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Design and Construction of Field-Scale Lysimeters for the Evaluation of Cover Systems at the Antamina Mine, Peru

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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 research program was initiated by Antamina, Teck, and the University of British Columbia to determine the most suitable type of cover system for the waste rock dumps at Antamina. The climate regime at the mine site presents special challenges given its high elevation with high rainfall during summer periods, followed by low to negligible precipitation during winter months. The covers were constructed of native, low permeability materials and topsoil, with the aim to reduce net infiltration and oxygen entry to underlying waste rock. Runoff and infiltration through the covers systems is captured in 15 m x 15 m x 2.5 m lysimeters and directed to a water conveyance system to 10 tipping buckets that continuously monitor flow rate. Ten thermal conductivity sensors were installed to measure matric suction and weather instrumentation was installed to obtain site-specific precipitation and net radiation data. This paper presents a summary of the design, construction, and early flow observations for the four cover systems under evaluation.

Introduction

A research program was initiated six years ago in 2005 by Compañia Minera Antamina S.A. (Antamina), Teck and the University of British Columbia (UBC) to assess the hydrological, geochemical and weathering characteristics of waste rock at the Antamina mine (Peru). 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 was developed in 2008 to help refine the current closure plan for Antamina's 1,539 Mt waste rock dumps (Golder, 2007).

The purpose of cover material on top of waste rock dumps containing ‘potentially acid-generating’ material is to function as oxygen and water barriers, 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 infiltration to underlying waste rock via the combination of a low-permeability and a store-and-release cover. The low-permeability cover works as a barrier to infiltration and to limit oxygen entry, whereas the store-and-release acts as a medium growth layer for vegetation. This cover study will evaluate the performance of four different cover systems and a control system, by measuring the resulting water infiltration 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:

- 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.
- Laboratory testing to complete the characterization of the materials used to build the cover systems and determine input parameters for numerical models.
- 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.

This paper will focus on the first component, including details of the design and construction, and will present early results from the four cover systems.

Site Characteristics

Antamina mine, one of the largest zinc and copper producers in the world, is located at approximately 270 km north-east of Lima, at an average altitude of 4,300 meters above sea level, in the north-central Peruvian Andes.

The climate regime 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 between 5.5°C and 6.0°C.

Surficial geology at the Antamina valley is comprised of glacial till deposited between 10 to 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 40 cm 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 grater than 30 m in the Quebrada Yanaccocha (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.

These 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.

Design and Construction of Lysimeters and Cover System

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 with two sets of drainage pipes to collect runoff and infiltration (Figures 1 and 2a). Drainage from runoff and infiltration piping is directed to separate 1 m^3 tanks, for a total of 10 tanks in this study (Figure 2b). 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.

