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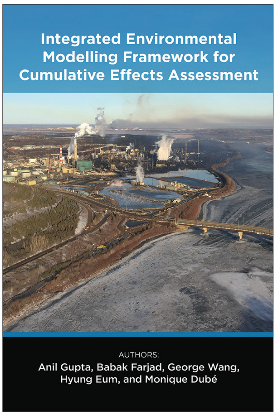

INTEGRATED ENVIRONMENTAL MODELLING FRAMEWORK FOR CUMULATIVE EFFECTS ASSESSMENT

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5.0 MODELLING IN THE ATHABASCA RIVER BASIN – CASE STUDY

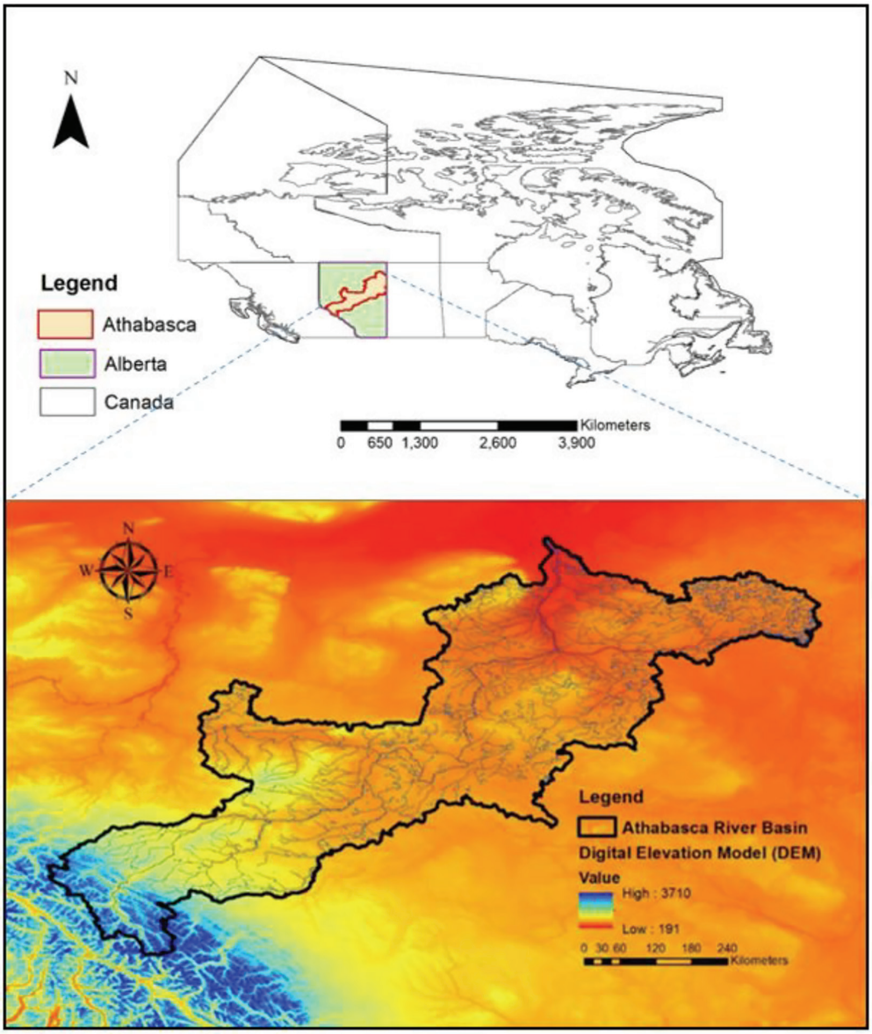
The Athabasca River, located in Alberta, Canada, originates at the Columbia Ice Fields near the Alberta–British Columbia border and flows approximately 1300 km northeast before entering Lake Athabasca at the northeastern corner of Alberta (Figure 8). Water from Lake Athabasca flows into the Slave River and joins the Mackenzie River, which eventually enters the Arctic Ocean. The elevation of the watershed varies from more than 3000 m a.s.l. in headwaters in the Columbia Icefield to about 205 m a.s.l. at its outlet in Lake Athabasca. The Athabasca River basin is physically and ecologically diverse and covers an area of approximately 159,000 square kilometers. The region is endowed with many natural resources such as forests, coal, minerals, agriculture, and oil and gas. The Athabasca oil sands are large deposits of bitumen or extremely heavy crude oil and are the largest reservoir of crude bitumen in the world and the largest of three major oil sands deposits in Alberta (along with the nearby Peace River and Cold Lake deposits).

Interest in bitumen from the oil sands dates back to the 1930s, when intensive industrial development of the region began, and reached a peak in the late 1960s. In the mid 1990s, new project applications and the expansion of existing oil sands operations were underway. As a result, the lower Athabasca watershed was getting more attention for CEA in response to the large-scale oil sands operations that can disturb environmental conditions in the watershed. In-situ and open pit mining developments can directly affect subsurface and surface hydrological processes such as runoff, soil moisture, and infiltration. For instance, the utilized steam-assisted gravity drainage (SAGD) has a potential to modify the hydrogeological regime of the basin. A part of the surface water used in SAGD operations (i.e., steam production and then injection) is lost to the bitumen recovery. (It occupies the space previously occupied by oil in formations.) In response to the changes in environmental conditions, the Alberta government took steps to initiate several strategies and plans. In the late 1990s, the Alberta government designed its Regional Sustainable Development Strategy (RSDS) to address potential cumulative environmental effects in the Athabasca oil sands area. The aim of the RSDS was to provide a framework for managing cumulative environmental effects and to ensure sustainable development in the Athabasca oil sands area. The strategy prioritized 72 environmental issues which had been divided into a list of 14 themes and 3 priority categories that should be assessed in response to the oil sands development.

