University of Alberta

Evaluation of groundwater flow and salt transport within an undrained tailings sand dam.

by

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Dedication

For Michael and My Family

Abstract

Groundwater flow and salt transport in an undrained tailings sand dam is investigated at Syncrude Canada's Mildred Lake Oil Sands mine, in northeast Alberta. Two dimensional groundwater flow and salt transport are characterized using field data from two detailed piezometer transects. Calibrated steady-state groundwater flow and transient salt transport models simulate existing and future flow systems and flushing of process water. Dyke topography creates nested flow patterns, which are modified in some cases by variations in hydraulic conductivity. Greater relief of the backward-sloped bench design compared with forward-sloped benches results in larger local flow systems, a deeper water table, flushing of process water and focused discharge. Under the existing flow conditions captured by the model, salts will flush in decades at the local scale (bench) and centuries at the intermediate scale (perimeter dyke). The future flow regime will depend strongly on recharge rates across the reclaimed dam.

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Introduction

1.1 Introduction

The Athabasca Oil Sand Deposit in northeastern Alberta, with a current reserve of 175 billion barrels, is the second largest petroleum deposit in the world (CAPP, 2005a). It accounts for over 30% of Canada's total oil production and yields over one million barrels of crude oil per day (CAPP, 2005b). Oil sands near the surface are mined in open pits, and the bitumen is separated from the host sand by a froth flotation aqueous slurry process and then upgraded to crude oil (List *et al.*, 1997). The separation of oil from sand produces large volumes of tailings. These tailings are composed of sand, fines (clay and silt), residual bitumen, and process affected water and are piped in a slurry to large storage facilities (List *et al.*, 1997). Tailings require long-term storage due to aquatic toxicity of the process water (Mackinnon, 1981).

Shallow water table depth, capillary rise, leaching, seepage, erosion and transport of tailings constituents (*i.e.*, metals, hydrocarbons, naphthenic acids and salts) are the common concerns associated with tailings dams (Barth, 1986). Groundwater flow and/or chemical processes within tailings structures have been investigated in numerous studies (*e.g.*, Al and Blowes, 1999; Ellerbroek and Jones, 1997; Hunter, 2001; Johnson *et al.*, 2000; Plewes *et al.*, 1997). In sulfide metal impoundments, the environmental concern is the oxidization of sulfide minerals, and a high water table is ideal to minimize oxygen ingress and subsequent oxidization of metals (Al and Blowes, 1999; Ellerbroek and Jones, 1997). A shallow water table, or thick zone of tension saturation above the water table, results in conditions favourable for evaporative losses and salts precipitating at the ground surface (as in Al and Blowes, 1999). However, in tailings sand dams where metal oxidization is not a concern but geotechnical stability and seepage of brackish process water into reclamation soils *are*, high water tables are not desirable. Typically, tailings sand dams have internal drains to collect seepage and consequently have a lower water table (*e.g.*, Hunter, 2001; Mittal, 1981; Plewes *et al.*, 1997).

The study site, Syncrude's Southwest Sand Storage (SWSS) Facility, is different from most other tailings sand dams, because it is not internally drained (List *et al.*, 1997). Accordingly, the groundwater flow system and movement of salts associated with the process water are likely to be different from previously studied tailings sand dams.

1.2 Study Site – Southwest Sand Storage Facility (SWSS)

The SWSS is a large tailings sand dam located at Syncrude's Mildred Lake Operations, 40 km north of Fort McMurray, Alberta (Figure 1-1). It is 25 km^2 in area, 40 m high, and contains nearly 300 million cubic metres (Mm^3) of tailings sand (Purhar, 2004). The SWSS was originally designed to accommodate 60% of the tailings sand produced during oil sand extraction over a twenty-five year period; however, its projected maximum size was reduced from 750 Mm^3 (List *et al.*, 1997) to 365 Mm^3 following the development of composite tailings technology (AEE, 1997). Composite tailings are a mixture of tailings sand, and mature fine tailings spiked with lime or gypsum to promote flocculation (List *et al.*, 1997). Composite tailings are stored elsewhere at the Mildred Lake Operations mine site.

Construction of the SWSS began in 1991. It is being built over time from the large volumes of tailings sand piped from the extraction plant. The tailings sand placed at the SWSS makes up the perimeter dyke, the internal beaches and tailings pond (Figure 1-1). Tailings sand is primarily sand and water, and when deposited is described as fine sand with infrequent thin, horizontal, clayey silt layers (McKenna, 2002). A series of bench and slope pairs join to form the terraced slope of the perimeter dyke. The dyke slope is shallow (20H:1V) and was designed to take into account low shear strength and relatively high pore pressure response to loading of the underlying clay shale foundation. The shallow slope of the perimeter dyke was initially achieved by alternating 10H:1V slopes (~100 m) with 100 m benches (Klohn Leonoff, 1991). After 1995, the benches were constructed with an outward tilt, to promote drainage of the outer slopes (AEE, 1997).

All the slurried tailings sand that is not used for perimeter dyke construction is discharged behind the dyke, and forms the beach. Following discharge, coarser tailings settle out first, near the discharge point, while finer tailings settle further away, within the tailings pond (List *et al.*, 1997). Where the beach transitions to the pond, there is a strong inter-layering of sand and fines (McKenna, 2002). An estimated volume of 40 Mm^3 of mature fine tailing remains within the tailings pond (Purhar, 2004). Fine tailings are a mixture of fine sand, silt and clay-size particles in water with a trace of bitumen (Suthaker and Scott, 1996). The perimeter dyke is surrounded by a perimeter ditch around the outside edge, lateral berm channels on the lower benches, and swales, flumes or channels that direct water off the benches to the perimeter ditch. The seepage and surface runoff collected in the ditch is recycled to the processing plant or is maintained within the mine system (Purhar, 2004). Fluid balance of the tailings pond is managed by a decant system, which controls the volume of water transferred from the SWSS to the West In-Pit tailings facility (Purhar, 2004). The structure is without internal drainage (Klohn Leonoff, 1991), except for one small filter drain in the northwest corner (Purhar, 2003).

Syncrude plans to return developed land at the mine to a capability equivalent to or better than the predevelopment state, although land uses may be different (Syncrude, 2001). At closure, the SWSS will consist of reclaimed and vegetated terraced slopes around the perimeter and a large flat platform at the top draining to a small pond/wetland in the southwest corner. The steps involved in reclamation are to establish surface water drainage, reslope the post-mining landscape, cap the landform with reclamation materials (peat – mineral layers and mixes), establish vegetation, and, finally, monitor and maintain the landscape (Syncrude, 2001). The planned end land use will be a non-harvestable forest system and an environment for human recreation, wildlife and traditional land uses. Reclamation is under way on the perimeter dyke of the SWSS (Figure 1-1) and is scheduled to be completed by 2015, with reclamation certification in 2023 (Syncrude, 2001).

Syncrude has established a number of detailed research areas on reclaimed land ranging from one to one hundred hectares in size. These research areas provide an understanding of the fundamentals of ecosystem performance on various mine substrates, including tailings sand, saline sodic overburden and coke. The tailings sand research has proceeded in two designated research areas, in Cells 32 and 46 at the SWSS (Figure 1-1). The more established research area in Cell 32 was built in 2000 and is located on the east side of the SWSS. Research area in Cell 32 is 25 hectares across the terraced slope of the perimeter dyke (Syncrude, 2004). The other research area in Cell 46 is located on the west side of the SWSS and extends from top to toe of the perimeter dyke. Monitoring of this area began in 2002. Research instrumentation installed at the research areas includes weather stations, TDR probes and neutron tubes for soil moisture, and runoff frames (*e.g.* Chaikowsky, 2003, Macyk, 2000; Macyk *et al.*, 2002), as well as plots used for soil and vegetation surveys (*e.g.*, Burgers, 2005; Chaikowsky, 2003).

As the research program at the SWSS began, there were two key concerns: the depth of the water table and the process water's potential to salinize the reclamation materials over time. There were indications of water logging, salinization and sodification of tailings sand slopes due to high water tables with associated process water, and lack of internal drainage (Macyk, 2000; Syncrude, 2001). Chaikowsky (2003) found on Cell 32 that neither water logging nor salinity was an issue in the topsoil and near the soil/tailing-sand interface. The soil maintains adequate moisture making it appear to be hospitable for vegetation. However, some high electrical conductivities, sodium absorption ratios and water logging occurred in certain areas, near the lower berm channel and at the base of the structure. Burgers (2005) concluded during his investigation of vegetation and soil interactions that salinity was higher on Cell 46 than Cell 32, and sodicity, nutrient deficiencies and low reclamation soil depths were affecting revegetation success on Cell 46.

Both high water tables and salinity can be a concern when reclaiming a landscape. High water tables or water-logging cause poor aeration in the root zone, with effects ranging from reduced growth to the death of plants (National Research Council, 1993). Shallow groundwater leads to the accumulation of salts near the soil surface under certain climatic conditions. The evaporative flux draws salt to the ground surface with a rising water table, instead of a downward leaching flux that exists in deeply drained soils (Namken *et al.*, 1969). Salinity affects plant germination as well as seedling and vegetative growth, and disrupts specific plant functions, such as photosynthesis and turgor pressures. In addition, elevated electrical conductivity and sodium affect the soil permeability and structure. Soils can breakdown and the clay minerals disperse and swell, leading to increased runoff and soil erosion. Typically, the primary source of salts is chemical weathering of minerals present in soil and rocks (National Research Council, 1993). However, at the SWSS, the main source of salts is from the brackish process water associated with the deposited tailings sand (Chapter 2).

Previous groundwater investigations at the SWSS reflect the concern with high water tables and/or the movement of salts (Burgers, 2005; Chaikowsky, 2003; Liggett, 2004; Macyk, 2000; McKenna, 2001; Molson, 1997; Skopek, 1996). The groundwater flow regime across the perimeter dyke was previously simulated numerically (McKenna, 2001; Skopek, 1996). Skopek (1996) predicted the water table could be at relatively shallow depths for significant portions of the downstream slope. However, sensitivity of the numerical model to the range of provided recharge and hydraulic conductivity values meant that performance data was required from the SWSS to predict current flow regime accurately. A groundwater divide was hypothesized to exist near the top of the dyke based on model predictions by McKenna (2001) and observations of active springs on the beach (Skopek, 1996).

Molson (1997) simulated the flushing of process water from the SWSS using a non-linear density-dependent transport approach. The high vertical concentration gradients throughout the section of the SWSS reflected low mixing of recharge and process water because of dominant horizontal flow and low vertical dispersivities used in the model. Recharge flushed shallow process water before flushing the deeper process water. Most of the brackish process water is predicted to be flushed within 274 years. Molson (1997) compared the density-dependent simulations with simulations that did not consider density variation and found there were no density dependant effects. The fluid density contrasts between fresh recharge water and the salty process water (3000 mg/L) were relatively low, and total dissolved solids concentrations were an order of magnitude lower than seawater. A linear flushing model, used by both McKenna (2001) and Liggett (2004) determined the timeframe of process water flushing from the SWSS. McKenna (2001) found that the perimeter dyke of the SWSS would take several centuries to flush. Liggett (2004) calculated similar flushing times (270 years) for the whole SWSS. Plug flow and constant discharge were assumed during flushing calculations.

Syncrude monitors groundwater levels in a piezometer network at the SWSS (Purhar, 2004). In 2003, groundwater levels across the structure were recorded between the ground surface and eight metres below (Purhar, 2004). Water levels have decreased in piezometers since their installation, except in areas where there has been active beaching (Chapter 2; Purhar, 2004). In the early years of construction, high water tables and seepage on slopes and benches were reported (AEE, 1997; Skopek, 1996). Localized seepage remains evident throughout the structure, as seen by wet slopes, and small gullies (Chapter 2; Purhar, 2004).

Electromagnetic surveys of the perimeter dyke slope, completed in 2001, indicated some waterlogged areas, mostly at the toes of the slopes (Syncrude, 2004). The observed resistivity patterns from the survey data were reminiscent of nested local and intermediate groundwater flow systems as described by Tóth (1963) and indicated possible flushed zones and process water near the ground surface.

Previous investigations provided the initial framework for developing a conceptual model of groundwater flow and salt transport at the SWSS. These investigations, whether numerical modelling, groundwater monitoring, or determining physical properties of the tailings sand (McKenna, 2002), were done independently of each other. However, to improve interpretation and understanding of groundwater flow and salt transport, the various groundwater data required integration and rigorous interpretation.

1.3 Purpose and Scope

Uncertainty about the water table location, the groundwater flow regime within the SWSS and whether salts from process water were moving into newly placed reclamation soil, prompted this groundwater investigation. In addition, the long-term groundwater response and movement of salts at the SWSS was not understood. The purpose of this research is to develop an integrated understanding of groundwater flow and salt transport at the SWSS at local and intermediate scales, more specifically at the bench and dam spatial scales. The benefits of the research include improved evaluation and design of perimeter dyke slopes and information required for reclamation planning. Additional benefits include the transfer of understanding of the system to operators of similar structures in the oil sands, or elsewhere, and an understanding of how traditional flow and transport models can be applied to similar large, man-made structures. Overall, the research will facilitate better long-term environmental management of this site and future sites.

The research is completed in two stages: field characterization, followed by numerical modelling. The first step is to characterize the current groundwater flow systems and salt distribution, observe changes over a one-year period, and identify controls on flow and salt movement. The field data is collected from installed instrumentation along two detailed research transects. Transect 31 (A to A') is immediately north of Cell 32 (in Cell 31) and Transect 46 (B to B') is in the middle of Cell 46 (Figure 1-1).

The second step is to develop a conceptual model, simulate current groundwater flow and salt transport with numerical models, and sensitivity test the models. In addition, the models are used to predict the long-term response of the flow system under different management scenarios (*e.g.*, reduced recharge and a closed tailings pond). All numerical modelling is along Model Transect (A to A"), which extends from the toe of the perimeter dyke to the middle of the tailings pond in Cell 31 (Figure 1-1).

1.4 Objectives

The objective of this thesis is to understand groundwater flow and salt transport at the local and intermediate scales in the SWSS. This is achieved by undertaking more specific research objectives:

1. Field characterization of hydraulic heads and temporal changes over a one-year period along two-dimensional profiles, in Transects 31 and 46.
2. Field characterization of salt distributions and temporal changes over a one-year period along two-dimensional profiles, in Transects 31 and 46.

3. Evaluation of groundwater flow and salt transport processes, using existing groundwater numerical models along Model Transect (A to A"). Field data is used to calibrate the groundwater flow model, so it can be used for salt transport modelling and as a predictive tool.

4. Sensitivity analysis of groundwater flow model by changing components affecting the system: hydrologic inputs, boundary conditions, and physical properties.

5. Prediction of the long-term behaviour of the groundwater flow system under different possible future conditions along the Model Transect (A to A").

1.5 Thesis Summary

The objective of this thesis is to develop an understanding of groundwater flow and salt transport at the Southwest Sand Storage Facility, at Syncrude's Mildred Lake Mine Operations, near Fort McMurray. In Chapter 2, the two-dimensional groundwater flow and salt distributions are characterized, using field data from detailed piezometer transects. Chapter 3 incorporates understanding of the groundwater flow and transport of salts into conceptual models and investigates current and future flow scenarios and flushing times of salts with numerical models. The results are summarized in Chapter 4.

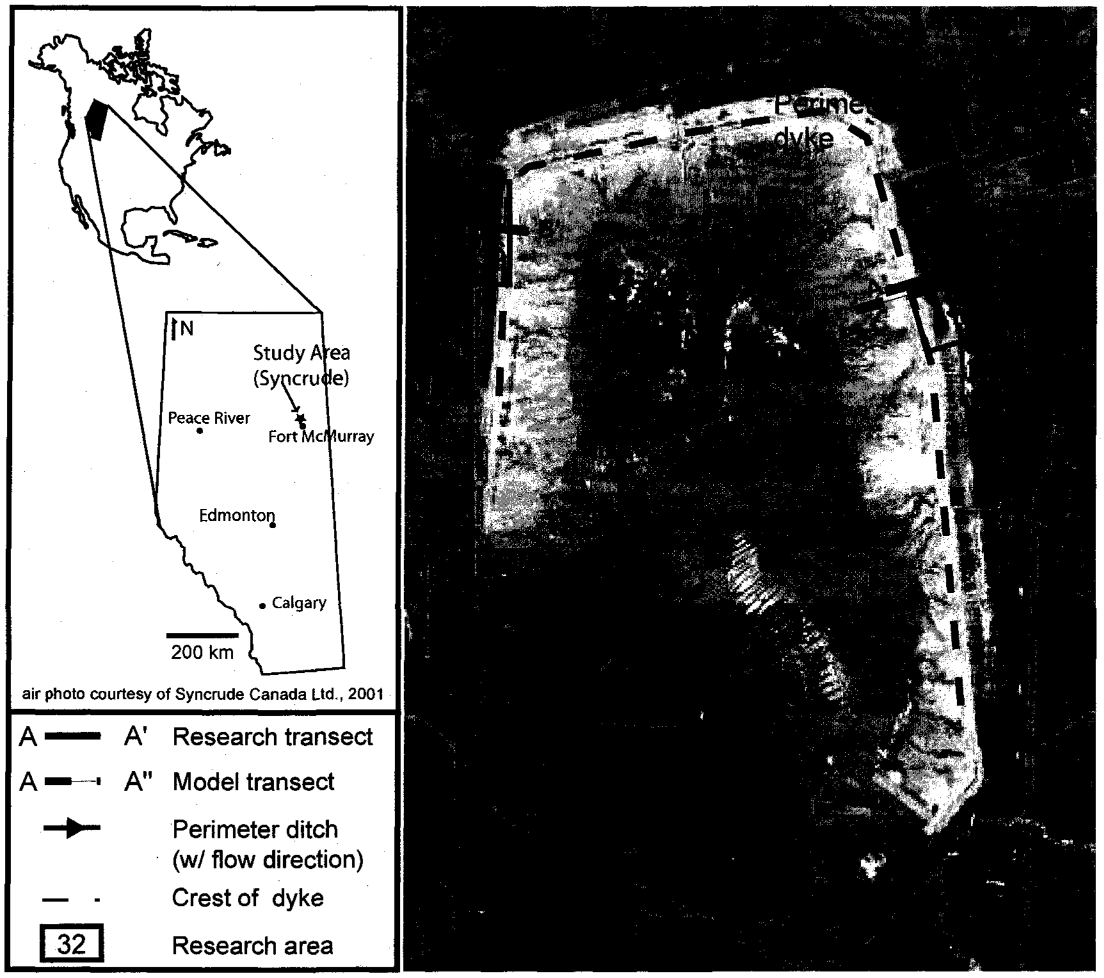

Figure 1-1. Research Transects 31 (A - A') and 46 (B - B') and Model Transect (A to A") at the Southwest Sand Storage Facility. Darker areas on the perimeter dyke indicate reclaimed areas in 2001. Insets show locations within Alberta and North America (top left).

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Chapter 2

Characterization of groundwater flow and salt distribution within an undrained tailings sand dam.

2.1 Introduction

The Athabasca Oil Sands Deposit in northeastern Alberta, with a current reserve of 175 billion barrels, is the second largest petroleum deposit in the world (CAPP, 2005a). It accounts for over 30% of Canada's total oil production and yields over one million barrels of crude oil per day (CAPP, 2005b). Oil sands near the surface are mined in open pits, and the bitumen is separated from the host sand by a froth flotation aqueous slurry process (List *et al.*, 1997). The separation of oil from sand produces large volumes of tailings, composed of sand, fines (clay and silt), residual bitumen, and process affected water, which are piped to large storage facilities (List *et al.*, 1997). The impounded tailings will cover a significant portion of the mined landscape and will need to be reclaimed at the time of closure. Closure and reclamation challenges for tailings include reclaiming soft tailings that have poor traffic-ability because of high water tables, salt migration and re-establishing the surface hydrology (Syncrude, 2001).

The Southwest Sand Storage Facility (SWSS) is Syncrude Canada's second largest storage facility at Mildred Lake Operations, 40 km north of Fort McMurray, Alberta (Figure 2-1). It is different from other large dams in the area because it is a sand storage facility without internal drains and has a shallow perimeter slope (Klohn Leonoff, 1991). As a result of the dyke design and poor quality process water associated with the tailings sand, there are challenges in reclaiming the SWSS. There are indications of waterlogging, salinization and sodification of the slopes due to high water tables and a lack of internal drainage (Syncrude, 2001). Studies in research areas at the SWSS have focused on vegetation (Burgers, 2005), and soil moisture and chemistry (*i.e.,* salinity and nutrients) of topsoil (Burgers, 2005; Chaikowsky, 2003), where the interaction with groundwater has not been explicitly considered. Uncertainties about the water table location and the groundwater flow regime within the dam, and questions about whether or not salts from process water are moving into newly placed reclamation soil, prompted a groundwater investigation.

Groundwater flow systems have been studied extensively in uranium and metal sulphide tailings impoundments (*e.g.,* Al and Blowes, 1999; Ellerbroek and Jones, 1997; Johnson *et al.*, 2000). An undrained sulphide tailings impoundment at Kidd Creek Mine, Timmins, Ontario has shallow water table depths (1.5 to 5 m) and discharge of process water within the impoundment. Fewer studies exist for tailings sand dams. Many of the investigated tailings dams are internally drained (Hunter, 2001; Mittal, 1981; Plewes *et al.*, 1997), which alters the groundwater flow and movement of salts by lowering the water table. Understanding the flow systems within undrained tailings sand dams is necessary to manage the structures.

The study objective is to develop an understanding of groundwater flow and salt transport at different scales within the SWSS. The current groundwater flow systems and salt distributions are characterized, and changes over a one-year period are observed. In addition, the controls on flow and salt movement are identified. To understand possible physical controls on groundwater flow and salt transport, the stratigraphies of deposited tailings sand within the research areas are interpreted, using historical survey data, and overlain with measured hydraulic conductivity distributions. The results permit a comparison of the performance of alternative perimeter dyke designs and suggest strategies to improve reclamation success. This knowledge will facilitate better long-term environmental management of existing sites and the design of future undrained tailings dams.

2.2 *Study Area*

2.2.1 Southwest Sand Storage Facility (SWSS)

The SWSS is located 7 km southwest of the extraction plant at Syncrude Canada's Mildred Lake Operations (List *et al.*, 1997). It covers an area of 25 km^2, is almost 40 m high at its crest and contains nearly 300 million cubic metres of tailings sand (Purhar, 2004). The facility consists of a perimeter dyke, a beach, and a tailings pond (Figure 2-1). Since 1991, the structure has been gradually constructed using two basic methods: dyke construction via lifts, and beaching (List *et al.*, 1997). The perimeter dyke was built by mounding, spreading and compacting sand with bulldozers (AEE, 1997). Tailings slurry not used for perimeter dyke construction is discharged near the crest of the dyke, which forms shallow internal beaches and a small pond. Coarser tailings settle out first, near the discharge point, while finer tailings settle further away, within the tailings pond (List *et al.*, 1997). At the beach/pond transition area, which moves over time, there is a strong inter-layering of sand, fines and bitumen (McKenna, 2002). The average tailings composition is 91, 8 and 1% of sand, silt and clay, respectively (Gan, 2001) and the sand is a light grey to brown fine quartz. The tailings slurry contains about 50%, by volume, of water (Savoie, 2003).

Process water in the tailings slurry is typically alkaline and is sodium bicarbonate dominant (Mackinnon, 2003) with high concentrations of Na^+, SO_4^{2-}, HCO_3^- and Cl^- ions. Total dissolved solids (TDS) concentrations in the process water deposited at the SWSS increased from about 1500 to 3200 mg/L between 1991 and 2002 (Liggett, 2004).

Fluid balance of the tailings pond is managed by a decant system, which controls the volume of water transferred out of the SWSS to the West In-Pit tailings facility (Purhar, 2004). Seepage and runoff water from the perimeter dyke collect in the perimeter ditch and are recycled back to the plant or retained within the mine waste water system (Purhar, 2004). Localized seepage is evident throughout the structure, as indicated by wet slopes and small gullies (AEE, 1997; Purhar, 2004).

The underlying ground surface had gentle relief, sloping downward, at a gradient of 0.5 to 1.0%, to the northeast (Klohn Leonoff, 1991). Underlying geology consists of predominantly fine-grained, unconsolidated Quaternary, Holocene, and Pleistocene deposits above the Cretaceous Grand Rapids, Clearwater, and McMurray Formations (Klohn Leonoff, 1991). The water table around the SWSS is shallow, on average 1.3 m deep (List *et al.*, 1997), and the regional groundwater flows northeast towards the Athabasca River. The underlying glacial till and lacustrine deposits (Pleistocene), and marine shale (Clearwater Formation), are described regionally as having low permeability (Hackbarth and Nastasa, 1979) and the hydraulic conductivity (K) of glaciolacustrine deposits and glacial till beneath the SWSS are two to three orders of magnitude lower than the tailings sand (Esford, 2003; Klohn Leonoff, 1990).

Fort McMurray experiences cold winters and warm summers, with mean average monthly temperatures ranging from -18.8°C to +16.8°C. The average annual precipitation is 456 mm/year (Environment Canada, 2004) and the average annual potential evapotranspiration is 493 mm/yr (Hackbarth and Nastasa, 1979). Over half of the rain falls from June through September, and evapotranspiration rates exceed precipitation in May through August (Hackbarth and Nastasa, 1979).

2.2.2 Research Transects 31 and 46

A 917 m long study transect (A to A') was selected in Cell 31 running from toe to top of the east side of the perimeter dyke. A second, 415 m long, transect (B to B') was chosen through the middle of Cell 46 on the west side of the SWSS (Figure 2-1). Cell numbers refer to spatially subdivided operational areas of the

SWSS. These locations were chosen because they were adjacent to or within established research areas on Cells 32 and 46, aligned with existing instrumentation (*e.g.*, neutron access tubes), and accessible with drilling equipment. On-site meteorological data is collected at weather stations near each transect. The selection of two different detailed transects, which run from bottom to top of the SWSS, allowed investigation at two spatial scales: local (bench) and intermediate (dam). Instrumentation of these two transects allowed a comparison between areas with different dyke geometries (*i.e.,* bench designs), construction histories and ages.

The perimeter dyke across Transect 31 was built as a series of five bench and slope pairs (A through E, Figure 2-2). Benches A and B are backward-sloped (*i.e.,* slightly tilted in towards the perimeter dyke crest) whereas Benches C, D and E are forward-sloped (*i.e.*, tilted out towards the perimeter ditch) to prevent water from ponding (AEE, 1997). Benches D and E were designed shorter and flatter than Bench C to reduce the area of drainage of the downstream slopes (AEE, 1997). Adjacent to Benches A and B are engineered Channels A and B designed to collect seepage and runoff water and drain the water to the south and ultimately to the perimeter ditch.

Transect 46 is about half the length of Transect 31 and has only two benches and slopes (Figure 2-2). Bench C on Transect 46 is tilted outward and Bench D is short and flat. The perimeter ditch collects seepage and runoff from the perimeter dyke and water drains to the north.

Benches and Slopes A and B on Transect 31 are reclaimed with an average of 0.8 m of peat-mineral mixture deposit (Macyk *et al.*, 2002), which are salvaged peat, glaciolacustrine deposits, and glacial tills from the Mildred Lake Site (Syncrude, 2001). Bench and Slope C have approximately 0.4 m of layered peat (0.15 m) over mineral deposit (0.25 m) (Macyk *et al.*, 2002), which has been thinly covered with sand blown from the tailings beach. Benches D and E are reclaimed with mineral deposits as on C but peat is currently stored on the upper two benches and slopes, in windrows. Tree species such as trembling aspen, Siberian larch, hybrid poplar, white spruce, jackpine, and dogwood were planted in areas on Benches and Slopes A and B (Qualizza, 2004). In addition, there is considerable groundcover from horsetails, fireweed, dandelion, sowthistle and yellow and white sweet clover (Wilkinson, 2004). In 2003, young vegetation extended to midway up Slope C, with only sparse vegetation growing on Bench C. Benches and Slopes C and D on Transect 46 have been reclaimed with approximately 0.4 m of layered peat over mineral deposits (Macyk *et al.*, 2002). No trees have been planted, but there is sparse ground cover.

2.3 Materials and Methods

2.3.1 Groundwater

Either a 1 inch hand auger or a 3 ½ inch portable solid-stem auger drill was used to install ninety-five shallow piezometers or water table wells in July and August, 2002. A total of twenty-two piezometer nests were installed 30 to 50 m apart along the two transects (Figure 2-2). Generally, nests were positioned near toe, mid-slope, crest and mid-bench positions. At each nest, a water table well (1 to 1.5 m screens) was placed across the water table. Piezometers (0.3 m screen) were installed from 1 m below the water table up to 9 m deep, spaced vertically by 2 m. In addition to the nests, 11 single shallow piezometers were installed in the channels and perimeter ditches across the two transects to about 1 m below the ground. Each well or piezometer was constructed of 0.025 m diameter PVC pipe and the machine slotted (0.5 mm) screens were covered in filter cloth. Each piezometer and water table well was named by location (*e.g.*, GW01) and approximate depth (m) (*e.g.*, 1.5). WT was included at the end of the name if it was a water table well (*e.g.*, GW01-1.5WT).

A casing hammer drill rig was used to install eight deeper piezometers into the tailings sand on the crest of each bench (Figure 2-2). The 6" hollow drill casing was kept free of tailings sand during piezometer installation by filling it with water labelled with a sodium bromide tracer (Davis *et al.*, 1980). Bromide was used because it exists at negligible concentrations of < 0.1 mg/L (Mackinnon, 2005) in tailings process water. One to three piezometers were installed, spaced 7 to 9 m apart vertically, starting at 2 m above the original ground surface into the tailings sand. Deep piezometers were constructed of 0.051 m diameter PVC pipe and a 0.51 m long sump was attached below the 1.5 m screen to collect sand or fine sediments that might enter the piezometer. Screens were covered in filter cloth and machine slotted (0.5 mm).

