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EVALUATION OF MAN-MADE SUBAQUEOUS DISPOSAL OPTION AS A METHOD OF CONTROLLING OXIDATION OF SULFIDE MINERALS: COLUMN STUDIES

MEND Project 2.12.1e

This work was done on behalf of MEND and sponsored by Aur Resources Inc.,
Noranda Inc.,
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EXECUTIVE SUMMARY

In 1995, a collaborative project using the Louvicourt site to demonstrate the effectiveness of subaqueous tailings disposal in artificial containment structures under shallow water covers was initiated under the Mine Environment Neutral Drainage Program. The project was managed by Golder Associés as the lead consultants with Aur Resources, Canada Centre of Mining and Energy Technoloy (CANMET), INRS-EAU (University of Quebec), the University of British Columbia, SENES Consultants and the Noranda Technology Centre as collaborators. The role of CANMET in the project was to investigate, through column studies, four scenarios of subaqueous tailings disposal that might be applicable to the Louvicourt site upon mine closure.

Tailings samples collected over a period of a month by site personnel from the backfill circuit of the Louvicourt mill were shipped to CANMET with a layer of process water maintained over the tailings at all times. These were transferred in slurry and allowed to settle and form the bottom layer in four series of triplicate columns (0.3 m inner diameter), each simulating a different scenario of subaqueous tailings disposal. The column setup was as follows:

- Series 1: 0.3 m water directly overlying tailings
- Series 2: 0.3 m water overlying 0.3 m peat as an intermediate layer over the tailings
- Series 3: 0.3 m water overlying 0.3 m sand as an intermediate layer over the tailings
- Series 4: 1.0 m water directly over tailings

In other words, the column experiment was designed to evaluate the effectiveness of two water depths (0.3 m and 1.0 m) and two intermediate barriers (peat and sand) to prevent weathering of submerged tailings. Both the peat and sand used in the column studies were locally available material sampled by mine personnel from within the Louvicourt property. To facilitate replenishment of the water cover as needed during the study, the process water in each column was replaced by untreated Ottawa River water at startup.

The column studies consisted of two major phases. Phase I, which lasted for 200 days, focused on oxygen diffusion and ionic fluxes under conditions of a circulated water cover. In the first 100 days, the water cover in each column was circulated but not aerated. In the second 100 days, aeration of the water cover was also included. Phase II, which lasted for 13 months, incorporated precipitation, runoff and drawdown events at rates comparable to those observed in the field. The impact on the chemistry of the water cover and porewater in each series of columns was investigated. Both Phases I and II commenced with a new batch of natural water as water cover such that only the porewater in each column retained remnant effects of the previous stage of testing.

The test results showed that, especially during Phase I, sulfide oxidation, efflux of porewater sulfate and perhaps also dissolution of minor secondary sulfates contributed to increasing sulfate concentrations in the water covers directly overlying the tailings. A slight pH depression was observed in the overlying water in the peat and sand columns during Phase I. This could be caused by acidity released in the hydrolysis of Fe and Mn near the water/solids interface and/or oxidation of entrapped sulfide contamination. After the initial flushing of stored weathering products, however, both peat and sand provided an effective diffusion barrier to suppress chemical weathering of the underlying tailings. Largely controlled by the alkalinity balance in the water covers, the 1.0 m simple water cover without an intermediate barrier layer appeared to outperform the 0.3 m water cover in suppressing sulfide oxidation and metal leaching in the submerged tailings under the laboratory test conditions. In any case, precipitation of iron oxyhydroxides at the water/tailings interface and drawdown limited the efflux of undesirable metals to the overlying water column. Only minor dissolved zinc was found diffusing from the tailings porewater to the overlying water column.

Since the column studies were conducted under laboratory conditions that differed significantly from those occurring in the field, caution must be exercised in extending conclusions drawn from the column studies directly to the Louvicourt site. Further work recommended to supplement the current investigation include the following:

1. Post-test solids characterization to confirm geochemical processes taken place
2. Correlation of results of the column studies with field monitoring data
3. Lysimeter testing of a 1.0 m water cover with less alkalinity content to clarify its long-term performance under well oxygenated conditions
4. Investigation of the rate of carbonate depletion in the test solids and its long-term implications

A thorough understanding of the important and relevant physical, chemical and biological processes associated with subaqueous tailings disposal will facilitate the design of practical, walk-away solutions for the decommissioning of mine sites, like the Louvicourt Mine, which utilize the water cover technology to suppress sulfide oxidation in reactive tailings.

SOMMAIRE

En 1995, un projet conjoint a été entrepris au site de la mine Louvicourt, dans le cadre du Programme de neutralisation des eaux de drainage dans l'environnement minier, afin de démontrer l’efficacité de la déposition subaquatique des résidus dans des structures de confinement artificielles sous de couvertures aqueuses peu profondes. Le projet a été géré par Golder Associés qui agissait à titre de consultants principaux avec Aur Ressources, le Centre canadien de la technologie des minéraux et de l'énergie (CANMET), l’INRS-EAU (Université du Québec), l’Université de la Colombie-Britannique, SENES Consultants et le Centre de technologie Noranda. Le rôle de CANMET dans le projet était d’analyser, en effectuant des études en colonnes, quatre scénarios de déposition subaquatique des résidus qui pourraient éventuellement convenir au site de la mine Louvicourt, lorsque celle-ci serait fermée.

Des échantillons de résidus prélevés sur une période d’un mois du circuit de remblayage par le personnel de la mine Louvicourt ont été envoyés à CANMET. Pendant l’expédition, ils étaient continuellement recouverts d’une couche d’eau de traitement. On a transféré ces résidus sous forme d’une pulpe qu’on a ensuite laissé précipiter comme couche de fond de quatre séries de trois colonnes identiques (d’un diamètre intérieur de 0,3 m). Chaque série simulait un scénario différent pour la déposition subaquatique. La configuration des colonnes était la suivante :

- Série 1 : couverture aqueuse de 0,3 m directement sur les résidus
- Série 2 : couverture aqueuse de 0,3 m sur une couche intermédiaire de tourbe disposée sur les résidus
- Série 3 : couverture aqueuse de 0,3 m sur une couche intermédiaire de sable disposée sur les résidus
- Série 4 : couverture aqueuse de 1,0 m sur les résidus

En d’autres mots, l’étude en colonnes visait à évaluer dans quelle mesure des couches de deux épaisseurs (0,3 m et 1,0 m) et deux barrières intermédiaires (tourbe et sable) permettaient de prévenir l’altération des résidus submergés. La tourbe et le sable utilisés dans les études en colonnes étaient disponibles localement et ont été prélevés sur la propriété de la mine Louvicourt par le personnel de la mine. Afin de faciliter le remplacement de la couverture aqueuse pendant l’étude, on a utilisé, au début, à la place de l’eau de traitement de la mine, de l’eau non traitée provenant de la rivière des Outaouais.

L’étude en colonnes comportait deux phases principales. La phase I, qui s’est étendue sur 200 jours, portait surtout sur la diffusion d’oxygène et les flux ioniques dans une couverture aqueuse en circulation. Au cours des 100 premiers jours, l’eau de la couverture aqueuse était en circulation, mais elle n’était pas aérée. Pendant les 100 derniers jours, la couverture aqueuse était en circulation et était aérée. Au cours de la phase II, qui s’est étalée sur une période de 13 mois, il y a eu précipitation, ruissellement et rabattement à des taux semblables à ceux observés sur le terrain. On a étudié les répercussions de ces phénomènes sur la chimie de la couverture aqueuse et des eaux interstitielles de chaque série de colonnes. On a, au début de chaque phase, utilisé de nouveaux lots d’eau naturelle

comme couvertures aqueuses, de sorte que seule l'eau interstitielle de chaque colonne retenait les effets résiduels de l'étape précédente de l'étude.

Les résultats de l'étude ont montré que, plus particulièrement pendant la phase I, l'oxydation des sulfures, l'écoulement des sulfates à partir de l'eau interstitielle et peut-être également la dissolution de quantités mineures de sulfures secondaires ont contribué à l'augmentation de la teneur en sulfate de la couverture aqueuse disposée directement sur les résidus. On a détecté, au cours de la phase I, une faible baisse du pH dans la couverture aqueuse des colonnes avec de la tourbe et avec du sable. Cette diminution pourrait résulter de l'acidification provoquée par l'hydrolyse du Fe et du Mn près de l'interface eau/solide, et/ou de l'oxydation de contaminants sulfurés piégés. Toutefois, après le lessivage initial des agents d'altération accumulés, tant la tourbe que le sable constituaient une barrière de diffusion efficace permettant de supprimer l'altération chimique des résidus sous-jacents. La couverture aqueuse de 1,0 m sans couche intermédiaire semblait plus efficace que la couverture aqueuse de 0,3 m pour freiner l'oxydation des sulfures et la lixiviation des métaux dans les résidus submergés, dans des conditions de laboratoire; ce phénomène est contrôlée en grande partie par le bilan d'alcalinité dans les couvertures aqueuses. Quoi qu'il en soit, la précipitation des oxyhydroxydes de fer à l'interface eau/résidus et le rabattement limitaient le flux de métaux indésirables vers la colonne d'eau sus-jacente. Seules de faibles quantités de zinc dissous diffusaient à partir de l'eau interstitielle des résidus vers la colonne d'eau sus-jacente.

Il faut faire preuve de circonspection en extrapolant directement au site de la mine Louvicourt les conclusions des études en colonnes, puisque ces dernières ont été réalisées en laboratoire, c'est-à-dire dans des conditions fort différentes des conditions observées sur le terrain. Parmi les travaux additionnels recommandés pour compléter cette étude, on compte :

1. La caractérisation des solides après les essais en colonnes afin de confirmer les processus géochimiques qui sont survenus.
2. La corrélation des résultats des essais en colonnes avec les données obtenues des parcelles expérimentales.
3. L'exécution d'essais lysimétriques sur les couvertures aqueuses de 1,0 m moins alcalines, afin de clarifier leur performance à long terme dans des conditions bien oxygénées.
4. La détermination du taux d'appauvrissement en carbonate et de ses conséquences à long terme dans les solides ayant fait l'objet d'essais.

Une bonne compréhension des processus physiques, chimiques et biologiques importants et pertinents lors de la déposition subaquatique des résidus facilitera l'élaboration de solutions pratiques ne nécessitant aucune intervention ultérieure après la fermeture du site qui, comme la mine Louvicourt, utilisent la technologie des couvertures aqueuses pour freiner l'oxydation de sulfures dans les résidus réactifs.

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1.0 INTRODUCTION

1.1 Project Inception

The Louvicourt Mine, located about 20 km east of Val d'Or, Quebec, hosts a polymetallic Cu-Zn-Au massive sulfide orebody discovered in 1989. Flotation tailings contain pyrite and other sulfide minerals, and are classified as potentially acid generating. From the start of mine production in 1994, tailings not used for paste backfill have been discharged directly to an engineered impoundment, where they are stored beneath a water cover designed to prevent the onset of acid rock drainage (ARD) during mine operation and following closure.

In 1994 the Mine Environment Neutral Drainage (MEND) program solicited a proposal to demonstrate the effectiveness of water covers in artificial containment structures in inhibiting sulfide oxidation and preventing ARD. A proposal to conduct integrated laboratory and field studies using tailings from the Louvicourt Mine was accepted by MEND and the co-funders (Noranda, Aur, Teck) in January 1995. The project was to be managed by Golder Associes as the lead consultants with Aur Resources, Canada Centre for Mineral and Energy Technology (CANMET), INRS-EAU (University of Quebec), SENES Consultants, The University of British Columbia and the Noranda Technology Centre (NTC) as collaborators (Golder Associes Ltée, 1994). CANMET submitted a proposal, under this umbrella agreement, which was approved and signed in April of 1995.

1.2 Project Objectives

The general objectives of the overall MEND project were:

- to demonstrate the effectiveness of shallow water covers as a permanent means of preventing the oxidation of sulfide minerals and the consequent formation of ARD; and,

- to examine the effectiveness, cost and method of placement of wet organic barriers as an alternative (or supplemental) technology to very shallow water covers.

These objectives were to be realized through detailed laboratory (NTC, CANMET) and field (Aur, INRS-EAU) investigations followed by data interpretation and predictive model development (SENES).

The objectives of the column studies carried out by CANMET were:

- to study oxygen diffusion and the role of water cover in controlling dissolved oxygen availability to reactive tailings disposed under water;
- to assess the migration of residual mill reagents and reaction products via simulated surface and groundwater regimes;
- to determine the effects of sand and organic covers in reducing oxygen diffusion to tailings and upward migration of ionic species from tailings; and,
- to provide pertinent data for modeling downstream water quality and metal loading parameters from reactive tailings disposed under water.

In addition, CANMET undertook mineralogical assessments of tailings placed in the field test cells constructed at the Louvicourt site in 1996 and covered with 0.3m of water. Details on the field-cell construction are given in Golder (1997). The results of mineralogical and related analyses on samples collected in 1996 and 1998 are detailed in Paktunc and Wilson (1997) and Paktunc (1999), respectively.

1.3 Site Description

The Louvicourt deposit is located approximately 20 km east of Val d'Or in Quebec, Canada. It is a Cu-Zn-Au massive sulfide deposit discovered by Aur Resources in 1989. The ore reserve is approximately 12.5 million tonnes grading 3.6% Cu, 1.5% Zn, 0.29 g/t Ag, and 0.84 g/t Au. The underground mine started operations in 1994 and mill throughput has been approximately 4300 tonnes per day. The mill produces Cu and Zn concentrates with accessory precious metal content. Approximately 60% of the cycloned tailings is returned to the underground mine as paste backfill, and the remaining 40% is discharged to a tailings impoundment for permanent storage.

The tailings basin is 9 km from the mine site and covers 96 hectares. Clay and bedrock with low-permeability underlie the basin. The tailings are discharged into the basin through a floating pipeline and are stored in the impoundment under a permanent water cover to minimize the onset of ARD resulting from sulfide oxidation. The initial water cover depth at mill start-up was 3.0 m, which is gradually decreasing as the basin fills with tailings. A minimum water cover depth of 1.0 m is to be maintained throughout operation and after closure.

Meteorological data over the last 30 years show that above-zero average monthly temperatures are maintained for only seven months (April through October) per year. The local area receives on average 0.92 m of precipitation per year while the tailings pond receives additional water as run-off from the surrounding catchment area, for a total estimated water input of 1.37 million m^3 per annum. After closure, the estimated annual water balance for the 96-hectare tailings basin predicts a positive balance with annual discharges of approximately 540,000 m^3 water.

1.4 Water Cover Background

The tailings management area for the Louvicourt site is designed to maintain a minimum of 1 m of water above the tailings after closure. With its low oxygen diffusion coefficient ($2x10^{-9}$ m^2/s) and low oxygen solubility (8.6 g/m^3 at 25^oC), water is considered the most economical and effective oxygen limiting cover material for temperate climatic zones where the average annual precipitation exceeds total evaporative losses. The calculated oxygen diffusion flux into water-covered mine waste is approximately 3000 times less than for air exposed, unsaturated wastes (Davé, 1992).

While a water cover significantly reduces the oxidation of reactive mine wastes, oxidation is not completely eliminated. Shallow water covers (<2 m) contain a finite amount of dissolved oxygen, typically 8.6 mg/L of O_2 at 25^oC, which is available to the waste surface. Fluxes of dissolved oxygen into various mine tailings deposits, ranging between 0.2 and 100 $g/m^2/yr$, have been reported in the literature (Section 3.3.1). In addition, re-suspension or disturbance of the deposited waste material by wind-induced waves, ice, vegetation or wildlife may increase the available surface area of the reactive waste to dissolved oxygen.

Intermediate barriers between the water and reactive mine waste have been proposed to further minimize oxidation, based on their physical or chemical properties or both. Organic materials such as wood waste, municipal sludge, peat and compost may act as oxygen sinks, consuming oxygen at the water/barrier interface (Reardon and Moodle, 1985; Brown, 1991; Pierce, 1992; Pierce et al., 1994; Senes, 1994). Inert materials or physical barriers such as low-sulfur tailings or sand may also reduce the oxygen ingress into the waste by acting as diffusion barriers.

To investigate alternatives of water cover disposal for the Louvicourt tailings, this project addresses four specific disposal options. These are: two water depths over the tailings of 0.3 and 1.0 m; an intermediate barrier of peat (0.3 m) between the tailings and water cover; and, an intermediate barrier of sand (0.3 m) between the tailings and water cover.

1.5 Scope of Report

This report consists of six sections. Section 1 provides a brief account of the project background and scope. A concise description of the Louvicourt ore deposit and site conditions is also included. Section 2 describes the methodology used in the column studies, including sampling procedures, experimental design and analytical methods. Section 3 presents the results of the column studies. Based on the test results, Section 4 discusses four major issues the laboratory investigation has been designed to address. These are:

1. role of water cover in controlling the availability of dissolved oxygen to submerged tailings;
2. effects of intermediate barrier in suppressing oxidation and contaminant transport;

3. influence of drawdown, runoff and precipitation on water chemistry; and,
4. relative merits of various options of subaqueous disposal of tailings.

Conclusions drawn from the column studies are furnished in Section 5 and recommendations for further work are detailed in Section 6.

2.0 EXPERIMENTAL METHODOLOGY

Laboratory experiments were undertaken to determine the oxidation and leaching characteristics of the Louvicourt tailings deposited and maintained under saturated conditions. Dissolved oxygen (DO) profiles and contaminant fluxes into the overlying water column were assessed for four different subaqueous disposal scenarios, including two water depths and two types of intermediate barriers.

2.1 Material Selection and Sampling Procedure

2.1.1 Tailings

Fresh, unoxidized mill tailings were collected by site personnel from the backfill circuit of the Louvicourt mill between May and June, 1995. Ten 35-gallon drums were filled in parallel at a frequency of one sampling per week over a one-month period. The length of the sampling period was chosen based on the observed variation in tailings composition (Appendix 1) and ensured that a representative sample of the total tailings was obtained.

A layer of process water was maintained over the tailings at all times while filling the drums, during shipping and on receipt prior to column loading, to minimise oxidation of the fresh tailings. Additional process water was used to slurry the tailings before placing them in the columns.

2.1.2 Intermediate Barriers

Both the sand and peat used as intermediate barriers are materials locally available at the site. The sand and peat samples were collected by site personnel and shipped to CANMET. The sand was taken from a quarry located just to the southeast of the mill. The peat samples were also obtained in the vicinity of the mill, just behind the #2 headframe.

2.1.3 Water Cover

Locally available natural water from the Ottawa River was used for the water cover, replacing the process water overlying the tailings on start-up of the experiment. To meet the needs of various stages of the column studies, water from the mid-depth of the river was sampled on an as-needed basis from the raw water supply line of the Britannia Pilot Plant in Ottawa.

2.2 Column Design and Set-up

The columns containing the tailings were cylindrical, flanged lysimeters with an inner diameter of 30 cm and made from clear, 1.25 cm-thick PVC. Each column was approximately 2.2 m in height, with a grey PVC flange connecting the 1.2m bottom section to the 1m upper section. The bottom of each column was closed with a grey PVC platform, 3.2 cm thick, grooved to accept the circular section. Each column was fitted with an array of ports to allow for sampling at various depths.

The bottom of each of the columns was lined with a 10 cm-thick layer of inert, high-density polyethylene beads obtained from Novacor. This layer of beads was sandwiched between two layers of 1 mm-thick geotextile filter cloth. The assembly acted as a bed support and a filter preventing the downward migration of tailings.

The tailings were loaded as a slurry. The high-solids content of the slurry (~70 %) resulted in efficient, uniform material settling. In total, 12 columns were prepared as outlined in Figure 2.1, each setup simulating one disposal scenario in triplicate. Columns A, E, and I represented a simple subaqueous disposal option with a 0.3 m water cover (Series 1). The Series 2 columns (B, F, J) contained a 0.3 m intermediate peat layer and the Series 3 columns (C, G, K) a 0.3 m intermediate sand layer. Columns D, H, and L, referred to as Series 4, had a 1 m water cover directly overlying the tailings. Columns with a simple water cover contained approximately 140 kg of tailings with a settled height of 1 m while those with an intermediate barrier of peat or sand contained approximately 92 kg of tailings to a settled height of 0.67 m.

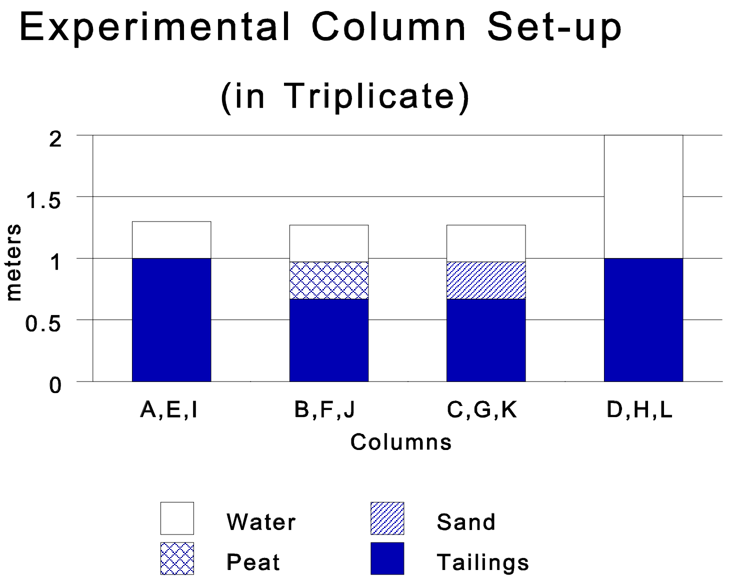

Figure 2.1 Experimental Column Set-up

2.3 Experimental Design and Schedules

Following the settling period and initial monitoring (in the absence of water cover mixing) in the first year, two distinct water flow conditions were imposed on the columns:

Phase I	Circulated water cover: February 1997-October 1997; and,
Phase II	Circulated water cover subjected to drawdown and precipitation events: November 1997 - December 1998.

2.3.1 Initial Monitoring: Uncirculated Water Cover

The materials in the columns, once loaded, were allowed to settle and equilibrate for a period of one year. During this time the water cover was not circulated. Periodic DO measurements were taken at two depths in the water cover and 16 depths in the submerged solids. For the overlying water, DO measurements were made at 7 and 28 cm above the solid/water interface for the 0.3 m water covers and 7 and 82 cm above the tailings/water interface for the 1.0 m water covers. For porewaters, measurements were made at 0, 1, 3, 5, 7, 9, 14, 19, 24, 30, 40, 50, 60, 70, 80 and 90 cm below the water/solids interface in each column. Selected overlying water and porewater samples were also analyzed so as to aid with focusing the monitoring and analysis programs in Phases I and II.

Towards the end of this initial monitoring phase and in between setups for subsequent phases of the study when the water cover was left stagnant, slimy green algae patches were observed to develop on the surface of the submerged solids and the column walls. The algae were carefully removed prior to the start of the Phases I and II operation. The amount of biomass occurring in the columns during the experiment was considered insignificant to affect the results of the study.

2.3.2 Phase I: Circulated Water Cover

Dissolved oxygen profiles and ionic fluxes from the solids porewater to the overlying water column were assessed in Phase I. Started in February, 1997, this phase ran for 200 days.

The overlying water was replaced with natural waters on Day 0 of Phase I, after which a constant water depth of 0.3 m (Series 1, 2, and 3) or 1.0 m (Series 4) was maintained. The columns were monitored over this period for DO, pH, Eh, electrical conductivity (EC), total alkalinity, total acidity, sulfate, ferrous iron and total dissolved Al, Ca, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, S and Zn. The water covers were sampled at two depths a total of 12 times. In addition, a total of 7 porewater samplings at 5, 14, 30 60 and 90 cm below the water/solids interface were recorded for each of the columns during this time.

The overlying water in the columns was circulated to minimize the development of concentration gradients. During the first 100 days this was done without active aeration, drawing out water just below the air/water interface and returning it via a closed loop to the water column near and above the water/solids interface. As of Day 100 the water columns were both circulated and aerated, ensuring that the water covers entrapped enough oxygen, providing a condition of or close to dissolved oxygen saturation.

2.3.3 Phase II: Precipitation and Drawdown

The impact of precipitation events and porewater drawdown on the dissolved oxygen, surface and porewater quality profiles was assessed in Phase II.

Started in November of 1997, this phase ran for 13 months. Drawdown from the base of the columns was initiated on Day 0, and simulated precipitation events were started on Day 28. During the first month, sampling was concentrated on assessing ionic fluxes into the overlying water column. Thereafter, precipitation events and the collection of runoff were introduced. Sampling of porewaters, runoff, and drawdown was conducted in addition to sampling the overlying water column.

The estimated post-operational water balance including precipitation and runoff into the Louvicourt tailings management area, local evaporation, and drawdown were used to define appropriate volumes of water addition and removal from the columns in Phase II. Table 2.1 compares these field values with those imposed in Phase I and Phase II. The input and overflow volumes for Phase II were set conservatively, in part to offset lower evaporation rates in the laboratory. The potential upwelling of groundwater was not considered.

Table 2.1: Water Input and Output (in meter/year)

	Input	Evaporation	Overflow	Drawdown	Samples
Field[1]	1.43	0.51	0.56	0.36	-
Phase I	0.33	0.10	-	-	0.23
Phase II	0.85	0.10	0.25	0.36	0.12

[1] Michael Li, Private communication, September 1997

The 0.85 m/yr input for any given column corresponded to approximately 2 L of water every third week to maintain a constant water level, and an additional precipitation event of 4 L every 9 weeks. A drawdown of 0.36 m/yr was simulated by removal of approximately 70 mL/day from the base of the column at a rate of 0.5 mL/min. for approximately 2.5 hr each day.

The water covers were sampled from two ports a total of 6 times within the first month to establish the water cover characteristics and, where possible, initial fluxes of contaminants into the overlying water. Depth profiles, started on Day 28 were measured every 9 weeks in conjunction with precipitation and runoff events. The columns were monitored for DO, pH, Eh, EC, alkalinity, acidity, sulfate, ferrous iron and total dissolved Al, Ca, Cu, Fe, K, Mg, Mn, Na, S and Zn.

In addition to the depth profiles, the daily effluent or drawdown sample was collected over a three-week period and analyzed as a composite sample.

2.4 Analytical Procedures

Each of the four disposal scenarios was run in triplicate. Thus, unless otherwise noted, all values reported in subsequent sections are averages of individual measurements from the three replicate columns.

2.4.1 Dissolved Oxygen

Peristaltic pumps were used to obtain all water samples from the columns at a maximum flow rate of 5 mL/min and a minimum rate of 0.5 mL/min. All sample ports, except at the base of the columns (Port 0) were fitted with rubber septa. A 23 bore needle, inserted into the septa and attached to a narrow bore tubing allowed the sample to be drawn out of the ports. The DO readings were taken on-line, in a cell fitted with a DO probe placed at the discharge end of the pump. The sample exiting the cell was then collected and used for the analysis of primary parameters and various elements.

An Orion DO field probe was used to measure dissolved oxygen. Daily calibration of the probe was performed for accurate zero and saturation readings. In addition, prior to and after taking each column profile, DO saturated water was pumped through the system to purge it. Dissolved oxygen data are reported as concentrations (in mg/L). Slight variations in readings for saturated water were seen as a function of temperature which ranged from approximately 16° to 28°C over the Phases I and II sampling periods.

2.4.2 Primary Parameters

The primary parameters of pH, redox potential and electrical conductivity (EC) were measured in water samples as collected, prior to their filtration. A standard, glass-body combination pH electrode with a saturated Ag/AgCl reference electrode was used to measure pH. The redox potential was measured using a platinum electrode and a calomel (Hg/Hg_2Cl_2) reference electrode. Eh could then be calculated from the measurement by adding a value of +244 mV, the potential difference between the calomel and the reference hydrogen electrodes. EC was measured using a small-volume (5 mL) field conductivity cell.

After filtration through a 0.45µm filter, total acidity and alkalinity in a water sample were measured by titrametric methods. Total acidity was measured as the maximum potential acidity by first lowering the pH of the sample solution to below 4 and oxidizing the reduced ionic species with a few drops of 30% hydrogen peroxide. The sample was then titrated with a standard NaOH solution to pH 8.3 using a potentiometric titration method.

Total alkalinity was determined by potentiometric titration of a sample aliquot with a standard solution of strong acid (H_2SO_4). A two endpoint (pH 4.5 and 4.2) technique was used which determined the actual inflection point or equivalence point of the titration.

2.4.3 *Ferrous Iron Analysis*

Porewater for ferrous iron analysis was collected at various depths from the sample ports using 10-mL syringes, which were directly submitted for analysis, minimizing sample handling and exposure to air. All samples were analyzed within 5 hours of collection.

A flow injection analysis system, developed by CANMET (Graham, 1996) was used to analyze for ferrous iron. The procedure is applicable for solutions containing > 0.1 µg/mL ferrous and total iron. Fe(II) forms a stable complex with 2,4,6-tris(2'-pyridyl)-1,3,5-triazine, even in the presence of Fe(III). The resulting color is measured by a spectrophotometer at 595 nm.

2.4.4 *Sulfate Analysis*

Sulfate concentrations in filtered solution samples were analyzed by high-pressure ion chromatography (HPLC). The anions were separated using a resin consisting of a sytrene divinylbenzene copolymeric core on which a thin layer of an anion-exchange latex had been deposited. The separation of the anion was controlled by their different affinities for the stationary phase. A suppressor was then used to lower the background conductivity of the carbonate eluent and to increase sensitivity. Within the suppresser column the sample anion was converted to a highly ionized and conducting acid and the eluent, to a weakly conducting carbonic acid. The sulfate ion was then measured using a conductivity detector.

2.4.5 *Elemental Analysis*

Filtered samples (0.45 µm filter) were acidified with ultrapure nitric acid prior to submission for elemental analysis. Quantitative elemental analyses were performed by ICP-AES (Thermo Jarrell Ash IRIS simultaneous inductively coupled plasma-atomic emission spectrometer) for Ca, Mg, Na, K, S, total Fe, and Zn. For the analysis of Al, Cu and Mn, an ICPMS (VG PlasmaQuad inductively coupled plasma mass spectrometer) was used. Typical detection limits for the metals were below 0.05 mg/L. However, the limits varied with the method of detection, element and with the total dissolved solids content. Average detection limits are presented in Table 2.2.

In addition to column samples, the natural water, blanks and high and low concentration standard solutions were also submitted for analysis on a regular basis. The low and high standard solutions were custom prepared and had similar composition and matrix to the overlying and porewaters of the columns, respectively.

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Table 2.2: Typical Concentration Ranges and Detection Limits for Elemental Analysis

Element	**Method of Determination**	**Concentration Range (ppm)**	**Detection Limit Ranges (ppm)**
Al	ICPMS	D.L. - 4	< 0.01-0.1
Ca	ICP-AES	D.L. - 600	< 0.01
Cu	ICPMS	D.L. - 0.5	< 0.005 - 0.05
Fe_{tot}	ICP-AES	D.L. - 250	< 0.05
K	ICP-AES	D.L. - 50	< 0.2 – 2
Mg	ICP-AES	D.L. - 150	< 0.01
Mn	ICPMS	D.L. - 15	< 0.001
Na	ICP-AES	D.L. - 100	<1 – 10
S	ICP-AES	D.L. - 500	< 1
Zn	ICP-AES	D.L. - 1.6	< 0.005 - 0.05

2.5 Leach Test Procedures

Although not part of the original scope, leach tests were conducted on the tailings and on samples of the intermediate barrier materials, sand and peat. The intent was not to classify the materials as toxic or non-toxic but to assess their relative potential to impact the quality of the overlying water in the test columns.

Two samples each of the sand, peat and tailings were subjected to leach testing according to the Quebec Leaching Protocol (Quebec LEP; Government of Quebec 1985) and a modification of the Quebec LEP in which natural waters replaced the standard leachant, buffered acetic acid. In December of 1997 the Quebec LEP was replaced by the less aggressive TCLP (Toxicity Characteristic Leaching Procedure) in Quebec (Government of Quebec, 1997). A comparison of the three leach protocols is given in Table 2.3.

Table 2.3: Comparison of Leaching Protocols - TCLP, Quebec LEP and Modified LEP

Protocol	Sample Preparation	Sample Mass	Leachant	Liquid-to-solid ratio	Method of Contact	Duration
Quebec LEP	No liquid/solid phase separation	5-100g dry weight basis	Buffered acetic acid (pH 4.5)	10:1	End-over-end agitation	24 h
Modified LEP	Same as Que. LEP	Same as Que. LEP	Natural water (pH ~ 7)	Same as Que. LEP	Same as Que. LEP	Same as Que. LEP
TCLP	Liquid/solid phase separation	Min. 100g (liquid & solid)	Choice of acetic acid solution: pH 4.93 (buffered) or pH 2.88	20:1	End-over-end agitation	18 h

The sand and peat samples were grab samples collected from the site by mine personnel in mid 1997. The tailings samples were taken from the original, dried head sample, the composition of which is reported in Section 3.

3.0 RESULTS

3.1 Material Characterization

3.1.1 Tailings Characterization

Tailings from each of the 10 barrels received were allowed to settle for one month after receipt and then sampled using 1-inch diameter cores to assess the degree of variability between barrels and to obtain a composite head sample. Three cores were taken from each barrel and combined. The core samples were extruded using N_2 and the composite samples dried at 70^{o}C under inert conditions.

The composite samples from each barrel were characterized for particle size distribution and chemical composition to assess the homogeneity of the tailings between barrels. The individual results from each barrel are presented in Appendix 2 while the average results are given below. Based on these results, the contents of the barrels were individually slurried and then loaded into the columns without further mixing as the compositional variations among the barrels was considered insignificant.

3.1.1.1 Particle Size Distribution

The average particle size distribution of the Louvicourt tailings received is shown in Figure 3.1. The majority of the material is in the silt to fine-sand size range with a K_{80} of 50 µm. The data are consistent with the grain size distribution of the Louvicourt flotation tailings reported earlier (Noranda, 1996).

