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Concurrence of aqueous and gas phase contamination of groundwater in the Wattenberg oil and gas field of northern Colorado

Huishu Li, Ji-Hee Son, Kenneth H. Carlson*

Department of Civil & Environmental Engineering, Colorado State University, Fort Collins, CO 80523-1372, United States

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ABSTRACT

The potential impact of rapid development of unconventional oil and natural gas resources using hydraulic fracturing and horizontal drilling on regional groundwater quality has received significant attention. Major concerns are methane or oil/gas related hydrocarbon (such as TPHs, BTEX including benzene, toluene, ethybenzene and xylene) leaks into the aquifer due to the failure of casing and/or stray gas migration. Previously, we investigated the relationship between oil and gas activity and dissolved methane concentration in a drinking water aquifer with the major finding being the presence of thermogenic methane contamination, but did not find detectable concentrations of TPHs or BTEX. To understand if aqueous and gas phases from the producing formation were transported concurrently to drinking water aquifers without the presence of oil/gas related hydrocarbons, the ionic composition of three water groups was studied: (1) uncontaminated deep confined aquifer, (2) suspected contaminated groundwater - deep confined aquifer containing thermogenic methane, and (3) produced water from nearby oil and gas wells that would represent aqueous phase contaminants. On the basis of quantitative and spatial analysis, we identified that the "thermogenic methane contaminated" groundwater did not have similarities to produced water in terms of ionic character (e.g. Cl/TDS ratio), but rather to the "uncontaminated" groundwater. The analysis indicates that aquifer wells with demonstrated gas phase contamination have not been contacted by an aqueous phase from oil and gas operations according to the methodology we use in this study and the current groundwater quality data from COGCC. However, the research does not prove conclusively that this the case. The results may provide insight on contamination mechanisms since improperly sealed well casing may result in stray gas but not aqueous phase transport.

1. Introduction

Groundwater quality can be influenced by natural conditions such as topography, aquifer lithology, and by human activities (Hearne et al., 1995) such as disturbances from oil and gas drilling and production activities (Kharak et al., 2013). The four most probable fluid transport mechanisms from deeper hydrocarbon formations to groundwater and aquifers are: 1) vertical and lateral gas migration along natural geologic fractures and faults; 2) stray gas migration through unsealed or improperly sealed oil and gas production wellbores; 3) gas and aqueous phase migration through casing breaches and failure; and 4) percolation from surface spills of produced water—the water produced from oil and gas extraction and a mixture of shale formation water and fracture fluids (Toril, 1999).

The first two pathways are likely to be combined together and create a cross transport mechanism: gas leaked from an improperly sealed wellbore migrates through natural geological structures into groundwater or the aquifer (McMahon et al., 2013). Although fluid migration can occur naturally along preexisting natural faults and fractures over geological time scales (e.g. millions of years), (Johnson and Rice, 1990; Sharma et al., 2014) the impermeable formations above and below by the Laramie-Fox Hills aquifer in northeast Colorado make the natural migration mechanism itself less likely to occur. In addition, since the aquifer is confined, percolation from surface spills in the Wattenberg oil and gas field of the Denver–Julesburg (D–J) Basin in Colorado are not likely to contaminate the aquifer.

Oil and gas wells in the D–J Basin are about 1.83–2.44 km deep into sandstone or Niobrara shale while the depth of Laramie-Fox

* Coresponding author.
E-mail address: kcarlson@engr.colostate.edu (K.H. Carlson).

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Hills aquifer ranges about 0.06–0.18 km (Robson, 1981) Laramie-Fox Hills aquifer is a deep confined bedrock aquifer in between Laramie confining layer (top) that is up to 0.12 km thick and the Pierre confining layer (bottom) that is up to 2.44 km thick (Knepper, 2002).

Therefore, the most likely fluid transport mechanism to the aquifer is either produced water leaking through corrupted casing or gas migration up from the producing formation along a poorly sealed wellbore, or both. In general, the lack of well integrity, primarily faulty oil and gas well casing, is considered the most conceivable path of gas fluid migration (Osborn et al., 2011; Stempvoort et al., 2005; Taylor et al., 2000). Casing failure can also allow aqueous (e.g. produced water) and non-aqueous phase liquids (NAPLs) to travel from the producing oil and gas wellbore into the aquifer which lays a few kilometers above the producing formation (Entrekin et al., 2011).

Oil and gas production wells in the U.S. are typically constructed according to the well construction guidelines published by the American Petroleum Institute (API) (API, 2009). The casing of either vertical or horizontal oil and gas wells are structured with multiple steel pipe layers—generally four layers: conductor casing, surface casing, intermediate casing, and production casing—with cement sheaths around the casings in order to isolate oil/gas producing formations from aquifers by preventing hydraulic connectivity between them (Supporting Information (SI), Fig. A.1).