Saturated tailings sand collapsed easily around piezometers to form adequate sand packs and seals. Once the solid-stem augers were removed, the shallow piezometers were vibrated by hand through liquefied sand to the desired depth. Water table wells often required a sand pack to 0.05 m above the screened interval. The deeper piezometers required no sand pack, because sand collapsed around the screen when the drill casing was pulled out of the ground. Any open borehole annulus above the collapse depth (usually the water table) or the sand pack was filled with medium bentonite chips.

Water levels were measured approximately semi-monthly from August 2002 until October 2003 excluding November 2002 to March 2003, inclusive. Manual water level measurements commenced in April 2003, but could not be recorded in many of the piezometers until late May or June because the water was frozen.

Saturated hydraulic conductivity values for 71 piezometers (in nests or at selected single piezometers) in the tailings sand were estimated by the Hvorslev method (1951).

Average linear velocities through the SWSS were calculated using Darcy's Law, together with an estimate of porosity, as described in Freeze and Cherry (1979):

$$\bar{v} = -\frac{K}{n}\frac{\Delta h}{\Delta l} \qquad (1)$$

where K is the hydraulic conductivity (m/s), $\Delta h/\Delta l$ is the hydraulic head gradient (dimensionless) and n is the volumetric porosity (dimensionless). Porosity for tailings sand is 0.40 (McKenna, 2002).

2.3.2 Surface water and seepage

Surface water levels were measured with a staff gauge by attaching stainless steel rulers to angle iron driven into the ground. Gauges were installed and surveyed in the surface waters in Channels A and B and the ditches at the bottom of Transects 31 and 46 (Figure 2-2). Commencing in September 2002, water levels were measured twice a month, when the gauges were ice free, in conjunction with piezometer readings. All gauges were resurveyed in May 2003 to account for heaving over the winter.

Groundwater seepage from sediment at the toes of Transects 31 and 46 was measured with seepage meters. The seepage flux was estimated by measuring the volume of water collected in a bag attached to each seepage meter over a period of time (Lee, 1977). The seepage meter design (after Lee, 1977) was a 0.285 m diameter hard plastic bucket cut 0.20 m tall. The collection bags (28 by 27 cm) were preloaded with 0.25 L of surface water and emptied of air (Shaw and Prepas, 1989). On Transect 31, two seepage meters were installed into the sand in the perimeter ditch near the upstream edge, where the height of the standing water was greater than 0.1 m. On Transect 46, three seepage meters were installed into sand and peat at the toe of the dyke in the perimeter ditch in about 0.3 m of standing water. Seepage measurements were made twice each month, from early June 2003 until September 2003; however, seepage meters on

Transect 31 were exposed by the end of July and measurements were no longer possible.

2.3.3 Geochemistry

Groundwater was collected over a one-year period from all piezometers excluding the eleven single piezometers. Groundwater was sampled in September/October 2002 from all the 0.025 m piezometers on Transects 31 and 46 and the 0.051 m piezometers along Transect 46. In late May/early June 2003, all piezometers except five on Transect 31, but only three on Transect 46 were sampled as the water in the other piezometers was frozen. All piezometers were sampled in July and September 2003.

Groundwater samples were collected using a low flow method (Puls and Barcelona, 1996), to minimize disturbance by purging. Electrical conductivity (EC), pH, dissolved oxygen (DO), temperature, and the volume of purged water were recorded as groundwater passed through a flow-through cell. Water was extracted at a rate of 40 or 125 mL/min, depending on which of the two peristaltic pumps was used. At the same time, drawdown in the piezometers was monitored. Once drawdown and field parameters had stabilized, groundwater samples were collected in 125 mL glass jars and the samples were stored on ice.

Water samples were divided into turbid and non turbid samples based on their clarity. Turbid samples were centrifuged to separate suspended solids from water. Thirty-five millilitre samples were then filtered using a 0.45 μm filter into 90 mL specimen jars for laboratory analysis.

Surface water samples were collected adjacent to staff gauges in May, July and September 2003. At each sampling round, triplicate samples were collected and then processed in the same manner as groundwater samples.

Spiked sodium bromide water used to fill the hollow drill casing was placed in 1 L polyethylene containers at the time of each installation. The samples were filtered and bottled using the same method as for groundwater samples.

All water samples were analyzed at Syncrude Laboratories in Edmonton, Alberta, for pH, and EC, and anion, cation, trace metal, ammonia, and alkalinity CO_3/HCO_3 concentrations. Bromide was included in anion analyses to determine if groundwater samples contained any drilling water. TDS concentrations in groundwater samples from 0.051 m piezometers that contained drilling water were adjusted. The adjustment was made based on the percentage of drilling water remaining (Appendix A).

Split and duplicate samples were collected to estimate the error associated with laboratory analysis and sampling technique. The maximum error for TDS concentrations between duplicate samples was estimated at 1 to 2%. Samples with greater than a 5% difference between cation and anion concentrations were resubmitted. Based on up to a possible 5% error associated with each sample, spatial and temporal changes in TDS were analyzed in groundwater samples and considered significantly different numbers between sampling rounds and with depth if 5% error bars for compared samples did not overlap.

2.3.4 Dam Stratigraphy

The stratigraphies along Transects 31 and 46 were interpreted from tailings sand depositional history (Appendix B). Digital contour maps (1 m contour interval) from 1991, and 1995 to 2003, were used to reconstruct changes in the ground surface between each year. The original design report (Klohn Leonoff, 1991) and revised design study (AEE, 1997) provided additional information, especially for 1991 to 1994. Other data used in the reconstruction included the 2002 surveyed dyke elevation at instrumentation locations. Stratigraphic units were defined by their "depositional" history: (a) constructed/reworked material on the dyke; (b) contained beaching; and, (c) free deposition by beaching. These three categories provide a more detailed description of the depositional environment than the two basic methods (dyke construction and beaching) used to describe general dam construction in the site description (section 2.2.1).

2.4 Results

2.4.1 Hydrostratigraphy

Figure 2-3 shows the interpreted stratigraphies, with placement years, of Transects 31 and 46. Deposition of tailings sand started in 1992 along Transect 31. Coarse tailings sand was discharged between a sand starter dyke (Bench A) and a parallel earthen dyke approximately 400 m west (Klohn Leonoff, 1991). In 1994, Bench B was built, tilted inward at a slope of < 1% above this control zone (contained beaching), and consisted of three constructed dykes (AEE, 1997). Bench C and its associated beach were built between 1995 and 1998, and Bench C was built tilted out at a slope of 2%. On Bench C, the constructed dykes formed a staircase, with narrower dykes built upslope of the previous dykes, instead of directly on top as on Bench B. Forward-sloped Bench and Slope C were constructed with an overall steeper slope (6%) than backward-sloped Benches and Slopes A and B (5%).

Transect 46 required no control zone. Instead, the toe and base of the perimeter dyke was built, starting in 1996, by dyke construction and beaching. The staircase positioning of constructed dykes on Benches C and D was similar to Benches C and D on Transect 31, except Bench C was sloped out at 4% and the overall slope of bench and slope remained at 6%. Tailings sand added north of Transect 46, in early 2003, elevated the beached sands behind Bench D by 3 m.

Measured saturated K of tailings sand along Transects 31 range from 5.8×10^{-7} to 1.6×10^{-5} m/s, with a geometric mean of 3.0×10^{-6} m/s (n= 48). Tailings sand deposited along Transect 46 has a similar K range of 4.0×10^{-7} to 9.8×10^{-6} m/s, but a lower geometric mean of 1.3×10^{-6} m/s (n=23). The two calculated averages are within less than half an order of magnitude.

The spatial K distribution varies across Transect 31 (Figure 2-4). The sand bench, part of Bench A, the control zone, the toe of Slopes C and B, Bench C, the upper half of Slope C, and sands beached in 1997 and 1998 have a higher K than the geometric mean (3.0×10^{-6} m/s). The geometric mean of the constructed dykes (3.1×10^{-6} m/s), control zone (3.3×10^{-6} m/s), and beached sand (2.7×10^{-6} m/s) show no trends or correlation between method of material placement and K.

The spatial K distribution across Transect 46 identified K zones of less than 1×10^{-6} m/s, at the toe of Slope C, adjacent beached sands placed in 1996 and in tailings beached in 1998 beneath Bench D (Figure 2-4). The constructed dykes (1.6×10^{-6} m/s) and beached sands (9.8×10^{-7} m/s) indicated no obvious trends between material placement method and K.

2.4.2 Water table configuration

The water tables along Transects 31 and 46 were a subdued profile of the bench and slope topography (Figure 2-4). A representative water table location for each transect was selected to represent a typical configuration over the study year. The dates selected for analysis, along Transects 31 and 46, were August 28, 2003 and October 7, 2002, respectively. In addition, the water table location across Transect 46 on October 20, 2003 is presented because the water table and beach positions were dramatically different than at the beginning of the study due to beaching.

The water tables measured at the top of both transects were higher than the tailings pond elevation, indicating a groundwater divide (Figure 2-4). For

Transect 31, the water table at GW15 was 383.9 metres above sea level (masl), over two metres above the 2003 pond water elevation (381.6 masl). On Transect 46, the water table at GW23 was 382.6 masl and within a metre of 2002 pond levels (381.7 masl). By Fall 2003, the water table had increased to 383.9 masl.

Between piezometer nest GW15 and staff gauge SG01, the water table was within 1 m of the ground surface over 23% of Transect 31 (Figure 2-4). Proximity of the water table to the ground surface increased in bench and slope pairs closer to the dyke toe. The water table was within 1 m across 36% of A, 22% of B, 13% of C and 0% of D. The water table was shallower than 0.1 m across the sand bench, the perimeter ditch, and across Channels A and B. The water table depth was greatest at the bench crests where it was 2.24 m at A (GW03), 4.31 m at B (GW07), 3.05 m at C (GW11) and 5.39 m at D (GW15).

Between piezometer nest GW23 and staff gauge SG04, the 2002 water table was within 1 m of the ground surface across 57% of Transect 46 (Figure 2-4). At the bench scale, the water table was within 1 m across 81% of C and 10% of D. The water table across Bench and Slope C had a maximum depth (1.41 m) at GW18, below the crest of Bench C. The water table depth increased beneath Slope D up to Bench D to a maximum of 5.31 m. The water table rose in the fall of 2003 and lay within 1 m of the ground surface across 93% of the transect.

The seasonal responses of the water table at the crests of the Benches A and B were different than at the crest of Bench C, Transect 31 (Figure 2-5). Benches A and B had a water table elevation that was highest in the spring (up by 0.29 m from the previous fall), but decreased over the summer and fall. In contrast, Bench C had a lower water table (by 0.36 m) in the spring compared with previous the fall. The water table increased by 0.45 m from spring to fall. Significant water table elevation increases corresponded to early summer and fall precipitation events. Bench D on Transect 31 had a similar seasonal water table response to Bench C.

On Bench C, Transect 46, seasonal water table fluctuations followed similar trends to Bench C, Transect 31; however, the magnitude of the seasonal response was greater (Figure 2-5). One notable difference was that the water table declined 0.60 m through the summer months of July and August. On Bench D, Transect 46, the water table response was similar to Bench C, Transect 46, in the summer and fall; however, it was higher in the spring than the previous fall due to beaching.

2.4.3 Surface water levels

Over the one-year study period, measured surface water levels did not fluctuate more than 0.10 m except in the perimeter ditch; however, some trends were observed. On Transect 31, surface water levels in the perimeter ditch increased (+0.25 m) between fall and spring, decreased (-0.04 m) through the summer months, and increased again in the fall to late spring levels. However, the perimeter ditch received sediment from upstream over the winter and spring, which raised ground surface and water levels in the ditch. Water levels in Channels A and B remained constant (-0.01 m (A)) or increased (+0.09 m (B)) between the fall and spring and then decreased through the summer (-0.05 m (A)) and (-0.02 m (B)). Fall water levels in these channels increased to near the late spring levels. Surface water in Channel B drained south, whereas water in Channel A appeared stagnant. On Transect 46, water levels in the perimeter ditch increased over the winter (+0.05 m), decreased during the summer months (-0.10 m), and remained constant through the fall.

By early April 2003, after the first significant snowmelt, the channels and ditches had collected considerable amounts of water and ice. On Transect 31, there was 0.37 m of ice in Channels A and B, and the ice thickness in the perimeter ditch was at least 0.65 m. The collection of ice in Channels A and B preceded elevated groundwater tables across adjacent Benches A and B. A depth of ice of 0.55 m was measured in the perimeter ditch, on Transect 46.

2.4.4 Hydraulic head distribution

Hydraulic head distributions across Transects 31 and 46 were determined by contouring head data by linear interpolation. For the interpolation, it was assumed that the tailings sand was approximately homogeneous. Flow diagrams were created by superimposing flow lines on the distribution of hydraulic head (Figure 2-6). The Transect 31 flow diagram shows local flow systems superimposed on an intermediate flow system. Groundwater flow, in local systems, was towards the east from Benches A, B and C, to the toe of the downhill slope. At the intermediate scale, groundwater travelled from the top of the perimeter dyke towards the perimeter ditch.

On Transect 46, groundwater travelled west in shallow local flow systems such as the one positioned at the crest of Bench C (Figure 2-6). Groundwater flow at the intermediate scale flowed from the top of the perimeter dyke towards the dyke toe. A groundwater divide separated the intermediate flow systems on Transects 31 and 46 from groundwater that flowed from the beach towards the tailings pond.

The average horizontal gradient across each of the Benches and Slopes A, B and C, on Transect 31, was 0.05 in August 2003. Across Bench and Slope C, on Transect 46, the gradient was 0.06 in October 2002. Locations closer to the groundwater divide, such as Benches and Slopes D on Transects 31 and 46, had horizontal gradients of 0.03. However, beached tailings sand deposited in early 2003 on Transect 46 increased the horizontal gradient, across Bench and Slope D to 0.04 by October 2003.

The velocity of the horizontal groundwater flow between piezometer nests was estimated using Equation 1 and the geometric mean estimated for each transect. On Transect 31, groundwater velocities across Benches and Slopes A, B, C and D were 11, 11, 18 and 3.9 m/yr. The groundwater velocity across the perimeter dyke was 11 m/yr. The velocity of groundwater flowing through the sand bench adjacent to the perimeter ditch was 17 m/yr. The K's used for geometric mean calculation for the sand bench were the average K estimated at the seepage meters (Lee and Cherry, 1978) and the K at GW27-1 at the toe of Slope A.

The groundwater velocities across Benches and Slopes C and D on Transect 46 were 5.4 m/yr and 6.4 m/yr, respectively in October 2002. Groundwater flowed across the perimeter dyke at a rate of 4.4 m/yr, less than half the velocity across the perimeter dyke on Transect 31.

Vertical gradients measured within piezometer nests indicate whether groundwater flow is away from or towards the water table. On Transect 31, the calculated vertical gradients in the shallow groundwater (0 to 3 below the water table) indicated downward flow across the benches and part of the slopes and upward flow at the toes of the slopes (Figure 2-6). The calculated vertical gradients were larger at 0.09 on the crest of Bench B (GW07) than the gradient of 0.02 on Bench C (GW11), which indicated greater downward flow at Bench B. Vertical groundwater flow near Channels A and B was upward at the slope toes and downward towards the bench crests. Near the perimeter dyke crest (GW15), towards the top of the intermediate flow system, a vertical gradient of +0.02 indicated downward flow. At the dyke toe, groundwater flow was upward at the perimeter ditch (GW30 = -0.01), the toe of Slope A (GW01 = -0.01; GW27 = -0.05), and at the mid-Slope A (GW02 = -0.05).

On Transect 46, vertical gradients in the shallow groundwater (0 to 3 m below the water table) within piezometer nests alternated between upward and downward along the transect length (Figure 2-6). Hydraulic gradients below the crest of

Bench C (GW18 = -0.04), mid-Bench C (GW20 = -0.02) and near the toe of Slope D (GW22 = -0.02) indicated upward groundwater flow. At the top of the perimeter dyke (GW23), the gradient was +0.02. At the toe of Slope C (GW16 = -0.03) and in the perimeter ditch (GW34 = -0.05) groundwater flow was upward.

Vertical groundwater velocities within piezometer nests were estimated using Equation 1 and the harmonic mean within the shallow piezometers (0 to 3 m below the water table). Groundwater velocities at the perimeter ditches on Transects 31 and 46 were calculated using an average seepage meter flux from July 2003 (31) and September 2003 (46). On Transect 31, the maximum vertical groundwater velocities in the recharge areas of Benches A, B, C and D were 1.1, 12, 7.8, and 4.7 m/yr, respectively. Groundwater velocities in discharge areas were 7.1 (GW30 (perimeter ditch)), 8.0 (GW02 and GW27(A)), 1.6 (GW01), 58 (GW24(B)), and 50 (GW29(C)) m/yr.

On Transect 46, the maximum vertical groundwater velocities in recharge areas were 4.5 just below mid-Slope C (GW17), 3.3 at the crest of Bench C (GW19), 1.0 up from mid-Bench C (GW21), and 1.9 on Bench D (GW23) m/yr. Groundwater velocities in discharge areas were 4.0 at the perimeter ditch (GW34), 1.5 at the toe Slope C (GW16), 2.0 below crest of Bench C (GW18), 5.3 at mid-Bench C (GW20) and 1.0 up from the toe of Slope D (GW22) m/yr.

2.4.5 Groundwater Seepage

Seepage fluxes into the perimeter ditch of Transect 31 ranged from 2.2×10^{-7} to 4.0×10^{-7} m/s. In the perimeter ditch at the toe of Transect 46 seepage fluxes were between 3.3×10^{-8} and 1.7×10^{-7} m/s. The measured seepage fluxes at both locations decreased over the 2003 season.

2.4.6 Total dissolved solids in groundwater

Groundwater sampled at the SWSS is alkaline, sodium-bicarbonate dominant, transitioning to sodium-chloride dominant, according to Back's (1961) hydrochemical classification. The sodium-bicarbonate waters were found in older tailings on Transect 31 (*i.e.,* Bench A). An average groundwater sample had a field pH of 7.9 (±0.5), a field electrical conductivity (EC) of 4.0 (±0.7) mS/cm, a total dissolved solids (TDS) concentration of 2900 (± 400) mg/L, and a dissolved oxygen concentration of 0.3 (±0.5) mg/L. One standard deviation is shown after each average value in parentheses. The major contributors to TDS in the groundwater were sodium (Na^+), bicarbonate (HCO_3^-), chloride (Cl^-), and sulphate (SO_4^{-2}). The relative importance in equivalent weights of cations is generally $Na^+ >> Ca^{2+} > Mg^{2+}$ (97:2:1) and of anions is $HCO_3^- > Cl^- > S0_4^{-2}$ (45:41:14).

The average TDS of the groundwater across Transect 31 over the study year was 2900 mg/L and ranged from 1300 to 4200 mg/L. The July 2003 TDS distribution, contoured by linear interpolation, was selected as representative of the one-year study period (Figure 2-7). The distribution shows that at mid-Slope A, the TDS concentration was higher in the shallow groundwater (3400 mg/L) than surrounding groundwater. The shallow groundwater TDS concentrations on the crest of Bench B (1400 mg/L) and the toe of Slope B (2400 mg/L) were the lowest along the profile. Shallow groundwater on Bench C had TDS concentrations greater than 4000 mg/L. Generally, TDS increased from the toe to the top of the perimeter dyke. The field EC's were greater than 4.0 mS/cm above Bench B (Figure 2-7).

The average TDS concentration at Transect 46 over the study year was 3000 mg/L, and within a range from 2400 to 3900 mg/L. The October 2002 TDS distribution (Figure 2-7) was selected as representative of the one-year study period. In general, TDS increased from the toe to the top of the perimeter dyke.

Shallow groundwater above mid-Slope C had TDS concentrations greater than 3000 mg/L and EC's greater than 4.0 mS/cm. There were no low TDS zones.

Figure 2-8, groundwater TDS versus age of tailings, shows that TDS is higher in more recently deposited tailings. Only the shallow groundwater on the crest of Bench B on Transect 31 had a lower TDS (1400 mg/L) in July than the original process water at that location. The maximum TDS on Bench C was higher (4200 mg/L) than when tailings sand were originally deposited (~2900 mg/L), and higher than the estimated maximum TDS of any process water deposited at the SWSS (~3500 mg/L).

Groundwater samples in all piezometer nests were examined to determine if trends in TDS corresponded to depth. At 5 shallow nest locations on Transect 31, TDS varied with depth in July 2003 (Figure 2-9). At mid-Slope A (GW02), the TDS increased from 2700 to 3400 mg/L towards the water table, with increased relative concentrations of Na^+ and Cl^-. On the crest of Bench B (GW07), the shallow groundwater had a low TDS, lower relative concentrations of Na^+ and Cl^- and higher concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{-2} compared with the average groundwater sample. On Bench C (GW12 and GW11), the TDS was higher near the water table than at depth. However, at the middle of Bench C, the relative ion concentrations near the water table were lower in Na^+ and Cl^- and higher in Ca^{2+}, Mg^{2+}, and SO_4^{-2}. At the toe of Slope D (GW13), TDS decreased towards the water table. The changes in shallow water composition at the toe of Slope D were similar to mid-Bench C. In the deeper piezometers (> 9 m) on Bench D, TDS was higher at 15 m depth compared to the 24 and 33 m depths (Figure 2-7).

On Transect 46, only GW23 showed a trend with depth in October 2002. At Bench D (GW23), TDS was higher in the shallow groundwater at 7 m and 12 m, than at 19 m depth (Figure 2-7). Generally, groundwater chemistry remained constant with depth; however, Ca^+ and Mg^+ ion concentrations were slightly higher in the shallow groundwater at GW21 (Figure 2-10).

The TDS relationship with depth remained constant over the one-year study period in most piezometer nests. In five locations on Transect 31, there were changes between seasons or over the study year (Figure 2-9). The TDS concentrations in the shallow groundwaters on Bench A (GW03, GW04) varied throughout the season, but were highest in the spring. In addition, the shallow groundwater had higher relative concentrations of Ca^{2+} and Mg^{2+}. At mid-Slope B (GW06), TDS near the water table was lower in the spring than the summer. On Bench C (GW12), the TDS concentrations were higher in spring and summer than either the fall of 2002 or 2003. At the toe of Slope D (GW13), groundwater TDS near the water table decreased by 1200 mg/L over the year.

On Transect 46, a TDS change was evident in only one piezometer nest (Figure 2-10). The TDS of the shallow groundwater below mid-Slope C (GW17) was 600 mg/L lower in the summer of 2003 and returned to its previous concentration in the fall (3000 mg/L).

2.4.7 Total dissolved solids in surface water

Surface waters sampled in the perimeter ditch (SG01), Channels A (SG02) and B (SG03), on Transect 31, and in the perimeter ditch (SG04) on Transect 46 are alkaline, sodium-bicarbonate dominant (Channel A, Transect 31), or saline, sodium-chloride dominant elsewhere (Back, 1961). A typical (*i.e.,* average) surface water sample from Transect 31 had a laboratory pH of 8.3 (±0.2), laboratory EC of 3.8 (±0.6) mS/cm and TDS of 2900 (±300) mg/L. Transect 46 had an average laboratory pH of 8.0 (±0.2), laboratory EC of 3.3 (±0.7) mS/cm, and TDS of 2300 (±500) mg/L.

The surface water chemistry was similar to the groundwater chemistry with sodium (Na^+), bicarbonate (HCO_3^-), chloride (Cl^-), and sulphate (SO_4^{-2}) as the major constituents. Mg^{2+} and Ca^{2+} concentrations were slightly elevated in the perimeter ditch on Transects 31 and 46. In addition, there were slightly elevated concentrations of Ca^{2+} and SO_4^{-2} in Channels A and B on Transect 31.

On Transect 31, surface waters in the perimeter ditch were 2900 mg/L in the spring (May) and decreased gradually to 2400 mg/L in the fall (September). Channel A had a higher TDS in the spring (3300 mg/L), which decreased in the summer (2900 mg/L) and stayed constant through to the fall. This range of TDS concentration was higher than in the groundwater at the toe of Slope B (GW05-3; 2400 to 2700 mg/L). Channel B had a higher TDS in the spring (3100 mg/L), which decreased in the summer (3000 mg/L) and remained constant. The surface water TDS concentrations were the same as adjacent groundwaters (GW09-2; 2900 to 3100 mg/L).

On Transect 46, TDS of the surface water in the perimeter ditch cycled from 2300 mg/L in spring to 1800 mg/L in summer and back up to 2800 mg/L in fall. The range of TDS concentrations were lower than the groundwater at the adjacent toe of Slope C (GW16-4; 2900 to 3100 mg/L).

2.5 Discussion

2.5.1 Groundwater flow systems

Groundwater flow through the SWSS along Transects 31 and 46 is characterized by nested local and intermediate flow systems through the relatively homogeneous and permeable fine sand (Figure 2-6). On Transect 31, three local flow systems exist, one for each of the lower bench and slope pairs. Flow systems are recharged on the benches and parts of the slopes and discharge at the toes of the slopes at observed seepage faces. Local recharge areas exist across Benches and part of Slopes A and B including part of the channel adjacent to the bench and across Bench and Slope C and Slope D. Local discharge areas exist below mid-Slope A, and at the toe of Slopes B and C. The channels behave as groundwater flow-through systems (Meyboom, 1967) capturing discharge from local and intermediate flow systems and recharging some of the groundwater on the down-gradient side (Winter, 1986). The intermediate flow system is recharged across Bench D, Bench and Slope E and on the upper beach. Discharge is into the perimeter ditch, at the toe of Slope A onto the adjacent sand bench, and into Channel A.

On Transect 46, local flow systems are very shallow and are superimposed on the dominant intermediate system. Recharge and discharge areas extend between piezometer nests (~ 30 m). The local flow systems are recharged below mid-Slope C (GW17), at the crest (GW19) and towards Slope D (GW21) on Bench C, and on Bench D (GW23). Groundwater discharge areas are at the toes of Slope C (GW16), below the crest of Bench C (GW18), mid-Bench C (GW20), and near the toe of Slope D (GW22). The larger intermediate flow system is recharged at the top of the perimeter dyke and discharges below the crest of Bench C and at the toe of Slope C. Discharge from local and intermediate flow systems is not focused; therefore, the groundwater discharges along a large expanse of the transect with seepage observed at the toe of Slope C. These nested flow systems on the perimeter dyke, though common in natural flow systems (Tóth, 1963), do not exist typically in tailings dams which usually are internally drained (*e.g.,* Hunter, 2001; Mittal, 1981; Plewes *et al.*, 1997).

High water tables may have a negative impact on the success of reclamation due to water logging and high TDS groundwater near the reclamation soil and vegetation (National Research Council, 1993). The water table is less than 1 m below the ground surface on Transect 31 at the sand bench, toe of Slope A, across Channel A, and part of Bench A, toe of Slope B, Channel B and part of Bench B, toe of Slope C and mid-Bench C (Figure 2-4). On Transect 46, the water table is within 1 m of the ground surface from the toe of Slope C to mid-Slope C and across Bench C. Along both transects, the water tables are shallower near to the toe of the perimeter dyke, a result of both local and intermediate flow converging in an area where the aquifer is thin, resulting in more intense flow (Tóth, 1963). The shallow water tables coincide with areas of high soil moisture content reported for Cell 32 (Chaikowsky, 2003) and for Cell 46 (Burgers, 2005).

The water table positions along each transect varied through the one-year field study. Groundwater on Benches A and B are recharged primarily in the spring (Figure 2-5), likely from waters that pond in Channels A and B after snowmelt. The Nebraska Sandhills study area (Winter, 1986), where the climate and sandy geologic setting are comparable to the SWSS, has similar spring recharge timing and increase of the water table elevation (~ 50 to 100 cm). The seasonal water table response on Bench C shows less spring recharge and more recharge later in the season than Benches A and B. This is likely due to reduced infiltration as the ground was frozen until early June limiting its capacity to absorb water (confirming Granger *et al.*, 1984), or because there are no channels to collect and focus snowmelt (see Hayashi *et al.*, 2003). The water table elevation increases throughout the season, likely because there are no plants to intercept precipitation or remove water by transpiration (Peck and Williamson, 1987). Other tailings dams report increases of the water table elevation from snowmelt and precipitation events (*e.g.*, Al and Blowes, 1999).

On Bench C, Transect 46, groundwater is primarily recharged by precipitation in the fall as evidence by increases in the water table elevation after fall precipitation events. The groundwater is not recharged in the spring as the shallow groundwater was frozen (see Granger *et al.*, 1984). Evaporation from shallow groundwater lowered the summer water table by 0.6 m. The water table responsiveness to large precipitation events indicates that the water table on Bench C can become very shallow, as seen in October 2003, intersect the reclamation materials and promote runoff. Hence, a lower TDS of surface water is observed in the perimeter ditch. In addition, the water table position at the top of the perimeter dyke increases with nearby beaching; a response which has been observed previously at other tailings sands dams (*e.g.* Plewes *et. al*, 1997).

2.5.2 Salt distribution and movement

Generally, most groundwater sampled at the SWSS has a similar TDS concentration and chemical composition as the input tailings process water. TDS concentration of groundwater increases towards the top of the perimeter dyke because the process water TDS increases over time in the deposited tailings (Liggett, 2004). Groundwater TDS on the perimeter dyke is currently greater than when originally deposited (Figure 2-8) as older process water has been replaced by newer higher TDS process water.

Despite these general trends, there is variation in shallow groundwater chemistry of the local flow systems on Transect 31, as the groundwater interacts with the hydrologic cycle (Tóth, 1963). In late spring of 2003, elevated TDS concentrations in shallow groundwater compared with depth on Benches A and C (Figure 2-9) resulted from dissolution and recharge of soluble salts from near the ground surface or from a rising water table (Jagannadha Sarma *et al.*, 1979). Based on nearby soil-moisture measurements, Chaikowsky (2003) suggests a similar hypothesis: that low salinity in the topsoil and near the soil/sand interface was in part due to downward percolation of water, forcing salts to remain at depth. Reclamation soil has higher average concentrations of Ca^{2+} and Mg^{2+} ions (Chaikowsky, 2003; Macyk *et al.*, 2002) than are found in process water and would be the source of these ions in the shallow groundwater on the benches. Recharge from low TDS precipitation dilutes shallow groundwater, as seen on the crest of Bench B and at the toe of Slope D (as described by Whittemore *et al.*, 1989; Jagannadha Sarma *et al.*, 1979). The higher TDS concentration, relative to the maximum TDS of process water, in the shallow groundwater on Bench C, may be due to historical or current evaporation. Salt may accumulate in the shallow groundwater, where the water table is close to the ground surface at mid-Bench C (Salama *et al.*, 1999).

