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Unraveling complex hydrogeological settings: a multidisciplinary approach to identifying a new disposal zone

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Summary

Steam-based in-situ thermal processes are used to recover bitumen from the Athabasca Oil Sands where the deposits are too deep to mine. Despite high water recycle rates, steam generation typically produces a wastewater stream requiring disposal. Wastewater is commonly disposed into the basal McMurray aquifer beneath the bitumen reservoir. This practice can create operational challenges for steam injection processes, hence alternative disposal zones are highly desired. A large zone of anomalously high salinity in the Lower Grand Rapids Formation has identified a potential candidate for disposal. Devon led a detailed investigation of geologic mapping, groundwater flow modelling, and geochemical and isotopic studies to better understand the hydrogeologic system in this area. The integration of these studies has produced a new conceptual model that challenges the existing understanding of the sources and distribution of salinity within the Grand Rapids Formation.

The investigation found that a zone of low horizontal and vertical groundwater flow velocities occurs between areas of high recharge beneath the pre-glacial Christina and Wiau Channels. This zone of relative flow stagnation has preserved the geochemical signature of connate groundwater in the Grand Rapids while the surrounding areas have been diluted by younger recharge. Through close integration of geoscience disciplines, the high salinity zone within the Lower Grand Rapids aquifer has been demonstrated as a viable alternative for wastewater disposal.

Introduction

The oil sands deposits of Alberta represent a significant economic asset for Canada. Safe and responsible development of these resources is the goal of industry and the Government of Alberta. In areas where the oil sands are too deep to mine, the resource is typically recovered through in situ thermal processes: primarily Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulations (CSS). It is common practice for wastewater from steam generation to be injected into subsurface via disposal wells. The most commonly used disposal zone for SAGD operations is the basal McMurray aquifer (WorleyParsons, 2010). Use of the McMurray for disposal creates operational challenges as the aquifer is often in direct hydraulic communication with the overlying bitumen resource. The Canadian Oil Sands Innovation Alliance (COSIA) is addressing this challenge through the development of technologies to reduce disposal volumes and the evaluation of other potential regional or sub-regional disposal options.

Devon Canada has investigated a number of potential disposal zone alternatives to support its Jackfish and Pike SAGD projects. These have included the Devonian Keg River carbonates and remote disposal in the East McMurray (beyond the bitumen edge). While neither of these options was found to be viable, a highly saline zone was identified in the Lower Grand Rapids Formation that was considered a potential candidate. However, the source of salinity was unknown and the hydrodynamics of the zone were poorly understood. For example, the Grand Rapids Formation was considered non-saline in this area by the Alberta Energy Regulator (2015).

Devon has completed detailed mapping, groundwater flow modelling, geochemical and isotopic studies to better resolve this complex hydrogeological system. The integration of these studies has produced a new conceptual model that challenges the existing understanding of the sources and distribution of salinity within the Grand Rapids.

Geologic and Hydrogeologic Setting

The late Cretaceous Grand Rapids Formation of the upper Mannville Group represents a regional regression event (Bachu *et al.* 1993). Beneath Devon's Jackfish and Pike project areas (Townships 73-76, Ranges 3–7W4). Devon has subdivided the Grand Rapids Formation into three major coarsening-upward units (A, B and C). The Grand Rapids C, commonly referred to as the Lower Grand Rapids, consists of unconsolidated quartzose sands bounded at the top and bottom by shale. It is interpreted to have been deposited in a fluvial to fluvially-dominated deltaic setting. The Grand Rapids C is relatively flat-lying and occurs at approximately 300 m depth. The Grand Rapids C aquifer comprises the lower porous sand portion that is typically 20 and 40 m in thickness (Figure 1, upper panel).

The Grand Rapids Formation is overlain by up to 100 m of low permeability Colorado Shales. However, in places the Colorado Shales have been partially to completely eroded by pre-glacial and sub-glacial channels (Andriashek, 2003). The Upper Grand Rapids (A unit) subcrops along the thalweg of the pre-glacial Christina Channel, which contains areas of re-worked sub-glacial deposits and over-deepening of sections. The narrow, sub-glacial Sunday Creek Channel has, in places, eroded through the entirety of the Grand Rapids to the underlying Clearwater shales. Approximately half the thickness of Colorado shales has been removed beneath the southern pre-glacial Wiau Channel, which runs approximately east-west through Township 73 (Figure 1).

