Design of Tailings Dams on Large Pleistocene Channel Deposits
A Case Study – Suncor's South Tailings Pond

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ABSTRACT

A number of current and planned tailings facilities in the Athabasca oil sands region are located over large meltwater channel deposits. This paper outlines key design and operational considerations for these facilities, using Suncor's South Tailings Pond (STP) as a case study. Weak foundation conditions associated with Clearwater Formation shales, and management of seepage from the tailings facility into the underlying aquifer required a number of interrelated design elements. Upstream and downstream cross-channel pumping well fields and cut-off walls will be used to intercept seepage. The channel is a confined aquifer for a significant reach of the impoundment and pressures within the channel are predicted to become artesian at the toe of the dykes in response to pond rise. Pressure relief wells will be used to manage these artesian pressures. An observational approach has been adopted for the management of seepage and the pressure relief well system.

RÉSUMÉ

Plusieurs parcs à résidus dans la région des sables bitumineux de l'Athabasca sont situés sur de larges dépôts de sable de l'époque glacière. Cet article expose les principales considérations de design et d'opération de ce type d'aménagements. Le parc à résidus sud (STP) à Suncor est présenté comme étude de cas. La conception des digues a été régie par une combinaison de facteurs dont la faible capacité portante des shales de la Formation de Clearwater et la gestion des écoulements sous les digues. Des réseaux de puits de pompage situés en amont et en aval du dépôt de sable et un mur d'étanchéité seront utilisés pour intercepter les eaux d'écoulement. Le dépôt de sable est un aquifère confiné sous la majeure partie du parc et des pressions artésiennes sont prévues dans l'aquifère sous le pied des digues lorsque le niveau de bassin va monter. Des puits seront installés afin de réduire les pressions artésiennes prévues. Une approche empirique a été adoptée pour la gestion de l'écoulement et le système de puits.

1 INTRODUCTION

A number of current and planned tailings dams within the Athabasca oil sands region are located over large Pleistocene glacial meltwater channel deposits, posing associated design and operational challenges.

Oil sands mine operations require large external tailings dams, typically in excess of 10 km^2 in area, which are needed to store tailings until deposition in mined out pits is feasible. The decision to locate external ponds over these regional scale alluvial deposits is driven by mine economics, land availability and regulations limiting ore sterilization.

The design of Suncor's South Tailings Pond (STP) is presented as a case study to illustrate a number of the above design challenges. This paper outlines the operating requirements, site assessment and the design of the STP.

2 PROJECT DESCRIPTION

The STP is the third external tailings facility to be constructed at Suncor's Millennium mine, located north of Fort McMurray. The existing external ponds include Pond 8A, a tailings storage pond, and Pond 8B, a water clarification pond. The STP is located immediately to the south of Ponds 8A/8B, and occupies an irregular area 4 km by 4.5 km in plan (refer Figure 1). Key features in proximity to the STP include, the Athabasca River, about 2 km west of the site at it nearest point; McLean Creek, which runs southeast-northwest through the site and eventually flows into the Athabasca River; the Steepbank Uplands which forms the eastern boundary of the STP; and Wood Creek and associated wetlands immediately to the north.

The STP is to provide fluid (water and fine tailings) storage for the Millennium Mine until 2013, when in-pit storage for tailings becomes available. The design dyke elevation for the STP is El. 390 m, with a maximum design height of 42 m and a storage capacity of 366 Mm^3 of tailings.

The starter dyke elevation is El 362 m, and has a maximum height of 14 m. The dyke elevation will be raised annually by tailings cell construction of approximately 4 m. Cell construction will commence in 2006 and will be complete in 2013. The design is based on Suncor's established tailings dyke construction methods using cell construction to provide containment, and direct pipeline discharge to beaches. The hydraulic cells are constructed during the summer months, with beaching during the winter period.

