Groundwater Control for Tailings Dams Built on Large Pleistocene Channel Deposits. A Case Study of Integrated Systems at Suncor’s South Tailings Pond.

Warren Vincent-Lambert  
*Klohn Crippen Berger Ltd., Calgary*

Mike Bowron  
*Suncor Energy Inc., Fort McMurray*

Chris Langton  
*Klohn Crippen Berger Ltd., Calgary*

Brett Stephens  
*Klohn Crippen Berger Ltd., Calgary*

**Abstract**

This paper provides a review of the engineered systems implemented at the south tailings pond (STP) for seepage mitigation and pressure relief, and the continued advancement in understanding the hydrogeological systems being managed. A brief recap of the project, the site hydrogeology and pertinent design criteria are provided, together with information on the design, installation, functionality and performance of the engineered groundwater control systems. The STP, an oil sands external tailings storage facility was commissioned in July 2006. Three of four principal seepage mitigation and pressure relief design elements have been installed in the Wood Creek Sand Channel (WCSC) aquifer. These are the Northwest Wellfield, the Southwest Cut-off Wall and the passive relief well system. Following the design basis, an observational approach was adopted, and the requirements for additional seepage mitigation design elements are assessed through ongoing performance monitoring for the tailings structure and the groundwater control systems, and using improved hydrogeological understanding gained from the application of geophysical technology.

**Introduction**

Suncor’s South Tailings Pond (STP) is one of the first, and now one of several, oil sands external tailings dams constructed over buried Pleistocene glacial meltwater channel aquifers. One of the significant challenges facing the STP and other similarly located structures is the control of groundwater for both environmental protection, and geotechnical stability of the dam. These challenges were identified during the design process for STP and a variety of engineered mitigation measures were incorporated into the final design of the tailings dam.

The STP has been operational for over five years and the success of the mitigation systems is now becoming evident.

**Project description**

The STP is the third external tailings facility to be constructed at Suncor’s Millennium Mine, located north of Fort McMurray. The STP is located immediately to the south of Ponds 8A and 8B, and occupies an irregular area 4 km by 4.5 km in plan (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 has been diverted around the southern and western boundaries of the STP through constructed wetlands.
and runs southeast-northwest, eventually flowing into the Athabasca River; the Kame sands uplands which form the eastern boundary of the STP; and Wood Creek and associated wetlands immediately to the north. The STP provides water and fine tailings storage for the Millennium Mine. 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.

![Figure 1: STP Site Location (August, 2010)](image)

**Site Hydrogeology**

**Wood Creek Sand Channel**

The most significant hydrogeological feature of the STP site is the Wood Creek Sand Channel (WCSC), so named following the construction of the Wood Creek Dam, part of the Pond 8A seepage mitigation system, and which completely cut-off the aquifer at that location. The WCSC, a buried Pleistocene glacial meltwater channel, runs from southeast to northwest across the STP site, extending under the west dyke of Pond 8A and through Wood Creek. The channel comprises fining upward sequences of gravels, sands and silts, with a glacial till cap providing a confining layer over a large portion of the channel. The channel is incised into the Clearwater Formation strata (generally clay shales with numerous thin carbonate-cemented siltstone beds). In some areas the WCSC is incised through the Clearwater Formation and the base of the channel is in direct contact with the McMurray Formation sediments.

Andriashek (1991) considers that the WCSC is an extension of the Clark Channel, a major regional scale buried channel system. This interpretation was further supported by published maps, and air photo interpretation confirmed the presence of surficial sandy material towards the south. For original 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. Subsequent field investigations and hydraulic testing indicate that connection between the WCSC within the STP site area and the Clark Channel to the southeast is unlikely.
Within the STP site area, the WCSC morphology comprises a main channel, lateral over bank deposits and tributary channels. These lateral extensions of the aquifer provide additional flow paths for groundwater and potential connections to the Athabasca River. The main channel ranges from 1km to 2km in width and from 10m to 50m in sand thickness. The tributary channels provide flow paths to the west and southwest and range in width from 200m to 600m, and 10m to 30m in sand thickness. Over bank deposits range from 1m to 10m in thickness. Hydraulic conductivities within the WCSC aquifer vary considerably, both laterally within the channel as well as vertically, ranging from $6.9 \times 10^{-6}$ m/s to $1.2 \times 10^{-3}$ m/s.

