APPENDIX 4-VI

HYDROGEOLOGY EFFECTS ANALYSIS METHODS

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1 HYDROGEOLOGY EFFECTS ANALYSIS METHODS

This appendix summarizes the methodologies used for the hydrogeology effects analysis.

Through the construction, operation and reclamation phases of the Project, activities which have the potential to affect groundwater resources include:

- the operation of surface facilities;
- groundwater withdrawal from the Upper Clearwater water sand, Empress Channel Aquifer and Empress Terrace Aquifer;
- wastewater disposal into the McMurray water sand; and
- steam injection.

A detailed description of the criteria used for the assessment is presented in Volume 2, Section 3. In the following sections, specific methods used to measure and evaluate the potential effects compared to baseline hydrogeological conditions are discussed.

1.1 ASSESSMENT OF THE EFFECTS TO GROUNDWATER QUANTITY DUE TO GROUNDWATER WITHDRAWAL AND WASTEWATER INJECTION

The assessment of the effects to groundwater quantity and levels due to utility water withdrawal from the Ethel Lake Aquifer (Existing and Approved Case for Phase 1, 2 and 2B) and the Empress Terrace Aquifer (Phase 3, Plant 3B) was completed using the method of Theis (1935, Equation 1.1-1). This equation solves for the horizontal propogation of decreased water levels due to groundwater pumping:

Equation 1.1-1 $$s = \frac{Q}{4 \pi T} W(u)$$

Where:

$$u = \frac{r^2 S}{4 T t}$$

s = drawdown at a point in space due to pumping (L);

Q = pumping rate (L^3/t);

T = transmissivity of the aquifer (L^2/t);

W(u) = the well function of u represented by an infinite series (dimensionless);

r = distance of point considered from pumping well (L);

S = storativity (dimensionless); and

t = time (t).

The major assumptions within the Theis Equation are:

1) the aquifer is homogeneous and isotropic;
2) the aquifer has infinite areal extent;
3) the discharging well fully penetrates the aquifer;
4) the well has an infinitesimal diameter;
5) the water removed from storage is discharged instantaneously with decline in head; and
6) the aquifer is confined and receives zero recharge.

For the purpose of this assessment, assumptions 1, 3, 4 and 5 are reasonably well satisfied. As described in Appendix 4-II, Section 5.3, the Ethel Lake and Empress Terrace aquifers are areally extensive but the full areal extents of the aquifers are largely unknown.

The Theis equation is a conservative approach in that it does not consider recharge from units above or below the aquifer. The effects of recharge and finite areal aquifer extent are offsetting and for this reason, it is interpreted that the Theis Equation will provide a reasonable approximation of drawdown for the purposes of this assessment.

The assessment of the potential effect to groundwater quantity and levels due to wastewater injection into the McMurray water sand and water withdrawal from the Empress Channel Aquifer and Upper Clearwater water sand was completed using a numerical solution of groundwater flow (Equation 1.1-2). This work assumes that a Representative Elementary Volume (REV; Bear 1972) of the porous medium exists and can represent the effective hydraulic behavior of the medium.

Groundwater flow within the Regional Study Area (RSA) was interpreted to be normal gravity-driven flow and can be represented by the fluid continuity equation:

Equation 1.1-2 $$\frac{\partial}{\partial \times}\left(K_x \frac{\partial h}{\partial \times}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}$$

Where:

x, y, z = the principal components of space (L);

h = hydraulic head (L);

S_s = specific storage (L^{-1});

K = hydraulic conductivity (L/t); and

t = time (t).

The major assumptions within the continuity equation and in this application are that the fluid is incompressible, groundwater flow follows Darcy's Law and the fluid throughout the study area has a constant density.

Groundwater flow was simulated in this study using the three-dimensional FEFLOW simulator developed by WASY Ltd. (2004). The FEFLOW was used to solve for mass conservative groundwater flow within fully saturated porous media using finite element discretization of the media. A summary of the numerical model construction and calibration process is included in Appendix 4-VII. The numerical model allowed for the incorporation of temporally changing pumping and injection schedules at the MEG Energy Corp. (MEG) Christina Lake Regional Project (CLRP) and other in-situ oil sands projects in the RSA, and simulates the lateral and vertical propagation of water levels changes away from the simulated pumping or injection wells over time.

The effects of the simulated water level changes to aquifers/water sands were evaluated with respect to the initial available head and the change in potential productivity. The evaluation methodology is described in the following section.

1.1.1 Evaluation of Water Withdrawals With Respect to Productivity

The predicted change in water levels as a result of groundwater withdrawal was interpreted in terms of productivity. The 20-year safe yield (Q_{20}) or theoretical pumping rate that a well could be pumped for 20 years without exceeding the available drawdown is used as an analogue for productive capacity or aquifers/water sands in Alberta. The Q_{20} equation was first developed by Farvolden (1959) and is defined as:

Equation 1.2-1 $$Q_{20} = 0.68 * T * H_A * 0.7$$

where:

T = transmissivity [L^2/T];

H_A = available drawdown defined as the difference between the hydraulic head in the aquifer/water sand and the top of the aquifer/water sand[L]; and

F_S = safety factor.

