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A Spatiotemporal Exploration of Water Consumption Changes Resulting from the Coal-to-Gas Transition in Pennsylvania

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SUMMARY

During the early stages of Pennsylvania's coal-to-gas transition, production and generation of coal and natural gas contributed to a yearly 2.6–8.4% increase in the state's water consumption. Although some areas experienced no change in water consumption, others experienced large decreases or increases. Consumption variations depended on available natural gas resources and pre-existing power-generating infrastructure.

This analysis estimates monthly water consumption associated with fuel extraction and power generation within Pennsylvania watersheds between 2009 and 2012. It also provides the first comprehensive representation of changing water consumption patterns associated with the state's coal-to-gas transition at the sub-basin level.

The analysis shows that water consumption for natural gas energy extraction and production increased throughout the period, while for coal extraction and production it decreased. Water use for natural gas generation increased 67%, particularly in the Philadelphia and Pittsburg areas; water use for hydraulic fracturing increased nine fold in southwest and northeast Pennsylvania. By contrast, water use for coal extraction and production decreased 13%. In some areas, increased water consumption resulting from hydraulic fracturing was offset by decreased water consumption for power generation as plants switched from coal to natural gas. An interactive map and chart highlighting the changes can be accessed at www.nicholasinstitute.duke.edu/hydraulic-fracturing.

Executive Summary

The U.S. energy sector is shifting its focus from coal to natural gas, and this transition has fueled divergent perspectives on policy implications and environmental impacts (e.g., McJeon et al. 2015; Brandt et al. 2014). The use of natural gas for power generates lower greenhouse gas emissions (in the short term) and air pollution than coal and is better positioned to meet increasingly stringent environmental regulations such as the Clean Power Plan (EPA 2015; Pratson et al. 2013). The coal-to-gas transition has more subtle, complex implications for water resources. On the one hand, converting from coal to natural gas for electricity generation can reduce the amount of water consumed for power plant cooling by as much as 65% (Diehl and Harris 2014). On the other hand, expansion of hydraulic fracturing to extract natural gas resources increases water consumption, which may stress local water supplies (Gilmore et al. 2014).

Understanding water consumption in fossil resource extraction and power generation necessitates an evaluation of the timing and location of that consumption. Traditionally, life cycle assessments (LCAs) provide estimates of water consumption for power plants without incorporating specific locations or the timing of water consumption, which leads to questions about how changes in a sector may affect consumption patterns and local water supply. With some notable exceptions in air pollution (e.g., Tessum et al. 2012), LCAs do not typically include a spatial or a temporal component. Inclusion of spatial and temporal considerations is an important milestone in translating LCA results to actual impacts on local resources.

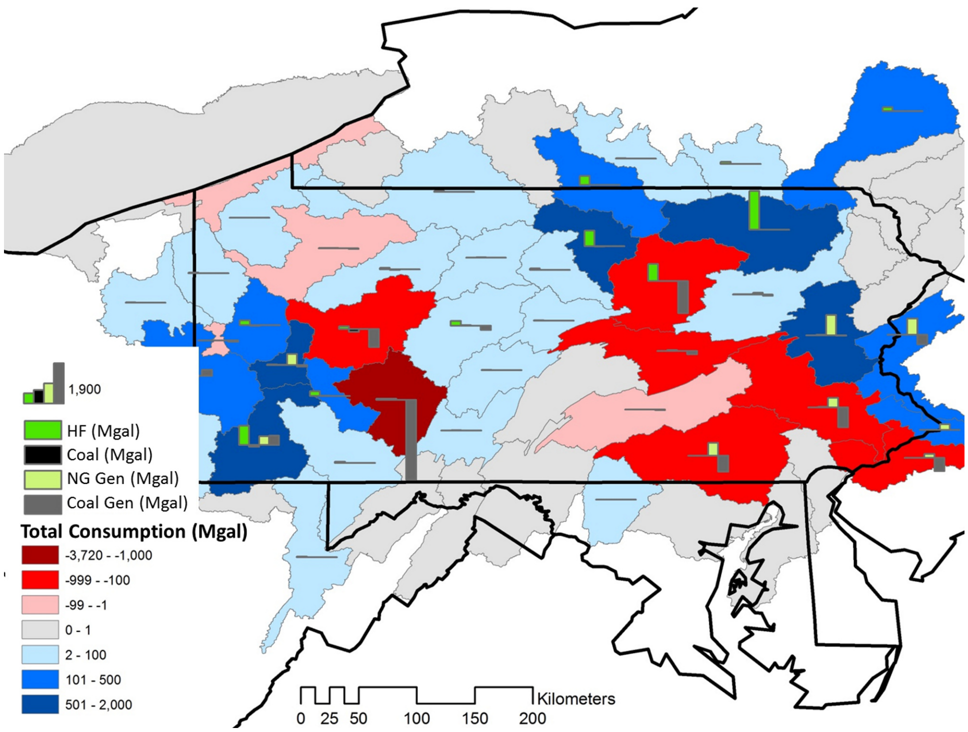
This paper develops an approach to estimate water consumption changes during the coal-to-gas transition at a spatial and temporal resolution higher than that undertaken by previous studies. Furthermore, it considers the transition from coal to natural gas in both the fuel extraction and power generation processes. The analysis focuses on Pennsylvania between 2009 and 2012, a period for which the necessary data are available. The evolution of water consumption is documented at a monthly temporal resolution and at a sub-basin (HUC-8) spatial resolution. Pennsylvania is an ideal region for this analysis because it has experienced both an increase in shale gas extraction and significant changes in its power generation fleet.

We found that overall water consumption in Pennsylvania related to fuel extraction and power generation (both coal and natural gas) increased from 80.1 billion gallons (Bgal) in 2009 to 82.2 Bgal in 2012, a 3%, increase. This increase was not uniform, however; the spatial and temporal variation associated with the coal-to-gas transition was notable. The southwest and northeast sub-basins with growing hydraulic fracturing activity experienced the greatest increase in water consumption, while the southeast sub-basins (major metropolitan areas that generated power from coal plants) experienced a decrease in water consumption (Figure ES1). Water consumption for both hydraulic fracturing and natural gas electricity generation increased steadily, whereas water consumption for coal extraction and for electricity generation peaked in 2011 and 2010, respectively, and has since declined. Annual water consumption peaked in 2010 at 86.8 Bgal (Table ES1).

Our analysis supports previous research findings, but it reconciles two opposing perspectives on the water implications of the coal-to-gas transition. First, shale gas resource extraction uses more water in a shorter amount of time than conventional extraction, making the spatial and temporal aspects of water consumption a critical component of any study of hydraulic fracturing's impacts on water resources. Second, the transition from coal to natural gas power plants decreases water consumption. More importantly, our analysis uncovers the spatial distribution and temporal fluctuations in the magnitude of water consumption related to this transition.

- From 2009 to 2012, hydraulic fracturing increased, raising water consumption for fuel extraction in Pennsylvania within each sub-basin with hydraulic fracturing activity.
- During this period, water consumed by coal power decreased by 13% while natural gas increased by 67%, which still resulted in a net decrease of 6% total water consumed for electricity generation across the state.
- The change in water consumption patterns varies by sub-basin, depending on fuel extraction and power-generating activities. Basins with hydraulic fracturing will increase their water consumption if there are no opportunities to transition from coal to natural gas-fired plants; however, basins where coal-fired plants transition to natural gas may decrease their overall water consumption.

Figure ES1. Change in overall water consumption between 2009 and 2012 for the coal-to-gas transition



Note: The bars for each sub-basin represent the magnitude of the increase or decrease in water consumption for each sector: gas extraction (Hydraulic Fracturing – HF), coal extraction, natural gas power (NG Gen), and coal power (Coal Gen). The color of each sub-basin denotes the absolute level of water consumption increase or decrease between 2009 and 2012.

Table ES1. Total water consumed in Pennsylvania as a result of coal and gas extraction and power generation (million gallons)

	Gas Extraction	Coal Extraction	Coal Power	Natural Gas Power	Total
2009	857	2,614	70,212	6,381	80,064
2010	3,529 ↑	2,831 ↑	72,787 ↑	7,622 ↑	86,768 ↑
2011	7,149 ↑	2,983 ↑	67,810 ↓	8,011 ↑	85,953 ↓
2012	7,542 ↑	2,578 ↓	61,411 ↓	10,682 ↑	82,212 ↓

Note: Circled arrows indicate whether consumption increased or decreased from the previous year.

The policy implications of this work span various decision-making levels. At the local level, decision makers approving permits and crafting policies to manage environmental impacts should consider local water implications of coal-to-gas transitions. For example, sub-basins with increasing shale gas extraction activity will experience water consumption increases if coal plants cannot be retired. In other cases, water consumption may decrease if coal plants can be replaced by a natural gas plant within the sub-basin. In short, the implications of the coal-to-gas transition on water depend on the location of shale gas plays and the pre-existing infrastructure of thermoelectric power plants. Relatively high temporal resolutions allow decision makers to identify and (if necessary) address peaks in consumption associated with power generation and hydraulic fracturing activity as well as to manage seasonal fluctuations in water availability.

At the national level, decision makers seeking to understand the possible implications of new technology developments and broad sectoral transitions should take into account other environmental and resource impacts, such as water. Early on, decision makers would benefit from evaluating possible water consumption trends in related sectors (e.g., the impact of lower natural gas prices on other major resource users, such as power generation), because these trends could have unanticipated localized impacts. National-level agencies could, for example, conduct regional analyses to identify areas in which new technology developments can have significant water consumption impacts or benefits. State and local agencies could then be alerted to the need for more detailed analysis in specific locations.

Introduction

Shale gas became economically attractive in the United States in the early 21st century when techniques for hydraulic fracturing and horizontal drilling were coupled to enable increasingly cost-effective shale gas extraction. Wells with this combination of technology are referred to as "unconventional" and have contributed to what many refer to as the "coal-to-gas transition" (Wigley 2011). Unconventional wells may refer to shale gas, coal-bed methane, tight gas, and other emerging extraction methods. This paper focuses on unconventional wells drilled to extract shale gas.

The rapid growth of shale gas wells increased shale gas production by 540%, from 2,116 billion cubic feet (BCF) in 2008 to 11,415 BCF in 2013 (EIA 2015). The high water consumption of unconventional gas extraction compared with that of conventional gas extraction has been the subject of many studies (Mielke et al. 2010; Williams and Simmons 2013). Mielke et al. (2010) reported that water consumption increases from 0 gallons per million British thermal units (gal/MBtu) for conventional gas extraction technology to 1.3 gal/MBtu for shale gas extraction, although water consumption intensity for shale gas extraction varies widely, depending on well type, geology, and technology.

Technological advances arising from the combination of horizontal drilling and hydraulic fracturing led to the recent boom in natural gas production. Abundant natural gas reserves and high levels of drilling activity have driven average natural gas prices in the United States down from peaks exceeding $12/MBtu in 2008 to steadily below $3/MBtu in 2015 (EIA 2015). The lower gas prices have changed the economics of coal and gas power generation in the United States, which, in addition to expectations about future federal carbon policies, are contributing to a switch from coal to gas. Changes in the power generation fleet (coal, natural gas, oil, biogas, hydro, nuclear, wind, and solar) are driven by multiple factors, including lower gas prices, market economics in the chemical and petrochemical industries, environmental regulations, improved technology, and local rulings that affect power generation investments. The transition from coal to gas in the electric sector is generally known to conserve water (Mielke et al. 2010; Grubert et al. 2012). On average, combined cycle natural gas plants consume approximately 65% less water per kilowatt hour (KWh) than coal power plants. While water consumption for shale gas extraction is increasing, the decrease in water consumption associated with a coal-to-gas transition in electricity suggests that local water impacts may not be trivial and may vary, depending on power plants and shale gas extraction opportunities within a region.

Water is often referred to as a "local" issue in that the amount of surface water in an area is contained within a watershed; the quantity of water generally increases as it flows downstream. Water availability varies temporally, depending on weather, land cover, and demand, as well as spatially between adjacent watersheds and within single watersheds.

In spite of the local nature of water, no study appears to have evaluated the impact on water consumption associated with the rapid expansion of shale gas extraction and the increase in gas power generation at the expense of coal power within a river basin. Using data from Pennsylvania, which has been an important player in shale gas extraction and where the power generation fleet has experienced a shift from coal to gas, this paper estimates the monthly water consumption within a sub-basin (average area is 3,150 km^2) that is related to hydraulic fracturing and coal extraction as well as to natural gas and coal electricity generation between 2009 and 2012, thereby capturing the changing landscape of water consumption in the coal-to-gas transition. It is the first analysis, of which we are aware, to estimate the water consumption impacts of both fossil fuel extraction and fossil power generation at a sub-basin level.

This analysis compares water consumption (water that is removed from a source and not returned), *not* water withdrawals (water diverted from a source regardless of whether it is later returned). Compared with electricity generation, fuel extraction tends to be consumptive (water withdrawals equal water consumption). In contrast, power production accounted for 41% of all freshwater withdrawals in the United States in 2010 (Maupin et al. 2014), yet only 3–4% of the water withdrawn is consumed (Diehl and Harris 2014).

This study makes two main contributions: (1) it develops a method to estimate water consumption associated with fuel extraction and power generation at a spatial and temporal resolution higher than that of previous studies, and (2) it provides a comprehensive picture of the changing water consumption patterns in the coal-to-gas transition while accounting for both fuel extraction and power generation.

We found that some sub-basins experienced a net increase in water consumption because of increased hydraulic fracturing. Other basins experienced the opposite effect: increases in water consumption for hydraulic fracturing were offset by decreases in water consumption in power generation as plants switched from coal to natural gas. These findings show that to properly address the water consumption impacts of the coal-to-gas transition, policy and investment decisions in the water and energy sectors must account not only for the spatial and temporal characteristics of water consumption, but also for water consumption in related sectors.

The remainder of this paper provides information on fuel extraction, power generation, and life cycle assessment and describes the analysis in terms of geography and types of human activity as well as methods and data used. It concludes with discussions of results and their implications for policy and future research.

