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Hydrogeologic Assessment in Support of the Development of the Peace River Oil Sands Deposit: A Case Study Concerning a Pilot-Scale *in-situ* SAGD Operation

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ABSTRACT

Steam Assisted Gravity Drainage (SAGD) is common technology for recovering bitumen reserves from the Athabasca Oil Sands Deposit of north-east Alberta. The SAGD process requires a reliable and long term source of make-up water and commonly requires a suitable wastewater disposal zone. Identifying and securing access to aquifers that can be developed either as source water aquifers or as wastewater disposal zones is an important design milestone for companies developing SAGD projects.

The increasing number of SAGD projects in the Athabasca Area has resulted in a growing, publicly available hydrogeologic dataset (i.e., published reports, pumping tests, detailed hydrostratigraphic mapping, Energy Resources Conservation Board (ERCB) project updates). Athabasca Area SAGD applications/developments typically rely on the leveraging of this public hydrogeologic data with additional project specific hydrogeologic mapping and testing. By comparison, *in-situ* SAGD oils sands projects have not been widely developed in the Peace River Oil Sands Deposit of north-west Alberta, and as such, there is a comparative lack of publicly available hydrogeologic data available to support detailed hydrogeologic assessments in this region.

Through the review of limited published regional reports, public databases and petrophysical analysis, this study developed a preliminary hydrogeologic assessment of the Peace River Oil Sands Deposit in the Buffalo Head Hills of Alberta. This assessment is suitable for an Alberta Energy and Utilities Board (EUB) application of a pilot-scale project with limited empirical hydrogeologic data being available. It provides insight on aquifer extent, aquifer deliverability, aquifer salinity and includes an impact evaluation.

Two potential source aquifers and several wastewater disposal zones were identified in this assessment. It was concluded that the Paddy/Cadotte Aquifer and the Bluesky Aquifer were the most feasible units for groundwater sourcing and wastewater disposal, respectively, for a SAGD project proposing development of the Peace River Oil Sands Deposit in the Buffalo Head Hills. In addition, characteristics of the Paddy/Cadotte and Bluesky aquifers in this area are favourable when considering conflicts with other groundwater users and/or negative environmental impacts.

INTRODUCTION

SAGD technology requires a suitable and reliable source of water for steam generation, as well as, a suitable wastewater disposal aquifer. Increasing SAGD development in Alberta is mainly concentrated on the Athabasca Oil Sands deposit south of the city of Fort McMurray in an area sometimes referred to as SAGD alley (Figure 1). As such, a growing database of hydrogeological data is available for this region. In comparison, SAGD development of the Peace River Oil Sands deposit in Alberta is essentially non-existent and, therefore, little hydrogeological data exists for this area. Table 1 summarizes the available data for both the Athabasca and Peace River Oil Sands deposits.

