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Karstic Devonian Limestone as a Transmitter of Groundwater Flow from Overlying Oil Sands

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Introduction

A number of mathematical models for groundwater flow have previously been developed in the area of the Athabasca Oil Sands based on the assumption that groundwater flow is essentially limited to the Quaternary and Cretaceous layers. The Basal Sands of the oil sands are usually assumed to be the regional aquifer transmitting groundwater laterally. The Basal Sands are not continuous when considered at the scale of leases. Furthermore, the karst in the Devonian limestone has usually been ignored during field investigations and in conceptual and numerical groundwater simulation models. In many places this karst lies directly under the Athabasca Oil Sands. The presence of a continuous karst layer immediately below the Cretaceous layers would provide effective pathways for groundwater flow and pressure changes between injection and depressurization wells and, possibly, flow towards the Athabasca River. In addition, the presence of permeable karst also affects the Steam-Assisted Gravity Drainage (SAGD) operation as pressure losses will occur into the Devonian karst. Therefore higher pressures likely need to be applied and the danger of surface escapes of steam is thus increased. Operating costs will increase as well.

Rationale

Hence it is of some practical importance to determine whether widespread downward flow of groundwater is occurring through the oil sands into the underlying karstic limestone and lateral flow within that limestone towards the regional discharge area, the Athabasca River. To this end we have developed 2D groundwater flow models within a vertical geological cross-section located within the DCEL lease OSL 25 D. Figure 1 shows the location of the lease and the geologic cross-section within an EIA by DCEL (Deer Creek Energy Ltd., 2005, Fig. 5.1.1). Figures 2, 3[A] and 4[A]) depict the equipotential lines within the same cross-section as provided by Millennium EMS Solutions Ltd (Millennium, 2005, Fig. 5). The cross-section in Figure 2 irrefutably shows downward flow of groundwater from the surface recharge zone towards the bottom of the oil sands. The question now is whether the flow continues laterally within the discontinuous sand layer of the Basal Sands or whether it progresses deeper into the continuous karstic Devonian limestone layers.

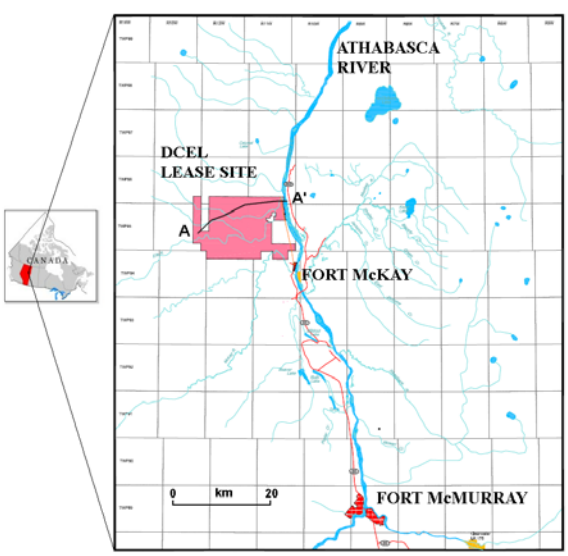

Fig. 1 *Location of cross-section A-A' on DCEL lease site OSL 24. Site map modified from DCEL, 2005, Fig. A.5.1.1 . Cross-section A-A' was added based upon Millennium (2005, Fig.1). The outline of Canada and Alberta stem from The Atlas of Canada (atlas.gc.ca) © 2001 with permission of Natural Resources Canada.*