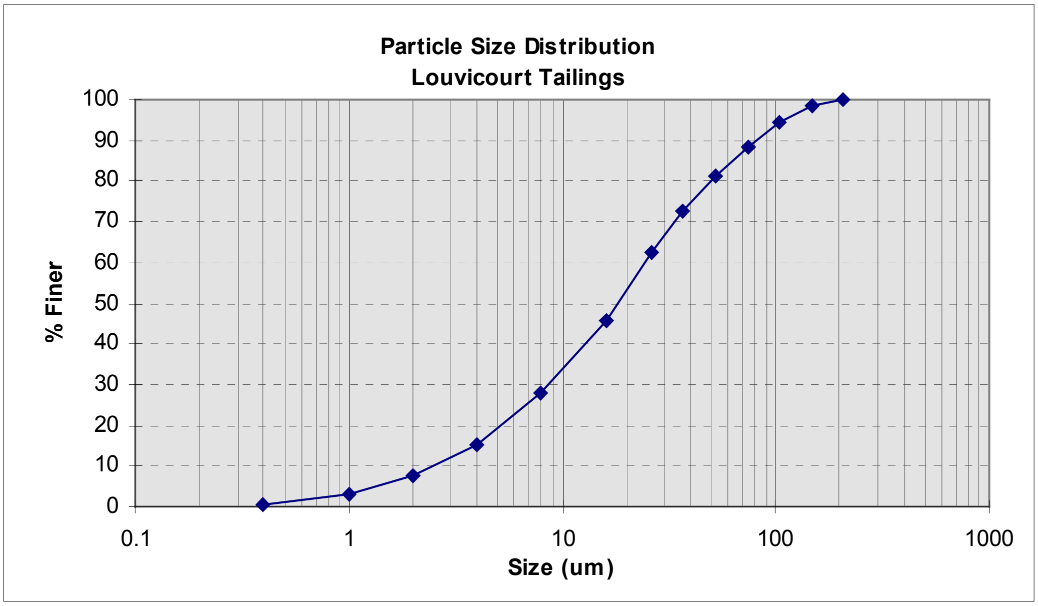

Figure 3.1 Average Particle Size Distribution of Louvicourt Tailings

3.1.1.2 Chemical Composition

The average analytical results from the 10 composite core samples for a selected number of analytes are given in Table 3.1. The tailings contain an average of 17.2% S (ranging from 16.0-19.4%) and 19.8% Fe (ranging from 17.2-20.8%). These values are consistent with those reported for four tailings samples obtained during the same month of sampling for humidity cell tests: including 15.8% S (ranging from 15.0 - 17.4%), 21.0% Fe (ranging from 20.1-22.5%), 0.11% Cu and 0.36% Zn (Noranda, 1996).

Table 3.1: Chemical Analysis of Louvicourt Tailings Received

Analyte	S	Fe	SO_4	Al	As	Ca	Cu	Mg	Mn	Pb	Zn
Mean (%)	17.2	19.8	0.68	3.8	0.064	1.6	0.092	2.4	0.17	0.065	0.33
Std. Dev. (%)	0.94	1.01	0.16	0.15	0.01	0.08	0.010	0.07	0.01	0.020	0.05

3.1.1.3 Mineralogical Characterization

Whole rock analysis and mineralogical characterization were carried out on fresh tailings samples representative of the two field test cells constructed in September of 1996 (Paktunc, and Wilson, 1997). The samples were studied by a combination of scanning electron microscopy, X-ray microanalysis, image analysis and X-ray powder diffraction techniques. The test results can be summarized as follows:

> The tailings are fine grained and are characterized by high SiO_2 (34-45 wt%), Fe (14.5-21.1 wt%) and S (9.0-17.6 wt%), with the bulk sulfur values being tied to sulfide minerals. Pyrite is the dominant sulfide and constitutes 16-54 wt% of the samples. Pyrrhotite, chalcopyrite, sphalerite, arsenopyrite and galena occur in trace quantities. The dominant carbonate minerals are ankerite and magnesian siderite while silicate minerals include quartz, micas, chlorite and feldspars. In both field test cells, the tailings exhibit significant heterogeneity in geochemistry and mineralogy.

3.1.1.4 Acid Base Accounting

The Modified ABA test (MEND, 1991) was conducted on the head sample for the tailings. A fizz test was included in the test procedure.

The test results gave a neutralizing potential of 49 kg $CaCO_3$ equivalent per tonne of tailings. Using the average values of 17.2% and 0.68% for total sulfur and sulfate respectively, the net neutralization potential of the tailings is calculated to be -466 kg $CaCO_3$ equivalent per tonne of tailings. Thus, while the tailings have some neutralizing capacity, they have a high potential for acid generation.

3.1.2 Natural Water Source

Water for the overlying water covers was obtained in regular batches as required from the Ottawa River, just upstream from the Britannia Water Treatment Plant. Analyses of the pre-treated water, available from the treatment plant, indicated acceptable metal concentrations as well as acceptable variation in concentration over a one-year period. However, the water is slightly colored, indicative of enrichment in dissolved organics.

The Britannia water used in the water covers ranged in pH from 6.0 to 7.3, conductivity from 71 to 91 µS/cm, and contained an average total alkalinity of 24 mg $CaCO_3$/L. Sulfate and total iron concentrations averaged 9 and 0.08 mg/L, respectively. Additional average elemental concentrations analyzed by CANMET are as follows: 9 mg/L Ca, 35 µg/L Cu, 2 mg/L K, 2 mg/L Mg, 1 µg/L Mn, 4 mg/L Na, 3 mg/L S and 0.01 mg/L Zn.

The natural water used contributed some alkalinity to the system. Moreover, trace quantities of sulfate, iron and other metals such as copper and zinc were also introduced. Site runoff into the tailings management area may show similar contributions. A grab sample from near the two field cells indeed exhibited a pH value of 6.97 and an alkalinity content of 24.5 mg/L $CaCO_3$. The dissolved Cu concentration of 35 µg/L in the Britannia water appears to be anomalous. Independent sampling of the river from a different location by the Geological Survey of Canada gave a lower average value by an order of magnitude (J. Vaive, personal communication, November, 1999). Apparently, a significant portion of the elevated copper content originates from contamination in the piping delivering the raw water supply from which the water used in the column experiment was collected.

3.1.3 Process Water Characterization

Plant process water from the Louvicourt Mine was used to slurry the tailings for column loading, and was the initial porewater in the columns. The chemistry of this process water was described in Noranda (1996). It had a high pH (10.3 to 11.5) and contained appreciable levels of sulfate (660 to 1050 mg/L, including contributions from thiosalts expressed in terms of sulfate) and moderate levels of Ca and Na (on the order of 80 and 10 mg/L, respectively). All other metals and semi-metals were reported as very low or below detection. The analyses of the process waters are presented in Appendix 3.

3.2 Initial Monitoring

The materials in the columns, once loaded, were allowed to settle and equilibrate for a period of one year. During this time the water cover was not circulated and periodic DO measurements were taken with depth. Results from these initial measurements and the subsequent analysis of the water covers (Appendix 4) indicated the following:

- DO content in the tailings porewater became undetectable (<0.2 mg/L) below the first 10 cm of the tailings surface in Series 1 and 4.

- Sand and peat layers acted as diffusion barriers and oxygen consumers, further reducing the availability of DO at the barrier/tailings surface.

- Both the local sand and peat, used as intermediate barriers, have the potential to impact on the initial quality of the overlying water cover.

- No significant concentrations of thiosalts ($S_2O_3 < 1$ mg/L) were measured in the tailings porewaters or in the overlying water column at the end of the initial monitoring period.

- The species of concern which warranted further monitoring include sulfate, ferrous iron particularly in the sand and peat layers, calcium, copper, magnesium, manganese and zinc.

These preliminary findings helped to focus the monitoring programs in Phase I and II.

3.3 Phase I: Circulated Water Cover

Prior to the commencement of Phase I, the overlying water in each column was replaced by a new batch of natural water from the Ottawa River. Patchy algae observed to develop on the column walls and the surfaces of the submerged solids were also carefully removed. Unless otherwise stated, plots and descriptions of chemical profiles presented below are based on the average of individual measurements made on the three replicate columns in each series.

3.3.1 Dissolved Oxygen Profiles

The measured DO profiles for the 4 disposal scenarios under a circulated water cover are presented in Figure 3.2. The DO content is reported in parts per million (mg/L) rather than percent saturation. Variations in the maximum oxygen concentrations measured in part reflect temperature variations over the sampling periods. Initial DO contents (Day 0) were at or very near saturation for the water covers. Subsequent measurements (Day 7 through Day 70) for all disposal scenarios indicated a drop in DO content over time, the most significant reductions being observed in Series 1 and 4 which had a direct water cover/tailings interface.

A detailed profile of four columns (E, F, G, H) representative of the four disposal options is presented in Figure 3.3. Readings were taken on Day 100 just prior to re-saturation of the water column. Results from these profiles indicate that:

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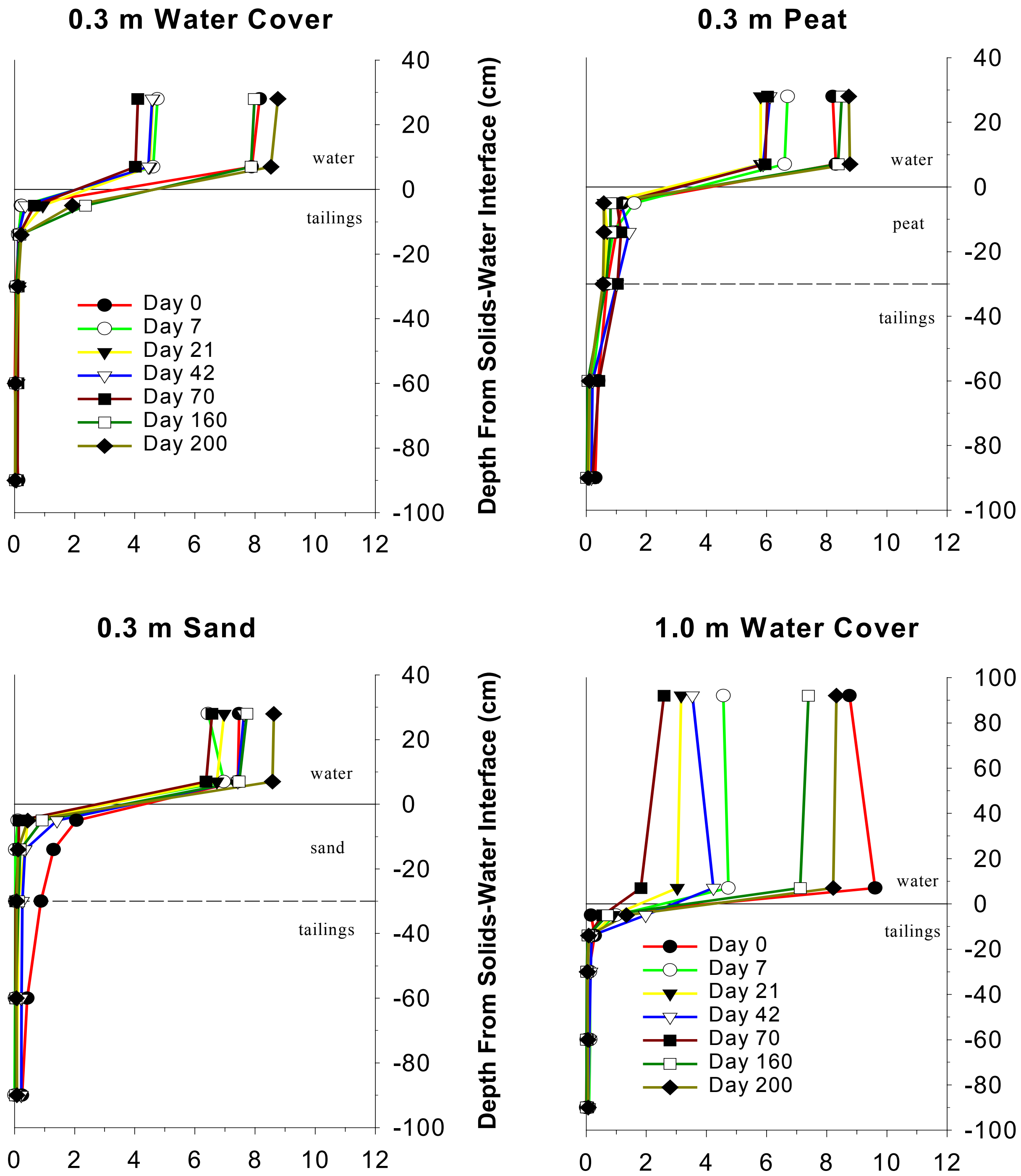

Figure 3.2 Mean Dissolved Oxygen (mg/L) Profiles over Time for Series 1-4 (Phase I)

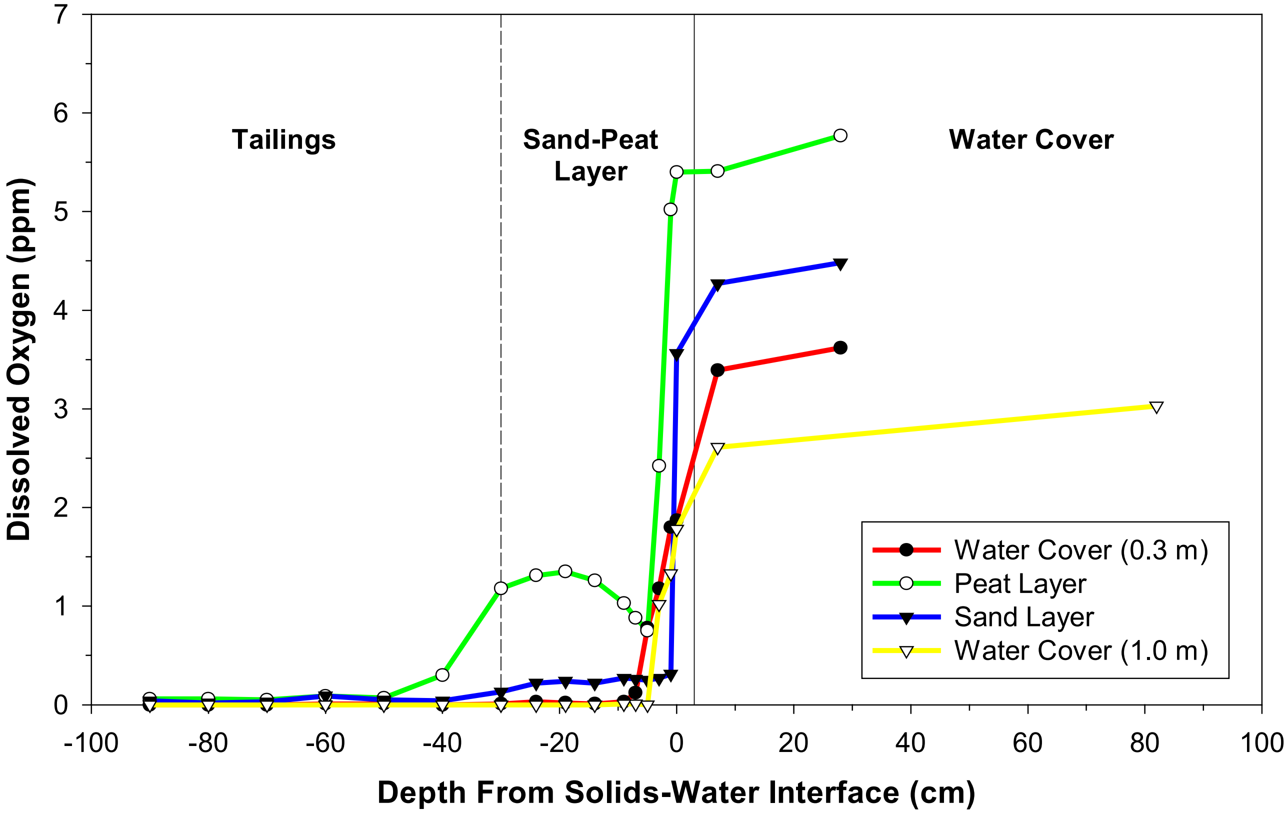

Figure 3.3 Dissolved Oxygen (mg/L) Profiles for Series 1-4, Day 100 (Phase I).

- no significant DO gradients were established in the overlying water of the columns;

- the tailings utilized available DO in the water covers at a rate exceeding the diffusion of oxygen from the atmosphere into the circulated water cover;

- in addition to acting as a diffusion barrier, the sand intermediate layer also behaved as an effective oxygen consumer, reducing the flux of DO from the water cover into the tailings below; and,

- the peat intermediate layer showed less propensity to scavenge DO than the tailings and was less effective in limiting the availability of DO at the tailings interface than the sand.

The contrasting behavior of sand versus peat is somewhat surprising. One would expect the peat to consume oxygen more readily than sand. A possible explanation is that the peat involved has reached an advanced stage of oxidation, largely depleted of readily oxidizable material. The acidic porewater observed in the peat layer lends support to the mature nature of organic decay. The sand, on the hand, was sampled from within the mine site. Fine-grained sulfide particles could have been incorporated in the sand deposit by atmospheric transport, the subsequent oxidation of which gave rise to the observed high oxygen consumption.

After Day 100, the circulated water was returned to the water cover above the surface of the water, allowing surface agitation and re-saturation of the water cover with respect to dissolved oxygen. DO concentrations increased to near saturation for the water covers in Series 1, 2, and 3. For Series 4, the measured values remained slightly below saturation. This could have resulted from the reduced height above the surface of the water cover from which the re-circulated water was dropped. Figure 3.4 is a detailed plot of DO profiles for the representative columns E, F, G, and H on Day 160.

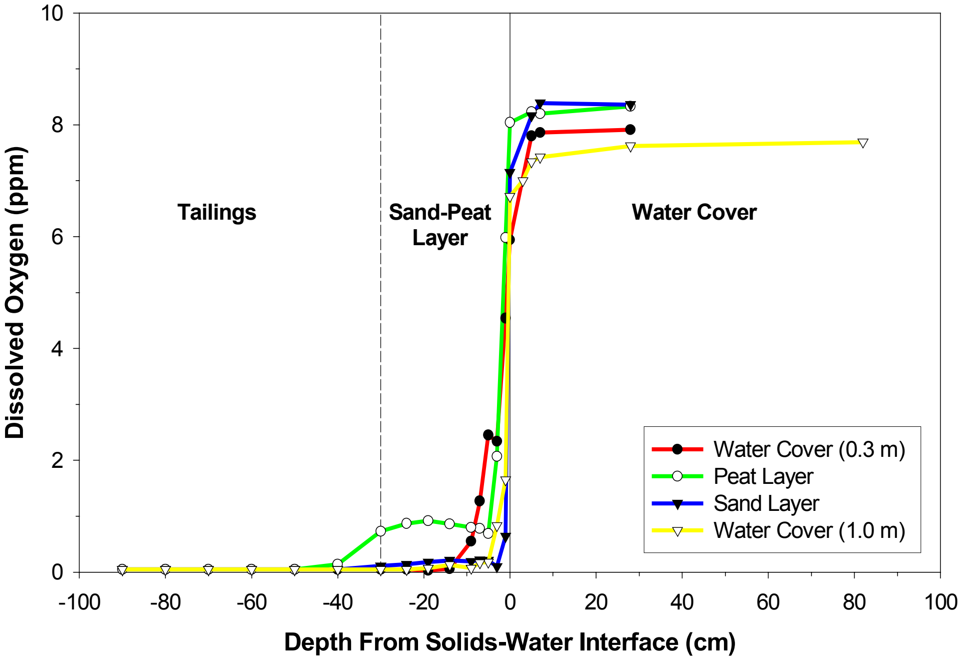

Figure 3.4 Dissolved Oxygen (mg/L) Profiles for Series 1-4, Day 160 (Phase I)

The measured DO profiles showed pronounced gradients across the tailings-water interface, from saturated values around 9.12 mg/L (20° C) in the overlying water to values below 0.2 mg/L or the detection limit a few centimeters below the interface. Assuming steady state, the flux can, to a first approximation, be estimated by modeling one-dimensional oxygen diffusion into the tailings using Fick's First Law, i.e.,

$$F = -D_{eff}(dC/dz)$$

where, F is the mass flux of oxygen (mass per unit area per time), C is the concentration of dissolved oxygen, and z is the depth from the interface. The term D_{eff} is the effective diffusion coefficient and represents the degree of resistance a medium imposes on the driving force. The reader is referred to David et al. (1995), Nicholson et al. (1995), Morin (1993), Davé (1992), Yanful (1991) and Scharer et al. (1991) for further details.

In water, the bulk molecular diffusion coefficient of oxygen, D, is 2×10^{-9} m^2/s. The effective diffusion coefficient of oxygen in subaqueously disposed tailings is dependent on the porosity, η, and the tortuosity, τ, of the tailings. That is,

$$D_{eff} = D\,\eta.\tau$$

Taking η and τ as 0.4 and 0.2, respectively (Yanful, 1991), D_{eff} is calculated to be 1.6×10^{-10} m^2/s. With this value of effective oxygen diffusion coefficient, dissolved oxygen fluxes were calculated based on the oxygen profiles observed during Phase I on Day 160 (Table 3.2). The results compare well with those reported in the literature (Table 3.3). The rate of oxygen consumption by the sand is similar to those of the tailings under a direct water cover (0.3 m and 1.0 m). The smaller flux into the peat layer reflects a deeper oxygen penetration and possibly a slower oxygen rate.

As explained earlier, the reason for the observed higher oxygen consumption by sand relative to the peat possibly lies in the contamination of the sand with fine-grained sulfides and the depletion of readily oxidizable organic material in the peat. The fact that the calculated values for tailings covered directly by a water column of two different depths (0.3 and 1 m) supports the conclusion that the depth of water cover has little effect on the flux of oxygen into the tailings.

Table 3.2: Calculated Fluxes Based on DO Profiles Observed in the Experimental Columns

Oxygen Flux (J)	Disposal Scenario
5.7 $g/m^2/y$	A 0.3 m deep water cover, mixed and maintained at near saturation levels with respect to DO (Series 1)
6.3 $g/m^2/y$	A 1.0 m deep water cover, mixed and maintained at near saturation levels with respect to DO (Series 4)
3.8 $g/m^2/y$	Tailings covered by a 0.3 m deep layer of peat in turn covered by a 0.3 m deep water cover, mixed and saturated. (Series 2)
6.0 $g/m^2/y$	Tailings covered by a 0.3 m deep layer of sand in turn covered by a 0.3 m deep water cover, mixed and saturated. (Series 3)

The calculated fluxes shown in Table 3.2 correspond to tailings that have been under water for approximately 18 months. The flux of dissolved oxygen is expected to reduce with time, as the reactive sulfides at, and just below, the tailings surface are slowly oxidized. Assuming that the tailings surface remains undisturbed, a non-reactive diffusion layer will develop.

The experimental set-up dictates the measurement of DO at set intervals defined by the column ports. As such, the existence or absence of a thin (<1 cm) layer of water at the liquid/solid interface, as modeled by Li (1997), has not been confirmed.

Table 3.3: Estimated Dissolved Oxygen Fluxes

Oxygen Flux (J)	Disposal Scenario	Reference
0.47 g/m^2/y	Theoretical, based on 1.0 m unmixed water cover above tailings containing 20% pyrite	Dave, 1992
3.49 g/m^2/y	Theoretical, based on 1.0 m DO saturated water cover above tailings containing 20% pyrite	
31.5 g/m^2/y	Theoretical, based on subaqueously disposed tailings of 50um size containing 15% pyrite	Morin, 1993/ Davé, 1997
52.3 g/m^2/y	Theoretical, assuming steady state between oxygen availability and consumption.	Scharer, 1991/ Davé, 1997
7.9 g/m^2/y	Calculated from measurements on weathered waste rock, tailings, weathered tailings and pyrrhotite tails, the latter two overlain with compost and low sulfur tails respectively.	Davé, 1997
0.27 g/m^2/y	Calculated from measurements on pyrrhotite tailings, 95% sulfides covered with continually mixed fresh water	Mugo, 1997
0.51 g/m^2/y	Calculated from measurements on pyrrhotite tailings, 95% sulfides covered with continually mixed sea water.	
0.95-3.2 g/m^2/y	Calculated from measured oxidation rates in sub-aqueous tailings.	David et al. 1995 Mugo, 1997
1.8 g/m^2/y	Oxygen flux estimated for Equity Silver Tailings Pond	Mugo, 1997
85 g/m^2/y	Theoretical, for tailings overlain by a standard, well mixed water cover.	Li, 1997
61 g/m^2/y	Theoretical calculation for tailings overlain by a 2 mm thick laminar layer followed by a water cover	
0.4 g/m^2/y	Theoretical, for tailings overlain by a 10 mm thick laminar layer followed by a water cover	

3.3.2 Primary Parameters

3.3.2.1 pH

The pH of the tailings porewater during Phase I varied little over the 200 days, and was slightly alkaline to neutral (approximately pH8 to pH7) as shown in Figure 3.5. In the absence of an intermediate barrier, all samples taken below the interface represent tailings porewater. With the presence of a barrier of peat or sand, only the last two data points in the graphs (at -60 and -90 cm) represent tailings porewater. The data point at the -30 cm mark has been collected at the peat/ or sand/tailings interface.

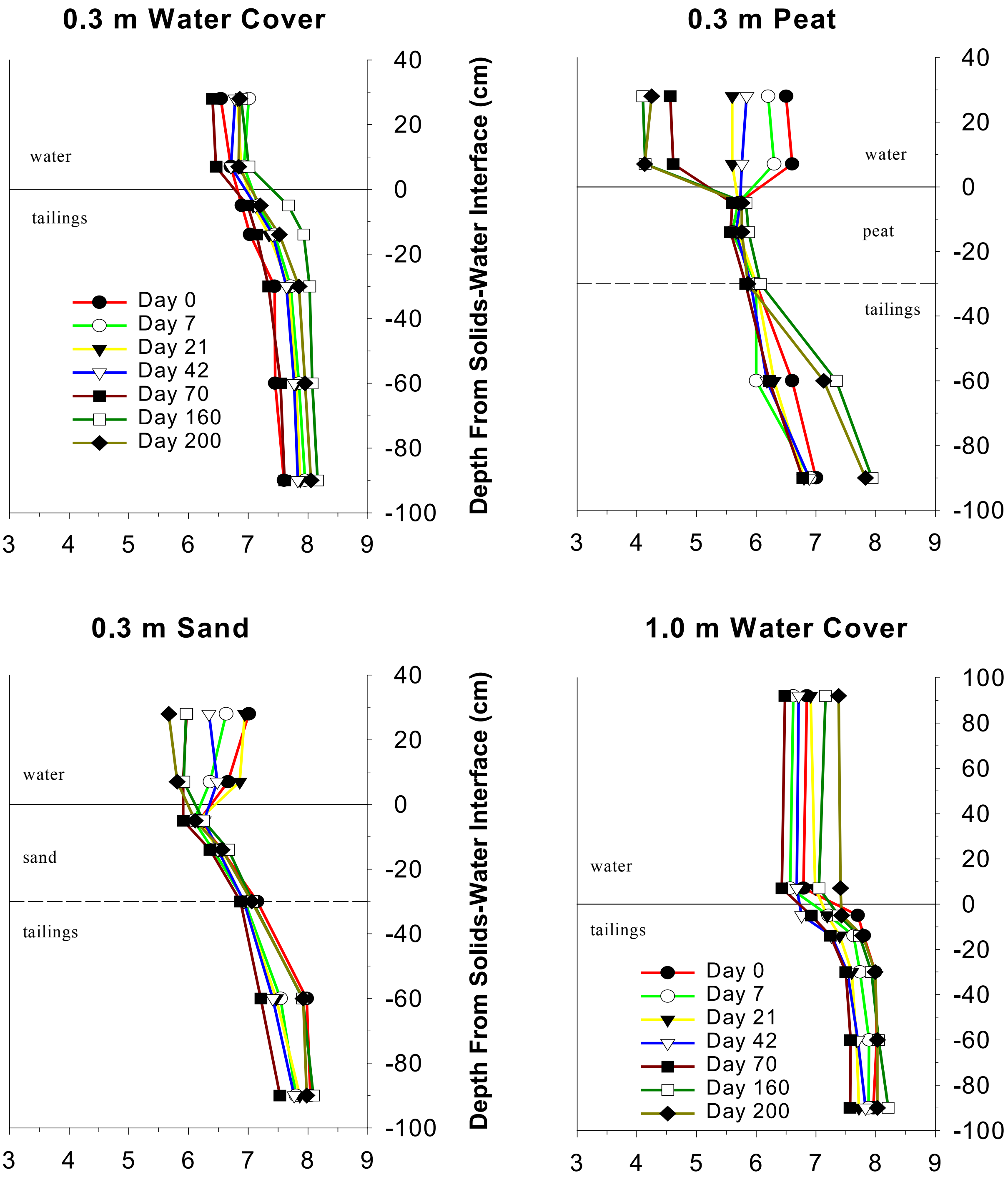

Figure 3.5 Average pH Profiles over Time for Series 1-4 (Phase I)

For the Series 1 columns (with 0.3 m water cover directly on tailings) there was little systematic changes in pH over 200 days in the water cover. The pH did not differ much from that of the Britannia water, which averaged about pH 6.8. The pH of the water cover in the Series 4 columns (1.0 m water depth) increased from near-neutral to approximately 7.5, indicative of diffusion of base from the tailings porewater to the overlying water cover. Alternatively, it can also be said that protons were consumed by tailings in-situ, giving rise to diffusion of H^+ into the tailings.

Slightly acidic porewater (pH~5.5) was observed in Series 2 within the peat layer, indicative of the presence of organic acids. Within a month the overlying water column reached a similar pH. Over the next 4 months the pH dropped to a low value of ~4 and appeared to stabilize. The steady decline in pH indicates that the peat must be releasing acid.

Slightly acidic to neutral porewaters were also observed in the Series 3 columns within the sand. Column C and G maintained near neutral pHs in the overlying water column over the duration of Phase I while for Column K, the pH began to decrease around Day 42 and dropped to 3.5 by Day 160. The impact of the reduced pH is reflected in the increased concentrations of dissolved sulfate, Cu, Mn and Zn in the overlying water column as discussed in a later section.

3.3.2.2 Conductivity

The conductivity of the tailings porewaters for the duration of Phase I varied little from column to column (Appendix 5, Figure A5-1) and ranged from 1600-2000 µS/cm. The high conductivity measurements correlate well with sulfate concentrations.

Columns in Series 1 and 4 showed reduced porewater conductivity with time near the water/tailings interface and increasing conductivity readings for the overlying water covers. Consistent with the larger volume of water in Series 4 (1 m water depth versus 0.3 m), the conductivity values observed in Series 1 by Day 200 (820 µS/cm) were approximately threefold that in Series 4 (320 µS/cm).

Conductivity measurements in the peat porewater were significantly lower than those in the tailings. The data revealed an established gradient from the tailings to the overlying water column through the peat layer. This resulted in similarly low conductivity values (relative to Series 1 and 4) of around 150 µS/cm by Day 200 in the overlying water covers.

During the early stages of Phase I, elevated conductivity values, relative to those in the tailings porewater, were measured in the sand porewaters. Diffusion of ionic species from the sand layer occurred both into the tailings porewater as well as into the water cover over time. Similar to that observed in the peat layer, a gradient was then established by the end of Phase I through the sand to the overlying water. Conductivity values of approximately 225 µS/cm were measured by Day 200 in the overlying water.

3.3.2.3 Redox Potential

A sharp drop in redox potential was typically observed in all columns below the water/solids interface (Figure A5-2). Values of Eh in the overlying waters ranged between +290 and +540 mV while below the water cover, values dropped to as low as +40 to +90 mV in the tailings. Although some of the Eh measurements were suspect (for example, most of the Day 70 data could be erroneous), given the alkaline pH of the tailings porewater, the generally depressed Eh values were not low enough to effect significant sulfate reduction.

3.3.2.4 Acidity and Alkalinity

The tailings porewaters for all columns showed no acidity and a limited alkalinity of approximately 25 mg/L (Figures A5-3 and A5-4, respectively) over the course of Phase I. The peat layers showed some limited additional acidity and alkalinity, both of which decreased over the duration of Phase I. While the sand layers had more alkalinity than acidity in the porewater, no increase in alkalinity was observed in the overlying water columns over the duration of Phase I.

In all columns the overlying water showed an initial alkalinity consistent with the alkalinity of the natural water (~ 24 mg/L). The net alkalinity available in the overlying water columns dropped with time, and by Day 200 all of the columns containing peat (B, F, and J) showed a net acidity as did columns A (0.3m simple water cover) and K (sand). For Column K, a significant drop in pH was also observed.

3.3.2.5 Sulfate

With the exception of overlying waters in columns with an intermediate peat barrier (Series 2), sulfate concentrations in all water covers followed an increasing trend with time. The increase in sulfate concentration is most prominent in the Series 1 columns (~ 40 to 450 mg/L) and relatively smaller in the Series 3 and 4 columns (~20 to 75 and ~ 10 to 100 mg/L, respectively). Sulfate concentrations in the overlying water of columns with a peat layer remained significantly lower (≤ 50 mg/L) throughout Phase I.

Sulfate concentrations in the tailings porewaters in all the columns were consistently between 1000 to 1200 mg/L in all columns (Figure 3.6). The initial porewater sulfate concentration in the sand layer, however, was as high as 1500 mg/L suggesting that the layer was also a source of sulfate. This led to the development of concentration gradients both towards the underlying tailings and the overlying water. In contrast, the peat layer did not appear to contain any additional sulfate and a simple concentration gradient was established directly from the underlying tailings through the peat layer to the overlying water.

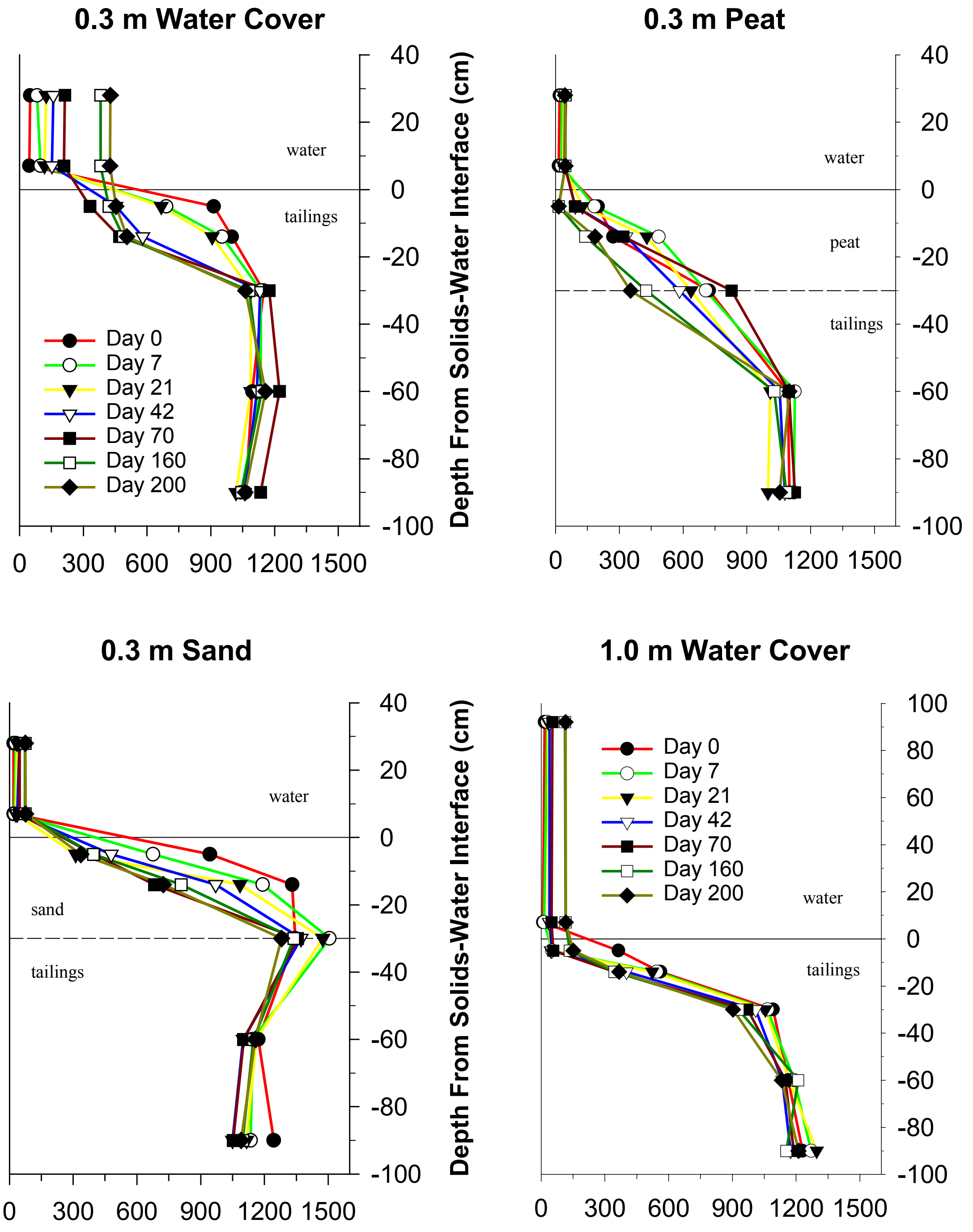

Figure 3.6 Average Sulfate Concentration (mg/L) Profiles over Time for Series 1-4 (Phase I)

3.3.3 Elemental Analyses

Concentration profiles of Fe, Al, Ca, Cu, Mg, Mn, K, Na, S, and Zn in the columns over time for Phase I are shown in Appendix 5 (Figures A5-5 to A5-14). Both total and ferrous iron concentrations are presented.