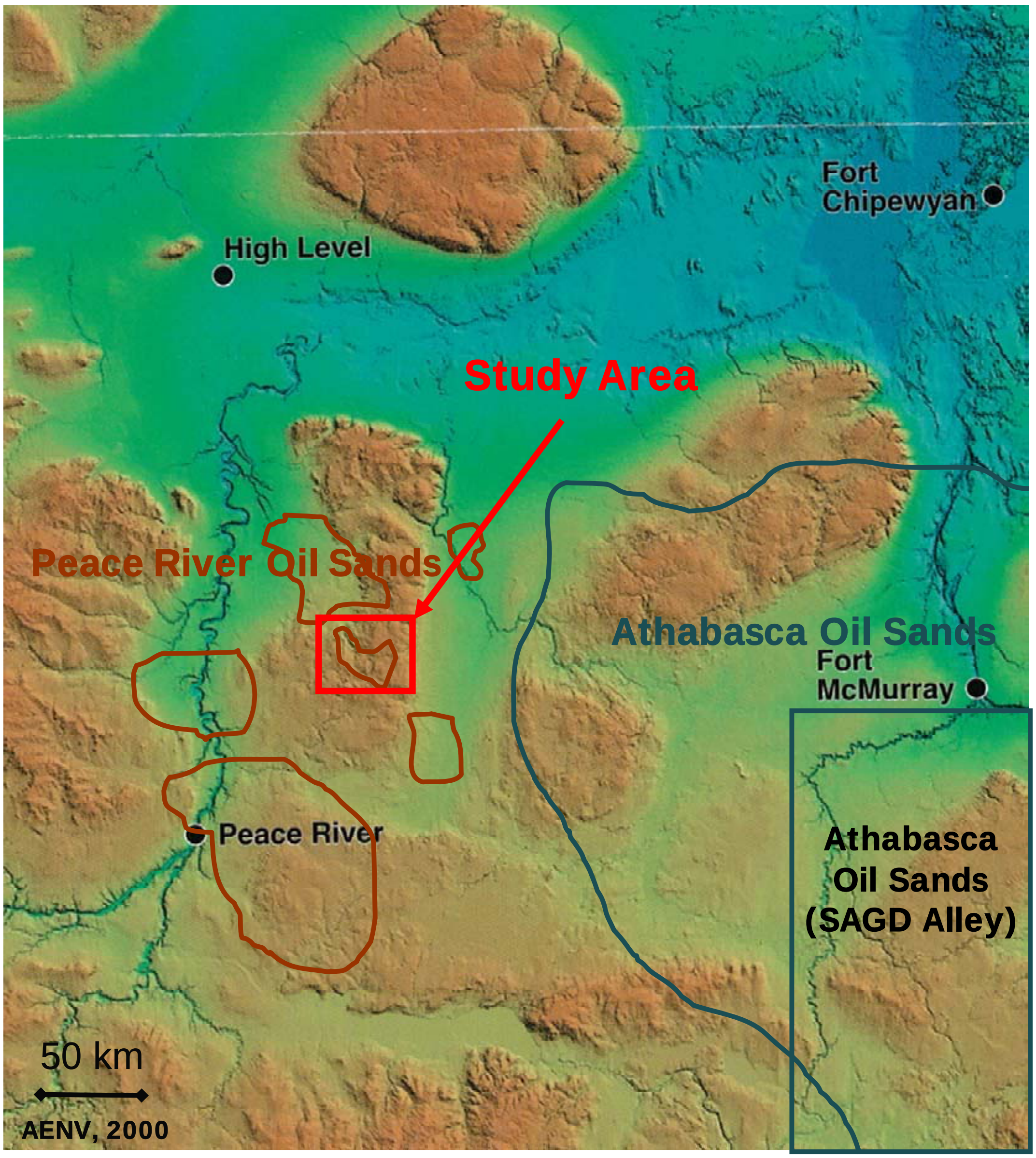

Figure 1: ***Study Area.*** **Peace River Oil Sands deposit Buffalo Head Hills of Northern Alberta.**

Database		SAGD Alley	Study Area
Traditional Hydrogeology Data	Aquifer Chemistry Samples	>900	3
	Pumping Tests	>60	0
Industry Data	Projects	13	0
	Industry wells	>16,500	143
	DST	>1,650	2

Table 1. ***Database for SAGD Alley vs. the Study Area.*** **In terms of traditional hydrogeologic data, there is very little data available for the Study Area.**

Drilling and testing deep aquifers can be very expensive. Hence, it is imperative that feasible aquifers are identified before the drilling and testing programs are initiated. Identifying feasible aquifers in the Peace River Oil Sands region can be challenging given the lack of available hydrogeological information.

This study will outline a process that will use public industry data in the absence of traditional hydrogeologic data to perform a hydrogeologic characterization. The hydrogeological characterization will include parameters such as aquifer salinity, extent, thickness, permeability and pressure. This characterization will be used to identify a promising wastewater disposal zone and source water zone in the study area to test for SAGD development.

GEOLOGIC SETTING

The study area is located in the Buffalo Head Hills of Alberta. A geologic subcrop map is provided as Figure 2. A geologic column and assigned hydrostratigraphic units are illustrated on Figure 3. This paper focuses on the Bluesky and Paddy/Cadotte geologic units.

