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Understanding Shallow and Deep Flow to Assess the Risk of Hydrocarbon Development on Groundwater Quality

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SUMMARY

In the Haldimand sector of Gaspé, Québec, Canada, a study was carried out to assess the potential risk on a shallow fractured rock aquifer system due to development of a tight sandstone petroleum reservoir. Petroleum exploration wells are being drilled in the forested core of a hilly 50 km2 peninsula by the sea (up to 200 m amsl) and where local residents rely on groundwater wells for their water supply. The study used existing hydrogeological, geological and petroleum exploration data and more recently acquired field characterization data. Groundwater and surface water sampling within a 2 km radius of a proposed new drill pad. All samples were subject to chemical analyses. Fracturing controls groundwater flow especially in the upper 15 m of the rock aquifer. Recharge occurs on topographic highs where the glacial till cover is thin. Quite wide variations in groundwater geochemistry were encountered. Groundwater residence times can thus be quite long. Methane is of mixed origin but is preferentially associated with the relatively more evolved water types. The SALTFLOW model was used to simulate density-dependent groundwater flow and salt transport within the peninsula as well as the adjacent highlands along a 2D vertical section.

Introduction

There has been a rapid development of unconventional hydrocarbon resources in North America over the past decade. This development is spreading over geographic areas that have never before experienced upstream oil and gas (O&G) operations. Especially in these new areas, environmental concerns are being raised, notably when hydraulic fracturing (or fracking) is involved. Even though some regulations have been updated, regulatory frameworks still need to be adapted to the new types of operations involved with unconventional resources. However, the adaptation of regulations is hampered by the paucity of scientific data and the poor understanding of the risks involved.

Since 2010, shale gas and unconventional hydrocarbon development has been the subject of a series of public inquiries in Québec (Canada) and has been the focus of intense public debate. A new regulation requires a hydrogeological characterization of all new O&G drill sites. The objective of the present study was to define the hydrogeological context of the Haldimand sector of Gaspé, Québec, Canada, where the drilling of a horizontal well in a tight sandstone reservoir was halted by a municipal regulation aimed at protecting the local water supply. Based on this characterization, we assessed the risk to groundwater quality and to local groundwater users (residential and municipal) related to existing decommissioned and operational oil wells and the planned new Haldimand No.4 horizontal borehole. Finally, this work aimed to provide an example study of what is now required by the new provincial regulation. Figure 1 shows the Haldimand sector of Gaspé, where the study was carried out. Petroleum exploration wells have been drilled in the forested core of a hilly 50 km^2 peninsula by the sea, including two relatively recent wells in the tight sandstone reservoir. Residents on the periphery of the peninsula rely on shallow (20-40 m) wells for their water supply. The present municipal surface water supply and a well field are found south of the study area.

