters.

The high percolation rates observed in the field (Table 6-2) are higher than the modeled results for the base case, but still less than those for the two higher K_{sat} numerical models that were completed for the sensitivity analysis. According to the sensitivity analysis and the discussion above, saturated hydraulic conductivities higher than the base case, such as the Lysimeter #1 field results, are not expected to increase the net percolation through the cover systems. This occurs since for higher values of K_{sat}, percolation is controlled by the quantity of precipitation and is only reduced by the amount of evapotranspiration.

CHAPTER 7. CONCLUSIONS AND RECOMENDATIONS

The data available to date is insufficient to draw major conclusions for the performance of each independent cover system. Only one full wet and dry season of precipitation records for Lysimeter #1 and approximately 10 to 11 months for the remainder of the lysimeters is available for the present study. Additionally, vegetation has not developed to its full capacity and may further influence percolation rates via evapotranspiration. More comprehensive results are expected as the cover study matures over the next few years. Nevertheless, some interesting trends can already be observed and will have to be confirmed by further assessment of the cover systems performance over the following years. These trends are:

- Lysimeter #3 (control) is the lysimeter showing the most net percolation between April 20, 2011 to February 14, 2012, with 70% of precipitation reporting as percolation. This is consistent with the expected performance of the control lysimeter.
- Lysimeter #5 (compacted silty till + topsoil) presents the least net percolation between April 20, 2011 and February 14, 2012, with 53% of precipitation reporting as percolation.
- Lysimeters #1 (compacted clayey till + topsoil) and #4 (topsoil) show similar net percolation response, with 62% and 63% of precipitation reporting as percolation over the assessed period of time. Lysimeter #2 (non-compacted clayey till) also presented the same trend during its first month and a half, before disconnecting from the datalogger.
- To date, no runoff has been generated from any of the lysimeters. In addition, no evidence of water ponding on the surface of the topsoil on any cover system, nor on the exposed face of the waste rock in the control lysimeter, was observed.
- Since there is no runoff, evapotranspiration, and to a lesser degree storage with subsequent release, are the only mechanisms available to reduce net percolation in the cover systems.

- Transpiration from the cover systems is estimated to reduce percolation by approximately 7%, as indicated by the water balance, between the control lysimeter and Lysimeter #4 (topsoil). According to the results from the predictive numerical model sensitivity analysis, the performance of the cover system may not significantly improve with increased vegetation. This should be confirmed by updating the predictive numerical models with climate data from Punto B.
- Compaction of the low permeability layers (i.e. clayey till and silty till) has no major effect in reducing net percolation. Based on the limited available data, the difference between net percolation reported from Lysimeter #1 and Lysimeter #2 is minimal.
- The composition of the glacial till (i.e. clayey or silty, coarser or finer) does not appear to be a major factor in determining the effectiveness of the barrier layers of the cover systems. The difference in net percolation between Lysimeter #1 and Lysimeter #5 is only 8.5%, with Lysimeter #5 reporting the lowest percolation. This observation is probably due to a combination of the construction method used to build barrier layers along with the variations in grain size distribution of the glacial till.
- Hydraulic conductivities values of the glacial till observed in the field are higher than the values obtained from laboratory testing. Variability in the glacial till and water flowing through macro-pores is probably the primary reason for this difference.
- Comparisons carried out between the field experiment results and numerical model predictions prior calibration indicated a significant disagreement. The primary issue being the prediction of runoff for the non-calibrated numerical models in contrast to the absence of observed runoff in the field experiment. This can be attributed to the inability to replicate in the field the low permeability of the glacial till measured in the laboratory. According to the non-calibrated results of the numerical model, along with the sensitivity analysis carried out in the predictive numerical model, decreasing the saturated hydraulic conductivity of the barrier layer by one order of magnitude (from 7x10-8 m/s to 7x10-9 m/s) has the potential to reduce net percolation from 62% to 13%.

A point worth mentioning is that an improvement in the performance of the cover systems can be achieved by reducing the saturated hydraulic conductivity of the low-permeability layers. This can be accomplished either by using different materials for the construction of the low-permeability covers (not the most attractive alternative given the availability of native material at the mine site) or by decreasing the hydraulic conductivity of the low-permeability covers.

The cover system field experiment has two limitations that may be affecting the performance of the compacted low-permeability covers; and these need to be taken into consideration when assessing the results of the study. First of all, the glacial till layers in lysimeters #1 and #5 had to be constructed using 150 mm and 200 mm lift thicknesses since the available compaction equipment was too small to properly compact thicker layers. These construction thicknesses have the potential to negatively affect the saturated hydraulic conductivity of the cover systems. It is possible that the presence of 100 mm particles in the glacial till produced zones of the low-permeability layers with not enough fines around the coarser particles to reduce the hydraulic conductivity to the initially desired values. Building the full-scale waste dump covers in 300 mm thicknesses will improve the possibilities of having enough fines around the rocky coarse particles that may reduce the hydraulic conductivity of the cover. Likewise, at least two 300 mm layers should be used to build the low-permeability layers of the cover systems since the inherent variability of glacial till may produce a non-homogeneously graded cover. Finally, the glacial till placed in the lysimeters was dryer than the optimum water content established by the standard Proctor test (Daniel, 1981). Compacting a soil in this state is known to affect its hydraulic conductivity, producing a material that is more permeable. This could be improved during the construction of the full-scale waste dump covers by compacting the low permeability layers of the cover system at water contents 1% to 2% higher than the optimum water content from the standard Proctor test. The reduction in the hydraulic conductivity of the compacted glacial till that can be achieved by implementation of these two recommendations requires further investigation.

The performance of the cover systems may also be improved by reducing the thickness of the topsoil layer, thus reducing its storage capacity and aiding in the generation of runoff. Results from the numerical model sensitivity analysis evaluating this option indicate that the use of topsoil layers of 100 mm or thinner may be required to significantly increase runoff generation in the cover systems, and such soil layer thicknesses may prove difficult to construct after closure of the waste rock dumps. Nevertheless, it would be interesting to evaluate the possibility of removing the topsoil layer from the cover systems and placing the vegetation directly on the (most likely not compacted) glacial till low permeability layers. Growing vegetation on the low permeability layers will however have the consequence of increasing the hydraulic conductivity of the till due to root penetration. Additionally, clayey glacial till exposed to the environment may also desiccate and crack, increasing even further its permeability. Ideally, these scenarios will be evaluated after field data, including the effect of root penetration into Antamina's glacial till and its exposure to the environment, becomes available.

7.1 Recommendations for Further Investigation

The next stage of the cover study at Antamina should address a number of topics directed at improving the current confidence on the results obtained from the field experiment and the predictive numerical models. The accuracy of the current evapotranspiration predictions should be revised by updating the numerical models with actual matric suction records obtained from the cover systems and climate data (net radiation, wind speed, relative humidity and air temperature) from Punto B, and by observing the evolution of the performance of the cover systems in the following years. Any further reduction in percolation values will probably be linked to an improvement in the evapotranspiration capacity of the cover systems. *In situ* hydraulic conductivity tests are also recommended to confirm the input in the predictive numerical models, and to validate the conclusions made in this thesis about the performance of the cover systems. These field tests should be conducted with the low-permeability layers of the cover systems. The use of a Guelph permeameter, or similar instrument, is recommended for this task. Finally, the assessment of the cover systems as oxygen barriers is still pending and the previously installed oxygen sampling tubes should aid in this evaluation.

7.2 Closing Remarks

Conclusions presented in this thesis should be verified in subsequent years when new field data becomes available that confirm the long-term performance of the cover systems. A number of assumptions had to be made to complete the assessment of the first year performance of the cover systems, such as estimated precipitation events when records were unavailable, covers suction and covers temperature. The installation of a weather station capable of measuring net radiation, air temperature, wind speed and relative humidity at Punto B will also improve the confidence in the results obtained in further stages of this research program. The predictive numerical models created as part of this thesis should also be updated when new percolation records and weather data becomes available, and a new calibration should be conducted to confirm the first one made based on some estimated parameters.

Even if the cover study conducted at Antamina is still in an initial stage, early results from this research exemplify the importance of directly observing the performance of cover systems as a continuum, which encompasses climate and cover characteristics. None of these can be assessed individually, and cover designs cannot be imported from one site to another without keeping in mind all the variables that affect their efficiency. The results from this study will also feed into additional studies, which may include an assessment of sloped covers at Antamina.

Field-scale experiments, such as the one described in this thesis, should be implemented at early stages of the life of any mine site, since they require several years before meaningful results and conclusions are obtained. The results and conclusions may help improve waste management and operational practices at the mine, in addition to the mine closure plans. The cover study conducted at Antamina differs from many other cover systems assessments around the world due to the integration of field data from this field-scale study with laboratory results and numerical modelling. The incorporation of field scale performance testing, under site-specific conditions, will help constrain and improve final cover designs and may reduce costs. Finally, it should be mentioned that field-scale experiments cannot stand alone, and that the best results are always attained when as many tools as possible are available. In this case, this represents a combination of laboratory testing, numerical modelling, field-scale experiments, and experience.