On Transect 46, there is little evidence that recharge dilutes shallow (*i.e.*, 1 m below the water table) groundwater. The shallow local flow systems do not recharge precipitation deeply into the groundwater. There are no low TDS zones and no changes over the year in the shallow groundwater TDS, except at GW17 (Figure 2-10). The shallow groundwater at GW17 had lower TDS during the summer 2003, due to recharge of precipitation. In addition, there are small increases in Ca^{2+} and Mg^{2+} ions in the shallow groundwater at one of the local recharge areas (GW21), probably leached from reclamation soils by recharge. More long-term data is required on Transect 46 to determine any temporal trends in the groundwater chemistry.

Soil salinization commonly occurs in areas of groundwater discharge or of rising water tables, when mineralized pore-water continually evaporates and causes minerals to precipitate (Salama *et al.*, 1999). On Transect 31, there are no increases in TDS within proximity of the water table in discharge areas, except at mid-Slope A. Discharge of process water at mid-Slope A and the toe of Slope A has occurred longer than at any other discharge area because it is the oldest bench. Channels A and B act as flow-through systems for a portion of the discharged water and associated salts. Currently, the channels have not accumulated significant salts and only exhibit a slight increase in surface water TDS in Channel A relative to adjacent groundwater. In discharge areas on Transect 46, there are no increases of TDS within 1 m of the water table; however, precipitated salts were observed at the ground surface in discharge areas adjacent to the perimeter ditch and below the crest of Bench C during the summer.

Salinization is a concern when proceeding with reclamation at the SWSS as the process water exceeds a TDS of 3000 mg/L and an EC of 4.0 mS/cm.

Four mS/cm is the critical value where generally plant growth becomes impacted by salts (Edwards, 1985; Marschner, 1986). Local and intermediate discharge areas (*e.g.,* mid-Slope A, 31) have the greatest potential for reclamation soil and groundwater salinization from process water, as the upward salt fluxes would usually be the greatest (Salama *et al.*, 1999). Also, recharge areas, where there are high water tables and evaporation is possible (*e.g.,* Bench C, 31 and 46), have the potential for salt accumulation in shallow groundwater and in the reclamation soil (Salama *et al.*, 1999). Finally, recharge areas, where the water table is low and recharged by precipitation (*e.g.,* Bench B, 31), are of least concern for soil or groundwater salinzation, as shallow groundwater becomes flushed of process water containing salts.

2.5.3 Influences on flow systems and salt movement

If the SWSS remains undrained, its topography and hydraulic properties, and the Fort McMurray climate will continue to control the dam's groundwater flow system. Backward and forward sloped benches have different local groundwater flow and TDS patterns, as the two designs possess different topographic relief and slope (Tóth, 1963). Backward-sloped benches have greater local topographic relief, but less overall slope. Increased relief at the ground surface usually results in greater depth of the local flow system (Tóth, 1963). The bench design also results in a deeper water table at the bench crest, as seen on Bench A on Transect 31, when compared with Bench C on Transect 46, which have similar positions in the intermediate flow system (Figure 2-6). Local flow systems can recharge precipitation deeper into the groundwater, diluting high TDS process water as on Bench B and toe of Slope D and flushing salts down from near the surface to below the water table as seen on Benches A and C (Whittemore *et al.*, 1989). Bench B, on Transect 31, has the greatest relief due to bench design, greatest vertical gradients and highest dilution of TDS in the shallow groundwater. The steeper overall slope of the forward-sloped Bench and Slope C on Transect 46, compared with backward-sloped Bench and Slope A on

Transect 31, translates to greater lateral flow towards the perimeter dyke toe and shallower depth of local flow (Tóth, 1963).

The higher average K on Transect 31 contributes to a lower water table, higher groundwater flow and discharge rates, and greater changes of TDS in the shallow groundwater. On Transect 46, the lower K elevates the water table closer to the ground surface, and decreases the rate of flow and discharge of groundwater and salts. In addition, the lower K constructed dyke at the perimeter dyke toe modifies nested groundwater flow patterns (Freeze and Witherspoon, 1967) by causing a discharge area to occur below the crest of Bench C (Figure 2-6).

Evapotranspiration influences the groundwater flow system and salt transport at only a few locations on Transects 31 and 46. Shallow groundwater at mid-Bench C on Transect 31 has higher TDS concentrations than anticipated likely due to evaporation. In addition, the shallow water table on Bench C on Transect 46 decreased in the summer due to losses from evaporation. The depth to the water table is a controlling factor on the amount of evapotranspiration (Salama *et al.*, 1999). At the SWSS, evapotranspiration draws water upwards when water table depth is less than 1 m (Bews and Barbour, 2000). Evapotranspiration causes soil salinization as the evaporative flux (*i.e.,* discharge) draws salt upwards from the groundwater to the ground surface instead of downward leaching flux that exists in deeply drained soils (Namken *et al.*, 1969). Evaporation from high water tables causing soil salinzation has been reported in east central Alberta (*e.g.,* Hendry *et al.*, 1990) and Australia (*e.g.,* Peck and Williamson, 1987), where potential evapotranspiration generally exceeds precipitation, as it does in Fort McMurray.

2.6 Conclusions

There are nested local (bench) and intermediate (dyke) flow systems on Transect 31. Groundwater is recharged on the benches and part of the slopes and discharge is focused at the toes of the slopes. The water table is at less than 1 m below the ground surface across 23% of the transect. The local flow systems are connected to the hydrologic cycle indicated by variable TDS: low TDS where recharge of precipitation occurs and high TDS in the shallow groundwater in the spring from flushing of salts.

On Transect 46, the shallow local flow systems are superimposed on a dominant intermediate flow system. Recharge and discharge locations alternate between piezometer nests. Subsequently, discharge is along a large expanse of the transect. The water table is less than 1 m below the ground surface across 57% of the transect. No low TDS zones, changes in shallow groundwater chemistry or trends of TDS with depth confirm minimal groundwater interaction with the hydrologic cycle. However, the high water table conditions suggest it is possible for the water table to be affected by evaporation.

A key influence on the flow system is the topographic relief of the backward-sloped bench which creates deep local flow systems, deep water tables, flushing of process water and focused discharge at the toes of slopes. On Bench C on Transect 46, the water table is shallow and discharge is along a large expanse of the transect due to lack of topographic relief. The groundwater flow system is modified by changes in hydraulic conductivity.

The understanding of stratigraphy, the flow system and salt movement at the SWSS are integral in developing an accurate conceptual model. Groundwater flow and transport models are additional tools that can be used in the future to improve the understanding of groundwater flow and salt transport in an undrained tailings sand dam.

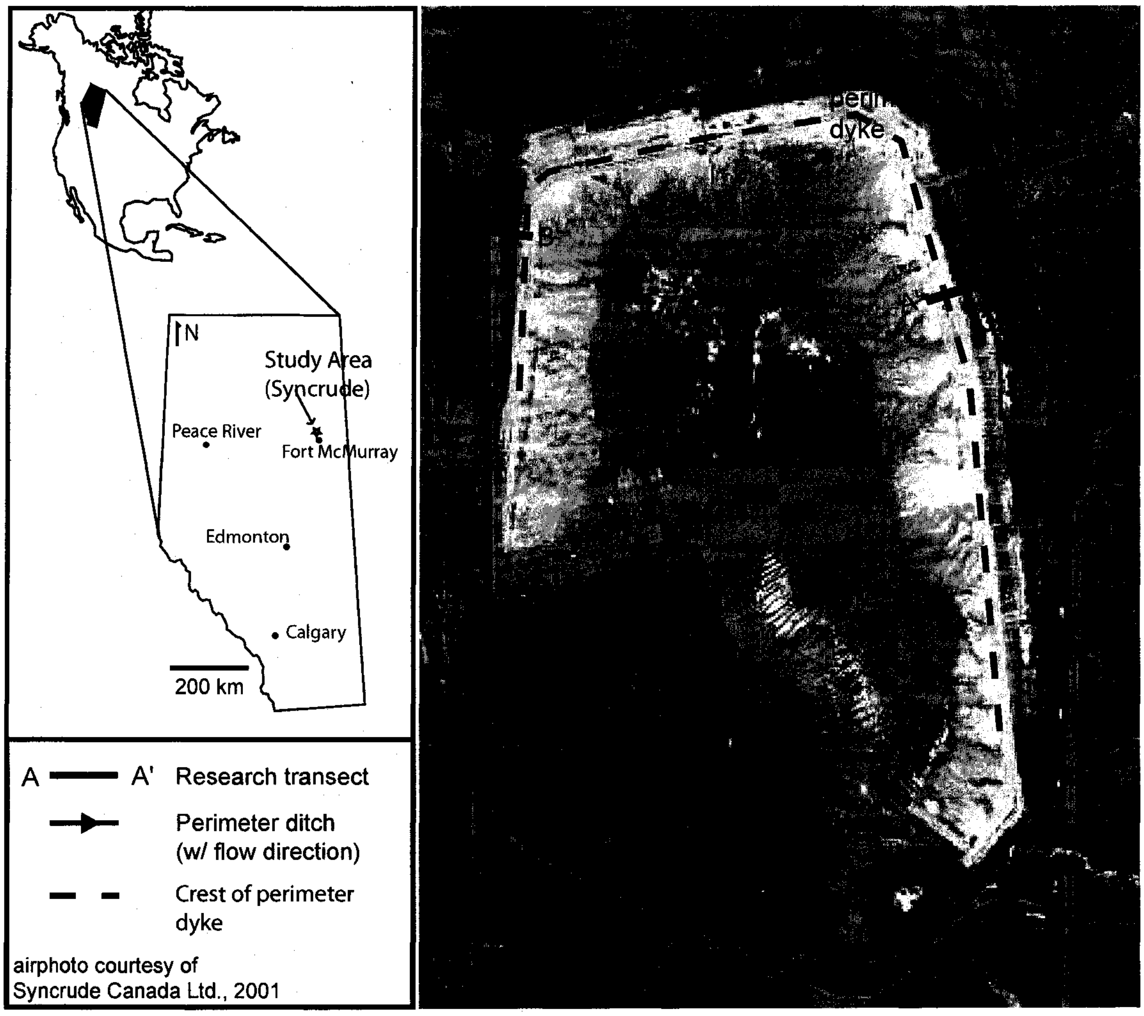

Figure 2-1. Research Transects 31(A - A') and 46 (B - B') at the Southwest Sand Storage Facility. Darker areas on the perimeter dyke indicate reclaimed areas in 2001. Insets show locations within Alberta and North America (top left).

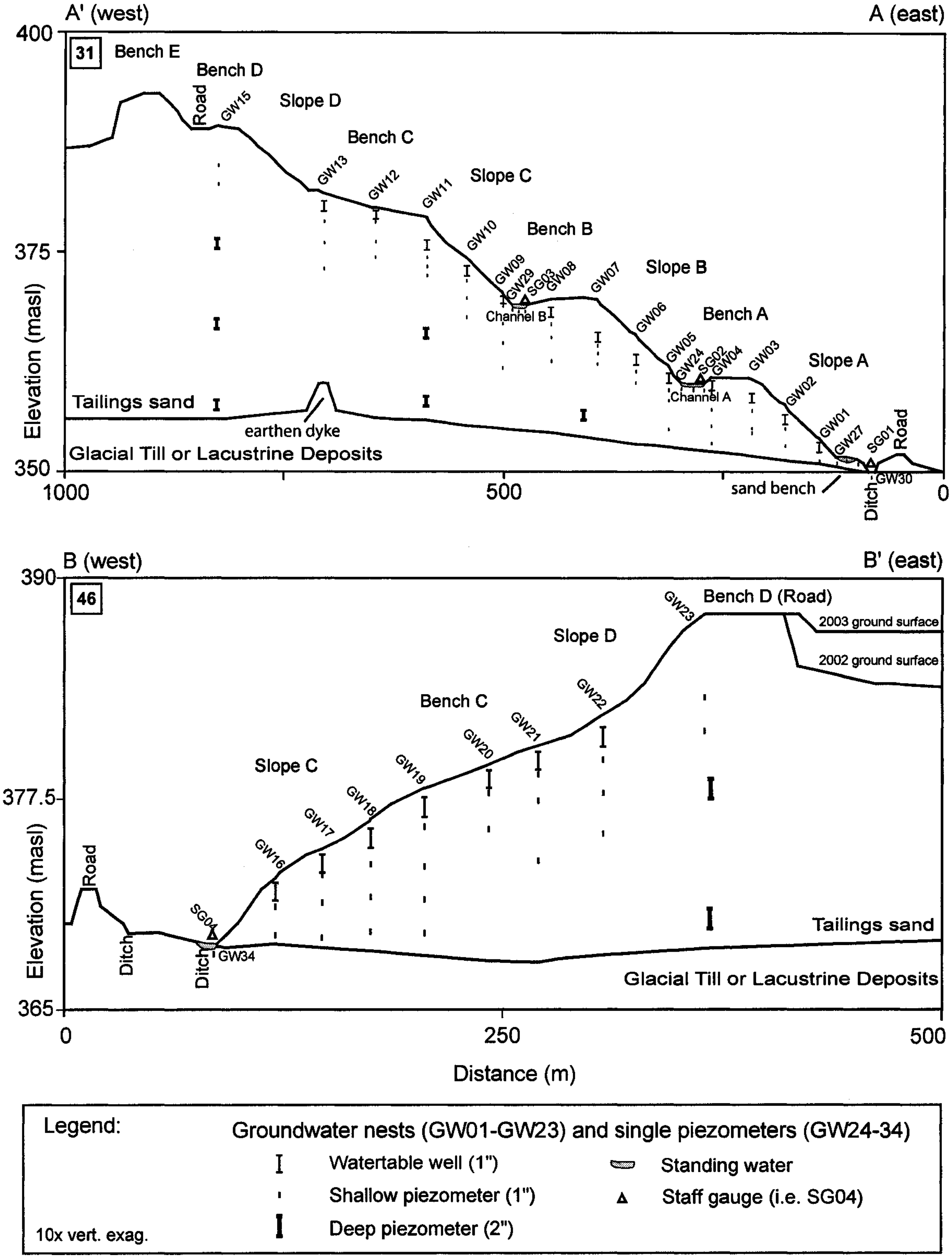

Figure 2-2. Cross-sections of Research Transects 31(top) and 46 (bottom). Note the 50 % scale differences. Seepage meters are located next to the piezometer in the perimeter ditch on Transects 31 and 46. Screen lengths and locations are indicated for wells and piezometers.

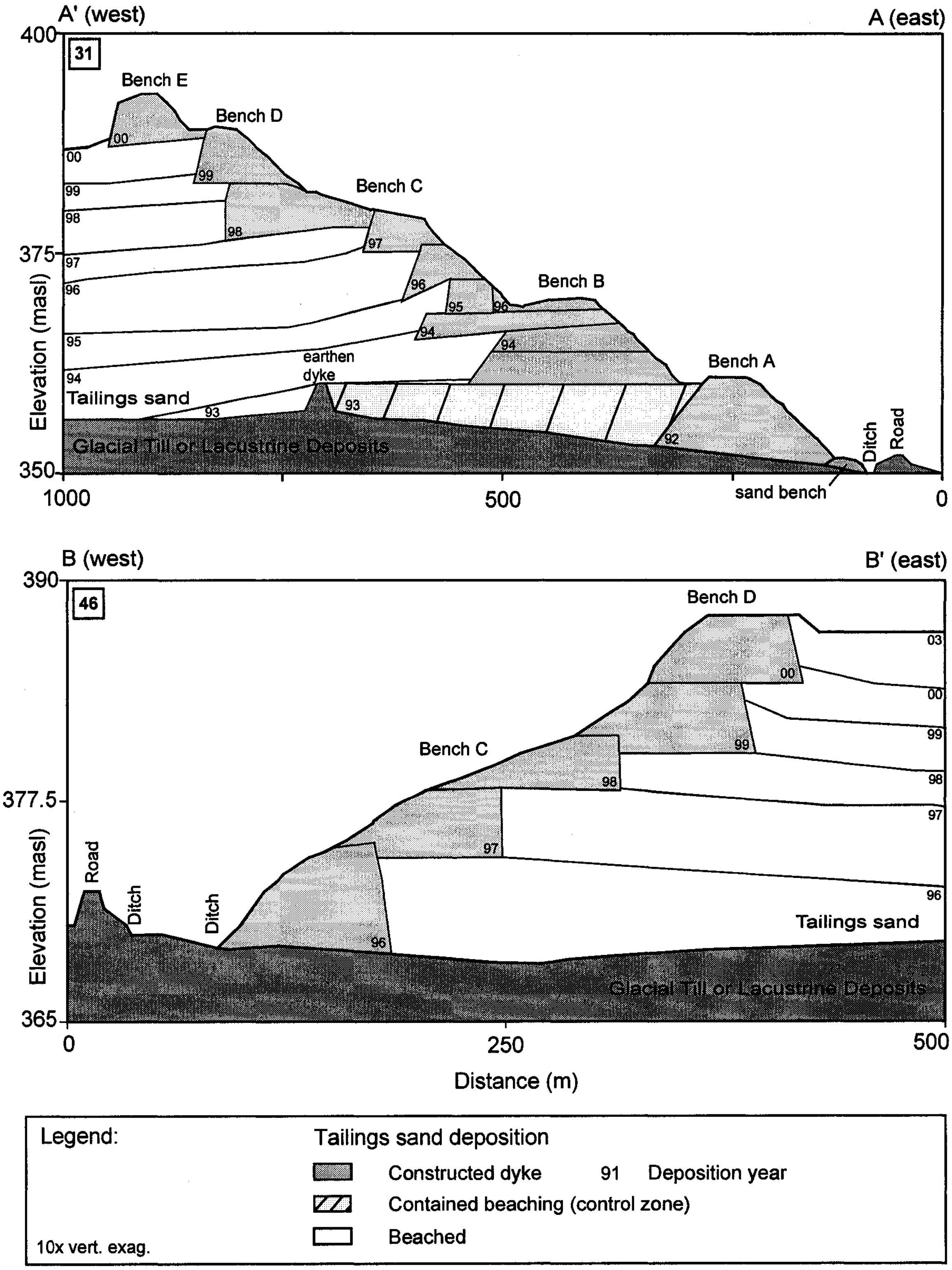

Figure 2-3. Geologic cross-sections across Transects 31(top) and 46 (bottom), with different tailings deposition zones and year of deposition. Note the 50% scale difference between cross-sections.

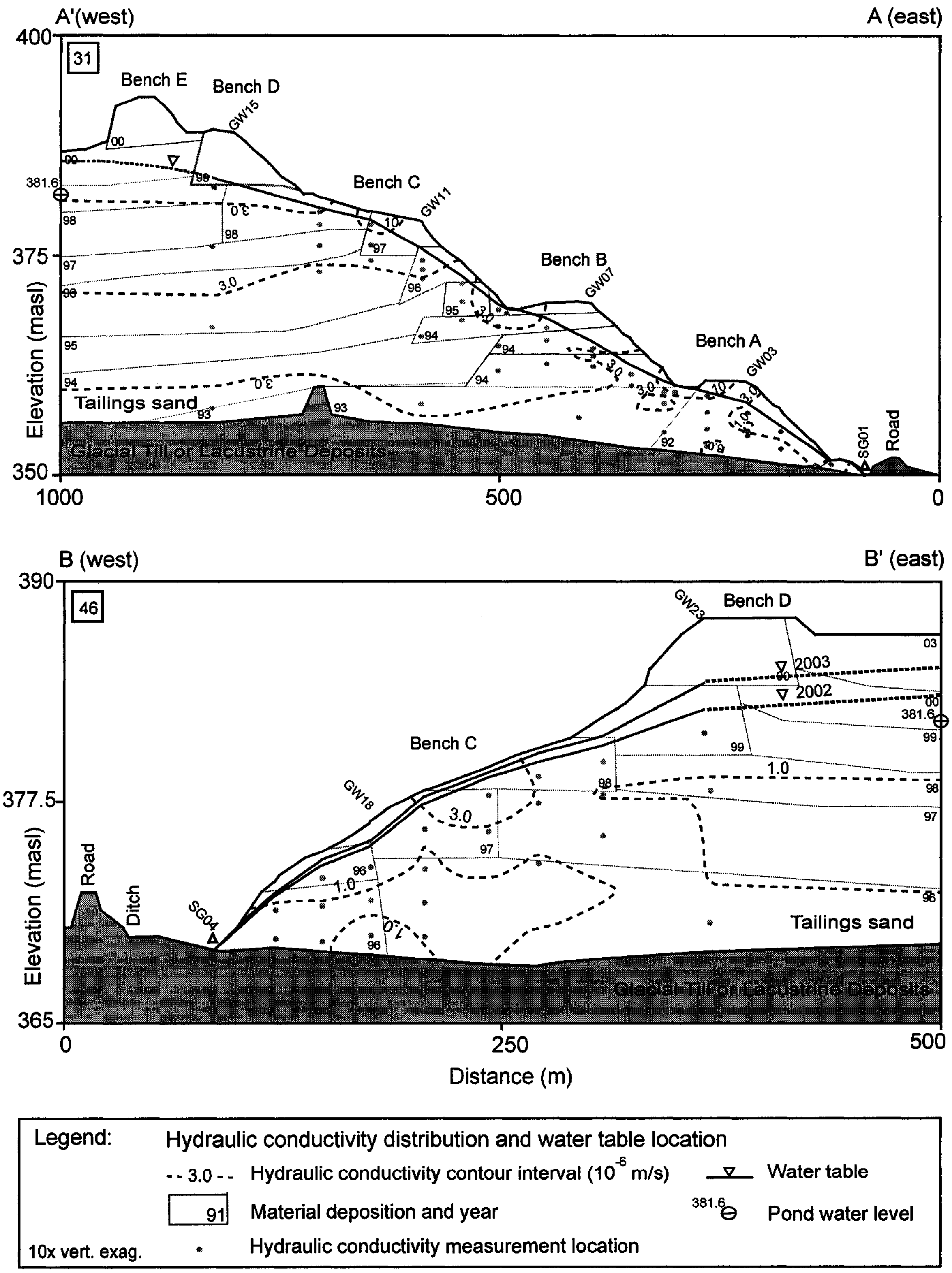

Figure 2-4. Hydraulic conductivity distributions and water table locations across Transects 31 (top: August 2003) and 46 (bottom: October 2002 & 2003). K's contoured by linear interpolation and constrained by units from perimeter dyke crest towards the pond.

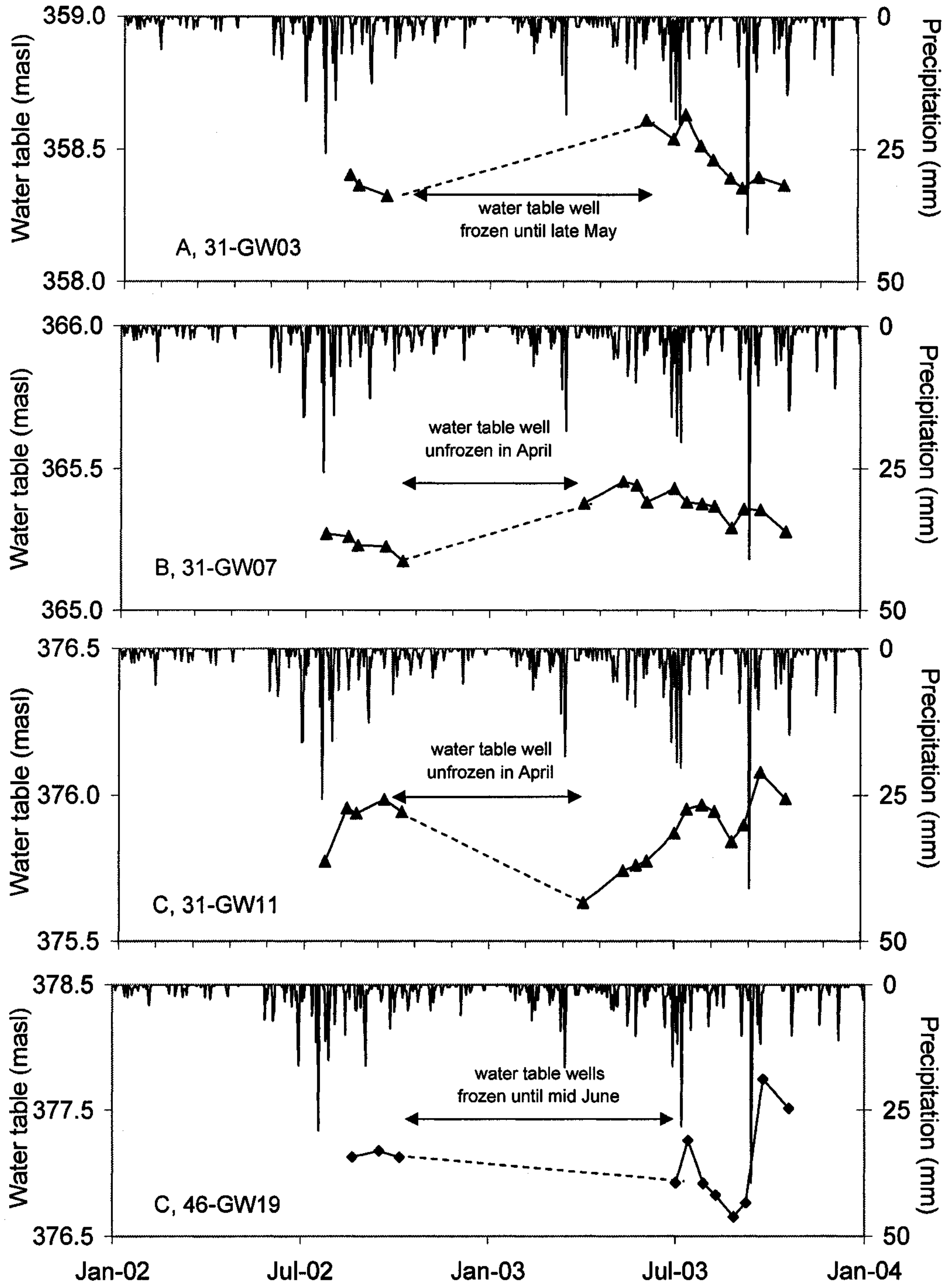

Figure 2-5. Seasonal water table response at the crests of Bench A (GW03), Bench B (GW07) and Bench C (GW11) on Transect 31 and Bench C (GW19) on Transect 46. Rain data from SWSS plus snow data from Ft McMurray Airport shown across the top axis (Okane, 2004; Environment Canada, 2004). Note change in vertical scale for Transect 46.

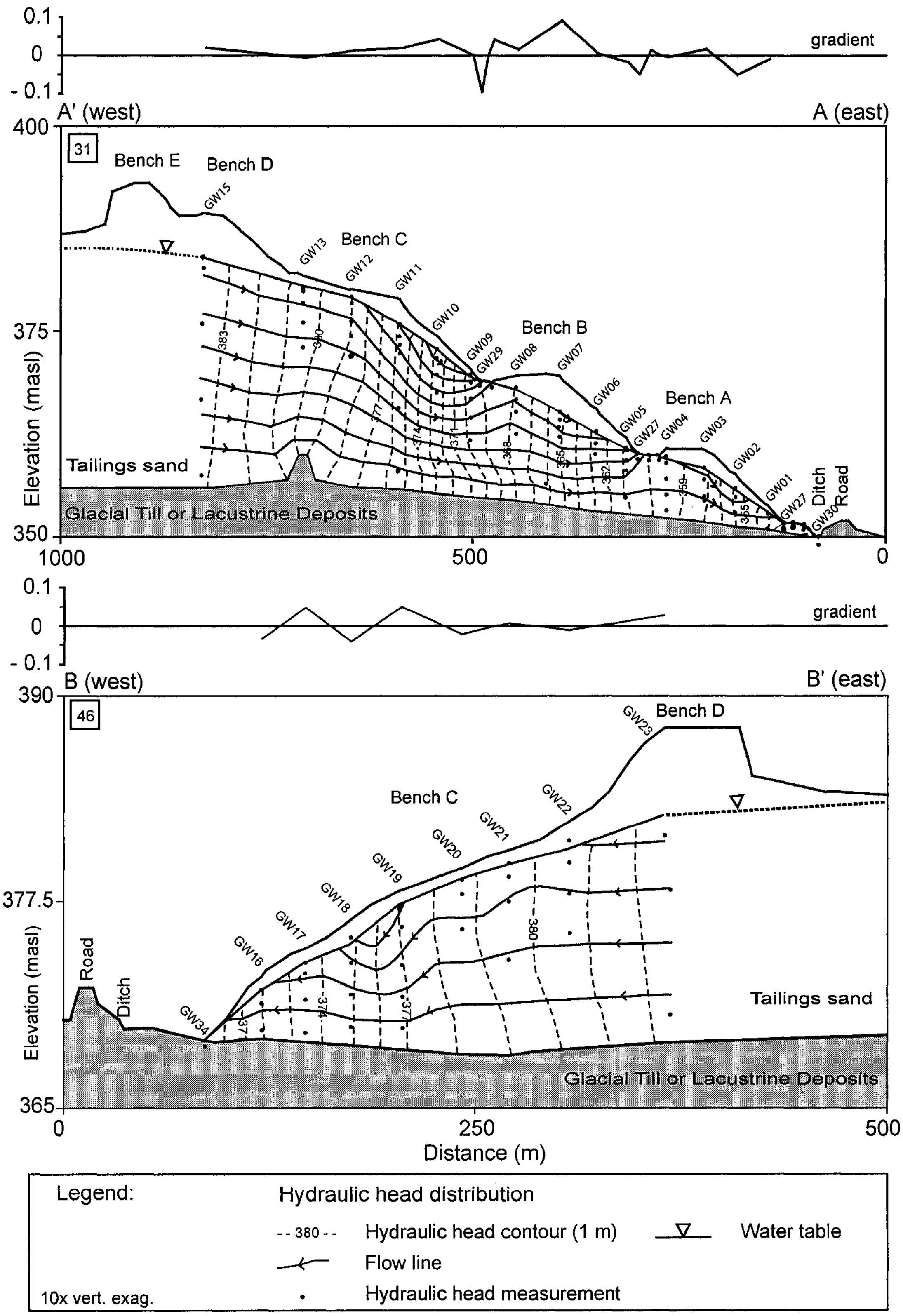

Figure 2-6. Flow diagrams across Transects 31 (top: August 2003) and 46 (bottom: October 2002). Hydraulic head data contoured by linear interpolation. The vertical gradient in each piezometer nest and piezometers across channels are shown above each flow diagram. Note the 50% difference in scale.