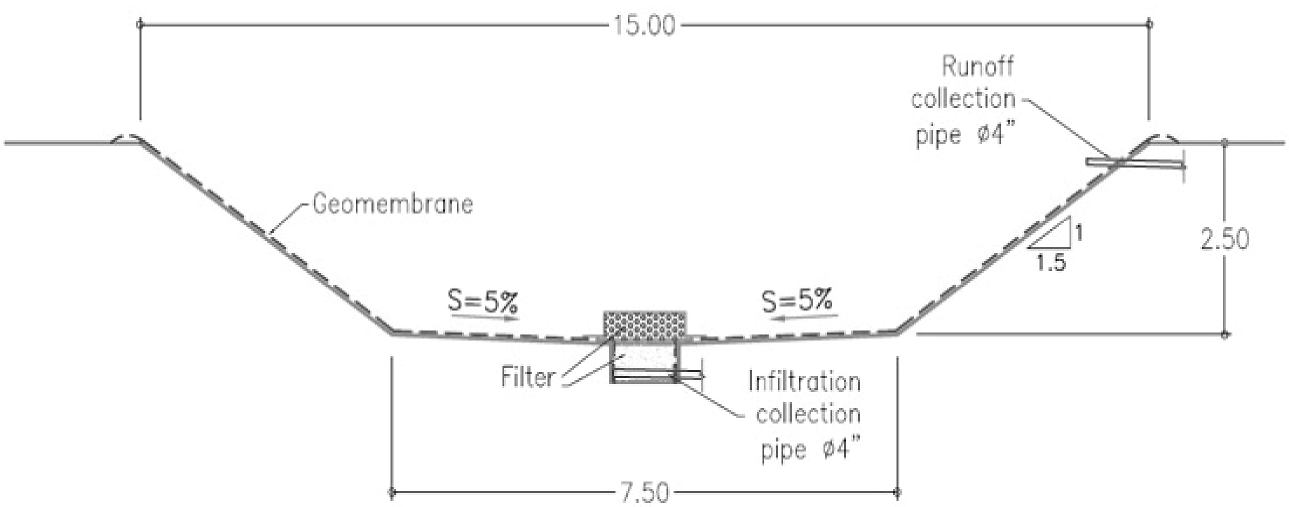

Figure 1: Lysimeter schematic (dimension in metres). Lysimeters 1, 2, 4 and 5 were covered with a 5.42 mm bituminous geomembrane (Coletanche NTP 4), while Lysimeter 3 was covered with two layers of a 2 mm HDPE geomembrane.

(a) (b)

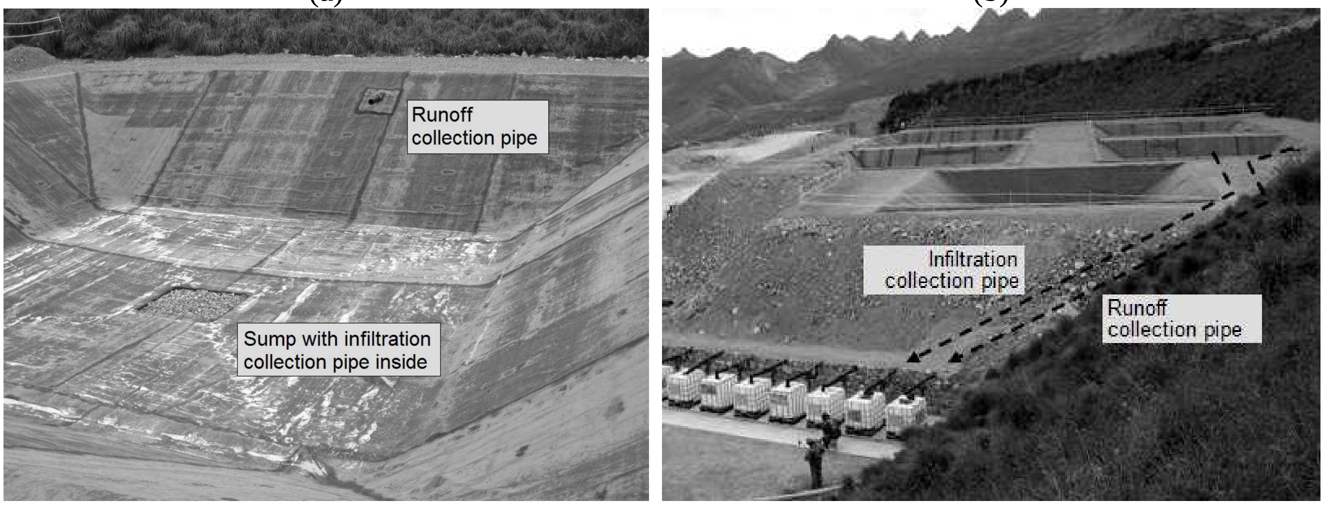

Figure 2: Photos of (a) Lysimeter 2 showing bituminous geomembrane, runoff collection pipe and sump; and (b) lysimeters and tanks in an early stage of the construction.

