PREDICTIVE SIMULATIONS USING THE 3D REGIONAL GROUNDWATER SOLUTIONS GROUNDWATER FLOW MODEL SOUTHERN ATHABASCA OIL SANDS

About this COSIA Water Environmental Priority Area (EPA) study

In-situ oil sands producers in the South Athabasca Oil Sands (SAOS) region use non-saline and saline groundwater for makeup water. For continued development of their projects, operators must understand the long-term usability of the aquifers and potential interactions from other operator activities.

To advance the understanding of water resource utilization and management, COSIA undertook the Regional Groundwater Solutions (RGS) project which used a numerical groundwater flow model to simulate the head distribution within the key aquifers used for oil sands water withdrawals and disposal within the SAOS.

The project team chose to update an existing, older SAOS regional groundwater model developed by Alberta Environment and Parks (AEP). In return for use of the model, COSIA agreed to provide AEP with all updates and improvements to the model. The improved SAOS model was provided to AEP (Monitoring Branch) in March 2017 along with supporting documentation (the Model Calibration and Construction report).

The attached report, “Predictive Simulations Using the 3D Regional Groundwater Solutions Groundwater Flow Model Southern Athabasca Oil Sands” by Matrix Solutions July 2017, documents the results of the RGS project. Three potential water forecasts were developed and simulated to explore uncertainty in future growth of in-situ oil sands production within the SAOS region. These were identified as Status Quo, Medium Growth, and High Growth scenarios, which are outlined in Table A below:

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COSIA’s Interpretation of the Results

The COSIA RGS team requested that the authors of the report (Matrix Solutions) present conclusions simply as statements of fact with respect to predicted effects on regional aquifer pressures.
Forward simulations covered a period of 62 years from 2013 to 2075. Timing of peak effects varied spatially but in general occurred between 2030 and 2040 when industry water demand was projected to be highest. Effects were evaluated relative to a benchmark of 50% reduction to aquifer water levels (i.e. available head), which is aligned with the criterion laid out for non-saline water use within the Alberta Conservation and Allocation Policy for Oilfield Injection (2006). Although this criterion does not apply to non-saline aquifers it nonetheless serves as a useful reference for evaluating impacts on pressures in all aquifers (many of the aquifers used by industry are saline aquifers).

The report found that for all three scenarios (including the high growth) aquifer drawdown was less than the benchmark over 99% of the aquifer area. The small areas (<1%) where more than a 50% reduction in available head was predicted are not considered significant from a regional water resource evaluation perspective. Such areas were found to occur close to operations, where best practices and compliance with existing provincial regulations should preclude such an occurrence or would otherwise require corrective action to remedy.

Predictive analysis in the report demonstrates the aquifers within the SAOS regional would not experience unacceptable pressure reductions due to oil sands water production under any of the three potential/hypothetical future development scenarios. In other words, there is sufficient groundwater available to support future growth of the SAGD oil sands without adverse impacts on the sustainability of water resources. It also should be noted that the majority of the water used by the SAGD industry consists of saline or non-potable groundwater from deep aquifers. Furthermore, the results of the study suggest that existing regulations and policies are sufficient to ensure that groundwater resources are well managed within the SAOS region.

Simulation results are subject to uncertainty as a numerical model is a simplified representation of a natural system. Additionally, technologies and development plans will change over time. Hence, the predictions presented herein should be verified through continuation of existing monitoring programs. In that respect, the results presented herein could provide a basis for evaluating results from future regional groundwater monitoring conducted through the Government of Alberta’s Oil Sands Monitoring (OSM) program.
PREDICTIVE SIMULATIONS USING THE
3D SOUTHERN ATHABASCA OIL SANDS
GROUNDWATER FLOW MODEL
REGIONAL GROUNDWATER SOLUTIONS PROJECT

Report Prepared for:
CANADA’S OIL SANDS INNOVATION ALLIANCE

Prepared by:
MATRIX SOLUTIONS INC.

July 2017
Calgary, Alberta
PREDICTIVE SIMULATIONS USING THE
3D SOUTHERN ATHABASCA OIL SANDS
GROUNDWATER FLOW MODEL
REGIONAL GROUNDWATER SOLUTIONS PROJECT

Report prepared for Canada’s Oil Sands Innovation Alliance, July 2017

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APEGA Permit to Practice
Permit No. P5540

DISCLAIMER

We certify that this report is accurate and complete and accords with the information available during the site investigation. Information obtained during the site investigation or provided by third parties is believed to be accurate but is not guaranteed. We have exercised reasonable skill, care and diligence in assessing the information obtained during the preparation of this report.

This report was prepared for Canada’s Oil Sands Innovation Alliance. The report may not be relied upon by any other person or entity without our written consent and that of Canada’s Oil Sands Innovation Alliance. Any uses of this report by a third party, or any reliance on decisions made based on it, are the responsibility of that party. We are not responsible for damages or injuries incurred by any third party, as a result of decisions made or actions taken based on this report.
EXECUTIVE SUMMARY

Canada’s Oil Sands Innovation Alliance (COSIA) retained Matrix Solutions Inc. to conduct predictive simulations and uncertainty analysis using the recently updated groundwater flow model for the Southern Athabasca Oil Sands (SAOS) region (Matrix 2016). The objective of the project was to evaluate the potential range of change in aquifer pressures from groundwater withdrawals and disposal associated with future in-situ oil sands production within the SAOS region. The evaluation is regional in scope and addresses potential cumulative effects of oil sands development. It was not intended, nor is it sufficiently detailed, to evaluate local effects from individual projects.