The productivity of the unit is proportional to changes in the available drawdown and the change in productivity is proportional to the induced change in water level associated with groundwater withdrawal or injection (Δs). For the purposes of this assessment the change in productivity is defined by Equation 1.2-2:

Equation 1.2-2 $$Change\ in\ Productivity = \frac{\Delta s}{H_A} * 100$$

The magnitude of the potential effect on productivity was assessed using the following three levels:

- *Low Effect* – If the predicted change in productivity is less than 15%, the effect may be detectable; however, potential conflicts with other users would likely not result.
- *Moderate Effect* – If the predicted change in productivity is between 15 and 30%, the effect would likely be detectable; however, conflicts with other users would likely not result.
- *High Effect* – If the predicted change in productivity is greater than 30%, potential conflicts with other users could result.

In the instance that high effects are predicted, the lateral extent of the effect, duration of the effect and the location of other potential users are considered.

1.2 ASSESSMENT OF THE EFFECT TO GROUNDWATER QUALITY DUE TO WASTEWATER INJECTION

Wastewater injection into the McMurray water sand is predicted to change water quality in that water sand. Given that increases in hydraulic head result from wastewater injection, the potential exists for wastewater to migrate away from the injection wells. Project-related potential water quality effects were assessed based on previous quantitative assessments of migration distances from adjacent projects and physical properties of the McMurray water sand and overlying aquitards (Appendix 4-II).

1.3 ASSESSMENT OF THE EFFECT OF STEAM INJECTION

Prolonged injection of high-temperature steam has the potential to increase water temperatures and effect water quality in the rock and sediments in contact with the Steam Assisted Gravity Drainage (SAGD) well bores. This phenomenon has been observed by Canadian Natural (2006) at the Primrose East Project. For the purpose of this assessment, it was assumed that the extent of water quality effects are limited to the area of elevated groundwater temperatures and that heat transport near the well bore can be described solely by the principles of conduction and forced convection (advection). The potential extent and magnitude of temperature change downgradient of the well bore can be described by the one-dimensional conduction-convection equation:

Equation 1.4-1 $$\frac{\partial}{\partial \times}\left(K_e \frac{\partial T}{\partial \times}\right) - \left(n\ \rho_w\ c_w\ V_x\ \frac{\partial T}{\partial x}\right) = \rho'\ c'\ \frac{\partial T}{\partial t}$$

where:

$\times$ = principal component of space in the direction of maximum groundwater flow (L);

T = temperature (T);

K_e = effective thermal conductivity (E/(LTt));

n = porosity (%);

ρ_w = density of water (M/L^3);

c_w = specific heat capacity of water (E/(MT));

ρ’ = density of rock and water (M/L^3);

$c^{'}$ = specific heat capacity of rock and water (E/(MT)); and

V_x = groundwater velocity in the direction of maximum groundwater flow (L/t).

For the purpose of the effects assessment, the following was assumed:

- the typical life-span of a steam injection well is 10 years;
- the initial reservoir temperature is 6°C;
- the temperature of the steam and well bore is 292°C;
- the temperature at the edge of the well bore is equal to the temperature of the steam (292°C);
- specific heat capacities of the assessed formations were based on Domenico and Schwartz (1997);
- thermal conductivity of the assessed formations were based on Domenico and Schwartz (1997);
- representative groundwater flow velocities for the Ethel Lake Aquifer, the Empress Terrrace Aquifer, and the Undifferentiated Overburden Aquifer/Aquitard were calculated based on observed gradients and hydraulic conductivities described in Appendix 4-II, Section 5.3; and
- representative groundwater flow velocities for the remaining assessed formations were based on the results of the calibrated steady-state groundwater flow model Appendix 4-VII, Attachment A.

A summary of the input parameters for this assessment is included in Table 1.

Table 1 Summary of the Input Parameters for the Steam Injection Assessment

Unit	Calculated Groundwater Flux [m/s]	Porosity [%]	Heat Capacity [Cal/Kg·˚C]	Thermal Conductivity of Rock or Soil [Cal/m·sec·˚C]
Undifferentiated Overburden Aquifer/Aquitard	7×10^{-8}	15	220	0.3
Ethel Lake Aquifer	8×10^{-7}	30	118	0.9
Empress Terrace Aquifer	2×10^{-8}	30	118	0.9
Empress Channel Aquifer	8×10^{-7}	30	118	0.9
Lower Grand Rapids water sand	3×10^{-8}	30	118	0.9
Upper Clearwater water sand	1×10^{-8}	30	118	0.9
Middle Clearwater water sand	4×10^{-8}	30	118	0.9

A finite difference approximation to the one-dimensional conduction-convection equation (Equation 1.4-1) was solved using fully explicit finite difference approximations.

The simulated change in temperature was then evaluated based on the following levels of magnitude:

- *Low Effect* – If the predicted change in temperature is less than 1˚C, the change is likely too small to influence mineral solubilities.
- *Moderate Effect* – If the predicted change in temperature is between 1˚C and 5˚C, the change in temperature might influence mineral solubilities and the magnitude of effect is considered moderate.
- *High Effect* – If the predicted change in temperature is greater than 5˚C the effect is considered high because changes to mineral concentrations have been linked to temperature changes of this magnitude at other projects (Canadian Natural 2006).

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