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Community concern and government response: Identifying socio-economic and demographic predictors of oil and gas complaints and drinking water impairments in Pennsylvania.

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Abstract

Oil and gas development has led to environmental hazards and community concerns, particularly in relation to water supply issues. Filing complaints with state agencies enables citizens to register concerns and seek investigations. We evaluated associations between county-level socio-economic and demographic factors, oil and gas drilling, and three outcomes in Pennsylvania between 2004–2016: number of oil and gas complaints filed, and both the number and proportion of state investigations of water supply complaints yielding a confirmed water supply impairment (i.e., “positive determination”). We used hierarchical Bayesian Poisson and binomial regression analyses. From 2004–2016, 9,404 oil and gas-related complaints were filed, of which 4,099 were water supply complaints. Of those, 3,906 received investigations, and 215 yielded positive determinations. We observed a 47% increase in complaints filed per $10,000 increase in annual median household income (MHI) (Rate Ratio [RR]: 1.47, 95% credible interval [CI]: 1.09–1.96) and an 18% increase per 1% increase in educational attainment (RR: 1.18, 95% CI: 1.11–1.26). While the number of complaints filed did not vary by race/ethnicity, the odds of a complaint yielding a positive determination were 0.81 times lower in counties with a higher proportion of

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marginalized populations (Odds Ratio [OR]: 0.81 per 1% increase in percent Black, Asian, and Native American populations combined, 95% CI: 0.64–0.99). The odds of positive determinations were also lower in areas with higher income (OR per $10,000 increase in MHI: 0.35, 95% CI: 0.09–0.96). Our results suggest these relationships are complex and may indicate potential environmental and procedural inequities, warranting further investigation.

Keywords

complaints; environmental justice; hydraulic fracturing; oil and gas development; unconventional oil and gas development

1. Introduction

Unconventional oil and gas development (UOGD) has grown rapidly in the United States, particularly in the Marcellus Shale region of Pennsylvania (PA), where more than 12,000 UOGD wells have been drilled to date [1]. Whereas conventional oil and gas extraction uses vertical drilling, UOGD combines horizontal drilling with hydraulic fracturing, the injection of large quantities of water and chemicals into a rock formation, to tap previously inaccessible oil and gas deposits [2]. UOGD has been linked to numerous environmental health hazards, including drinking water impairments, air emissions, earthquakes, noise, and traffic accidents [3–10]. The proximity and density of UOGD have been associated with negative human health outcomes, including preterm birth, low birthweight, asthma, mental health issues, and cancer, as presented in several recent reviews [8, 11–16]. Issues related to water supply impairment (quality or availiability) continue to be of major concern to residents of the Marcellus Shale region [17, 18]. In PA alone, the drinking water for more than three million residents is sourced from private groundwater wells [19], which may be vulnerable to contamination and are not covered by state and federal regulations and monitoring. Documented cases of groundwater and surface water deterioration have occurred through spills or improper disposal of hydraulic fracturing fluid or wastewater, releases of hydrocarbons into groundwater, as well as withdrawals of large volumes of freshwater in areas where water is limited [10, 20–23].

Consideration of whether environmental health hazards are distributed unequally or whether there is unequal protection of environmental policies and standards are two principles at the core of environmental justice [24]. These principles, along with many others drafted at the 1991 First National People of Color Environmental Leadership Summit in Washington, D.C., were intended to guide policies and programs aiming to reduce the unequal burden of environmental exposures on marginalized groups, particularly Black/African American, Native American/Indigenous, and Hispanic and Latinx communities. The ability of marginalized communities to organize politically and maintain power over their environment has long been minimized. In addition to the economic and social disenfranchisement of communities of color and low income communities, these communities are often also disproportionately burdened with environmental hazards compared to white and upper class communities [25, 26]. These environmental burdens include, but are not limited to, the siting of hazardous waste sites and landfills, poor air and water quality, and lack of access to urban green space [27–35].

Environmental health burdens associated with UOGD specifically have been shown to be differentially distributed based on socio-economic or demographic factors [36–38]. Ogneva-Himmelberger and colleagues [39] identified an association between the placement of UOGD wells and PA populations living in poverty, though they did not observe this relationship in Ohio or West Virginia. UOGD waste disposal wells in Texas were disproportionately located in communities of color [40] and in Ohio in areas of lower income [41]. An analysis in Colorado noted a larger proportion of low-value housing nearest to UOGD wells in two of the three examined regions [42]. Moreover, many economic benefits of UOGD are experienced at the municipal, regional, and corporate rather than individual levels due to arrangements like split estates (i.e., separation of surface and subsurface property/mineral rights, which is permissible in PA [43]). In Colorado, large discrepancies between the owners of surface rights and mineral rights for the same land have been observed, with only 36–57% of mineral rights being owned by the surface owner in the three regions [42]. In a similar study in Texas, 61% of mineral rights owners did not experience environmental burdens as they lived far from the drilling sites [44]. This literature, considered together with the limited epidemiologic literature, suggests that those living near UOGD sites may bear significant environmental and health burdens while reaping fewer benefits.