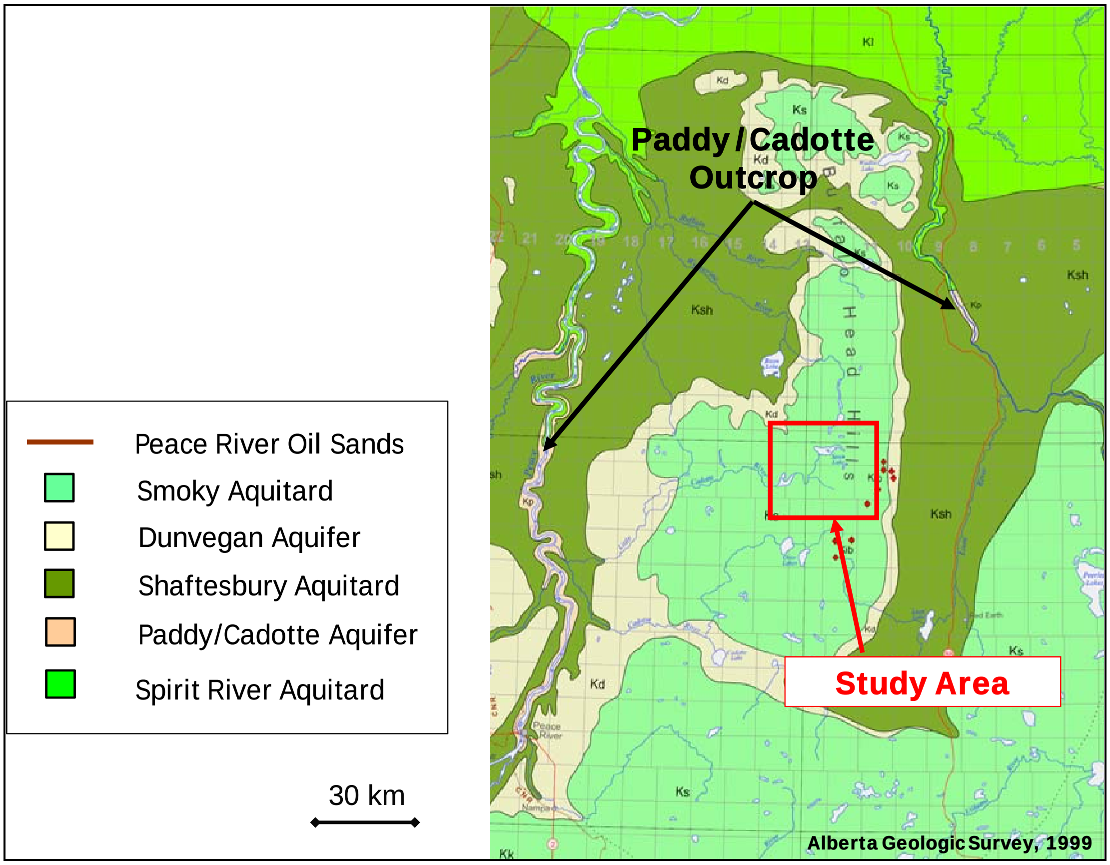

Figure 2: ***Geologic Subcrop Map.*** **The Paddy/Cadotte Aquifer outcrops along the Peace River and Wabiskaw River.**

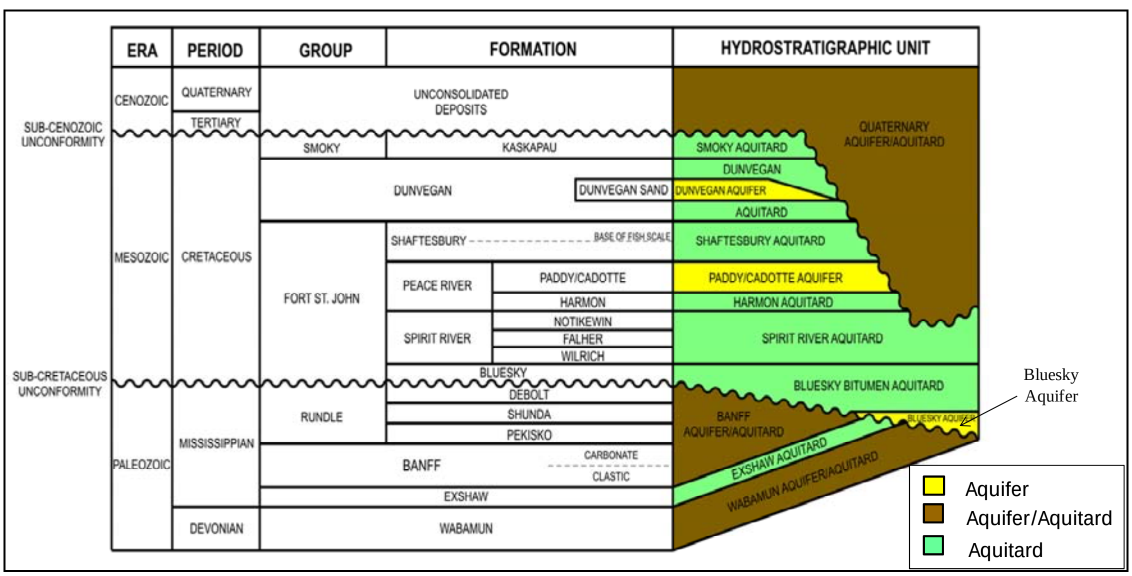

Figure 3: ***Geologic Column and Assigned Hydrostratigraphic Units.*** **The water-saturated sands of the Bluesky Formation are referred to as the Bluesky Aquifer. The Water-saturated sands of the Paddy/Cadotte Member of the Peace River Formation are referred to as the Paddy/Cadotte Aquifer. Note: most geologic units are believed to act as aquitards and restrict the movement of groundwater.**

The Bluesky Formation is a weakly cemented, clean sandy estuarine deposit that was constrained by the structure of the underlying sub-cretaceous unconformity. The sands of the Bluesky Formation are often saturated with bitumen but in some instances the lower part of the formation is saturated with water. The water-saturated sands are referred to as the Bluesky Aquifer in this study.