Background

Fuel Extraction

Widespread extraction of coal has occurred since the industrial revolution. Coal mining processes are typically categorized into surface and underground mines, depending on the depth and thickness of the coal seam. The amount of water used in coal mining depends on mine location (underground or on the surface) and size (Mielke et al. 2010). Additional water is used to wash coal to remove sulfur and impurities.

Natural gas traditionally has been extracted through conventional wells that are drilled vertically and that tap into pockets of natural gas. Water is required only during the drilling phase; little to no water is required to stimulate the flow of gas back up into the well. In contrast, shale gas wells are drilled into formations that contain natural gas throughout the rock layer and that require millions of gallons of water to fracture the rock and create space for the natural gas to flow up into the well. As a result, water use for unconventional wells is much greater than that for conventional wells.

Power Generation

Coal has long been the dominant fuel for electricity generation; the first coal-fired plant was built in the United States in 1882 (Speight 2012). The use of coal to produce energy in the United States decreased from 1.02 B short tons per year in 2009 to 0.89 B short tons in 2012 (EIA 2015b). During that period, the amount of natural gas used to produce energy in the United States increased from 22.9 (BCF) in 2009 to 25.5 BCF in 2012 (EIA 2015c). Power generated from new natural gas-fired plants has approximately 65% lower emissions intensity, defined as the level of emissions per unit of energy, than coal plants (Diehl and Harris 2014). In principle, natural gas provides an opportunity to reduce climate impacts in the short term. In the long term, greenhouse gas emissions associated with a buildup of gas extraction and gas power facilities may lead to an overall emissions increase (McJeon et al. 2015; Brandt et al. 2014).

Shifting patterns of energy production will also change water consumption patterns as new regions experience growing oil and gas activity, coal plants retire, and new natural gas plants and other sources of renewable power come online. Water is used in the thermoelectric process to create electricity by converting water into high-pressure steam to drive turbines; the techniques for cooling steam also affect the amount of water used. Natural gas combined cycle (NGCC) plants require approximately 35% of the water required by coal power plants (Diehl and Harris 2014).

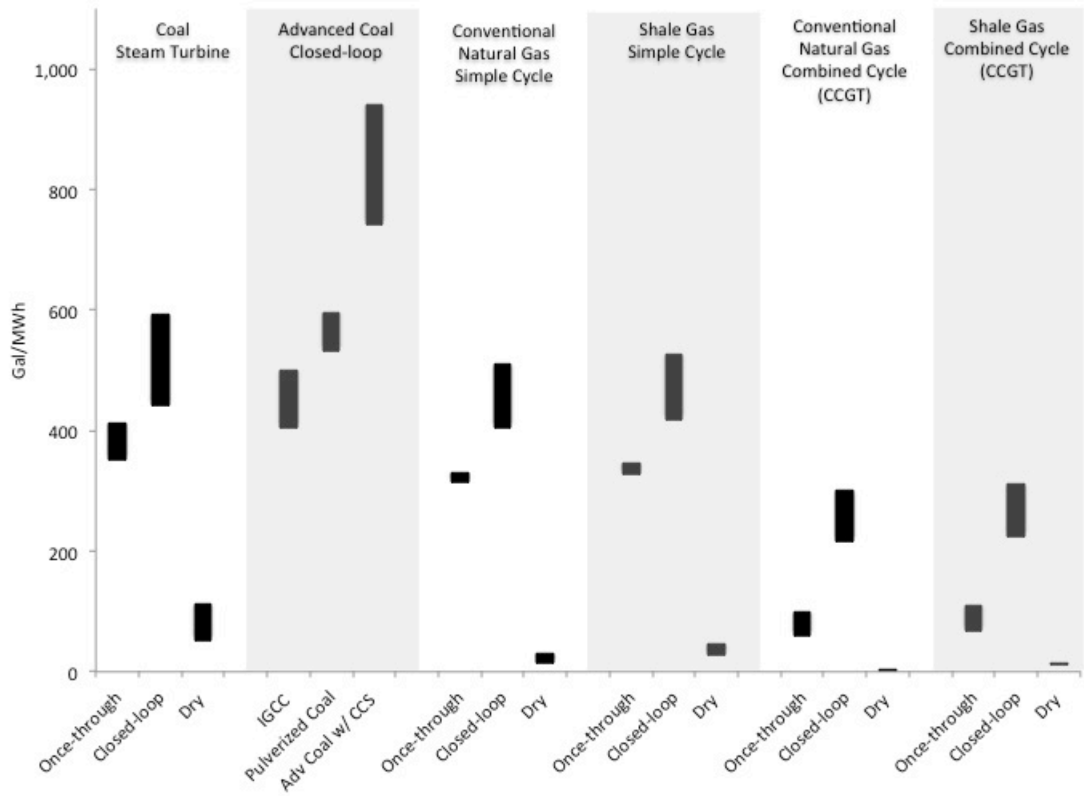
Life Cycle Assessment

Life cycle assessment (LCA) is a method for examining the potential environmental impacts associated with a particular activity or service from materials extraction to waste disposal (cradle to grave). This analysis uses a life cycle perspective to determine water consumption changes during both coal and natural gas processes of extraction and electricity generation. Here, *extraction* refers to the removal of coal and natural gas from the ground. LCAs typically exclude spatial and temporal information and provide aggregated results only for natural resource use (Reap et al. 2007). The inclusion of geographical variation is still in development, particularly for water (Koelher 2008). Surface water, unlike gas emissions, is spatially constrained to watersheds; the volume flowing from upstream to downstream depends on many factors such as precipitation, land cover, and water demand. Analysis at a fine temporal and spatial resolution is more important for water than for greenhouse gas emissions. Without a spatial and temporal component, LCAs of water consumption for energy extraction and generation are not sufficient to determine localized impacts on water budgets.

Water consumption for shale gas extraction has typically been addressed at a national, state, or river basin scale (Jordaan et al. 2013; Murray 2013; Nicot and Scanlon 2012) and has not been investigated at higher spatial and temporal resolutions. Jordaan et al. (2013) highlighted the importance of increasing spatial resolution from the state level, and although Grubert et al. (2012) recognized the role of site-specific data in improving the accuracy of water consumption estimates, their results were presented at the resolution of the state. Furthermore, LCAs of coal and natural gas electricity generation have been limited in capturing the spatially and temporally heterogeneous impacts of the coal-to-gas transition. When LCAs are applied to relatively fine spatial resolutions, in this case river basins, the prevalence of dry conditions within regions begin to emerge, and areas that were previously thought to be unaffected by the choice of electricity generation are shown to be sensitive to that choice—that is, to be more likely to have that choice limited by the potential for water shortages (Pfister et al. 2011; Sovacool and Sovacool 2009). This paper builds on previous LCAs to examine the cumulative impacts of interconnected sectors by exploring the changes in water consumption at a high temporal (monthly) and spatial (sub-basin) scale. Understanding local water consumption due to developments in highly related sectors allows policy makers and investors to identify areas at low or high risk for water shortages as well as risk-mitigating approaches and technologies.

There are two contrasting views on how the growth of shale gas extraction is affecting water consumption. In one view, shale gas extraction is increasing water consumption; in the other, shifting from coal power plants to natural gas power plants is decreasing overall water consumption. Whereas the fossil fuel extraction community focuses on the amount of water used per well and the relative impact on local streams, the power generation community focuses on water consumption per megawatt of thermoelectric power using non-spatial LCAs that find that hydraulic fracturing does not significantly change water use intensity (Figure 1). However, this finding does not match the reality of restrictions on water withdrawals for oil and gas during times of low flow (e.g., Detrow 2012). Only by incorporating spatial and temporal considerations can LCAs capture actual impacts to local resources.

Figure 1. Influence of technical and fuel characteristics on water consumption for electricity generation



Source: Modified from Jordaan et al. (2011).
Note: Three types of cooling technology were assessed: once-through, closed-loop, and dry cooling. Coal-fired electricity generation technologies included steam generation, integrated gasification combined cycle (IGCC), pulverized coal, and advanced coal technologies with carbon capture and storage (Adv Coal w/ CCS). Natural gas technologies include steam generation and combined cycle natural gas. Two cases for natural gas fired electricity were assessed: (1) conventional natural gas and (2) shale gas using hydraulic fracturing.

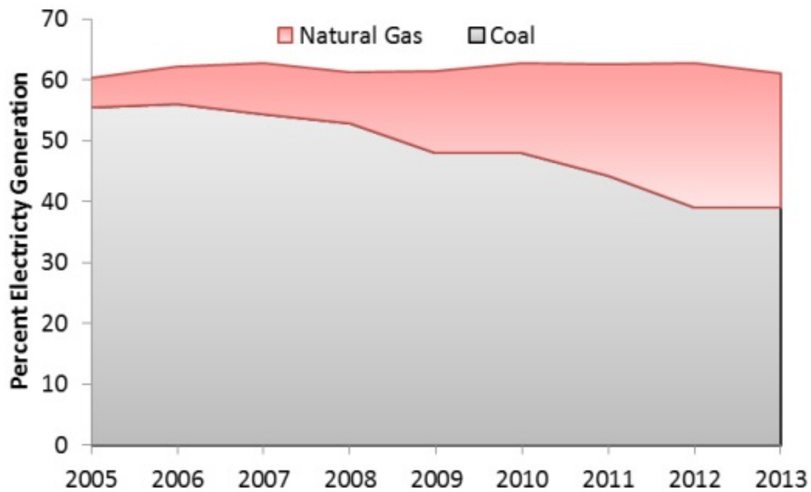
Study Area and Objectives

Coal-to-Gas Transition in Pennsylvania

In Pennsylvania, both coal and shale gas extraction and electricity generation have changed dramatically since 2008. Thus, exploring spatial and temporal variation in water consumption with expansion of shale gas extraction and natural gas electricity generation provides insight into the localized impacts of energy sector changes on water consumption. Although this paper focuses on the coal-to-gas transition in Pennsylvania, its analysis could be applied to other regions undergoing a similar transition.

Shale gas drilling began in the Marcellus Formation in Pennsylvania in 2005; by the end of 2013, more than 6,700 wells had been drilled (PADEP 2013). During that period, Pennsylvania's natural gas extraction increased by a factor of 19, from 168,500 million cubic feet (Mmcf) to 3,259,000 Mmcf (EIA, 2015d), contributing to 27% of U.S. production (EIA 2015a). In addition, Pennsylvania nearly doubled its natural gas consumption, from 691,600 Mmcf to 1,222,000 Mmcf (EIA 2015d), while the amount of coal consumed for electricity generation decreased from ~54.5 M short tons to 42 M short tons (EIA 2015e). The share of natural gas contributing to electricity generation in the state increased from 5% in 2005 to 24% in 2012, while coal-fired generation decreased from 55% to 39% (Figure 2) (EIA 2013).

Figure 2. Changes in coal and natural gas power generation in Pennsylvania, 2005–2012



Although water is seemingly abundant in Pennsylvania, seasonal fluctuations in water availability combined with changing patterns of water consumption and withdrawals for energy may mean that regulation and policy are required to limit impacts to local water supply. Pennsylvania has abundant surface water resources with more than 83,260 stream miles (van Rossum et al. 2007) spread across three major river basins: Delaware, Ohio, and Susquehanna (Figure A1 in the appendix). Although precipitation is fairly constant year round, streamflow is greatest in the winter and spring months (e.g., the Upper Ohio River has a median streamflow of 1,700 cubic meters per second, or cms, in March and 290 cms in August). The decrease in streamflow results from increased evaporation due to warmer temperatures, increased vegetation water needs, and increased human water demand. In 2010, 92% of freshwater withdrawals were taken from surface water supplies across the state (Maupin et al. 2014).

Coal mines and natural gas wells are concentrated within regions, resulting in large spatial variation across the state. In addition, the water demand for coal mining is relatively constant with production, whereas the water demand for hydraulic fracturing is concentrated in a two-to-five day period. The highly concentrated period of consumption for hydraulic fracturing can pose limits to drilling activity if water sources are predominantly on small streams, during dry periods (summer or drought), or both. The cumulative impacts of multiple wells withdrawing water from a small stream during the summer or during a drought could pose significant water scarcity risks and adverse ecological impacts (SRBC 2013). Such risks can be managed at the basin level by entities such as the Susquehanna River Basin Commission (SRBC). The SRBC was signed into law in 1970 by Congress and the legislatures of New York, Pennsylvania, and Maryland to manage shared water resources. In accordance with its mandate, the SRBC regulates water acquisitions and issues permits for withdrawals that constrain their volume, rate, and timing. The SRBC requires that all water withdrawals from oil and gas must cease when streamflow drops below 20–25% of normal; the withdrawals may not resume until streamflow rises above the predetermined threshold. The SRBC suspended water withdrawals due to dry conditions in both 2011 and 2012 (Detrow 2012).

Water consumption for electricity generation also varies on the basis of factors such as environmental influences, demand, loads, and dispatch algorithms. Demand tends to peak in the summer and winter months with heating and cooling needs. During the summer, increased water consumption is required in electricity generations due to relatively low temperature differences between cooling water and combustion.

Objectives

In the United States, the rapid expansion of hydraulic fracturing and natural gas production represents a significant, continuing shift in both energy extraction and generation patterns as well as related water consumption patterns, which are spatially and temporally dynamic. This study aims to improve the spatial and temporal resolution of LCA methods for interlinked sectors of fossil resource extraction and power generation, thereby increasing understanding of the water implications of energy production and generation choices within Pennsylvania.

Methods

LCAs of water consumption are typically non-spatial (Reap et al. 2007), with a few exceptions that include state-level analysis (e.g. Jordaan et al. 2013). This study estimates the monthly water consumption of fuel extraction and thermoelectricity generation that is related to coal and natural gas within sub-basins in Pennsylvania.