Materials

Golder Associates conducted laboratory tests on the native soils used in this study, to assess their physical properties and their potential as cover materials. Specifically, these laboratory tests included: saturated hydraulic conductivity, USCS classification and standard Proctor compaction tests. Of the four previously mentioned native soils only two were used in this study, topsoil and till. Colluvial, fluvial and organic soils were not tested given their scarce availability and poor suitability to function as covers.

Topsoil was selected as the medium growth layer and only one topsoil sample was tested. Two samples of till were tested (from different locations), given the glacial till variability at Antamina. Results from these tests verified their heterogeneity in regards to composition and grain size distributions, and glacial till was divided into two types; a clayey, coarser glacial till; and a silty, finer glacial till. Table 1 summarizes the results of the properties assessment tests and the tests performed in the materials actually used for the construction of the cover systems.

Table 1: Cover materials laboratory tests results

Material	Gravel (%)	Sand (%)	Fines (%)	Liquid Limit	Plasticity Index	K_{sat}* (m/s)	USCS Classification	USCS Description
Clayey till	31	21	48	36	15	2.1×10^{-9}	GC-CL	Clayey gravel with sand to sandy/gravelly lean clay with gravel/sand.
Silty till	18	14	68	52	22	7.3×10^{-8}	MH	Gravelly elastic silt with sand to sandy elastic silt.
Topsoil	11	12	77	78	27	4.6×10^{-6}	OH	Sandy organic silt.

*Clayey and silty till saturated hydraulic conductivities were tested on samples compacted at 95% of the maximum dry density of standard Proctor test. Topsoil was testes in a loose state.

Intrusive Class A was the preferred type of waste rock for the experiment for two reasons: its classification as the most reactive or 'potentially acid-generating' material, and because it is one of the most common reactive materials that will be placed in the waste dumps, according to the long-term planning at Antamina.

Cover systems

Lysimeters 1, 2, 4, and 5 were partially filled and Lysimeter 3 was completed filled with intrusive, Class A material, in October 2009. The four cover systems (Table 2) were installed in August - September 2010. The cover systems were designed to consist of a barrier component (cover material 1) and a growth medium and store and release cover (cover material 2). The former reduces water infiltration and air diffusion through the cover and the latter reduces infiltration by triggering evapotranspiration (Table 2).

Table 2: 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	No cover (Control)	-	No cover	-
4	-	-	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 waste rock and cover materials in the lysimeters using a crawler excavator, to desired elevations exemplified by Figure 3. 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. A vibrating plate compacted the corners and sides of the cover layers.

