THE EFFECT OF A SOIL COVER ON DUMP RESPIRATION AND SEEPAGE QUANTITY AND QUALITY[1]

M. Phillip[2], M. O'Kane, B. Dawson, W. Kuit

Abstract: During May 15 – 17, 2006, four fatalities occurred at a partially reclaimed waste rock dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada. The fatalities occurred at the toe of the dump in a seepage monitoring station that is connected hydraulically, via a pipe and dump toe drain, to the acid generating waste rock capped with a 1-meter till cover. Following standard reclamation practices for the site, the cover system was placed to foster revegetation and limit infiltration. Since August 2006, the dump has been heavily instrumented in stages to test the initial hypothesis that changes in ambient meteorological parameters controlled respiration. The data collected also provides the opportunity to examine cover effectiveness. Automated and manual measurements gather a variety of data, including air velocity and seepage flow in the pipe connecting the toe drain and monitoring station; site meteorology; cover moisture content and temperature; and, internal temperature, gas composition, and pressure potential at 34 locations. Seepage quality results have been obtained at least monthly since May 2006. Vent locations have been discovered on the covered surface with depressed oxygen levels. Monitoring has shown that from fall to spring approximately 1.2 M m^3 of air, or nearly four times the estimated void space, enters the dump through the drainage pipe and exits through the cover. This paper evaluates the inability of the cover, even at high saturation conditions, to limit airflow and examines the changes in seepage quantity and quality.

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Introduction

During May 15 – 17, 2006, four fatalities occurred at the partially reclaimed No. 1 Shaft Waste Dump at the closed Teck Cominco Sullivan Mine near Kimberley, British Columbia, Canada (see Fig. 1). The fatalities occurred at the toe of the dump in a seepage monitoring station that was often used without incident, even as recently as one week prior to the fatalities.

Subsequent to the fatalities of May 15 - 17, 2006, Teck Cominco sought advice from University of British Columbia (UBC) experts and from a technical consulting firm as to the potential underlying causes of the tragedy. Based on inspections of the No. 1 Shaft Waste Dump site, analyses of monitoring station air samples taken shortly after the tragedy and their knowledge of the processes that occur in covered waste dumps, both groups came to realize that movement of oxygen-depleted air from the dump into the monitoring station was a likely causal factor. Further details on the initial post-incident investigation can be found elsewhere (Phillip and Hockley, 2007).

Figure. 1. Location of Kimberley, British Columbia, Canada.

This realization led to recommendations for technical investigations into the chemical and physical processes affecting air in the No. 1 Shaft Waste Dump and monitoring station. The investigation program is being guided by a Technical Panel that consists of independent experts from UBC, staff from the British Columbia Ministry of Energy, Mines and Petroleum Resources and Teck Cominco, and their respective technical advisors.

It was hypothesized that the 400 mm pipe connecting the drain to the monitoring station was the primary conduit between the atmosphere and dump waste rock, and that changes in atmospheric conditions resulted in *in situ* waste rock pore-gases entering the monitoring station. To investigate the respiration behavior of the dump, monitoring equipment was installed in two phases. Implemented in August 2006, the initial phase of the investigation involved monitoring the dump cover, site meteorology and the monitoring station. This monitoring is continuing and the overall program was significantly expanded in March 2007 with additional instruments to examine internal dump temperatures, pressures, and gas composition.

This paper focuses on data gathered from instruments installed during the initial phase of the investigation, which provide an opportunity to examine responses by the cover system to different conditions and how those responses affect respiration. An evapotranspirative cover was installed on the No. 1 Dump to promote vegetation and to minimize acid rock drainage (ARD) loadings and volumes requiring treatment. An evapotranspirative cover minimizes ARD by storing moisture within the cover until vegetative and atmospheric demands can remove the moisture. When limiting ARD there are generally two approaches: limit oxygen (airflow) and water (net percolation), or limit water (Swanson et al., 1997). Data from the Sullivan Mine No. 1 Waste Dump suggest that limiting water is more achievable for an evapotranspirative cover in an arid or semi-arid climate.

Average annual precipitation at the site is approximately 400 mm, with approximately 40% recorded as snow. Based on Environment Canada data from nearby Cranbrook, mean annual temperature is approximately 5^{o}C, with extremes of 37^{o}C and -40^{o}C. The site can be characterized on an annual basis as arid to semi-arid since a moisture deficit occurs annually. However, the site typically experiences hot dry summer conditions and can experience humid fall and winter conditions. It is not uncommon for rainfall to occur during the winter months. Spring freshet contributes significantly to flow in surface drainage courses. Annual potential evaporation at the site is generally in the range of 700 mm.

Background

The Sullivan mine, which operated from 1909 to 2001, was one of the world's largest underground Pb-Zn-Ag mines. Its metal values were accompanied by an abundance of pyrrhotite, which resulted in prolific acid generation in the mine and its waste materials. The No.1 Shaft Waste Dump was created during the 1940's to 2001, principally by the deposition of waste rock from the No. 1 Shaft. The dump curves along the slope below the shaft in a southwest to northeast orientation (see Fig. 2). The height from the upper flat portion of the dump to the toe is approximately 55 m. The dump is comprised of approximately 2.6M t of primarily sulfidic waste rock. The estimated dump volume is 1M m^3 with approximately 30% void space. Characterization of the No. 1 Dump waste rock has shown average carbonate and sulfide content of 0.8% and 1.5%, respectively; net NP ranges from 4.2 to -160 kg $CaCO_3$/t.