Three water forecasts were developed to explore uncertainty in future growth of in situ oil sands production with the SAOS region. These were identified as Status Quo, Medium Growth, and High Growth scenarios. The water forecasts estimate the rates of source water withdrawal and waste water disposal; the vast majority of which occur within the Mannville Group aquifers.

For the Empress Channel, Lower Grand Rapids, Clearwater A, Clearwater B, and Basal McMurray Sand aquifers, all three predictive scenarios have resulted in a maximum simulated change in available head of less than 50% for more than 99% of respective aquifer area over the 62 year simulation period. Since the objective of the Regional Groundwater Solutions modelling project was to evaluate regional effects, the small areas (where more than 50% reduction in available head were predicted) are not considered significant. These occur close to operations where compliance with existing provincial regulations would preclude such an occurrence.

In addition to the operational uncertainty, the uncertainty in calibrated parameters was quantified using the Null Space Monte Carlo (NSMC) methodology on the Medium Growth predictive scenario. A total of 300 realizations with independent parameter sets were used in this effort. Outcomes from these realizations were summarized in the report figures, tables, and appendices. Uncertainty as to the rate of future project development and the associated water requirements was determined to likely be the greatest uncertainty on potential future cumulative effects.
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APPENDIX B  Predictive Uncertainty - Realization Parameter Sets
APPENDIX C  Predictive Uncertainty Analysis - Empress Aquifer
APPENDIX D  Predictive Uncertainty Analysis - Lower Grand Rapids Aquifer
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APPENDIX G  Predictive Uncertainty Analysis - McMurray Basal Sands Aquifer
1 INTRODUCTION

Canada’s Oil Sands Innovation Alliance (COSIA) retained Matrix Solutions Inc. to conduct predictive simulations using the recently updated Southern Athabasca Oil Sands (SAOS) groundwater flow model (Matrix 2016). Simulations were based on three potential water forecasts, developed by the COSIA Regional Groundwater Solutions (RGS) project group, that represent different scenarios of potential future growth for the in-situ oil sands industry.

This report provides a discussion on predictive uncertainty (Section 4), the basis of water source and disposal forecast scenarios (Section 5), methods applied for available head calculation (Section 6), results from the three forecasted water use scenarios (Section 7), and a discussion on the uncertainty in the calibrated parameters (Section 8).

2 OBJECTIVES

The objective of the RGS project was to evaluate the potential range of change in aquifer pressures from groundwater withdrawals and disposal associated with future in-situ oil sands production within the SAOS region. Key questions included how projected regional pressure changes in aquifers compare to the available head and how these changes compare to the Alberta Water Conservation and Allocation Guideline for Oilfield Injection (AENV, 2006). The evaluation was intended to be regional in scope. As such, any interpretation of the results presented herein should be viewed from a regional perspective; the model is not intended to be used for evaluation of local effects. Individual projects are required to be evaluated individually through a rigorous environmental impact assessment process under the Alberta Environmental Protection and Enhancement Act. The model was constructed primarily to evaluate effects within the Mannville Group aquifers where the majority of industry-related water withdrawals and disposal occur. Further discussion of the limitations inherent in the model conceptualization, construction and calibration are provided in a separate report (Matrix 2016).

3 BACKGROUND

In 2013, COSIA initiated the RGS project. The RGS project required a regional-scale numerical model, incorporating the hydrostratigraphy and hydraulic properties in the SAOS area as well as the extensive and comprehensive dataset of all operators, in order to evaluate effects from different scenarios of potential, future industrial development. COSIA considered a number of existing models to serve as a base for developing the new model and selected the SAOS model that was originally developed for the Government of Alberta (GoA) by WorleyParsons Canada Services Ltd. (2010; currently Advisian WorleyParsons Group). COSIA obtained permission from the GoA to use and update the SAOS model in 2013.
The RGS project group retained Matrix to finalize the construction and calibration of the SAOS groundwater model by implementing several of the key recommendations from an independent review. The model updates and calibration results are documented in Matrix 2016. The following report documents the results of the predictive simulations based on scenarios developed by the COSIA RGS group.

4 PREDICTIVE UNCERTAINTY

As with any prediction of future outcomes, there is a degree of uncertainty in hydrogeological predictions. Sources of prediction uncertainty for a numerical groundwater flow model include:

- conceptual model
- operational (groundwater use) uncertainty
- uncertainty in the calibrated parameters

Conceptual model uncertainty is caused by incomplete or biased process representation, errors in the specification of initial and boundary conditions, as well as errors in the model parameters not subject to calibration. Conceptual model here refers to the discretization and thicknesses of the hydrostratigraphic units, the assigned boundary conditions, and the overall dimensions of the groundwater model that are believed to best represent the regional groundwater flow system. A single deterministic conceptual model is considered here rather than many stochastic conceptual models and, as such, conceptual model uncertainty was not quantified as part of this assessment. Details on the deterministic conceptual model of regional groundwater flow are provided in previous reports (Matrix 2016 and WorleyParsons 2010).

Operational uncertainty is the topic of Sections 3 and 5 where the different growth scenarios are discussed. The overall uncertainty associated with the predicted operational scenarios is difficult to quantify. Groundwater usage for each scenario can be overestimated or underestimated depending on numerous factors influencing industry practices (e.g. technology) and rate of project development (e.g. economy). The prediction uncertainty relative to the operational uncertainty was explored through the simulation of the Status Quo, Medium Growth, and High Growth predictive scenarios.

