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Elucidating hydraulic fracturing impacts on groundwater quality using a regional geospatial statistical modeling approach

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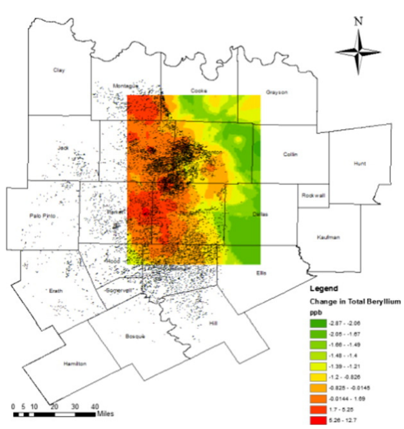
HIGHLIGHTS

- Migration pathways from fractured wells to groundwater are poorly understood
- Geospatial modeling correlated groundwater chemicals to Barnett fractured wells
- Increased Beryllium strongly associated with hydraulically fractured gas wells
- Indirect evidence of pollutant migration via microannular fissures in well casing
- Large-scale and spatial approach needed to detect groundwater quality changes

GRAPHICAL ABSTRACT



A relative increase in beryllium concentrations in groundwater for the Barnett Shale region from 2001 to 2011 was visually correlated with the locations of gas wells in the region that have been hydraulically fractured over the same time period.

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ABSTRACT

Hydraulic fracturing operations have been viewed as the cause of certain environmental issues including groundwater contamination. The potential for hydraulic fracturing to induce contaminant pathways in groundwater is not well understood since gas wells are completed while isolating the water table and the gas-bearing reservoirs lay thousands of feet below the water table. Recent studies have attributed ground water contamination to poor well construction and leaks in the wellbore annulus due to ruptured wellbore casings. In this paper, a geospatial model of the Barnett Shale region was created using ArcGIS. The model was used for spatial analysis of groundwater quality data in order to determine if regional variations in groundwater quality, as indicated by various groundwater constituent concentrations, may be associated with the presence of hydraulically fractured gas wells in the region. The Barnett Shale reservoir pressure, completions data, and fracture treatment data were evaluated as predictors of groundwater quality change. Results indicated that elevated concentrations of certain

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Bottom-hole pressure
Geographic Information Systems (GIS)
Cluster analysis
Micro annular defects

groundwater constituents are likely related to natural gas production in the study area and that beryllium, in this formation, could be used as an indicator variable for evaluating fracturing impacts on regional groundwater quality. Results also indicated that gas well density and formation pressures correlate to change in regional water quality whereas proximity to gas wells, by itself, does not. The results also provided indirect evidence supporting the possibility that micro annular fissures serve as a pathway transporting fluids and chemicals from the fractured wellbore to the overlying groundwater aquifers.

1. Introduction

Hydraulic fracturing is a technology used in oil and gas production to increase hydrocarbon recovery from low-permeability formations. During a hydraulic fracturing operation, fluid is injected into an oil and gas well at high pressures—a process that fractures the rock of the hydrocarbon bearing formation thereby increasing its hydraulic conductivity and the rate of flow of oil and gas from the formation to the wellbore. Hydraulic fracturing techniques, developed as early as 1949, have significantly improved since the 1980s such that they currently allow production from low-permeability shale formations that have historically been considered a non-producible resource (Murray, 2013). The first hydraulic fracturing treatment in a horizontal wellbore was performed in 1992 in the Barnett Shale. However, the combined advances in horizontal drilling and hydraulic fracturing (in addition to other novel technologies such as use of high-volume of fracturing fluids, clustered-multi-well pads, and long laterals) have propelled fracturing of horizontal wells to become an industry standard practice in the development of low-permeability shale formations (Smith and Hannah, 1996).

Hydraulic fracturing use has increased significantly since the mid-2000s and has become a subject of controversy concerning potential risks to human health and the environment (Finkel and Hays, 2013; Rahm, 2011; Walton and Woocay, 2013; McKenzie et al., 2012; Preston et al., 2014; Ziemkiewicz et al., 2014; Eaton, 2013; Meng, 2015; Révész et al., 2012; and Werner et al., 2015). Research is needed to address health and safety issues in the development of oil and gas resources including the cumulative impacts of tightly spaced wells that are more difficult to quantify (Vidic et al., 2013).