**Kame Deposit**

A deposit called the Kame is located on the east side of the STP and forms a localised upland to the surrounding area, rising from 360 m to 400 m above sea level. The deposit generally underlies the shallower organic and muskeg sediments and is typically comprised of stratified silt, sand, gravel and water-born cobbles. This unit is generally less than 15 m thick, but can be up to 20 m thick in places. The Kame boundary has been interpreted at depth from geophysical site investigations, while the extents of the deposit at surface have been delineated using geophysical surveys, aerial photograph interpretation and topographic assessments.

Groundwater flow patterns within the deposit are radial from the high ground towards lower lying areas thus providing a westward gradient towards the STP and a resultant hydraulic containment for shallow seepage potentially migrating eastwards from the STP.

**Design Performance Criteria**

The key environmental and geotechnical performance criteria for the STP, which relate to groundwater control are:

- Protection of McLean Creek and off lease regional groundwater systems from process-affected water seepage.
- Maintain pore pressures of less than 5 m artesian head above original ground elevation, at the downstream toe of the dykes located over the WCSC.

**Engineered systems – design and installation**

**Northwest Wellfield**

The installed design of the Northwest Wellfield is a refinement of the original 2004 design. The refinement came about through application of an updated geological model and improved hydrogeological understanding of the WCSC in the northwest area of the STP site. This data was gained from additional geological drilling, Electrical Resistivity Tomography (ERT) geophysics performed across the WCSC, and through a 20 day pumping test performed in the WCSC at the northwest corner of the proposed STP.

The improved understanding of the channel morphology and hydraulics at that time allowed for a reduction in the total number of pumping wells from 19 wells at 80m spacing, to 7 wells at 80m spacing (Figure 2).
Well designs were then optimized to meet various criteria for installation, operation and economic efficiency. The criteria and corresponding design features are summarised in Table 1.

Table 1: Well Design Features for Optimized Installation and Operational Performance

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Design Feature</th>
<th>Corresponding Performance Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well efficiency</td>
<td>304mm screen diameter</td>
<td>Higher flow without turbulent flow</td>
</tr>
<tr>
<td></td>
<td>v-wire wrapped screen</td>
<td>Larger open area, higher capacity</td>
</tr>
<tr>
<td></td>
<td>Graded sand pack installation</td>
<td>Improved efficiency</td>
</tr>
<tr>
<td>Maximum drawdown</td>
<td>Screen located at base of aquifer</td>
<td>Maximize drawdown</td>
</tr>
<tr>
<td>Longevity of wells</td>
<td>Stainless steel screens</td>
<td>Reduced corrosion</td>
</tr>
<tr>
<td></td>
<td>Di-electric couplers</td>
<td>Reduced galvanic corrosion</td>
</tr>
<tr>
<td></td>
<td>Limited screen length</td>
<td>Reduced potential for air intake in screen</td>
</tr>
<tr>
<td>Installation efficiency</td>
<td>Universal screen slot size selected</td>
<td>Pre-ordered screens optimized field time</td>
</tr>
<tr>
<td></td>
<td>Dual-rotary drilling method</td>
<td>Reduced aquifer damage, improved well installation quality, reduced well development times</td>
</tr>
<tr>
<td>Operational efficiency</td>
<td>Flexible risers for pumps</td>
<td>Reduced installation and removal time</td>
</tr>
<tr>
<td></td>
<td>Variable speed pumps and control</td>
<td>Accurate pump adjustment for drawdown control, improved pump efficiency</td>
</tr>
</tbody>
</table>
During the installation process the final number of pumping wells installed was reduced to six, as the depth of channel aquifer encountered was much less than expected on the eastern edge of the channel. Based on the drawdown targeted for the well field, the well in question would have had an effective lifespan disproportionate to the cost of installation and operational benefit.