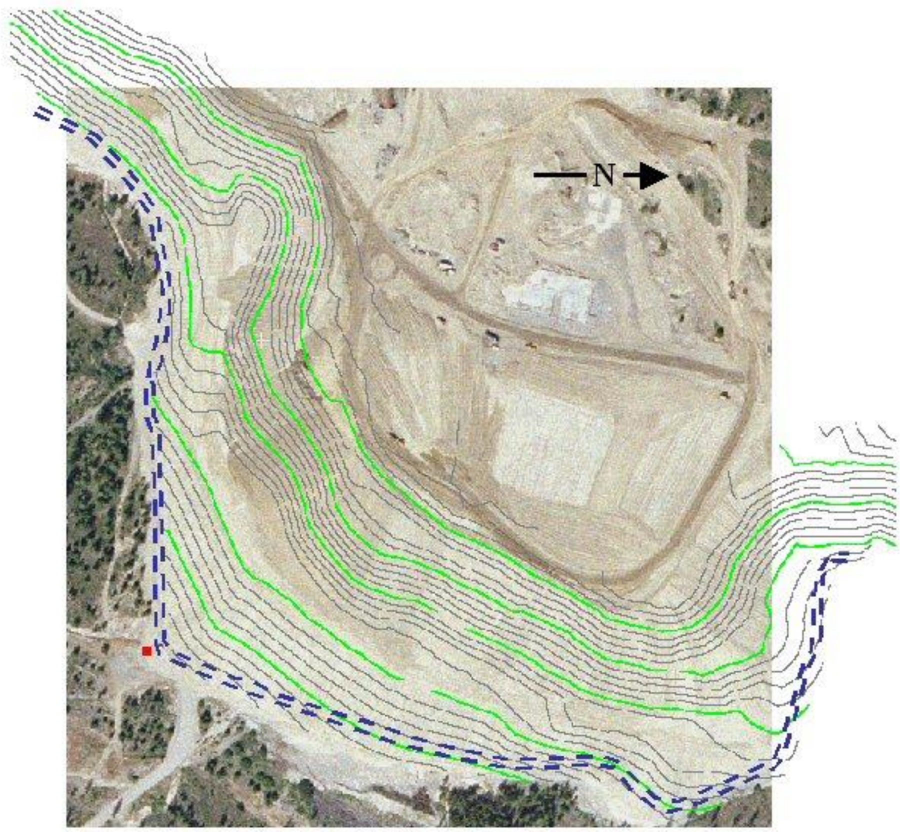

Figure 2. No. 1 Shaft waste dump. The drain, formerly the ditch, is shown with blue dashed lines along the toe. The monitoring station is the red square at the southeast corner of the dump.

In the early 1990s, Teck Cominco began to examine the water quality downstream of the waste dump and it was found to be affected by ARD emanating from the dump. To eliminate an impact on the receiving waters it was determined by Teck Cominco that the ARD water coming out of the waste rock dump would be collected and treated at Teck Cominco's Drainage Water Treatment Plant (DWTP) (Cominco Ltd., 1991). After examining the soils downstream of the dump it was discovered that the dump was placed on a glacial till layer of material overtopped with granular materials. The granular zones were producing springs of contaminated water. In 1995, a drainage ditch was placed around the toe of the dump to collect water and pipe it to the DWTP. This proved to be very effective at intercepting the contaminated water and resulted in substantial improvement in receiving water quality.

After the toe-drainage ditch was put into operation, ARD flow rate and water quality monitoring was implemented. This information was to be used to determine the effectiveness of the reclamation techniques. In 1995, a V-notch weir was installed. However, the weir was subject to icing over and it was difficult to obtain a water sample in the winter. In 1997, the weir was surrounded with large concrete blocks and covered by a small building. This became known as No.1 Shaft Waste Rock Dump Monitoring Station (see Fig. 3a).

In 2004, the toe ditch was reworked by placing a low permeability lining in the ditch and on the downstream slope using compacted glacial till. The ditch was then filled in with coarse rock over topped by finer rock followed by a filter layer of material (see Fig. 3b). This was carried out to allow waste rock to be placed up to and partially over the ditch when the dump was reprofiled for reclamation and geotechnical stability. In 2004 the waste rock in the dump was reprofiled up to and partially covering the toe drainage ditch. In 2005, a 1.0 m thick layer of glacial till soil cover was placed over the waste rock and the ditch. The till cover was placed in two lifts, using large dozers. The upper third to a half of this layer is then ripped to decrease density and provide for a layer of cover material amenable to root development and eventual formation of a sustainable vegetation cover. As a result of placing the cover material, surface, or uncontaminated water, would run off the dump but the contaminated water emanating from the waste dump would be collected. A cross section of the filled ditch, the dump drain and the pipe connection to the monitoring station is shown in Fig. 3c.

The till cover material is a generally non-plastic well-graded material with a relatively low air entry value (AEV) in the non-compacted condition (approximately 10 kPa). Compacting the till cover material at optimum moisture conditions and standard Proctor energy increases the AEV from 10 kPa to 30 kPa, and decreases the laboratory saturated hydraulic conductivity by at least 3 orders of magnitude (from approximately 1 x 10^{-3} cm/s to 1 x 10^{-6} cm/s).

The 1.0 m thick dump cover of glacial till was completed in October 2005, under wet conditions. It was left un-vegetated over the winter. In preparation for seeding, the cover was ripped in May 2006, about one week prior to the fatalities. To avoid influencing initial investigation results, seeding was deferred until Fall 2007 and little vegetation existed on the cover until Summer 2008.