Colorado is one of the biggest oil and gas producing states in the United States, ranked 6th in natural gas production (45.4 km^3) and 7th in oil production (0.01 km^3) in 2013 (State profiles and energy estimates, 2014). In 2008, The Colorado Oil and Gas Conservation Commission (COGCC), the regulatory agency in Colorado, completed a series of regulations of wellbore integrity for new oil and gas wells to protect groundwater and aquifers. For instance, COGCC Rule 317 requires that surface casing runs at least 15 m (50 ft) below the depth of the deepest aquifer for well control and aquifer protection, and also requires that production casing is cemented above all production zones to create a hydraulic seal (Colorado oil and gas commission 300 Series Rules, 2014).

Although the COGCC regulates wellbore integrity and continuously performs intensive inspections of oil and gas production wells, there is still a risk of faulty casing strings or cementing along wellbores.

Two possible transport mechanisms for two different fluid types: gas and aqueous phases into the confined bedrock aquifers in a unique circumstance of the D–J Basin are illustrated in Fig. 1.

Gases are transported through the subsurface more efficiently and quickly compared to the aqueous phase. Stray gases including thermogenic methane gas can escape from producing wells though circumferential fractures and unsealed or improperly sealed casing strings along the wellbore (Fig. 1-A), (Dusseault and Gray, 2000) leading the methane gas to leak into the aquifer.

Another pathway for fluid migration is casing breaches or leakages (Fig. 1-B). Casing breaches allow gas migration as well as migration of aqueous phase contaminant of produced water into aquifer, but the risk of aqueous phase contamination varies depending on production pressure (Chafin, 1994). The leaked gas or aqueous phase contaminants will flow out through groundwater (Gurevich et al., 1993; EPA, 1996) and eventually contaminate the drinking water well.

Previously, we investigated a relationship between oil and gas activity and dissolved methane concentration in the drinking water aquifer and found a relatively low level (<2% of 223 water samples) of thermogenic methane contamination in the area (Li and Carlson, 2014). Although the previous study did not find detectable concentrations of TPHs and BTEX in the aquifer samples containing thermogenic methane, there is still a possibility that the aquifer samples containing thermogenic methane were also contaminated by the aqueous phase of produced water.

Therefore, it is important to understand the ionic composition of the aquifer containing thermogenic methane to determine if aqueous phase contaminants were transported into the aquifer concurrently with the gas phase contaminant. The ionic composition— organic and inorganic characteristics—of the water co-produced with oil and gas is expected to be significantly different from those of confined bedrock aquifers (Land and Prezbindowski, 1981).

Three groups of water studied here are: (1) uncontaminated deep confined aquifer (not containing thermogenic methane gas nor oil/gas related hydrocarbons, (TPHs and BTEX); (2) deep confined aquifer containing thermogenic methane (THGW), and (3) produced water (PW) from nearby horizontal oil and gas wells, that would represent aqueous phase contaminants.

The objective of this study is (1) to distinguish ionic compositions of three different water groups in Wattenberg Field, an area highly developed in oil and gas production activities, and (2) to identify whether the aquifer wells contaminated by thermogenic methane (2nd water group) was also influenced by aqueous phase contaminants (3rd water group) without the presence of oil/gas related hydrocarbon by comparing ionic compositions of each water group.

Occurrence of produced water features in the confined bedrock aquifer might indicate that a hydraulic connectivity existed between the producing zone and aquifer, (Warner et al., 2012) which is more likely due to a casing breach. The presence of thermogenic gas without aqueous phase contaminants in the aquifer might suggest that stray gas migration along a poorly sealed wellbore is the likely mechanism.

2. Materials and methods

2.1. Study area: Laramie-Fox Hills aquifer and Wattenberg Field

Water wells in our study area were completed in the sandstone and siltstone Laramie-Fox Hills aquifer. The upper Laramie-Fox Hills aquifer is comprised of sandstone from the lower Laramie formation, and the lower part of the aquifer consists of the Fox Hills formation (Robson and Banta, 1987). Both the Laramie formation and Fox Hills formation in our study area contain carbonaceous shale, sandstone and lignitic coal seams (Weimer, 1973).

Historically, the Laramie-Fox Hills aquifer has three characteristic water types: (1) NaHCO3, groundwater influenced by limestone, (2) CaSO4, groundwater influenced by gypsum formations and (3) NaCl, typical of marine or deep, ancient water (Hern, 1989). High TDS water appeared in the northern and eastern margin of Laramie-Fox Hills aquifer since the groundwater flows toward the northeast and soluble minerals were transported by groundwater into those areas (Robson and Andrew, 1981). Iron, which is naturally insoluble compared with other minerals, is dissolved in water in Laramie-Fox Hills aquifer due to a reducing environment in bedrock of Laramie-Fox Hills aquifer rich in electron donating organic matter.

The Wattenberg Field is a highly developed oil and gas area located in the D–J Basin, (Weimer et al., 1986) and one of the largest natural gas deposits in the United States that has been the site of conventional production for over forty years. It recently became known for natural gas extraction and production (Weimer et al., 1986) that produced 7.96 km^3 of natural gas and 0.007 km^3 of oil in 2013 (COGCC, 2014). Most of the oil and gas wells drilled in the Wattenberg Field before 2011 were vertical wells and horizontal well drilling dominated in 2012 and after (COGA, 2012).