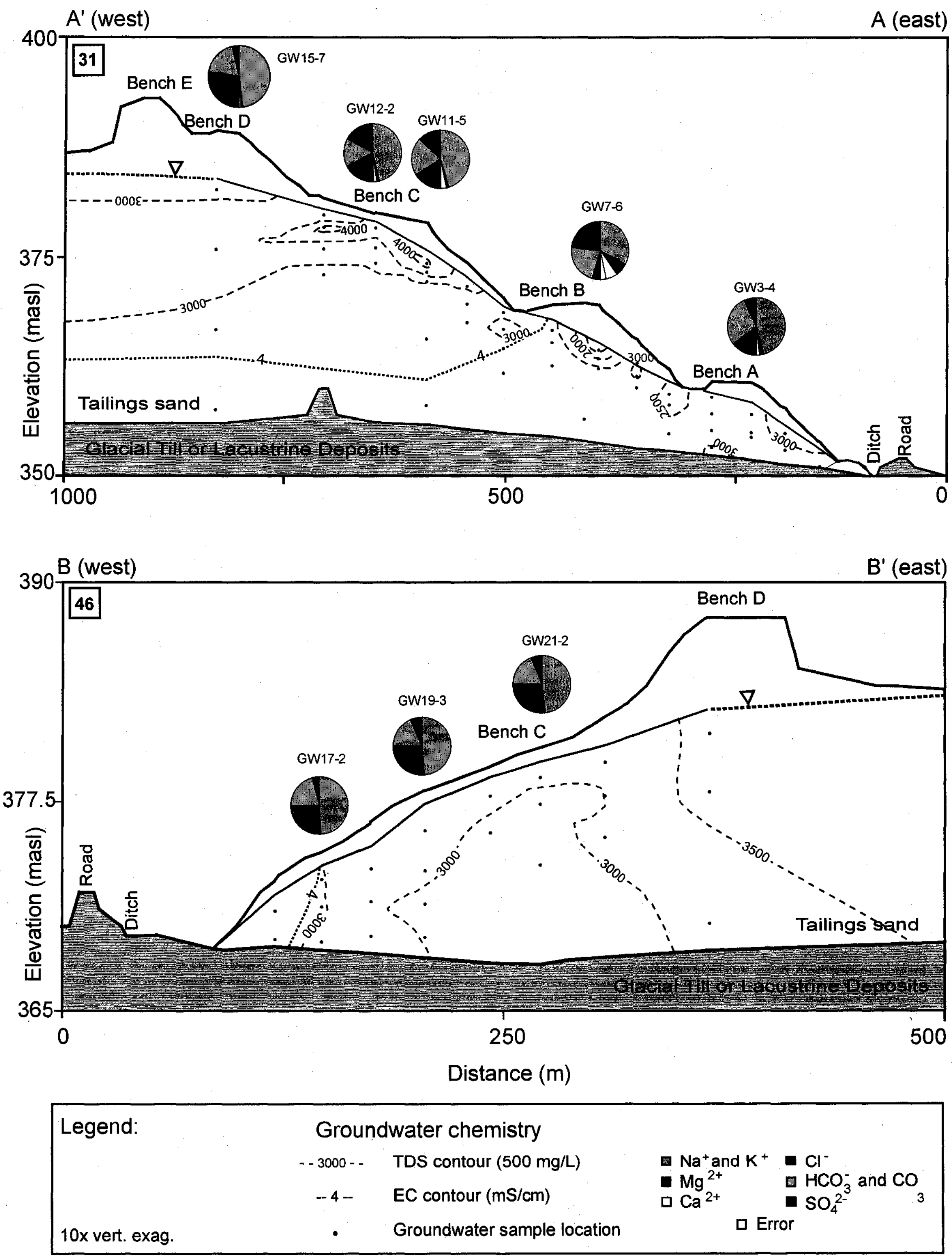

Figure 2-7. Groundwater total dissolved solids (mg/L) distributions across Transects 31 (July 2003) and 46 (September 2002). Electrical conductivity (EC) contour indicates locations where EC was generally above 4 mS/cm. Pie charts indicate relative concentrations of major ions in shallow groundwater.

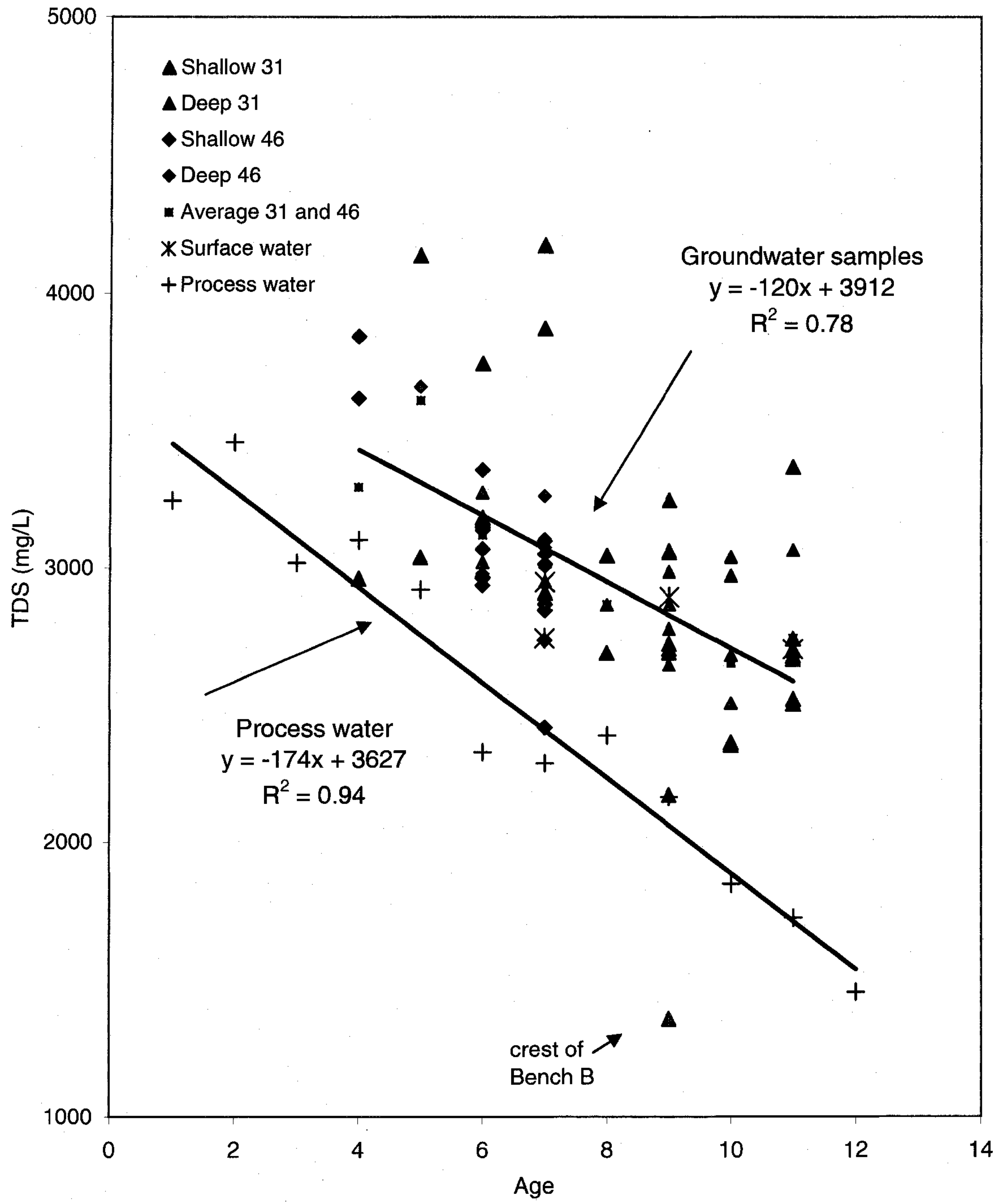

Figure 2-8. Groundwater total dissolved solids concentrations from Transects 31 and 46 (July 2003) compared to tailings age. The line indicates the change in average TDS with age. Historical TDS of process water placed at the SWSS between 1991 and 2002 is included (Liggett, 2004). The "deep" groundwater samples are from deep piezometers (> 9 m) and the deepest piezometer in the shallow groundwater nests.

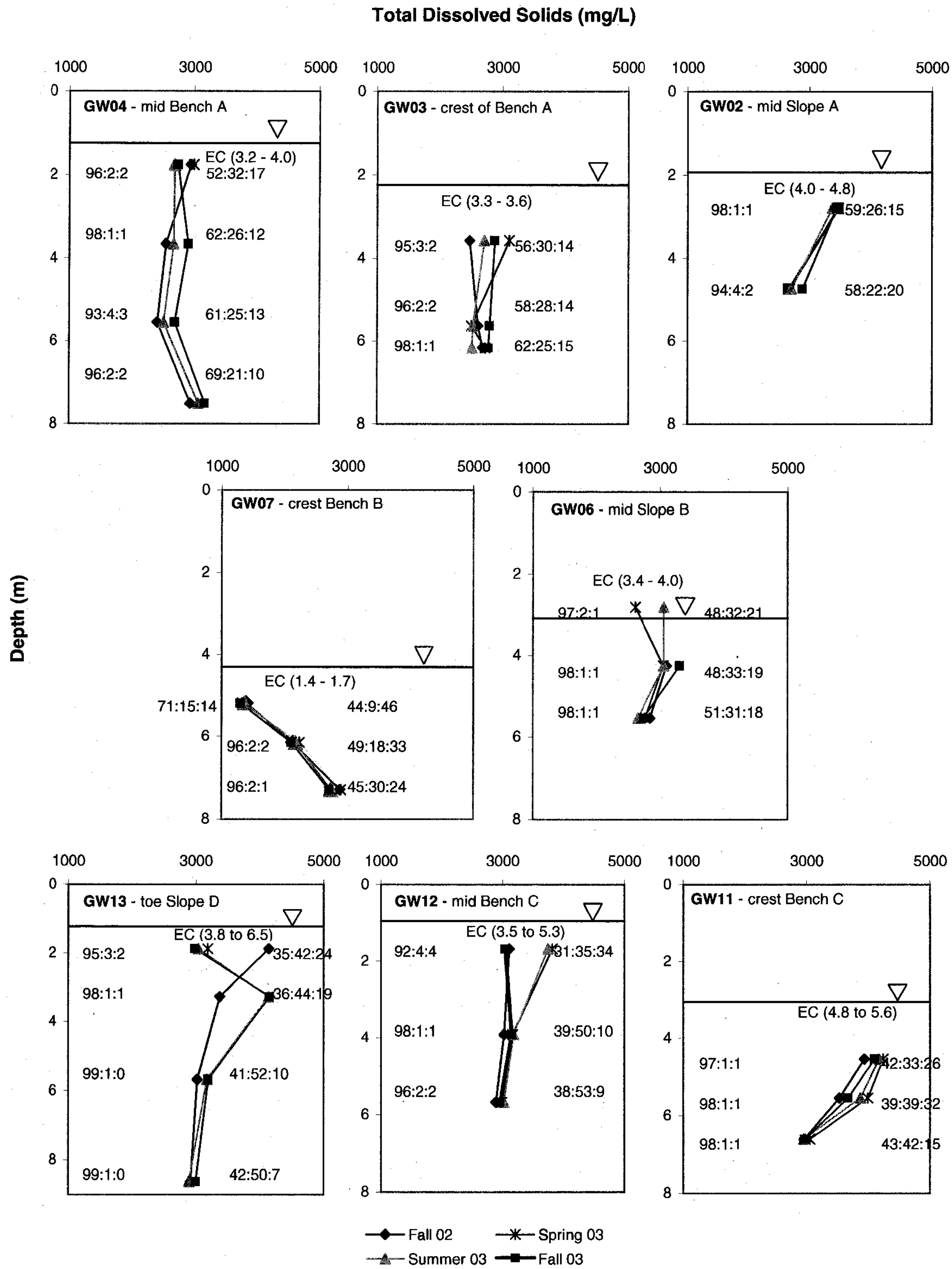

Figure 2-9. Groundwater total dissolved solids with depth in selected piezometer nests on Transect 31. Only those piezometers which indicated a trend with depth or shallow groundwater changed during the study year are shown. The one year range of field electrical conductivity (mS/cm) in the shallowest piezometer and water table location (August 2003) are indicated. Relative concentrations of major cations (Na:Ca:Mg) and anions (HCO_3:Cl:SO_4) shown for Summer 2003.

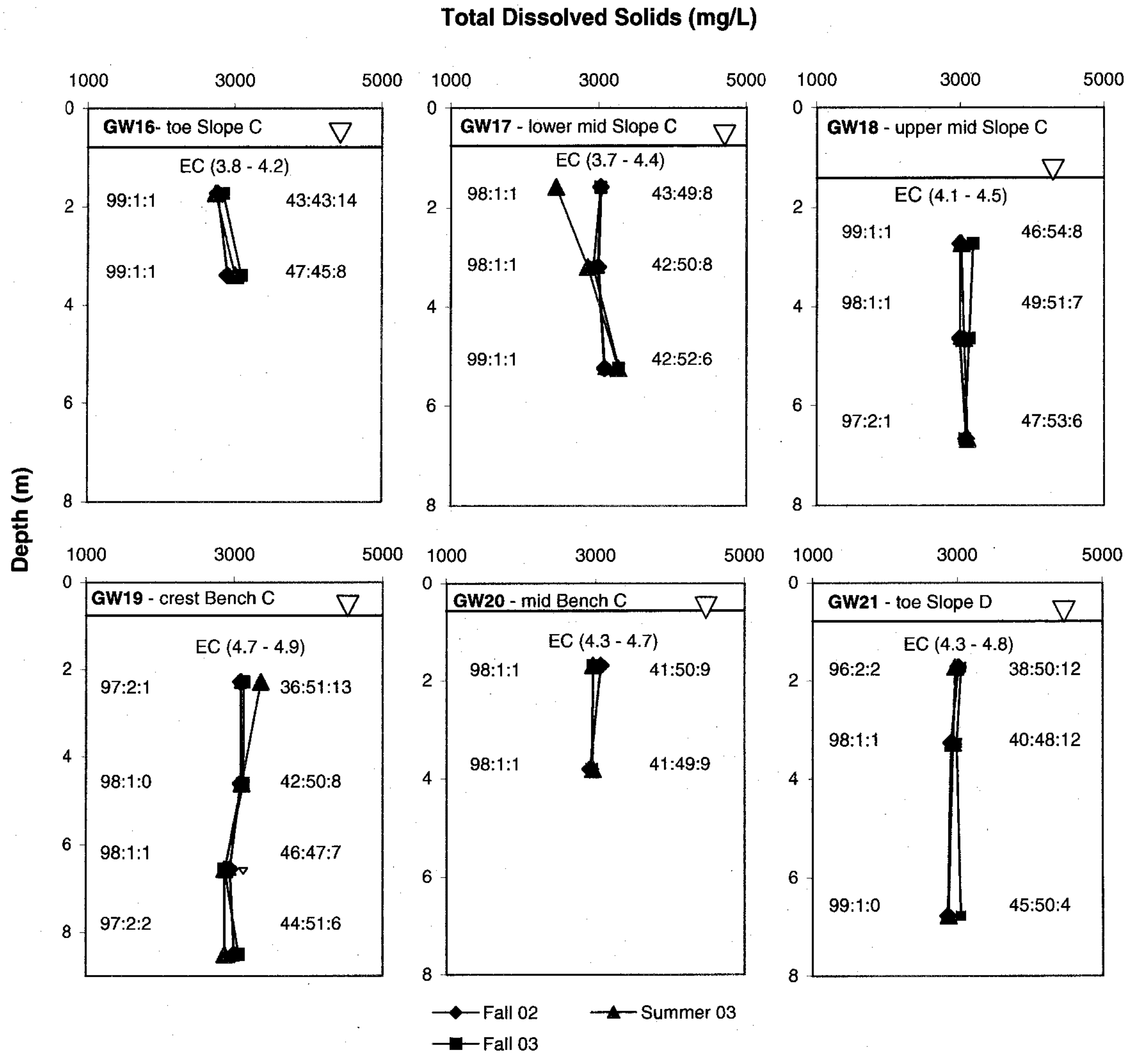

Figure 2-10. Groundwater total dissolved solids with depth in piezometer nests on Bench and Slope C on Transect 46. The one year range of field electrical conductivity (mS/cm) in the shallowest piezometer and water table location (October 2002) are indicated. Relative concentrations of major cations (Na:Ca:Mg) and anions (HCO_3:Cl:SO_4) shown for Fall 2002.

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Chapter 3
Modelling of groundwater flow and salt transport within an undrained tailings sand dam.

3.1 Introduction

The Athabasca Oil Sands Deposit in northeastern Alberta, with a reserve of 175 billion barrels, is the second largest petroleum deposit in the world (CAPP, 2005a). It accounts for over 30% of Canada's total oil production and yields over one million barrels of crude oil per day (CAPP, 2005b). Oil sands near the ground surface are mined in open pits, and the bitumen is separated from host sand. The separation of oil from sand produces large volumes of tailings, which are composed of sand, fines (clay and silt), residual bitumen, and process water that is piped to large storage facilities (List *et al.*, 1997). The impounded tailings will cover a significant portion of the mined landscape and will need to be reclaimed at the time of closure. Closure and reclamation challenges for tailings include reclaiming soft tailings with poor traffic-ability because of high water tables, salt migration and re-establishing the surface hydrology (Syncrude, 2001).

The study site, the Southwest Sand Storage Facility (SWSS), is located at Syncrude Canada's Mildred Lake Base Mine operations, 40 km north of Fort McMurray, Alberta, Canada (Figure 3-1). It is important to understand the current and future hydrogeological responses within the dam to manage and reclaim the SWSS effectively. Information that needs to be incorporated into any plans for the SWSS include the long-term water table depth, recharge and discharge areas, and flushing times for salty process water. How the flow systems within an undrained tailings dam like the SWSS will evolve over time is not well understood. Previous studies of tailings sand dams have focused on groundwater in tailings dams with internal drains (*e.g.,* Hunter, 2001; Mittal, 1981; Plewes *et al.*, 1997), which collect seepage and lower the water table. The hydrogeological investigation of an undrained tailings dam (though not an oil sands tailings dam) in Timmins, Ontario, found high water tables and the discharge of low quality process water within the impoundment (Al and Blowes, 1999). Numerical simulations, combined with field characterization of groundwater flow are useful to improve the understanding of groundwater flow system to optimize placement of reclamation materials (as concluded by Al and Blowes, 1999).

Numerical modelling was used at the SWSS to predict future responses. Long-term steady-state seepage regime modeled by Skopek (1996) suggested that the water table could be at the ground surface along more than 50% of the downstream slope. Molson (1997) simulated mine tailings flushing and his model predicted that the dam would be almost flushed within about three hundred years, with low mixing of recharge and process water. These studies included estimates of material properties for the site, but ignored the influence of bench and slope topography of the perimeter dyke. These studies were not calibrated with water level or seepage data from the SWSS and incorporated no groundwater chemistry data from the site. Further investigation was needed.

The objective of this research is to investigate groundwater flow and salt transport at the SWSS using numerical models. Conceptual and numerical models of the SWSS are built, based on results from field investigation (Chapter 2). Steady-state groundwater flow and transient transport of salts are quantified, and possible future flow systems are predicted under conditions thought to represent future hydrologic inputs. The knowledge gained from this study will contribute to understanding groundwater flow and salt transport in tailings sand dams, to enable better long-term management and reclamation of these undrained structures, by Syncrude and other tailings dam operators.

3.2 Study Site

The SWSS is located in the southwest corner of Syncrude Canada's Mildred Lake Base Mine operations, 40 km north of Fort McMurray, Alberta, Canada

(Figure 3-1). Fort McMurray experiences long cold winters and warm summers, with the mean average monthly temperature ranging from -18.8°C to +16.8°C (Environment Canada, 2004). The average annual precipitation is 456 mm/year (Environment Canada, 2004) and the average annual potential evapotranspiration is 493 mm/yr (Hackbarth and Nastasa, 1979). Over half of the rain falls from June through September, and evapotranspiration rates exceed precipitation in May through August (Hackbarth and Nastasa, 1979).

The original ground surface beneath the SWSS had gentle relief, sloping downward at 0.5 to 1% to the northeast. The underlying glacial till and lacustrine deposits (Pleistocene), and marine shale (Clearwater Fm.), are described regionally as low permeability (Hackbarth and Nastasa, 1979), and the hydraulic conductivity (K) of glaciolacustrine deposits and glacial till beneath the SWSS are two to three orders of magnitude lower than the tailings sand (Esford, 2003; Klohn Leonoff, 1990).

The SWSS covers an area of 25 km^2, is almost 40 m high at its crest and contains nearly 300 million m^3 of tailings sand (Purhar, 2004). The SWSS, under construction since 1991, consists of a perimeter dyke, beach, and tailings pond (Figure 3-1). On the east side of the SWSS in Cell 31, the perimeter dyke has a shallow (20H: 1V) slope, and is tiered in a series of five benches and slopes, labeled A through E (Figure 3-1). Cell numbers refer to spatially subdivided operational areas of the SWSS. Benches A and B are slightly inward tilted by <1%, with a constructed berm channel adjacent to the bench/slope interface. These channels are designed to divert water along the perimeter dyke (Klohn Leonoff, 1991). Bench C is forward tilted by >2% to prevent water from ponding (AEE, 1997). Benches and Slopes A and B are reclaimed with an average of 0.80 m of peat-mineral mixture deposit (Macyk *et al.*, 2002), which are suitable salvaged peat, glaciolacustrine deposits and glacial tills from Mildred Lake Site (Syncrude, 2001). Bench and Slope C have about 0.40 m of layered peat (0.15 m) over mineral deposit (0.25 m) (Macyk *et al.*, 2002) thinly covered with sand blown from the tailings beach. Benches and Slopes D and E are partially reclaimed with mineral deposits as on C. Various trees species are planted in areas on Benches and Slopes A and B (Qualizza, 2004). In 2003, considerable vegetative groundcover extended to midway up Slope C, with sparse vegetation growing on Bench C.

Deposited tailings sand consist primarily of sand and process water. Tailings sand is predominantly 91% sand with small grain size fractions of silt (8%) and clay (1%) (Gan, 2001). Within the deposited tailings sand, there are infrequent thin, horizontal, clayey silt layers (McKenna, 2002). The process water is sodium bicarbonate to sodium chloride dominant, with high concentrations of Na^{+}, SO_4^{2-}, HCO_3^{-}, and Cl^{-} (Chapter 2). It is typically alkaline and has a total dissolved solids (TDS) concentration, which has increased from about 1500 to 3200 mg/L from 1991 until 2002 (Liggett, 2004). Process water, runoff water and some of the fine tailings in the tailings pond are pumped out by a decant system, which controls the pond level (Purhar, 2004).

3.3 Conceptual Model

The conceptual model was developed along a 2D transect (A to A") that extends 2820 m from the toe of the perimeter ditch to the centre of the tailings pond (Figure 3-1). This transect is perpendicular to groundwater flow on the perimeter dyke (Appendix C) and intersects discharge locations on the beach, channels and perimeter ditch. The cross-section allows the incorporation of the pond, beach and perimeter dyke into the conceptual model and numerical models, while integrating previous field hydrogeological investigation results from the perimeter dyke (A to A') and interpreted hydrostratigraphy.

A conceptual hydrogeological model of 2D groundwater flow and salt transport through the perimeter dyke (A to A') is developed in Chapter 2. The bench and slope topography on the perimeter dyke forms nested local and intermediate groundwater flow systems as described by Tóth (1963). A groundwater divide separates the groundwater flow on the perimeter dyke from the beach and the tailings pond. The water table is shallow at the toes of slopes and deeper on the crests of benches; however, only 23% of the water table is closer than 1 metre to the ground surface, due to the tailing sand hydraulic conductivity and backward-sloped bench design. Focused groundwater discharge occurs on the dyke, where the slope breaks at the toes of Slopes A, B and C, and in the perimeter ditch.

Local flow systems interact with the hydrologic cycle (Tóth, 1963). Precipitation recharges the groundwater, and dilutes the shallow groundwater (process water). Channels focus snowmelt for recharge and behave as groundwater flow-through systems for seepage water and associated salts discharge at the adjacent slope toe.

The interpretation of tailings sand depositional history along a 2D transect (A to A") result in a "man-made" geologic framework for the conceptual model (Figure 3-2; Appendix B). Stratigraphic units are defined by their "depositional" history: (a) constructed/ reworked material on the dyke; (b) contained beaching and (c) free deposition by beaching. The perimeter dyke is built in lifts of reworked tailings, and contained beaching. Dyke construction is by pouring tailings sand in a slurry between sand dykes. The slurry is spread and compacted by bulldozers (AEE, 1997). The contained beaching is tailings poured between a sand starter dyke (Bench A) and an earthen dyke, which runs parallel and upstream of the toe of the dam. The beach and tailings pond is built by beached sand where tailings are discharged in a slurry from near the crest of the dyke, which create long shallow internal beach slopes. Coarser tailings settle out first near the discharge point, and finer tailings settle further away in the pond (List *et al.*, 1997). At the beach/pond transition, there is strong inter-layering of sand and fines, including bitumen (McKenna, 2002).

Different zones of hydraulic conductivity (K) and different types of material placement were identified previously on the perimeter dyke (Chapter 2, Figure 2-4). The stratigraphic units of similar K values and deposition method are grouped together to form nine hydrostratigraphic units (Figure 3-2; listed in Table 3-1). For simulations, the initial K value for each of the nine units is the geometric mean of K values determined within the unit. The anisotropy ratio is 10 (McKenna, 2002). The beached tailings on the beach and below the pond are grouped into one of the two beached sand hydrostratigraphic units.

3.4 Modelling Methodology and Set-up

3.4.1 Modelling Strategy

The purpose of building a numerical model was to replicate the existing flow conditions within the SWSS. A model that accurately simulates the current flow system can be used to determine movement of salts, over time, under the present day conditions, and predict possible future groundwater responses at the SWSS.

The SEEP/W and CTRAN/W models (GEO-SLOPE, 2002a; 2002b) were used to investigate groundwater flow and salt transport. respectively. SEEP/W was chosen, because it is a finite-element model that easily generates a grid to represent the geometry of the perimeter dyke, which pinches out towards the east. The model also simulates both saturated and unsaturated flow, and allows seepage faces. The flow field is accurately represented by including seepage faces where the water table interacts with the ground surface (Romano *et al.*, 1999). The results of the groundwater numerical code have been previously tested (Chapuis *et al.*, 2001). CTRAN/W is a finite-element model formulated to analyze saturated and unsaturated contaminant transport and using the flow solutions from SEEP/W. CTRAN/W allows salts to exit the model at seepage faces as physically exist in the field, but without evapoconcentration.

3.4.1.1 Steady-state Groundwater Flow and Transient Salt Transport

Groundwater flow and salt transport were investigated along a 2D model domain (A to A") (Figure 3-2). First, the groundwater system was calibrated to existing hydraulic head data. As an additional check, the simulated seepage was compared to estimated seepage data. A sensitivity analysis of responses to variations in material properties and boundary conditions determined which parameters were most important to represent the groundwater flow system at the SWSS. Secondly, the transient transport of salts within the current groundwater flow system was simulated along the same 2D profile, by both advective particle tracking and a full advection-dispersion analysis. The rationale for the modelling approach was as follows.

Groundwater flows from the top of the perimeter dyke outwards to the perimeter ditch (Chapter 2; Appendix C). A groundwater divide between the crest of the dyke and the tailings pond was inferred, so groundwater also flows through the beach towards the tailings pond. The groundwater divide could not be measured because there was no safe access to the beach. Based on the water table configuration (including piezometers out of the primary section), the groundwater flow was parallel to the 2D model transect (A to A").

The flow system is near steady-state under present recharge conditions. The hydraulic heads remained generally constant over the year of investigation (fall 2002 to fall 2003), except for small changes in the spring and fall from recharge. Since 2000, there have only been small volumes of tailings sand poured along the study transect and it is expected that only small volumes will be added in the future. In addition, the 2000 level of water in the tailings pond was within approximately 2 m of the 2003 level. Considering the previous points and the steady-state water balance data available for the SWSS (Appendix D), analyzing the groundwater flow system as steady-state was appropriate.

Particle tracking analysis was chosen to determined the approximate travel times of water (and salts) through current local and intermediate flow systems. The advective-dispersive transport analysis assumed conservative and non-reacting conditions and was selected to understand flushing processes over the next 300 years. Salts were allowed to leave the model where seepage occurred, as there was little evidence of evapoconcentration of salts in the groundwater (Chapter 2). Density dependent simulations were not performed because Molson (1997) concluded density dependent flow does not influence salt transport at the SWSS.

3.4.1.2 Future Flow Systems

The groundwater flow system, and subsequently the transport of salts, may change in the future at the SWSS, depending on pond and tailings management, climate, and reclamation practices. The calibrated steady-state groundwater flow model was used to predict the possible future groundwater responses under different future scenarios. There are three future scenarios with decreased recharge and two scenarios with either bitumen layers across the tailings pond or fine tailings stored in the tailings pond. The presence of a tailings pond was not specified in the future scenarios, because it will not be maintained following closure (Syncrude, 2001).