3.3.3.1 Tailings Porewater

Tailings porewaters contained levels of, Ca, Mg, and Na on the order of, 200, 100 and 90 mg/L, respectively. Over the course of Phase I these concentrations decreased near the water/tailings and barrier/tailings interfaces consistent with the diffusion of these species according to the evolving concentration gradients. Concentrations of dissolved Fe were consistently less than 1 mg/L in the tailings porewater while dissolved Cu, Mn, and Zn values were all less than 0.2 mg/L.

3.3.3.2 Peat Porewater

The concentration profiles for dissolved Ca, Mg and Na indicated the development of a concentration gradient across the peat layer from the tailings porewater to the overlying water column. The fluxes of dissolved sulfate, Mg, and Ca to the overlying water are estimated in Section 3.3.3.4.

Elevated concentrations of dissolved Fe, primarily ferrous iron, Mn, and Al were observed in the peat porewater relative to those observed in the tailings porewater. For all three species, concentrations within the peat layer decreased over the course of Phase I. For neither dissolved Fe nor dissolved Mn was a significant subsequent increase in concentration observed in the overlying water cover. The dissolved concentrations of Fe, Mn and Al remained < 0.02, < 2 and < 0.5 mg/L, respectively, over the course of Phase I.

Concentrations of dissolved Cu and Zn in the peat porewater remained low at less than 0.05 and 0.2 mg/L, respectively. These values varied little from those observed in the tailings porewater below the peat layer.

3.3.3.3 Sand Porewater

Similar to the peat layer, the concentration profiles for dissolved Mg and Na indicated the development of a gradient through the sand layer from the tailings porewater to the overlying water column.

Compared to tailings porewater, elevated concentrations of dissolved Ca and sulfate were observed in the sand porewater, presumably indicative of gypsum dissolution. These concentrations decreased over the course of Phase I and showed an expected impact on both the underlying tailings porewater and overlying water cover quality.

Elevated concentrations of dissolved Fe, primarily Fe^{2+}, and Mn were also observed in the sand as well as the peat layers. While the dissolved Fe concentrations in the sand layer were tenfold less than those in the peat layer, dissolved Mn concentrations were fivefold greater in the sand. For both dissolved Fe and Mn the observed concentrations decreased with time.

Unique to the columns containing a sand layer, dissolved concentrations of Zn showed a sharp spike just below the water/sand interface (Figure A7-14). Not observed in Column C, the peak varied in intensity from 1.0 mg/L in Column G to 1.5 mg/L in Column K. Over the duration of Phase I, this concentration spike decreased as the zinc migrated out into the overlying water column.

Concentrations of Al and Cu in the sand layer porewater varied little from the values observed in the tailings porewater below and were generally less than 0.5 and 0.05 mg/L, respectively.

3.3.3.4 Water Covers

Changes in water cover quality in Phase I were most pronounced for Series 1 and related primarily to increases in dissolved concentrations of sulfate, magnesium and calcium with time. These increases were also observed in Series 4 (albeit in approximately a threefold dilution) and in Series 2 and 3. Estimates of contaminant flux for these species were calculated based on initial average concentration changes observed in the overlying water for the four disposal scenarios according to the following equation:

$$J = \Delta Ct \, [\, V / A \,]$$

where, J = flux (mg/m^2/day), ΔCt = initial concentration change (mg/L/day), V = volume of the water column (m^3), and A = area of the water/tailings interface (m^2). Fluxes for sulfate, magnesium and calcium are presented in Figure 3.7. The impact of the intermediate layers in controlling the migration of dissolved sulfate, Mg, Ca into the overlying water is evident by comparing the Series 1(0.3 m), 2 (peat), 3 (sand) and 4 (1 m) results. While almost identical fluxes of the three dissolved species are transmitted to the two simple water covers of different depth (Series 1 and 4), the fluxes to the water covers in the covers containing a peat or sand barrier (Series 2 and 3) are at least two times lower. As suggested by the flux equation given above, the calculated flux, J, of any of the three conservative species will increase or decrease with time in accordance with the evolving values of the concentration changes, ΔCt, detected in a water cover.

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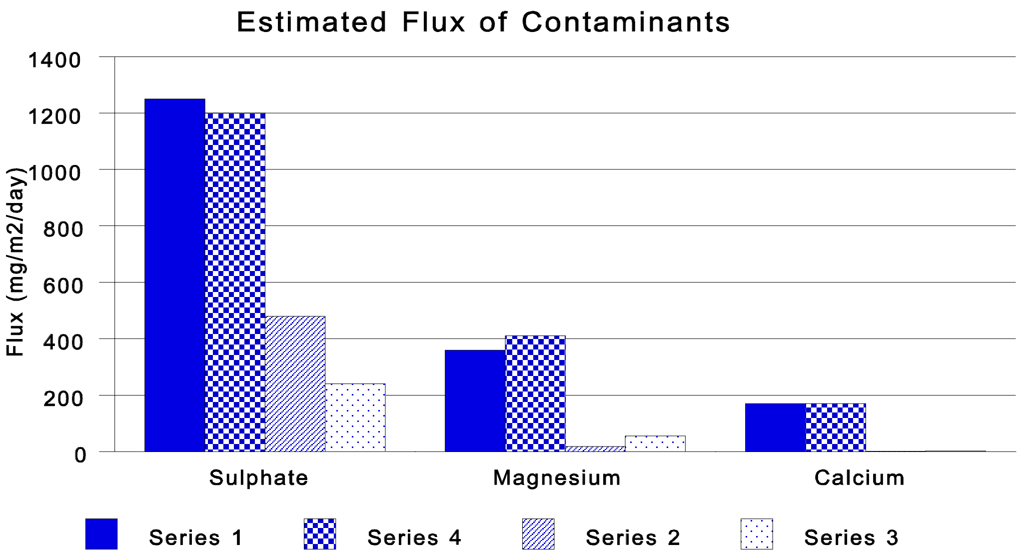

Figure 3.7 Estimated Initial Fluxes of Sulfate, Magnesium and Calcium to the Water Covers in Phase I

Unlike dissolved sulfate, Mg and Ca, dissolved Fe and Mn concentrations in the overlying water column for both Series 1 and 4 remained low (<0.01 mg/L). In the case of dissolved Mn, these were well below concentrations of 0.2 mg/L observed in the tailings porewaters.

Dissolved Cu and Al concentrations in the overlying water for Series 1 and 4 showed no significant trends over the duration of Phase I, remaining below 0.05 and 0.5 mg/L, respectively. Dissolved Zn concentrations in Series 1, however, increased in the overlying water column with time to approximately 0.5 mg/L; a similar trend appeared to be developing in Series 4 prior to completion of Phase I.

As observed in Series 1, little to no increase in concentrations of dissolved Fe or Mn were observed in the water covers above the peat and sand intermediate layers. While significant concentrations of dissolved Fe and Mn were present within the peat and sand layers, these species were precipitated at the solid/liquid interface.

Concentrations of dissolved Zn in the water covers overlying peat remained below 0.2 mg/L over the duration of Phase I although the later profiles show some increases in concentration. Similarly, dissolved Cu concentrations were relatively consistent around 0.03 mg/L over the 200 days.

The concentrations of dissolved Zn and Cu in the water covers overlying sand, however, showed an increase with time. In Figures A5-14 and A5-8 results which have been averaged for the triplicate columns C, G, and K are presented. Two of the three replicates showed no significant increased concentration of either zinc or copper. The increases documented for Day 160 and Day 200 were

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primarily observed in Column K. The concentration levels in the overlying water of the three replicate columns containing sand is illustrated below in Figure 3.8. The contrast in water cover chemistry obviously reflects the heterogeneity of the sand used as a barrier layer in the columns.

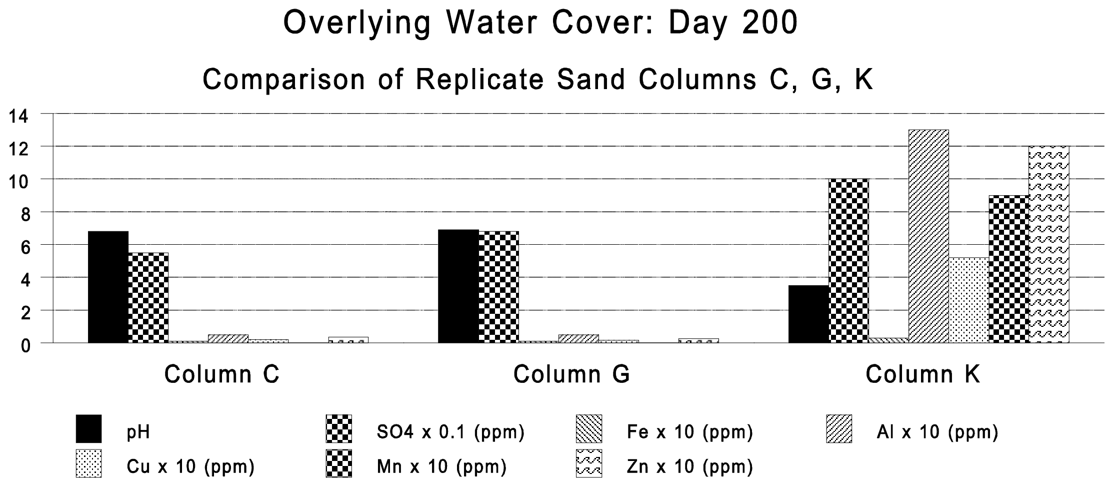


Figure 3.8 Comparison of Overlying Water Quality in the Sand Columns, C, G and K, at the End of Phase I

3.3.4 Leaching Characteristics of Tailings, Sand and Peat

The results of the Quebec LEP and modified LEP tests are given in Tables 3.4 and 3.5, respectively. The data include final pH as well as elemental concentrations in the filtered leachate. In the case of the peat samples, pressure filtration (0.45 µm) was required to separate the solids from the liquid phase. A number of observations may be made:

- For the sand and tailings samples, the concentrations of leached metals using the Quebec LEP are generally higher than those observed for the modified test.

- Based on the results shown in Table 3.5, the sand samples had little potential for contributing contaminants to the overlying water column when natural water was involved. Under more aggressive conditions, represented in Table 3.4, minor amounts of Al, Cu, Fe, Mn and Zn could be leached.

- The leaching of the peat samples gave rise to measurable quantities of metals. The peat was sampled in a mineralized area with a history of mining activity. It may be expected to contain some level of locally available minerals and/or associated metals.

- The concentrations of contaminants leached from the peat show considerable variability, consistent with the expected heterogeneity of the material. Leachates from the two sand samples also differ significantly in dissolved Al, Ca and Fe, again reflecting the highly heterogeneous nature of the sand deposit at the mine site from which the samples were collected and used in the column study as an intermediate barrier.

- The pH of the natural water was raised slightly by contact with the sand samples while contact with the peat lowered the pH (Table 3.5), consistent with the acidity/alkalinity data. A slight pH depression was observed in the natural water during contact with the tailings, possibly reflecting the build-up of a small amount of acidic efflorescence when the tailings were air-dried to provide a suitable sample for the leach test.

- Based on the leaching results for the tailings, the metals of greatest concern include Zn, Mn and Cu. This is consistent with earlier testing (Noranda 1996) which showed negligible or extremely low releases of metals except for Zn and Mn based on TCLP tests.

Table 3.4: Leachate Chemistry Based on Quebec LEP (Buffered acetic acid leachant)

Sample	pH	Al ppm	Ca ppm	Cu ppm	Fe ppm	K ppm	Mg ppm	Mn ppm	Na ppm	S ppm	Zn ppm
Blank	4.4	<0.1	0.3	<0.01	<0.05	0.86	<0.01	0.02	na	<1	0.007
Peat - 1	4.1	0.41	16	<0.01	0.17	3.3	3.4	0.38	na	3.1	0.062
Peat - 2	3.7	2.2	25	0.07	0.24	11	27	2.1	na	400	0.5
Sand - 1	4.4	1.7	37	0.04	0.88	3.6	1.0	0.89	na	<1	0.031
Sand - 2	4.4	9.5	0.89	0.02	0.31	1.2	<0.01	0.11	na	<1	0.052
Tails-1	4.8	0.87	548	3.3	51	11	173	20	na	363	55
Tails- 2	4.7	1.1	558	3.9	51	11	177	19	na	377	56

The leachate chemistry data shown in Tables 3.4 and 3.5 demonstrate that the peat and sand used as intermediate barrier layer in the column study are highly heterogeneous. In particular, in terms of leachable Al and Ca under buffered acidic conditions, Sand 1 and Sand 2 are radically different. It appears as if the former is enriched in calcite and the latter in gibbsite ($Al(OH)_3$). The leachate of Peat 2 is also enriched in virtually all elements analyzed compared to the Peat 1 leachate under both leaching conditions. It appears that Peat 2 is naturally contaminated with some mineralized material not unlike the tailings in composition. The observed heterogeneity implies that the intermediate barrier layers incorporated in the columns may not necessarily have the same composition of the grab samples analyzed. This fact must be taken into consideration in the interpretation of the column test results.

Table 3.5: Leachate Chemistry Using Modified Quebec LEP (Natural waters leachant)

Sample	pH	Al ppm	Ca ppm	Cu ppm	Fe ppm	K ppm	Mg ppm	Mn ppm	Na ppm	S ppm	Zn ppm
Blank	6.6	<0.1	9	0.012	<0.05	0.8	2.1	<0.01	3.7	2.9	<0.01
Peat - 1	4.1	0.31	5.3	0.009	0.14	0.83	1.1	0.13	1.6	5.5	0.063
Peat - 2	2.5	41	98	0.1	0.27	13	68	8.3	8.9	390	3.2
Sand - 1	7.1	0.16	12	<0.01	0.13	1.1	1.4	<0.01	3.8	3	<0.01
Sand - 2	7.1	<0.09	7	<0.01	0.014	0.49	1.8	<0.01	3.5	3.4	<0.01
Tails - 1	6.0	<0.1	335	0.51	0.012	4.7	85	8.8	4.6	392	16
Tails - 2	6.0	<0.1	332	3.52	0.012	4.7	85	8.6	4.5	394	17

In contrast, the two tailings tested under both conditions gave rise to leachates of nearly identical composition except possibly in dissolved copper. This suggests that the tailings are more uniform in composition and inter-column variation in the column test results should be less severe. The high dissolved Ca and S (sulfate expressed as S) contents (approximately 8 mM and 12 mM, respectively) in the natural water leachate are rather intriguing. The excess of S over Ca on a molar basis suggests that gypsum dissolution may not be the primary cause. Significant contributions of the leached ions can easily be derived from the efflorescence formed during sample preparation from evaporation of the associated tailings porewater. As chlorite constitutes a significant portion of the gangue minerals in the tailings, it is not difficult to account for the release of Mg (about 3.5 mM) by cation exchange reactions.

3.4 Phase II: Circulated Water Cover with Drawdown and Runoff

All the raw monitoring and analytical data pertaining to the Phase I and Phase II test work are furnished in Appendix 7 on a computer disk. The water chemistry profiles depicted and described below are based on averaged results of the triplicate columns in each series during Phase II. Prior to the commencement of Phase II, the overlying water in each column was replaced by a new batch of natural water from the Ottawa River and patchy algae removed from side of the columns and at the water/solid interface without disturbing the underlying solids. Thus only the porewaters in the solids retained the remnant effects of Phase I testing.

3.4.1 Dissolved Oxygen Profiles

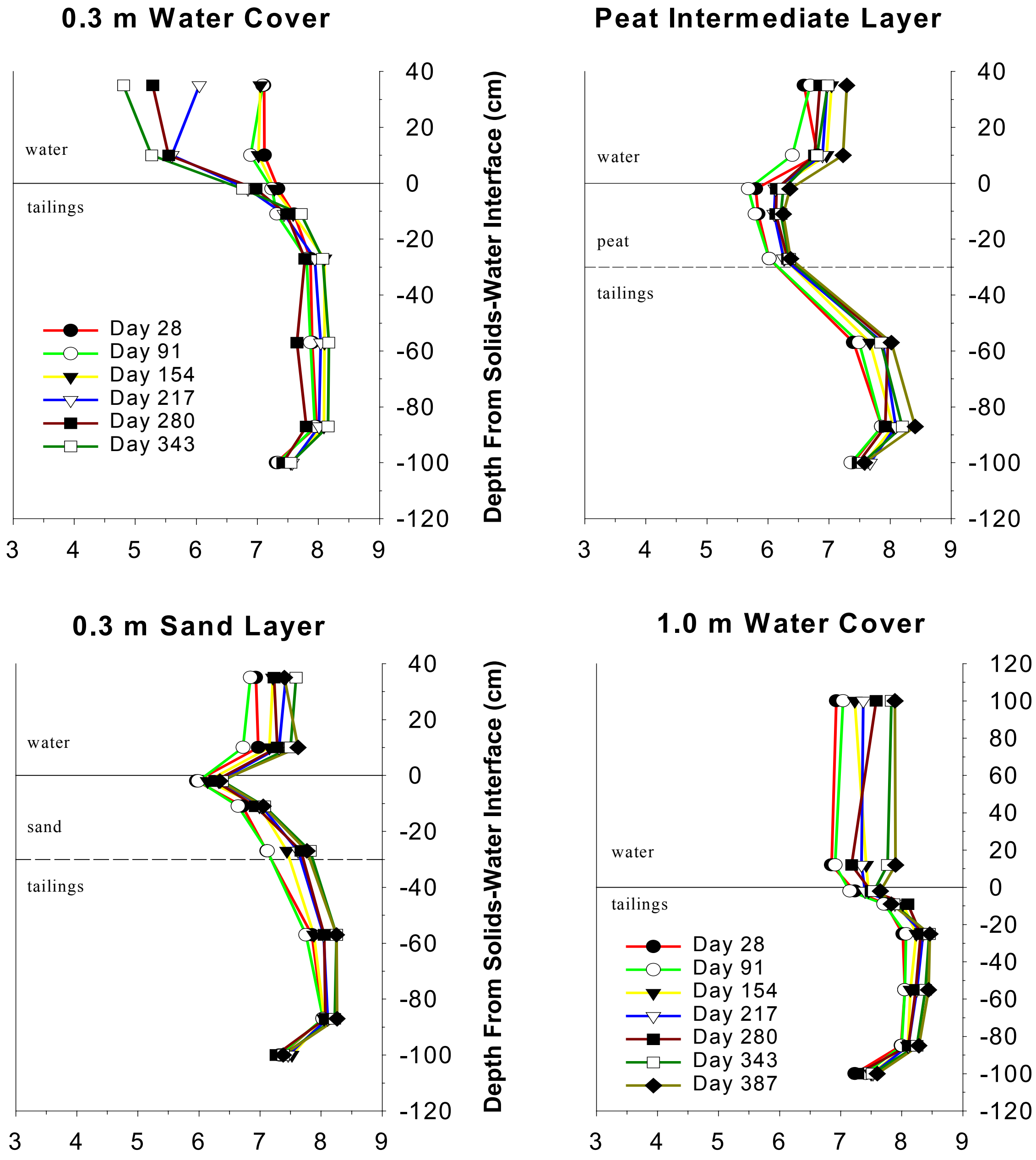
Profiles of DO concentrations associated with the four subaqueous tailings disposal options are shown in Appendix 6 (Figure A6-1). The overlying water columns in all cases were at or close to saturation with dissolved oxygen. The measured concentrations vary from about 8 to 9 mg/L. In the columns without an intermediate barrier, dissolved oxygen penetrated at least 10 cm below the tailings surface. As discussed later, this anomalous depth of DO penetration could be in part exaggerated due to sampling artifacts. Nonetheless, within this penetration zone, the porewater DO concentration in the tailings with a 0.3-m water cover was generally higher than that in tailings beneath a 1.0 m water cover, possibly reflecting a greater depletion of reactive sulfides at the surface of tailings under the shallow water cover. In contrast, practically no dissolved oxygen was detected in the porewaters of tailings overlain by a 0.3-m intermediate barrier of peat or sand. As evidenced by the small hump corresponding to the peat layers in the DO profiles of the Series 2 columns, trapped air in the peat layer had not yet been completely depleted.

3.4.2 Primary Parameters

3.4.2.1 pH

As shown in Figure 3.9, of the four subaqueous disposal scenarios, only the 0.3m water cover directly overlying the tailings exhibited a decreasing pH with time. The measured pH in these columns dropped below a value of 7 after about 200 days and appeared to stabilize at pH≈5 towards the end of the testing. In all the other three scenarios, average measured pH in the overlying water remained near-neutral to slightly basic (pH~7 to ~8). A slight increasing trend was observed in the sand and the 1m water cover columns but relatively erratic pH values were measured in the overlying water of the peat columns.

Greater than about 15 cm below the water/tailings interface, the porewater pH of tailings with a simple water cover (0.3 m or 1 m) remained slightly basic with a measured value of approximately 8. Above this depth, a steep concentration gradient occurred across the water/tailings interface. The porewater of the peat barrier remained slightly acidic (pH~6) and this slightly impacted the porewater pH of the underlying tailings within 30 cm from the peat/tailings interface by the end of the drawdown period. This is consistent with the downward percolation of organic acid at the rate drawdown. In the columns containing a sand barrier (Series 3), a strong pH depression occurred just beneath the water/sand interface. The minimum pH recorded here was about 5.5 and appeared to increase with time. The pH depression is likely the result of acid generated in the oxidation and subsequent hydrolysis of the reduced iron and manganese to precipitate the corresponding hydroxides near the water/sand interface. The drawdown samples collected from the base of all the columns also showed a lower pH relative to the porewater pH of the tailings. This again is likely due to acid generated in hydrolysis reactions.


0.3 m Water Cover

Peat Intermediate Layer

0.3 m Sand Layer

1.0 m Water Cover

Figure 3.9 Mean pH Profiles over Time for Series 1-4 (Phase II)

3.4.2.2 Conductivity

For the simple water covers (i.e., directly over the tailings), the measured conductivity showed an increasing trend with time (Figure A6-2). The increase is more prominent with the 0.3m water cover (from ~ 100 to ~ 500 µS/cm) than with the 1-m water cover (from ~ 100 to ~ 250 µS/cm). The conductivity of the overlying water in the columns with a peat or sand intermediate barrier remained unchanged throughout Phase II. The averaged measured values were on the order of 50 µS/cm, essentially the same as that of the local water used in the experiment.

With drawdown, the tailings porewater conductivity in all columns exhibited an overall decreasing trend with time. With the exception of columns containing a peat barrier, the conductivity of the drawdown samples collected from all columns showed a narrow range in measured values, 1600 - 1800 µS/cm, comparable to the tailings porewater conductivity measured in Phase I. Values slightly below 1200 µS/cm, however, had been measured in the drawdown samples from the peat columns towards the end of Phase II (Figure A6-2).

3.4.2.3 Redox Potential

Similar to that observed in Phase I, a sharp drop in redox potential was generally evident in all columns below the water/solids interface (Figure A6-3). Values of Eh in the overlying waters ranged between +290 and +590mV while below the water covers, most values dropped significantly and were as low as +40 to +90 mV in the tailings. As suggested by the departure of the Day 28 Eh profile from the rest of the profiles in all the columns (Figure A8-3), more than a month was apparently required for the systems to equilibrate and establish stable redox conditions. Alternatively, this is an artifact of switching from grab sample to in-line redox measurements.

3.4.2.4 Acidity and Alkalinity

Tailings porewaters from all columns except those of Series 1 were practically devoid of any acidity (Figure A6-4). Small amounts of acidity, up to 40 mg/L $CaCO_3$, were detected in the porewaters of tailings with a 0.3-m water cover at a depth of ≥ 60 cm from water/tailings interface. This probably resulted from the downward migration of dissolved Fe and Mn with drawdown. Measured porewater acidity in the peat and sand layers also peaked (to ~60 to 80 mg/L $CaCO_3$) just below the water/peat or sand interface, again suggesting local concentration of dissolved Fe and Mn. However, as indicated by a pH value of ≤6, hydrogen acidity also occurred in the peat porewaters. Except for the Series 1 columns, the overlying water in all columns were characterized by very low acidity (generally ≤ 25 mg/L $CaCO_3$). In the Series 1 columns, total acidity showed an increase with time, reaching a high value of 50 mg/L $CaCO_3$ towards the end of Phase II.

The alkalinity content of the overlying waters in the four series of columns ranged from 0 to ~30 mg/L $CaCO_3$. The measured values in the Series 1 columns appeared to decrease with time, reaching 0 mg/L $CaCO_3$ at the end of Phase II, while those of the Series 4 columns increased with time, reaching a maximum of ~30 mg/L $CaCO_3$ (Figure 3.10). The alkalinity of the overlying waters in the two series of columns with an intermediate barrier layer changed little, with measured values close to that of the natural water (~20 mg/L $CaCO_3$). Given the column setup, dissolution of carbonates at the surfaces of the submerged solids is the only likely source of additional alkalinity and acid generation via sulfide oxidation the most likely cause of alkalinity depletion. The contrast in the evolution of alkalinity concentrations in the Series 1 and 4 water covers thus appears to suggest that carbonate dissolution at the water/tailings interface occurred faster than sulfide oxidation in the Series 4 columns; and, the reverse was true for the Series 1 columns.

In contrast to the simple distribution of measured alkalinity in the overlying water of all columns, the porewater alkalinity in the solids exhibited a more complicated pattern. A maximum porewater alkalinity was observed in all series and its location in the profile varied with the disposal scenario (Figure 3.10). The porewater alkalinity in the Series 2 columns (with a peat barrier layer) showed the most complicated pattern. The alkalinity maximum appeared to have migrated from the peat layer to the underlining tailings shortly before Day 154 and its measured value increased significantly with time until near the end of Phase II. On Day 343, the alkalinity maximum in the Series 2 columns was located about 30 cm below the peat/tailings interface and its measured value was 275 mg/L $CaCO_3$, about an order of magnitude higher than most tailings porewater alkalinity in columns of the other series. Given that the porewater in the peat was originally acidic, the alkalinity maximum probably reflects maximum carbonate dissolution in the tailings solids resulting from the neutralization of the downward migrating acidity and the generation of bicarbonate in the process.

The alkalinity maxima in the other series of columns assumed a smaller value and did not appear to vary much with time. In the Series 1 columns with a 0.3 m water directly over the tailings, the alkalinity maximum with a value of ~40 mg/L $CaCO_3$ was located at ~30 cm below the water/tailings interface. The alkalinity maximum in the Series 3 columns with a sand intermediate layer was located at the sand/tailings interface and had a higher value of ~80 mg/L $CaCO_3$. The Series 4 columns with a 1.0 m water cover directly over the tailings had an alkalinity maximum at <10 cm below the water/tailings interface with a value of ~ 50 mg/L $CaCO_3$. As with the peat-containing columns, the location of the alkalinity maxima in these series of columns probably corresponded to where maximum carbonate dissolution was occurring.

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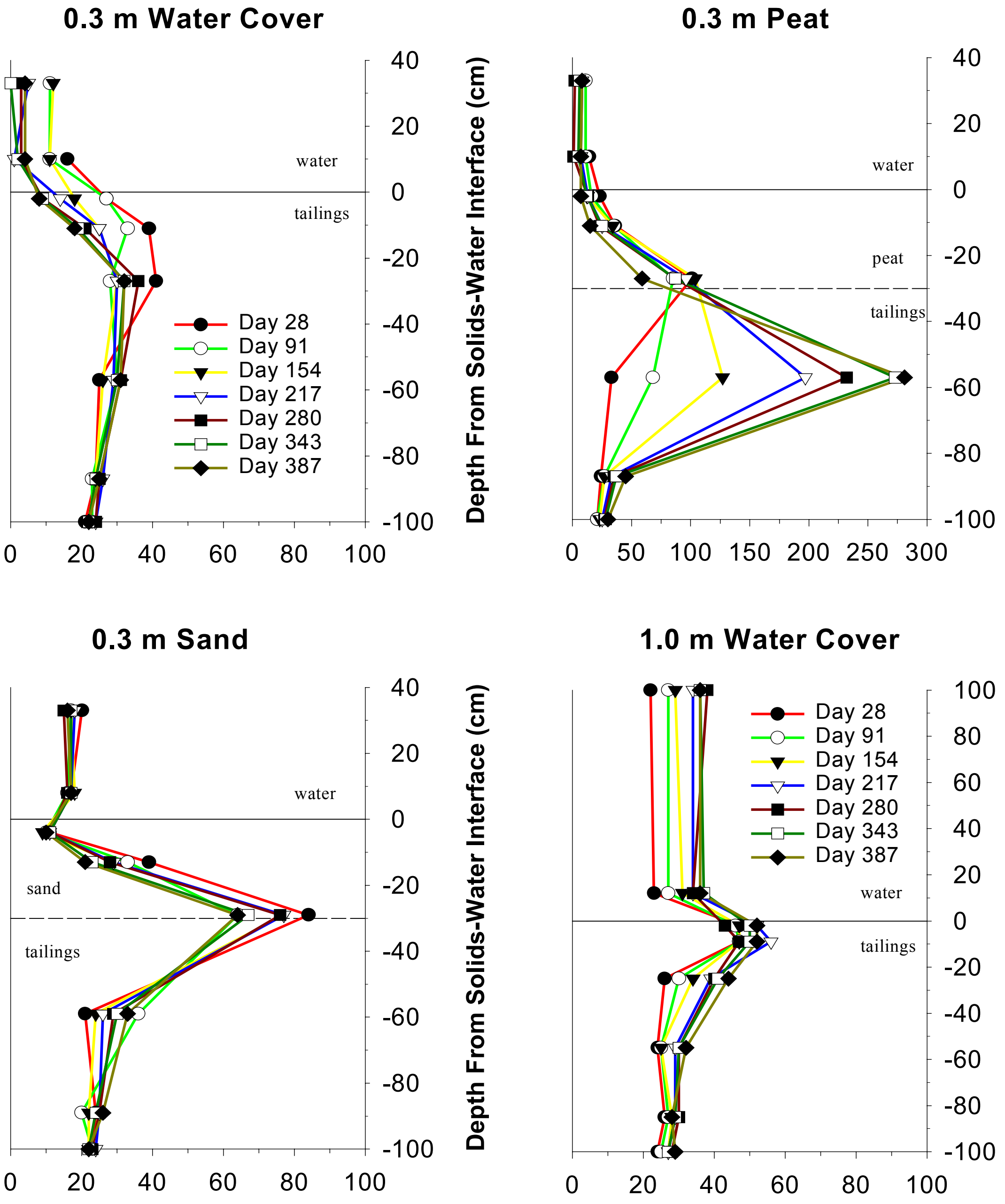

Figure 3.10 Mean Total Alkalinity (mg $CaCO_3$/L) Profiles over Time for Series 1-4 (Phase II)

3.4.2.5 Sulfate

The sulfate concentration profiles (Figure 3.11) essentially mimic the conductivity profiles (Figure A8-2) in pattern, both with the overlying waters and the porewaters. Only the 0.3m water cover directly overlying the tailings (Series 1) showed a significant increase in average sulfate concentration with time, from ~50 to ~220 mg/L. The overlying water in the columns with a peat or sand intermediate layer had a consistently low sulfate concentration of ~10 mg/L, comparable to that of the natural water used in the experiment. Despite a twofold increase from ~10 to ~20 mg/L, the temporal increase in sulfate concentration in the 1m water cover was relatively small compared to that observed in the Series 1 columns. As will be discussed in greater detail in a later section, this could have resulted from both a greater dilution in the deeper water cover of the Series 4 columns and a lesser extent of sulfide oxidation occurring in the underlying tailings. The tailings porewater sulfate concentration in all columns showed a prominent decrease with time, reflecting that the sulfate generation rate in the solids layers was considerably lower than the flushing rate. Incidentally, judging from the near complete absence of sulfate in the porewaters of the peat layer, the peat barrier probably did not contain any reactive sulfide or soluble sulfate minerals.

3.4.3 Elemental Analyses

Concentration profiles of dissolved Fe, Al, Ca, Cu, Mg, Mn, K, Na, S and Zn in each series of columns with time over the duration of Phase II are compiled in Appendix 6 (Figures A6-5 to A6-14). Both total and ferrous iron concentrations are presented (Figures A6-5a, 5b). Since only a limited few of the analyzed elements would serve to reveal geochemical reactions and/or processes occurring in each scenario of subaqueous tailings disposal, only pertinent elements are described and discussed below. For example, the S data allow an independent check on the sulfate analyses. The profiles of the two parameters essentially mimic each other, so the S profiles (Figure A6-13) will not be discussed any further.