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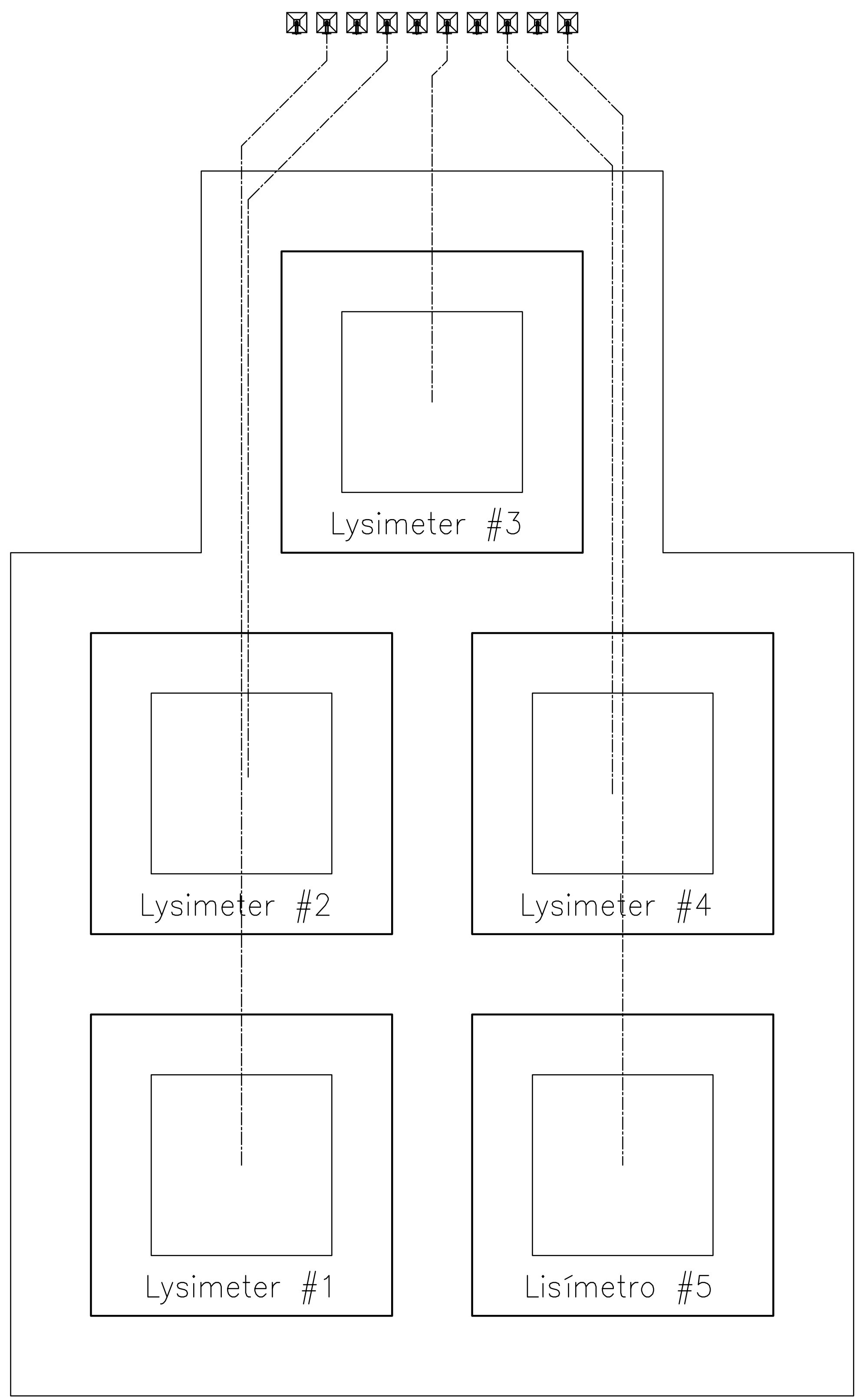
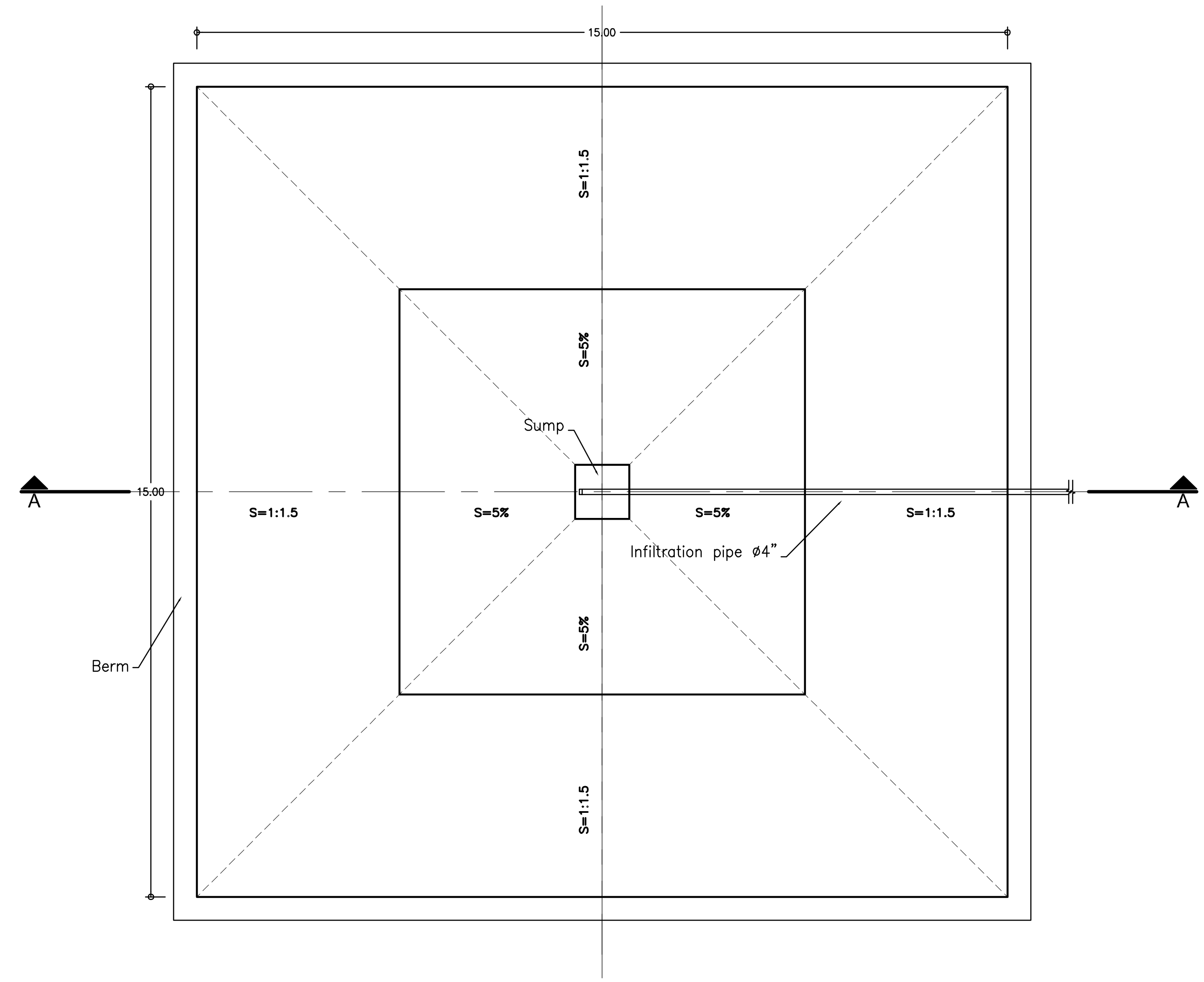
APPENDIX A: DRAWINGS