Groundwater recharge was reduced to between 5 mm/yr and 50 mm/yr (~1% to 11% of annual precipitation (P = 456 mm/yr)) in the decreased recharge scenarios to reflect a possible range of recharge expected when reclamation is complete. This range of recharge falls between previously modelled recharge estimates (Appendix D). Both the bitumen layers and fine tailings scenarios were modelled over the same range of recharge (5 to 50 mm/yr). In other tailings structures, at the tailings pond/beach transition and in the tailings pond, bitumen layers are reported to limit infiltration (Hunter, 2001; Skopek, 1996). About 40 Mm^3 of low K fine tailings exists at the SWSS in the tailings pond (Purhar, 2004).

The future amount and location of the fine tailings are unknown. However, fine tailings are thought to exist primarily in the pond.

The approximate travel times of water and salts in future flow systems were estimated by particle tracking.

The approximate timeframes for draining the SWSS from current flow system to the possible future flow systems under decreased recharge scenarios were predicted using a simple transient flow model (Appendix E).

3.4.2 Boundary and Initial Conditions

Model boundaries were chosen to follow selected groundwater flow boundary features (Figure 3-2). Along the top model boundary, two different types of boundary conditions were applied. Specified heads of 382.0 metres above sea level (masl), approximated from a digital contour map, represented ponded water in the tailings pond at the west end of the domain (1968 to 3000 m). A head value of 349.8 masl was specified in the perimeter ditch. Between the tailings pond and the perimeter ditch, along the top of the model, different specified fluxes, representing recharge rates, were applied as boundary conditions depending on whether the landscape was bare tailings sand (130 mm/yr) or reclaimed tailings sand (50 mm/yr). These values fall within the ranges of 110 to 140 mm/yr for bare tailings sand and 0 to 100 mm/yr for reclaimed tailings sand, estimated by water balance modeling for the SWSS (Appendix D). The higher value was applied between the edge of the tailings pond and the bottom of Bench (and Slope) C. The lower value was applied to the reclaimed areas across Benches (and Slopes) A and B. Seepage faces were allowed to develop anywhere along the top of the entire model between the tailings pond and the perimeter ditch. The bottom boundary was along the underlying low-K glacial till and lacustrine deposits, and the left boundary was in the middle of the tailings pond. These boundaries were assigned zero-flux conditions.

Particles were assigned for forward tracking across recharge areas for the current steady-state flow system on the benches and the top of the perimeter dyke, and travel times were recorded through the saturated zone.

Figure 3-2 illustrates the boundary and initial conditions for the transport model. Across the top of the entire model domain, a zero mass-flux boundary was applied, which assumes that water, where recharged in the flow model, has a TDS concentration of 0 mg/L. A free-exit boundary was assigned at seepage faces at the toes of Slopes A, B and C, in the perimeter ditch, across the beach and tailings pond. This allowed mass to leave, by both advection and dispersion, where seepage existed.

The initial distribution of TDS across the model domain was determined by combining two data sources. Between the groundwater divide and the perimeter ditch, TDS concentrations were determined from groundwater samples collected during the summer 2003 (Chapter 2). From the middle of the tailings pond to the groundwater divide, each yearly beached sand layer was assigned the average TDS concentration of the process water at the time it was beached (Liggett, 2004). The TDS concentrations of beached sand were assumed not to have changed significantly since deposition, due to low groundwater velocities from the groundwater divide to the tailings pond.

During future scenario modeling, specified fluxes of 5 to 50 mm/yr were applied uniformly across the entire top of the model domain. The fine tailings scenario had recharge applied across the top of the entire model domain, whereas the bitumen layers scenario had recharge applied across only the beach and perimeter dyke.

Particles were assigned for forward tracking on the possible future flow scenarios from the same locations as on the current steady-state flow model. Travel times were recorded through the saturated and unsaturated zones.

3.4.3 Spatial and Temporal Discretization

The finite-element grid (not shown) of the detailed model had 75,044 nodes and was a combination of 74,417 quadrilateral and triangular elements generated using the SEEP/W graphical user interface. The domain was primarily quadrilateral elements; however, triangular elements were required along the top and bottom model boundaries to fit the topography. The toes of Slopes A, B and C, and at the perimeter ditch were constructed of quadrilaterals so that the (transport) free-exit boundary could be properly applied along seepage faces (GEO-SLOPE, 2002b).

The horizontal discretization (Δx) was 2 m between 182 m and 1072 m along the model transect. Between 1072 m and 1092 m, there was a transition zone where the discretization increased to 6 m, whereupon Δx remained at 6 m to 3000 m. In the vertical direction, the discretization (Δz) was 0.2 m. The grid was positioned between 349.8 to 393.0 masl and varied in thickness from 0 m to 37 m. The grid and time-step discretization was chosen to maintain Peclet and Courant criteria numbers, at almost all nodes, below the suggested limits of 10 (Huyakorn and Pinder, 1983) and 1 (Anderson and Woessner, 1991), respectively. In addition, the detailed grid was required to achieve convergence while modelling with the selected unsaturated parameters (Chapuis *et al.*, 2001). A ten-day time step was used for advective-dispersive transport analysis.

3.4.4 Model Parameters

Geometric mean K values, ranging from 1.6×10^{-6} to 8.5×10^{-6} m/s, were assigned to each of the nine hydrostratigraphic layers in the model (Figure 3-2). In the future modelling scenario, fine tailings below the pond (1968 to 3000 m) was represented as a low K hydrostratigraphic zone of 5×10^{-9} m/s, a median extrapolated from Suthaker and Scott (1996). Initial anisotropy (K_x/K_z) assigned to the model for tailings sand was 10 as suggested by McKenna (2002). Porosity (n), longitudinal (α_L) and vertical transverse (α_T) dispersivities were 0.40, 10 and 0.1, respectively, for all simulations.

For unsaturated zone parameters, a sandy silt volumetric water content (VMC) function was selected (GEO-SLOPE, 2002a) (Figure 3-3). It was not possible to use the VMC function of typical tailings sand (fine sand) due to difficulties with model convergence. The porosity of the sandy silt VMC function was adjusted from 0.45 to 0.40 to match the reported value of the tailings sand (McKenna, 2002). The unsaturated hydraulic conductivity functions were predicted by the van Genuchten (1980) method (Figure 3-3). Thus, saturated and residual water contents were 0.4, and 0.07. A lower limit $k_{min} = 3.0 \times 10^{-3}$, was imposed on the relative permeability (as in Beckers and Frind, 2001).

3.4.5 2D Steady-state Flow Model Calibration

The aim of the calibration process is to develop the best possible representation of the system. The model was calibrated by manual adjustments of K, K_x/K_z and recharge to achieve a good match of simulated and observed heads. In addition, for each adjustment, the flow solution was checked by comparing seepage values from the model to those estimated from the field. K was adjusted within the range observed in the field (Table 3-1) and K_x/K_z was adjusted between 1 and 20, a limit proposed by a previous tailings sand characterization (McKenna, 2002).

The fit between the observed and simulated head data was tracked throughout the calibration process by three quantitative measures 1) mean error (ME), 2) mean absolute error (MAE) and 3) root mean squared error (RMS) as suggested by Anderson and Woessner (1991):

$$ME = 1/n\sum_{i=1}^{n}(h_m - h_s)_i$$

$$MAE = 1/n\sum_{i=1}^{n}\left|(h_m - h_s)_i\right|$$

$$RMS = \left[1/n\sum_{i=1}^{n}(h_m - h_s)_i^{\,2}\right]^{0.5}$$

where n is the number of calibration points, h_m is the measured hydraulic head and h_s is the simulated hydraulic head.

Heads used for calibration were measured from 57 piezometers and water table wells on the perimeter dyke on August 28, 2003 (Figure 3-1). The water levels were assumed to represent steady-state conditions, because the late summer data set excluded the observed transient response to seasonal inputs of recharge in the spring and fall of 2003 (Chapter 2). In addition, the average 2003 water level from a Syncrude piezometer (SP31-02-01), located ~300 m from the top of the perimeter dyke, on the beach, about 500 m north of the model transect (A to A") provided a calibration target for the beach area (Figure 3-1).

Model seepage values were also compared to observed seepage values. The seepage flux at the perimeter ditch was determined from the average of measurements taken, in July 2003, from seepage meters (Lee, 1977). Seepage fluxes at the toes of Slopes A, B and C were estimated by Darcy's law using the K and gradient calculated in selected piezometers.

3.4.6 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated steady-state groundwater flow model to quantify the uncertainty in the calibrated model. Calibrated values for K, K_x/K_z, recharge, and boundary conditions selected at the tailings pond were varied systematically. The tested values were +/- one quarter, one half and one order of magnitude for K, a ratio of 1 to 100 for K_x/K_z, +/- 25% and 50% for recharge and 380 to 384 masl for the pond level. K and K_x/K_z changes were applied to all hydrostratigraphic units.

Model sensitivity is illustrated by graphs that compare changes in parameters to changes in flow system response. Flow system responses were quantified by determining changes in heads at the crests of Benches A, B, C and D, seepage fluxes at the toe of Slopes A, B, and C and into the perimeter ditch, and the length of the wetted slope on Slopes A, B and C. The wetted slope was defined as being the distance up the slope where the water table was within 0.5 m of the ground surface.

3.5 Results

3.5.1 Groundwater Flow Modelling

3.5.1.1 Model Calibration

The calibration process resulted in a solution that had a good match to observed head and seepage data (Figure 3-4). Calibrated flow model results are referred to as the *current* groundwater flow system. At the majority of calibration points, the simulated and observed heads are within 0.5 m. The ME is –0.11 m and the MAE is 0.27 m. The RMS error is 0.34 m, which is small compared to the observed total head difference across the study area (~36 m). Most of the error is due to an overestimation of heads at the toes of slopes on the perimeter dyke, which could be due to unaccounted-for heterogeneities of the resloped tailings sand, or unspecified evapotranspiration.

Seepage values have more uncertainty associated with them than the head measurements (Anderson and Woessner, 1991). Seepage is highly dependent on sediment K, which is more heterogeneous than represented in the calibrated flow model. Nonetheless, seepage values from the model are within 20% of all the observed values.

The calibrated K values (Table 3-1) are within the range of K values determined for each hydrostratigraphic unit and close to, or the same as, the initial K (Figure 3-2). Beached materials have higher K_x/K_z ratios (20) compared to the constructed dykes, except for Bench B. The calibrated K_x/K_z ratios of constructed dykes vary from 20 (B) and 10 (A) to 5 (C & D). The resloped Toes B and C had the lowest K_x/K_z ratios of 1.

In the *current* flow system, the distribution of recharge on Benches A and B is 86 mm/yr (19% of P), and 32 mm/yr (7% of P) across Slopes A and B (Figure 3-5). The difference in recharge between the benches and slopes is logical, as the slopes would promote more runoff. The recharge is higher in the part of Channels A and B adjacent to the bench where there is standing water (205 mm/yr or 45% of P). Calibrated recharge is 158 mm/yr (35% of P) between the tailings pond and the toe of Slope C. The relative higher rate of recharge on the unreclaimed sand is expected, due to the lack of vegetation and reclamation soil to intercept precipitation.

3.5.1.2 Groundwater Flow

The *current* groundwater flow system along the study area is separated in two by a groundwater divide (Figure 3-5). The groundwater divide is estimated to exist at about 1152 m along the study area, approximately 100 metres towards the beach from Bench E. The flow system below the beach is long and flat, with a horizontal gradient of 0.004 (east), whereas the steeper perimeter dyke has a horizontal gradient of 0.044 (west). On the perimeter dyke, groundwater flow forms nested flow systems with local flow systems associated with the benches and slopes, and an intermediate flow system extending from the groundwater divide to the perimeter ditch.

Travel times, determined by particle tracking, of water moving through the SWSS are shorter in the local flow systems (decades) as compared to the intermediate flow systems (centuries). The maximum travel times of particles tracked from Benches A, B and C are 16, 18, and 27 years, respectively. Travel times through the intermediate scale on the perimeter dyke side of the divide range from 78 to 426 years, with the longest travel times for water starting at the water table near the divide. The maximum travel time is over 2500 years for water moving from the divide to the tailings pond.

In the *current* flow system, the primary recharge areas are at higher elevations and the main discharge areas are at the lower elevations (Figure 3-5). Most recharge is applied to the upper beach, and Benches and Slopes E, D, and C. Smaller recharge areas, both in flux and extent, exist on Benches and part of Slopes B and A. Recharge volumes are highest in the downstream part of Channels A and B, adjacent to Benches A and B where there is standing water. Discharge occurs at the toes of Slopes A, B, and C, into the perimeter ditch and on the bottom three-quarters of the beach. Wetted slope lengths were estimated at 46, 10 and 14 m for Slopes A, B and C. The wetted slope lengths will likely be shorter, as the model overestimates the water table height at the toes of the slopes.

3.5.1.3 Sensitivity Analysis

The groundwater flow solution was most sensitive to changes in K. The K was varied over two orders of magnitude and impacted the water table, seepage flux and wetted slope length (Figure 3-6). A global 10-fold increase in K decreased the water table by 9.3 m at the crest of Bench D and eliminated the groundwater divide from the flow system. A decrease in K, by one order of magnitude, increased the water table across the model domain, and caused the structure to be almost entirely saturated, with additional seepage on Slopes D and E. Seepage flux at selected monitoring points at the toes of slopes increased or decreased when the K was increased or decreased, respectively. For a higher K scenario, seepage was focused at higher rates to discharge points lower in the flow system (*i.e.,* perimeter ditch). Wetted slope lengths increased significantly with lowered K; however, Slope B responded less than other slopes due to lower K Bench B unit adjacent to the higher K Toe B unit. None of these alternate scenarios are compatible with existing observations.

Through the calibration process, changing the K of the hydrostratigraphic units individually allowed the identification of those units whose K influenced the flow system the most. It was determined that changing the K of Contained Beaching, Benches C and D, and Lower Sand Beach units considerably altered the water table location. As the K of the Contained Beaching unit was decreased, the water table declined across Bench A, and as the K was increased, the water table declined across Bench C. The K of the lower beach sands influenced the height of the water table across Bench D. Measured seepage flux was most impacted by K of hydrostratigraphic units at the slope toes such as Sand Bench, Bench A and Toe C. Of note is that, as K was decreased on the Sand Bench, so did the seepage flux into the perimeter ditch. However, this action increased seepage and wetted slope length at the toe of Slope A. The shift of the groundwater divide position was greatest with changes in K of Benches C and D, and Lower Beach Sand units. A higher K of either unit shifted the groundwater divide towards the tailings pond.

The groundwater model was also sensitive to changes in recharge. The responses of the water table, seepage flux and wetted slope length were greatest with changes in recharge in the upper part of the flow system (Figure 3-6). The water table on Bench D declined 3.0 m, when recharge was decreased by 50%. Seepage flux at the toes remained generally constant when varying recharge, except at the toe of Slope C. Recharge was not a sensitive parameter with regards to wetted slope length within ranges tested on Benches and Slopes A and B. Wetted slope length increased on Bench C by 30.5 m and 38.6 m with 25% and 50% additional recharge. The groundwater divide existed even in the low recharge case (-50%). Thus, the calibrated recharge fluxes relative to the calibrated / measured K values appear to be representative.

The groundwater model solution was generally insensitive to realistic changes in K_x/K_z, pond elevation and pond location. An exception to this is that higher K_x/K_z in the hydrostratigraphic units at the toes of slopes (*i.e.*, Toe C) increased the wetted slope length and decreased the seepage flux at the toe; however, the overall flow system remained unchanged. None of the changes simulated at the tailings pond altered the flow system on the perimeter dyke. This is to be expected because of the small range simulated and the existence of a groundwater divide.

3.5.2 Solute Transport Modelling

Transient transport simulations with dispersion estimate flushing times of process water from the dyke, assuming the *current* steady-state flow system remains unchanged. The timeframe of the transport simulations is from present (2003) to three hundred years into the future. The solute distributions are illustrated at 25, 100 and 300 years (Figure 3-7). After 25 years, salts will begin to flush on both sides of the groundwater divide and on the upper benches. The shallow groundwater in the local flow systems on Benches A and B will also be diluted by recharge. Between 25 and 100 years, the upper half of the flow system on the perimeter dyke will be flushed almost completely of process water. Over the same time, the front of fresh recharge water will move a small distance towards the tailings pond from the groundwater divide. The perimeter dyke will be flushed almost entirely by 300 years. This differs from the salt concentrations below the tailings pond, which will remain almost unchanged after 300 years.

Breakthrough curves of TDS in shallow and deep piezometers on Benches B and C demonstrate flushing of local flow systems before the intermediate systems (Figure 3-8). Shallow groundwater in local flow systems on Benches B and C will begin to flush within 10 years. In contrast, deeper groundwater in the intermediate flow system will not start flushing until about 50 years.

Breakthrough curves at locations on the seepage face, at toe of Slopes A, B and C, and on the lower beach demonstrate changes in groundwater TDS over the simulation timeframe (Figure 3-8). On the perimeter dyke, recharge will flush process water faster from benches towards the top of the perimeter dyke. Seepage at the toes of Slopes A, B and C will be at TDS concentrations above 1000 mg/L until around 100, 100 and 25 years, respectively. By 150 years, TDS of discharge water at all the monitored points on the perimeter dyke will be less than 500 mg/L. Concentrations of TDS at the toe of the beach will decrease minimally from approximately 3250 to 2650 mg/L over the 300 year simulation time (Figure 3-8). The high TDS process water will discharge into the channels on Benches A and B, at the toe of Slope A onto the sand bench, into the perimeter ditch, on the lower three quarter's of the beach and into the tailings pond. Assuming a 1 m profile width, the total initial mass of TDS in the 2D profile of the perimeter dyke (between groundwater divide and dyke toe) is 22 tonnes. Over the simulation timeframe, the mass of TDS will decrease across the profile, by exiting the groundwater flow system, to 15 tonnes at 25 yrs, 6 tonnes at 100 yrs, and less than 1 tonne at 300 yrs.

A qualitative assessment compared evidence of flushing in the field (Chapter 2) with the 10-year model results (Figure 3-8). Both the model concentration results and field groundwater samples indicate recharge water mixed with process water in local flow systems on Benches B and C. Deeper groundwater samples and model concentrations from the intermediate flow system show no evidence of flushing of process water. This is expected since flushing of the intermediate system is predicted to start after about 50 years.

3.5.3 Future Flow Scenario Modelling

The groundwater flow conditions will change with the closure of the tailings pond and the ensuing decrease in recharge as vegetation develops. Future steady-state groundwater flow scenarios are illustrated for the 50 mm/yr (11% of P), 24 mm/yr (5% of P) and 5 mm/yr (1% of P) cases (Figure 3-9). The *current* flow system is closest to the predicted 50 mm/yr future flow scenario; however, the water table will decrease by 4.7 m near the top of the perimeter dyke on Bench D. The previously described (Section 3.5.1.2) local and intermediate flow systems will exist; however, seepage flux at the toe of Slope C will decrease by 91%. At 24 mm/yr, the water table will drop relative to the *current* flow system, by 7.9 m near the top of the perimeter dyke, and seepage will no longer exist at the toe of Slope C. Local flow systems will remain on lower Benches A and B, and the seepage flux at the toe of Slope B will decrease by 52%. At less than 24 mm/yr, the groundwater divide will disappear and groundwater will flow from beneath the tailings pond to the perimeter ditch, which will alter the flow regime significantly. At 5 mm/yr of recharge, no local flow systems will remain, and all the flow from the entire structure will discharge to the perimeter ditch and the toe of Slope A. The water table will decline 16.2 m from the *current* flow system, and discharge at the perimeter ditch and the toe of Slope A will reduce by 9% and 48%, respectively. Travel times of groundwater from benches on the perimeter dyke will increase from decades to centuries as recharge decreases (Table 3-2). Under the low recharge scenario of 5 mm/yr, particles traveling from beneath the tailings pond could take up to 3800 years to discharge at the perimeter dyke toe.

The possible future conditions, such as bitumen layers and fine tailing storage, will affect the flow system only under low recharge scenarios. With 5 mm/yr recharge, the future flow scenarios with either bitumen layers or fine tailings storage in the tailings pond are compared to those with only tailings sand in the pond, as described in the conceptual model (Figure 3-10). No recharge across the tailings pond, as simulated in the bitumen layer scenario, will decrease the water table by 3.9 m near the crest of the perimeter dyke on Bench D, and seepage into the perimeter ditch will reduce by 25%. Fine tailings, with its low K properties, will limit flow from the tailings pond. Consequently, the water table will be 3.4 m lower, and seepage will decrease by 17%. The water table across the tailings pond will remain at the ground surface if fine tailings are present. In the 24 mm/yr recharge case, there is minimal difference in the flow solutions between the three scenarios – 24 mm/yr recharge, 24 mm/yr recharge with bitumen layers and 24 mm/yr recharge with fine tailings (not shown) - due to the separation of flow systems by the groundwater divide. Both flow systems for fine tailings and bitumen layers scenarios have longer travel times than without (Table 3-2). In all three scenarios, travel times are longer than higher recharge scenarios in part due to the thick unsaturated zones.

The time it might take for the SWSS to drain once reclamation is complete and the tailings pond is closed (Appendix E) will depend strongly on the amount of recharge. At 50 mm/yr recharge (11% of P), the future steady-state flow system will be reached within 50 years; however, under low recharge scenario of 5 mm/yr (1% of P) the dam will still be draining at 1000 years. Fifty percent of the head loss at the perimeter dyke crest will happen within 5 and 50 years, for the 50 mm/yr and 5 mm/yr recharge scenarios, respectively.

3.6 Discussion

3.6.1 Groundwater Flow Model

This current groundwater flow model is an improvement on the previous flow models by Molson (1997) and Skopek (1996). The model is more representative of the SWSS, as it uses detailed hydraulic and geologic data, incorporates the perimeter dyke topography and uses different recharge values for reclaimed and non-reclaimed areas. In addition, the conceptual model was checked by calibrating the model results against field data. The hydraulic conductivity distributions remained consistent with the field data, while recharge values were adjusted to match the observed and simulated heads and seepage fluxes.

The numerical groundwater flow model accurately describes the observed flow regime, including nested local and intermediate flow systems on the perimeter dyke, a groundwater divide located between the perimeter dyke and tailings pond, and the locations of recharge and discharge. Local recharge areas identified in the model generally match those locations identified as recharge areas in the field characterization (Chapter 2). Seepage faces in the model located at the toes of Slope A, B and C and in the perimeter ditch coincide with observed seepage faces on the perimeter dyke. The representative description of the flow system allows for confidence in results from solute transport and future scenario modelling.

The flow model results are sensitive to changing hydraulic conductivity. Hydraulic conductivity is an important parameter to be honoured in the model as increasing the hydraulic conductivities resulted in the disappearance of the groundwater divide. The nine hydrostratigraphic units (Figure 3-2) provide enough detail of the

K spatial distribution to capture its influence on groundwater flow and allow good model calibration. The model is more sensitive to changing the hydraulic conductivity of certain hydrostratigraphic units, such as Contained Beaching and Lower Beached Sands. The hydraulic conductivity of tailings sand should be considered when designing tailings sand structures that are undrained because it affects the water table depth.

The flow model results are sensitive to changing recharge values. The different recharge values selected for the reclaimed and unreclaimed areas are necessary for calibration. The calibrated recharge values fall within the predicted values from previous large scale water balance modelling. However, the recharge flux of 158 mm/yr (35% of P) across the unreclaimed area of the calibrated numerical model is just higher than the range of 110 to 140 mm/yr previously predicted by AEE (1997). The lower recharge on Slopes A and B (32 mm/yr) may be due to the steeper slope and greater number of planted trees relative to adjacent Benches A and B (86 mm/yr). Reclamation decreases recharge to the flow system due to increased evapotranspiration and runoff. Once the upper benches, slopes and beach are reclaimed, recharge rates at those locations will decrease and may approach rates on Benches and Slopes A and B.

3.6.2 Process Water Flushing in a Nested Flow System

Recharge will flush the process water in the groundwater approximately ten times more quickly in the local flow systems than the intermediate flow systems, under the *current* flow conditions (Figure 3-5). The faster flushing is because waters in local systems have shorter residence times. Breakthrough curves of TDS concentrations at the crest of benches in the local flow systems indicate process water will be diluted with recharge earlier than deeper locations in the intermediate flow system (Figure 3-8). Groundwater chemistry samples collected at the site confirm flushing of shallow process water by recharge at various locations and none in the deeper piezometers (Chapter 2). Similar predictions are discussed by Molson (1997) in previous mine tailings flushing simulations of the SWSS, which found that recharge water should flush out the shallow process water first. The dilution of shallow groundwater by recharge with lower TDS concentrations is expected (Whittemore *et al.*, 1989). Flushing of shallow groundwater in recharge areas (*e.g.,* benches) means that reclamation soil and plants will be in contact with fresher water instead of the previously deposited process water.

Groundwater TDS concentrations will decrease first at discharge locations at the toes of slopes higher in the flow system (Figure 3-8). This occurs because the *current* flow model has higher recharge rates on the beach and upper benches. In addition, groundwater closer to the perimeter dyke toe has higher relative volumes of process water from the intermediate flow system, which will take longer to flush. Based on simulation results, vegetation in the discharge areas (*i.e.,* channels and toes of slopes) on the perimeter dyke will have to initially tolerate groundwater TDS concentrations of 3000 mg/L and TDS concentrations at some locations will stay greater than 2000 mg/L for decades. Currently, TDS concentrations are greater towards the top of the perimeter dyke because TDS concentrations in the process water have increased over time (Liggett, 2004). In the future, this is predicted to change and start to resemble a more natural geochemical evolution in flow systems. Typically, the groundwater chemistry of natural systems has the lowest TDS concentrations in shallow groundwater near to the recharge areas and in local flow systems, and higher TDS at discharge locations of the intermediate flow system (Tóth, 1999). Ultimately, salts from the process water will be flushed from the perimeter dyke before 300 years.

Flushing of the beach will take up to 2600 years (Figure 3-5) because of low groundwater velocities between the upper beach and tailings pond. The TDS concentrations of seepage out of the beach will not decrease significantly over the next 300 years (Figure 3-8). Thus, the high water table and potential seepage of salts across three-quarters of the beach could make it a challenge to reclaim.

In addition, the steady-state flow model is simplified and omits evapotranspiration processes. Evaporation of process water from the shallow water table on the beach, and tailings pond may evapoconcentrate salts.

3.6.3 Future Flow Scenarios

The range of recharge of 5 to 50 mm/yr modelled in the future scenarios result in very different flow systems and ultimately the transport of salts (Figure 3-9). Different flow systems at the SWSS would require different management decisions because of different water table depths, flow systems, seepage rates and flushing rates for salts. The Rehm *et al.* (1982) study of the Falkirk study area, North Dakota, whose climate is similar to Fort McMurray, determined recharge rates for a variety of geologic settings. The “covered sand” (a couple of metres of till over sand), which could be compared to reclaimed Benches and Slopes A and B, has a recharge rate of 60 mm/yr. Skopek (1996) proposed a range of 50 to 100 mm/yr recharge based on infiltration data from the reclaimed areas of the mine site, with most data supporting the lower end of the range. This previous study of a natural site, and the SWSS water balance modelling by Skopek (1996) agree with the average recharge value of 53 mm/yr (~12%) from the *current* flow model for reclaimed areas.

Considering the different recharge scenarios, the future flow system will more likely resemble that of the 50 mm/yr recharge scenario. A groundwater divide will exist on the beach separating flow on the perimeter dyke from the beach and tailings pond. The nested groundwater flow systems will also remain. The water table is likely to remain high across the SWSS, and discharge rates will be maintained at the toes of the Slopes A and B, into the Channel A, into the perimeter ditch and on the beach. Travel times of water and salts moving from Benches A and B will remain the same, while water and salts travelling from Bench C and from the groundwater divide will take longer. The timeframe to reach this future flow system could be only decades depending on the progress of reclamation and closure at the SWSS.

The bitumen layers and fine tailings storage in the tailings pond will not likely impact the flow system on the perimeter dyke under 50 mm/yr recharge. The role of fine tailings in the Tar Island Dyke tailings dam at Suncor is different than the SWSS, because there is no groundwater divide separating the flow system of the perimeter dyke from the tailings pond (Hunter, 2001). In the Tar Island Dyke, the fine tailings form a hydraulic barrier to flow limiting the flux of process water from pond into the perimeter dyke. As a result, the water table in the tailings pond is perched above the water table in the perimeter dyke (Hunter, 2001). At the SWSS, the perched tailings pond may not exist under the recharge conditions proposed due to high water tables across the perimeter dyke.

The future flow scenario testing illustrates the importance of recharge on the future flow regime. Recharge through the reclamation cover will likely vary with the type of reclamation material, the soil thickness, and type of vegetation. Recharge across the reclaimed Benches and Slopes A and B is through about 1 m of mineral soil. It is possible with thinner or layered soil cover like the 0.40 m cover on Bench C that this recharge number could be greater. More confidence in modelling of future flow systems would be possible if a smaller range of recharge is estimated or different recharge rates were determined for the range of existing reclamation soil covers. Characterizations of natural systems have provided water balances with narrower estimates of recharge (*i.e.,* Hayashi *et al.*, 1998).

3.7 Conclusions

The *current* groundwater flow model described above accurately describes the flow system, including the nested flow systems on the perimeter dyke, recharge and discharge areas, the groundwater divide on the beach, and flow system between the groundwater divide and tailings pond. This *current* flow model is reliable and can be used for transport modelling and future flow scenario testing with confidence.

The local flow systems on the benches of the perimeter dyke will flush process water within a couple of decades, and the shallow groundwater in the recharge areas will start to flush within 10 years. In contrast, the intermediate flow system on the perimeter dyke and on the beach will take hundreds to thousands of years to flush the process water. The results show the importance of local flow systems, and their position in the flow system in terms of salt flushing. How to create local flow systems is important to consider when designing and reclaiming other sand tailings structures, where flushing is desirable, and the water table is high because the structure is undrained.

There are major differences in the possible future flow systems depending on the amount of recharge. If recharge is 50 mm/yr because of selected reclamation practices, than the flow system will be similar to the *current* flow system and the seepage of process water and high water tables will be an issue indefinitely at the SWSS. The information provided from modelling will help in the future management of the SWSS and other undrained tailings sand dams.