3.4.3.1 Tailings Porewater

Ca, Mg, K and Na on the order of 200, 120, 45 and 90 mg/L, respectively, were the major dissolved metals detected in the tailings porewater of all columns. Except near the water/tailings interface in the columns without an intermediate barrier (Series 1 and 4), the concentrations of all of these metals showed a prominent decrease with time (Figures A6-7, 8, 11 and 12). In the Series 1 and 4 columns, due to drawdown as well as efflux to the overlying water cover, the concentrations of these metals clustered at much lower values within 20 cm below the water/tailings interface. Typical measurements were 50 mg/L Ca, 20 mg/L Mg, 5 mg/L K and 8 mg/L Na for the shallow porewater in tailings under a 0.3-m water cover. For columns with a 1.0m water cover, the corresponding measurements were 25, 10, 4 and 7 mg/L, respectively.

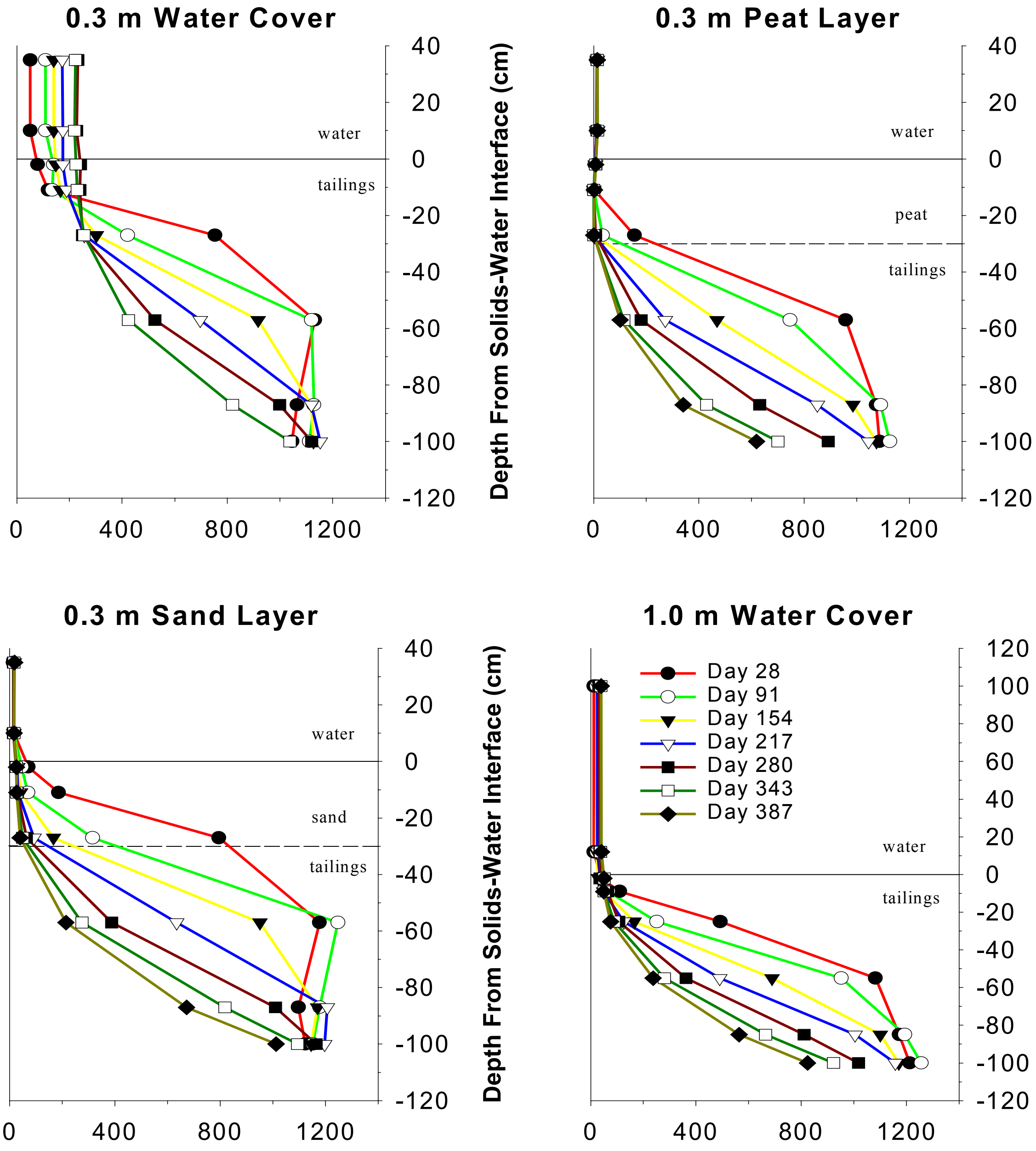

Figure 3.11 Mean Sulfate Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

Dissolved Cu, Mn and Zn concentrations were consistently <0.01, <0.3 and <0.1 mg/L, respectively, in the tailings porewaters of all columns except near the water/tailings interface in the Series 1 columns. In the latter case, with the gradual development of slightly acidic conditions at the interface, up to 0.05 mg/L Cu, 1.8 mg/L Mn and 0.7 mg/L Zn were measured in the tailings porewater towards the end of Phase II (Figures A6-8, A6-10 and A6-14, respectively).

Technical difficulties were encountered in the analysis of dissolved Al and Fe^{2+} resulting in varying detection limits. This gave rise to chemistry profiles with abundant plotting artifacts. Only highly anomalous dissolved Al and Fe^{2+} analyses can thus be discerned. Nevertheless, based on the data presented in Figures A6-5a, b and A6-6, it is possible to deduce that the tailings porewater in all columns contained little (<0.5 mg/L) dissolved Al, Fe(total) and Fe^{2+} except that just beneath the peat/tailings interface in the Series 2 columns. Here, up to 38 mg/L Fe^{2+} was measured, probably a result of both drawdown and diffusion of dissolved iron from the peat layer.

3.4.3.2 Peat Porewater

Compared to the tailings porewater, the peat porewater was enriched in dissolved total Fe, Fe^{2+}, Al, Cu, Mn and Zn. The highest measured concentrations for these metals were 160, 120, 1.4, 0.03, 1.0 and 0.1 mg/L, respectively. Maximum Cu and Zn were observed near the water/peat interface while the others were observed near the peat/tailings interface. Except for dissolved Cu and Zn, the concentration of all of the dissolved trace metals appeared to slightly decrease with time.

The peat porewater, on the other hand, was relatively impoverished in dissolved Ca, Mg, K and Na. The highest measurements were 50, 20, 15 and 30 mg/L, respectively. All of these were observed at the peat/tailings interface and appeared to decrease with time. A concentration gradient for each of these major cations was established from the tailings through the peat layer to the overlying water without any additional contribution from the peat.

3.4.3.3 Sand Porewater

Relative to the tailings porewater, the sand porewater was enriched in dissolved Fe (total and Fe^{2+}), Ca (only initially), Cu, Mn, and Zn and impoverished in dissolved Mg, K and Na. The maximum measurements were 4 and 3 (for total Fe and Fe^{2+}), 260, ~60, 3.8 and 0.7 mg/L, respectively for the enriched cations and 55, 27 and 33 mg/L, respectively, for the impoverished cations. Except for the concentration of dissolved Cu and Zn, which peaked near the water/sand interface, the concentrations of all the other cations in the sand porewater had their highest value near the sand/tailings interface.

Based on its porewater chemistry, the sand appeared to be a contributor of dissolved Fe, Ca, Cu, Mn and Zn instead of behaving just as an inert diffusion barrier. The released metals could have originally been associated with iron and manganese oxides/oxyhydroxides in the sand, which underwent reductive dissolution after submergence in the columns. The concentration of all the detected dissolved metals in the sand porewater, however, showed significant decrease with time.

3.4.3.4 Water Covers

Changes in dissolved metal concentrations in the water covers during Phase II were most prominent for the Series 1 columns. The changes included increases in dissolved concentrations of Ca (20 to 50 mg/L), Cu (0.02 to 0.12 mg/L), Mg (8 to 28 mg/L), Mn (0 to 1.8 mg/L) and Zn (0.05 to 0.75 mg/L) with time. Dissolved concentrations of total Fe, Al, K and Na remained consistently low at values comparable to the background concentrations in the natural water used in the experiment or below the analytical detection limits of the respective elements.

Small amounts of dissolved Cu and Zn with concentrations of 0.02±0.01 and 0.05±0.04 mg/L, respectively, were the only anomalous cations found in the water cover in the Series 2 columns with a peat intermediate barrier. The dissolved Cu concentration was in fact lower than the background Cu concentration in the natural water used in the experiment (~0.03 mg/L), suggesting that the peat ± the underlying tailings actually acted as a sink to dissolved Cu in the water column.

Although anomalous concentrations of dissolved Mn and Zn were observed in the sand porewater, little dissolved Mn and Zn (<0.3 and 0.03 mg/L, respectively) was found in the water covers of the Series 3 columns. The dissolved metal of interest was Cu which decreased in concentration from 0.03 to 0.01 mg/L during Phase II, again suggesting that the underlying solids acted as a sink to dissolved Cu in the water cover. Dissolved concentrations of Fe, Al, Ca, Mg, K and Na all remained consistently low at the background values of the natural water or below the analytical detection limits of the respective elements.

Dissolved concentrations of Ca and Mg in the 1-m water cover increased slightly and the dissolved Cu concentration decreased slightly during Phase II. All the other dissolved metals were either at the background level of natural water used or below the analytical detection limit of the respective elements.

3.4.3.5 Quality of Runoff and Drawdown Water

The water quality in the collected runoff did not differ significantly from that of the bulk of the water covers indicative of rapid mixing. The drawdown water samples taken from the base of the columns were generally devoid of trace metals despite a slight drop of pH relative to the tailings porewaters. The slight drop in pH probably resulted from the oxidation and subsequently hydrolysis of minor amounts of dissolved iron in the composite samples collected over three weeks. The concentrations of dissolved sulfate, Ca and Mg in the drawdown samples also decreased slightly with time suggesting that mineral dissolution or oxidation rates were lower than the flushing rate.

3.5 Summary Observations and Calculated Loadings for Phases I and II

To facilitate discussing the implications of the test results, cumulative efflux loadings of selected parameters occurring during the two phases of the study are compared in Table 3.6 and salient bservations on changes in water chemistry summarized in Tables 3.7 and 3.8, respectively. Positive

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entries in Table 3.6 indicate efflux of the pertinent parameters to the overlying water and negative entries reflect loss of a parameter from the water column. Based on the data presented, it is clear that unless acidic conditions developed in a water cover, the underlying solids served as a sink to dissolved Cu but a source of dissolved Zn under all conditions. In addition, by Day 217 of Phase II, the peat and sand layers had depleted most of their soluble metal content and became simply inert diffusion barriers. However, it is not clear whether or not the apparent loss of dissolved K in the water covers of Series 2, 3 and 4 during Phase II is related to the patchy algal growth occasionally observed in the columns.

Table 3.6 Cumulative Efflux Loading of Selected Parameters to the Water Covers

	Units	Series 1 (0.3 m)	Series 2 (peat)	Series 3 (sand)	Series 4 (1.0m)
Phase I					
SO_4 Day 100	g	4.85	0.76	0.97	4.57
SO_4 Day 200	g	8.86	0.78	1.40	7.51
Zn Day 100	mg	2.33	1.80	4.73	0.00
Zn Day 200	mg	7.13	0.71	7.86	2.26
Al Day 200	mg	-3.05	6.13	4.69	-3.05
Ca Day 200	g	1.83	0.05	0.31	2.07
Cu Day 200	mg	-0.35	-0.32	3.12	-0.57
K Day 200	mg	85.9	-15.9	4.24	-20.5
Mg Day 200	g	0.78	0.00	0.04	0.80
Mn Day 200	mg	-0.02	1.76	6.23	-0.07
Na Day 200	mg	175	98.7	96.5	0.14
Phase II					
SO_4 Day 217	g	3.49	0.08	0.13	1.16
Zn Day 217	mg	10.8	0.21	0.11	1.77
Al Day 217	mg	0.04	1.42	-0.59	-0.59
Ca Day 217	g	0.64	-0.06	0.01	0.55
Cu Day 217	mg	0.34	-0.34	-0.41	-0.50
K Day 217	mg	9.97	-12.2	-21.9	-14.9
Mg Day 217	g	0.33	-0.01	0.00	0.21
Mn Day 217	mg	28.3	0.39	-0.03	-0.03
Na Day 217	mg	9.23	-3.39	0.00	-6.47

A detailed examination of the information presented in Tables 3.6, 3.7 and 3.8 will aid with identifying major parameters and mechanisms controlling mass transfer between the solid and liquid phases for the duration of the testing. The information will also allow an assessment of the performance of the four options of subaqueous disposal of the Louvicourt tailings.

Table 3.7 Summary Features and Observations of Phase I

Phase I: Mixed water cover

100 days circulated water without aeration + 100 days circulated water with aeration

Series 1: 0.3m water cover directly on tailings

- Significant increases in dissolved sulfate, Ca, Mg and Zn concentrations in water cover especially after 100 days but pH remained in near-neutral range.
- Dissolved oxygen in tailings porewater became non-detectable (<0.2 mg/L) ~8 cm below the water/tailings interface to Day 100 and ~15cm below the interface to Day 200.

Series 2: 0.3m water cover with a 0.3m peat intermediate barrier over the tailings

- Decrease in pH in water cover with time, dropping to pH~4 on Day 200 without significant increases in dissolved sulfate, Ca or Mg.
- Porewater pH in peat layer remained slightly below 6 throughout Phase I.
- Total acidity, total dissolved Fe, Fe^{2+} and dissolved Al in the peat porewater peaked in the middle of the peat layer while total alkalinity and dissolved Mn peaked at the peat-tailings interface.
- Peat layer apparently contained trapped air pockets resulting in a measured dissolved oxygen concentration of ~1 mg/L at the peat tailings interface.

Series 3: 0.3m water cover with a 0.3m sand intermediate layer over the tailings

- pH in water cover dropped to slightly below 6 after Day 100 accompanied by prominent increases in dissolved Al, Cu and Zn.
- Dissolved Zn in the sand porewater peaked near the sand/water interface, total dissolved Fe, Fe^{2+} and dissolved Mn in the middle of the sand layer, and dissolved sulfate, Ca as well as Cu near the sand/tailings interface.
- Dissolved oxygen dropped to below detectable level at sand/tailings interface.

Series 4: 1m water cover directly on tailings

- Slight increases in dissolved sulfate, Ca, Mg and Zn in water cover but pH remained near neutral.
- Lowest and slightly below saturation level of dissolved oxygen in the water cover; dissolved oxygen in tailings porewater dropped to below detection limit ~5 cm below the water/tailings interface without aeration and ~10 cm below the interface with aeration.

Table 3.8 Summary Features and Observations of Phase II

Phase II: Mixed water cover with runoff and drawdown

Series 1: 0.3m water cover directly on tailings

- pH in water cover dropped below 7 after ~200 days and to ~5 on Day 343 with accompanying significant increases in dissolved sulfate, Ca, Cu, Mg, Mn and Zn.
- Detectable dissolved oxygen (≥0.2 mg/L) was measured as much as 27 cm below the water/tailings interface.

Series 2: 0.3m water cover with a 0.3m peat intermediate barrier over the tailings

- Slight increases with time in porewater pH in the peat layer (clustered around 6) and pH in the water cover (~6.5 to 7).
- Dissolved Zn in the peat porewater peaked at the water/peat interface; acidity and dissolved Al in the middle of the peat layer, dissolved Fe and Mn at the peat/tailings interface; and, the alkalinity peak had migrated into the underlying tailings with time.
- Dissolved oxygen was not detected in the tailings porewater although up to 0.5 mg/L was still measured in the peat layer.

Series 3: 0.3m water cover and a 0.3m sand intermediate sand layer on the tailings

- A pH depression (minima at pH 5.5) occurred in the sand porewater just below the water/sand interface but pH in the water cover increased slightly from ~6.8 to 7.6.
- Acidity and dissolved Zn in the sand porewater peaked near the water/sand interface; alkalinity, total dissolved Fe and dissolved Mn peaked at the sand/tailings interface; and, the dissolved Ca peak appeared to migrate into the underlying tailings after 90 days.
- Dissolved oxygen was not detected (≤0.2 mg/L) in the tailings porewater.

Series 4: 1m water cover directly on tailings

- pH of the water cover increased from ~7 to ~8; slight increases in alkalinity, dissolved sulfate, Ca and Mg as well as slight decrease in dissolved Cu.
- Tailings porewater alkalinity peaked at ~9cm below the water/tailings interface and dissolved Mn near the interface.
- Detectable dissolved oxygen (≥0.2 mg/L) was measured to at least 9cm below the water/tailings interface.

3.6 Supplementary Dissolved Oxygen Measurements

Upon comparing preliminary results of the column study with those obtained in the field, it became clear that the DO penetration depths observed in the laboratory columns differed significantly from those measured in the two field test cells. In an attempt to resolve the discrepancy, Mr. Bernard Vigneault of INRS-EAU, Quebec University, was invited to conduct micro-electrode DO and pH measurements at CANMET on June 17-18, 1999 with the same equipment as used in the field.

Five columns, E (0.3m), F (peat), G (sand), H (1.0m) and I (0.3m) were re-activated for two weeks prior to the measurements. Water cover circulation with aeration and drawdown were applied to the first four columns while drawdown was omitted for Column I. Salient observations are summarized below:

1. For all practical purposes, the DO microelectrode could not penetrate the substrate to a depth of much more than 1 cm and the pH microelectrode 4 cm without risking damaging the microelectrodes.
2. Readings for oxygen saturation with the CANMET in-line DO sensor and the microelectrode were the same and both gave zero oxygen concentration in nitrogen-purged water.
3. Passing the nitrogen-purged water through the in-line cell, however, gave 0.33 mg/L dissolved oxygen, suggesting that the cell is susceptible to oxygen intrusion from the atmosphere.
4. For the columns with a simple water cover (E and H) and the column containing a peat intermediate barrier layer (F), the DO profiles measured with the microelectrode indicated complete oxygen depletion between 2 and 6 mm below the water/solid interface. Readings comparable to those obtained in Phases I and II (up to 0.5 mg/L) were obtained using the CANMET in-line probe at greater depths.
5. For the column containing a sand intermediate barrier (G), oxygen penetrated to a greater depth (>1.5 cm) as measured by the microelectrode.
6. When the DO microelectrode was inserted in a duplicate in-line cell, measurable DO content (up to 1.39 mg/L) was registered by the microelectrode in porewater drawn from a depth of ~9 cm below the water/tailings interface in Column E (0.3m simple water cover). The corresponding CANMET in-line DO measurement was 0.64 mg/L. The anomalous microelectrode reading in this case could have resulted from the fact that water contained in the cell was open to the atmosphere when the measurement was made.
7. A pH depression generally extended to a depth greater than 1 cm below the water/solid interface in all columns as measured by the pH microelectrode.

The implications of these observations and the overall comparative exercise are as follows:

a) The uncertainty of CANMET in-line cell DO measurements versus INRS-EAU microelectrode measurements could be as high as 0.5 mg/L, which could be taken as a systematic error inherent in the CANMET in-line cell design. However, the exercise reaffirms the consistency of measurements made by CANMET and INRS-EAU in the laboratory and the field, respectively.

b) If sulfide oxidation is the primary cause of pH depression and availability of oxygen is essential for sulfide oxidation, the micro-pH profiles are not entirely compatible with the micro- DO profiles. Areas of intense pH depression span at least 1 to 2 cm in the columns with simple water cover (0.3 m and 1.0 m) when completion oxygen depletion occurs within millimetres from the water/tailings interface.

c) Whereas the oxygen penetration depths observed in the columns studies appear to be excessive, the deduced oxygen fluxes (often assumed to reflect oxygen consumption rates) for the two simple water cover options (0.3 and 1.0 m) are comparable to those reported in the literature for similar tailings studies. The depletion of DO in millimetres instead of centimetres will lead to an order of magnitude higher calculated fluxes, suggestive of highly reactive tailings. If this is really the case, given the fact that the tailings in the columns have been exposed to oxygen saturated overlying water for over three years under laboratory conditions, the surface layers of the tailings should be largely depleted of reactive sulfides and become passive diffusion layers. Then, dissolved oxygen should penetrate lower into the underlying fresh tailings. Furthermore, peeper results for DO from lysimeter testing of Voisey Bay tailings under a fresh water cover also suggested oxygen penetration in centimetres (Mugo et al., 1997). The mineralogical study of material from the two field test cells (Paktunc, 1999) also appears to support sulfide oxidation occurring at depth greater than millimetres. More work in terms of post-mortem material characterization is thus required to clarify the issue.

4.0 DISCUSSION

In the column studies, four scenarios of subaqueous tailings disposal involving two water depths (0.3 and 1.0 m) and two types of intermediate barriers (peat and sand) were investigated. Phase I of the investigation focused on oxygen diffusion and ionic fluxes under conditions of a well-mixed water cover. Phase II introduced the complications of runoff/precipitation and drawdown and investigated their effects on oxygen availability and water chemistry. Results obtained allow a closer examination of the significance of water cover depth, the roles of intermediate barriers, the impacts of precipitation/runoff and drawdown as well as the relative merits of the four investigated options of storage of tailings under water. These issues are discussed below following a brief elaboration on inter-column variability and data integrity, especially dissolved oxygen measurements.

4.1 Inter-Column Variability and Data Integrity

The column testing has been conducted in triplicate. However, to facilitate data description and interpretation, only average results have been depicted and discussed in the previous sections. A review of all the different kinds of data acquired during the course of the column study, taking into consideration calculated coefficient of variation for key parameters measured, confirms that the tailings are relatively uniform in composition. This gives rise to only minor differences in the evolution of water chemistry in individual columns of the Series 1 and 4 experiments (0.3 and 1.0 m simple water cover, respectively). The sand and peat materials, however, are highly heterogeneous, rendering high inter-column variability (>50%) in many measured parameters in the overlying water and porewater in the intermediate layers, especially in Phase I of the study. With almost complete fluxing of soluble weathering products at the commencement of the Phase II work, most parameters showed much lower inter-column variability (<30%) in subsequent measurements.

As suggested by the results of supplementary dissolved oxygen measurements with the aid of personnel and instrument from INRS-Eau, the absolute DO measurements at low levels (less than about 0.5 mg/L) and the absolute depths of DO penetration may be in doubt. Technical problems also appear to have affected the accuracy of some Eh measurements. In addition, the relatively high and variable detection limits from one batch of sample to another for dissolved Al, Cu and Fe make interpretation of low level data nearly impossible. Nonetheless, taken as a whole, these data sets are useful for identification of trends and anomalous concentrations. Running the test columns in triplicate also helps to identify analytical excursions, which are ignored in subsequent data interpretation. The analytical precision and limits of quantification for critical parameters like pH, sulfate, alkalinity and dissolved Ca and Mg are excellent. The evolution of these parameters during the course of the testing reflects chemical reactions that have occurred, especially sulfide oxidation and alkalinity generation and depletion. The high quality of these data allows us to infer with confidence that sulfide oxidation has occurred to varied extent in different column series and that alkalinity balance is a critical factor in the performance of a water cover.

4.2 Impact of Water Cover Depth

The significance of water depth in controlling oxidation of sulfide minerals in the submerged tailings and the chemistry of the overlying water can be assessed by comparing the results obtained from the Series 1 (0.3 m) and Series 4 (1.0 m) columns. We shall address the issue of oxygen diffusion first, then changes in water cover chemistry and conclude with comments on other considerations.

In Phase I, with the water circulated but not aerated, the shallow water cover in the Series 1 columns was 50 to 60 per cent saturated in DO while the saturation level in the deeper water cover in the Series 4 columns was 40 to 50 per cent. These values indicate that the rate of oxygen consumption by the submerged tailings was higher than that of oxygen diffusion from the atmosphere to the overlying water. The oxygen fluxes calculated after the commencement of aeration of the water covers were not significantly different for the two water depths. This could be interpreted as evidence that the rate of oxidation was independent of water depth. However, the incorporation of precipitation/runoff and drawdown events in Phase II of the study led to a deeper penetration of DO in the submerged tailings in the Series 1 columns compared to the Series 4 columns (17 versus 10 cm below the water/tailings interface). This suggests that more extensive sulfide oxidation has occurred beneath the shallower water cover than the deeper water cover. The eventual acidification of the water cover in two out of three Series 1 columns in Phase II further attests to more extensive sulfide oxidation beneath the shallower water cover. However, since the transport of DO in Phase II involved both diffusion and downward migration of oxygenated water, Fick's law no longer applied. Oxygen fluxes are therefore not calculated for Phase II.

With respect to the water cover chemistry, the Series 1 columns differ significantly from the Series 4 columns. On the one hand, the calculated fluxes of dissolved sulphate, Mg and Ca from the submerged tailings in Phase I were within experimental error for the 0.3-m and 1.0-m water covers. On the other hand, the actual concentrations of dissolved species in the overlying water of the Series 4 columns on Day 200 were significantly lower than those for the Series 1 columns. This may be explained by a threefold dilution effect associated with the deeper water cover. In Phase II, however, with the gradual development of slightly acidic conditions in the overlying water of the Series 1 columns (to pH~5), the disparity in dissolved ion concentrations in the Series 1 and Series 4 water covers can no longer be accounted for by dilution alone. It must relate to the kinetics of chemical reactions occurring in the respective series of columns, especially at the water/tailings interface. In this regard, the role of sulfide oxidation by ferric ion is perhaps particularly relevant. Ferric ion, the generation of which ultimately depends on the availability of oxygen, is a more potent oxidizer than dissolved oxygen (Singer and Stumm, 1970; Nordstrom, 1982). Acidic conditions gradually developed in shallow water cover of the Series 1 columns favor the formation of increasing amounts of dissolved ferric ion to enhance rapid sulfide oxidation at the tailings surface. With both the pH and alkalinity content of the overlying water in the Series 4 columns showing an increasing trend with time during Phase II, little ferric ion can stay in solution to enhance sulfide oxidation because of the greater stability of ferric hydroxide. Obviously, this argument holds true only if the replenishing water (like the natural water used in the column testing) contains excess alkalinity to counteract small amounts of acid generated at the tailings surface.

Assuming that the water cover is well mixed, the benefit obtained from maintaining a 1.0m versus a 0.3m water cover over the tailings is therefore primarily one of stability. From a chemical standpoint, a deeper water cover will lead to a greater dilution, which in turn gives rise to lower chemical activities of reactive species, e.g., Fe^{3+}, at the tailings surface. A solution of lower ionic strength and thus electrical conductivity will also dampen metal leaching mechanisms like galvanic sulfide oxidation which can significantly affect water quality (Kwong and Lawrence, 1994; Kwong, 1995; Kwong et al., 1997). From a physical perspective, erosion of the tailings surface in water cover impoundments must be prevented in order to minimize contact between oxygen and tailings. The two principal factors affecting bed stability under a body of water are entrainment forces imposed on the sediment bed (shear stress imposed by water movement) and the resistance of the sediment to entrainment (which in turn is related to grain size and sediment density). Given similar environments, increased water depth will result in decreased shear stresses at the tailings surface. In practice, there are a number of additional considerations in setting the water depth. These include disturbance of the tailings bed surface by ice, vegetation or other activities; significant drought and precipitation events; natural topography as well as integrity of the base and engineered structures. Depth criteria for water covers have been proposed to minimize waste re-suspension (MEND, 1998) based on the characteristics of the waste itself, the expected critical sheer stress at the water/waste interface and the maximum ice thickness.

4.3 Functionality of the Peat and Sand Intermediate Barriers

Locally available peat and sand from the Louvicourt Mine were tested as potential intermediate barrier materials in the Series 2 and 3 columns, respectively, of the laboratory study. Both of these media behaved as a reactive barrier, at least at the early stages of the testing. The functionality of the peat and sand as intermediate barriers is elaborated below.

4.3.1 Peat

Relative to the tailings themselves, the locally available peat is less effective in scavenging dissolved oxygen. From the shape of the DO profiles obtained from the Series 2 columns, there is little doubt that oxygen was consumed in the peat layer. However, non-negligible levels of DO were measured in the peat layer in both Phases I and II such that not only was DO available at the peat/tailings interface but that the concentrations exceeded levels available at the sand/tailings interface. Moreover, Eh measurements in the peat porewater suggest that the peat has not been effective in maintaining a strongly reducing condition to effect sulfate reduction. It is likely that the peat used in the experiment is partially weathered. Its efficiency as an oxygen sink is expected to further decrease with time. As such, the peat layer has been observed to serve as an insert diffusion barrier with respect to the transport of major conservative species like dissolved Ca, Mg and sulfate during the testing, attenuating the efflux of these species from the tailings porewater to the water cover. This is demonstrated by a simple concentration gradient across the entire thickness of the peat layer in the depth profiles of these species recorded in both Phase I and II of the study.

In addition to its poor performance as an oxygen barrier, the peat is a source of acidity. This is clearly indicated by the total acidity and pH values measured within and above the peat intermediate layer in the Series 2 columns. Given the low dissociation constants of most organic acids compared to those of strong inorganic acids, the stored acidity in the peat porewater is greater than that reflected by the modest porewater pH (~5). This gives rise to the potential problem of organic acids impacting on the solubility and hence mobility of metals. Water quality monitoring of the Series 2 columns during Phase I and II of the testing clearly indicate that the peat intermediate barrier is a source of dissolved aluminum, manganese and ferrous iron and perhaps also small quantities of copper and zinc. However, although the peat porewaters were enriched in these metals, concentrations in the overlying water remained low. Precipitation as a hydroxide or oxyhydroxide due to changing pH or sorption onto precipitating solid phases were likely responsible for their depletion in the water column. A distinctive orange layer observed at and near the peat surface is indicative of iron oxide precipitation at the peat/water interface.

4.3.2 Sand

Like peat, the sand layer in the Series 3 columns behaved both as a reactive medium and an inert diffusion barrier, depending on the chemical species involved. Calculated effluxes for dissolved sulphate, Ca and Mg into the overlying water column are a fraction of the values calculated for the 0.3m water cover with no intermediate barrier (Series 1), attesting to its function as a diffusion barrier. The shape of DO profiles recorded in both Phases I and II, on the other hand, indicates that the sand is effective in scavenging oxygen, eliminating the availability of measurable DO at the sand/tailings interface. Detailed reactions involved in the oxygen consumption process are not clear. It appears that both the formation of oxyhydroxides at the surface of the submerged sand layer and the oxidation of remnant sulfides play a role but the former is perhaps more dominant. Some circumstantial evidence is provided below.

In Phase I, porewater in the sand layer showed significantly higher total alkalinity than the tailings porewater. Despite this observation, the overlying water covers showed a somewhat larger drop in total alkalinity and increase in total acidity with time than in Series 1. This is interpreted to be the result of efflux of hydrogen acidity generated in the precipitation of oxyhydoxides near the water/sand interface. The precursor of the hydrolysis reaction is a homogeneous reaction involving the oxidation of reduced metal ions like Fe^{2+} and Mn^{2+}, which would consume oxygen faster than a heterogeneous reaction like sulfide oxidation. In Phase II, however, the efflux of acidity apparently could not keep up with additional alkalinity introduced through drawdown and precipitation events. Consequently, with the progress of the testing, the pH, acidity and alkalinity of the overlying water gradually approached those of the natural water used.

The sand intermediate barrier also appears to be a source of dissolved Al, Cu, Mn and Fe^{2+}. Furthermore, a spike in dissolved Zn has been detected just below the water/sand interface in both Phases I and II. It is possible that the zinc was originally associated with secondary iron and manganese oxides in the sand layer and became mobilized when the secondary oxides began to dissolve with a developing reducing environment. Sorption onto the re-precipitating oxyhydroxides near the sand surface has limited the subsequent efflux of zinc into the overlying water unless acidic conditions start to develop in the water column. The latter case actually occurred with Column K in Phase I, giving rise to dissolved Cu and Zn concentrations of 0.5 and 1.3 mg/L, respectively, by Day 160 and concentrations of dissolved Al and Mn of approximately 1 mg/L.

4.3.3 Concluding Remarks

In short, an intermediate layer of either locally available peat or sand offers reductions of DO concentrations at the solids/tailings interface. Both the peat and sand layers also attenuate the efflux of conservative ions like dissolved Ca, Mg and sulfate from the underlying tailings. However, since neither of the media is inert chemically, careful consideration must be given to the short-term impacts that these materials may have on water quality, and whether these impacts outweigh the longer-term benefits.

4.4 Chemical Effects of Runoff/Precipitation and Drawdown

With the incorporation of precipitation, runoff and drawdown events in Phase II, the results obtained present a more realistic picture of what can be expected under field conditions than the Phase I results. The obvious short-term and long-term impact of inputting water to the tailings impoundment through natural precipitation or runoff is the dilution of the water cover. The significance of the dilution effect on the water cover quality depends on the extent of evaporation as well as the magnitude of efflux of ionic species from the submerged tailings. Drawdown events have the potential to impact groundwater quality. With downward migration of water, transport of dissolved species is affected both by diffusion and advection processes. In addition, some chemical reactions may start to occur as the original porewater is gradually replaced by a solution of a different composition. Based on the results obtained in Phase II of the column study, an array of effects can be traced to the downward percolation of the overlying water in the columns. Some of the more important observations are discussed below.

With regard to oxygen diffusion, the introduction of a drawdawn of 0.36 m/yr in Phase II appears to have only a minor effect on the availability of DO to the submerged tailings. While detectable DO has penetrated to a greater depth in the Series 1 columns (27 cm versus 15 cm in Phase I), the rate of ingress (~0.8 mm/day) is essentially the same as that observed in Phase I. For the Series 2 columns containing a peat intermediate layer, a reduced concentration of DO has been measured at the peat/tailing interface compared to that observed in Phase I. This probably reflects the gradual depletion of trapped air pockets in the peat layer. For the Series 3 columns with a sand intermediate layer, no detectable DO has reached the underlying tailings as before. In the Series 4 columns with a 1.0m water cover, the depth of DO penetration has remained largely unchanged from that of Phase I. Probably, the small amounts of DO carried by the drawdown water have been rapidly consumed by sulfide oxidation in tailings directly under a water cover (Series 1 and 4) and oxidation of reduced species of dissolved iron and manganese in the peat and sand intermediate layers (Series 2 and 3).

The effects of drawdown on the chemistry of the overlying water and porewaters of the submerged solids, however, are significant. This is particularly noticeable with the Series 2 columns containing a peat intermediate barrier between the 0.3m water cover and submerged tailings. In contrast to the observation made in Phase I, the overlying water has not turned acidic even though the duration of the Phase II testing is approximately 70% longer. Consequently, efflux of contaminants is minimal compared to that observed in Phase I. Furthermore, a downward migration of a concentration spike in total alkalinity from the peat/tailings interface to the tailings is evident. Given the fact that the peat porewater is slightly acidic, its downward percolation will lead to the dissolution of carbonates in the tailings solids along its flow path. While the acid is neutralized, the released bicarbonate ion is reflected in the total alkalinity measurements. Because of the low dissociation constants of organic acids, the reaction with carbonates in the tailings solids will extend deeper into the tailings than a simple neutralization reaction between downward migration hydrogen ions and carbonate minerals.

