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Groundwater flow and solute transport modelling of an oil sands mine to aid in the assessment of the performance of the planned closure landscape

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Abstract

Syncrude is updating the Mildred Lake Mine (Lease 17/22) closure plan for regulatory submission in 2011. The role of groundwater in closure landscape design and performance was assessed to support the regulatory submission and closure planning generally. A three-dimensional MODFLOW-SURFACT groundwater flow model was developed to help understand past, current, and expected future groundwater flow and solute transport conditions.

Hydraulic properties, climate data, and groundwater recharge and discharge estimates were compiled from regional and site specific references. The data were used to develop a conceptual hydrogeologic model and numerical models to simulate pre-development, current (2008), and closure (0 to 200 years after closure) conditions. The groundwater modelling study was developed at the lease-scale (i.e. a roughly 250 km^2 lease within a 900 km^2 model domain) to meet the current industry and regulatory closure needs. The simulation results provided insight on dominant groundwater flow and solute transport patterns on the scale of hundreds of metres to kilometres and helped inform groundwater management decisions and at a lease-wide scale. Smaller scale models would be needed to evaluate processes occurring at smaller scales of interest contained within the lease, such as within planned closure watersheds and landforms.

Results of the hydrogeologic analysis were integrated with overall closure planning. Groundwater modelling results were used to aid in the assessment of groundwater interactions with the designed surface water drainage network, groundwater flow directions and velocities for tracking potential solute flow pathways, groundwater and surface water quality, wetland design, and salt management for the reclaimed landscape.

1 Introduction

The Athabasca Oil Sands, located in northeastern Alberta, Canada, are large deposits of bitumen that occupy the pore spaces of sands, silts and clays, accounting for one of the largest known reserves of oil in the world. Syncrude Canada Ltd. (Syncrude) is the largest producer of oil sands synthetic crude oil using truck and shovel open pit extraction methods. The Mildred Lake mine (Mildred Lake) is Syncrude's largest development, encompassing 256 km^2 between the MacKay River and the Athabasca River. Mildred Lake includes the Base Mine, North Mine, the upgrader facility plant site, and currently five tailings storage facilities: Mildred Lake Settling Basin (MLSB), East-In-Pit (EIP), West-In-Pit (WIP) or Base Mine Lake (BML), Southwest-In-Pit (SWIP), and Southwest Sand Storage (SWSS) (Figure 1). Construction at Mildred Lake began in 1973, and mining at the Base Mine started in 1977 with subsequent oil production and tailings deposition commencing in 1978 in the MLSB Dyke (Syncrude Canada Ltd., 2011). Mining is complete in the Base Mine and ongoing in the North Mine, and will continue there until approximately 2023. The North Mine will eventually be filled with tailings and stripped materials and include the North Mine South Pond (NMSP), North Mine Centre Pond (NMCP), and the End Pit Lake (EPL). Similar to Base Mine, the North Mine closure landscape will include many in-pit and above ground waste dumps comprising materials (mostly saline sodic Clearwater Formation and lean oil sands) stripped to mine out the oil sands.