One avenue available to residents for addressing concerns about UOGD activities is through the filing of environmental complaints. A complaint generally refers to a report filed by a resident with the intent of alerting municipalities to an observed or perceived hazard or grievance, which may then be investigated or remediated. Complaints may reflect a combination of physical presence of a problem, empirical observation of a problem, perceived impact and active reporting of the problem, or lack of municipal response to a problem. All of these factors may be influenced by socio-economic status (SES). Socio-economic and demographic factors are particularly thought to impact the need for municipal services and issue awareness [45, 46]. There is also evidence that the speed and number of governmental responses to citizen-filed complaints can vary by SES [45, 47], with lower SES neighborhoods typically receiving slower and fewer responses. For example, a study of 311 reports (non-emergency municipal service requests) in the United States found that several major cities showed a pattern of shorter response time in wealthier areas [48]. Areas with legacies of pollution or other environmental health threats may also lack trust in their government [49]. A recent and well-publicized example pertaining to water supply issues is the Flint, Michigan water crisis, which began in 2014, where lead contamination of drinking water and government failures disproportionately impacted minority and low income communities. A study conducted in 2016 indicated that only 11% of the residents of Flint agreed with the statement “I trust my local government” as compared to the rest of the state, where 80% reported trusting their government [50]. Such a lack of trust could translate into decreased citizen-initiated reporting of issues and decreased meaningful engagement if citizens do not believe that their reporting will make a difference. Further, analyses of the water crisis in Flint, Michigan indicate that citizen complaints alone were not sufficient to convince municipal officials of an issue or to raise awareness in the media [51]. It was not until citizens allied with scientists and nationally recognized activists that municipal action began. In the case of UOGD, even if hazards, such as spills or pollution, were equally distributed throughout shale-producing areas, the recognition and reporting of the hazards as well as the municipal response to them may be distributed unequally.

PA is an important location for research into the reporting of and response to UOGD-related hazards. In addition to the >12,000 UOGD wells drilled to date, PA has been the site of at least 16 health studies [8], of which 14 observed significant associations between UOGD exposure and adverse health outcome such as asthma, birth defects and decreased birth weights, and cardiovascular disease. The state also reported nearly 1,300 spills related to UOGD over the industry's first decade (2005–2014), and this may be an underestimate, as many spills go unreported [52]. There is an opportunity to better understand patterns of residents' observations and perceptions of impacts of oil and gas development through their own reporting of complaints.

In PA specifically, an oil and gas-related complaint may be filed with the PA Department of Environmental Protection (PADEP) by any landowner, water purveyor, or otherwise affected individual (Figure 1) [53]. According to the PADEP website, a complaint may be filed by completing an online Environmental Complaint form or by calling a toll-free line to report complaints. The complaint form requires the location of the complaint (county and township), and optional fields to provide name, address, a description of the issue, directions to locate the issue, and the party responsible for the issue. The complaint can be filed anonymously and no other individual-level data are collected through the online form. Filing a complaint related to water quality or supply prompts an investigation including laboratory analysis by PADEP within 10 business days of the filing. Beyond barriers related to trust and meaningful engagement, complainants may face logistical barriers such as understanding the complaint process, access to the tools necessary to file the complaint (e.g., a reliable internet connection), or access to the physical office that receives complaints. For a determination (an investigation and resulting decision as to whether water contamination is present and whether it is attributable to oil and gas activities) to be issued by PADEP, a complaint first needs to be filed to prompt an investigation. Complaints related to water quality or supply issues are collectively classified by PADEP as "water supply complaints," and proceed to the investigation stage. Investigations of water supply complaints can result in positive determinations (i.e., confirmation of water impairment), negative determinations (i.e., no evidence of water impairment), or undetermined status. Causes of positive determinations include contamination with natural gas, oil, brine components, metals, sediment/turbidity, and drill cuttings, as well as diminishment of water supply [10].

The goals of this analysis are to evaluate whether socio-economic or demographic factors are associated with (i) number of complaints filed, (ii) number of positive determinations made after an investigation was conducted, and (iii) proportion of water supply investigations yielding a positive determination. Examining both numbers and proportions provide different but complementary information on whether SES can influence the number of complaints filed and determinations made in a community and whether a water supply complaint is more likely to receive municipal recognition based upon community SES or demographic profile. Understanding differences in reporting and outcomes can inform additional surveillance, guide outreach and education, and identify procedural inequities in distribution of public health resources to ensure equitable protections and enforcement of environmental policies and regulations.