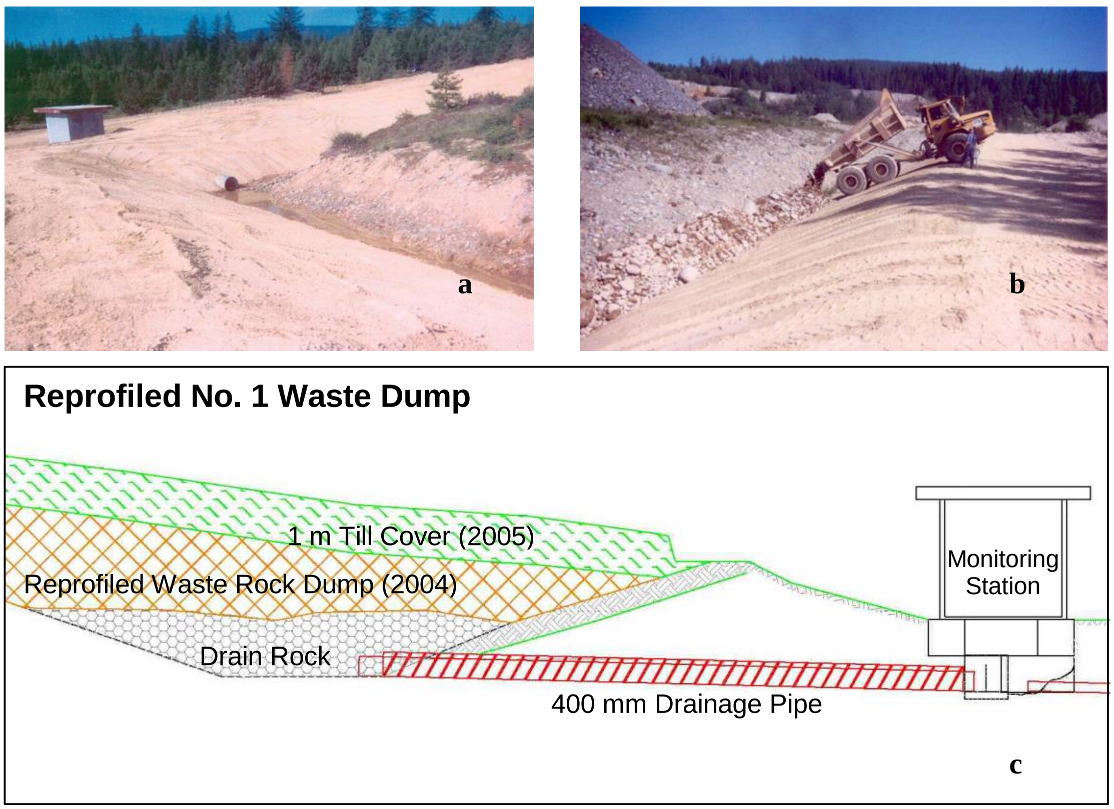

Figure 3. The monitoring station prior to reclamation (a). Drain rock being placed in the ditch (b). Cross-section showing drain rock, waste rock and till cover in former ditch with 400 mm pipe conveying seepage to monitoring station (c).

Materials and Methods

The Phase 1 installation of monitoring equipment, in August 2006, included instruments to automatically track conditions within the monitoring station. Air flow into and out of the 400 mm pipe is measured with an RM Young 85000 ultrasonic anemometer. Drainage flow is monitored by measuring the weir water height with a Campbell Scientific SR50 ultrasonic ranging device. All of the monitoring instruments within the monitoring station are operated remotely from a heated instrument shed located a short distance downhill. All sensors are controlled by Campbell Scientific data-loggers.

The weather station was installed on a mid-slope bench above the monitoring station. The weather station measures air temperature and relative humidity (Vaisala HMP45C212), wind speed and direction (RM Young 05103), net radiation (Kipp & Zonen NR Lite), and rainfall (Texas Electronics TE525).

Soil moisture and temperature profiles within the till cover are monitored continuously at two locations: adjacent to the weather station on a relatively flat mid-slope bench surface (Lower) and above it on a slope near the top surface of the dump (Upper) (see Fig. 4).

Soil moisture and temperature are measured with paired Campbell Scientific 616 and 107B sensors, respectively. The sensors were installed by excavating a trench to the bottom of the cover and placing the sensors into undisturbed cover material at eight depths. Volumetric samples were collected to determine porosity and assist with developing material specific calibration curves. Table 1 provides details on sensor depths at the two *in situ* installations. The cover thickness at both locations was greater than the designed 1.0 m, likely due the challenge of placing material on a slope.

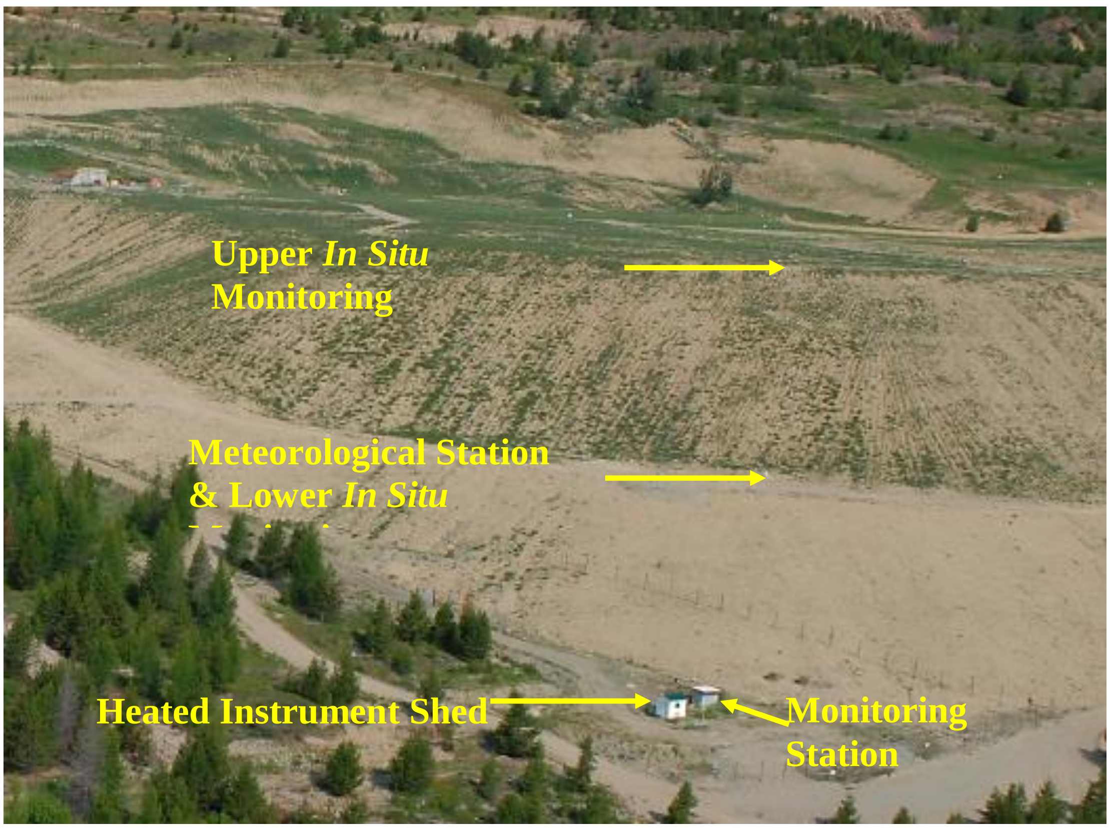

Figure 4. Layout of Phase 1 monitoring system on the No.1 Dump looking northwest (taken July 2008)

Table 1. *In situ* sensor profile depths.

Sensor Location	Depth (cm)	
	Lower Profile	Upper Profile
1	5	5
2	10	15
3	15	22
4	30	38
5	65	66
6	90	100
7	110	119
8	125	137
Cover-Waste Interface	130	149

Results and Discussion

Influences on *In Situ* Moisture Conditions

The soil cover moisture content is influenced by precipitation and the air and soil temperature, with lesser influence by location and cover thickness. Figure 5 shows the percent saturation for both soil profiles and the rainfall record from September 1, 2006 to August 31, 2008.