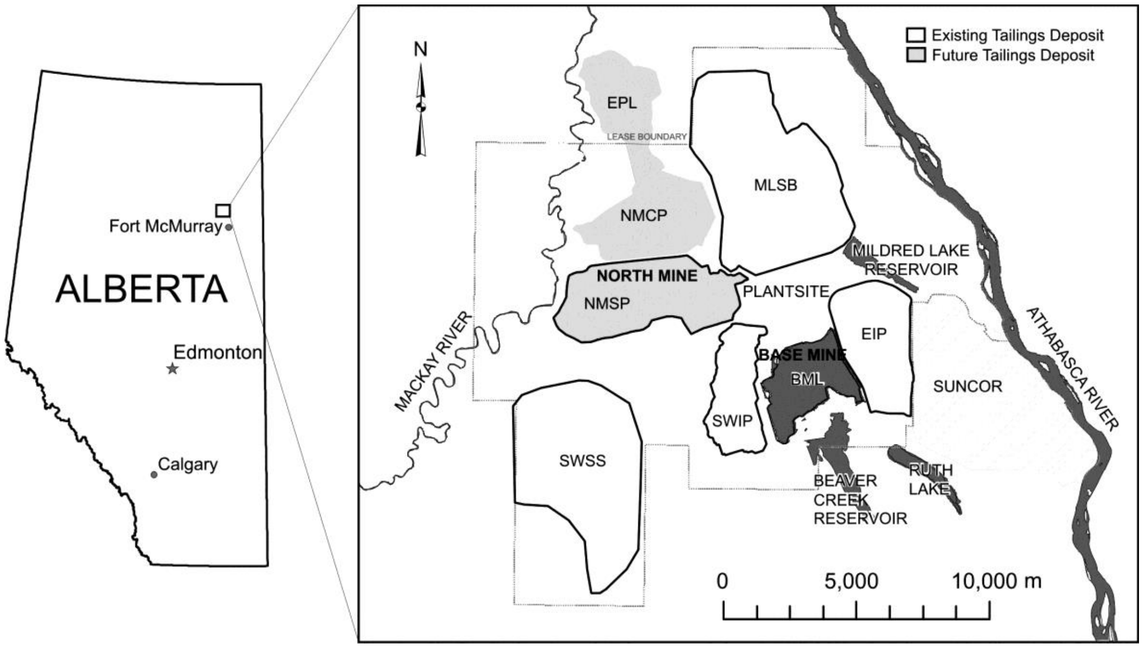

Figure 1 Mildred Lake mine location

As part of Syncrude's operations, closure planning is a regulatory requirement. This includes planning an effective post-mine landscape with acceptable groundwater flow and solute transport conditions. Closure planning is a process that begins with mine development, as construction during mine-life plays a key role in successful land reclamation and groundwater flow conditions. Tailings facilities are of high importance with respect to groundwater conditions, as they are typically saturated and contain elevated levels of dissolved constituents. A closure surface water drainage plan, including numerous wetlands, is also being designed and constructed as part of the mine closure plan and land reclamation.

Mine sites are required to present their mine closure plans to regulatory bodies. Mining companies are required to follow closure guidelines based on multiple legislative acts and national and provincial environmental laws (Garcia, 2008). Included in the closure submission is the prediction of the post-mining groundwater regime. Although there are no specific guidelines, strategies exist for groundwater modelling for mine closure (NBLM, 2006). A lease-scale closure modelling study was previously carried out at Mildred Lake in 1998 (Golder, 1998). The need for a more detailed study that included additional data collection, research, and mine closure planning conducted since 1998 was identified for the 2011 Closure Plan submission.

The objectives of this study were to:

- Meet Syncrude's regulatory requirement to address groundwater conditions at closure.
- Evaluate movement of groundwater in the planned closure landscape as controlled by the closure land surface and hydrostratigraphy.
- Evaluate lease containment of groundwater seepage to aid water management planning.
- Support planning of wetland locations and extents.

2 Methodology

Prior to construction of the site-wide closure groundwater model, a geologic model was developed for the site. Regional and site-specific hydrogeologic property data were compiled to aid in selecting appropriate material properties to implement in the model. A conceptual hydrogeologic model was subsequently created for the Mildred Lake lease. A 2008 conditions groundwater model was developed and calibrated to observed hydraulic heads and measured flows within the lease. Solute transport simulations were carried out to evaluate whether the 2008 model developed could adequately reproduce observed solute migration at the site. Finally, a three-dimensional groundwater model was created using the planned closure topography and design features to assess groundwater conditions for Syncrude's current closure plan.

The groundwater model domain is of the lease-scale, encompassing 900 km^2. This scale of a model provides qualitative insight into the post closure groundwater flow and transport conditions. Smaller scale models with a more refined mesh would be required to evaluate details of processes occurring within the lease and at the sub-watershed and landform scales.

3 Site hydrostratigraphy

The regional scale geology has been well characterised for the Athabasca Oil Sands in numerous studies over the past 50 years (e.g. Carrigy, 1959; Hackbarth and Nastasa, 1979; Flach, 1984). Hydrostratigraphic units have been classified from regional lithologic units by the Alberta Research Council (Bachu et al., 1993) and Alberta Environment (2009). Classifications were developed by identifying sequences of aquifers (geologic layers that are considered permeable and have a potential to transmit water) and aquitards (geologic layers that transmit water very slowly).

Hydrostratigraphic units within the project area include, from top to bottom, Quaternary overburden (primarily low permeability glaciolacustrine clays and tills with limited sand and gravel deposits), Grand Rapids Formation, Clearwater Formation, Clearwater Wabiskaw Member, McMurray Formation, thin and discontinuous McMurray Formation water sands, and the Devonian formations. The Devonian units studied include the Waterways Formation, Beaverhill Lake Group, Prairie Evaporite Formation, Methy Formation, and La Loche Formation.

Mining activity has altered the landscape within the Mildred Lake site. Natural deposits have been mined out and replaced with tailings sand (TS), composite tailings (CT), thickened tailings (TT), mature fine tailings (MFT), coke, sulphur blocks, and various engineered and non-engineered fills. These mining materials have been placed in-pit, in dumps, and in above ground tailings storage facilities.

4 Hydrogeologic property data

A detailed review and summary of available hydrogeologic parameter data in the Fort McMurray region was carried out to aid in the selection of defensible parameters for the groundwater models. A total of 148 sources were used in obtaining the hydrogeologic property data, including 19 manuscripts, 51 Environmental Impact Assessment (EIA) reports, 66 reports prepared by or for Syncrude, and 12 university theses. The documented hydrogeologic parameters include horizontal hydraulic conductivity (K_h), vertical hydraulic conductivity (K_v), specific yield (S_y), specific storage (S_s), and storativity (S). Parameter data were grouped based on the hydrostratigraphic units previously defined. Quaternary deposits were further broken down to encompass the typical overburden materials observed in the Fort McMurray region. Devonian units were classified by hydrostratigraphic unit but Upper Devonian formations were also grouped, which included the Devonian Waterways/Beaverhill Lake Group. The majority of the data obtained for mining materials were from Syncrude internal reports.