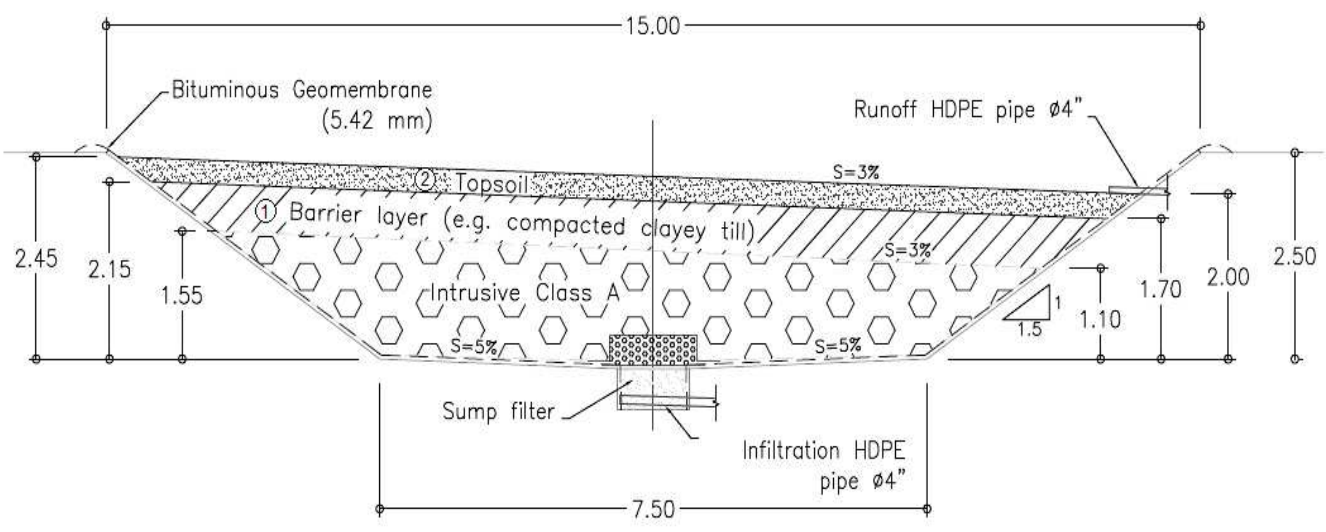

Figure 3: Schematic showing Lysimeter 1 and compacted clayey till cover system.

The light weight and reduced compaction capacity of the 800 kg vibrating roller required a modification in the initially desired construction procedure of the cover systems. Compaction of glacial till layers was specified as 95% of the maximum density of the standard Proctor test, within ±2% moisture content from the optimum moisture content. To achieve this specification, clayey till layers in Lysimeter 1 had to be constructed and compacted in four layers of 150 mm thick, while silty till layers in Lysimeter 5 had to be constructed and compacted in three layers of 200 mm thick. Nuclear density tests were carried out as part of the construction QA/QC program following ASTM-2922, by Golder Associates. A number of compaction tests were carried out 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 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, which, according to the classification tests performed on the clayey and silty till, were respectively 7% higher and 1.3% drier than the optimum moisture content from the initial standard Proctor tests. Intermittent rain 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 already compacted layers in the lysimeters had to be protected by plastic sheets as well, to avoid their soaking and the potential negative effect it could have on the subsequent cover layers.

Vegetation

High elevation and climate regime of the Antamina mine affects the kind of vegetation suitable for the topsoil layer of the cover systems. Vegetation selected for these layers was native *Calamagrostis sp.* (locally known as Ichu) and *Trifolium repens* (locally know 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.

Figure 4: Lysimeter 4 with Ichu already in place (January 2011).

Instrumentation

Ten tipping buckets, one per tank and collection pipe, were installed to quantify runoff and infiltration through the cover systems. Ten wooden boxes were built around the tanks and tipping buckets to shield the instruments. Tipping buckets were placed on manually adjustable plastic bases, attached to a concrete plate, which allows the regulation of the instruments level. Tipping buckets and tanks were installed almost at the same elevation. A water conveyance system directs water to the from the tank to the tipping buckets (Figure 5). Given the pipe outflow location, a certain amount of water has to be stored in the tank before it can flow into the tipping buckets. Tipping buckets data is collected with a Campbell Scientific CR1000 datalogger, which is uploaded via telemetry on a daily basis. Power for the datalogger is provided by solar power panel installed at site.

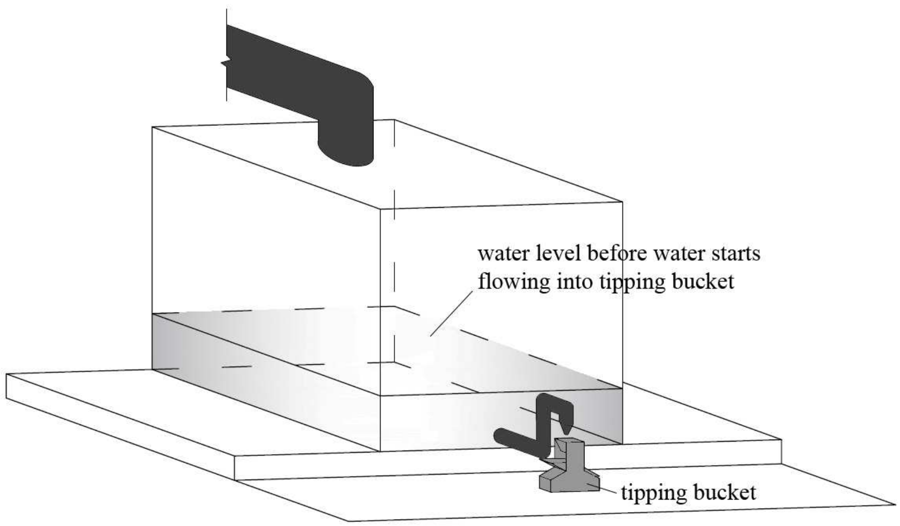

Figure 5: Schematic of a tipping bucket installed next to a tank.