Water Consumption Data for Shale Gas Extraction

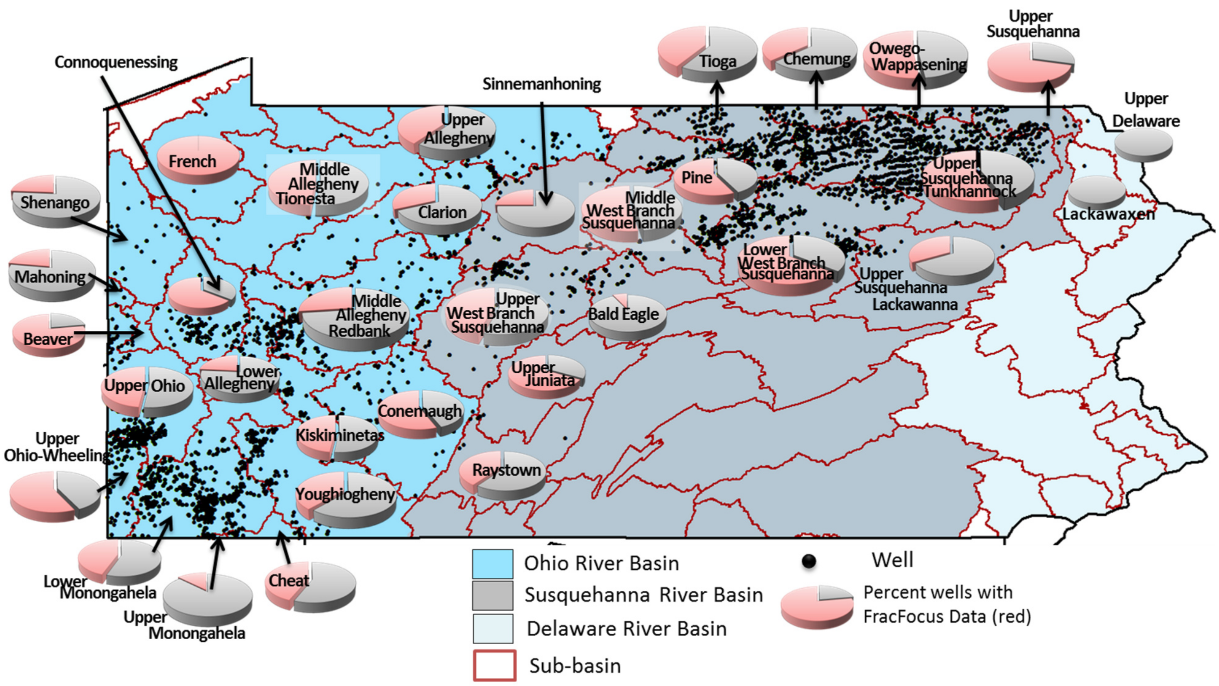
Obtaining a fine spatial and temporal resolution of water consumption for energy production and extraction is difficult because no regulations require the industry to report on water sources and therefore no unified database exists (Sullivan et al. 2015; Nicot et al. 2014). The oil and gas industry will use the water sources that are most readily available and economic at the time they are ready to fracture a well. In Pennsylvania, surface water resources are typically abundant, and this analysis assumes that the industry attempts to extract water from nearby resources to reduce piping and trucking costs (Nicot et al. 2014; Mitchell et al. 2013; Kargbo et al. 2010). Gilmore et al. (2014) found that most truck trips to haul water were less than 10 miles in the Susquehanna River Basin. As a result, the assumption of this analysis is that water extraction occurs within the same sub-basin as the wells being fractured. This assumption was used to refine the spatial resolution of water withdrawals for hydraulic fracturing to a sub-basin (average of 3,100 km^2), rather than to use an entire river basin (71,000 km^2 for the Susquehanna) or state scale.

Oil and gas production data for the Marcellus Shale was obtained from the Pennsylvania Department of Environmental Protection (PADEP 2014). This database was supplemented with data obtained from DI Desktop (2014), which is a database designed to provide information regarding U.S. oil and gas production and drilling permits. This database was used to check the quality of the PADEP dataset with regard to spud date (the day drilling of the well began) and well type (vertical or horizontal). There were 10,062 unique wells in the PADEP database at the end of 2013.

The FracFocus Chemical Disclosure Registry was used to obtain the amount of water withdrawn to fracture a well (a single value that includes freshwater and recycled water) and the completion date (FracFocus 2014). Pennsylvania joined FracFocus in 2011, and oil and gas submissions of water use and chemical disclosures to FracFocus became mandatory in 2012. Little data are available for wells completed prior to 2011. Additionally, the compliance of operators reporting to FracFocus has been slow, resulting in missing data (Soraghan 2013). More than 60% of Pennsylvania wells had reported to FracFocus between July 2011 and December 2013 (Table A1 in the appendix). Wells reported in the PADEP do not contain information on completion dates or volumes of water used; therefore, estimates of each were computed for those wells missing FracFocus data as detailed below. An estimated 4,857 wells were fractured between 2009 and 2012.

The PADEP database provides coordinate locations for all wells. Intersection of these locations with the polygonal boundaries of sub-basins (HUC8) in a Geographic Information System (GIS) indicated that 34 sub-basins had hydraulic fracturing activity. The average sub-basin size was ~3,100 km^2 and contained 1 to 1,963 wells (average = 215). Wells with FracFocus data are present in all sub-basins except within the Delaware River Basin (n = 3 vertical wells). Sub-basins with more than 200 wells had at least 40% FracFocus coverage (Figure 3; Table A2 in the appendix).

Figure 3. Well locations overlaying sub-basin boundaries



Note: Pie charts indicate the percent of wells with FracFocus data within each sub-basin.

Fracture Dates and Water Volumes

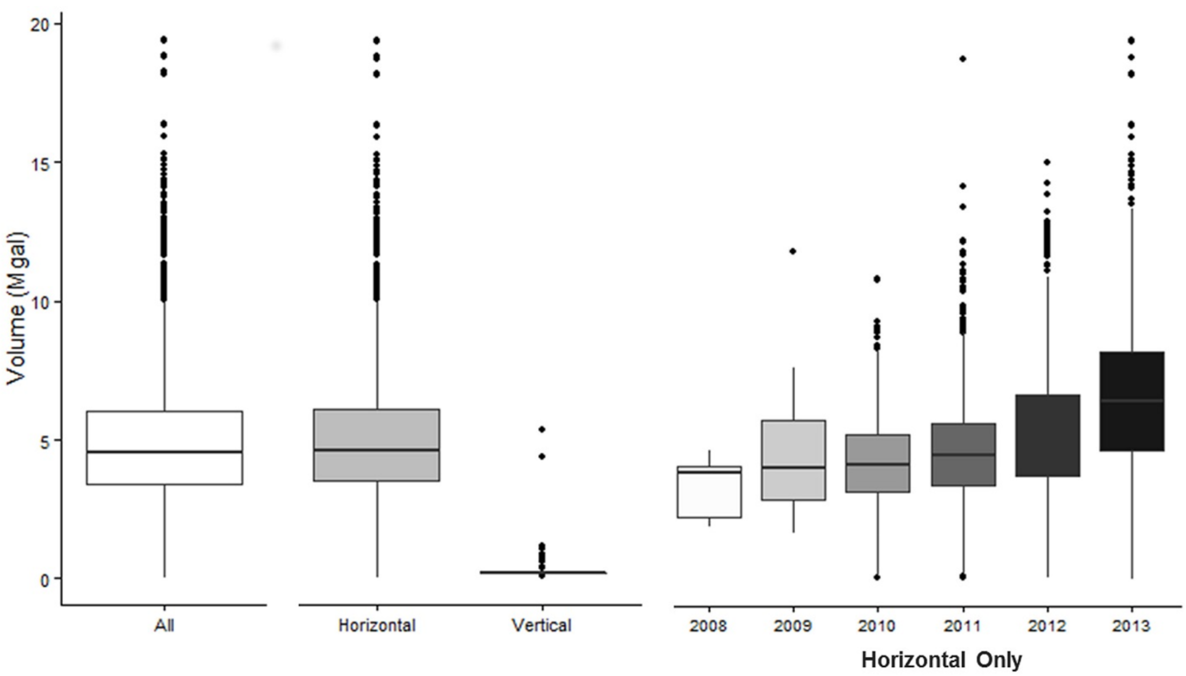
FracFocus data (completion data and water volume) were available for approximately half of all wells in this analysis. Spatial, temporal, and operator differences in FracFocus reporting are large. Spatial variation in FracFocus coverage ranges from 0% to 100% within a sub-basin; no spatial patterns of under-reporting are evident (Figure 3 and Table A2 in the appendix). The two sub-basins reporting more than 1,000 wells had 44% to 56% coverage. Temporal variation in reporting is clear; a sharp increase occurred between 2010 and 2011 (Table A1 in the appendix), after Pennsylvania officially designating FracFocus as its medium to meet chemical disclosure regulations. Therefore, wells fractured after 2010 are more likely to have data regarding fracturing date and water volumes.

The amount of water used at individual wells can vary widely within a play due to geological variation in the rock formation, well length and depth, operator methods, and technological improvements (Kargbo et al. 2010; Soeder and Kappel 2009). The volume of water injected into Marcellus wells has been found to range from 2 to 13 Mgal with an average of 4 Mgal per well (Clark et al. 2013; Nicot et al. 2014; Vengosh et al. 2014). Due to the known variability in water use, linear regressions were applied to the 3,647 wells with FracFocus data to assess the factors associated with different lag times between when a well was drilled (spud date) and when it was fractured (completion date) as well as to estimate the volume of water used.

When assessing the factors associated with lag time (number of days), the spud year was a significant factor; the number of lag days decreased by an average of 70 days each year, presumably as experience and technology improved. A few of the operators and most of the sub-basins were found to be statistically significant predictors of the time between drilling and fracturing a well. These statistically significant factors of spud year, operators, sub-basin, and well type (horizontal or vertical) were applied to estimate the lag time for wells without FracFocus data and therefore to estimate the wells' completion date.

Factors associated with differences in the volume of water used to fracture a well were then analyzed. Again, the spud year was statistically significant; an average of an additional 0.47 Mgal was used each year, presumably as horizontal well lengths increased (Nicot et al. 2014). The type of well—vertical or horizontal—was statistically significant; vertical wells used an average of 4 Mgal less water than horizontal wells (Figure 4).

Figure 4. FracFocus reported water volumes used to fracture wells by well type and spud year



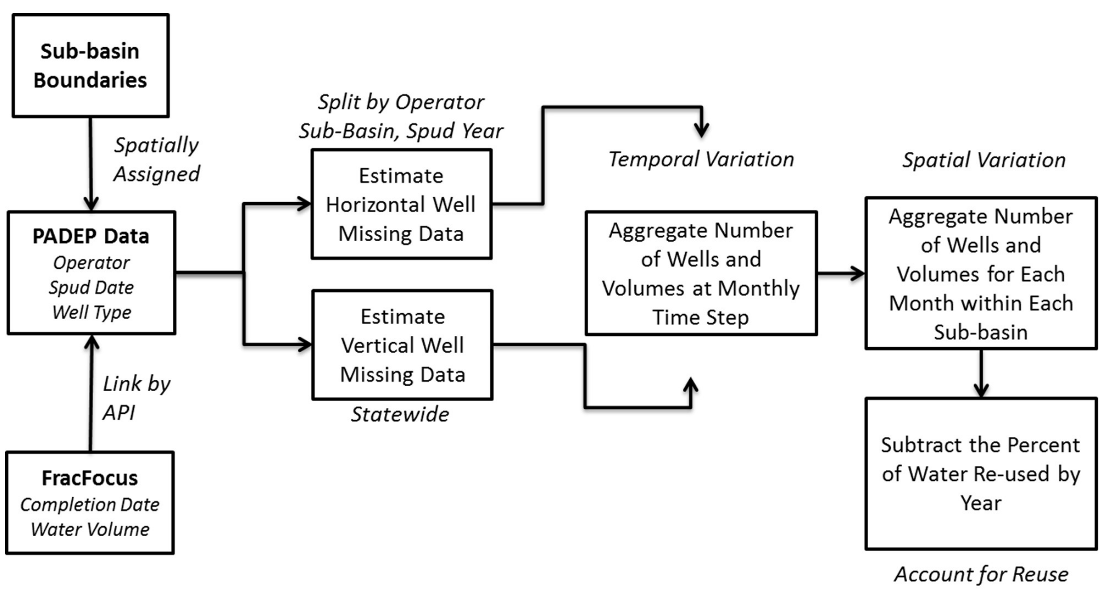
There were 6,453 horizontal wells managed by 49 operators. However, most wells were fractured by a few operators; six operators accounted for 58% of all horizontal wells (57% of FracFocus data). Individual operators, sub-basin, and spud year were all significant factors used to estimate the fracture date and volume of water for those wells without FracFocus data (Figure A2 in the appendix). Median water volumes for wells owned by operators who had no reported FracFocus values were imputed on the basis of spud year and sub-basin.

Of Pennsylvania's 843 vertical wells (12%), only a small fraction (n=77, 9%) had FracFocus data. Only 11 of 51 operators reported to FracFocus and only 3 of the 11 operators reported more than 5 wells. Given the limited data available to estimate water use for vertical wells, the analysis applied the median time lag between spud date and completion date for all vertical FracFocus wells to those missing data. It also applied the median water volume for vertical wells reported in FracFocus to those wells with missing data. Well water volumes estimated for use in vertical fracturing accounted for a small percent of total estimated water consumption (0.8%). Given the small contribution of vertical wells to total water consumption (they make up only 12% of the total number of wells and use less water than horizontal wells), the lower reliability of the estimates for vertical wells is unlikely to have an impact on water use results at a sub-basin level.