Finally, the uncertainty in the calibrated parameters occurs when multiple model parameter sets can reproduce observations from historical data. Each of these multiple parameter sets will produce a set of unique results when used for predictive simulations. The prediction uncertainty due to uncertainty in the calibrated parameters was quantified and is discussed in Section 6.

5 BASIS OF WATER SOURCE AND DISPOSAL FORECAST SCENARIOS

Water source and disposal usage scenarios for the SAOS region were developed by the RGS project team. For the current modelling effort, the forecasts were based on economic conditions (oil prices) and
knowledge of both COSIA and non COSIA projects in September 2016 for in-situ Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) projects in the SAOS region.

The forecasts for this project were divided into three different potential growth scenarios to reflect the uncertainty of if or when commodity prices will recover to higher levels than in September 2016, when these forecasts were established. These scenarios are summarized in Table A as follows.

**TABLE A  Forward Scenarios**

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Project by project water demand forecasts were allocated into the above categories according to their relative maturity ranging from existing operating projects, to “bolt-on” expansions through to announced but not yet approved greenfield developments.

For COSIA projects, the operators provided forecasts for source and disposal rates from 2013 through 2075. The status of non-COSIA projects was reviewed based on information reported in the *Spring 2016 Alberta Oil Sands Industry Quarterly Update* (AOSI 2016) and on published source and disposal rates reported in publically available applications to the Alberta Energy Regulator (AER). If there was a project that had an application into the AER, and the AOSI 2016 project size was similar to the application, then the planned yearly water volumes in the application documentation were used. For these projects, the planned yearly water volumes were shifted to either the most recent start year reported in AOSI (2016) or, if the reported start date was to be determined (TBD), the yearly water volumes were shifted 5 years later than previously published dates. In the case where a project was listed in the AOSI 2016 without published yearly water volumes forecast or the project size had significantly changed from published AER rates from documentation, then the bitumen production rates in cubic metre per day (m³/day) were multiplied by a factor of 0.6 to estimate yearly water volumes until 2050 then reduced by a factor of 0.3 for water supply to account for expected future improved water efficiency. Water disposal volumes were calculated by multiplying the bitumen production rates by 0.4. In two cases, where the AOSI 2016 indicated projects were either suspended or production reduced, the published rates were down-scaled accordingly for the Status Quo scenario and assumed to resume to nameplate capacity under the Medium Growth scenario.
While all reasonable attempts were made to develop realistic water source and disposal demand forecasts it must be recognized that the final compilations are subject to a high degree of uncertainty. The rates developed under the Status Quo scenario have the highest confidence as most of these projects are already operating. Nonetheless, operating practices can and do change over a project’s lifecycle in a manner that cannot always be forecast (generally towards improvements in water efficiency). This uncertainty increases with time into the future for all three water forecast scenarios. The timing and size of future project development under the Medium Growth and High Growth forecasts are problematic as most of these projects were uneconomic at 2016 oil prices. This is particularly true for the High Growth case that assumes a return to significantly higher oil prices than in September 2016 for the Status-Quo case. Hence, the modelling results documented in this report should be regarded as indicative of potential outcomes to hypothetical “what if” scenarios as opposed to reliable predictions of effects on groundwater resources.

Detailed project-by-project water demand forecasts from COSIA participants remain confidential and have been kept on file at COSIA and have not been shared amongst the member companies. This was purposely done as the goal of the RGS project is focused on the evaluation of regional effects and not to highlight any specific project. Additionally, while the rate and growth and water demands of an individual project are subject to local variations in reservoir quality and operating conditions, detailed project-level forecasts become less important when evaluating the regional effects from the aggregate source and disposal requirements of all SAGD and CSS projects in the SAOS region.

The overall water source and disposal demand for each scenario is illustrated in Figure 1. The peak water demand for Status Quo, Medium Growth, and High Growth scenarios are approximately 46,500 m³/d, 73,700 m³/d and 122,000 m³/d, respectively. The peak water demand for all scenarios occurs in 2026.

The overall water source and disposal demand per aquifer for each scenario is illustrated in Figure 2. The main regional aquifer providing source water for the Status Quo and Medium Growth scenarios is the Lower Grand Rapids Aquifer. It is forecasted that water will be sourced from the Lower Grand Rapids and McMurray Basal Sand aquifers equally for the High Growth scenario with peak water consumption of 42,400 and 47,200 m³/d, respectively (Table B). The information from Figure 2, “Overall Water Demand Per Scenario,” is summarized hereafter in Table B.

**TABLE B Water Use per Aquifer as Peak and Percentage Overall**

<table>
<thead>
<tr>
<th>Aquifer Formation</th>
<th>Scenario #1 Status Quo</th>
<th>Scenario #2 Medium Growth</th>
<th>Scenario #3 High Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empress</td>
<td>2,400 m³/d peak, 4% of total use</td>
<td>3,800 m³/d peak, 5% of total use</td>
<td>4,200 m³/d peak, 3% of total use</td>
</tr>
<tr>
<td>Lower Grand Rapids</td>
<td>31,600 m³/d peak, 70% of total use</td>
<td>38,400 m³/d peak, 55% of total use</td>
<td>42,400 m³/d peak, 36% of total use</td>
</tr>
<tr>
<td>Clearwater A</td>
<td>6,000 m³/d peak, 12% of total use</td>
<td>11,900 m³/d peak, 16% of total use</td>
<td>18,800 m³/d peak, 14% of total use</td>
</tr>
</tbody>
</table>
The McMurray Basal Sand Aquifer is the main regional aquifer used for disposal fluids in all three scenarios. The Lower Grand Rapids Aquifer is also forecasted as being used for disposal in the Medium Growth and High Growth scenarios but represents less than 5% (5,360 m³/d) of the overall projected disposal demand of those scenarios. Disposal into Devonian aquifers (e.g. Keg River Formations) was not included in the forward simulations as the isolated use of this formation would not be of consequence for predicting cumulative effects on water pressures.