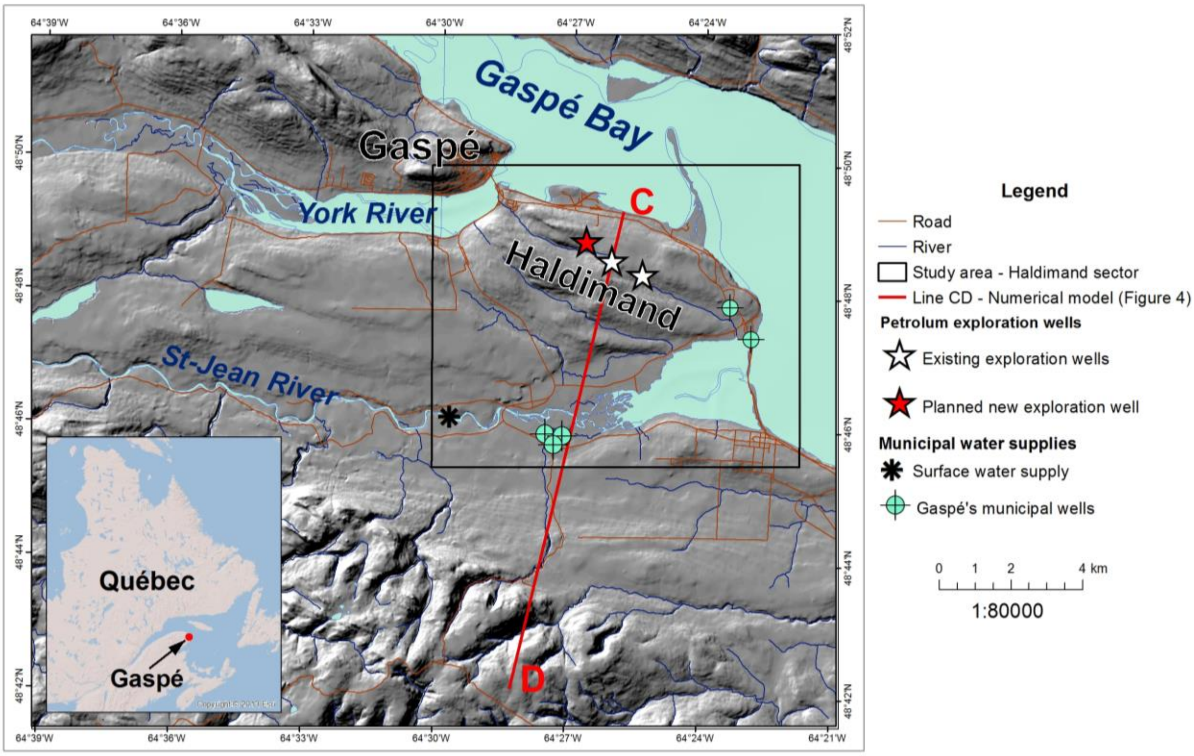

Figure 1 *Location and context of the study area. The rectangle outlines the local Haldimand sector. The line labelled C-D indicates the location of the 2D numerical model (Figure 4).*

Methods

The study involved the definition of 1) the geological context and natural fractures, 2) the hydrogeological context based on numerous maps, and 3) the groundwater geochemical conditions. On this basis, conceptual and numerical models of the study area were developed and the local risk to groundwater quality was assessed. The study used existing hydrogeological, geological and petroleum exploration data and more recently-acquired field characterization data. Field work involved 1) the installation of 17 observation wells that were hydraulically tested, 2) 103 groundwater and surface water samples, mostly within a 2 km radius of the future oil well drill pad, and 3) geophysical logging of the open-hole observation wells. All samples were subject to chemical analyses including major and minor inorganics, a wide range of organics, dissolved light hydrocarbon gases and methane (CH_4) isotopes, where present. More specialized analyses were applied to samples from the observation wells (stable isotopes of water, tritium, ^{13}C and ^{14}C of dissolved inorganic carbon [DIC], noble gases [Ne, Ar], CFCs and SF_6, and acid extractable organics [AEOs]). The data were used to 1) describe the orientation and density of fractures in the shallow fractured rock aquifer and at depths down to the reservoir (700 to 900 m); 2) define hydrogeological conditions on the basis of various maps (surficial sediment thickness, bedrock surface topography, potentiometric surface, groundwater depth, rock aquifer confinement, DRASTIC vulnerability, etc.), 3) estimate groundwater recharge based on soil moisture balance and well hydrographs, 4) classify groundwater types and interpret geochemical processes, 5) interpret the origins of methane and the associated geochemical processes on the basis of its isotopic signature and the concentrations of ethane and propane, 6) identify potential preferential migration paths from the reservoir to the aquifer, 7) develop a conceptual model of the aquifer system, 8) develop a 2-D variable-density numerical model, and 9) assess the risk to groundwater quality from petroleum exploration drilling.

Results

The top of the oil reservoir is 700 to 900 m deep. Down to the depth of the oil reservoir, the rock underlying the study area is made up of sandstones and mudstones, which are porous and fractured. The rock represents a continuous regional aquifer exploited from 0 to 40 m (mean 20 m), mostly by open boreholes cased only through the surficial sediments. The rock is partly covered mostly by low permeability glacial till (0-7 m thick) that is absent on topographic highs where recharge occurrs. Fracturing was found to control groundwater flow, which occurs mostly in the upper 15 m of the rock aquifer since the density of fractures, especially open ones with apparent flow, sharply decreases past the upper 20 m below the top surface of the rock under surficial sediments (Figure 2).

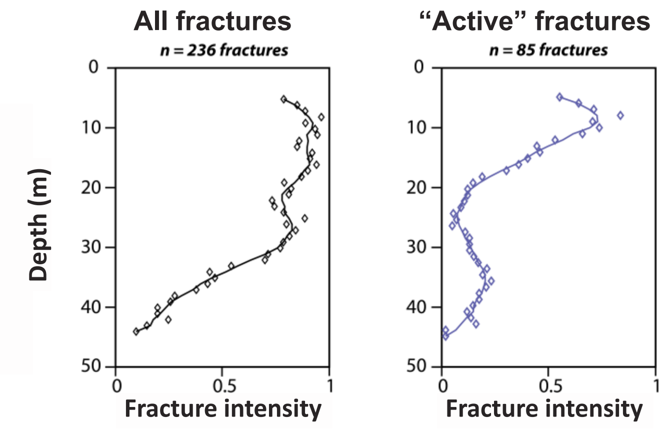

Figure 2 *Total fracture intensity (m^{-1}) (left) in open observation wells from an acoustic televiewer, compared to the intensity of hydraulically active fractures (right) identified using a heat pulse flowmeter and downhole fluid conductivity and temperature probes. Natural groundwater flow (upward or downward) was detected by the flowmeter in 7 of the 8 observation wells logged.*