Water Volumes Over Time for Each Sub-Basin

Regressions were used to estimate fracture date and volume of water for wells missing FracFocus data. This information was used to determine the number of wells and the cumulative water volume consumed by hydraulic fracturing for each month between 2009 and 2012—data that matched the water use data available for coal extraction and electricity generation. Between 2009 and 2012, an estimated 4,857 wells were fractured. The estimate of the number of wells fractured during this period at the sub-basin level agrees with published studies. For example, the estimate of 2,282 wells in the Susquehanna River Basin nearly equals the SRBC (2013b) records for 2,226 well completions during the study period. Lastly, the volume of water used for hydraulic fracturing was summed within each sub-basin at a monthly time step (Figure 5).

Figure 5. Schematic illustrating the process used to estimate water volumes within a sub-basin over time



Recycled Water Used for Hydraulic Fracturing

In Pennsylvania, a growing percentage of flowback (water injected for shale gas extraction that returns to the surface) and produced water (water that was originally in the shale formation and that flows to the surface) are recycled and used for hydraulic fracturing in place of freshwater resources. The return flow from a hydraulically fractured well in the Marcellus is relatively low at 6% to 12% of what is injected (Maloney and Yoxtheimer 2012; Hansen et al. 2013).

Because FracFocus data do not distinguish whether water used for hydraulic fracturing originated from a freshwater source or was recycled, this analysis used estimates from Hansen et al. (2013), who reported that 6% of water used for hydraulic fracturing was from recycled sources in 2010, increasing to 10% in 2012. By extrapolation from the trend implied by those numbers, it was estimated that 5% of water used for hydraulic fracturing was from recycled sources in 2009 and 7% of that was from those sources in 2011. According to PADEP data, the percent of return flow that was recycled had grown to 70% (853 Mgal) in 2012 (Patterson and Maloney, submitted). If 853 Mgal of recycled wastewater was used to fracture wells (Patterson and Maloney, submitted), it would mean that 13% of the water used for hydraulic fracturing in 2012 was recycled wastewater (given that 6,407 Mgal of water is estimated to have been used for hydraulic fracturing in 2012). Thus numbers in this analysis and in Hansen et al. (2013) are in good agreement. This analysis subtracted the percent of water reused from the total water volume by year to estimate only freshwater volumes.

Water Consumption Data for Coal Extraction

Coal location data were obtained from the Mine Safety and Health Administration (MSHA) Mines Data Set, and coal production estimates were obtained from the Employment/Production Data Set (yearly) (MSHA 2015). Data sets were combined using the mine's unique ID. To estimate water consumption, the analysis applied water intensity values to mining (amount of water required for each MMBtu of coal produced) on the basis of coal mine type from Mielke et al. (2010) to the production values for each coal mine (Table A3 in the appendix). Water intensities ranged from 1 gal/MMBtu for underground mines to 6 gal/MMBtu for surface mines, plus an additional 1–2 gallons for washing. Data are reported using monthly time steps because that was the temporal resolution available for power and gas extraction. Although the assumption that coal production is constant throughout the year introduces some uncertainty, the order of magnitude provides a baseline for understanding how water consumption for fuel extraction compares with that for electricity generation.

Water Consumption Data for Electricity Generation

The location of and the electricity generated by power plants were extracted and compiled from EIA's Annual Electric Generator Dataset (EIA-860) and Annual Electric Utility Dataset (EIA 923) at a monthly time step. The water intensity (gallons per MWh) of different types of power generation and technologies were compiled from Mielke et al. (2010) and updated with operational values from Macknick et al. (2011) (Table A4 in the appendix). The water intensity values were then applied to the monthly power generation by plant type and technology. Data from the EPA's Emissions and Generation Resource Integrated Database (eGRID; http://www2epa.gov/energy/egrid) were used to fill data gaps. Key assumptions about cooling technology for power plants at specific sites were sourced from the Union of Concerned Scientists (2011) power generation database.

Results

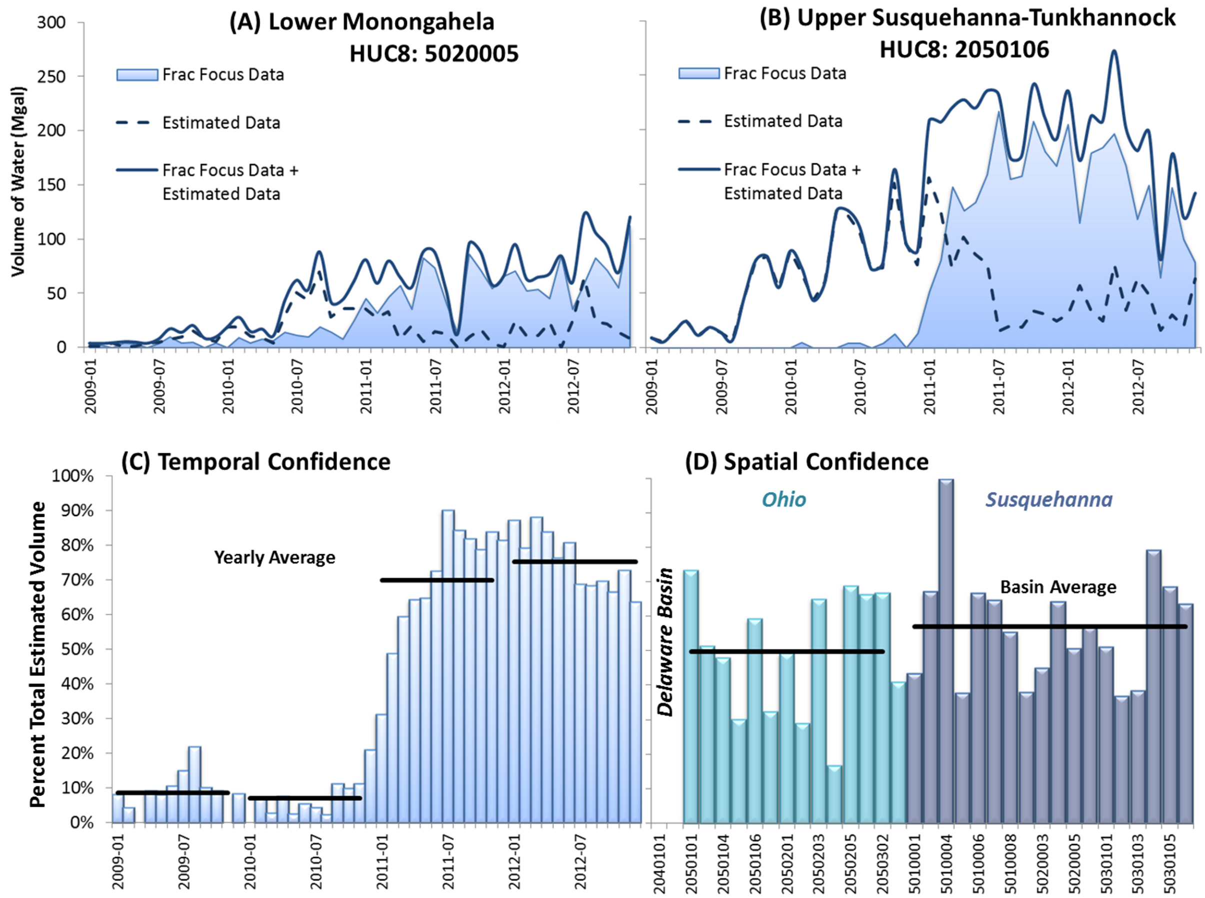
Natural Gas Extraction: Hydraulic Fracturing

Monthly Water Consumption

During the study period (2009–2012), 5,027 wells were fractured. FracFocus data were available for 2,516 (50%) of those wells (Table A1 in the appendix). The lack of high-resolution temporal and spatial data on freshwater resources extracted for hydraulic fracturing requires estimation of the timing and volumes of water used for hydraulic fracturing in the remaining 50% of wells. This estimation introduces uncertainty into the analysis, as illustrated by summing water consumption in a sub-basin according to FracFocus data (Figure 6A and 6B) with estimated water consumption by wells for which no FracFocus data are available. Estimates of water consumption prior to 2011 are greater than those after 2011, which is to be expected given that FracFocus was not officially utilized by Pennsylvania until 2011. In contrast, FracFocus data represent more than 70% of water consumption estimates for sub-basins in which the majority of hydraulic fracturing activity occurred between 2011 and 2013 (Figure 6).

By aggregating all hydraulic fracture data, we found FracFocus to include some 9% of the estimated water volumes prior to 2011. From 2011 to 2012, FracFocus represented more than 70% of the estimated water volumes used for hydraulic fracturing (Figure 6C). When exploring the percent of FracFocus-reported water consumption compared with the total amount of water consumption after estimating volumes for wells not represented by FracFocus data, we found that variability by sub-basin ranged from 16% to 100%. FracFocus included an average of 50% of water volume estimates in sub-basins in the Ohio River Basin, and an average of 57% of those estimates in the Susquehanna River Basin (Figure 6D).

Figure 6. Percent of estimated freshwater volume included in FracFocus data

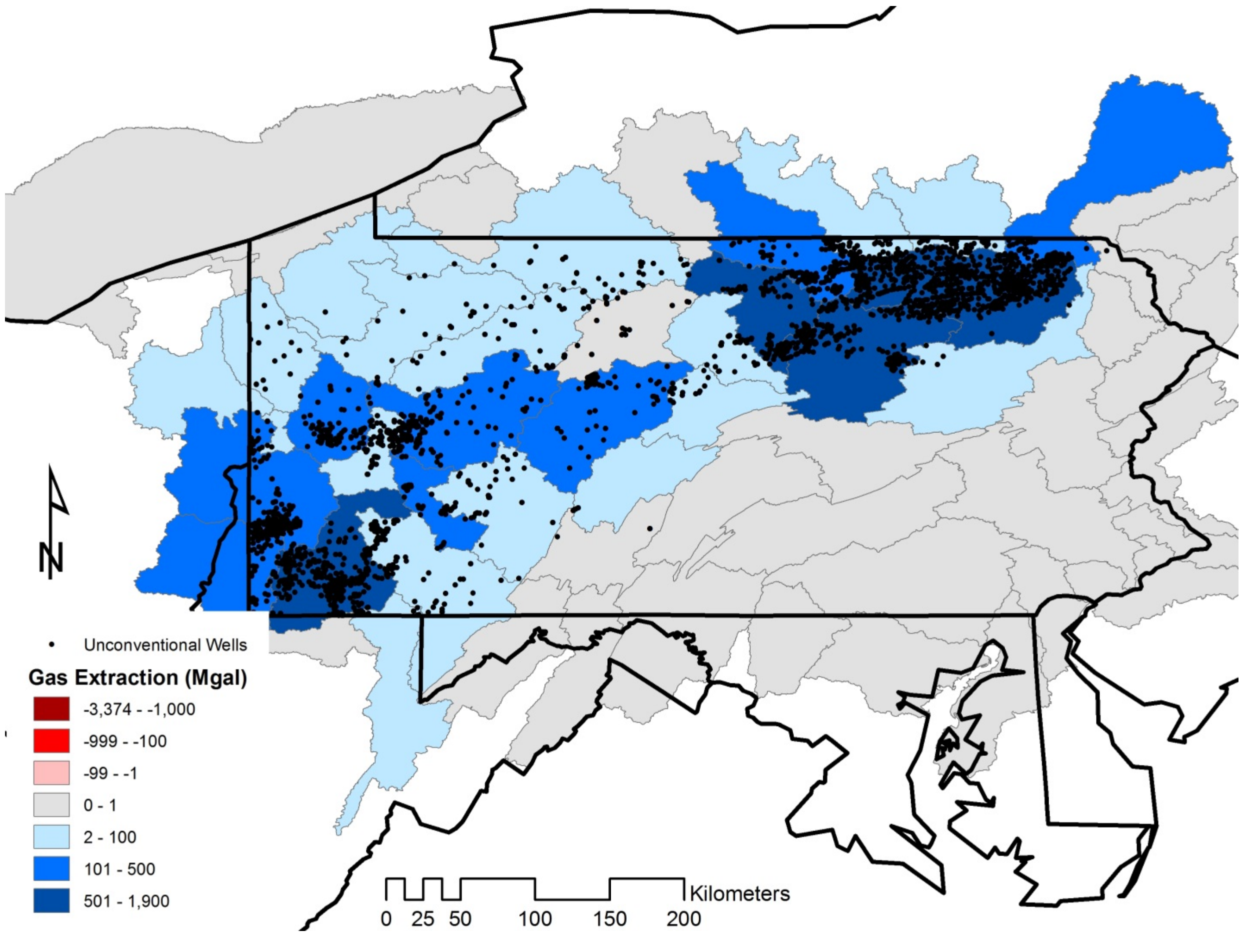


Note: (A) and (B) reflect two basins with high unconventional well activity and show the total estimated water volume in comparison with the volume of water reported to FracFocus, (C) reflects the percent of water volume reported by FracFocus (100%: FracFocus-reported volume + estimated volume), and (D) reflects the percent of water volume from FracFocus data by sub-basin.

Changes in Water Consumption for Hydraulic Fracturing Over Time

The amount of water used for hydraulic fracturing increased from 2009 to 2012 (Figure 7). Peak shale gas activity occurred in Pennsylvania in 2012 (Sullivan et al. 2015). The greatest increase in water consumption was in the Upper Susquehanna-Tunkhannock Basin (HUC 2050106), where 1,833 Mgal more water was utilized for hydraulic fracturing in 2012 than in 2009. Two other sub-basins in the Susquehanna River Basin also had a water use increase of more than 500 Mgal due to unconventional well activity: Pine (HUC 2050205) increased by 746 Mgal and the Lower West Branch Susquehanna (HUC 2050206) by 810 Mgal. In the Ohio River Basin, one sub-basin had a water use increase exceeding 500 Mgal: Lower Monongahela (HUC 5020005). Areas outside of these peak zones of activity experienced a more modest increase in water use (Figure 7). Because hydraulic fracturing was relatively new to Pennsylvania in 2009, no decreases in water use for natural gas extraction are seen.