Similarly, a pH depression has not developed in the shallow water covers of the Series 3 columns containing a sand interlayer including the most reactive Column K. The efflux of contaminants is therefore suppressed. In the Series 4 columns with a 1.0m water cover, pH and alkalinity in the overlying water have been observed to increase with the progress of testing, slowly approaching the corresponding background measurements of the natural water used in the experiment. However, the efflux of dissolved Zn is only marginally reduced, reflecting the mobility of dissolved Zn even in solutions with near-neutral pH values. A continuous supply of Zn can readily be derived from oxidative dissolution of sphalerite by galvanic interaction, which does not effect significant pH changes unless the sphalerite is Fe-bearing (Kwong, 1995). In the Series 1 columns with a 0.3m water cover directly overlying the tailings, the alkalinity carried by the drawdown water is apparently insufficient to counteract the acid produced by sulfide oxidation in the upper layers of the tailings bed. This has led to the acidification of the overlying water (to pH values of 4 to 5) in two of the three columns in the series with concomitant increases in efflux loadings of contaminants to the water cover.

It should be emphasized that the apparent beneficial effects associated with precipitation/runoff and drawdown events in the Series 2, 3 and 4 columns primarily relate to the alkalinity content (~24 mg/L $CaCO_3$) of the natural water used in the testing. The input of additional alkalinity to the submerged solids contributes to counteract, at least partially, acid generating processes occurring there. If the drawdown water contains less alkalinity, the contrast in water quality of the overlying water and efflux loadings for the Series 1 and Series 4 columns will be less prominent or may not occur at all in the long run. Furthermore, since carbonate minerals are generally more soluble than sulfide minerals even in a near-neutral solution, drawdown may eventually deplete the submerged solids of their neutralization potential. The long-term implication of carbonate depletion with drawdown deserves further investigation.

4.5 Comparison of Under –Water Disposal Scenarios

One of the primary goals of conducting the column studies described above is to evaluate various possible scenarios of subaqueous disposal of Louvicourt tailings. Based on the testing results, the relative merits of the four options investigated are briefly discussed below.

While a 0.3 m water cover directly overlying tailings (Option 1) significantly reduces the amount of oxygen reaching the submerged reactive mine waste, it appears to be insufficient to completely arrest sulfide oxidation and metal leaching in the long term. Increasing concentrations of dissolved sulfate and metals, especially Zn, have been detected in the water cover as early as in Phase I. The deterioration of the quality of the water cover has persisted in Phase II culminating in the eventual slight acidification with concomitant increase in contaminant concentrations. Largely dependent on the alkalinity balance at a site, this option may not perform as well as anticipated.

The incorporation of a peat intermediate layer between a 0.3 m water cover and the tailings (Option 2) has greatly reduced but not eliminated the access of dissolved oxygen to the reactive tailings. Pockets of air appeared to have been trapped in the peat layer, giving rise to detectable concentrations of DO at the peat/tailings interface. In addition, the peat is a source of acidity and a suite of dissolved metals including Al, Fe, Fe, Mn as well as possibly Cu and Zn. Although the precipitation of iron and manganese hydroxides and oxyhydroxides at the water/peat interface serves to reduce metal efflux in the laboratory columns, the short- and long-term performance of a peat intermediate layer under field conditions requires further investigation. Depending on the composition and state of weathering of the peat found as well as on the method of installation, the use of an alternative source of peat as an intermediate barrier may render better results than those observed in the current study.

Like the locally available peat, the sand used as an intermediate barrier in Option 3 is also an oxygen scavenger and a source of a few dissolved metals, notably Fe, Mn and Zn. The oxidation, hydrolysis and re-precipitation of iron and manganese near the water/sand interface are suspected to be accountable for the slight pH depression observed in the water cover in Phase I. With the ameliorating effects of precipitation/runoff and drawdown, the water quality has significantly improved in Phase II. Not carrying a persistent source of acidity in the form of poorly dissociated organic acids, the sand appears to be a better intermediate barrier than peat.

With the minimum oxygen penetration depth and least significant changes in the water cover chemistry throughout the three years of study, the 1.0 m water cover option appears to be most effective in reducing sulfide oxidation and aqueous contaminant transport among the four options studied in the short term. From a chemical perspective, if the surface runoff in the Louvicourt area carries as much alkalinity as the natural water used in the column studies, there is no reason to suspect that a1.0 m water cover will not function as well in the field as in the laboratory.

In closing, it should be reiterated that the above assessment of disposal options is based solely on column test results obtained under laboratory conditions. With subzero temperatures prevailing at the Louvicourt site eight months a year, it can be expected that chemical reactions will occur at a lower rate in the field than in the laboratory. Under the circumstances, a simple 0.3m water cover may well be sufficient to retard sulfide oxidation, rendering acceptable water quality in both the water cover and groundwater discharge. On the other hand, wave action in the water cover has not been taken into account in the column studies. In short, conclusions drawn from the column studies cannot be directly applied to the field without due consideration of the site conditions. To compare the column test results with field monitoring data, one should also bear in mind that instead of fresh tailings, tailings that have been stabilized under laboratory conditions for over a year were used in the major investigative phases of the column studies. Any reactive products generated in the milling process such as thiosalts could have been depleted prior to the regular monitoring and analyses in Phases I and II of the investigation. The column test results are thus more applicable to predicting the medium- to long-term instead of the short-term impacts of various options of subaqueous tailings disposal.

5.0 CONCLUSIONS

Integrating the observations and test results of the Phases I and II investigation of four subaqueous disposal options using Louvicourt tailings, the following conclusions can be drawn:

1. While water covers serve to effectively limit the availability of oxygen (in terms of reduced concentrations), they do not totally eliminate sulfide oxidation in submerged tailings in the absence of a more effective oxygen scavenger than reactive sulfides. Largely depending on the alkalinity balance in a tailings disposal facility, a deeper water cover can be more effective in arresting metal leaching. This is because water chemistry significantly affects the nature (i.e., detailed mechanisms) and rate of oxidative sulfide dissolution despite dissolved oxygen is the ultimate oxidant.

2. Intermediate layers like peat and sand may act as source or sink some of dissolved constituents, depending on their chemical composition. While they generally serve to reduce access of dissolved oxygen to submerged tailings, such materials must be characterized in detail to assure their inert nature prior to incorporation as a diffusion barrier. This will avoid unwarranted impact to the water covers as noted in the sand- and peat-containing columns during Phase I of the investigation.

3. Chemical processes occurring at the water/solid interface (e.g., co-precipitation or sorption with oxyhydroxides) and drawdown appear to have served to limit the efflux of undesirable parameters like dissolved copper and zinc to the overlying water. To decipher the detailed reactions involved and to more accurately delineate relevant chemical gradients, a sampling design with a much higher resolution than that employed in the current study is required. Chemical reactions associated with drawdown may also have significant impact on groundwater quality and cannot be ignored in water cover studies.

In short, a thorough understanding of the important and relevant physical, chemical and biological processes associated with subaqueous tailings disposal will facilitate the design of practical, walk-away solutions for decommissioning mine sites utilizing a water cover to suppress sulfide oxidation in reactive tailings.

6.0 RECOMMENDATIONS

The current study has provided valuable insight into potential impacts of various options for subaqueous disposal of Louvicourt tailings under the laboratory conditions. However, further work is required to confirm various processes presumed to have taken place during the testing and to validate the long-term performance of the different disposal options. Salient items include the following:

1. Post-test solids characterization including detailed sampling of the interface layers to confirm geochemical processes taken place, especially to provide direct evidence of sulfide oxidation and metal leaching.

2. Correlation of the results of completed laboratory test work with those obtained from the two test plots.

3. Lysimeter testing of water covers with less alkalinity content to clarify the long-term performance of a shallow cover versus a deep cover under well oxygenated conditions.

4. Investigation of the rate of carbonate depletion in the test solids under the different scenarios and of their long-term implications.

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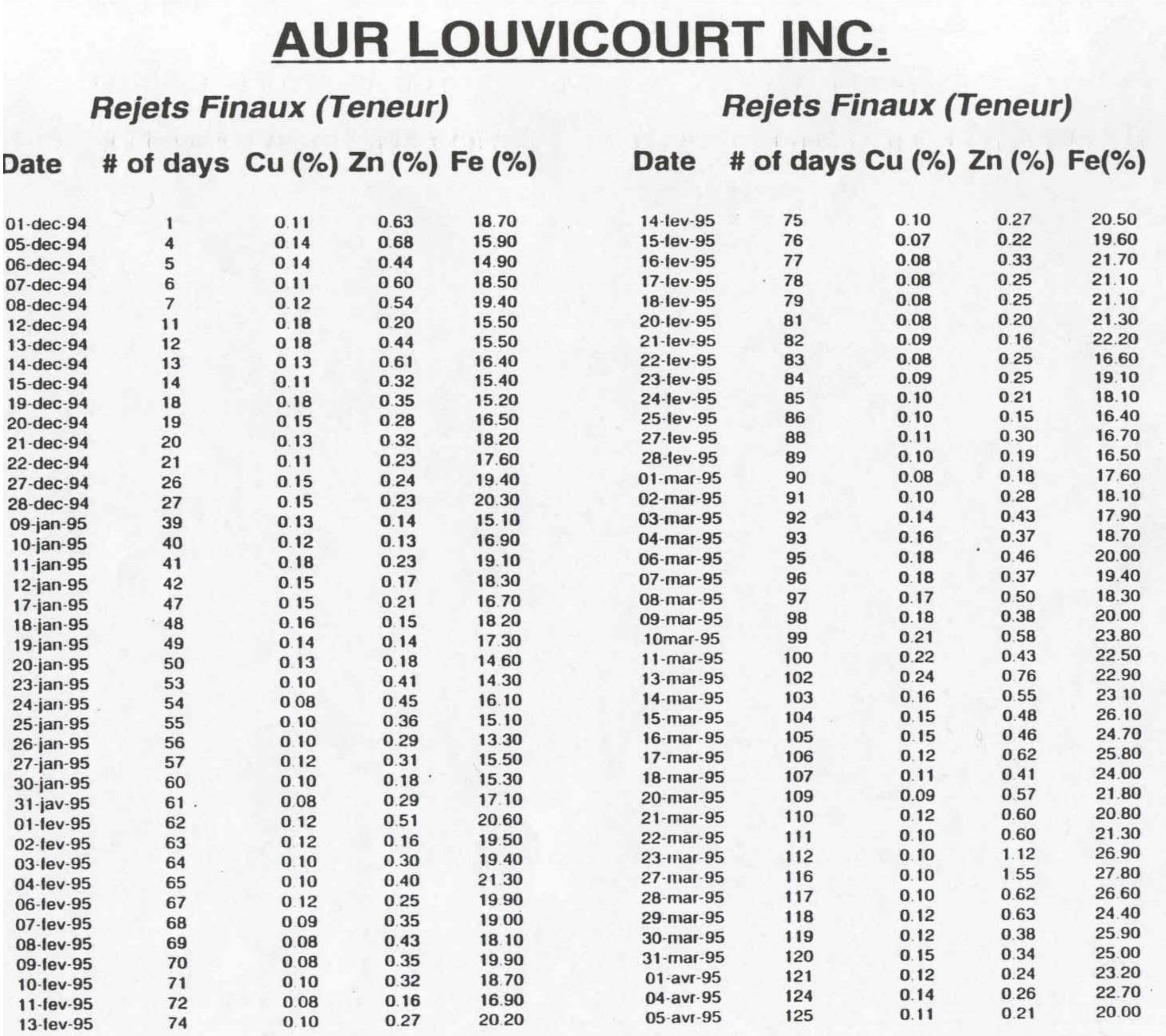
APPENDIX 1

Data of Louvicourt Tailings Composition Variation with Time



AUR LOUVICOURT INC.

Rejets Finaux (Teneur)

Date	# of days	Cu (%)	Zn (%)	Fe (%)
01-dec-94	1	0.11	0.63	18.70
05-dec-94	4	0.14	0.68	15.90
06-dec-94	5	0.14	0.44	14.90
07-dec-94	6	0.11	0.60	18.50
08-dec-94	7	0.12	0.54	19.40
12-dec-94	11	0.18	0.20	15.50
13-dec-94	12	0.18	0.44	15.50
14-dec-94	13	0.13	0.61	16.40
15-dec-94	14	0.11	0.32	15.40
19-dec-94	18	0.18	0.35	15.20
20-dec-94	19	0.15	0.28	16.50
21-dec-94	20	0.13	0.32	18.20
22-dec-94	21	0.11	0.23	17.60
27-dec-94	26	0.15	0.24	19.40
28-dec-94	27	0.15	0.23	20.30
09-jan-95	39	0.13	0.14	15.10
10-jan-95	40	0.12	0.13	16.90
11-jan-95	41	0.18	0.23	19.10
12-jan-95	42	0.15	0.17	18.30
17-jan-95	47	0.15	0.21	16.70
18-jan-95	48	0.16	0.15	18.20
19-jan-95	49	0.14	0.14	17.30
20-jan-95	50	0.13	0.18	14.60
23-jan-95	53	0.10	0.41	14.30
24-jan-95	54	0.08	0.45	16.10
25-jan-95	55	0.10	0.36	15.10
26-jan-95	56	0.10	0.29	13.30
27-jan-95	57	0.12	0.31	15.50
30-jan-95	60	0.10	0.18	15.30
31-jav-95	61	0.08	0.29	17.10
01-fev-95	62	0.12	0.51	20.60
02-fev-95	63	0.12	0.16	19.50
03-fev-95	64	0.10	0.30	19.40
04-fev-95	65	0.10	0.40	21.30
06-fev-95	67	0.12	0.25	19.90
07-fev-95	68	0.09	0.35	19.00
08-fev-95	69	0.08	0.43	18.10
09-fev-95	70	0.08	0.35	19.90
10-fev-95	71	0.10	0.32	18.70
11-fev-95	72	0.08	0.16	16.90
13-fev-95	74	0.10	0.27	20.20

Rejets Finaux (Teneur)

Date	# of days	Cu (%)	Zn (%)	Fe(%)
14-fev-95	75	0.10	0.27	20.50
15-fev-95	76	0.07	0.22	19.60
16-fev-95	77	0.08	0.33	21.70
17-fev-95	78	0.08	0.25	21.10
18-fev-95	79	0.08	0.25	21.10
20-fev-95	81	0.08	0.20	21.30
21-fev-95	82	0.09	0.16	22.20
22-fev-95	83	0.08	0.25	16.60
23-fev-95	84	0.09	0.25	19.10
24-fev-95	85	0.10	0.21	18.10
25-fev-95	86	0.10	0.15	16.40
27-fev-95	88	0.11	0.30	16.70
28-fev-95	89	0.10	0.19	16.50
01-mar-95	90	0.08	0.18	17.60
02-mar-95	91	0.10	0.28	18.10
03-mar-95	92	0.14	0.43	17.90
04-mar-95	93	0.16	0.37	18.70
06-mar-95	95	0.18	0.46	20.00
07-mar-95	96	0.18	0.37	19.40
08-mar-95	97	0.17	0.50	18.30
09-mar-95	98	0.18	0.38	20.00
10mar-95	99	0.21	0.58	23.80
11-mar-95	100	0.22	0.43	22.50
13-mar-95	102	0.24	0.76	22.90
14-mar-95	103	0.16	0.55	23.10
15-mar-95	104	0.15	0.48	26.10
16-mar-95	105	0.15	0.46	24.70
17-mar-95	106	0.12	0.62	25.80
18-mar-95	107	0.11	0.41	24.00
20-mar-95	109	0.09	0.57	21.80
21-mar-95	110	0.12	0.60	20.80
22-mar-95	111	0.10	0.60	21.30
23-mar-95	112	0.10	1.12	26.90
27-mar-95	116	0.10	1.55	27.80
28-mar-95	117	0.10	0.62	26.60
29-mar-95	118	0.12	0.63	24.40
30-mar-95	119	0.12	0.38	25.90
31-mar-95	120	0.15	0.34	25.00
01-avr-95	121	0.12	0.24	23.20
04-avr-95	124	0.14	0.26	22.70
05-avr-95	125	0.11	0.21	20.00

APPENDIX 2

Particle Size Distribution and Chemical Composition for Tailings as Received

Table 1: Chemical Analysis of Tailings Received (in %)

CHEMICAL ANALYSIS OF THE TAILING CORES FROM DRUMS 1 - 10												
	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	AVE	SD
S	19.4	18.2	17.4	16.7	16	16.7	17.5	16.8	17.1	16.3	17.2	0.94
SO4	0.79	1.07	0.6	0.55	0.54	0.57	0.63	0.61	0.64	0.79	0.68	0.16
Fe	20.4	19.1	19.9	20.7	20.1	20.3	19.9	17.2	20.8	19.1	19.8	1.01
As	0.07	0.06	0.07	0.07	0.05	0.07	0.07	0.06	0.07	0.06	0.064	0.01
Cu	0.11	0.09	0.09	0.09	0.09	0.09	0.08	0.1	0.09	0.09	0.092	0.01
Pb	0.07	0.09	0.07	0.05	0.04	0.1	0.05	0.06	0.07	0.04	0.065	0.02
Zn	0.4	0.33	0.38	0.26	0.22	0.37	0.36	0.32	0.33	0.33	0.33	0.05
Al	3.6	3.9	3.6	3.9	4	3.7	3.6	4	3.8	3.9	3.8	0.15
Ca	1.4	1.6	1.5	1.5	1.5	1.6	1.6	1.7	1.6	1.6	1.6	0.08
Mn	0.17	0.16	0.17	0.19	0.17	0.18	0.17	0.15	0.18	0.17	0.17	0.01
Mg	2.3	2.4	2.3	2.5	2.5	2.4	2.4	2.4	2.5	2.4	2.4	0.07

Table 2: Size Distribution of Tailings Received

PARTICLE SIZE DISTRIBUTION of THE TAILING CORES FROM DRUMS 1-10												
MICRONS	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	AVE	SD
209	100	100	100	100	100	100	100	100	100	97.9	99.8	0.6
148	100	98.4	100	97.9	98.1	100	100	96.9	97.6	94.6	98.4	1.59
105	97.8	93.5	94.3	95	95	96.6	96.3	92.4	94.2	86.6	94.2	2.79
74	94.5	84.8	88.9	90.5	89.9	92	91.9	85.9	89.1	74.5	88.2	5.06
52	88.9	76.3	82.8	83.5	82.4	85.4	85.9	77.8	81.8	65.6	81	5.93
37	79.7	68.7	75.2	74.4	73.3	76.3	77.6	68.7	72.8	58.6	72.5	5.44
26	67.6	59.3	65.4	63.6	63.1	65.4	66.9	58.9	62.4	49.8	62.2	4.74
16	48.8	42.6	48.5	46.6	46.5	48	49.2	43.1	45.8	36.6	45.6	3.51
8	29.7	26.4	30.2	28.4	28.5	29.4	30.2	26.1	27.8	23.2	28	2
4	15.7	13.7	16.6	15.2	15.3	15.9	16.4	14	14.9	12.8	15.1	1.11
2	8	6.9	8.6	7.7	7.8	8.2	8.4	7.1	7.6	6.3	7.7	0.65
1	3.2	2.3	3.5	3.1	3.2	3.4	3.4	2.9	3.1	2.1	3	0.42
0.4	0.3	0	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0	0.3	0.14

APPENDIX 3

Data of Plant Process Water

TABLEAU 5.13 Analyse chimique-Phase liquide- Rejets de flottation

Paramètre	Procédé avec SO_2 (1)	Procédé avec $NaCN/ZnSO_4$ (2)
pH	10,32	11,52
Conductivité (µs/cm)	1 306	1 831
Solides en suspension (mg/l)	2,4	19
Turbidité (UTN)	3,63	4,88
Solides totaux dissous (mg/l)	233	1 330
Dureté totale (mg/l)	730	825
Alcalinité totale (mg/l)	47	120
Sulfate (mg/l)	644	590
Sels sulfureux (equiv. SO_4) (mg/l)	406	70
Nitrate (mg/l)	0,73	0,93
Ammoniaque (equiv N de NH_3 et NH_4) (mg/l)	1,2	1,35
Phosphore total (mg/l)	0,14	0,26
Phosphore dissous (mg/l)	0,00026	0,00026
Cyanures (total) (mg/l)	0,023	7,94
Métaux totaux (mg/l)		
Ag	<0,005	<0,005
Al	1,35	2,34
As	<0,005	<0,005
Ba	0,03	0,037
Be	<0,01	n.d.
Ca	80	n.d.
Cd	<0,0005	<0,0005
Co	<0,05	n.d.
Cr	<0,05	n.d.
Cu	0,022	11 600 (3)
Fe	0,059	0,21
Hg	0,0001	0,0001
Mg	0,54	n.d.
Mn	<0,05	n.d.
Mo	0,07	0,081
Na	9,9	n.d.
Ni	<0,01	0,69
Pb	<0,001	0,013
S	82	n.d.
Sb	<0,005	<0,005
Se	0,2	0,58
Si	0,7	n.d.
Sr	<0,2	n.d.
Te	<0,1	n.d.
Zn	0,013	0,113

(1) Correspond à environ 80% du temps d'opération

(2) Correspond à environ 20% du temps d'opération

(3) Un excès de $CuSO_4$ est soupçonné lors de l'essai de flottation ayant fourni cet échantillon d'eau

Source : Ressources Aur Inc.

APPENDIX 4

Comparison of Overlying Water Quality: Post Preliminary Assessment (Day 360) and Post Phase I (Day 200)

Welcome Screen Search Report List

Louvicourt Tailings

Comparison of Overlying Water Quality: Post-Preliminary Assessment (Day 360) and Post-Phase I (Day 200)*

Analyte**	Preliminary Assessment				Phase I				Britannia Water
	0.3 m	Peat	Sand	1.0 m	0.3 m	Peat	Sand	1.0 m	
Sulphate	780	294	684	418	427	46	75	115	10
Fe (total)	<0.1	0.13	0.15	<0.1	0.01	0.02	0.02	0.01	<0.01
Al	0.14	9.1	2.8	0.28	<0.1	0.5	1.4	<0.1	<0.1
Ca	224	69	191	59	95	11	24	38	9
Cu (ppb)	12	110	804	13	30	23	180	11	36
K	20	8	13	9	8	3	4	3	2
Mg	66	6	15	16	40	2	4	13	2
Mn (ppb)	8	616	2878	10	3	87	300	1	1
Na	na	na	na	na	12	9	9	6	4
S	296	94	213	68	150	16	28	41	3
Zn	0.25	0.4	4.2	<0.1	0.39	0.1	0.42	0.09	0.01
Conductivity (uS/cm)	1300	530	1000	460	820	140	220	330	2

* Overlying water replaced with Britannia water on Day=0 for both Preliminary Assessment and Phase I

** Units in ppm unless otherwise noted

APPENDIX 5

A Compilation of Selected Phase I Chemical Profiles

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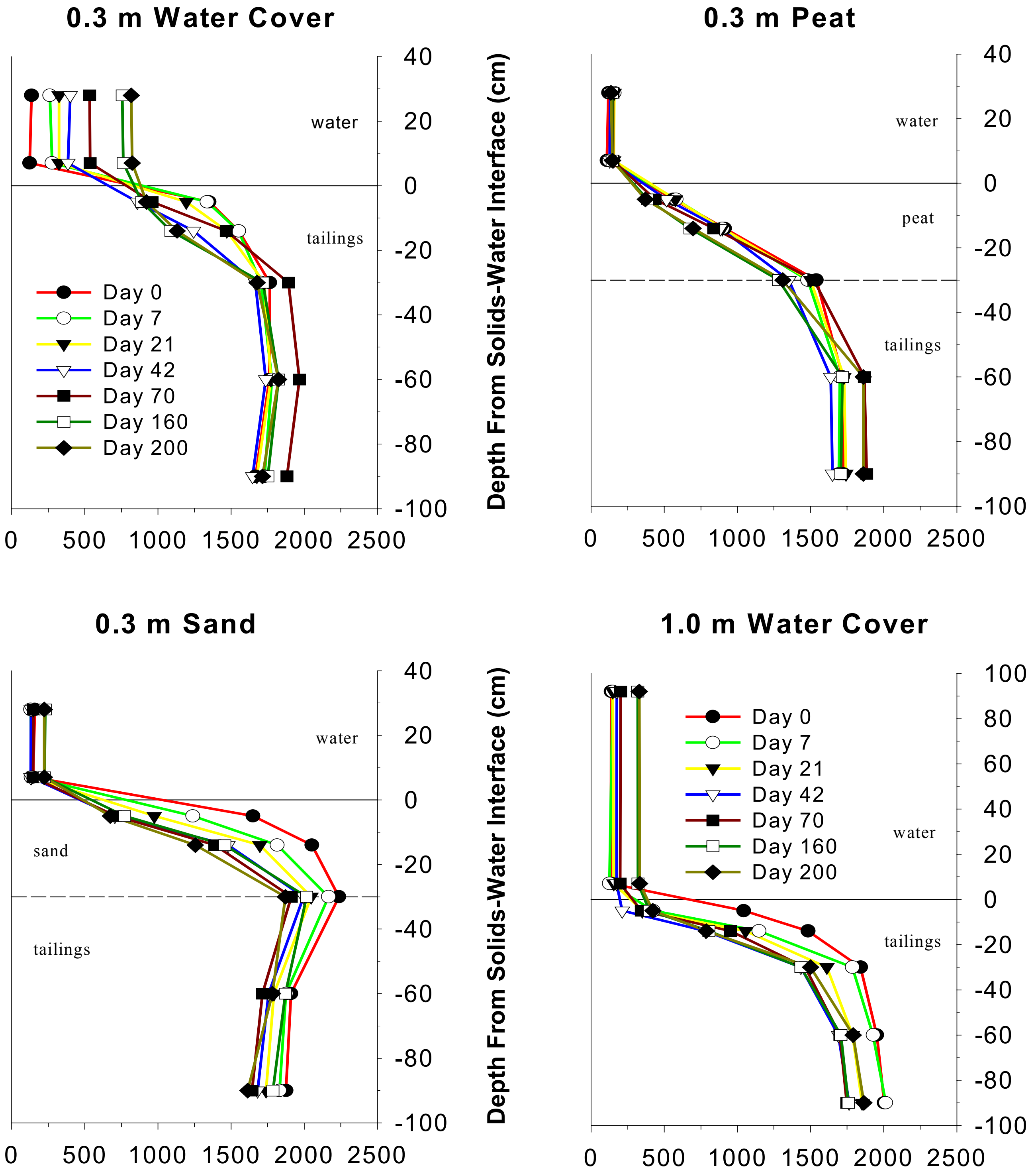

Figure A5-1 Mean Conductivity (µS/cm) Profiles over Time for Series 1-4 (Phase I).

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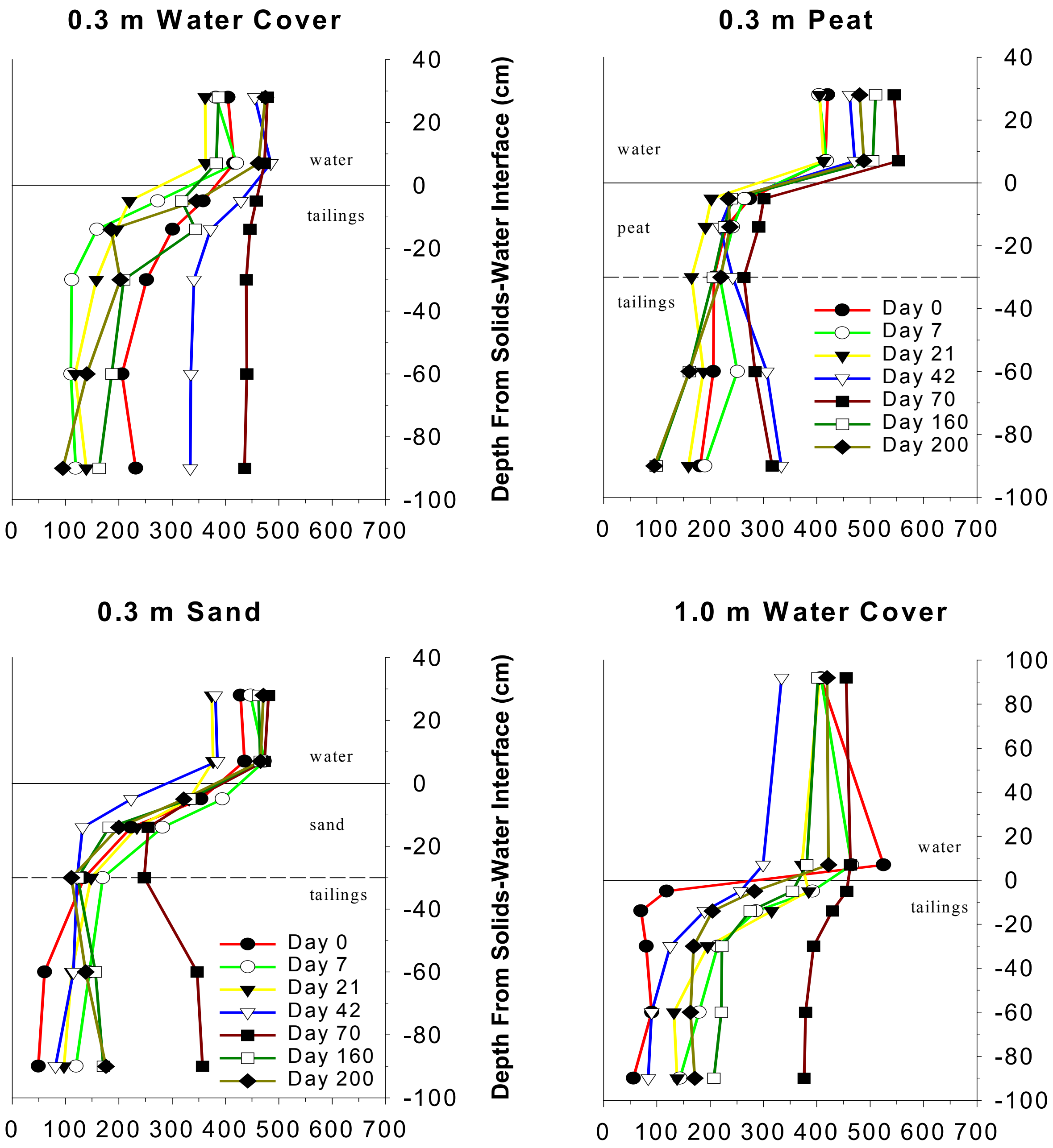

Figure A5-2 Mean Eh (mV) Profiles over Time for Series 1-4 (Phase I).

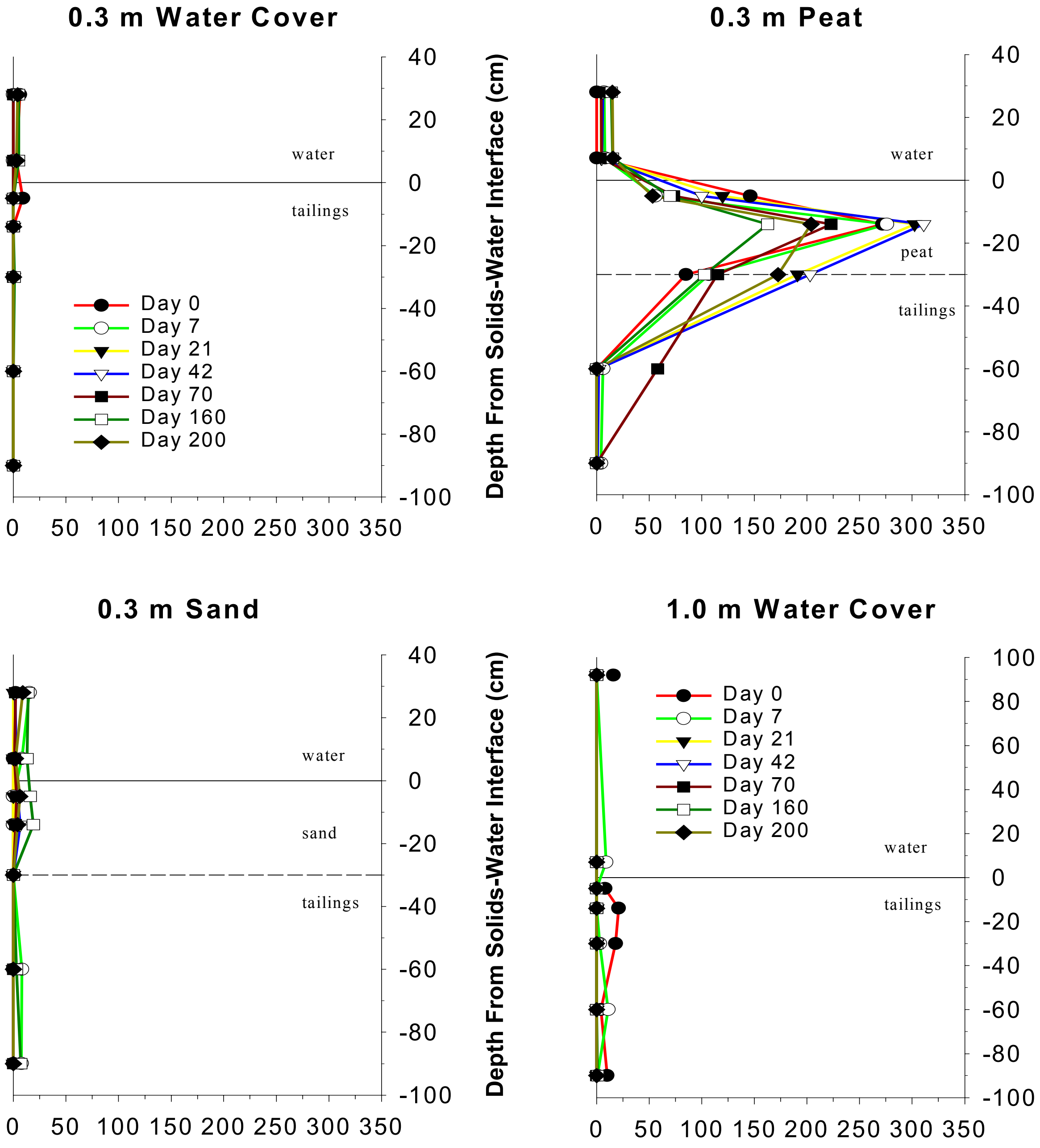

Figure A5-3 Mean Total Acidity (mg $CaCO_3$/L) Profiles over Time for Series 1-4 (Phase I).

