Hydraulic Performance of the Seepage Collection Ditches at the Albian Sands Muskeg River Mine

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The tailings pond at the Muskeg River Mine is a large structure with a 11 km-long ring dyke that contains process affected water (PAW) and tailings sand. The dyke is made of permeable tailings sand and therefore it is equipped with seepage collection ditches that are designed to collect water from drains in the dyke but also to intercept seepage water not collected by the drains and transmit it to the seepage pond for recycling. The effectiveness of this seepage collection system was examined at the downgradient end of the tailings pond (Study Area) where near-surface permeable sand is present.

Piezometric level measurements were performed and water samples were collected from a network of 21 piezometers and drive points, and at several other critical locations. Concentrations of major chemical tracers of PAW such as naphthenic acids (NAs) show signs of migration of PAW in the permeable sand deposit, beyond the dyke. This interpretation is supported by stable O and H isotope analysis of water. The interpretation of the piezometric and chemical data revealed that the PAW has migrated past the Inner Ditch but not beyond the Outer Ditch. Elevated hydraulic heads beyond the Outer Ditch prevented further migration. Groundwater locally converges and discharges as surface water in the wet area between the two ditches. Thus, the collection ditch system is currently working effectively to contain PAW.

Numerical modeling of the Study Area was able to reasonably recreate the observed hydraulic conditions. Based on these simulations, it is possible that PAW may be migrating through a permeable layer of sand under the bottom of the dyke and pond, and eventually discharging into the wet area between the ditches. The estimated amount of PAW seepage discharged into the wet area is small compared to the total dyke drainage collected by the ditches.

These conditions described above, however, may change with the progress of the current dyke expansion work. The wet area between the ditches will be buried and the local hydraulic condition is expected to alter. This may reverse the hydraulic gradient across the Outer Ditch and perhaps will facilitate migration of PAW beyond the Outer Ditch. It is recommended that the following key chemical parameters be used in future groundwater quality monitoring efforts to track PAW migration at the Muskeg River Mine: Na^+ Cl^- , SO_4^{2-} , and Ca^{2+} ions, stable isotopes of hydrogen and oxygen, and Naphthenic acids (NAs.)

Acknowledgements

I can still clearly remember the moment I first stepped into my office in the CPH building where I later would spend a substantial amount of my life at the University of Waterloo. The deserted windowless room of CPH 2385B simply looked like a prison cell.

In spite of my terrible first encounter with my office, I had very good times afterwards, especially during my second year. A few students moved into the office for company: Bo, Mehrnaz, Youngsam, Sara, and Weiwei. I always appreciated their presence which was a sort of indirect support, and encouragement to me. They always kept me entertained so I didn't have to feel bored or isolated while I was working on my thesis.

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The text for this section has been proof-read by Ashley Bisonnette, Naoki's student of Japanese language and his French language teacher and by Bo Cheyne, Naoki's office mate.

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List of Figures and Tables Attached

List of Abbreviations

ASE:	Albian Sands Energy Inc.
ASL:	Above Sea Level
ASTM:	American Society for Testing and Materials
BC:	Boundary Condition
Conc. :	Concentration
F. :	Formation (as in geology)
GL :	Ground Level
HGT:	High Groundwater Table condition
INDM	Inner Ditch Model
INTDM	Inter Ditch Model
K:	Hydraulic conductivity
LGT:	Low Groundwater Table condition
LMWL:	Local Meteoric Water Line
amsl:	Above Mean Sea Level
MDL:	Maximum Detection Limit
NA:	Naphthenic Acid
N/A:	Not Applicable
OUDM	Outer Ditch Model
PAW	Process Affected Water
PSV:	Primary Separation Vessel
STD:	Standard Deviation
SWL:	Static Water Level
TDS:	Total Dissolved Solids
USCS:	Unified Soil Classification System

1. Introduction

1.1. Problem Statement

1.1.1 Oil sand Mining

In 2003 the US Energy Information Administration (EIA) and Oil and Gas Journal confirmed that Canada has the second largest oil reserve (179 billion barrels) in the world. Most of this oil (98 %) is in oil sands which accounts for 80% of the world total oil sand reserve and is equivalent to 30 % of the world extractable crude oil reserve. Canada's oil sands mostly occur in three deposits in the province of Alberta: Peace River, Cold Lake, and Athabasca. The Athabasca deposit, located to the north of Fort McMurray, is by far the largest of all with a total deposit of 1.37 trillion barrels. In this area, about 110 billion barrels of crude oil is considered mineable from the surface (Woynillowicz et al., 2005) because the ore depth is less than 75 m. The average total production for 2004 from the Athabasca mines was about 660,000 barrels per day. This production is expected to increase for the next few decades as conventional oil production decreases. Canadian Association of Petroleum Producers (CAPP, 2005) estimates that the production will increase to 2.7 million barrels per day by 2015, and the Alberta Chamber of Resources has a vision of increasing production to 5 million barrels per day by 2030.

Canada's oil sand mining has a long history. Experimental oil sand mining and extraction started in the 1940's at a plant in Bitumount, which was sponsored by Oil Sands Limited and the Government of Alberta. However, it was only in the late 1970s that private companies started large scale commercial productions. The first commercial production began in 1967 when Suncor (then Canadian Oil Sands Company) started open pit mining of the Athabasca deposit. They were later joined by Syncrude in the early 1970's. Around the turn of the century, the Alberta government formed a task force to boost the oil sands industry and offered relaxed taxation and a favorable royalty scheme to oil sands companies. As a result this government intervention and increasing world prices, the production of oil sands doubled between 1995 and 2004 to 1.1 million barrels per day. In December 2002, that Albian Sands Energy Inc. (ASE) started production at the Muskeg River Mine. Now ASE is the third largest oil sands mining company in the region, producing about 155,000 barrels of crude oil each day.

1.1.2 Environmental Issues

Despite its tremendous potential as a future energy source, there are some controversial issues about oil sands mining such as the energy intensive nature of oil sands mining and processing, and its environmental impact (Woynillowicz et al., 2005).

Tailings management is one of the most persistent environmental issues associated with oil sands mining because of its sheer scale. The tailings are huge in volume (the volume of fine tailings produced by Syncrude and Suncor alone is expected to exceed 1 billion cubic meters by 2020 (Woynillowicz et al., 2005). Tailings water contains high concentrations of salt and organic acids called naphthenic acids (NAs). NAs are a complex mixture of highly branched cyclic and non-cyclic organic chemicals and are the most significant environmental contaminants resulting from petroleum extraction from oil sands deposits (Rogers et al., 2002). Thus proper management of the tailings during and after the completion of mining is critical from the viewpoint of environmental protection. The oil sand companies are required by law to take measures to minimize contamination and damage to the environment. These measures include land reclamation, and water monitoring. However there is no specific discharge limit for NAs and current practice followed by ASE and others is to contain all PAW within tailings ponds.

Currently there are two disposal options available to handle oil sand mine tailings:

1) disposal in abandoned mine pits, or
2) disposal in tailings ponds external to the mined pits.

Both options are expected to bring about some environmental impact because they disturb the original groundwater system by introducing highly concentrated waste materials on site. The first option ensures that the tailings are stored in the ground so that it minimizes impact to surface water and the shallow groundwater system. Unfortunately, external tailings ponds are required in the early stages of mining, before pit space is opened for tailings disposal. The external tailings pond is even more problematic: they are usually large and only enclosed by a tailings dyke and a perimeter ditch. The dyke is usually made of permeable tailings sand. Leakage must be collected by drains installed in the dyke and uncollected seepage must be intercepted and also collected. Thus some tailings water will be constantly released through the dyke and, if not successfully intercepted and collected, potentially into the surrounding environment. A future issue is the fate of such seepage water after the mining operation and associated collection cease.

1.1.3 Previous Studies

Mackinnon et al. (2005) published a report on the migration of process affected water (PAW) downgradient of the dyke at the Mildred Lake Settling Basin at the Syncrude mine. The seepage collection ditch at this facility was installed in the permeable sand at the toe-berm. Water samples collected at several locations along the potential migration path were used to demonstrate that PAW had reached the Lower Beaver Creek that flows along the edge of the toe-berm. Although the PAW was eventually attenuated at a point a few kilometers downstream of the toe-berm due to dilution, the PAW apparently bypassed the seepage collection ditch and migrated through the shallow sand aquifer over a few hundred of meters. No quantitative aspects of PAW migration were discussed.

Oiffer (2006) looked into the chemical characteristics of a PAW plume in the shallow sand deposit adjacent to a tailings dyke. No signs of NA attenuation by biodegradation were apparent but weak sorption of NA and ammonium was indicated. No adverse migration of toxic metals was noted.

Hunter (2001) looked into transient movement of PAW through a tailings pond at the Suncor mine, using hydraulic head data, geophysical loggings of boreholes, and a numerical simulation model of the dyke seepage. She found that seepage from the tailings pond is effectively obstructed by the presence of impermeable silt-clay deposits on the bottom of the tailings pond and thin films of bitumen in the tailings sand that makes up the dyke body. Reduced infiltration from the pond generated an unsaturated zone under the pond. Dewatering of the permeable sand dyke over time represents a continuing, but declining source of PAW to the dyke seepage collection system and to the surrounding groundwater. This study did not focus on the role of the seepage collection ditches.

Albian Sands Energy Inc. (ASE) is monitoring groundwater to observe the potential influence of mining activity on the groundwater. The annual report on the results of groundwater monitoring for 2003 (KOMEX, 2004) concluded that there were no signs of groundwater contamination in the shallow quaternary aquifer beyond the ditches adjacent to the tailings pond/dyke under consideration in the present study. However, no monitoring wells were installed in the Study Area where surficial sand is extensively distributed.

In September 2004 a preliminary site investigation visit by Dr. N. Thomson and Dr. J. Barker of the University of Waterloo revealed the existence of surface sand at the southern edge of the tailings pond. Recognizing the potential risk of this migration pathway, ASE supported the University of Waterloo's proposal to study the hydraulic performance of the seepage collection ditch system in this area.

1.2. Thesis Objectives

The main objective of this research is to evaluate the performance of the seepage collection ditch system to contain PAW within the drainage ditches at the tailings pond at the ASE Muskeg River Mine, especially considering the presence of surficial sand and planned dyke expansion. This objective was achieved by investigating the local water (surface water and groundwater) flow system involving the tailings pond, the outer and inner seepage control ditches, and migration of PAW chemicals, especially naphthenic acids (NAs).

1.3. Research Methodology

To achieve this objective, the following methods were employed:

- Field investigations, involving the installation of piezometers and water level monitoring equipment, and sampling and analyses of groundwater, aquifer material, and tailings material.
- Groundwater flow and advective transport modeling

1.4. Thesis Scope

Chapter 2 describes the present conditions of the Study Area. Chapter 3 provides a detailed description of the laboratory and field methods employed in this study. Chapter 4 presents the results of these laboratory experiments and field monitoring activities and provides a brief explanation of the data. Chapter 5 is dedicated to numerical modeling to simulate the observed groundwater behavior through the tailings dyke and downgradient aquifers. Chapter 6 discusses the results and interpretation of the finding in terms of groundwater hydraulics and PAW migration. Finally, Chapter 7 presents the conclusions and recommendations for future research. The Appendix mainly contains the raw data used in this research.

2. Study Site

2.1. Site Description and Hydraulic System

2.1.1 Location

The Muskeg River Mine of ASE (Shell Canada Lease 13) is located about 75 km north of Fort McMurray, in northern Alberta (see **Fig. 2.1**). The mine site is situated between the Athabasca River (west) and the Muskeg River (east). The northern part of the mine is dedicated to open pit mining and the tailings pond is located in the south of the mine near the confluence of the two rivers.

This research project focuses on a relatively small 1 km^2 area on the southern edge of the tailings pond (Study Area), and an area located on the south-east edge of the tailings pond (~1 km to the east of the Study Area) where the stratigraphy suggests that the potential for groundwater impact is lower (Control Site). See **Fig. 2.2** for locations of these sites. The Study Area is bounded by a large tailings dyke to the north and a perimeter road (non-paved) to the south. These two features are topographically high and the area between them is low-lying due to the removal of topsoil and sand during dyke construction. As a result, there are some heaps of soil to the north and east, and a wet area in the middle (see **Fig. 2.3**).

2.1.2 Mining Process

Oil sands mining is a series of two distinctive processes: the upstream and downstream operations. The upstream operation includes actual excavation of ore and extraction of bitumen while the downstream operations include upgrading of the extracted bitumen. The following provides a brief overview of upstream operations that are relevant to this research (see also **Fig. A 2.1** for mining process at ASE).

<u>Surface mining and conditioning</u>

Once the mining area is selected, the topsoil and vegetation are removed. The oil sand ore is excavated at a bench cut in an open pit where a large cable shovel digs out the ore and dumps it into large hauler trucks. Where the formation is rigid, explosives are used to break the soil loose. Approximately 4 tonnes of material (two tones of rock and soil above the deposit and two tones of oil sands) have to be removed to produce one barrel (159 liters) of synthetic crude oil (Woynillowicz et al., 2005). The ore is transported to the prime crusher or the sizer to break up large chunks of oil sand into smaller pieces and to remove large boulders and plant fragments. The crushed oil sand is mixed with warm water and hydraulically transported to the extraction site. This mixture is "conditioned" for extraction during the course of transportation.

Extraction

Hot water extraction process is employed to separate bitumen from minerals of the conditioned oil sand. The conditioned oil sand ore (slurry) is mixed with hot water (80^{o}C), low pressure steam, and citrate (process acid) in a large primary separation vessel (PSV) where fine mineral particles settle down in the bottom. The steam keeps the slurry warm and facilitates separation while the caustic helps to disseminate the bitumen into the fluid phase by raising the pH. The separated bitumen forms a froth that is a fluffy mixture of air bubbles, bitumen, water and minute mineral particles. Two other layers of middlings and sand form underneath the froth. The froth is skimmed off for bitumen. The middle layer (middlings) in this vessel is also taken out for bitumen extraction and only the bottom sediment goes to the tailings pond. The middlings goes through a scavenger process where the material is aerated under agitation to generate froth that contains the residual bitumen blobs. This froth is combined with the primary froth and is allowed to settle after a diluent (light hydrocarbon designed to decrease viscosity) is added. This is then centrifugally separated and most mineral matter is removed. About 90% of the bitumen is thus recovered from oil sand ore through these processes.

2.1.3 Geology

The geology of the Athabasca oil sand area is composed of the following 3 units:

1). Quaternary glacial/glacio-fluvial deposits and wetland deposit
2). Cretaceous McMurray formation
3). Pre-Cretaceous bed rocks

1). Quaternary glacial drift and wetland

The surface deposits in the mine are made up of a complex combination of glacial deposits, and other deposits of younger ages. The glacial deposits are made mainly of tills which are partly covered by the late Pleistocene sand and gravel deposits. The Holocene overburden deposits are mostly peat layers locally called “Muskeg”. Their spatial distribution has not been confirmed in detail. The following sections give accounts of some deposits that are important for this study.

Surficial sand

One of the major components of the Quaternary deposits is the Pleistocene sand that is locally called “pf-sand”. This term is used in the following sections. Pf-sand is reported to be widely present in the Syncrude mine and to form a layer with an average thickness of 5 to 12 m (Oiffer, 2005). In the Muskeg River Mine, the distribution of pf-sand is smaller and sporadic. The sand is found only at several locations in the mine along with sand/gravel deposits.

The pf-sand and associated granular deposits of larger grain size are thought to have been deposited by a catastrophic flood event in the late Pleistocene (9,900 years BP) that discharged about 8.6 km^3/hour of fresh water from glacial lake Agassiz into the Athabasca river channel (Smith and Fisher, 1993). The flood formed the current Clearwater and Lower Athabasca spill way. The sand was therefore deposited along the current river courses of the Athabasca and closely associated with other coarser sediments such as boulder deposits, and sand with gravel and boulders that were formed by the same flood event. A peat layer developed over much of the glacio-fluvial deposits and fluvial sand and gravel deposits in the Athabasca mine area. In the Muskeg River Mine, much of the peat was stripped off prior to mining operations but where it is left intact, the thickness is usually ~ 4 m.

2). Cretaceous McMurray formation

The McMurray formation is the source of oil sand and is classified into the lower, middle and upper units (Carrigy, 1959). Due to its depositional variation that extends from fluvial to marine, the deposits occur in many different forms such as shale, sand, and conglomerate. The sediments are considered to have deposited in fluvial, deltaic, and estuarine sedimentary environments during the early Cretaceous time (Mossop, 1980). The formation generally dips southwest at 4.8 m/km (Hackbarth and Nastasa 1979). Although its sedimentary structure is very complex, some researchers have attempted to delineate smaller scale sedimentary units with the use of boring-core data and the sequence stratigraphic approach (e.g., Mathison, 2003).

The McMurray formation is exposed at surface or occur relatively shallow along the Athabasca River due to erosion (mostly less than 75 m), which makes the surface mining of oil sands possible. In the Muskeg River Mine, it is mostly the estuarine deposits that occur at the surface. High bitumen content is found in coarse sediments of estuary and fluvial channels.

3). Pre-Cretaceous bedrocks

The bedrock in the Athabasca oil sand area is Devonian shales and carbonate rocks, which are only exposed on the bottom of the Athabasca River. The bedrock is bounded by an unconformity with the overlying McMurray formation. It has a regional bedding structure consistent with the McMurray formation (Hackbarth and Nastasa, 1979).

The original stratigraphy of the Study Area is compiled in **Table 2.1** based on the information obtained from ASE and field observations. Peat and pf-sand layers are absent at the Control Site and the McMurray Formation with a thin layer of glacial deposit is present at the ground surface.

2.1.4 Hydrogeology

The regional hydrogeology of the Athabasca oil sands area was compiled by Hackbarth and Nastasa (1979). They recognized 3 hydrogeologic units: 1) the K-Q, 2) D-1, and 3) D-2. The first unit, K-Q is of most interest in this study and is composed of the Cretaceous McMurray formation, and Pleistocene and Holocene deposits. This unit is generally characterized by dominantly downward or horizontal groundwater flows due to zones of contrasting hydraulic conductivity. This is considered to be caused by the existence of unsaturated zones within the unit developed by draining of groundwater from the escarpment of the Athabasca River. The unsaturated zones extend up to 10 km from outcrop into the units of high hydraulic conductivity. The TDS of the water is commonly around 5,000 mg/L.

The area has a topographic high of Muskeg Mountain (about 600 m) about 10 km to the east of the Athabasca River while the western side of the river is relatively flat with the highest elevation of 450 m. Thus the surface and groundwater in general drains towards the Athabasca River. The general groundwater flow in the shallow aquifers in the Muskeg River Mine area trends southwest and southeast towards the Athabasca and Muskeg Rivers.

According to RAMP (2004), the average annual precipitation at the airport is 443 mm for the period from 1944 - 2004. Most of the rain occurs in the months of June, July and August. The annual average of daily temperature from 1971 to 2000 is 0.7 ^{o}C (Environment Canada).

2.1.5 Dyke structure and Hydraulic System

An oil sand tailings pond is often enclosed by a large ring dyke. The dyke is usually made of the tailings sand produced as a result of bitumen extraction and thus called a tailings dyke. Tailings dykes are normally constructed upon the original ground. The base of a dyke, commonly called “an overburden starter dyke”, is constructed with relatively impermeable materials such as lean oil sand (LOS). Coarse tailings are used to construct the rest of the dyke over the starter dyke. The dyke is usually raised and expanded as the water level in the pond rises. This sequential staged construction (expansion) method of the dyke is classified into the upstream, downstream, and centerline methods (see **Fig. A 2.2**).

Since a tailings dyke is a permeable structure, an internal drain system is installed to remove excess pore water in the dyke body. The drained water is then collected by a ditch that runs along the perimeter of the dyke. The water then flows in the ditch to a seepage pond and is eventually pumped back to the tailings pond. The ditch also serves to intercept seepage of shallow groundwater. This combination of a permeable dyke, drains and a perimeter ditch is the system typically used in the oil sands mining industry to manage tailings water seepage.

The primary design purpose of such a dyke is to avoid catastrophic failure of the dyke while minimizing construction cost. No additional effort beyond groundwater monitoring is made to ensure PAW seepage into the surrounding environment does not occur. In this sense the ditch is the last line of defense against seepage. To date, we have not seen detailed hydrogeological studies to support the design of collection ditches as dyke seepage containment systems. Also, there are no standardized guidelines for ditch construction, likely reflecting the variety of specific site conditions encountered in the oil sands mining region.

At the Muskeg River Mine, the tailings pond is bordered by a 11 km-long dyke which is nearly 200 m wide at the base and over 20 m high. The current top elevation is 303 m amsl (June 2005). The base of the dyke (overburden starter dyke) is made of lean oil sand and the upper section is made of tailings sand according to the tailings staging plan of ASE (Klohn Crippen, 2002). The top soil was removed under the starter dyke prior to dyke construction. It has two internal drainage systems at the elevation of about 291 m and 300 m. They are made of a perforated collector pipe placed in a bed of gravel and sand (see **Fig. 2.4**). Two perimeter ditches are installed on the south side (downgradient) of the tailings pond. The Inner Ditch is an unlined temporary structure while the Outer Ditch is lined and permanent. A seepage pond is located about 500 m to the east of the Study Area to store water from the ditches (see **Fig. 2.2**). ASE has a “zero discharge policy” concerning water quality management and so is committed to contain any seepage of PAW from the dyke and tailings pond.

2.1.6 Characteristics of Tailings

The waste materials from the extraction process are called tailings and are made up of a mixture of sand, clay and fine silts, and water that contains dissolved salts and some hydrocarbons. Tailings are hydraulically discharged with pumps and pipelines into the tailings pond where they are allowed to settle.

The following three different types of tailings are produced at different stages of the extraction in the Muskeg River Mine. They have different characteristics in terms of ratio of major components and amount produced. The physical properties of each tailings are summarized in **Table A 2.1** in the Appendix.

- Coarse tailings : coarse fraction from the Primary Separation Vessel
- Thickened tailings : from the thickener
- TSRU tailings : Tailings from Tailings Solvent Recovery Unit

The coarse and thickened tailings account for most of the tailings volume. Some of the coarse tailings are used in hydraulic construction of tailings dykes. This process inevitably introduces PAW into the area surrounding the dykes because the water contained in the tailings eventually drains out of the dykes. This PAW introduced by dyke construction is called “construction water” as opposed to “tailings water” that seeps from the tailings pond.

2.2. General Field Observations

2.2.1. Site Conditions

The field work was performed in four phases: Fall 2004, Summer 2005, Fall 2005, and Spring 2006 (**Table 2.2**). The First Phase of field work was dedicated to installation of piezometers in the Study Area and at the Control Site, and to obtain some baseline chemistry and hydraulic data. The Second Phase of field work was conducted in anticipation of dyke expansion in the Study Area. Three additional piezometers were installed (two in the Study Area and one at the Control Site) and pressure transducers equipped with on-board data loggers were installed in these piezometers for long-term monitoring. The Third Phase of field work was conducted to download the data from instruments before winter and prior to the start of the full-fledged dyke expansion work. The Fourth Phase of field work was conducted to wrap-up the field work by retrieving the loggers and collecting chemical and hydraulic data from all piezometers that survived burial due to the dyke expansion.

The work performed during each phase of field work is described in detail in the following sections and summarized in **Table 2.2**. Images of the site conditions, and completed piezometers are presented in the photo section of the Appendix.

The following are the major observations made during each phase of field work.

< General Site condition >

- The south side of the area between the two ditches is low-lying (designated as Wet Area in **Fig. 2.3**) due to the removal of surface deposits.
- Ponds were observed in the Wet Area in Summer and Fall of 2005, and Spring of 2006. The Wet Area was inundated and the ground surface around the two piezometers, BtD-S and OuD-N, was completely submerged in about 5 cm of water during Fall 2005 and Spring of 2006.
- Groundwater seepage was observed at the foot of the peat soil heap (see **Photo-1** in the Appendix).
- The ground was frozen and covered with snow in the Wet Area in the First Phase but not in the Third Phase
- The topsoil at the Control Site is about 0.5 m thick and contains boulders.
- The temporary ditch for dyke expansion work had been excavated at the Control Site by the Third Phase.
- The excavated temporary ditch is about 2 m wide and 1.5 m deep with no lining.
- Sand is exposed on the bottom of the temporary ditch about 100 m to the north of the Control Site.

< pf-Sand >

- The area where the piezometers were installed is underlain by a thin layer of pf-sand.
- The thickness of pf-sand is variable in the Study Area (1 to 3 m).
- The sand is medium to coarse with some pebbles (up to a few cm in diameter) and gray to yellowish gray, looking very uniform in composition.
- A thin gravel layer is typically found at the bottom of the sand layer
- The topsoil (peat soil and some pf-sand) in the Wet Area has been removed, exposing the pf-sand in this area.
- In the Study Area, pf-sand is underlain by very impermeable oil- clay/silt of the McMurray formation.
- The exploratory drilling in the Second Phase revealed that the thickness of pf-sand along the haul road is largest at OuD-S, thins out to the east and remains rather uniform to the west (see **Fig. A 2.3**).

<Ditches>

- The Inner Ditch is a temporary structure; the flow direction in the ditch was confirmed. The width is about 6.3 m between the banks, and 1.25 m deep in cross-section between the Inner Ditch piezometers (see **Fig. 2.5**)

- The Outer Ditch is a permanent structure: the flow direction in the ditch was confirmed. The width is about 3.5 m across and about 0.5 m deep (see **Fig. 2.5**).
- The entire perimeter (in cross-section) of the Outer Ditch is lined with ~30 cm thick lean oil sand layer (including oil clay/silt)
- The outer ditch water was in contact with the surface water of the ponds in the Wet Area by a few small temporary shallow channels and the water was found to be slowly moving towards the ditch in Summer and Fall 2005, and Spring 2006 (see **Photo A-3** in the Appendix).
- The depth of water in the Inner Ditch was around 15 cm while the water depth in the Outer ditch was as deep as 40 cm (hard to define due to soft and sticky bottom sediment) in Summer 2005.
- A flow rate measurement in the Outer ditch was conducted 500 m downstream of OuD-DVP during the Third Phase. A crude measurement estimated the rate to be around 50 L/s.

<Dyke>

- The dyke has two collector pipes (200 mm perforated pipe with a woven sock) installed inside along its perimeter at elevations of about 292 m and 300 m respectively. The smaller outtake drainpipes connected to these collector pipes release seepage water into the Inner Ditch at the dyke toe berm (see **Fig. 2.4**, and **Photos A-2** in the Appendix).
- The dyke expansion was originally planned for the Summer of 2005, starting in the area between the dyke and perimeter ditch with a sand toe berm. The south side of the dyke was planned to be raised to an elevation of up to 314 m later. All installations located north of the Outer Ditch were expected to be buried with the dyke expansion.
- The dyke expansion work in the Study Area was delayed until early November 2005. The expansion work was underway on the dyke crest near the Study Area and around the toe berm area at the northeastern part of the tailings pond dyke during the Second and Third Phase of field work. It had not started in the toe berm area at the Control Site yet.
- The elevation of the dyke crest at the south of the tailings pond was 303 m amsl in June 2005 and 310.5 m amsl in Nov. 2005.

<Tailings Pond>

- The tailings settling pond was constructed directly on the original ground surface without removing the topsoil except for the area directly underneath the starter dyke. The pond has cloudy water and the bottom material sampled at the southern end of the pond is fine sand with little clayey material.
- The pond has cloudy water (grayish in color) and the water level in the pond was 299.77 m amsl on March 6, 2005.

2.2.2. Information Obtained from ASE

The data and information obtained from the ASE Inc. include:

- Topographic maps of the southern area the tailings pond
- Tailings staging plan (cross-section of the dyke) and related drawings
- The flow rate of tailings to the tailings pond
- Details of groundwater chemistry (KOMEX, 2004) in the Mine
- Some information on the geological log of monitoring wells near the Study Area (KOMEX, 2004)
- Geological logs of exploratory boreholes near the Study Area
- The record of water level in the tailings pond
- The record of flow measurements from dyke outtake pipes
- Hydraulic parameters for typical dyke materials (material properties)
- Pictures taken during the initial groundwork for dyke construction

<Topographic survey>

A topographic survey of the installed piezometers was conducted by ASE in February 2005 after the First Phase of field work. Another survey of the installed 5.1 cm (2-inch) piezometers was conducted in August 2005 after the Second Phase of field work. The coordinates of the piezometers and drive points, and their ground and top-of-casing elevations were surveyed. The results are given in **Table A-2.3** in the Appendix.

Simple topographic survey of the ditches was carried out by the author using a surveyor's rod, a tape measure, and an Abney level. The above piezometers were used as reference points. **Fig. 2.5** was prepared based on these survey results. A typical topographic cross-section of the Study Area along the transect indicated on the map of **Fig. 2.3** was constructed based on all this survey data. It is shown in **Fig. 2.6** that includes the Tailings Dyke.

<Dyke expansion method, schedule, and material>

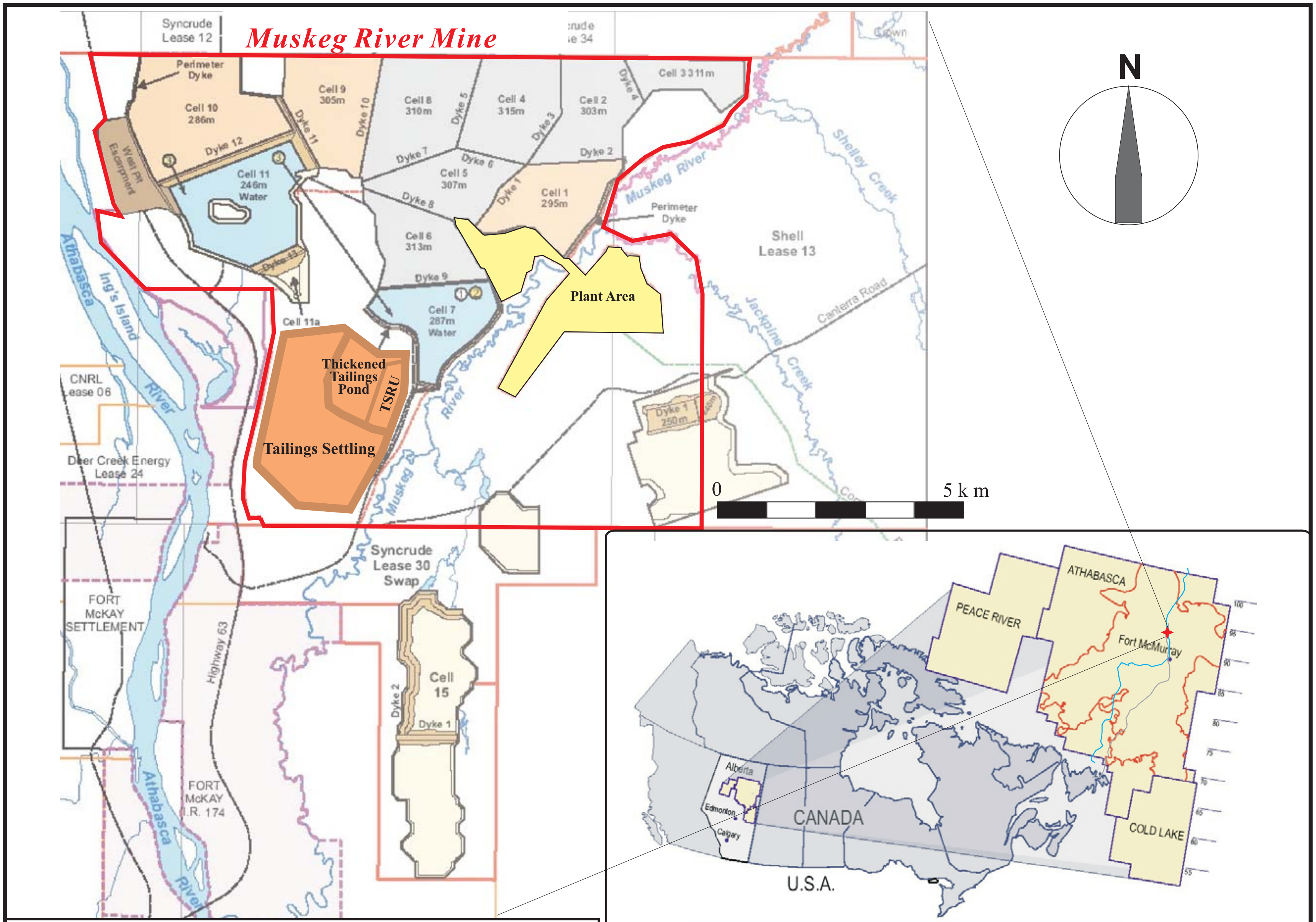
According to the tailings engineers at ASE (Amy Kachurowski and Megan Storrar), the construction method for dyke expansion is based on cell construction as follows (see also **Fig. A 2.4**):

1) A temporary ditch is excavated 20 m away from and along the Outer Ditch to collect effluent water during the construction.
2) The area between the existing dyke toe berm and the temporary ditch is divided into two strips

of 20 m width (inner) and the rest (outer).

3) Rectangular cells are constructed first on the outer strip with tailings sand.
4) Tailings sand and water mixture is poured into the cells by a pipeline.
5) The surface is raised by four meters and leveled and compacted by dozers.
6) The same is repeated for the inner strip that is raised to 303 m.

The tailings material (mixture of sediment and water) used for the cell construction is transferred directly from the extraction plant through a pipeline. The material is called “coarse tailings” and its general properties are given in **Table 2.3**. The dyke expansion work at the Study Area was first planned for the Summer of 2005 and delayed until the Winter of 2006, then it was eventually changed to dry construction due to a technical problem.



Modified after PEMBINA 2005

Fig. 2.1 Location of Muskeg River Mine

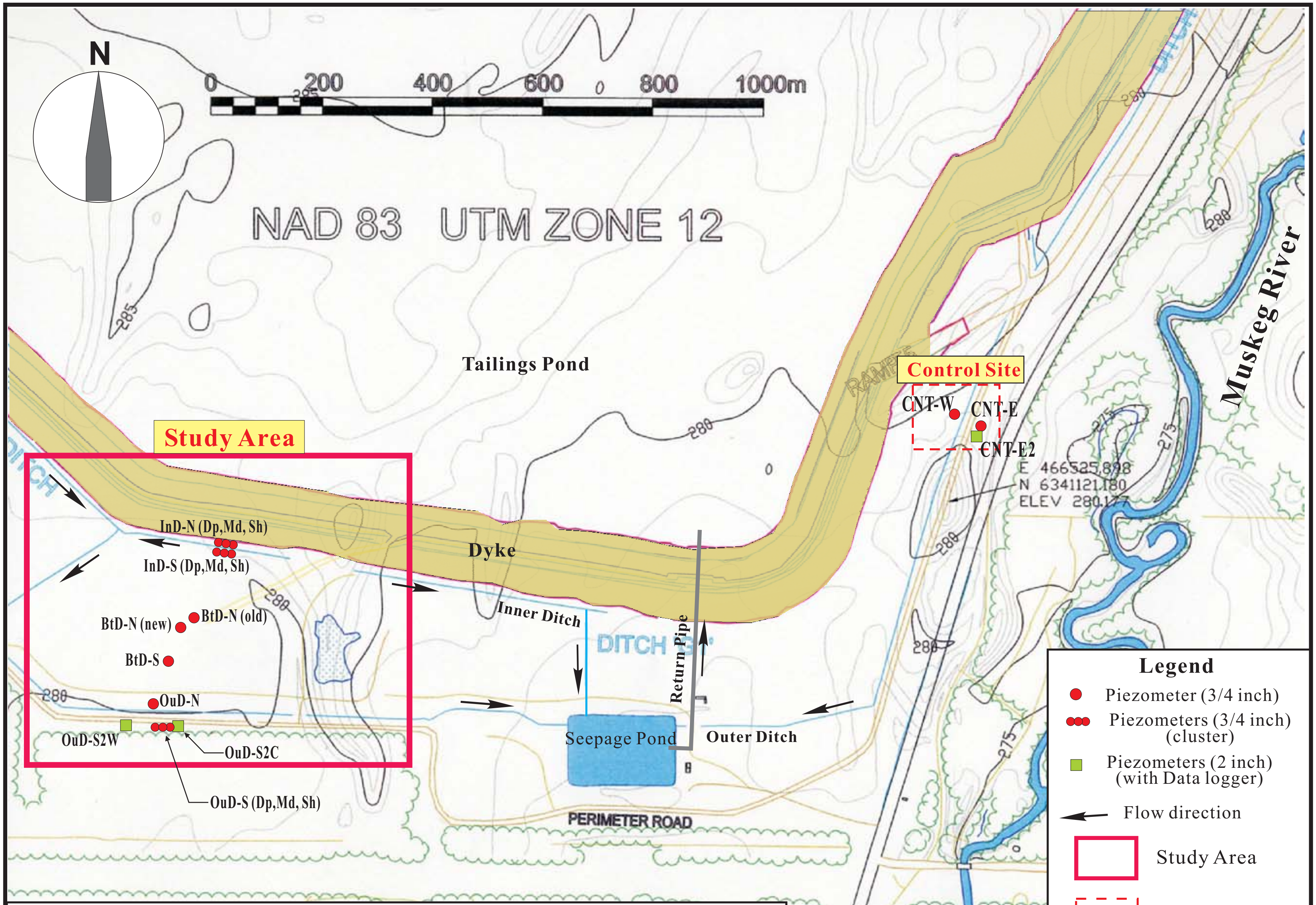


Fig. 2.2 Study Area and Location of Piezometers

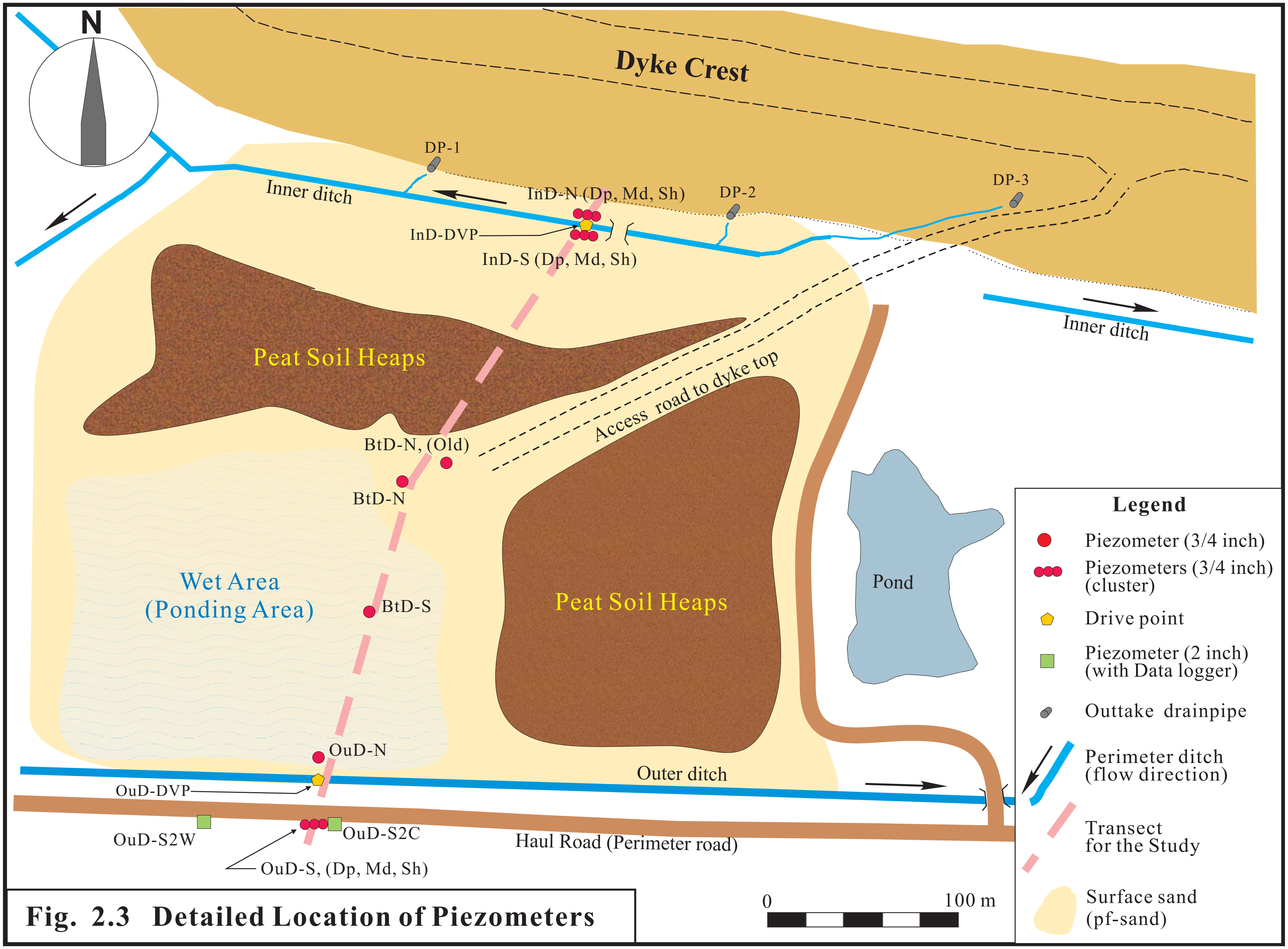
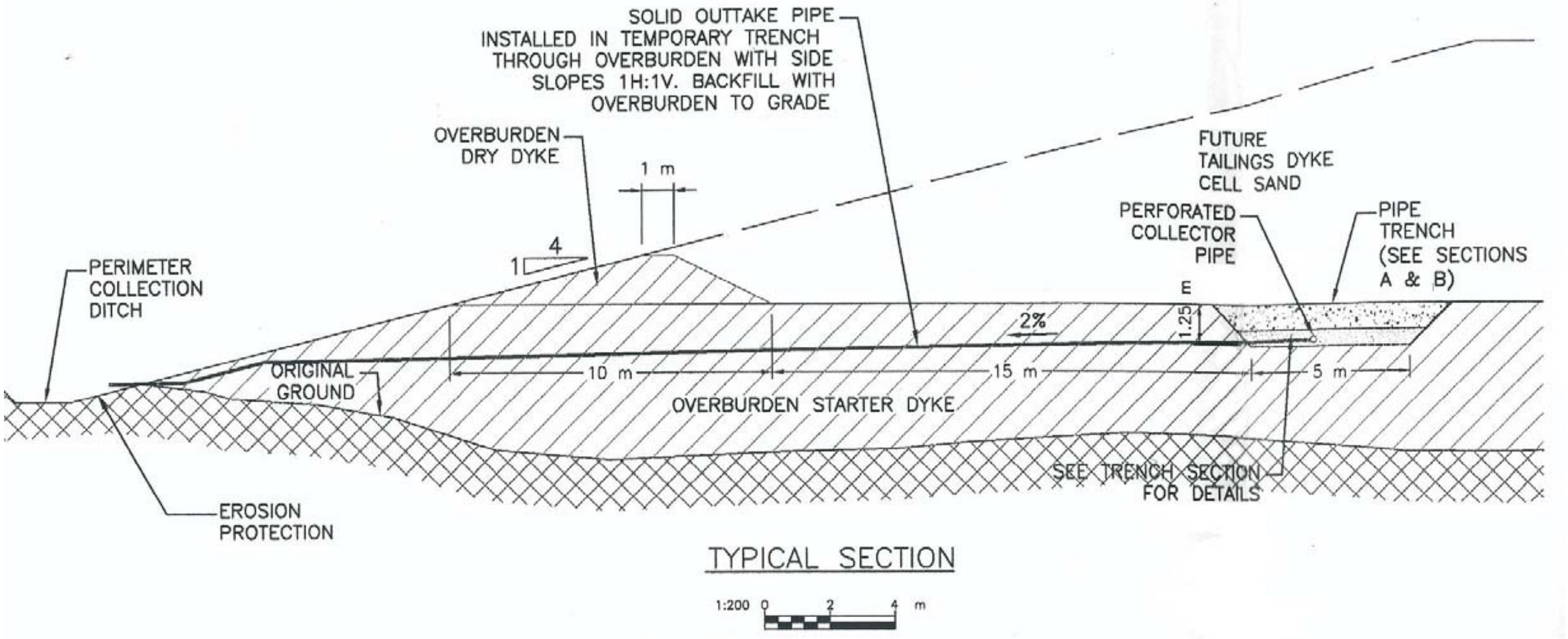
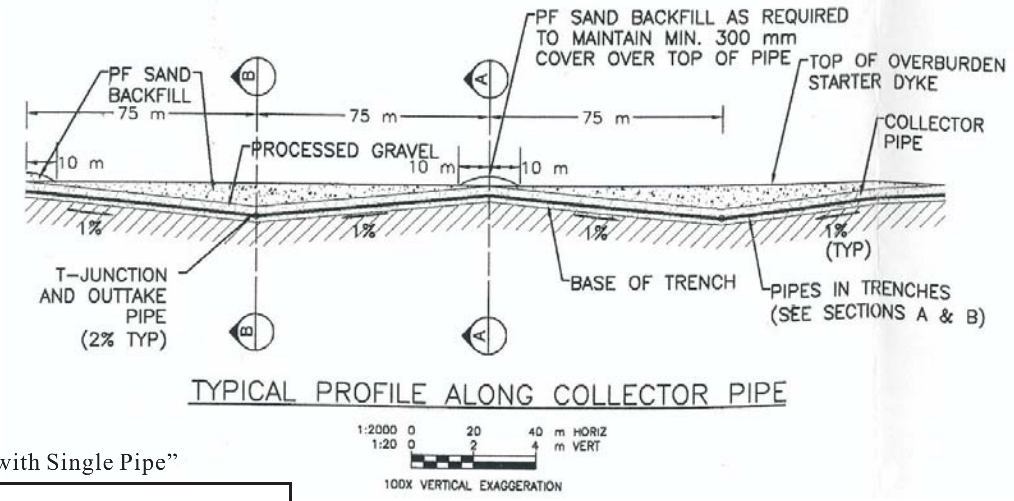


Fig. 2.3 Detailed Location of Piezometers





* Drawings after ASE Report, Sep. 2002
titled “Alternate A: Processed Gravel Filter Drain with Single Pipe”

Fig. 2.4 Typical Dyke Inner Drainage System

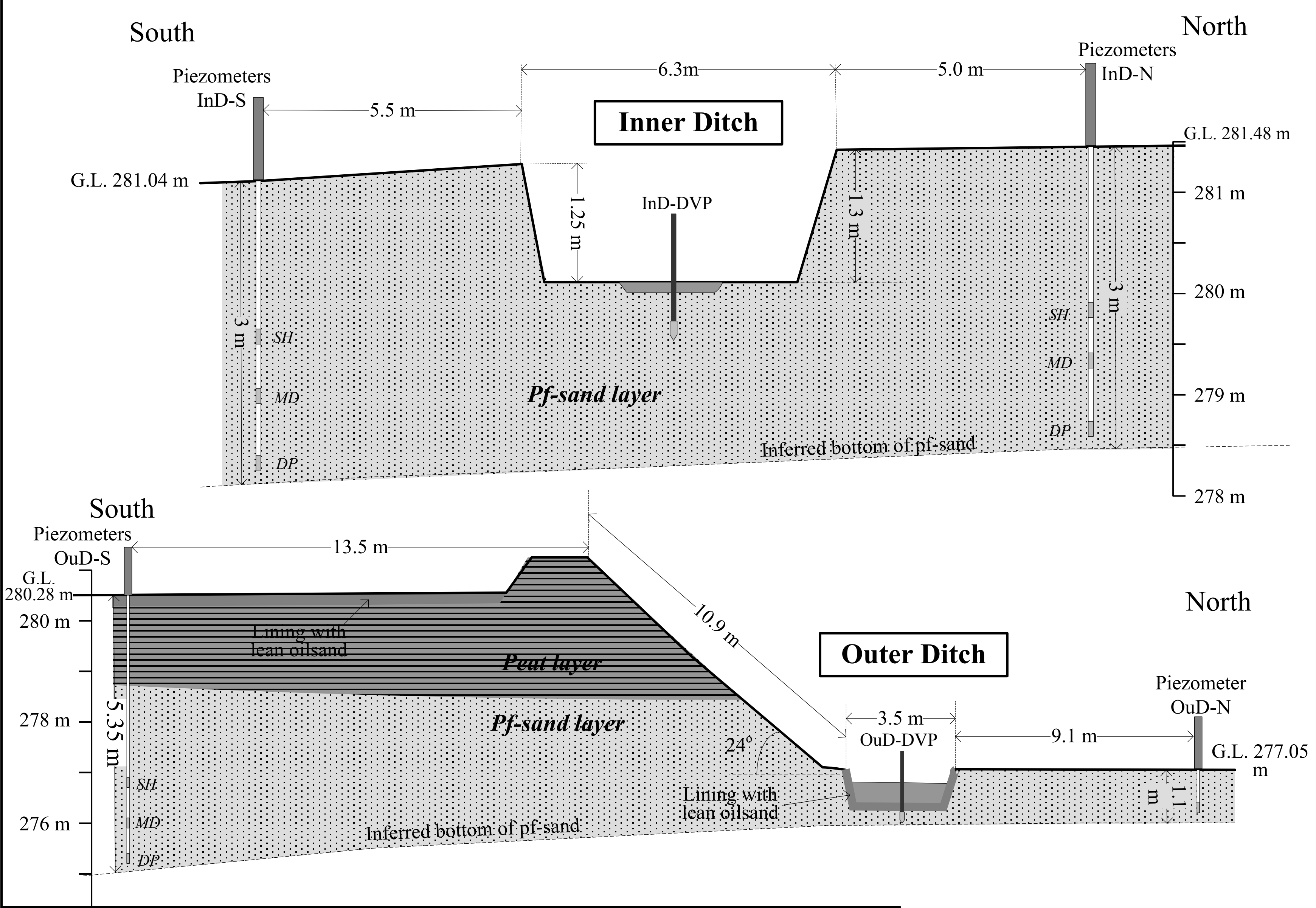
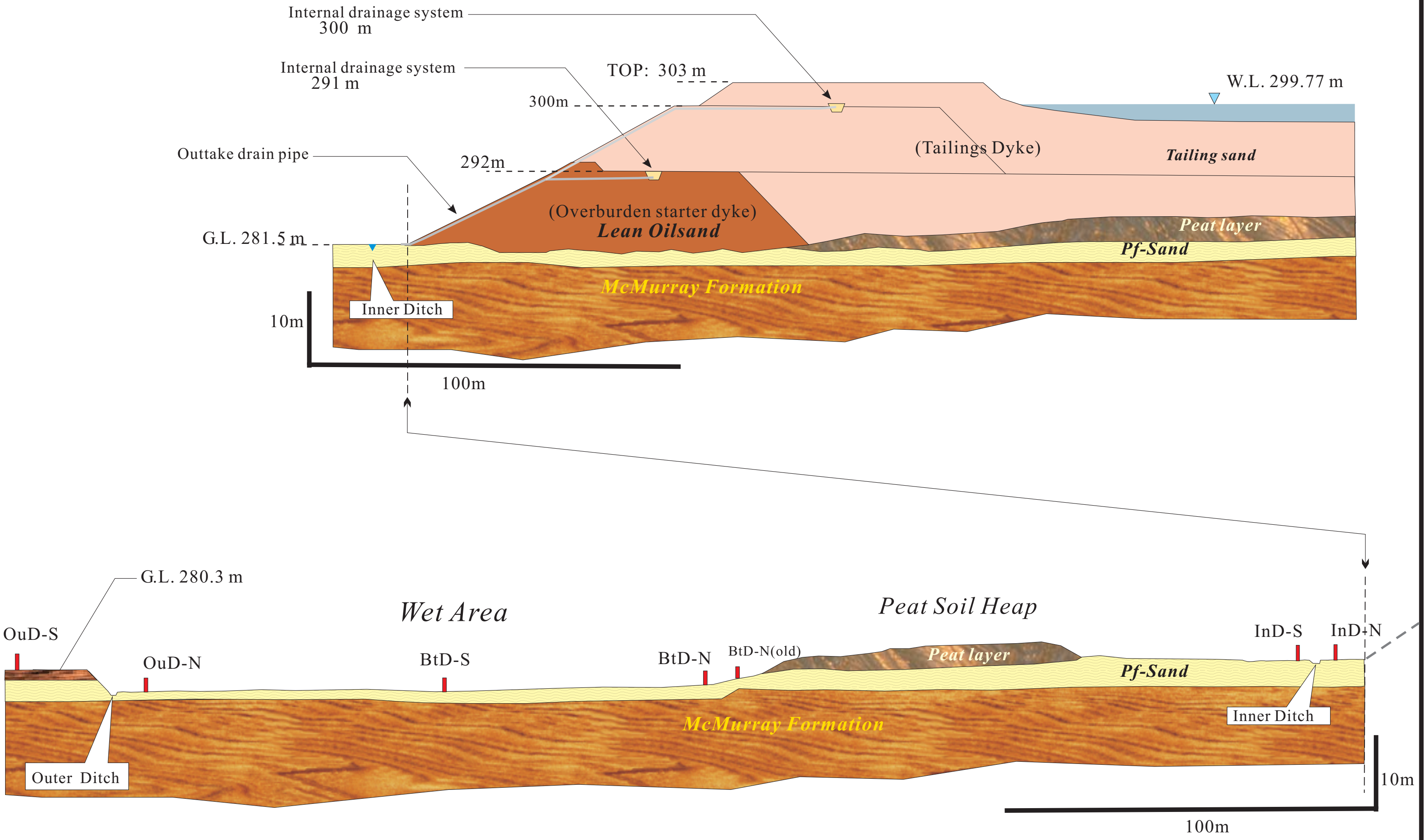


Fig. 2.5 Geometry of Inner and Outer Ditch (Cross-sectional Profile)



* Pf-sand under the dyke and the tailings pond is hypothetical

Fig. 2.6 Schematic Cross-Section of the Study Area and the Tailings Dyke

Table 2.1 General Stratigraphy of the Study Area

Layer	Age	Thickness (m)	Material	Characteristics
Surface soil	Holocene	0.2 – 0.5	Organic soil	Permeable, negligible in the study
Peat*	Holocene	1 - 3	Decomposed plants	Black, Unconsolidated porous, Low permeability
Pf-sand*	Pleistocene	1 - 3	Medium-Coarse sand	Gray, Coarse, Loose and poorly consolidated, High permeability, Quaternary
McMurray Formation	Late Cretaceous	50	Sand ~ silt with bitumen	Virtually Impermeable, unconformably in contact with pf-sand

* Does not exist at the Control Site

Table 2.2 Summary of Field Work Performed

Work Item	Phase 1	 2	 3	 4
Field investigation	✓	✓	✓	✓
Installation of piezometers and drive points, data loggers	✓	✓	-	-
Exploration drilling	✓	✓	-	-
Water sampling from the piezometers, drive points, pond, ditches	✓	✓	✓	✓
Soil/sediment sampling	✓	-	-	-
Interview with ASE engineers and data collection	✓	✓	✓	✓

Phase		Period	
1	First	Fall 2004	October 25 to November 1, 2004
2	Second	Summer 2005	June 13 to June 18, and July 9 to July 12, 2005
3	Third	Fall 2005	October 31 to November 1, 2005
4	Fourth	Spring 2006	May 29 to June 1, 2006

Table 2.3 Average Properties of the Tailings Material (year 2005)

Discharge	12,175 m^3/h	Density	1,402 kg/m^3
Temperature	20 ^oC	Solid ratio	46 % (volumetric)

Combined properties for Coarse, Thickened, and TSRU Tailings

3. Field Monitoring and Laboratory Methods

It is important to quantitatively characterize the Study Area in order to evaluate the flow system and groundwater chemistry. Hydraulic head and flow measurements provide basic data for the interpretation of the hydraulic system of the Study Area. Groundwater and surface water samples were collected to develop an understanding of PAW impacts downgradient of the tailings pond. For hydrostratigraphic units, hydraulic conductivity values were estimated by standard laboratory methods. The following sections discuss how such measurements were conducted.