Ten Fredlund Conductivity Sensors (FTC-100) were installed in the centre of the covers to indirectly measure soil matric suction. FTC-100 sensors are located at approximately 150 mm deep in all the topsoil layers, and at 500 mm and 700 mm deep in all the glacial till layers (Figure 6). FTC-100 sensors are connected to a suction sensor controller. Suction data is downloaded every two weeks. Power supply for the datalogger is provided by a second solar power panel installed at site.

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 0.318 cm (1/8”) inner diameter. Tubing for oxygen measurements were protected from damage from waste rock placement by PVC and HDPE piping. Tubing laid horizontally 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. All oxygen measurements are measured with a portable gas analyser.

Two rain gauges were already operating prior the construction of the experiment, approximately 100 m away from the lysimeters. Precipitation data is collected with a Campbell Scientific CR1000 datalogger, and is uploaded via telemetry on a daily basis. One net radiometer was installed on Lysimeter 4 for estimation of evaportranspiration from the cover system. These rain gauges and net radiometer will provide precipitation and net radiation data for the completing the numerical models and accurate water balances of each lysimeter.

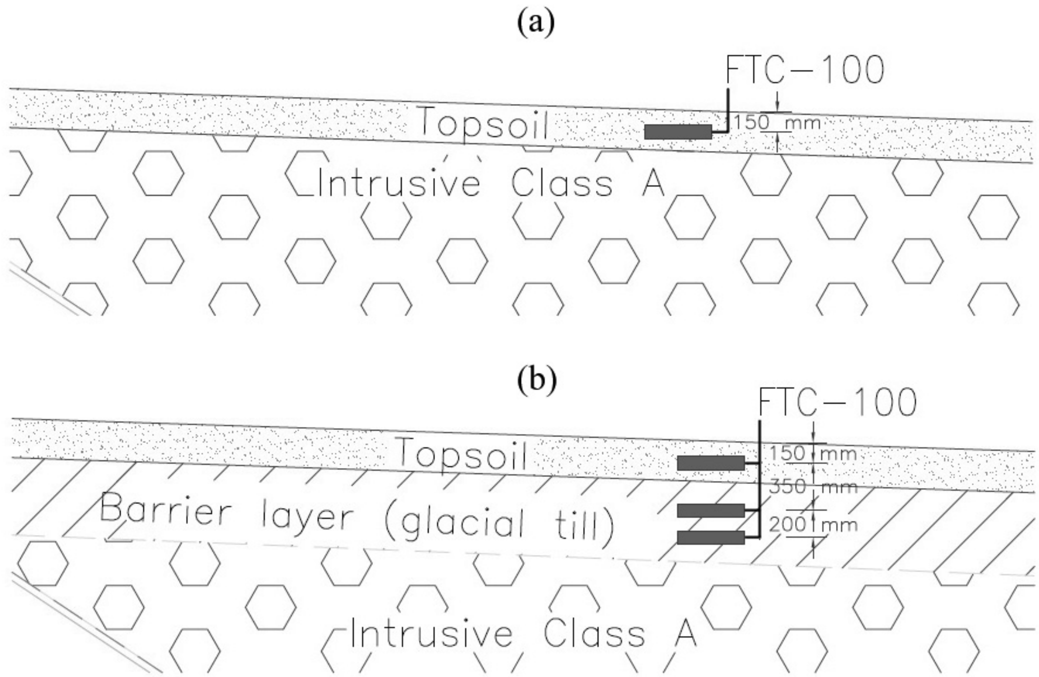

Figure 6: Schematics of FTC-100 sensors located in (a) Lysimeter 4 and (b) Lysimeters 1, 2 and 5.