6 AVAILABLE HEAD

Hydraulic head and percentage change in available hydraulic head were chosen as indicators for quantifying the effects of the forward water use simulations. The available head is the indicator used in the Water Conservation and Allocation Guideline for Oilfield Injection (AENV 2006), a regulatory guideline that strives to support the conservation and management of water and prevent the excess use of non-saline water for enhanced recovery of hydrocarbon resources. Conservation of non-saline groundwater is realized by restricting the long term yield of a given aquifer to a maximum of one half in the immediate vicinity of the water source well. This is accomplished by limiting the drawdown in the production aquifer, as measured in an observation well at a distance of 150 m from the production well, to 35% of available head during the first year of operation and no more than 50% of available head over the life of the project. This regulatory guideline applies specifically to non-saline groundwater and, as such, is not applicable to saline aquifers (e.g.: greater than 4,000 mg/L). Although the McMurray Basal Sand, Clearwater B, Clearwater A and parts of the Lower Grand Rapids aquifers can be saline, a 50% change in available hydraulic head was used as a common reference for both non-saline and saline aquifers discussed in Section 5 of this report (though it has no basis in regulation for saline aquifers).

The available head for the Empress Channel, Lower Grand Rapids, Clearwater A, Clearwater B and McMurray Basal Sand aquifers were calculated using the simulated steady-state (i.e., pre-development) hydraulic heads minus the top of aquifer structure elevation from the 2016 SAOS numerical model. Calculated available head distribution is presented spatially in Figures 3 through 7.

Given that the main objective of the assessment is to identify significant potential regional effects on aquifer pressures, all areas with calculated available head greater than 10 m were shown on generated figures and were considered for evaluating changes in aquifer productivity. Areas with calculated available head less than 10 m occur in the Lower Grand Rapids and McMurray Basal Sand aquifers in the northern portion of the model domain and were not considered in this assessment.
7 FORWARD SIMULATION RESULTS

This section of the report provides a discussion on the results for the Status Quo, Medium Growth, and High Growth scenarios, using the deterministic calibrated parameter set. The forward simulations ran for a period of 62 years, from January 2013 through December 2074.

For each scenario and each of the selected major regional aquifers, a figure presenting the spatial distribution of the simulated changes in hydraulic and available hydraulic head is provided for the years 2020, 2030, 2040 and 2050 (Figures 8 through 22). By convention, decreases in reported hydraulic heads and available heads correspond to negative values, and conversely, positive reported values correspond to head increases.

Results from all scenarios are discussed on a per aquifer basis in Sections 5.1 through 5.5 and changes in the simulated flow budget are presented in Section 5.6.

7.1 Empress Channel Aquifer

Regionally, simulated changes in hydraulic head in the Empress Channel Aquifer are less than 10 m and correspond to changes of available head that are generally less than 10% for all scenarios and selected years (Figures 8 through 10). As summarized in Table 1, the sum of simulated areas with greater than 50% change in available head is limited to an area of less than 0.3 km² in year 2040 for the High Growth scenario (Table 1).

7.2 Lower Grand Rapids Aquifer

The Lower Grand Rapids is the main regional aquifer providing source water aquifer for Status Quo and Medium Growth scenarios in the SAOS region (Figure 2). It is forecasted that water will be sourced from the Lower Grand Rapids and McMurray Basal Sand aquifers equally for the High Growth scenario with peak water consumption of 42,400 m³/d and 47,200 m³/d, respectively. For all scenarios, simulated change in hydraulic heads is greater in the southeastern portion of the model domain with decreases between 75 m and 100 m in year 2040 (Figures 11 through 13). Given the available head is greater than 200 m in this area, the calculated change in available head remains below a 50% decrease.

In the northern portion of the model domain, the simulated decrease in hydraulic head in the Lower Grand Rapids Aquifer is less than 30 m. Due to the available head being less than 50 m in this area, the percent change in available head is greater than what is observed in the southern portion of the model domain. For the year 2040, the total areas with a decrease in available head greater than 50% are estimated to be 13.9 km², 21.7 km², and 31.3 km² for Status Quo, Medium Growth, and High Growth scenarios, respectively (Table 1).

Mounding of less than 5 m is simulated in the Lower Grand Rapids Aquifer in the vicinity of Township 80 Range 1 W4M for the Status Quo and Medium Growth scenarios. At this location, the Upper, Middle and
Lower Clearwater aquitards are interpreted to be absent and the Wabiskaw Aquifer/Aquitard overlying the McMurray Basal Sand Aquifer is particularly thin, which resulted in vertical pressure propagation from disposal in the McMurray Basal Sand Aquifer. Mounding is also simulated in Township 74 Range 5 W4M for the High Growth scenario, and is caused by disposal activities in the Lower Grand Rapids Aquifer at this location.

