GeoConvention 2015
GEOSCIENCE
new horizons
Telus Convention Centre • 4-8 May 2015 • Calgary, AB Canada

Risk-based Investigation for Thermal Mobilization of Heavy Metals in Groundwater

Rudy Maji, Matt Neuner, Solaleh Khezri and Don Haley
Golder Associates Limited

Summary

A risk-based groundwater modelling study was completed to assess the potential threats of thermal mobilization of heavy metals in groundwater due to the in-situ oil sands operations. A three-dimensional heat and mass transport model was constructed and calibrated to aid in developing a conceptual design for a risk analysis framework for monitoring and management of groundwater around high temperature well bores. The potential sensitive receptors near the study area were identified and the thermal mobilization and migration pattern of arsenic was predicted during the in-situ operation and recovery periods. Based on the results obtained from this screening-level risk-based analysis, it is anticipated that except under certain conditions the majority of in-situ oil sands development sites may not require detailed investigations, monitoring and mitigation measures specifically for thermal plumes.

Introduction

Many chemical constituents are naturally present in sediments throughout Alberta and have the ability to be mobilized by subsurface heating. As thermal in-situ oil sands production became established in the late 1990s, increased levels of arsenic were observed in groundwater down-gradient of several steam injection wells in the Cold Lake area. Laboratory and field tests have attributed these elevated arsenic concentrations to the heating of subsurface sediments and subsequent release of arsenic to groundwater. With the increase of in-situ oil sands operations in the northeast Alberta, there is a potential growing risk of thermal plume migration due to convection and conduction from the vertical portion of the steam assisted gravity drainage (SAGD) wells in the shallow aquifers. It has been documented that elevated temperatures can cause arsenic (As) that was previously immobile to become mobilised (Fennell 2008). For mobilisation to occur, however, certain conditions are to be satisfied:

- The chemical species must be present in the sediments.
- They must be available to be mobilized, which will be influenced by where and how they are associated with the sediments (i.e., located within a mineral lattice; occluded into the surface layers of a mineral; adsorbed onto a mineral surface).
- The geochemical and microbial conditions must be appropriate for mobilization from the sediments (e.g., pH and redox conditions and microbial activity conditions must be favourable).
- The system must lack attenuating mechanisms that may retard movement (e.g., adsorption) or sequester constituents from solution (e.g., mineral precipitation).

If all the above criteria are met and there is a potential risk of constituent mobilization, groundwater modelling can be used as a screening tool to provide input into the risk assessment. If the risk at a particular site is considered significant, site-specific models (deterministic or stochastic) can be developed to help evaluate and quantify the risk. In this study, groundwater flow and transport models were constructed to simulate the development and migration of thermal and contaminant plumes down-gradient of SAGD well pads. The simulation results were used to develop the conceptual design of a risk-assessment framework in support of groundwater monitoring and management.

Theory and Method

A three-dimensional numerical groundwater flow and transport model was constructed using a generic hydrostratigraphic framework that is representative of northeastern Alberta to assess the migration of thermal and metal plumes from the area adjacent to SAGD injection wells. The model includes multiple well-pads, chosen based on the availability of geologic data and the presence of nearby streams, which are interpreted to be the closest environmental receptors of concern. The model was calibrated to reasonably match the appropriate amount of heat loss that occurs radially outward from the vertical portion of the steam injection wells during SAGD operations. Steaming at SAGD well-pads was simulated for 4 decades followed by a 100-year of recovery simulation without any steam injection to evaluate the thermal and As plume movement after the cessation of steaming.

The three-dimensional numerical groundwater flow model was constructed using FEFLOW 6.2, a finite element modelling package developed by the WASY Institute in Germany (Diersch 2014). FEFLOW is capable of simulating transient groundwater flow, solute and heat transport in three-dimensional heterogeneous and anisotropic media under a variety of hydrogeologic boundaries and stresses. The borehole heat exchanger (BHE) module was used to model the heat loss from the vertical portion of the steam injection wells to the surrounding formations. The numerical model domain is 3 km long, 1.4 km wide and 90 m thick.

Thermal mobilization and transport of As, in conjunction with geochemical assessments of representative subsurface conditions, were completed using a modified distribution coefficient (i.e., Kd) approach. The Kd parameter value is dependent on the mineralogical and geochemical conditions present at the site. Different scenarios with varying geochemical and physical characteristics are simulated in order to begin to develop criteria for when As migration is a potential concern. The threshold temperature for As mobilization, the Kd estimate and the rate of As mobilization were assumed from the published literature (Fennell 2008).

Based on the numerical modelling results, a conceptual design of a risk-assessment framework was developed. This includes a preliminary assessment of the physical and geochemical conditions that must be present at SAGD well pads in order for off-site migration of As to pose a potential risk to the natural environment.

Results

The simulation results include the prediction of groundwater temperature and water quality in the aquifers and at neighbouring streams. The maximum temperature in the aquifers was simulated to be approximately 100 ˚C to 150 ˚C at the interface of the steam injection wells and porous media. The 20 ˚C thermal plume extends to about 150 m to 200 m from the well-pads. After the cessation of steaming the simulated plume size increases with time due to diffusion and dispersion. However, the overall plume temperature decreases with time, and the most significant decline occurs within the first 10 years when the temperature gradient is greatest. After 100 years, the centroid of the temperature plume traveled approximately 200 m from its location immediately after the cessation of steaming. The simulated As plume migration patterns are similar to those of the thermal plumes.

The simulation results suggest that the thermal mobilization of As (and potentially other heavy metals) is a local scale issue. Therefore, the risk of As contaminantion depends on the location of a sensitive receptor in relation to the SAGD well-pad. The screening-level risk assessment utilizes a small amount of site-specific data on hydraulic and geochemical parameters.

Conclusions

The following conclusions are made:

- The simulation results suggest that the thermal and As plumes travel only a few hundreds of meters from the SAGD well-pad; hence As mobilization is a local-scale problem for the parameter ranges simulated thus far;
- If the thermal and/or contaminant plumes originating from SAGD operations intersect any receptors (e.g., streams or production wells), there will be potential environmental risks. Conversely, if the

receptors are far removed from the plumes, then the risks will be minimal due to natural attenuation processes;

- The change in temperature in the porous medium around a steam injection well is affected by:
    - Loss of heat from the injection well through the well casing;
    - Groundwater velocity; and
    - Formation heterogeneity.
- The As concentrations are influenced by:
    - The threshold temperature when As mobilization starts;
    - The amount of solid As present in the sediments and reactivity of the As; and
    - The site specific distribution coefficient (Kd), which is primarily controlled by the porous medium heterogeneity, mineralogy, pH/REDOX conditions, clay content, etc.
- Based on the results presented here, from a risk perspective, it is anticipated that except under certain conditions the majority of SAGD well pads may not require detailed investigations or extensive monitoring for thermal and potentially, heavy metal plumes.

Acknowledgements

This work was partially funded by Brion Energy. The authors would like to thank Michael De Luca of Brion Energy for sharing the data and providing technical reviews of this project. We would also like to thank Dr. Carlos A. Rivera of DHI for providing us many useful suggestions on how to model the temperature dependent mass transport in FEFLOW.

References

Diersch, H.G. 2014. FEFLOW v. 6.2 Finite Element Subsurface Flow and Transport Simulation System. WASY Institute for Water Resources Planning and System Research Ltd., Berlin, Germany.

Fennell, J. 2008. Effects of Aquifer Heating on Groundwater Chemistry with a Review of Arsenic and its Mobility.