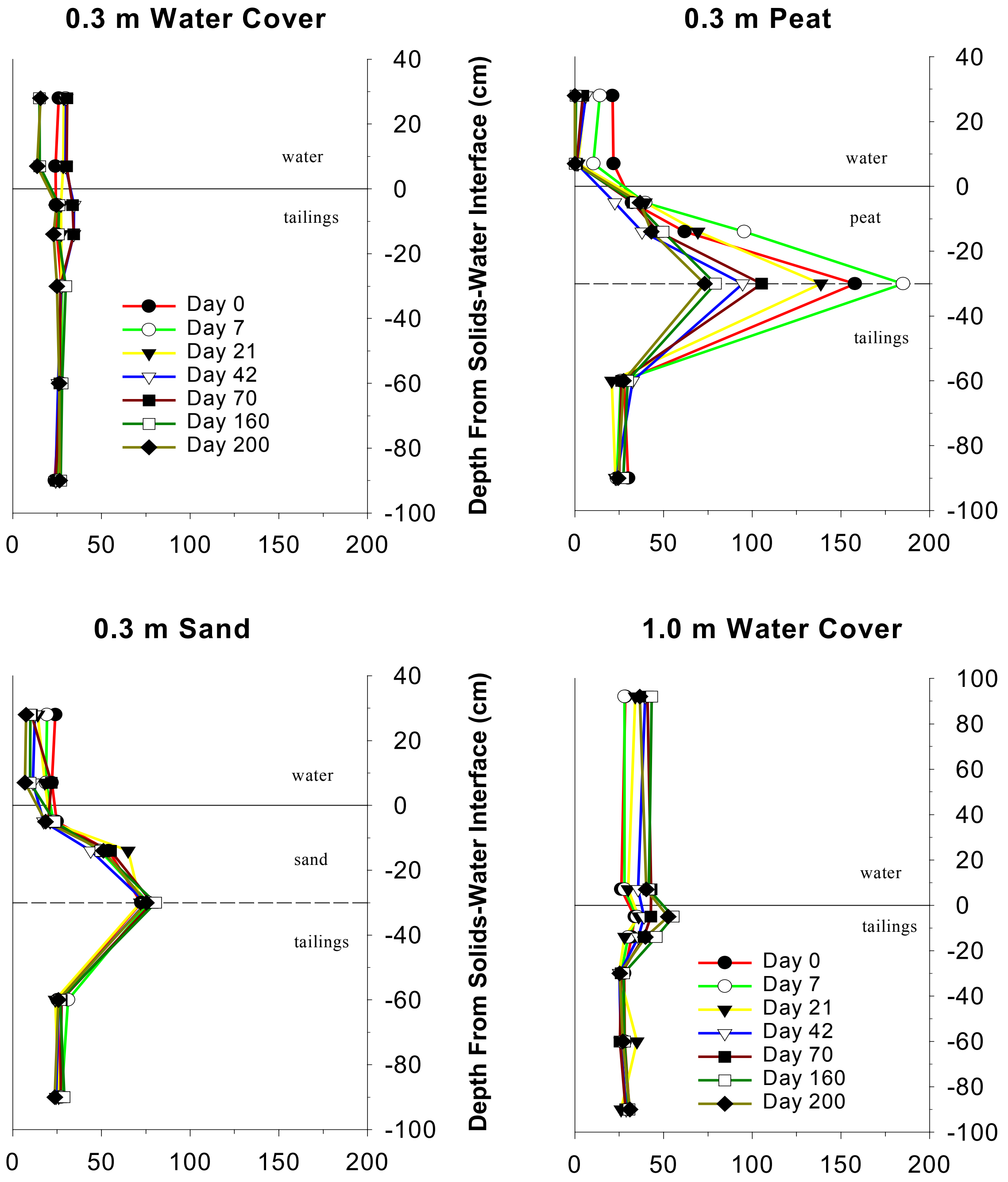

Figure A5-4 Mean Total Alkalinity (mg $CaCO_3$/L) Profiles over Time for Series 1-4 (Phase I).

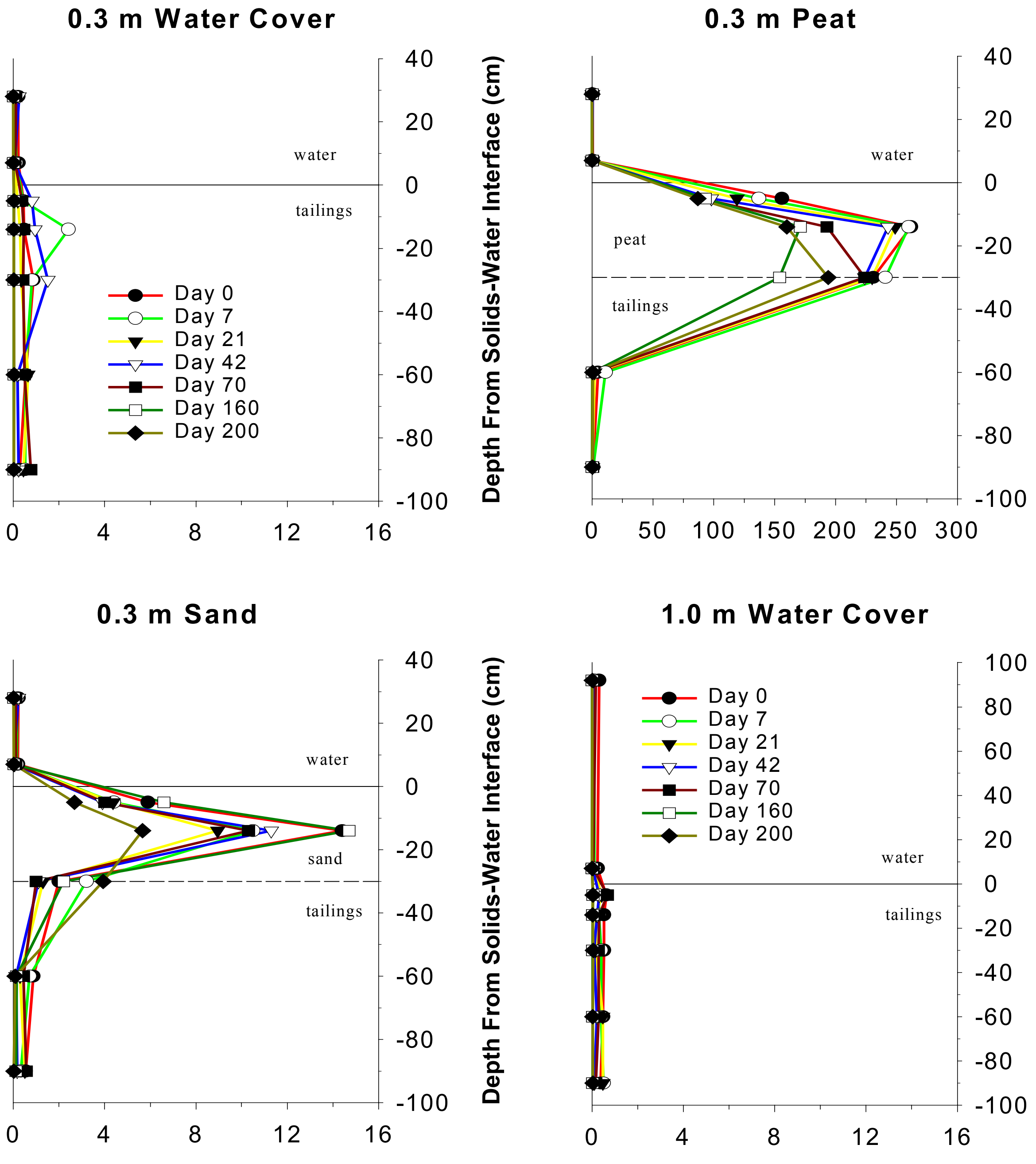

Figure A5-5a Mean Total Iron Concentration (mg/L) Profiles over Time for Series 1-4 (Phase I).

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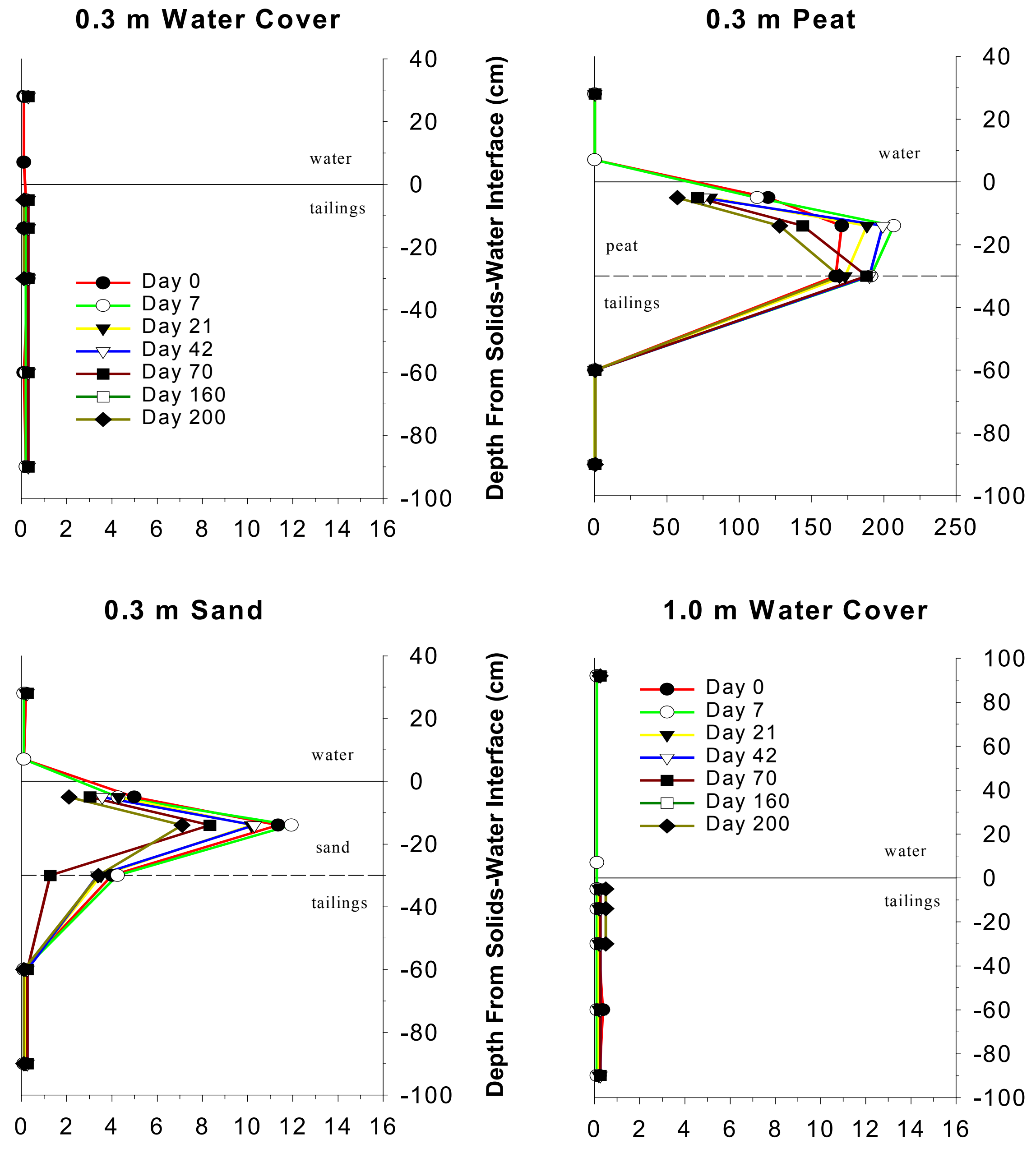

Figure A5-5b Mean Ferrous Iron Concentration (mg/L) Profiles over Time for Series 1-4 (Phase I)

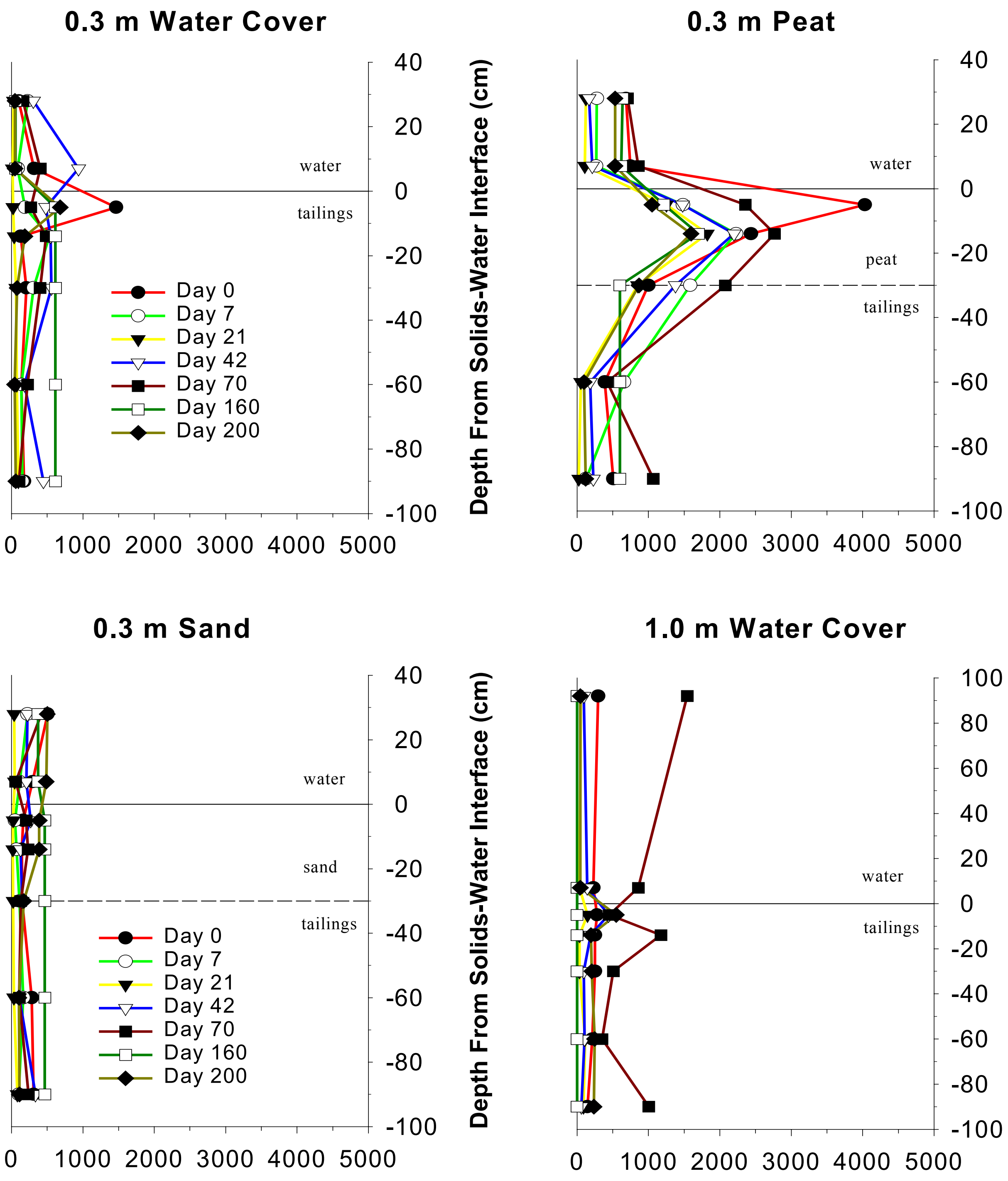

Figure A5-6 Mean Dissolved Aluminum Concentration (µg/L) Profiles over Time for Series 1-4 (Phase I).

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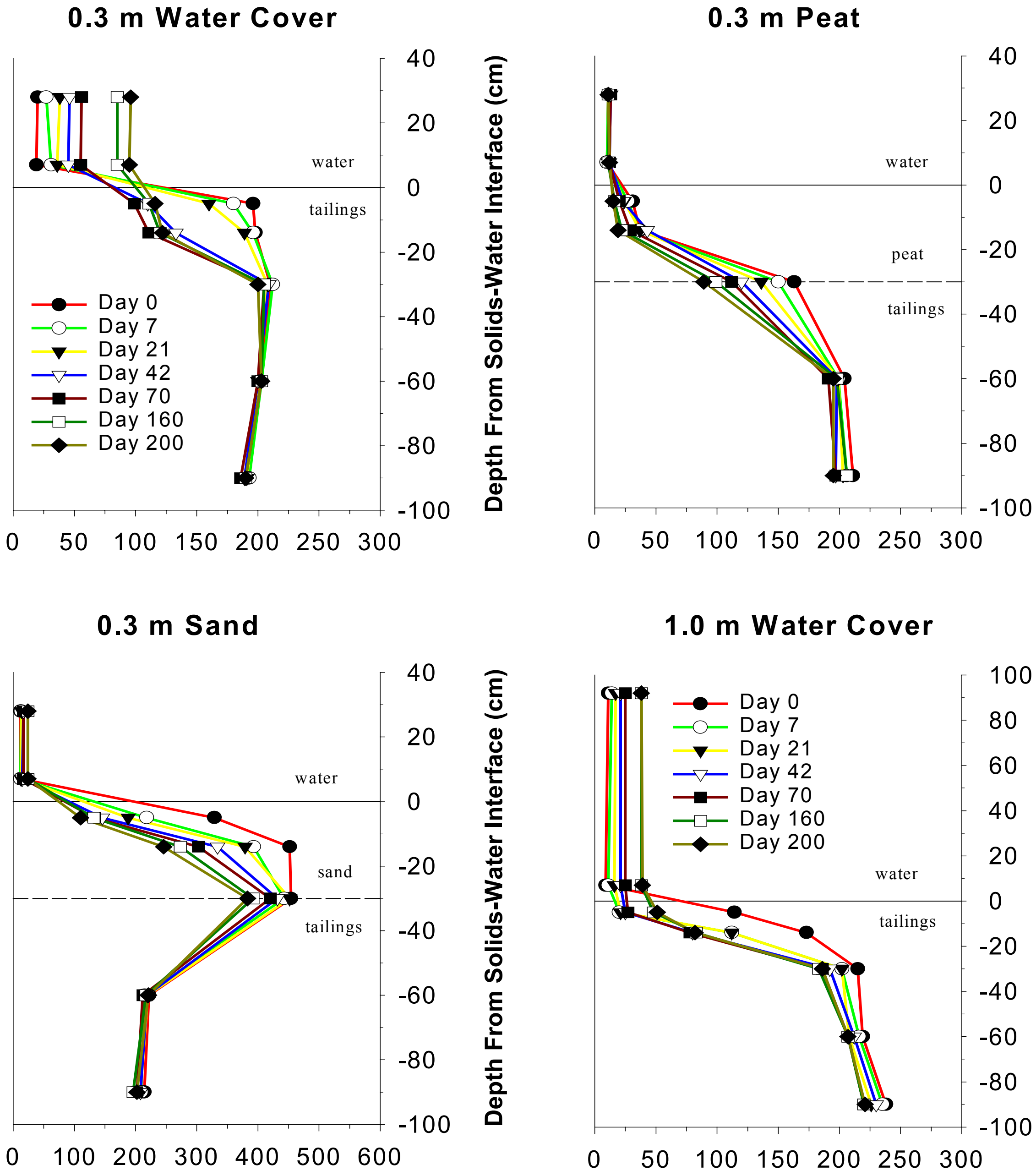

Figure A5-7 Mean Dissolved Calcium Concentration (mg/L) Profiles over time for Series 1-4 (Phase I).

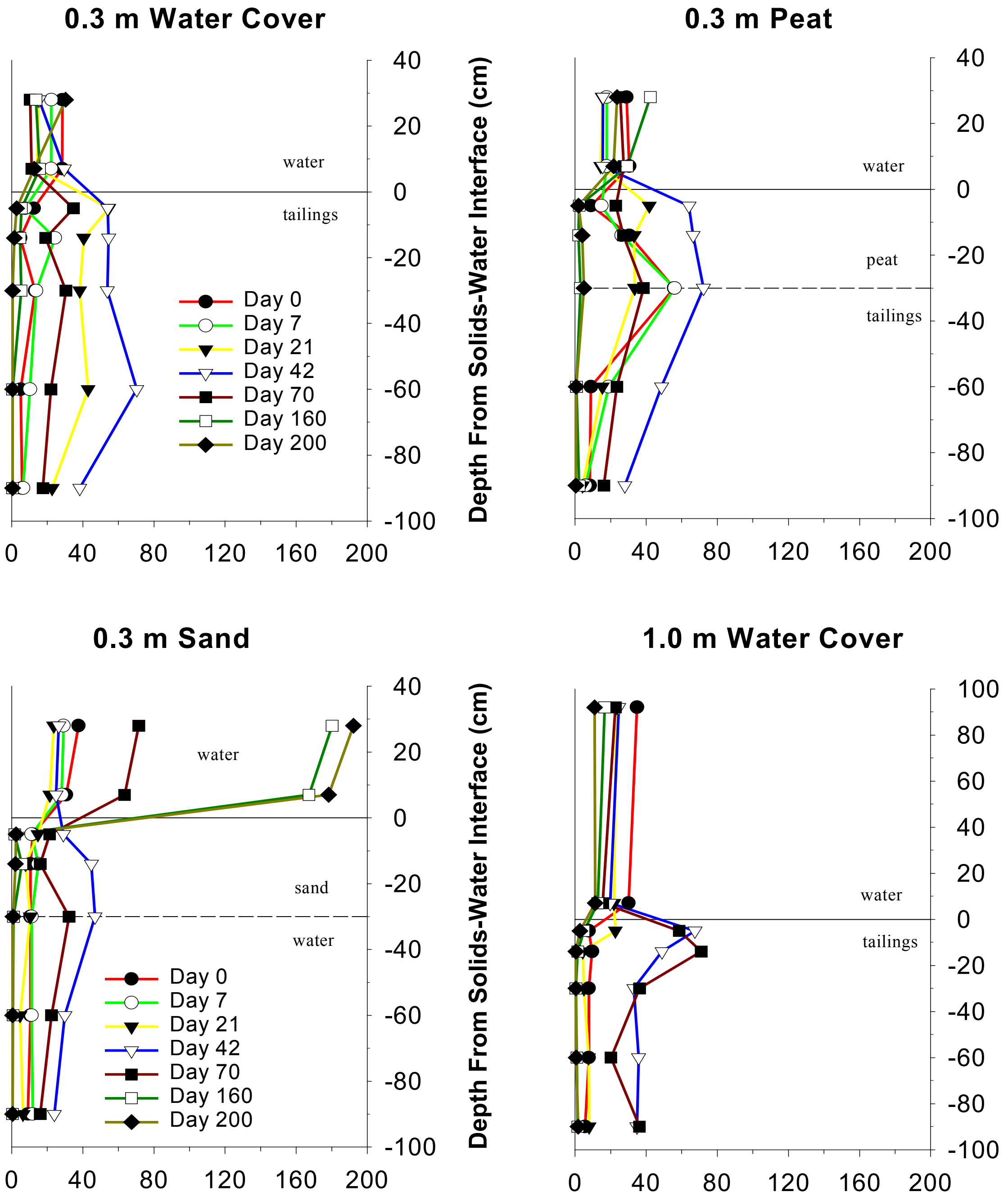

Figure A5-8 Mean Dissolved Copper Concentrations (µg/L) over Time for Series 1-4 (Phase I).

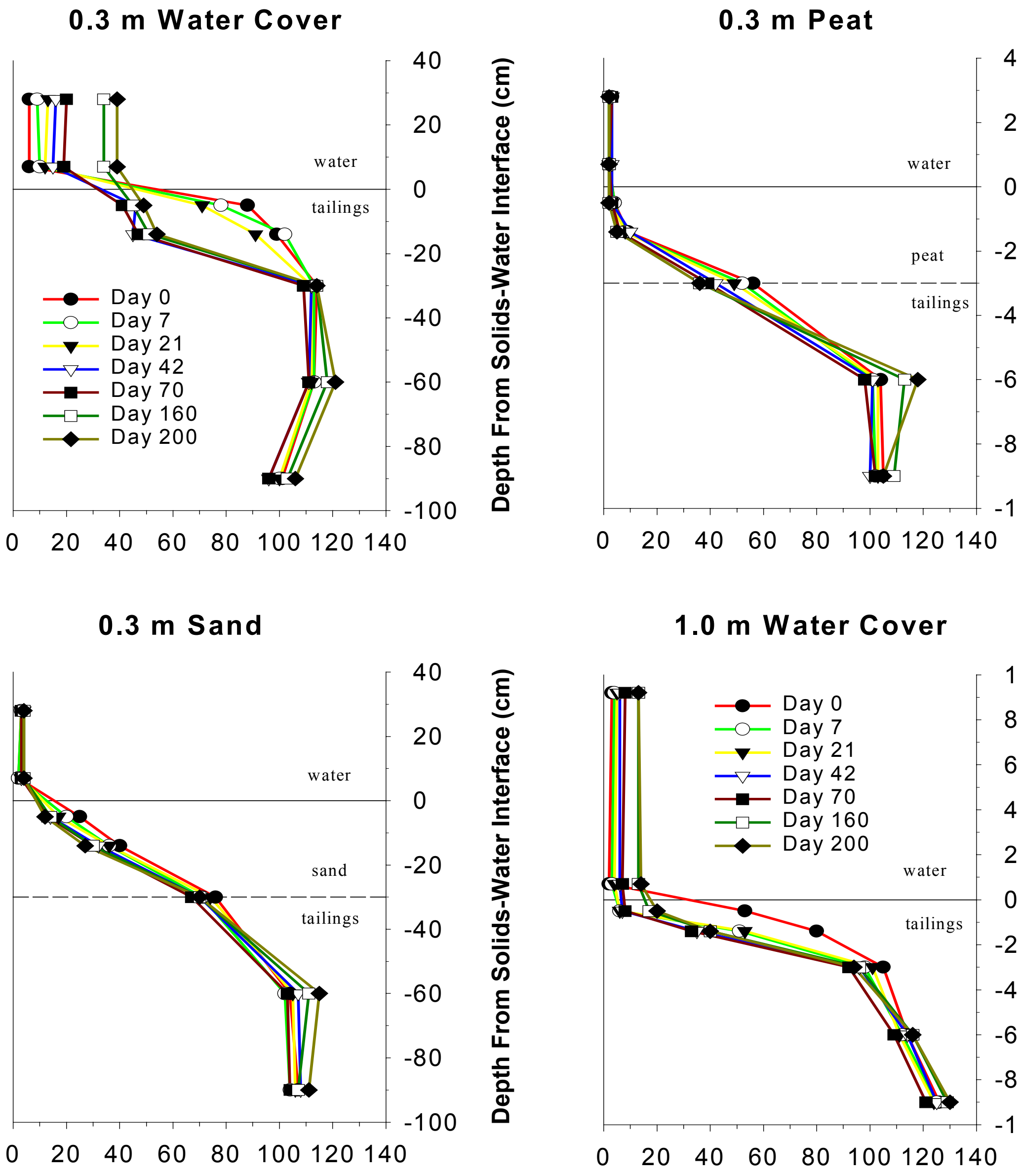

Figure A5-9 Mean Dissolved Magnesium Concentrations (mg/L) over time for Series 1-4 (Phase I).

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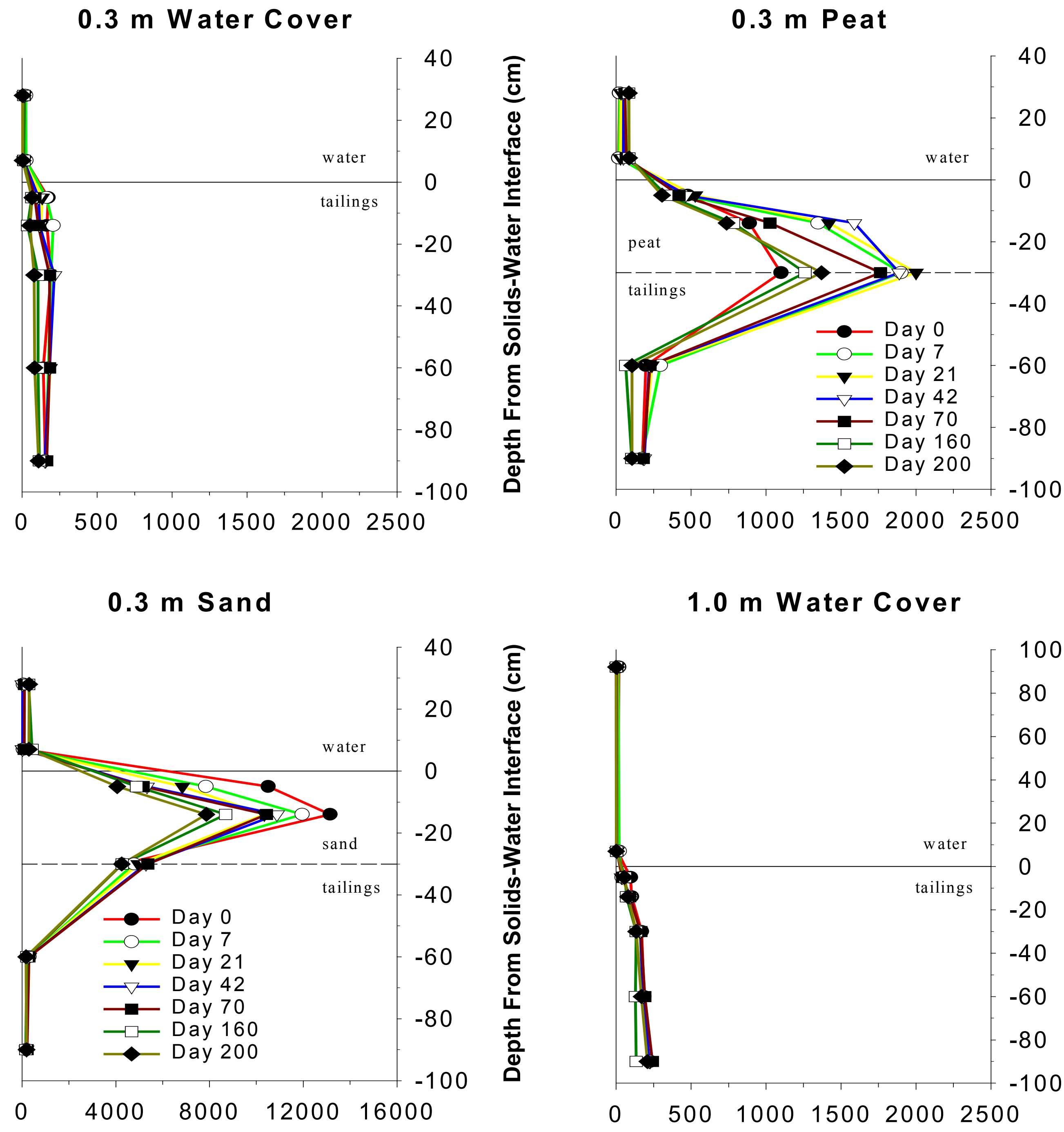

Figure A5-10 Mean Dissolved Manganese Concentrations (μg/L) over Time for Series 1-4 (Phase I)

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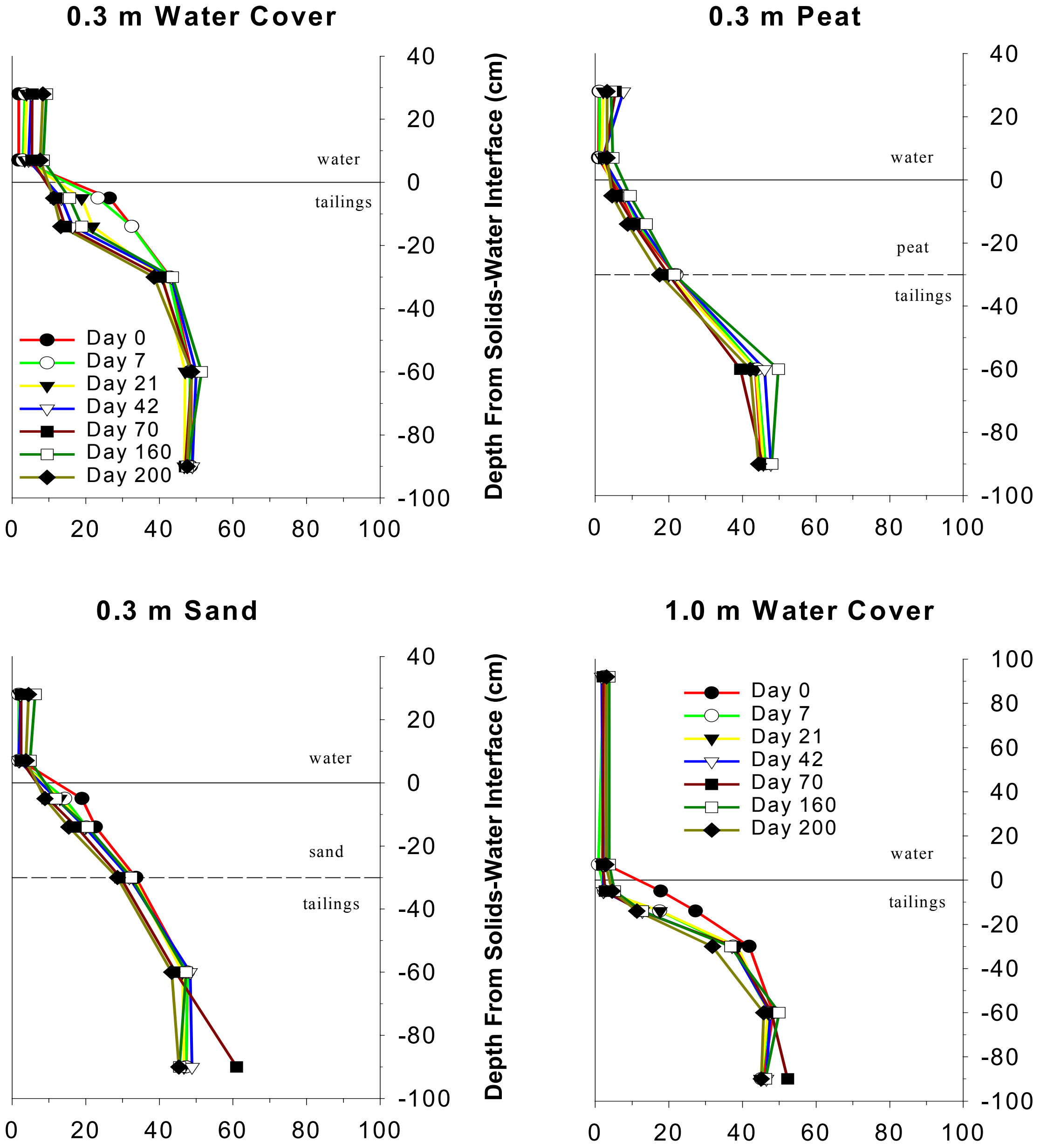

Figure A5-11 Mean Dissolved Potassium Concentrations (mg/L) over Time for Series 1-4 (Phase I).