Precipitation clearly affects the cover during periods of rainfall. During the field season (spring to fall) the percent saturation falls in response to drainage and atmospheric demand (especially evident at the 5 cm depth), but spikes upward in response to significant rainfall events. Atmospheric demand is primarily due to evaporation, due to the delay in seeding. While vegetation did take hold in 2008, Fig. 4 clearly shows very little if any vegetation at the two *in situ* monitoring locations.

Precipitation in the form of snow influences the cover saturation with the co-influence of air and soil temperature. During the winter approximately 1.0 m of snowfall is present across the dump, generally insulating the cover from atmospheric temperature. Even if the ground freezes prior to significant snowfall (as occurred in November 2007) the entire cover eventually thaws due to the elevated internal temperature caused by the exothermic sulfide oxidation reactions.

With the cover surface just above freezing, the snow in contact with the ground melts and delivers moisture to the cover throughout the winter. This moisture delivery can be influenced by air temperature as seen in Fig. 5 and in more detail in Fig. 6. While the cover doesn't become frozen during periods of colder temperatures, the rate of snow melt decreases, allowing for drainage to surpass infiltration and causing the saturation level to drop.

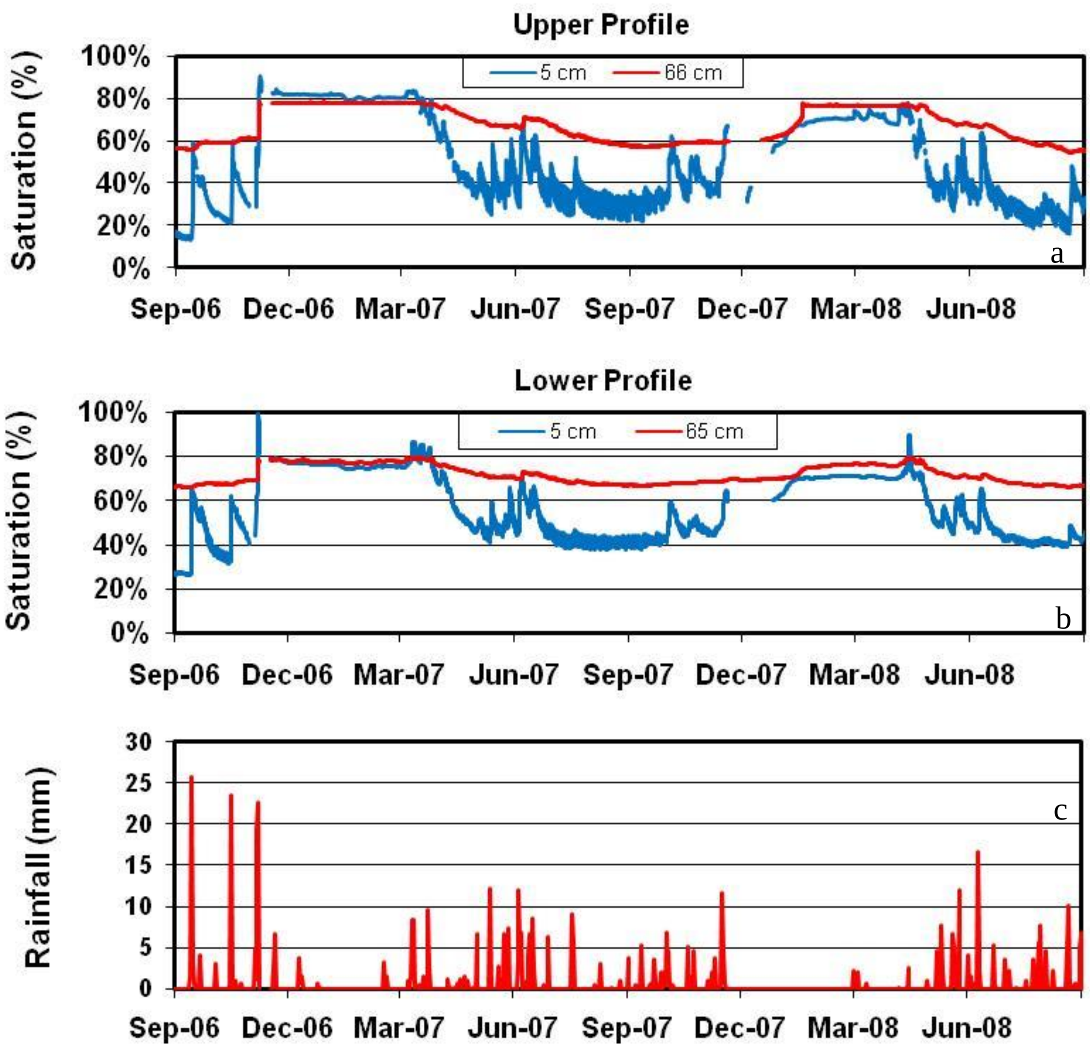

Figure 5. Upper and Lower profile soil cover degree of saturation at a depths of 5 cm and of 65/66cm of the cover (a and b) and rainfall (c).