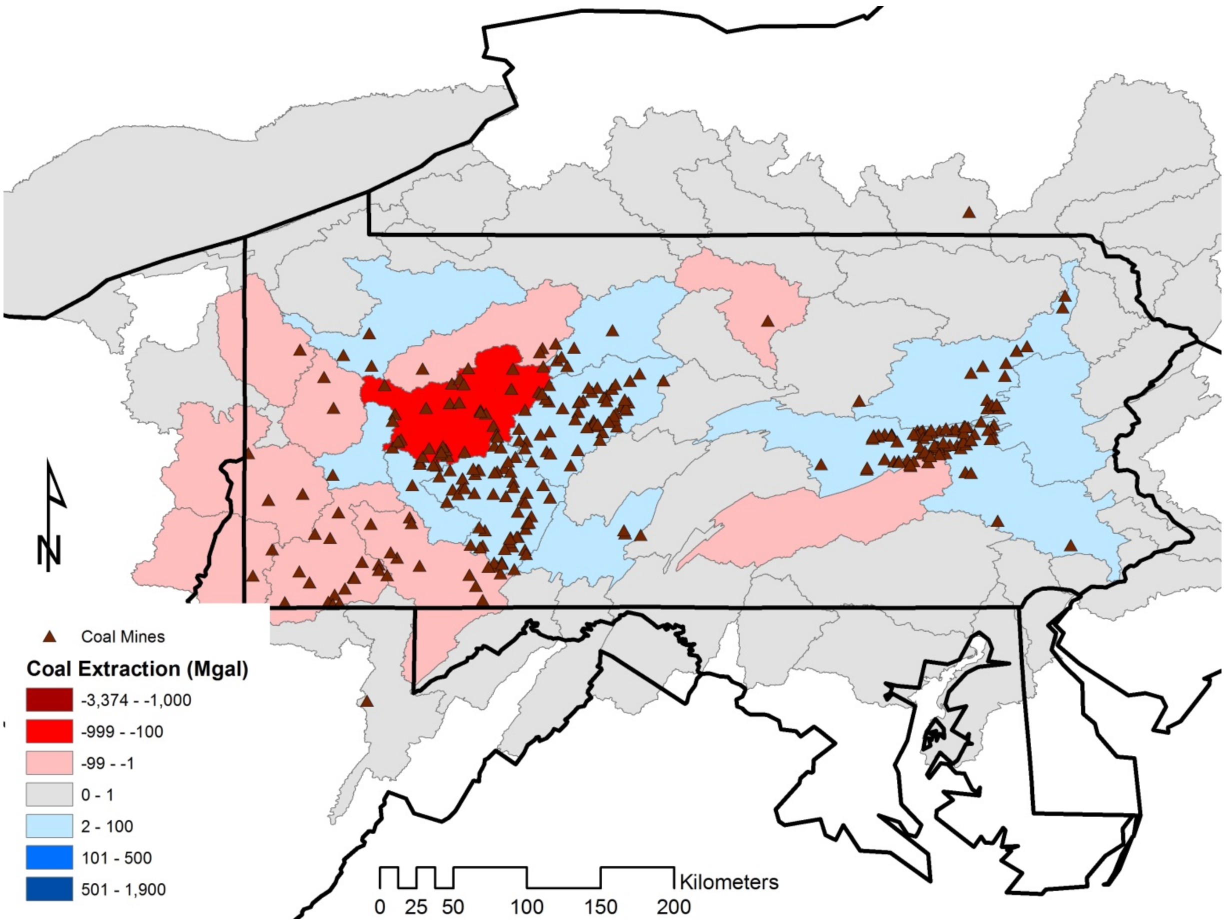
Figure 7. Change in amount of water used for hydraulic fracturing, 2009–2012.



Coal Extraction

During the study period, Pennsylvania had 328 coal mines, of which 247 were surface mines and 81 were underground mines. Areas of active coal mining overlap with hydraulic fracturing in the southwest and western sections of the state; coal mining occurs just south of areas of hydraulic fracturing in eastern Pennsylvania (Figure 7 and Figure 8). Coal production, and therefore water consumption, decreased in the southwest portions of the state (177 Mgal decrease in the Ohio River Basin) and increased in the middle and eastern regions (141 Mgal increase throughout the Susquehanna River Basin). All changes in water use associated with coal extraction were moderate, fluctuating less than 100 Mgal between 2009 and 2012, with the exception of a 130 Mgal decrease in the Middle Allegheny-Redbank Sub-basin (Figure 8).

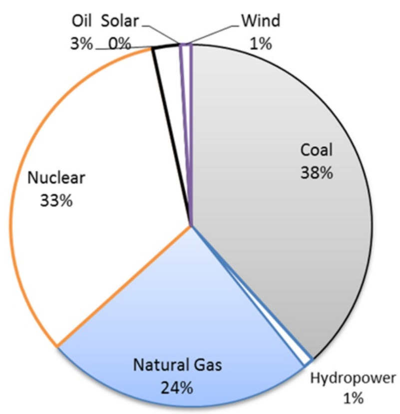
Figure 8. Change in the amount of water used for coal extraction, 2009–2012



Power Generation

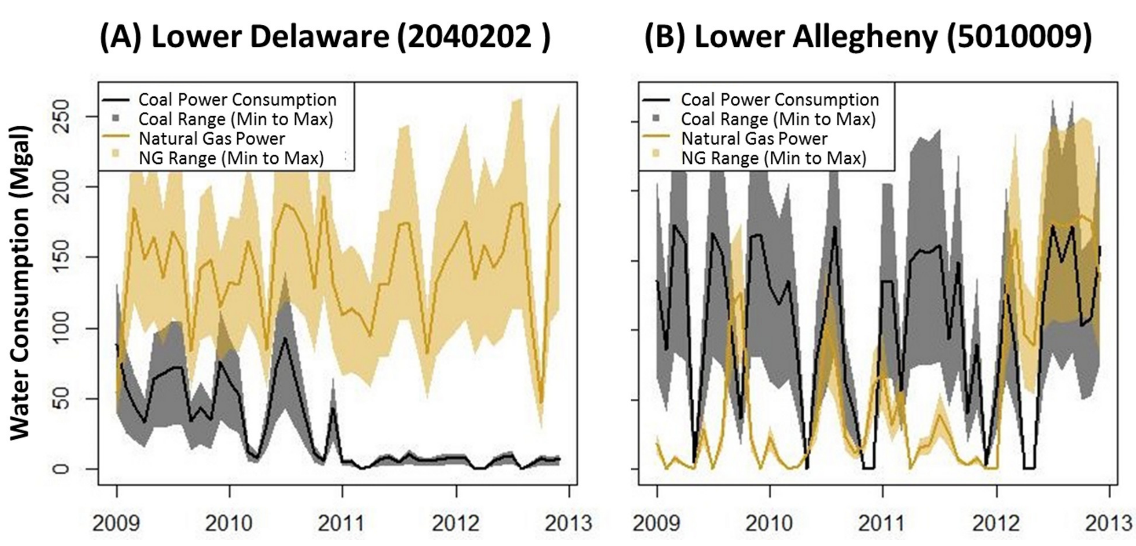
During the study period (2009–2012), the number of power plants in Pennsylvania increased from 218 to 224. Of these plants, 29% used natural gas (N=65), and 16% used coal (N=37). The number of solar plants increased from 4 to 17, while the number of wind plants increased from 19 to 27. The number of nuclear plants and hydropower plants remained constant at 5 and 19, respectively. Coal, nuclear, and natural gas produce 96% of the electricity generated in Pennsylvania (Figure 9). Although the number of natural gas and coal plants changed little between 2009 and 2012, the amount of electricity generated by those plants changed significantly. In 2009, coal was responsible for 48% of the electricity generated, while natural gas was responsible for 14%. In 2012, coal generation decreased, producing 38% of the state's electricity, while natural gas generation increased, producing 24%. The remaining fuels contributing to electricity generation changed by less than 2% during this period.

Figure 9. Percentage of electricity generated by fuel type in 2012



Between 2009 and 2012, Pennsylvania had 102 natural gas and coal power plants in operation. In this analysis, water use for all but one or two of these plants (depending on the year) was estimated on the basis of power production and water use intensities gathered from the literature, thereby introducing a degree of uncertainty—especially with regard to a small fraction of installed capacity (e.g., 3.4% of electricity generated in 2012) for which information on cooling technology was lacking. The analysis quantified the magnitude of spatial and temporal uncertainty by comparing the average water use intensity for all power plants within a sub-basin on a monthly time step with the minimum and maximum water use intensities from the literature (Figure 10). The more power plants generating electricity in a sub-basin, the higher the uncertainty regarding consumptive water use due to the range of water intensity for each plant; however, the trend of increasing or decreasing water use remains constant regardless of whether the analysis employs minimum, average, or maximum water intensities to estimate power plants' water use.

Figure 10. Range of estimated water consumption by natural gas (ng) and coal-fired power plants in two sub-basins



Note: The solid line represents the average intensity used in the analysis. The shaded area represents the range of values using the minimum and maximum reported water use intensities.

__Natural Gas Power Generation__

Four new natural gas power plants started producing electricity between 2009 and 2012, raising the total of natural gas power plants to 65. The data show that the amount of electricity generated by natural gas increased from 31.7 million MWh in 2009 to 54.6 million MWh in 2012. The increase in electricity generated by natural gas is greatest in the southeast and southwest corners of the state, where Philadelphia and Pittsburg are located, respectively (Figure 11). As natural gas power plants began to produce more energy, they also consumed more water. The greatest increase occurred in the Lehigh Sub-basin (HUC 2040106), where 966 Mgal more water was consumed between 2009 and 2012 (Figure 12).

Figure 11. Change in the amount of electricity produced (MWh) by natural gas plants, 2009–2012

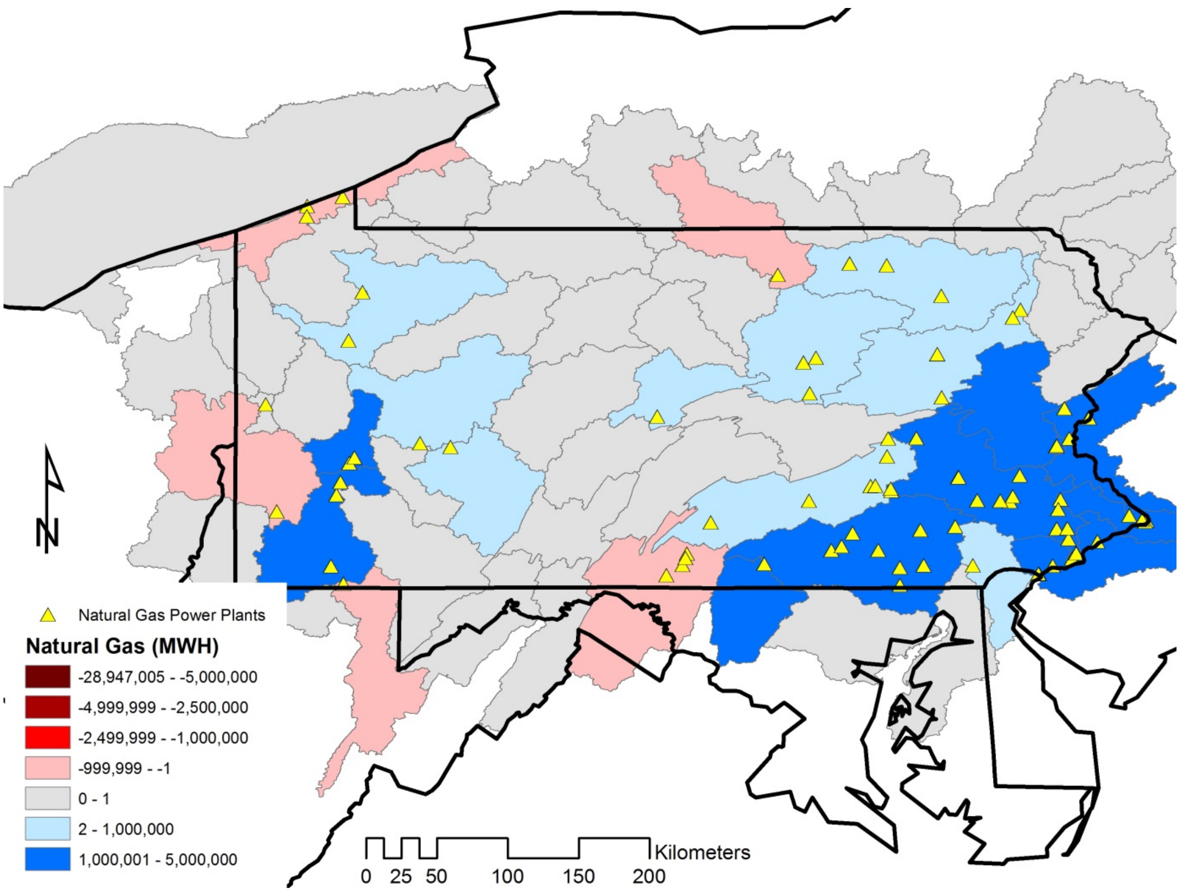
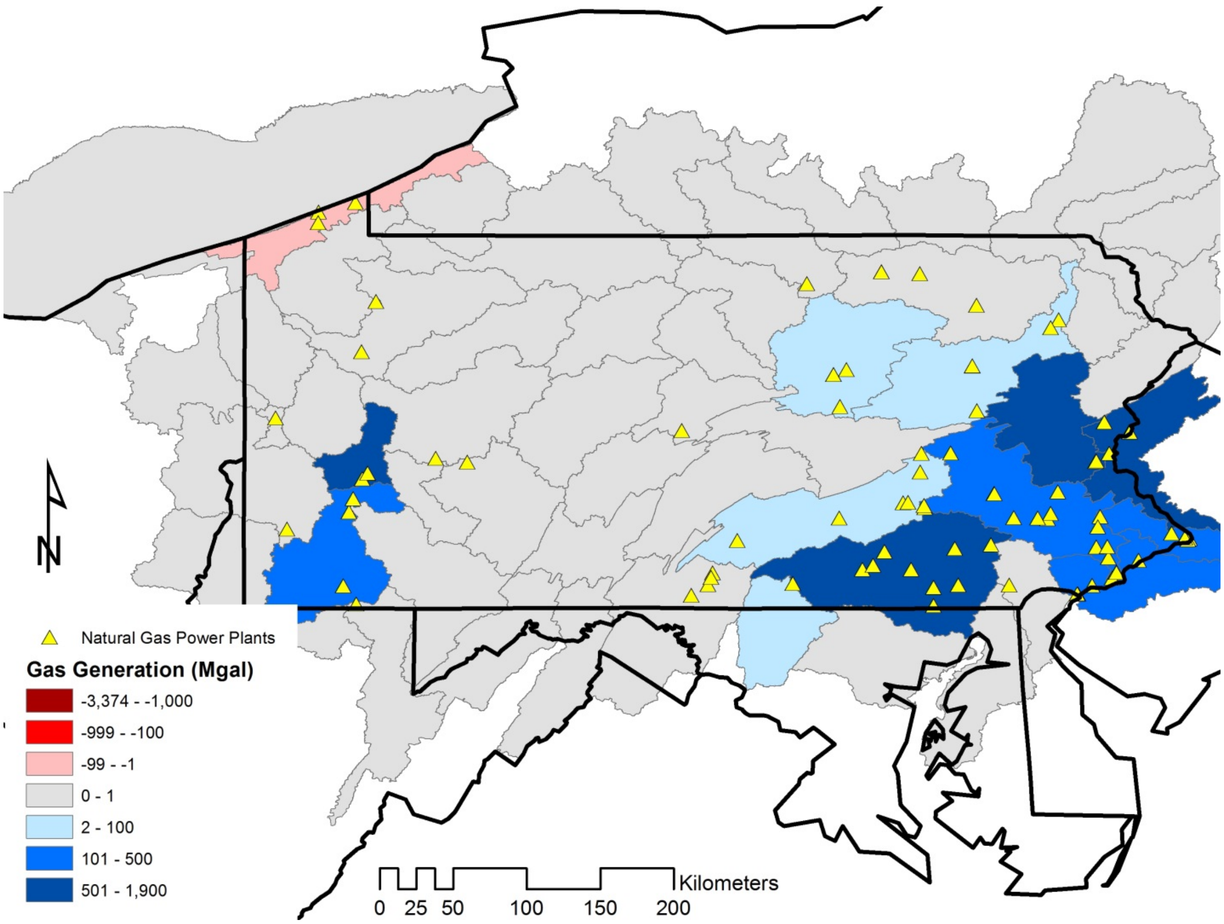