Salinity Distribution

Pore-water salinity distribution within the Grand Rapids C aquifer was mapped from deep resistivity logs using Archie's equation to derive a resistivity of water (Rw). A stong linear relationship was found between Rw and total dissolved solids (TDS) from a data set of 14 groundwater samples, ($r^2 = 0.96$). A significant lateral TDS concentration gradient (Figure 1, lower panel) was identified with non-saline conditions (TDS < 4,000 mg/L) in north and west tranistioning to highly saline conditions (TDS up to 50,000 mg/L) in south half of Township 73, Ranges 4 and 5. From a potential useage perspective, water quality in the Grand Rapids C aquifer can be divided into three zones: i) Non-saline "fresh" (TDS <4,000 mg/L); ii) Moderate salinity (TDS 4,000 to 20,000 mg/L) suitable for SAGD source water; and iii) High salinity (TDS >20,000 mg/L) consistent with typical SAGD wastewater. Salinity levels in the deeper basal McMurray aquifer (TDS 15,000 to 20,000 mg/L) were found to be lower than that of the overlying Grand Rapid C aquifer, as well as less spatially variable.

Geochemistry and Isotopes

A geochemical assessment revealled distinct water types in the high salinity zone in comparison to adjacent lower salinity waters in the Grand Rapids, Quaternary, and underlying McMurray Formations (Integrated Sustainability, 2015). Major ion distrubutions did not reveal much difference between the water types within, and outside, the high salinity zone of the Grand Rapids C. With exception of the Quaternary water samples, all bedrock formation water samples yielded a Na-Cl hydrochemical type.

Assessment of selected trace elements, dissolved organics, and isotopes (stable and radiogenic) was more successful in differentiating porewaters sampled from the high salinity zone. In particular, lithium, strontium, and dissolved organic carbon (DOC) had elevated concentrations in samples from the high salinity zone, consistent with increased residence time and enhanced solubilization of matrix minerals and resident organic matter. Stable isotopes of oxygen (δ^{18}O) and hydrogen (δ^{2}H) yielded values consistent with waters recharged during more recent times (i.e., in the last 30,000 years). This was also confirmed by age dating using ^{14}C. Samples with the highest salinity exhibited notably less negative δ^{18}O and δ^{2}H values suggesting a stronger influence from isotopically heavier porewater associated with the Late Cretaceous Period (i.e., connate water). δ^{13}C values of the DOC and DIC fractions returned more negative values from samples collected in the high salinity zone, consistent with isolated geochemical conditions and related diagentic processes (i.e., hydrochemical separation and/or isolation).