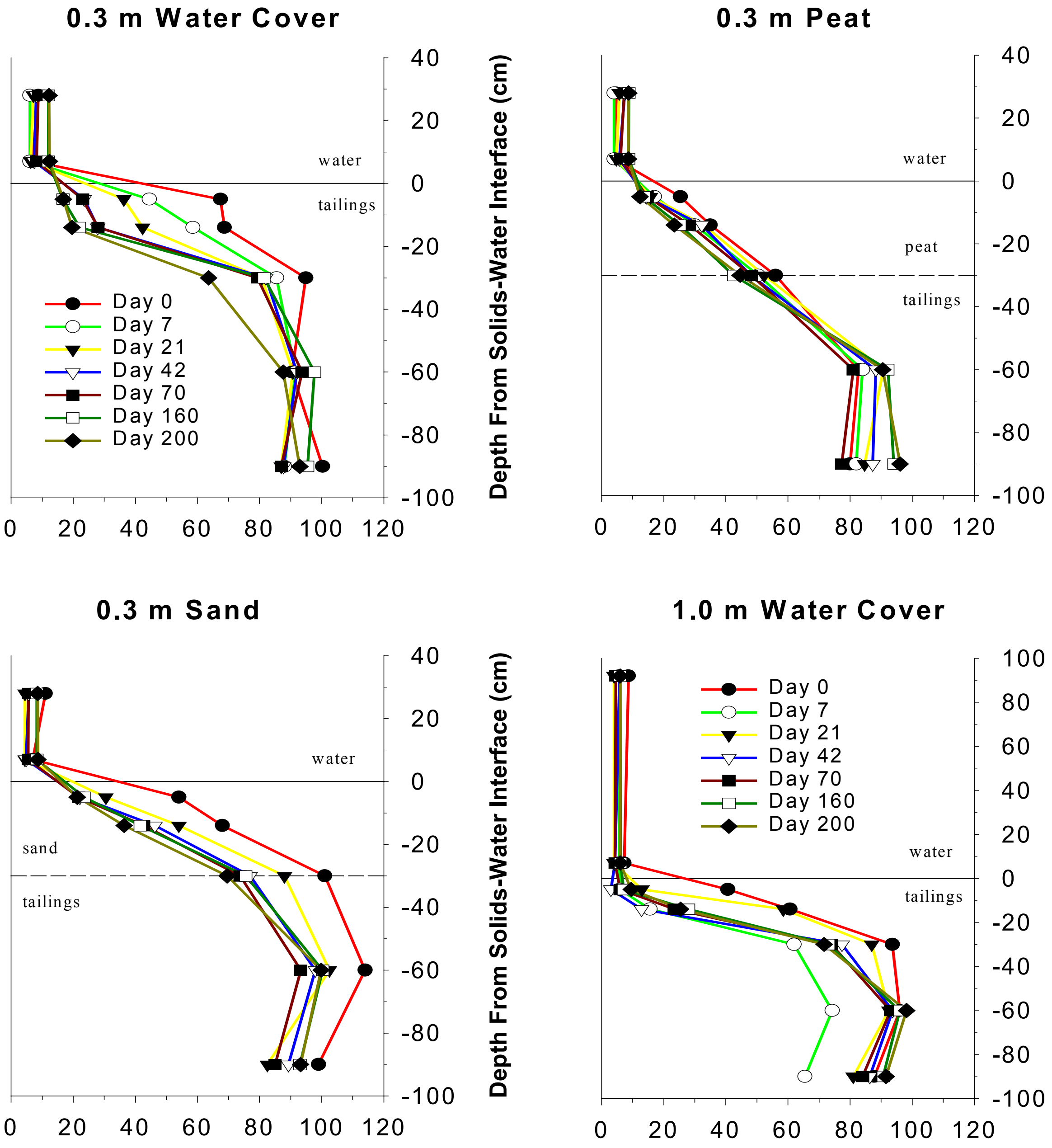

Figure A5-12 Mean Dissolved Sodium Concentrations (mg/L) over Time for Series 1-4 (Phase I).

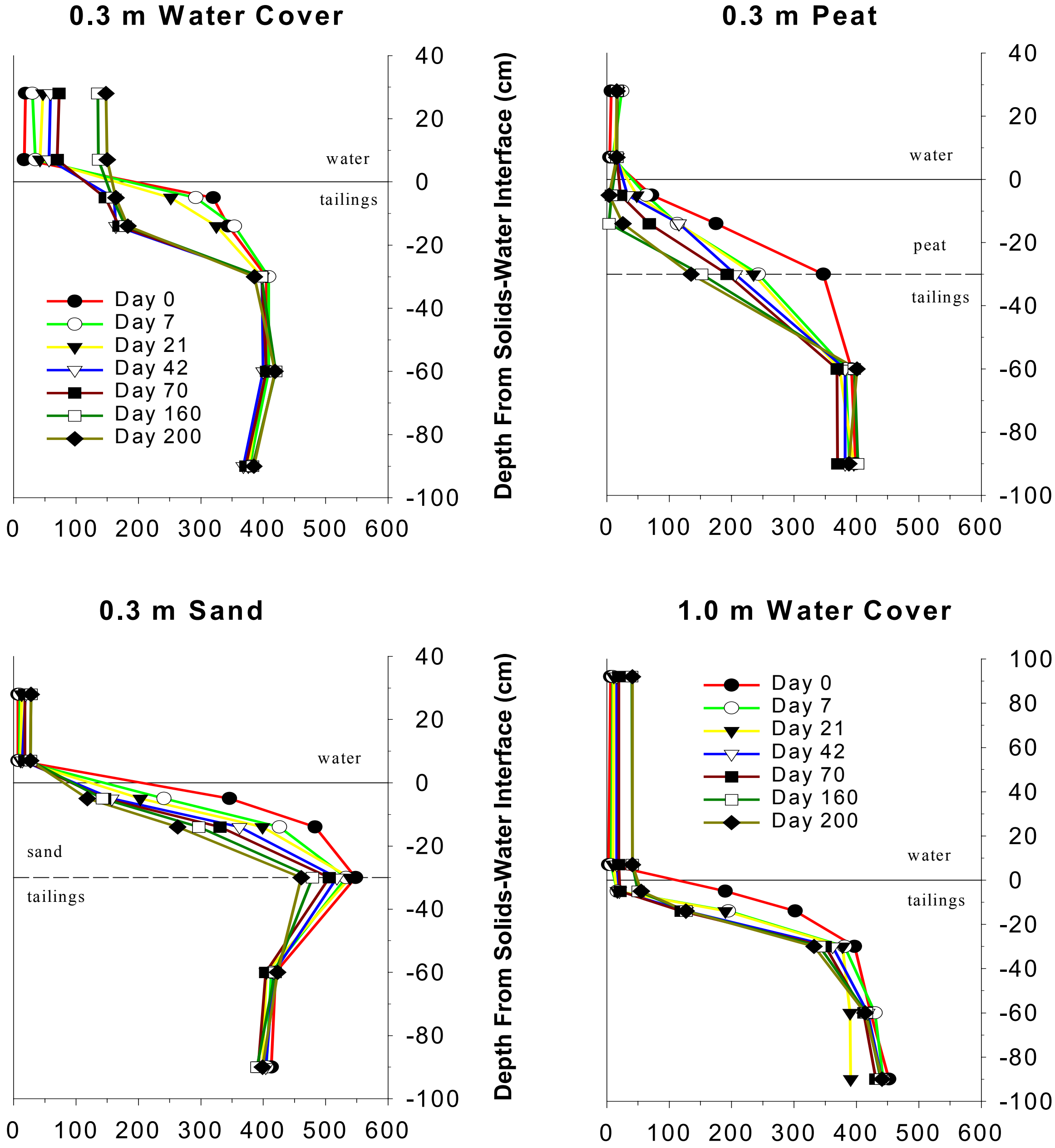

Figure A5-13 Mean Dissolved Sulfur Concentrations (mg/L) over Time for Series 1-4 (Phase I)

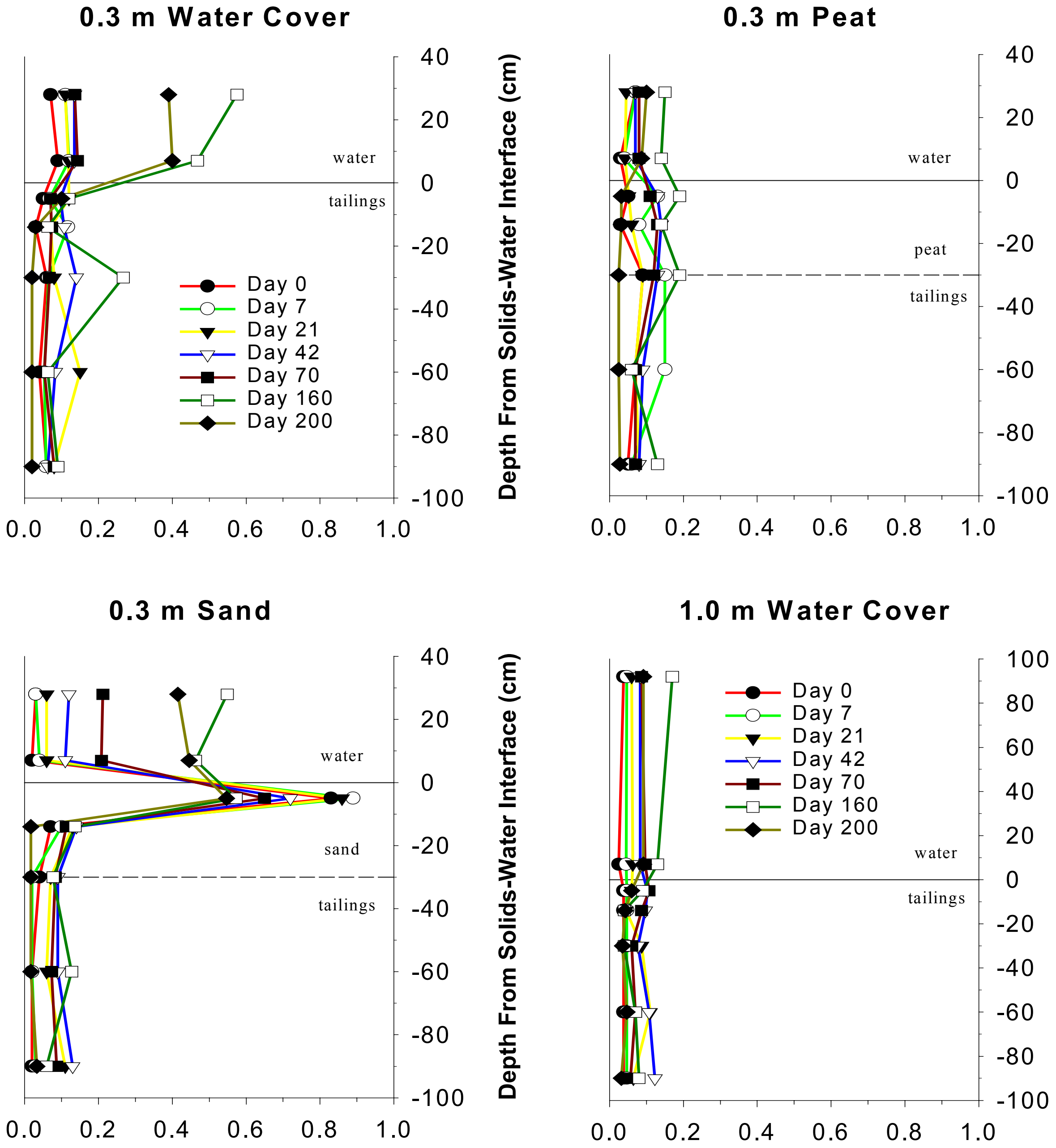

Figure A5-14 Mean Dissolved Zinc Concentrations (mg/L) over Time for Series 1-4 (Phase I)

APPENDIX 6

A Compilation of Selected Phase II Chemical Profiles

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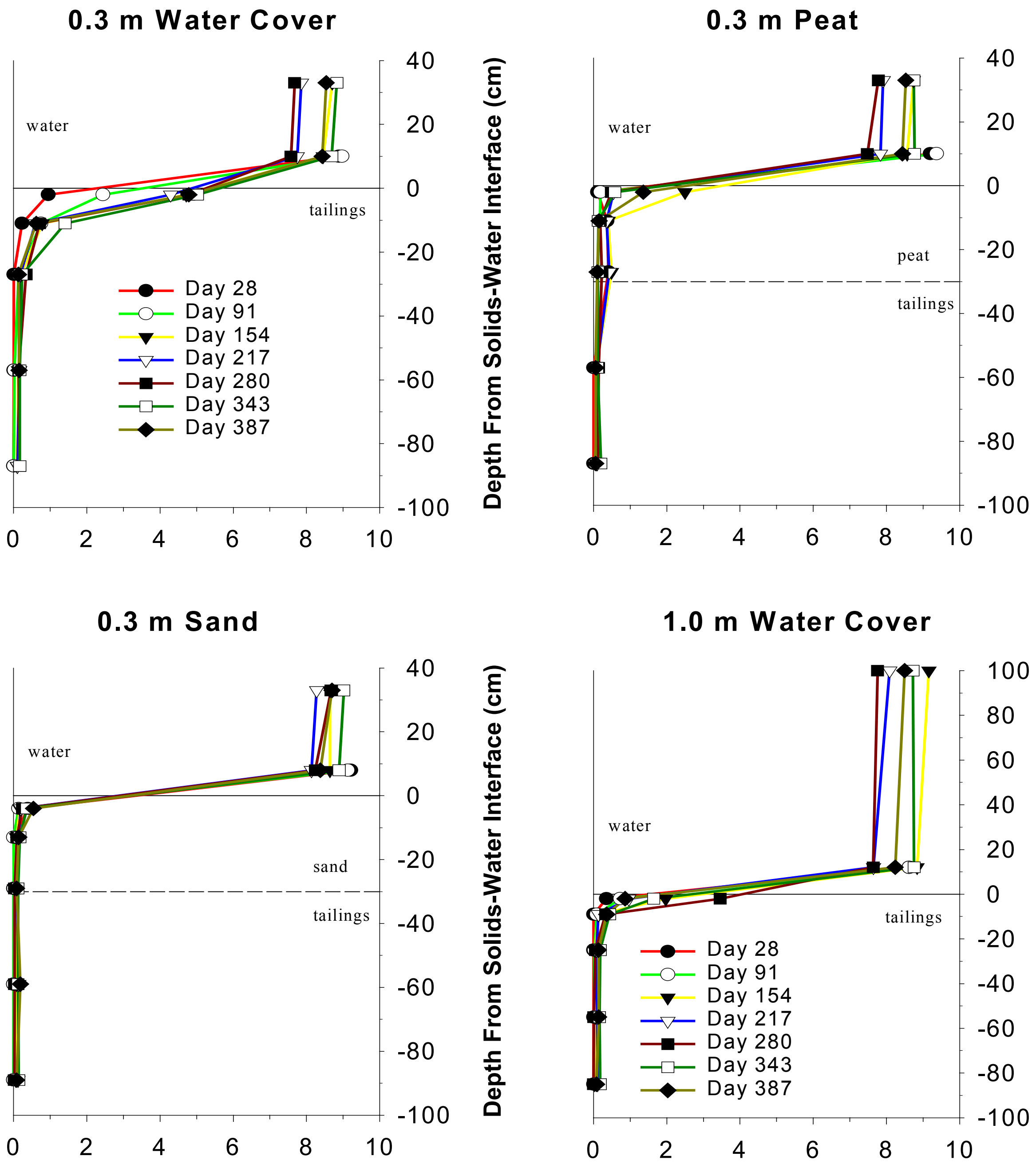

Figure A6-1 Mean Dissolved Oxygen (mg/L) Profiles over Time for Series 1-4 (Phase II).

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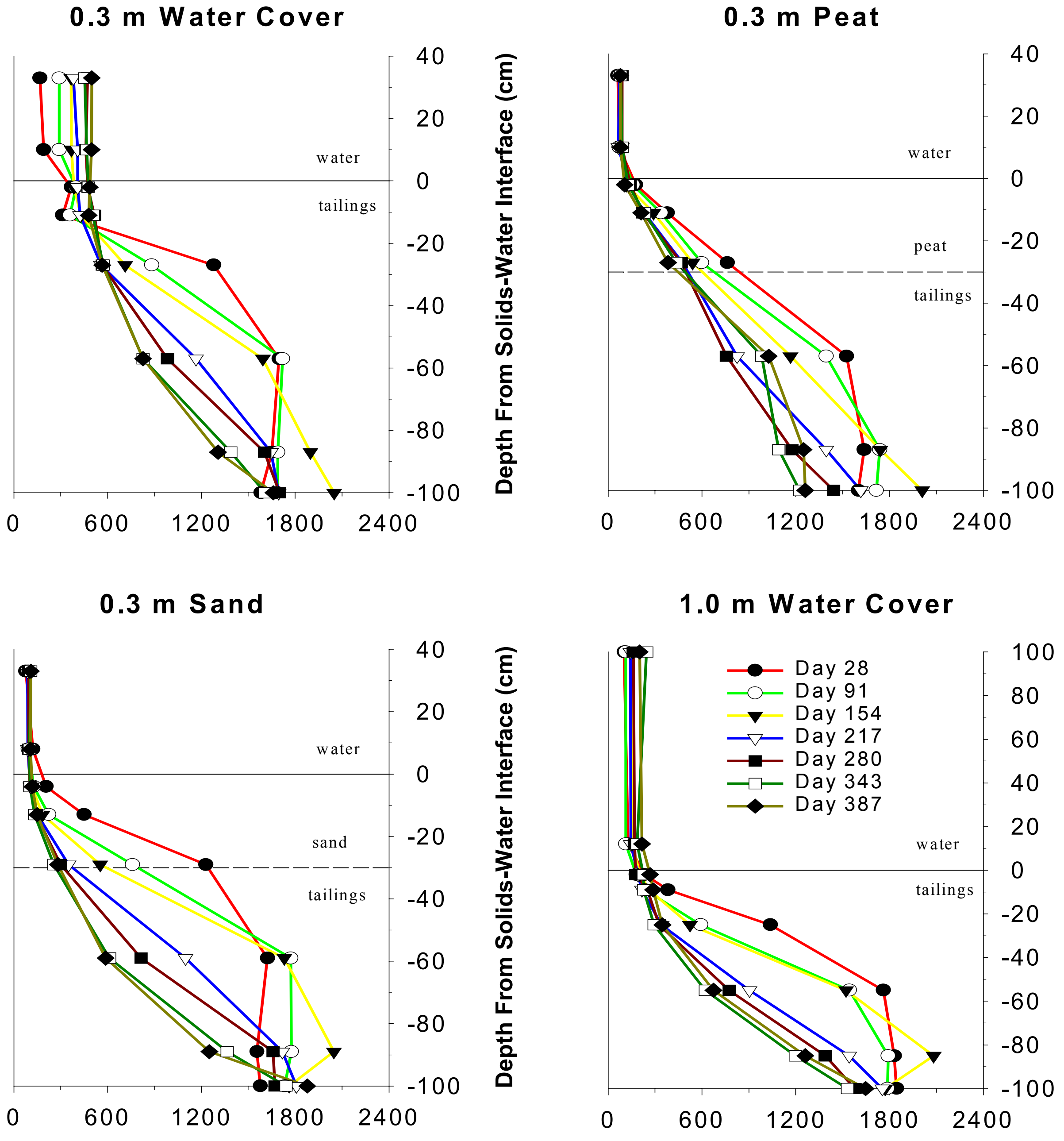

Figure A6-2 Mean Conductivity (µS/cm) Profiles over Time for Series 1-4 (Phase II)

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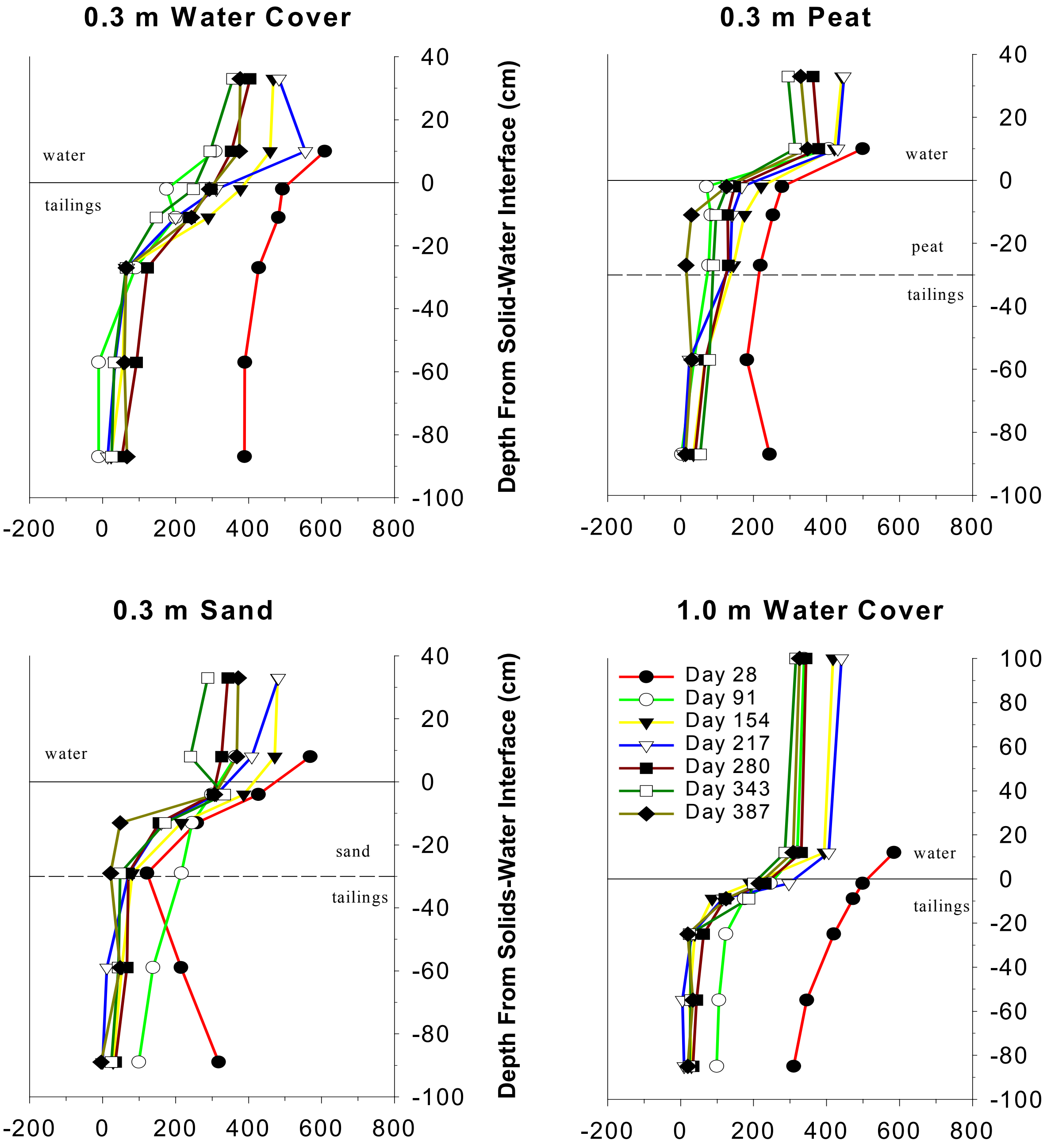

Figure A6-3 Mean Eh (mV) Profiles over Time for Series 1-4 (Phase II)

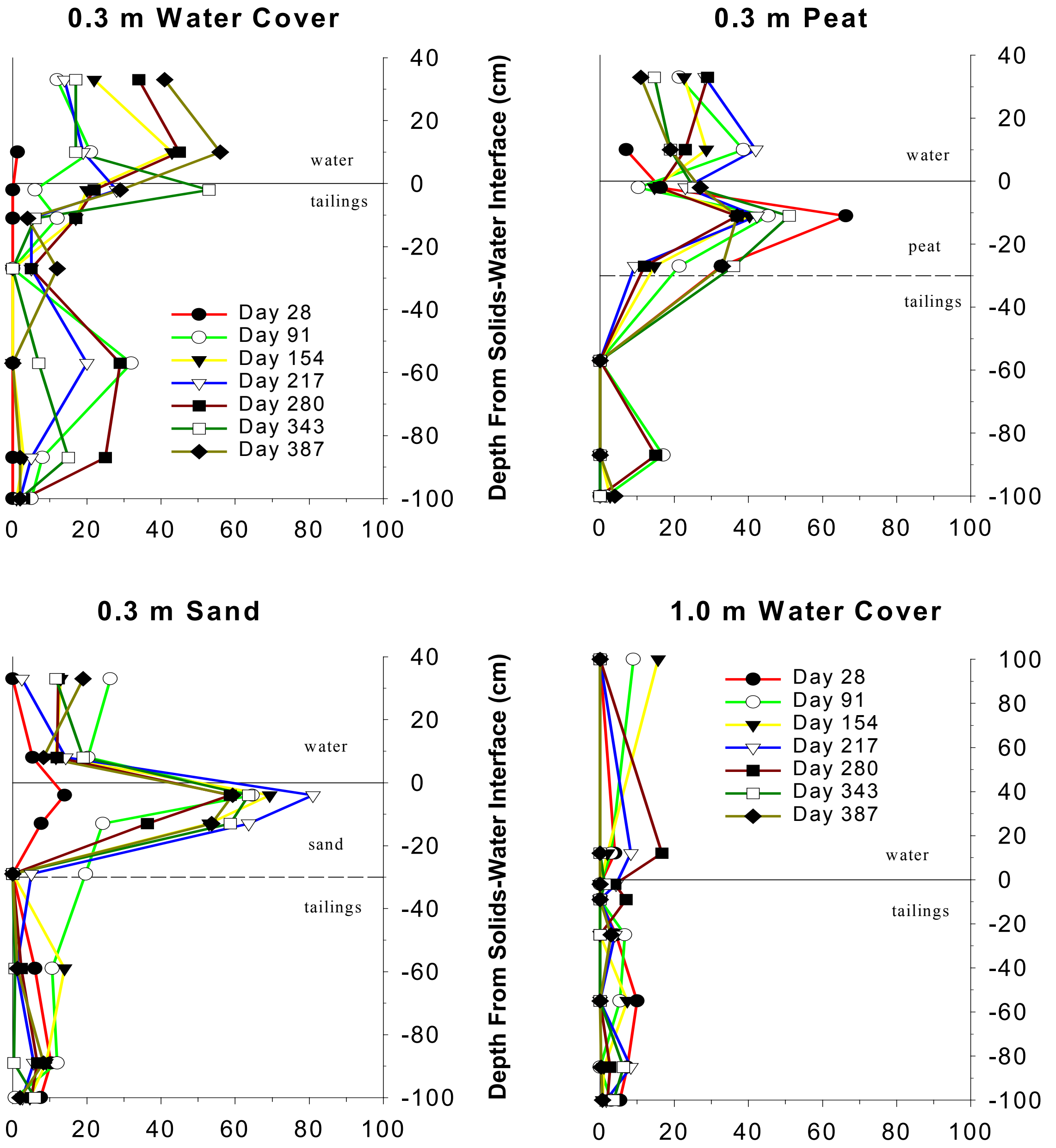

Figure A6-4 Mean Total Acidity (mg $CaCO_3$/L) Profiles over Time for Series 1-4 (Phase II)

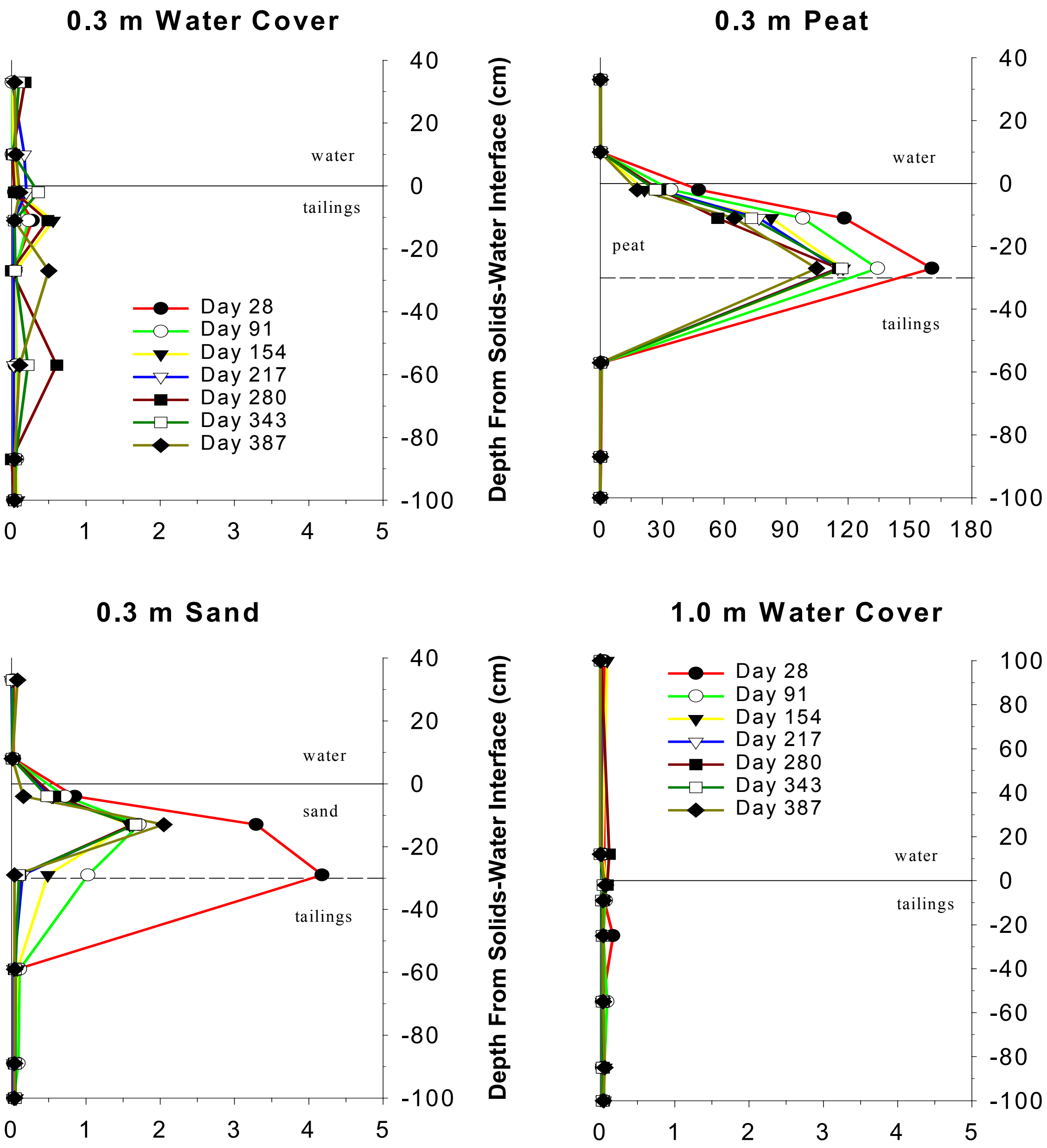

Figure A6-5a Mean Total Dissolved Iron Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

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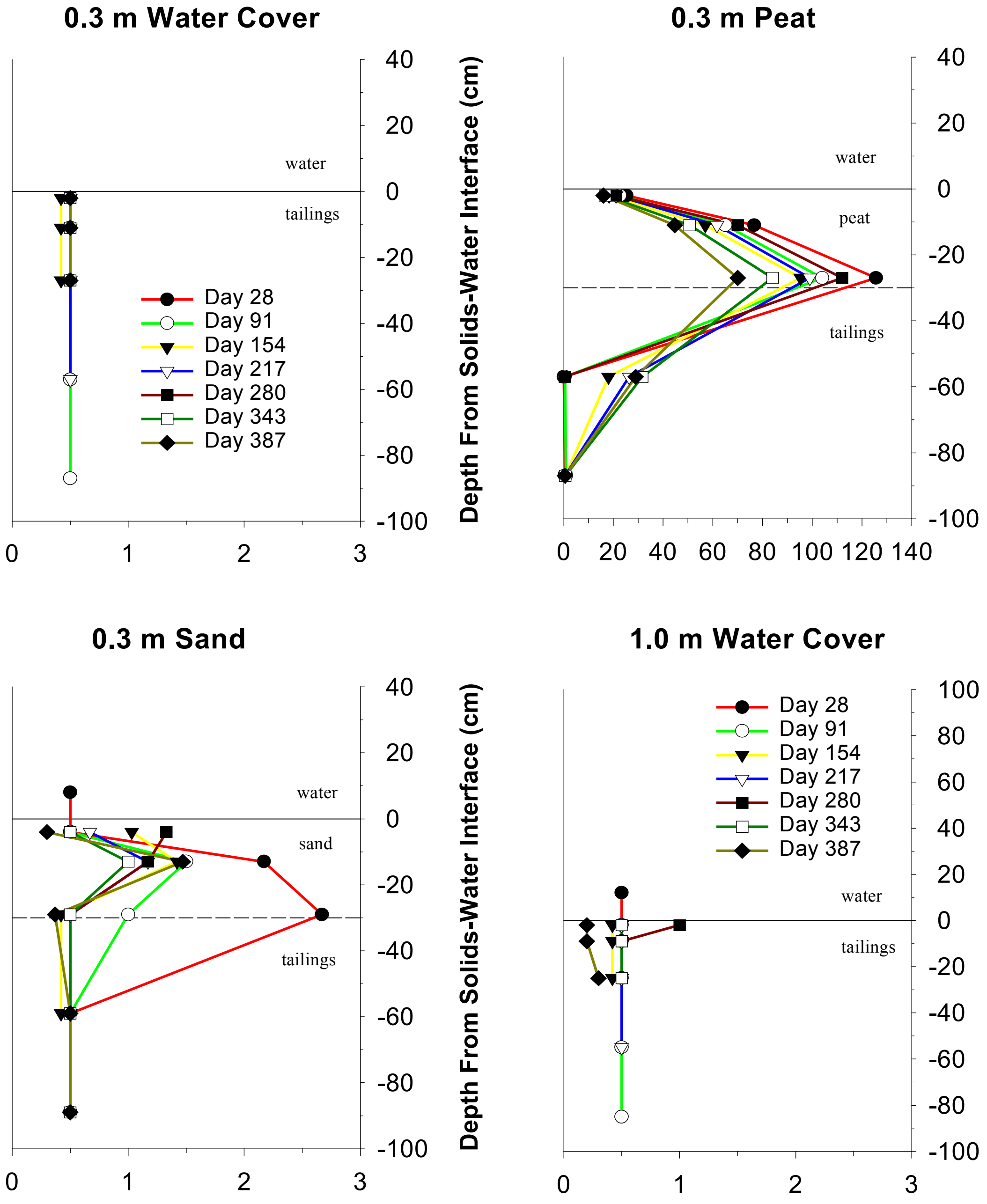

Figure A6-5b Mean Ferrous Iron Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