3.1. Piezometer and Pressure Transducer Installation

1) First Phase

A total of 15 piezometers (1.9 cm (3/4 inch) dia,) were installed along with 3 drive points (1.9 cm (3/4 inch) dia.) as listed in **Table 3.1**. The locations of the piezometers and drive points are shown in **Fig. 2.2 and Fig. 2.3.**

In the Study Area, piezometers were installed on both banks of the two ditches, and in the area between the ditches so they formed a transect along the direction of inferred general groundwater flow (see **Fig. 2.3**). At the Control Site two piezometers were also installed on both banks of the Outer Ditch. A truck-mounted rig with a 15.2 cm (6-inch) solid stem auger was employed to sink boreholes. The depth of the pf-sand aquifer was first confirmed by exploratory drilling and piezometers were pushed into each borehole by the rig. At locations where a sufficient layer of pf-sand was encountered, a cluster of piezometers was installed to assess potential vertical variation of groundwater hydraulic head and chemistry. Three piezometers designed to screen the bottom, middle, and top portions of the pf-sand layer were placed about 1 m apart. The screened section was packed with in situ sand (naturally developed) and a swelling bentonite packer was placed directly above the screen to seal the borehole annulus. A 1.9 cm (3/4 inch)-diameter PVC casing was extended to about 80 cm above the ground surface. A steel protective housing was installed over each piezometer. Details of the installations are given in **Table A-2.3** and the installation method is illustrated in **Fig. A 3.1** in the Appendix. Data on other exploratory boreholes is given in **Table A-3.1**.

Drive points were installed in both the Inner and Outer Ditches in the Study Area, and in the Outer Ditch at the Control Site. A plastic sampling tube was attached to the inner pipe of the drive point, and a 1.9 cm (3/4-inch) diameter steel extension pipe was screwed onto the drive point over the plastic tube. The drive points were installed manually by hammering them between 0.5 to 1 m into the ground.

2) Second Phase

During this phase of field work, 3 piezometers were installed: one immediately next to the cluster of OuD-S, another 60 m west of the cluster on the haul road, and the third beside CNT-E at the Control Site (See **Figs. 2.2 and 2.3, and Table 3.2**). All of these piezometers were equipped with a pressure transducer and data logger.

Each piezometer was composed of 5.1 cm (2-inch) diameter PVC pipe and 10 slot PVC screen, and was installed by a truck-mounted rig with a 15.2 cm (6-inch) diameter solid-stem auger. The installation procedure involved the following steps (see **Table A-2.3** in the Appendix for additional details):

1. A 15.2 cm (6-inch) hole was augured to a specified depth (to the bottom of pf-sand).
2. A 5.1 cm (2-inch) PVC pipe with a specified length of screen with a plastic cap at the bottom was placed in the hole.
3. A gravel pack was placed around the annular space around the screen, and the remaining annular space was filled with bentonite to near ground surface.
4. The pipe was capped with a plastic cap, and a protective outer housing was installed.

To record long-term fluctuations of water level and temperature a pressure transducer (Solinst levelogger Model 3001 LT) was placed in piezometers OuD-S2W and CNT-E2. These instruments are self-contained compact pressure-tansducers with on-board memory for data recording. In piezometer OuD-S2C a pressure-transducer and electric conductivity probe (Solinst levelogger Model 3001 LTC) was placed to continuously measure conductivity in addition to water pressure and temperature. A barometric logger was also installed in piezometer OuD-S2C. Each instrument was suspended by a 0.4 mm (1/62 inch) stainless wire with one end clamped at the top of the tube. Each instrument was placed at around 50 cm below the static water level observed in October 2004 which was assumed to be the annual lowest level. Since the instruments directly measure absolute pressure heads of the water, the barometric logger was used concurrently to correct these measurements for barometric variations. Detailed specifications and operational settings of the data loggers are given in **Table 3.3**.

3.2. Field Observation of Water Levels and Sampling

3.2.1 Water Level and Flow Rate Measurement

(1) Piezometers

The field measurements of ground and surface water were conducted as follows:
The static level of groundwater was manually measured at each piezometer and drive point during each Phase of field work. The levels were measured with a hand-held water level meter. The depth to the water level was recorded to a 0.5 cm resolution from the mark on the top of casing pipe. The measurements were conducted in the same day, typically within a few hours and those for a cluster within 10 minutes. The surface water elevations (such as those of ditches and ponds) were also recorded by measuring the distance from the top of the mark on the installations located in a pond/ditch to the surface of the water the same way as described above.

(2) Drain pipes and the Outer Ditch

The flow rate of the water draining from the dyke was measured at 3 outtake drainpipes (DP-1, 2, and 3) near the Study Area (see **Fig. 2.3** for location) in both the Second and Third Phases. The flow rates were measured with a 4-litre container with a large opening and a stopwatch. The measurements were repeated three times and the average was taken. A flow rate measurement in the Outer ditch was conducted 500 m downstream of OuD-DVP during the Third Phase. A 5 m-long straight section of the ditch with a reasonably uniform width was selected (see **Photo A-3** in the Appendix). The cross-sectional flow area was measured at the middle point of the section. Then flow velocity was measured with a makeshift float and a stopwatch, and this was repeated 3 times.

3.2.2 Sampling

(1) First Phase

Water samples were collected from all the piezometers and drive points except those that produced extremely small amounts of water (screened in the McMurray Formation). Water samples were also collected from the Inner and Outer Ditches just upstream of the drive points, the tailings pond (close to the southern edge of the pond and at the center), and at the outlet of the return pipe from the plant (sampled by ASE personnel). Water was sampled from piezometers using a Waterra pump and a peristaltic pump. Each piezometer was purged by removing at least three casing volumes of water before sampling. One set of water samples was sent directly to Maxxam Analytics Inc. (Maxxam, former PSC Analytical Services) in Edmonton for analyses of major inorganic ions. The other set was sent back to the Organic Chemistry Laboratory of the University of Waterloo for analyses of total NA (see **Table A-3.2 (a)** in the Appendix for details).

Several disturbed samples of pf-sand and peat were taken from the boreholes drilled near the Inner Ditch, Outer Ditch and in the area between the two ditches for hydraulic conductivity estimation. The samples were scraped off the auger bit after the smeared surface was carefully removed. Attempts were also made to collect some undisturbed samples by pushing a plastic casing into the ground using the drilling rig; however, few samples were collected due to poor recovery. Some sediment samples were also scooped off from the bottom of the tailings pond and the ditches.

(2) Second Phase

During the Second Phase of field work, water samples were obtained from all the locations as sampled during the First Phase, and from several new locations. These new locations were dyke outtake drainpipes and the piezometers at the Control Site. Water samples were collected in the same manner as during the First Phase. One water sample was collected at the Control Site (CNT-E) over three days because it was extremely unproductive. Another sample at the same location was taken from the newly installed larger diameter piezometer (CNT-E2) which was more productive. It was not possible to obtain a water sample from the drive point in the Outer Ditch due to suspected clogging, and from the drive point at the Control Site that had been damaged. Water samples were collected from the tailings pond return pipe (which is considered to be representative of tailings water) prior to this field survey and sent to the University of Waterloo by ASE. See **Table A-3.2 (b)** in the Appendix for details.

One set of water samples was sent directly to Maxxam in Edmonton for analyses of major inorganic ions. Another set of water samples taken from selected piezometers was sent to the Environmental Isotope Laboratory at the University of Waterloo for stable isotope (^{18}O and ^{2}H) analysis, and the other sets to the Organic Chemistry Laboratory of the University of Waterloo for total and detailed naphthenic acid analysis (NA characterization).

(3) Third Phase

A total of 6 water samples were collected from selected locations within the Study Area (see **Table A-3.2 (c)** in the Appendix for details). One sample was taken from the pond (surface water) in which BtD-S was located. One set of water samples was sent directly to Maxxam in Edmonton for analyses of major inorganic ions. The other set was sent back to the Organic Chemistry Laboratory of the University of Waterloo for analyses of total NA.

(4) Forth Phase

In order to confirm the migration of PAW across the Outer Ditch over the Winter of 2006, a total of 6 water samples were collected from the piezometers that had survived burial and from the tailings pond (see **Table A-3.2 (d)** in the Appendix for details). One set of water samples was sent directly to Maxxam in Edmonton for analyses of major inorganic ions. The other set was sent back to the Organic Chemistry Laboratory of the University of Waterloo for analyses of total NA

3.2.3 Groundwater Monitoring

Groundwater levels, and temperature were continuously monitored from July 12, 2005 to May 28, 2006 at three installations (OuD-S2C, OuD-S2W, CNT-E2). At piezometer OuD-S2C, conductivity was also monitored. The primary purpose of this hydraulic head monitoring was to detect changes in groundwater levels in response to the anticipated dyke expansion that was initially planned for the Summer of 2005. However, this construction work actually started in the Winter of 2006 in the Study Area and had not made much progress before the retrieval of the data loggers in May 2006. In addition, the dyke expansion plan was eventually changed from hydraulic construction to dry construction that does not involve PAW. Therefore, data from two piezometers in the Study Area only represent the initial stage of the dyke expansion by dry construction. On the other hand, the piezometer CNT-E2 was able to capture changes in groundwater level in the Control Site due to the hydraulic construction that was under way near this location. This piezometer, however, was demolished in February 2006 due to road expansion.

3.3. Laboratory Experiments

The grain size distribution and laboratory permeability tests of soil samples were conducted to quantitatively evaluate their hydraulic properties in the Earth Science Laboratory of the University of Waterloo.

(1) Grain size analysis

Soil samples were first dried in an oven at 105°C, cooled and weighed. The sample was put into a stack of sieves and shaken with a sieve shaker and the retained soil on each sieve was weighed. The sieve loss (sieve loss = starting weight - cumulative weight passing) was assured to be less than ±1% of the starting weight. The data were plotted on semi-log graph with grain size on the horizontal axis and the percent passing (finer than) a given size on the vertical axis. The samples were also classified according to the "Unified Soil Classification System (USCS) " modified from ASTM D2488. The details of this procedure are given in **Section A-1** in the Appendix.

(2) Falling head permeability tests

Soil samples were tested for hydraulic conductivity using the falling head permeameter. The experiment measures the time a certain amount of water takes to seep through a disturbed soil sample contained in a cylinder. The detailed procedure for the test is given in **Section A-2** in the Appendix. The hydraulic conductivity (K) of a sample in the falling head permeability test was calculated using (Freeze and Cherry, 1979)

$$K = \frac{a \cdot l}{A \cdot t} \cdot \ln\left(\frac{H_0}{H_1}\right) \qquad \left[\frac{cm}{s}\right]$$

where a *(cm²)* is the cross-sectional area of the tube, l *(cm)* is the thickness of the soil sample, A *(cm²)* is the cross-sectional area of the soil sample cylinder, and t *(second)* is the time for the water head to fall from H_0 to H_1.The tests were performed 3 to 7 times depending on the variations of the individual results.

3.4. Quality Control

In order to maximize the quality of the data used for this study:

- The instruments used in the field were all calibrated with proper standard solutions and other physical references immediately before their use.
- The laboratory experiments for grain size and permeability were conducted in accordance with the procedures recommended by ASTM or equivalent protocols.
- Several duplicate samples were tested to confirm the reliability of analysis data for the water samples sent to the commercial laboratory (see **Table A 4.1** in the Appendix).

Table 3.1 Summary of Piezometers and Drive Points Installed during the First Phase of Field Work

Area	Piezometer	Drive points	Total
Study Area	9 (3 clusters x 3)	2	15
	4 individual		
Control Site	2	1	3
Specifications	Geoinsight, PrePak well screen, 1.9 cm (3/4 inch) diameter, 10.2 cm (4 inch) long, 65 mesh stainless steel	Solinst Model 615, 1.9 cm (3/4 inch) diameter 20 cm long, stainless steel	

Table 3.2 Summary of Piezometers and Data-loggers installed during the Second Phase of Field Work

Area	Piezometer	Data logger	Logger model
Study Area	1 (OuD-S2C)	1	3001 LTC
		1	3001 LT (Barometric)
	1 (OuD-S2W)	1	3001 LT
Control Site	1 (CNT-E2*)	1	3001 LT
Total	3	4	

* Installed outside the study area,
see **Fig. 2.2** and **Fig. 2.3** for location of piezometers

Table 3.3 Pressure Transducer Details

Piezometer	Model	Monitoring Item*			Monitoring Interval
OuD-S2C	3001 LTC	WL	Temp	EC	1 hour
	3001 LT (Barometric)	AP	Temp	-	1 hour
OuD-S2W	3001 LT	WL	Temp	-	1 hour
CNT-E2	3001 LT	WL	Temp	-	1 hour

* Temp: temperature of water/air, WL: static water level in terms of pressure, EC : electric conductivity
AP: atmospheric pressure

4. Results and Discussion of Field and Laboratory Observations

4.1. Water level Monitoring

4.1.1 Discrete Measurements

(1) Piezometers

The manual measurements of groundwater levels at the installed piezometers suggest that general groundwater flow is south along the installed monitoring transect (see **Fig. 4.1)**. The high hydraulic head of ~305 m in the tailings pond is reduced down to ~280 m at InD-N located directly at the tip of the dyke toe berm. The hydraulic head at the southern edge of the Study Area is about 277.5 m (see also **Table 4.1**). The lowest hydraulic heads were observed in piezometers installed in the Wet Area; the southern part of the area between the ditches (see **Fig. 2.3**). The relative hydraulic head distribution pattern remained unchanged during this research. The hydraulic head in the piezometers OuD-N and BtD-S that were found in the pond were the same as the surface water level of the pond.

(2) Drainpipes and the Outer Ditch

The discharge rates measured at the 3 outtake drain-pipes in June and November 2005 ranged from 0.4 to 0.67 L/s (see **Table A 2.2** in the Appendix). The average flow rate was found to be 0.6 L/s. This is consistent with the data obtained from ASE during the Fourth Phase of field work (see **Fig. 6.4**). Since one outtake drain-pipe normally covers a 150 m wide section of the dyke as shown in **Fig. 2.4**, the seepage rate per meter length of dyke is estimated to be 4 x 10^{-3} L/s/m (0.6 L/s / 150 m = 0.346 m^3/day/m). The approximate average flow rate in the Outer Ditch was estimated to be 0.05 m^3/s.

4.1.2 Continuous Measurement

All continuous water elevation data presented here have been corrected for barometric pressure variations and calibrated to manually measured water levels (**Figs. 4.2 - 4.4**). The daily total precipitation recorded at the Aurora climatologic station located to the south east of the mine is also shown on **Figs. 4.2-(a) – 4.4-(a)** to examine correlation between precipitation and groundwater levels. Note that these daily total precipitation data are shown in such a way that the precipitation appears to concentrate in the last hour of each day (at 23:00).

(1) Groundwater fluctuations in the Study Area

Data from the two piezometers (OuD-S2C and OuD-S2W) show both short-term and long-term fluctuations (see **Figs. 4.2 and 4.3**).

<OuD-S2C>

The water level at this location appears to fluctuate up to 5 cm per day as shown in **Fig. 4.2-(a)**. No distinct fluctuation pattern is recognized and rainfall does not seem to affect this fluctuation. Since the data has been corrected for barometric changes, the cause of this short-term fluctuation is not clear. **Fig. 4.2-(b)** shows the long-term fluctuation of the water level. The water level shows a gradual increase from mid May until mid August 2005 where it levels off at around 277.49 m amsl until mid September. Then it gradually decreases towards late April 2006. Of note are the 6 sharp drops in water elevation during the winter, probably indicative of some effect of dyke construction.

The groundwater temperature record shows a gradual increase from 1.5^{o}C in July 2005 to ~4 ^{o}C towards early October and then starts decreasing to a low of 1.2 ^{o}C on 20th May 2006. No short-term fluctuations are recognized. While the peaks in daily mean air temperature occur through early July to late August, the highest groundwater temperature is recorded around early October, suggestive of a time lag of one or two months between air and groundwater temperature peaks.

The recorded conductivity data was corrected for offset by a laboratory measured value from the same piezometer. The conductivity data shows very small short-term fluctuations of ± 0.05 mS/cm and is considered to be measurement noise. The long-term fluctuation pattern is similar to that of the groundwater temperature in that the conductivity gradually rises from an initial value of 1.75 mS/cm in July 2005 to 1.83 mS/cm around mid October 2005 and gradually decreases to the initial level by mid May 2006. It does not seem to capture any unusual changes in groundwater chemistry.

<OuD-S2W>

The water level data from the piezometer installed about 60 m to the west of the "OuD-S" cluster has a similar pattern as that observed in OuD-S2C (see **Fig. 4.3**). In this case however there was a 7 cm difference between the pressure transducer hydraulic head and manually measured hydraulic head. This difference is presumed to be due to a barometric efficiency problem caused by insufficient ventilation in the piezometer casing. In spite of this error, these data still reveal long-term seasonal fluctuation patterns similar to that at OuD-S2C. The sharp drops during the winter are also clearly observed.

The temperature monitoring record shows a similar pattern to that of OuD-S2C except that a higher maximum of 3.9 ^{o}C was reached around mid October 2005, nearly a month later than at OuD-S2C. Although the two piezometers are only 63 m away and static water level is almost the same, the saturated thickness of pf-sand is much thinner at OuD-S2W as shown in **Fig A 2.3** and hence higher temperatures would be expected due to the different flow system dynamics.

At these two piezometers, there is no apparent correlation between daily precipitation and short-term water level fluctuation. Considering the fact that the amount of rain is relatively small (maximum 21.2 mm /day and commonly less than 5 mm/day) during the monitoring period, and that the aquifers are overlain by a few meters of low-permeability layers of peat, precipitation probably does not have a large impact on the groundwater level.

(2) Water level fluctuations at the Control Site

The data from the piezometer installed at the Control Site (CNT-E2) show a distinct pattern over both the short and long term. These pressure data are believed to suffer from the same barometric efficiency problem as discussed above at OuD-S2W, but the difference here was ~5 cm. The record is available only up to late February 2006 because of demolition. As shown in **Fig 4.4**, the fluctuation in this piezometer is as large as 14 cm in the short-term and nearly a meter over the long-term. There is no meaningful pattern in the short-term fluctuations and it has no correlation with precipitation. This is consistent with the findings from the two piezometers in the Study Area. Meanwhile, the long-term pattern shows two distinct broad peaks/drops and many spikes and drops towards the end of the monitoring period. However, its general trend is similar to the patterns observed in the Study Area in that the water level increases from mid July 2005 and remain high until early September 2005. The large drop in mid-August and several spikes in October are probably due to the local dyke construction work. According to a tailings engineer, Megan Storrar of ASE, the construction work had already started in August near the Control Site and thus this may have affected the local groundwater flow conditions.

4.2. Water Chemistry

4.2.1 Field Measurements

Field parameters listed in **Table A 2.2** show that the pH of the groundwater is mostly neutral except for ditch waters that have relatively higher values of around 8. The temperature of the deeper groundwater in the OuD-S piezometers are relatively stable throughout a year and ranges between 4 to 8 ^{o}C. The temperature of the shallow groundwater (BtD-S, BtD-N) on the other hand, range between 3 to 15 ^{o}C.

This trend clearly reflects the influence of ambient temperature. It should be also noted that the values recorded by data loggers are about 2 degrees lower than field measurement values. This is presumed to be a result of sampling bias associated with the manual measurements. The pH and EC measurement results are also consistent with the laboratory measurement values.

4.2.2 Inorganic Ions

(1) Tailings pond water

PAW is believed to be the source of contamination in the Study Area. Water samples (6 in total) from the tailings pond were collected at different locations and times during this study for comparison purpose and the analytical results are presented in **Table 4.2.** All water samples were collected from the tailings pond surface and analyzed by the Maxxam laboratory except for the tailings return line sample. This sample was taken from the return pipe by ASE and analyzed by ALS laboratories (formerly Enviro-Test Laboratories) and represents the initial water entering the tailings pond. The data for the 5 older samples show that the tailings pond water has very uniform chemistry as indicated by the statistical values on the right columns. The last sample taken in May 2006 has relatively higher concentrations of most parameters. However this water was sampled about 3 weeks after tailings discharge was ceased due to maintenance and thus it is not representative. The major indicator species used for tracing tailings pond water (shaded entries in **Table 4.2**) show relatively small spatial and temporal variations.

(2) Groundwater and ditch water

Figs. 4.5 and **4.6** show spatial variations of major chemical parameters along the N-S transect. The tailings water is characterized by high concentrations of Na^+ and Cl^-, a high pH value and, low SO_4^{2-} and Ca^{2+} concentrations. Note that in these figures the concentration shown at each piezometer cluster is the average concentration observed at the three piezometers in the cluster. This feature is inherent both in ditch water (surface water) and in groundwater samples downgradient. The samples from both the Inner and Outer Ditches have high pH, and Na^+ and Cl^- values. The groundwater samples down-gradient of the Tailings Pond exhibit similar characteristics until the Wet Area: Na^+ and Cl^- ion concentrations more than 20 and 5 mg/L and SO_4^{2-} and Ca^{2+} ion concentrations less than about 300 and 200 mg/L respectively. A clear change in water chemistry is recognized between piezometers BtD-N and BtD-S where Na^+ and Cl^- concentrations that remained high significantly drop. On the other hand, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and EC (electric conductivity) values rise in this area. The samples from the Control Site show similar concentrations of inorganic ions to the samples from OuD-S piezometers with slightly elevated Na^+ and Cl^- concentrations.

Although the two temporal profiles (Oct. 2004 and June 2005) show similar patterns as described above, the Na^+ and Cl^- concentrations at BtD-S are higher in the June 2005 profile. Specifically, Na^+ and Cl^- concentrations increased significantly from 19.8 and 24.1 mg/L to 81.9 and 55.3 mg/L respectively. In contrast, the concentrations of SO_4^{2-}, Ca^{2+} and EC significantly dropped. Na^+ and Cl^- are known to be very conservative and often used as tracers, and in this case we conclude that the high Na^+ and Cl^- values are a primary representation of the influence by PAW. Since the parameters at the other piezometers remaining relatively unchanged, it appears that the seepage water migrated towards the south during the 8 months between October 2004 and June 2005. The temporal change in spatial variation pattern is also shown in **Fig. 4.7** which also includes data for several water samples obtained during the field survey in November 2005 and May 2006. The spatial variation pattern for these subsequent samples are similar to that of June 2005, indicating little changes occurred after June 2005.

No clear depth-dependent variation in chemistry is recognized at the Inner Ditch except for the slight increase in hardness, EC, and pH towards ground surface. However, a clearer trend is observed at the south side of the Outer Ditch where the concentration of SO_4^{2-}, Ca^{2+} and Mg^{2+} all decrease towards the surface (see **Table A 4.1** in the Appendix). The cause of this trend is not clear at this point but it does not involve essential tailings water indicator parameters.

The outtake drain-pipe water has a very similar chemistry to that of the water in the Inner Ditch with only slightly higher concentrations of most ions (see **Table A-4.1 (b)** in the Appendix). When these values are compared to those of the groundwater from InD-N and InD-S, they are also relatively similar to each other except that the outtake drain-pipe water has higher concentrations of SO_4^{-2} and Mg^{+2} and a slightly lower Ca^{+2} concentration. The drain water appears to have a chemical composition different from tailings pond water with significantly higher concentrations of EC (1330 vs 1020 mg/L), SO_4^{2-}(281 vs 70 mg/L), Ca^{2+} (119 vs 13 mg/L) and lower concentrations of Na^+ (113 vs 184 mg/L), Cl^-(60 vs 104 mg/L). The pH is also slightly less than that of the tailings pond water.

The chemistry of the surface water sample from the pond in which BtD-S is located was compared to the chemistry of the groundwater from BtD-S. The two water samples show a very similar inorganic chemical composition (see **Table A-4.1 (c)** in the Appendix), suggesting that this surface water is receiving discharged groundwater.

Overall, the chemical evolution trend along the N-S transect from the north (tailings pond) to the south (outer ditch) is characterized by an increase in the concentrations of SO_4^{2-} and Ca^{2+} and a decrease in pH, and the concentrations of Na^+ and Cl^- ions.

4.2.3 Naphthenic Acids

Naphthenic acids are a highly soluble group of organic acids with structures shown in **Fig. 4.8**. Elevated concentrations of naphthenic acids in combination with salt in PAW have negative effect on aquatic life (Leung et al., 2003).

(1) Total naphthenic acid concentration

The distribution of total NA concentration along the N-S transect is shown in **Fig. 4.5 (b) and 4.6 (b)** and data is given in **Table A 4.2** in the Appendix. The concentrations of NAs follows a similar trend to the Na^+ and Cl^-. In this case also, a drop in its concentration occurs in the Wet Area; between BtD-N and OuD-N in both the October 2004 and June 2005 profiles. Unlike the inorganic chemistry profiles, however, no advance of the NAs between October 2004 and June 2005 is recognized.

The water from the dyke outtake drain-pipe has the same amount of NAs (11.6 mg/L) as the water in the Inner Ditch while that in the tailings pond is 28.2 mg/L. This suggests that the NAs also decrease as Na^+/Cl^- does during the seepage through the dyke. Meanwhile the waters from the piezometers on both sides of the Inner Ditch show elevated but variable NAs concentrations. The surface water and groundwater samples at BtD-S have similar NA concentrations (see **Table A-4.2**), supportive of the finding in inorganic chemistry. The water sample from the Control Site has a NA concentration of 4.4 mg/L which is considered to represent the maximum contribution from the lean oil sands of the McMurray formation as background.

(2) Naphthenic acid characterization

Naphthenic acids are a diverse group of carboxylic acids and are classified into several groups in terms of “z” value and “n” value. The former is related to the number of carbon rings in a molecule (see **Fig. 4.8**) and the latter is the carbon number of the molecule, thus proportional to the molecular mass. Clemente et al., (2004) reported that NAs can biodegrade under aerobic conditions and the rate of degradation is higher for lower molecular weight molecules having lower “n” values. Thus the characterization and comparison of NAs based on “z” and “n” values is expected to provide some information on the attenuation and fate of these chemicals in PAW (Gervais, 2004).

NAs from three groundwater samples and two ditch water samples obtained along the N-S transect, and one tailings water sample were analyzed for detailed NAs composition. The results shown in **Fig 4.9** and the data presented in **Table A 4.3** in the Appendix indicate that all the samples have similar distribution of species. The group with z = -4 is the most common type accounting for 25 to 35 % of the total. In terms of molecular size, the "n" number 12 to 14 are most abundant species. This general distribution pattern is different from the one reported by Gervais (2004) who analyzed naturally occurring groundwater from the McMurray formation in the north east of the Muskeg River Mine. These samples from the McMurray formation have much lower proportion of NA species with z=-4 and n= 12 and 14, and relatively higher proportion of species with z = 0. This is considered to reflect the difference in the source of NAs.

In spite of the general similarity in the NA distribution pattern for all the samples, OuD-N has a noticeably lower proportion of NA species with n = 10 to 13 and slightly higher proportion of species with n = 15 or larger, than other samples. Gervais (2004) pointed out that biodegradation of NA is characterized by a decrease in species with n less than 15 based on the laboratory experiments on NA samples from the Athabasca oil sand mines. On the other hand, OuD-N also has the lowest total NA concentration of 2.6 mg/L. This makes the characterization of this sample less reliable. Thus, this NAs distribution pattern for the sample from OuD-N only indicates a minimal possibility of biodegradation.

4.2.4 Stable Isotopes

To track the PAW we employed stable isotopes of hydrogen and oxygen as conservative chemical species. Gervais (2004) found that stable isotopes of oxygen and hydrogen were useful in identifying PAW at the Suncor and Syncrude mines. The mixture of water and oil sand is heated to around 90°C and some evaporation occurs from the ponds and sand placement on dykes, which changes the isotopic ratio of the water. Thus some degree of stable isotopic change or fractionation is expected to occur during the extraction and disposal process. This effectively labels the PAW isotopically, and such water can be distinguished from groundwater derived by normal recharge of precipitation.

Twelve samples including tailings water and ditch water were analyzed and the results are presented in **Fig. 4.10**. The upper panel shows the isotopic value of hydrogen versus oxygen using the delta (δ) notation. More negative delta values indicate relative depletion in the heavy isotopes (^{18}O or ^{2}H). Local precipitation commonly falls on the local meteoric water line (LMWL). Gervais (2004) selected a LMWL for the oil sands area as: $\delta^{2}H$ (‰) = $5.36\delta^{18}O$ (‰) – 47.95. Evaporation causes the residual water to become enriched in the heavy isotopes of oxygen (^{18}O) and hydrogen (^{2}H) and so moves the position of the original water from the LMWL to the right and below the LMWL. Many groundwater samples are well-removed from the tailings pond samples and from the LMWL. Tailings Pond and ditch waters plot below and to the right of the LMWL, indicating they are likely evaporated. The groundwater from BtD-N is intermediate, suggesting it is a mixture of local precipitation and tailings water.

It appears that water with $\delta^{2}H$ values more than –140 ‰ and $\delta^{18}O$ values more than –17 ‰ may have a component of PAW. Examining the lower panel of **Fig. 4.10** with this in mind, it would appear that the ditch waters contain PAW, but that the ground waters south of BtD-N do not. This is generally consistent with the interpretation based on the other chemical indicators of PAW. Stable isotopes appear to provide another indication of PAW and so their use should be continued in groundwater studies at the ASE's tailings pond.

4.2.5 Overall Observations

The PAW can is characterized by higher concentrations of Na^{+} and Cl^{-} ions and lower concentrations of SO_4^{2-} and Ca^{2+} ions compared with the natural groundwater. These characteristics of the PAW also correspond with a high concentration of NA and larger δ (delta) values of hydrogen and oxygen stable isotopes. PAW was tracked using these tracers and was found in the Inner and Outer Ditches, and groundwater to the north of OuD-N. Along the N-S transect, concentration changes of these parameters occur within the dyke, and between OuD-N and BtD-S in the Wet Area. Detailed NA analysis indicates that these changes are likely attributed to sorption and mixing with unaffected water rather than biodegradation.

4.3. Grain Size Analysis Results

The results of the grain size analysis are listed in **Table A-4.4** in the Appendix. The data were plotted on semi-log graph with grain size on the horizontal axis and the percent passing (finer than) a given size on the vertical axis (see **Fig. 4.11**). The samples were also classified according to the "Unified Soil Classification System (USCS) " modified from ASTM D2488.

In order to characterize each sample, the uniformity coefficient ($Cu = D_{10}/D_{60}$) and the coefficient of curvature ($Cc = D_{30}/D_{10}D_{60}$)) were calculated by linearly interpolating D_{10}, D_{30}, and D_{60} on the grain size distribution plots. Based on the grain size characteristics, the samples are categorized either SW, SW-SM or SP under the USCS classification system. **Table 4.3** summarizes the sample characteristics including the calculated coefficients.

The samples are generally moderately-graded medium ~ coarse sand with some fines. An average of 4.7% passes the 63 μm sieve, and an average of 47.3% falls between 500 μm to 1 mm. The samples contain up to 13.7% (average 6.1%) of over-sand sized grains. There are slight variations in grain-size distribution among samples but no clear trend can be recognized in terms of sampling location and depth (see **Fig. 4.11**).

The hydraulic conductivity (K, cm/s) of the samples was estimated based on the method proposed by Hazen (1911) using

$$K = C \cdot (D_{10})^2 \cdot (1 + 0.0429 \cdot T) \qquad \left[\frac{cm}{s}\right]$$

where D_{10} is the grain size (in mm) where 10% (by weight) passes through the sieve, T is the water temperature (in °C), and C is a constant related to grain uniformity (clayey and non-uniform sands: between 0.4 and 0.8, clean and uniform sands: between 0.8 and 1.2). In this case the value of C = 0.8 was used to represent moderately graded coarse sand. A field temperature of 10 ^{o}C was assumed. The results listed in **Table 4.4** indicate that the average calculated hydraulic conductivity is 4.3 x 10^{-2} cm/s and the maximum and minimum are 1.18 x 10^{-1} and 1.2 x 10^{-2} cm/s respectively.

4.4. Permeability Tests Results

The same 12 sand samples and one peat sample were tested for hydraulic conductivity using the falling head permeameter test. The values obtained were averaged after some outlier values were excluded. The results are summarized in **Table 4.5,** and the details of each test are given in **Table A-4.5** in the Appendix. The measured values of most of the samples are in the order of 10^{-2} cm/s. In some tests, results showed unusually high or low values than the other measurements for the same sample. This is considered to be caused by rearrangement of fines in the samples due to unrealistically high flow velocities in the test cylinder and so are not considered to properly represent the sample's hydraulic conductivity. No clear lateral or vertical trend in hydraulic conductivities was observed in terms of sample location. The calculated hydraulic conductivity values range from 2.0 x 10^{-3} to 8.9 x 10^{-2} cm/s with a mean (geometric) of 2.1 x 10^{-2} cm/s.

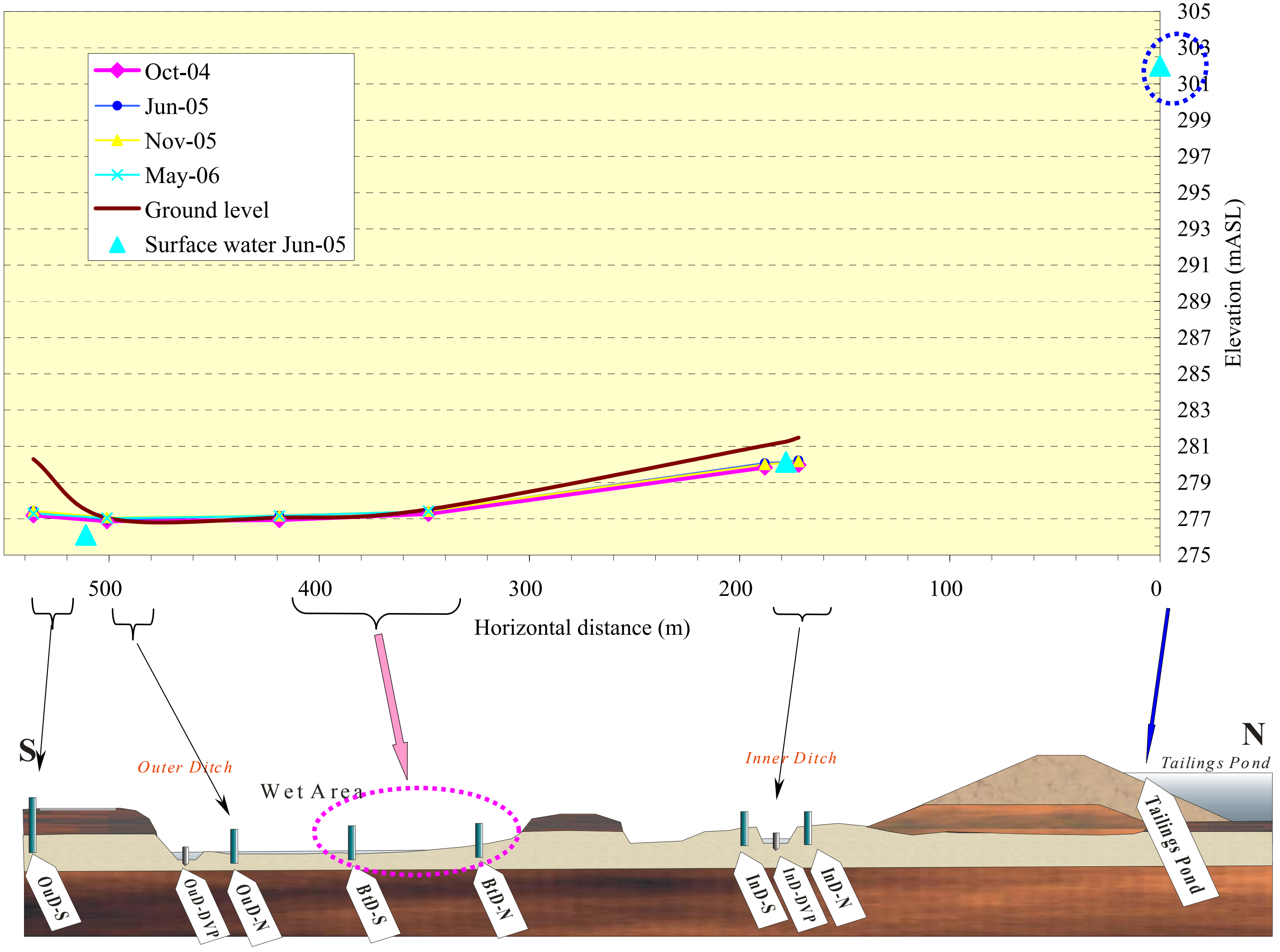
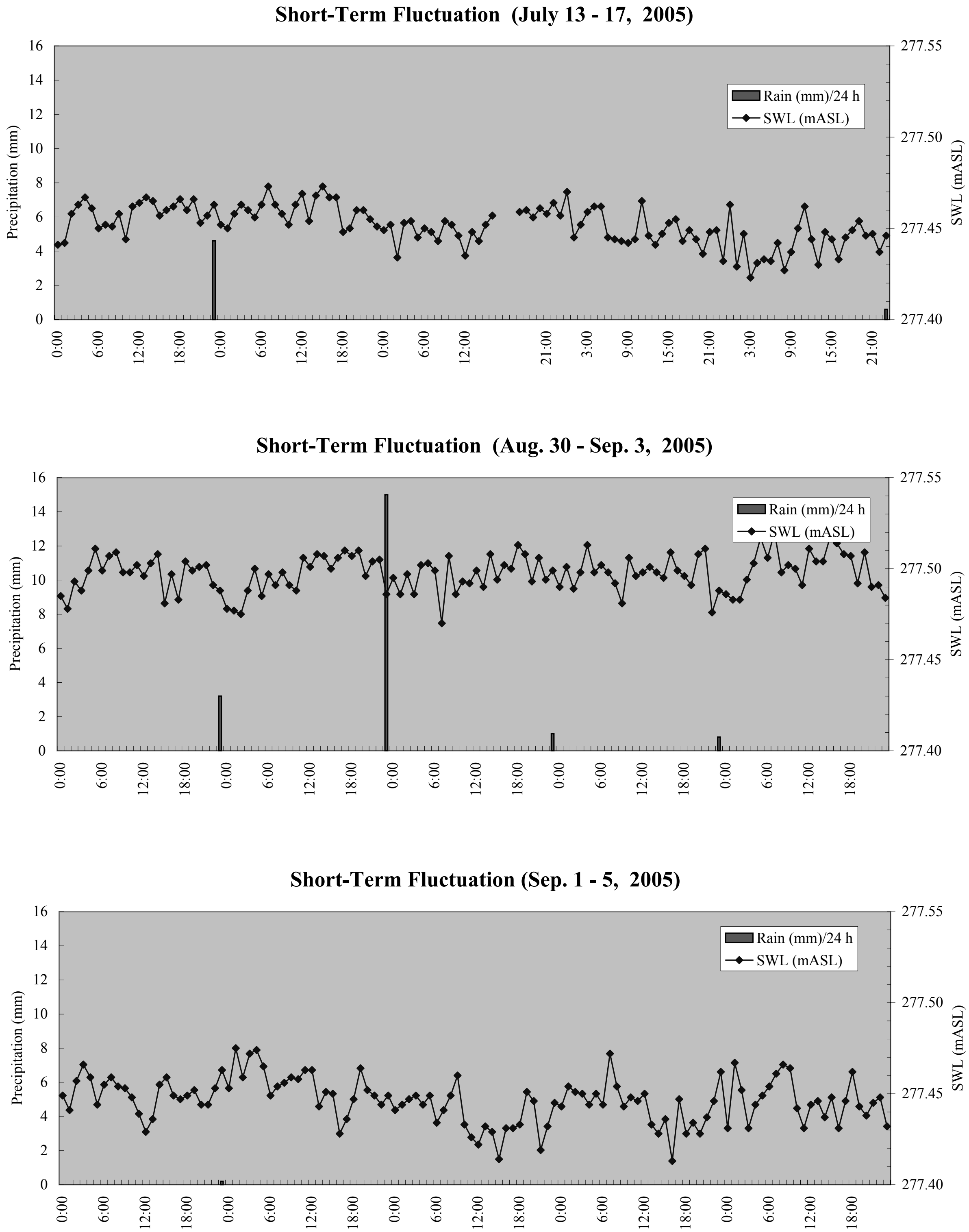


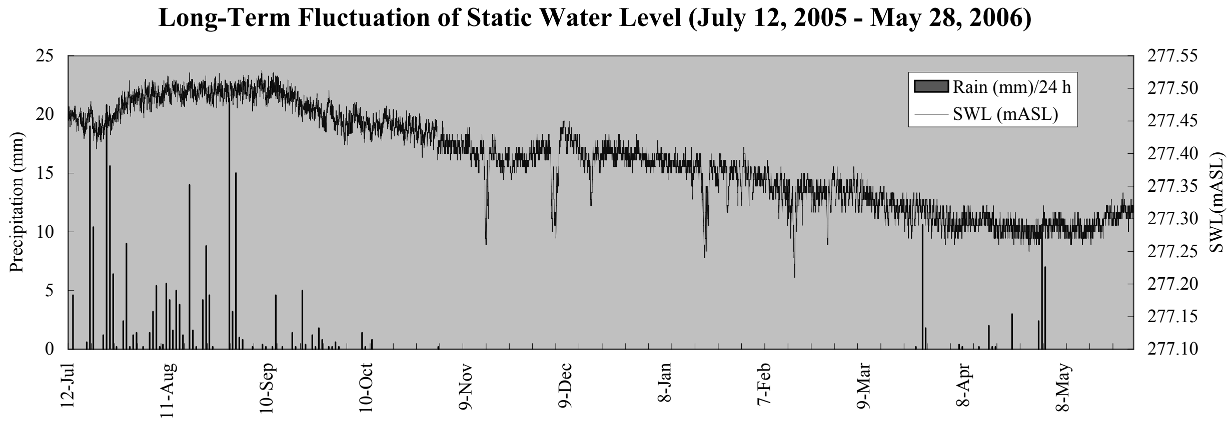
Fig. 4.1 Groundwater and Ground Surface Elevation (Oct. 2004 - May 2006)

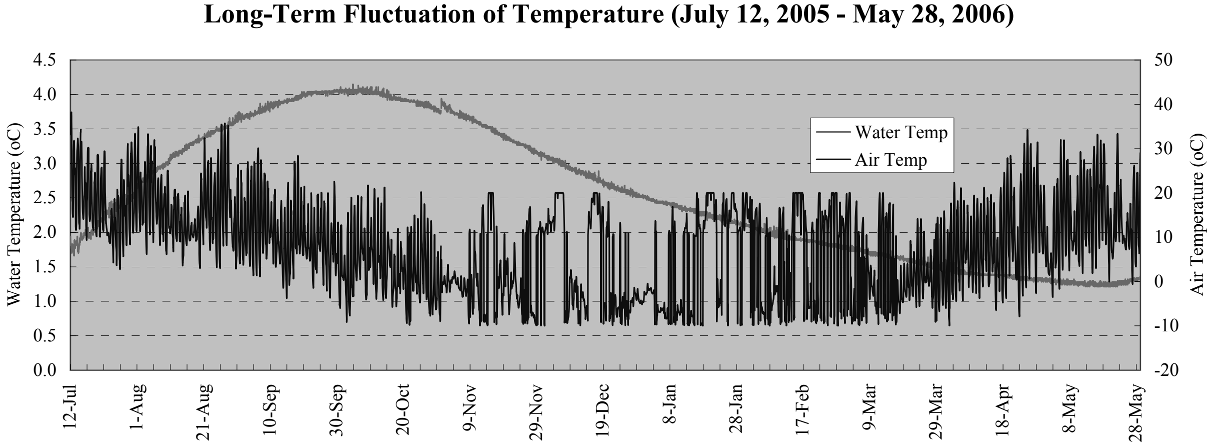

Short-Term Fluctuation (July 13 - 17, 2005)

Short-Term Fluctuation (Aug. 30 - Sep. 3, 2005)

Short-Term Fluctuation (Sep. 1 - 5, 2005)

Fig. 4.2-(a) Short-Term Water Level Fluctuation at OuD-S2C


Long-Term Fluctuation of Static Water Level (July 12, 2005 - May 28, 2006)


Long-Term Fluctuation of Temperature (July 12, 2005 - May 28, 2006)

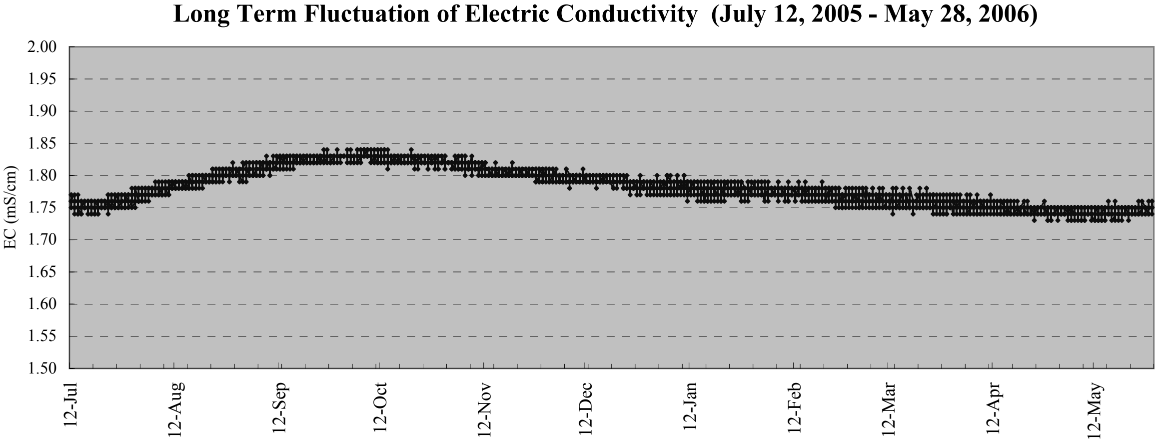
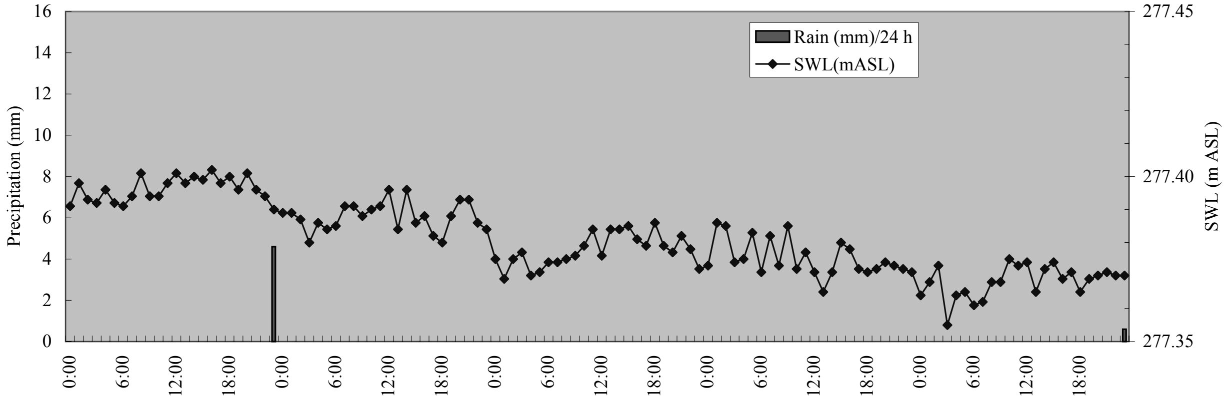
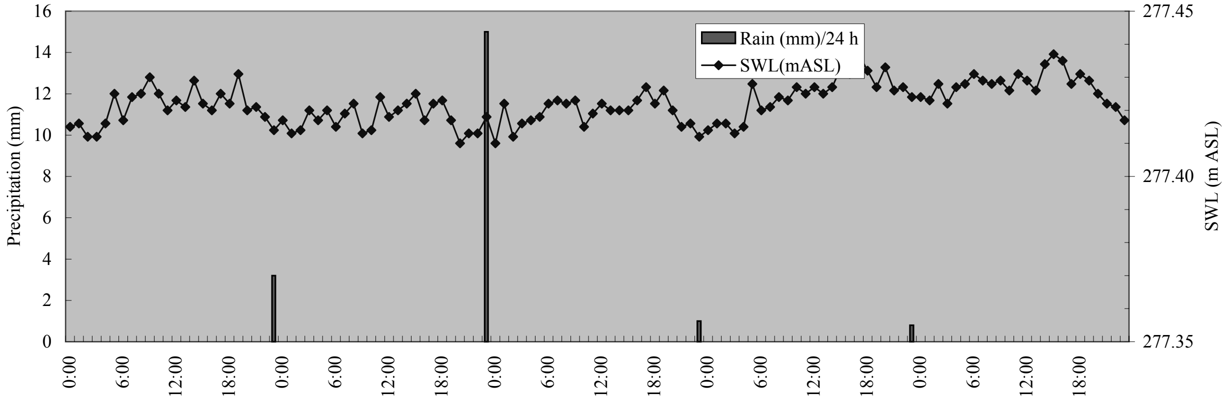

Long Term Fluctuation of Electric Conductivity (July 12, 2005 - May 28, 2006)

Fig. 4.2-(b) Long-Term Water Level Fluctuation at OuD-S2C

Short-Term Fluctuation (July 13 - 17)



Short-Term Fluctuation (Aug. 30 - Sep. 3)



Short-Term Fluctuation (Oct. 1 - 5)

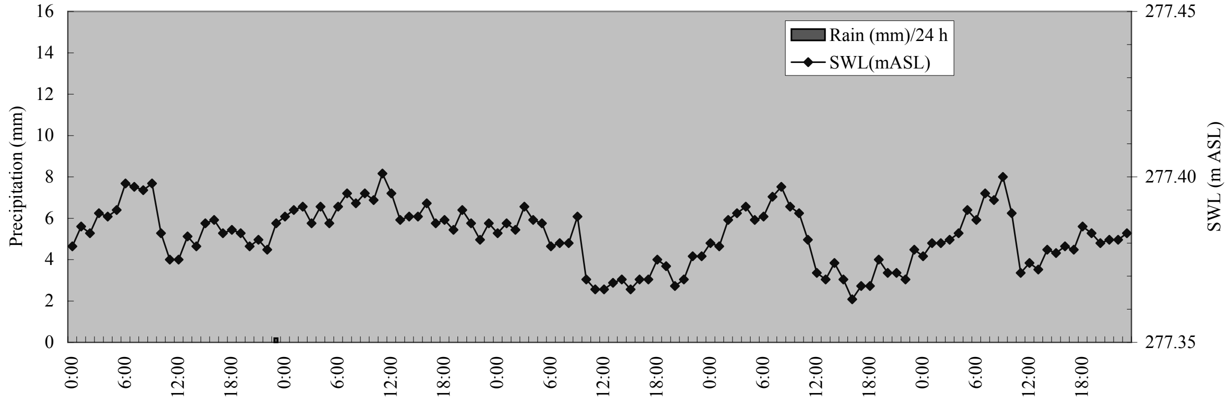


Fig. 4.3-(a) Short-Term Water Level Fluctuation at OuD-S2W

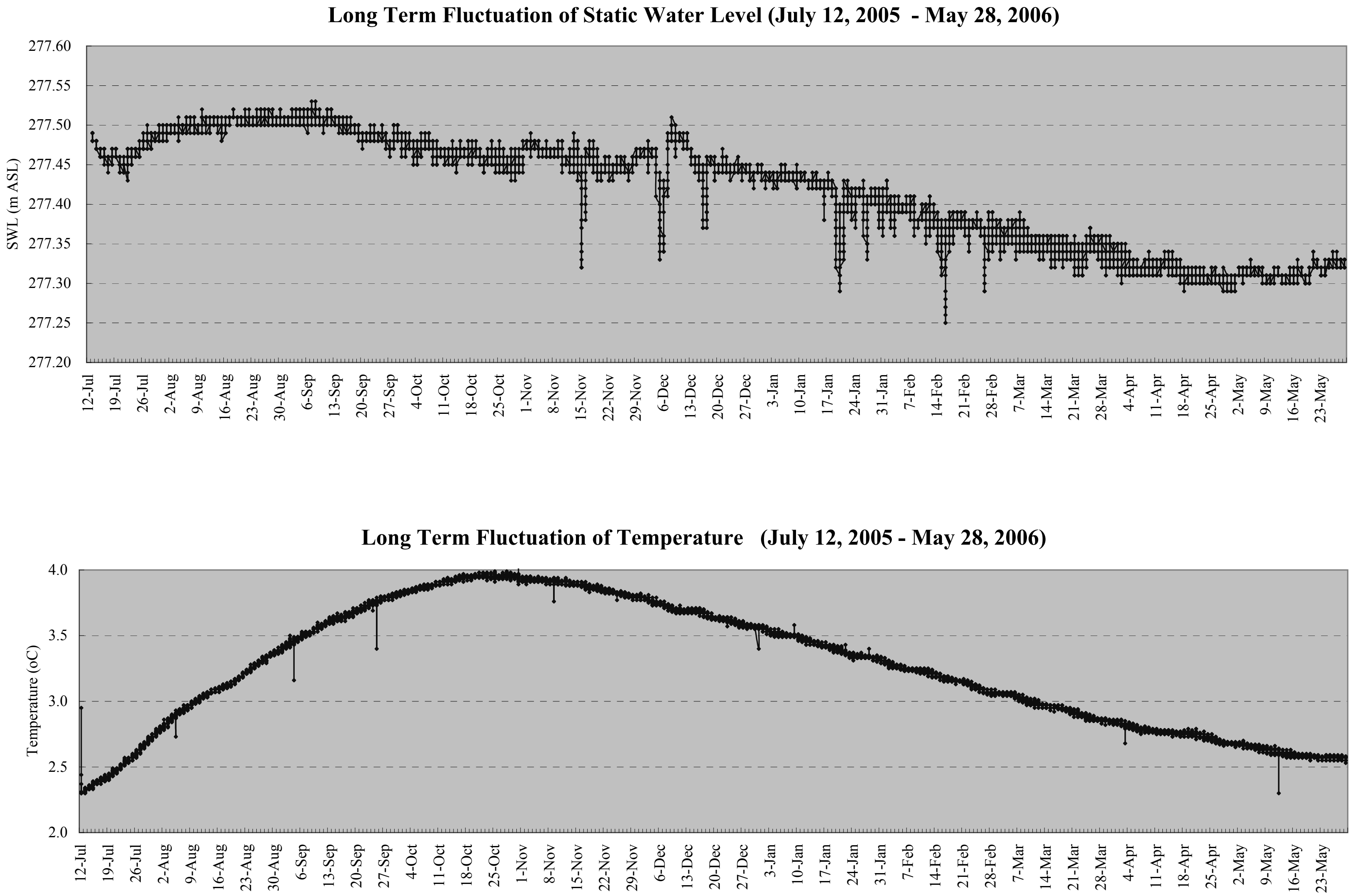
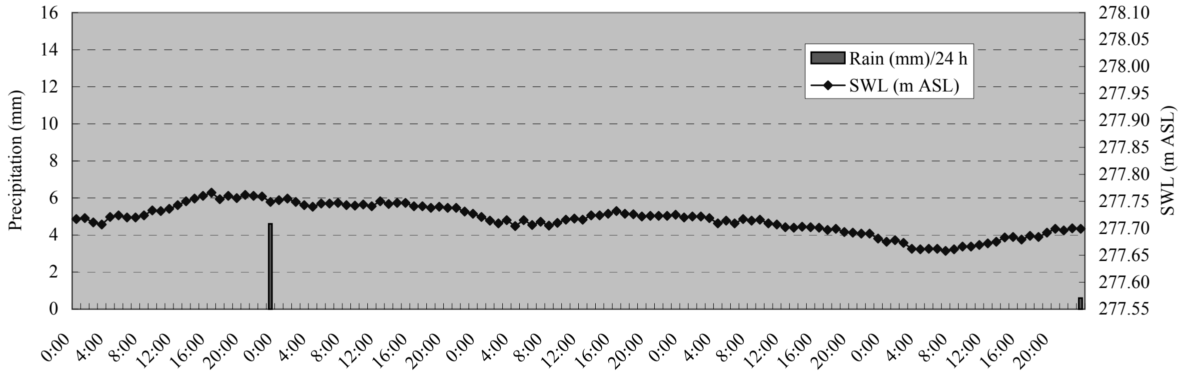
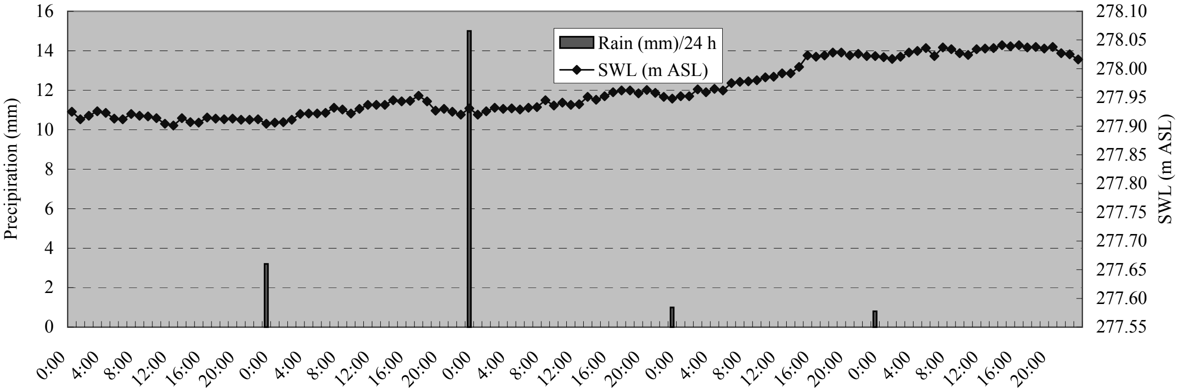