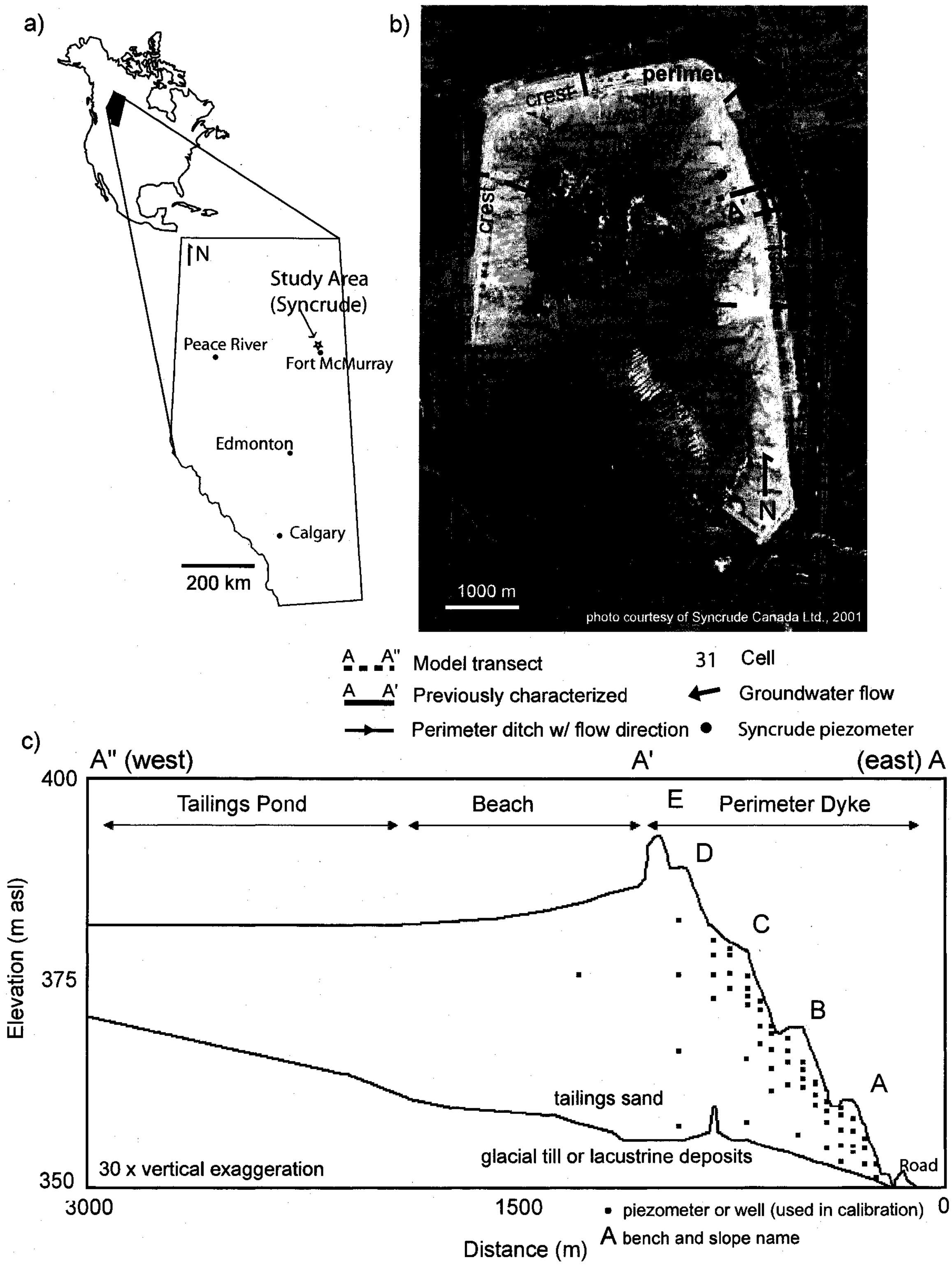

Figure 3-1. Maps of a) the study site within Alberta, b) aerial photo of the Southwest Sand Storage Facility, and c) the model profile (A to A") showing perimeter dyke, beach and tailings pond, and the locations of piezometers and wells used in model calibration.

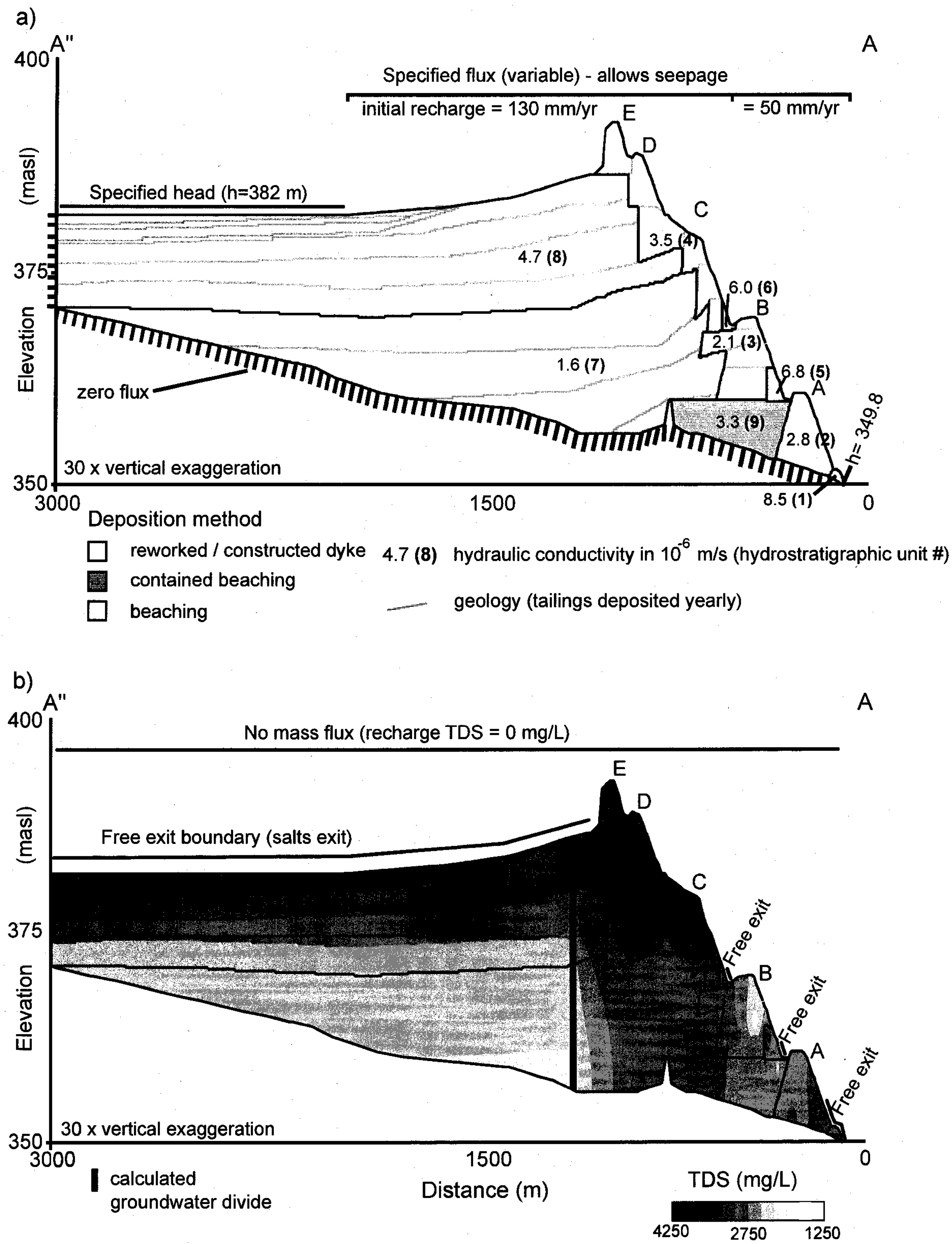

Figure 3-2. Hydrostratigraphy, boundary conditions, and initial conditions for the 2D a) flow and b) transport numerical models. Hydrostratigraphic units shown are listed in Table 3.1. The TDS distribution was determined by linear interpolation on the east side of the groundwater divide.

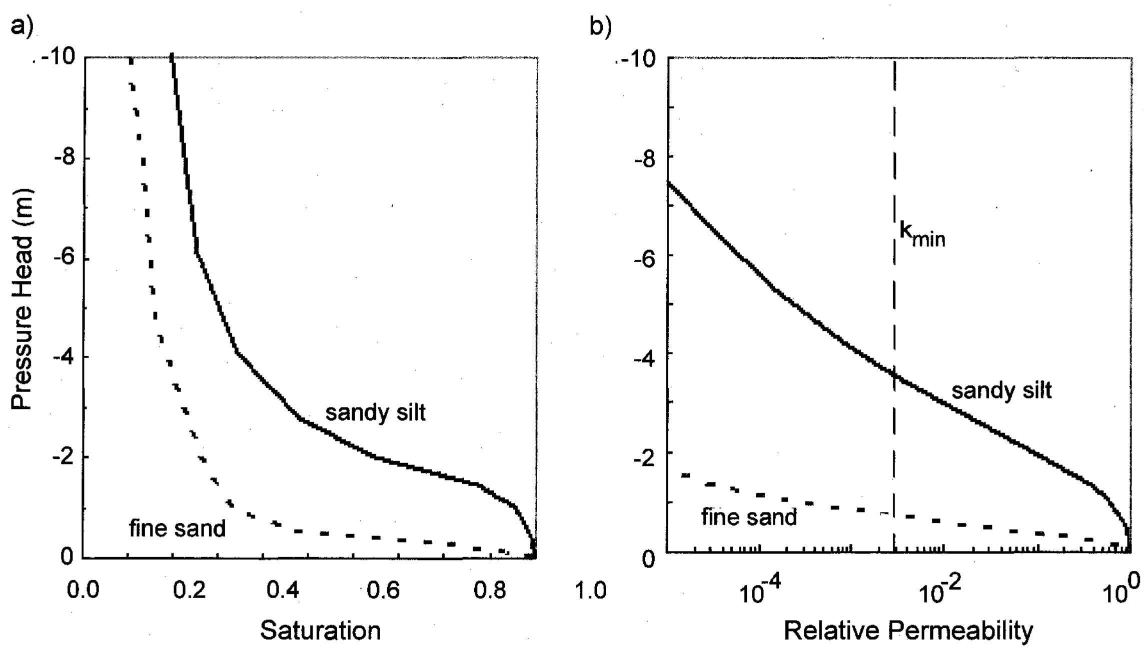

Figure 3-3. (a) Pressure head versus saturation and (b) pressure head versus relative permeability for fine sand (tailings sand) and sandy silt. Volumetric water content versus saturation for sandy silt and fine sand are used to generate the hydraulic conductivity function by van Genuchten method (1980). A lower limit (k_{min}= 3 x 10^{-3}) was imposed on the relative permeability.

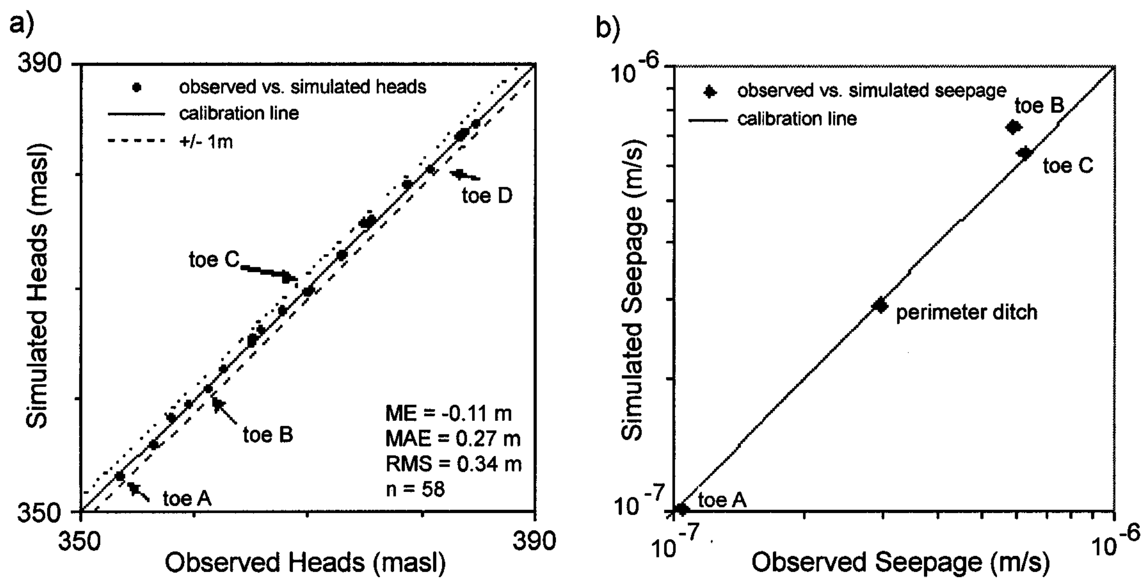

Figure 3-4. Simulated versus observed (a) heads and (b) seepage for the calibrated flow model.

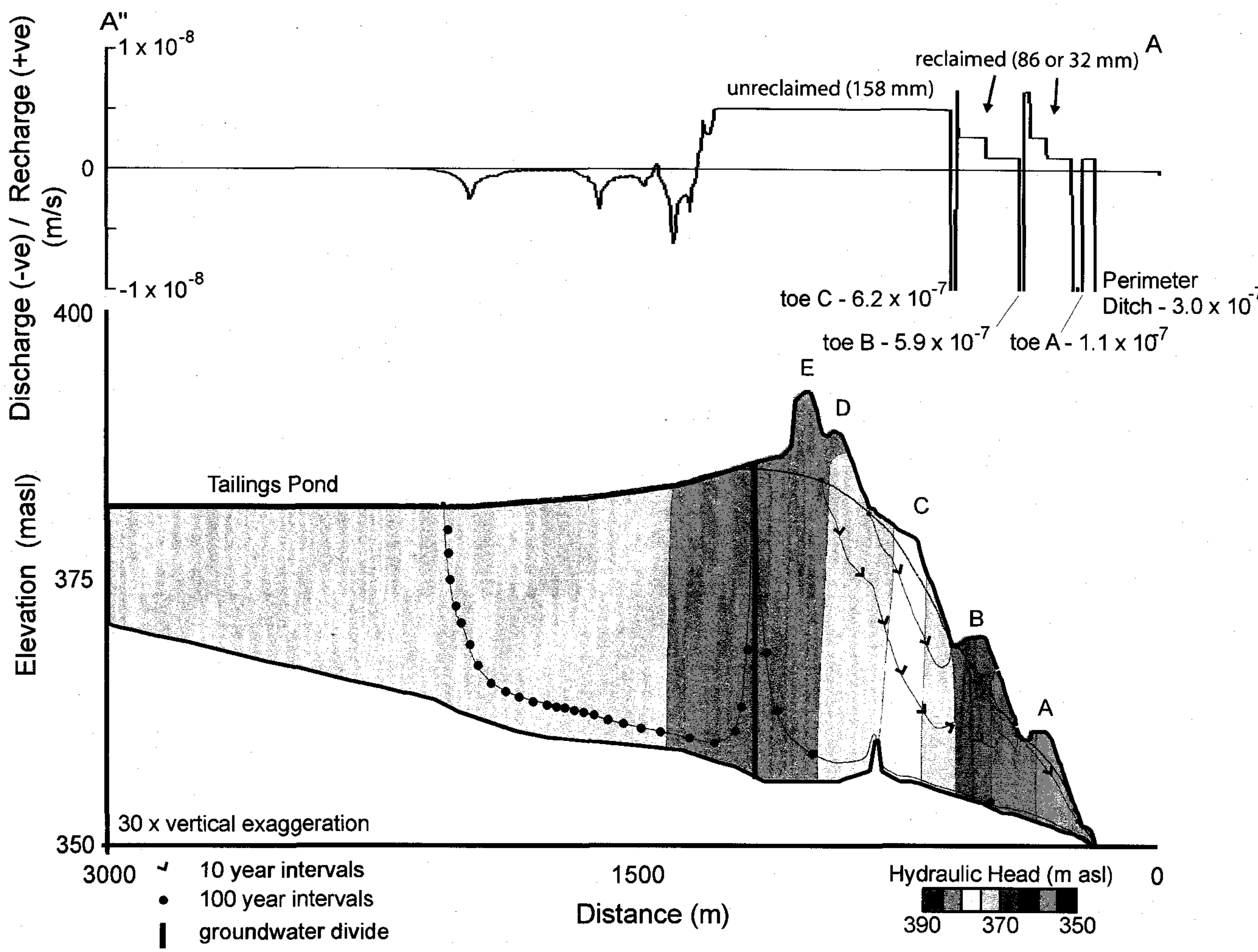

Figure 3-5. Calibrated steady-state hydraulic head distribution across Model Transect (A to A"). Recharge/discharge profile and particles tracked at local and intermediate scales are shown. Focused discharge exceeds graph scale and discharge values are given at those locations. Irregular discharge on the beach is due to microtopography.

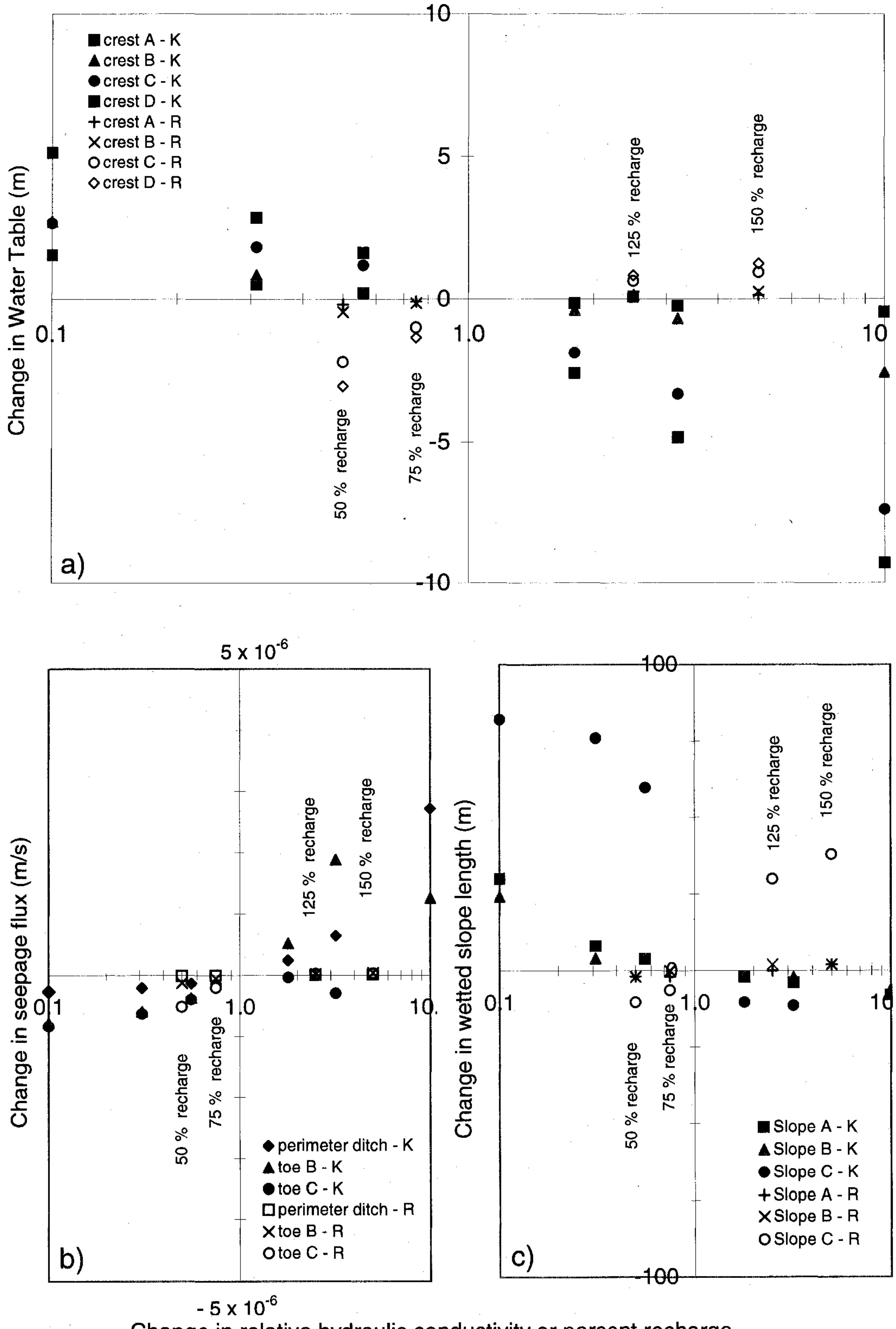

Figure 3-6. Sensitivity graphs showing changes to a) water table, b) seepage flux, and c) wetted slope length with changes in hydraulic conductivity (K) (over 2 orders of magnitude) and recharge(R) (+/- 50%, +/- 25%).

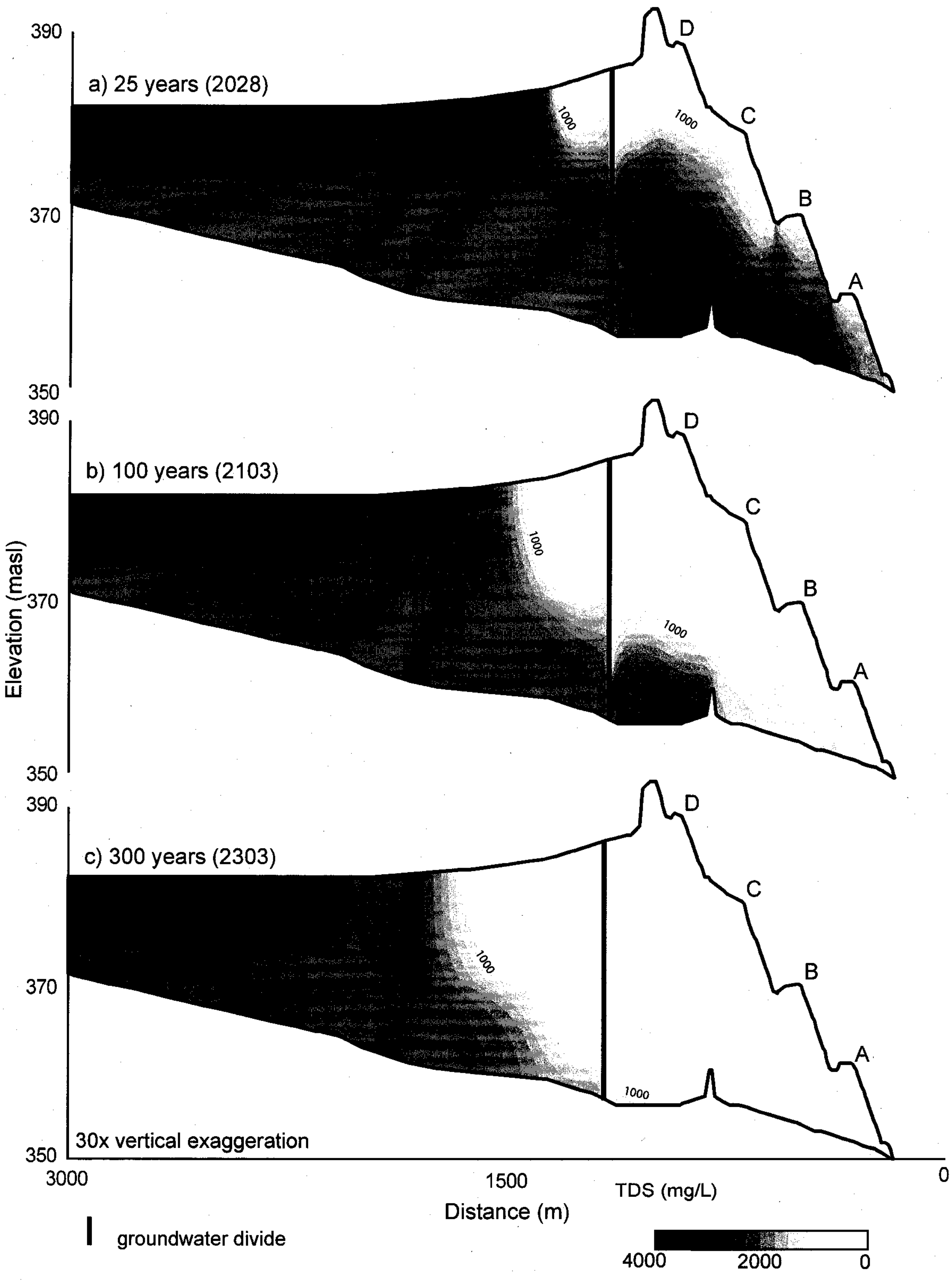

Figure 3-7. Groundwater total dissolved solids distributions in a) 2028, b) 2103, and c) 2303 under the current steady-state flow system. Note that the range of TDS is different than the initial conditions in Figure 3-2.

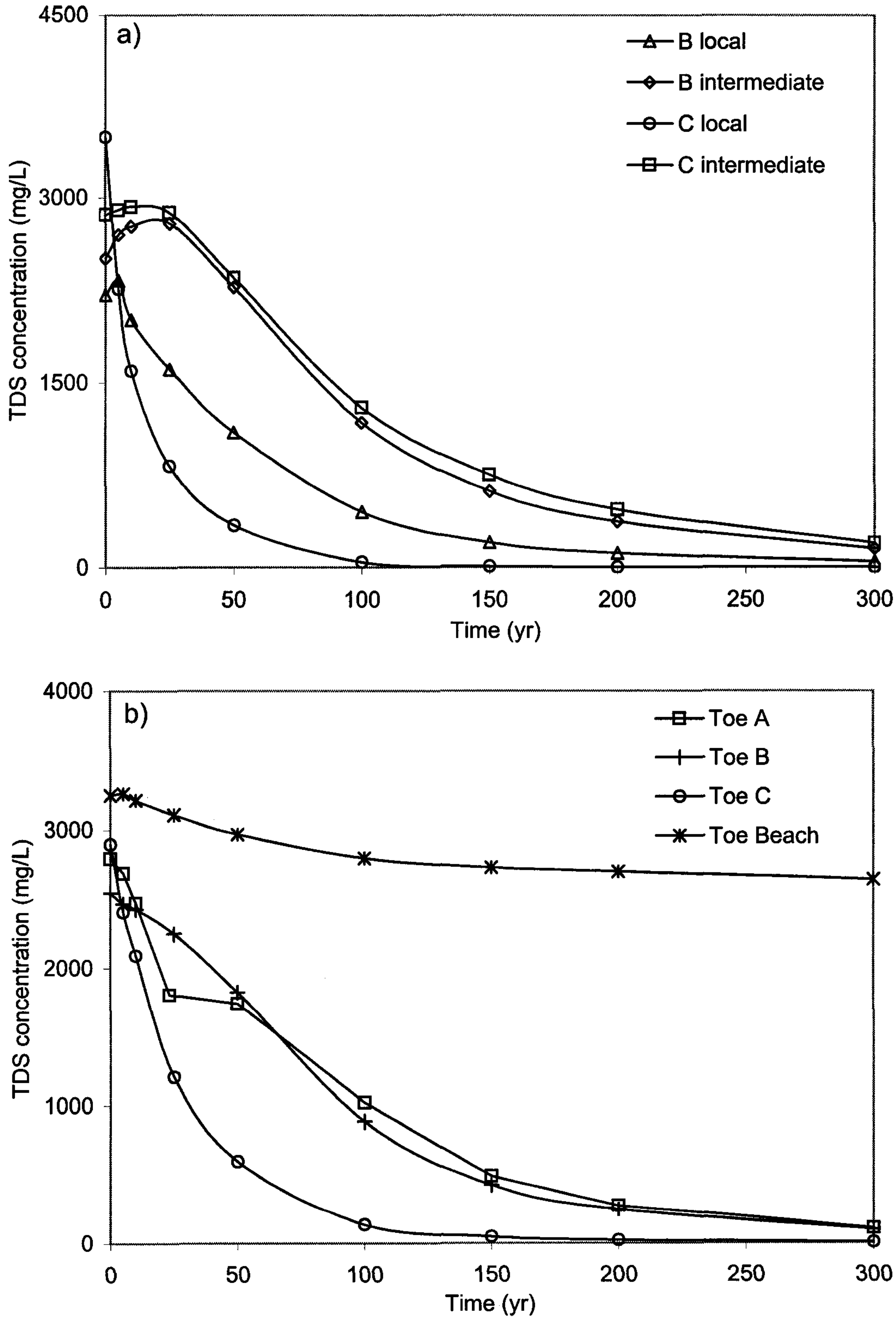

Figure 3-8. TDS breakthrough curves at shallow and deep piezometers at the (a) crests of Benches B and C, and at the (b) toes of Slopes A, Band C, and the beach.