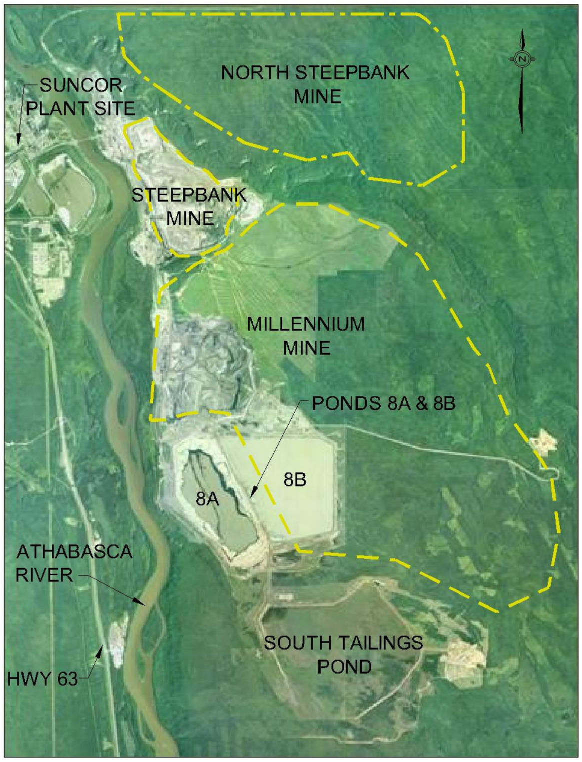

Figure 1 STP Site Location (August, 2005)

The pond will be used to store fine tailings and water from 2013 to 2035. Transfer of fine tailings to in-pit storage will be carried out from 2029 to 2035. Following fluid transfer, the pond will be breached and closure of the facility will commence.

3 FIELD INVESTIGATIONS

An initial scoping level site investigation and design was completed by AMEC in 2002. The 2003 site investigation completed by KCBL comprised 21 drill holes, and a limited number of monitoring wells were constructed. Surface geophysics totalling 12 line km of electrical resistivity tomography (ERT) was completed Worley Parsons Komex. The ERT proved to be a valuable tool in delineating the Wood Creek Sand Channel (WCSC), a Pleistocene meltwater channel and key design feature, trending from southeast to northwest across the site. The success of this application on the STP site is due to the stratigraphy and relative resistivity contrasts between the channel sands and gravels, and the underlying Clearwater Formation.

In 2004, an additional 154 holes were drilled and more than 70 were completed as monitoring wells in the kame, WCSC and the residual STP footprint and surrounding geology. Over 120 slug tests were completed and two pumping wells were established, one in the northwest WCSC and the second in the southeast WCSC segment. Step, constant discharge and recovery tests were carried out to establish WCSC storage and transmissivity characteristics for groundwater modelling during the design process. A further 35 km of ERT profiling were completed to improve the delineation of the WCSC channel morphology and surficial sand deposits.

Additional investigations following design have included:

- A 20 day aquifer test in the northwest WCSC to establish aquifer boundary conditions;
- Additional ERT on selected dyke sections for confirmation of foundation conditions;
- Installation and commissioning of northwest wellfield pumping and monitoring well arrays.
- Test pitting to assess the nature and extent of surficial sand deposits, and completion of a limited drilling program for the southwest WCSC cut-off wall.

Additional investigation of the kame and WCSC interaction is in progress and further ERT work is planned to improve the current understanding of the WCSC morphology in the area of the spill point, which is an area of groundwater discharge from the WCSC into McLean Creek and a key seepage design consideration.