In 2008, the Government of Alberta commenced a comprehensive initiative to develop a new approach for managing cumulative effects by releasing a land-use framework, known as the Lower Athabasca Regional Plan (LARP). The LARP is a comprehensive, forward-thinking, and legally binding roadmap that enhances environmental management, addresses growth pressures, and supports both human and ecosystem needs, while balancing social, environmental, and economic outcomes. The regional plan considers the cumulative effects of all activities on air, water, and biodiversity. Five environmental management frameworks were developed under the Lower Athabasca Regional Plan, including the Air Quality, Surface Water Quality, Groundwater, Surface Water Quantity, and Tailings Management frameworks. A biodiversity management framework is being developed.

In 2012, the Governments of Alberta and Canada embarked on a new plan, known as the Joint Oil Sands Monitoring Program (JOSM), to ensure a comprehensive and systematic monitoring and reporting of environmental conditions in the lower Athabasca River basin to support sustainable resource development.

Figure 8. Athabasca River Basin (ARB)



The above-mentioned programs, plans, and strategies were composed of different themes and sub-themes to build an understanding of the environment as a whole and to ensure that any major environmental impacts are considered. As a result, many individual studies were conducted with a focus being on either theme or environmental processes. Some of the environmental modelling studies in the region (especially in the oil sands areas) are described in the following sections.

5.1 Hydrodynamic and water quality modelling in the Athabasca River

Water quality modelling of the Athabasca River began in 1984 when the first model was implemented using Water Quality for River and Reservoir Systems (WQRRS) for the main stem from Hinton to Lake Athabasca (Charles Howard and Associates Ltd., 1984). The calibration process was challenging due to limited monitoring data (e.g., hydraulic, non-point and point source loadings, and in-stream water quality data). Flows under ice cover could not be simulated. A dissolved oxygen simulation model named DOSTOC (Dissolved Oxygen STOChastic model) had been widely used since its development in 1987, originally for the Planning Division of Alberta Environment (HydroQual Consultants Inc. & Gore and Storrie Ltd., 1989). In 1988, trial runs of the DOSTOC model were undertaken for the Athabasca River using data collected during the 1987 and 1988 winters (Culp & Chambers, 1994). The model was used to simulate the water quality in the Athabasca River under various levels of development in the basin and low flow conditions during ice-coved periods. The calibration of the DOSTOC model was updated with data collected during winter synoptic surveys in 1988, 1989 (Macdonald & Hamilton, 1989), and 1990 (Macdonald & Radermacher, 1992), and then further evaluated and validated by the Northern River Basins Study (NRBS) using winter survey data obtained in 1991 and 1992 (Macdonald & Radermacher, 1993) as well as 1993 and 1994 (Chambers et al., 1996; Pietroniro, Chambers, & Ferguson, 1998). The DOSTOC model is a component of the Stochastic River Quality Model (SRQM) that consists of three modules: DOSTOC for dissolved oxygen, NUSTOC for nutrients, and UNSTOC for user-specified substances.

The model was formulated as a one-dimensional steady state model and based on the analytical solution to the stochastic version of the Streeter-Phelps equation, assuming that random parameters follow normal distributions. The model can be run in either deterministic or stochastic mode. Hydraulic characteristics of the river were represented by the Leopold-Maddock equations, which are exponential functions relating mean depth, top width, and mean velocity to river discharge. Ice cover processes were not simulated, and effects were implemented by assuming zero volatilization and reduced photolysis and biodegradation rates. Water quality processes represented in the model include atmospheric reaeration, decay of BOD, and nitrogenous oxygen demand (NOD) in the water column, photosynthesis and respiration, and benthic SOD (McCauley, 1997).The calibrated model was used to evaluate the impacts of pulp and paper industry development in the region. It was determined that although the treated pulp effluents from two mills (Wildwood at Hinton and Millar Western at Whitecourt) would increase BOD and ammonia concentrations directly downstream of the mills, the impact is negligible further downstream on the river. As the DOSTOC model is a steady state model over a short period, it could not capture the cumulative effects over time from spatially distributed sources.

During the NRBS, one-dimensional dynamic models with separate and interacting water column and bed sediment compartments were also developed to simulate the fate and transport of organic chemicals for the Athabasca (Hinton to Old Fort) and Wapiti/Smoky Rivers, using the USEPA's Water Quality Analysis Simulation Program version 4 (WASP4) (Golder Associates Ltd., 1997a, 1997b). The Leopold-Maddox method was added to WASP4 code so that water column velocities, cell volumes, and mass exchange areas would be updated at each timestep for the water column segments. This approximate approach is suitable for gradually varied flows. A sediment transport algorithm for the Athabasca River, developed by Krishnappan et al. (1995) was incorporated in WASP4 to predict resuspension and deposition rates within the Athabasca River contaminant fate model. Out of the seven selected organic chemicals, the best calibration over the two-year period of 1992-1993 was achieved for 2,3,7,8-TCDF. For other substances, especially phenanthrene, observed data were so sparse, or conflicting, that it was not possible to evaluate the calibration. By incorporating the sediment transport algorithm into WASP4, the model predicted a very dynamic exchange of sediment between the water column and bed, with an accumulation of fine bed sediment over the late fall and winter, removal by resuspension during the spring freshet, and very little net accumulation during the summer.