Plan view - Unfilled Lysimeters
(Lysimeters #1, #2, #3, #4 y #5)
Not to scale

PROJECT: ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3			
LYSIMETERS LAYOUT AND DESIGN			
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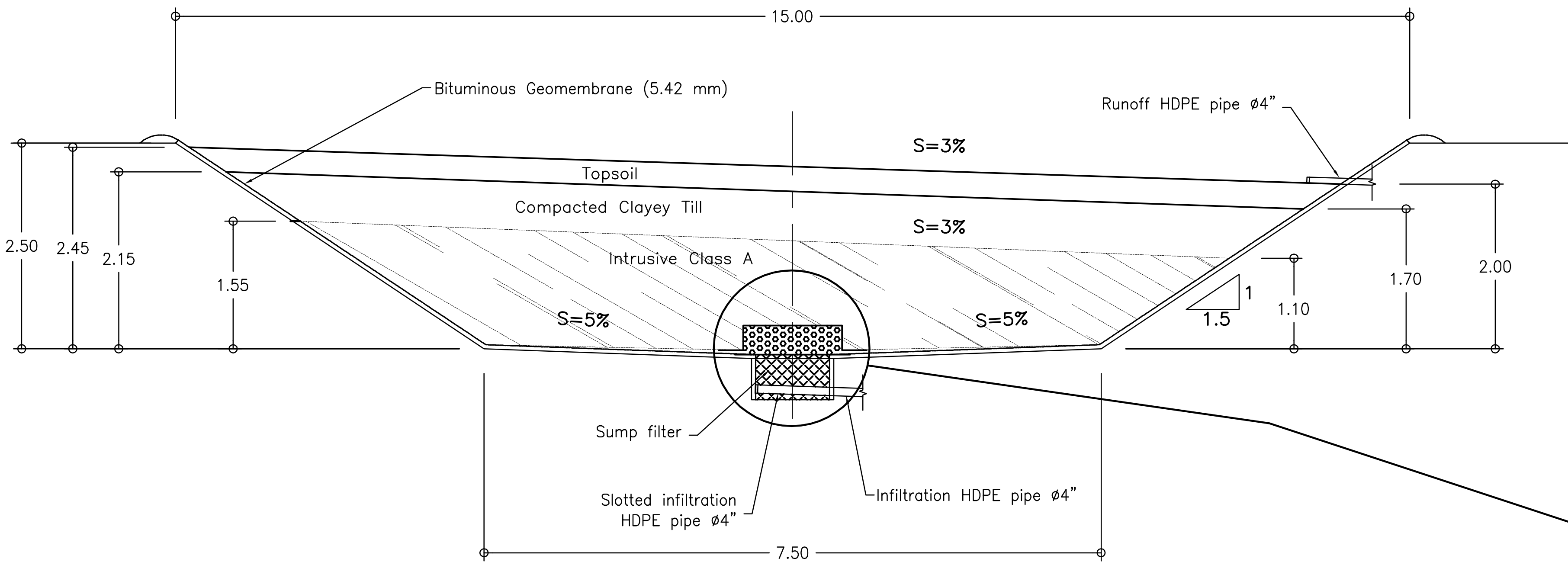
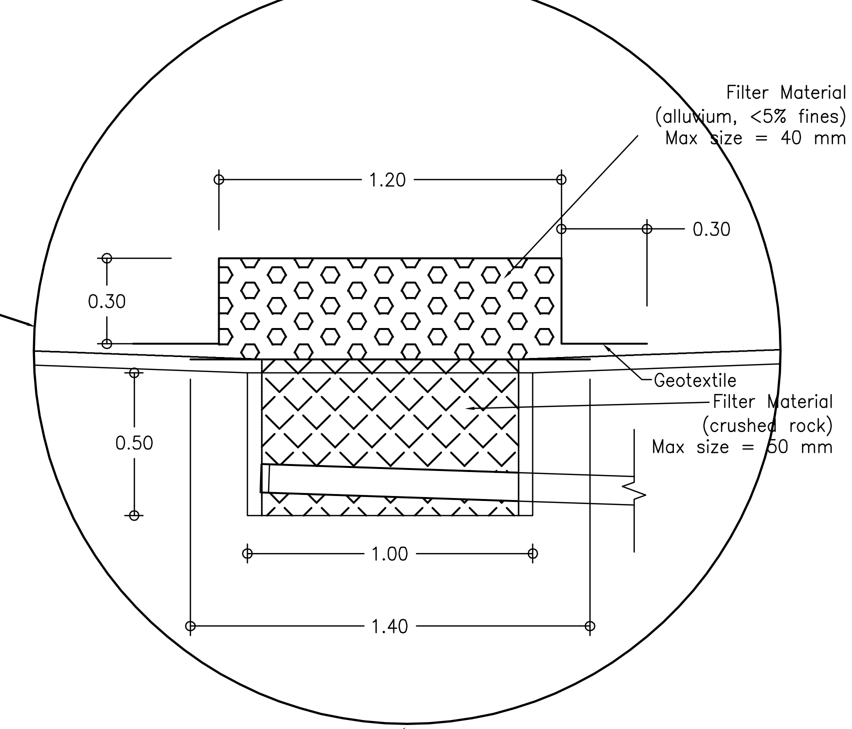
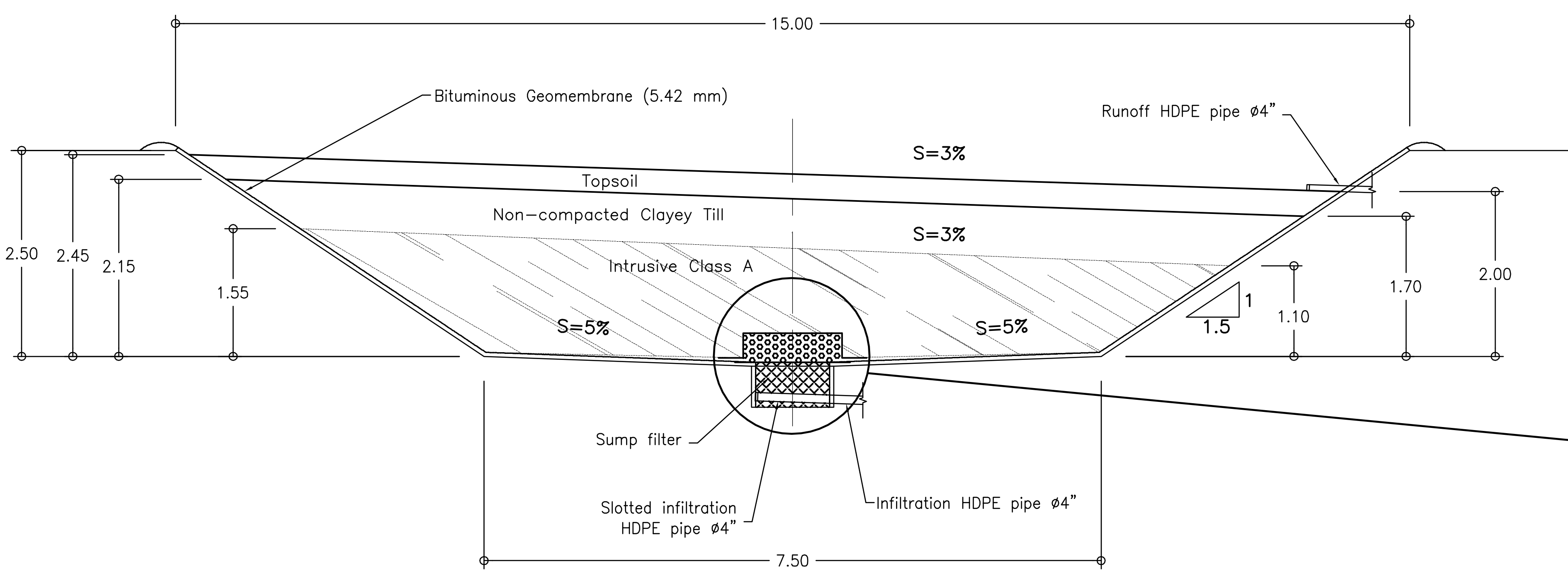


Cross Section A-A
(Lysimeter #1 - Stage 3)
Not to scale





Cross Section A-A
(Lysimeter #2 - Stage 3)
Not to scale

PROJECT:
ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3

LYSIMETERS #1 AND #2 DETAILS

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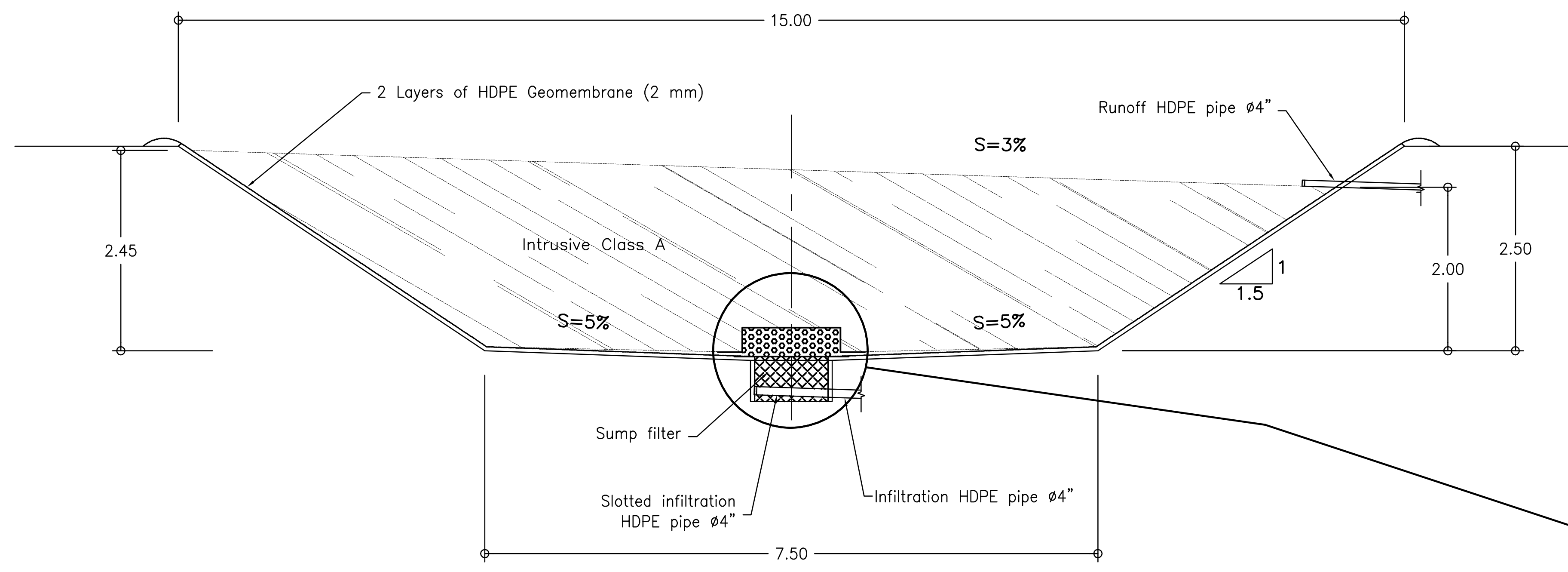