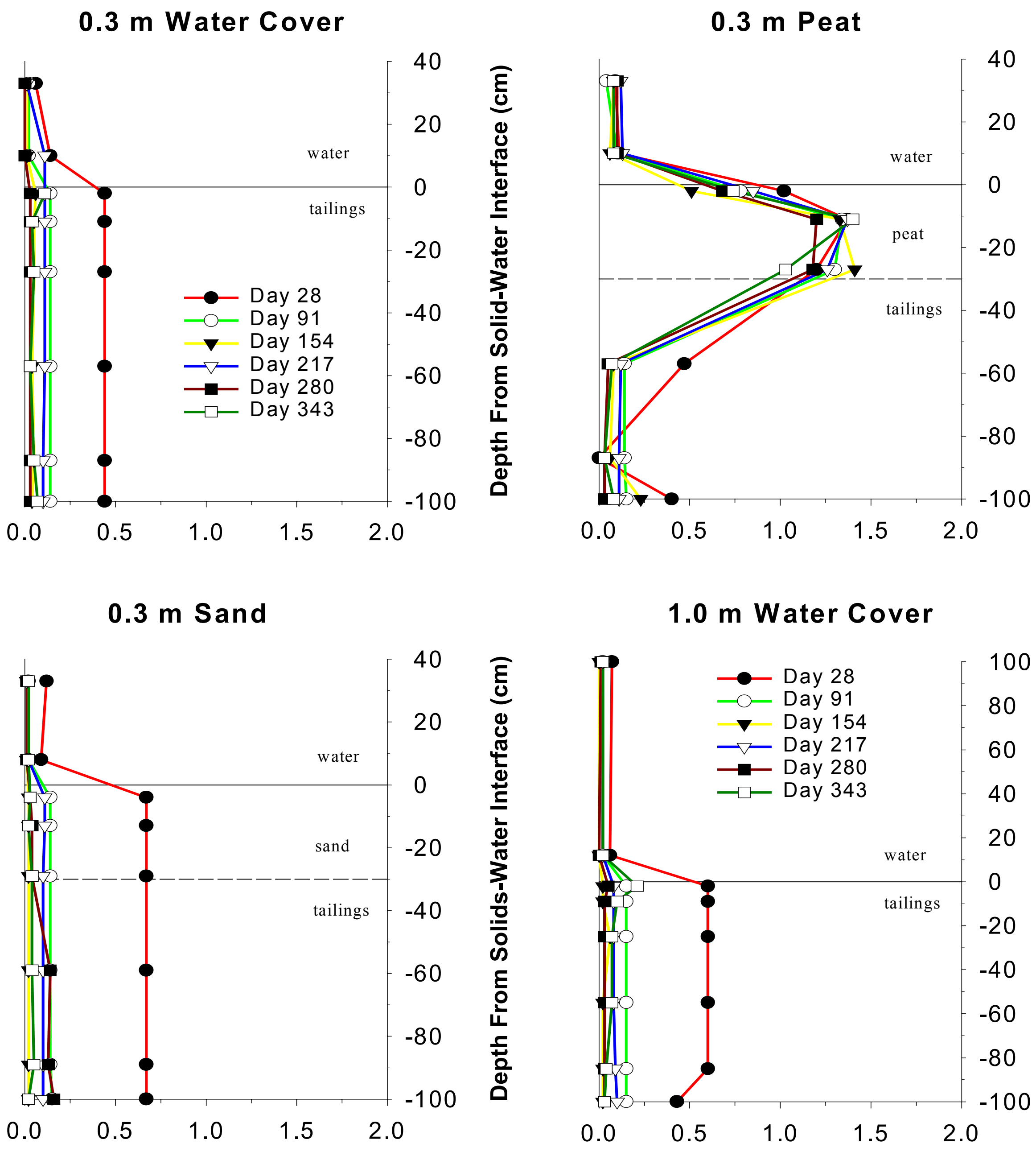

Figure A6-6 Mean Dissolved Aluminum Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

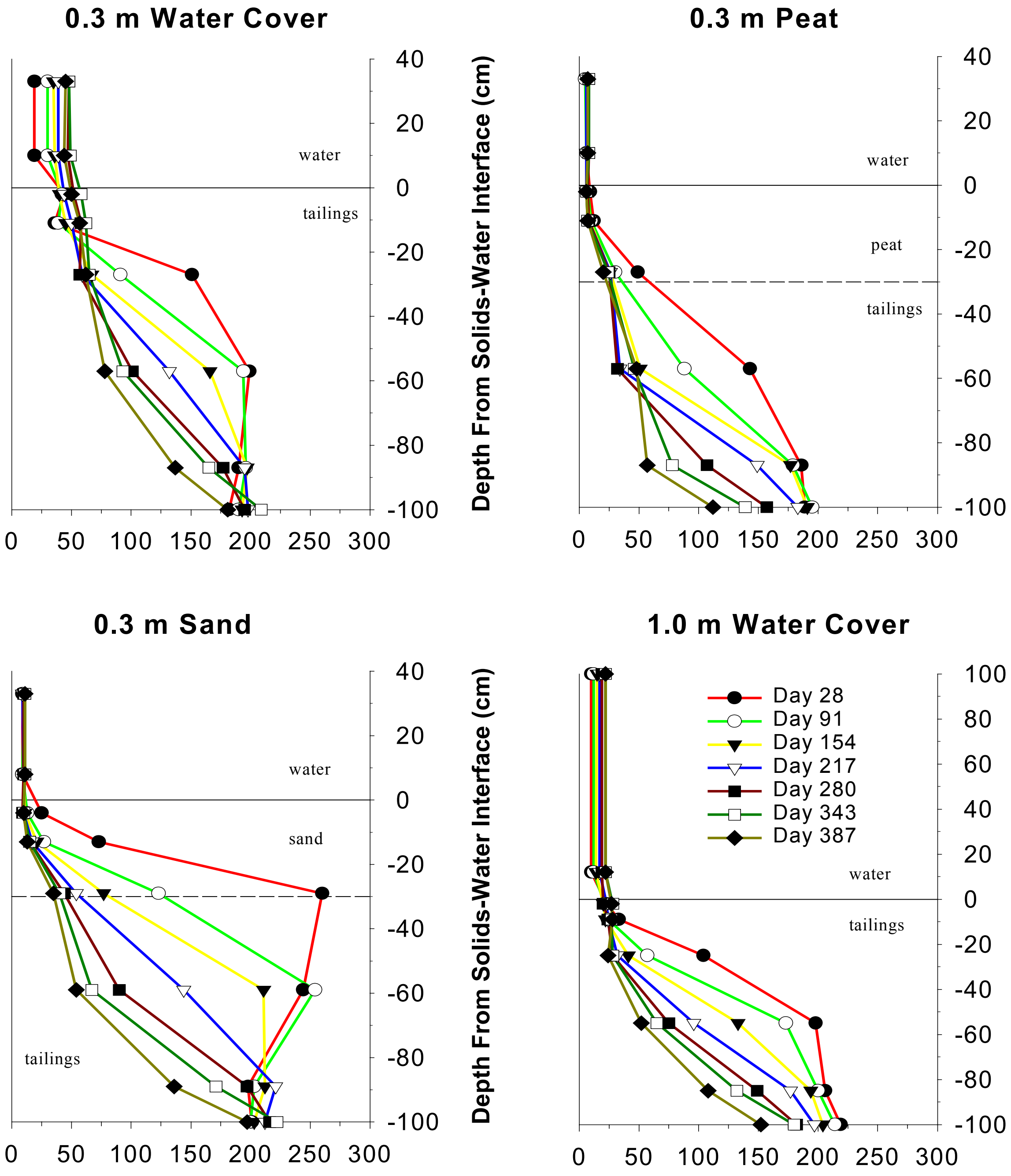

Figure A6-7 Mean Dissolved Calcium Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

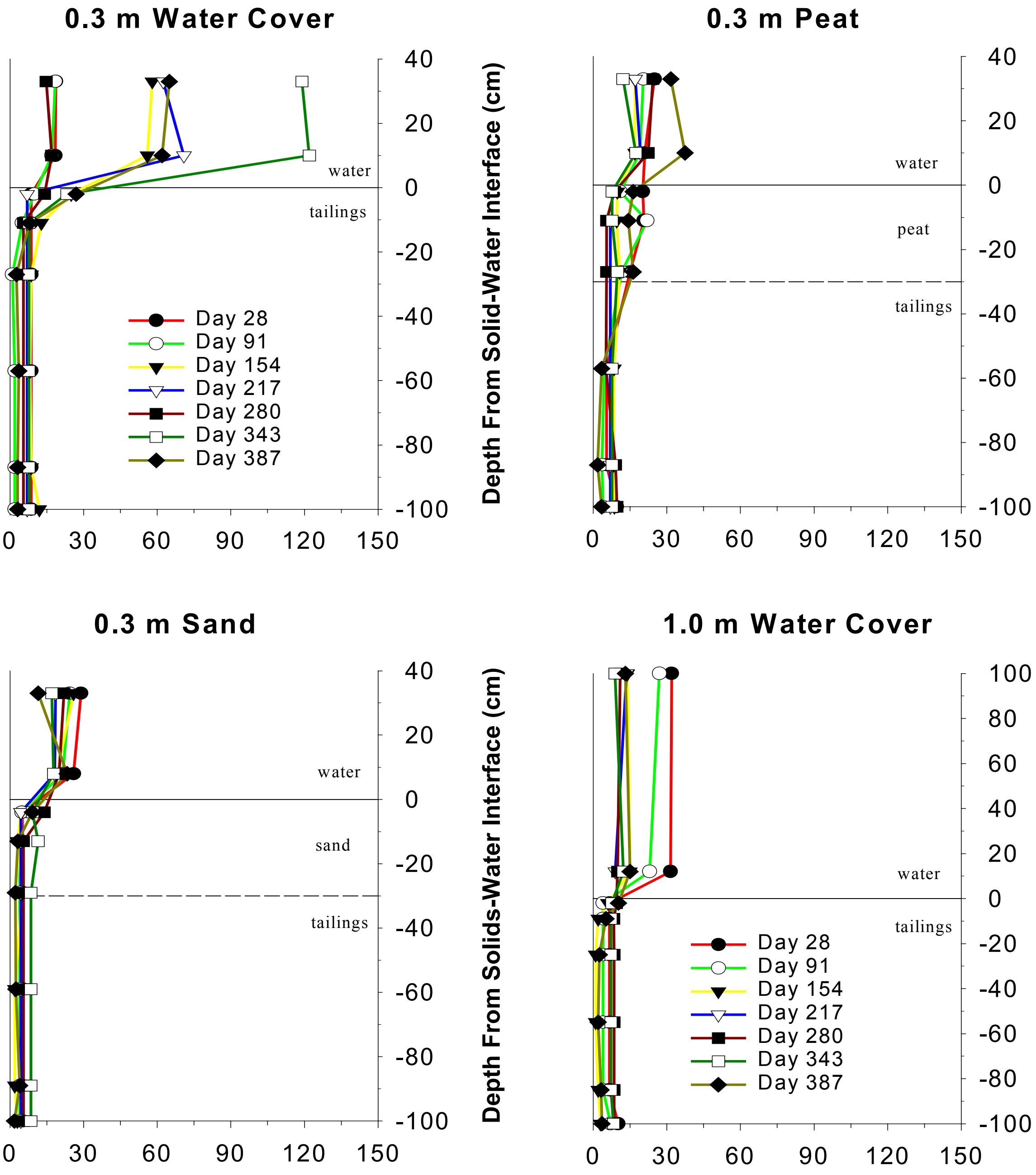

Figure A6-8 Mean Dissolved Copper Concentration (µg/L) Profiles over Time for Series 1-4 (Phase II)

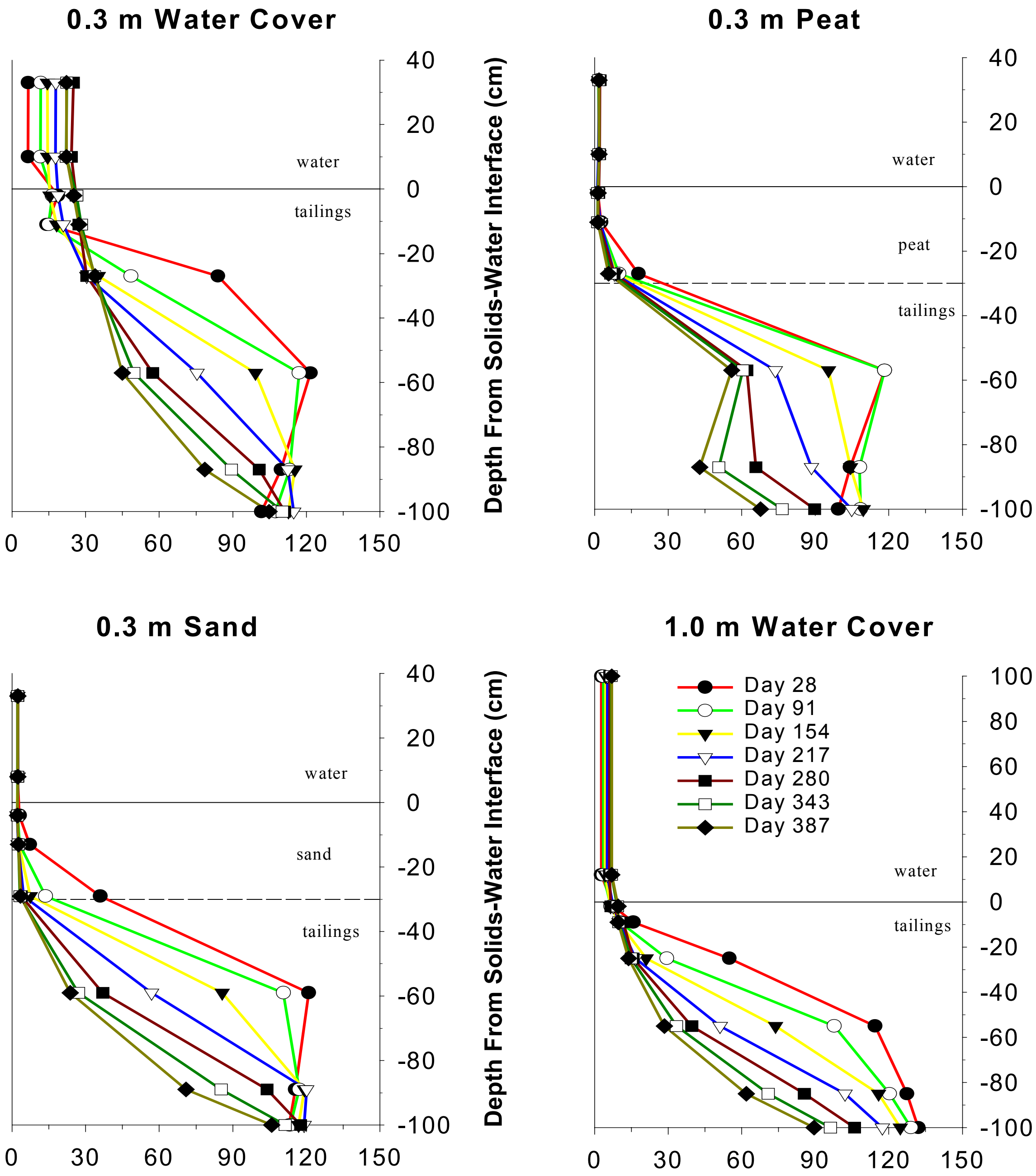

Figure A6-9 Mean Dissolved Magnesium Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

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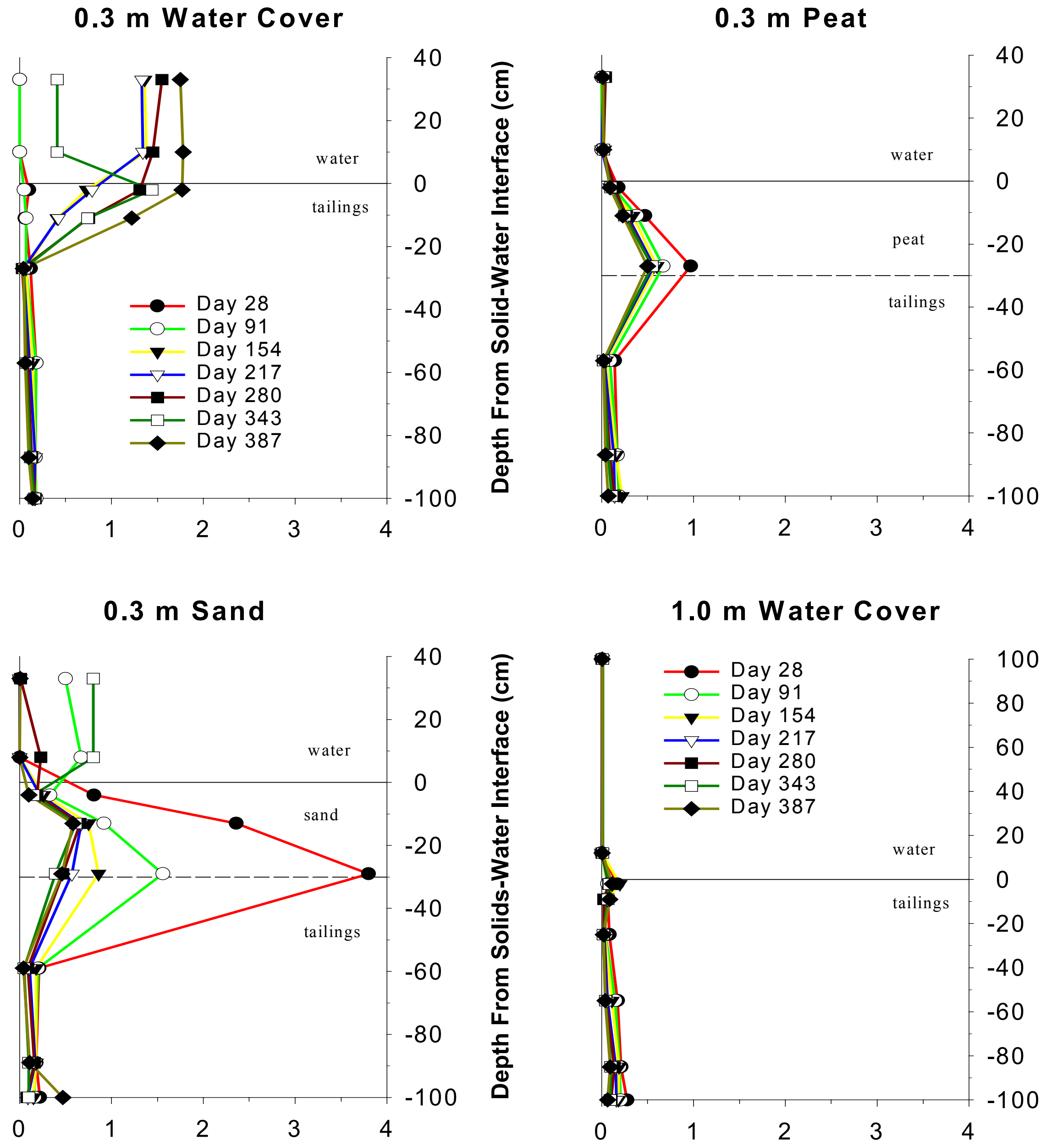

Figure A6-10 Mean Dissolved Manganese Concentration (mg/L) Profiles over Time for Series 1-4 (Phase II)

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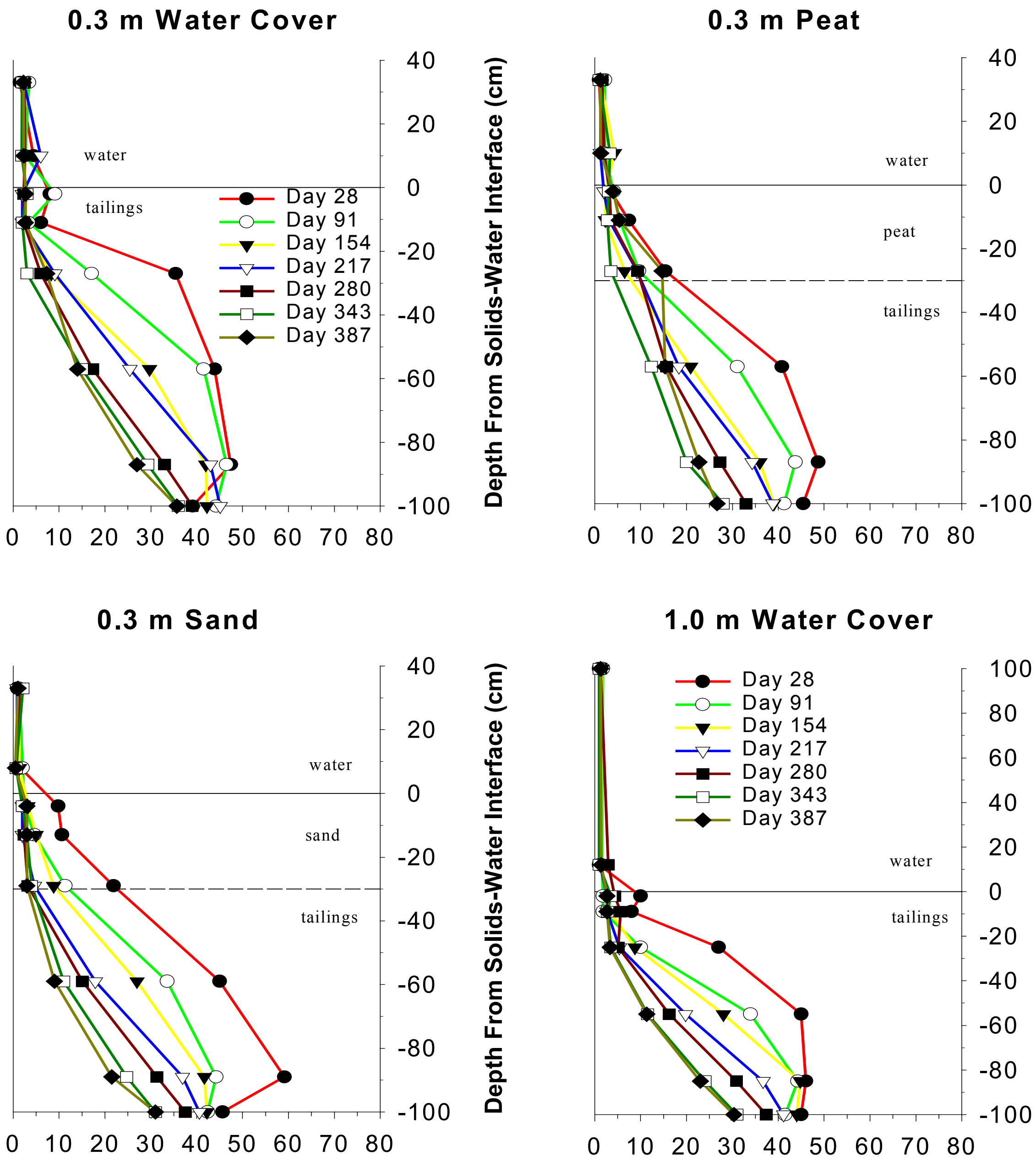

Figure A6-11 Mean Dissolved Potassium Concentrations (mg/L) over Time for Series 1-4 (Phase II)

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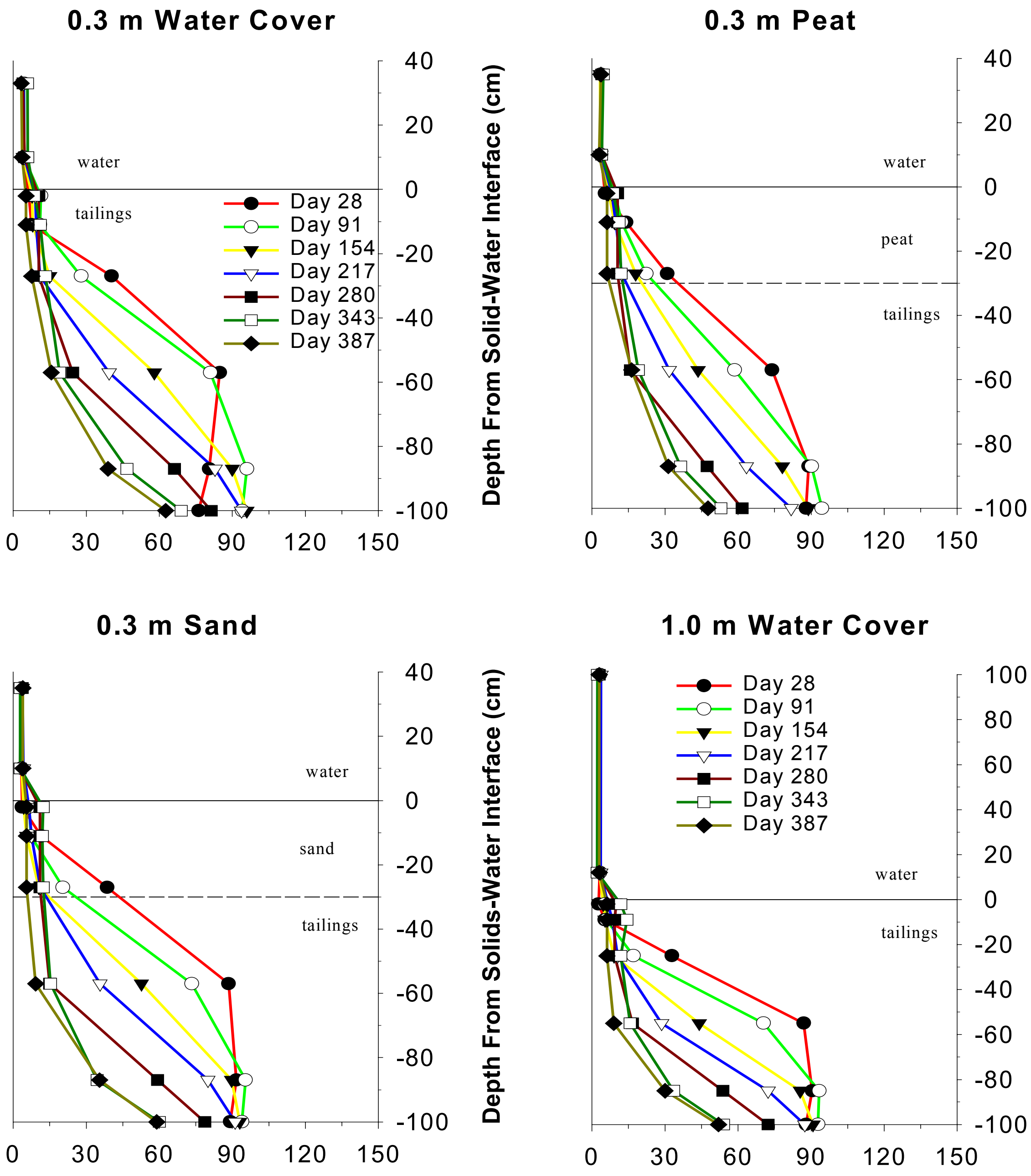

Figure A6-12 Mean Dissolved Sodium Concentrations (mg/L) over Time for Series 1-4 (Phase II).

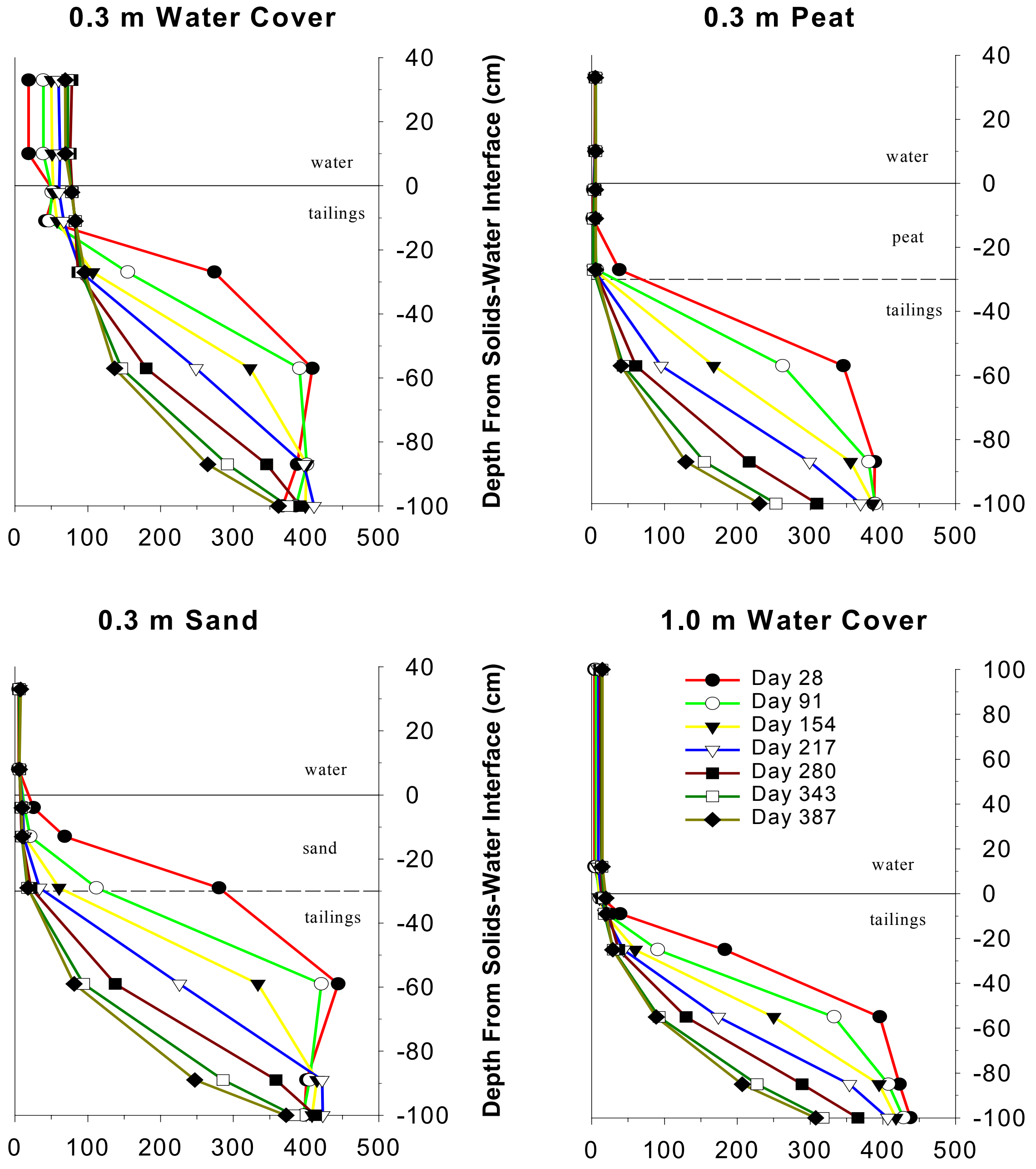

Figure A6-13 Mean Dissolved Sulphur Concentrations (mg/L) over Time for Series 1-4 (Phase II)

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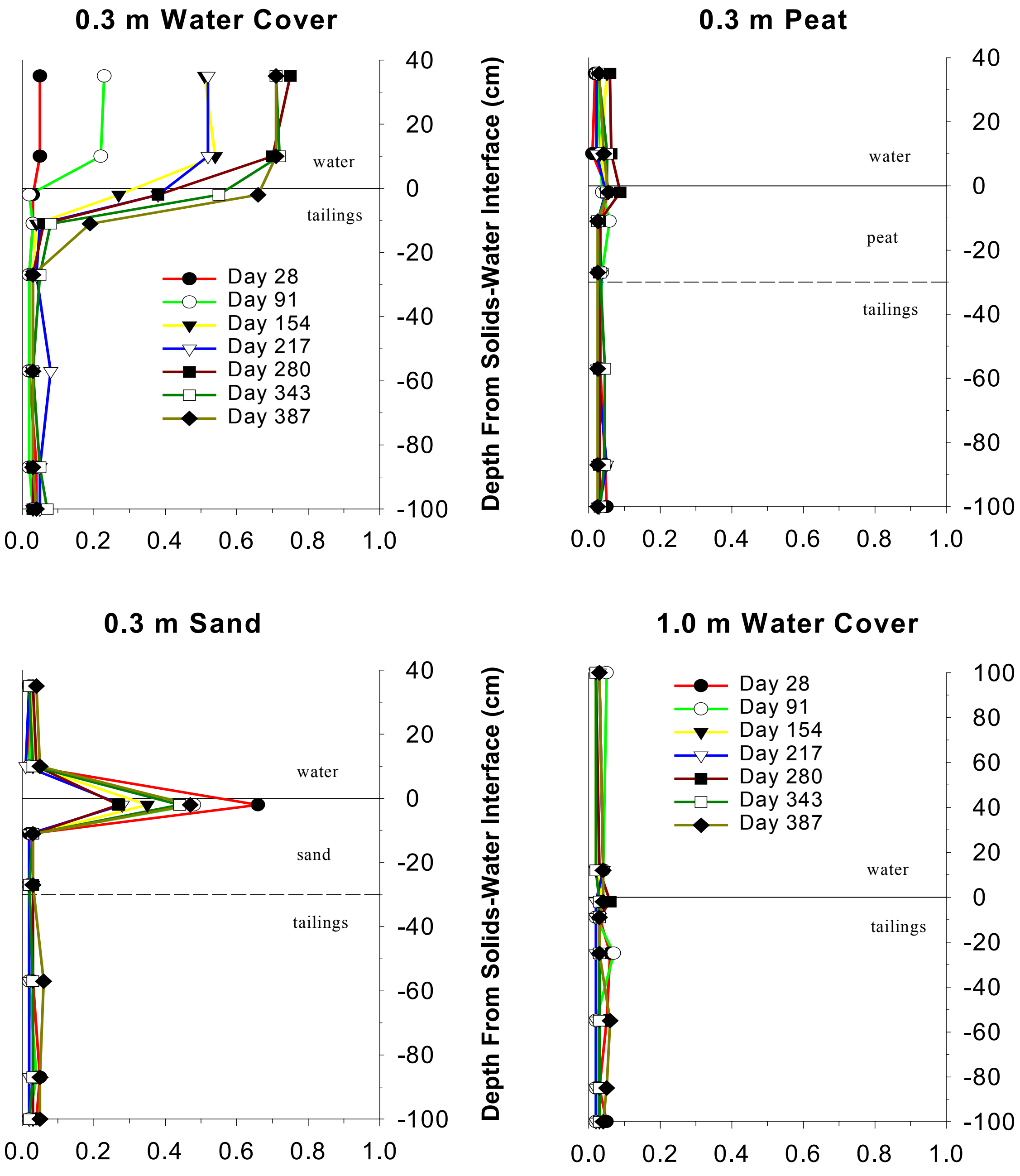

Figure A6-14 Mean Dissolved Zinc Concentrations (mg/L) over Time for Series 1-4 (Phase II)

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APPENDIX 7

A Tabulation of Raw Monitoring and Analytical Data (attached disk)