The data were grouped as either measured (i.e. field and laboratory) or model property values. The majority of the measured hydraulic conductivity data were obtained from single well response tests in standpipe piezometers screened in a hydrostratigraphic unit. Other data were from pumping tests, drill stem tests, laboratory tests, analytical solutions, and other tests conducted in the field. Modelled data were those that had been used in previous analytical and numerical groundwater modelling studies.

Although a large range of hydraulic conductivity values was observed for most hydrostratigraphic units, most of the data were clustered, with first and third quartiles generally falling within two orders of magnitude (Figure 2). Hydraulic conductivity variation is expected due to local and regional scale heterogeneity. Measured vertical hydraulic conductivities are typically approximately one to two orders of magnitude lower than horizontal hydraulic conductivities (Table 1), which can be explained by stratigraphic layering. The modelled hydraulic conductivities selected for the present study were generally close to measured geometric mean values.

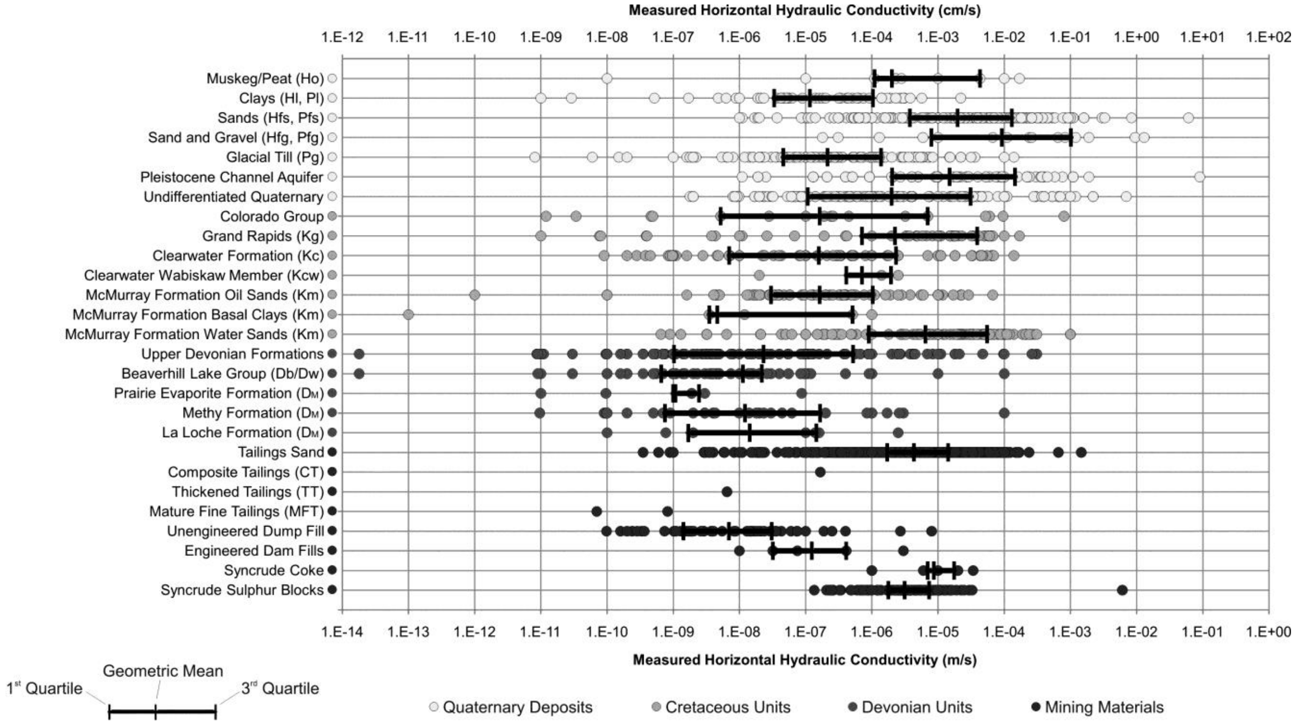

Figure 2 Measured horizontal hydraulic conductivity for the Fort McMurray region

A literature review on groundwater recharge rates was also conducted, but limited available data made the study difficult. Most available recharge rates were from previous modelling studies, with rates between 4 and 110 mm/year for sand and gravel overburden, 0.1 and 39.5 mm/year for low permeability tills and glaciolacustrine deposits, 45 and 158 mm/year for unreclaimed tailings sand, and 21 and 110 mm/year for reclaimed tailings sand.