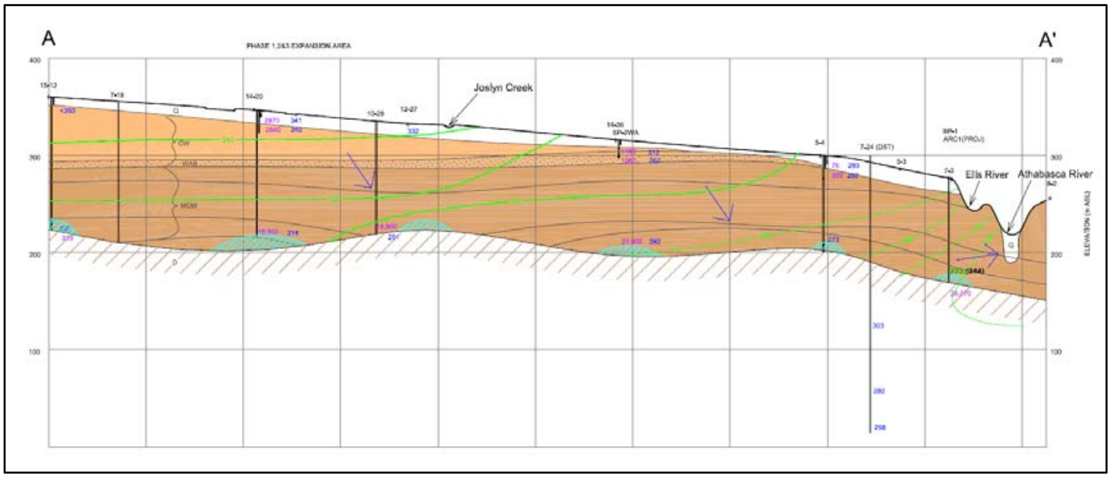

Fig. 2 *Cross-section A-A'. Millennium, 2005, Fig. 5. The geologic layers are from top to bottom: the Quaternary (Q - white), the Cretaceous Clearwater Formation (CW), Wabascab member (WAB), the McMurray Formation (MCM) with the oil sands, the discontinuous Basal Water Sands (blue) and the Devonian limestone (D - white). Vertical exaggeration is about 20x.*

Mathematical Model Calculations

As part of an assessment of an EIA for Joslyn North Mine, WDA Consultants prepared and simulated two conceptual models and, in addition, reported the results in Weyer (2006). In Model 1 we assumed that groundwater flow within the limestone karst is negligible (Figure 3). This assumption had also been made by Millennium (2005). The Devonian limestone had been assumed to be impermeable and the Basal Sands below the oil sands were assumed to be the lateral transmitter of regional groundwater flow. In the second simulation (Model 2) the karstic sandstone was assumed to be highly permeable (Figure 4). The aim of the simulations was to determine which model assumptions would replicate the equipotential lines measured in the field (Figure 2).

In Model 1 flow is limited to the layers above the Devonian limestone. In Model 2 groundwater is allowed to flow into the karstic limestone. The applied model is FLONET/TR2, developed at the University of Waterloo and has been successfully applied in many projects worldwide (Molson and Frind, 2012).

Figure 3[A] shows, for comparison purposes, the equipotential lines depicted in Figure 2, while Figure 3[B] shows the FE grid of Model 1. Figure 3[C] shows the contrast in hydraulic conductivities and anisotropies we assigned to the individual layers. When working with assumed contrast hydraulic conductivities equipotential lines and stream lines can be accurately calculated, while velocities and fluxes cannot. The Model 1 results are presented in Figure 3[C] and 3[D]. Profile 3[C] depicts the distribution of equipotential lines as they were calculated in the model. Obviously the resultant equipotential lines are sub-vertical and therefore fundamentally different from the lateral extension of equipotential lines as measured in the field (Figures 2 and 3[A]). The responding flow lines are shown in Profile 3[D]. The discontinuous Basal Sands concentrate the groundwater flow in the areas where they occur. Between the occurrences of Basal Sands, groundwater flow is quasi-lateral through the oil sands. In general, groundwater flow would be strongly impeded due to the low permeability of the oil sands in combination with the distance travelled within them.

In our experience the results achieved have been predicated by the lack of an extensive and continuous high permeability layer under the oil sands. As this layer cannot be the discontinuous Basal Sands, it is more likely the continuous layer of karstic Devonian limestone. This concept will be tested in Model 2.

Model 2 (with permeable, karstic Devonian limestone; yellow in Figure 4[A]), indeed replicates the lateral extension of equipotential lines within the oil sands and the layers above them (Figure 4[C]). The model domain in this case extended into the karstic limestone (Figure 4[B]). The assumed contrasts in permeabilities are shown in Profiles 4[C] and 4[D]. Assigning these permeability contrasts is sufficient to calculate the direction of groundwater flow. Profile 4[D] depicts the corresponding groundwater flow directions from the surface recharge downwards into the karstic limestone and laterally through the karstic limestone towards the regional discharge areas, the Athabasca River and the Ellis River, a local tributary.