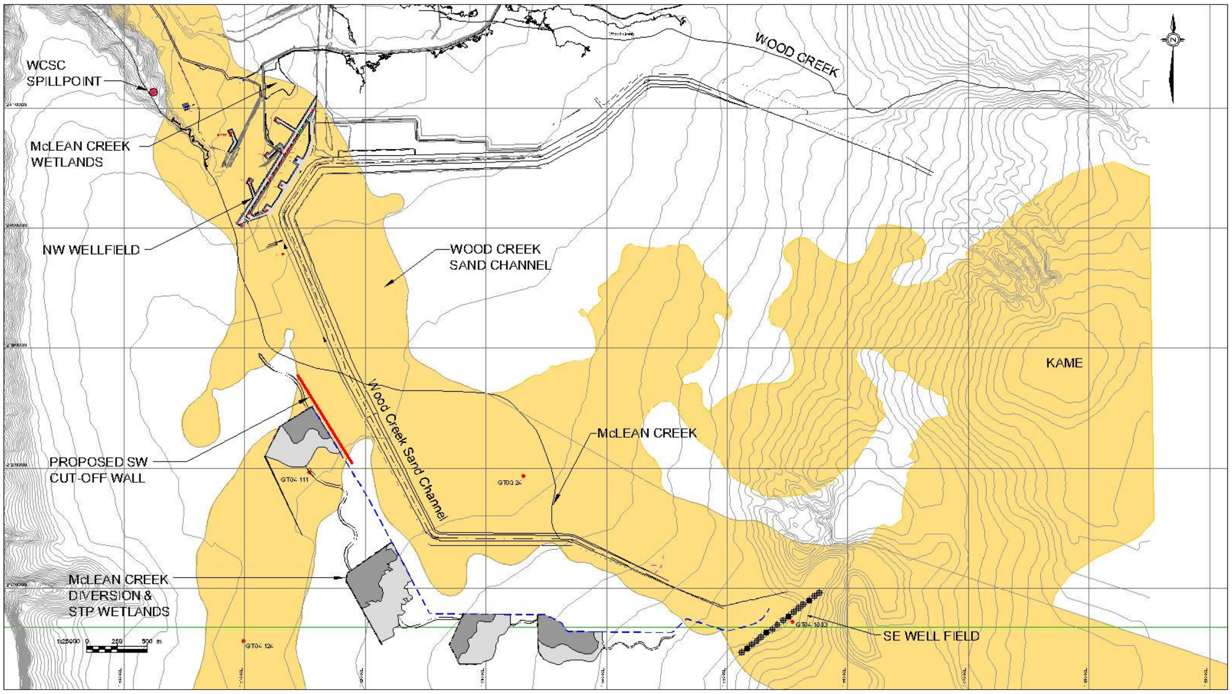

Figure 2 STP General Arrangement (1 km grid shown)

4 SITE GEOLOGY

The general stratigraphic profile at the STP comprises in descending order:

- a surface layer of Holocene organic soil (muskeg);
- Pleistocene glacial till;
- Cretaceous Clearwater Formation clay shales;
- Cretaceous McMurray Formation oil sands; and
- Devonian Waterways Formation limestone.

The Cretaceous McMurray Formation and the underlying Devonian limestone are sufficiently deep that they do not influence the design of the STP, and are not discussed further.

4.1 Holocene and Pleistocene Soils

The soils overlying the Clearwater Formation comprise the following major units listed in descending order:

- **Holocene Soils (Ho):** These soils are muskeg deposits that are generally continuous across the site but are thicker within closed topographic lows where drainage is poor. The muskeg thickness is up to 4 m but is generally 1 m to 2 m thick and is typically comprised of silts, peat, and organic soil containing roots, wood fragments, trace clay, commonly with a fibrous texture, generally ranging in colour from brown to black.
- **Pleistocene Glaciolacustrine Soils (Pl):** These soils are discontinuous lenses of fine sands, silts and clays. The clays are typically of medium to high plasticity, and of firm to stiff consistency and where present, is 1 m to 2 m thick.
- **Pleistocene Glacial Tills (Pg)**: The Pg unit comprises clayey till (Pgtc), silty till (Pgt), sandy till (Pgts) and/or Clearwater-derived till (Pgc), as well as rafted (PgKc) Clearwater, or ice-thrusted (Kcip) Clearwater. The unit underlies muskeg or shallow glaciofluvial sands and gravels. Thickness typically varies up to 26 m. Upper till units are often sandy, and the clay content typically increases with depth. Lower units closely reflect the composition of the underlying parent Clearwater Formation and generally have medium to high plasticity, but plasticity is lower than the underlying Clearwater. Shear zones may be present in discontinuous blocks of transported Clearwater (rafts) that can be present in the glacial till.
- **Pleistocene Glaciofluvial Sands and Gravels (Pfs and Pfg):** These are dense basal sands and gravels within the WCSC that overlie Clearwater Formation. No glacial till was encountered at the base of the WCSC.

4.2 Cretaceous Clearwater Formation

The Clearwater Formation (Kc) underlies the glacial till (Pg) and the WCSC throughout the site, apart from portions of the base on the northwest segment of the WCSC, which can be in contact with McMurray Formation. The contact between these units is an erosional unconformity that rises away from the Athabasca River. The top of the Clearwater varies from approximately El. 323 m in the west to El. 338 m in the east.