5 Conceptual model

The study area is generally composed of thin, discontinuous deposits of permeable surficial sands and gravels within an overall low permeability environment. Prior to mine development, groundwater flow occurred primarily within the permeable overburden with significantly less flow in the permeable horizons of the Cretaceous deposits (i.e. Clearwater Formation, Wabiskaw Member, and McMurray Formation water sands) (Figure 3). Groundwater flow in the overburden was governed by topographic highs to the west and southwest of Mildred Lake (Thickwood Hills), the low vertical permeability of the underlying Clearwater Formation clays, and the deeply incised river valleys to the west (MacKay River), north (MacKay River), and east (Athabasca River). Groundwater flow was generally horizontal in the higher permeability horizons and vertical in the lower permeability units, with large vertical gradients typically observed. Small amounts of vertical seepage that pass through these formations are thought to recharge the McMurray Formation water sands at its base (Wallick and Dabrowski, 1982).

Mine development at Mildred Lake has resulted in numerous influences to groundwater flow patterns and the introduction of new materials (i.e. TS, CT, TT, MFT, engineered and unengineered fills, coke, and sulphur blocks). Open pit mining has created groundwater discharge areas due to topographic lows. Above-ground tailings storage facilities including MLSB and SWSS along with smaller scale overburden dumps have created groundwater mounds that result in groundwater flowing outward from each footprint. Due to the low permeability native formations, seepage within the lease is captured with drains and site wide ditches and contained within the lease. Solute migration has been observed within the lease through the limited permeable sands and gravels east of MLSB and north of SWSS only.

The planned closure topography and geology will comprise permeable above ground and in-pit tailings deposits relative to the surroundings. Groundwater flow conditions will comprise numerous local flow fields, such that groundwater seepage will primarily report to the planned surface water drainage within the lease.

Table 1 Regional hydrogeologic parameter summary

	K_h (m/s)		K_v (m/s)		S_y (-)		S (-)	S_s (m^{-1})
Geologic Unit	**Meas'd**	**Mod'd**	**Meas'd**	**Mod'd**	**Meas'd**	**Mod'd**	**Meas'd**	**Mod'd**
Quaternary Deposits								
Muskeg/Peat (Ho)	2.0E-06	3.0E-07		9.5E-08		0.05		
Clays (Hl, Pl)	1.2E-07	1.3E-08	8.0E-09	3.2E-09				2.9E-02
Sands (Hfs, Pfs)	2.0E-05	2.9E-05		1.0E-05		0.2	5.9E-04	5.4E-05
Sand and Gravel (Hfg, Pfg)	9.2E-05	2.1E-04	5.1E-05	3.3E-06	0.22		1.6E-04	
Glacial Till (Pg)	2.1E-07	9.8E-08	3.0E-08	3.1E-08		0.1–0.2		1.9E-04
Pleistocene Channel Aquifer	1.5E-05	2.4E-04	1.3E-06	7.8E-06	0.22	0.2	1.6E-04	2.7E-04
Undifferentiated Quaternary	2.0E-06	8.4E-07		4.7E-08		0.2		3.2E-05
Bedrock								
Colorado Group	1.6E-07							
Grand Rapids (Kg)	2.2E-06	1.2E-07	9.7E-08	3.3E-09		0.2	3.9E-05	2.7E-05
Clearwater Formation (Kc)	1.6E-07	2.4E-09	7.7E-10	2.0E-10		0.2	3.9E-05	5.0E-05
Clearwater Wabiskaw Member (Kcw)	4.1E-07	4.3E-08		7.8E-09		0.2		
McMurray Formation Oil Sands (Km)	1.6E-07	4.0E-09	2.7E-09	4.8E-10		0.2		1.5E-05
McMurray Formation Basal Clays (Km)	4.6E-09	3.4E-09	2.0E-10	3.4E-10				8.0E-06
McMurray Formation Water Sands (Km)	6.5E-06	1.4E-05	8.6E-08	2.1E-06		0.2	2.0E-04	1.9E-05
Upper Devonian Formations	2.3E-08	7.1E-08	5.8E-09	1.5E-09				2.0E-05
Beaverhill Lake Group (Db/Dw)	1.1E-08	1.6E-07	5.8E-09	3.2E-10				
Prairie Evaporite Formation (D_M)	1.1E-09			3.2E-13				1.0E-05
Methy Formation (D_M)	1.2E-08	2.0E-07		2.4E-09				1.0E-03
La Loche Formation (D_M)	1.4E-08							
Mining Materials								
Tailings Sand	4.4E-06	6.6E-06	7.3E-07	5.2E-07		0.2		1.3E-03
Composite Tailings (CT)	1.7E-07	6.9E-09	1.7E-08	3.3E-09				
Thickened Tailings (TT)	6.5E-09	3.7E-10	6.5E-10	1.0E-10				
Mature Fine Tailings (MFT)		5.1E-09	7.0E-11	8.5E-10		0.2		6.0E-03
Un-engineered Dump Fill	6.9E-09	3.2E-07		4.2E-08		0.2		3.2E-04
Engineered Dam Fills	1.2E-07	4.7E-08		1.8E-08				
Syncrude Coke	8.6E-06	1.3E-05				0.2–0.35		
Syncrude Sulphur Blocks	3.1E-06	1.0E-02	1.7E-06			0.008–0.044		

Meas'd = Measured. Mod'd = Modelled. * All values are geometric means of available data, with the exception of S_y.