Cross Section A-A
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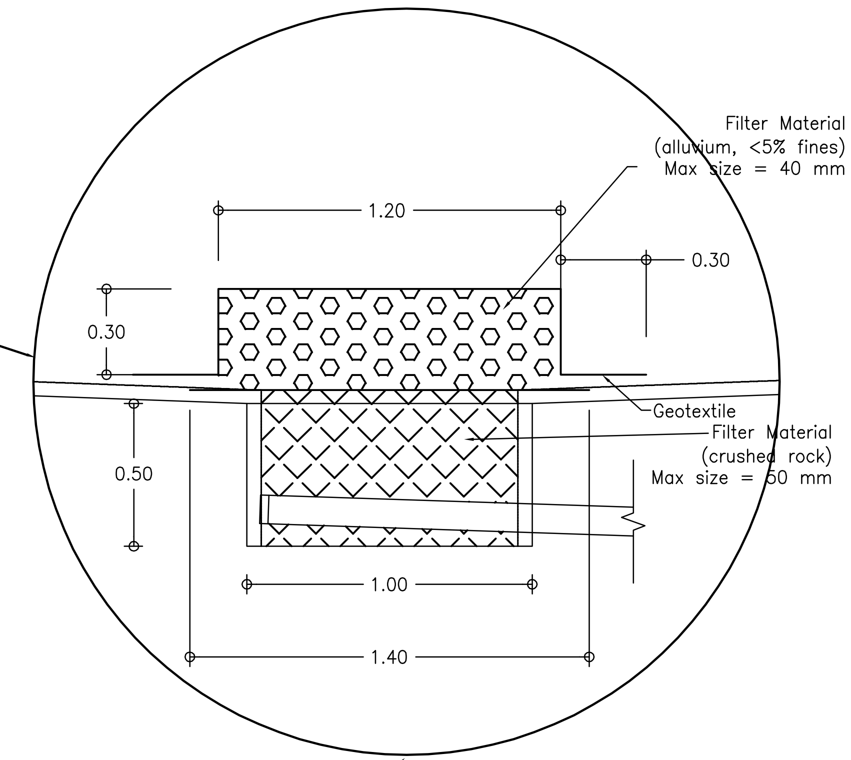
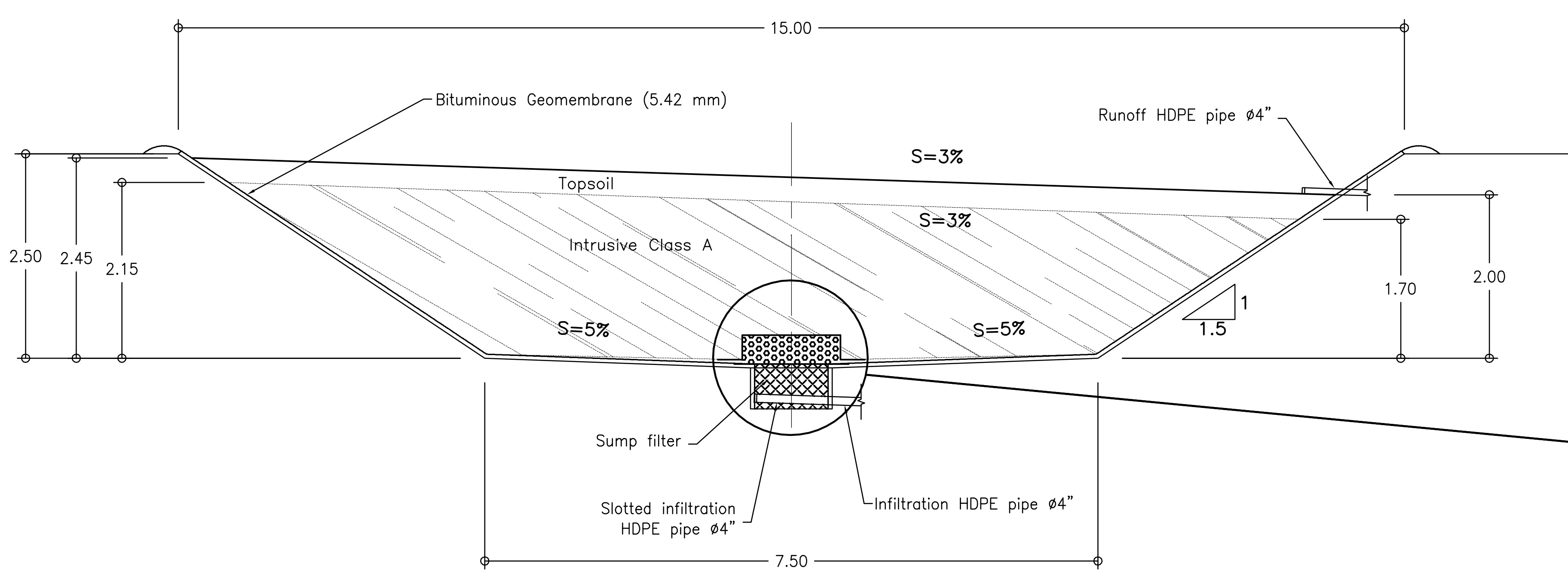
Not to scale





Cross Section A-A
(Lysimeter #4 - Stage 3)
Not to scale

PROJECT: ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3			
LIYSIMETERS #3 and #4 DETAILS			
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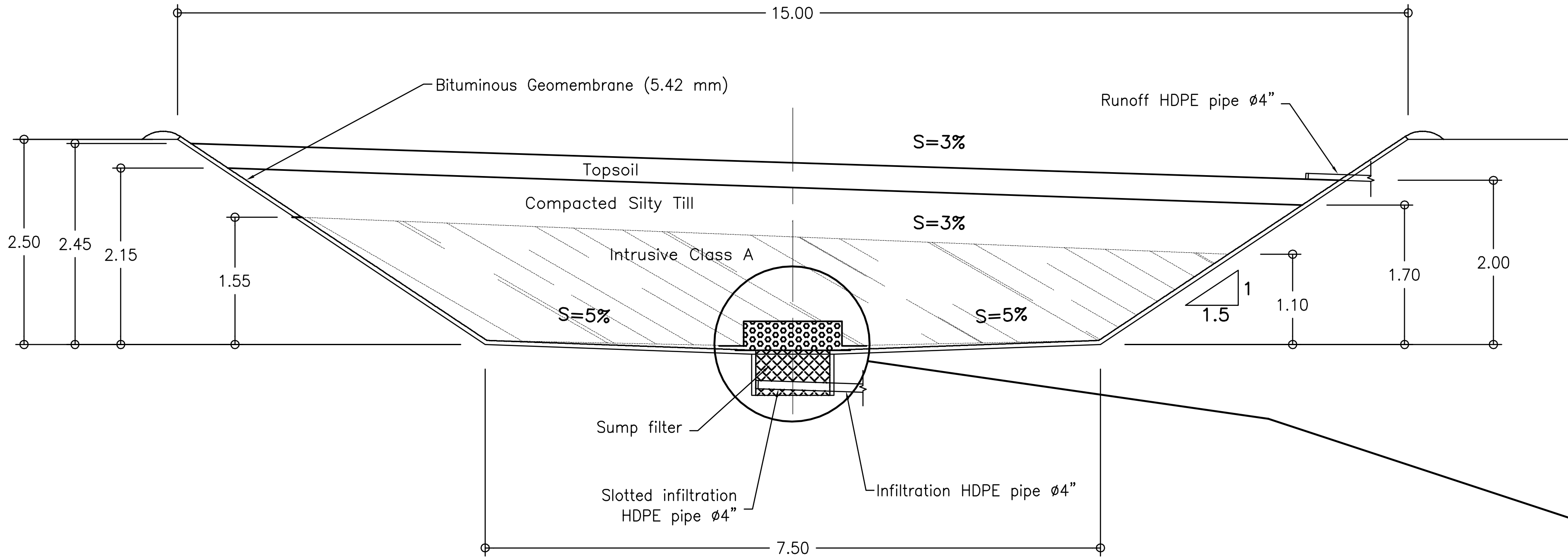