Fig. 4.3-(b) Long-Term Water Level Fluctuation at OuD-S2W

Short-Term Fluctuation (July 13 - 17, 2005)



Short-Term Fluctuation (Aug 30 - Sep 3, 2005)



Short-Term Fluctuation (Oct 1 - Oct 5, 2005)

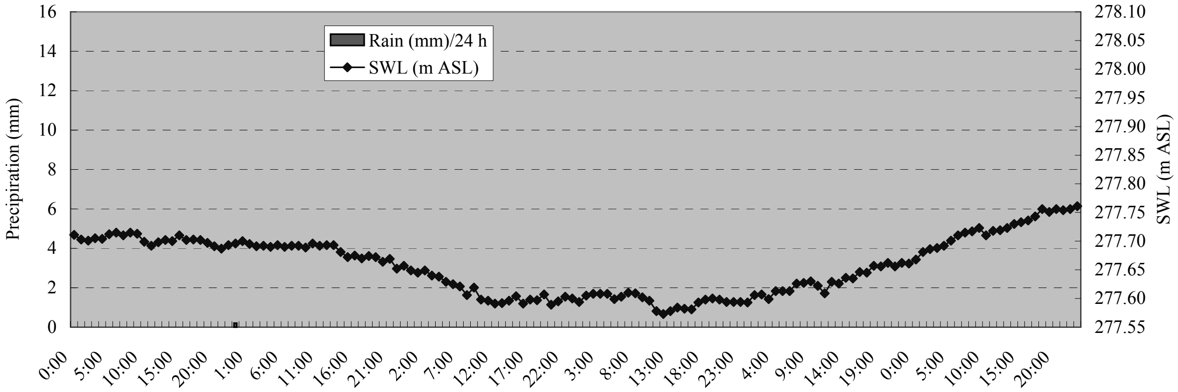
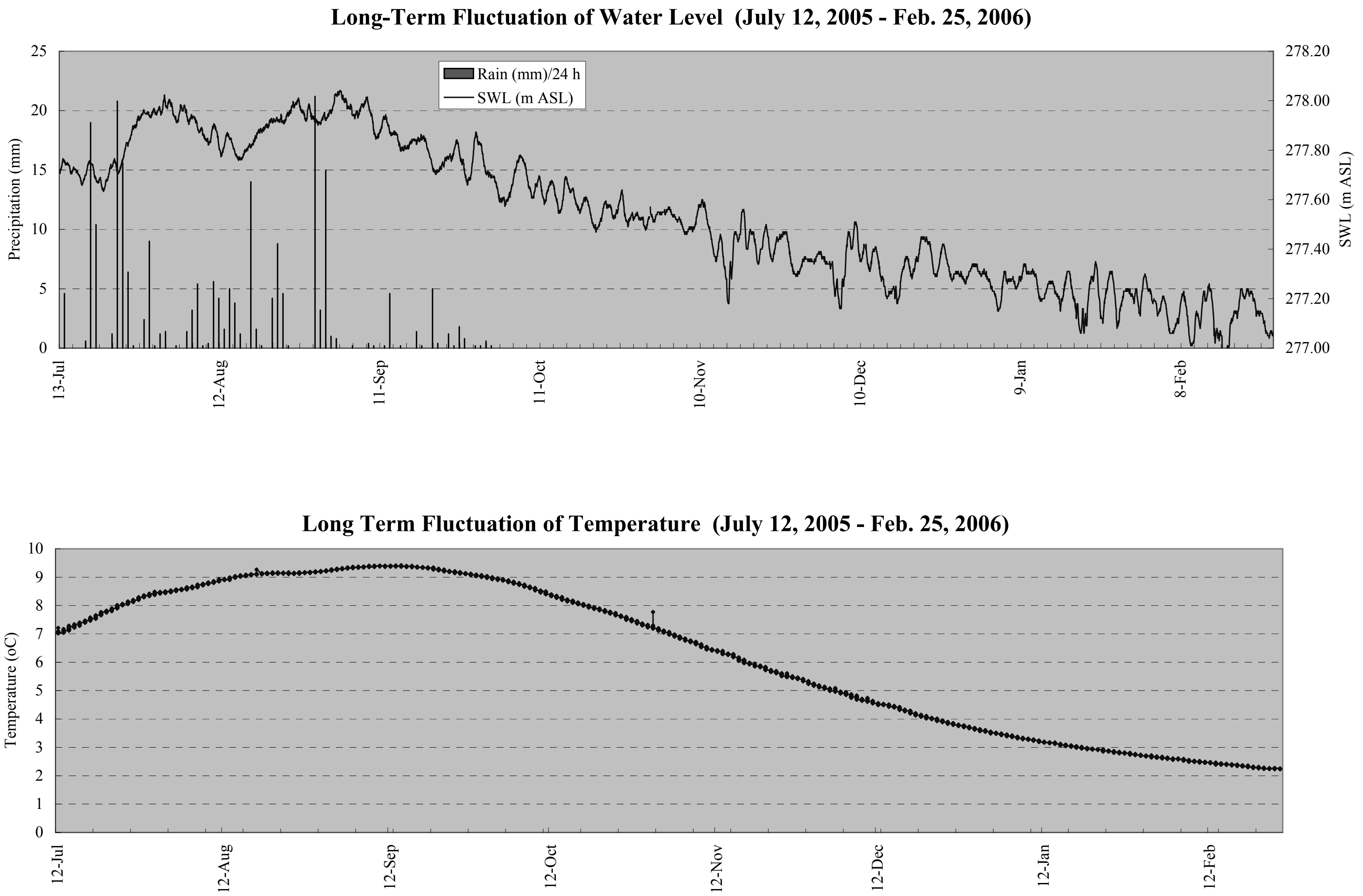
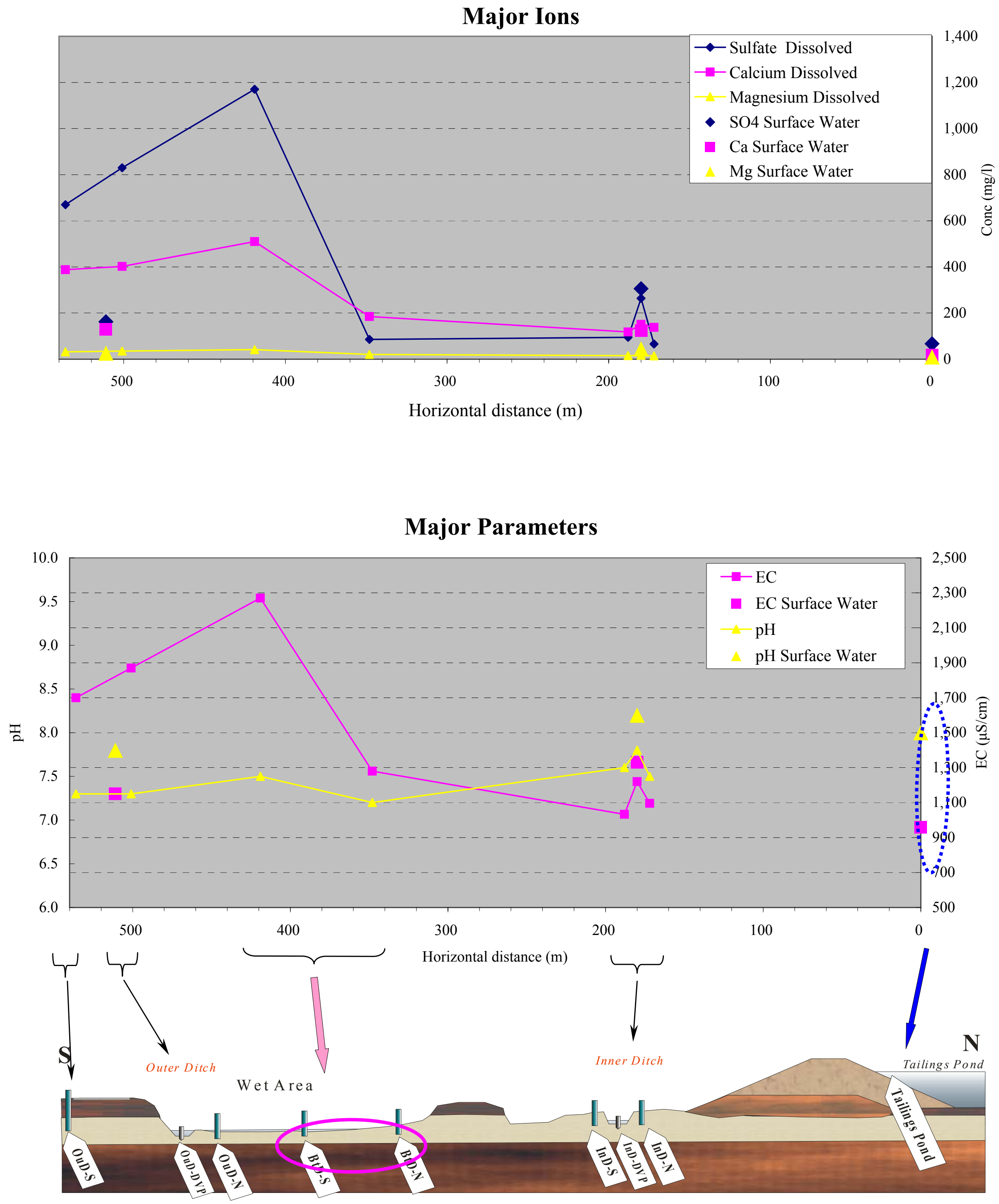


Fig. 4.4-(a) Short-Term Water Level Fluctuation at CNT-E2


Long-Term Fluctuation of Water Level (July 12, 2005 - Feb. 25, 2006)

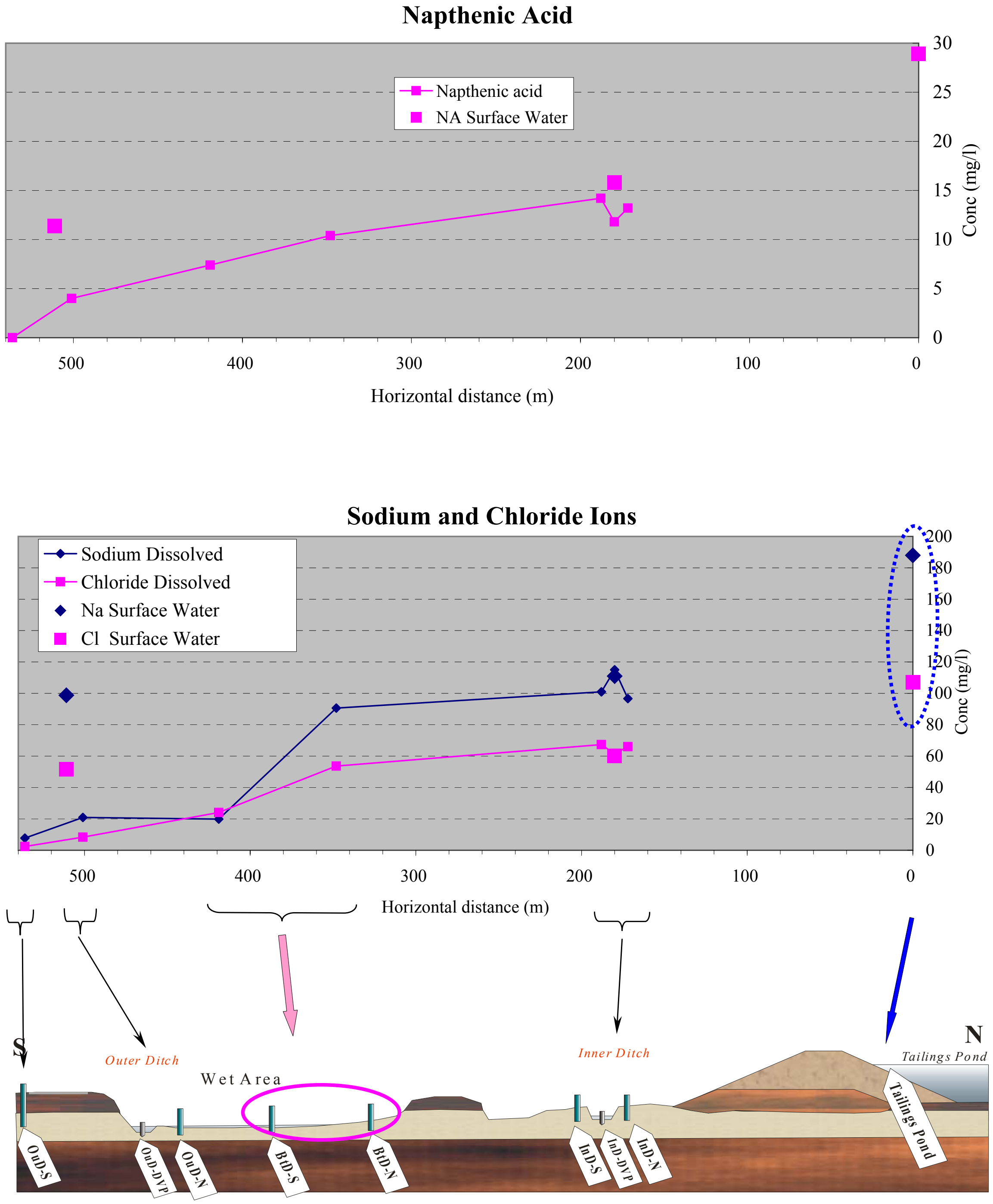
Long Term Fluctuation of Temperature (July 12, 2005 - Feb. 25, 2006)

Fig. 4.4-(b) Long-Term Water Level Fluctuatinon at CNT-E2



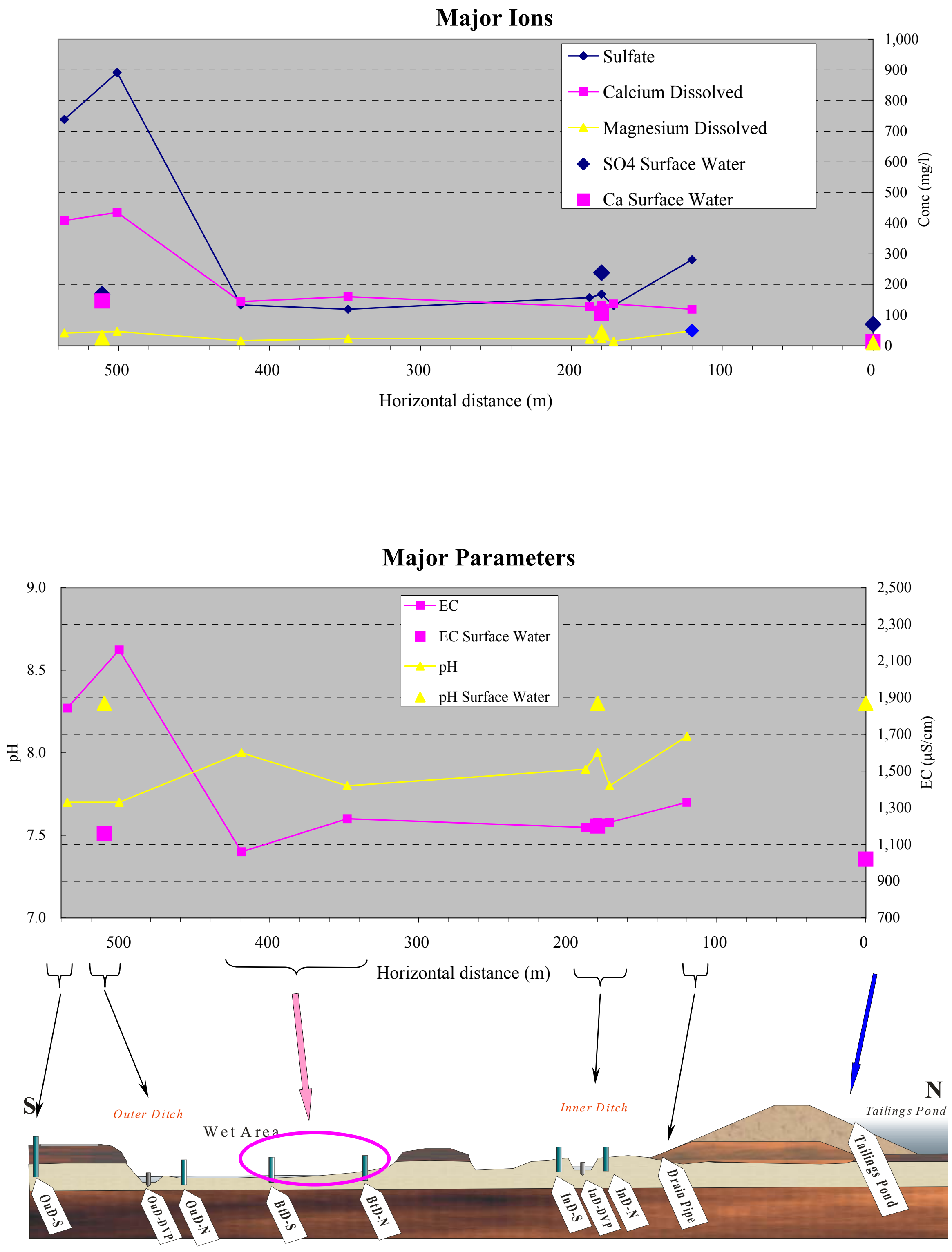
* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.5-(a) Spatial Variation of Water Chemistry, Major ions, pH, EC (Oct. 2004)



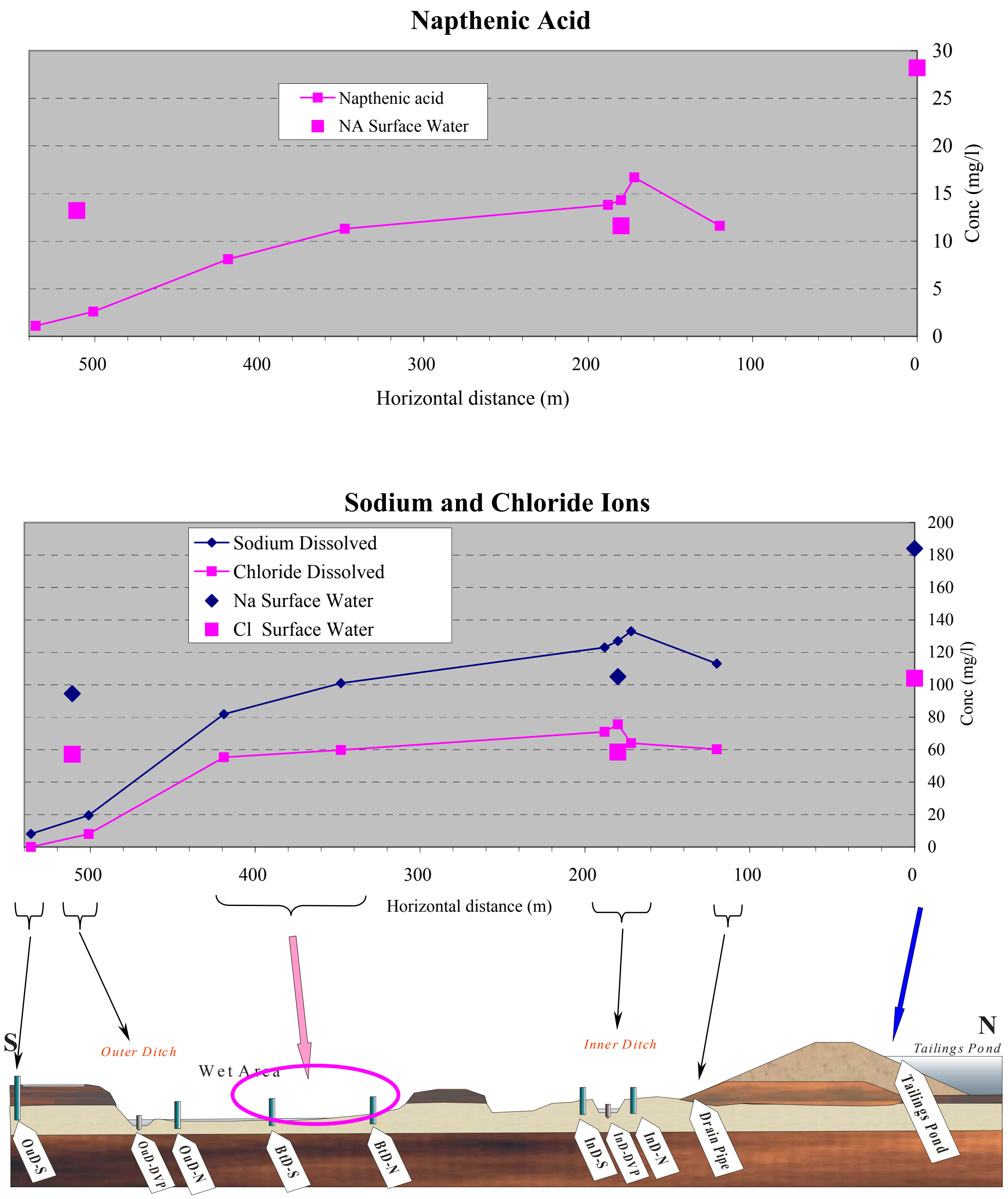
* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.5-(b) Spatial Variation of Water Chemistry, NAs, Na^+, Cl^- (Oct. 2004)



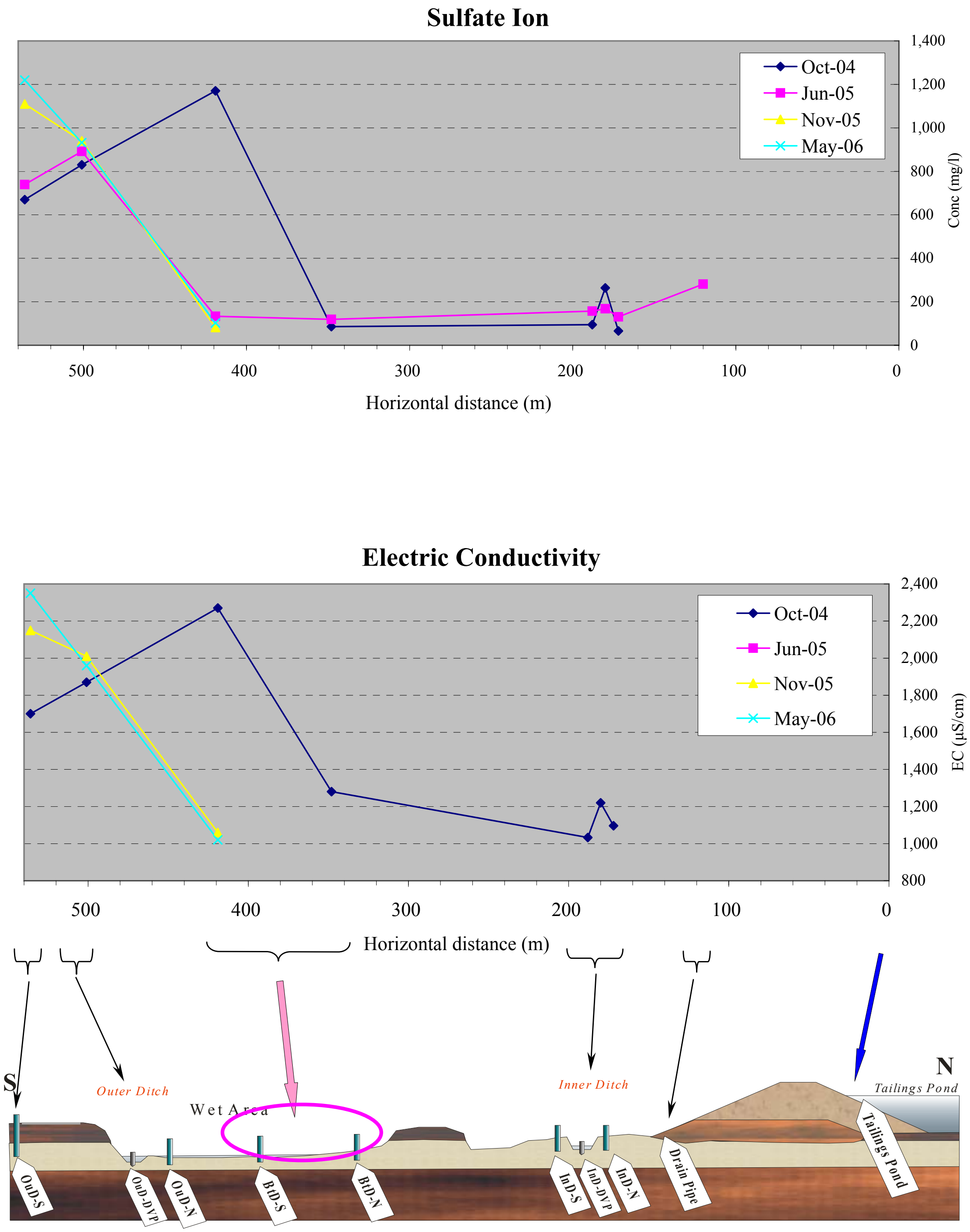
* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.6-(a) Spatial Variation of Water Chemistry, Major ions, pH, EC (June 2005)



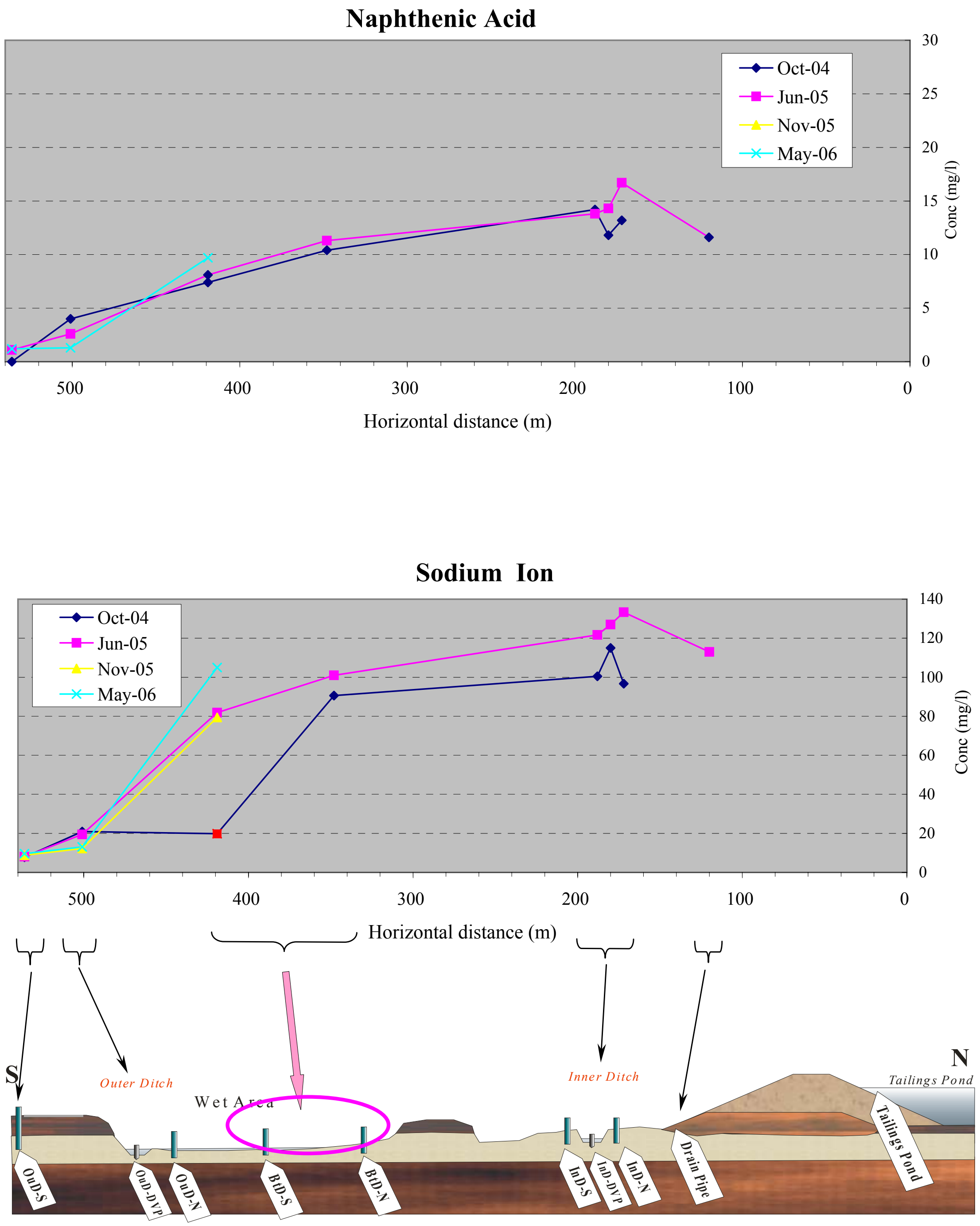
* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.6-(b) Spatial Variation of Water Chemistry, NAs, Na^+, Cl^- (June 2005)



* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.7-(a) Temporal and Spatial Profile of Major Tracers along Transect (Oct 2004 -- May 2006)



Naphthenic Acid

Sodium Ion

* Average values are shown for clusters of piezometers (InD-N, InD-S, OuD-S)

Fig. 4.7-(b) Temporal and Spatial Profile of Major Tracers along Transect (Oct. 2004 - May. 2006)

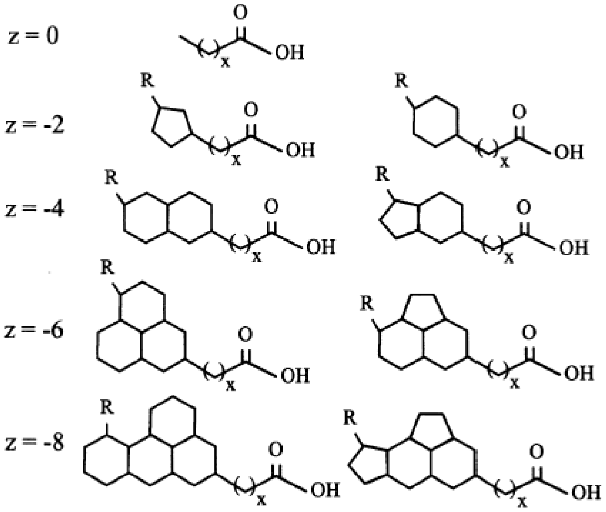


Fig. 4.8 Structure of NAs (after Rogers et al 2002)

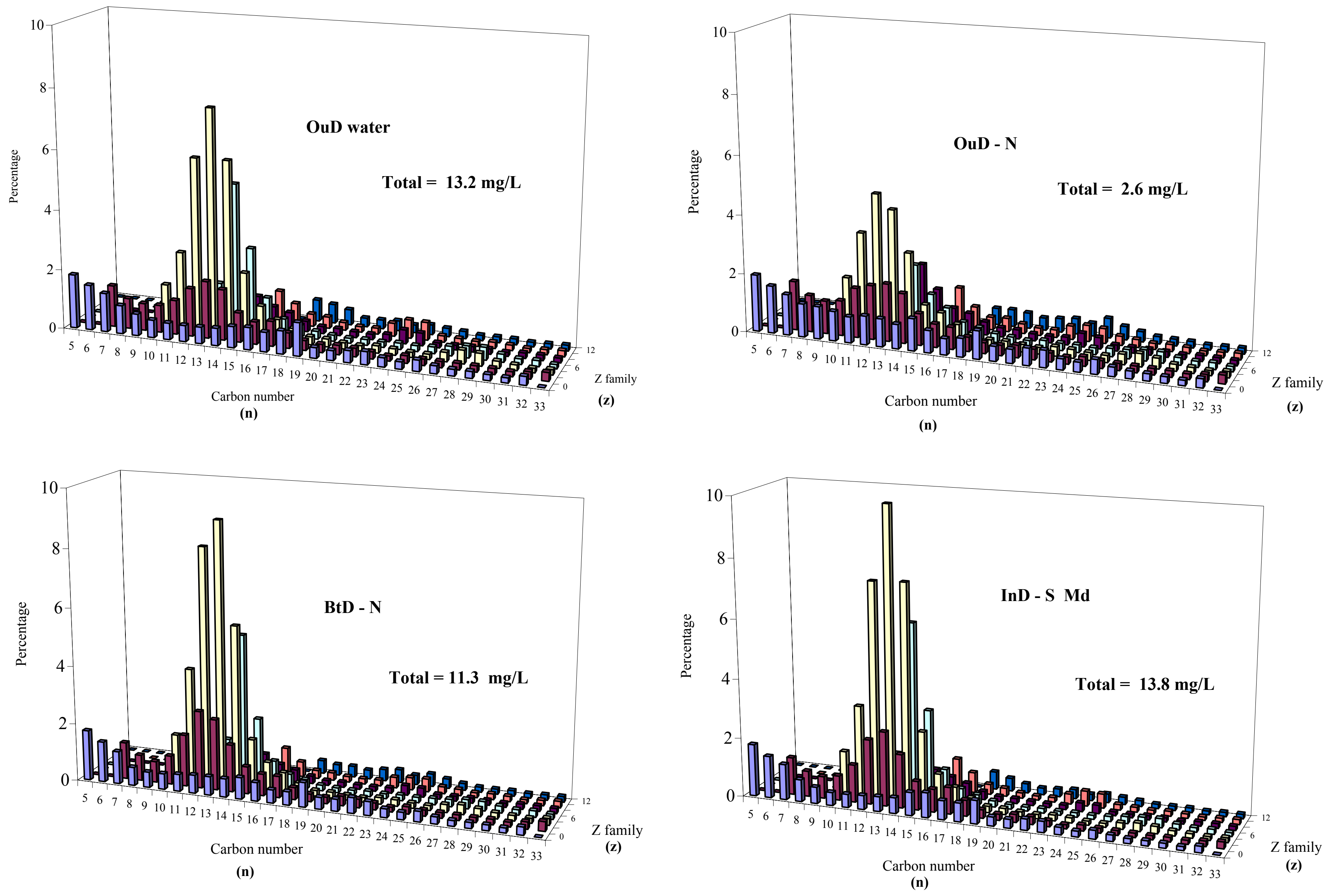


Fig. 4.9 Naphthenic Acid Characterization by "z" and "n" values (1/2)

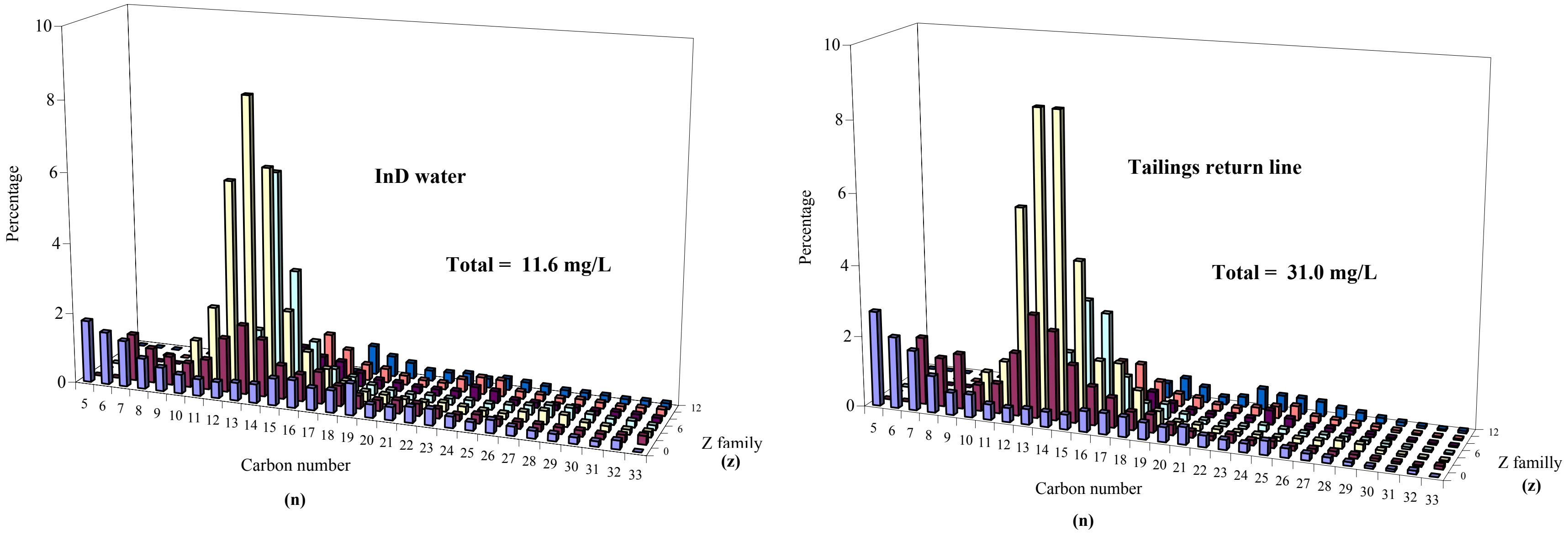


Fig. 4.9 Naphthenic Acid Characterization by "z" and "n" Values (2/2)

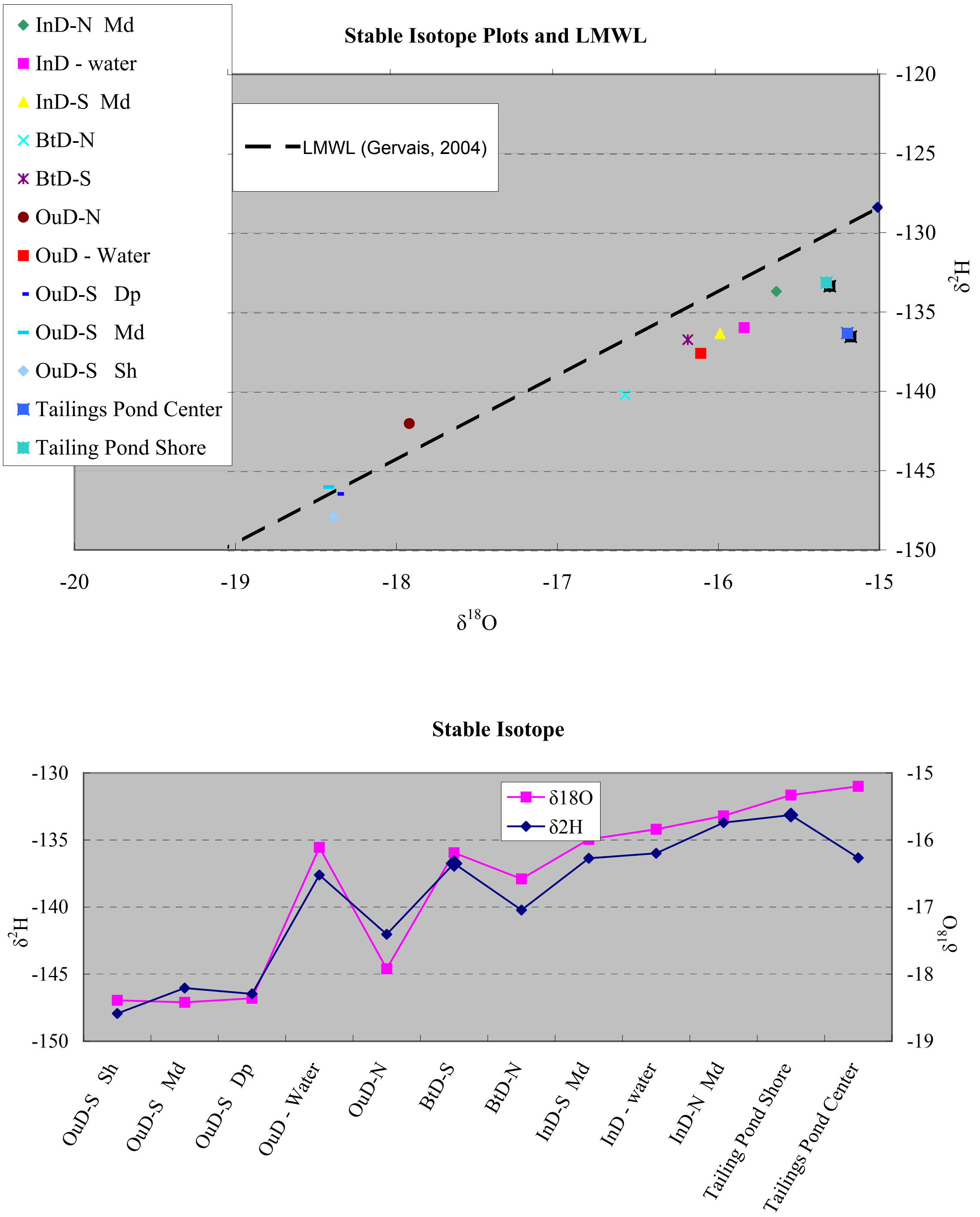
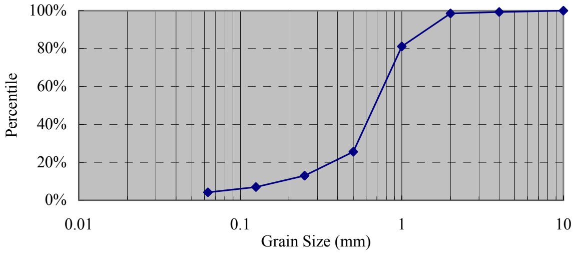


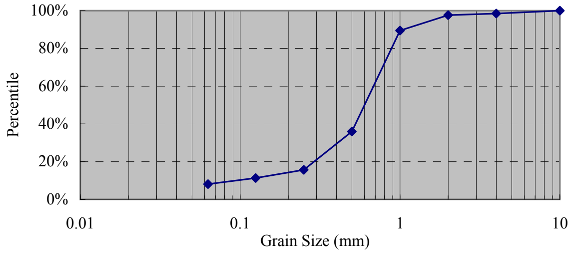
Fig. 4.10 Spatial Variation of Stable Isotopes

InD-S Auger

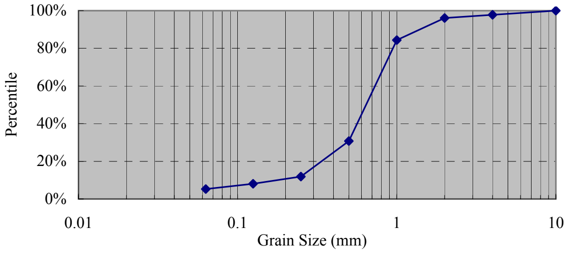
InD-S, Auger 0.5m



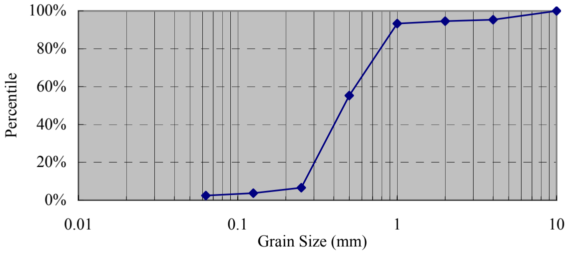
InD-S, Auger 1.4m



InD-S, Auger 2.2m

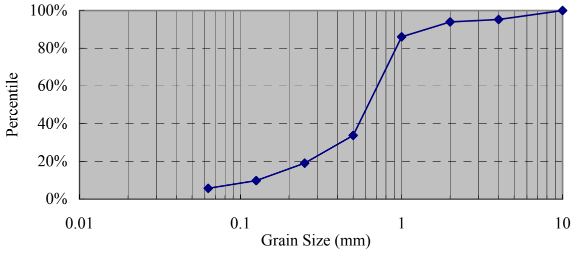


InD-S, Auger 3.0m

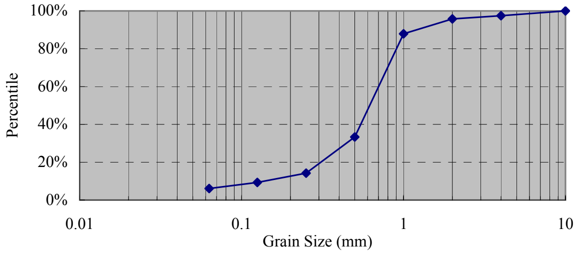


InD-S Core

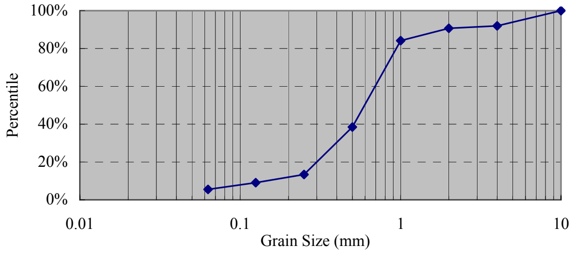
InD-S, Core 1.0m



InD-S, Core 2.0m



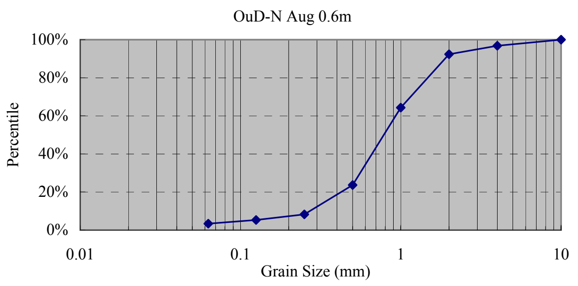
InD-S, Core 3.0m

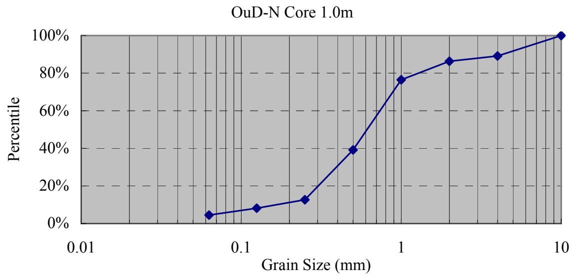


Note : the charts are arranged by borehole locations and depth

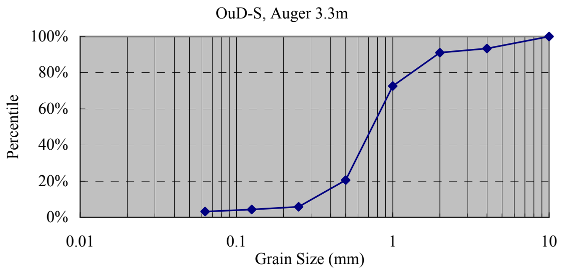
Fig. 4.11 Grain Size Distribution of Tested Samples (1/2)

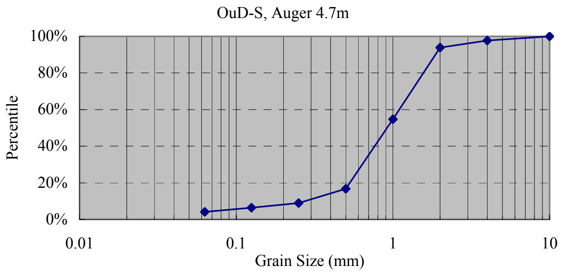
OuD-N Auger/Core

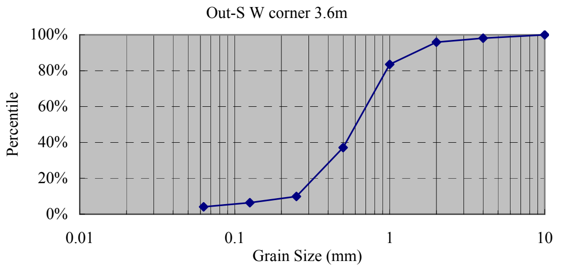

OuD-N Aug 0.6m


OuD-N Core 1.0m

OuD-S Auger


OuD-S, Auger 3.3m


OuD-S, Auger 4.7m


Out-S W corner 3.6m

Note : the charts are arranged by borehole locations and depth

Fig. 4.11 Grain Size Distribution of Tested Samples (2/2)

Table 4.1 Record of Static Water Level Measurements

	Group	ID	Static Water Level (m ASL)						Observations
			Oct-04	Jun-05	Jul-05	Oct-05	Feb-06	May-06	
1	InD-N	Dp	279.99	280.24	280.17	280.18	-	-	Demolished in winter 2006
2	InD-N	Md	279.99	280.24	280.17	280.17	-	-	Demolished in winter 2006
3	InD-N	Sh	279.97	280.21	280.15	280.15	-	-	Demolished in winter 2006
4	InD-S	Dp	279.81	280.06	279.99	279.99	-	-	Demolished in winter 2006
5	InD-S	Md	279.85	280.10	280.04	280.03	-	-	Demolished in winter 2006
6	InD-S	Sh	279.84	280.08	280.02	280.01	-	-	Demolished in winter 2006
7	InD-DVP		-	280.14	-	280.09	-	-	Ditch water level was the same as groundwater level in June-05, It was 10cm higher than groundwater level in Oct-05
8	BtD-N	new	277.27	277.41	277.41	277.42	-	277.42	
9	BtD-N	old	dry	278.59	-	278.51	-	278.56	Installed but dry in Oct-04
10	BtD-S		276.93	277.18	277.17	277.17	-	277.16	Level same as the pond water in Oct. and June 05
11	OuD-N		276.87	276.95	276.97	277.07	-	277.04	Level same as the pond water in Oct. 05
12	OuD-DVP		276.32	276.11	-	-	-	-	Ditch water level same in Oct-04, 2 cm higher in DVP than Ditch water
13	OuD-S	Dp	277.20	277.44	277.44	277.43	-	277.29	
14	OuD-S	Md	277.17	277.45	277.46	277.44	-	277.30	
15	OuD-S	Sh	277.19	277.44	277.45	277.44	-	277.29	
16	CNT-E		277.10	277.48	277.60	277.44	277.01	-	demolished in March 2006
17	CNT-W		277.45	277.43	277.44	277.20	-	-	demolished in March 2006
18	CNT-DVP		-	275.84	-	-	-	-	demolished in March 2006
19	OuD-S2C		-	-	277.45	277.44	277.23	277.32	
20	OuD-S2W		-	-	277.44	277.45	277.45	277.33	
21	CNT-E2		-	-	277.73	277.58	277.06	-	demolished in March 2006

ASL : Above Sea Level

Table 4.2 Variation of Tailings Water Chemistry

Sample ID			Oct-04	Jun-05	Jun-05	Jul-05	Feb-06	May-06	Statistics ***		
			South Shore	Center	South Shore	100 m from	*Tailings return line	**South Shore	Mean	STD	STD/Mean
Parameter	Unit	MDL									
pH	-	0.1	8.0	8.2	8.3	8.1	8	8.4	8.1	0.1	1.4%
Conductivity	uS/cm	1	959	1020	1020	1080	994	1280	1,015	39.6	3.9%
Total Dissolved Solids	mg/L	10	623	550	551	628	-	755	588	37.5	6.4%
Computed TDS		20	562	646	660	876	557	834	660	115.8	17.5%
Hardness ($CaCO_3$)	mg/L	0.5	82	70	70	84	70	72	75.1	6.3	8.4%
Alkalinity (Total as $CaCO_3$)	mg/L	1	256	251	253	309	270	362	268	21.6	8.1%
Carbonate (CO_3)	mg/L	1	< 0.5	0	0	<1	<5	7	-	-	-
Bicarbonate (HCO_3)	mg/L	1	312	307	309	377	330	427	327	26.3	8.0%
Hydroxide (OH)	mg/L	1	< 0.5	0	0	<1	<5	<1	-	-	-
Dissolved Chloride (Cl)	mg/L	1	107.0	104	104	111	118	143	109	5.3	4.8%
Nitrate (N)	mg/L	0.2	0.31	0	0	<0.2	0.1	<0.2	-	-	-
Nitrite (N)	mg/L	0.06	0	0.007	0	<0.06	<0.05	<0.06	-	-	-
Dissolved Sulphate (SO_4)	mg/L	1	67.1	69.7	69.8	68.8	66.9	83	68.5	1.2	1.8%
Dissolved Calcium (Ca)	mg/L	0.05	17	13.1	13.1	12.4	14.5	13.7	14.0	1.6	11.4%
Dissolved Iron (Fe)	mg/L	0.006	0.058	1.33	1.27	9.39	0.12	0.032	2.4	3.5	144.7%
Dissolved Magnesium (Mg)	mg/L	0.05	9.6	9.11	9.12	12.8	8.3	9.13	9.8	1.6	16.0%
Dissolved Manganese (Mn)	mg/L	0.001	0.022	0.056	0.058	0.126	0.07	<0.001	0.1	0.0	50.9%
Dissolved Potassium (K)	mg/L	0.2	19.40	15.4	15.8	26.3	14.4	14.6	18.3	4.4	23.9%
Dissolved Sodium (Na)	mg/L	0.05	188.0	184	184	201	172	274	186	9.3	5.0%
Date of Sampling	Y/M/D		2004/11/1	2005/6/18	2005/6/18	2005/7/11	2006/2/15	2006/5/30			

* This sample was analyzed by ASE (ALS laboratories)

**This sample was taken 3 weeks after the suspension of plant operation

*** Statistics calculated for the first five samples from the left

The shaded entries are those used in the graphs

Table 4.3 Grain Size Characteristics of Samples

No	Sample ID	D_{60} (mm)	Soil Type* (USCS)	C_c	C_u	Visual Description
1	InD-S, Auger 0.5m	0.810	SW	1.904	4.29	Yellow sand
2	InD-S, Auger 1.4m	0.725	SW-SM	2.499	7.21	Silty yellow sand
3	InD-S, Auger 2.2m	0.773	SW-SM	1.655	4.12	Slightly yellowish grey sand
4	InD-S, Auger 3.0m	0.562	SP	0.912	2.10	Light grey medium sand
5	InD-S, Core 1.0m	0.751	SW-SM	1.973	5.85	Yellowish poorly sorted
6	InD-S, Core 2.0m	0.745	SW-SM	1.950	5.19	Yellowish poorly sorted
7	InD-S, Core 3.0m	0.736	SW-SM	1.540	4.83	-
8	OuD-N Aug 0.6m	0.947	SP	1.265	3.39	grey sand
9	OuD-N Core 1.0m	0.779	SW-SM	1.244	4.42	grey sand, poorly sorted
10	OuD-S, Auger 3.3m	0.879	SP	1.237	2.74	Light grey medium sand
11	OuD-S, Auger 4.7m	1.135	SP	1.413	4.00	Coarse grey sand
12	OuD-S W corner 3.6m	0.746	SP	1.007	2.97	slightly silty grey sand

* see section A-1 in the Appendix for soil type

Table 4.4 Hydraulic Conductivity (K) Estimated by the Hazen Method

No	Sample ID	D_{10}	K (cm/s)
1	InD-S, Auger 0.5m	0.189	4.1×10^{-02}
2	InD-S, Auger 1.4m	0.100	1.2×10^{-02}
3	InD-S, Auger 2.2m	0.188	4.0×10^{-02}
4	InD-S, Auger 3.0m	0.267	8.2×10^{-02}
5	InD-S, Core 1.0m	0.128	1.9×10^{-02}
6	InD-S, Core 2.0m	0.144	2.4×10^{-02}
7	InD-S, Core 3.0m	0.152	2.7×10^{-02}
8	OuD-N Aug 0.6m	0.279	8.9×10^{-02}
9	OuD-N Core 1.0m	0.176	3.6×10^{-02}
10	OuD-S, Auger 3.3m	0.321	1.18×10^{-01}
11	OuD-S, Auger 4.7m	0.284	9.2×10^{-02}
12	OuD-S2W corner 3.6m	0.251	7.2×10^{-02}
	Mean (geometric)	0.207	4.3×10^{-02}

Table 4.5 Summary of Permeameter Tests

Sample		Soil type* (USCS)	Hydraulic conductivity (K) (cm/s)	Remarks
1	InD-S, Auger 0.5m	SW	8.5×10^{-03}	
2	InD-S, Auger 1.4m	SW-SM	1.1×10^{-02}	
3	InD-S, Auger 2.2m	SW-SM	5.2×10^{-02}	
4	InD-S, Auger 3.0m	SP	1.4×10^{-02}	Sieved sample**
5	InD-S, Core 1.0m	SW-SM	2.0×10^{-03}	
6	InD-S, Core 2.0m	SW-SM	4.9×10^{-02}	
7	InD-S, Core 3.0m	SW-SM	2.4×10^{-02}	
8	OuD-N Auger 0.6m	SP	8.9×10^{-02}	
9	OuD-N Core 1.0m	SW-SM	4.3×10^{-02}	
10	OuD-S, Auger 3.3m	SP	1.9×10^{-02}	Sieved sample**
11	OuD-S, Auger 4.7m	SP	3.2×10^{-02}	
12	OuD-S W corner 3.6m	SP	2.4×10^{-02}	
13	OuD-S, Peat	N/A	8.5×10^{-04}	

* see section A-1 in the Appendix for soil type

** sample tested after sieving

5. Modeling

5.1. Background and Purpose

To provide some insight into the groundwater flow system in the Study Area, groundwater flow and advective transport modeling was performed. The objective of this modeling effort was to estimate potential seepage paths, and the degree of mass input of PAW to the pf-sand aquifer and to the collection ditches.