The Clearwater is a marine deposit comprised of predominately clay shales with numerous thin carbonate cemented siltstone beds. The Clearwater has been divided by others into eight sub-units for the purpose of stratigraphic correlation in this area. Each of the sub-units is identified on the basis of specific marker beds determined from natural gamma and density geophysical logs as described in Isaac (1982). The oldest sub-unit is the glauconitic Kcw, which conformably overlies the McMurray Formation. The upper sub-units are designated Kca through Kcg. In the vicinity of the STP, the upper, younger Clearwater sub-units have been completely eroded. The youngest sub-unit present at the site is Kcd, which subcrops over the eastern portion of the site. The lower Kcb and Kca sub-units subcrop towards the west as the erosional unconformity drops toward the Athabasca River valley. Kcw underlies the entire site and is overlain by one or more of the younger Kca, Kcb, Kcc and Kcd units.

Core logging identified shear zones in the Clearwater clay shales at this site, characterized by smooth slikensides and striated surfaces, where low angles of shearing resistance are expected. Similar weak shear zones have been observed in Clearwater cores from Dyke 11A which forms part of Pond 8A, and the Mildred Lake Settling Basin (Nicol 1994) at Syncrude. These weak shear zones have caused foundation movements within portions of both dykes.

5 HYDROGEOLOGY

The primary aquifers on the site are the WCSC, and a relatively elevated Kame deposit which forms the eastern boundary of the STP.

5.1 Wood Creek Sand Channel (WCSC)

The WCSC was named following the construction of the Wood Creek Dam, which formed part of Pond 8A, and completely cut off the meltwater aquifer at that location. The WCSC cuts across the STP footprint from southeast to northwest, from where the channel alignment continues to the northwest under tailings Dyke 11A, and through Wood Creek (Figure 2). The channel is typically capped with organics and glacial till, suggesting that the channel was active prior to final glacial retreat in the area, and the channel sediments are dense due to the glacial loading. The channel base typically rests unconformably on Clearwater Formation strata, but in places the channel is incised into McMurray Formation.

Andriashak (1991) considers that the WCSC is an extension of the Clark Channel, a major regional scale buried channel system. This interpretation is further supported by published maps, and air photo interpretation confirmed the presence of surficial sandy material towards the south. For design purposes, these data were collated and the WCSC was interpreted to extend to the southeast of the STP, with a likely connection to the Clark Channel.

Recent site investigation data suggests that extension of the WCSC southeast of the STP is tenuous, and further work is planned to clarify the channel morphology and orientation to the south and east.

Detailed drilling, well installation and aquifer testing programs carried out from 2004 to 2006 in the channel section northwest of the STP have shown that the channel section morphology is variable and sedimentary characteristics vary both vertically through the profile and horizontally across the channel. The channel form represents a combination of two fluvial systems. The lower channel section is interpreted as the original channel thalweg. Sediments in this section of the profile typically comprise coarse grained sands and gravels. Fines content in the units varies, and the presence of relatively high fines contents in some units suggests a proximal source for the sediment. Aquifer potential in the thalweg is typically significant, with permeabilities typically in the range 0.1 to 100 m/day. A general fining upward in the sequence is evident.

The upper channel section is significantly wider and is interpreted as a lower energy fluvial environment with both channel and overbank facies. Extensive sediment reworking is likely to have occurred in a braided and/or meandering fluvial system. Fining upward in the sequence is generally apparent, and hydraulic conductivities vary widely. Typical hydraulic conductivity values for the various Pleistocene units in the STP investigation area are presented in Table 1.

Exploration drilling and aquifer tests have shown that although continuous hydraulic connection in the channel is observed, the lower channel section is the principal aquifer. Delayed response to pumping in the lower section, has been measured in these lower permeability upper channel sediments.

Table 1 Summarized Permeability Results – Strata Specific

Strata	Number of Sites	Number of Tests	Permeability m/day Minimum	Maximum	Median
Slug Testing					
*Glacial Till	29	41	1.3×10^{-3}	7.8×10^{-1}	2.1×10^{-2}
Intertill Sand	9	15	1.4×10^{-2}	8.2	0.1
WCSC	32	63	0.6	100	56
Kame	4	7	7.6×10^{-3}	8.1	2.0
Pumping Tests					
WCSC	2	3	8	87	36

*= Glacial Till includes silt.