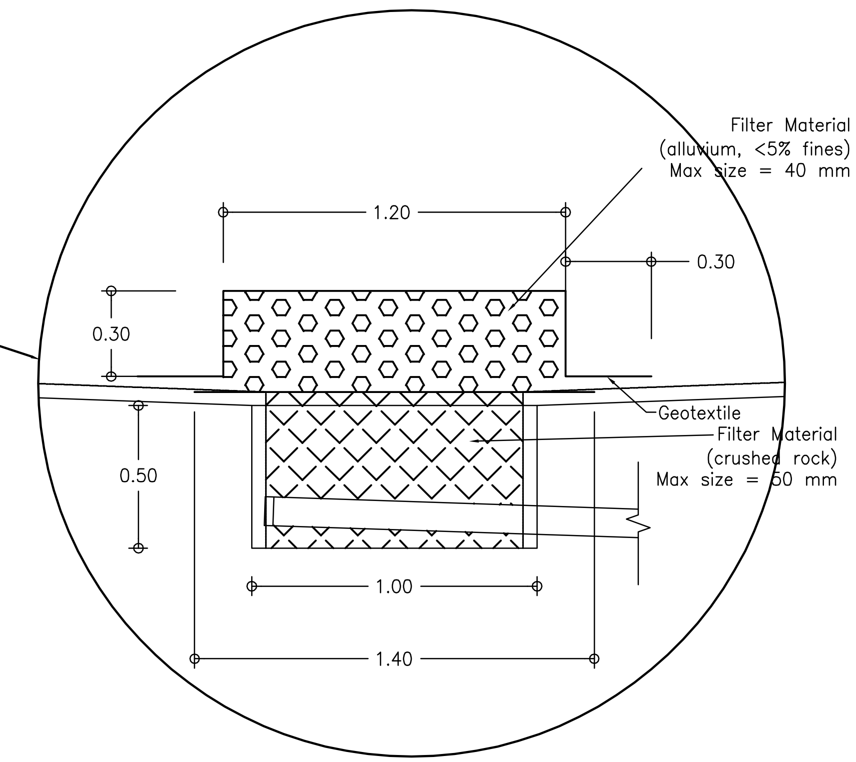

Cross Section A-A
(Lysimeter #5 - Stage 3)
Not to scale

PROJECT: ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3							UBC
LYSIMETER #5 DETAILS							
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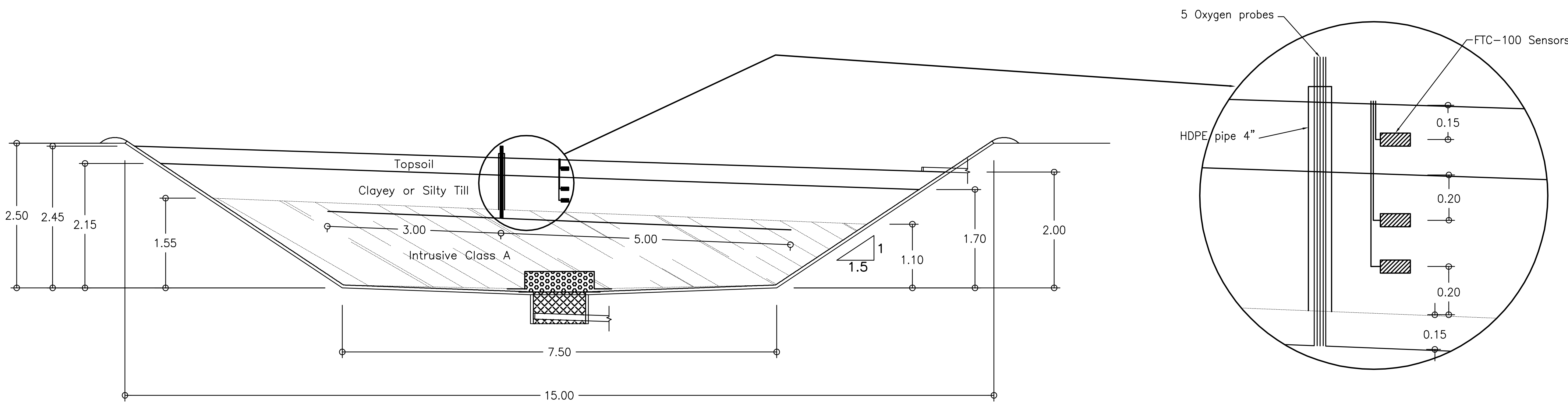
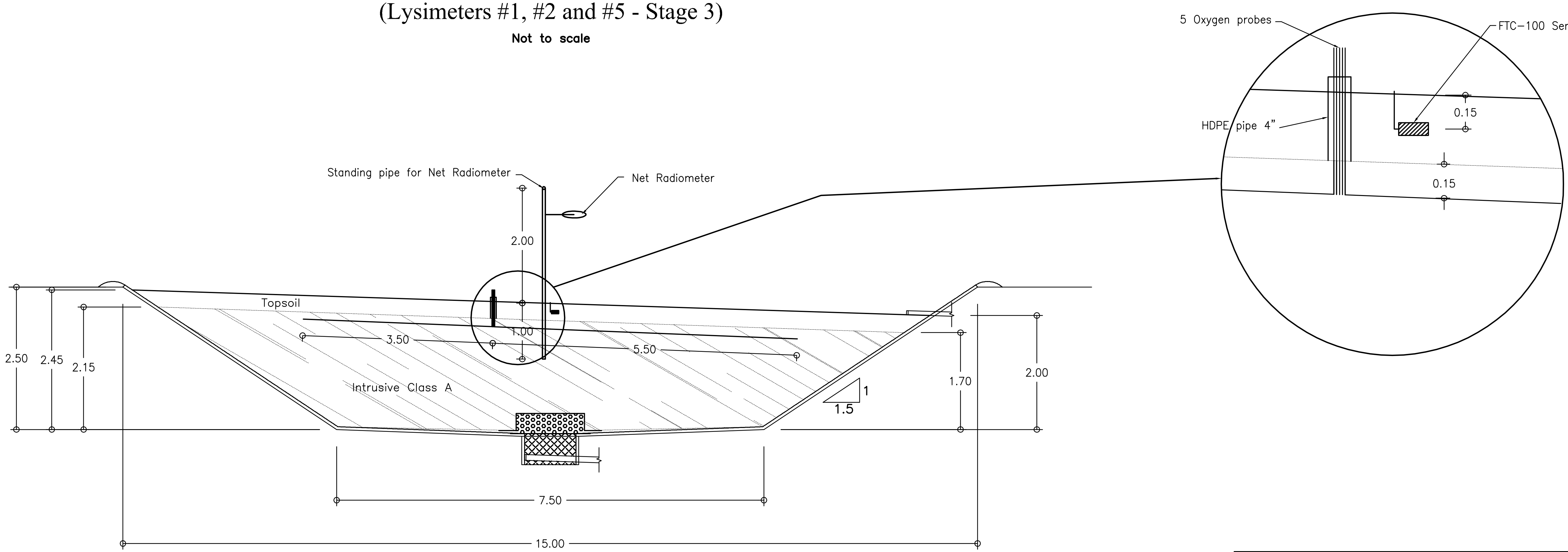