Two spatial scales were explored: 1) a 2-D conceptual model of a typical cross-section of the tailings pond dyke, and 2) a 2-D conceptual model of the potential flow pathways downgradient of the dyke (see **Fig. 5.1**). MODFLOW 2000 (USGS, 2000) and MODPATH (USGS, 1994) were used as the numerical modelling engines, along with Visual MODFLOW (Waterloo Hydrogeologic Inc., 2002) as the pre/post processing platform. The hydraulic conductivity data obtained through the laboratory tests and from ASE was used as initial model parameters along with observed hydraulic heads and discharge rates from the outtake drain-pipes. Scenario and sensitivity analyses were conducted to investigate a broad range of issues including the effectiveness of the collection ditch systems.

These flow models were used to provide a first approximation of the flow system and thus were not intended to provide a detailed representation of the system consistent with the limited field information available. The compartmental approach consisting of four independent models used here to model the Study Area was employed for simplicity and considered appropriate to model areas of significantly different spatial scale and high aspect ratio. We acknowledge that some inconsistencies will arise and these may lead to a degradation in modeling accuracy, especially in characterizing the flow across the boundaries of adjacent compartmental models.

5.2. Conceptual Model

(1) Dyke seepage model

A 2-D steady state model of a vertical cross-section of the dyke was created based on the information obtained during the field surveys. The model is designed to represent the dyke as of late October 2004. Due to the uncertainty in geology under the starter dyke and the tailings pond, the following two scenarios were investigated.

- Scenario 1: with pf-sand under the dyke and the tailings pond

- Scenario 2: without pf-sand under the dyke and the tailings pond

Scenario 1 and 2 represent the dyke with and without a permeable pf-sand aquifer under the starter dyke and the tailings pond to conduct seepage respectively. The results from these simulations were used to:

1). Evaluate the likelihood of each case (Scenario 1 or 2),
2). Evaluate the flow rate into the pf-sand at the toe berm and,
3). Identify characteristics of the PAW pathway for the scenario judged more likely in item 1.

(2) Downgradient models

The downgradient region of the Study Area was also modeled. As illustrated in **Fig 5.1**, the model region was divided into the following 3 independent spatial domains due to their contrasting cross-sectional geometries:

Inner Ditch Model (INDM) : 2D steady state model for the Inner Ditch
Inter Ditch Model (INTDM) : 2D steady state model for the section between the ditches
Outer Ditch Model (OUDM) : 2D steady state model for the Outer Ditch

INDM : 2D model across Inner Ditch

This model simulates a typical vertical cross-section of the Inner Ditch in order to evaluate:
1) the seepage rate through the bottom of the ditch (pf-sand), and
2) groundwater flux across the ditch.

INTDM: 2D model of quasi horizontal flow

This model simulates the 300 m-long vertical cross-section of the area between the two ditches from the downgradient edge of the Inner Ditch to the upgradient edge of the Outer Ditch. Due to its high aspect ratio, the model is regarded as quasi-one dimensional. The results from this model are used to evaluate the horizontal flow rate and also the amount of groundwater seepage (discharge) into the surface water in the Wet Area.

OUDM: 2D model across Outer Ditch

The model simulates a typical vertical cross-section of the Outer Ditch and the remaining downgradient section across the haul road. The results are used to confirm the reverse hydraulic gradient across the ditch inferred from the water level measurements, and to evaluate changes in flow rate across the ditch due to the recorded water level fluctuation.

The outcome of this piece-wise modeling of downgradient region is eventually combined to evaluate the entire seepage pathway. The upgradient input of a model is matched to the downgradient output of the model immediately upgradient of it.

The following factors limit the model accuracy, which has to be taken into account when interpreting these modeling results:

- Physical properties of geologic materials and dyke materials were only estimated through a limited number of laboratory experiments and the typical values reported by ASE. At the field scale, materials such as tailings sand at the bottom of the pond is considered to show very high anisotropy and heterogeneity due to intercalated thin layers of bitumen (as reported by Hunter 2001).
- Due to the absence of official as-built cross sectional drawings of the dyke and official topographic survey data across the ditches, the model cross-sections were prepared based on planned cross-sectional drawings for the dyke and a simple survey conducted by the author using minimum equipment with surveyed piezometers as references. The resultant cross-sectional profiles in **Fig. 2.5**, therefore, do not have the same level of accuracy as that of an ordinary surveyed topographic drawings.

5.3. Model Design

5.3.1 Dyke Seepage Models

(1) Model structure

The spatial extent and grid structure of the models are listed in **Table 5.1** along with some key information on the model structure. Grid spacing was designed sufficiently small in zones of high hydraulic gradients to capture abrupt changes in flow. The drain system at 300 m was not included in this model because this is designed to drain the future extension of the dyke and will not affect this model. One meter thick cross-section of the dyke was modeled.

(2) Assignment of hydraulic conductivity values for materials

The hydraulic conductivity values of geologic and dyke materials for initial model simulations were based on the results of laboratory experiments (for pf-sand and peat) and also on the information obtained from ASE (for the other materials) and are summarized in **Table 5.2**. The details on the estimation method are given in **Table A 5.1** in the Appendix. The hydraulic conductivity zone distribution for the models is shown in **Fig. 5.2**.

(3) Boundary conditions

The boundary zones and conditions of the models are summarized in **Table 5.3** and shown on **Fig. 5.3**. The values for each boundary condition are either those measured in the field or those provided by ASE. Since the model only simulates a typical downgradient section of the tailings pond, an upgradient constant head boundary (Upgradient 2) was assigned along the model right edge to allow for the contribution of the tailings pond that exists further upgradient.

5.3.2 Downgradient Models

(1) Model structure

The same consideration as in the dyke seepage model was taken for the grid spacing and hydraulic conductivity value selections for these models. The grid spacing is smaller in INDM and OUDM models than in the dyke seepage model due to scale difference. One meter thick cross-sections were modeled. **Table 5.4** and **Fig. 5.4** show the outline of these downgradient models. For INTDM, the mound of the McMurray formation observed at BtD-N (old) was omitted because it is considered to be a local feature and does not represent the typical cross-section of the model region.

(2) Assignment of hydraulic conductivity values for Materials

The downgradient models mainly involve pf-sand with oil sand of the McMurray formation to a minor extent. A thin layer of fine deposit (as tailings sand) on the bottom of the Inner Ditch was also assigned. For the Outer Ditch, a 0.3 m thick lean oil sand lining was assigned along the entire wetted-perimeter of the ditch. The same hydraulic conductivity values as listed in **Table 5.2** are used, and their spatial distribution is shown in **Fig. 5.4**.

(3) Boundary conditions

Since no meaningful vertical gradient was observed at any piezometers, a constant head was assigned to both the upgradient and downgradient edges of each model (Model Left/Right Edge). The observed hydraulic head values at the piezometers were used. No recharge from precipitation was considered in these models because precipitation seems to have little effect on groundwater as discussed in Section 4.1.2. In order to simulate the groundwater seepage in the Wet Area, a seepage face was assigned for this area with an assumption that the seepage water was quickly removed by flowing off this area into the

Outer Ditch. Also a constant head was assigned for the Inner Ditch to test the effect of surface water. For this simulation a thin layer of fine deposit on the bottom of the Inner Ditch was assumed to be present as part of input for its boundary condition.

Since there is seasonal variation in observed boundary heads, the largest heads observed in June 2005 and smallest in October 2004 (see **Table 4.1**) were used to represent the two different conditions of high groundwater table (HGT) and low groundwater table (LGT) respectively. The boundary conditions of the models are summarized in **Table 5.5** and their zone assignment is illustrated in **Fig. 5.5**.

5.4. Calibration and Sensitivity Analysis

5.4.1 Model Calibration

(1) Dyke seepage model calibration

The two models for Scenario 1 and 2 were manually calibrated to the average measured discharge of 0.35 m^3/day/m from the 3 outtake drain-pipes (see Section 4.1.1). The calibration was performed by perturbing the hydraulic conductivity value of the tailings dyke because this is the dominant material in the dyke body through which seepage water moves and also it carries the highest uncertainty due to possible complex stratification. The following conditions were satisfied for each simulation:

- The change in the hydraulic conductivity values of the other materials was kept at a minimum
- No seepage occurs on the dyke seepage face (outflow from the seepage face is approximately zero).
- The change in anisotropy of the tailings dyke is kept at a minimum and within the range specified in **Table A 5.1**.
- The hydraulic conductivities of the dyke and geologic materials remain within a reasonable range if they had to be changed. This range was arbitrary set to be within a single order of magnitude from the initial values (given in **Table 5.2**) for calibration.

(2) Downgradient model calibration

Simulations were performed for the two different hydraulic conditions of HGT and LGT as discussed in Section 5.3.2. Since the models are considered simple quasi-one dimensional, the observed heads in piezometers located between the downgradient and upgradient model edges were used as model inputs for simplicity. The models were only calibrated to the inflow rate from the model immediately upgradient to assure continuity. Calibration was performed by changing the hydraulic conductivity of pf-sand up to a half order of magnitude.

(3) Calibration results

Dyke seepage model

The two models (Scenario 1 and 2) were calibrated by adjusting only the hydraulic conductivity value of the tailings sand within a reasonable range. The results are presented as an equipotential map of the model region that also shows pathlines of particles and flow velocity vectors (see **Fig. 5.6**). The results are also summarized in **Table 5.6**.

The outflow from the internal drain system was calibrated to the measured value of 0.35 m^3/day/m. The outflows from the other boundaries are also listed in **Table 5.6**. Although each model (scenario) was calibrated with a reasonable value of K for the tailings sand, the resultant flow systems are contrasting. With a conductive pf-sand layer, Scenario-1 has a high outflow rate of 4.39 m^3/day/m from the model left edge (downgradient 1 boundary) while Scenario-2 has a negligible outflow rate of 0.0029 m^3/day/m.

Downgradient models (HGT)

The three downgradient models were calibrated for observed highest head condition of June 2005 (HGT), and the results are summarized in **Table 5.7** and in **Figs. 5.7 – 5.9**.

The outcome of the INDM indicates that water exchange occurs through the ditch bottom: groundwater seeps out of the upgradient side and ditch water seeps into the groundwater through the downgradient side (see **Fig. 5.7**). The resultant outflow from the model left edge is 0.24 m^3/day/m. The inflow from the model right edge is 0.36 m^3/day/m. The modeled condition is considered to be an extreme case of dynamic equilibrium between the ditch water and groundwater. Actual exchange of water between the ditch and groundwater may be less due to complexity of the bottom properties.

The results of INTDM indicate that the flow in the pf-sand is horizontal and the hydraulic gradient is uniform down to BtD-N. Most water discharges to the Wet Area between piezometers BtD-N and BtD-S, resulting in a extremely small flow component of nearly zero around OuD-N. The resultant seepage rate into the Wet Area is 0.24 m^3/day/m.

The OUDM model recreated the anticipated reverse flow towards the Outer Ditch. A smaller hydraulic conductivity had to be assigned along its upgradient edge (Model Right Edge) to adjust the outflow to be 0.002 m^3/day/m in consideration of continuity with INTDM model. As a result, most groundwater from the south side of the ditch seeps out at the edge of the Outer Ditch (see **Fig. 5.9**). This discharge, however, is expected to occur somewhere a little further upstream between OuD-N and BtD-S because of the excess head near the model right boundary. This condition would be better captured with a continuous model rather than the compartmental approach used here. The seepage rate around OuD-N is 0.34 m^3/day/m. The seepage through the wetted-perimeter of the Outer Ditch was simulated in a separate trial and it revealed that the seepage rate into the dry ditch through the lining is as small as 0.07 m^3/day/m. Considering the fact that the ditch water is usually nearly bankful and has a high hydraulic head, the seepage into the ditch is regarded as negligible.

Downgradient models (LGT)

The lowest head condition of October 2004 (LGT) was also simulated. The results are summarized in **Table 5.8** and in **Figs. 5.7 -5.9**.

Since the water level at InD-DVP is not available for the INDM model, the stage of the water in the Inner Ditch and the head in InD-DVP were assumed to be 279.91 m by linear interpolation from the heads on both sides of the ditch. The result indicates that the groundwater seeps out of the upgradient side of the bottom of the ditch and ditch water seeps in through the other half of the bottom the same way as in the HGT simulations. The resultant outflow from the model left edge is 0.29 m^3/day/m, and inflow from the model right edge is 0.26 m^3/day/m. The model simulated less inflow and more outflow with increased seepage into the ditch compared with HGT case. Again this modeled condition is considered an extreme case of dynamic equilibrium between the ditch water and groundwater.

The outcome of INTDM is similar to that for the HGT simulations. The flow in the pf-sand is uniform and horizontal with a slightly smaller hydraulic gradient up to BtD-N. Most water discharges into the Wet Area between piezometers BtD-N and BtD-S, resulting in a extremely small flow rate of nearly zero around OuD-N. The resultant seepage rate into the Wet Area is 0.30 m^3/day/m.

OUDM model was calibrated the same way as for the HGT simulations. Both inflow and seepage are smaller than those for HGT condition with a seepage and inflow both being 0.14 m^3/day/m. This suggests that all the inflow into the model region discharges around OuD-N.

5.4.2 Sensitivity Analyses

(1) Dyke seepage model

A sensitivity analysis was conducted for the two calibrated dyke seepage models (Scenario 1 and 2) to examine the effect of uncertainty in:

- Hydraulic conductivity of the dyke and geologic materials,
- Upgradient and downgradient boundary conditions

on the flow rate from each of the four model boundaries; especially for the internal drain and model left edge.

The analysis was conducted using each calibrated model as the base case with hydraulic conductivity values for the materials listed in **Table 5.2** and boundary conditions as previously described. Each of the six hydraulic conductivity values and two boundary conditions was reduced or increased one at a time up to a several orders of magnitude depending on the response.

For the model parameters that were found important through this analysis, additional analyses were performed to investigate the effect of anisotropy.

(2) Downgradient models

Since the INDM is essentially one-dimensional and the groundwater flow moves nearly horizontally through the pf-sand layer, the outflow responses to changes in heads and pf-sand hydraulic conductivity are directly proportional to these values. The major uncertainty lies in the stage of water in the Inner Ditch and in the hydraulic conductivity of the bottom sediment in the ditch.

The INDM model for the LGT condition was used to investigate the effect of changing stage of ditch water and hydraulic conductivity of the bottom sediments. In October 2005, the stage of the ditch water was found to be 0.1 m higher than the groundwater level in InD-DVP, and a thin layer of fine sediment was observed on the bottom of the ditch. A preliminary simulation with the higher head in the ditch produced a reverse flow towards InD-N, which would not occur due to the higher head upgradient of InD-N in the dyke seepage model. Thus, a higher head of 280.49 m calculated for the tip of the dyke slope (10 m upgradient of InD-N) from the dyke seepage model was used as a general head boundary along the model right edge so that the model would not produce this reverse flow condition.

(3) Sensitivity analyses results

Dyke seepage model

The results were shown on scatter diagrams in **Fig. 5.10** with the flow from the model boundaries on y-axis and the perturbed parameter on x-axis. The results are also presented in a table format in **Table A 5.2** in the Appendix.

In order to examine the sensitivity in the vicinity of the initial value (the values for the base case), $\Delta Q/\Delta K$ and $\Delta Q/\Delta h$ were calculated for a change in 10% of initial hydraulic conductivity (K) and 0.1% of boundary hydraulic head (h) for both increasing (+) and decreasing (-) directions. The results are given in **Table 5.9**.

Overall, the following three parameters are considered to have the most impact on the flow rate from the internal drain and the model left edge in the following order:

1. pf-sand K value (not applicable for Scenario 2)
2. topsoil (peat layer) K value
3. tailings dyke K value

In both Scenario 1 and 2, the internal drain cell K value and downgradient boundary head value have little effect on any of the flow rates of concern.

A detailed sensitivity analysis was conducted for Scenario 1 on these three sensitive model parameters. The anisotropy ratio (K_z/K_{xy}) was perturbed in increasing and decreasing directions from the base anisotropy value for the calibrated model (K_{xy} was fixed at the base value and K_z was changed). The results are presented in **Fig. 5.11** and show that anisotropy has a negligible effect on flow rates of concern.

Downgradient models

The results of the sensitivity analysis for the INDM model are given in **Fig. 5.12** and **Table A 5.3**. The results show that the stage of the ditch water has some impact on the outflow and inflow of the model while it has much smaller effect on the net seepage rate through the bottom of the ditch. On the contrary, the hydraulic conductivity of the bottom sediment has little effect on the outflow and inflow rates and a large impact on the net seepage rate. Note that the seepage under "Ditch Bottom" is a sum of flow rates into and out of the model. As described earlier, the ratio is variable depending on the flow system. It can be seen that for a higher stage, more water seeps into the model domain and the smaller K_z value of the bottom sediment, less water seeps into the model domain (see **Table A 5.3**).

5.5. Interpretation and Discussion

The results of the model calibration for both Scenario 1 and 2 indicate that both scenarios are possible as an independent case; however the two models have contrasting flow systems. The outflow from the Scenario 2 is negligible while it is as large as 4.39 m^3/day/m for Scenario 1 (see **Table 5.6**).

Viability of each case, therefore, was further confirmed from the perspective of continuity requirement with the INDM model. Preliminary simulations with a linear INDM model for the HGT and LGT conditions indicated that the groundwater outflow for a given combination of observed heads is around 0.27 m^3/day/m on average. This value falls somewhere between the two outflow rates of 4.39 and 0.028 m^3/day/m calculated from Scenario 1 and Scenario 2 respectively. This suggests that the modeled geologic structure underneath the dyke does not adequately capture observed conditions and changes to model structures or equivalent hydraulic conductivity are required to generate an outflow of 0.27 m^3/day/m. The results of the sensitivity analysis suggest that this condition can only be achieved by changing the property of pf-sand for both scenarios. Assuming that the downgradient outflow of 0.27 m^3/day/m is representative, the dyke seepage model was re-calibrated using both the outflow from the model left edge of 0.27 m^3/day/m and the outflow from the internal drain of 0.35 m^3/day/m as calibration targets. Calibration was achieved by reducing the thickness of pf-sand layer in the calibrated Scenario 1 model to ~ 0.1 m. Details of this calibration effort and results are given in **Fig. A 5.1**. This result indicates that a very thin layer of pf-sand is likely to exist underneath the dyke as a conduit for seepage water.

The findings from the INDM sensitivity analysis suggest that interaction between the ditch and groundwater is possible with a raised stage in the ditch and it is also highly dynamic. However, this model could not be calibrated to the hydraulic head at InD-N. The observed hydraulic head at InD-N for the LGT (October 2005) conditions was 279.98 m while the head in the model was about 280.30 m. This is a significant difference for a model of this scale. As discussed in more detail in Chapter 6, such situations probably occur during transient conditions.

The suspected reverse flow (south to north) across the Outer Ditch was recreated in the OUDM model. The outflow as seepage discharge around OuD-N was calculated to range from 0.14 to 0.34 m^3/day/m. This is combined with the seepage of 0.24 to 0.30 m^3/day/m from INTDM model to give a total seepage discharge into the Wet Area of 0.44 and 0.58 m^3/day/m for low and high head conditions (LGT and HGT conditions) respectively (see **Table 5.7 and 5.8**).

It has to be noted that the models explored here only captured one possible steady-state condition and therefore are limited in reflecting transient behavior of this hydraulic system. For example, the observed water stage in the ditch and in the Wet Area is highly transient. Also the freezing ground surface during mid-winter is expected to prevent groundwater seepage into the Wet Area. Nevertheless the models provide a reasonable indication of the general groundwater flow regime in the Study Area.

5.6. Summary

The following provides the summary of the findings that have been discussed in this chapter:

1). this modeling effort supports the potential for a seepage path underneath the tailings dyke.

2). the flow rate of groundwater from the dyke to the pf-sand for the two scenarios ranges from 0.028 to 4.39 m^3/day/m of dyke length. However, based on continuity consideration, the actual outflow may be about 0.3 m^3/day/m.

3). Water exchange occurs through the bottom of the Inner Ditch and the maximum inflow rate into the model ranges from 0.11 to 0.16 m^3/day/m. The out-flux through the pf-sand under the ditch is about 0.27 m^3/day/m.

4). The flow under the Outer Ditch is a reverse flow towards the Wet Area and the flow rate ranges from 0.14 to 0.34 m^3/day/m.

5). The total groundwater discharge into the Wet Area is calculated to be about 0.5 m^3/day/m.

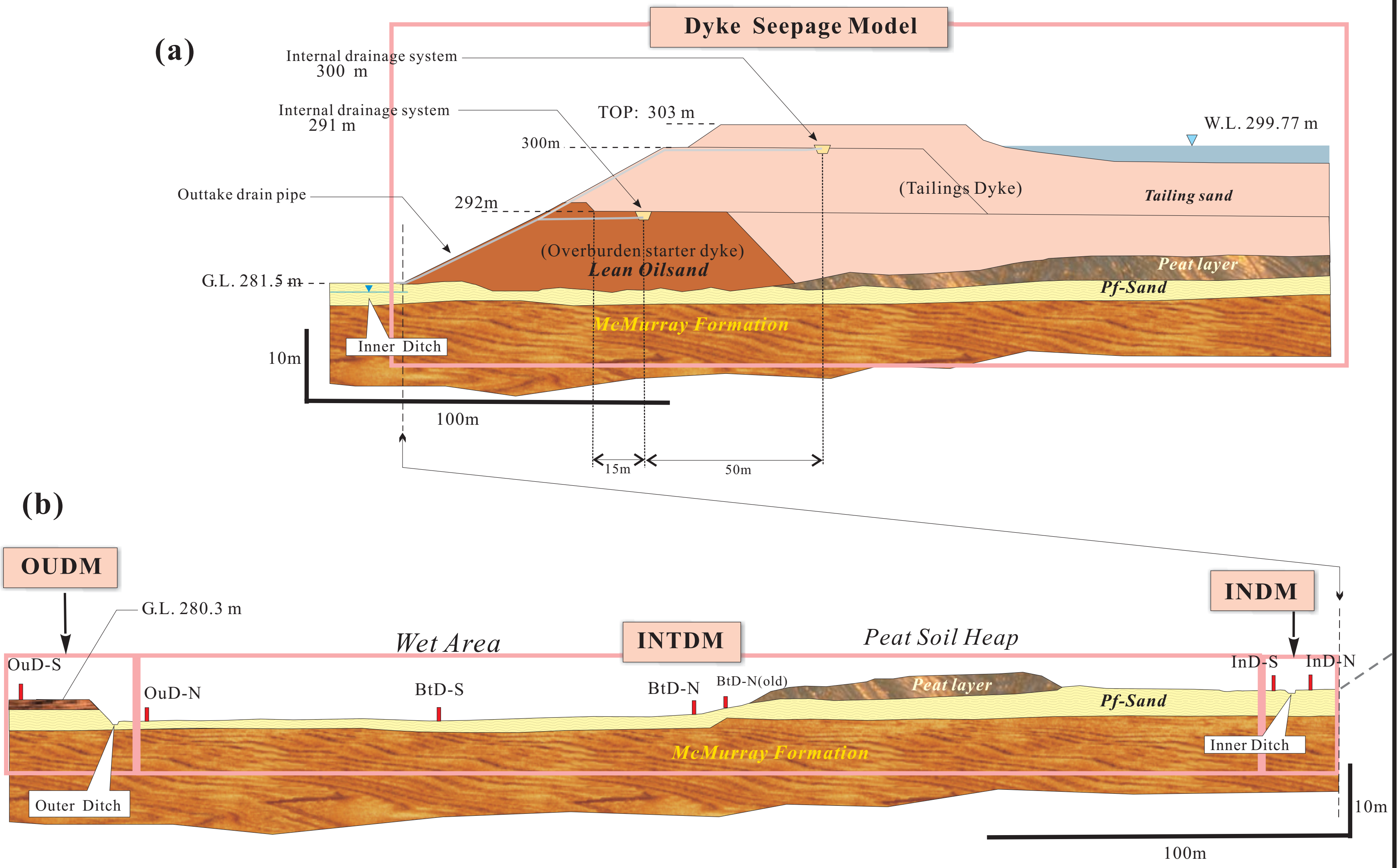


Fig. 5.1 Schematic Cross-Section of (a) Dyke Seepage Model and (b) Three Downgradient Models

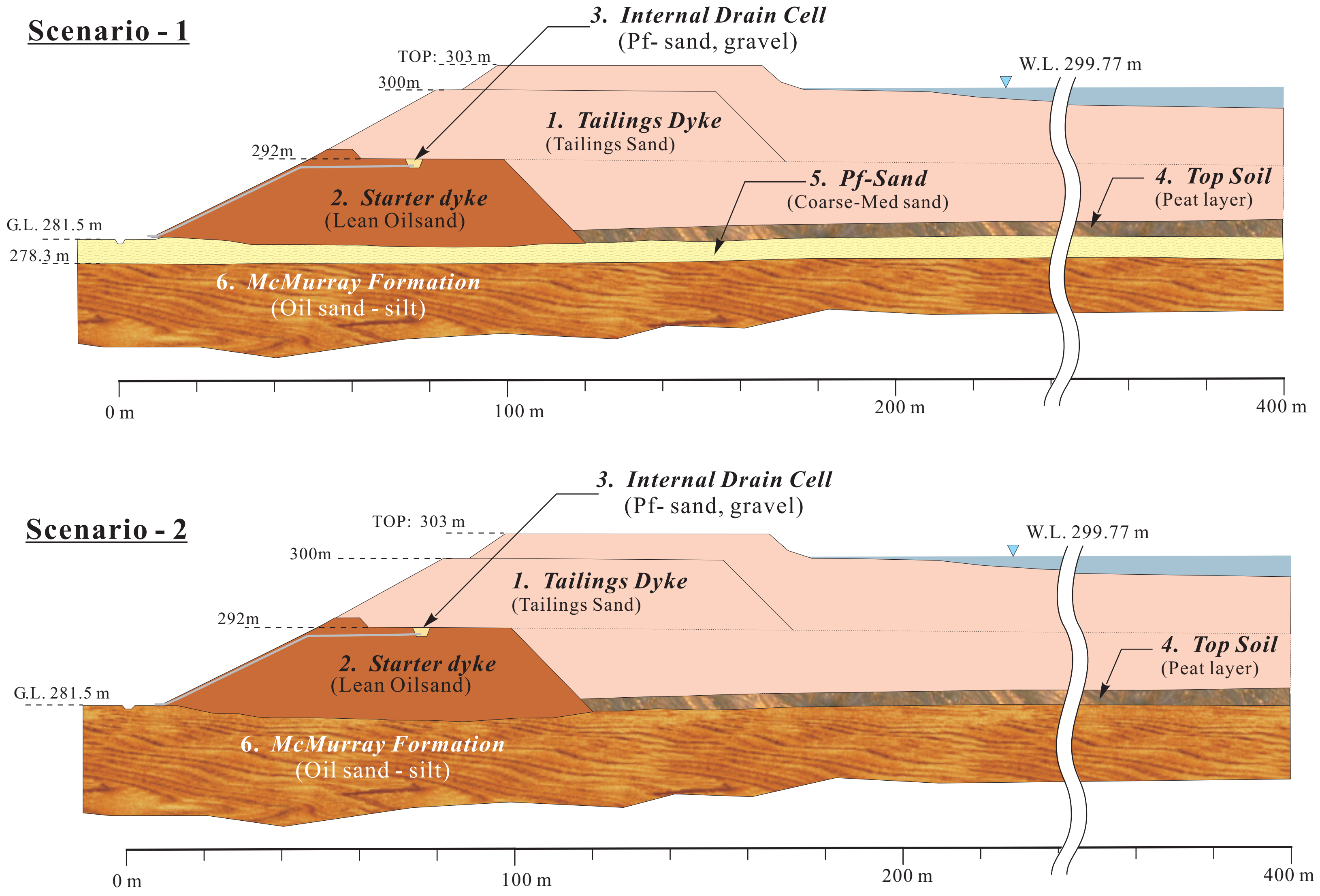
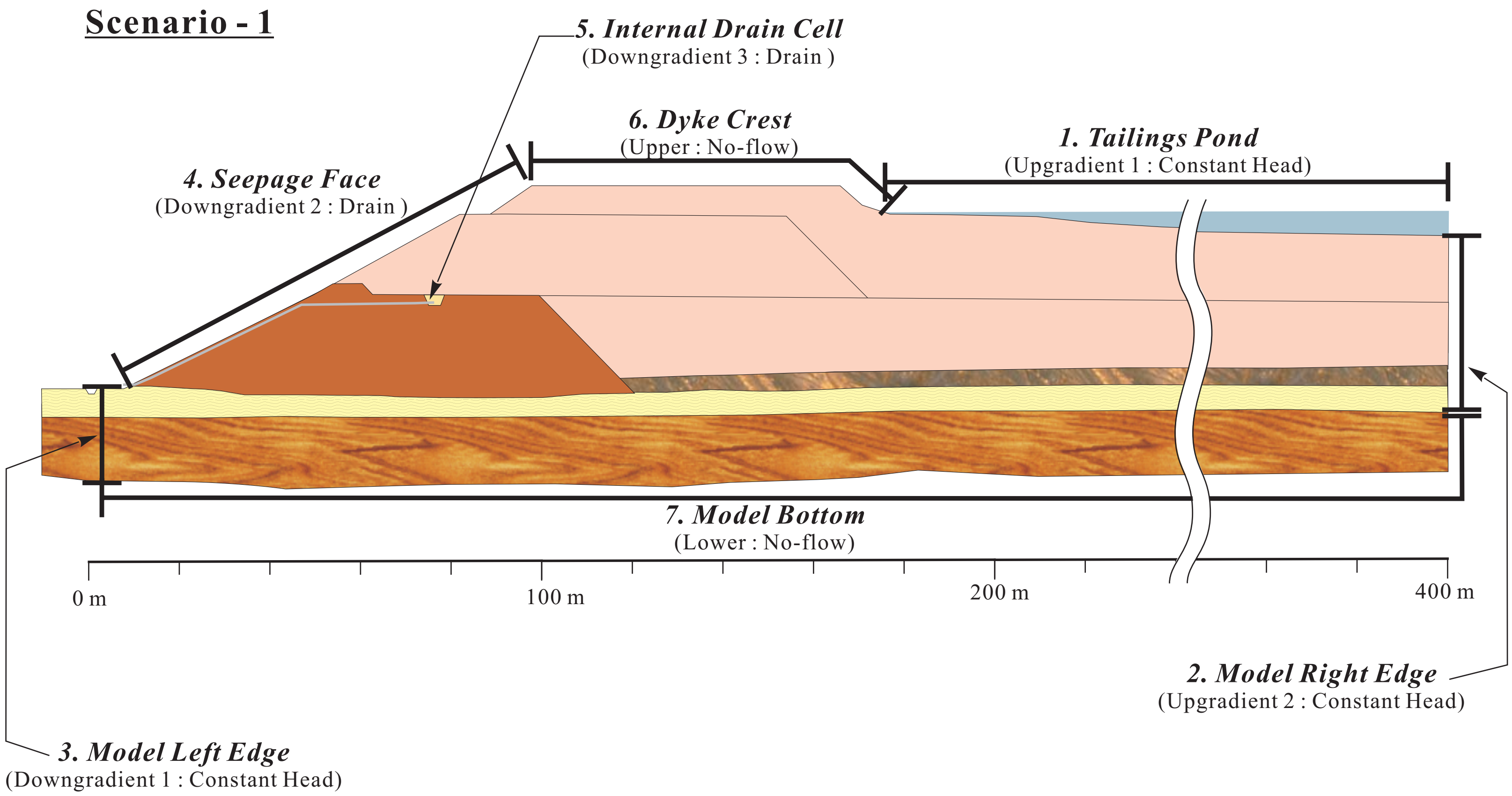


Fig. 5.2 Hydraulic Conductivity Zone Distribution for Dyke Seepage Model



Boundary zone assignment is the same for Scenario - 2

Fig. 5.3 Boundary Zone Assignment for Dyke Seepage Model

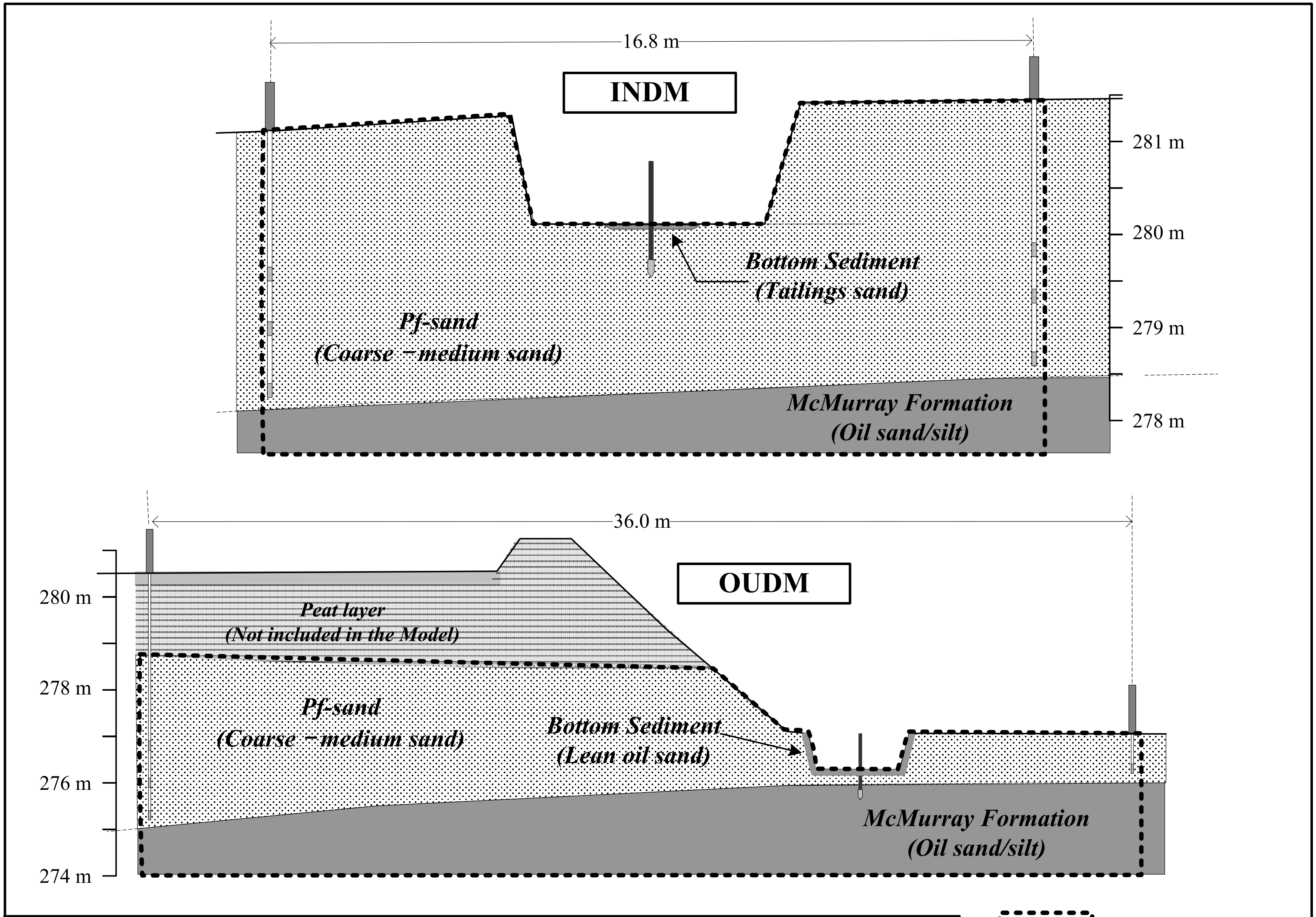


Fig. 5.4-(a) Hydraulic Conductivity Zone Assignment for the INDM and OUDM

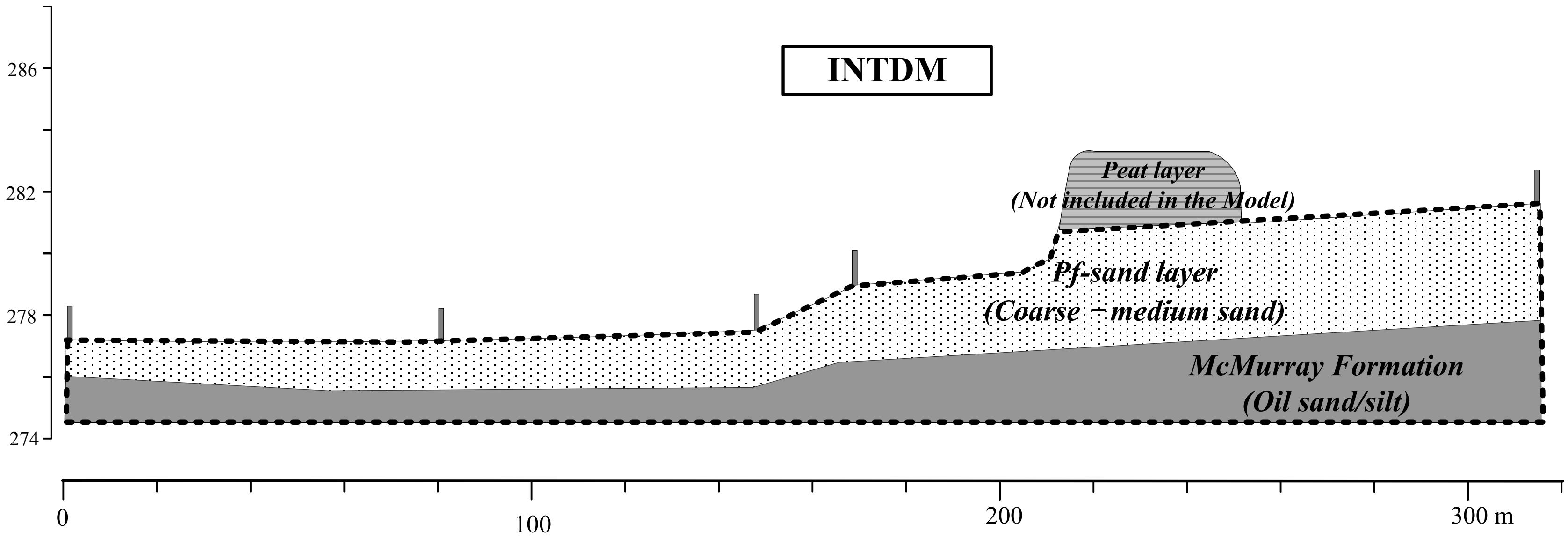


Fig. 5.4-(b) Hydraulic Conductivity Zone Assignment for the INTDM

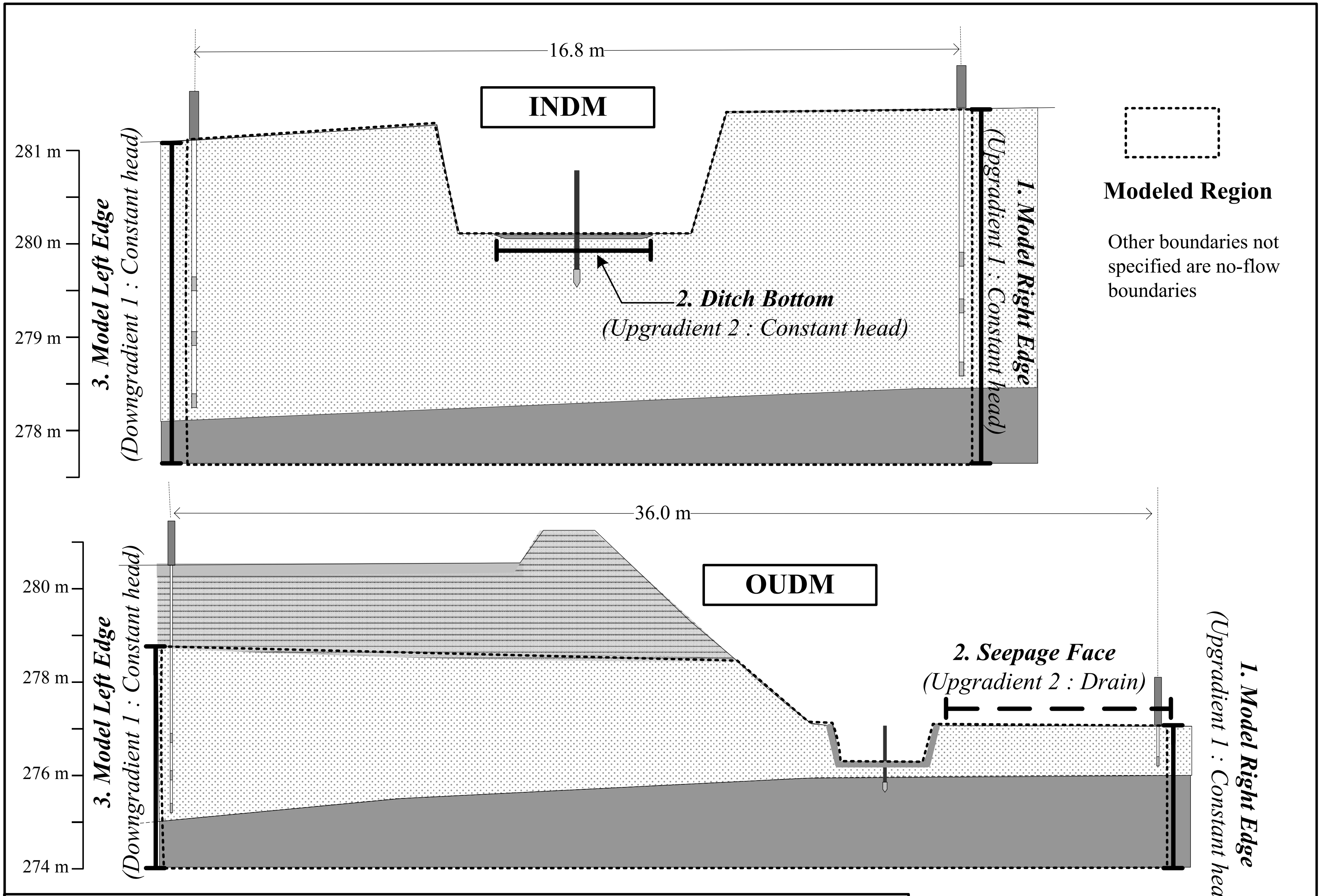
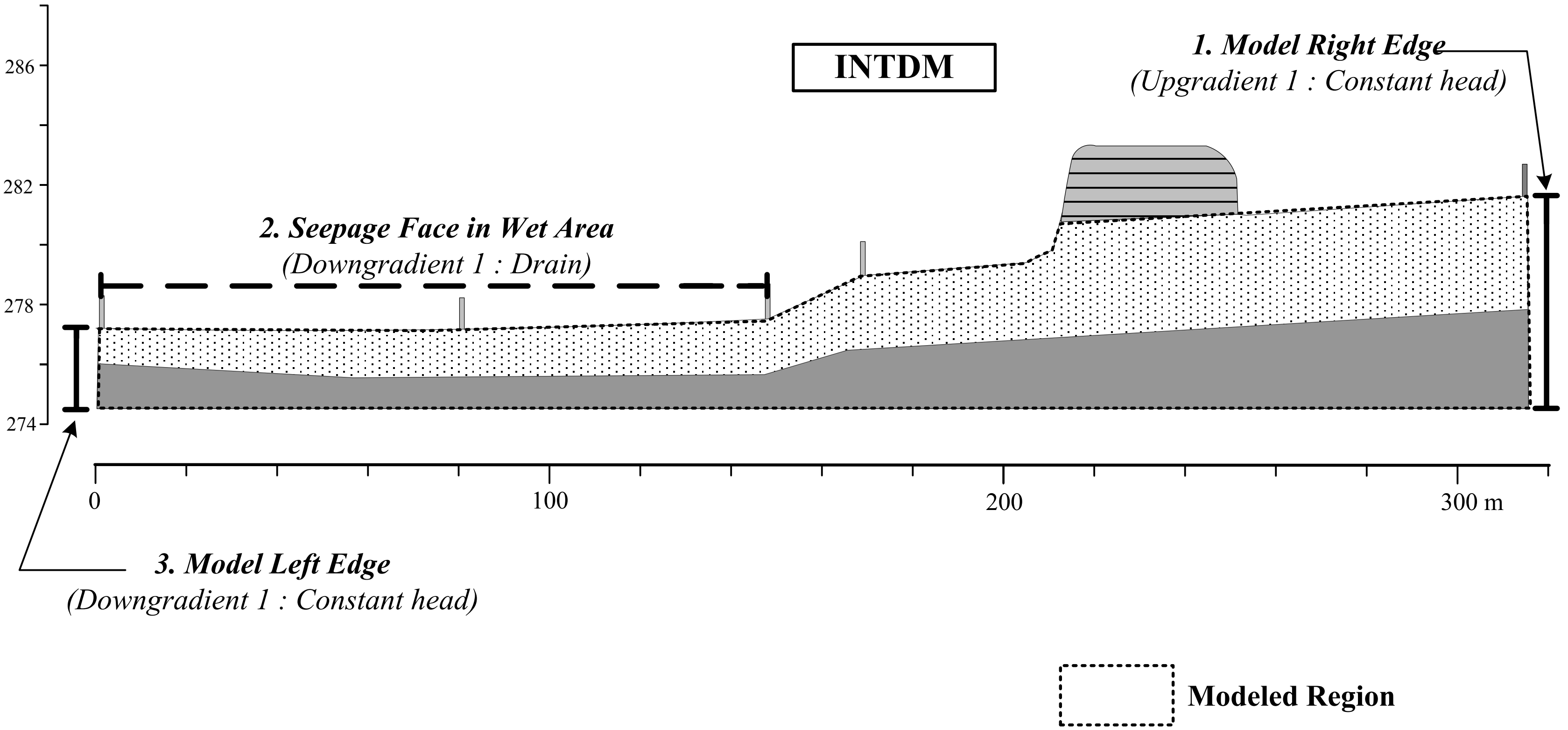
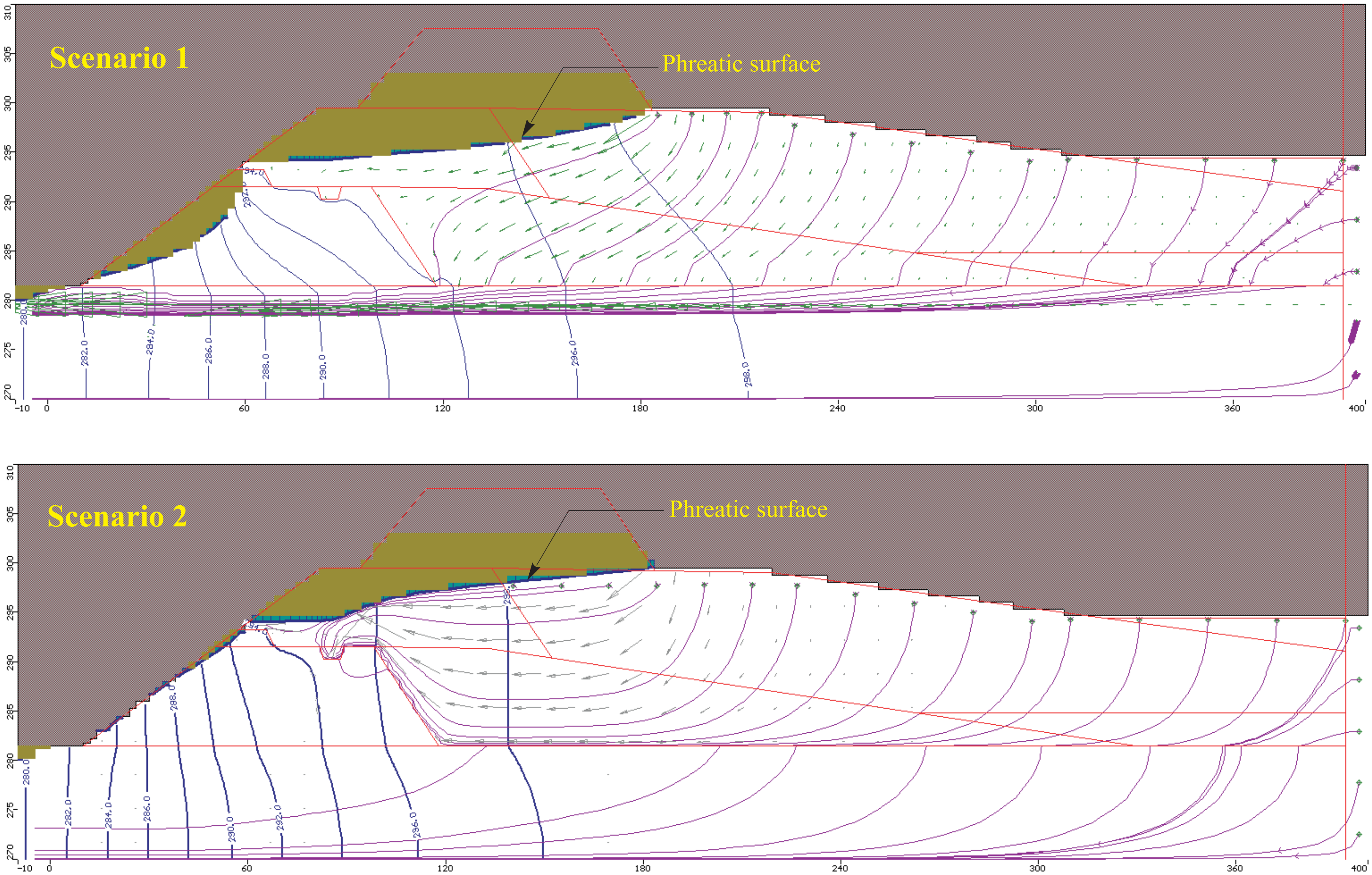


Fig. 5.5 -(a) Boundary Zone Assignment for the INDM and OUDM



Other boundaries not specified are no-flow boundaries

Fig. 5.5 -(b) Boundary Zone Assignment for the INTDM



- ◆Blue lines represent equi-potential lines with hydraulic head values (m amsl)
- ◆Arrows represent flow vectors
- ◆ Purple lines represent pathlines of particles

Fig. 5.6 Calibrated Dyke Seepage Models

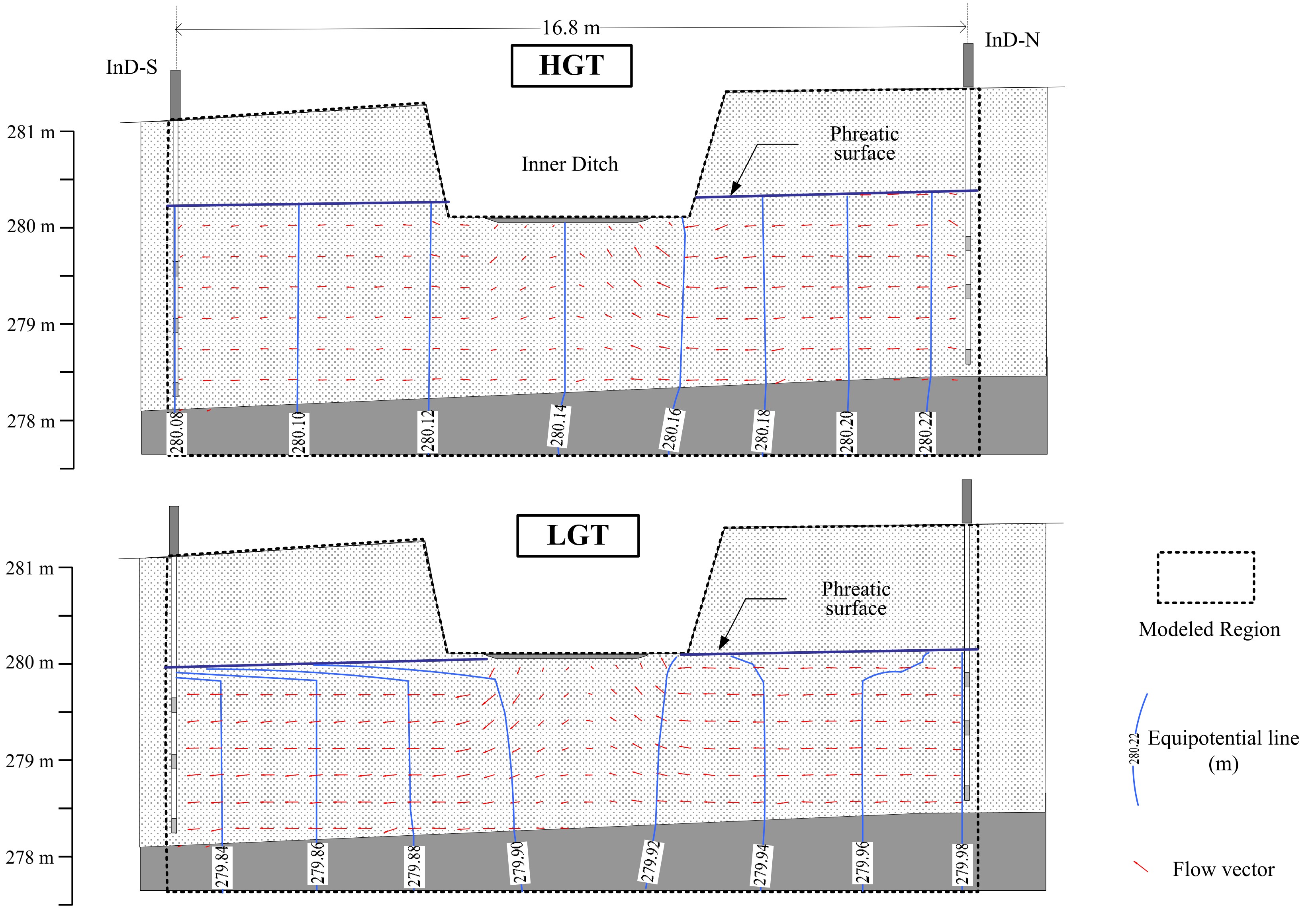


Fig. 5.7 Calibrated Downgradient Models (INDM)

