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Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA

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HIGHLIGHTS

• Hydraulic fracking has damaging impacts on the environment in Marcellus Shale region.
• Hydraulic fracking endangers public health in the state of Pennsylvania.
• Distance based methods are developed to do risk assessment of fracking wells.
• Spatial kernels are created to quantify and map population risks.
• Bandwidth of spatial kernels is determined by spatial dependence and semivariogram.

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ABSTRACT

Hydraulic fracturing, also known as fracking, has been increasing exponentially across the United States, which holds the largest known shale gas reserves in the world. Studies have found that the high-volume horizontal hydraulic fracturing process (HVHFP) threatens water resources, harms air quality, changes landscapes, and damages ecosystems. However, there is minimal research focusing on the spatial study of environmental and human risks of HVHFP, which is necessary for state and federal governments to administer, regulate, and assess fracking. Integrating GIS and spatial kernel functions, we study the presently operating fracking wells across the state of Pennsylvania (PA), which is the main part of the current hottest Marcellus Shale in US. We geographically process the location data of hydraulic fracturing wells, 2010 census block data, urbanized region data, railway data, local road data, open water data, river data, and wetland data for the state of PA. From this we develop a distance based risk assessment in order to understand the environmental and urban risks. We generate the surface data of fracking well intensity and population intensity by integrating spatial dependence, semivariogram modeling, and a quadratic kernel function. The surface data of population risk generated by the division of fracking well intensity and population intensity provide a novel insight into the local and regional regulation of hydraulic fracturing activities in terms of environmental and health related risks due to the proximity of fracking wells.

1. Introduction

Hydraulic fracturing (or fracking) has played a vital role in the development of US natural gas and oil resources in the last ten years. Fracking involves the use of water pressure to create fractures in shale rocks making natural gas or oil escape and flow out to ground. Fracking has been widely applied to places, in which conventional technologies are not effective for gas and oil production. According to an estimation by the U.S. Geological Survey, there is a total of nearly 750 trillion cubic feet natural gas located in the contiguous U.S., and about 86% of the total is in the Northeast, Gulf Coast, and Southwest regions. Fracking has largely improved the ability to profitably extract natural gas and oil from low-permeability geologic plays such as those present in shale.

Fracking has resulted in significant hopes and opportunities for development in shale play regions. Marcellus is the largest shale play, which holds about 410.3 trillion cubic feet of natural gas (INTEK, 2011). The industry chain of hydraulic fracturing has been established in the Marcellus Shale region creating about 245,000 new direct and indirect jobs in the state of Pennsylvania (PA), and tens of billions of dollars have been invested directly and indirectly into PA's economy (EnergyFromShale, 2014). For example, Williamsport, PA, a ghost town due to lumber industry depression, has now become one of the fastest growing cities in US with an unemployment rate several points lower than the national average. The town of Williamsport could soon be known as a capital of the shale revolution in the Marcellus Shale region. Now, fracking is often used by the media and public for shale gas development, in fact it becomes an umbrella term that does not only mean the well stimulation technique, but also includes the overall process including activities of horizontal/directional

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drilling, the establishment of compressor facilities, the laying of gas gathering lines and potential water lines, and the construction of multi-well pads. In other words, it is high-volume horizontal hydraulic fracturing process (HVHFP), which drives economic growth and job creation in numerous communities across the West Coast, Rocky Mountain, Mid-Continent, Gulf Coast, and Northeast, in the U.S.

Although there are significant pros of HVHFP, it has crucial drawbacks due to environmental degradation (Sovacool, 2014). In the UK, hydraulic fracturing activities have higher terrestrial toxicity than other energy resources, and shale gas could be a sound environmental option only if the process of fracking is under a stringent set of regulations (Stamford and Azapagic, 2014). One fracking well typically needs about 20 million liters of water (Howarth et al., 2011a). The water requirement is problematic because substantial geologic evidence that natural vertical flow drives contaminants, such as brine, to near the surface from deep evaporite sources has been found (Myers, 2012). Some of these quantities can be quite large, with 10% to 35% of initial chemical-water injections returning to the surface as flowback before production begins (Sovacool, 2014). Operations such as improper well casing and lax on-site waste waters to rage practices, and even the fracking itself could allow natural gas constituents to migrate into underground aquifers and private wells (Argetsinger, 2012). Not only does water for fracking consume fresh water resources and pollute aquatic habitats, the transportation of such large amounts of water also creates air quality and other environmental issues.