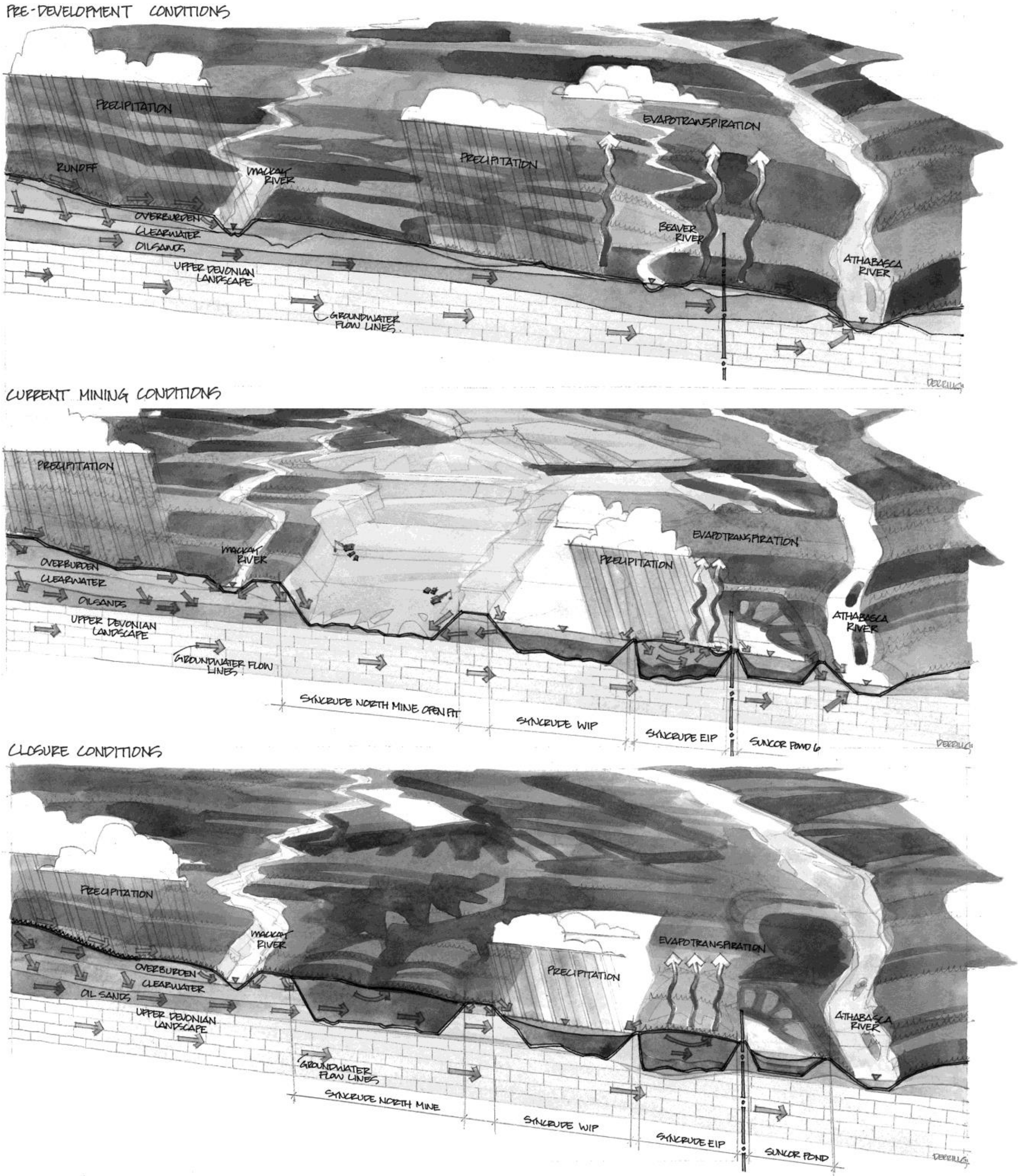

Figure 3 Pre-development, current mining, and closure conditions for Mildred Lake Mine

6 Numerical model

6.1 Model development

A pre-mine development, a 2008 layout, and a closure plan layout three-dimensional steady-state groundwater flow model were created to simulate groundwater flow directions using controlling features of the conceptual model. Groundwater Vistas (version 5.51; ESI, 2007), a graphical user interface, was used to develop the MODFLOW-SURFACT (version 3.0, Hydrogeologic Inc., 1996) groundwater flow model. The pre-development version of the model was used to define the undisturbed extents of hydrostratigraphic units prior to mining. Nine layers were included in the model with the top being assigned as the estimated pre-development ground surface. The base of the model was set to be 40 m below the surface of the Devonian formations and the elevations of the remaining layers were generally set at stratigraphic contacts to represent the hydrogeologic units. The 2008 layout model included three additional layers above the pre-development model to represent materials placed during mining operations. The top of the 2008 model was assigned as the ground surface using 2008 topographic contours. The closure model also included twelve layers; similar to the 2008 model the three top layers were adjusted to reflect the planned closure topography.