2. Methods

2.1 Oil and gas complaints

The analysis of complaints included all oil and gas-related complaints filed in counties with any oil and gas drilling from 2004–2016, the years for which we had data from all available sources. The primary data source for the complaints analysis included all oil and gas-related complaint records obtained from the PADEP by the Public Herald, a nonprofit investigative news organization, through the Emergency Planning and Community Right-to-Know Act. Each complaint record included the county and municipality of filing, the date received, the first response date, the date resolved (if available), and a PADEP-assigned category (e.g., abandoned/unregistered, pollution, property damage, spill response, water supply, etc.). A short text description of the complaint was included with each record. Thirteen PADEP-assigned complaint categories were preserved; those with fewer than 50 total complaints per category were combined into one category, labeled “other,” (n=12) to yield a total of 14 categories.

We also obtained a publicly available database specific to water supply complaints from the PADEP website [1], which provides information specific to investigated water supply complaints and the resulting determinations. We used this dataset to verify that all publicly reported water supply complaints were included in the dataset obtained by the Public Herald as a validation of our data source (Figure 2).

2.2 Water supply determinations

Our analyses of determinations were restricted to water supply complaints because that is the PADEP category that is eligible for investigation and determinations. The primary data source for water supply determinations was PADEP’s publicly available resolved water supply complaint and determination database [1]. This database includes information on positive determinations (i.e., confirmed water impairment), negative determinations (i.e., the water was confirmed as not impaired), and instances where an investigation was inconclusive or not conducted. We excluded water supply investigations that did not lead to a positive or negative determination (n=32) from our analyses.

2.3 Socio-economic and demographic factors

We obtained socio-economic and demographic data from the 2000 and 2010 United States Decennial Census and the 2011–2016 American Community Survey five-year estimates; data were aggregated at the county level to match the geographic unit of the complaints data [54]. We selected variables from both socio-economic and demographic domains. Socio-economic variables include percent unemployed, percent of the population with income below the poverty line, annual median household income (MHI, in $USD), and highest educational attainment for those 25 years of age and older (less than high school degree, high school degree or General Educational Development (GED) equivalent, some college,

college degree, or more than a college degree). Demographic variables extracted from the Census include total population per county, percent of the population by race (White, Black, Asian, Native American, Hawaiian, and other) and percent of the population with Hispanic ethnicity. Due to small percentages of people identifying in race categories other than White, we aggregated Black, Asian, Native American, Hawaiian, and other non-White races into one category (referred to as African American/Black, Asian, Native American/Alaska Native, and other non-White race, abbreviated as AAN), recognizing that the large heterogeneity within this category is a limitation.

2.4 Oil and gas drilling data

To account for the influence of new oil and gas wells drilled in a county on the number of complaints, oil and gas drilling records were obtained from PADEP. We obtained the number of active conventional and unconventional wells drilled per county per year between January 1, 2004 and December 31, 2016, excluding wells that PADEP categorized as plugged, operator-reported as not drilled, proposed but never materialized, reclamation complete, uncharted mined through, abandoned, DEP abandoned, DEP orphan, inactive, or regulatory inactive. Only counties with conventional or unconventional drilling were included in final analyses.

2.5 Statistical analyses

We used descriptive statistics to evaluate the distributions of socio-economic and demographic factors, oil and gas wells drilled, and oil and gas complaints and types of positive and negative determinations across drilled counties for the years 2004 to 2016. We plotted complaints by PADEP-assigned category by year to display temporal trends. We assessed correlations between continuous and ordinal SES and drilling variables using Spearman's rank correlations ($r_{Spearman}$) both to understand relationships within the data and to assess collinearity for regression modeling.

We conducted regression analyses to evaluate the associations between socio-economic factors and oil and gas wells drilled and three county-level outcomes: counts of complaints, counts of positive determinations, and proportion of water supply investigations resulting in a positive determination. All regression analyses were conducted in the Bayesian framework at the county level; the unit of analysis was county-year. For counts of complaints and positive determinations, we used hierarchical Poisson regression models to calculate rate ratios (RR) and 95% credible intervals (CIs) for each of the predictors. For the proportion of investigations resulting in a positive determination, we used hierarchical logistic regression to calculate odds ratios (OR) and 95% CIs. All models were fitted using the S.CARmultilevel function in the CARBayes package in R [55, 56]. The models included a county-specific spatially correlated random effect (i.e., following the Leroux version of the conditional autoregressive (CAR) model) to account for correlation between outcomes collected from different years within the same county (i.e., repeated measures) as well as spatial correlation between outcomes from neighboring counties [55]. They also included observation-level random effects to account for overdispersion in the case of the Poisson regression models and replication in the case of the logistic regression models. When defining the CAR model, neighboring counties were those sharing a border. All Poisson regression models included an internally standardized offset variable based on the population of each county across time and the total number of complaints or determinations across all counties and years (i.e., expected number of complaints/determinations based on the overall observed rate and county-level population size in a given year) [57]. Each model also included a linear time effect variable to control for large-scale changes in the outcomes across time. Weakly informative prior distributions were assigned to all introduced model parameters. Full details on the statistical modeling framework are given in Appendix A.