7.3 Clearwater A Aquifer

Simulated changes in hydraulic heads in the Clearwater A Aquifer are greatest in the southeastern portion of the model domain, with an overall head decrease of nominally 75 m in 2040 (Figures 14 through 16). Considering that the simulated source well locations are mainly in the northern half of the model domain, this result suggests vertical pressure propagation due to water withdrawal from the overlying Lower Grand Rapids Aquifer.

Mounding of less than 5 m is simulated in the Clearwater A Aquifer in the vicinity of Township 80 Range 1 W4M for the Status Quo and Medium Growth scenarios. At this location, the Middle and Lower Clearwater aquitards are interpreted to be absent and the Wabiskaw Aquifer/Aquitard overlying the McMurray Basal Sand Aquifer is thin, which resulted in vertical pressure propagation from disposal in the McMurray Basal Sand Aquifer. Mounding is also simulated in Township 74 Range 5 W4M for the High Growth scenario, interpreted to be caused by pressure propagation of disposal activities in the overlying Lower Grand Rapids Aquifer.

Overall, the simulated change throughout the model domain is generally a decrease of less than 20% of available head. Local areas (< 3.3 km²) near water production wells with greater than 50% decrease in available head were simulated (see Table 1).

7.4 Clearwater B Aquifer

Simulated change in hydraulic heads in the Clearwater B Aquifer is the greatest in the central portion of the model domain with predicted decreases of more than 40 m by year 2040 (Figures 17 through 19). The simulated change in available head throughout the model domain is generally less than a 20% decrease and no areas with more than 50% decrease were simulated (Table 1).

Mounding of less than 10 m is simulated in the Clearwater B Aquifer for the Status Quo and Medium Growth scenarios and occurs in the vicinity of Township 80 Range 1 W4M. At this location, the Lower Clearwater Aquitard is absent and the Wabiskaw Aquifer/Aquitard overlying the McMurray Basal Sand Aquifer is thin, which resulted in vertical pressure propagation from disposal in the McMurray Basal Sand Aquifer.
7.5 Basal McMurray Sand Aquifer

The Basal McMurray Sand Aquifer is the main regional aquifer for wastewater disposal in the SAOS region. Simulated decrease in available head is therefore marginal throughout the model domain for all scenarios and selected times (Figures 20 through 22). The exception is an area in the northwest of the domain where the aquifer is interpreted to be spatially discontinuous and therefore in weak hydraulic communication with other parts of the aquifer.

Mounding due to disposal is greatest in 2040 with changes of up to 100 m in the eastern portion of the model domain where the McMurray Basal Sand Aquifer is thickest.

As shown in Figure 2, the saline water withdrawal is forecasted to increase from approximately 10,000 m³/day to 42,000 m³/day, between the Medium Growth, and High Growth scenarios. As a result, mounding is reduced and there is less simulated vertical pressure propagation to overlying aquifers, particularly in the vicinity of Township 80 Range 1 W4M (Figure 22).

7.6 Simulated Flow Budget

The simulated steady-state flow budget is presented in Table 2. Based on the steady-state water budget, 67% of the assigned recharge discharges to head-dependent fluid transfer BCs representing rivers on the top slice of the model and 11% of the assigned recharge discharges to constant head BCs representing lakes on the top slice of the model. Approximately 21% of assigned recharge is simulated to discharge to head-dependent fluid transfer BCs after a long flow path through major aquifers in the model domain.

For each scenario, the changes in flow budget from steady-state conditions at the different model components are also included in Table 2 for the year 2040. The simulated change in flow budget from aquifers to surface water features from the head-dependent Cauchy boundary condition is greatest for the High Growth scenario at 7,958 m³/day, which represents a decrease of approximately 7% of the steady-state condition, or approximately 1% of total flow budget. The McMurray Basal Sand Aquifer head-dependent Cauchy boundary condition present in the southeastern portion of the model domain increased its outflow by 12,780 m³/day, which is mainly due to simulated disposal wells within 5 km from the boundary condition and represents 17% of the disposal rate into this aquifer in the year 2040, or approximately 2% of total flow budget. The change in flow budget for the remaining model components, other than wells boundary conditions, are considered marginal. Finally, the water imbalance for all scenarios was less than 0.001% of the total flow budget.

8 UNCERTAINTY IN CALIBRATED PARAMETERS

Null Space Monte Carlo (NSMC) methodology was used to quantitatively explore the predictive uncertainties associated with the calibrated parameters from the 2016 SAOS numerical model (Matrix 2016). NSMC is an uncertainty analysis technique which uses parameter covariance and solution space reduction to generate parameter sets which are physically reasonable, adequately cover the
model parameter ranges, and maintain a decent degree of misfit with measured values. A detailed description of the NSMC methodology is included in Appendix A.

8.1 Parameter Set Realizations

A total of 300 parameter set realizations were tested using the Medium Growth scenario predictive simulation. Each realization was composed of the 748 base parameters used in the 2016 SAOS calibration process.

Each realization was tested against the calibrated solution measurement objective function to ensure that the realization’s parameter set produced a measurement objective function value that was within 10% of the deemed calibrated solution. A smaller cut-off of less than 10% would reduce the parameter space being explored in the uncertainty analysis and a larger cut-off of greater that 10% would include parameter sets in the uncertainty analysis that do not adequately reproduce observation data. The cut-off selected for this analysis is comparable cut-offs used in other published studies (e.g., Tonkin and Doherty 2009). Figure A shows measurement objective function values from all realizations ordered by increasing measurement objective function from left to right.