Subsequent to the installation of the wells, step-testing was performed on each well to obtain well-specific data for pump and flow rate specification. Based on the step-tests it was decided to reduce the number of wells commissioned to five, as a result of a low permeability zone in the aquifer, which resulted in poor yields in one of the wells.

Installation and testing of the well field was completed by May 2006. Commissioning occurred on May 18, 2006, followed by continuous operation.

**Southwest Cut-off Wall**

A cut-off wall was proposed in the 2004 design report for STP to provide a hydraulic cut-off across the southwest channel (Figure 5), a tributary channel of the WCSC. Numerical modelling had indicated that seepage originating from the STP may flow towards the southwest down the channel and beyond the lease boundaries. The decision to install a cut-off wall rather than another pumping well field was based on being the best technical solution for the hydrogeological setting, lower capital and NPV costs, and being a preferred option for regulatory approval.

Additional site investigation data collected in 2006, which included sonic core drilling and ERT, indicated a more extensive channel feature than originally anticipated; however, the updated hydrogeological understanding still supported the construction of a soil-bentonite cut-off wall. The northern limit of the channel had not been conclusively identified, therefore additional field work was recommended prior to construction. At this stage, the cut-off wall design called for an 1100 m long wall, up to 33 m in depth, 1 m wide, and with a nominal hydraulic conductivity of less than $1 \times 10^{-9}$ m/s. Construction of the cut-off wall would require the use of a long-stick backhoe and a clamshell excavator.

Additional field investigations (drilling and ERT) conducted in 2006 and 2007 provided the basis for a change in the alignment of the cut-off wall, resulting in a 200 m reduction in wall length, and improved certainty of tying into the low permeability strata on either side of the channel.

Detailed laboratory testing performed in 2007 yielded specifications for the soil-bentonite mixtures, which enabled the use of excavated material for backfill, and groundwater extracted from the WCSC for slurry preparation. The range for bentonite addition to achieve the desired hydraulic conductivity varied between 2% and 4%, depending on the nature and mix of the excavated material.

Construction of the cut-off wall was successfully completed over a period of two summer seasons ending in 2008. Subsequently, standpipe piezometers have been installed up-stream and down-stream of the cut-off wall to provide performance monitoring data (water levels and chemistry) for the structure.

**Passive Depressurization System**

A system of passive pressure relief wells was proposed to control artesian pressure build-up in the WCSC resulting from seepage and increasing head with the rise of the STP during operations. Without mitigation measures in place, numerical modelling using Modflow software, showed that WCSC pore pressures would rise to 20 m above ground elevation. To maintain a factor of safety of 1.3, a piezometric surface less than 5 m above original ground elevation must be maintained.
Preliminary design of the relief well network was completed using the method set out by the U.S. Army Corps of Engineers (1992). This resulted in a design calling for a staged installation of 304 passive wells to be completed between 2008 and 2010, with spacing between wells starting at 100m and reducing to 25 m by 2010. Initial modelling was deemed conservative as it did not account for any potential depressurization benefit gained from the operation of the northwest well field.

An updated geological model and a new three-dimensional finite element groundwater model using FEFLOW software were used to update the relief well network design in 2007. Transient calibration of the FEFLOW model incorporated operational data from the northwest well field; however the drawdown effects of the well field were still ignored to provide some conservatism to the design approach. Based on the revised modelling a design incorporating 71 passive wells at 100 m spacing was produced. Specifications for maximum distance from the downstream toe of the dykes and the elevation of discharge at individual wells were also provided. A monitoring network encompassing standpipe piezometers centred between passive relief wells in critical and representative areas of the WCSC was also specified. This network would provide performance data as well as detailed geological information at potential future passive well locations.

Similar to the northwest well field, the designs of the passive relief wells were optimized for longevity, operational efficiency and ease of installation. To achieve these objectives all wells were specified to use six inch diameter stainless steel v-wire screens and stainless steel casing, with threaded couplings. Two specifications for well screen slot size and graded sand packs were determined based on particle size analyses along the length of the WCSC, which allowed for pre-ordering of materials and field based decisions on screen selection for individual installations. Significant effort was also put into specifying the outlet elevation for individual wells. By optimising the outlet elevation relative to ground elevation and the invert of the collection ditch into which the wells discharge, the maximum drawdown benefit would be obtained from each well, resulting in increased well interference and potential long term savings through a reduced need for infill wells.