Subsequently, a one-dimensional model, WASP7 (water quality analysis simulation program), was set up using a kinematic wave routing scheme and was hydrodynamically calibrated and validated for the Lower Athabasca River with 1999–2008 data (Kannel & Gan, 2013). The model represented the field data quite well except during winter seasons (mid-November to April). The model was applied to investigate the potential impact of oil sands processed water (OSPW) in the event that OSPW, which contained naphthenic acids (NAs), was accidentally discharged to a stretch of the Athabasca River, simulating NAs as a lumped state variable and assuming it is degraded by natural dilution, biodegradation, sorption, photodegradation, or combinations of these processes. NAs in the Lower Athabasca River were predicted to be sensitive to changes in the discharge rate and concentrations of OSPW, as well as the rates of photodegradation and biodegradation.

Numeric modelling of flow and transport processes in the Athabasca Oil Sands Region is challenging due to the complex morphology, cold climate, and highly variable flows in the river. Being located in northern Alberta, the Lower Athabasca River has some special hydrodynamic and water quality characteristics, especially the ice formation, jams, melting and break-up processes, and the relatively long ice-cover period for the river. Early attempts to model flow in the Lower Athabasca River used one-dimensional models that were implemented based on approximate and simplified rectangular cross-sections to represent channel geometry. Khanna and Herrera (Khanna & Herrera, 2002) applied the cdg1-D model in the Lower Athabasca River basin to estimate high flows during open-water season. The cdg1-D model, originally developed at the University of Alberta, solves the St. Venant equations by the finite element method using the characteristic dissipative Galerkin (cdg) scheme. Trillium Engineering and Hydrographics Inc. (Trillium Engineering and Hydrographics Inc., 2003) conducted field surveys to measure transverse mixing coefficients and travel time in the Lower Athabasca River during ice-covered winter low flow periods at five key locations (short reaches) downstream of the Firebag River, Ells River, Muskeg River, Steepbank River, and Fort McMurray. A HEC-RAS model for each reach was constructed to evaluate the hydraulic roughness and to predict water levels and mean velocities for a range of discharges. Two-dimensional flow characteristics required for the mixing analysis were evaluated using a lateral discharge distribution approach. Two methods of evaluating transverse mixing coefficients were employed: (i) an analytical model with reach-average hydraulic characteristics and (ii) a numerical model, TRSMIX, which employed local hydraulic characteristics. These dimensionless coefficients may be applied over the range of typical winter discharges that occur as long as the river is ice-covered.

Hydrodynamic and fish habitat modelling have been performed for reaches of the Lower Athabasca River and Peace-Athabasca Delta using the River2D model calibrated with synoptic bathymetry and hydrometric survey data obtained during summer and winter (ice-covered) periods as part of a multi-year program led by the Surface Water Technical Group of the Cumulative Environmental Management Association (CEMA) (AMEC-nhc, 2009). The program aimed to assess in-stream flow needs and evaluate fish habitats for open water and winter conditions for the Lower Athabasca River, in which five study segments along the Lower Athabasca River were investigated, including: Reach #1 – Athabasca Delta below Embarras, Reach #2 – Embarras, Reach #3 – Poplar Point, Reach #4 – Bitumount, and Reach #5 – Northlands. River2D is a two-dimensional finite element-based numerical hydrodynamic model that was developed at the University of Alberta to simulate the depth-averaged flow characteristics in a river segment (Steffler & Blackburn, 2001). To match measured velocities and water levels, a range of roughness heights was adopted for the calibration of flows: 3.0 mm for sand, 500 mm for the cobble regions, and 10 mm for ice at Reach #4 (Trillium Engineering and Hydrographics Inc., 2004, 2005); 10 mm for sand and 150 mm for ice at Reach # 2 (Northwest Hydraulics Consultants Ltd., 2007a), and 1 mm for sand and 150 mm for ice at Reach #3 (Northwest Hydraulics Consultants Ltd., 2007b). Katopodis and Ghamry (2005) conducted similar ice-covered hydrodynamic model calibrations and comparisons for three reaches of the Lower Athabasca River (Fort McKay below Peter Lougheed Bridge, Bitumount, and Northlands). It was found that the applied bed and total roughness along the thalweg profiles for Bitumount and Northlands Reaches were comparable for similar substrate sizes. The Northlands Reach has the coarsest bed materials over most of the thalweg profile, the Peter Lougheed Reach has the finest ones, and the Bitumount Reach is in-between. Although the applied ice roughness differed between the three reaches, its low values had a small effect on the composite roughness.