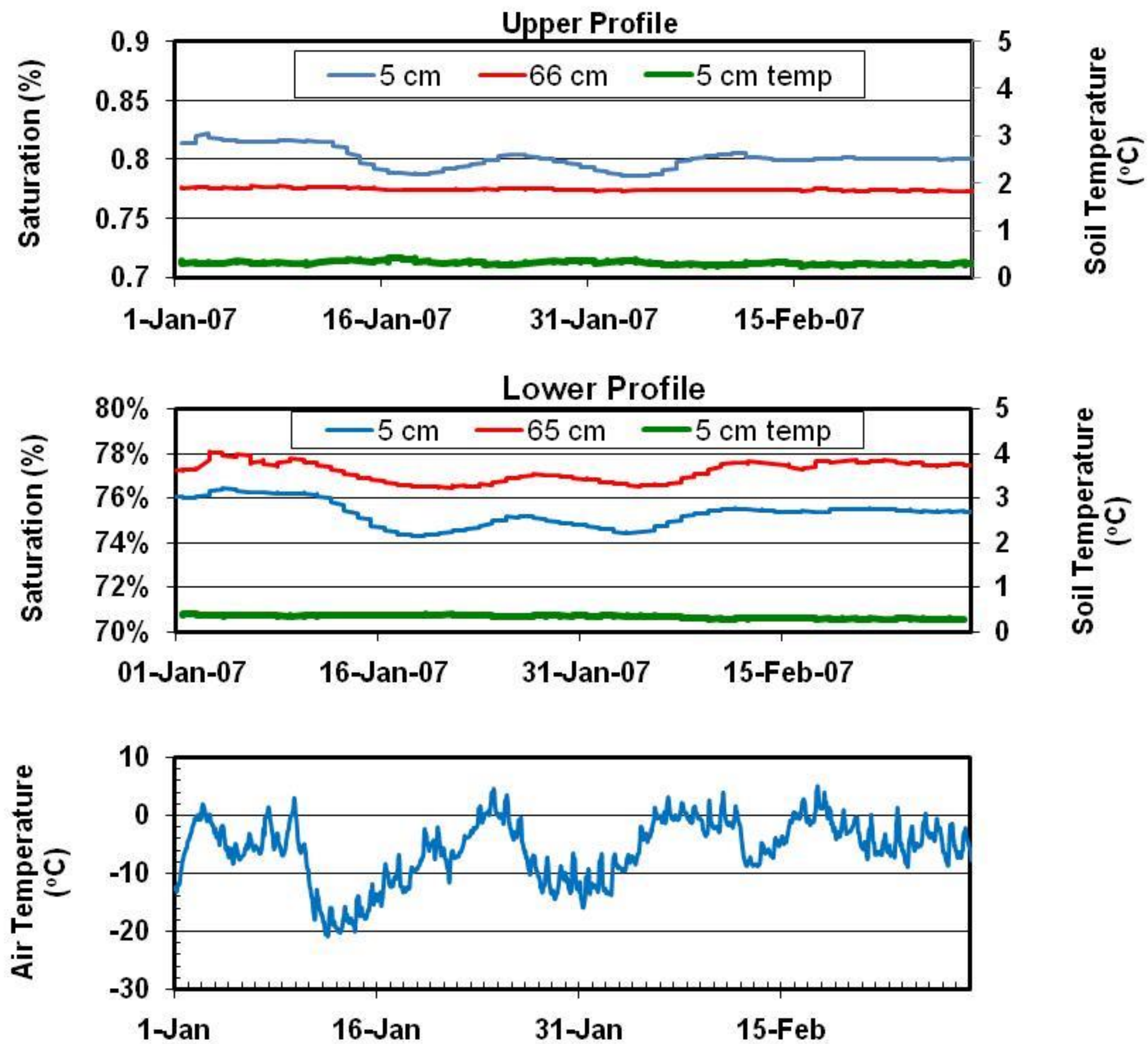

Figure 6. Changes in degree of saturation and soil temperature at two cover profiles in response to air temperature changes.

Location and cover thickness also play a part in the saturation conditions shown in Fig. 5. The Lower profile is on a mid-slope bench and is more sheltered from direct solar radiation and wind than the Upper profile located just below the crest. This is seen in the upper profile having lower saturation conditions during the field season than the lower profile. Location also plays a role during spring melt. The lower profile shows higher saturation conditions, likely due to run-on from the slope above.

The effect of cover thickness can be seen by comparing the total cover saturation conditions during the field season. While the difference in saturation at the 5 cm depth is approximately 15 basis points, the difference in total *in situ* moisture conditions is quite small due to the upper profile's additional cover thickness, and therefore greater storage at depth where water content is relatively constant.

Respiration Control

The relationship between atmospheric air temperature and air velocity in the 400 mm pipe has been well documented (see Phillip *et al*, 2008). Respiration is similar to a chimney effect due to the internal dump temperature being within the annual air temperature range. During the winter when internal air is warmer than the atmospheric air, the warmer and less dense internal air rises up through the dump and fresh air is pulled in at the toe; during the summer the opposite is true. The pivot point, the air temperature at which respiration air flow changes direction, has increased from approximately 10.8 °C to 12.3 °C (see Fig. 7). Each fall to spring period, approximately 1.2 Mm^3 of air enters the dump at the toe, or roughly four times the estimated pore space. Based on a review of conditions from May 15-17, 2006, it is believed that air temperature controlled respiration during the time of the incident.