5.2 Kame Deposit

A deposit called the Kame is located on the eastern periphery of the STP in the area of the headwaters of Wood Creek and McLean Creek. This naming convention is based on initial surficial mapping interpretation of the area. Excavation into the unit identified it to be fluvial in nature, fine on the margins and coarse grained at the centre associated with high energy deposition. This original naming convention was retained for record keeping purposes for the STP project.

The base of the deposit rises eastward in the lease area from an elevation of roughly 360 m to 400 m above sea level. Groundwater levels are relatively elevated in the kame and groundwater flow is generally from east to west and follows the topography.

6 STP Design

The key design issues for the STP are:

- Challenging dyke design requirements over weak Clearwater Formation clay shales;
- Reducing artesian pressures at the dyke toe caused by porewater pressures within the WCSC;
- Protection of McLean Creek and off lease regional groundwater systems from process-affected water seepage; and
- Surface water design to maintain a closed circuit system for process affected water, and to divert and reconstruct natural waters systems around the facility.

These elements of the design are discussed in the following sections.

6.1 Clearwater Shale Foundation

The STP is underlain by weak Clearwater Formation clay shales at variable depths. Perimeter slope angles of the STP dykes are controlled by low residual strength shear bedding planes in the Clearwater. Shear strength is further reduced as most of the dyke load is taken up by pore pressure increases in the Clearwater, which will not dissipate over the operational life of the impoundment.

Dyke stability over the pre-sheared Clearwater clay shales relies heavily on the passive shear resistance of the overlying units. In general, the thicker the overlying unit, the steeper the dyke slopes. To develop the passive resistance at the toe, movements along these pre-sheared layers are expected. This mechanism was observed at Syncrude’s Mildred Lake Settling Basin and is described in Nicol (1994).

Table 2 summarizes the design criteria adopted for stability assessments of the STP dykes. Material parameters are based on laboratory data from field exploration and Suncor site data. Clearwater shale design strengths are based on back analysis of performance data from Pond 8A dykes.

6.2 Perimeter Dyke Alignment

The perimeter dyke alignment was selected to maximize tailings storage by positioning the dyke toe with deeper Clearwater units where steeper dyke slopes are possible. Along the North Dyke, there was little flexibility as the weak Clearwater Formation is close to the surface. Three stabilizing berms are required in the North Dyke to meet Suncor’s operational requirements of tailings dykes slopes no flatter than 10H:1V

Along the South Dyke and West Dyke, the toe was positioned over the alignment of the WCSC and the depth to Clearwater is greater. The thick dense to very dense sands and gravels of the WCSC allow steeper slopes than for shallow Clearwater. The steeper slopes also result in a modest increase in storage capacity for the STP.

Table 2 – Material Strength Parameters

Unit	Cohesion (kPa)	Effective Friction Angle	Pore Pressure (kPa)	Density (kN/m^3)
Dyke Embankment Fill				
- Lean oil sand/dry Tills	0	33°	$r_u = 0.25$	19.5
- Clearwater shale/wet tills	0	22°	$r_u = 0.25$	19.0 - 19.5
Tailings Sand				
- Cell	0	34°	Piezometric	19.5
- Sub-aerial beach	0	32°	Piezometric	19.5
- sub aqueous beach	0	28°	Piezometric	18.5
- sub aqueous beach (liquefied strength)	Cu/p'=0.1	-	-	18.5
Foundation				
- Pleistocene Lacustrine	0	26°	$\bar{B} = 0.7$	20.0
- Glacial Till	0	30°–34°	$\bar{B} = 0.4–0.5$	21.0
- Glacio-fluvial sand (WCSC)	0	33°–36°	Piezometric	21.0
- Clearwater (cross bedding)	0	17°	$\bar{B} = 0.8$	21.0
- Clearwater (bedding shear)	0	7.5°	$\bar{B} = 0.8$	21.0

6.3 Pressure Relief Wells

Pressure relief wells are required to reduce artesian pore water pressures within the WCSC downstream of the perimeter dykes for the STP. Groundwater modelling of the pore water pressures in the WCSC predicted unmitigated artesian pressures in the WCSC of the order of 20 m above existing ground surface levels. The elevated pore water pressures are a result of the rising STP pond, and the WCSC being a confined aquifer. Artesian pressures at the toe of the dyke reduce the passive resistance of soil units above the Clearwater, and may result in boils downstream of the dykes if unrelieved.