In the Peace-Athabasca Delta, 2D-River models were developed and calibrated for the two divergence areas under each of the open water and under-ice conditions. The ice thickness data obtained in the winter survey was processed to produce River2D ice input files (AMEC-nhc, 2009). A River1D model for the Peace-Athabasca Delta was also developed at the University of Alberta (Andrishak & Hicks, 2009, 2011), for the primary purpose of simulating river discharges across the Lower Athabasca Region to provide boundary conditions for more detailed (e.g., River2D) hydraulic and habitat modelling at flow divergence sites. Both 1D- and 2D-River models for the Peace-Athabasca Delta were updated in 2014 with new survey data (Hatfield Consultants, 2014). Note that the 1D- and 2D-River models for the Lower Athabasca River and Peace-Athabasca Delta were all calibrated with steady-state runs under steady-state conditions and specified temporally constant ice thickness inputs interpolated from data collected from synoptic surveys. Steady-state runs were performed for fish habitat modelling and assessment due to their limited functionality for unsteady modelling. Efforts were made and preliminary results were obtained by updating the 1D-River (Andrishak et al., 2008) and 2D-River model (Wojtowicz et al., 2009) to include thermal ice processes to simulate the freeze/thawing of the Athabasca River.

Integrated hydrodynamic and water quality modelling over a continuous period covering open-water and under-ice conditions in the Athabasca Oil Sands Region started in the late 2000s. A two-dimensional vertically-averaged Environmental Fluid Dynamics Code (EFDC) model with hydrodynamic and eutrophication water quality models for the Lower Athabasca River from Fort McMurray to Old Fort was developed by TetraTech in 2009. The model was used to simulate an eight-year period from 2000 to 2007 with a partial calibration due to limited monitoring data. The model was enhanced by Dynamic Solutions International LLC

(DSI) in a scoping study by updating model bathymetry to the best available data and adding preliminary setup of sediment and toxics modules without calibration. The model did not simulated the ice formation and melting processes but required external inputs for ice cover thickness (Dynamic Solutions International LLC., 2012). A two-dimensional laterally averaged model for the Upper Athabasca River (Hinton to Grand Rapids) was developed using CE-QUAL-W2 to simulate the hydrodynamics, and DO including the ice formation and melting processes over the period from 2000 to 2006 (Martin et al., 2013). The modelling results indicated that the DO concentration in the Upper Athabasca River was very sensitive to the sediment oxygen demand (SOD), which represented about 50% of the DO sink in winter. The model was applied under steady-state winter low-flow scenarios to predict assimilation capacity for the BOD load. The CE-QUAL-W2 model has also been utilized to develop for CEMA a general two-dimensional laterally averaged integrated hydrodynamic and water quality model, simulating oil sand pit lakes. Named CEMA Oil Sands Pit Lake Model (OSPLM), it can simulate potential water quality implications of mature fine tailings placement in pit lakes (Berger & Wells, 2014; Golder Associates Ltd. & ERM, 2012; Prakash et al., 2015; Vandenberg et al., 2014).

Modelling the fate and transport of fine sediments and associated chemical constituents in the Lower Athabasca River originating from natural and potential anthropogenic sources is recognized as a subject of increasing importance, as studies have shown that the concentrations of sediment-associated chemicals such as PAHs and heavy metals in the Lower Athabasca River are affected by development activities (Droppo et al., 2018). To quantify and model the sources, transport, and fate of chemicals, a reliable integrated hydrodynamic, sediment transport and water quality model of the Lower Athabasca River is needed. Experimental and field assessment of sediment dynamics and associated chemicals in the Lower Athabasca River and tributaries have been investigated in several previous studies under the JOSM program. Droppo and Krishnappan (Droppo & Krishnappan, 2016) applied a modelling approach combining two existing models (RIVFLOC and MOBED) to simulate the hydrophobic, cohesive sediment transport in the Ells River. Using fine sediment transport parameters derived from laboratory flume experiments (e.g., settling velocity of sediment as a function of floc size and the critical shear stresses for deposition) and the calculated flow field from the MOBED model (using field survey data such as cross-sectional geometry, river slope, grain size of bed material, and discharge), the RIVFLOC model was used to predict the transport characteristics of the hydrophobic Ells River sediments. Although flocculation was shown to occur with increasing floc size downstream, there was a breakpoint at approximately 50 μm where the settling velocity decreased with increasing floc size due to a decreasing floc density. The high bed shear stresses in the Ells River also negated the influence of flocculation on settling. The entrapment process was thus concluded as an important aspect of sediment dynamics within high-energy cobble/gravel bed rivers, particularly where sediments are hydrophobic like those from the McMurray Formation in Northern Alberta.

It is well known that integrated watershed and water body modelling systems or tools are needed to support the assessment of cumulative effects from climate change, land use changes, developments, and operational activities in the oil sands region. Nevertheless, there is no existing modelling system or tool that possesses the capability to simulate dynamic interactions among environmental and human sub-systems and their impacts on water quality and the aquatic habitat health of the Lower Athabasca River, accumulated over both spatial and temporal scales. A unique, comprehensive, and practical system for integrated watershed and water quality modelling in the Athabasca Oil Sands Region was developed by Golder Associates, which has been applied to support a series of environmental impact assessment (EIA) studies of oil sands development projects (Golder Associates Ltd., 2003a, 2003b, 2004a, 2004b; Teck Resources, 2011). The component models include, CALMET/CALPUFF air quality dispersion model, regional 3D MODFLOW groundwater model, MT3D solute-transport model, regional HSPF hydrologic model, CE-QUAL-W2 Pit lake hydrodynamic model, Golder Pit Lake Water Quality Model, quasi-dynamic 2D ARM (Athabasca River Model) water quality model, steady-state sediment quality model, and habitat suitability models. Component models were calibrated for historical periods. Future scenarios and non-point source loadings were estimated based on the watershed modelling of LULC changes and development scenarios, with the consideration of operational releases from oil sands development as well as withdrawals from the Lower Athabasca River. As HSPF is a semi-distributed watershed model, the system does not simulate fully distributed interactions between surface and subsurface water. Being a tool supporting project EIAs, the system predicts impacts under certain future snapshot scenarios and does not simulate the cumulative effects over time. Some general impacts predicted by the integrated modelling system (Teck Resources, 2011) include:

i. Drawdown propagation due to basal water depressurization will largely be constrained to the mining project area. Groundwater levels will begin to recover following shutdown of depressurization pumping, and the groundwater flow model predicts that far future groundwater levels would be similar to those of predevelopment.