Variables were standardized prior to inclusion in the models for stability. For each model, we collected 1,000,000 posterior samples after discarding the first 100,000 during a burn-in period. These samples were thinned by a factor of 100 to yield 10,000 nearly independent posterior samples from which to draw inference. Convergence was assessed by monitoring the Geweke diagnostic for all model parameters [58]. Regression output was transformed by applying an interpretability scalar to all posterior samples for each variable, dividing by the standard deviation of the variable, and exponentiating the resulting values. The final RR or OR estimate and 95% CI for each variable is given as the posterior mean and the 2.5^{th} and 97.5^{th} posterior quantiles, respectively. While we calculated CIs for significance testing and to convey the precision of the estimates, estimates that do not reach the threshold of statistical significance may still have public health relevance. Thus, we mainly describe magnitude and direction of effect, and our results emphasize patterns in the data rather than significance.

The final multivariable models included the number of conventional and unconventional wells drilled per county per year as drilling-related predictors. Demographic and socio-economic indicators were selected *a priori* based upon associations in the literature, the independent relationship of each variable with the outcomes, and correlations with other variables. When constructing the final models, we aimed to represent all socio-economic and demographic domains while avoiding strong correlations between variables. When two variables were highly correlated ($r_{Spearman} \geq 0.80$), we based our selections upon stability of effect estimates, model fit criteria, and maximizing public health relevance. The following socio-economic and demographic variables were included in the final models: median household income (MHI), percent living below the poverty line, percent unemployed, percent AAN, percent Hispanic ethnicity, and percent 25 years of age and older with a high school diploma or equivalent.

3. Results

3.1 Oil and Gas Complaints and Determinations

Between 2004 and 2016, 9,404 oil and gas-related complaints were filed with PADEP in our counties of interest. The most common complaint category was “Water Supply” (n=4,099, 43.6%), which included aesthetic water issues (e.g., odor and color), water pollution, and water supply interruptions or depletions (Figure 3). A total of 4,064 of those complaints (99%) were reported publicly in PADEP’s online database of water supply complaints. An investigation was not completed for two of those complaints (0.05%), and 30 complaints were marked as “undetermined” (0.7%), though no additional details or reasons were available in publicly available materials. A total of 3,906 reported water supply complaints received completed investigations by PADEP during our study years, and of those investigations, 215 (5.5%) resulted in positive determinations (Figure 2). A total of 3,691 negative determinations (94.5%) were made. Following water supply complaints, the next most common category of complaint was “Spill Response” (n=1,128, 12.0%), which encompassed reports of hydraulic fracturing fluid, brine, and produced wastewater spills, drilling mud spills, and spills or leaks of oil and gas. Other complaint categories included pollution (n=929), property damage (n=737), general (n=671), leaking gas (n=437), location (n=395), abandoned/unregistered (n=388), odor (n=180), gas migration (n=146), leaking oil (n=143), oil or gas well incident (n=84), and other (n=67). These complaint types do not trigger investigations and are handled via a different mode of reporting [1].

In terms of temporal trends, the number of annual complaints rose rapidly after the introduction of UOGD in PA in 2005 (Figure 4). Drilling intensity increased sharply after 2005 (n=2 unconventional wells drilled) to a peak in 2011 (n=1,586 unconventional wells drilled). Complaints filed per year increased from 396 in 2004 to 1,152 in 2011, decreasing afterward aside from a second small peak in 2015. Positive determinations followed a similar pattern to complaints, though the first determinations were not made until 2007, with a maximum in 2010 of 52 before falling sharply.