The Paddy/Cadotte Member of the Peace River Formation is a weakly cemented clean sandy prograding shoreface deposit. The Paddy/Cadotte Member is referred to as the Paddy/Cadotte Aquifer in this study.

Three important observations from Figures 2 and 3 include the fact that the Paddy/Cadotte Aquifer subcrops in the region (~40 km away from project area); the Bluesky Aquifer does not subcrop in the region and the fact that the depositional basin is dominated by aquitards.

AQUIFER CHARACTERIZATION CRITERIA

Three criteria for selecting aquifers to test for this study include:

i. Salinity
ii. Productivity
iii. Responsible Use

METHODOLGY

Salinity

Salinity is an important parameter when evaluating the potential use of an aquifer due to regulatory and project design considerations. In Alberta, an aquifer is considered saline if the total dissolved solids (TDS) concentration of the pore water is greater than 4,000 mg/L (AENV, 2006). If the TDS concentration of an aquifer is less than 4,000 mg/L then the responsible use of that aquifer is administered by Alberta Environment (AENV) through the mechanism of requiring any water wells in this aquifer to be licensed.

Salinity is also an important parameter when considering the compatibility with SAGD technology in terms of steam generation. TDS concentration is an indicator of a water's quality. The higher the TDS the more difficult and expensive it becomes to treat the water to use for steam generation. Typically, water with a TDS concentration greater than 10,000 mg/L is considered undesirable for SAGD make-up water.

Given the relatively small number of TDS concentrations available for the area, Archie's Law (1942) was implemented in order to estimate aquifer salinity and to fill in the data gaps. Archie's Law is a mathematical method of calculating TDS concentrations from petrophysical logs. Petrophysicall logs that contain porosity and resistivity information for select aquifers can be used to estimate aquifer salinity by means of the following equation:

Equation 1:

$$R_t = a\phi^{-m} S_w^{-n} R_w$$

where:

ϕ	Porosity
R_t	Resistivity of the fluid saturated rock
R_w	Resistivity of the brine
S_w	Brine saturation
m	Cementation exponent of the rock (usually in the range 1.8–2.0)
n	Saturation exponent (usually close to 2)
a	Constant

Then, an empirical relationship between resistivity and TDS exists (Rakhit, 1997):

Equation 2:

$$R_w = TDS^{-0.854\,387} \times 4.516\,86$$

Productivity

Aquifer productivity is dependent on three general parameters; aquifer extent and thickness, aquifer permeability and acceptable pressure change. Given an understanding of these three parameters, aquifer productivity can be estimated using the Farvolden Method for calculating long-term safe yield of an aquifer (Farvolden, 1959).

Equation 3:

$$Q_{20} = (0.68)(Kb)(AH)(0.7)$$

where:

Q_{20}	Long-term safe yield
K	Hydraulic conductivity
b	Aquifer thickness
AH	Available head

Characterization of *K*, *b*, and *AH* in an area with limited hydrogeologic data is discussed in the following three sections.

Aquifer Extent and Thickness

Aquifer extent and thickness of the Paddy/Cadotte and Bluesky aquifers were reasonably well delineated by reviewing 143 petrophysical logs collected by industry in the vicinity of the study area. Aquifers were chosen based on a gamma response of < 60 API, >30% porosity and a resistivity <10 ohm-m.

Aquifer Permeability

Aquifer testing has not been conducted on the Bluesky or Paddy/Cadotte aquifers in the study area. Therefore, in order to estimate aquifer productivity the permeability must be approximated by some other means. Aquifer permeability was estimated by reviewing core plug data (8) collected from the Bluesky Formation and comparing to petrophysical logs.

Since core plug data from the Paddy/Cadotte Aquifer was not available a relationship between core and petrophysical logs was established and extrapolated to the Paddy/Cadotte Aquifer. This relationship, combined with published permeability estimates for weakly cemented, clean sandstones and analogues from similar geologic units in the Athabasca Oil Sands area was used to estimate the permeability of the Paddy/Cadotte Aquifer.

Acceptable Pressure Change

Acceptable pressure change refers to the amount of pressure head you can increase or decrease in an aquifer before that aquifer becomes damaged. To quantify an acceptable pressure, the ambient or static pressure of the aquifer must be estimated and the change in pressure (positive or negative) must be understood.

In terms of aquifer injectivity (positive pressure), the acceptable pressure change is constrained by the fracture pressure of a given geologic unit. If too much water is added to the aquifer and the pressure increases beyond the fracture pressure the aquifer may fracture. ERCB directive 051 suggests a pressure head of 1,000 m (10,000 kPa) for an aquifer at a depth of 650 m below ground surface (mbgs) is acceptable before the aquifer will become damaged (ERCB, 1994).