Relief wells were selected to manage the artesian pressures at the toe of the STP dykes, as they:

- represent an established technology with documented use in a large number of water supply dykes and flood control levees;
- provide a flexible control measure that can be expanded if the initial system requires modification. In the case of the STP, this flexibility allows for the staged installation of the wells to match the increasing pond elevation, and resultant artesian pressures, during tailings placement;
- can be constructed to penetrate the full thickness of the aquifer to ensure performance is not affected by low permeability lenses present within an aquifer;
- are a passive system which does not rely on power or pumping elements to function; and
- are able to be installed following completion of construction of the STP starter dykes and surface drains.

Middlebrooks (1946) provides a good summary of design and operation of relief wells used for dams and levees.

The preliminary design of the relief well network is based on the method set out by the U.S. Army Corps of Engineers (1992) for the design, construction and maintenance of relief wells. The method provides the well penetration and spacing required to maintain a predetermined average piezometric head down slope of a structure such as a dyke. A maximum average artesian head of 5 m above existing ground surface was adopted for the STP design. The required well spacing is a function of the total head, and well penetration into the aquifer. Full penetration of the WCSC aquifer is required to maximize the spacing between individual wells in the network. For the STP at a final pond elevation of 387 m, a nominal well spacing of 25 m with fully penetrating relief wells is proposed.

The pressure relief well network will be installed in stages, at wider initial spacing to match the rise in pressure. The current schedule for installation of the initial wells affords time for additional monitoring and possible field trials prior to full implementation. The initial installations of wells are programmed for summer 2008. Transient data from the operation of the Northwest Wellfield (refer Section 6.5) will be incorporated into a three-dimensional finite element FEFLOW model. This model will provide a tool for initial design and ongoing assessment of the pressure relief network.

Currently work is in progress to develop procedures for winter operation of the pressure relief wells. This work will include field trials to observe winter operation of relief wells, and required maintenance issues in advance of installation of the pressure relief network.

6.4 Surface Water Management

The surface water management design for the STP includes management of seepage water from the tailings dykes, diversion of natural water courses around the structure, management of pressure relief water and construction of riparian habitat to compensate for the construction of the STP.

All process affected (PA) water from the internal drains within tailings dykes, the relief wells, the outer faces of the STP dykes and any other sources will be collected in perimeter ditches and pumped back to the pond as part of a closed water management system. With time it has been assumed that the groundwater in the WCSC will become process affected and has therefore been included within the closed water circuit for the project.

The McLean Creek alignment flowed through the footprint of the STP. To enable construction of the impoundment, McLean Creek was diverted around the South Dyke and West Dyke of the STP (Figure 1). The STP Wetlands have been constructed within the diversion area to compensate for habitat lost beneath the footprint of the STP and the eventual loss of the existing McLean Creek Wetlands, associated with mining operations to the north of the STP.

6.5 Seepage Management

The STP has been preferentially aligned over the WCSC to take advantage of the sand/gravel foundation as a supporting medium for the pond dykes. However, areas of limited glacial till, exposed sand (WCSC) and kame all provide potential direct recharge pathways for the migration of PA seepage from the STP into the underlying WCSC and the regional groundwater system.

PA seepage from the pond will migrate through two major pathways. The first is through the sand tailings dykes. Seepage will be collected using internal filter drains and will be recycled to the pond in a closed circuit system. The second pathway is vertical seepage through the foundation materials into the WCSC, and lateral flow in the channel, which will predominantly follow current regional channel groundwater flow to the north.

Approximately 50% of the STP (dyke and cell) overlies the WCSC, which provides three potential pathways for seepage of PA water to enter the WCSC and migrate through the channel to the surrounding environment (Figure 2). Potential exit points for seepage are to McLean Creek spill-point to the northwest (NW wellfield), to the regional groundwater system to the southwest (SW cut-off wall), and to the regional groundwater system southeast (SE wellfield). As previously mentioned the northern section of the WCSC was cut-off by the construction of the Wood Creek Dam.