Figure 12. Change in the amount of water consumed (Mgal) by natural gas power plants, 2009–2012



Coal Power Generation

During the study period (2009–2012), the number of coal-fired power plants decreased from 38 to 37; however, the amount of electricity generated by coal fell by 9%, from 105.8 MWh to 86.5 MWh. Decreases in the amount of electricity generated by coal plants occurred mainly in the southeast and west central portions of the state (Figure 13). As coal power plants produced less electricity, they also consumed less water; water consumption in the Conemaugh Sub-basin (HUC 5010007) was 3,800 Mgal lower in 2012 than in 2009. The amount of electricity and water consumed by coal power plants increased in the southwest corner of the state between 2009 and 2012 (Figure 14).

Figure 13. Change in the amount of electricity produced (MWh) by coal power plants, 2009–2012

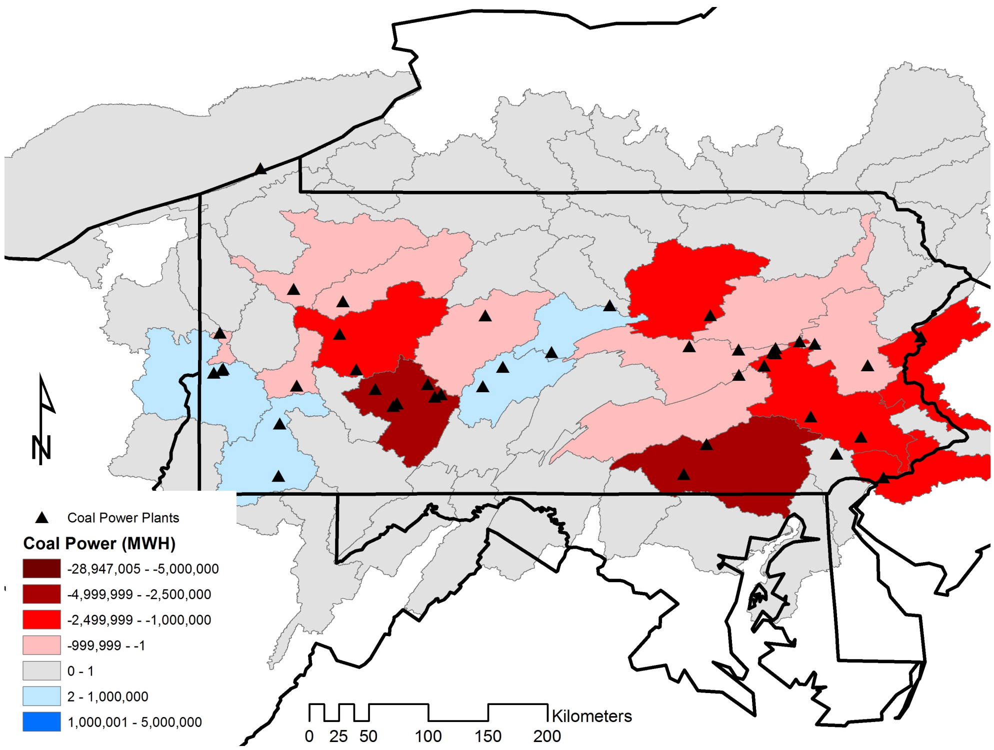
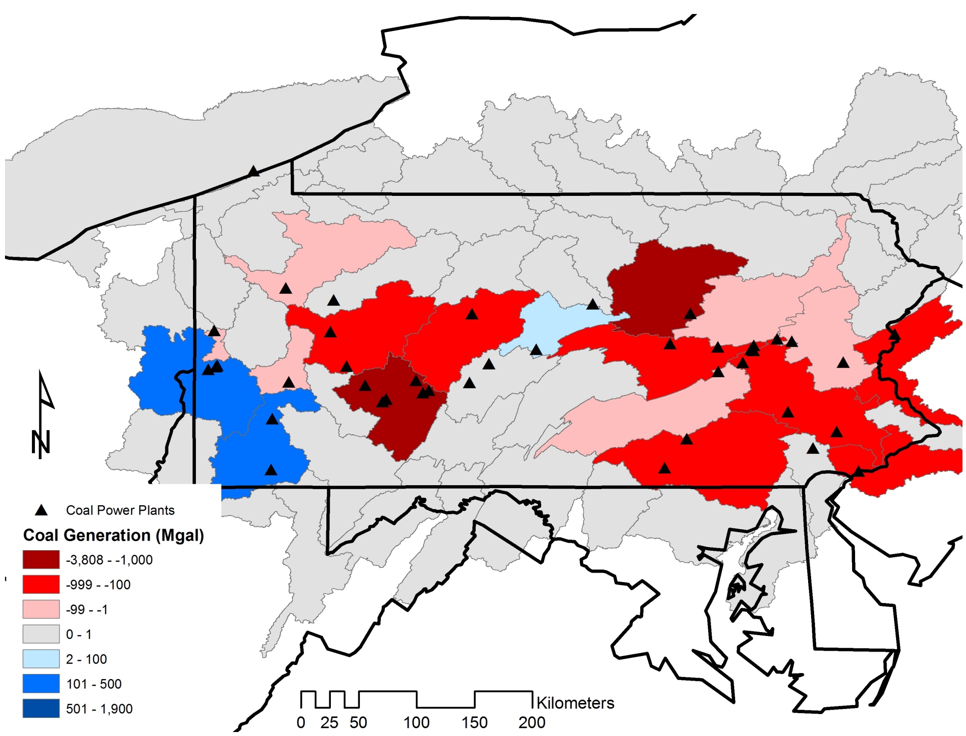


Figure 14. Change in the amount of water consumed (Mgal) by coal power plants, 2009–2012

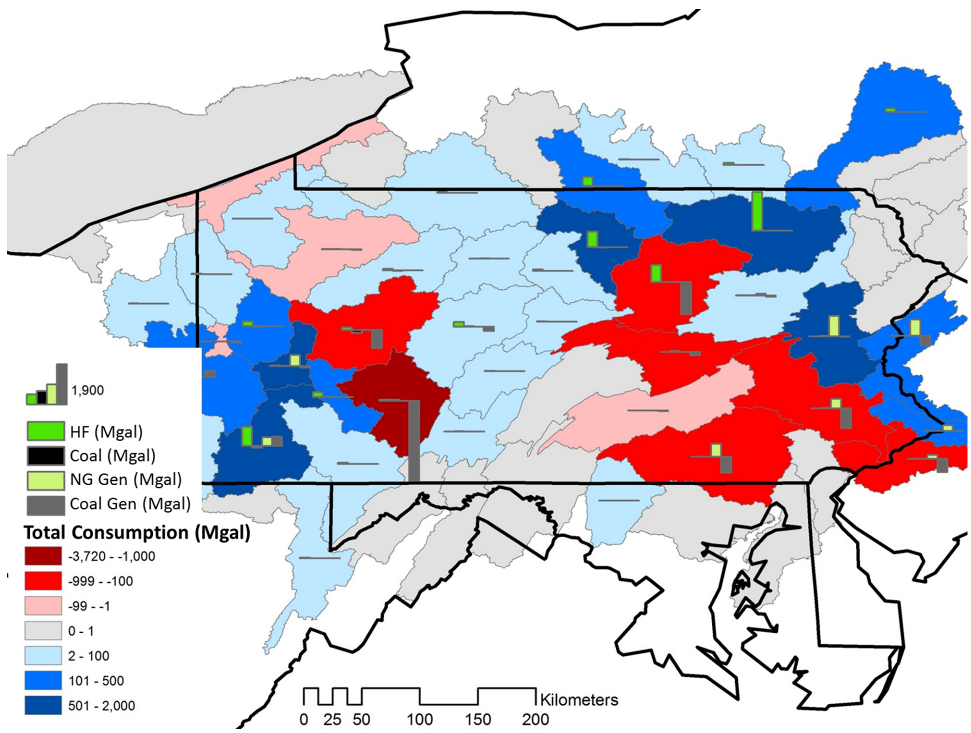


Total Change in Water Consumption between 2009 and 2012

In Pennsylvania, overall water consumption for the coal-to-gas transition, with respect to extraction and electricity generation, increased from 80,064 Mgal in 2009 to 82,213 Mgal in 2012 (an increase of 2,149 Mgal). However, variability in the sign (increase or decrease) and magnitude of the change in water consumption among sub-basins is wide. The largest decrease in water consumption was 3,720 Mgal in the Conemaugh Sub-basin (HUC 5010007). The largest increase in water consumption was 1,833 Mgal in the Upper Susquehanna-Tunkhannock Sub-basin (HUC 2050106) (Figure 15).

All basins experiencing decreases in overall water consumption also had decreases in water consumption by coal-fired power plants (Figure 14) that compensated for any increases in water consumption due to natural gas extraction or production. In contrast, those basins with the greatest increase in overall water consumption nearly all had increases in shale gas fracturing activities; the exception were basins in the southeast corner of Pennsylvania, where the growth in natural gas energy production drove increases in overall water consumption for the coal-to-gas transition.

Figure 15. Change in overall water consumption for the coal-to-gas transition, 2009–2012



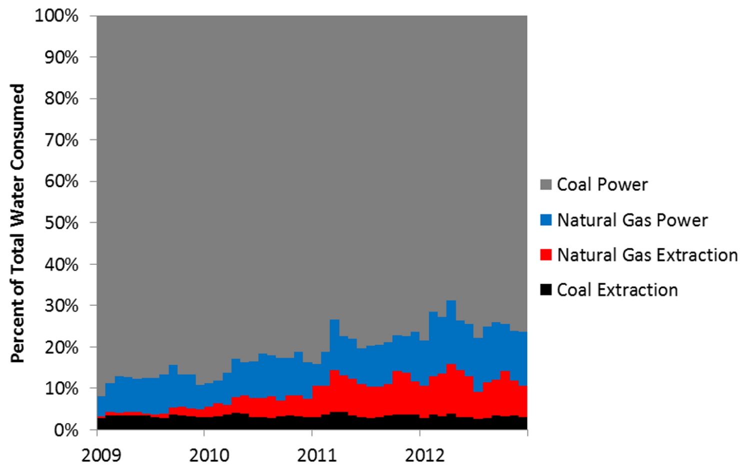
Note: The bars for each sub-basin represent the magnitude of the increase or decrease in water consumption for each sector: gas extraction (Hydraulic Fracturing – HF), coal extraction, natural gas power (NG Gen), and coal power (Coal Gen). The color of each sub-basin denotes the absolute level of water consumption increase or decrease between 2009 and 2012.

Temporal Variation in Water Consumption

In addition to spatial changes in water consumption, the temporal evolution of water consumption was explored for energy extraction and generation. In Pennsylvania, coal electricity generation was responsible for the majority of water consumption, although its contribution to the total amount decreased from 88% in 2009 to 75% in 2012 as a result of the decrease in coal power generation (Figure 16).

During that same period, water consumption for hydraulic fracturing increased from 1% to 9% of annual water consumption, while natural gas electricity generation increased from 8% to 13%. The amount of water used for coal extraction remained constant throughout the period at 3% of annual water consumption.