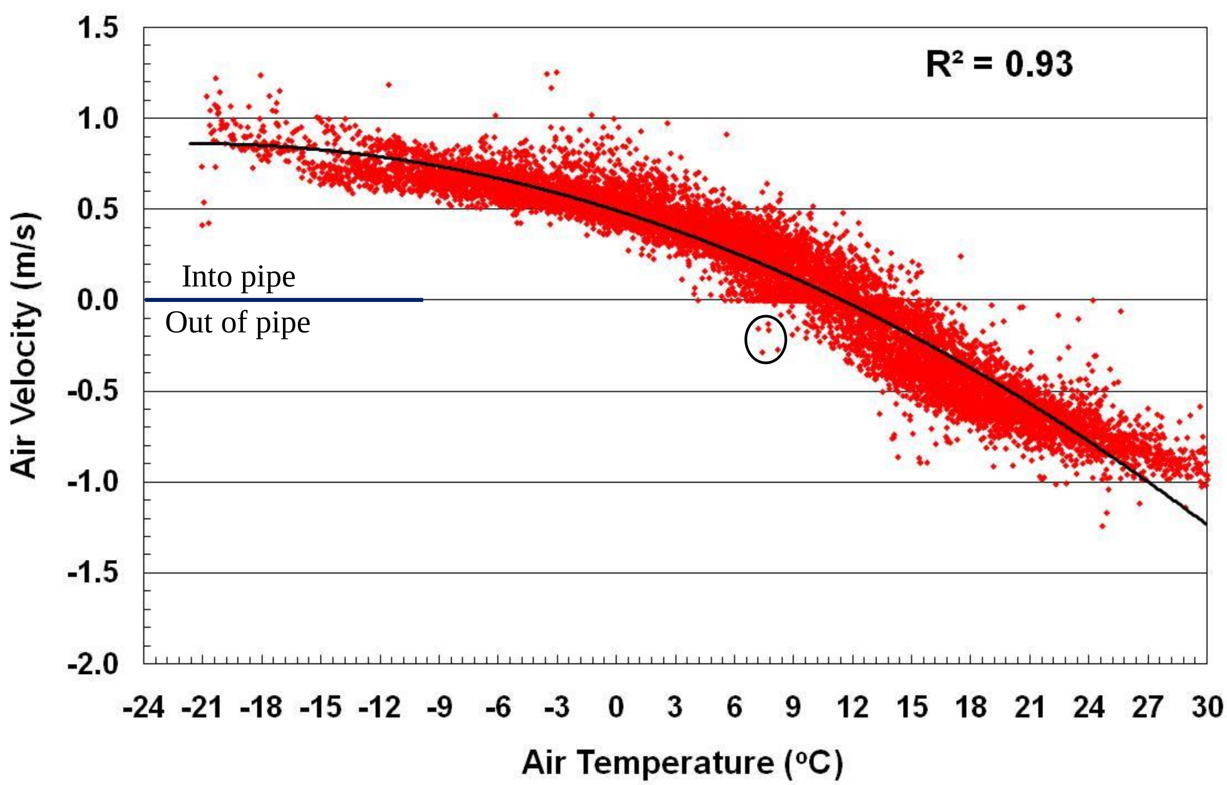

Figure 7. Air Velocity versus Air Temperature in the 400 mm pipe. The data within the oval are from the March 12, 2007 barometric pressure-controlled respiration event.

In over two years of monitoring, there has only been one time when the air temperature and air velocity relationship has broken. For five hours on March 12, 2007, negative air velocity (air exiting at the dump toe) occurred at air temperatures that commonly result in positive air velocity. The event occurred after a winter of snow melting into the unfrozen cover, after nearly two straight days of above-freezing temperatures causing snowmelt, immediately after a significant rainfall event and during a time of falling barometric pressure. This event is the only recorded event of barometric pressure- controlled respiration.

The stage was set for high moisture conditions in the cover material by the previously described delivery of melting snow moisture to the unfrozen cover throughout the winter. Additional moisture was added to the cover during nearly continuous days of positive temperatures (March 4-12) resulting in loss of snowpack. Then from 7pm on March 11 to 5am on March 12, 11.9 mm of rainfall was recorded at the site, increasing saturation conditions to a point where the cover was, in effect, sealed to airflow (see Fig. 8).

While saturation conditions in the cover material were increasing, the barometric pressure was falling. This resulted in the internal dump pressure being greater than the barometric pressure. Because the airflow across the cover was significantly limited due to high *in situ* moisture condition, this difference in pressure was "released" through the 400 mm drainage pipe, resulting in a negative air velocity.

The exact degree of saturation in the cover material that allowed dump respiration to be controlled by barometric pressure is unknown. The highest saturation recorded during this period at the Upper and Lower profiles were 83% and 87%, respectively; however, dump and cover are both very heterogeneous. Geophysical resistivity surveys and drilling have shown a dump comprised of various materials with wide-ranging particles sizes. Premature snow-melt areas (PSAs) develop on the dump surface and can be hundreds of square meters in size and completely clear of snow before the spring melt begins. The PSAs are believed to be areas of diffuse but increased pore gas flux through the cover. In addition, small vents have been discovered on the dump surface, mostly but not always, occurring within PSAs. Oxygen concentrations as low as 6% have been measured at the ground surface at the vents.

While there is general respiration airflow through the dump and cover, there are certainly numerous macroflow paths that are preferential; the amount of moisture needed to prevent airflow across the cover system is unknown. Even with such an advantageous site as the

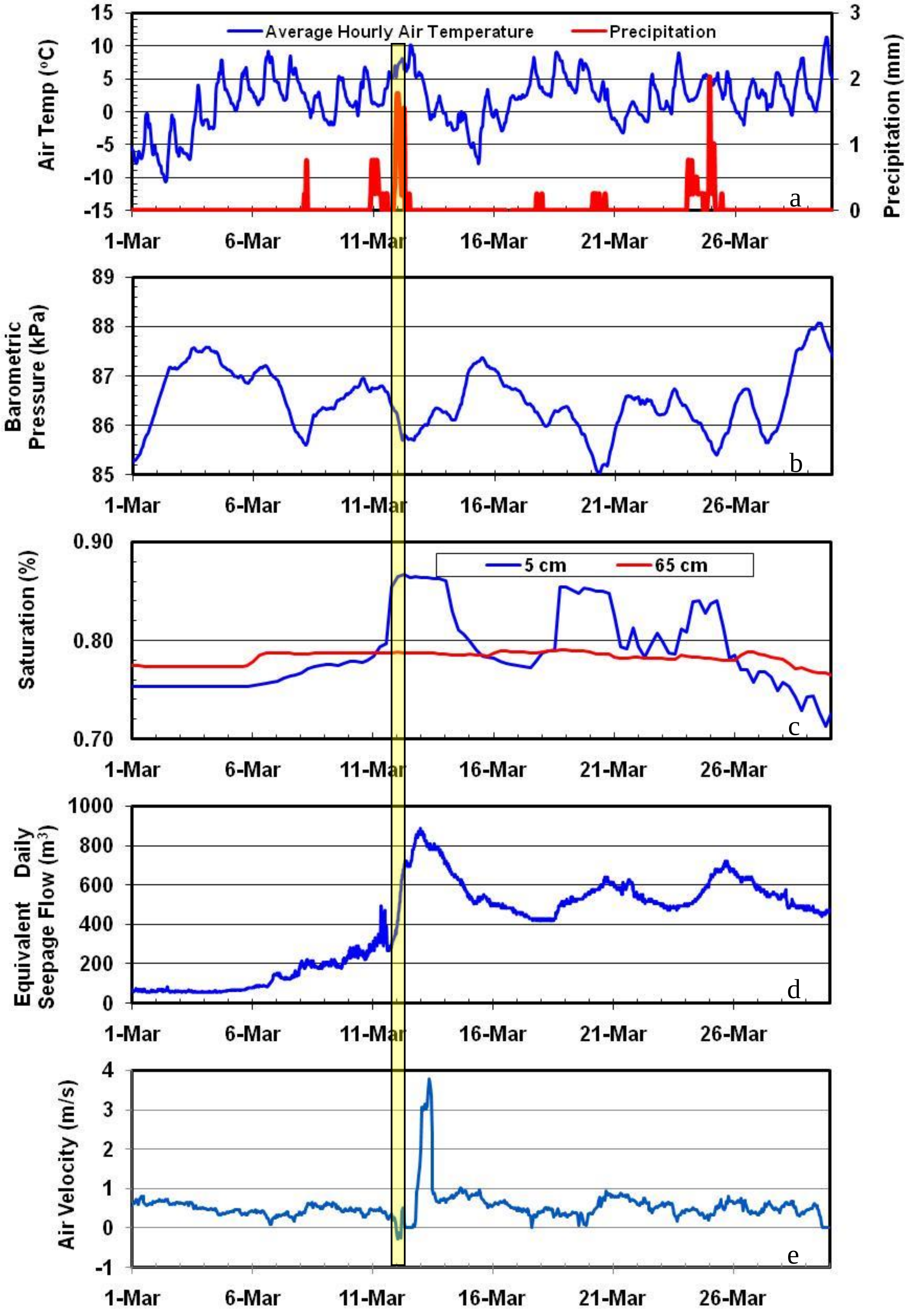

Figure 8. Site parameters from March 2007, highlighted on the period of barometric pressure control of March 12: air temperature and precipitation (a), barometric pressure (b), cover soil saturation (c), seepage flow (d), and air velocity in the 400 mm pipe (e).