Another key design consideration for the passive relief system was the ability of the wells to operate passively at low flows (less than 0.5 ℓ/s) throughout winter, when air temperatures average -18°C and regularly drop below -30°C. To provide design parameters for winterization, several trials were conducted at the STP site. These trials addressed variability in parameters such as discharge rate, air temperature, water chemistry, water temperature, outtake pipe material and gradient of discharge. Based on these trials specifications were developed for the outtakes from the passive wells.

Installation of the passive relief network was initiated in 2008, with 53 passive relief wells installed at a nominal spacing of 100 m (Figure 3). Field adjustments were made to spacing between wells as dictated by geological and site conditions encountered, however changes in spacing were limited to a maximum of 15 m to ensure well interference effects were still achievable during operation. Sixteen passive relief wells deemed to be within the zone of significant drawdown of the northwest well field were not installed as part of the initial program. Based on the operational drawdown data and a calculated rate of recharge of the WCSC to artesian pressures given a catastrophic failure of the northwest well field, the risk to the STP structure through not installing the 16 wells was deemed negligible.

Well outtake installations and resultant commissioning of the passive relief wells occurred in a staged fashion during from 2008 to 2011, with minor design changes being implemented to the outtake designs in 2010 based on operational data collected during the first full winter of system operation. Currently 38 of the 53 passive relief wells have been equipped with outtakes.
Engineered systems – operational performance

Northwest Wellfield

The northwest wellfield has been pumping continuously since May 2006.

Operational monitoring of the system includes continuous water level measurement using pressure transducer data loggers within the pumping wells, and in 14 monitoring wells immediately upstream and downstream of the pumping well field. Instantaneous flow measurements, totalised flow volume and manual water level measurements are collected fortnightly from the pumping wells. This data is used to assess well performance and make any adjustments to pumping rates. Manual water levels are collected from the monitoring wells on a monthly basis to provide calibration levels for data logger records. Initial monitoring frequencies were higher than the current schedule. The increased initial measurement frequency provided higher definition of, and facilitated quicker response to, changing aquifer conditions prior to achieving a pseudo steady state condition in the WCSC aquifer.

In addition to flow and level data, water chemistry data is collected from the monitoring well network by means of physical samples, as well with pressure transducers equipped with electrical conductivity and temperature sensors. The water chemistry data is used to monitor performance of the well field with respect to the environmental criteria. Figure 4 provides an example of recorded flow rates, water levels and target operating level for an individual pumping well. The figure demonstrates the reduction in flow over time in response to the drawdown created within the aquifer. The pumping well rates have been adjusted over time to maintain the operational pumping levels within the wells near or at the target operating level for each well. This control has resulted in minimal shutdowns and maintenance and almost continuous pumping for over five years.
To date the wellfield has extracted over 7 million m$^3$ of water from the WCSC, with a maximum combined pumping rate of 101 ℓ/s achieved during that period. The wellfield is currently pumping at a combined rate of approximately 29 ℓ/s to maintain the drawdown exerted on the WCSC aquifer. Effective drawdown of approximately 14 m below original piezometric level has been created along the wellfield alignment, with the cone of depression extending up to two kilometres up and downstream of the wellfield (Figure 5). This drawdown is providing sufficient hydraulic containment within the WCSC to meet the design criteria and regulatory commitments.
Southwest Cut-off Wall

The cut-off wall constructed across the southwest channel of the WCSC has been providing an effective hydraulic barrier to flow since construction was completed in 2008. Operational monitoring of the cut-off wall performance is accomplished by water level and chemistry measurements collected upstream and downstream of the cut-off wall. Water level data presented in Figure 6 show a mounding effect created on the upstream (eastern) side of the cut-off wall, demonstrating the hydraulic barrier effect to groundwater flow. Chemistry data collected from the monitoring well network confirms the assessment of effective operation of the cut-off wall.