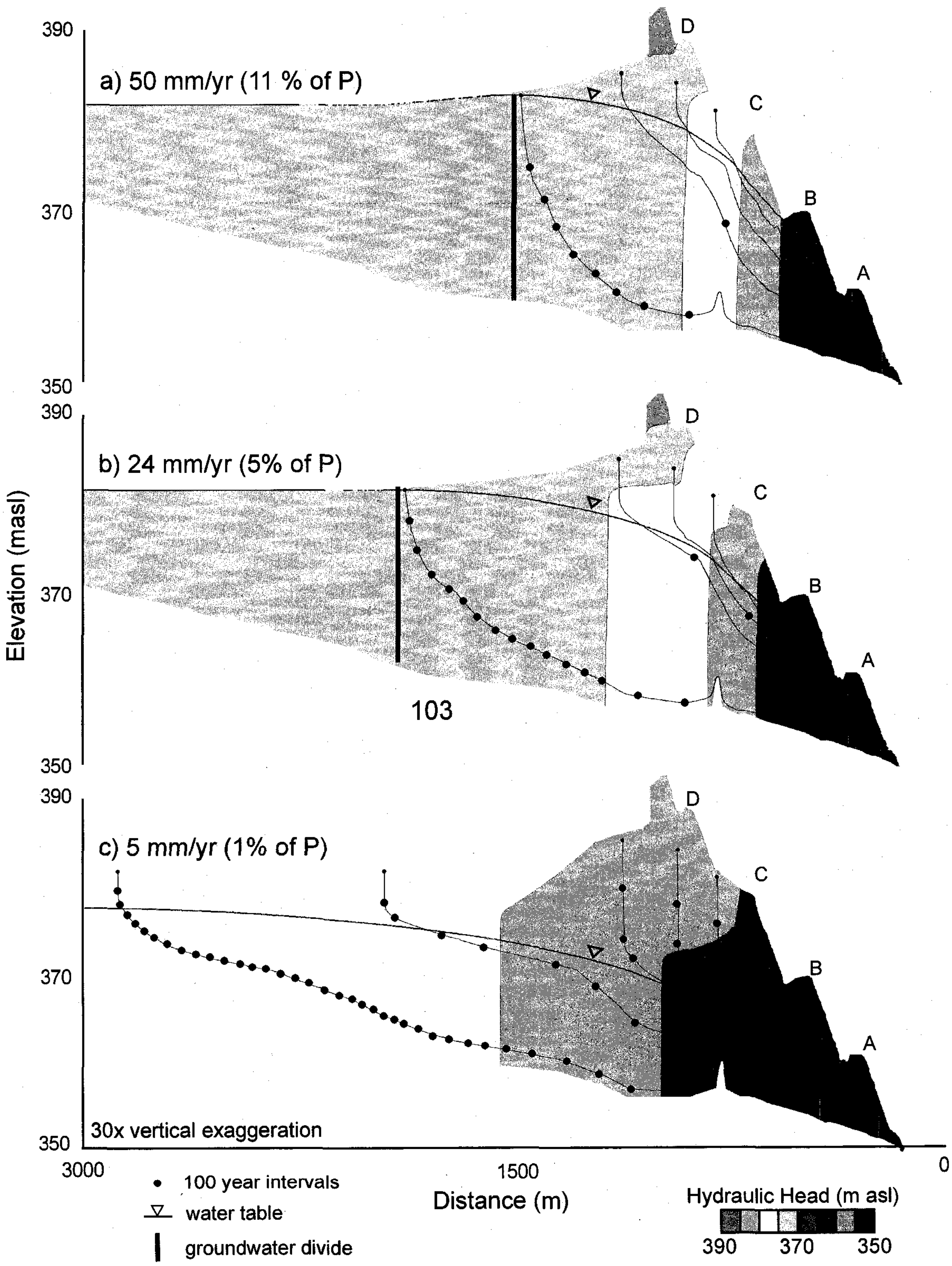

Figure 3-9. Simulated future steady-state flow systems with uniform recharge of a) 50 mm/yr, b) 24 mm/yr and c) 5 mm/yr. Percent of annual precipitation (456 mm/yr) shown. Particles tracked from the same position as in the calibrated steady-state flow model except for additional particles tracked from pond or groundwater divide.

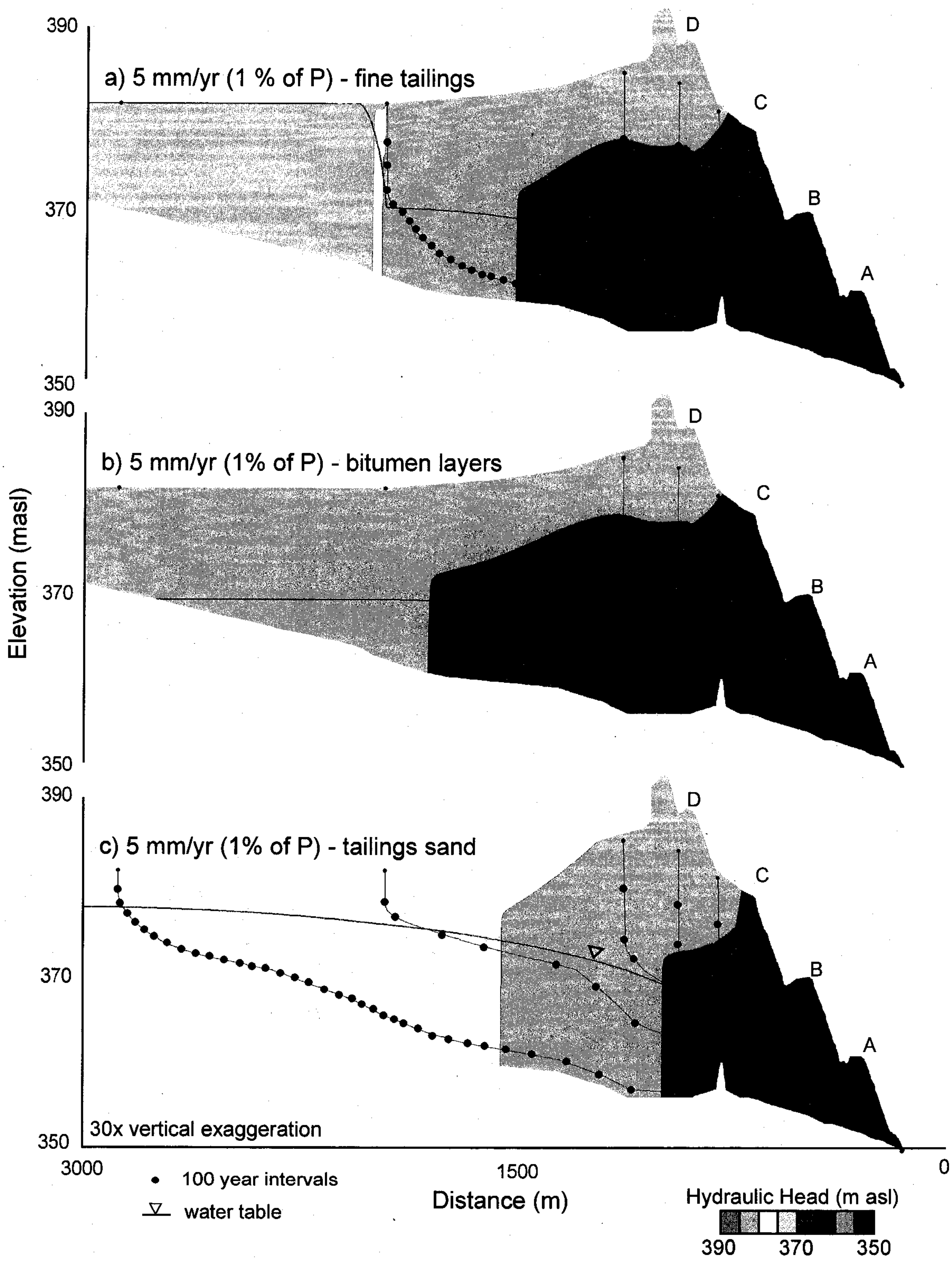

Figure 3-10. Simulated future SWSS flow systems with uniform recharge of 5 mm/yr for different materials in the tailings pond. Selected materials were a) fine tailings, b) bitumen layers at the ground surface and c) tailings sand.

Table 3-1. Hydraulic conductivity and anisotropy ratio values for hydrostratigraphic zones of the calibrated steady-state groundwater flow model.

Hydrostratigraphic Zone	Range of K (m/s)	Hydraulic Conductivity (m/s)	Anisotropy Ratio (K_x/K_z)
1 - Sand Bench	1.9×10^{-6} to 2.1×10^{-5} *	7.0×10^{-6}	10
2 - Bench A	5.8×10^{-7} to 1.2×10^{-5}	3.0×10^{-6}	10
3 - Bench B	1.1 to 3.7×10^{-6}	2.1×10^{-6}	20
4 - Bench C & D	2.1×10^{-6} to 1.2×10^{-5}	2.5×10^{-6}	5
5 - Toe B	3.6×10^{-6} to 1.6×10^{-5}	7.5×10^{-6}	1
6 - Toe C	5.3 to 6.9×10^{-6}	6.5×10^{-6}	1
7 - Lower Beach	1.0 to 3.7×10^{-6}	1.6×10^{-6}	20
8 - Upper Beach	2.0 to 8.9×10^{-6}	4.7×10^{-6}	20
9 - Contained Beaching	2.0 to 5.9×10^{-6}	3.3×10^{-6}	10

* upper limit of hydraulic conductivity calculated from seepage meter measurements.

Table 3-2. Travel times (yr) of groundwater moving through the SWSS under current steady-state flow system and possible future flow systems.

Particle Start Location	Scenarios					
	Current Steady-State Flow System	R= 50 mm/yr	R= 24 mm/yr	R= 5 mm/yr	R = 5 mm/yr Bitumen Layers in Pond	R= 5 mm/yr Fine Tailings in Pond
Bench A	16	16	17	91	154	147
Bench B	18	18	38	299	350	344
Bench C	27	71	119	574	696	684
Groundwater Divide	426	896	1606	-	-	-
Tailing Pond	-	-	-	3782	-	-

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Chapter 4
Summary

4.1 *Groundwater Flow and Salt Transport*

The hydrogeological investigation results described in Chapter 2, along Transects 31 (A to A') and 46 (B to B') at the Southwest Sand Storage Facility (SWSS), show nested local and intermediate groundwater flow systems on the perimeter dyke. A groundwater divide currently separates the groundwater flow on the dyke from the beach and the tailings pond.

Some aspects of the groundwater flow system in Transects 31 and 46 are different due to different designs of the perimeter dyke:

- On Transect 31, only 23% of the water table is closer than 1 metre to the ground surface, due to the backward-sloped bench design and the higher hydraulic conductivity at the dyke toe. Local flow systems extend from bench to adjacent slope toe. Consequently, there is dilution and downward salt migration in the shallow groundwater on Benches A, B and C due to recharge of precipitation. Focused groundwater discharge occurs on the dyke where the slope breaks at the slope toes (*i.e.,* channels).

- On Transect 46, 57% of the water table is closer than 1 metre to the ground surface. This increased proximity of the water table is due to the low relief provided by the forward-sloped bench design and the lower hydraulic conductivity of the tailings sand at the perimeter dyke toe. The local flow systems are shallow and small, and discharge of process water occurs at a number of locations, not just at the toe of the slopes. There is minimal flushing of the process water, as there is no dilution of shallow groundwater by recharge. Nor are significant amounts of flushed salts leached from reclamation soils down to the shallow groundwater.

The conceptual and numerical models developed for the SWSS along the Model Transect (A to A") in Chapter 3 include hydrostratigraphy, boundary conditions and applied recharge. The calibrated numerical flow model accurately describes the flow system, by including the site specific perimeter dyke geometry and the relevant hydraulic conductivity distribution, and by including the seepage faces, which allow water and salts to leave the model.

Under the existing nested flow system on the perimeter dyke, local flow systems (bench and slope) will take decades to flush existing process water, whereas the intermediate flow systems on the perimeter dyke will take centuries. Fresh groundwater traveling from the groundwater divide to the tailings pond will take thousands of years. Process water will flush from the perimeter dyke within a few hundred years, with benches towards the top flushing first. The discharge of process water at greater than 1000 mg/L TDS will continue in discharge areas for longer than 25 years.

The groundwater flow regime is likely to remain similar in the future, preserving the nested flow systems, the groundwater divide, and seepage locations and rates. The future flow regime will ultimately depend on the amount of recharge to the groundwater on the reclaimed structure. Mature fine tailings, and bitumen layers in the tailings pond, as conceptualized in the alternate management scenarios outlined in Chapter 3, will have minimal influence on the groundwater flow system on the perimeter dyke, if the groundwater divide remains.

4.2 Applications to Tailings Sand Dam Reclamation

Research results that will assist reclamation planning include the water table profiles, the TDS distributions, and the locations of recharge and discharge areas. The water table profiles across Transects 31 and 46 provide the depth to the water table, including important areas where the water table is at or near the ground surface. The detailed description of the shallow groundwater chemistry allows those reclaiming the SWSS to understand the groundwater conditions near some of the existing reclamation soils and vegetation. Future groundwater chemistry data collection and analysis will provide additional helpful information to determine salt transport processes at the water table.

After the water-table depth, the most important piece of information is the identification of the various locations of groundwater discharge. Based on this information, appropriate vegetation, which can tolerate process water, can be placed at those locations. The areas identified as recharge zones, with deeper water tables and low TDS in the shallow groundwater, will be more hospitable for a greater variety of vegetation that will be used in reclamation.

4.3 Perimeter Dyke Design

The groundwater investigation brought to light the importance of the design of the perimeter dyke on the groundwater flow and transport of salts. The backward-sloped benches (found at Benches A and B on Transect 31) by their design provide greater topographic relief than forward-sloped benches. The backward-sloped benches have larger local flow systems and promote deeper and faster flushing of the process water by recharge. The forward-sloped benches, on the other hand, do not function as effectively to generate local flow systems and flush process water. The relatively lower hydraulic conductivity of the constructed dyke and beaching at the toe of Transect 46 results in higher water tables than occurs on Transect 31.

4.4 Future Research

The implications of the perimeter dyke design on groundwater flow and salt transport should be considered by others designing and reclaiming similar tailings dams without internal drainage. The finite-element numerical models SEEP/W and CTRAN/W work well for modelling steady-state groundwater flow and transient salt transport. These models can be used by those designing similar undrained tailings structures to understand the implications of perimeter dyke design on the flow system and process water flushing.

Future research is recommended to improve the current understanding of groundwater flow and salt transport. The future research should include further field data collection and analysis, as well as additional numerical modelling.

4.4.1 Field Data

The understanding of groundwater flow and salt transport can be improved with additional data. Long-term data from Transects 31 and 46 should include:

- geochemistry of groundwater at and near the water table,
- long-term hydraulic head measurements, and
- long-term geochemistry (*i.e.,* TDS, cations and anions) measurements.

The groundwater samples collected during the investigation described in Chapter 2 were typically from 1 metre or more below the water table. Accordingly, changes in chemistry at the water table, such as dilution or salt accumulation were not possible to determine. If groundwater samples are collected across the water table, then salt concentrations and transport processes in the shallow groundwater will be clearer. This data will be especially useful for analysis of salt movement on Transect 46, where currently no shallow groundwater chemistry trends are available.

Long-term water level and geochemistry data will help determine whether there are changes to the groundwater flow system, the water table depth and the shallow groundwater geochemistry. Discharge areas (*e.g.,* toes of slopes) and recharge areas with high water tables, will be particularly important areas to be monitored for long-term changes in the water table depth and shallow groundwater salt concentrations.

4.4.2 Numerical modelling

The current steady-state flow model adequately describes flow and transport processes along the Model Transect (A to A"). Additional modelling may reduce some uncertainties associated with the completed numerical modelling results. Additional data may allow researchers to:

- recalibrate the groundwater flow model as additional data is obtained, especially if this data becomes available for the beach or pond; and
- calibrate the transport model, after the long-term water quality record is established along the Model Transect (A to A").

The numerical modelling of groundwater flow and salt transport at the SWSS was of necessity simplified by certain assumptions. Groundwater flow was assumed to be at steady-state. The influence of evapotranspiration on groundwater flow and salt movement was ignored. Future research can consider the transient nature of the groundwater flow system and its impact on salt transport. Similarly, seasonal recharge and tailings placement inputs and evapotranspiration outputs can be incorporated into a transient flow model, if data becomes available. If groundwater flow is modelled across Transect 46 on the west side of the SWSS, then evapotranspiration from the shallow water table should be incorporated into the modelling to represent groundwater and salt movement accurately.

There is a large range of possible future flow systems. To reduce the uncertainty with modelling these future flow systems, the range of recharge values input into the model needs to be narrowed. This refinement can be achieved by water balance modelling the range of possible future hydrology conditions at the SWSS. Reclamation soil thicknesses, soil type and types of vegetation all influence recharge to the groundwater flow system. By discovering the extent to which each of these factors will influence recharge at the SWSS, future researchers will be better able to understand and quantify the modelling results in order to provide the most accurate future flow system.

Appendix A

Adjustment of Total Dissolved Solids Concentrations in Deep Piezometers to Account for Drilling Fluid

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The drilling and completion of deep piezometers (> 9 m) into the tailings sand was completed using a casing hammer drill rig. Initial attempts to install the piezometer through the bottom of the drill casing resulted in tailings sand entering the casing almost immediately after the plug in the bottom of the casing was opened. To balance hydrostatic pressures, water was used to fill the casing and prevent tailings sand from entering during piezometer installation. The water was spiked with sodium bromide. A sample of the water used during each piezometer installation was analyzed for cations and anions, including bromide, and total dissolved solids (TDS) concentrations were calculated. Bromide was selected to determine the presence of drill water in groundwater as it is found at negligible concentrations of 0.1 mg/L in tailings process water (confirmed by Mackinnon, 2005).

All groundwater samples collected from piezometers over the course of the investigation were analyzed for cations and anions including bromide. Recorded concentrations of bromide in both drilling water and groundwater samples allowed an estimate of the percentage of drilling water remaining in deep piezometer at the time of groundwater sample collection. The adjusted TDS of groundwater sampled at the piezometers was calculated by changing the TDS of groundwater samples based on the percentage of drill water remaining. The adjusted TDS of groundwater is an estimate of the TDS of the groundwater at deep piezometer sampling points if groundwater had not been affected by introduced drilling water.

The adjustment calculations were as follows:

1. Calculate TDS concentrations (mg/L) in measured groundwater samples and drilling waters.

   $$C = \sum cations + \sum anions$$

2. Calculate fraction of drill water in measured groundwater samples.

   $$f_d = \frac{B_m}{B_d}$$

3. Calculate fraction of process water in measured groundwater samples.

   $$f_g = 1 - f_d$$

4. Adjust TDS concentration (mg/L) of groundwater samples.

   $$C_g = \frac{C_m - (f_d * C_d)}{f_g}$$

where f_d is the fraction of drill water, f_g is the fraction of process water in the measured groundwater, B_m is the bromide concentration of the measured groundwater sample, B_d is the bromide concentration of the drilling water, C_m is the TDS concentration of the measured groundwater, C_d is the TDS concentration of drilling water and C_g is the TDS concentration of the groundwater. Initial and adjusted TDS of groundwater samples are shown in Table A1. Only those groundwater samples with bromide detected were adjusted.

References

Mackinnon, M.D., 2005. Personal communication regarding bromide concentrations in tailings process water. Syncrude Canada Ltd.

Deep Piezometer ID	Location	Sample Date	C_m	B_m	B_b	f_d	C_d	f_g	C_g
			Initial Groundwater TDS (mg/L)	Groundwater Bromide Concentration (mg/L)	Drilling Water Bromide Concentration (mg/L)	Fraction Drilling Water	Drilling Water TDS (mg/L)	Fraction Process Water	Adjusted Groundwater TDS (mg/L)
GW11-15	Cell 31	29-May-03	2867	14.0	960	0.01	1491.88	0.99	2887
GW11-15	Cell 31	20-Jul-2003	2858	7.5	960	0.01	1491.88	0.99	2869
GW11-15	Cell 31	16-Sep-2003	2824	8.5	960	0.01	1491.88	0.99	2836
GW11-23	Cell 31	29-May-03	3125	26.0	1010	0.03	1568.69	0.97	3166
GW11-23	Cell 31	20-Jul-2003	3025	10.0	1010	0.01	1568.69	0.99	3040
GW11-23	Cell 31	16-Sep-2003	3089	19.0	1010	0.02	1687.56	0.98	3116
GW15-15	Cell 31	30-May-03	3589	17.0	1100	0.02	1687.56	0.98	3618
GW15-15	Cell 31	17-Sep-2003	3214	19.0	1100	0.02	1687.56	0.98	3241
GW15-24	Cell 31	30-May-03	2884	80.0	1020	0.08	1581.76	0.92	2995
GW15-24	Cell 31	21-Jul-2003	2824	35.0	1020	0.03	1581.76	0.97	2868
GW15-33	Cell 31	29-May-03	2628	18.0	135	0.13	443.46	0.87	2964
GW15-33	Cell 31	22-Jul-2003	2467	27.0	135	0.20	443.46	0.80	2973
GW23-12	Cell 46	22-Sep-2002	3263	175	960	0.18	1494.04	0.82	3658
GW23-12	Cell 46	3-Jul-2003	3735	29.0	960	0.03	1494.04	0.97	3804
GW23-19	Cell 46	22-Sep-2002	2878	105	960	0.11	1523.36	0.89	3044

Table A1. Adjusted Groundwater TDS Concentrations for deep piezometers (0.051 m) installed with casing hammer rig. NaBr spiked water used during drilling.

Appendix B

Southwest Sand Storage Facility Stratigraphic Interpretations

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Two cross-sections, on the east (A to A") and west (B to B") sides of the Southwest Sand Storage Facility (SWSS), were selected for stratigraphic interpretation (Figure B1). The interpretation was a reconstruction of tailings sand depositional history. Sections of the interpreted stratigraphies were included in the field characterization results, along Transects 31 and 46 (Chapter 2). The entire interpreted stratigraphy on the east side of the SWSS (A to A") was used as the geologic framework for the hydrostratigraphy developed for the conceptual model along Model Transect 31 (Chapter 3).

The depositional history was reconstructed using various data including:

- digital contour maps of the SWSS for 1991, and 1995 to 2003;
- Southwest Tailings Disposal Site - Detailed Design (Klohn Leonoff, 1991);
- Southwest Sand Storage Landscape Design Study (AEE, 1997); and,
- SWSS ground surface elevations at the groundwater instrumentation locations.

The digital contour maps of the SWSS were provided by Syncrude Canada Ltd. (Huebner, 2003 and 2004). The digital surfaces were created and digitized from aerial photographs. The dam and original ground surface topographies were delineated by 1 m contour intervals. The data used to reconstruct the stratigraphy were extracted by taking UTM coordinates and ground surface elevations at locations wherever the two stratigraphic cross-sections (A to A" and B to B") crossed a 1 m contour interval. The x, y and z coordinates were used to create the 2D ground surface profiles for each year. Rod and level surveying at piezometer nests, single piezometers, and staff gauges determined the ground surface elevations at the research instrumentation locations.

Stratigraphic units were defined by their "depositional" history: (a) constructed/ reworked material on the dyke; (b) contained beaching; and (c) free deposition by beaching (Klohn Leonoff, 1991). The delineation between constructed dykes and beached tailings was estimated, based on breaks in slope evident at the edge of constructed dykes. Starter dykes built at the edge of the constructed dykes were obvious in the ground surface profiles (*i.e.,* year 1996 on Stratigraphic Cross-section 31). The geometries of cells were estimated based on design specifications (*i.e.*, dykes 3 to 5 m height) (Klohn Leonoff, 1991).

On Stratigraphic Cross-section 31, the original ground surface was extracted from the 1991 digital contour map. The perimeter sand bench position and width, and Bench A width were based on the original design report (Klohn Leonoff, 1991). The more recent landscape design study by AEE (1997) provided information about the details of construction. These included the location of contained beaching between Bench A and an earthen starter dyke (1992 to 1994), the beached tailings (1993 and 1994), and constructed dykes on Bench B (1994). The constructed dykes and beached tailings locations above Bench B were determined from the 1995 to 2003 digital contour maps. The interpretation by AEE (1997) of tailings sand placement, helped define the geometry of constructed cells on Slope C, and at the crest of Bench C. The current ground surface across the cross-section was estimated using a combination of elevation data from the 2002 digital contour maps, surveyed instrumentation (2002) on the perimeter dyke, and 2003 digital contour map data on the beach and at the tailings pond. The ground surface elevations on the perimeter dyke did not change between 2002 and 2003. Figure B2 illustrates the interpretation of tailings sand deposition across Stratigraphic Cross-section 31.

On Stratigraphic Cross-section 46, the original ground surface was developed from the 1991 digital contour map. The construction of Transect 46 began in 1995, and stratigraphic interpretation was based solely on digital contour maps (1995 to 2003). The elevation of the current ground surface was estimated from the 2003 digital contour maps and surveyed ground elevations (2002) at research instrumentation locations. Figure B3 illustrates the interpretation of tailings sand deposition across Stratigraphic Cross-section 46.

The age of tailings sand placed along Stratigraphic Cross-section 31, between 1991 and 1994, was based partly on details provided by AEE (1997). The age of Bench A, the contained beaching, and Bench B was estimated based the ages provided of nearby beached tailings sand. The age of deposited materials placed after 1994, along both stratigraphic cross-sections, was interpreted from the digital contour maps.

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Klohn Leonoff Ltd., 1991. Southwest Tailings Disposal Site Detailed Design, Summary Report. Syncrude Canada Ltd.

Huebner R., 2003. Contour maps of the SWSS for 1991, and 1995 to 2002. GPS Systems Specialist. Survey, Technologies and Resources. Syncrude Canada Ltd.

Huebner R., 2004. Contour maps of the SWSS for 2003. GPS Systems Specialist. Survey, Technologies and Resources. Syncrude Canada Ltd.

Legend: A ▬ ▬ ▮ A" Stratigraphic cross-section

—▶— Perimeter ditch (w/ flow direction)

photo courtesy of the SWSS Syncrude Canada Ltd., 2001

Figure B1. Aerial photograph of the Southwest Sand Storage Facility showing the locations of Stratigraphic Cross-sections 31(A to A") and 46 (B to B"). Cells delineate areas subdivided for tailings sand placement.

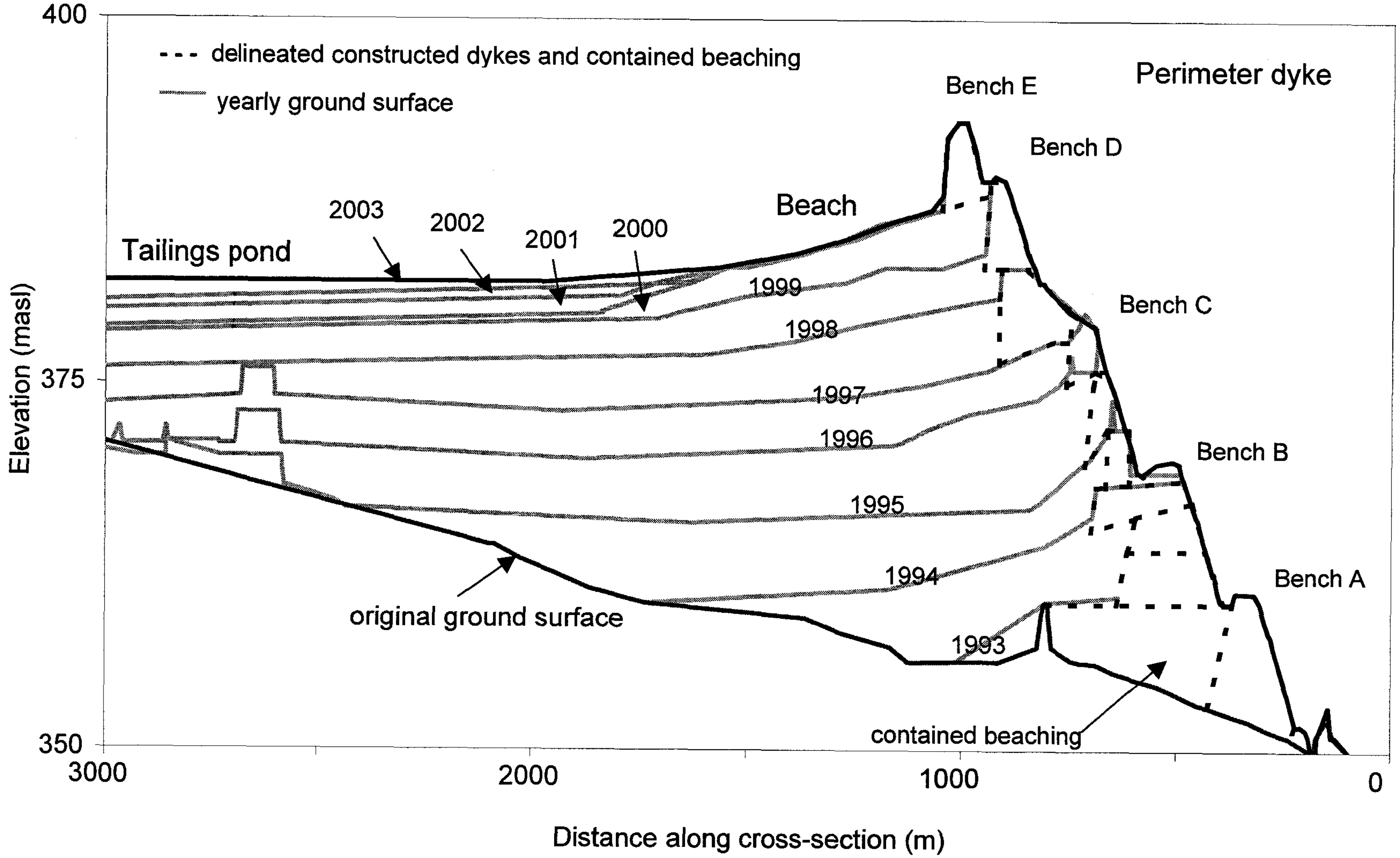

Figure B2. Stratigraphic Cross-section 31 showing the interpreted delineation between beached sand, constructed dykes and contained beaching.