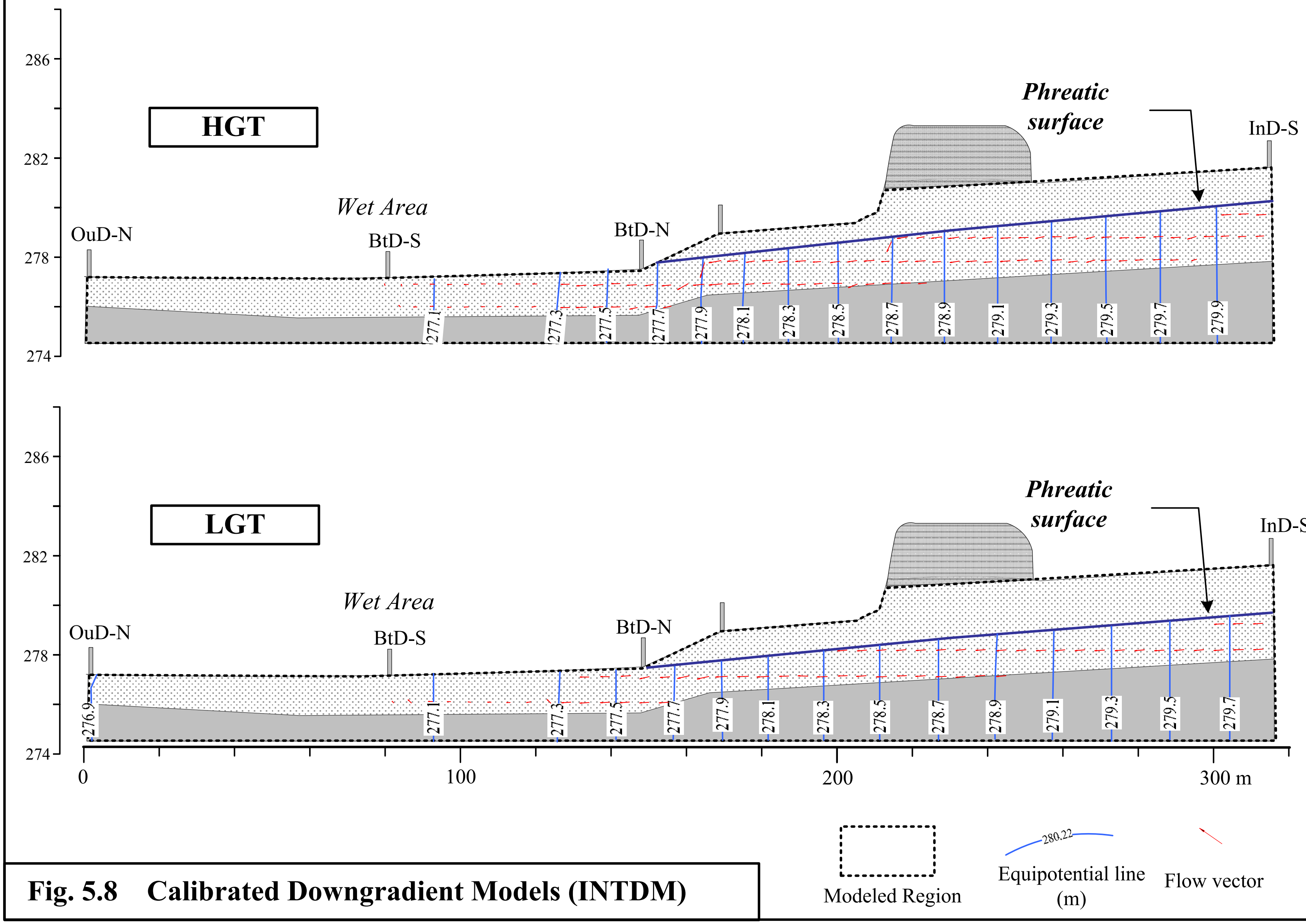


Fig. 5.8 Calibrated Downgradient Models (INTDM)

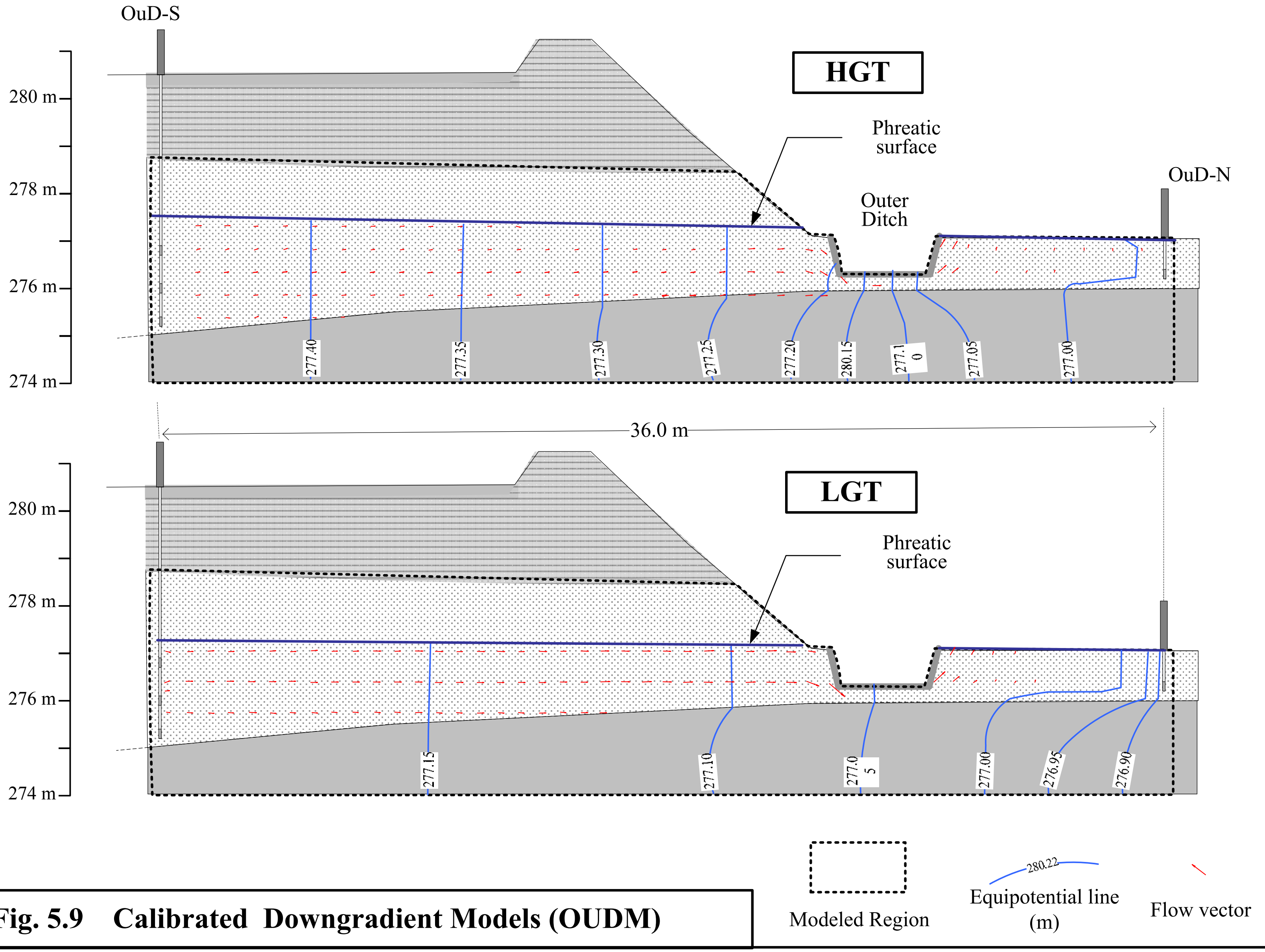


Fig. 5.9 Calibrated Downgradient Models (OUDM)

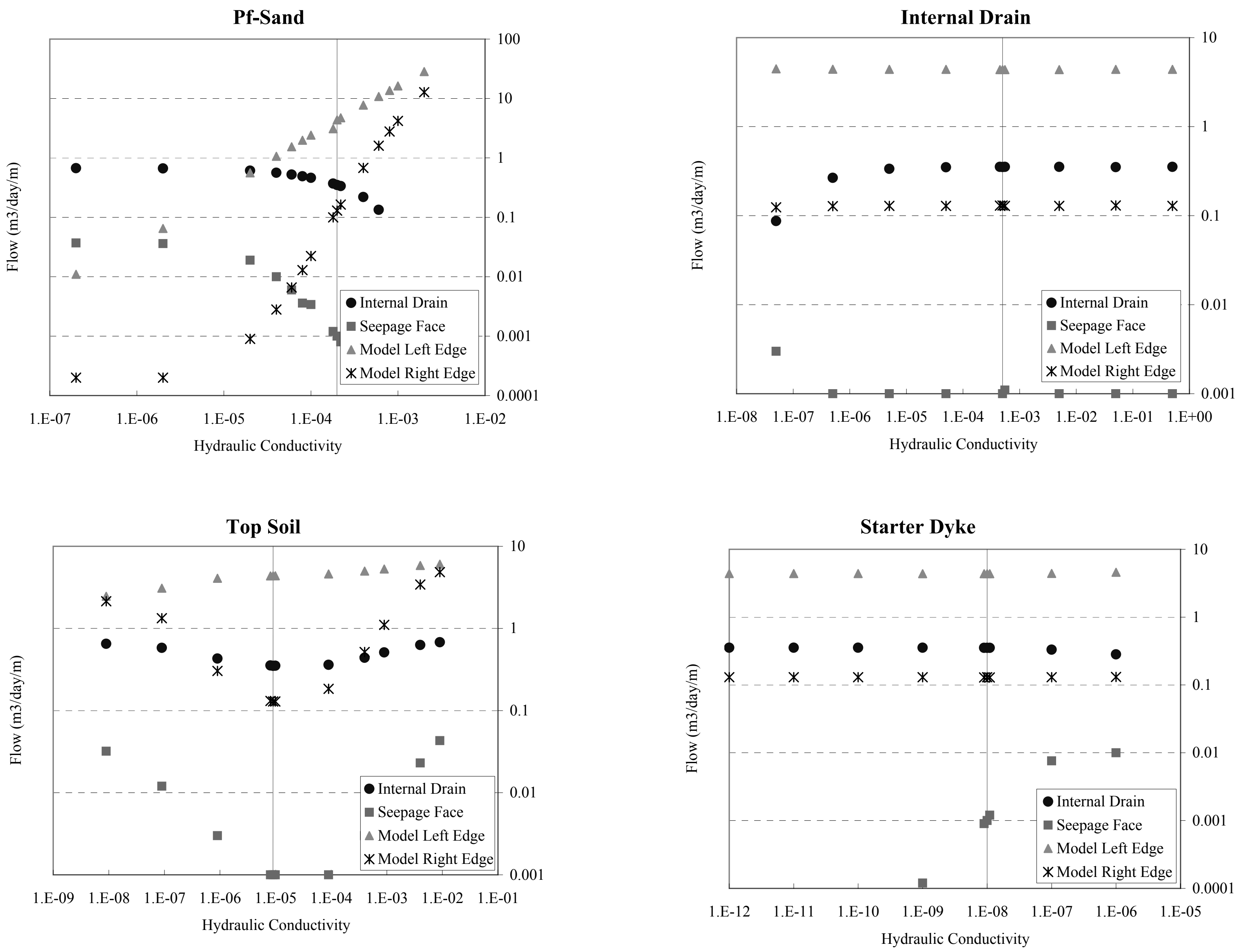


Fig. 5.10 -(a) Sensitivity of Flow to Scenario-1 Model Parameters (1/2)

The vertical line on the graphs indicates initial values

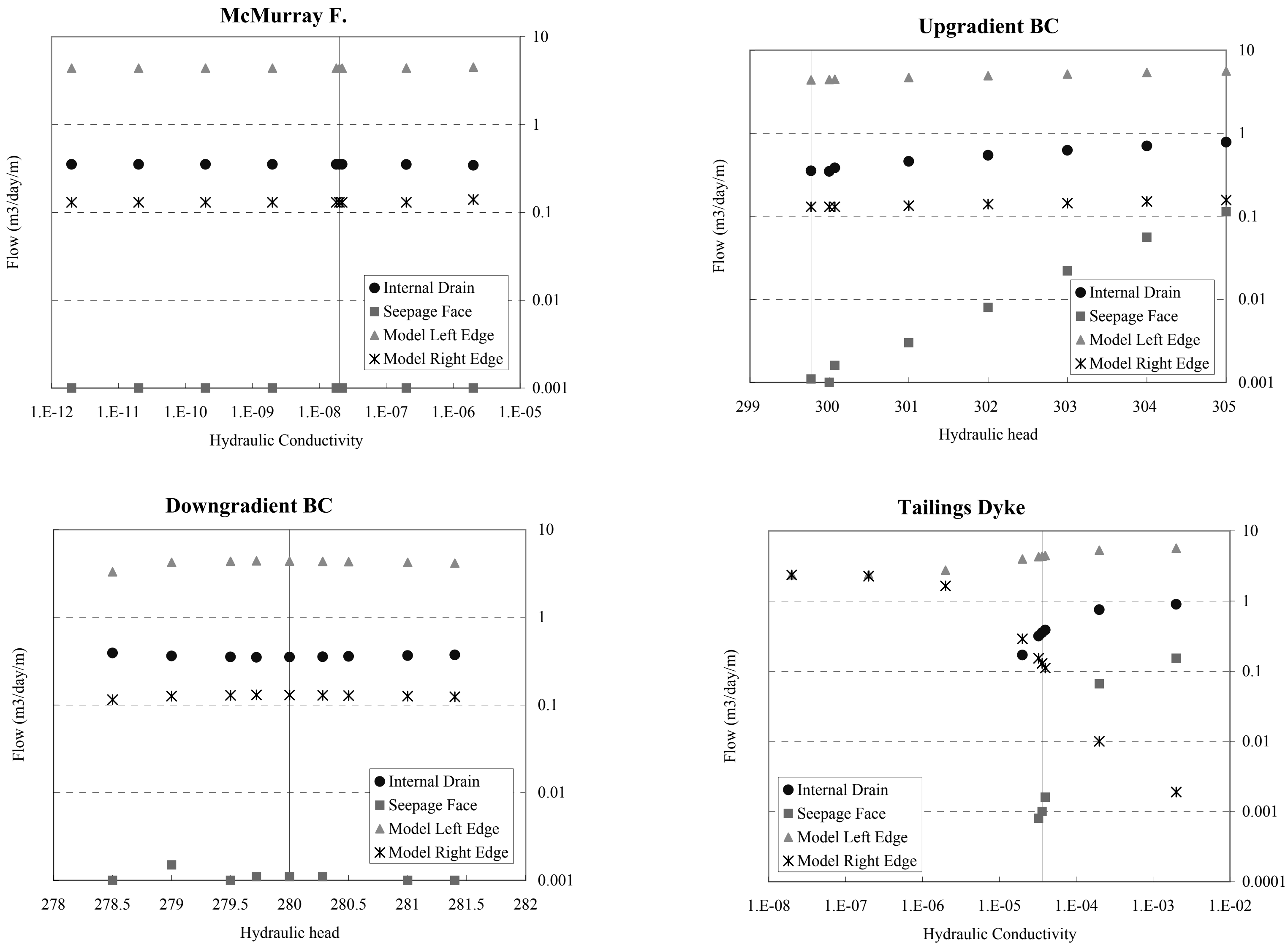


Fig. 5.10 -(a) Sensitivity of Flow to Scenario-1 Model Parameters (2/2)

The vertical line on the graphs indicates initial values

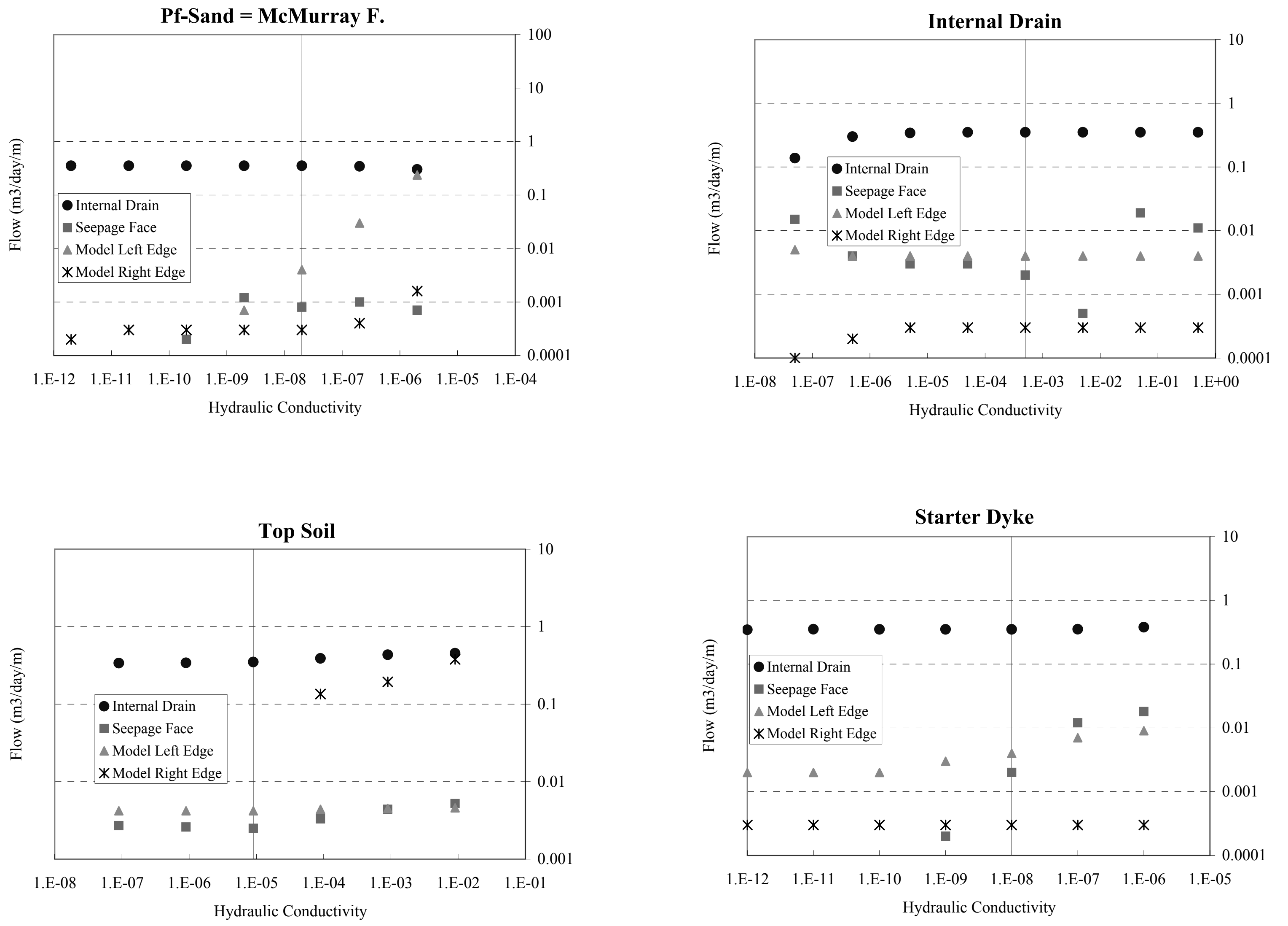


Fig. 5.10-(b) Sensitivity of Flow to Scenario-2 Model Parameters (1/2)

The vertical line on the charts indicates the initial value

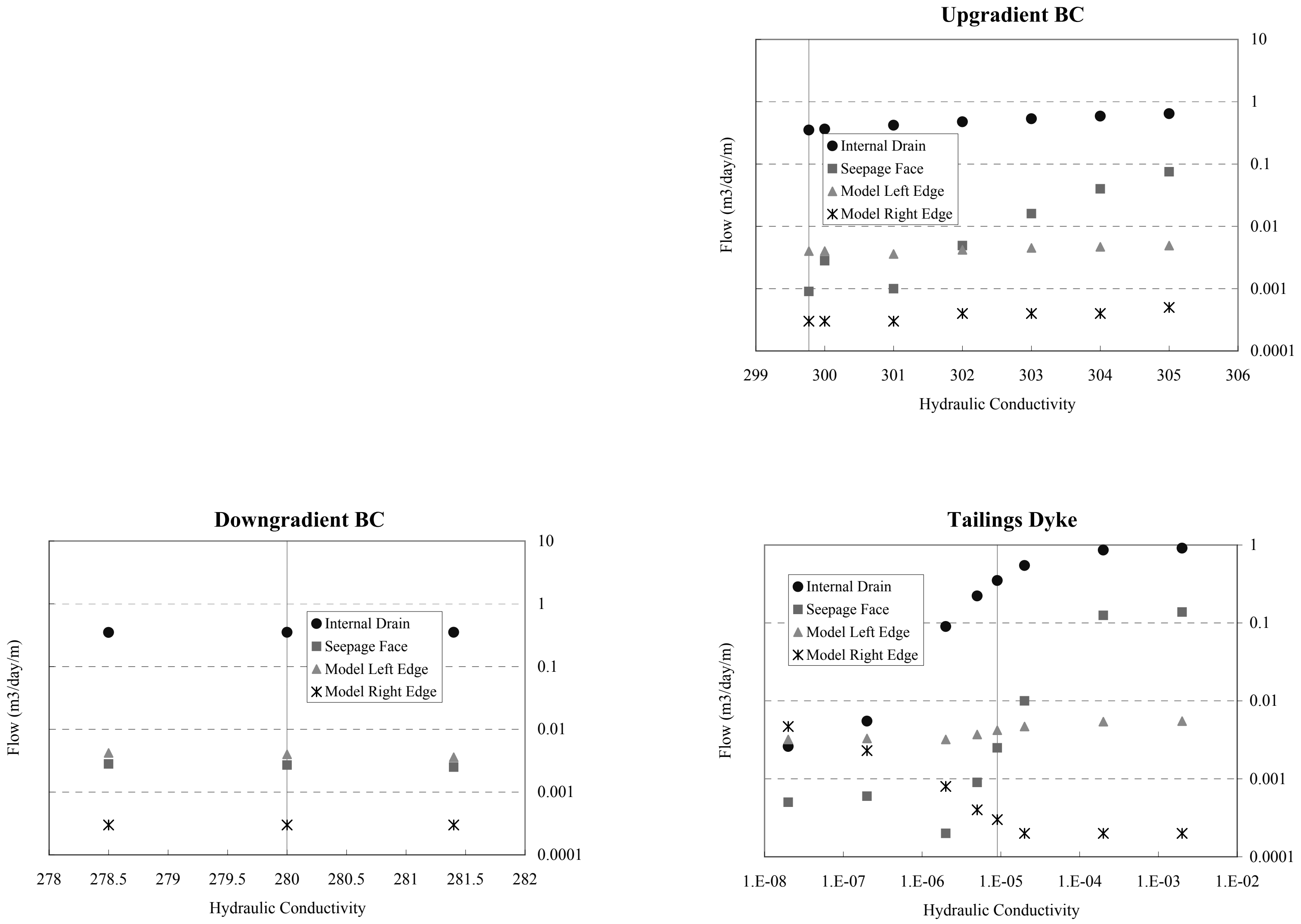
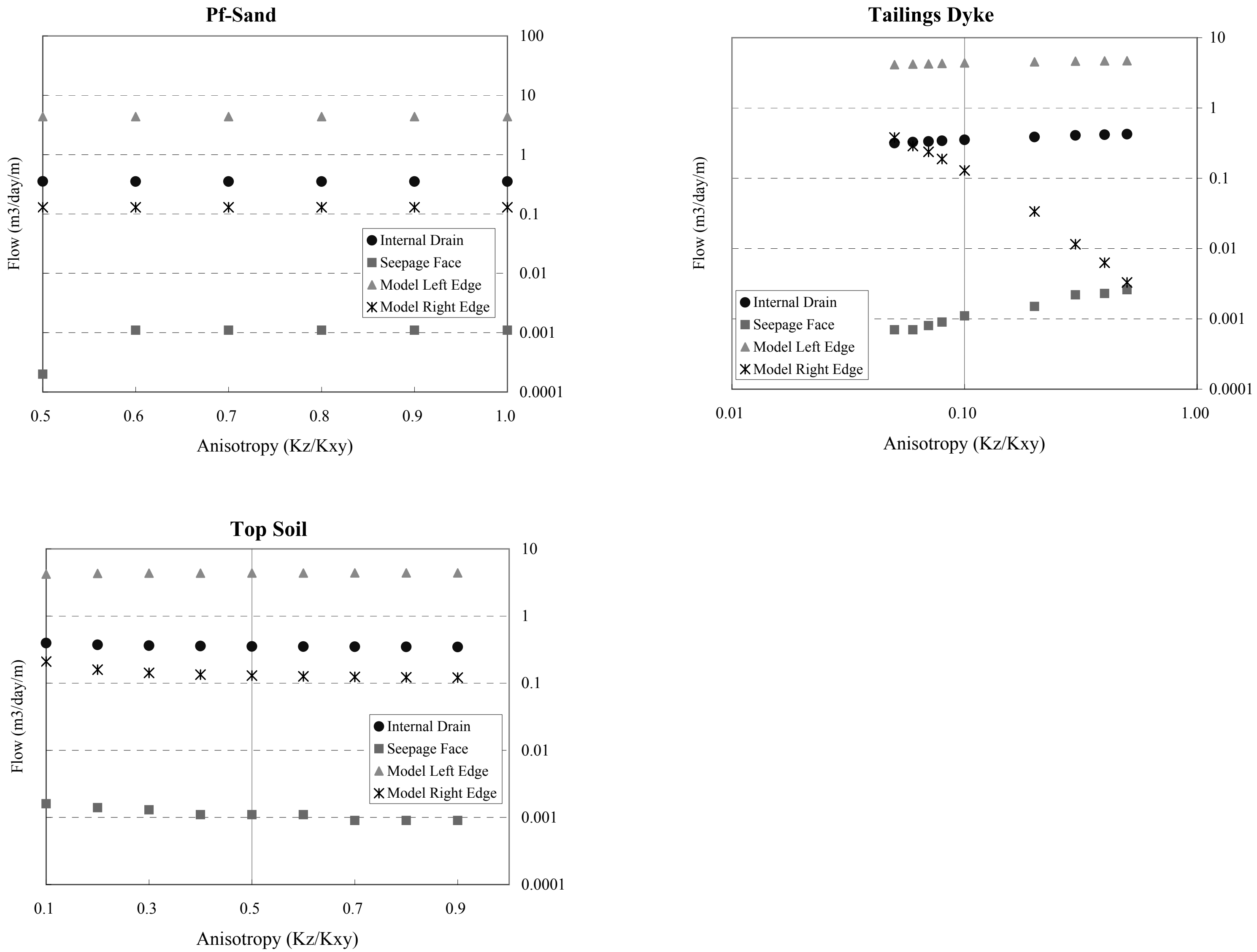


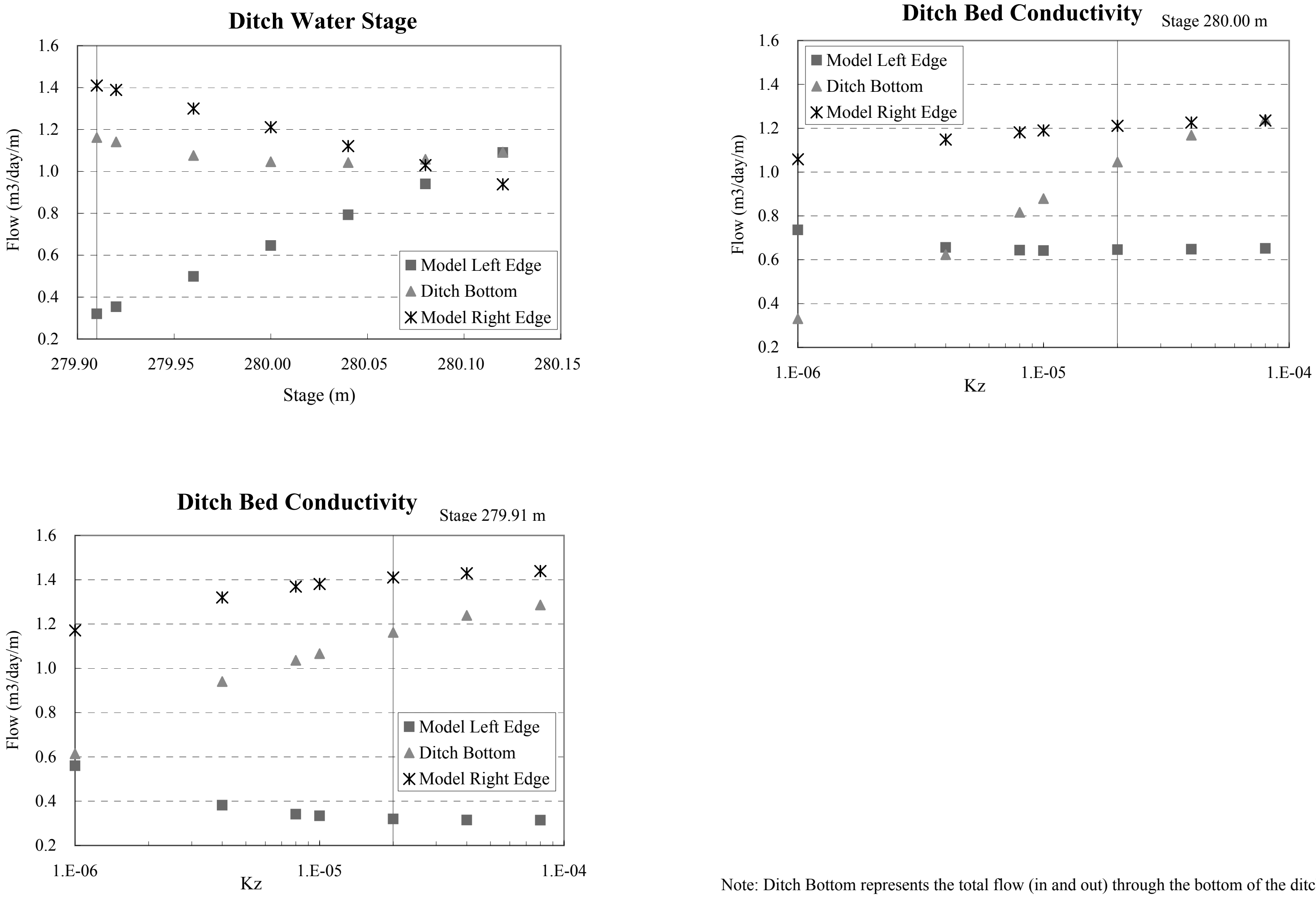
Fig. 5.10-(b) Sensitivity of Flow to Scenario-2 Model Parameters (2/2)

The vertical line on the charts indicates the initial value



The vertical line on the charts indicates the initial value

Fig. 5.11 Sensitivity of Flow to Anisotropy of Model Parameters for Scenario - 1



Note: Ditch Bottom represents the total flow (in and out) through the bottom of the ditch
Note: the vertical line on the charts indicates the initial value

Fig. 5.12 Sensitivity of Flow in DSTM 1 Model to Major Parameters

Table 5.1 Outline of Structure of Dyke Seepage Model

Property/feature	Value/description
Horizontal extent (x direction)	410 m
Vertical extent (z direction)	40 m (270 to 310 m amsl) partially inactive
Width (y direction) *	1 m
Number of columns	121 for 410 m
Number of layers	51 (1-8 inactive) for 40 m
Number of rows	1 for 1 m
Average grid size in m (x, y, z)	3.38 m, 1 m, 0.78 m
Hydraulic conductivity zone (material)	1: Tailings dyke (tailings sand) 2: Starter dyke (lean oil sand) 3: Internal drain cell (pf-sand and gravel) 4: Top soil (peat soil) 5: Pf-sand (coarse-medium grained sand) 6: McMurray F. (oil/lean oil sand/silt)
Budget zones **	2: Internal drain cell at 291 m amsl 3: Seepage face along the dyke slope 4: Model left edge in pf-sand (or in equivalent thickness of McMurray Formation) 5: Model right edge top to bottom 1: Rest of the model domain
Boundary zones and conditions	7 boundary zones with constant head, no flow, drain as specified in **Table 5.3**
Particle tracking	forward tracking along the upgradient boundaries

Note :

* one meter thick section of dyke is modeled

** a zone, usually corresponds with the model boundaries for which inflow/outflow rates are calculated. budget zone 1 is a general zone representing the rest of the cells budget zones are not assigned.

Table 5.2 Initial Hydraulic Conductivity Values

	Model domain	Material	K_{xy} (m/s)	Anisotropy (K_z/K_{xy})	Method
1	Tailings dyke	Tailings sand	2×10^{-5}	0.1	ASE
2	Starter dyke	Lean oil sand	1×10^{-8}	0.5	ASE
3	Internal drain cell	Pf-sand, gravel	5×10^{-4}	1	ASE
4	Top soil	Peat	9×10^{-6}	0.5	EXP
5	Pf-sand	Coarse – med sand	2×10^{-4}	1	EXP
6	McMurray F.	Oil sand	2×10^{-8}	0.1	ASE

Method; ASE: mainly based on information from ASE, EXP: mainly based on laboratory tests

Table 5.3 Boundary Zones and Conditions for the Dyke Seepage Model

BC and type	detail
1. Tailings pond	Constant Head
Upgradient 1	The constant head boundary of 299.77 m amsl by the water surface elevation in the tailings pond.
2. Model Right Edge	Constant Head
Upgradient 2	Constant head boundary (299.77 m) along the right hand vertical edge of the model domain to account for the contribution from upgradient (not specified for the McMurray formation)
3. Model Left Edge	Constant Head
Downgradient 1	Constant head boundary of 280 m amsl along the left edge of the model domain.
4. Seepage Face	Drain
Downgradient 2	Drain boundary specified along the entire slope of the dyke with drain elevations set at the top of each cell. The conductance is set at 0.01 m^2/day considering the material properties and cell size.
5. Internal drain	Drain
Downgradient 3	Drain boundary specified as a single drain cell to simulate the internal drain-pipe with a drain elevation set at 290.60 m amsl based on **Fig. 2.4**. The conductance is set at 0.1 m^2/day, considering the material properties and cell size.
6. Dyke Crest	No flow
Upper	No recharge and no flow condition are applied to this boundary.
7. Model Bottom	No flow
Lower	No flow condition is applied to this boundary.

Table 5.4 Outline of the Structures of Downgradient Models

	OUDM	INTDM	INDM
Horizontal extent (x direc.)	36 m	316 m	12 m
Vertical extent (z direc.) / Elevation	7.9 m (274.3 to 282.2 m)	10 m (274.6 to 284.6 m)	7.6 m (277.6 to 282.2 m)
Width (y direc.) *	1 m	1 m	1 m
Number of columns	102	211	66
Number of layers	43	38	40
Number of rows	1	1	1
Average grid size in m (x, y, z)	0.37, 0.18, 1	1.54, 0.26, 1	0.27, 0.19, 1
Hydraulic conductivity zones	1. pf-sand 2. McMurray F. 3. Bottom sediment	1. pf-sand 2. McMurray F.	1. pf-sand 2. McMurray F. 3. Bottom sediment
Budget zones **	1. Rest of the cells 2. Model left edge 3. Model right edge 4. Wet Area	1. Rest of the cells 2. Model left edge 3. Wet Area 4. Model right edge	1. Rest of the cells 2. Model left edge 3. Ditch bottom 4. Model right edge
Boundary zones and conditions	Following boundary zones as specified in **Table 5.5** - Constant Head along upgradient and downgradient edges of the model. - Constant Head in Inner Ditch to simulate ditch water - Drain along Wet Area with drain elevations set at the top of ground surface		

Note : * one meter thick section of dyke is modeled

** a zone, usually corresponds with the model boundaries for which inflow/outflow rates are calculated. budget zone 1 is a general zone representing the rest of the cells budget zones are not assigned.

Table 5.5 Boundary Zones and Conditions for the Downgradient Models

INDM (Inner Ditch Model)	
1. Model Right Edge	Constant head
Upgradient 1	Constant head boundary of around 280 m amsl (observed heads at InD-N): 280.23 m (HGT), 279.98 m (LGT)
2. Ditch Bottom	Constant head
Upgradient 2	Constant head boundary (as river boundary) along the wet bottom of the ditch to account for the recharge through the bottom of the ditch. 0.05 m of ditch bed deposit with a K value of 2x10^{-5} m/s, Stage at 280.14 m (HGT), 291.91 m (LGT)
3. Model Left Edge	Constant head
Downgradient 1	Constant head boundary of around 280 m amsl (observed heads at InD-S): 280.08 m (HGT), 279.83 m (LGT)
INTDM (Model for area between the ditches)	
1. Model Right Edge	Constant head (identical to Downgradient 1 in INDM)
Upgradient 1	Constant head boundary of around 280 m amsl (observed heads at InD-S) : 280.08 m (HGT), 279.83 m (LGT)
2. Seepage Face in Wet Area	Drain
Downgradient 1	Drain boundary along the Wet Area to simulate the discharge/seepage in the area.
3. Model Left Edge	Constant head
Downgradient 2	Constant head boundary of around 277 m amsl (observed heads at OuD-N) : 276.95 m (HGT), 276.87 m (LGT)
OUDM (Outer Ditch Model)	
1 Model Right Edge	(same as downgradient 2 in INTDM)
Upgradient 1	Constant head boundary of around 277 m amsl (observed heads at OuD-N): 276.95 m (HGT), 276.87 m (LGT)
2. Seepage Face in Wet Area	Drain
Upgradient 2	Drain boundary along the ground surface between the ditch and OuD-N.
3. Model Left edge	Constant head
Downgradient 1	Constant head boundary of around 277.5 m amsl (observed heads at OuD-S) : 277.44 m (HGT), 277.19 m (LGT)

Note : flow is calculated only for pf-sand portion of each zone

Constant head is assigned along the whole saturated thickness of the model including oil sand

Table 5.6 Parameters for Calibrated Dyke Seepage Models

		Scenario - 1	Scenario - 2
Tailings sand K_{xy}*		3.6×10^{-5} m/s	7.5×10^{-6} m/s
K values for other materials		Same as the initial value	Same as the initial value
Anisotropy (K_z /K_{xy})		Same as the initial value	0.4
Flow** (m^3/day/m)	Internal drain	0.350	0.347
	Seepage face	0.001	0.0074
	Model left edge	4.39	0.0029
	Model right edge	0.13	5.5×10^{-7}

* Kz = 0.1 x Kxy

** Flow is calculated as discharge per unit width of the model section

Table 5.7 Parameters for Calibrated Downgradient Models (HGT)

		INDM	INTDM	OUDM
pf-sand K (m/s)		2 x 10^{-4}	1.9 x 10^{-4}	2 x 10^{-4}
Reference		280.14 m at InD-DVP	277.61 m at BtD-N	N/A
Flow (m^3/day/m)	Model Left Edge	0.24	0.00	0.34
	Seepage In*	0.11	0.00	N/A
	Seepage Out**	0.22	0.24	0.34
	Model Right Edge	0.36	0.24	0.00

* Into the model and, ** Out of the model (through the seepage face or ditch bottom)

Table 5.8 Parameters for Calibrated Downgradient Models (LGT)

		INDM	INTDM	OUDM
pf-sand K (m/s)		2 x 10^{-4}	2.8 x 10^{-4}	2 x 10^{-4}
Reference		280.01 m at InD-DVP	277.58 m at BtD-N	N/A
Flow (m^3/day/m)	Model Left Edge	0.29	0.00	0.14
	Seepage In*	0.16	0.00	N/A
	Seepage Out**	0.13	0.30	0.14
	Model Right Edge	0.26	0.29	0.00

* Into the model and ** Out of the model (through the seepage face or ditch bottom)

Table 5.9 Marginal Sensitivity of the Dyke Seepage Models

			Scenario 1				Scenario 2			
Model domain			IND	SF	MLE	MRE	IND	SF	MLE	MRE
Hydraulic conductivity (ΔQ/ΔK)	Pf-sand	-	-1,000	-10	63,500	1,500	0.00	0.00	0.00	0.00
		+	-700	-10	18,150	1,700	0.00	0.00	0.00	0.00
	Top soil	-	-4,444	0	22,222	-2,222	1,111	0	0	33
		+	2,222	0	-11,111	0	0	1,111	0	22
	Tailings dyke	-	10,000	56	22,222	-6,667	30,000	21,889	0	0
		+	9,167	167	22,222	-5,000	7,778	6,667	0	0
	Starter dyke	-	0	100,000	0	1,000,000	0.00	0.00	0.00	0.00
		+	0	200,000	0	-1,000,000	0.00	0.00	0.00	0.00
	internal drain	-	-20	4	200	10	0.00	0.00	0.00	0.00
		+	20	2	-200	-20	0.00	0.00	0.00	0.00
	McMurray F.	-	0	0	0	0	0.00	0.00	0.00	0.00
		+	0	0	0	0	0.00	0.00	0.00	0.00
Head (ΔQ/Δh)	Upgradient BC	-	-	-	-	-	-	-	-	-
		+	0.10	0.00	0.30	0.00	0.1	0.0	0.0	0.0
	Downgradient	-	0.01	0.00	-0.10	0.00	0.00	0.00	0.00	0.00
		+	0.01	0.00	-0.11	0.00	0.00	0.00	0.00	0.00

The +/- signs under model domain indicates the direction of change in model parameters

IND: Internal Drain, SF: Seepage Face, MLE: Model Left Edge, MRE : Model Right Edge

6. Discussion

6.1. Groundwater Flow System in the Study Area

6.1.1 General Groundwater Flow

The inferred local horizontal groundwater flow direction in the Study Area is generally to the south (away from the dyke) and thus the water seeping from the dyke and ditch may impact groundwater to the south. **Fig. 6.1** summarizes potential groundwater flow pathways in the Study Area. The flow Pathway No. 1 originates in the dyke and exits through the internal drain system; this is the seepage component that the ditches are originally designed to collect. The flow Pathway No. 2 begins in the tailings pond through the bottom of the dyke passing underneath the starter dyke. These two flow components combine to form the flow Pathway No. 3 that discharges into the Wet Area. The flow Pathway No. 4 enters under the Outer Ditch and discharges into the Wet Area. Finally the flow components No. 3 and 4 combine to form flow Pathway No. 5 that discharges into the Outer Ditch as surface water.

The results of the four groundwater sampling rounds and groundwater flow modeling suggest that the seepage water from the dyke migrates under the Inner Ditch through the pf-sand layer towards the Wet Area. This was supported by the INDM model as discussed in Chapter 5. Groundwater appears as surface water at the foot of the soil heap, about 150 m to the south of the Inner Ditch. This groundwater discharges into the area between BtD-S and BtD-N and results in extensive ponding observed in the Wet Area to the south of soil heap through Spring to Fall. **Photo A-3** in the Appendix, taken in Oct. 2005, shows that the two piezometers, BtD-S and OuD-N, are located in these shallow ponds. The levels of surface water outside the piezometer pipes were nearly equal to the groundwater levels inside the pipes at the time the photo was taken. This suggests the groundwater and surface water were in hydraulic equilibrium. The chemistry data of the two water samples taken at BtD-S in Oct. 2005 also confirms this hydraulic connection, as groundwater and adjacent surface water had the same chemical compositions. This scenario was recreated in the INTDM model. The incoming flow from upgradient all discharges as surface water in the Wet Area.

The groundwater beneath the Outer Ditch, on the other hand, has an inward hydraulic gradient towards the north from the piezometer OuD-S to OuD-N (see **Fig. 6.2**). This suggests that the groundwater is flowing north, under the Outer Ditch toward the Wet Area. This condition was recreated in the OUDM model. The lack of a clear indication of PAW in piezometers to the south of the Outer Ditch is consistent with this groundwater flow direction.

6.1.2 Water Level Fluctuations

(1) Cause of groundwater level fluctuation

There are several possible causes for the observed water level fluctuations and these include:

1) barometric change,
2) precipitation,
3) natural seasonal fluctuation, and
4) artificial disturbance in local flow system.

As explained earlier, precipitation probably does not have large impact and barometric effects have been corrected. Thus these two factors can be excluded.

It is natural to expect that there is seasonal water level fluctuation that reflects the long-term precipitation pattern. In northern Canada, typically the recharge in winter is nearly zero because precipitation simply accumulates as snow. Significant recharge occurs throughout spring to summer as a result of snow melt. As described earlier, the water level fluctuations in the piezometers near the Outer Ditch seem to manifest a typical seasonal fluctuation; however, this cannot explain the short-term fluctuation patterns.

If we can assume that the long-term water level fluctuation patterns recorded at the two piezometers (OuD-S2C and OuD-S2W) in the Study Area represent the natural seasonal fluctuation, we would expect a similar, smooth pattern at the Control Site as well, although the degree of fluctuation may be different. However, the pattern at the Control Site shows some drops and spikes in water level in spite of the overall similarity in the long-term patterns. These acute changes can probably be attributed to an artificial disturbance to the local flow system at the Control Site, since the other factors cannot explain this fluctuation pattern. According to ASE, construction work was actively under way near the Control Site during this study period and it included excavation of a temporary ditch along the eastern side of the tailings pond (planned in parallel with the Outer Ditch about 20 m away toward the dyke) during the Summer of 2005. The employees of ASE observed the ditch was filled with water soon after the excavation. Near the Study Area, the construction work started in the Winter of 2005/2006. The sharp drops in water levels recorded during the Winter at both OuD-S2C and OuD-S2W probably reflects disturbance by the construction work and therefore likely affected the water table. The scope of this thesis originally included the effect of such disturbance on the local groundwater system; however, due to the delay and the changes in the construction plan, no further discussion is provided on this issue.

(2) Effect of groundwater level fluctuation

The water level fluctuation is considered to be a manifestation of change in the local groundwater regime. In the downgradient models discussed in Chapter 5, for a simple linear model involving no interaction with surface water, the INDM model produced an outflow of 0.25 - 0.27 m^3/day/m and the flow is nearly horizontal. The outflow rate thus is simply proportional to the hydraulic gradient determined by the hydraulic head at both edges of the model. The maximum seasonal difference in the groundwater level was found to be 0.25 m for the monitoring period across the Inner Ditch (see **Fig. 6.2**); and this would theoretically bring about a 20 % change in the outflow rate for this linear model.

The observed sharp drops in groundwater level in the piezometers on the south side of the Outer Ditch may have temporarily affected the local flow regime. However the degree of drop is no more than 0.15 m and it is not sufficiently large to reverse the flow across the Outer Ditch. Furthermore, such drops typically last less than 12 hours, which is not a significant duration in comparison with much slower movement of groundwater in the pf-sand. Thus the impact of such fluctuations is considered minimal.

6.2. PAW Migration and Collection Ditch System

6.2.1 Potential Pathways in the Dyke

As suggested by the dyke seepage model discussed in Chapter 5, seepage of tailings water into the pf-sand may also be occurring through the bottom of the tailings pond extending under the dyke. Typically, the thickness of topsoil (peat) is about 2 m and the thickness of the pf-sand is 3 m around the Study Area. ASE's record of exploratory boreholes drilled prior to the construction of mine facilities reveals that some of the boreholes struck thick (0.1 ~ 3 m) pf-sand in the south of the tailings pond and even under the starter dyke adjacent to the Study Area (see **Fig. A 6.1**). Thus, pf-sand likely exists under the dyke and it can act as a conduit of seepage water. The higher SO_4^{2-} and Mg^{2+} concentrations in the outtake drain-pipe water compared with the groundwater to the north of the Inner Ditch also supports that the two waters come through different seepage pathways.

The chemistry of groundwater samples suggests that tailings water is also found in groundwater immediately upgradient of the Inner Ditch. Since groundwater essentially flows towards the south with a sufficient gradient (0.12 to 0.17 m over 17 m, see **Fig. 6.2**), the ditch water will not effectively influence the north side of the Inner Ditch. The part of the dyke dewatered by the internal drain system is considered hydraulically separated from the pf-sand layer by the practically impermeable starter dyke as shown in **Fig. 5.1**. Thus the drainage water is not expected to impact groundwater underneath the starter dyke either. This suggests that there is a separate seepage flow pathway that originates from underneath the tailings pond (component 2 in **Fig. 6.1**): the tailings water seeps through the bottom of the pond through the peat layer and into pf-sand that extends under the dyke and pond. This seepage component was simulated with the dyke seepage model discussed in Chapter 5 and the outflow rate is about 0.3 m^3/day/m. The model indicates that most of this seepage water comes from the southern edge of the tailings pond near the beach. The dyke seepage model with a pinched pf-sand layer under the starter dyke (see Section 5.5) indicates that the migration of PAW along Pathway No.1 takes ~600 days and along Pathway No.2 takes ~700 days to travel from the south shore of the tailings pond to discharge at InD-N on the dyke toe berm.

6.2.2 Collection Ditch System

The seepage collection ditches (perimeter ditches) are designed to collect and transfer seepage water back into the pond. In this section, the effectiveness of the Inner and Outer Ditch system in the Study Area is discussed from this perspective.

The bottom of the Inner Ditch is covered with a thin layer of fine sediment, otherwise, pf-sand is exposed on the bottom and sides of the Inner Ditch. Thus, ditch water has the potential to seep into the pf-sand and vice versa depending on the hydraulic head difference. The similarity of chemical characteristics of waters in the drive point, surrounding piezometers, and the Inner Ditch, particularly in terms of the key tracers (Na^+, Cl^-, pH and EC) also supports ditch water - groundwater interaction. The water in the drive point is closer to ditch water than to the groundwater, in terms of concentrations of SO_4^{2-}, and Mg^{2+}. Thus, it is likely that the groundwater immediately under the Inner Ditch is derived, in part, from the ditch. The modeling results of the INDM model suggests that even with no hydraulic head difference, there is a possibility of some exchange of the waters through the bottom of the ditch. The simulated maximum possible seepage rate into the ditch is up to 0.22 m^3/day/m, and from the ditch is 0.16 m^3/day/m with no hydraulic head difference in the ditch. These flow rates appear too high considering the chemistry of the waters sampled from the installations. The actual exchange rate is probably much lower. The modeling results also indicate that groundwater takes about 35 days to migrate across the Inner Ditch and an additional 320 days to discharge into the Wet Area to the south of BtD-N under HGT conditions. So it is not surprising that PAW was found in the Wet Area.

The same evaluation cannot be made for the Outer Ditch because the drive point was clogged and did not produce water. It is likely, however, that no significant seepage will occur through the bottom or sides of the Outer Ditch since it is lined with low permeability oilsand. This is supported by the fact that the chemistry of the water in the ditch and the surrounding groundwater are quite different as discussed in Section 4.2. Field observations (pond water flowing into the ditch) and higher hydraulic heads on the south side of the ditch both indicate that the groundwater is moving under the Outer Ditch with little interaction with the ditch water. OUDM model results indicates that groundwater takes about 45 days to migrate across the Outer Ditch under HGT conditions. The groundwater discharges into the Wet Area around OuD-N and then flows slowly into the Outer Ditch (see **Fig. 6.1**). This interpretation was recreated with the OUDM model, and the modeling results suggest that there is a significant groundwater flow of up to 0.34 m^3/day/m across the ditch towards the Wet Area (Pathway No. 4).

The flow velocity in the Outer Ditch in the Study Area is too small to be used to estimate the flow rate. However, a flow rate of about 50 L/s was measured downstream of the Study Area. This measurement is consistent with the sum of the measurements of outtake drain-pipe outflows (69 L/s) conducted by ASE.

Part of the water in the Outer Ditch is from the surface water in the Wet Area that is essentially the seepage of the groundwater coming from the north and south of the Outer Ditch (flow Pathway 3 and 4 in **Fig. 6.1**). The contribution of groundwater inflow to the flow in Outer Ditch for the HGT was estimated from the model simulations as:

- From the north (Pathway No. 3): 0.24 m^3/day/m
- From the south (Pathway No. 4): 0.34 m^3/day/m

If the area of contribution is defined as ~250 m stretch along the Outer Ditch where substantially thick pf-sand is possibly distributed (see **Fig. 2.3**), then the contribution of groundwater seepage to the ditch flow rate is approximately 1.7 L/s (145 m^3/day = (0.24 + 0.34 m^3/day/m) x 250 m). If the contribution of PAW (Pathway No. 3) is only considered, the value is even smaller, 0.69L/s (0.24 m^3/day/m) x 250 m). This is a small fraction (< 4%) of the total flow observed in the Outer Ditch (50 L/s). Much of this flow must be from the dyke drains collected in the Inner Ditch.

In summary, the ditches in the Study Area appear to be effectively collecting the groundwater seepage and the water from the drain-pipes, and transmitting this water to the seepage pond. The mass loading of PAW to the environment is likely negligible. However, this is mainly a result of the elevated hydraulic head on the south of the Outer Ditch, which causes an inward hydraulic gradient. If hydraulic conditions change in the dyke and Wet Area, the presence of pf-sand under both ditches may allow process-affected groundwater to migrate outside of this barrier system. This possibility must be considered as dyke construction proceeds.

6.2.3 Migration of PAW

The PAW in the tailings pond has a different chemistry from the natural groundwater and is best characterized by elevated NAs (over 5 mg/L), Na^+ (over 20 mg/L) and Cl^- (over 5 mg/L) concentrations and by hydrogen and oxygen isotopic signature (over -140 and -17 ‰ respectively). These parameters are, therefore, can be used to effectively track PAW. It is clear that the PAW is found in the pf-sand to the south of the dyke. The process affected groundwater in the pf sand, however, has significantly lower concentrations of these tracers compared with the tailings water. This finding is contrary to that reported by Mackinnon et al., (2005) where the water found in the collection system at the Syncrude mine is almost identical chemically to that in the tailings pond. The reason for this change is not clearly known but perhaps due to dilution of PAW by precipitation during seepage through the dyke.

Fig. 4.7 summarizes the spatial distribution of key tracer concentrations in four temporal profiles. As of November 2005, the PAW had reached piezometers BtD-S but not OuD-N. The PAW front that can be defined as a steep spatial concentration gradient in cross-sectional profiles is located somewhere between BtD-S and OuD-N (see **Fig. 6.1**). The results of the stable isotope analysis also support the inorganic tracer findings. One possible explanation to this observation is that the process affected groundwater from the north discharges into the Wet Area upgradient of BtD-N while natural groundwater from the south discharges around OuD-N. This results in the area between the two piezometers as the meeting point of the two groundwater components.

These conditions described above, however, may change with the progress of the current dyke expansion work. The Wet Area between the ditches will be buried and the local hydraulic condition is expected to alter. This may reverse the current hydraulic gradient across the Outer Ditch and could facilitate PAW migration beyond the Outer Ditch.

6.3. Impact of Dyke Construction on the Hydraulic System

The planned hydraulic expansion of dyke in the Study Area was delayed for the Winter of 2005/2006 and was eventually changed to dry construction that does not involve tailings water. The dyke is now being constructed by dumping dry mine waste materials instead of over-saturated tailings sands. Therefore the anticipated introduction of PAW to the Study Area by the placement of tailings is no longer an issue and so is not discussed in detail. However the construction will still affect the local flow system by eliminating the topographic depression in the Wet Area and by introducing excess load onto the underlying sediments. This may still lead to a reversal of the local hydraulic gradient across the Outer Ditch as illustrated in **Fig. 6.3**.

The highly fluctuating groundwater level observed over the research period at the Control Site and some sudden decrease in groundwater levels recorded during the Winter of 2005/2006 in the Study Area suggest possible effects of dyke expansion work on the local shallow groundwater system. If we consider the fact that the temporary ditch excavated near the Control Site was immediately filled with water, it is likely that some of this water was derived from the local aquifer as the groundwater in this aquifer drained into the temporary ditch. The water that filled the ditch, in this case, probably came from the overburden sand and gravel layer locally distributed above the McMurray formation to the north of the Control Site. This granular deposit was observed in the temporary ditch about 100 m north of the Control Site.