Contrary to the near-surface part of the rock, fracturing was found to be sparse at depth based on Formation MicroImager (FMI) data available from 215 to 1200 m depth from the Haldimand No.2 borehole. An efficient cap rock was found to isolate the oil reservoir, based on a comparison between available reservoir pressures and estimated hydrostatic and dynamic water pressure gradients, the latter being based on groundwater modelling results.

Fifteen short duration (≈1 hr) pumping tests indicated a moderate hydraulic conductivity in the order of 10^{-6} m/s for the fractured rock aquifer. Hydrogeological conditions and a conceptual model were defined on the basis of numerous maps: surficial sediment thickness, bedrock surface topography, potentiometric surface, groundwater depth, rock aquifer confinement, DRASTIC vulnerability, etc. Aquifer recharge, reaching up to 500 mm/y in topographic highs, was estimated on the basis of soil moisture balance and the interpretation of well hydrographs. Groundwater divides correspond to surface water divides and are well-defined due to the varying topography. Vulnerability varies from moderate to very high: so there would be direct effects from potential surface spills of contaminants. Streams would be receptors of surface contamination at the oil well sites. However, residential and municipal wells would not be direct receptors from such contamination. Strategically-placed observation wells would allow the detection of contamination down-gradient of oil well sites.

Figure 3 (left) shows a Piper diagram of major ion proportions with samples grouped on the basis of cluster analysis of multiple chemical parameters. Quite wide variations in groundwater geochemistry were encountered, with a complex spatial distribution of non-evolved (Ca-HCO_3) and evolved (Na-HCO_3 and Na-Cl) groundwater often found in close proximity. Some of this variability is attributed to the mixing of water from various depths in the open wells themselves. Evolved groundwater types are affected by Na-Ca cation exchange or mixing with marine water. Based on ^{14}C data, groundwater residence times can be quite long (> 10k y), but evidence of modern (< 50 y) water is found in almost all groundwater, based on CFC/SF_6 and tritium data. Groundwater geochemistry is thought to result from the relatively shallow evolution of groundwater in the aquifer since geochemical signatures are not consistent with a direct deep source of saline water. Based on its isotopic composition and the concentrations of ethane and propane (Figure 3, right), methane was found to be predominantly of biogenic origin, but also included a thermogenic fraction. High methane concentrations are associated with the relatively more evolved water types. The geochemistry shows no indications of preferential flow paths that could link the deep reservoir part of the system with the shallow fractured rock aquifer. If it were to occur, contamination of shallow groundwater with deep methane, saline connate waters, or reservoir oil could be recognized from their chemical and isotopic signatures.