Air pollution is another important environmental issue. Large emissions with an average of 34 g CH_4/s (2.937 tons/day) per well from seven hydraulic fracking pads were checked and quantified in the drilling phase (Caulton et al., 2014). Howarth et al. (2011b) concluded that 3.6–7.9% of life-time shale gas production migrates to the atmosphere through venting or leaking over the lifetime of a well and that 1.9% of the total gas production is emitted as methane through well completion. The U.S. EPA reports that "chronic inhalation or oral exposure to methanol may result in headache, dizziness, giddiness, insomnia, nausea, gastric disturbances, conjunctivitis, visual disturbances (blurred vision), and blindness in humans" which quantifies methane exposure as a health hazard. The organic compounds are brought above ground in the fracking flowback or produced water, which often are put into open impoundments (frack ponds), where the waste water releases its organic compounds into the air. 37% of the chemicals used during fracturing and natural gas production have been found to be volatile and be airborne. 71% of the volatile chemicals can harm the cardiovascular system and blood, 66% can harm the kidneys, and the chances of exposures to volatile chemicals are significantly increased when they are inhaled by humans or are even taken in and absorbed through the skin (Colborn et al., 2011). Additionally, most fracking wells rely on diesel powered pumps to inject and control water, which results in dangerous levels of volatile hydrocarbons around and near to fracking wells including but not limited to benzene, toluene, formaldehyde, ground-level ozone, and other pollution from drills, compressors, and other machinery (Sovacool, 2014). In fracking well areas of Texas, Wyoming, and Colorado communities and researchers have blamed the release of CH_4, CO_2, and other volatile organic chemicals (VOCs) from processing plants and diesel exhaust trucks for ozone (O_3) and other air quality problems (Kargbo et al., 2010). In addition, local citizen's complaints allege that petrochemical pollution has caused adrenal and pituitary tumors, headaches, nausea, joint pain, respiratory problems, and other symptoms (Brown, 2007). In summary, HVHFP results in the significant environmental and public health risks at fracking well sites as discussed above.

Distance has been recognized as a critical factor for environmental risk assessment of HVHFP (Meng and Ashby, 2014), and current studies have shown enough evidence of possible health impacts (Werner et al., 2015). On numerous occasions fracking has been established as a danger to human health and the environment (Mrowka, 2014). Land surface environment and landscapes at and near fracking sites have been largely changed or damaged (Meng, 2014). Residents living nearer to a fracking well experience an increased human health risk due to exposure to huge gas emissions, produced water or flowback, and the offgas from flowback. Many studies on inhalation exposure to petroleum hydrocarbons in occupational settings and residences near gas fields, oil fields, gas leaking, oil spills, and petrol stations show an increased risk of eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute myelogenous leukemia, and multiple myeloma (Brosselin et al., 2009; Kim et al., 2009; White et al., 2009). Most of the petroleum hydrocarbons observed in these studies are present in and around fracking well sites. Lupo et al. (2011) found that maternal exposure to high levels of benzene is associated with an increase in birth prevalence of neural tube defects. Mckenzie et al. (2012) found that public health risks resulting from air emissions during the development of fracking are most likely to occur in residents living nearest to a fracking well, and particularly residents living within 0.8 km from a fracking well are at a higher health risk than those farther away with benzene as the major contributor to the risk. Coons and Walker (2008) also found that significant ambient benzene emissions exist within close proximity to a fracking well (<0.8 km), which resulted in significant public health problems. Methane concentrations in drinking water wells within 1 km of a fracking well can reach potentially explosive levels (Osborn et al., 2011). In a study conducted by Jackson et al. (2013), methane concentrations were found to be six times higher and ethane concentrations to be 23 times higher at residences within 1 km of a shale gas fracking well than the concentrations at distant residences, and propane was also detected in water wells within approximately 1 km of a fracking well. Another field inventory shows that water supply owners who reported changes to their water supply after drilling are located within 3000 ft (0.914 km) of a Marcellus gas well (Boyer et al., 2011). A recent working paper suggested that a distance within at least 2.5 km from a gas well is detrimental to fetus development due to the exposure to shale gas development (Hill, 2013). Sub-surface pathways exist and gas mixtures are found in groundwater by the trace study of ethane (C_2H_6) with microbial methane (CH_4) and a range of C and H isotopic compositions of CH_4 (Revesz et al., 2010).

Local seismicity associated with high pressure fluid injection into fracking wells has been studied (Ellsworth et al., 2012) and wastewater injection into deep wells also resulted in small earthquakes within an approximate 1 km radius to a deep well (Kim, 2013), which indicates fracking with high pressure has the potential to cause small earthquakes. In fact, a field study shows that 7 h after the first and deepest hydraulic fracturing stage in the Eola field located in Garvin County, Oklahoma, USA, 50 earthquakes of small magnitude (1 to 2.8 Md) had been observed and measured within 3.5 km from fracking sites; high fluid pressure and its variations at well bottoms are sufficient to encourage seismicity (Holland, 2011). In the last few years, Texas has experienced hundreds of small to medium earthquakes as boomed drilling due to hydraulic fracturing, and the Texas Railroad Commission has since announced new rules to restrain fracking operations (Henry, 2014).

Distance becomes a vital aspect of environmental and societal risk assessment of fracking, and proximity within 1 km to a fracking well is a recurring critical value (Meng and Ashby, 2014). Within 1 km distance to a fracking well, significant risks to environment, damaging impacts on natural resources, and public health risk have been observed and measured in the above-discussed studies. In this paper, we first propose a distance based risk analysis of population and environment at risk of fracking. Based on distance analyses of fracking, we map the environment and population at different levels of risks. Using spatial kernel techniques, we finally develop an intensity based risk method to quantify, summarize, and map population at risk of fracking in the state of PA, USA.