**FIGURE A Objective Function Distribution of Parameter Set Realizations**

Individual parameter distributions and statistics from the 300 realizations are provided in Appendix B. Table B1 presents the calibrated values of the individual parameters along with the minimum, mean,
and maximum value of each parameter’s distribution. The statistical summary table is followed by 748 figures illustrating the distributions of the separate parameters. Parameters with wider range of values are the parameters less constrained by observations. Conversely, parameters with narrower ranges of values are the parameters best constrained by observations from the calibration dataset. The results are generally consistent with the sensitivity analysis ranking described in the 2016 RGS report (Matrix 2016; Section 6). Variation in parameters sensitivity was expected, given the Jacobian matrix was re-computed without regularization observations.

8.2 Uncertainty Quantification

To efficiently quantify the prediction uncertainty in calibrated parameters from the 300 parameter set realizations, theoretical observation locations where selected for each aquifer. The centre of each township was selected in the area where the aquifer is present and the prediction from the calibrated solution parameter set showed noticeable change in hydraulic heads. The Empress Channel Aquifer is an exception, as more locations were selected for this aquifer due the relative complexity of the aquifer outline.

Appendices C through G provide all the details on the timing of maximum changes in hydraulic heads and available head over the entire simulated time period of 62 years. Appendix C, D, E, F, and G provide results for Empress Channel, Lower Grand Rapids, Clearwater A, Clearwater B, and McMurray Basal Sand aquifers, respectively. Each appendix begins with a table summarizing the timing and magnitude of maximum simulated hydraulic head changes at the theoretical monitoring locations. The summary table is then followed by a figure showing spatial distribution of the theoretical monitoring locations. Finally, two sets of figures (a statistical summary figure and a time series figure) summarizing results from all realizations at theoretical monitoring locations with greater than 10% change in available head are provided. An example figure set is shown below in Figures B and C.

8.2.1 Statistical Summary Figure

Figure B is an example figure from Appendix C. The figure title corresponds to the aquifer acronym, township, and range. Figure B theoretical monitoring well is completed in the Lower Grand Rapids Aquifer and located in centre of Township 71 Range 7 West of the 4th Meridian. Theoretical monitoring well location is shown as a red star in the inset map displayed in the legend box.

The statistical summary figure illustrates the results from the 300 parameter set realizations. First, in the top left corner is a scatter plot of maximum simulated hydraulic head change (and change in available head) versus the date on which that change occurred. Each data point represents the result from a single realization. Red horizontal and vertical lines shows, respectively, the calibrated set of parameter predicted maximum head change and the date on which it occurred. Below the scatter plot is a histogram showing the distribution of date of maximum head change and to the right of the scatter plot is a histogram showing the distribution of maximum head change. Note that the plotted points and
histograms correspond to the dates and magnitudes of maximum change for individual realizations. Maximum change was considered a useful indicator for comparing against the reference threshold of 50% decrease of available head.

For theoretical monitoring locations located in vicinity of a source or disposal well, the date of maximum head change usually coincide with the pumping schedule of this well and therefore the maximal change for all realizations is occurring on a single date, although the magnitude varies between realizations.

Finally, a summary of the different statistics illustrated on the histograms is included on the lower right corner of the figure. These statistics are also presented in respective appendix’s summary table, to ease comparison with other theoretical monitoring locations.

8.2.2 Time Series Figure

Figure C is an example of the time series figures provided in the appendices. The figure title corresponds to the aquifer acronym, township, and range, identical to the titles of the statistical summary figures. It illustrates the time series results from each of the 300 realizations. The time series from the calibrated parameter set is shown by a red line, and the theoretical monitoring location is shown in the inset map, in the figure’s legend block. These figures provide insight on the timing and duration of various magnitude of change in hydraulic head that is not limited to the maximal amplitude, as it is for the statistical summary figure.

FIGURE B Example Chart - Monte Carlo Summary
8.3 Interpretation of Uncertainty in Calibrated Parameters

Maps showing the 95% confidence interval for the year 2040 were compiled for each selected regional aquifer for both the change in hydraulic heads and available head (Figures 23 through 32). The year 2040 was selected because the spatial extent and magnitude of the effects were generally the greatest for this year. The selection of a specific time of interest was used to better visualize the spatial distribution and facilitate the discussion of uncertainty.

The uncertainty in calibrated parameters can be assessed spatially by looking at the variation between the 2.5% and the 97.5% percentile predicted change in available head from the Medium Growth scenario 300 realizations. As an example, for the Lower Grand Rapids (Figure 26), the percentage change in available head is consistently lower than 10% in the centre of the model domain between Townships 77 and 80. For the same area, the predicted change in available head from the High Growth scenario is greater than 10%, suggesting that the operational uncertainty (Section 4) is the highest source of uncertainty in the predictions made using the 2016 SAOS numerical model for that given area and aquifer.

Note that for locations with greater percent change of available heads the total available head should be considered alongside the percentage change. For example, the north west of the Lower Grand Rapids has a monitoring location (LGR_T85R12_C) where change in available head ranges from -19% to -81.1% for the 95% confidence interval (Figure 26). This appears extreme relative to the 95% confidence interval results for the rest of the aquifer, but can be easily explained by examining the available head at this location.
location. This monitoring location has 32 m of available head (Appendix D - Table D1), significantly less than the 200 m or more of available head in the south east of the formation (Township 70 through 72).