Results

Infiltration results were first recorded in February 2011, however consistent data uploading from all lysimeters was not achieved until late April due to technical problems. No runoff has been registered by any lysimeter to date, and inspection of the 1 m^3 tanks revealed no water collection as of July 10^{th}. The absence of water indicates no runoff has occurred by any of the cover systems since installation (October 2010). Approximately 70% of the total precipitation on Lysimeter 1 was reported as infiltration (Figure 7b). Net infiltration through covers was only reduced by evapotranspiration, since no runoff was measured.

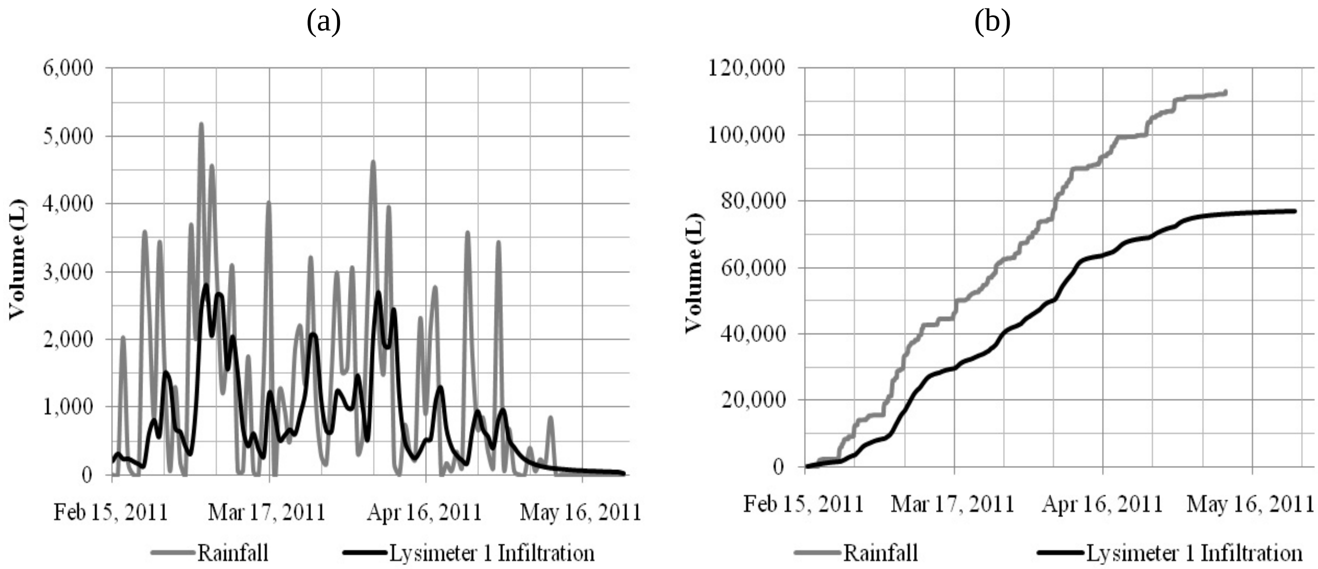

Figure 7: Rainfall and Lysimeter 1 infiltration between February 15th and May 10th, 2011: (a) Daily and (b) accumulated.

Net infiltration values recorded from the five lysimeters after April 20, 2011 are very similar (Figure 8). Rainfall occurred at the cover study site with an average intensity of $4x10^{-8}$ m/s, very similar to the expected saturated hydraulic conductivities of the compacted glacial tills, and lower than the rest of the covers and waste rock. This indicates that net infiltration has been more dependent on rainfall intensity than on the water barrier hydraulic conductivity. Rainfall intensities as seen in the recorded period of this study have not been high enough to generate runoff from the topsoil placed on the covers, since the intensities do not exceed the infiltration capacity of the topsoil.