The framework for seepage management is a commitment to the environmental protection of McLean Creek and to the preservation of regional groundwater resources. For McLean Creek this is a commitment to manage seepage flows from the STP, such that concentrations of contaminants (particularly napthenic acids) do not reach concentrations that cause an adverse environmental impact. The commitment in terms of seepage migration in groundwater is that there is to be no movement of contaminants across lease boundaries; and no uncontrolled passage of contaminated groundwater to the surface water bodies.

6.5.1 Seepage Mitigation Design Options

The process of selection for the STP seepage mitigation design was an iterative, consultative process with the client which started in early 2003 and was completed in mid-2004. Throughout the process, mitigation options (and combinations thereof) were raised and ranked based primarily on:

- Achieving low or manageable risk in terms of environment impacts, technical feasibility (of success), flexibility in design, and performance based monitoring facilitating a reasonable response time to changes in the system;
- Minimization of cost, both capital and operating;
- Meeting the STP operational plans with minimal impact to tailings schedules and site layouts; and
- Ready integration into existing mining and tailings operations.

A combination of pumping wells and a cut-off wall were selected as the optimum design solution for seepage control.

Pumping wells in the main aquifer areas carry several advantages to the overall design including a history of successful use, effective cut-off induced across the whole aquifer due to designed interference effects, the ability to quickly expand or decommission the system as monitoring deems necessary, and this option represents proven technology in the oil sands and other industries across Canada.

6.5.2 Seepage Design Elements

A groundwater model was established and calibrated to steady state to assist in the seepage management design.

In the northwest, to protect aquatic resources against adverse environmental impact in McLean Creek, STP seepage will be managed using a system of interception pumping wells. The wells were installed in February 2006 and a commissioning trail was initiated in May. A comprehensive monitoring program is in place to monitor the development of draw-down in the channel. The design intent is to reverse the current groundwater flow gradient in this portion of the channel, such that any seepage is intercepted by the pumping wells, and a reversal in groundwater gradient is established between the pumping wells and the spill point in McLean Creek (Figure 2). System performance to date is in accordance with the design.

In the southwest channel of the WCSC, a cut-off wall will be constructed in 2007 to intercept PA seepage. This design may require a limited number of pumping wells upstream of the wall to manage pore pressure build up in this area. Instrumentation and a monitoring program will be in place prior to commissioning, to measure pore pressures, groundwater quality, and to assess performance of the cut-off wall.

In the southeast segment of the channel, relatively reduced pond head and channel hydrogeological conditions combine to limit the anticipated extent of a PA migration and unmitigated seepage is unlikely to move beyond the lease boundary. Groundwater gradients in the WCSC channel in this area are to the north, mitigating against seepage travelling southeast in the channel. Interception pumping wells are currently included as the seepage mitigation design option. The requirement for the wells will be assessed and based on performance monitoring data, once the STP is in operation.

Groundwater gradients naturally mitigate against STP seepage to the east. However, investigations are currently in progress, building on the initial investigations to date, to characterize the kame deposit and optimize seepage design elements, prior to inundation of the eastern STP area in 2008 when pond elevation reaches the base of the kame deposit at approximately 375 m elevation.

The current groundwater model will be revised in due course based on the 2005 and 2006 investigation data and operational monitoring data. Transient calibration will allow use of the model as predictive tool for ongoing seepage design optimization, and as a closure planning tool. An academic research program has been commissioned to determine actual pond seepage rates and to assess natural contaminant attenuation potentials of the foundation sediments and the WCSC. These data will be then be available for further model refinement and ultimately closure design.

7 CONCLUSIONS

The location of tailings facilities over major Pleistocene meltwater channel deposits can pose significant design challenges. For the STP, this required an integrated approach to engineering of dyke slopes, PA seepage and pore pressure management in the aquifer. For these projects an integrated project team comprising geotechnical, hydrology, environmental and hydrogeology disciplines are needed.

Management of seepage into the meltwater channels is the key design consideration for STP in terms of dyke stability and environmental compliance. The STP seepage management system is large and requires a long term commitment to operation and maintenance.

An observational approach to the design and operation of the STP has been adopted and approved. This approach recognizes the scale of the project, uncertainties within the available data, and provides flexibility and contingency for the operation and development of the tailings impoundment. A commitment to a high level of operational monitoring and maintenance of dyke stability and seepage management systems is implicit in this approach.

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