6.4. Transient Seepage Behavior

The discussion of the groundwater system in the previous sections primarily assumed that the system was in steady state. However, there are always transient components in the system such as the higher water level in the Inner Ditch as discussed briefly in Chapter 5. Another issue of interest is the transient behaviour of the flow in the tailings dyke.

The source of water feeding the groundwater to the south of the dyke is a mixture of construction water contained in the tailings and upgradient groundwater, the tailings pond water. The construction and tailings pond waters cannot be chemically distinguished. The tailings dyke has been successively raised by upstream hydraulic construction and this is followed by an increase in the pond water stage. Thus, both waters can be found in the seepage from the dyke with different degrees of contribution depending on the status of the dyke and pond. The seepage driven only by the rather steady hydraulic head in the tailings pond can be regarded as the “base flow”.

Fig. 6.4 shows changes in the water level in the tailings pond and the measured drain flow rates from the outtake pipes 1 - 3 in the Study Area over the last 3 years (Sep. 2002 – Dec. 2005). There are two sharp spikes in the drain flow in 2003 and other minor peaks in both 2004 and 2005. These increases in drain flow all correspond to discrete cell construction activities taking place in the vicinity of the Study Area. These data indicate that most of the construction water drains out of the dyke in a few months in the earlier stages and up to six months at later stages of dyke construction/expansion. Thus the seepage flow coming from the tailings pond probably accounts for most of the background or "base flow". It can be clearly noticed that the step-wise increase in base-flow corresponds to the increase in water level in the tailings pond and the dyke elevation. The remarkably high flow rates peaks associated with cell construction in 2003 may be due to the more rapid dyke drainage because, at this time, the volume of the dyke was smaller (the crest elevation was 292 m amsl before the construction). In later years the construction water takes longer to drain through the larger dyke, leading to reduced peak flows. The peaks in drain flow are not as high as in 2003 after the dyke was raised to 300 m and increased in volume. Although it is not possible to chemically distinguish construction water and tailings pond water, this observation makes it possible to distinguish the timing of drainage of the two waters to some extent.

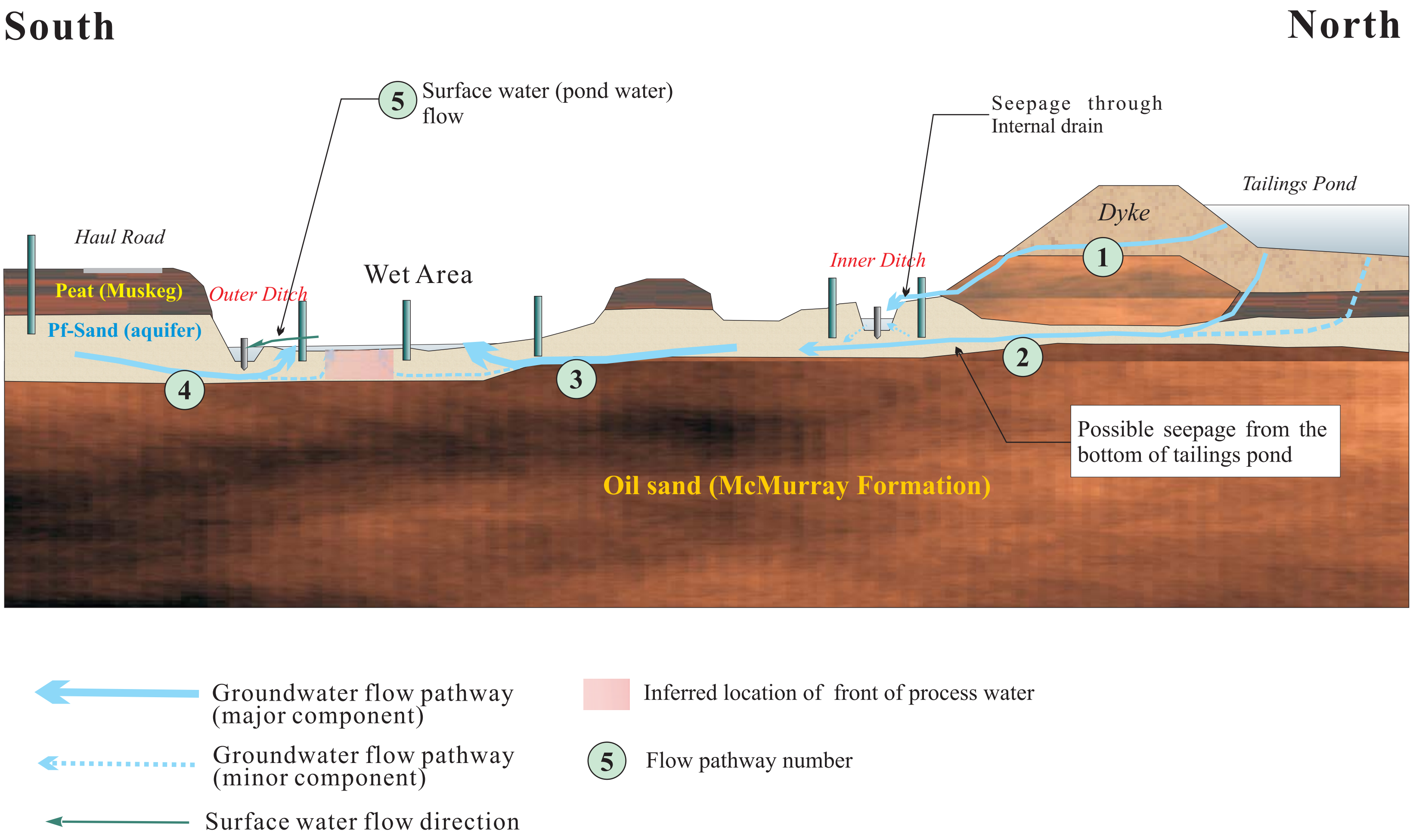


Fig. 6.1 Schematic of Potential Groundwater Flow Pathways in the Study Area

Not-to-scale

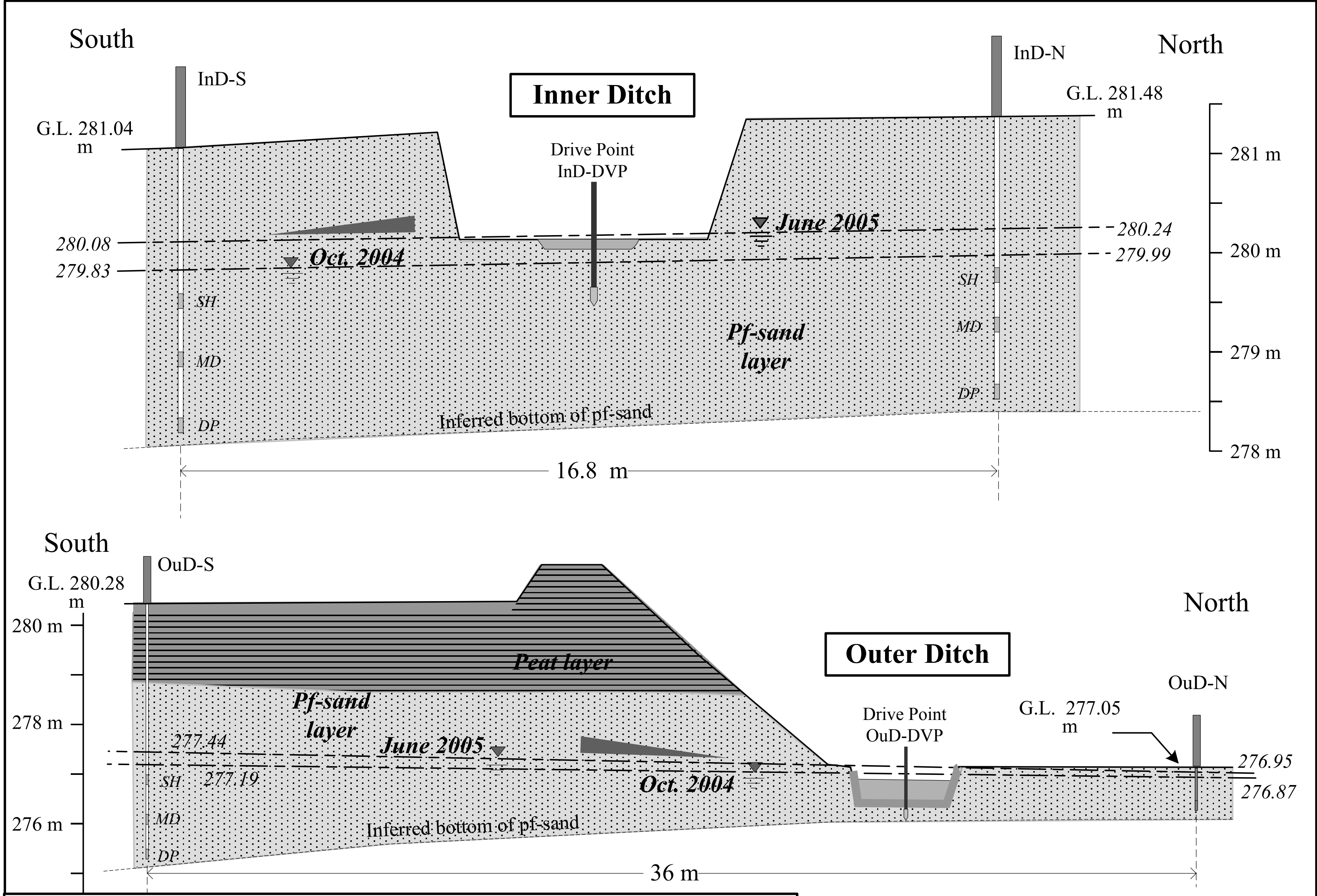


Fig. 6.2 Seasonal Change in Water Level across the Ditches

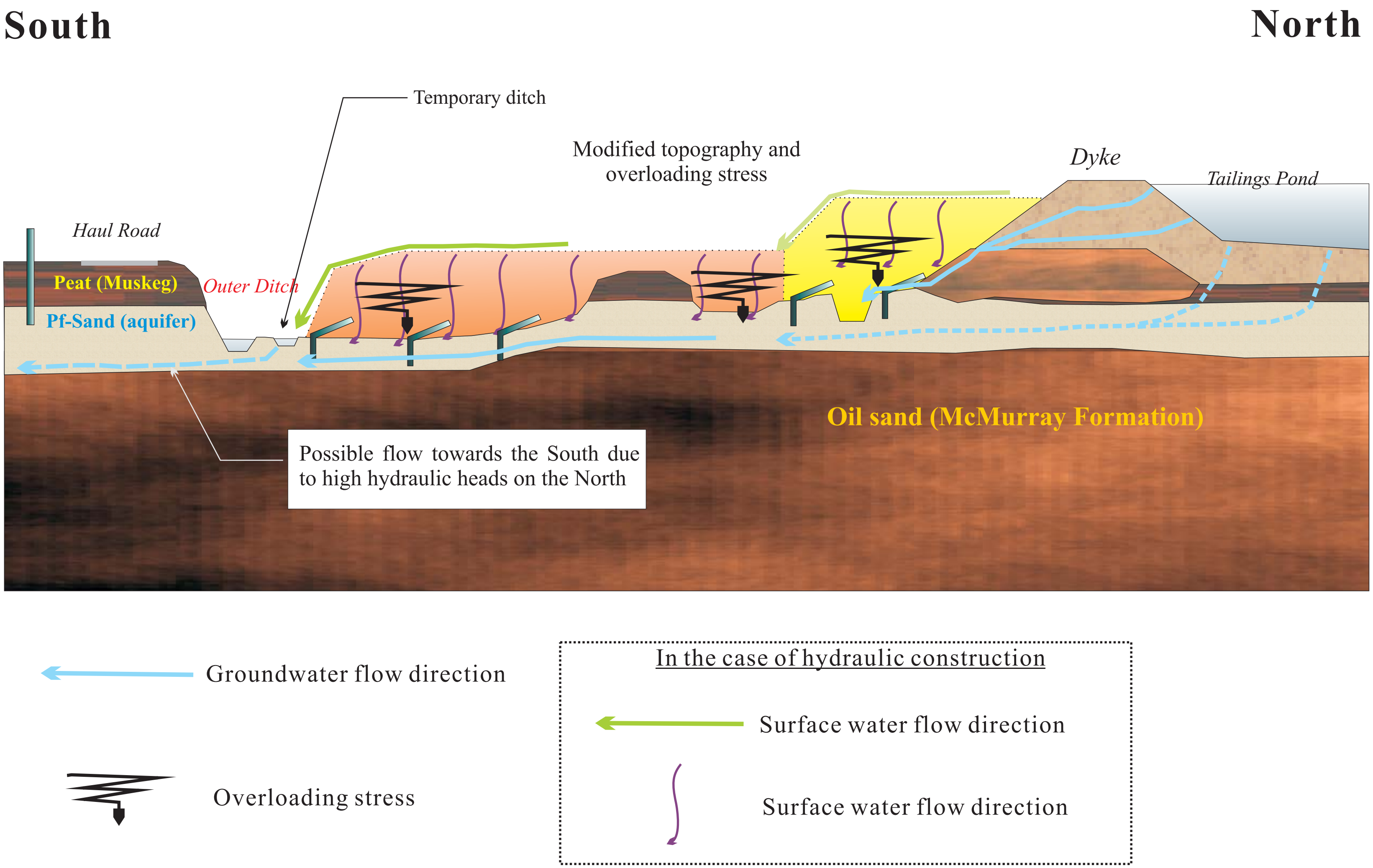


Fig. 6.3 Altered Hydraulic System during and after Dyke Expansion

Not-to-scale

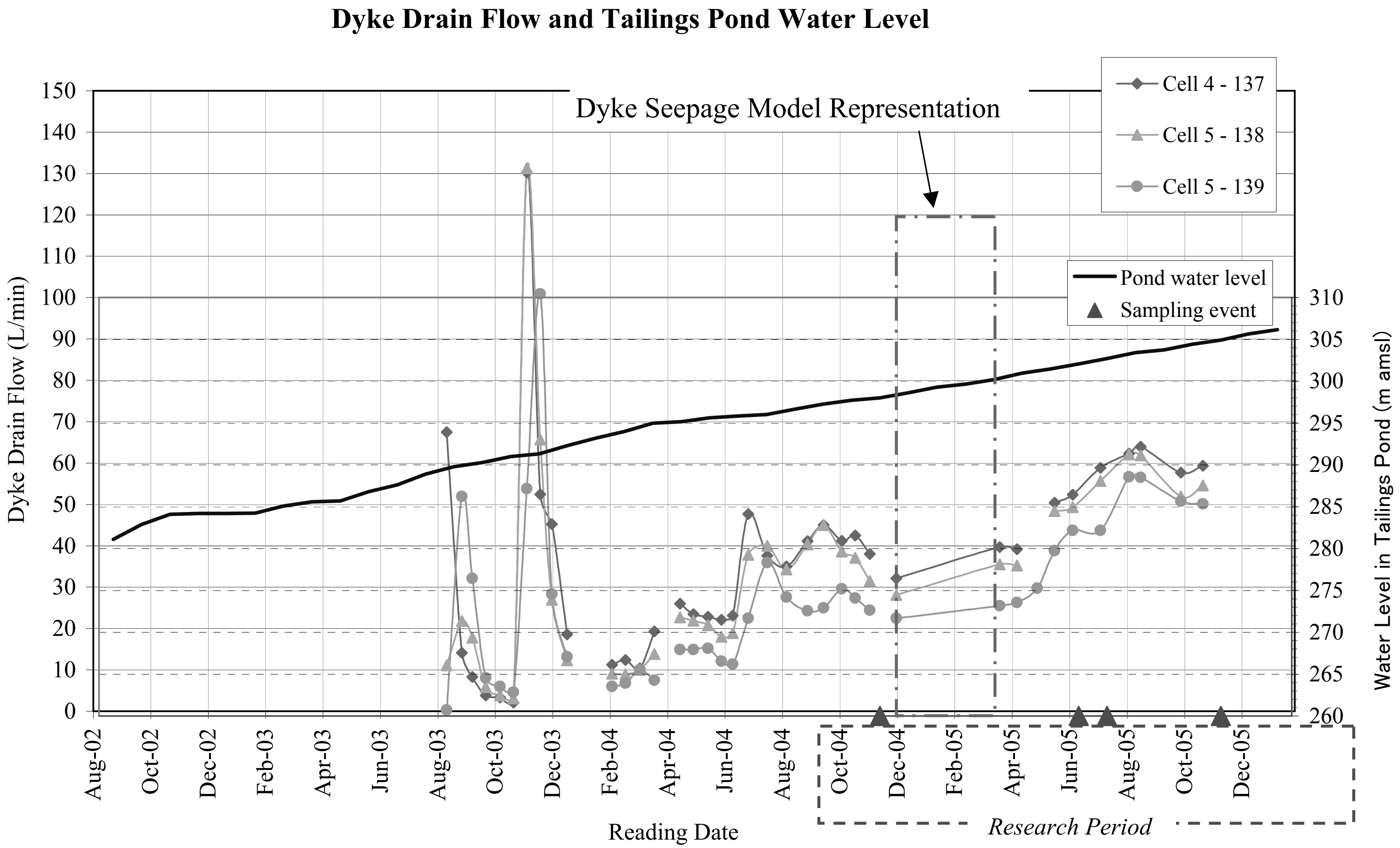


Fig. 6.4 Transient Behaviour of Dyke Drain Discharge and Tailings Pond Water Level

7. Conclusions and Recommendations

7.1. Conclusions

7.1.1 Hydraulic System and PAW Migration

Dyke seepage water is assumed to be drained by the internal drain system; however, the outcome of this research has indicated the existence of an additional PAW seepage pathway through the bottom of the tailings pond and into the permeable pf-sand aquifer. It is likely that a thin layer of pf-sand exists under the dyke and is transmitting a ~0.3 m^3/day/m of seepage water into the pf-sand aquifer. This component of seepage water migrates southward in the pf-sand and discharges in the Wet Area. The rest of the dyke seepage water in the Study Area is collected by the internal drainage system and released into the Inner Ditch. It was also determined that the groundwater and ditch water in the Inner Ditch possibly interact with each other to some extent.

Chemical profiling, including stable isotopes and NA characterization revealed migration of PAW towards the Outer Ditch with no clear sign of attenuation within the pf-sand aquifer. The front of PAW has remained somewhere between OuD-N and BtD-S from November 2005 to May 2006. Currently the inward hydraulic gradient across the Outer Ditch prevents migration of PAW under the Outer Ditch.

7.1.2 Effectiveness of Ditch System

The seepage collection ditch system in the Study Area is serving effectively to collect seepage water from the dyke outtake drain-pipes; however, installation of the system neglected to consider the presence of permeable pf-sand in the Study Area. As a result, some seepage water migrates under the Inner Ditch through the pf-sand and some ditch water migrates into the pf-sand through the bottom of the ditch. Although the migration of PAW beyond the Outer Ditch is prevented due to the inward hydraulic gradient across the Outer Ditch, changes to the hydraulic conditions could allow PAW to move beyond the Outer Ditch. Such conditions could be created by the on-going dyke expansion work. From this point of view, the ditch system has the following two potential concerns with regard to the “zero discharge policy”:

1) No lining of the Inner ditch
2) Insufficient excavation depth of the Outer Ditch

As a result of these issues, there is a potential for PAW to migrate off site.

7.2. Recommendations

(1) Ditch system design in the presence of surficial sand

As indicated by this study, a collection ditch system may not work as designed to capture seepage from a tailings pond and dyke in the presence of a permeable surface layer. In the case of the Muskeg River Mine, the advance of PAW in the Study Area is controlled by the inward hydraulic gradient across the Outer Ditch. However, migration of PAW beyond ditch systems has been reported in other studies of similar sites (Oiffer 2005; Mackinnon, 2005) where much thicker surface sand layer is present. The design of the collection ditch system should be reviewed to minimize seepage into shallow groundwater in such conditions. Lining of all ditches including temporary ones is recommended when no seepage flow is expected from the bottom of the dyke. If deep seepage is anticipated, deeper excavation of ditches would be the only viable solution.

(2) Hydraulic placement of tailings sand enhances the migration of contaminated water

At the ASE site, on-going dyke expansion is expected to change the hydraulic system observed during this study. The location of the front of process affected groundwater may advance further south as a result of this change, and additional PAW may be introduced. It is recommended that the groundwater flow and chemistry be monitored downgradient during and after the expansion, especially if pf-sand is believed to extend to the south. Additional monitoring is recommended if hydraulic cell construction is employed.

(3) Chemical tracers to track PAW

This Study has revealed the effectiveness of stable isotopes of hydrogen and oxygen as tracers of PAW and is consistent with the findings reported by Gervais (2004). Therefore the use of these chemical parameters, as a supplement to conventional inorganic tracers, to track PAW migration for future research and groundwater monitoring programs at the Muskeg River Mine is recommended. Based on the data collected as part of this research, the key chemical parameters that can be used for future groundwater quality monitoring efforts near the Study Area are listed below along with respective threshold concentrations that indicate the presence of PAW.

- Na^+ and Cl^- ions (over 20 and 5 mg/L respectively indicative of PAW)
- SO_4^{2-} and Ca^{2+} ions (less than about 300 and 200 mg/L respectively indicative of PAW)
- Stable isotopes of Hydrogen and Oxygen delta values (over -140 and -17 ‰ respectively

indicative of PAW)

- Naphthenic acids (over 5 mg/L indicative of PAW)

(4) Issues and Suggestions for future research in the Study Area

- Confirmation of the effect of dyke expansion construction on the local groundwater flow system in the Study Area or the effect of hydraulic dyke expansion on other sites with similar conditions will be of interest.
- Contaminant attenuation or dilution during seepage through the dyke body should be further examined since it is contrary to the findings at the Syncrude mine.
- Characteristics of transient behavior of groundwater in the Study Area should be further investigated.

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APPENDIX

Appendix

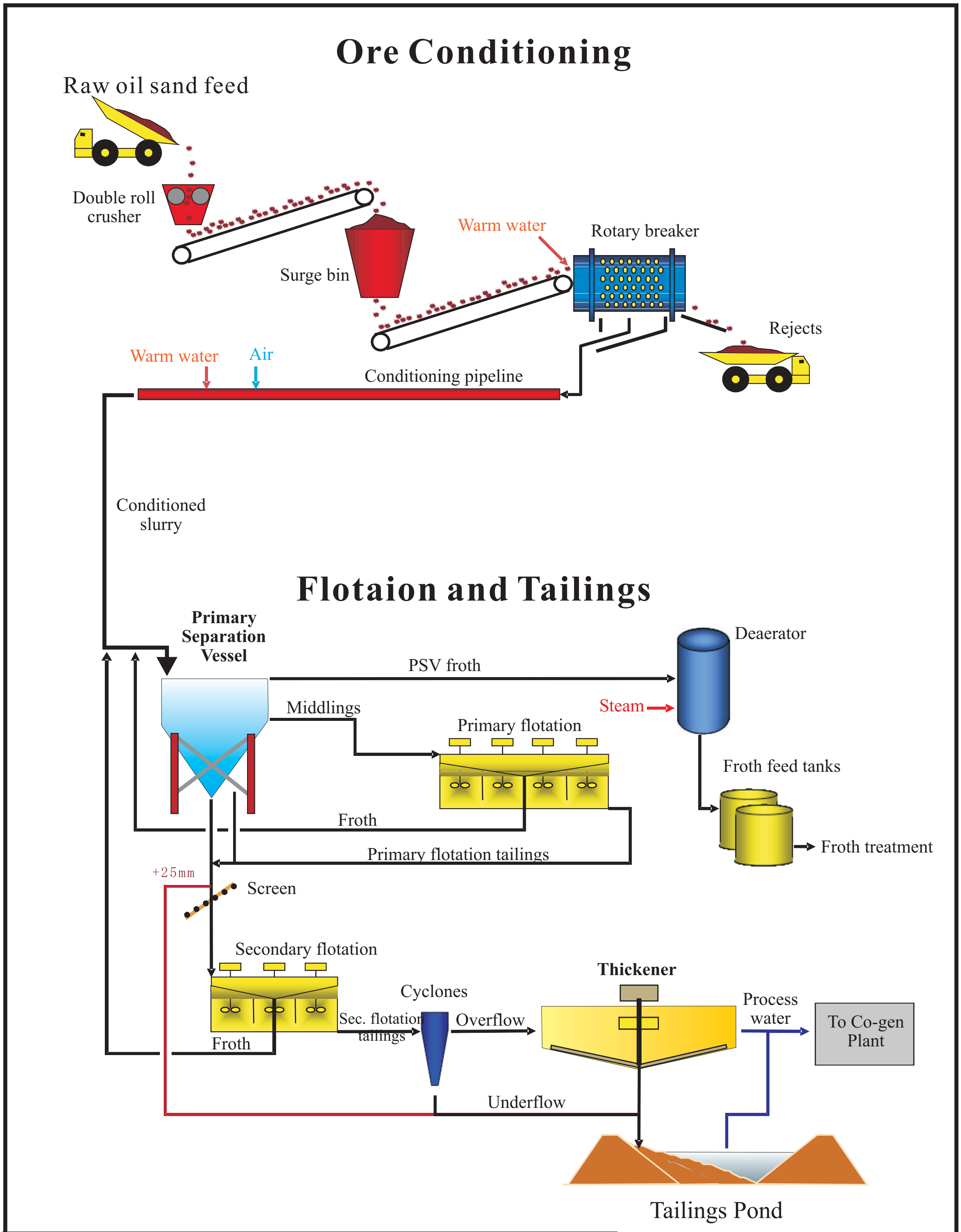
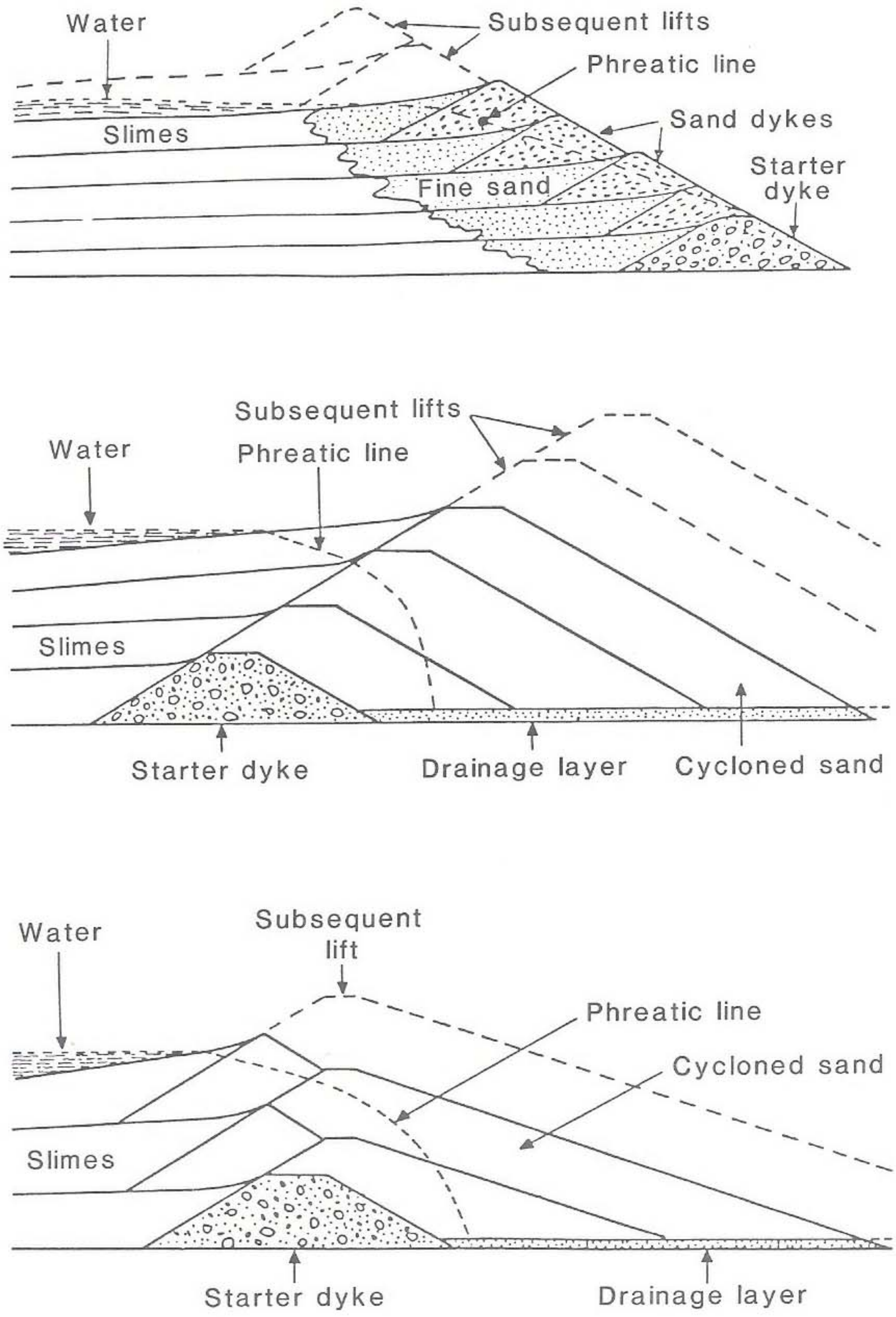


Fig. A 2.1 Oil Sand Mining Process at ASE

Modified from ASE



After Gordon M. Ritcey 1989, Tailings Management Problems and Solutions in the Mining Industry

Fig. A 2.2 Staged Dyke Expansion Method

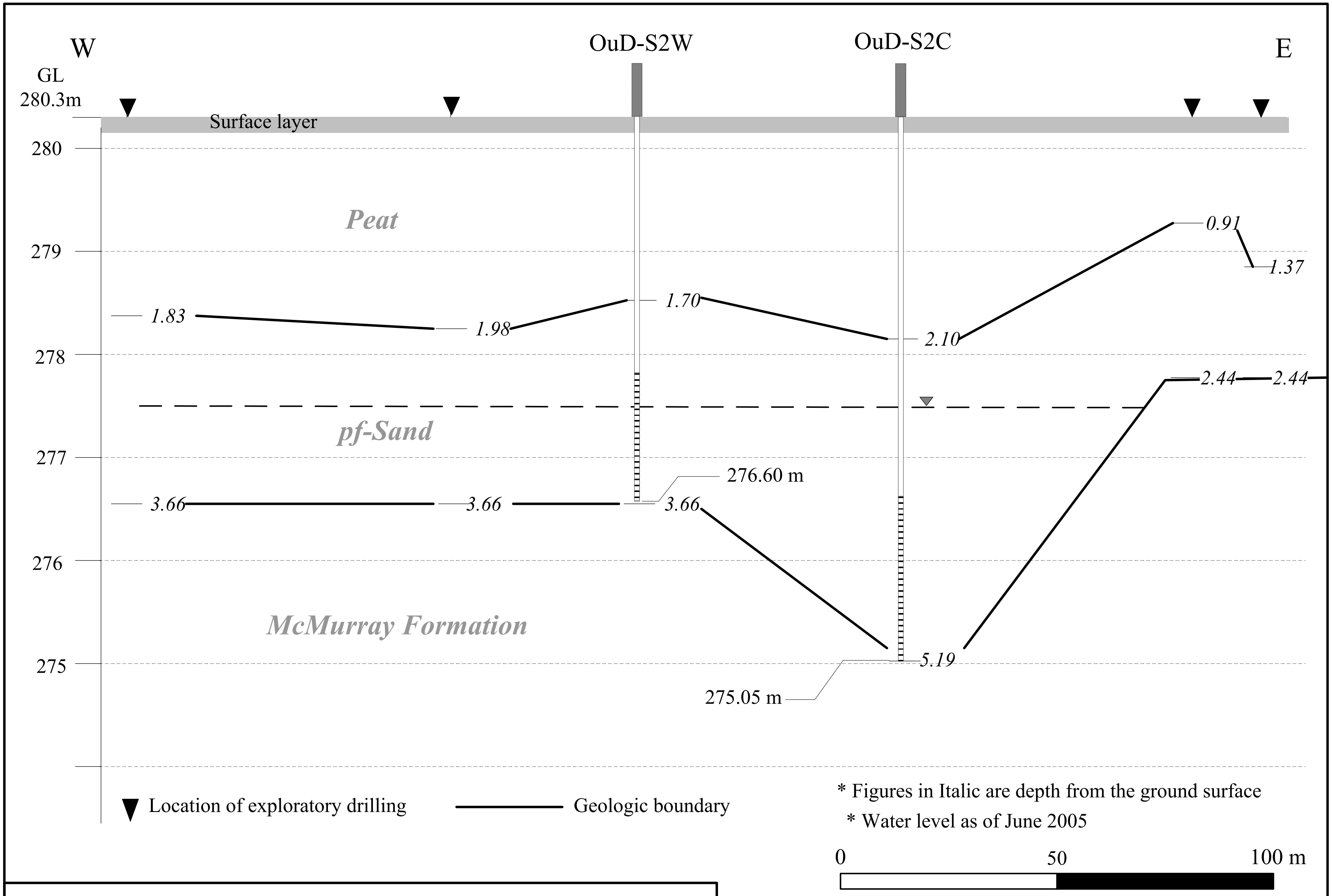


Fig. A 2.3 Stratigraphic Profile along the Haul Road

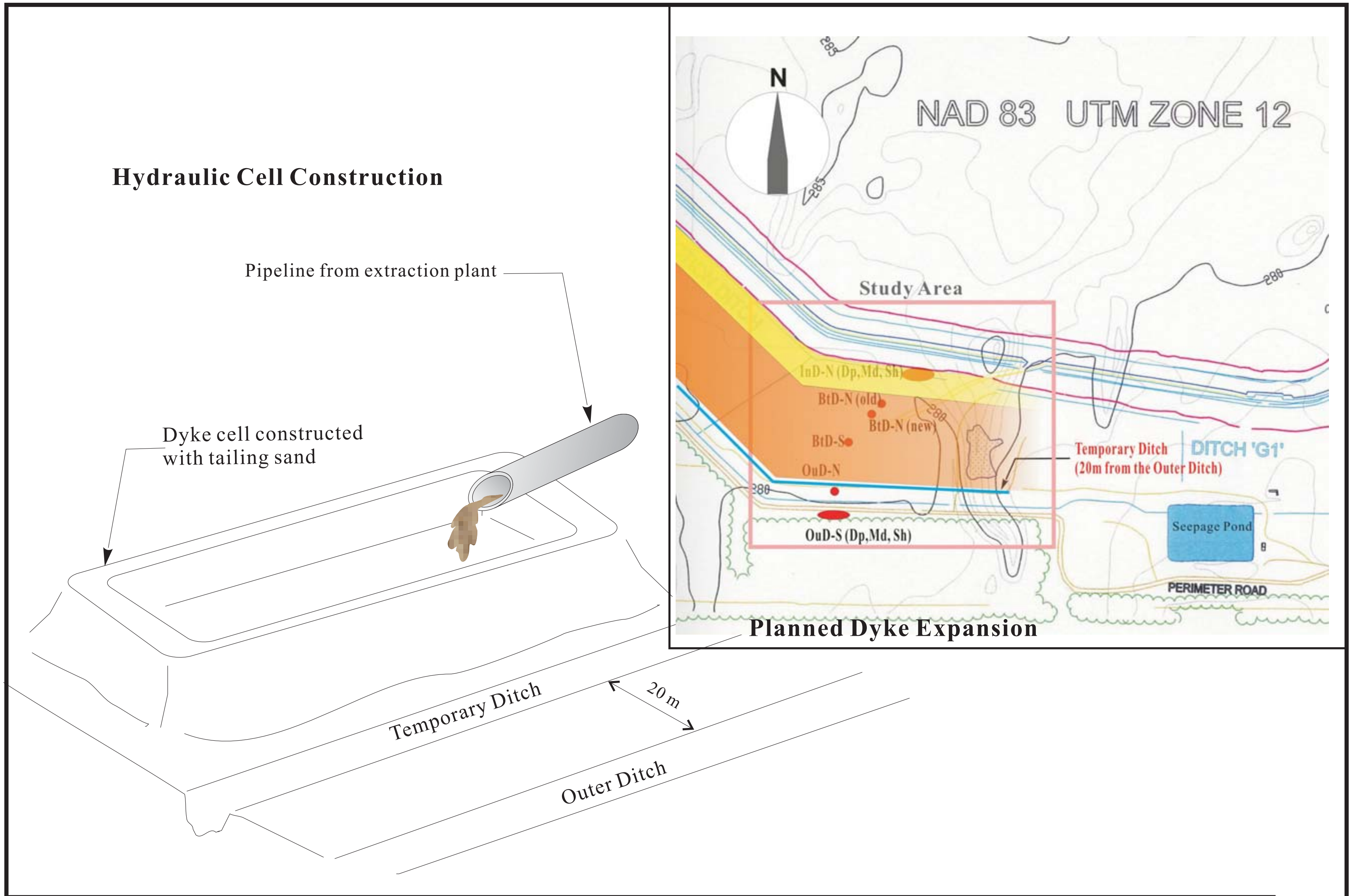


Fig. A 2.4 Schematic of Dyke Expansion Method and Procedure at the Muskeg River Mine

Step 1
Hollow Steel Casing with disposible drive point at base is pushed into ground to desired

Step 2
Insert Pre-Assembled Monitoring Well into Casing

Step 3
Hollow Steel Casing is removed. Pre-Assembled Monitoring Well Remains in Place.

Step 4
Pre-Assembled Monitoring Well Remains in Place and Protective Outer Housing is

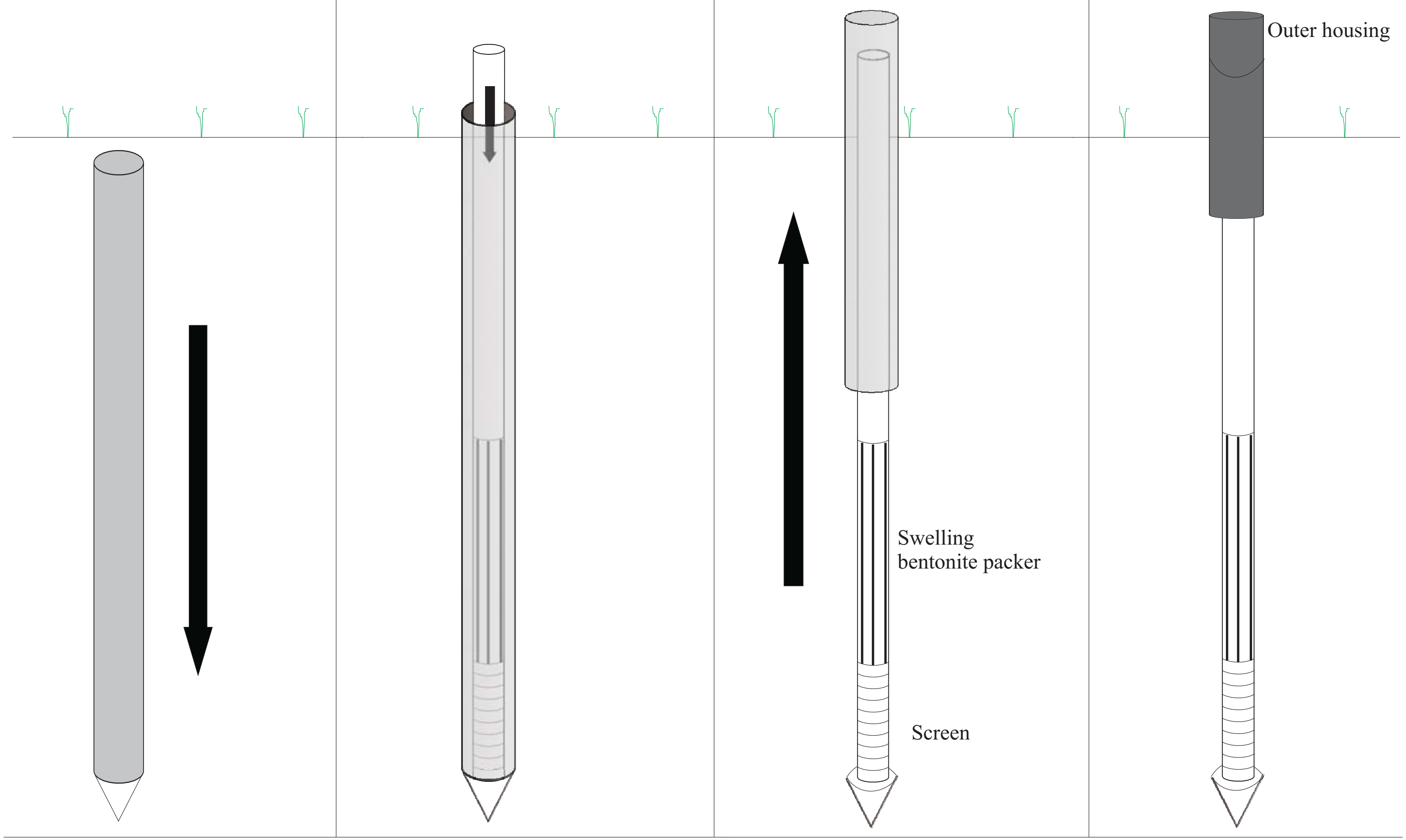


Fig. A 3.1 Monitoring Piezometer Installation

Modified from. Oiffer, 2005

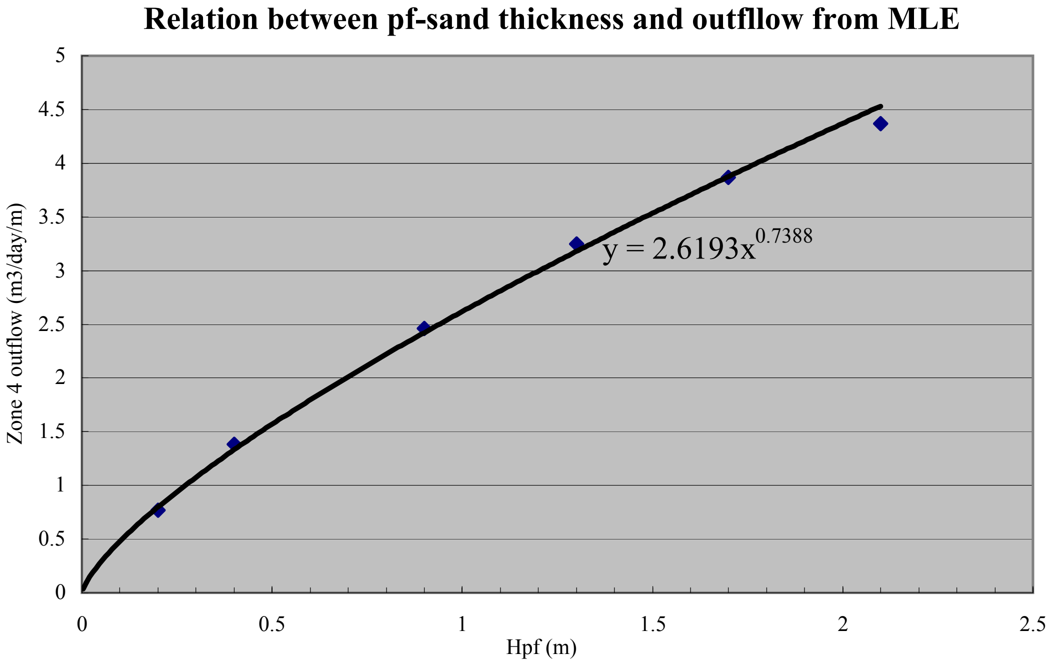
Hpf (m)	Outflow MLE (m^3/day/m)	K tailings sand
2.1	4.37	3.6x10-5
1.7	3.87	3.1x10-5
1.3	3.25	2.6x10-5
0.9	2.46	2.0x10-5
0.4	1.38	1.3x10-5
0.2	0.77	1.0x10-5
0.07	0.37	extrapolated
0.048	0.28	extrapolated

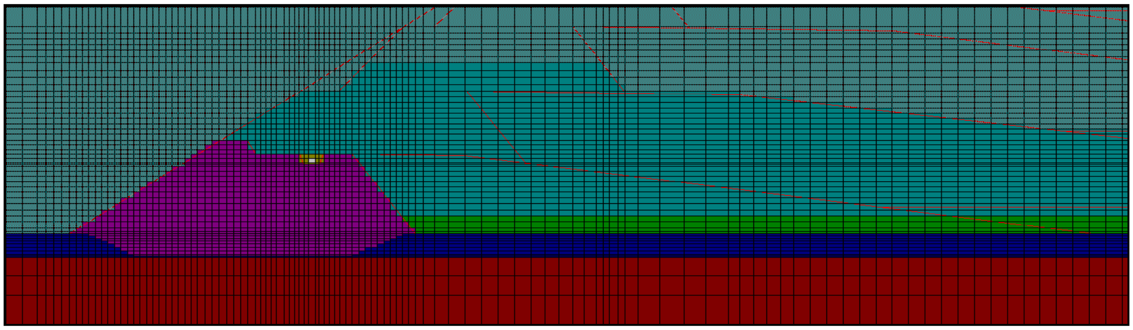
Hpf: thickness of pf-sand

Method

For each given thickness of pf-sand in the left talbe, hydraulic conductivity of tailings sand wa changed to match the outflow from the internal drain of $0.35m^3$/day/m.

The result was plotted on the scatter diagram below and extrapolated with the regression curve shown on the graph to estimate the thickness of pf sand reqired to get max and min outputs from ModelLleft Edge (MLE)





Distribution of pf-sand (area in blue) under the dyke for the calibrated

Fig. A 5.1 Re-calibration of Dyke Seepage Model to INDM Model

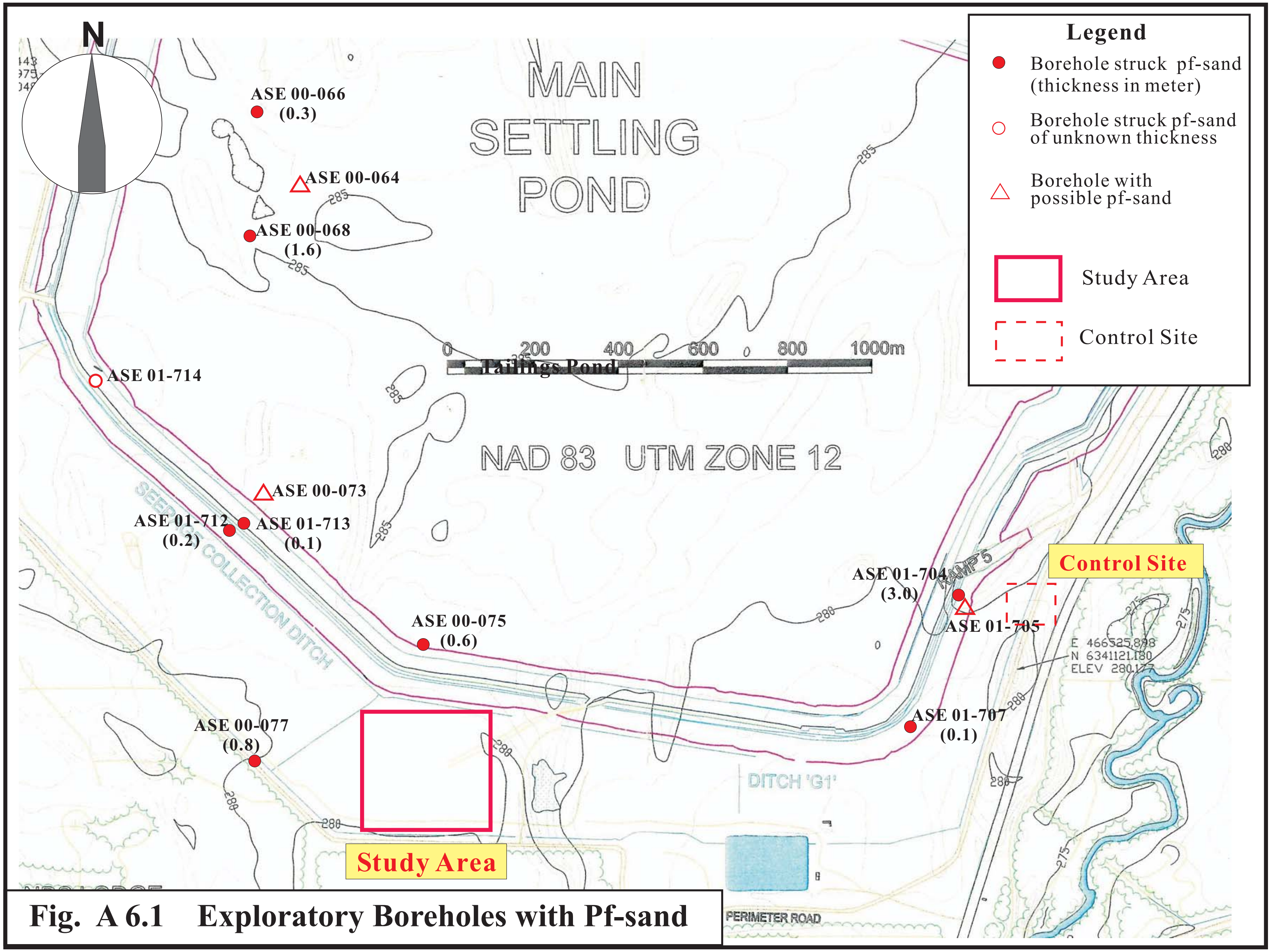


Fig. A 6.1 Exploratory Boreholes with Pf-sand

Table A 2.1 Physical Composition of Three Different Tailings

	Coarse	Thickened	TSRU
Water	3.12 Mt	1.29 Mt	0.69 Mt
Hydrocarbon	0.03 Mt	0.03 Mt	0.08 Mt
Sand	4.81 Mt	0.61 Mt	0.06 Mt
Fines	0.51 Mt	0.70 Mt	0.12 Mt
Clay in fines	0.17 Mt	0.24 Mt	0.03 Mt
Total mineral	5.32 Mt	1.30 Mt	0.18 Mt
Sand : Fine	9.4 : 1	0.87 : 1	0.5 : 1
Clay : Water	0.05 : 1	0.19 : 1	0.04 : 1
Solid %	63 %	50 %	27 % inc. H-C
D_{50}	200 to 300 µm	40 µm	N/A

Source : ASE 2003, Mt: million tones for September 2003

Table A-2.2 Results of Field Parameter Measurements

	Group	ID	Oct. 2004				June-July 2005					Oct. 2005					June. 2006					Remarks
			Temp (^{o}C)	pH	EC	Date	Temp (^{o}C)	pH	EC	Flow rate (L/s)	Date	Temp (^{o}C)	pH	EC	Flow rate (L/s)	Date	Temp (^{o}C)	pH	EC	Flow rate (L/s)	Date	
Piezometers																						
1	InD-N	Dp	8.4	7.90	922	29-Oct	14.7	7.20	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
2	InD-N	Md	7.5	7.90	868	29-Oct	14.6	7.30	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
3	InD-N	Sh	7.1	6.60	1192	29-Oct	15.9	7.10	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
4	InD-S	Dp	9.0	7.06	929	29-Oct	12.8	7.50	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
5	InD-S	Md	9.1	7.04	925	29-Oct	14.0	7.40	-	N/A	16-Jun	8.0	-	-	N/A	31-Oct	-	-	-	N/A	-	
6	InD-S	Sh	7.6	7.03	962	29-Oct	16.0	7.38	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
7	InD-DVP		6.1	7.54	1261	29-Oct	-	-	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
8	BtD-N	new	7.5	7.70	1155	29-Oct	11.5	6.99	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
9	BtD-N	old	-	-	-	29-Oct	-	-	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
10	BtD-S		4.2	7.11	2070	29-Oct	15.4	7.25	-	N/A	16-Jun	5.6	-	-	N/A	31-Oct	11.9	-	-	N/A	30-May	
11	OuD-N		2.4	6.93	1692	29-Oct	13.2	6.82	-	N/A	16-Jun	3.5	-	-	N/A	31-Oct	13.4	-	-	N/A	30-May	
12	OuD-DVP		-	-	-	-	-	-	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	clogged
13	OuD-S	Dp	4.5	6.62	1875	29-Oct	7.8	7.00	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
14	OuD-S	Md	4.5	6.71	1443	29-Oct	7.4	7.00	-	N/A	16-Jun	4.7	-	-	N/A	31-Oct	6.3	-	-	N/A	30-May	
15	OuD-S	Sh	4.2	6.95	1357	29-Oct	7.9	7.36	-	N/A	16-Jun	-	-	-	N/A	-	-	-	-	N/A	-	
16	CNT-E		-	-	-	-	-	-	-	N/A	-	-	-	-	N/A	-	-	-	-	N/A	-	unproductive
17	CNT-W		-	-	-	-	-	-	-	N/A	-	-	-	-	N/A	-	-	-	-	N/A	-	unproductive
18	CNT-DVP		-	-	-	-	-	-	-	N/A	-	-	-	-	N/A	-	-	-	-	N/A	-	bent
19	OuD-S2C		N/A	N/A	N/A	N/A	7.3	-	-	N/A	11-Jul	-	-	-	N/A	-	4.4	-	-	N/A	30-May	
20	OuD-S2W		N/A	N/A	N/A	N/A	7.2	-	-	N/A	11-Jul	-	-	-	N/A	-	6.6	-	-	N/A	30-May	
21	CNT-E2		N/A	N/A	N/A	N/A	-	-	-	N/A	-	-	-	-	N/A	-	-	-	-	N/A	-	
Ditches																						
	InD water		5.6	8.15	1393	29-Oct	18.4	-	-	-	16-Jun	4.9	-	-	-	1-Nov	-	-	-	-	-	
	OuD water		2.4	7.70	1226	29-Oct	18.1	7.96	-	-	16-Jun	-	-	-	50	1-Nov	-	-	-	-	-	
	CNT-D		5.3	7.93	1052	29-Oct	-	-	-	-	-	5.3	-	-	-	1-Nov	-	-	-	-	-	
Tailings Pond																						
	Taillings Pond		-	-	-	-	18.3	-	-	N/A	18-Jun	-	-	-	N/A	-	-	-	-	N/A	-	south
Drain pipes																						
	DP 1		-	-	-	-	-	-	-	0.40	19-Jun	-	-	-	0.67	1-Nov	-	-	-	-	-	west
	DP 2		-	-	-	-	11.5	-	-	0.57	19-Jun	-	-	-	0.73	1-Nov	-	-	-	-	-	near east
	DP 3		-	-	-	-	-	-	-	0.67	19-Jun	12.9	-	-	0.67	1-Nov	-	-	-	-	-	far east

Table A-2.3 Location and Depth of Installed Piezometes and Drive Points

	Group	ID	GPS coordinates		Stick up	Top of tube*	Screen Depth**	Screen Length	Ground Level	Pf-sand Thickness	Remark
			Lat. N	Long. W	(m AGL)	(m ASL)	(m BGL)	(m)	(m ASL)	(m)	
1	InD-N	Dp			0.85	282.350	2.95	0.10	281.470	3.20	
2	InD-N	Md	57.12.672	111.34.528	0.84	282.350	2.15	0.10	281.480	3.20	
3	InD-N	Sh			0.75	282.260	1.65	0.10	281.480	3.20	
4	InD-S	Dp			0.86	281.910	2.95	0.10	281.050	3.20	
5	InD-S	Md	57.12.664	111.34.527	0.85	281.910	2.25	0.10	281.030	3.20	
6	InD-S	Sh			0.86	281.890	1.45	0.10	281.040	3.20	
7	InD-DVP				-	280.899	1.00	0.20	-	1.83	
8	BtD-N	new	57.12.596	111.34.620	0.86	278.390	1.46	0.10	277.520	1.83	
9	BtD-N	old	57.12.601	111.34.601	1.04	280.010	0.60	0.10	278.915	0.70	Dry, replaced by new
10	BtD-S		57.12.558	111.34.637	0.86	277.950	1.33	0.10	277.059	1.60	
11	OuD-N		57.12.516	111.34.663	0.85	277.950	0.85	0.10	277.050	1.10	
12	OuD-DVP				-	277.268	1.00	0.20	-	0.75	Clogged, no water production
13	OuD-S	Dp			0.78	281.070	5.32	0.10	280.290	3.50	
14	OuD-S	Md	57.12.496	111.34.670	0.88	281.170	4.75	0.10	280.310	3.50	
15	OuD-S	Sh			0.89	281.171	4.00	0.10	280.290	3.50	
16	CNT-E		57.12.771	111.33.216	0.83	280.360	3.77	0.10	279.530	0.00	Little water
17	CNT-W		57.12.777	111.33.257	0.86	279.470	1.85	0.10	278.590	0.00	Little water
18	CNT-DVP				-	277.776	0.50	0.20	-	0.00	Little water, bent in winter
19	OuD-S2C		57.12.493	111.34.664	0.81	281.091	5.19	1.53	280.227	2.00	2 inch dia., installed in Summer 2005
20	OuD-S2W		57.12.496	111.34.727	0.88	281.202	3.66	1.22	280.265	3.50	2 inch dia., installed in Summer 2005
21	CNT-E2		57.12.766	111.33.216	0.79	280.291	3.66	0.92	279.418	0.00	2 inch dia., installed in Summer 2005
	DP-1 ***		57.12.680	111.34.609	-	-	-	-	-	-	Located at the toe-berm
	DP-2 ***		57.12.669	111.34.463	-	-	-	-	-	-	Located at the toe-berm
	DP-3 ***		57.12.675	111.34.311	-	-	-	-	-	-	located at a higher elevation, halfway on the slope

InD: Inner Ditch,
OuD: Outer Ditch,
BtD: Between Ditch
CNT: Control

- N : North side
- S : South side
- W : West side
- S : East side

AGL : Above Ground Leve
BGL : Below Ground Leve
FTT : From Top of inner tube (stick up)
ASL : Above Sea Level

* Elevation at the top of inner plastic pipe (stick-up)
** Screen depth : depth to the bottom of screen below ground surface
*** Outake pipes from the internal drainage system

Table A 3.1 Location and Log of Exploratory Boreholes

S/N	Area	Northing (57-)	Easting (111-)	Ground Elev. (m amsl)	Bottom of layer from Ground Level (m)			Date drilled	remarks
					Surface layer	Peat	pf-sand		
1	InD-S	12.649	34.477	-	-	-	2.75	10/25/2004	pf-sand is brownish, McMurray F. is silty-clayey
2	InD-S	12.644	34.552	-	-	-	2.28	10/25/2004	pf^sand is brownish, a lot of gravel toward the bottom, McMurray is clayey
3	InD-S	12.665	34.686	-	-	-	2.71	10/25/2004	pf-sand top 40 cm brownish, includes pebbles (many toward bottom)
4	InD-S	12.654	34.617	-	-	-	2.20	10/25/2004	pf-sand is brownish with some thin black organic films, grey below 0.7m
5	InD-S	12.638	34.579	-	-	-	2.71	10/25/2004	pf-sand top 1m brownish, gravel is seen at the bottom, grey and loose. McMurray is clayey
6	OuD-S	12.495	34.615	-	-	0.75	3.00	10/25/2004	Peat is black and fine with plant roots at the top. Pf-sand is dry with some gravel, partly black. McMuray F. is very clayey
7	InD-S	12.663	34.531	-	-	-	-	10/27/2004	Core and off-auger samples were taken at 0.5, 1.4, 2.2, 3.0m.
8	OuD-S	12.494	34.663	280.3	0.15	2.29	5.01	10/27/2004	The interface between the peat and pf-sand interfingers. Pf-sand is wet at 3.26m.
9	CNT	12.523	34.382	-	-	-	-	10/29/2004	Black fine peat soil with boulders -- black/brown silt and clay
10	BtD-N	12.601	34.601	278.9	-	-	1.83	10/29/2004	pf-sand is very course with gravel. McMurray F. is sticky. Piezometer installed.
11	OuD-S2C	12.493	34.664	280.2	0.2	2.1	5.00	7/9/2005	Piezometer installed 5m to the east of OuD-S Dp.
12	OuD-S	12.493	34.578	-	0.6	1.37	2.44	7/9/2005	-
13	OuD-S	12.494	34.593	-	0.3	0.92	2.44	7/9/2005	Surface layer is oilsily and sandy soil. Pf-sand is made of sily grey sand with rounded pebbles, grading into corase grey sand toward the bottom, dry.
14	OuD-S	12.496	34.727	-	0.3	1.68	3.66	7/9/2005	pf-sand top 0.3m brownish, partly silty up to 2.44m, grey and wet after this depth. 2 in-piezometer installed.
15	OuD-S	12.498	34.773	-	ND	1.98	3.66	7/9/2005	peat is black and partly brown. Pf-sand is black at top 0.2m. McMurray F. is silty clay..
16	OuD-S	12.500	34.851	-	ND	1.83	3.66	7/9/2005	Peat is brownish. Top of pf-sand is silty with max 5cm dia peble.