In terms of aquifer deliverability (negative pressure), the pressure in an aquifer can only be reduced by so much before the water level in an aquifer drops below the top of the aquifer thus damaging the aquifer. In addition, non-saline aquifers are regulated by AENV and minimum pressure reductions are outlined in AENV guidelines. Acceptable pressure change was characterized by reviewing limited ambient pressure data from the ERCB database for the Bluesky Formation. Using this information with a conceptual understanding of the hydrogeological system, estimates of ambient pressure were extrapolated for the Paddy/Cadotte Aquifer.

Responsible Use

Responsible use of the Bluesky and Paddy/Cadotte aquifers refers to the sustainable use of these aquifers without causing undue environmental impacts. Responsible use was established by understanding where these aquifers have an increased potential for interaction with shallow potable aquifers and surface water bodies. Both the Bluesky and Paddy/Cadotte aquifers are overlain by thick extensive aquitards that minimize the vertical connectivity of theses aquifers. However, the Paddy/Cadotte Aquifer does subcrop in the region and this would be an area of potential impact to surface water bodies. In order to estimate the probability and magnitude of an interaction with surface water bodies, drawdown at the Paddy/Cadotte Aquifer subcrop was estimated using the methods of Theis (1935).

Equation 4:

$$dd = \frac{Q}{4\pi Kb} W(u) \qquad u = \left\{ \frac{r^2 Ssb}{4Kbt} \right\}$$

where:

dd	drawdown
W	well function
Q	pumping rate
K	hydraulic conductivity
b	aquifer thickness
r	radius
Ss	specific storage
t	time

RESULTS

Salinity

Based on three chemistry samples and 143 TDS estimates using Archie's Law (Equations 1 and 2) in the vicinity of the study area, the salinity of the Bluesky and Paddy/Cadotte aquifers was characterized. Figure 4 is a histogram summarizing the estimated pore water salinity for the Bluesky and Paddy/Cadotte aquifers in the vicinity of the study area.

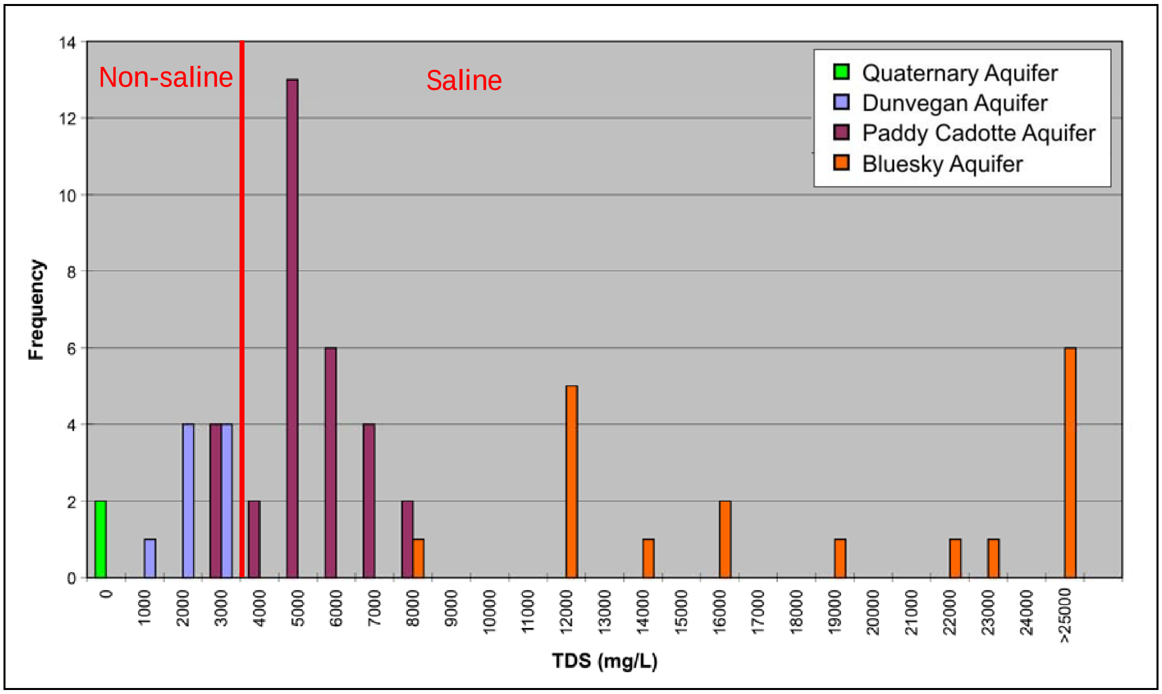

Figure 4: ***Histogram of Estimated Salinity.*** **The Bluesky Aquifer is very likely saline and the Paddy/Cadotte Aquifer is likely saline.**

TDS concentration estimates of the Bluesky Aquifer are consistently over 8,000 mg/L and typically over 10,000 mg/L. Based on these salinity estimates, the Bluesky Aquifer is most likely considered saline.