3.2 County Demographics, Socio-economic Factors, and Oil and Gas Development

The characteristics of the 36 counties with unconventional or conventional drilling between 2004 and 2016 are presented in Table 1. County population size ranged from 4,807 to 1,281,666 individuals, with a median of 62,761. The most prevalent race across counties was white (median 95.6%, inter-quartile range [IQR] 93.2%–97.4%). Hispanic ethnicity (median 0.9%) ranged from 0.3% to 7.5%, with an IQR of 0.6%–0.9%. In terms of SES, the median annual household income was $39,522, and the range was $27,451 to $63,345. The percentage of the population below the poverty line ranged from 7.0% to 20.5% (IQR 11.7%–14.9%), and percent unemployment ranged from 0.7% to 6.1% (IQR 3.4%–4.6%). Median educational attainment was 46.2% with a high school diploma or GED (IQR 44.4%–49.6%) and 18.1% (IQR 14.8%–20.6%) holding a college degree.

Thirty-three counties had at least one unconventional well drilled during that time, while the other three had only conventional drilling. The counties with the highest number of complaints were Washington (n=1,066), Susquehanna (n=648), Bradford (n=647), and Greene (n=576); these were also the counties with the greatest number of new wells drilled over the study time period (Figure 5). Washington is among the most populous counties with oil and gas activity with over 205,000 residents (242.5 residents per square mile), while Susquehanna and Bradford are less populated with around 43,000 (52.7 per square mile) and 62,000 (54.6 per square mile) residents, respectively [54]. All three are considered to be rural by the state of PA [59].

3.3 Predictors of Complaints

Multivariable spatial models reveal several significant associations between socio-economic and demographic factors and number of complaints (Table 2). Two of the six examined socio-economic and demographic factors were significantly associated with the occurrence of complaints. MHI was positively associated with complaints, with a 47% increase in rate of complaints per $10,000 increase in annual income (RR: 1.47, 95% CI: 1.09–1.96). Educational attainment, as estimated by percentage of population aged 25 and older with a high school diploma or GED, was also positively associated with complaints (RR: 1.18, 95% CI: 1.11–1.26, per 1% change). Percent unemployed was associated with a 12% increase in rate of complaints filed per 1% change (RR: 1.12, 95% CI: 0.95–1.31), while percentage of the population living below the poverty line was not associated with complaints (RR: 0.97, 95% CI: 0.89–1.05). Race and ethnicity of the population were not associated with number of complaints. There was a 3% decrease in rate of complaints filed with each 1% increase in AAN population, as well as an 8% increase with each 1% increase in Hispanic population (RR: 0.97 and 95% CI: 0.92–1.02 and RR: 1.08 and 0.85–1.34, respectively). As for drilling factors, the rate of filing of complaints increased by 62% per 50 UOG wells drilled per county-year (RR: 1.62, 95% CI: 1.09–1.96), and increased 22% per 50 conventional wells drilled per county-year (RR: 1.22, 95% CI: 1.17–1.28).

3.4 Predictors of Number of Positive Determinations

In contrast to the positive association between MHI and rate of complaints, MHI was not associated with positive determinations (RR 0.86, 95% CI: 0.18–2.72, Table 2). The rate ratio was elevated for educational attainment (RR: 1.14), representing a 14% increase in rate of positive determinations per 1% increase in the percentage of the population with a high school diploma (95% CI: 0.96–1.35), and the association was similar in magnitude to that between complaints and educational attainment. Percent AAN was the clearest predictor of number of positive determinations; a 27% decrease in rate of positive determinations was observed per 1% increase in AAN population (RR: 0.73, 95% CI: 0.55–0.93). Conversely, percent Hispanic ethnicity was associated with a 100% increase in rate of determinations (RR: 2.00, 95% CI: 0.89–3.81). Associations with drilling factors were consistent with those of counts of complaints (RR: 2.08, 95% CI: 1.40–3.04 per 50 UOG wells and RR: 1.37, 95% CI: 1.15–1.64 per 50 conventional wells) though slightly larger in magnitude. Overall, there was more uncertainty around the estimates for determinations, as evidenced by wider credible intervals, likely because the number of positive determinations was much lower than the number of complaints (n=215 vs. n=9,442).

3.5 Predictors of Proportion of Water Supply Investigations Resulting in Positive Determinations

The associations observed for proportion of water supply investigations resulting in positive determinations were consistent with those observed for counts of determinations (Table 2). The odds of an investigation yielding a positive determination were 0.35 times less per $10,000 increase in MHI (95% CI: 0.09–0.96). For demographic factors, the odds of a positive determination were 0.81 times less for each 1% increase in AAN population (95% CI: 0.64–0.99) and 1.81 times more for each 1% increase in Hispanic population (95% CI: 0.90–3.23). The odds of an investigation yielding a positive determination were 1.44 times higher for every 50 UOG wells drilled (OR: 1.44, 95% CI: 1.07–1.94) and 1.11 times higher for every 50 conventional wells drilled (OR: 1.11, 95% CI: 0.95–1.29). The associations with drilling factors were generally consistent in direction and magnitude across all models.