Table A-3.2 (a) Details of Collected Samples for the First Phase, Fall 2004

	Group	ID	GPS coordinates		Water		Sediment			Remark
			Lat. N	Long. W	Routine*	NA**	Scoop***	Auger / depth	Core / depth	
1	InD-N	Dp			1	1		3m sand coarse brown 3.6m oil silt		3m core
2	InD-N	Md	57.12.672	111.34.528	1	1		2.2m sand coarse brown\		
3	InD-N	Sh			1	1		0.5m sand brown 1.4m sand brown	1m, 2m, 3m, 4m	
4	InD-S	Dp			1	1				
5	InD-S	Md	57.12.664	111.34.527	1	1				
6	InD-S	Sh			1	1				
7	InD-DVP				1	1				
8	BtD-N	new	57.12.596	111.34.620	1	1				
9	BtD-N	old	57.12.601	111.34.601	-	-				
10	BtD-S		57.12.558	111.34.637	1	1				
11	OuD-N		57.12.516	111.34.663	1	1		0.6m coarse sand	1m, sand	
12	OuD-DVP				-	-				
13	OuD-S	Dp			1	1		4.7m coarse sand brown		
14	OuD-S	Md	57.12.496	111.34.670	1	1		3.25m coarse sand		
15	OuD-S	Sh			1	1		0.7m peat soil		
16	CNT-E		57.12.771	111.33.216	-	-		3.8m oil sand		McMurray F. oil silt
17	CNT-W		57.12.777	111.33.257	-	-				
18	CNT-DVP				-	-				
19	InD		57.12.664	111.34.527	1	1	1			
20	OuD		57.12.516	111.34.663	1	1	1			
21	CNT-D		57.12.777	111.33.257	1	1	1			
22	Taillings Pond				1	1	1	bottom, 0.5 m below WL		near south shore
23	Drain Pipe				-	-				
24	Taillings return pipe				1	1				Sampled by ASE
25	Pipe to Plant				-	-				
26	Pipe from Plant				-	-				
	Total				18	18	4	11	5	

* Routine : Inorganic ions and major parameters for water potability

** NA : Total napthenic acid concentration

*** Samples scooped off the bottom

Table A-3.2 (b) Details of Collected Samples for the Second Phase, Summer 2005

	Group	ID	GPS coordinates		Water				Remark
			Lat. N	Long. W	Routine*	NA**	NA Detail***	Stable Isotope	
1	InD-N	Dp			1	1	-	-	
2	InD-N	Md	57.12.672	111.34.528	1	1	-	1	
3	InD-N	Sh			1	1	-	-	
4	InD-S	Dp			1	1	-	-	
5	InD-S	Md	57.12.664	111.34.527	1	1	1	1	
6	InD-S	Sh			1	1	-	-	
7	InD-DVP				1	1	-	-	
8	BtD-N	new	57.12.596	111.34.620	1	1	1	1	
9	BtD-N	old	57.12.601	111.34.601	-	-	-	-	
10	BtD-S		57.12.558	111.34.637	1	1	-	1	
11	OuD-N		57.12.516	111.34.663	1	1	1	1	
12	OuD-DVP				-	-	-	-	
13	OuD-S	Dp			1	1	-	1	
14	OuD-S	Md	57.12.496	111.34.670	1	1	-	1	
15	OuD-S	Sh			1	1	-	1	
16	CNT-E		57.12.771	111.33.216	1	-	-	-	Sampled in 3 days
17	CNT-W		57.12.777	111.33.257	1	-	-	-	Sampled in 3 days
18	CNT-DVP				-	-	-	-	
	OuD-S2C		57.12.493	111.34.664	1	1	-	-	
	OuD-S2W		57.12.496	111.34.727	1	1	-	-	
	CNT-E2		57.12.766	111.33.216	1	1	-	-	
19	InD water		57.12.664	111.34.527	1	1	1	1	
20	OuD water		57.12.516	111.34.663	1	1	1	1	
21	CNT-D water		57.12.777	111.33.257	-	-	-	-	
22	Pond water		57.12.558	111.34.637	-	-			surface water at BtD-S
23	Taillings Pond	center	57.13.101	111.34.874	2	1	-	-	
	Taillings Pond	south	57.12.951	111.34.510					
24	Drain Pipe	NE	57.12.669	111.34.463	1	1	-	-	
25	Talilings return pipe				-	-	-	-	Sampled by ASE
26	Pipe to Plant				-	-	-	-	
27	Pipe from Plant				-	-	1	-	
	Total				23	20	6	10	

* Routine : Inorganic ions and major parameters for water potability

** NA : Total naphthenic acid concentration

*** NA detail: Characterization of naphthenic acid

Table A-3.2 (c) Details of Collected Samples for the Third Phase, Fall 2005

	Group	ID	GPS coordinates		Water				Remark
			Lat. N	Long. W	Routine*	NA**	NA*** Detail	Stable Isotope	
1	InD-N	Dp			-	-	-	-	
2	InD-N	Md	57.12.672	111.34.528	-	-	-	-	
3	InD-N	Sh			-	-	-	-	
4	InD-S	Dp			-	-	-	-	
5	InD-S	Md	57.12.664	111.34.527	1	1	-	-	
6	InD-S	Sh			-	-	-	-	
7	InD-DVP				-	-	-	-	
8	BtD-N	new	57.12.596	111.34.620	-	-	-	-	
9	BtD-N	old	57.12.601	111.34.601	-	-	-	-	
10	BtD-S		57.12.558	111.34.637	1	1	-	-	
11	OuD-N		57.12.516	111.34.663	1	1	-	-	
12	OuD-DVP				-	-	-	-	
13	OuD-S	Dp			-	-	-	-	
14	OuD-S	Md	57.12.496	111.34.670	1	1	-	-	
15	OuD-S	Sh			-	-	-	-	
16	CNT-E		57.12.771	111.33.216	-	-	-	-	
17	CNT-W		57.12.777	111.33.257	-	-	-	-	
18	CNT-DVP				-	-	-	-	
	OuD-S2C	2in	57.12.493	111.34.664	-	-	-	-	
	OuD-S2W	2in	57.12.496	111.34.727	1	1	-	-	
	CNT-E2	2in	57.12.766	111.33.216	-	-	-	-	
19	InD water		57.12.664	111.34.527	-	-	-	-	
20	OuD water		57.12.516	111.34.663	1	1	-	-	
21	CNT-D water		57.12.777	111.33.257	-	-	-	-	
22	Pond water		57.12.558	111.34.637	1	1	-	-	surface water at BtD-S
23	Taillings Pond	center	57.13.101	111.34.874	-	-	-	-	
	Taillings Pond	south	57.12.951	111.34.510	-	-	-	-	
24	Drain Pipe	NE	57.12.669	111.34.463	-	-	-	-	
25	Talings return pipe				-	-	-	-	
26	Pipe to Plant				-	-	-	-	
27	Pipe from Plant				-	-	-	-	
	Total				7	7	0	0	

* Routine : Inorganic ions and major parameters for water potability

** NA : Total naphthenic acid concentration

*** NA detail: Characterization of naphthenic acid

Table A-3.2 (d) Details of Collected Samples for the Fourth Phase, Spring 2006

	Group	ID	GPS coordinates		Water				Remark
			Lat. N	Long. W	Routine*	NA**	NA*** Detail	Stable Isotope	
1	InD-N	Dp			-	-	-	-	piezometer demolished
2	InD-N	Md	57.12.672	111.34.528	-	-	-	-	piezometer demolished
3	InD-N	Sh			-	-	-	-	piezometer demolished
4	InD-S	Dp			-	-	-	-	piezometer demolished
5	InD-S	Md	57.12.664	111.34.527	-	-	-	-	piezometer demolished
6	InD-S	Sh			-	-	-	-	piezometer demolished
7	InD-DVP				-	-	-	-	piezometer demolished
8	BtD-N	new	57.12.596	111.34.620	-	-	-	-	
9	BtD-N	old	57.12.601	111.34.601	-	-	-	-	
10	BtD-S		57.12.558	111.34.637	1	1	-	-	
11	OuD-N		57.12.516	111.34.663	1	1	-	-	
12	OuD-DVP				-	-	-	-	
13	OuD-S	Dp			-	-	-	-	
14	OuD-S	Md	57.12.496	111.34.670	1	1	-	-	
15	OuD-S	Sh			-	-	-	-	
16	CNT-E		57.12.771	111.33.216	-	-	-	-	piezometer demolished
17	CNT-W		57.12.777	111.33.257	-	-	-	-	piezometer demolished
18	CNT-DVP				-	-	-	-	
	OuD-S2C	2in	57.12.493	111.34.664	1	1	-	-	
	OuD-S2W	2in	57.12.496	111.34.727	1	1	-	-	
	CNT-E2	2in	57.12.766	111.33.216	-	-	-	-	
19	InD water		57.12.664	111.34.527	-	-	-	-	
20	OuD water		57.12.516	111.34.663	-	-	-	-	
21	CNT-D water		57.12.777	111.33.257	-	-	-	-	
22	Pond water		57.12.558	111.34.637	-	-	-	-	surface water at BtD-S
23	Taillings Pond	center	57.13.101	111.34.874	-	-	-	-	
	Taillings Pond	south	57.12.951	111.34.510	1	1	-	-	
24	Drain Pipe	NE	57.12.669	111.34.463	-	-	-	-	
25	Talings return pipe				-	-	-	-	
26	Pipe to Plant				-	-	-	-	
27	Pipe from Plant				-	-	-	-	
	Total				6	6	0	0	

* Routine : Inorganic ions and major parameters for water potability

** NA : Total naphthenic acid concentration   *** NA detail: Characterization of naphthenic acid

Table A-4.1 (a) Results of Water Analysis (Major Ions) Fall 2004 (1/2)

			Inner Ditch North Side			Drive Point	Inner Ditch South Side			Duplicate
Lab ID			34,053,668	34,053,678	34,053,670	34,053,679	34,053,669	34,053,673	34,053,683	34,053,674
Sample ID :			IND-N-DP	IND-N-MD	IND-N-SH	IND-DVP	IND-S-DP	IND-S-MD	IND-S-SH	IND-S-Ctl
Parameter	Unit	MDL*								
PHYSICAL										
pH	pH units	0.1	7.4	7.5	7.6	7.8	7.4	7.5	7.8	7.4
Conductivity	uS/cm	1	1,010	958	1,320	1,220	1,010	1,020	1,070	1,020
Residue Filterable 1.0u (TDS)	mg/L	10	656	623	855	790	659	661	696	664
Computed TDS	mg/L		595	549	811	817	621	608	685	612
Hardness Total -D	mg/L		359	367	483	447	335	339	398	342
GENERAL INORGANICS										
Alkalinity Phen. 8.3 as CaCO3	mg/L	1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Alkalinity Total as CaCO3	mg/L	1	398	385	549	338	388	365	427	376
Carbonate as CO3	mg/L		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Bicarbonate as HCO3-	mg/L		485	469	669	412	473	445	521	458
Hydroxide as OH-	mg/L		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
ANIONS										
Chloride Dissolved	mg/L	0.5	68.1	72.0	59.3	61.4	69.8	66.9	65.0	67.7
Ion Balance	%		2.4	1.5	-0.4	0.4	0.1	1.7	-2.5	1.9
Total Anions	meq/L		10.95	10.34	15.06	13.98	11.42	10.99	12.80	11.08
Total Cations	meq/L		11.5	10.7	14.9	14.1	11.5	11.4	12.2	11.5
Computed Conductance	uS/cm		1,150	1,080	1,540	1,550	1,190	1,170	1,310	1,180
Conductivity % Diff.	%		13	12	15	24	16	14	20	14
NITROGEN										
Nitrate Nitrogen Dissolved (N)	mg/L		0.02	0.03	0.04	0.09	0.02	0.05	< 0.02	0.03
Nitrate+Nitrite (N)	mg/L	0	0	0	0	0	0	0	< 0.02	0
Nitrite Nitrogen (N)	mg/L	0.01	0	< 0.005	0	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
SULFATE										
Sulfate	mg/L	0.5	51.3	29.3	116.0	264.0	80.7	86.2	117.0	79.6
METALS DISSOLVED										
Dissolved Calcium (Ca)	mg/L	0.05	122	125	168	151	112	113	128	114
Dissolved Iron (Fe)	mg/L	0.005	0.089	0.012	0.040	0.015	0.142	0.231	0.013	0.129
Dissolved Magnesium (Mg)	mg/L	0.1	13.1	13.3	15.4	17.0	13.5	13.8	19.1	13.9
Dissolved Manganese (Mn)	mg/L	0.001	0.344	0.944	0.475	0.500	0.366	0.388	0.949	0.367
Dissolved Potassium (K)	mg/L	0.20	5.36	4.00	3.73	5.95	6.93	6.88	6.63	7.03
Dissolved Sodium (Na)	mg/L	0.1	96.4	73.7	120.0	115.0	106.0	102.0	93.5	104.0
Sample type :			Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater
Sampled on:			2004/11/1	2004/11/1	2004/11/1	2004/11/1	2004/11/1	2004/11/1	2004/11/1	2004/11/1

* MDL : Maximum detection limit

Table A-4.1 (a) Results of Water Analysis (Major Ions) Fall 2004 (2/2)

Area Between Ditch		Outer Ditch North	Outer Ditch South Side			Duplicate	Ditch Water			Pond Water
34,053,667	34,053,680	34,053,676	34,053,685	34,053,684	34,053,677	34,053,681	34053682	34053675	3405367	34053672
BtD-N	BtD-S	OUD-N	OUD-S-DP	OUD-S-MD	OUD-S-SH	OUD-S-DP ctl	IND Water	OUD Water	CNT-DITCH	TAILLING POND
7.2	7.5	7.3	7.3	7.4	7.2	7.3	8.2	7.8	7.9	8.0
1,280	2,270	1,870	2,010	1,590	1,500	2,010	1,330	1,150	1,180	959
832	1,480	1,210	1,310	1,040	972	1,310	863	749	765	623
781	1,900	1,530	1,690	1,230	1,130	1,680	894	722	744	562
547	1,440	1,150	1,360	1,030	913	1,340	495	430	378	82
< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
569	209	384	414	437	399	413	376 (1)	404	387	256
< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
694	255	468	505	533	486	503	458	492	472	312
< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
53.6	24.1	8.3	2.4	1.7	1.9	2.2	60.2	51.6	53.9	107.0
1.0	1.0	-2.4	0.2	1.0	-0.8	-0.1	-1.4	0.9	0.9	3.8
14.67	29.27	25.18	27.41	20.56	18.96	27.32	15.63	12.92	13.09	9.54
15.0	29.9	24.0	27.5	21.0	18.7	27.3	15.2	13.2	13.3	10.3
1,500	3,580	2,860	3,190	2,330	2,130	3,170	1,700	1,380	1,410	1,070
16	45	42	45	38	35	45	24	18	18	11
0.04	0.04	0.04	< 0.02	< 0.02	0.04	0.04	0.73	0.12	0.19	0.31
0	0	0	< 0.02	< 0.02	0	0	1	0	0	0
< 0.005	0	< 0.005	< 0.005	< 0.005	0	< 0.005	0	0	0	0
85.4	1,170.0	830.0	917.0	567.0	525.0	913.0	306.0	162.0	183.0	67.1
185	510	402	473	360	330	468	125	129	111	17
0.036	0.020	0.040	0.041	0.058	0.055	0.037	0.021	0.101	0.025	0.058
20.6	41.3	35.2	42.5	31.6	21.6	41.7	44.5	26.2	24.4	9.6
0.162	0.506	0.519	0.537	0.386	0.651	0.553	0.957	0.525	0.670	0.022
3.88	5.76	4.12	2.03	1.96	4.73	2.24	19.20	10.90	13.60	19.40
90.6	19.8	20.9	8.8	7.9	6.6	9.2	111.0	98.8	125.0	188.0
Groundwater 2004/11/1	Groundwater 2004/11/1	Groundwater 2004/11/1	Groundwater 2004/11/1	Groundwater 2004/11/1	Groundwater 2004/11/1	Groundwater 2004/11/1	Surface water 2004/11/1	Surface water 2004/11/1	Surface water 2004/11/1	Surface water 2004/11/1

* MDL : Maximum detection limit

Table A 4.1-(b) Results of Water Analyses (Major Itons) Summer 2005 (1/2)

			Inner Ditch North Side			Drive Point	Inner Ditch South Side			Area Between Ditch		Outer Ditch North Side
Lab ID			831429	831428	831425	831442	831433	831432	831431	831434	831435	831437
Sample ID			IND-N-DP	IND-N-MD	IND-N-SH	IND-DVP	IND-S-DP	IND-S-MD	IND-S-SH	BtD-N	BtD-S	OUD-N
Parameter	Unit	MDL*										
PHYSICAL												
pH	-	0.1	7.9	7.8	7.7	8	7.9	7.9	7.9	7.8	8	7.7
Conductivity	uS/cm	1	1190	1160	1310	1220	1150	1220	1210	1240	1060	2160
TDS (computed)	mg/L	10	720	698	771	748	674	747	729	733	633	1630
TDS (Mesured)	mg/L	20	766	642	828	800	738	796	784	786	676	1830
Hardness (CaCO3)	mg/L	0.5	400	400	390	420	380	420	430	500	430	1300
GENERAL INORGANICS												
Alkalinity (PP as CaCO3)	mg/L	1	0	0	0	0	0	0	0	0	0	0
Alkalinity (Total as CaCO3)	mg/L	1	386	340	500	359	340	360	354	442	329	363
Carbonate (CO3)	mg/L	1	0	0	0	0	0	0	0	0	0	0
Bicarbonate (HCO3)	mg/L	1	471	415	610	437	415	439	432	540	402	443
Hydroxide (OH)	mg/L	1	0	0	0	0	0	0	0	0	0	0
ANIONS												
Dissolved Chloride (Cl)	mg/L	1	73.9	61.8	56.4	75.6	72.3	73.9	67.1	59.8	55.3	8
Ion Balance	N/A	0.01	1.1	1.1	1.08	1.11	1.13	1.09	1.11	1.11	1.12	1.02
Total Anions	meq/L	N/A	12.5	11.9	13.7	12.8	11.6	12.9	12.5	13	10.9	26.1
Total Cations	meq/L	N/A	13.8	13.1	14.8	14.2	13.1	14	13.8	14.4	12.2	26.5
Conductivity (calc.)	uS/cm	1	1100	1100	1100	1100	1000	1100	1100	1100	990	2100
Conductivity % Diff.	%											
NITROGEN												
Nitrate (N)	mg/L	0.2	0	0	0	0	0	0	0	0	0	0
Nitrite (N)	mg/L	0.005	0	0	0	0.008	0	0	0.007	0	0	0
Nitrate + Nitrite	mg/L	N/A	0	0	0	0.008	0	0	0.007	0	0	0
SULFATE												
Dissolved Sulphate (SO4)	mg/L	1	131	160	101	168	131	171	168	119	133	892
METALS DISSOLVED												
Dissolved Calcium (Ca)	mg/L	0.05	131	137	140	131	116	129	135	160	144	435
Dissolved Iron (Fe)	mg/L	0.006	1.88	0.073	0.331	2.15	2.19	1.96	0.15	0.727	0.142	0.326
Dissolved Magnesium (Mg)	mg/L	0.05	18.5	13.8	10.6	23.2	22.5	22.7	21.8	23.2	16.4	46.5
Dissolved Manganese (Mn)	mg/L	0.001	0.258	1.18	1.84	0.367	0.341	0.323	0.117	0.096	0.008	0.677
Dissolved Potassium (K)	mg/L	0.2	4	4.2	2.3	5.6	5.8	5.4	5.8	3	4.2	4.8
Dissolved Sodium (Na)	mg/L	0.05	127	115	158	127	119	127	119	101	81.9	19.5
Sample type			Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater
Sampled on	Y/M/D		2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16	2005/6/16

Table A 4.1-(b) Results of Water Analyses (Major Itons) Summer 2005 (2/2)

Outer Ditch South Side			Control Site			Ditch		Tailings Pond		Dyke Drain Pipe
831449	831446	831444	831451	831452		831430	831439	831453	831454	831455
OUD-S-DP	OUD-S-MD	OUD-S-SH	CNT-E	CNT-W		IND WATER	OUD WATER	TAILINGS POND-C	TAILINGS POND-S	DYKE DRAIN PIPE
7.8	7.7	7.7	8.3	8		8.3	8.3	8.2	8.3	8.1
2060	1900	1570	1060	714		1200	1160	1020	1020	1330
1700	1480	1060	626	347		749	714	550	551	834
1710	1520	1190	666	434		790	654	646	660	854
1400	1300	880	130	290		450	470	70	70	500
0	0	0	2	0		0	0	0	0	0
319	360	384	429	343		297	357	251	253	315
0	0	0	2	0		0	0	0	0	0
389	439	468	519	418		362	436	307	309	385
0	0	0	0	0		0	0	0	0	0
0	0	0	3	1		58.5	57.1	104	104	60.2
1.09	1.12	1.01	1.06	0.93		1.11	1.12	1.05	1.04	1.11
26.4	23.2	17.8	10.9	7.2		12.6	12.3	9.41	9.46	13.9
28.9	25.9	18	11.6	6.72		13.9	13.7	9.84	9.84	15.4
2200	2000	1500	900	570		1100	1100	850	850	1200
0	0	0	0.03	0		0.35	0.03	0	0	0.49
0.037	0.005	0	0.026	0		0.005	0	0.007	0	0.008
0.037	0.005	0	0.059	0		0.355	0.03	0.007	0	0.498
962	768	487	107	14.7		238	168	69.7	69.8	281
493	437	298	36.3	75.2		105	146	13.1	13.1	119
0.214	1.48	0.975	1.95	0.068		0.246	0.476	1.33	1.27	0.153
46.5	44.7	33.4	8.4	24.4		44.7	26	9.11	9.12	49.2
0.57	0.427	0.735	0.289	1.5		0.771	0.122	0.056	0.058	1.05
1.5	1.3	3.4	8.2	3.3		16	6.5	15.4	15.8	17.4
9.37	8.3	6.5	202	20.1		105	94.5	184	184	113
Groundwater 2005/6/16	Groundwater 2005/6/16	Groundwater 2005/6/16	Groundwater 2005/6/16	Groundwater 2005/6/16		Surface water 2005/6/18	Surface water 2005/6/18	Surface water 2005/6/18	Surface water 2005/6/18	Groundwater 2005/6/18

Table A 4.1-(c) Results of Water Analyses (Major Ions) Summer 2005

			2 inch piezometers			**Tailings Pond**
Lab ID						
Sample ID			CNT-E2	OuD-S2W	OuD-S2C	TAILINGS POND 100M
Parameter	Unit	MDL				
PHYSICAL						
pH	-	0.1	7.9	7.6	7.7	8.1
Conductivity	uS/cm	1	732	2450	1760	1080
Total Dissolved Solids	mg/L	10	419	2090	1410	628
Computed TDS		20	482	1580	1440	876
Hardness (CaCO3)	mg/L	0.5	370	1600	1100	84
GENERAL INORGANICS						
Alkalinity (PP as CaCO3)	mg/L	1	<1	<1	<1	<1
Alkalinity (Total as CaCO3)	mg/L	1	375	448	357	309
Carbonate (CO3)	mg/L	1	<1	<1	<1	<1
Bicarbonate (HCO3)	mg/L	1	457	546	435	377
Hydroxide (OH)	mg/L	1	<1	<1	<1	<1
ANIONS						
Dissolved Chloride (Cl)	mg/L	1	5	1	<1	111
Ion Balance	N/A	0.01	0.9	0.97	1.01	1.07
Total Anions	meq/L					
Total Cations	meq/L					
Conductivity (calc.)	uS/cm	1	680	2600	1900	950
Conductivity % Diff.	%					
NITROGEN						
Nitrate (N)	mg/L	0.2	0.2	<0.2	<0.2	<0.2
Nitrite (N)	mg/L	0.06	0.08	<0.06	<0.06	<0.06
Nitrate + Nitrite	mg/L		0.3	<0.2	<0.2	<0.2
SULFATE						
Dissolved Sulphate (SO4)	mg/L	1	45	1210	753	68.8
METALS DISSOLVED						
Dissolved Calcium (Ca)	mg/L	0.05	108	515	390	12.4
Dissolved Iron (Fe)	mg/L	0.006	0.088	0.232	0.15	9.39
Dissolved Magnesium (Mg)	mg/L	0.05	24.5	85.5	38.6	12.8
Dissolved Manganese (Mn)	mg/L	0.001	0.173	0.646	0.468	0.126
Dissolved Potassium (K)	mg/L	0.2	4.6	2.1	3.2	26.3
Dissolved Sodium (Na)	mg/L	0.05	5.77	7.28	7.24	201
Matrix			Groundwater	Groundwater	Groundwater	Surface water
Sampled on	Y/M/D		2005/7/11	2005/7/11	2005/7/11	2005/7/11

* MDL: Maximum Detection Limit

Table A 4.1-(d) Results of Water Analysis (Major Ions) Fall 2005

			Inner Ditch	**Area between ditches**		**Outer Ditch**			
Sample ID			InD-S Md	BtD-S	BtD-S pond	OuD-N	OuD-S Md	OuD-S2W	OuD water
Parameter	Unit	MDL*							
PHYSICAL									
pH	-	0.1	7.7	7.8	8	7.3	7.3	7.2	8.1
Conductivity	uS/cm	1	1130	1060	1090	2010	2150	2640	1300
Total Dissolved Solids	mg/L	10	687	633	663	1750	1930	2520	838
Computed TDS (calc)	mg/L	20	750	670	706	1730	1790	2500	856
Hardness (CaCO3)	mg/L	0.5	370	420	440	1400	1600	2000	450
GENERAL INORGANICS									
Alkalinity (PP as CaCO3)	mg/L	1	<1	<1	<1	<1	<1	<1	<1
Alkalinity (Total as CaCO3)	mg/L	1	389	419	443	416	363	460	401
Carbonate (CO3)	mg/L	1	<1	<1	<1	<1	<1	<1	<1
Bicarbonate (HCO3)	mg/L	1	474	511	490	508	443	561	490
Hydroxide (OH)	mg/L	1	<1	<1	<1	<1	<1	<1	<1
ANIONS									
Dissolved Chloride (Cl)	mg/L	1	77	59	59	1	1	2	67
Ion Balance	N/A	0.01	1.03	1.02	1	1.05	1.03	1.02	1
Total Anions	meq/L		12.4	11.8	12.4	27.9	30.5	40.2	14.8
Total Cations	meq/L		12.7	12	12.4	29.4	31.5	41.1	14.8
Conductivity (calc.)	uS/cm	1	1100	990	1000	2300	2400	3000	1200
Conductivity % Diff.	%								
NITROGEN									
Nitrate (N)	mg/L	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Nitrite (N)	mg/L	0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Nitrate + Nitrite	mg/L		<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
SULFATE									
Dissolved Sulphate (SO4)	mg/L	1	118	82	90	940	1110	1490	235
METALS DISSOLVED									
Dissolved Calcium (Ca)	mg/L	0.05	110	136	142	494	540	616	121
Dissolved Iron (Fe)	mg/L	0.006	0.136	0.056	0.076	1.48	0.961	1.4	0.061
Dissolved Magnesium (Mg)	mg/L	0.05	22.4	20	21.5	49.6	49.9	120	35.9
Dissolved Manganese (Mn)	mg/L	0.001	0.385	0.094	0.156	0.685	0.497	1.4	0.156
Dissolved Potassium (K)	mg/L	0.2	6.2	4.6	4.6	4.1	1.8	3.1	12.7
Dissolved Sodium (Na)	mg/L	0.05	120	79.4	79.5	12.3	8.79	7.74	125
Sample type			Groundwater	Groundwater	Surface Water	Groundwater	Groundwater	Groundwater	Surface Water
Sampled on	Y/M/D		2005/11/1	2005/11/1	2005/11/1	2005/11/1	2005/11/1	2005/11/1	2005/11/1

* MDL: Maximum Detection Limit

Table A 4.1-(e) Results of Water Analysis (Major Ions) Spring 2006

			Tailings Pond	Area between ditches		Outer Ditch south side		
Sample ID			Near south shore	BtD-S	OuD-N	OuD-S Md	OuD-S2C	OuD-S2W
Parameter	Unit	MDL*						
PHYSICAL								
pH	-	0.1	8.4	7.7	7.3	7.2	7.2	7.1
Conductivity	uS/cm	1	1280	1020	1960	2350	2290	2010
Total Dissolved Solids	mg/L	10	755	635	1700	2150	2140	1740
Computed TDS (calc)	mg/L	20	834	694	1770	2210	2180	1830
Hardness (CaCO3)	mg/L	0.5	72	370	1400	1800	1700	1500
GENERAL INORGANICS								
Alkalinity (PP as CaCO3)	mg/L	1	6	<1	<1	<1	<1	<1
Alkalinity (Total as CaCO3)	mg/L	1	362	380	362	396	335	362
Carbonate (CO3)	mg/L	1	7	<1	<1	<1	<1	<1
Bicarbonate (HCO3)	mg/L	1	427	463	442	484	409	496
Hydroxide (OH)	mg/L	1	<1	<1	<1	<1	<1	<1
ANIONS								
Dissolved Chloride (Cl)	mg/L	1	143	59	1	<1	<1	<1
Ion Balance	N/A	0.01	1.05	1.06	1.08	1.1	1.07	1.07
Total Anions	meq/L		13	11.4	26.7	33.4	33	27.7
Total Cations	meq/L		13.7	12.1	28.8	36.6	35.4	29.6
Conductivity (calc.)	uS/cm	1	1100	980	2200	2700	2700	2300
Conductivity % Diff.	%							
NITROGEN								
Nitrate (N)	mg/L	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Nitrite (N)	mg/L	0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Nitrate + Nitrite	mg/L		<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
SULFATE								
Dissolved Sulphate (SO4)	mg/L	1	83	102	932	1220	1260	938
METALS DISSOLVED								
Dissolved Calcium (Ca)	mg/L	0.05	13.7	116	486	613	599	471
Dissolved Iron (Fe)	mg/L	0.006	0.032	0.069	0.056	0.257	0.061	0.99
Dissolved Magnesium (Mg)	mg/L	0.05	9.13	19.4	47.1	66.8	61.7	68.5
Dissolved Manganese (Mn)	mg/L	0.001	<0.001	0.652	0.652	0.601	0.667	1.9
Dissolved Potassium (K)	mg/L	0.2	14.6	5	5.1	1.9	3.6	4.5
Dissolved Sodium (Na)	mg/L	0.05	274	105	13.1	9.62	7.46	7.4
Sample type			Surface water	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater
Sampled on	Y/M/D		2006/5/30	2006/5/30	2006/5/30	2006/5/30	2006/5/30	2006/5/30

* MDL: Maximum Detection Limit

Table A 4.2 Results of Total Naphthenic Acid Analysis

Sample I.D.	Year 2004			Year 2005			Year 2005			Year 2005			Year 2006		
	Date Sampled	Date Analyzed	NA (mg/L)	Date Sampled	Date Analyzed	NA (mg/L)	Date Sampled	Date Analyzed	NA (mg/L)	Date Sampled	Date Analyzed	NA (mg/L)	Date Sampled	Date Analyzed	NA (mg/L)
InD-N Dp	29-Oct	10-Jan	15.2				5-Jun	15-Aug	14.7						
InD-N Md	29-Oct	10-Jan	12.5				5-Jun	15-Aug	14.3						
InD-N Sh	29-Oct	10-Jan	12.0				5-Jun	15-Aug	21.2						
InD-N Sh Dup	29-Oct	10-Jan	12.8				5-Jun	15-Aug	20.6						
InD-S Dp	29-Oct	10-Jan	15.6				5-Jun	15-Aug	14.2						
InD-S Md	29-Oct	10-Jan	15.5				5-Jun	15-Aug	13.8	Oct-05	22-Nov-05	14.5			
InD-S Sh	29-Oct	10-Jan	11.4				5-Jun	15-Aug	13.4						
InD-DVP	31-Oct	10-Jan	11.8				5-Jun	15-Aug	14.3						
BtD-N new	29-Oct	10-Jan	10.4				5-Jun	15-Aug	11.3						
BtD-S	29-Oct	1-Mar	**7.4**				5-Jun	15-Aug	8.1	Oct-05	22-Nov-05	8.5	30-May	16-Jun	9.7
BtD-S Dup	29-Oct	1-Mar	**7.8**										30-May	16-Jun	10.3
OuD-N	31-Oct	10-Jan	4.0				5-Jun	15-Aug	2.6	Oct-05	22-Nov-05	2.1	30-May	16-Jun	1.3
OuD-S Dp	29-Oct	10-Jan	ND				5-Jun	15-Aug	<1.0 (0.96)						
OuD-S Md	29-Oct	10-Jan	ND				5-Jun	15-Aug	<1.0 (0.72)	Oct-05	22-Nov-05	<1 (0.94)	30-May	16-Jun	1.2
OuD-S Sh	29-Oct	10-Jan	ND				5-Jun	15-Aug	1.7						
OuD-S2W							5-Jun	15-Aug	1.1	Oct-05	22-Nov-05	1.1	30-May	16-Jun	1.4
OuD-S2C							5-Jun	15-Aug	2.0				30-May	16-Jun	2.6
CNT-E2							5-Jun	15-Aug	4.4						
InD water	31-Oct	10-Jan	15.8				5-Jun	15-Aug	11.6						
OuD water	31-Oct	10-Jan	11.4				5-Jun	15-Aug	13.2	Oct-05	22-Nov-05	14.5			
CNT-D water	31-Oct	10-Jan	14.7												
Tailings Pond	1-Nov	10-Jan	28.9	20-Feb	12-Apr	29.9	5-Jun	15-Aug	29.3				30-May	16-Jun	15.5
Tailings Pond shore							5-Jun	15-Aug	28.2						
Incoming Pipeline				20-Feb	12-Apr	32.1									
Dyke Drain Pipe							5-Jun	15-Aug	11.6						
BtD-S pond										Oct-05	22-Nov-05	9.2			
Ind-S-Dpcl	29-Oct	10-Jan	15.4												
OuD-Dpcl	29-Oct	10-Jan	ND												

QUALITY ASSURANCE DATA

ACCURACY AND PRECISION OF STANDARDS AND METHOD DETECTION LIMIT

		NA (mg/L)	NA (mg/L)
SPIIKED CONC		25	150
MEASURED CONC	**AVG**	31.07	156.61
	STD	2.45	6.79
	N	3	4
	%S	7.9	4.3
	%E	24.3	4.4
	MDL	1.0	
	LOQ	2.0	

LEGEND

MDL - Method Detection Limit (based on 50x concentration factor)
LOQ - Limit of Quantification (2*MDL)
STD - standard deviation of replicate determinations
%S - relative percent standard deviation
Dup - duplicate

Table A-4.3 Results of Napthenic Acids Characterization Analysis

InD water

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	2	0	0	0	0	0	0	2
6	1	0	0	0	0	0	0	1
7	1	1	0	0	0	0	0	3
8	1	1	0	0	0	0	0	2
9	1	1	0	0	0	0	0	1
10	1	1	1	0	0	0	0	2
11	0	1	2	0	0	0	0	4
12	0	2	6	1	0	0	0	9
13	1	2	8	1	0	0	0	12
14	1	2	6	6	1	0	0	15
15	1	1	2	3	1	0	0	8
16	1	1	1	1	1	1	0	6
17	1	1	1	1	1	1	0	4
18	1	1	1	0	0	0	1	4
19	1	0	0	0	0	0	1	3
20	0	0	0	0	0	0	0	2
21	0	0	0	0	0	0	0	2
22	0	0	0	0	0	0	0	2
23	0	0	0	0	0	0	0	2
24	0	0	0	0	0	0	0	2
25	0	0	0	0	0	0	0	2
26	0	0	0	0	0	0	0	2
27	0	0	0	0	0	0	0	2
28	0	0	0	0	0	0	0	2
29	0	0	0	0	0	0	0	2
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	1
33	0	0	0	0	0	0	0	1
% by z N	16	17	32	18	7	6	5	100

InD - S Md

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	2	0	0	0	0	0	0	2
6	1	0	0	0	0	0	0	1
7	1	1	0	0	0	0	0	2
8	1	1	0	0	0	0	0	2
9	1	1	0	0	0	0	0	1
10	0	1	1	0	0	0	0	3
11	0	1	3	0	0	0	0	5
12	0	2	7	1	0	0	0	11
13	1	3	10	1	0	0	0	14
14	1	2	7	6	1	0	0	17
15	1	1	2	3	1	0	0	8
16	1	1	1	1	1	1	0	6
17	1	1	1	0	0	1	0	4
18	1	1	0	0	0	0	1	3
19	1	0	0	0	0	0	0	2
20	0	0	0	0	0	0	0	2
21	0	0	0	0	0	0	0	1
22	0	0	0	0	0	0	0	1
23	0	0	0	0	0	0	0	2
24	0	0	0	0	0	1	0	2
25	0	0	0	0	0	0	0	2
26	0	0	0	0	0	0	0	1
27	0	0	0	0	0	0	0	1
28	0	0	0	0	0	0	0	1
29	0	0	0	0	0	0	0	1
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	1
33	0	0	0	0	0	0	0	1
% by z N	15	18	36	16	6	5	4	100

BtD - N

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	2	0	0	0	0	0	0	2
6	1	0	0	0	0	0	0	1
7	1	1	0	0	0	0	0	2
8	1	1	0	0	0	0	0	2
9	1	1	0	0	0	0	0	1
10	1	1	2	0	0	0	0	3
11	1	2	4	0	0	0	0	6
12	1	3	8	1	0	0	0	13
13	1	2	9	1	0	0	0	14
14	1	2	6	5	1	0	0	14
15	1	1	2	2	1	0	0	6
16	1	1	1	1	1	1	0	5
17	0	1	1	0	0	1	0	3
18	0	0	0	0	0	0	0	3
19	1	0	0	0	0	0	0	2
20	0	0	0	0	0	0	0	2
21	0	0	0	0	0	0	0	2
22	1	0	0	0	0	0	0	2
23	0	0	0	0	0	0	0	2
24	0	0	0	0	0	0	0	2
25	0	0	0	0	0	0	0	2
26	0	0	0	0	0	0	0	2
27	0	0	0	0	0	0	0	2
28	0	0	0	0	0	0	0	2
29	0	0	0	0	0	0	0	2
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	1
33	0	0	0	0	0	0	0	1
% by z N	16	19	35	15	6	5	5	100

OuD - N

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	2	0	0	0	0	0	0	2
6	2	0	0	0	0	0	0	2
7	1	2	0	0	0	0	0	3
8	1	1	0	0	0	0	0	2
9	1	1	0	0	0	0	0	2
10	1	1	2	0	0	0	0	4
11	1	2	3	0	0	0	0	6
12	1	2	5	1	0	0	0	9
13	1	2	4	1	0	0	0	8
14	1	2	3	2	2	0	0	10
15	1	1	1	1	1	0	0	6
16	1	1	1	1	1	1	0	6
17	1	1	1	1	1	1	0	4
18	1	0	0	0	0	0	1	3
19	1	0	0	0	0	0	1	3
20	1	0	0	0	0	0	1	3
21	0	0	0	0	0	0	0	2
22	1	0	0	0	0	0	0	2
23	1	0	0	0	0	0	1	3
24	0	0	0	0	0	1	0	3
25	0	0	0	0	0	1	1	3
26	0	0	0	0	0	0	0	2
27	0	0	0	0	0	0	0	2
28	0	0	0	0	0	0	0	2
29	0	0	0	0	0	0	0	2
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	2
33	0	0	0	0	0	0	0	1
% by z N	21	20	25	12	9	7	6	100

OuD water

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	2	0	0	0	0	0	0	2
6	2	0	0	0	0	0	0	2
7	1	1	0	0	0	0	0	3
8	1	1	0	0	0	0	0	2
9	1	1	0	0	0	0	0	2
10	1	1	1	0	0	0	0	3
11	1	1	3	0	0	0	0	4
12	1	2	6	1	0	0	0	9
13	1	2	7	2	0	0	0	11
14	1	2	6	5	1	0	0	14
15	1	1	2	3	1	0	0	8
16	1	1	1	1	1	1	0	6
17	1	1	1	1	1	1	0	4
18	1	1	0	0	0	0	1	4
19	1	0	0	0	0	0	1	3
20	0	0	0	0	0	0	1	2
21	0	0	0	0	0	0	0	2
22	0	0	0	0	0	0	0	2
23	0	0	0	0	0	0	0	2
24	0	0	0	0	0	1	0	2
25	0	0	0	0	0	1	0	2
26	0	0	0	0	0	0	0	2
27	0	0	0	0	0	0	0	2
28	0	0	0	0	0	0	0	2
29	0	0	0	0	0	0	0	2
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	1
32	0	0	0	0	0	0	0	1
33	0	0	0	0	0	0	0	1
% by z N	17	17	31	16	7	6	5	100

Tailings return line

C No.	z number							C No.
	0	2	4	6	8	10	12	%
5	3	0	0	0	0	0	0	3
6	2	0	0	0	0	0	0	2
7	2	2	0	0	0	0	0	4
8	1	1	0	0	0	0	0	2
9	1	2	0	0	0	0	0	2
10	1	1	1	0	0	0	0	2
11	0	1	1	0	0	0	0	3
12	0	2	6	1	0	0	0	9
13	0	3	8	1	0	0	0	13
14	0	3	8	2	1	0	0	14
15	0	2	4	3	1	0	0	10
16	1	1	2	3	1	1	0	8
17	1	1	2	1	0	1	0	6
18	1	1	1	0	1	1	0	4
19	0	1	0	0	0	0	1	3
20	0	0	0	0	0	0	0	2
21	0	0	0	0	0	0	0	1
22	0	0	0	0	0	0	0	1
23	0	0	0	0	0	0	1	2
24	0	0	0	0	0	0	0	2
25	0	0	0	0	0	0	0	2
26	0	0	0	0	0	0	0	1
27	0	0	0	0	0	0	0	1
28	0	0	0	0	0	0	0	1
29	0	0	0	0	0	0	0	1
30	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0
% by z N	16	20	35	13	5	6	5	100

Table A-4.4 (a) Results of Sieve Analysis, Net Weight (g)

No	Sample ID	- 63µm	63 - 125 µm	125 - 250 µm	250 - 500 µm	500µm - 1mm	1- 2 mm	2 - 4 mm	4 mm -	Total	Sieve loss (g)	Sieve loss (%)
1	InD-S, Auger 0.5m	11.59	7.71	16.55	35.19	154.21	48.43	2.21	1.85	277.74	-0.02	-0.01%
2	InD-S, Auger 1.4m	23.82	9.52	12.93	60.10	158.17	24.32	2.29	4.63	295.78	0.08	0.03%
3	InD-S, Auger 2.2m	15.05	7.92	10.89	53.59	152.39	33.44	4.79	6.29	284.36	0.24	0.08%
4	InD-S, Auger 3.0m	9.44	4.84	10.95	185.71	145.12	4.81	3.07	17.66	381.6	-0.04	-0.01%
5	InD-S, Core 1.0m	16.00	11.55	26.39	41.48	147.90	22.58	3.58	13.40	282.88	0.19	0.07%
6	InD-S, Core 2.0m	23.17	12.20	18.87	72.94	208.24	30.32	6.36	9.63	381.73	0.2	0.05%
7	InD-S, Core 3.0m	15.77	10.21	12.35	72.10	130.88	18.85	3.52	23.15	286.83	0.21	0.07%
8	OuD-N Aug 0.6m	9.08	5.28	7.97	42.02	110.50	76.11	12.11	8.68	271.75	0.16	0.06%
9	OuD-N Core 1.0m	16.92	13.91	17.06	100.36	141.08	37.40	10.64	41.14	378.51	0.39	0.10%
10	OuD-S, Auger 3.3m	10.70	4.07	4.90	49.97	176.51	62.45	7.64	22.59	338.83	-0.04	-0.01%
11	OuD-S, Auger 4.7m	10.63	5.81	6.50	19.97	97.45	100.31	9.97	5.78	256.42	0.21	0.08%
12	Out-S W corner 3.6m	12.61	6.95	10.68	83.79	142.67	37.91	6.72	5.86	307.19	0.23	0.07%

Table A-4.4 (b) Results of Sieve Analysis, Cumulative Percentage (w %)

No	Sample ID	**Grain size (mm)**								Parameters calculated		
		0.063	0.125	0.25	0.5	1	2	4	10	D_{10}	D_{30}	D_{60}
1	InD-S, Auger 0.5m	4.2%	6.9%	12.9%	25.6%	81.1%	98.5%	99.3%	100.0%	0.189	0.540	0.810
2	InD-S, Auger 1.4m	8.1%	11.3%	15.6%	36.0%	89.4%	97.7%	98.4%	100.0%	0.100	0.427	0.725
3	InD-S, Auger 2.2m	5.3%	8.1%	11.9%	30.8%	84.3%	96.1%	97.8%	100.0%	0.188	0.490	0.773
4	InD-S, Auger 3.0m	2.5%	3.7%	6.6%	55.3%	93.3%	94.6%	95.4%	100.0%	0.267	0.370	0.562
5	InD-S, Core 1.0m	5.7%	9.7%	19.1%	33.7%	86.0%	94.0%	95.3%	100.0%	0.128	0.436	0.751
6	InD-S, Core 2.0m	6.1%	9.3%	14.2%	33.3%	87.9%	95.8%	97.5%	100.0%	0.144	0.457	0.745
7	InD-S, Core 3.0m	5.5%	9.1%	13.4%	38.5%	84.1%	90.7%	91.9%	100.0%	0.152	0.415	0.736
8	OuD-N Aug 0.6m	3.3%	5.3%	8.2%	23.7%	64.3%	92.3%	96.8%	100.0%	0.279	0.578	0.947
9	OuD-N Core 1.0m	4.5%	8.1%	12.7%	39.2%	76.4%	86.3%	89.1%	100.0%	0.176	0.414	0.779
10	OuD-S, Auger 3.3m	3.2%	4.4%	5.8%	20.6%	72.6%	91.1%	93.3%	100.0%	0.321	0.591	0.879
11	OuD-S, Auger 4.7m	4.1%	6.4%	8.9%	16.7%	54.7%	93.9%	97.7%	100.0%	0.284	0.675	1.135
12	Out-S W corner 3.6m	4.1%	6.4%	9.8%	37.1%	83.6%	95.9%	98.1%	100.0%	0.251	0.435	0.746

Table A 4.5 Results of Permeameter Test (1/13)

Sample No. 1 InD-S, Auger 0.5 m

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial
Initial head	**H0**	[cm]	165	165	165	165	215	*215*
Final head	**H1**	[cm]	95	95	95	95	95	*95*
Time	**t**	[s]	30.62	32.03	37.03	87	177	*1166*
Tube area	**a**	[cm²]	1.95	1.95	1.95	1.95	1.95	*1.95*
Sample thickness	**l**	[cm]	4.1	4.1	4.1	4.1	4.1	*4.1*
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	*11.52*
hydr. cond.	**k**	**[cm/s]**	**1.25E-02**	**1.20E-02**	**1.03E-02**	**4.40E-03**	**3.20E-03**	***4.86E-04***

avarage: 7.37E-03 [cm/s]

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.1 cm
d = 3.83 cm
A = 11.52 cm²

During the multiple trials, the velocity dropped greatly.

The water gets clouldy at hight pump rate.

The thickness of the sample was reduced by 5mm after tests.

H	t1	t2	t3	t4	t5	t6
215	-	-	-	-	-	-
165	0	0	0	0	0	0
125	-	-	-	26.34	51.61	624
95	30.62	32.03	37.03	87	177	1166
65	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (2/13)

Sample No. 2 InD-S, Auger 1.4 m

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial	7. Trial
Initial head	**H0**	[cm]	165	165	165	165	215	215	215
Final head	**H1**	[cm]	95	95	95	95	95	95	95
Time	**t**	[s]	57.75	32.53	33.97	35.75	50.35	51.91	53.37
Tube area	**a**	[cm²]	1.95	1.95	1.95	1.95	1.95	1.95	1.95
Sample thickness	**l**	[cm]	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**6.95E-03**	**1.23E-02**	**1.18E-02**	**1.12E-02**	**1.18E-02**	**1.14E-02**	**1.11E-02**

avarage: **1.08E-02 [cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²

tube (no. 2)
d = 1.58 cm
a = 1.95 cm²

Chamber:
Sample thickness l = 4.3 cm
d = 3.83 cm
A = 11.52 cm²

Water in the tube gets cloudy during the test.

Sample thickness was reduced by 4mm after tests.

Some fine washed out.

H	t1	t2	t3	t4	t5	t6	t7
215	-	-	-	-	-	-	-
165	0	0	0	0	0	0	0
125	29.02	16.11	16.42	-	23.33	24.08	25.42
95	57.75	32.53	33.97	35.75	50.35	51.91	53.37
65	-	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (3/13)

Sample No. 3 InD-S, Auger 2.2 m

			1. Trial	**2. Trial**	**3. Trial**	**4. Trial**	**5. Trial**	**6. Trial**	**7. Trial**
Initial head	**H0**	[cm]	165	165	165	165	215	215	215
Final head	**H1**	[cm]	95	95	95	95	95	95	95
Time	**t**	[s]	15.47	15.28	15.22	15.13	23.35	23.44	23.47
Tube area	**a**	[cm²]	3.89	3.89	3.89	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**5.18E-02**	**5.25E-02**	**5.27E-02**	**5.30E-02**	**5.08E-02**	**5.06E-02**	**5.05E-02**

avarage: 5.25E-02 [cm/s]

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.3 cm
d = 3.83 cm
A = 11.52 cm²

Water always clean during test.

Little change in sample thickness.

H	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**
215	-	-	-	-	0	0	0
165	0	0	0	0	8.33	8.43	8.27
125	8.14	8.05	8.08	8.06	-	-	-
95	15.47	15.28	15.22	15.13	23.35	23.44	23.47
65	-	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (4/13)

Sample No. **4** **InD-S, Auger 3.0 m**

			1. Trial	**2. Trial**	**3. Trial**	**4. Trial**	**5. Trial**	**6. Trial**
Initial head	**H0**	[cm]	165	165	165	165	165	215
Final head	**H1**	[cm]	95	95	95	95	95	95
Time	**t**	[s]	64.08	62.75	61.03	59.25	55.55	0
Tube area	**a**	[cm²]	3.89	3.89	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.5	4.5	4.5	4.5	4.5	4.5
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**1.31E-02**	**1.34E-02**	**1.38E-02**	**1.42E-02**	**1.51E-02**	**#DIV/0!**

avarage: **1.39E-02** **[cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.5 cm
d = 3.83 cm
A = 11.52 cm²

Fine washed out during test

H	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**
215	-	-	-			
165	0	0	0	0	0	
125	33.59	32.36	-	30.33	28.56	
95	64.08	62.75	61.03	59.25	55.55	
65	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (5/13)

Sample No. **5** **InD-S, Core 1.0 m**

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial	7. Trial
Initial head	**H0**	[cm]	165	165	165	165	165	165	165
Final head	**H1**	[cm]	95	95	95	95	95	95	95
Time	**t**	[s]	113.69	141.2	175.61	197.44	262.79	316.49	381.47
Tube area	**a**	[cm²]	1.95	1.95	1.95	1.95	1.95	1.95	1.95
Sample thickness	**l**	[cm]	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**3.37E-03**	**2.71E-03**	**2.18E-03**	**1.94E-03**	**1.46E-03**	**1.21E-03**	**1.00E-03**

avarage: **1.83E-03 [cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.1 cm
d = 3.83 cm
A = 11.52 cm²

The water only gets cloudy in the cylinder.