ii. Activities such as muskeg drainage and overburden dewatering during mine construction and operation will result in increased flows to receiving watercourses. Reductions in drainage area because of closed-circuit operation and the creation of pit lakes at closure will reduce flood flows to receiving waters.

iii. Oil sands developments were predicted to have negligible effects on acute and chronic toxicity and tainting potential in all receiving waters in the local and regional study areas. The proposed mitigation measures will ensure that acute and chronic toxicity and tainting potential will be at levels appreciably lower than the corresponding guideline or threshold values, and that additional adaptive management options exist in the event that they are required. The concentrations of several substances are predicted to increase above base case snapshots but remain below guidelines or chronic effects benchmarks (CEBs).

iv. Fish habitat in the local study area (LSA) is primarily of low value and composed of forage fish typical of the Athabasca Oil Sands Region. Construction of oil sands projects will result in the alteration or destruction of fish habitat and an associated loss of fish relative to abundance, but it will have no effect on fish or fish habitat diversity. The loss of fish habitat will be compensated for by the construction of the lake, which will offset the potential loss of fish habitat.

The ARM model, originally developed by Golder Associates and applied to EIAs of oil sands projects, is a two-dimensional vertically-averaged model based on an analytical solution to river dispersion equations under steady-state conditions, and implemented using VBA (*Visual Basic for Applications*) and the Microsoft Excel application. It has been updated by Four Elements Consulting Ltd. to include a new functionality for optimal regional substance load allocation in the Lower Athabasca River. Dynamic-link library (DLL) techniques were adopted to speed up computing time (Four Elements Consulting Ltd., 2014a, 2014b). A range of water quality parameters (including 11 general indicators such as chloride, TN and TP, 28 metals, 19 PAHs, total phenolics, and toxicity-chronic) can be simulated by the model. However, flow in the river was calculated using Leopold-Maddock equations rather than a hydrodynamic model. Similar to the DOSTOC model for the Lower Athabasca River, dynamic ice processes and river bed sediment transport processes cannot be simulated with the ARM configuration.

More recently, an integrated hydrodynamic and water quality modelling framework for the Lower Athabasca River was proposed by Environment Canada and Climate Change (ECCC), consisting of MIKE 11 for long-term one-dimensional simulations and EFDC for short-term detailed two-dimensional simulations, each externally coupled with a one-dimensional MIKE-ICE or CRISSP-1D model (Dibike et al., 2018; Kashyap et al., 2017; Shakibaeinia, Dibike et al., 2017; Shakibaeinia, Kashyap et al., 2016). A demonstrative rather than a full range of water quality parameters required for assessing impacts of oil sands development are configured in the models, including TSS, BOD, DO, phosphorus, and nitrogen components, three PAHs (pyrene, phenanthrene, and C1-benz[a] anthracenes/chrysenes) and three metals (lead, arsenic, and vanadium). The MIKE 11 model was developed for a 10-year historical period (2001-2010) and the EFDC model was calibrated over short periods under steady flow conditions. Both models were applied to hypothetical future scenarios. Non-point source loadings were estimated from limited measurements, rather than from watershed modelling of land use changes and development scenarios. The modelling framework is under further development to enhance the configuration and functionalities by restructuring the model grid for EFDC and cross-section profiles for MIKE 11, based on derived high-resolution DEM (Chowdhury, 2017). A two-dimensional hydrodynamic, sediment transport and water quality model for the Lower Athabasca River has been developed and calibrated using EFDC+ with a number of enhancements, including: extended model domain to cover the main channel and 10-year floodplain from the Athabasca River upstream of Fort McMurray to the Athabasca River near Old Fort; optimized model grid to improve computational burden to allow longer period (2000-2016) simulations in reasonable run-time; improved hydrodynamic model simulating dynamic ice cover formation and melting processes; cohesive and noncohesive sediment transport with the best available TSS and riverbed sediment data; and improved water quality (eutrophication and DO) and toxic (three representative toxics) modules by including all major tributaries, withdrawals and returns on the Lower Athabasca River, and point source effluents in the oil sands region (DSI, 2019). The river models are expected to be coupled with a distributed watershed model to achieve integrated watershed and river water quality modelling, as part of a multi-year mission to develop a comprehensive and integrated environmental modelling system for the cumulative effects assessment in oil sands region.

5.2 Atmospheric deposition and acidification modelling in the Athabasca Region

In 2003, RWDI West Inc. (2003) conducted a CALMET/CALPUFF modelling study for CEMA. The model was run for a one-year period to predict ambient concentrations and annual deposition rates for 39 priority substances in the Athabasca Oil Sands Region, that can then be used to screen potential human health risks using multimedia risk assessment techniques. The 39 priority substances, including SO_2, NO_x, and VOCs, were identified in the emission inventory of the oil sands region. Based on comparisons with available monitoring data, the highest level-of-confidence in model predictions is associated with the priority substances the emissions of which are well-defined, whereas a lower level-of-confidence is associated with emissions of priority substances from fugitive sources. For some contaminant-receptor combinations, the predicted ambient levels are so sufficiently low that a background term is required to allow for a representative comparison.