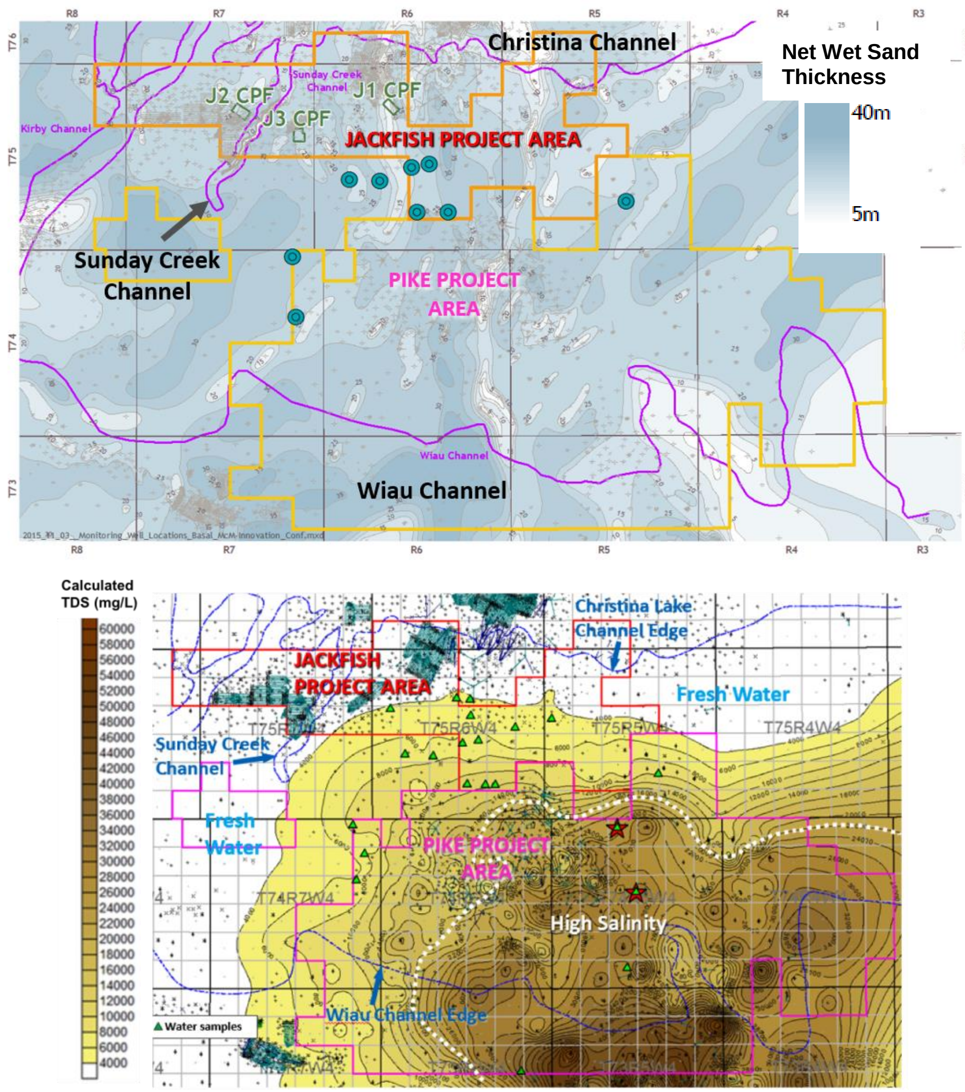

Figure 1. Net Wet Sand Isopach (upper panel) and Calculated Salinity (TDS) Distribution within the Grand Rapid C aquifer (lower panel)

Hydrodynamics

The Grand Rapids is regionally underpressured, which is typical of systems in hydrodynamic equilibrium with low permeability at upstream recharge and high permeability at downstream discharge (Barson et al., 2001). The overlying Quaternary sedments are normally pressured; hence Grand Rapids recharge is locally determined by vertical leakage through the intervening low permeability Colorado Group shales. Where the shales are thick, very little recharge occurs. Where the Colorado Group shales have been thinned or completely removed, considerably higher recharge rates can be expected. The significant influence of the the pre-glacial and sub-glacial channels on groundwater flow and salinity in the Lower Grand Rapids was previously noted by Rayner and Rosenthal (2008).

The deeply incised Christina, Sunday Creek and Kirby Channels provide pathways for downward flow of groundwater from the Quaternary sediments into the Grand Rapids Formation. Farther south, the partially incised Wiau Channel provides pressure communication resulting in hydraulic mounding in the Grand Rapids aquifers. The area between the two zones of higher hydraulic heads is characterized by very low horizontal groundwater flow velocities and represents a zone of relative flow stagnation.

The geologic units that result in spatially variable recharge are well mapped in the study area. Once the mapped geology was input into a regional-scale, three-dimensional numerical model of groundwater flow, the observed groundwater stagnation zone in Townships 74 and 75 was readily reproduced (Matrix 2012 and 2015).

Conceptual Model Summary

The north and westward freshening of Grand Rapids C groundwater (Figure 1, lower panel) is relatively easily explained via higher rates of fresh (TDS <1,000 mg/L) water recharge from Quaternary aquifers via the Christina, Sunday Creek and Kirby Channels. Determining the source of the high salinity zone in the Grand Rapids C aquifer is a greater challenge.

Recent investigations into elevated salinity in the Mannville Group sediments have revealed the potential for compromised formation integrity (and hydraulic seals) between deeper Devonian formations and shallower intervals (Cowie et al., 2015). The upward movement of highly saline pore water has been identified as a possible mechanism, following the dissolution of soluble salts in the middle Devonian and collapse of overlying strata, leading to pathways for cross-formational flow. Results of Devon's investigation revealed the presence of something quite different - a complex hydrogeological setting with non-saline pore waters (<4,000 mg/L TDS) juxtaposed to highly saline waters (up to 50,000+ mg/L TDS).

Controls on flow patterns, exerted primarily by buried channels, were identified based on geological evidence and groundwater flow modelling. Geochemistry of the Grand Rapids C aquifer and adjacent aquifers confirmed hydrochemical separation between intervals and potential pathways for fluid movement. Corroborating evidence from all three aspects revealed the presence of a localized hydrodynamic trap in the Grand Rapids C aquifer. The combination of factors has thus created conditions suitable for the hydraulic stagnation and the persistence of high salinity conditions.

Implications for Disposal

Project investigations suggest that the highly saline water in Grand Rapids C aquifer has been largely stagnant since at least the Tertiary period and probably much longer. Because the stagnant zone has been effective at preserving connate groundwater over the scale of tens of millions of years, the same zone can be inferred to be highly effective for containing wastewater. Further investigations were therefore undertaken to determine how disposal into this area would alter the natural hydrodynamic conditions and if injected fluid would remain contained within the high salinity zone. Numerical modelling results indicated that disposal at the proposed rates would not significantly alter the natural hydrodynamic conditions and that injected fluid would remain contained within the high salinity zone.

Conclusions

A multi-disciplinary investigation has provided a detailed characterization of complex hydrogeologic conditions. The Grand Rapids C aquifer has been shown to provide a viable alternative for SAGD waste-water disposal zone in the Pike Project area owing to its high natural salinity and high degree of natural hydrodynamic containment.

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