Cross Section A-A
(Lysimeters #1, #2 and #5 - Stage 3)
Not to scale



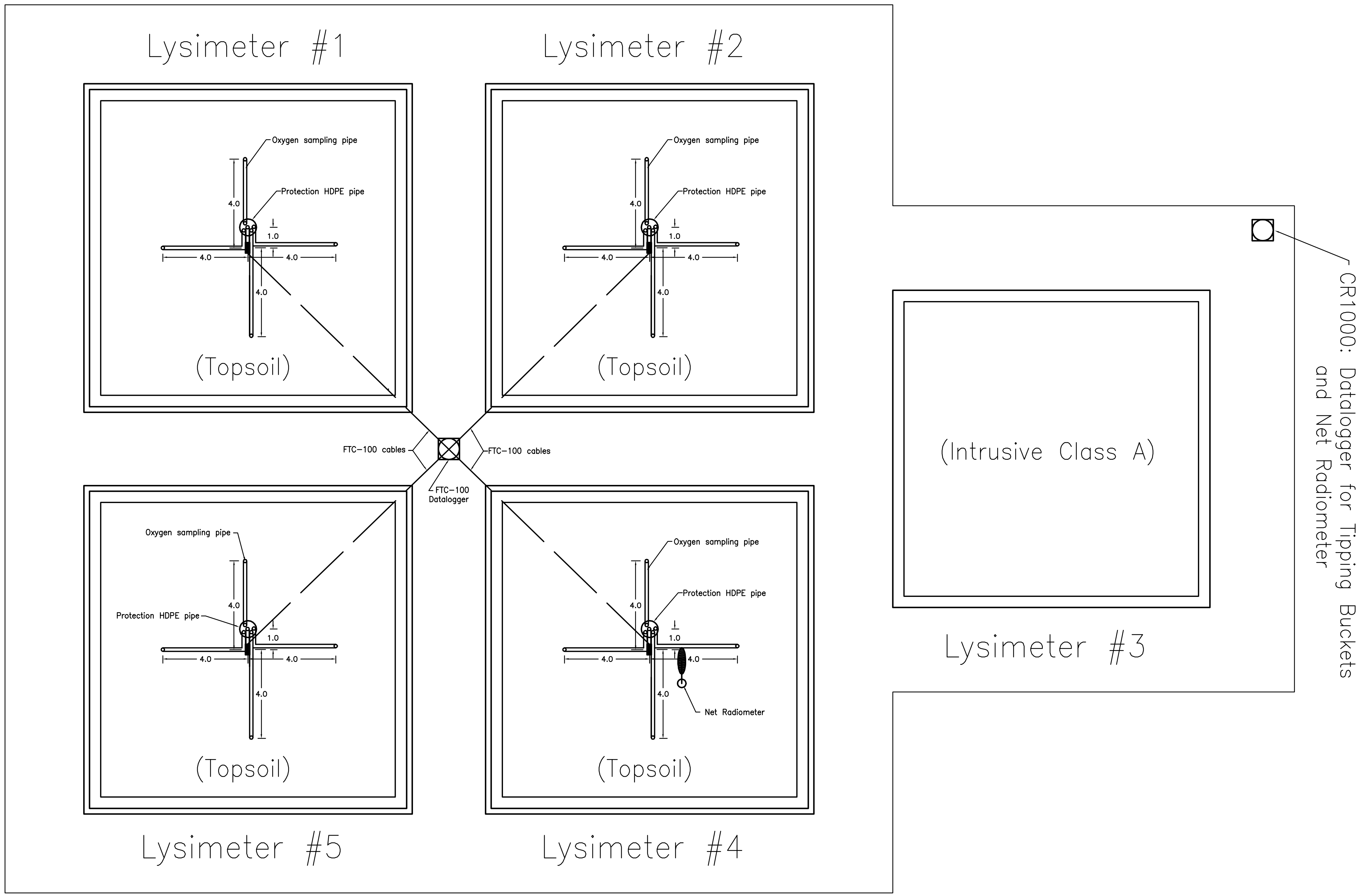
Cross Section A-A
(Lysimeter #4 - Stage 3)
Not to scale

PROJECT:
ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3

UBC

CROSS SECTIONS - INSTRUMENTATION DETAILS

DRAWING: UBC.CS-06	DRAWN: PU	DATE: FEB−2011	Page: 104



PROJECT: ASSESSMENT OF COVER SYSTEMS FOR WASTE ROCK AT ANTAMINA - CONSTRUCTION STAGE 3							
PLAN VIEW - INSTRUMENTATION DETAILS							
DRAWING:	UBC.CS-06	DRAWN:	PU	DATE:	FEB-2011	Page:	105

APPENDIX B: PHOTOS

Lysimeters Construction

Photo #1: Leveling the ground for construction of the lysimeters.

Photo #2: Cleaning topsoil from the side of the lysimeters area.

Photo #3: Carrying and placing material for the construction of the lysimeters.

Photo #4: Compacting placed material for the base of the lysimeters.

Photo #5: Installing piping system for run-off and infiltration.

Photo #6: Sump for infiltration piping system, prior the construction of the lysimeter.

Photo #7: Lay out of the base of the lysimeters.

Photo #8: Building the sloped walls of the lysimeters.

Photo #9: Lysimeter already built with one of its sides smoothed by a roller.

Photo #10: Bituminous liner installation on the lysimeters.

Photo #11: Bituminous liner installation on the lysimeters.

Photo #12: Lysimeter #2 with bituminous liner and run-off and infiltration piping systems already installed.

Photo #13: Lysimeter #5 with bituminous liner and sump for infiltration piping system already installed.

Photo #14: Installing liner in the lysimeters.

Photo #15: Completing run-off and infiltration piping system before the installation of the tanks.

Photo #16: Lysimeters, piping and tanks completed.

Photo #17: Lysimeter #4 with extra geomembrane liner and 4" oxygen pipes, which later were removed.

Photo #18: Part of the already built sump excavated and geotextile placed for the construction of the new filter.

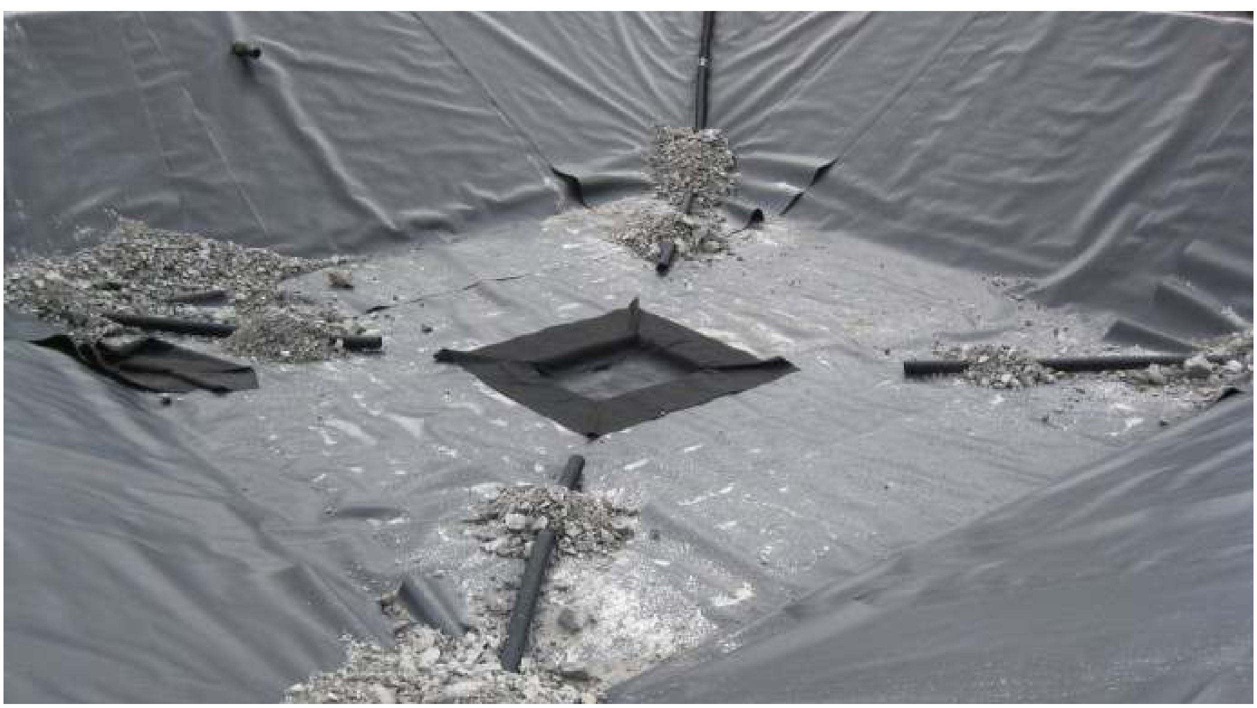


Photo #19: Building new filter with clean alluvial material.

Photo #20: New filter already built geotextile and oxygen pipes fixed with Class A Intrusive material.

Filling Lysimeters

Photo #21: Placing Class A Intrusive around new filter.

Photo #22: Placing Class A Intrusive in lysimeter #5.

Photo #23: Placing Class A Intrusive in lysimeter #5.

Photo #24: Class A Intrusive placed in lysimeter #1 by excavator.

Photo #25: Leveling Class A Intrusive in lysimeter #4.

Photo #26: Class A Intrusive already leveled in lysimeter #2.

Photo #27: Lysimeter #3 completed.

Photo #28: Oxygen pipe cut and capped with geotextile, below Class A Intrusive level.

Construction of Cover Systems

Photo #29: Topsoil stocked next to lysimeter #2.

Photo #30: Placing topsoil cover in lysimeter #4.

Photo #31: Spreading and leveling topsoil in lysimeter #4.

Photo #32: Building topsoil cover in lysimeter #4.

Photo #33: Building topsoil cover in lysimeter #4.

Photo #34: Topsoil cover already placed in lysimeter #4. Oxygen sampling tubes coming out of the cover in the middle of the lysimeter. Standing pipe next to oxygen sampling tubes for Net Radiometer.

Photo #35: Placing clayey till in lysimeter #2.

Photo #36: Leveling clayey till in lysimeter #1.

Photo #37: Clayey till layer in lysimeter #1 waiting for compaction.

Photo #38: Inspecting compaction test platforms.

Photo #39: Compacting test platforms with 800 kg roller.

Photo #40: Performing nuclear density test on compaction platform.

Photo #41: Compacting silty till in lysimeter #5.

Photo #42: Compacting clayey till in lysimeter #1.

Photo #43: Compacting sides and corners of silty till layer in lysimeter #5 with vibrating plate.

Photo #44: Performing nuclear density test in silty till in lysimeter #5.