CEMA considered applying one or both of two widely used air quality modelling systems, CALPUFF and/or CMAQ, for sulphur and nitrogen deposition modelling to assess historical, current, and future environmental exposures due to emissions from the oil sands industry and other sources in and around the Regional Municipality of Wood Buffalo (RMWB). ENVIRON International Corporation and Stantec Consulting Ltd. (2012) conducted a detailed evaluation and comparison of the performances of the CALPUFF and CMAQ modelling systems to understand the relative strengths and weaknesses of the two models for implementation of the Acid Deposition Management Framework (ADMF). It was determined that the differences between the two model outputs are strongly related to differences in the model inputs in spite of sharing the same data sources. There is no basis for choosing one model (CALPUFF vs. CMAQ) over the other. Both may be used, each with different advantages. The CALPUFF model has the advantage of consistency with previous ADMF studies and other EIA studies, predicts the peak one-hour SO_2 and NO_2 concentrations better than CMAQ, and requires a lower level of effort to apply. The CMAQ model has the advantage of improved chemistry algorithms and appears to perform better in simulating lower SO_2

and NO_2 concentrations and the wet deposition of sulphur and nitrogen compounds.

CALPUFF modelling (Exponent Inc., 2014) was also conducted to estimate acid deposition to provide input to the Model of Acidification of Groundwater in Catchments (MAGIC) to determine whether acid deposition-related changes to lakes and soils will or will not exceed defined thresholds. The CALPUFF model was calibrated with 2010 meteorology and observation data and then applied with 1980 representative year meteorology data, as well as with historical, base, and two future emission scenarios. The model was run for a one-year period to predict the annual dry, wet, and total depositions of acidifying sulphur and nitrogen compounds. The deposition measurement data was considered insufficient for a reliable comparison between measurements and predictions. In general, the predicted total Potential Acid Input (PAI) in 1980 is slightly lower than that in 2010 for the existing emission inventory. The area of peak total PAI is located in the Fort McKay area, which is the area with the largest emissions. The second highest peak area is located in the Bridge View area along the southern boundary of the domain.

A CMAQ modelling study was completed with the same source of data and procedures as Exponent's CALPUFF modelling (S. Cho et al., 2017). Similar findings were obtained that include (i) a predicted area of high sulphur and nitrogen deposition near the largest oil sands operations in Alberta's oil sands region, and predicted higher dry deposition than wet deposition in the study area; (ii) the predicted gross PAI (wet & dry) deposition increases from the historical to an existing case with further increases for the two future scenarios; and (iii) the nitrogen deposition predicted by the model, which comprises, on average, approximately 60% of the total PAI acidic deposition in the region.

ECCC calculated estimates of potential effects on ecosystems in the Canadian provinces of Alberta and Saskatchewan due to acidifying deposition (Makar et al., 2018). Based on a one-year simulation of a high-resolution implementation of the Global Environmental Multiscale-Modelling Air-quality and Chemistry (GEM-MACH) model, the critical loads of sulphur and nitrogen deposition (dry, wet, and total) for aquatic and terrestrial ecosystems were derived. The spatial extent of the regions exceeding critical loads varied between 1E+4 and 3.3E+5 km^2, for the more conservative observation-corrected estimates of deposition, with the variation dependent on the ecosystem and the critical load calculation methodology. Other findings of the study were outlined and include (i) the evaluation of the model simulation against two different sources of deposition data – total deposition in precipitation and total deposition to snowpack in the vicinity of the Athabasca oil sands, (ii) the variability of observed ions in wet deposition in precipitation (observed versus model sulphur, nitrogen, and base cation R^2 values of 0.90, 0.76 and 0.72, respectively), while being biased high for sulphur deposition, and low for nitrogen and base cations (slopes 2.2, 0.89 and 0.40, respectively), and (iii) the predicted potential ecosystem effects within each of the regions, represented by the ecosystem critical load datasets using a combination of 2011 and 2013 emissions inventories.

The Model of Acidification of Groundwater in Catchments (MAGIC) has been applied to soils and lake catchments in the oil sands region to determine sensitivity to acid deposition under two deposition scenarios (base case and double acid) (Whitfield et al. 2009, 2010, 2011; Whitfield and Watmough, 2010). The model simulated average monthly or annual soil solution and surface water concentrations for sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and pH, as well as exchangeable soil fractions of Ca^{2+}, Mg^{2+}, Na^+, and K^+. Lumped indicators include base cation (BC) and acid neutralizing capacity (ANC) for lakes, base saturation (%) and critical threshold, and molar base cation to aluminum ratio (BC:Al) for soil physicochemical characterization. The research demonstrated that lakes in the region would not be at risk of acidification under either deposition scenario. In contrast, forest soil weathering rates range from very low to moderate, and soil chemistry was predicted to change under both deposition scenarios.