Groundwater recharge rates ranging between 2% (e.g. dumps and in-pit dykes) and 31% (e.g. unreclaimed tailings sand) of average annual precipitation (~440 mm/year) were assigned to the water table in the upper active model layer. The recharge rates were limited by the capacity of the subsurface to accept water by using a ponding depth of 0 m above ground surface, preventing the groundwater table from rising above the model surface. A uniform maximum evapotranspiration rate of 633 mm/year was assigned to the upper active layer of the model along with extinction depths of 0.5–1.0 m. Water bodies were represented using general head boundaries, drains, and the river package. The three models are conceptually illustrated in Figure 3.

6.2 2008 steady state model

The 2008 groundwater model was calibrated using a systematic trial-and-error approach against field-observed average hydraulic heads at 646 monitoring locations. Average annual seepage collection rates in drains at the MLSB Dyke and the EIP and average annual groundwater extraction rates at remedial pumping wells located east of the MLSB were used as groundwater flow targets. Model parameters (e.g. hydraulic conductivity and recharge) were manually modified within acceptable limits as defined by the hydrogeologic property data review to improve the fit of the model predictions to the measured data. Simulated hydraulic heads were generally within 10 m of the measured values and the normalised root mean square (NRMS) for the calibrated model was 4.6%. Simulated flows to the MLSB dyke drains and EIP drains were within 14% and 11% of the measured flows, respectively. Simulated pumping rates at the remediation wells were within a factor of 2.5 from the measured pumping rates. Discrepancies arose from transient dewatering effects that were not represented in the steady-state flow model.

Groundwater flow results were consistent with the conceptual model. The combined seepage from the various tailings ponds was estimated to be 14,000 m^3/day, of which the majority was collected by seepage collection drains and ditches on site. However, some is estimated to be lost to the shallow overburden east of MLSB and north of SWSS.

6.3 Pre-development groundwater model

The hydrogeologic parameters selected for natural geologic units during the calibration of the 2008 model were applied to the pre-development model and simulated in a steady state analysis. Groundwater flow was predominantly towards the Athabasca River with localised groundwater flows towards smaller rivers such as the MacKay River and the Beaver River. The largest differences observed between the pre-development model and the 2008 model were the lack of groundwater mounding from tailings ponds and seepage from above ground tailings facilities, as well as groundwater depressions associated with the open pits.

6.4 2008 solute transport model

The groundwater model was further modified to reproduce chloride concentrations up to the year 2008 using a transient simulation with solute transport. Chloride was selected as a tracer due to elevated concentrations observed in process-affected water along with its generally conservative behaviour in groundwater systems. Due to the large model scale and grid block dimensions within the model, the transport simulations were qualitatively compared to the observed distribution of process-affected water in 2008 and temporal trends in chloride concentrations at monitoring wells.

A steady-state flow simulation representing pre-mining conditions was created to generate initial heads for the transport simulation. The distribution of recharge and evapotranspiration, tailings ponds elevations, and open pit size were all transiently increased to represent mine development from 1977 to 2008. Grid blocks containing groundwater flow boundary conditions were assigned third type (i.e. Cauchy) solute transport boundaries with inflow concentrations specified as 0 mg/L for all boundaries, with the exception of MLSB, SWSS, EIP, and WIP, which were applied variable concentrations using observed average annual chloride concentrations. Solute loading from overburden dumps and the placement of saturated tailings sand to construct the MLSB, SWSS, and to fill the EIP was simulated using the prescribed concentration package (PCN). Evapo-concentration of chloride was permitted above the specified evapotranspiration extinction depth, as it was assumed that groundwater removed by evapotranspiration would not remove solute.

Water quality data exists between 1977 and 2009 for 540 monitoring wells and piezometers distributed across Mildred Lake. General trends of solute transport were simulated well throughout the site using the transport model. The model adequately simulated transport of process water (as represented by chloride) through the sand and gravel overburden east of MLSB as well as transport of process water from SWSS through the South Spruce Channel towards the North Mine open pit. Simulations predict that significant solute migration from other process-affected areas (e.g. BML, EIP, dumps) is not occurring to date, consistent with the current conceptual model and available observations.

7 Closure numerical model results

Similar to the 2008 model for Mildred Lake, the closure model was first evaluated using a steady state flow simulation. The hydrogeologic parameters selected for natural geologic units during the calibration of the 2008 model were used to represent the closure hydrostratigraphy.