Figure 16. Percent of water consumed by sector in the coal-to-gas transition



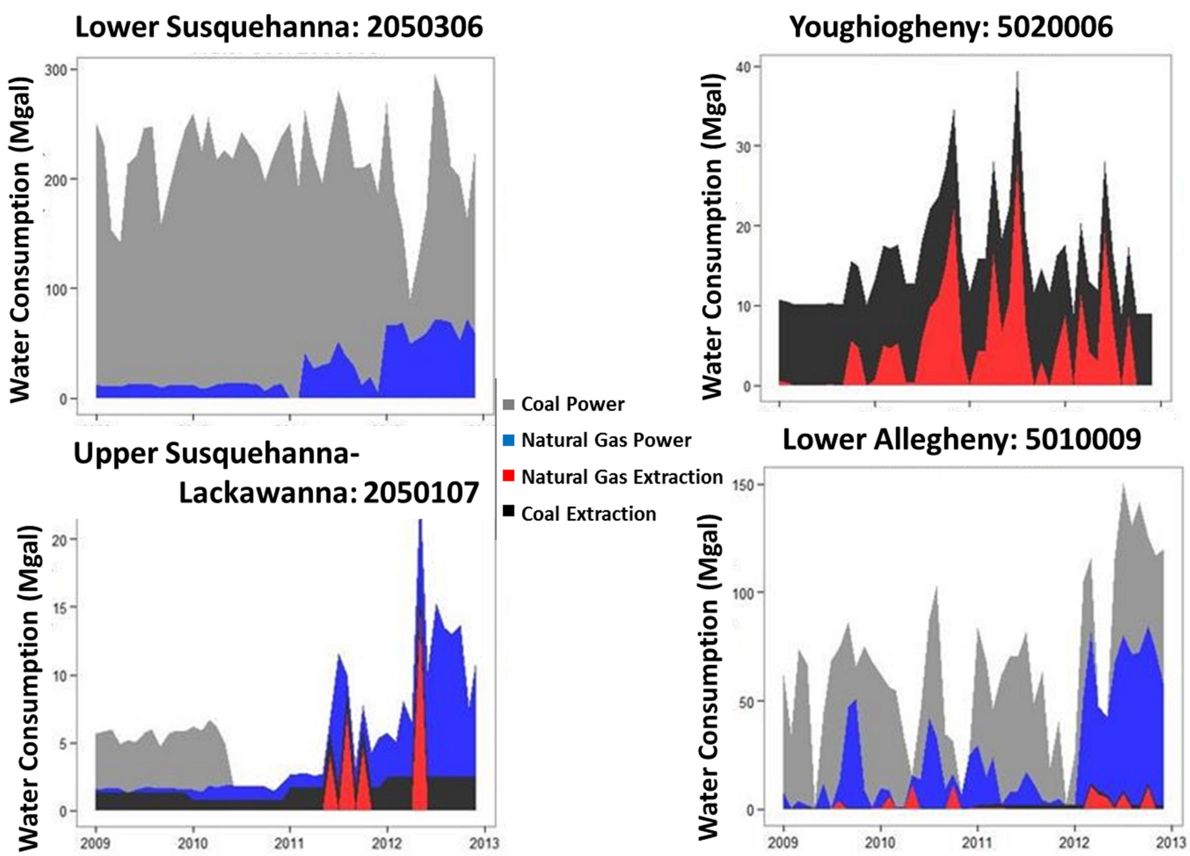
At a monthly scale, the volume of water used for hydraulic fracturing varied greatly. The average monthly volume within a sub-basin varied between 0 Mgal and 130 Mgal, with a standard deviation of between 0 Mgal and 81 Mgal. The median standard deviation was 1.7 Mgal, with a mean of 6.7 Mgal (approximately the range of volumes used to fracture a single well). The large variability is reflective of the high consumptive use of water during a short period for unconventional shale gas extraction (Figure 17).

Monthly temporal variation for coal was low (the standard deviation ranged from 0 Mgal to 9.1 Mgal, with a median of 0 Mgal and a mean of 0.5 Mgal) largely due to the assumption that annual coal water consumption was spread evenly throughout a year (Figure 17). As a result, all temporal variation for coal occurred annually.

Variation in monthly water consumption by both natural gas and coal electricity generation was high. The median standard deviation for both was zero across all sub-basins because some sub-basins had electricity generated entirely through nuclear, hydroelectric, oil, or renewable energy plants. The mean standard deviation for natural gas was 4.6 Mgal, with a maximum of 44.1 Mgal within a sub-basin. The standard deviation for coal electricity generation was a mean of 20.5 Mgal, with a maximum of 292 Mgal (Figure 17).

The sub-basin with the maximum standard deviation for coal electricity generation (HUC 5010007) had a range of monthly water consumption between 956 Mgal and 3,121 Mgal. The high monthly variation for electricity is not surprising given multiple types of power plants within sub-basins and seasonal fluctuations in energy demand.

Figure 17. Monthly variation by sector in coal-to-gas transition water consumption for select sub-basins



Note: The scale of the y axis varies from figure to figure.

Discussion

There is growing recognition of the importance of analyzing the relationship between various energy extraction and production technologies and their environmental impacts. In the case of water consumption for energy-related uses, most studies have presented those impacts without consideration of space or time, or have done so at relatively coarse spatial and temporal resolution, which tells an incomplete story. Furthermore, proponents and opponents of natural gas as a source of energy do not typically consider the relationship between energy investments and water consumption across industries that are highly linked (in this case, primarily through gas prices and environmental regulation).

This analysis demonstrates that while overall water consumption in Pennsylvania increased during the start of the coal-to-gas transition from 80.1 Bgal in 2009 to 82.2 Bgal in 2012 (3% increase), the spatial and temporal variation of that consumption was notable. Water consumption increased steadily for both hydraulic fracturing and natural gas electricity generation, whereas water consumption for coal extraction and electricity generation peaked in 2011 and 2010, respectively, and has since declined. During the study period, annual water consumption peaked at 86.8 Bgal in 2010, when all four investigated sectors were growing (Table 1). The southwest and northeast sub-basins experienced the greatest increase in water consumption, while the southeast sub-basins experienced a decrease in water consumption (Figure 15).

Table 1. Annual water consumed (Mgal) by sector, 2009–2012

	Gas Extraction	Coal Extraction	Coal Power	Natural Gas Power	Total
2009	857	2,614	70,212	6,381	**80,064**
2010	3,529	2,831	72,787	7,622	**86,768**
2011	7,149	2,983	67,810	8,011	**85,953**
2012	7,542	2,578	61,411	10,682	**82,212**

In the case of increased U.S. shale gas extraction, policy makers and analysts have focused on the spatial patterns of water consumption either for fuel extraction or for power generation—not both—and have done so at relatively coarse scales. We found high variability in the monthly water consumption for both energy extraction and electricity generation in the coal-to-gas transition (Figure 17); standard deviations varied between 0 Mgal (those basins without coal or natural gas energy extraction and generation) and 81 Mgal. Although thermoelectric power generation is the dominant source of water consumption in the coal-to-gas transition (Figure 16), in some sub-basins shale gas extraction processes are the dominant source (Figure 17).

Water consumption studies focused on Pennsylvania have estimated the annual water consumption for hydraulic fracturing to be 18–25 million cubic meters (Mm^3)/yr (4,755–6,600 Mgal) in the Susquehanna River Basin (Mitchell et al. 2013) and 10.4 Mm^3/yr (2,750 Mgal) in the Ohio River Basin from 2011 to 2012 (Richenderfer 2012). We found the volumes to range between 447 Mgal in 2009 to 5,020 Mgal in 2011 in the Susquehanna River Basin, and between 410 Mgal in 2009 and 2,615 Mgal in 2012 in the Ohio River Basin. Although these volumes are miniscule compared with the amount of water that flows through these basins annually (~332,800 Mm^3 in the Ohio River Basin), they can represent a significant amount of water if several wells draw water simultaneously from smaller streams. Water withdrawals have already been restricted at times for some watersheds within Pennsylvania (StateImpact Pennsylvania 2015). Within each of these river basins, this analysis further refined spatial scale by examining water consumption at the sub-basin scale (19 sub-basins within the Ohio River Basin and 18 within the Susquehanna River Basin). We found the volume of water consumption varied from 0 Mgal to 2,545 Mgal (HUC 2050106) within a sub-basin (or an average of 175 Mgal for those basins with hydraulic fracturing).

The coal-to-gas transition has impacts beyond fuel extraction and power generation. This study's examination of two major sectors was driven in part by the aim to develop a proof of concept by demonstrating that accounting for linked sectors results in different local water impacts. To project long-term (decadal) water consumption as a result of the coal-to-gas transition, researchers would need to model the whole economy and include factors such as price elasticities (McJeon et al. 2015). Analysis of broader economic and environmental impacts of changes in resources could incorporate this paper's insights to project future water consumption and availability in global models of the whole economy, although such models tend to be better suited to more aggregate spatial resolutions.

This analysis has limitations set by the lack of available data at monthly resolutions. Water consumption at monthly time scales had to be estimated for coal extraction. The timing and volume of water consumption by hydraulic fracturing had to be estimated for some wells. This analysis would also benefit from more granular data on water reuse. Water consumption for electricity generation was calculated using average water use intensities for different technologies, introducing uncertainty into the analysis. This uncertainty could be reduced if state- or federal-level data policies were enacted to standardize and perform quality control on collection of water withdrawal and consumption data in these two sectors. In addition, although our analysis is at a higher spatial and temporal resolution than other studies (monthly and sub-basin), even higher-resolution analyses may be necessary to understand how a specific river is affected by different types of energy-related infrastructure. Future work would include developing a model to include water availability, not just water demand, in the analysis.

Finally, we do not differentiate between different end uses for natural gas derived from shale; for example, natural gas produced in Pennsylvania may be exported from the state, used for electricity generation, or used for alternative end uses. The accepted method in LCA is to expand the system boundaries to include the alternative end uses (Rebitzer et al. 2004). If a portion of a product goes to one end use (e.g., home heating) and the rest goes to another (in this case, power generation), the resource use can be attributed to the end use in question (power generation). It is implied in the current analysis that all natural gas is used in electricity generation, which it is not. However, if only a fraction of the water consumption was attributed to electricity generation and the remainder was ignored, the cumulative water demand to a watershed would be underestimated. In the analysis, system boundaries include the full expansion of shale gas development in Pennsylvania so as to highlight the roles of both sectors in changing water consumption patterns associated with the low prices and abundance of natural gas. If researchers expand such spatiotemporal methods for other applications, they should cautiously apply system boundaries to ensure that water demands for different end uses are not double counted.

Policy Implications

The scale and nature of water impacts associated with the coal-to-gas transition have led to divergent perspectives. One perspective focuses on the expansion of hydraulic fracturing resulting in increased water consumption and stressors to small streams and local water supplies. The second perspective focuses on life cycle assessment of the electric sector's transition from coal to natural gas-fired generation, which leads to a net decrease in water consumption. Previous analyses have shown that the majority of water consumption for thermoelectric power generation is attributed to power generation rather than fuel extraction; however, it is known that rapid expansion in fuel extraction can lead to local restrictions on demand during times of low stream flow. Even in water-rich Pennsylvania, the Susquehanna River Basin has imposed restrictions on water withdrawal for use in shale gas operations. The challenge in applying LCA to water resources to derive meaningful policy recommendations is illuminating impacts within an area more localized than the state and over periods shorter than the lifetime of operating facilities.

This challenge is addressed in the present study by contributing a novel approach to incorporating spatial and temporal aspects in life cycle assessment. We found that overall water consumption for the coal-to-gas transition increased by 2,149 Mgal from 2009 to 2012 for the entire state of Pennsylvania. Although all sectors experienced water consumption increases from 2009 to 2012, decreases in coal extraction and coal power generation have resulted in a water consumption decrease from 86,768 Mgal in 2010 and to 82,213 Mgal in 2012 (Table 1). If coal-fired plants continue to transition to natural gas-fired plants, the coal-to-gas transition could result in a net decrease in overall water consumption within Pennsylvania.

Although results indicated an overall increase in water consumption during the study period, that consumption varied among sub-basins, some of which experienced decreases in water consumption (Figure 15). All basins experiencing decreases in overall water consumption also had decreases in water consumption from coal-fired power plants (Figure 14) that compensated for any increases in water consumption due to natural gas extraction or production. In contrast, those basins with the greatest increase in overall water consumption nearly all had increases in shale gas fracturing activities; the exception was basins in the southeast corner of Pennsylvania, where growth in natural gas electricity generation drove increases in overall water consumption for the coal-to-gas transition. This work indicates that to determine the water implications of transitions in energy systems, LCAs must be at a relatively high spatial and temporal resolution and must account for water consumption changes in both fuel extraction and power generation.