The TDS concentration estimates for the Paddy/Cadotte Aquifer range from 3,000 mg/L to 8,000 mg/L but are generally over 4,000 mg/L. Based on these salinity estimates, the Paddy/Cadotte Aquifer is likely considered saline.

Productivity

Aquifer Extent and Thickness

Aquifer extent and thickness of the Bluesky Aquifer and Paddy/Cadotte Aquifer in the study area are presented on Figures 5 and 6, respectively.

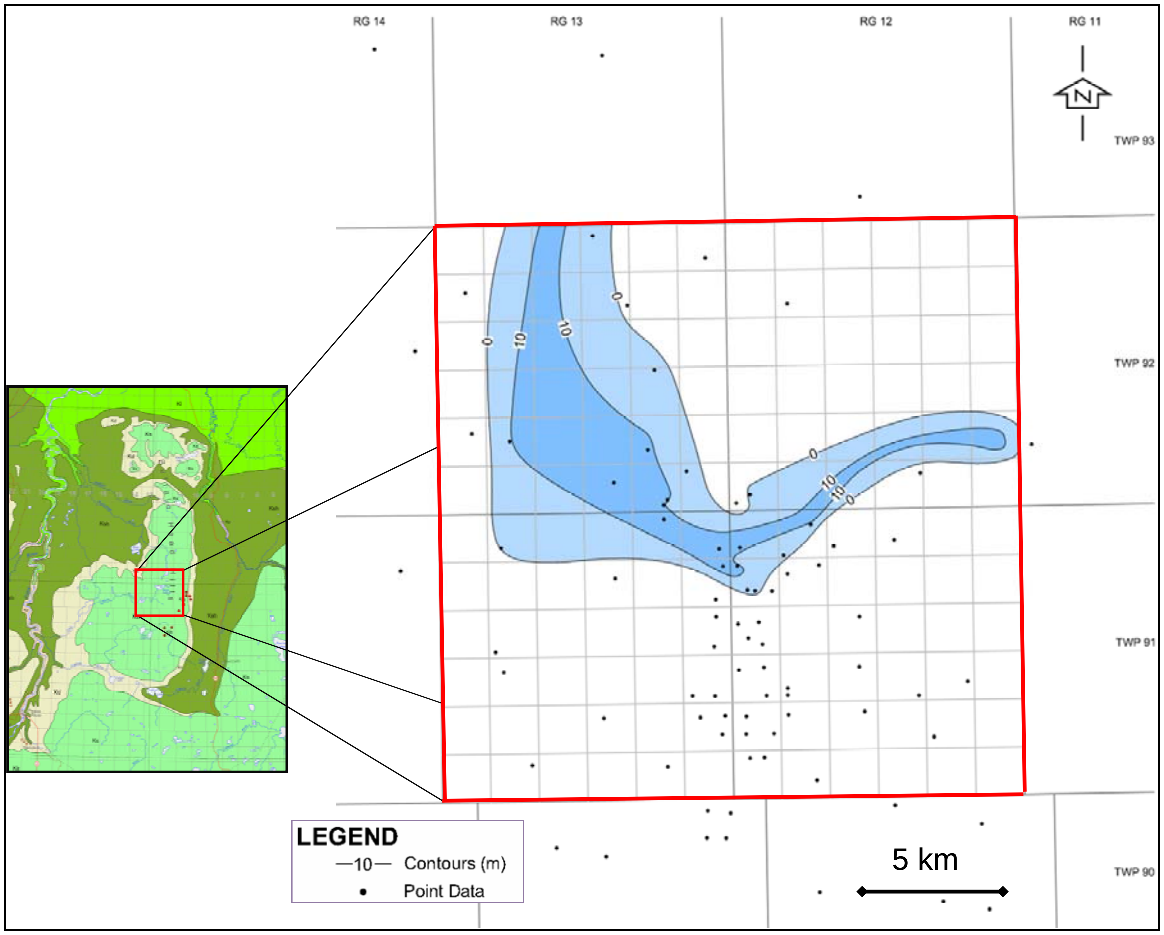

Figure 5: ***Isopach Map of the Bluesky Aquifer.*** **The Bluesky Aquifer is constrained by the structure of the sub-Cretaceous Unconformity and has an identified maximum thickness of 18 m.**