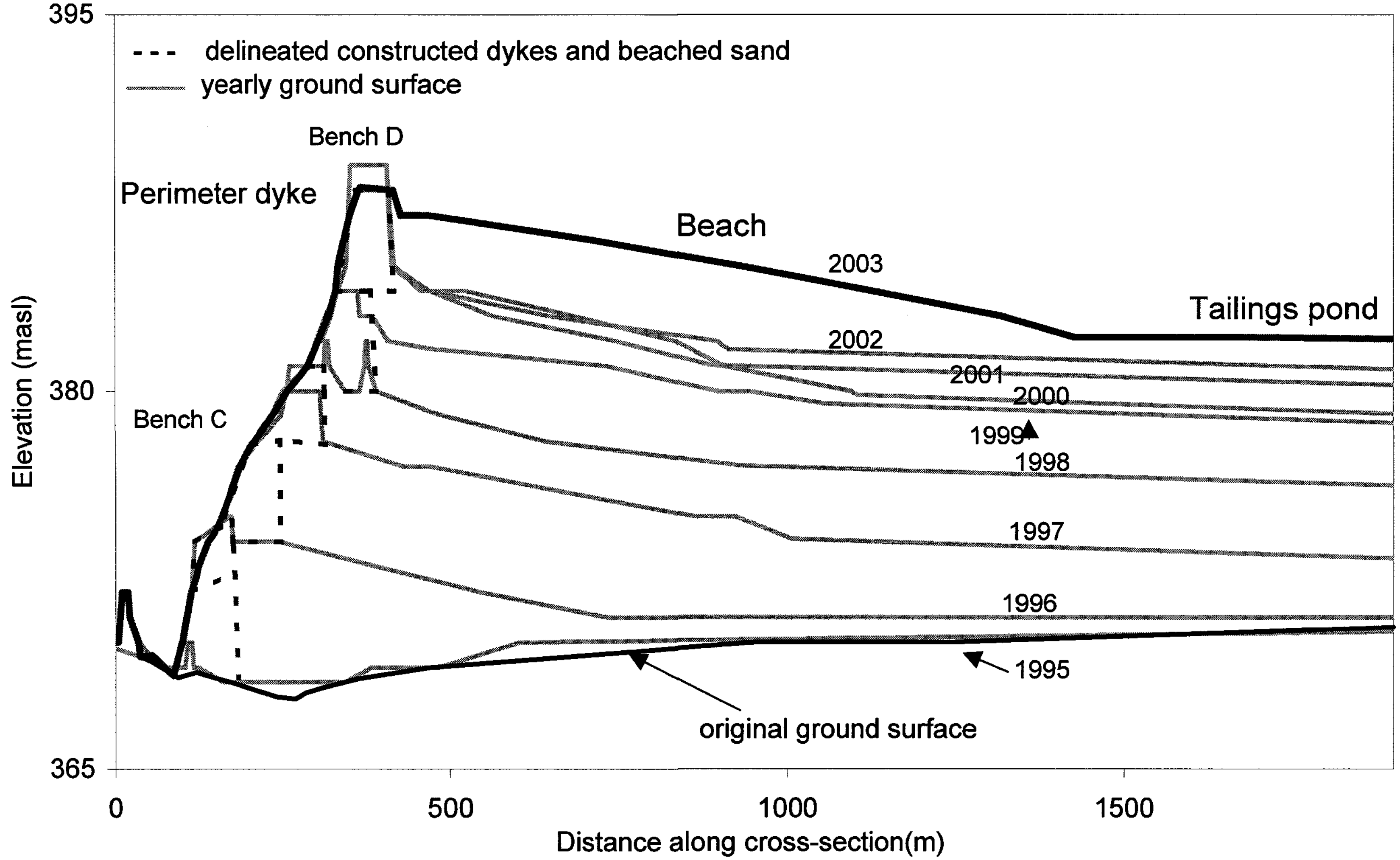

Figure B3. Stratigraphic Cross-section 46 showing the interpreted delineation between beached sand, and constructed dykes.

Appendix C
Southwest Sand Storage Facility Water Table Map

The water table of the Southwest Sand Storage Facility (SWSS) was mapped to better understand the groundwater flow direction in the entire structure prior to groundwater flow numerical modelling. The 2002 water table map is a linear interpolation of water level data that was contoured by hand and overlain on an aerial photo of the SWSS (Figure C1). The 2002 average water level measurements from Syncrude standpipes at the SWSS (Purhar, 2004), and selected piezometers and water table wells from the current investigation, were used in mapping. In addition, the water elevation and location of the tailings pond were read from the 2002 digital contour map (Huebner, 2003). The compiled groundwater levels used in mapping are reported in Table C1.

Groundwater flows perpendicular to the benches on the perimeter dyke, from the crest of the dyke towards the perimeter ditch. Thus, Transects 31 and 46 selected for investigation were parallel to the groundwater flow direction. Groundwater elevations measured in Syncrude standpipes, near the crest of the perimeter dyke, were higher than the pond elevation, confirming the existence of a groundwater divide.

References

Purhar, G. 2004. Southwest Sand Storage Facility 2003 Performance Report. Tailings Material Handling and Storage Technical Team, Extraction Department, Syncrude Canada Ltd.

Huebner R., 2003. Contour maps of the SWSS for 1991, and 1995 to 2002. GPS Systems Specialist. Survey, Technologies and Resources. Syncrude Canada Ltd.

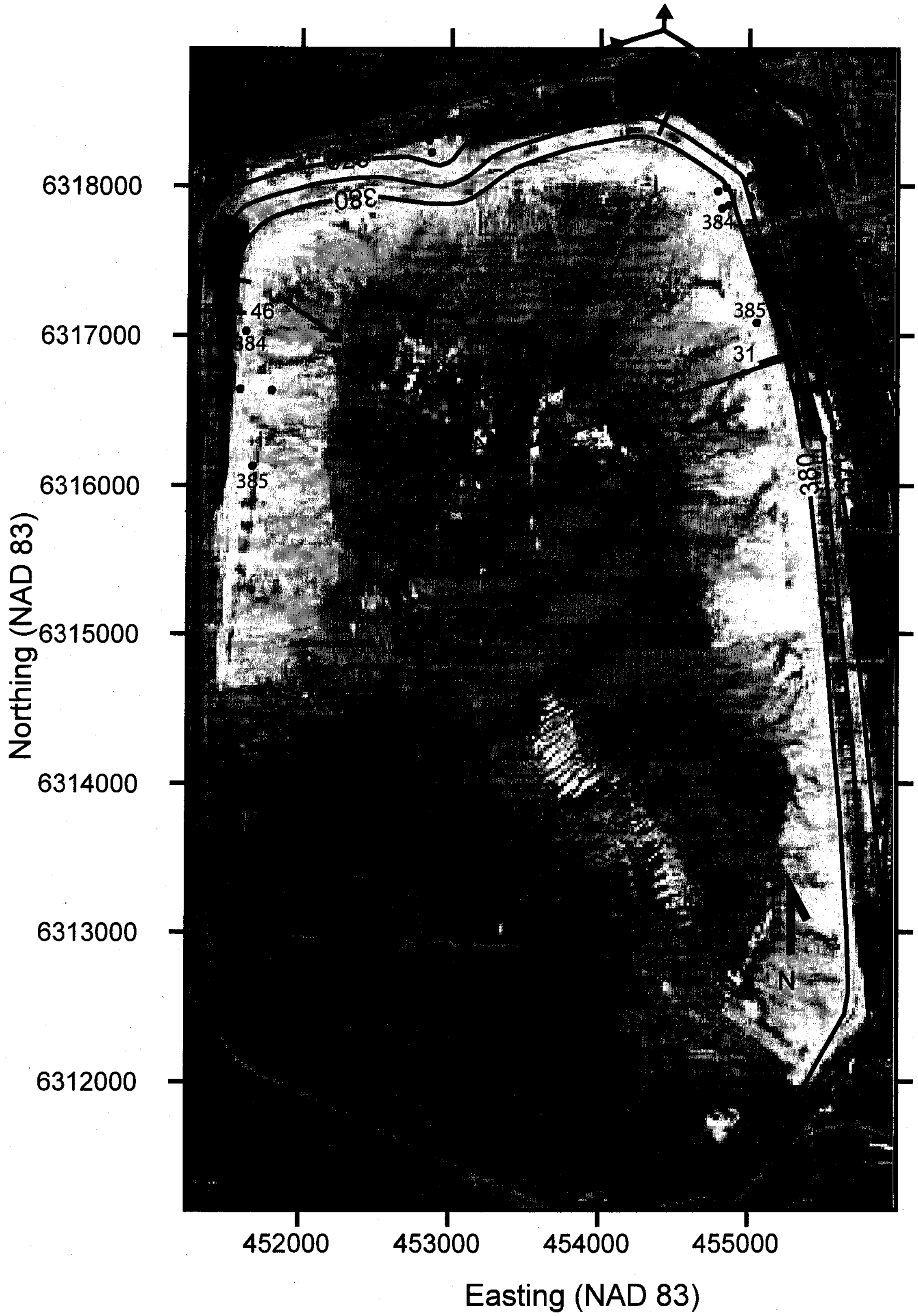

Figure C1. 2002 water table map of the Southwest Sand Storage Facility. Heads contoured by linear interpolation and bounded by the perimeter ditch.

Table C1. Water levels used for mapping 2002 water table at the SWSS

Piezo ID	Northing	Easting	2002 average
Research Piezometers			
GW01-1.5WT	6317057	455751.8	353.35
GW02-2.5WT	6317049	455713.7	355.82
GW03-3WT	6317031	455679.5	358.34
GW04-1.75WT	6317013	455636.9	359.62
GW05-2.2-WT	6316998	455591.6	360.87
GW06-3.8-WT	6316988	455556.0	362.59
GW07-5-WT	6316977	455513.2	365.23
GW08-2.5-WT	6316957	455464.0	368.03
GW09-1.5-WT	6316937	455411.7	369.63
GW10-2.5-WT	6316922	455373.8	372.81
GW11-4-WT	6316910	455330.4	375.92
GW12-1.5-WT	6316889	455275.1	379.39
GW13-2.5-WT	6316870	455219.6	380.84
GW15-7	6316842	455102.2	384.06
GW24	6316998	455606.2	360.23
GW26	6317007	455617.4	360.06
GW27	6317064	455769.8	351.69
GW29	6316937	455424.1	369.04
SG01	6317075	455808.9	349.67
SG02	6317011	455626.7	360.02
SG03	6316949	455435.4	368.75
GW16-1.5WT	6317169	451361.7	371.85
GW17-1.6WT	6317169	451388.5	373.60
GW18-2.15WT	6317167	451416.2	374.75
GW19-1.7WT	6317166	451446.0	377.14
GW20-1.6WT	6317163	451483.5	378.70
GW21-1.5WT	6317161	451511.9	379.63
GW22-2.25WT	6317159	451548.3	380.62
GW23-7	6317151	451605.9	382.60
SG04	6317190	451326.5	369.05

Coordinates are in NAD 83, Zone 12

Table C1 (cont'd). Water levels used for mapping 2002 water table at the SWSS

Piezo ID	Northing	Easting	2002 average
Syncrude Standpipes			
SP31-01-01	6317088	455051.1	385.37
SP31-01-04	6317143	455240.3	376.85
SP31-01-07	6317208	455457.4	364.91
SP31-95-05	6317479	455593.1	354.74
SP31-95-06	6317468	455554.9	357.37
SP31-95-08	6317409	455359.4	365.86
SP31-96-12	6317371	455227.5	372.43
SP32-01-01	6316320	455496.0	375.65
SP33-01-06	6315484	455557.7	376.81
SP33-01-07	6315469	455776.3	367.13
SP46-01-01	6317028	451631.5	383.64
SP46-01-04	6317050	451426.4	376.57
SP46-02-01	6316637	451408.9	376.12
SP46-02-02	6316644	451594.7	383.94
SP46-02-03	6316639	451805.8	383.72
SP45-02-01*	6316130	451679.9	384.72
SP48-99-01*	6318473	452814.0	361.51
SP48-99-02*	6318413	452832.4	363.08
SP48-99-03*	6318304	452847.5	366.28
SP48-99-04*	6318223	452863.9	369.22
SP49-98-01	6318431	453868.3	374.99
SP49-98-02	6318512	453856.7	370.15
SP49-98-03	6318673	453837.0	363.06
SP49-98-04	6318737	453829.9	358.45
SP50-95-14	6318758	454836.8	353.88
SP50-95-15	6318732	454822.7	356.21
SP50-95-16	6318702	454806.7	358.26
SP50-95-17	6318601	454751.4	359.98
SP51-95-04	6318192	455430.4	350.86
SP51-95-05	6318182	455394.7	352.67
SP51-95-06	6318167	455348.9	356.24
SP51-95-07	6318143	455267.2	360.04
SP51-96-01	6318137	455261.3	360.29
SP51-96-02	6318111	455145.4	366.43
SP51-96-04	6318082	455055.6	369.92
SP51-96-05	6318068	455009.7	372.61
SP51-01-01	6318153	455058.1	369.34
SP51-01-02	6318296	455095.8	364.64
SP51-01-03	6318362	455121.6	361.75
SP51-01-04	6318435	455137.8	359.26
SP51-01-05	6317965	454789.5	384.33
SP51-01-06	6317990	454847.0	380.72
SP51-01-07	6317853	454817.6	384.24
SP51-01-08	6317874	454863.1	381.76
SP51-01-09	6317941	455073.0	371.14
SP51-01-10	6317967	455199.7	366.17
SP51-01-11	6317931	455009.2	374.49
SP51-01-12	6318035	454976.5	374.63

* location estimated from standpipe map (Purhar, 2004)
Coordinates are in NAD 83, Zone 12

Appendix D
Recharge at the Southwest Sand Storage Facility

Previous Recharge Estimates

Recharge is defined as entry of water into the saturated zone together with the associated flow away from the water table within the saturated zone (Freeze and Cherry, 1979). Previous investigators have used different terms to describe recharge including infiltration and percolation. Skopek (1996), AEE (1997), and McKenna (2001) estimated a range of rates for infiltration, percolation and recharge, respectively, at the SWSS. These values were considered as the range of **recharge** rates when selecting the initial recharge values for the numerical flow model.

Skopek (1996) used the Water Evapotranspiration Simulation (WES) model to compute a simple water balance for a two-layer soil profile. The soil profile model was 0.7 m of reclamation soil over tailings sand. Material infiltration rates were based on measured values through reclaimed soils and tailings sand at Syncrude. The model calculated an infiltration rate of 50 to 100 mm/yr into the SWSS.

AEE (1997) estimated the amount of percolation through the top of the SWSS. SoilCover model was used to complete a water balance in both a uniform soil column and a layered soil system. Percolation, as well as other water balance components, were calculated for uniform tailings sand columns of different hydraulic conductivity. Percolation values for uniform tailings sand profiles ranged from 119 to 140 mm/yr for hydraulic conductivities between 1 x 10^{-6}m/s, and 1 x 10^{-5} m/s. The layered soil system modelled was a vegetated reclamation soil (0.3 m) over tailings sand. Two different soil characteristic curves for the reclamation soil were modelled: typical sand and typical clayey silt. Sandy soils resulted in percolation rates of 40 mm/yr, where as clayey silt soil percolation rates were estimated at 0 mm/yr. Hydraulic conductivity of tailings sand was fixed at 2×10^{-6} m/s for the layered soil model simulations.

McKenna (2001) used a recharge of 90 mm/yr for reclaimed tailings sand in a first-order landscape water balance completed for the SWSS; however, he thought a recharge range of 45 mm/yr to 180 mm/yr was possible.

2002 Recharge Calculation

Recharge was calculated for 2002 for a reclaimed area of the SWSS using a simple water balance calculation (Freeze and Cherry, 1979). A water balance estimate was possible in 2002 because all the necessary data was available if the change in storage was assumed to be zero. The water balance equation was rearranged to solve for recharge:

$$R = P - E_R - Q_s$$

where R is recharge, P is precipitation, E_R is evapotranspiration, and Q_s is surface water runoff. Using this equation, the estimated total recharge, through reclaimed tailings sand in 2002, was 107 mm/yr (Table D-1).

Recharge rate selection

Recharge rates were reviewed to select initial conditions for Model Transect 31 and were assigned across the top of the model. Two different area types, bare and reclaimed tailings sand, were identified as having different recharge values, which needed to be reflected by the selected initial flow model boundary conditions. An initial recharge amount of 130 mm/yr was chosen for bare tailings sand from the range of modelled values (119 to 140 mm/yr) proposed by AEE

(1997). A recharge value of 50 mm/yr was selected as initial model conditions for reclaimed areas. This value was selected as Skopek (1996) indicated that the majority of reported infiltration data supported 50 mm/yr. In addition, 50 mm/yr was near to the 40 mm/yr proposed by AEE (1997) for vegetated sandy reclamation soils. Recharge values, considered reasonable during calibration, ranged from 0 to 100 mm/yr for the reclaimed tailings sand and 119 to 140 mm/yr for bare tailings sand. The recharge values were considered reasonable because the relative distribution of recharge was logical (*e.g.,* more recharge on sand than the vegetated peat-mineral reclamation soil). In addition, the ranges were based on water balance modeling results for the SWSS.

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Table D1. 2002 water balance calculation for reclaimed area of the SWSS.

Water Balance Component	Amount (mm/yr)	Data Source
Precipitation	422	2002 Precipitation data from Fort McMurray Airport weather station (Environment Canada, 2004)
Evapotranspiration	280	2002 Actual Evapotranspiration calculated for reclaimed areas of the SWSS (Liggett, 2004)
Runoff	35	2002 Runoff data collected in runoff frames, Cell 32, by U of A Renewable Resources (Chaikowsky, unpublished)
Δ Storage	0	Assumed to equal zero – controlled pond elevation and only small amounts of beaching
Recharge	**107**	

Appendix E

Simple Transient Groundwater Flow Model

Modelling Methodology and Set-up

Simple transient groundwater flow simulations were run to determine the approximate time it would take the SWSS to drain and reach the proposed future steady-state flow systems. One of these future flow systems may be reached sometime after the closure of the SWSS, when inputs (*i.e.,* tailings inputs and recharge) have remained constant for some period. This additional transient groundwater flow modelling was completed in support of the main modelling presented in Chapter 3, and the results are discussed therein.

A simple 2D transient groundwater flow model simulated draining of the SWSS in SEEP/W (GEO-SLOPE, 2002a). Two simulations were run to determine the differences in time for groundwater flow systems to reach steady state with 5 mm/yr and 50 mm/yr of recharge across the top of the SWSS. The effects of mature fine tailings and bitumen layers were not considered while modelling transient groundwater flow. As a rough estimate of system change over time, the level of system details used in the model described in Chapter 3 (*i.e.*, hydrostratigraphy, K function) was deemed unnecessary.

The boundary and initial conditions used for the transient flow modelling are illustrated in Figure E1. The boundary conditions were similar to those of the *current* groundwater flow model, except there was no constant head applied at the tailings pond, and the recharge flux across the entire top of the model was either 5 mm/yr (1% of P) or 50 mm/yr (11% of P) of the annual precipitation (P = 456 mm/yr). The initial hydraulic head conditions used in the model were the observed heads in August 28, 2003 along Model Transect 31, used in the *current* flow model calibration. Heads across the groundwater divide were assigned from the *current* flow model solution.

The model grid spacing was large and approximated the SWSS topography (Figure E1). A simpler grid was created because the computational requirements of running the transient flow analysis on the detailed grid of the *current* flow model were excessive. The total number of nodes and elements of the grid were 1991 and 1902, respectively. The grid extended from 180 to 3000 m on the x axis and was positioned between 350 and 393 meters above sea level on the z axis with a maximum thickness of 37 m at the top of the perimeter dyke. The discretizations in the x and z directions were 30 m and 1 m. The temporal discretization for transient flow analysis was 10 days for 1000 years, equaling 36500 time steps.

The model parameters used for simple transient flow model are listed in Table E1. The hydraulic conductivity was an average of the calibrated hydraulic conductivities for the hydrostratigraphic units (excluding Toe B and C) in the *current* flow model. For unsaturated zone parameters, a sandy silt volumetric water content (VMC) function was selected (as in Chapter 3; Figure 3-3). Thus, saturated and residual water contents were 0.4, and 0.07. The chosen specific yield of 0.33 was close to 0.37 approximated by the Johnson (1967) method using the percentage of sand (91%), silt (8%) and clay (1%) in tailings sand (Gan, 2001).

The results of the two simulations are shown in Figures E2 and E3. Figure E2 shows the change in water table locations over time under the decreased recharge scenarios. Figure E3 is a drawdown plot of heads through time at the perimeter dyke crest. These results are discussed in Chapter 3.

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Table E1. Transient groundwater flow parameters

Parameter	Value (or range)	Source
K (m/s)	3.0×10^{-6} m/s	Current study, 2003
K_x/K_z	10	McKenna, 2002
n	0.4	McKenna, 2002
Aquifer compressibility (kPa^{-1})	0.00001	Freeze and Cherry, 1979
S_y	0.33	GEO-SLOPE, 2002a

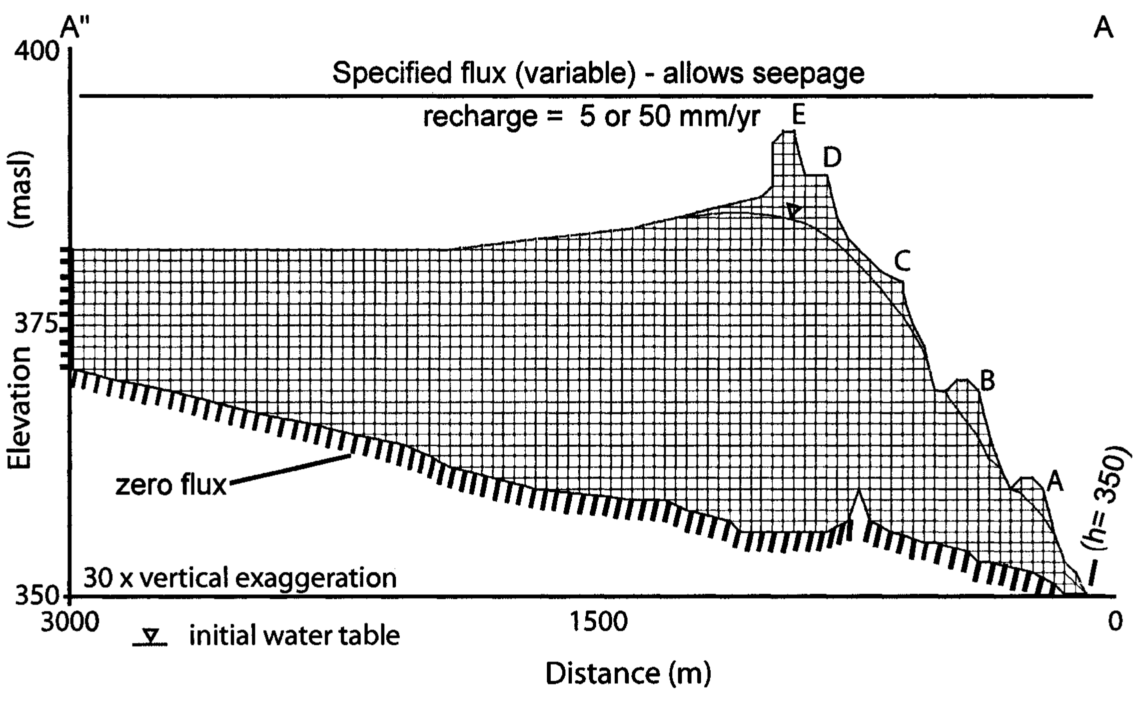

Figure E1. Boundary conditions, initial conditions and grid descritization of a simple transient groundwater flow model.

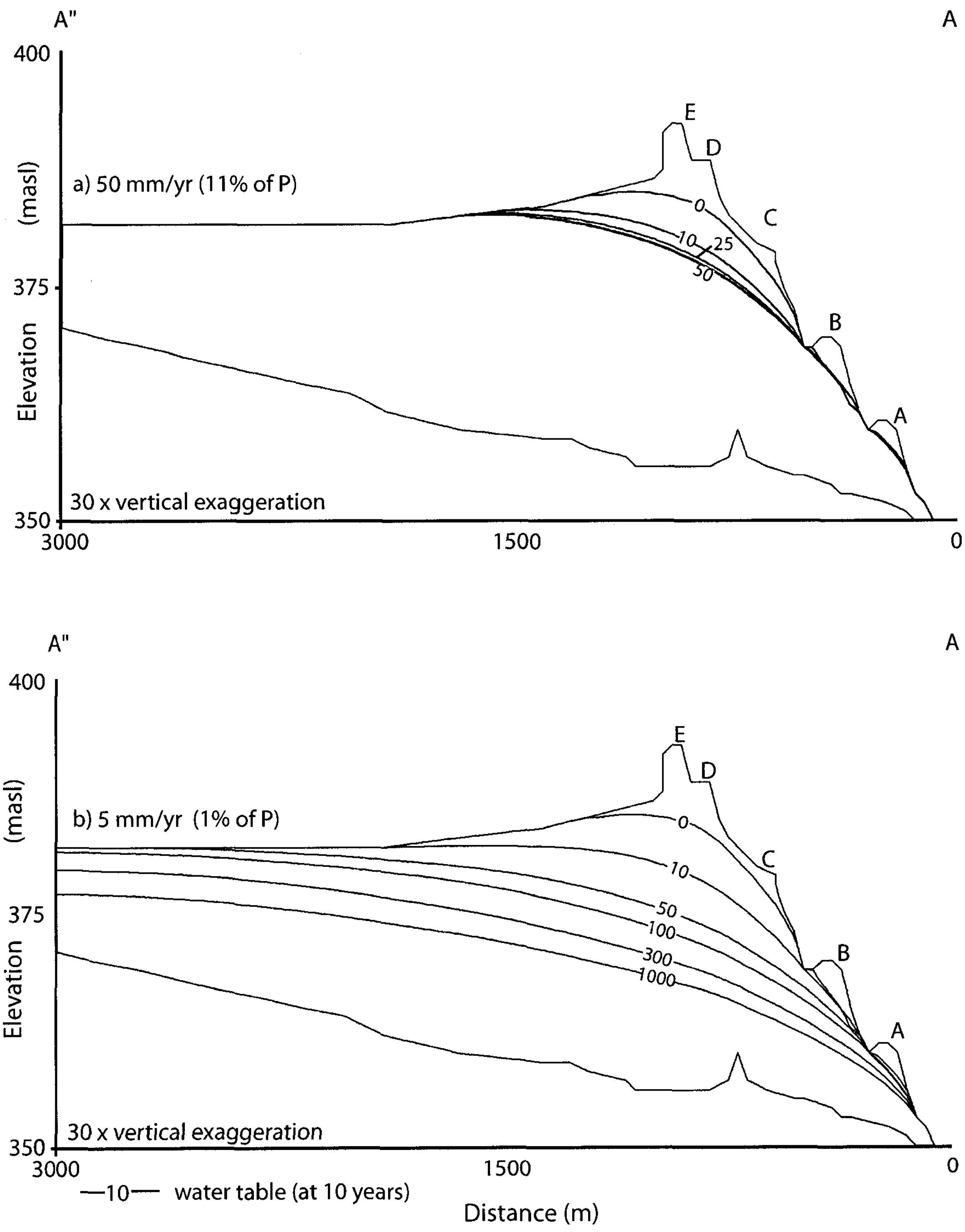

Figure E2. A simple 2D transient flow model which illustrates changing water table over 1000 years under different recharge conditions. Recharge fluxes of a) 50 mm/yr, and b) 5 mm/yr were applied to the model.

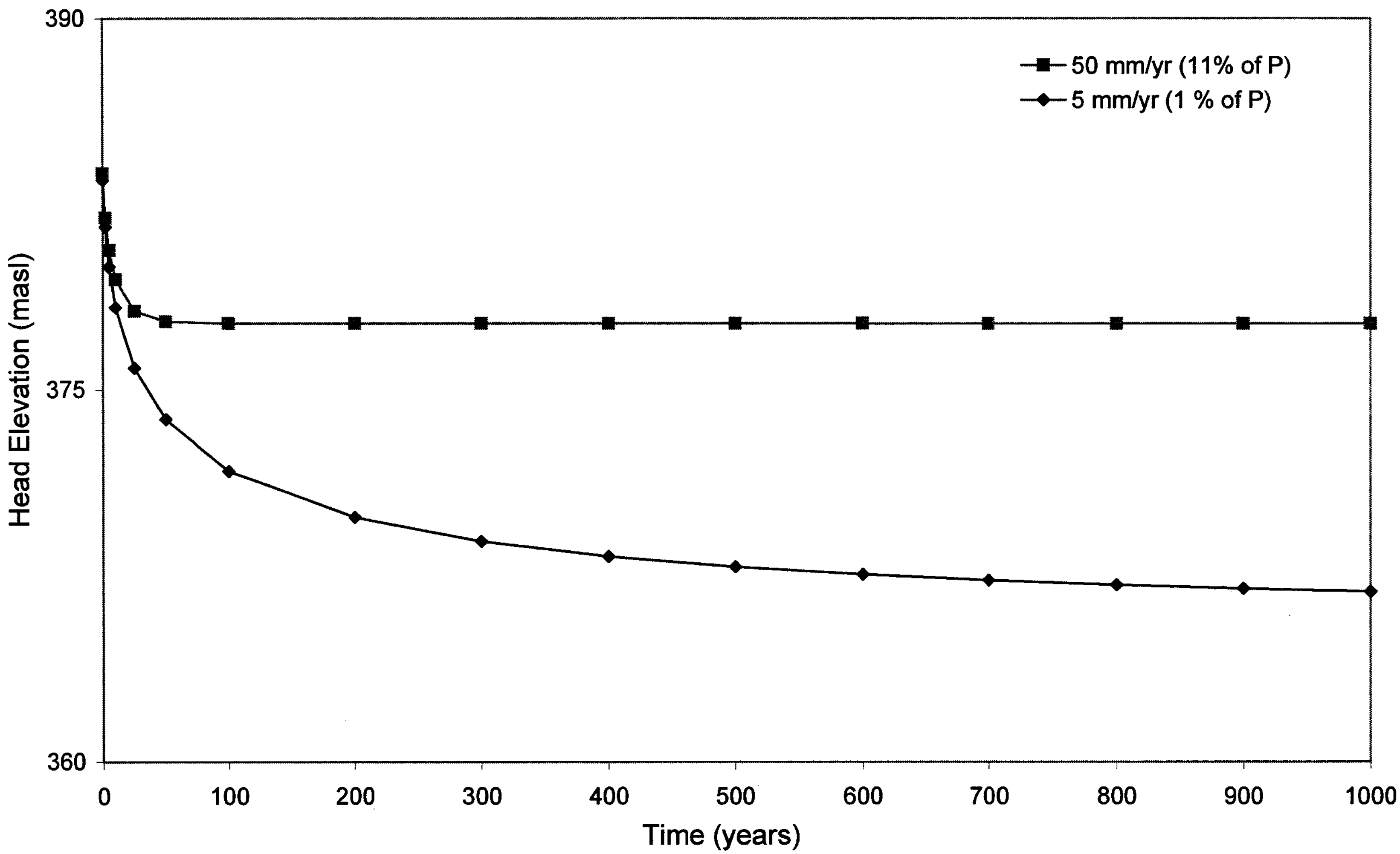

Figure E3. Drawdown near the perimeter dyke crest (Bench D) over 1000 years for 50 mm/yr (11% of P) and 5 mm/yr (1% of P) recharge scenarios.