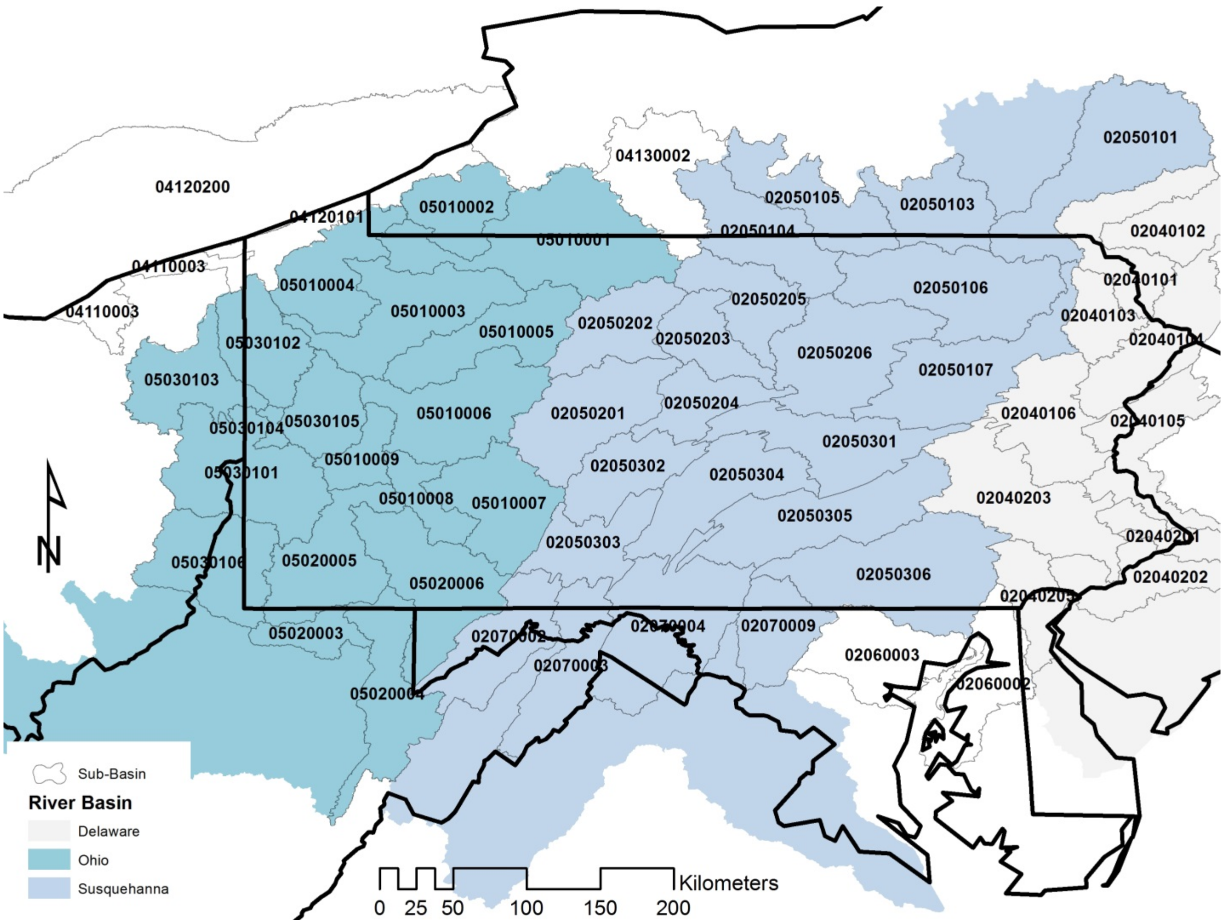
The policy implications of this work span various decision-making levels. At the local level, decision makers approving permits and crafting policies to manage environmental impacts should consider the broad water implications of coal-to-gas transitions. For example, sub-basins with increasing shale gas extraction activity could experience water consumption increases if, for instance, coal plants are unlikely to be retired. In other cases, water consumption may decrease if old coal plants are shut down and (perhaps) replaced by gas plants in the same or another sub-basin. In short, water impacts depend not on the coal-to-gas transition alone, but also on the spatial patterns associated with this transition over time and the water availability within a specific watershed. High temporal resolutions allow users to identify and (if necessary) address peaks in consumption. This type of analysis could allow policy makers to identify watersheds likely to experience the greatest water impacts from the coal-to-gas transition. Decision makers within shale gas operations, utilities, local governments, and river commissions, for instance, will find identification of regions at risk useful for various reasons related to investment decisions, technology choices, risk management, permitting, and regulation.

At the national level, the results of this analysis provide further evidence that the possible implications of new technology developments and broad sectoral transitions cannot be understood unless analyses take into account the local nature of certain natural resources (e.g., water). In the present case, results imply that policy makers need to evaluate early on the possible water consumption trends in related sectors resulting from low natural gas prices. Sectoral changes such as those resulting rom the coal-to-gas transition can significantly affect water budgets at the local level. Federal agencies like the U.S. Department of Energy and the Environmental Protection Agency could take on the task of informing state and local agencies of the need to conduct detailed water consumption assessments across more than one activity in areas that are likely to experience shortages.

To summarize, our approach highlights the need to examine water consumption of both fuel extraction and electricity generation at high spatial and temporal resolutions if decision makers are to understand the cumulative impacts of the coal-to-gas transition in the power sector. Examination of water consumption at different spatial scales may be useful for decision makers at multiple levels of government as well as for public and private enterprises. Shale operators, utilities, and governments can and do play a role in actively mitigating impacts to water resources in the coal-to-gas transition. Shale operators can increase water reuse, technology innovation (e.g. propane gel fracturing), use of water sources other than surface water when appropriate and modify the timing of water withdrawals from watersheds. Utilities with thermoelectric generators can adopt best-in-class cooling technologies to reduce water consumption, advance technology innovation, and consider alternative water sources. Governments may consider coordinating the activities of basin-level and watershed-level management groups such as the Susquehanna River Basin Commission. Additional policy tools that can be used to address local shortages include water markets (pricing), regulations and policies that require the application of new technologies and practices, withdrawal and consumption restrictions during periods of low flow, and protection of sensitive ecosystems.

Appendix: Supplemental Information

Figure A1. **River basin boundaries (shades) and sub-basin boundaries in Pennsylvania**



Note: HUC8 codes are presented for each sub-basin.

Table A1. Number of wells reported within the PADEP and FracFocus database

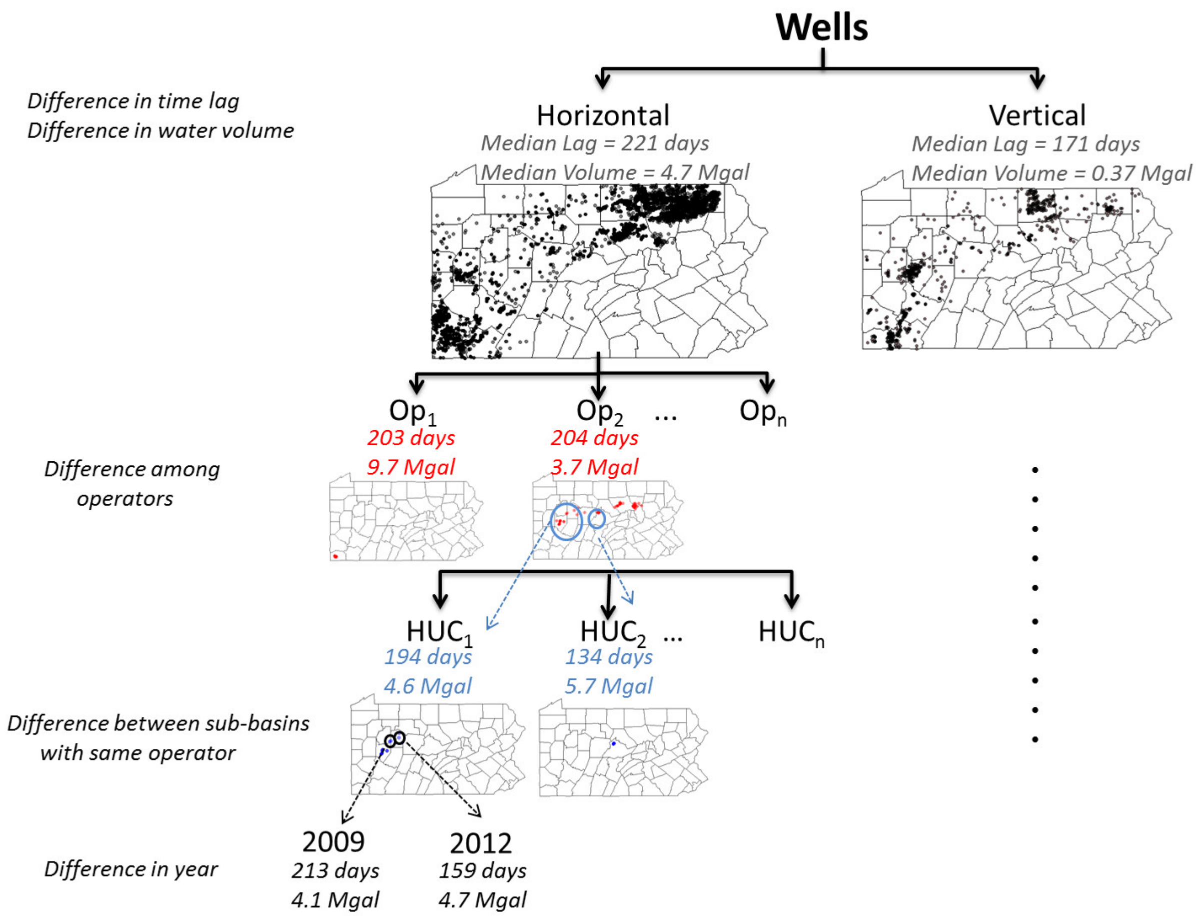
	Pre-2008[a]	2008	2009	2010	2011	2012	2013	Total
PADEP								
Wells	2,766	190	386	957	1,765	1,749	1,507	10,062
FracFocus								
Wells	0	2	19	54	1,104	1,262	1,131	3,674
Percent	0%	1%	5%	6%	63%	72%	75%	37%

[a] Includes wells for which no date is provided (NA).

Table A2. PADEP wells by sub-basin from 2008–2013 and wells with FracFocus data

	Sub-basin	HUC8	Area (km^2)	Wells	FracFocus	Percent
Delaware	Lackawaxen	2040103	1,489	1	0	0%
	Upper Delaware	2040101	2,963	2	0	0%
Ohio	Beaver	5030104	279	9	7	78%
	Cheat	5020004	3,541	16	7	44%
	Clarion	5010005	3,110	94	30	32%
	Conemaugh	5010007	3,419	75	42	56%
	Connoquenessing	5030105	2,087	218	140	64%
	French	5010004	3,080	1	1	100%
	Kiskiminetas	5010008	1,282	125	60	48%
	Lower Allegheny	5010009	1,233	102	24	24%
	Lower Monongahela	5020005	3,670	1,055	469	44%
	Mahoning	5030103	2,839	9	2	22%
	Middle Allegheny-Redbank	5010006	4,193	192	52	27%
	Middle Allegheny-Tionesta	5010003	4,193	31	15	48%
	Shenango	5030102	2,657	42	10	24%
	Upper Allegheny	5010001	6,452	87	35	40%
	Upper Monongahela	5020003	1,155	16	2	13%
	Upper Ohio	5030101	4,948	398	191	48%
	Upper Ohio-Wheeling	5030106	3,762	281	160	57%
	Youghiogheny	5020006	4,385	163	63	39%
Susquehanna	Bald Eagle	2050204	1,925	57	4	7%
	Chemung	2050105	3,018	98	36	37%
	Lower West Branch Susquehanna	2050206	4,507	714	458	64%
	Middle West Branch Susquehanna	2050203	1,952	103	54	52%
	Owego-Wappasening	2050103	2,602	58	30	52%
	Pine	2050205	2,443	462	264	57%
	Raystown	2050303	2,395	5	2	40%
	Sinnemanhoning	2050202	2,575	60	15	25%
	Tioga	2050104	3,446	566	233	41%
	Upper Juniata	2050302	2,468	3	2	67%
	Upper Susquehanna	2050101	5,700	143	101	71%
	Upper Susquehanna-Lackawanna	2050107	4,422	6	2	33%
	Upper Susquehanna-Tunkhannock	2050106	4,990	1,963	1099	56%
	Upper West Branch Susquehanna	2050201	3,977	141	64	45%
	TOTAL			**7,296**	**3,674**	**50%**

Figure A2. Schematic showing the process of estimating completion dates and water volumes



Operator Differences

Of the 64 well operators active in Pennsylvania during this time period, 36 drilled both horizontal and vertical wells, 15 drilled only vertical wells, and 13 drilled only horizontal wells. Horizontal and vertical wells have different fracturing water requirements. According to FracFocus data, horizontal wells used a median of 4.7 Mgal, whereas vertical wells used a median of only 0.37 Mgal.

Not all well operators reported water consumption; among those who did, those volumes ranged widely. For example, Noble Energy, Inc., used a median of 11.5 Mgal (n=12) to fracture wells, whereas Energy Corp of America used a median of 3.3 Mgal (n=59). Long et al. (2014) found that water use varied significantly by operator in California, and they found the operator to be one of the best predictors of water use per well.

Although 6,453 horizontal wells were operated by 49 operators, most were fractured by just a few operators. Nine operators with a total of 65 wells reported no information to FracFocus (n=65 or 1% of horizontal wells). Six operators managed more than 300 wells each and represented 58% of all horizontal wells (57% of FracFocus data). These operators were Chesapeake Appalachia LLC, Range Resources Appalachia LLC, Talisman Energy USA, SWEPI LP, Chevron Appalachia, Cabot Oil and Gas Corp, and EQT Production.

Sixty percent of vertical wells were managed by 4 operators (Atlas Resources LLC, SWEPI LP, Snyder Bros Inc., and Anadarko) and included 40 of the FracFocus wells.

Table A3. Water intensities applied to coal mines

	Appalachian (Underground)			Western (Surface)		
Stage	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**
Mining	1	1	1	6	6	6
Washing	0	1	2	0	1	2
Mining + Washing	**1**	**2**	**3**	**6**	**7**	**8**

Source: Intensities are taken from Mielke et al. (2010).
Note: Units are gallons per MMBtu.

Table A4. Water intensities applied to power plants in Pennsylvania

			Water Intensity (gal/MWh)		
Prime Mover	**Fuel**	**Cooling**	**Min**	**Max**	**Average**
Steam Turbine	Coal	Once Through	100	317	209
	Natural Gas		300	330	315
	Coal	Dry	0	30	15
	Natural Gas		0	30	15
	Coal	Recirculating	300	1,100	790
	Natural Gas		300	510	405
Combustion (Gas) Turbine	Natural Gas	None	0	0	0
Internal Combustion Engine	Natural Gas	None	0	0	0
Combined Cycle Steam	Natural Gas	Recirculating	130	300	215
Combined Cycle Combustion Turbine	Natural Gas	Recirculating	0	0	0
Combined Cycle Single Shaft	Natural Gas	Recirculating	130	300	215
Combined Cycle Total Unit	Natural Gas	Recirculating	130	300	215
Combined Cycle	Natural Gas	Dry	0	4	2
Combined Cycle	Natural Gas	Once Through	20	100	60

Sources: Water intensities were derived from Mielke et al. (2010), with several updates from Macknick et al. (2012). Prime mover codes were derived from EIA data, and cooling codes were derived from the Union of Concerned Scientists (2011).

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