4. Discussion

In our analysis of resident-initiated oil and gas complaints and PADEP investigations, there were 9,404 complaints, including 4,099 water supply complaints filed in drilled counties over a 12-year period in PA. A total of 3,912 water supply complaints were investigated between 2004 and 2016, resulting in 215 confirmed instances of water supplies being impacted by oil and gas activities. We identified several socio-economic and demographic factors that were associated with number of complaints filed and number of positive determinations made in PA, though relationships, in some cases, appeared to be complex. Additionally, both the number of conventional wells and the number of unconventional wells drilled were consistently positively associated with numbers of complaints and determinations. Understanding patterns in complaints and determinations can help inform communities as well as additional surveillance and distribution of public health resources to ensure equitable protections and enforcement of environmental policies and regulations.

Overall, our results support the hypothesis that communities with higher SES are more likely to file a complaint. In multi-variable models that controlled for oil and gas drilling activity, spatial autocorrelation, and confounding, the number of complaints was higher among counties with higher MHI. This could mean that wealthier areas with greater social capital are more likely to engage with their municipality and file a complaint, as seen in other literature [48, 60, 61]. This could be due to several reasons. For instance, wealthier residents could have greater awareness of issues or improved access to resources necessary to file a complaint [45, 60, 62]. It could also be that areas of lesser means are less likely to file complaints due to barriers to access such as understanding of and access to the complaint filing system, lack of time to devote to environmental and health concerns, and lack of trust in the municipality [45, 50]. The rate of complaints filed was also higher among counties with a greater proportion of individuals with high school level educational attainment. Overall, our results may support the hypothesis that relatively more educated communities may be filing more complaints. Academic achievement as an adolescent has been demonstrated to impact propensity to participate in political or community organizations as an adult [63]; this could also apply to use of municipal services.

While higher SES seemed to be associated with more complaints, this association was not consistent when we looked at determinations, as proportion of investigations yielding positive determinations was negatively associated with MHI. While wealthier areas with greater means may be more likely to engage with their municipality [46], they were not necessarily more likely to receive municipal recognition of a complaint despite filing more. Conversely, it could be that confirmed environmental issues occur more frequently in areas of lower SES; this would be consistent with observations in the literature of more potential hazards occurring in low SES areas [41]. However, there could be many other reasons for this relationship given such a small proportion of complaints yield more determinations. One reason could be the true absence of an issue, as positive determination requires confirmation of an issue through a laboratory analysis. Another reason could be that the investigation was not conducted at the right time. Because water supply issues may be transient, capturing empirical evidence during the right time and place can be challenging. The laboratory analyses may also not measure all possible contaminants, as thousands of chemicals may be used or produced by oil and gas activity [64].

While the number of complaints filed was similar across counties with different racial compositions, both the number and proportion of water investigations resulting in a positive determination were substantially lower in areas with a higher proportion of AAN groups (27% decreased rate of positive determinations made and 0.78 times the odds of a positive determination being made per 1% increase in AAN, respectively). First, it is possible that there were fewer impairments in areas with a higher proportion of AAN, resulting in fewer positive determinations. Alternatively, this finding may be highlighting some inequity in the determination process that warrants further investigation, namely that there could be less recognition, investigation, or acknowledgement of problems occurring in areas with a greater proportion of residents in historically marginalized groups [45, 47]. Although our study is unable to further examine the underlying factors due to limitations in the available data, other historical examples have shown that communities of color and low income communities are more likely to experience issues related to water contamination, such as public water system noncompliance or the presence of environmental contaminants [33–35].

Perhaps unsurprisingly, increased drilling activity was consistently associated with more complaints and determinations, with UOGD generally having a larger effect size than conventional drilling. It is possible that increased drilling activity makes the industry more visible to residents and thus leads to more complaints filed. As far as positive determinations, our results could mean that likelihood of an instance of water impairment may increase with increasing drilling activity. Brantley et al. [10], when examining complaints filed and determinations issued in PA between 2008 and 2012, previously estimated a low occurrence rate of water resource problems per UOGD well drilled, as only around 20 wells had been clearly identified as a source of contamination. However, the authors note that their estimates are obfuscated somewhat by the limited information released in these cases. They also note that nearly 20% of PA wells had received Notices of Violation (which encompass a range of problems, from administrative issues to workplace safety violations) from PADEP at the time, which may be indicative of many smaller incidents. Ultimately, our results indicate that increases in drilling activity are an important driver of both complaints and determinations.