With the annual atmospheric deposition rates generated by CALPUFF modelling, a modelling approach was implemented within Golder's comprehensive oil sands environmental modelling system for predicting the contributions and potential effects of aerially deposited PAHs and metals, as well as the impacts of snowpack and snowmelt on water quality from proposed oil sands developments (Dayyani, Daly, & Vandenberg, 2016). The contribution (loading) of snowmelt to surface water concentrations was estimated using two methods: a conservative mass balance approach adopted for metals, and an unsteady-state, mass balance, and multi-compartment fate model, or Coastal Zone Model for Persistent Organic Pollutants (CoZMo-POP). Simulations were run with a timestep of one hour. The model predicted that: i) under base case conditions, cadmium and chromium concentrations were both predicted to exceed guideline values in the Muskeg River; ii) All PAHs were predicted to remain below guidelines in surface water for both projects and under all assessment cases.

The model was thought to over-predict the concentration of metals in receiving water pathways because it did not account for retention of metals during snowmelt in the soil matrix. Refinements to the mass balance approach for modelling metals should focus on retention of metals on the landscape during the melt period. Refinements to CoZMo-POP might include application of the water-sediment partitioning module to predict sediment PAH concentrations.

5.3 Watershed modelling in the Athabasca Region

A variety of watershed models have been used in the region such as HSPF, SWAT, VIC, WATFOOD, and MISBA. Pietroniro et al. (2006) investigated the potential effects of climate change on the hydrological regimes of three large lakes and two inflow sources (from the Peace and Athabasca rivers) on the Peace-Athabasca Delta. They indicated that changes in climate can result in an earlier melt season, higher winter flows, an increase of flows (more at headwater), and a reduction of peak flow. Kerkhoven and Gan (2006, 2011) assessed the impact of climate change using the MISBA model. They reported a large decline in spring snowpack, annual runoff (-21%), mean maximum annual flow (-4.4%), and mean minimum flow (-41%) by the end of century for ARB. The decline in the average annual flows has been also reported by Golder Associates (2009) when they evaluated the climate impacts using the HSPF model. An increase in winter flows and a decrease in summer flows have been found in Eum et al. (2014) and in Leong and Donner (2015), through assessing the impacts of climate change on the hydrology of the region using VIC and Integrated

Biosphere Simulator – Terrestrial Hydrology Model with Biogeochemistry (IBIS-THMB), respectively.

5.4 Groundwater modelling in the Athabasca Region

CEA for groundwater requires a groundwater model with a mesh/grid that can conform to complex geology and hydrogeology and with the capability of simulating density-dependent flow and transport, as well as surface water-groundwater interactions. A group of 10 in situ oil sand operators (the SAOS Group) initiated a process in 2007 to develop a regional surface water-groundwater model for the oil sands in situ area south of Fort McMurray. They conducted a review of surface water-groundwater numerical modelling to select the most suitable model. MODFLOW and FEFLOW were selected with the capability of being coupled with surface water models – as MODHMS and FEFLOW/MIKE 11, respectively (WorleyParsons, 2010). Major groundwater modelling studies have been undertaken in the Lower Athabasca River watershed. For instance, in 2009, WorleyParsons Canada Services Ltd. developed a 3D MODFLOW groundwater model (2 km grid resolution) for the entire Lower Athabasca Regional Plan (LARP) region to assess the potential impacts from oil sands development. They indicated that the current drawdown for the various major aquifers was substantial and that the trend of drawdown was anticipated to decrease. Subsequently, modelling studies have been more regionally focused and based on operational purposes whereas the Athabasca Oil Sands (AOS) area has been split into the following three regions:

1. Northern Athabasca Oil Sands (NAOS) region, which mainly contains the surface mineable deposits. The boundaries of the NAOS study area are
    - North: starting in the northwest, the boundary follows the Sand River, Athabasca River, Firebag River, and Marguerite River sub-basin;
    - East: Alberta/Saskatchewan border;

- South: Athabasca and Clearwater Rivers; and
- West: northwest boundary follows the western extents of the Gardiner Lake and Snipe Creek sub-basins, then follows the Dunkirk River south to the western boundary of the MacKay River sub-basin, south to the Athabasca River.

2. Southern (SAOS) area where in situ extraction occurs in the region. The boundaries of the SAOS region are:
   - North: Athabasca and Clearwater Rivers;
   - East: Alberta/Saskatchewan border and Christina River Sub-basin;
   - South: Centre of Township (T) 69 from Range (R) 1 to 9 West of the Fourth Meridian (W4M) continuing along the Beaver River Basin; and
   - West: Southwest boundary follows the La Biche sub-basin to the confluence of the Athabasca and La Biche River. The boundary continues north along the Athabasca River.

3. Cold Lake region which has been given the name Cold Lake-Beaver River (CLBR) based on its location within the Beaver River Basin.

For the NAOS region, WorleyParsons Canada Services Ltd. developed a 3D FEFLOW model in 2012, which allows for a flexible mesh refinement, simulates density-dependent and fractured flow, and includes river flow interactions by linking the model to MIKE 11. The first phase of the model development was mainly focused on the configuration of the model and understanding the hydrology/hydrogeology of the region. They reported that the recharge rate ranges from 247 to 1,150 million m^3/year for the NAOS study area. The total annual discharge from groundwater to the Athabasca River (including its tributaries) ranges from 236 million m^3/year to 590 million m^3/year. In addition, as of October 2011, it was estimated that the rate of groundwater withdrawal was roughly 41.5 million m^3/year within the NAOS region. A FEFLOW model has been also used by WorleyParsons to model groundwater of the SAOS region in 2010. They reported that the recharge in the SAOS ranges from 290 million m^3/year to 1,500 million m^3/year. The total discharge from groundwater to the river ranges from 540 million to 1,350 million m^3/year. As of February 2009, it was estimated that the total annual non-saline allocation volume is more than 15 million m^3 within the SAOS region. In 2016, the FEFLOW model developed by WorleyParsons for the SAOS was further modified by MATRIX Solutions Inc., to improve the calibration of the model.