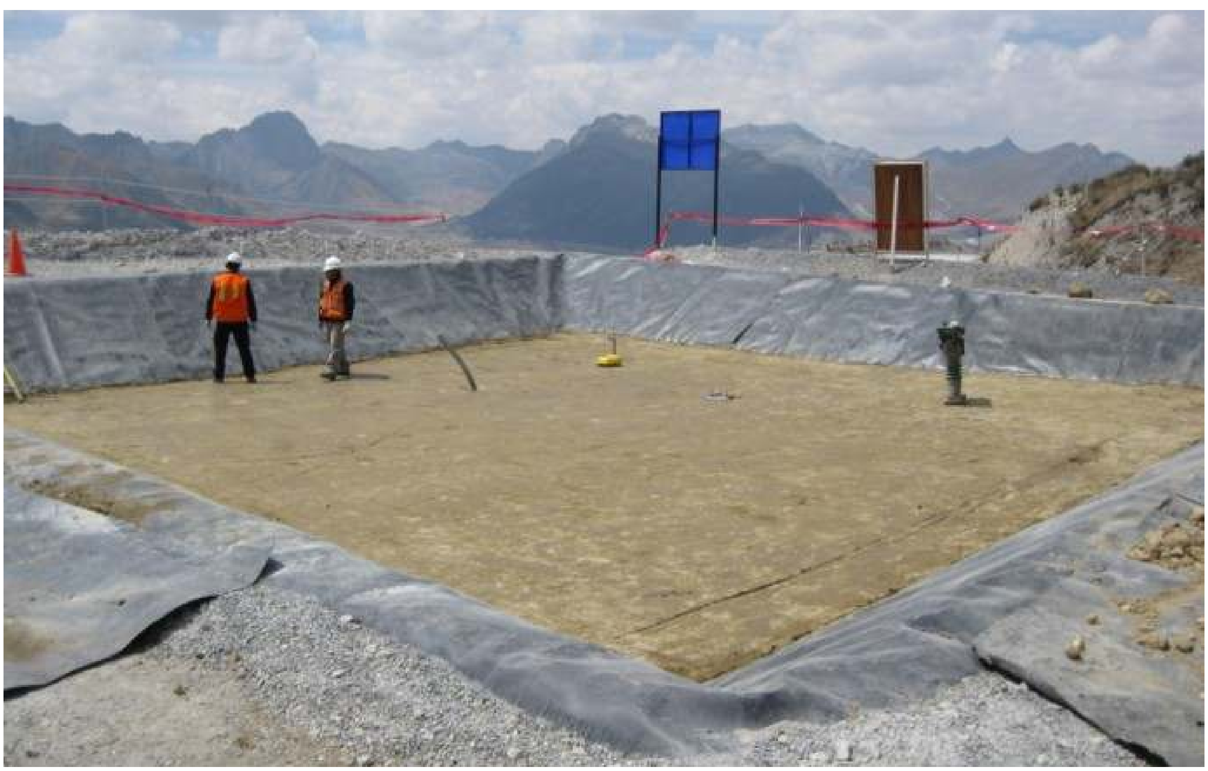


Photo #45: Covering silty till in lysimeter #5 with plastic sheets while getting ponded water out.

Photo #46: Silty till layer already compacted in lysimeter #5.

Photo #47: Placing topsoil layer in lysimeter #2.

Photo #48: View of the five cover systems already built in the lysimeters.

Photo #49: Samples taken from cover materials.

Photo #50: Borrow area for silty till.

Photo #51: Borrow area for silty till.

Photo #52: Clay found in silty till borrow area.

Instruments

Photo #53: Tipping bucket.

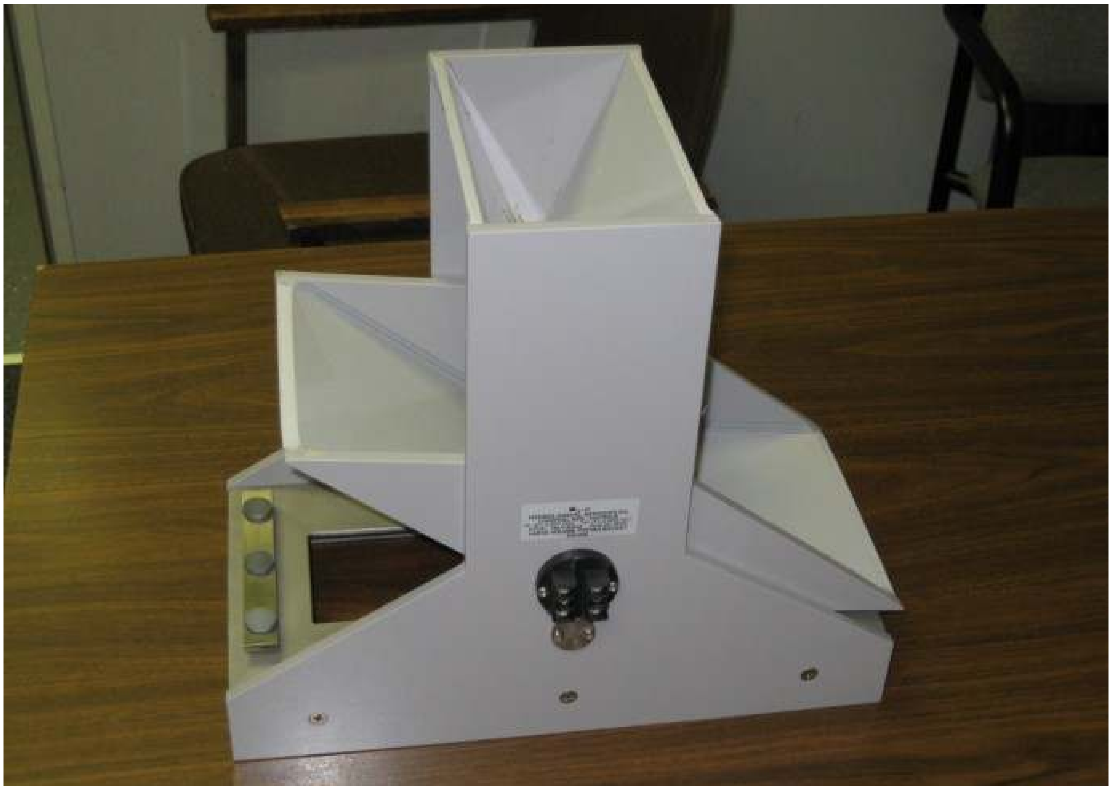


Photo #54: Tanks for collecting infiltration and runoff water.

Photo #55: Wooden boxes shielding tipping buckets and tanks.

Photo #56: Runoff pipe connection with tank.

Photo #57: Tipping buckets with wooden support, later replaced by a plastic base.

Photo #58: Plastic base for tipping buckets.

Photo #59: Tipping bucket placed on plastic base.

Photo #60: Calibration of tipping buckets.

Photo #61: Data logger station for tipping buckets and net radiometer.

Photo #62: Vertical PVC pipe showing the location of TC sensors after test pit excavation.

Photo #63: Horizontal PVC pipes left in the cover system to get a hole for TC sensors.

Photo #64: Pulling PVC pipes out of the cover.

Photo #65: Pulling PVC pipes out of the cover.

Photo #66: Pulling PVC pipes out of the cover.

Photo #67: Installing TC sensor in hole left by PVC pipe.

Photo #68: Installing TC sensor in hole left by PVC pipe.

Photo #69: Hole left in silty till cover by PVC pipe.

Photo #70: TC sensors installed in clayey till cover before filling the holes.

Photo #71: Holes filled with clayey till and expandable foam, with TC sensors inside.

Photo #72: Compacting TC sensors test pit with vibrating plate.

Photo #73: Test pit for installing TC sensors in lysimeter #2.

Photo #74: Installing TC sensors in lysimeter #2.

Photo #75: Installing TC sensors in lysimeter #2.

Photo #76: Filling TC sensors test pit in lysimeter #2.

Photo #77: Trench in topsoil cover for taking TC sensors cables to one of the corners of lysimeter #2.

Photo #78: Excavation for oxygen sampling tubes.