Other factors, such as changes in industry practices or regulations, may also influence the potential for impacts and the filing of complaints. For example, in 2012, PA passed Act 13, which was intended to increase regulatory oversight of oil and gas drilling through improved reporting and enact consistent environmental standards [53]. This act extended the liability area and timeline for unconventional oil and gas well operators suspected in instances of water impairment from 1,000 feet from the site and within 6 months to 2,500 feet and 12 months [10, 53]. The act also included the creation of an impact fee, allowing a county or municipality to impose a fee on unconventional wells within its borders. The funds from impact fees are collected by the PA Public Utility Commission and are to be distributed to local governments and state agencies for a variety of purposes [65]. These fees were anticipated to provide funds to support PADEP in both administering the oil and gas program and in addressing environmental issues. Notably, one study observed that public support for UOG-related projects in PA was positively associated with receipt of impact fees [66]. The act also outlined the criteria for water supply complaints and determinations. Number of determinations per year began to decline alongside drilling intensity beginning around 2011 (Figure 3). The introduction of Act 13 with its increased oversight and deterrents did not appear to alter the downward trajectory in number of determinations made, although its influence could be further investigated.

In addition to responding to and remediating issues around complaints, municipalities have made efforts to protect communities from UOGD activity through the establishment of setback distances (a required distance between a home or other occupancy and oil and gas activity). These distances vary substantially by state, ranging from 150 to 1,000 feet [67]. PA uses a state standard of 500 ft, which was extended from 200 ft by Act 13 [53]. Colorado is considered to have the most stringent standards of the drilled states, requiring oil and gas wells be 500 ft from single family homes and 1,000 ft from multi-occupant buildings, such as apartment complexes and schools. The efficacy of the current setback distances is a subject of debate [68, 69]. The mandated distances are being revisited in several states based upon the environmental and epidemiologic literature. In Colorado, for example, several environmental and public health organizations are pushing for an increased setback distance of 2,000 ft, including the Colorado Oil and Gas Conservation Commission [70]. The Environmental Health Project has also recommended that PA setback distances for oil and gas wells be extended to 3,281 ft (1 km) based upon the peer-reviewed literature [71]. Ultimately, even if setback distances become more stringent, many homes have already been placed in potentially harmful proximity to UOG activity. In these cases, primary prevention, such as reducing emissions from UOG activity, may become more important than setback distances.

This study highlights another dimension of the public and environmental health impacts of UOGD. The 5.4% of water supply investigations that led to a positive determination represent 215 instances of documented water impairment by oil and gas development. Given the many barriers to both incident reporting and water testing discussed previously, this is likely an underestimate of the true number of issues experienced by PA residents. Additionally, the approximately 60% increase in rate of complaints filed per 50 wells drilled per year should be considered in the context of the overall number of wells drilled; more than 12,000 unconventional wells have been drilled in PA. The number of complaints filed alone could reflect psychosocial stress and anxiety, which is another health endpoint relevant to UOGD [11, 72–75]. Psychosocial stress and anxiety can be related to perceived and observable issues, and is not necessarily limited to experiencing true hazard [11]. A perceived lack of household water security has been suggested as one such cause of stress among residents of heavily-drilled West Virginia [17, 18]. Negative mental health impacts have also been associated with lack of transparency of and access to environmental and public health information related to UOGD [76]. Moreover, the number of complaints may underestimate the actual harm as they relate to perceived and observable issues, and many other issues may go unreported. Our results demonstrate significant community concern related to UOGD.

Some challenges for this study were that we had limited power to investigate drivers of positive determinations due to the relatively small number issued during our time period. County-level aggregated data may obscure heterogeneity within small geographic areas, such as differences in SES by community. Likewise, certain SES variables had limited heterogeneity within the dataset, which hindered our ability to differentiate their impact. In particular, due to the homogeneity of the study population, we lacked the statistical power to appropriately investigate impacts to individual racial and ethnic groups. The socio-economic and demographic indicators used are also fairly simple, and do not capture the full contextural nature of social, cultural, and economic factors. While more detailed metrics that account for factors such as inequality in income distribution and racial segregation exist, we did not have the spatial resolution to apply them. In the datasets obtained from PADEP, categorization of complaints was inconsistent, and categories overlapped substantially (e.g., “water supply” and “pollution” could both contain complaints describing water pollution), making sub-analyses of specific types of complaints difficult. Further, individual-level data about complainants, such as race or gender, are not collected. This would be an interesting aspect to evaluate, as multiple studies have shown that women may be more likely to take action to address environmental concerns than men [77, 78]. Strengths of this study include the focus on complaints, which capture residents’ voices and experience about their observed or perceived issues or threats to their drinking water. The unique dataset we used would not have been available without the work of the investigative journalists at the Public Herald. Journalists and non-governmental organizations are frequently involved in abstracting data, which is a time- and often resource-intensive process. The Public Herald obtained this dataset through requests citing the Emergency Planning and Community Right-to-Know Act and compiled and processed the records they received into a clean, usable format. There is an opportunity for researchers to both leverage and complement the work of such organizations. We used robust epidemiologic and statistical methods to analyze a unique endpoint representative of citizen participation and perception to assess patterns in reporting and municipal response and to understand the impact of oil and gas activities. The volume of complaints filed also demonstrates serious public concern, particularly towards the impact of these activities on water resources. We identified multiple socio-economic and demographic predictors of complaints and positive determinations, including MHI, educational attainment, and race. Our findings, which indicate that these drivers may be multifaceted and complex, should be useful in guiding additional research needed to better understand the influence of specific factors.