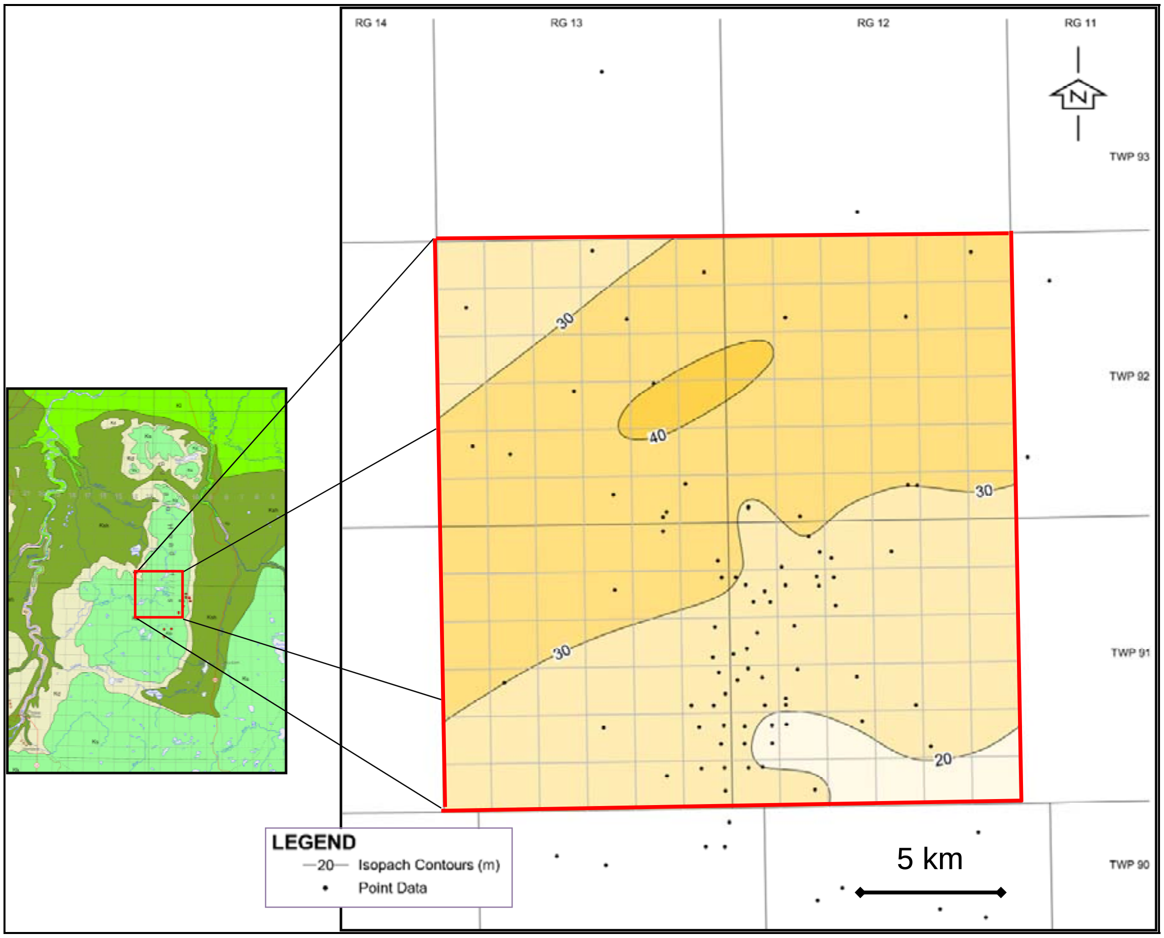

Figure 6: Ispoach Map of the Paddy/Cadotte Aquifer. The Paddy/Cadotte Aquifer is laterally extensive and has a representative thickness of approximately 25 m.

The Bluesky Aquifer occupies the structural lows of the sub-cretaceous unconformity and, therefore, has limited extent. The Bluesky Aquifer reaches a maximum thickness of 18 m.

The Paddy/Cadotte Aquifer is laterally extensive and ranges in thickness from 20 to 40 m. The average thickness of the Paddy/Cadotte Aquifer is approximately 25 m.

Aquifer Permeability

Eight core samples collected from the bitumen-saturated sands of the Bluesky Formation indicate permeabilities ranging from 4 to 10 D or approximately 4 x 10^{-5} to 1 x 10^{-4} m/s hydraulic conductivity. These permeabilities correspond to gamma measurements consistently less than 45 API and porosity measurements of greater than 30%.