Removal of the tailings ponds to represent post closure conditions resulted in overall water budgets for the model to be similar to pre-development conditions. MODPATH (Pollock, 1994), a flow particle tracking code, was used to evaluate groundwater flow paths, velocities, and groundwater divides within the closure landscape shown on Figure 4. The results indicate that the closure plan will result in many local groundwater systems within the lease. Due to the low permeability environment of the natural formations, in-pit facilities are dominated by recharge to the hummocks and small upland features, and discharge to the local lows within the landforms. The dumps, although they are higher than natural ground features, are of low permeability and yield small seepage flows to the site-wide closure drainage system.

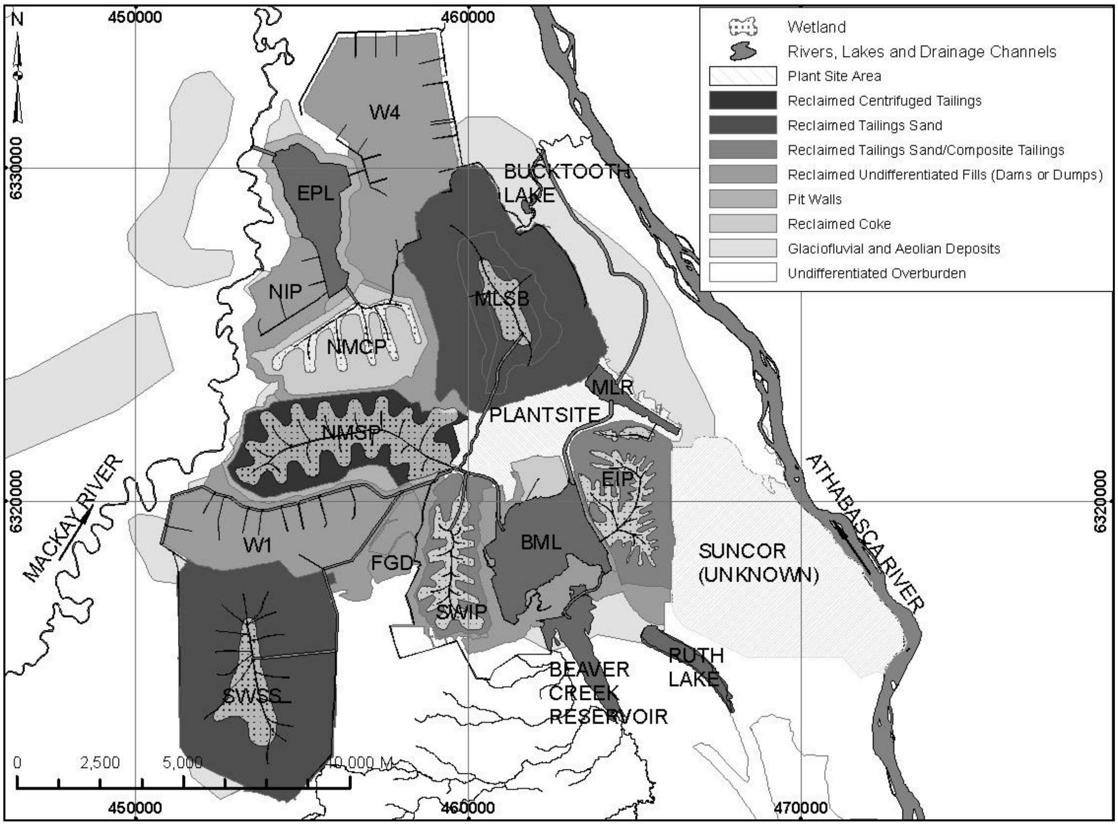

Figure 4 Closure landform and drainage design

The landforms of concern in terms of potential off-lease groundwater impacts include the above ground tailings facilities, MLSB and SWSS. The removal of the tailings pond water caps result in overall lowering of the hydraulic heads within the ponds and reduced hydraulic gradients. The SWSS is situated on low permeability glacial lacustrine deposits, with the exception of the South Spruce Channel. Mining at NMSP is predicted to cut off solute migration from SWSS in the post closure setting. As a result, groundwater seepage from SWSS will report to the in-pit tailings facility, as well as the site wide closure drainage features. Groundwater seepage from MLSB will continue through the sand and gravel east of MLSB (Figure 5); however, the large closure drainage channel planned east of MLSB is predicted to intercept groundwater originating from MLSB. Therefore, seepage within the lease is expected to report to the planned closure drainage system designed for the site.