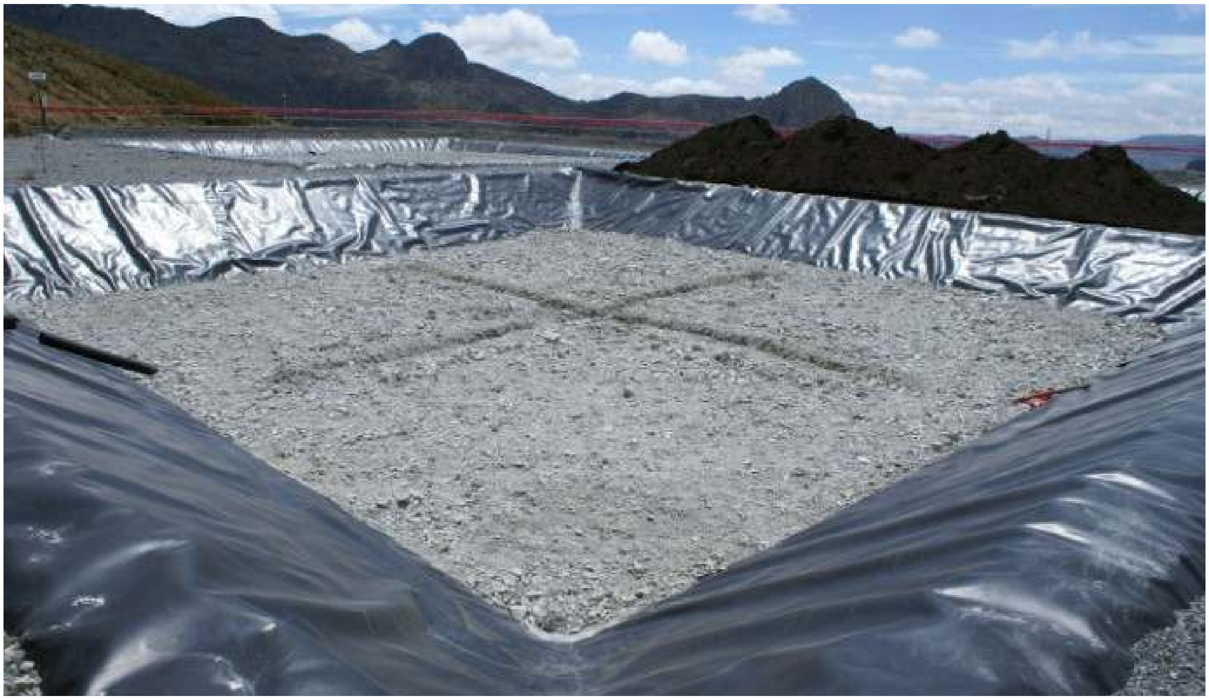


Photo #79: Placing PVC pipes for protecting oxygen sampling tubes.

Photo #80: Placing PVC pipes for protecting oxygen sampling tubes.

Photo #81: Sealing PVC pipes with expandable foam (see oxygen sampling tube inside).

Photo #82: Oxygen sampling tubes already installed in Class A Intrusive material. Black HDPE pipe will take the oxygen sampling tubes through the cover system.

Photo #83: Covering PVC pipes with fine sand for protection purposes.

Photo #84: Oxygen sampling tubes already installed in lysimeter #4.

Photo #85: Oxygen sampling tubes coming out of the cover system through HDPE pipe.

Photo #86: Net Radiometer installed in Lysimeter #4.

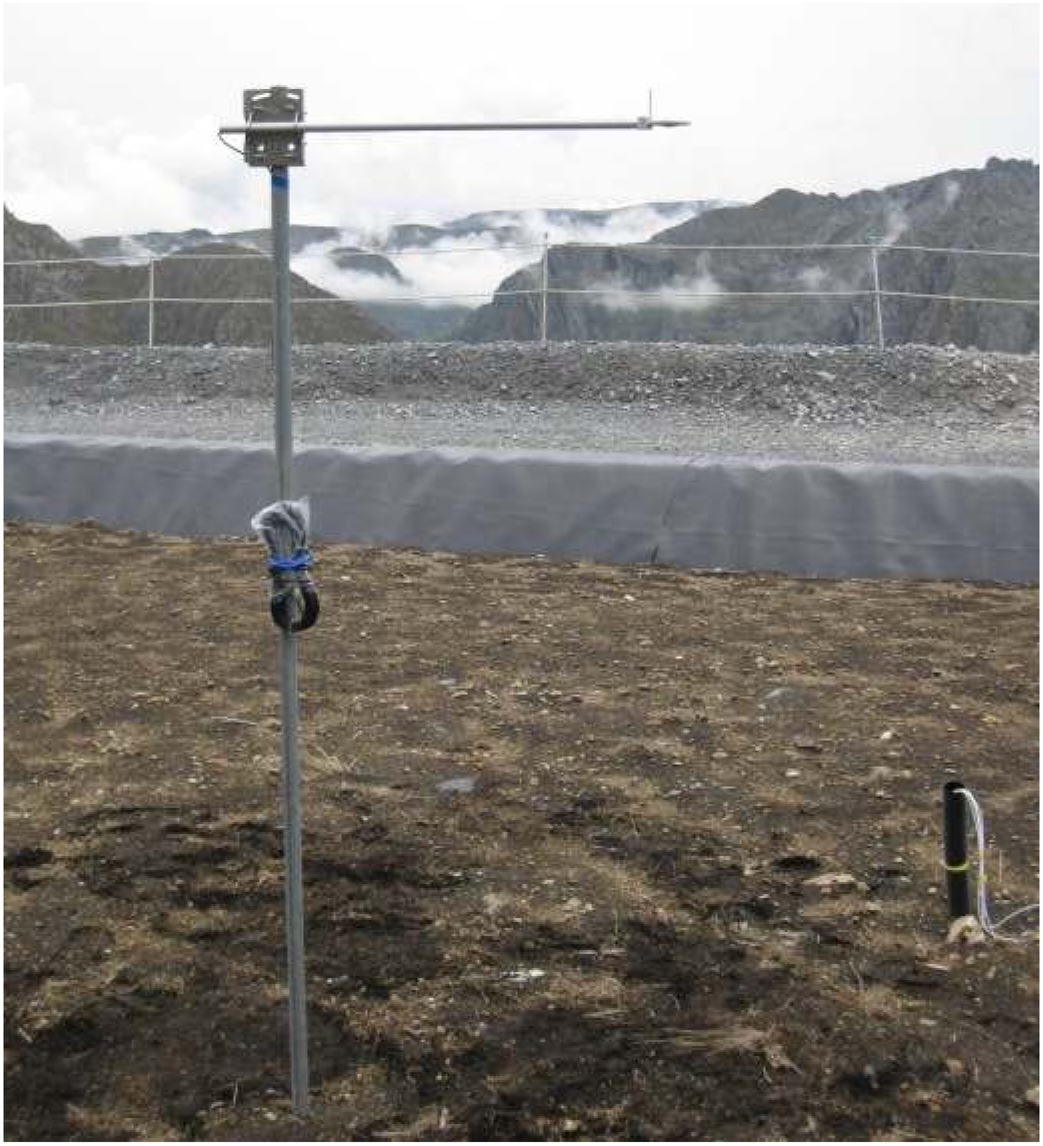


Photo #87: Transplanting *Calamagrostis sp*. (locally known as Ichu) to topsoil cover in lysimeter #1.

Photo #88: Transplanting *Calamagrostis sp*. (locally known as Ichu) to topsoil cover.

Photo #89: Sowing *Trifolium repens* (locally know as white clover) in topsoil layer in lysimeter #1.

Photo #90: Lysimeter #2 completed.

APPENDIX C: CR1000 PROGRAM AND WIRING DIAGRAM

CR1000 Tipping Buckets Program:

```
'CR1000
'Created by Short Cut (2.8)

'Declare Variables and Units
Public BattV
Public L1_I
Public L1_R
Public L2_I
Public L2_R
Public L3_I
Public L3_R
Public L4_I
Public L4_R
Public L5_I
Public L5_R

Units BattV=Volts
Units L1_I=tip
Units L1_R=tip
Units L2_I=tip
Units L2_R=tip
Units L3_I=tip
Units L3_R=tip
Units L4_I=tip
Units L4_R=tip
Units L5_I=tip
Units L5_R=tip
```

```
'Define Data Tables
DataTable(Tips,True,-1)
	DataInterval(0,30,Min,10)
	Totalize(1,L1_I,FP2,False)
	Totalize(1,L1_R,FP2,False)
	Totalize(1,L2_I,FP2,False)
	Totalize(1,L2_R,FP2,False)
	Totalize(1,L3_I,FP2,False)
	Totalize(1,L3_R,FP2,False)
	Totalize(1,L4_I,FP2,False)
	Totalize(1,L4_R,FP2,False)
	Totalize(1,L5_I,FP2,False)
	Totalize(1,L5_R,FP2,False)
EndTable

DataTable(Battery,True,-1)
	DataInterval(0,1440,Min,10)
	Minimum(1,BattV,FP2,False,False)
EndTable

'Main Program
BeginProg
	Scan(60,Sec,1,0)
		'Default Datalogger Battery Voltage measurement BattV
		Battery(BattV)
		'Generic Tipping Bucket Rain Gauge measurement LX_I
		PulseCount(L1_I,1,1,2,0,1,0)
		PulseCount(L1_R,1,2,2,0,1,0)
		PulseCount(L2_I,1,11,2,0,1,0)
		PulseCount(L2_R,1,12,2,0,1,0)
		PulseCount(L3_I,1,13,2,0,1,0)
```

```
        PulseCount(L3_R,1,14,2,0,1,0)
        PulseCount(L4_I,1,15,2,0,1,0)
        PulseCount(L4_R,1,16,2,0,1,0)
        PulseCount(L5_I,1,17,2,0,1,0)
        PulseCount(L5_R,1,18,2,0,1,0)
        'Call Data Tables and Store Data
        CallTable(Tips)
        CallTable(Battery)
    NextScan
EndProg
```

CR1000 Net Radiometer Program

Project: UBC/Antamina Cover Study
Documented By: P. Urrutia