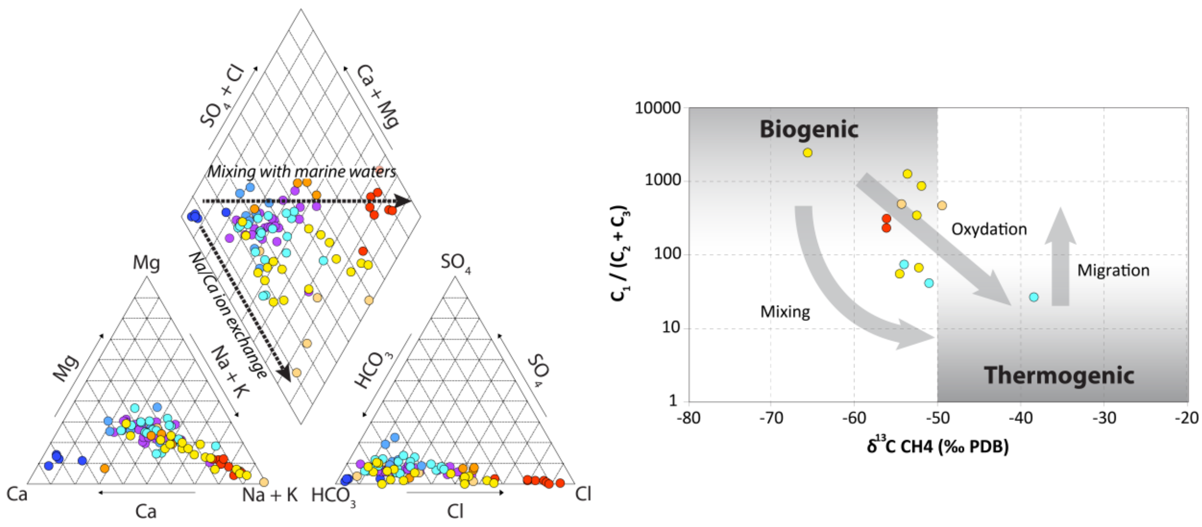

Figure 3 *Left: Piper diagram of the proportions of major ions in groundwater with samples grouped on the basis of cluster analysis. Right: interpretation of methane origin (biogenic versus thermogenic) based on methane (C_1) isotopic composition and its proportion versus ethane and propane (C_2+C_3).*

A numerical model using SALTFLOW was used to simulate density-dependent groundwater flow, salt transport and age transport within the peninsula as well as the adjacent highlands along a 13.5 km-long and 1 km-deep 2D vertical section. The model considers surface topography, material properties, recharge and discharge zones and the presence of three types of water having different salinities and densities (fresh, marine and connate waters). Modelling results are shown in Figure 4 for mass and age transport. Regional flow patterns extend from the highlands to the St-Jean River and the sea. Evolved groundwater is thus brought to surface by regional flow systems. Deep water from up-gradient meets shallow down-flowing water under the Haldimand sector, which leads to the presence of evolved groundwater with long residence time under the peninsula. The long residence times at depths below 200 m (from hundreds of thousands to over one million years) imply that deep contaminant releases that could be related to O&G wells would involve very long migration times to the surface (under the assumed model conditions with no preferential leakage along the wellbore).

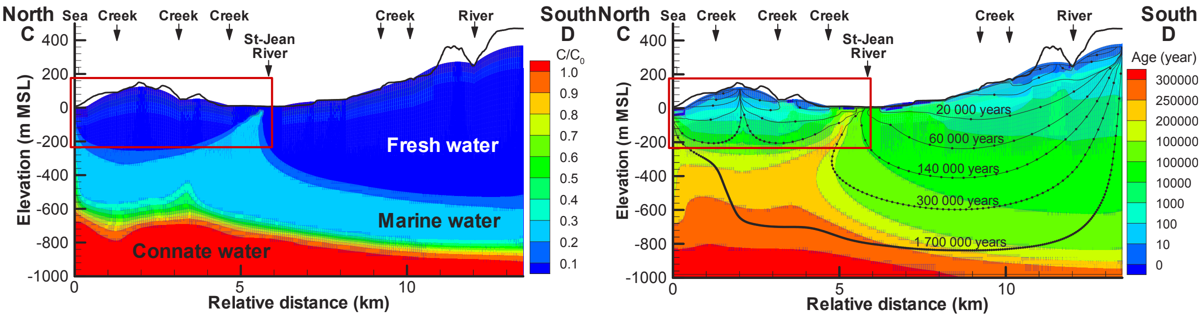

Figure 4 *Results of numerical modelling, with the red rectangle outlining the Haldimand study area. Left: simulated distribution of groundwater with different salinities and densities. Right: simulated groundwater residence times based on advective-dispersive age transport (color shading) compared to advective-only age estimation from particle tracking.*

Based on the local conditions defined by the characterization and modelling, the environmental risk for groundwater quality was assessed relative to 1) the criteria of the new regulation in Québec for O&G exploration operations, 2) the potential contaminant emission mechanisms related to hydrocarbon exploration operations (surface spills, leaks through O&G wells, migration through preferential paths, old O&G wells or permeable faults or fracture zones), and 3) the expected effects that contaminant releases would have for the specific conditions of the Haldimand sector. Surface spills are the most probable contaminant release mechanism and their impact would depend on aquifer vulnerability (which is high) and the nature of emitted fluids. Known risk mitigation measures can be implemented relative to surface spills. There are no indications of active natural preferential migration pathways from depth, but old O&G exploration wells go through the reservoir, so their decommissioning and the integrity of their casings and cementation should be verified.

Conclusions

The risk for groundwater quality from O&G exploration drilling has to be assessed on the basis of local hydrogeological conditions. This study contributes to the development of a framework to assess such a risk. Researchers and regulators have to do more work to consider the impact of potential contaminant emissions from the subsurface and develop optimal monitoring approaches for hydrocarbon drill sites, especially in relation to non-conventional resources.

Acknowledgements

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