Infiltration volumes were calculated with tipping buckets data corrected by calibrations provided by the manufacturer prior the installation of the instruments. Tipping buckets will be re-calibrated during the 2011 dry season, and will be calibrated again approximately every 6 months.

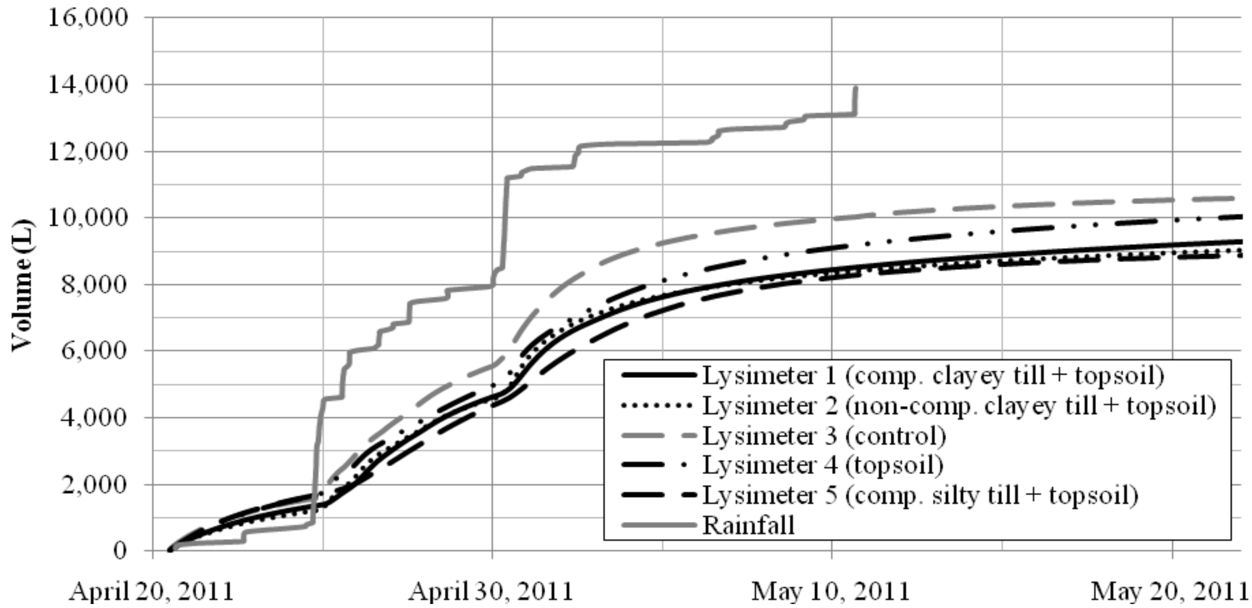

Figure 8: Accumulated rainfall and lysimeters net infiltration between April 20th and May 10th, 2011.

Conclusions

To date, data is insufficient to draw major conclusions on the performance of each independent cover system. Additionally, vegetation has not grown nor spread to its full capacity and may further influence infiltration rates via evapotranspiration. More representative results, for full scale waste dump covers is expected as the cover study matures in the subsequent years. Nevertheless, early results from this research exemplify the importance of looking at the performance of cover systems as a continuum, which encompasses both 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, like the one described in this paper, should be implemented at early stages of the life of a mine, since they require a number of 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. Antamina's cover study differs from many other cover systems worldwide due to the integration of field data from this field-scale study with laboratory results and numerical modelling. The incorporation of field-scale performance evaluation, under site-specific conditions, will help constrain and improve final cover designs and may reduce costs.

It should also be mentioned that field-scale experiments cannot stand alone, and that the best results are always attained when as many tools as possible are at our disposal. In this case this represents a combination of laboratory testing, numerical modelling, field-scale experiments, model calibration, and experience.

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