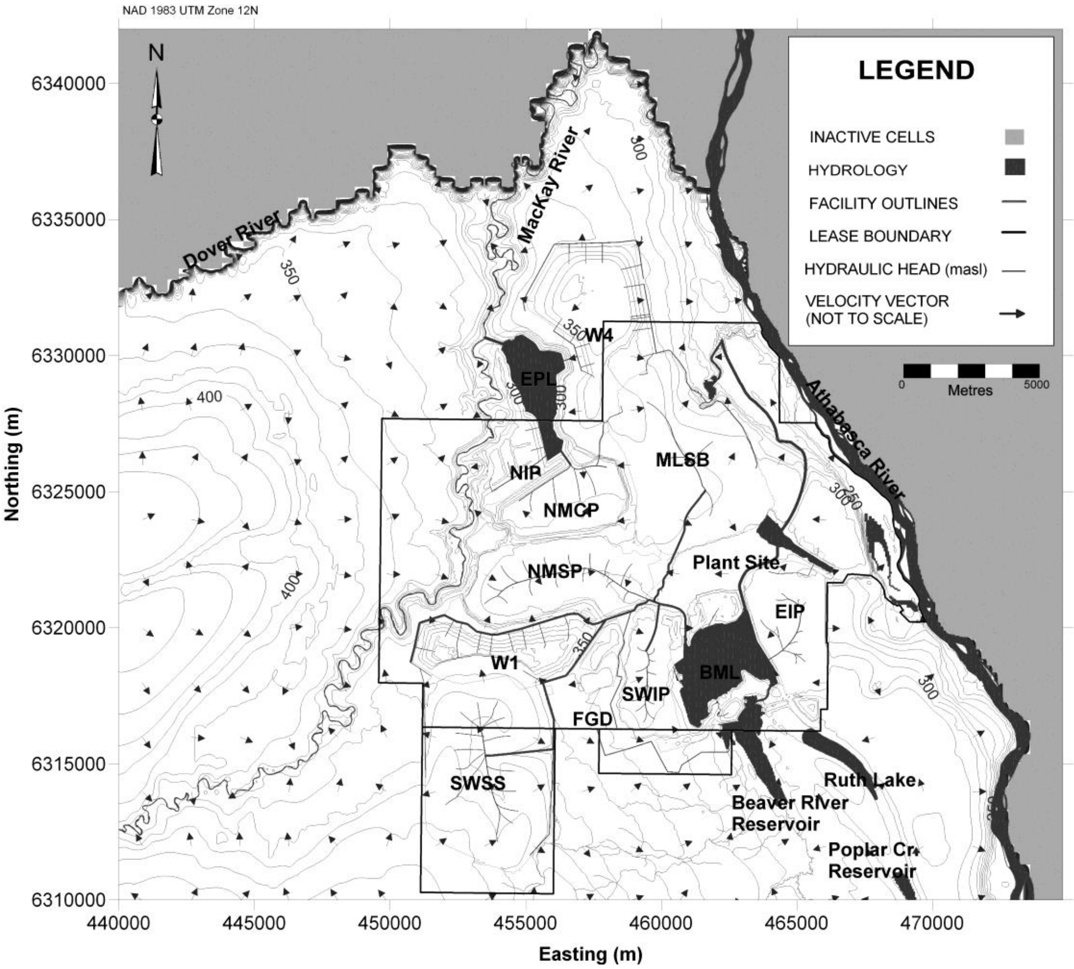

Figure 5 Closure groundwater simulation results

8 Integration with closure planning

The site-wide closure groundwater model was developed by using the planned closure topography and designs for the lease. Predicted groundwater discharge locations within the lease are currently planned for detailed wetland design (Figure 4). The groundwater model confirmed locations previously identified as likely locations for wetlands, and supported the expected wetland extents. Optimising the closure topography and surface water drainage design to support wetlands in these locations will be the focus of future research. Smaller scale studies will be required to better understand the individual water balances and water quality for the planned wetlands, as these will be areas of primary concern for salt management within the lease.

The groundwater model supports the hypothesis that the groundwater discharge can be collected by the closure surface water drainage network within the lease. Further studies of the mass loading to the drainage network will identify if the surface water will require further management or treatment prior to discharge from the lease.

9 Conclusions

Mine development at Mildred Lake has resulted in the change of groundwater flow patterns within the lease. Open pit mining has created groundwater discharge areas due to topographic lows. Above ground tailings facilities have created groundwater mounds that result in groundwater flowing outwards from these facilities. The seepage originating from the tailings facilities is currently contained within the lease. Vertical movement of the groundwater flow is restricted by the presence of natural formations of low hydraulic conductivity, with the exception of limited shallow sand and gravel overburden deposits.

Two areas, north of SWSS and east of MLSB, with potential for off-site seepage migration were identified during the 2008 conditions groundwater model studies. However, the closure modelling for the site suggests seepage originating in these areas will be captured by the planned site closure drainage network.

Groundwater flow conditions after mine closure will comprise numerous local flow fields, such that groundwater seepage will primarily report to the planned surface water drainage network within the lease. Some of these closure model predicted groundwater discharge areas are under consideration for the construction of wetlands in accordance with the Alberta Environment approval clauses and the Syncrude closure plan studies.

The closure groundwater model prepared meets requirements for Syncrude's closure plan submission. The model evaluated the post closure groundwater conditions using the most current planned closure topography and designs features for the lease. By first rigorously developing the geologic model and assessing and calibrating to 2008 conditions, a stronger representation of closure conditions has been developed for the Mildred Lake as compared to previous studies.

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