Some generalizations can be made about the results:

- Areas of forecasted high stress in the forward scenario have more uncertainty in the predicted outcomes
- Areas being better constrained by observations should have less uncertainty in the predicted outcomes
- Areas with higher parameter uncertainty could have that uncertainty reduced through further characterization if the magnitude of parameter uncertainty is a concern

Generalizations beyond this should be avoided and Matrix recommends looking at combined information from explored parameter variability, parameter uncertainty outcomes found in figures and/or appendices, and operational uncertainty captured by the three scenarios assessed, if readers are interested in a specific aquifer and/or area.

9 CONCLUSIONS

The update SAOS model has provided COSIA members with a tool to evaluate regional effects on aquifer pressures resulting from future source and disposal activities within the Mannville Group aquifers.

Using the 2016 SAOS numerical model, Matrix simulated three forecast water source and disposal usage scenarios to reflect the potential growth outlook for in-situ SAGD and CSS projects in the SAOS region. For the Empress Channel, Lower Grand Rapids, Clearwater A, Clearwater B, and Basal McMurray Sand aquifers, all three predictive scenarios have resulted in a maximum simulated change in available head of less than 50% for more than 99% of respective aquifer area over the 62 year simulation period. Since the objective of the RGS modelling project was to evaluate regional effects, the small areas (where more than 50% reduction in available head was predicted) are not considered significant. These occur close to operations where compliance with existing regulations (i.e., AENV 2006) would preclude such an occurrence.

Matrix examined operational uncertainty and uncertainty in calibrated parameters of the simulated changes in hydraulic head and available head from the 2016 SAOS model. Uncertainty as to the rate of future project development and the associated water requirements was determined to likely be the greatest uncertainty on potential future cumulative effects. Uncertainty in the calibrated parameters was quantified using a NSMC approach; uncertainty related to the structure of the conceptual model was not considered in this assessment.
A NSMC parameter uncertainty analysis was conducted on the Medium Growth water use scenario. Through this analysis, the prediction uncertainty in the calibrated parameters was quantified and results were summarized in figures, tables, and appendices at the centre of each township with expected hydraulic head change from industrials activities. Matrix recommends using the attached appendices and supplemental data if the reader is interested in predictive uncertainty at a specific location. Insight can be gained on areas where additional observations could provide the highest value to decrease predictive uncertainty due to uncertainty in the calibrated parameters.

10 REFERENCES


Figure RGS Predictive Simulations
Canada's Oil Sands Innovation Alliance

Scenarios Forecasted
Overall Water Demand

- Scenario #1 Status Quo
- Scenario #2 Medium Growth
- Scenario #3 High Growth
Disclaimer: The information contained herein may be compiled from numerous third party materials that are subject to periodic change without prior notification. While every effort has been made by Matrix Solutions Inc. to ensure the accuracy of the information presented at the time of publication, Matrix Solutions Inc. assumes no liability for any errors, omissions, or inaccuracies in the third party material.

Date: December 2016
Reviewer: G. MacMillan
Drawn: G. Liu

Canada’s Oil Sands Innovation Alliance
RGS Predictive Simulations
Lower Grand Rapids Aquifer Scenario #: Status Quo
YEAR 2020 - Simulated Change in Hydraulic Heads (m)
YEAR 2030 - Simulated Change in Hydraulic Heads (m)
YEAR 2040 - Simulated Change in Hydraulic Heads (m)
YEAR 2050 - Simulated Change in Hydraulic Heads (m)

YEAR 2020 - Change in Available Head (%)  
YEAR 2030 - Change in Available Head (%)  
YEAR 2040 - Change in Available Head (%)  
YEAR 2050 - Change in Available Head (%)

Legend
- BC Type 1: Constant Heads
- BC Type 3: Fluid Transfer
- Model Demand
- Stressed Flow Location
- Stressed Ground Grid

Change in Head (m)
- >100
- 50-100
- 25-50
- 10-25
- 0-10
- 1-1
- 1-10
- 10-20
- 20-30
- 30-50
- 50-75
- 75-100

Change in Available Head (%)
- >50%
- 50%-50%
- 30%-30%
- 10%-10%
- >10%
- 0-10%
- 10-20%
- 20-30%
- 30-50%
- 50-75%
- 75-100%

Canada's Oil Sands Innovation Alliance
RGS Predictive Simulations
Clearwater Aquifer
Scenario #1: Status Quo
Figure RGS Predictive Simulations
Canada's Oil Sands Innovation Alliance
K:\23386_RGS\calibration\FigureTemplateTL.potm
Canada’s Oil Sands Innovation Alliance
RCS Predictive Simulations
Empress Channel Aquifer
Change in Available Head
Year 2040 - 95% Confidence Interval

LEGEND

Model Domain

Aquifer present

Change in Available Head (%)

-100.0%  to -95.0%
-95.0%  to -10.0%
-10.0%  to 3.0%
3.0%  to 10.0%
10.0%  to 50.0%
50.0%  to 100.0%
>100.0%

Scale 1:1 800,000
NAD83 WGS84 Zone 12N

RGS Predictive Simulations
Canada’s Oil Sands Innovation Alliance
f:\drafting department\software\powerpoint\figure eia - letter landscape.potm
Canada’s Oil Sands Innovation Alliance
RPS Predictive Simulations
Clearwater A Aquifer
Change in Hydraulic Head
Year 2040 - 95% Confidence Interval

LEGEND

Change in Hydraulic Head (m)

-<100.0

-100.0 to -50.0

-50.0 to -10.0

-10.0 to 3.0

-3.0 to 3.0

3.0 to 10.0

10.0 to 50.0

50.0 to 100.0

>100.0

Model Domain

Aquifer present

Matrix Solutions Inc.
Environment & Engineering

Matrix Solutions Inc.