A heightened interest in the impact of hydraulic fracturing on groundwater exists since this subject is not as well understood despite the fact that several studies have been undertaken. Well casing failures, contaminant migration through fractures, surface spills, and/or wastewater disposal are all potential pathways that could lead to groundwater contamination. A risk-model by Rozell and Reaven (2012) proposed that disposal of wastewater had the highest risk for contaminating ground water while other studies demonstrated that contamination may be from the subsurface. Methane concentrations in groundwater (primarily in the Marcellus Shale), for example, were evaluated in some studies as an indicator of potential communication between water aquifers and gas wells; the distance to gas well operations was shown to be a statistically significant variable for methane concentrations in ground water samples by Osborn et al. (2011) and Jackson et al. (2013).

The study of methane concentrations alone, however, may not be a straightforward indication that groundwater contamination has occurred, particularly since other research studies have demonstrated that methane concentrations and chemical properties were correlated to the geophysical environment and topography (Molofsky et al., 2011; Warner et al., 2012; Molofsky et al., 2013), and to the distance to natural faults (Moritz et al., 2015). A study by Fontenot et al. (2013) evaluated heavy metal concentrations in groundwater as indicators of groundwater contamination and presented statistically significant higher median concentrations of heavy metals in water quality samples taken in proximity to natural gas extraction activities in the Barnett Shale region in Texas (the region studied in this work). The aforementioned studies suggested that some impact to groundwater from hydraulic fracturing operations could be observed; however, it is unclear whether the migration of methane gas coincided with the migration of other groundwater contaminants.

The toxic elements found in hydraulic fracturing wastewater streams should be considered in the study of hydraulic fracturing impacts on groundwater. These elements have the potential to contact the groundwater system and may serve as indicator variables for examining changes in groundwater quality related to hydraulic fracturing operations. Wastewater from hydraulic fracturing operations contains toxic elements originating in the shale and from chemicals used in the fracturing treatment including total dissolved solids, volatile substances, bromide, naturally occurring radioactive materials, and heavy metals such as arsenic, barium, beryllium, uranium, and zinc (Gordalla et al., 2013; Ternes, 2012; Rahm et al., 2013; Lester et al., 2015; and Chermak and Schreiber, 2014). Harkness et al. (2015) attributed the high bromide and chloride content in the wastewater to the brine from the shale reservoir; Rowan et al. (2011) demonstrated that high salinity mobilizes radionuclides, increasing exposure to radioactive waste such as radium 226.

Even less well understood than the impacts of fracturing on ground water quality are the potential pathways for pollutant migration to groundwater from the shale formations. The study presented in this paper addresses this knowledge gap and investigates gas migration as a transportation mechanism of contaminants into groundwater. Recent studies have concluded that ground water contamination is due to poor well construction (Jackson et al., 2013) and that leaks in the wellbore annulus are due to ruptured wellbore casings (Darrah et al., 2014). A study presented by Ingraffea et al. (2014) developed a risk assessment model for casing and cement impairment for oil and gas wells in Pennsylvania concluding that unconventional wellbores are at a greater risk for impairment than conventional wellbores, and periods of intense drilling have resulted in lowered wellbore integrity. Another study indicated that wellbore integrity failure rates vary significantly based on geographical region and noted that more wellbore monitoring would be required to better understand failure rates (Davies et al., 2014).

In this paper, the research presented differs from the aforementioned studies where groundwater contamination was attributed to a noticeable failure in the wellbore systems. The research presented in this work investigates how minor defects in the wellbore system, which are far more common than a major defect, may still be significant to cause widespread impacts of fracturing operations on groundwater. Gas can permeate through small cracks in the annular cement sheath (see Section 4). The working hypothesis is that the expansion of natural gas, released from the producing formation during the hydraulic fracturing process, is the mobilizing mechanism that allows chemicals in a gas–fluid mixture to make contact with the water table above the shale formation (in the case of wellbores with a defect in the annular cement sheath). Because the formation pressure in a well will drive the gas velocity and volume of gas generated, the reservoir pressure is examined as a predictor variable for elevated concentrations of indicator constituents in groundwater. It is presumed that a larger volume of gas flow will contribute to a greater accumulation of contaminants in the aquifer system.

Additionally, the expansion of gas hypothesis presented above dictates that groundwater quality changes, when present, will only be