Passive Depressurization System

The passive relief well system has been partially operational since 2009 and fully operational from 2010. Currently there are 14 wells passively discharging groundwater at a combined flow rate of up to 19 ℓ/s, and at individual flow rates between 0.1 ℓ/s and 3.1 ℓ/s. Water levels are measured monthly at each passive relief well and in each monitoring well forming part of the relief well network. This data provides time series characterization of the WCSC aquifer response to rising STP levels and performance data for the passive relief well system.

Figure 7 presents time-series water level data for passive relief wells along the south dyke of the STP. The data show that water levels are rising in response to STP operations, but have not yet reached the level of the passive discharge outlets, thus no levelling off is observed. In contrast, comparable data for the actively discharging wells along the west dyke show constant water levels as would be expected from a well discharging at a defined outlet elevation.

To assess the performance of the wells, water level data is viewed as cross sections running parallel to the dykes, representing the piezometric level of the WCSC relative to original ground elevation. Figure 8 provides an example of the west dyke data, showing current piezometric levels for the WCSC in the central region of the dyke at the elevation of the discharge outlets, reflecting discharging wells.
Wells north of DP08-51 are significantly below discharge outlet elevation, representing the drawdown effects of the NW Wellfield.

Figure 7: STP south dyke – passive relief well time series water levels

Figure 8: STP west dyke – passive relief well operational water levels

The data presented demonstrates the effectiveness of the passive relief wells at the current well spacing of 100 m. This contrasts with the original design which anticipated the need for passive relief wells at a spacing of 25 m by the same time in the operations of STP, thus demonstrating the value of applying a
staged implementation and observational approach to operational management when a level of uncertainty in hydrogeological interactions exists.

**Advanced Hydrogeological Characterization**

**Application of Airborne Geophysics for Aquifer Delineation**

As part of ongoing efforts to improve the efficiency and accuracy of hydrogeological characterisation in the Athabasca oil sands environment, Klohn Crippen Berger Ltd. hydrogeologists on behalf of Suncor Energy Inc., performed an evaluation of the use of airborne geophysics to identify and delineate buried channel aquifers. The STP site was selected as the test case due to the existing comprehensive data set and relatively detailed understanding of the local geology gained through conventional methods of geological evaluation. The potential for an improved understanding of the WCSC geometry was also seen as a motivation to test the technology on this site.

Fugro Airborne Surveys (Fugro) conducted the frequency domain electromagnetic (FDEM) surveys using their RESOLVE system. East-west flight lines were spaced at 100 m, with north-south tie-lines at 1000 m spacing.

Once the geophysical data had been processed by Fugro, the apparent resistivity outputs were compared to directly representative transects of ERT geophysical data and to borehole drill data. The results proved the FDEM surveys could identify shallow geological features with similar precision to the ground ERT surveys, with good correlation to drillhole data. Additionally the continuous spatial coverage provided by the airborne method yielded significant improvements in the regional scale delineating and understanding of geological features.

Examples of the FDEM outputs and comparative analysis are shown below. Figure 9 presents near surface EM responses, which clearly show the STP structure overlying the WCSC and the extensions of the channel features towards the northwest and southwest. Figure 10 presents an example of the comparative analysis undertaken to evaluate the airborne EM against ERT and drillhole data.

![STP - 10m depth slice showing WCSC feature](image-url)
**Conclusions**

The integrated approach to engineered groundwater control at the STP site has resulted in a system, which is meeting both the design intent for geotechnical stability criteria and environmental protection. Conservative design approaches combined with continuously updated and improved data sets and pragmatic thought processes have yielded system designs that are amenable to phased installation, reliable operation, and management and assessment using the observational approach. This has resulted in upfront capital savings and reduced operational costs with no loss in effectiveness of the system.

The application of advanced and innovative technology to geological and hydrogeological characterization, as demonstrated at the STP, provides practitioners with an expanded tool set with which they can achieve improved results in a more efficient and cost effective manner.

**Acknowledgements**

The authors wish to thank Suncor Energy Inc. for permission to publish this work. We also wish to acknowledge those colleagues who helped prepare and review the manuscript.

**References**