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### TABLE 1
Simulated Areas with Greater than 50% Change in Available Head

<table>
<thead>
<tr>
<th>Location</th>
<th>Scenario</th>
<th>Year 2020</th>
<th>Year 2030</th>
<th>Year 2040</th>
<th>Year 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empress Channel</strong></td>
<td>Status Quo</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Medium Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Grand Rapids</strong></td>
<td>Status Quo</td>
<td>4.9</td>
<td>8.0</td>
<td>13.9</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Medium Growth</td>
<td>5.1</td>
<td>17.4</td>
<td>21.7</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>High Growth</td>
<td>5.2</td>
<td>22.1</td>
<td>31.3</td>
<td>10.4</td>
</tr>
<tr>
<td><strong>Clearwater A</strong></td>
<td>Status Quo</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Medium Growth</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>High Growth</td>
<td>0.1</td>
<td>3.3</td>
<td>3.1</td>
<td>45.1</td>
</tr>
<tr>
<td><strong>Clearwater B</strong></td>
<td>Status Quo</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>McMurray Basal Sand</strong></td>
<td>Status Quo</td>
<td>9.9</td>
<td>38.2</td>
<td>42.4</td>
<td>45.1</td>
</tr>
<tr>
<td></td>
<td>Medium Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. Township = approx. 92 km²
2. Model Domain = 35,275 km²
3. 1.2 = available head decrease (i.e. Drawdown)
4. (1.2) = available head increase (i.e. Mounding)
<table>
<thead>
<tr>
<th>Model Component</th>
<th>Description</th>
<th>2016 RGS Model - Steady-State (m³/day)</th>
<th>Change from Steady-State Flow Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Scenario #1: Status Quo - Year 2040</td>
<td>Scenario #2: Medium Growth - Year 2040</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m³/day</td>
<td>% of total flow budget</td>
</tr>
<tr>
<td>Recharge</td>
<td>Distributed Source (Recharge) Top Slice - Boundary Condition</td>
<td>523,110 (5.4 mm/yr *)</td>
<td>0</td>
</tr>
<tr>
<td>Rivers</td>
<td>Surface Water (Rivers) Top Slice - Head-dependent flux (Cauchy) - Boundary Condition</td>
<td>-351,785</td>
<td>2,566</td>
</tr>
<tr>
<td></td>
<td>Aquifers to Surface Water (Rivers) - Head-dependent flux (Cauchy) - Boundary Condition</td>
<td>-108,877</td>
<td>-261</td>
</tr>
<tr>
<td>Lakes</td>
<td>Surface Water (Lakes) Top Slice - Constant Heads (Dirichlet) - Boundary Condition</td>
<td>-56,848</td>
<td>528</td>
</tr>
<tr>
<td>Empress Aquifer Constant Heads (Dirichlet) - Boundary Condition</td>
<td>6,728</td>
<td>36</td>
<td>0%</td>
</tr>
<tr>
<td>Grosmont Aquifer Constant Heads (Dirichlet) - Western Boundary Condition</td>
<td>-29,891</td>
<td>38</td>
<td>0%</td>
</tr>
<tr>
<td>Inter-basin Flow</td>
<td>Contact Rapids/Winnipegosis Aquifer Constant Heads (Dirichlet) - Western Boundary Condition</td>
<td>13,063</td>
<td>0</td>
</tr>
<tr>
<td>Lower Grand Rapids Aquifer - Head-dependent flux (Cauchy) - Southern Boundary Condition</td>
<td>426</td>
<td>271</td>
<td>0%</td>
</tr>
<tr>
<td>McMurray Basal Sand Aquifer - Head-dependent flux (Cauchy) - Southern Boundary Condition</td>
<td>-1,257</td>
<td>-11,845</td>
<td>2%</td>
</tr>
<tr>
<td>Beaverhill Lake/Cooking Lake Aquifer/Aquitard - Head-dependent flux (Cauchy) - West Southern Boundary Condition</td>
<td>8,621</td>
<td>-638</td>
<td>0%</td>
</tr>
<tr>
<td>Contact Rapids/Winnipegosis Aquifer - Head-dependent flux (Cauchy) - Southern Boundary Condition</td>
<td>-3,326</td>
<td>-115</td>
<td>0%</td>
</tr>
<tr>
<td>Wells</td>
<td>Injection Rate (+) - Disposal Wells</td>
<td>NA</td>
<td>46,473</td>
</tr>
<tr>
<td></td>
<td>Withdrawal Rate (-) - Supply Wells</td>
<td>NA</td>
<td>-35,566</td>
</tr>
<tr>
<td>Storage</td>
<td>Storage Release (+) / Capture (-)</td>
<td>NA</td>
<td>-1,488</td>
</tr>
<tr>
<td>Water Balance</td>
<td>Matrix 2016 RGS Model Water Balance</td>
<td>NA</td>
<td>-1,488</td>
</tr>
</tbody>
</table>

**Notes:**

Negative values indicate water leaving the model component (outflow)

* Model Domain Area (km²): 35,275