For the CLBR region, a MODFLOW groundwater model was developed by the Alberta Geological Survey in 2005 to better understand the regional water balances and groundwater flow regimes. It was reported that recharge rates estimated by the model were highest in the northeast and southeast of the domain area (13.2 mm/year and 7.6 mm/year, respectively) and were lower than 5 mm/year in the western portion.

5.5 Surface water and groundwater interactions in the Athabasca Region

Few attempts have been made to model surface water-groundwater (SW-GW) interactions. In a study conducted by WorleyParsons (Integrated Sustainability Consultants Ltd., 2013), the MODFLOW model was used for the lower Athabasca regional planning region and they found 50% exceedance of available drawdown in the basal McMurray Formation, especially in the mineable area. They also indicated that a more comprehensive modelling tool is required for CEA under multiple-stressors. A review of modelling studies for assessing the potential cumulative impacts to groundwater and surface water in the MacKay River watershed was conducted by the Cumulative Environmental Management Association (CEMA, 2014). It was predicted that groundwater discharge can reduce to -0.001 to 0.043 m^3/s when various oil sands projects are developed compared to the current condition 0.01-0.055 m^3/s. They indicated that many project EIAs used different models with different data sets and assumptions, which makes comparison of projects and impacts difficult. Kassenaar (2016) assessed the potential cumulative impacts to SW-GW from in-situ oil sands operations using GSFLOW in the MacKay River watershed. They indicated that drawdowns do not (on a watershed-scale) appear to grow over time. However, cumulative groundwater diversions appeared to create unsustainable local impacts under extreme and defined scenarios. Furthermore, the simulations showed that that groundwater diversions may significantly affect small to intermediate sized tributaries.

5.6 Land use/land cover modelling in the Athabasca Region

A State-and-Transition Model (STM) model was developed for CEMA and validated by Apex Resource Management Solutions Ltd. to simulate reclamation dynamics for the mineable oil sands region of Alberta, such that it supports the development of a Reclamation Classification System (RCS) (Daniel, 2011; Frid & Daniel, 2012). The model utilized landscape vegetation state and the probability of transition between states to find potential probabilities of changes. STMs can help managers establish a land classification system by describing the land units and phases in the system, including the relationships between the various units and phases. STMs explicitly recognize the relationship between management alternatives and land classification, ensuring that the classification system is management-oriented. A quantitative STM was developed which can be used to both conceptually and quantitatively model landscape level changes over time because of alternative reclamation scenarios. The model was parameterized with existing data from the Long-Term Plot Network and other CEMA projects.

The Alberta Biodiversity Monitoring Institute (ABMI) is one of the main sources of land use and land cover data which also provides new analytical methods and visualization approaches to deliver geospatial products, such as the ABMI province-wide wall-to-wall Human Footprint Inventory (HFI). The ABMI has also developed a predictive product, called Predictive Landcover (PLC), which classifies land cover into seven classes (open water, bog, marsh, swamp, fen, upland, and wetland general).

Another important product to support land use and land cover decision-making in Athabasca is ALCES, a landscape and mapping software.

ALCES has been applied to inform planners and stakeholders about possible future outcomes associated with land use and development.

5.7 Climate change in the Athabasca Region

Climate change can be considered as a natural stressor which needs to be taken into account along with other stressors for CEA. Climate change studies in the Athabasca watershed can be divided into two main categories: the assessment of climate change and variability, and the impact of climate change on environmental processes. Regarding climate change and variability in the Athabasca watershed, Bonsal and Cuell (2017) indicated that periodic extreme droughts and excessive moisture conditions are expected mainly due to persistent and mid-tropospheric circulation patterns that disrupt expected temperature and precipitation in the region (Bonsal & Cuell, 2017). Furthermore, substantial inter-annual variability with more drought-like summer and slightly wetter annual conditions, as well as decadal-scale variability are predicted over the entire region. On the other hand, according to the climate change impact studies, a comparison between current and future climate conditions in the watershed has indicated a significant shift towards an earlier melt season and also an increase in winter flows (Toth et al., 2006). The shortened snowfall season along with an increase in sublimation can result in a decline in the spring snowpack as well as an expected decline in average annual flows (Kerkhoven & Gan, 2011).

5.8 Limitation of modelling for cumulative effects assessment in the Athabasca Region

In order to build an understanding of changes in the environment and to ensure that the cumulative effects of the stressor/s are captured, CEA often requires to take into account: (i) the related theme and sub-theme areas and their environmental processes, (ii) interactions and feedback mechanisms between environmental processes (in different related theme and sub-theme areas), and (iii) both local and regional response scales.

However, the majority of modelling studies in Athabasca have the following limitations:

1. They often take into account either limited theme areas or environmental processes.
2. They often lack the capacity to capture the interactions between major system components.
3. They only consider either regional-scale response (which lacks the necessary detail on local-scale pathways) or local response (which might not be suitable for guiding a regional-scale decision-making process).