H	t1	t2	t3	t4	t5	t6	t7
215	-	-	-				
165	0	0	0	0	0	0	0
125	56.07	68.66	84.6	95.76	125.66	150.47	181.24
95	113.69	141.2	175.61	197.44	262.79	316.49	381.47
65	-	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (6/13)

Sample No. 6 InD-S, Core 2.0 m

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial
Initial head	**H0**	[cm]	165	165	165	*165*	*165*	*165*
Final head	**H1**	[cm]	95	95	95	*95*	*95*	*95*
Time	**t**	[s]	8.89	8.62	8.34	*8*	*36.9*	*36.99*
Tube area	**a**	[cm²]	1.95	1.95	1.95	*1.95*	*3.89*	*3.89*
Sample thickness	**l**	[cm]	4.5	4.5	4.5	*4.5*	*4.5*	*4.5*
Sample area	**A**	[cm²]	11.52	11.52	11.52	*11.52*	*11.52*	*11.52*
hydr. cond.	**k**	**[cm/s]**	**4.73E-02**	**4.87E-02**	**5.04E-02**	***5.25E-02***	***2.27E-02***	***2.27E-02***

avarage: 4.88E-02 [cm/s]

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²

tube (no. 2)
d = 1.58 cm
a = 1.95 cm²

Chamber:
Sample thickness l = 4.5 cm
d = 3.83 cm
A = 11.52 cm²

Water gets cloudy in the tube.

Fine washed out during the test.

Bubbles produced from the pump after traial 3.

H	t1	t2	t3	t4	t5	t6
215	-	-	-			
165	0	0	0	0	0	0
125	4.56	4.46	4.31	4.12	19.31	18.7
95	8.89	8.62	8.34	8	36.9	36.99
65	-	-	-	-		

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (7/13)

Sample No. **7** **InD-S, Core 3.0 m**

			1. Trial	**2. Trial**	**3. Trial**	**4. Trial**	**5. Trial**	**6. Trial**
Initial head	**H0**	[cm]	165	165	165	165	165	215
Final head	**H1**	[cm]	95	95	95	95	95	95
Time	**t**	[s]	34.82	33.57	32.36	38.14	0	0
Tube area	**a**	[cm²]	3.89	3.89	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.5	4.5	4.5	4.5	4.5	4.5
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**2.41E-02**	**2.50E-02**	**2.59E-02**	**2.20E-02**	**#DIV/0!**	**#DIV/0!**

avarage: **2.42E-02** **[cm/s]**

tube (no. 1)

d = 3.146 cm

a = 3.89 cm²

tube (no. 2)

d = 1.58 cm

a = 1.95 cm²

Chamber:

Sample thickness l = 4.5 cm

d = 3.83 cm

A = 11.52 cm²

H	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**
215	-	-	-	-		
165	0	0	0	0		
125	18.04	17.37	16.84	19.35		
95	34.82	33.57	32.36	38.14		
65	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (8/13)

Sample No. 8 OuD-N, Auger 0.6 m

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial	7. Trial
Initial head	**H0**	[cm]	165	165	165	165	215	215	215
Final head	**H1**	[cm]	95	95	95	95	95	95	95
Time	**t**	[s]	4.5	4.5	4.5	4.53	7	6.94	6.97
Tube area	**a**	[cm²]	1.95	1.95	1.95	1.95	1.95	1.95	1.95
Sample thickness	**l**	[cm]	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**8.92E-02**	**8.92E-02**	**8.92E-02**	**8.86E-02**	**8.48E-02**	**8.56E-02**	**8.52E-02**

avarage: **8.91E-02 [cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²

tube (no. 2)
d = 1.58 cm
a = 1.95 cm²

Chamber:
Sample thickness l = 4.3 cm
d = 3.83 cm
A = 11.52 cm²

H	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**
215	-	-	-	-	0	0	0
165	0	0	0	0	2.52	2.52	2.59
125	-	2.46	2.43	2.43			
95	4.5	4.5	4.5	4.53	7	6.94	6.97
65	-	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (9/13)

Sample No. **9** **OuD-N, Core 1.0 m**

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial
Initial head	**H0**	[cm]	165	165	165	165	165	165
Final head	**H1**	[cm]	95	95	95	95	95	95
Time	**t**	[s]	19.56	19.65	19.7	19.83	0	0
Tube area	**a**	[cm²]	3.89	3.89	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.5	4.5	4.5	4.5	4.5	4.5
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**4.29E-02**	**4.27E-02**	**4.26E-02**	**4.23E-02**	**#DIV/0!**	**#DIV/0!**

avarage: **4.26E-02** **[cm/s]**

tube (no. 1)

d = 3.146 cm

a = 3.89 cm²

tube (no. 2)

d = 1.58 cm

a = 1.95 cm²

Chamber:

Sample thickness l = 4.5 cm

d = 3.83 cm

A = 11.52 cm²

H	t1	t2	t3	t4	t5	t6
215	-	-	-			
165	0	0	0	0		
125	10.32	10.35	10.41	10.36		
95	19.56	19.65	19.7	19.83		
65	-	-	-	-		

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (10/13)

Sample No. 10 OuD-S, Auger 3.3 m

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial	7. Trial
Initial head	**H0**	[cm]	165	165	*165*	165	215	215	215
Final head	**H1**	[cm]	95	95	*95*	95	95	95	95
Time	**t**	[s]	47.09	51.45	*149.4*	65.53	61.52	54.22	47.58
Tube area	**a**	[cm^2]	3.89	3.89	*3.89*	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.5	4.5	*4.5*	4.5	4.5	4.5	4.5
Sample area	**A**	[cm^2]	11.52	11.52	*11.52*	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**1.78E-02**	**1.63E-02**	***5.62E-03***	**1.28E-02**	**2.02E-02**	**2.29E-02**	**2.61E-02**

avarage: 1.89E-02 [cm/s]

tube (no. 1)
d = 3.146 cm
a = 3.89 cm^2
tube (no. 2)
d = 1.58 cm
a = 1.95 cm^2
Chamber:
Sample thickness l = 4.5 cm
d = 3.83 cm
A = 11.52 cm^2

Water gets a little cloudy during the test both in tube and trough.
Sample thikness reduced by 1.5 to 2mm after test.

H	t1	t2	t3	t4	t5	t6	t7
215	-	-	-	-	-	-	-
165	0	0	0	0	0	0	0
125	24.24	26.15	64.07	30.6	28.15	24.84	21.43
95	47.09	51.45	149.4	65.53	61.52	54.22	47.58
65	-	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (11/13)

Sample No. **11** **OuD-S, Auger 4.7 m**

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial
Initial head	**H0**	[cm]	165	165	165	215	215	215
Final head	**H1**	[cm]	95	95	95	95	95	95
Time	**t**	[s]	28.09	27.84	27.41	42.72	42.25	40.29
Tube area	**a**	[cm²]	3.89	3.89	3.89	3.89	3.89	3.89
Sample thickness	**l**	[cm]	4.7	4.7	4.7	4.7	4.7	4.7
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**3.12E-02**	**3.15E-02**	**3.20E-02**	**3.04E-02**	**3.07E-02**	**3.22E-02**

avarage: **3.13E-02** **[cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.7 cm
d = 3.83 cm
A = 11.52 cm²

Water stayed clean during test.

Little change in the thickness of the sample.

H	t1	t2	t3	t4	t5	t6
215	-	-	-	0	0	0
165	0	0	0	15.65	14.93	14.21
125	14.77	14.68	14.43	-	-	-
95	28.09	27.84	27.41	42.72	42.25	40.29
65	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (12/13)

Sample No. **12** **OuD-S W, corner 3.6 m**

			1. Trial	2. Trial	3. Trial	4. Trial	5. Trial	6. Trial
Initial head	**H0**	[cm]	165	165	165	165	215	215
Final head	**H1**	[cm]	95	95	95	95	95	95
Time	**t**	[s]	33.59	33.09	33.15	0	0	0
Tube area	**a**	[cm²]	3.89	3.89	3.89	1.95	1.95	1.95
Sample thickness	**l**	[cm]	4.3	4.3	4.3	4.3	4.3	4.3
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52
hydr. cond.	**k**	**[cm/s]**	**2.39E-02**	**2.42E-02**	**2.42E-02**			

avarage: **2.41E-02** **[cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 4.3 cm
d = 3.83 cm
A = 11.52 cm²

Water stayed clear during test.

Little change in sample thickness

H	t1	t2	t3	t4	t5	t6
215	-	-	-			
165	0	0	0			
125	17.36	17.21	17.23			
95	33.59	33.09	33.15			
65	-	-	-	-	-	-

* Data in Italic is excluded from calculation of average

Table A-4.5 Results of Permeameter Test (13/13)

Sample No. **13 Peat**

			1. Trial	**2. Trial**	**3. Trial**	**4. Trial**	**5. Trial**	**6. Trial**	**7. Trial**	**8. Trial**	**9. Trial**	**10. Trial**	**11. Trial**
Initial head	**H0**	[cm]	165	165	165	165	165	165	165	165	*165*	*165*	*165*
Final head	**H1**	[cm]	95	95	95	95	95	95	95	95	*95*	*95*	*95*
Time	**t**	[s]	165.5	188.7	224.34	245.45	256.43	271.63	276.92	290.66	*459.75*	*466.52*	*455.65*
Tube area	**a**	[cm²]	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	*1.95*	*1.95*	*1.95*
Sample thickness	**l**	[cm]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	*2.1*	*2.1*	*2.1*
Sample area	**A**	[cm²]	11.52	11.52	11.52	11.52	11.52	11.52	11.52	11.52	*11.52*	*11.52*	*11.52*
hydr. cond.	**k**	**[cm/s]**	**1.18E-03**	**1.04E-03**	**8.74E-04**	**7.99E-04**	**7.65E-04**	**7.22E-04**	**7.08E-04**	**6.75E-04**	***4.26E-04***	***4.20E-04***	***4.30E-04***

avarage: **8.31E-04 [cm/s]**

tube (no. 1)
d = 3.146 cm
a = 3.89 cm²
tube (no. 2)
d = 1.58 cm
a = 1.95 cm²
Chamber:
Sample thickness l = 2.1 cm
d = 3.83 cm
A = 11.52 cm²

Trial 9 to 11 were conducted the next day.

H	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**	**t11**
215	-	-	-								
165	0	0	0	0	0	0	0	0	0	0	0
125	80.95	92.47	109.37	119.45	125.44	133.01	136.22	141.96	220.06	225	222.4
95	165.5	188.7	224.34	245.45	256.43	271.63	276.92	290.66	459.75	466.52	455.65
65	-	-	-	-							

* Data in Italic is excluded from calculation of average

Table A 5.1 Details on Material Parameter Estimation

	Model domain (material)	Anisotropy range	Heterogeneity	Estimation method
1	Tailings dyke (Tailings sand)	0.1- 0.5	High due to presence of fines layers and bitumen films	Based on geotechnical data from ASE of $K = 2x10^{-5}$ m/s and $K_z/K_{xy} = 0.1$. Consideration of layered structure of the tailings material in tailings pond (Hunter 2001, comments from ASE) also indicates high anisotropy. Grain size analysis data for tailings material (average grained mixture) gives $K = 9.3 \times 10^{-5}$ m/s.
2	Starter dyke (Lean oil sand)	0.5	Low	Based on geotechnical data from ASE of $K = 1x10^{-7} \sim 1x10^{-9}$ m/s. The mid value is used. Consideration of mixing and compaction during the construction for anisotropy.
3	Internal drain cell (Pf-sand, gravel)	1	Low	Based on the design of internal drain in which pf-sand and gravel are used as filters.
4	Topsoil (Peat)	0.1- 0.5	Intermediate possible layered structure	Based on the laboratory tests on the peat sample, in consideration of reported anisotropy values of $K_z/K_{xy} = 0.28$ (log $K_h/K_v = 0.55$) by Beckwith et al 2003.
5	Pf-sand (Coarse – med sand)	1 - 0.5	Low	Based on the laboratory tests on the sand sample, which gave $K = 2.1 \times 10^{-4}$ m/s. The sand is loose and looks uniform both in sample and field scale and the anisotropy is considered small.
6	McMurray F. (Oil sand)	0.1 - 0.5	Intermediate	Based on geotechnical data from ASE of typical $K = 1x10^{-8}$ m/s. KOMEX reports average $K = 1.3 \times 10^{-7}$ m/s with an anisotropy of $K_z/K_{xy} = 0.1$.

Table A 5.2-(a) Results of Sensitivity Analysis for Scenario 1

K, Pf-Sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
2.0E-07	0.671	0.037	0.011	2.00E-04	0.73
2.0E-06	0.665	0.036	0.065	2.00E-04	0.831
2.0E-05	0.611	0.019	0.56	9.00E-04	1.749
1.8E-04	0.37	0.0012	3.1	1.00E-01	8.36
2.0E-04	0.35	0.001	4.37	0.13	9.09
2.2E-04	0.336	0.0008	4.733	0.164	9.8
2.0E-03	1.00E-20	4.00E-05	28.41	12.78	56.82
2.0E-02	1.00E-20	2.00E-04	172.95	156.2	345.9
4.0E-05	0.564	0.01	1.066	0.0028	2.706
6.0E-05	0.525	0.006	1.538	0.0066	3.601
8.0E-05	0.492	3.60E-03	1.985	1.29E-02	4.47
1.0E-04	0.462	0.0034	2.414	0.0223	5.294
4.0E-04	0.22	4.40E-05	7.75	0.677	15.72
6.0E-04	0.134	3.90E-05	10.78	1.601	21.69
8.0E-04	1.00E-20	3.50E-05	13.63	2.79	27.26
1.0E-03	1.00E-20	3.30E-05	16.3	4.19	32.6

K, McMurray F., Oil sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
2.0E-12	0.352	0.001	4.38	0.13	9.11
2.0E-11	0.352	1.00E-03	4.38	0.13	9.11
2.0E-10	0.352	1.00E-03	4.38	0.13	9.11
2.0E-09	0.352	1.00E-03	4.38	0.13	9.11
1.8E-08	0.352	1.00E-03	4.38	0.13	9.11
2.0E-08	0.352	1.00E-03	4.38	0.13	9.09
2.2E-08	0.352	1.00E-03	4.38	0.13	9.1
2.0E-07	0.351	0.001	4.39	0.13	9.13
2.0E-06	0.344	0.001	4.51	0.14	9.37

K, Top Soil, Peat

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
9.0E-08	0.58	0.012	3.094	1.33	6.77
9.0E-07	0.43	0.003	4.08	0.304	8.59
8.1E-06	0.354	0.001	4.36	0.131	9.08
9.0E-06	0.35	0.001	4.38	0.129	9.11
9.9E-06	0.352	0.001	4.37	0.129	9.1
9.0E-05	0.36	0.001	4.61	0.184	9.58
9.0E-04	0.51	0.005	5.29	1.103	11.1
9.0E-09	0.65	0.032	2.46	2.14	5.6
9.0E-03	0.68	0.043	6.05	4.84	12.83
4.0E-04	0.44	0.003	4.99	0.517	10.42
4.0E-03	0.63	2.30E-02	5.84	3.42E+00	12.34

Downgradient BC, Constant head in pf-sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
278.5	0.392	0.001	3.3	0.115	8
279.0	0.363	0.0015	4.24	0.126	8.85
279.5	0.354	0.001	4.35	0.129	9.05
279.7	0.35	0.0011	4.403	0.1301	9.157
280.0	0.352	0.0011	4.375	0.13	9.104
280.3	0.355	0.0011	4.344	0.129	9.044
280.5	0.358	0.0002	4.31	0.128	8.99
281.0	0.366	0.001	4.23	0.126	8.82
281.4	0.373	0.001	4.15	0.124	8.67

K, Internal Drain Cell Sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
5.0E-08	0.087	0.003	4.46	0.124	9.01
5.0E-07	0.266	0.001	4.42	0.128	9.11
5.0E-06	0.336	0.001	4.4	0.129	9.14
5.0E-05	0.35	0.001	4.4	0.129	9.15
4.5E-04	0.353	0.0008	4.37	0.1295	9.09
5.0E-04	0.352	0.001	4.38	0.13	9.11
5.5E-04	0.353	0.0011	4.37	0.129	9.09
5.0E-03	0.354	0.001	4.38	0.129	9.12
5.0E-02	0.351	0.001	4.4	0.13	9.14
5.0E-01	0.353	0.001	4.4	0.129	9.16

Upgradient BC, Const. head of tailings pond

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
299.8	0.352	0.0011	4.375	0.13	9.1
300.1	0.383	0.0016	4.466	0.13	9.32
300.0	0.347	1.00E-03	4.43	0.13	9.23
301.0	0.459	3.00E-03	4.68	0.134	9.82
302.0	0.542	8.00E-03	4.92	0.14	10.38
303.0	0.623	2.20E-02	5.15	0.144	10.95
304.0	0.703	0.056	5.38	0.151	11.53
305.0	0.782	0.113	5.614	0.157	12.12

K, Starter Dyke, LOS

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
1.0E-12	0.354	8.00E-07	4.38	0.13	9.1
1.0E-11	0.354	9.00E-06	4.38	0.13	9.11
1.0E-10	0.354	8.50E-05	4.38	0.13	9.11
1.0E-09	0.354	1.20E-04	4.37	0.13	9.1
9.0E-09	0.353	9.00E-04	4.37	0.129	9.09
1.0E-08	0.353	0.001	4.37	0.13	9.09
1.1E-08	0.353	0.0012	4.37	0.129	9.09
1.0E-07	0.331	0.0076	4.41	0.13	9.16
1.0E-06	0.282	0.01	4.58	0.131	9.45

K, Tailings Dyke, tailings sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
2.0E-08	1.00E-20	1.00E-20	2.36	2.35	4.72
2.0E-07	1.00E-20	1.00E-20	2.4	2.26	4.8
2.0E-06	1.00E-20	1.00E-20	2.75	1.64	5.51
2.0E-05	0.17	5.00E-05	3.97	0.289	8.12
3.2E-05	0.317	8.00E-04	4.29	0.153	8.91
3.6E-05	0.353	1.00E-03	4.37	0.129	9.09
4.0E-05	0.386	1.60E-03	4.45	0.111	9.28
2.0E-04	0.751	0.066	5.3	0.01	11.42
2.0E-03	0.897	0.153	5.67	0.0019	12.44

Zone 2	Internal drain
Zone 3	Seepage face on the dyke slope
Zone 4	Left edge of the model, downstream
Zone 5	Right edge of the model, upstream
Zone 1	All the other cells

* Shaded entres are initial values

Table A 5.2-(b) Results of Sensitivity Analysis for Scenario 2

K, Pf-Sand = McMurray F.

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
2.0E-12	0.352	1.40E-05	9.40E-07	2.00E-04	0.352
2.0E-11	0.352	2.30E-05	9.40E-06	3.00E-04	0.353
2.0E-10	0.352	2.00E-04	9.00E-05	3.00E-04	0.352
2.0E-09	0.352	0.0012	7.00E-04	3.00E-04	0.355
2.0E-08	0.351	8.00E-04	0.004	3.00E-04	0.36
2.0E-07	0.343	0.001	0.03	4.00E-04	0.4
2.0E-06	0.3	7.00E-04	0.237	0.0016	0.77
1.8E-08	0.349	2.80E-02	0.0026	3.00E-04	0.383
2.0E-08	0.349	2.80E-02	0.0026	3.00E-04	0.383
2.2E-08	0.349	2.80E-02	0.0026	3.00E-04	0.383

Downgradient BC, Constant head in pf-sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
281.4	0.351	0.0025	0.0036	3.00E-04	0.36
281.0					
280.5					
280.0	0.351	2.70E-03	0.004	3.00E-04	0.361
279.5					
279.0					
278.5	0.35	0.0028	0.0042	3.00E-04	0.362
279.7	0.349	2.80E-02	0.003	3.00E-04	0.383
280.0	0.349	2.80E-02	0.003	2.90E-04	0.383
280.3	0.349	2.80E-02	0.003	2.80E-04	0.383

K, Top Soil, Peat

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
9.0E-08	0.339	0.0027	0.0042	7.10E-05	0.35
9.0E-07	0.341	0.0026	0.0042	8.30E-05	0.352
9.0E-06	0.35	0.0025	0.0042	3.00E-04	0.361
9.0E-05	0.39	0.0033	0.0044	0.135	0.403
9.0E-04	0.435	0.0044	0.0045	0.194	0.449
9.0E-03	0.454	0.0052	0.0046	0.379	0.468
8.1E-06	0.348	0.028	0.0029	0.00025	0.382
9.0E-06	0.349	2.80E-02	0.0029	2.80E-04	0.383
9.9E-06	0.349	0.029	0.0029	0.0003	0.384

Upgradient BC, Const. head of tailings pond

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
299.8	0.351	9.00E-04	0.004	3.00E-04	0.36
300.1					
300.0	0.363	2.80E-03	0.004	3.00E-04	0.374
301.0	0.42	1.00E-03	0.0036	3.00E-04	0.428
302.0	0.476	4.90E-03	0.0042	4.00E-04	0.489
303.0	0.532	1.60E-02	0.0045	4.00E-04	0.557
304.0	0.587	0.04	0.0047	4.00E-04	0.636
305.0	0.642	0.075	0.0049	5.00E-04	0.727
299.8	0.349	2.80E-02	0.0029	3.00E-04	0.383
300.1	0.361	0.041	0.0029	3.00E-04	0.408

K, Internal Drain Cell Sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
5.0E-08	0.138	0.015	0.005	1.00E-04	0.163
5.0E-07	0.299	0.004	0.004	2.00E-04	0.312
5.0E-06	0.341	0.003	0.004	3.00E-04	0.352
5.0E-05	0.349	0.003	0.004	3.00E-04	0.36
5.0E-04	0.35	0.002	0.004	3.00E-04	0.361
5.0E-03	0.35	5.00E-04	0.004	3.00E-04	0.358
5.0E-02	0.35	0.019	0.004	3.00E-04	0.361
5.0E-01	0.349	0.011	0.004	3.00E-04	0.376
4.5E-04	0.349	0.028	0.0029	0.0003	0.383
5.0E-04	0.349	0.028	0.0029	0.0003	0.383
5.5E-04	0.349	0.028	0.0029	0.0003	0.383

K, Tailings Dyke, tailings sand

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
2.0E-08	2.60E-03	5.00E-04	0.0032	0.0047	0.0095
2.0E-07	5.50E-03	6.00E-04	0.0033	0.0023	0.013
2.0E-06	9.00E-02	2.00E-04	0.0032	8.00E-04	0.097
9.0E-06	0.35	2.50E-03	0.0042	3.00E-04	0.361
2.0E-05	0.546	1.00E-02	0.0047	2.00E-04	0.565
2.0E-04	0.862	0.125	0.0054	2.00E-04	0.997
2.0E-03	0.91	0.138	0.0055	2.00E-04	1.06
5.0E-06	0.222	9.00E-04	0.0037	4.00E-04	0.231
8.1E-06	0.322	0.0093	0.0029	3.00E-04	0.337
9.0E-06	0.349	0.029	0.0029	3.00E-04	0.383
9.9E-06	0.356	0.035	0.0029	3.00E-04	0.396

K, Starter Dyke, LOS

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1
1.0E-12	0.345	4.00E-06	0.002	3.00E-04	0.349
1.0E-11	0.352	9.00E-06	0.002	3.00E-04	0.357
1.0E-10	0.351	2.00E-05	0.002	3.00E-04	0.357
1.0E-09	0.351	2.00E-04	0.003	3.00E-04	0.357
1.0E-08	0.35	0.002	0.004	3.00E-04	0.357
1.0E-07	0.352	0.012	0.007	3.00E-04	0.379
1.0E-06	0.38	0.018	0.009	3.00E-04	0.416
9.0E-09	0.349	2.80E-02	0.0029	3.00E-04	0.383
1.0E-08	0.349	2.80E-02	0.0029	3.00E-04	0.383
1.1E-08	0.349	2.80E-02	0.0029	3.00E-04	0.383

Zone 2	Internal drain
Zone 3	Seepage face on the dyke slope
Zone 4	Left edge of the model, downstream
Zone 5	Right edge of the model, upstream
Zone 1	All the other cells

* Shaded entres are initial values

Table A 5.3 Results of Sensitivity Analysis for INDM

(a) Response to Ditch Water Stage LGH based

	Zone 1	Model Left Edge	Seepage net	Seepage* (In / Out)	Model Right Edge	Head at InD-N
	m^3/day/m	m^3/day/m	m^3/day/m	-	m^3/day/m	m
279.91	1.45	0.32	1.16	1/10	1.41	280.26
279.92	1.44	0.35	1.14	0.053/1.088	1.39	280.27
279.96	1.44	0.50	1.08	2/8	1.30	280.28
280.00	1.45	0.65	1.05	2/8	1.21	280.29
280.04	1.48	0.79	1.04	2/8	1.12	280.31
280.08	1.52	0.94	1.06	3/7	1.03	280.32
280.12	1.56	1.09	1.09	0.622/0.47	0.94	280.34

(b) Response to Kz of Bottom Sediment with Stage 279.91m

	Zone 1	Model Left Edge	Seepage net	Seepage* (In / Out)	Model Right Edge	Head at InD-N
	m^3/day/m	m^3/day/m	m^3/day/m	-	m^3/day/m	m
2.E-04	1.54	0.31	1.32	2/8	1.45	280.26
8.E-05	1.52	0.31	1.29	1/10	1.44	280.26
4.E-05	1.49	0.32	1.24	1/10	1.43	280.26
2.E-05	1.45	0.32	1.16	1/20	1.41	280.26
1.E-05	1.39	0.33	1.07	1/20	1.38	280.27
8.E-06	1.38	0.34	1.04	1/20	1.37	280.27
4.E-06	1.32	0.38	0.94	0/1	1.32	280.28
1.E-06	1.18	0.56	0.61	0/1	1.17	280.30

(c) Response to Kz of Bottom Sediment with Stage 280.00 m

	Zone 1	Model Left Edge	Seepage net	Seepage* (In / Out)	Model Right Edge	Head at InD-N
	m^3/day/m	m^3/day/m	m^3/day/m	-	m^3/day/m	m
2.E-04	1.59	0.66	1.29	4/6	1.24	280.29
8.E-05	1.56	0.65	1.24	3/7	1.24	280.29
4.E-05	1.52	0.65	1.17	2/8	1.23	280.29
2.E-05	1.45	0.65	1.05	1/20	1.21	280.30
1.E-05	1.36	0.64	0.88	2/8	1.19	280.30
8.E-06	1.32	0.64	0.82	1/9	1.18	280.30
4.E-06	1.22	0.66	0.62	1/20	1.15	280.31
1.E-06	1.07	0.74	0.33	0/1	1.06	280.32

* Approximate ratio of flow into the model (In) to the flow out of the model (Out) estimated visually from the model output map

Section A-1 Grain Size Analysis Method Employed

A.1.1 Procedure

1. Mix the sample well in a plastic bag and divide it into four equal portions on a flat surface
2. Take the two portions located in diagonal positions
3. Take approximately 300g of sample by above method.
4. Oven-dry the sample at 105°C for 6 to 12 hours until it is completely dry.
5. Crush the sample gently if consolidated for efficient sieving
6. Remove any grains larger than 10mm in diameter and other large pieces such as plant roots.
7. Weigh the dry sample and make sure it is over 250g.
8. Weigh each sieve and record the weight (W_{sv}) up to the second decimal place in gram.
9. Set the sieves on the sieve shaker, with the smallest (63µm mesh size) at the bottom over a pan.
10. Shake the sieves for at least 10 minutes. Use a brush after the shaking for mesh size smaller than 500µm to make sure that all grains go through the sieve.
11. Weigh each sieve with the retained soil and record the weight (W_{so}) up to the second decimal place in gram.

Sieves and shaker set up

A.1.2 Used Equations

- weight retained

$$W_{si} = W_{so} - W_{sv} \qquad [g] \qquad \text{(A1-1)}$$

- % weight retained

$$A_i = \frac{W_{si}}{W_{od}} \cdot 100 \qquad [\%] \qquad \text{(A1-2)}$$

- cumulative % weight retained

$$A_{ci} = \sum A_i \qquad [\%] \qquad \text{(A1-3)}$$

- cumulative % passing

$$A_{pi} = 100 - A_{ci} \qquad [\%] \qquad \text{(A1-4)}$$

A.1.3 Classification of Soils

The results of the test are listed in **Table A-4.4** in Appendix. and the data were plotted on semi-log paper with grain size on x axis and the percent passing (finer than) of a given size on y axis. The samples were classified according to the “Unified Soil Classification System (USCS) ” modified from ASTM D2488.

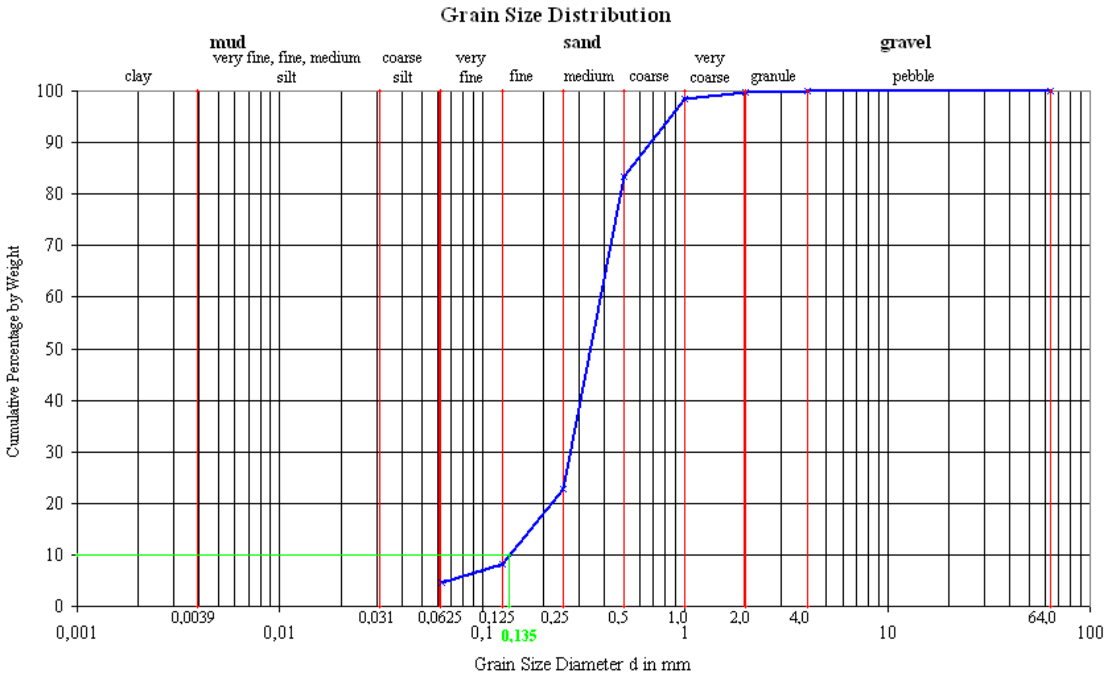
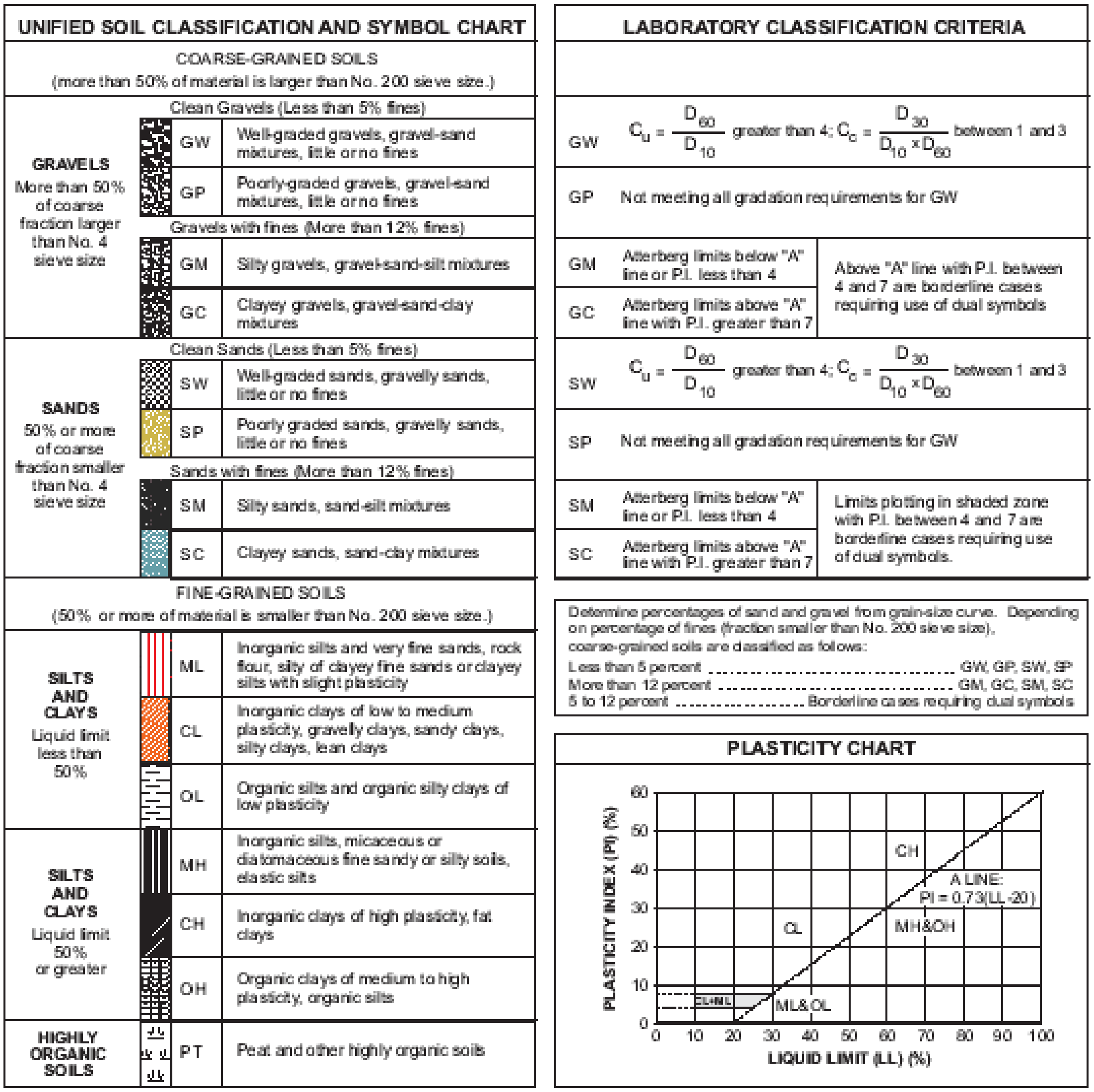


Fig. AT.1 Classification of Soil Based on Grain Size

The soil samples were classified and named based on the following classification system of USCS (see **Fig. AT.2**).



UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART			
COARSE-GRAINED SOILS (more than 50% of material is larger than No. 200 sieve size.)			
GRAVELS More than 50% of coarse fraction larger than No. 4 sieve size			Clean Gravels (Less than 5% fines)
	▨	GW	Well-graded gravels, gravel-sand mixtures, little or no fines
	▨	GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines
			Gravels with fines (More than 12% fines)
	▨	GM	Silty gravels, gravel-sand-silt mixtures
	▨	GC	Clayey gravels, gravel-sand-clay mixtures
SANDS 50% or more of coarse fraction smaller than No. 4 sieve size			Clean Sands (Less than 5% fines)
	▨	SW	Well-graded sands, gravelly sands, little or no fines
	▨	SP	Poorly graded sands, gravelly sands, little or no fines
			Sands with fines (More than 12% fines)
	▨	SM	Silty sands, sand-silt mixtures
	▨	SC	Clayey sands, sand-clay mixtures
FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.)			
SILTS AND CLAYS Liquid limit less than 50%	▨	ML	Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
	▨	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	▨	OL	Organic silts and organic silty clays of low plasticity
SILTS AND CLAYS Liquid limit 50% or greater	▨	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	▨	CH	Inorganic clays of high plasticity, fat clays
	▨	OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS	▨	PT	Peat and other highly organic soils

LABORATORY CLASSIFICATION CRITERIA		
GW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3	
GP	Not meeting all gradation requirements for GW	
GM	Atterberg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols
GC	Atterberg limits above "A" line with P.I. greater than 7	
SW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3	
SP	Not meeting all gradation requirements for GW	
SM	Atterberg limits below "A" line or P.I. less than 4	Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols.
SC	Atterberg limits above "A" line with P.I. greater than 7	

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:

Less than 5 percent .... GW, GP, SW, SP
More than 12 percent .... GM, GC, SM, SC
5 to 12 percent .... Borderline cases requiring dual symbols

PLASTICITY CHART

* The figure after Virginia Depertment of Transportation 2003

Fig. AT.2 Classification of soil based on USCS

Section A-2 PERMEAMETER TEST (FALLING HEAD)

A.2.1 THEORETICAL BACKGROUND

Laboratory experiments for hydraulic conductivity of the sand samples collected in the field survey were carried out. The permeameter test for hydraulic conductivity provides point values, and is performed on small soil samples. Saturated hydraulic conductivity (K) of a sand sample can be measured with two types of laboratory apparatus: constant head permeameter and falling head permeameter. This study used the falling head permeameter test. In this test, the time is measured for the head to fall in a tube (cross sectional area is given) from a starting mark (H_0) to a second mark (H_1). In order that the head decline be easily measurable in a finite time period, it is necessary to choose the tube diameter based on the permeability of soil being tested. For finer grain size, a smaller tube diameter must be used.

A.2.2 TEST EQUIPMENT

The following set of equipment was used to conduct the tests.

1. A Falling head permeameter apparatus (acryl sample cylinder):
    - top and bottom cap assembly
    - permeameter cylinder (3.83 cm in diameter)
    - two metal screens (mesh No. 140)
    - three screws
2. A Stop watch
3. A Tank with de-aired and de-ionized (DI) water
4. Tubes (various diameters)
5. Flexible Tubing for connecting 1 and 4
6. Water pump (peristaltic pump)
7. CO_2 gas tank
8. Stand

The set up of the whole apparatus is as shown in the following picture.

Permeameter set up

A.2.3 TEST PROCEDURE

1. De-aired (DI) water is prepared in the tank by applying vacuum.
2. Soil samples are dried under room temperature.
3. Soil sample is homogenized and placed in the permeameter cylinder.
4. Top of the sample is evened out by tapping the cylinder then the system is sealed by screws on the top cap.
5. the dry soil sample is de-aired with by gently passing carbon dioxide gas through the cylinder for at least one minute.
6. The cylinder is filled slowly with de-aired water until the water level in the tube up to the starting mark (H_0). H_0 Was set at 165 cm (or 215 cm) above the water level in the trough.
7. The valve is turned open to drain the water through the soil sample. The time "t" is measured for the head to fall with a stopwatch from H_0 to the second mark (H_1). H_1 is set at 95 cm above the water level in the trough with an intermediate reading was taken also at either 165 cm (when H_0 = 215 cm) or 125 cm. The cylinder is refilled and step 6 is repeat three to seven times depending on the variability of measured values.

A.2.4 Governing EQUATION

The hydraulic conductivity of a falling head permeability test can be calculated using the following equation (Freeze and Cherry, 1979).

$$K = \frac{a \cdot l}{A \cdot t} \cdot \ln\left(\frac{H_0}{H_1}\right) \qquad \left[\frac{cm}{s}\right] \qquad (4.1)$$

Where a $\left[cm^2\right]$ is cross sectional area of the tube, l $\left[cm\right]$ is thickness of the soil sample, A $\left[cm^2\right]$is cross sectional area of the soil sample cylinder, and t $\left[s\right]$is time the water head falls from H_0 to H_1.

A.2.5 Measurements and Data Collection

The falling head tests were run three to seven times depending on the variations of the individual results. The same samples were tested both for sieved samples and non-sieved samples to examine the difference. The obtained values were averaged after some outrageous values (if any) were excluded from the results.

The tests always started with an initial water head H_0 of 165 cm or 215 cm above the water trough where the pressure head is zero. Time readings were taken at an intermediate point of either 165 cm or at 215 cm in addition to the last mark of 95cm. The following results were calculated with a value H_1 of 95 cm above water trough and the time the water head needed to fall from H_0 to H_1. The intermediate readings were used to check the results.

Section A-3 TIPS ON RUNNING THE 2-D MODELS OF V-MODFLOW

1. Non-convergence problems

The numerical solution of the Dyke seepage model is highly non-liner due to the presence of the internal drain cell from which water is constantly draining depending on the hydraulic head above the cell. As a consequence, the model frequently experienced “non-convergence” errors. After all possible solutions had been tried, I was only able to avoid non-convergence problems in steady state models with trial and error. Since no single solution setting worked for every condition, I was never able to run a transient simulation satisfactorily and ended up wasting almost three months. Nevertheless the following tips will help avoid the problems for a given condition.

1) Assigning lowest plausible conductance values to drain boundaries.

Assigning a whatever conductance value that is large enough to ensure quick drainage along the seepage face or drain cell seems to highly increase the chance of no-convergence problem. The conductance should be kept at a minimum possible value, which can be calculated using the relevant model parameters.

2) Use of large iteration numbers in solver setting

Since the models simulate relatively smaller head changes of less than a meter, the head change criterion should be very small. I had to use a value in the order of 10^{-6}, otherwise I had budget imbalance and unrealistic solutions. Consequently, iteration number should be raised by a few couple of orders or more than the default values to ensure the solver reaches a solution.

3) Flexible solver options

The solver type has to be switched for some conditions. WHS solver does not always work well for the dyke seepage models. In many cases PCG worked better. Also, rewetting option can be used although activating rewetting does not always lead to a better result. LMG usually provided a solution but it was not realistic in many cases.

4) Existence of seepage face on a slope makes the model unstable

It seems that assigning drain cells along a slope results in instability of the model. You can either encounter non-convergence errors or if you reach a solution, it will not be usually a reasonable one: irregularly shaped phreatic surface with either many bumps and dents or vertically dropping phreatic surface over the internal drain.

In the INTDM model, I have experienced the convergence problem with the first model where I had a small mound of the McMurray formation under BtD-N (old). What happened was that the pf-sand layer was pinched due to this low-permeability mound and the water table fell below the top of this mound for the LGT (Low Groundwater Table) condition. Although McMurray formation was not completely impermeable in the model, the contrasting hydraulic conductivity value to the pf-sand made the model very unstable. I experienced the non-convergence problem so frequently for this simple model that I decided to omit this local mound.

2. Other problems

1) Program bugs

At first I was working with version 3.0 of Visual MODFLOW 2000 and frequently encountered an output error: the program could not show the graphical model output. So I took the file to my supervisor and it worked with no problem on his PC. We found that his version of Visual MODFLOW was slightly newer (minor version difference). Actually there was a patch program available to the older version. I was able to eliminate this problem to some extent after applying this patch program.

2) Graphical output problem encore

Even after the patch program was applied, I still had some kind of output problem where on the VMEngine tab, I encounter an error saying “List index out of bounds (-1)” when I tried to show a preview of the graphical output of the row of the model. I suspect that it is because the model contains only a single row but haven’t gotten around to confirm it yet.

3. Other tips

1) Map import on the vertical X-Z plane in Visual MODFLOW

The technical support of WHI officially confirmed that a map file cannot be displayed on the x-z plane of the model, which is necessary for 2-D cross-sectional modeling. However, this can be done just by importing a file after you have created a vertical cross-sectional model. The trick is that you don’t import the file at the beginning of model creation. A map file can be prepared by AutoCAD as an ordinary 2-D drawing on the x - y plane. Save it in dxf format and import it to the model using the MAP menu. The program will automatically show the map on the x-z plane of your model. This does not affect the model coordinate system in any ways, let alone the modeling results.

You may also have to adjust map coordinates to fit it to the model region because the coordinates created in AutoCAD may not exactly correspond to the model coordinates for some reasons (eg. multiple layers in AutoCAD).

2) Grid line overlapping

One time, several grid lines in the dyke seepage model accidentally overlapped for some reason. I did not recognize it at first but later I noticed one vertical grid line that appeared slightly thicker on the "Output" screen. It turned out that five or six grid lines overlapped. The model worked better after I got rid of them.

3) Sources of help

Since the technical support for this version of program had long been expired and I didn't have anyone who had on hand experience with Visual MODFLOW, I had to seek for sources of information on the Web. The following websites were consulted.

Yahoo groundwater modeling group.

You can ask and answer questions regarding groundwater modeling but can't expect to get answers for every question you ask.

http://groups.yahoo.com/group/gwmodel/

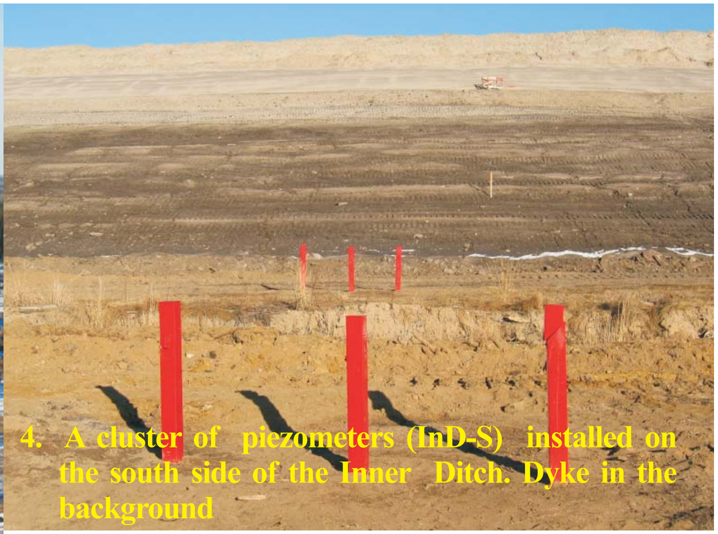
Waterloo Hydrologic Inc. 's website

This website offers some tips and tricks about their products.

Some documents are available in PDF format for free download.

http://www.waterloohydrogeologic.com/support.htm - tips

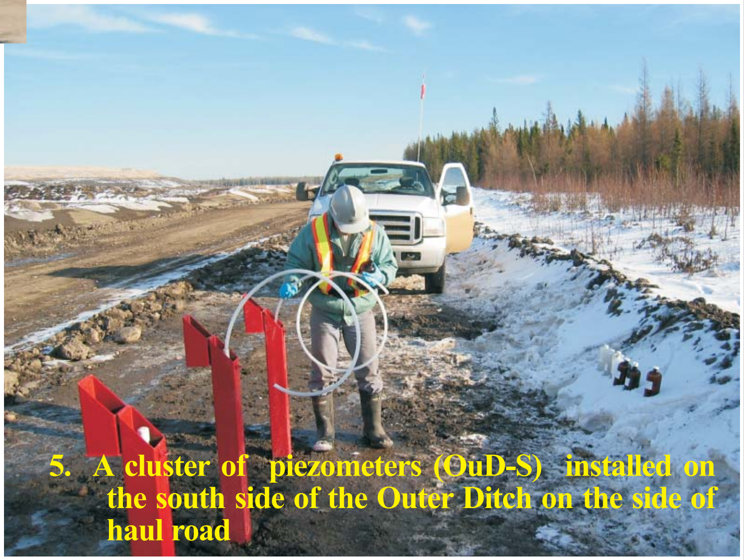
1. Overview of the Study Area, from the top of the dyke,



4. A cluster of piezometers (InD-S) installed on the south side of the Inner Ditch. Dyke in the background

2. Pf-sand exposed on the bottom of Inner Ditch

3. Drive point installed in Inner Ditch



5. A cluster of piezometers (OuD-S) installed on the south side of the Outer Ditch on the side of haul road

Photos A-1 Field Conditions in Fall 2004 (1/2)


6. Pf-sand with some pebble


8. Lean oil silt of McMurray Formation


9. Close up of photo 10, showing the boundary of peat layer (top) and pf-sand (below)


7. Installed 3/4 inch piezometer


10. Groundwater seepage (spring) at the foot of soil heap. Boundary between peat and pf-sand is

Photos A-1 Field Conditions in Fall 2005 (2/2)

1. Looking down at the Wet Area from the haul road,

2. Inner ditch, more water and vegetation, June

3. 2-inch piezometer installed at OuD-S2W,

Photos A-2 Field Conditions in Summer 2005 (1/3)

4. Flow measurement at a drainpipe, June

5. More water in Outer Ditch, June

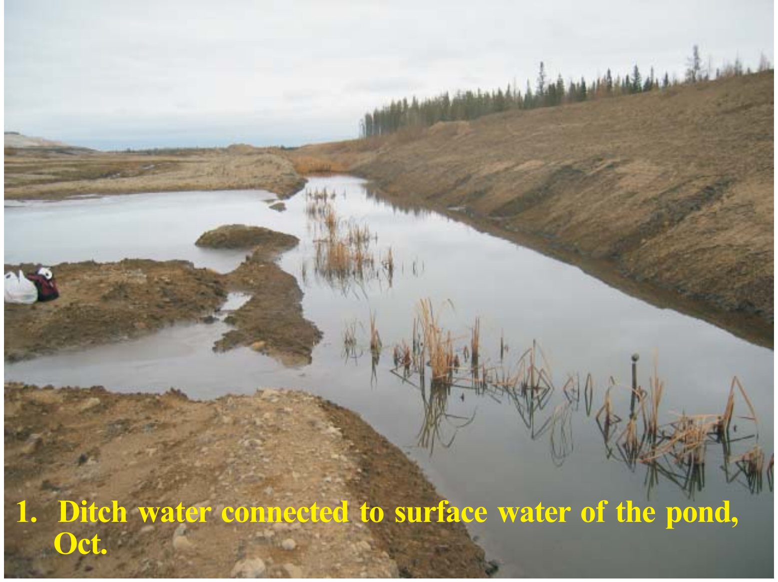
6. Asphaltine scum on the south shore of Tailings pond, June

Photos A-2 Field Conditions in Summer 2005 (2/3)

7. Installed 2-inch PVC piezometer, July

8. 2-inch piezometer installation, July

Photos A-2 Field Conditions in Summer 2005 (3/3)



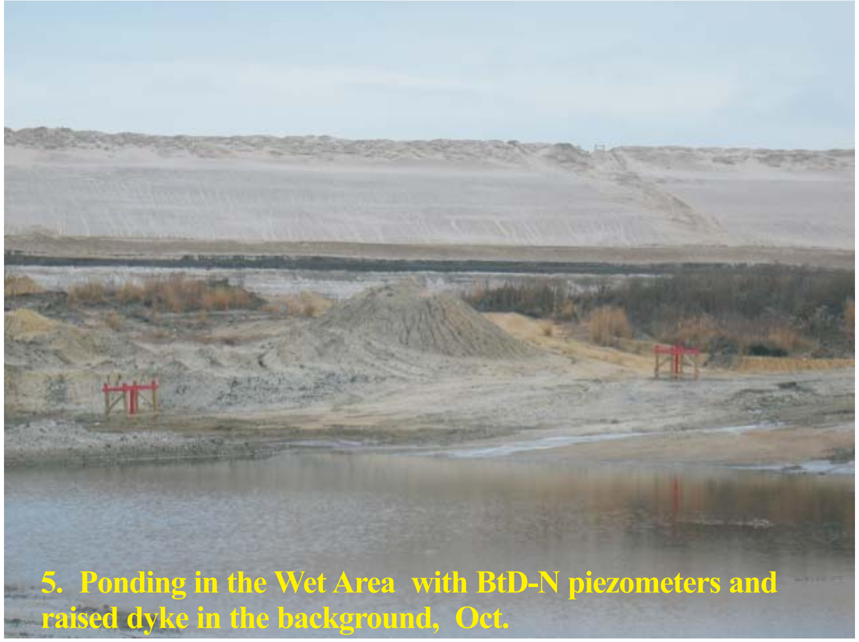
1. Ditch water connected to surface water of the pond, Oct.

2. Excavated temporary ditch near control site, Oct.

Photos A-3 Field Conditions in Fall 2005 (1/2)

3. Submerged piezometer at OuD-N, Oct.

4. Groundwater seeping out in the north of Wet Area, Oct.

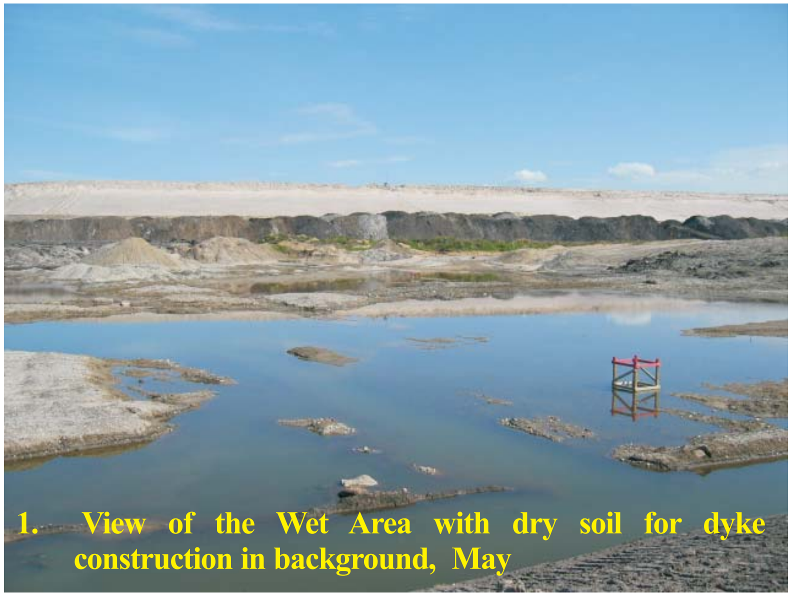


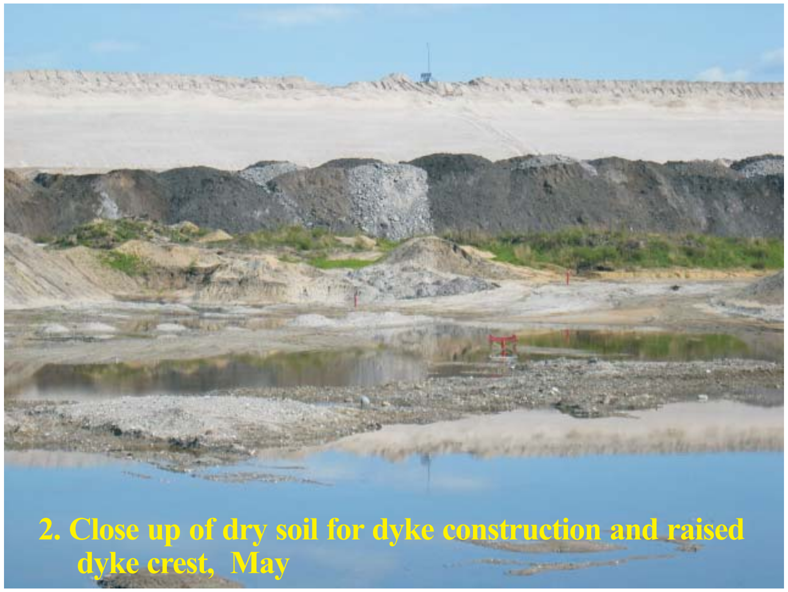
5. Ponding in the Wet Area with BtD-N piezometers and raised dyke in the background, Oct.

6. Flow measurement point in Outer ditch, Oct.

7. Submerged piezometer at BtD-S, Oct.

Photos A-3 Field Conditions in Fall 2005 (2/2)


1. View of the Wet Area with dry soil for dyke construction in background, May


2. Close up of dry soil for dyke construction and raised dyke crest, May


3. Outer Ditch and surface water in the Wet Area

Photos A-4 Field Conditions in Spring 2006