Sullivan No. 1 Waste Dump, with an unfrozen cover and moisture provided throughout the winter, the ability to deliver sufficient moisture across the entire site to effectively seal the cover system to airflow is rare. This does not mean that the cover does not aid in decreasing respiration rates; a numerical gas flow model of the No. 1 Dump showed that without a cover the velocity of airflow through the dump increased 50% to 80% (Lahmira and Lefebvre, 2008).

Figure 8 also shows that not only soil moisture, but also seepage flow at the 400 mm pipe, respond quickly to snow melt rates caused by air temperature changes. This rapid transfer of snowmelt to seepage suggests possible contributions through cover macropores and up-gradient sources that bypass the cover system.

Seepage Mass Loading

Automated seepage flow has been conducted from August 2006 until early 2008 when monitoring ceased due to sensor failure. The, entire Monitoring Station was removed October 2008 and replaced with a U-trap as a partial remediation action. Prior to May 2006, the flow was monitored on a varying basis with manual measurements of the V-notch weir; seepage samples were not always collected when flow was measured. In 2007, seepage sampling for chemical analysis occurred monthly, except for weekly sampling during the spring melt when the largest quantity of seepage flow is delivered. Twenty-five seepage samples were collected and analyzed in 2007.

Seepage flow and chemistry have varied over the years, as have the number of possible seepage sources. Aside from seepage caused by direct precipitation on the dump surface, both natural and mine-related activities likely contributed to seepage flow. The No. 1 Dump is on the side of a hill, and up-gradient surface runoff and shallow subsurface drainage contribute to seepage volume. During mine operations, underground maintenance resulted in slurries of mine water and rock being placed on the dump surface when the mine was active. Cooling water from compressor pumps on the dump contributed an unknown amount of water to the dump until 2002; however, based on seepage flows, the cooling water could have contributed approximately 30,000 m^3/yr and Zn concentrations were relatively low due to dilution (see Fig. 9). After the cooling water was eliminated, Zn concentrations began to rise. In 2004, the reprofiling effort disturbed the waste material; the entire dump was covered in 2005. In addition to providing for vegetative growth, the cover was designed to limit the ARD loadings and volumes requiring treatment.

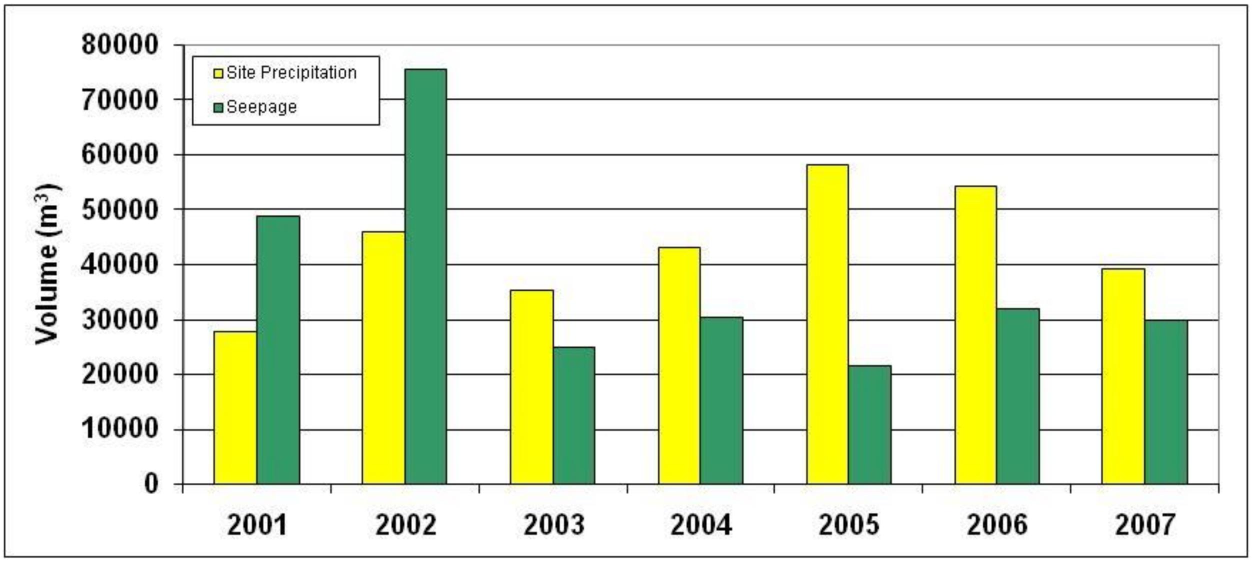

Figure 9. Total annual volume of seepage and precipitation that falls over the dump area. Seepage receives contributions from sources other than direct precipitation; cooling water is likely responsible for seepage volumes exceeding site precipitation in 2001-2002.

The combination of flow and chemistry data provides the opportunity to examine the mass of contaminants leaving the dump. Zinc was chosen for analysis in this paper because of its common nature at the mine and availability in limited chemical analyses. The chosen period of record is 2001 to 2007 because of the complete annual flow data available. Figure 10 displays dissolved Zn concentrations, seepage flow rates, and calculated total annual Zn loading.