Well log responses of the Paddy/Cadotte Aquifer are also consistently less than 45 API and greater than 30% porosity. Based on well log response and similar depositional environments and lithologies, the assumption is made that the Paddy/Cadotte and Bluesky aquifers have similar permeabilities. In other words, the horizontal hydraulic conductivity of the Paddy/Cadotte Aquifer is on the order of 4 x 10^{-5} to 1 x 10^{-4} m/s. This is consistent with analogues from the Athabasca Oil Sands area with similar lithologies. For the purposes of this study the horizontal hydraulic conductivity of the Paddy/Cadotte Aquifer was conservatively estimated at 1 x 10^{-5} m/s.

Acceptable Pressure Change

Drill stem tests (DSTs) performed on the Bluesky Formation indicated an ambient pressure of approximately 2,200 kPa or about 220 m of pressure head (~available head) at 650 mbgs. Approximately 220 m of head at 650 mbgs is well below the hydrostatic pressure gradient which is not unexpected given the presence of thick aquitards and subcropping units in the study area.

ERCB Directive 051 suggests a pressure head of 1,000 m of water is acceptable in the Bluesky Aquifer. If the ambient pressure in the Bluesky Aquifer is 220 m of water head, then the aquifer is anticipated to be able to "accept" a rate of injection that would result in less than a 780 m of head build-up.

The study area is an area with many wetlands and the water table is known to be very near ground surface. Therefore, the available head at 0 mbgs is assumed to be 0 m. Using the end members of 0 m of available head at ground surface and 220 m of available head at 650 mbgs, the estimated available head for the Paddy/Cadotte Aquifer at 450 mbgs is approximately 125 m. Given that the Paddy/Cadotte Aquifer subcrops in the region, a conservative estimate of 100 m of available head is used in this study.

Given a thickness of 25 m, a horizontal hydraulic conductivity of 1 x 10^{-5} m/s and an available head of 100 m, the estimated long-term safe yield of a water well completed in the Paddy/Cadotte Aquifer is anticipated to be on the order of 1,000 m^3/day using the Farvolden Method (Equation 3).

Responsible Use

Using the method of Theis (1935; Equation 4) and the following parameters the drawdown at the Paddy/Cadotte Aquifer subcrop was estimated to be less than 1 mm after five years of groundwater withdrawal (pilot-scale project lifespan).

Q = 1,000 m^3/day

K = 0.9 m/day

b = 25 m

r = 40 km

Ss = 1 x 10^{-6} m^{-1}

t = 5 years

DISCUSSION

Bluesky Aquifer

The salinity and extent of the Bluesky Aquifer limits this aquifer's suitability as a source water zone. A TDS concentration exceeding 10,000 mg/L would require significant treatment in order to be suitable for steam generation. The limited extent of the Bluesky Aquifer would also restrict the deliverability of this aquifer in terms of water production.

However, the Bluesky Aquifer is likely a good candidate to test as a wastewater disposal zone given its salinity, permeability and acceptable pressure change. Furthermore, the aquifer is not known to outcrop in adjacent river valleys. The acceptable pressure change is approximately 780 m of head build-up. In the author's experience, the rate of injection into a high permeability aquifer necessary to realize a 780 m head build-up would greatly exceed the wastewater disposal demand of a pilot-scale SAGD development.

Paddy/Cadotte Aquifer

The salinity and productivity of the Paddy/Cadotte Aquifer make it a promising aquifer to test for source water for SAGD development. The Paddy/Cadotte Aquifer is likely saline with estimated TDS concentrations ranging from 3,000 to 8,000 mg/L. Therefore, the pore-water quality is such that a groundwater diversion license would not be necessary and significant treatment in order to make steam would also not be necessary. An estimate deliverability of 1,000 m^3/day is considered adequate for a pilot-scale SAGD development.

Furthermore, sourcing water from the Paddy/Cadotte Aquifer for a pilot-scale SAGD development is believed to be a responsible use for this aquifer. In terms of impacting other groundwater users and surface water body levels, negligible environmental impacts are anticipated. Thick, extensive aquitards mitigate the vertical pressure propagation from the Paddy/Cadotte and Bluesky Aquifers, as well, the drawdown predicted at the Paddy/Cadotte outcrop is believed to be negligible.

CONCLUSIONS

This study supports the following conclusions:

- In the absence of traditional hydrogeologic data, industry data in the Peace River Oil Sands area (such as petrophysical logs, core samples and drill stem tests) coupled with a conceptual understanding of the hydrogeological system, was used to conduct a hydrogeological characterization suitable for identifying candidate aquifers that could be used for SAGD development.
- In this study area, the Bluesky Aquifer was identified as a promising wastewater disposal zone and the Paddy/Cadotte Aquifer was identified as being a promising source water supply zone to be tested for a pilot-scale SAGD development.
- The approach of integrating industry data with regional geologic mapping and a conceptual understanding of the hydrogeologic system can be applied to other areas with limited available hydrogeologic data for the purpose of preliminary project planning and the identification of candidate aquifers.

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