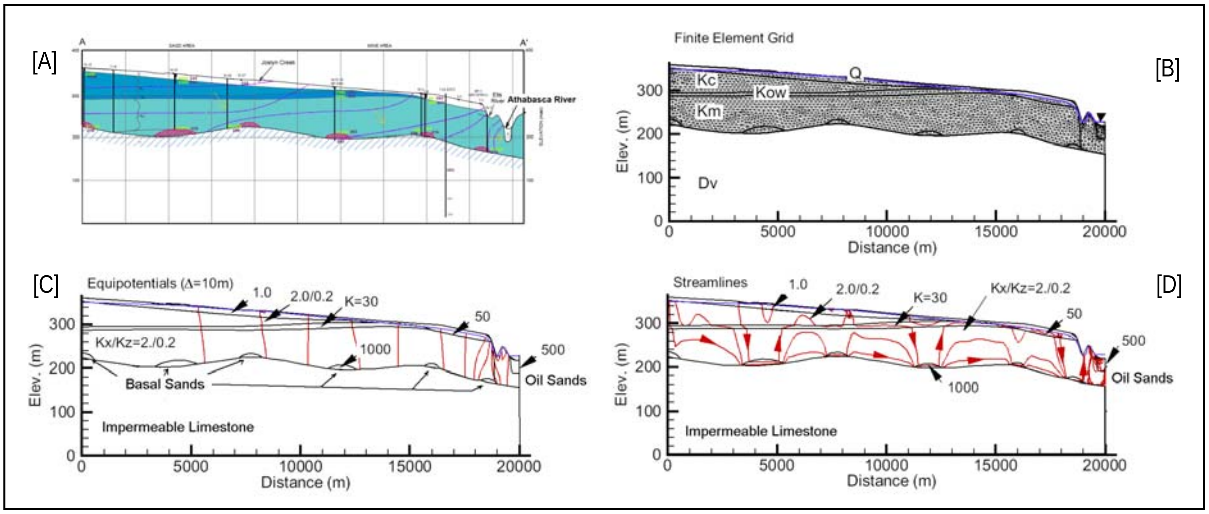

Fig. 3 *Model 1: [A] Equipotential lines determined from field measurements by Millennium (2005, Fig. 5), [B] Finite element grid, [C] Conductivity contrasts and resultant equipotential lines, and [D] resultant flow lines. Vertical exaggeration is about 20x.*

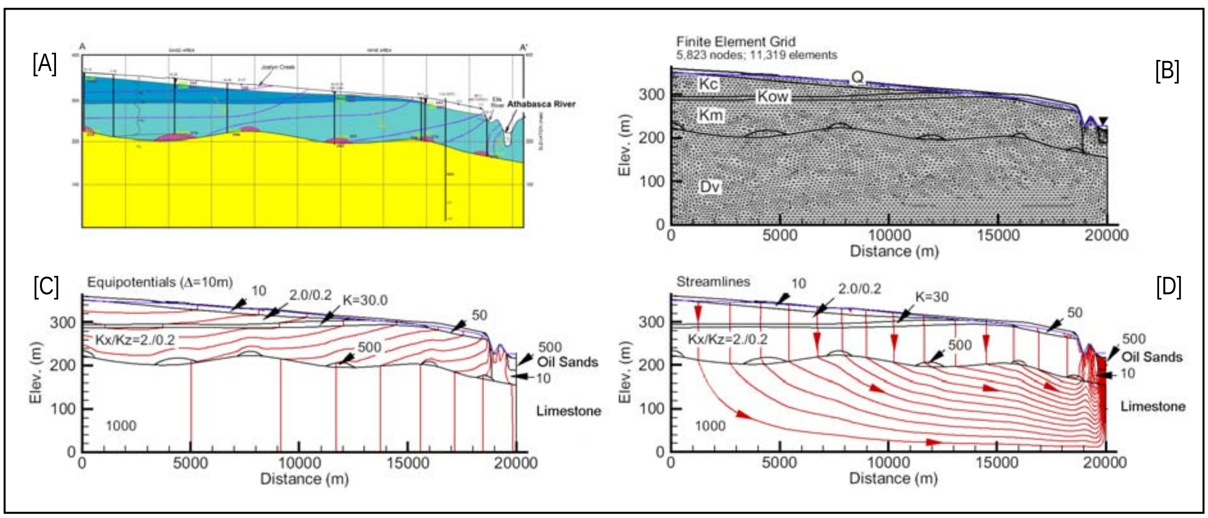

Fig. 4 *Model 2: [A] Equipotential lines determined from field measurements by Millennium (2005, Fig. 5), [B] Finite element grid, [C] Conductivity contrasts and resultant equipotential lines, and [D] resultant flow lines. Vertical exaggeration is about 20x.*

The similarity of the equipotential lines as measured in the field and as simulated in Model 2 (Figure 4) shows that, in recharge areas, groundwater flows downward through the Athabasca Oil Sands into the karstic limestone and then laterally towards the regional discharge areas.

Conclusions

A comparison of the simulation results with field data by Millennium (2005) confirms that within the Athabasca Oil Sands groundwater flow is through the oil sands layer downward into the Devonian limestone and from there into the Athabasca River and into lower reaches of its tributaries. This situation has practical implications for maintaining pressure in SAGD operations and for the planning, operation and dewatering of oil sands mines. For example, a need to raise steam pressures significantly above safe limits may have caused the operator of SAGD in the area of the models to drop, in 2010, its SAGD project in favour of mine development as reported by Scales (2010). The Devonian karst may also exert undesired effects on mine dewatering at this lease.

References

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