There is some amount of uncertainty in the data due to the sample size variety. Regardless, there does appear to be useful information in the loading results. From 2004, when reclamation began, to 2006 the mass loading increases. This could be expected due to the disturbance of the waste material during re-profiling. Resistivity surveys have shown the lower slope, created during re-profiling, to be very conductive, which is an indication of geochemical activity. Re-profiling greatly disturbs material and can expose fresh rock to oxidation. The decrease in mass loading from 2006 to 2007 is encouraging, but additional years of data will be necessary to confirm any trends. It is also possible that the 2006 results are artificially high due to the limited amount of data for that year; if so, 2007 may represent only a leveling-off of the mass loading. Taken in its entirety and discounting the 2006 result, it could also be said of Fig. 10c that the “reclamation” loadings seen in 2005 to 2007 are essentially within the range of “pre-reclamation" loadings and that reclamation has not adversely impacted the loadings. A longer-term view is required before passing judgement.

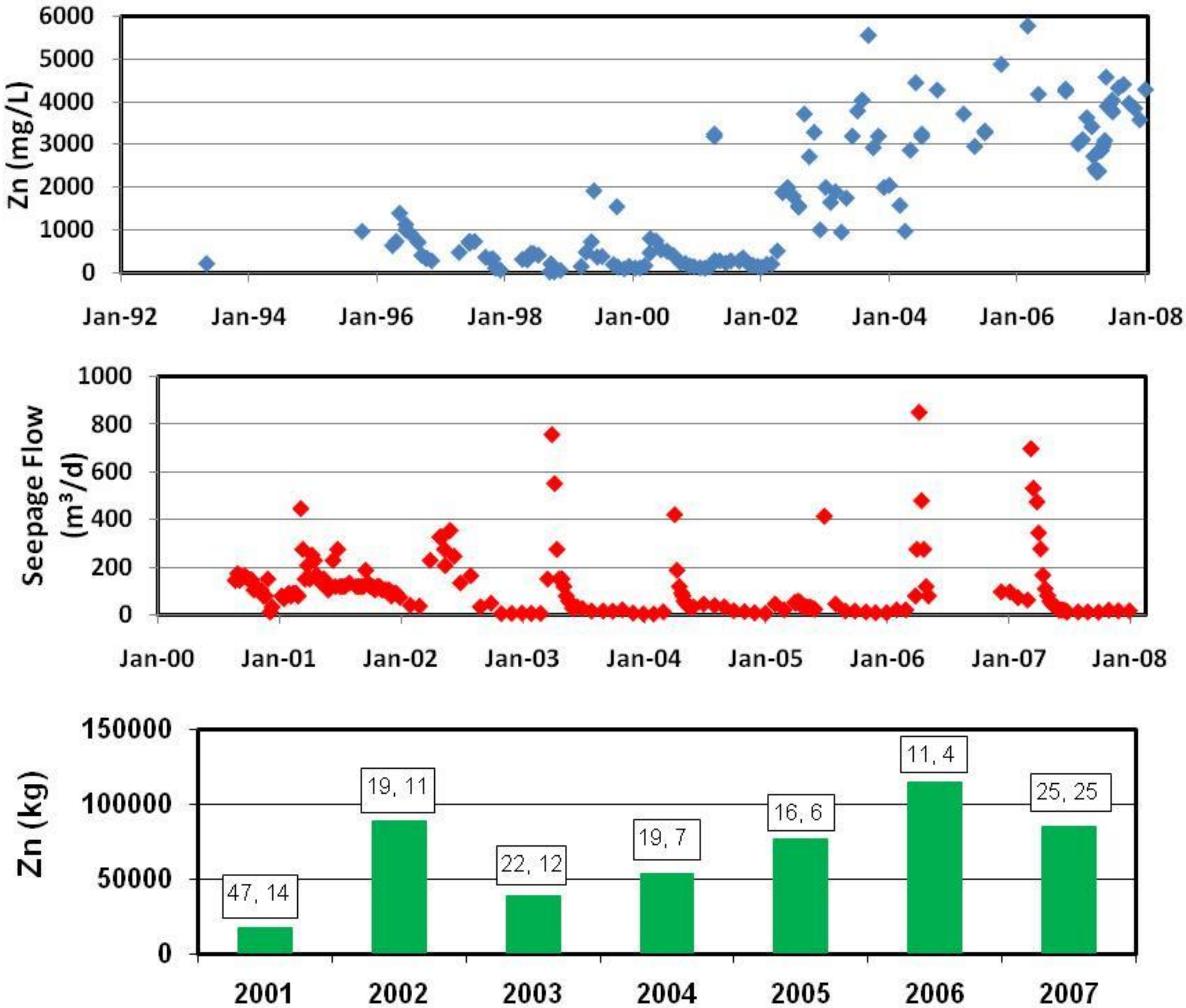

Figure 10. Zinc concentrations (a), Seepage flow rates (b), and Annual zinc mass in seepage (c). The two numbers above the bars in 9c are the number of flow measurements and chemistry analyses, respectively.

Conclusions

In an attempt to control sulfide oxidation of mine waste material, promote vegetation, and protect receiving waters, a 1.0 m glacial till store and release cover was constructed at the Sullivan Mine No. 1 Waste Dump. The cover system is influenced by air and internal dump temperature. During the winter the insulation of the snow cover and the exothermic oxidation reactions within produce an unfrozen cover that receives moisture from snow melting at the snow/cover interface, restoring moisture levels prior to the spring melt. For the two years of data collection there was very little vegetation on site and water content is nearly constant below depths of 100 cm. Differences in cover thickness and location between the two moisture profiles can be seen in the water content results.

No. 1 Dump respiration is strongly controlled by air temperature. Because the internal dump temperature is within the range of annual air temperature, the flow direction reverses throughout the year, producing alternating pore gas discharge along either the toe or top surface. Vents and premature snowmelt areas exist across the dump surface, suggesting preferential flow paths through the cover. In two years of monitoring, adequate moisture to “seal” the cover was only achieved once over a five-hour period. While the cover is relatively open to gas fluxes, the cover still greatly limits airflow through the dump.

The placement of the cover has reduced seepage flows, but metals concentrations have increased. The mass loading of Zn was calculated to determine the overall change in mass flow rates in the seepage. The mass loading results from the No. 1 Dump show that conclusions about mass loading results can be difficult to make. Frequent chemistry and flow monitoring, likely over several years, is necessary to reduce the uncertainty in such an analysis and to generate true trends. Mass loading did increase for the two years following re-grading, which may be expected given the inherent disturbance of this step. Possible explanations for the overall mass loading results range from encouraging (possible mass loading decrease in the second year following reclamation) to neutral (mass loading leveling off or within the range of pre-reclamation loading). The expectation that reclamation will immediately reduce impacts may not be warranted and long-term monitoring should be expected.

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