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Appendix A.

Statistical Modeling Details:

The specific modeling framework, using the Poisson regression models as an example, is given as

$$Y_{it} | \lambda_{it} \sim \text{Poisson}(\lambda_{it}),$$

$$\ln(\lambda_{it}) = \text{O}_{it} + \mathbf{x}_{it}^{\text{T}}\boldsymbol{\beta} + \phi_i + \theta_{it}$$

where Y_{it} is the count of interest (i.e., complaints, positive determinations) at county i during year t; λ_{it} is the expected number of counts; O_{it} is the previously described offset term; $\mathbf{x}_{it}$ is a vector containing all of the previously mentioned covariates that can vary by county and year (including linear time effect); $\boldsymbol{\beta}$ is the vector of regression parameters that describe the association between the covariates and the outcome; ϕ_i is the spatially-correlated random effect that is common across observations from the same county; and θ_{it} is the observation-level random effect distributed as $\theta_{it} \sim \text{N}(0, \sigma^2)$. The logistic regression framework is nearly identical other than we do not include an offset term in that model.

The spatially correlated random effects follow the Leroux version of the CAR model such that

$$\phi_i \Big| \boldsymbol{\phi}_{-i}, \rho, \tau^2 \sim N\left(\frac{\rho \sum_{j=1}^{n} w_{ij}\phi_j}{\rho \sum_{j=1}^{n} w_{ij} + 1 - \rho}, \frac{\tau^2}{\rho \sum_{j=1}^{n} w_{ij} + 1 - \rho}\right)$$

where n is the total number of counties in the analysis; $\boldsymbol{\phi}_{-i}$ is a vector of all spatial random effects with ϕ_i removed; $\rho \in (0,1)$ controls the level of spatial correlation in the data (i.e., values near zero indicate near independence); τ^2 describes the variability of the effects; w_{ij} describes the neighborhood connection between counties i and j, and is equal to one if the counties share a common border and is equal to zero otherwise. Counties are not neighbors of themselves such that $w_{ii} = 0$ for all i.

We assign prior distributions to the introduced parameters and favor weakly informative distributions to allow the data to drive the inference. Specifically, $\beta_j \sim \text{N}(0, 100{,}000)$, $\sigma^2 \sim$Inverse Gamma(1.00, 0.01), $\sigma^2 \sim$Inverse Gamma(0.01, 0.01), and $\rho \sim$Uniform(0,1).

Abbreviations:

UOGD	unconventional oil and gas development
RR	rate ratio
CI	credible interval
PA	Pennsylvania

PADEP	Pennsylvania Department of Environmental Protection
SES	socio-economic status
AAN	African American/Black, Asian, Native American/Alaska Native, and other non-White race combined

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Highlights:

- PA residents may file complaints to report hazards from oil/gas activity.
- Counties with higher socio-economic status were more likely to file complaints.
- # of complaints filed were similar in counties with different racial compositions.
- Higher % minority racial group associated with fewer confirmed impairments.
- Results highlight possible procedural inequities in the oil/gas complaint process.

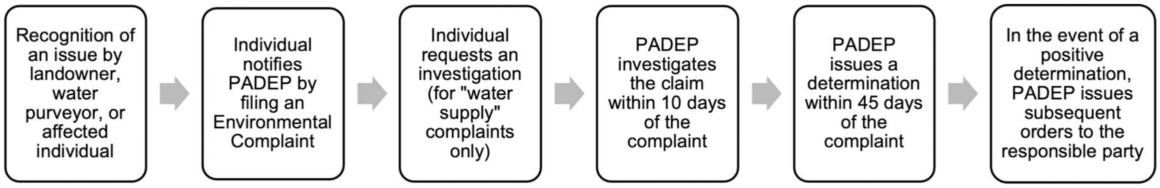

Figure 1. Process of complaint filing and issuing of determination.

Information obtained from Act 13, Code 78a.51. Protection of water supplies [53]. This process is specific to water supply complaints.

PADEP: Pennsylvania Department of Environmental Protection

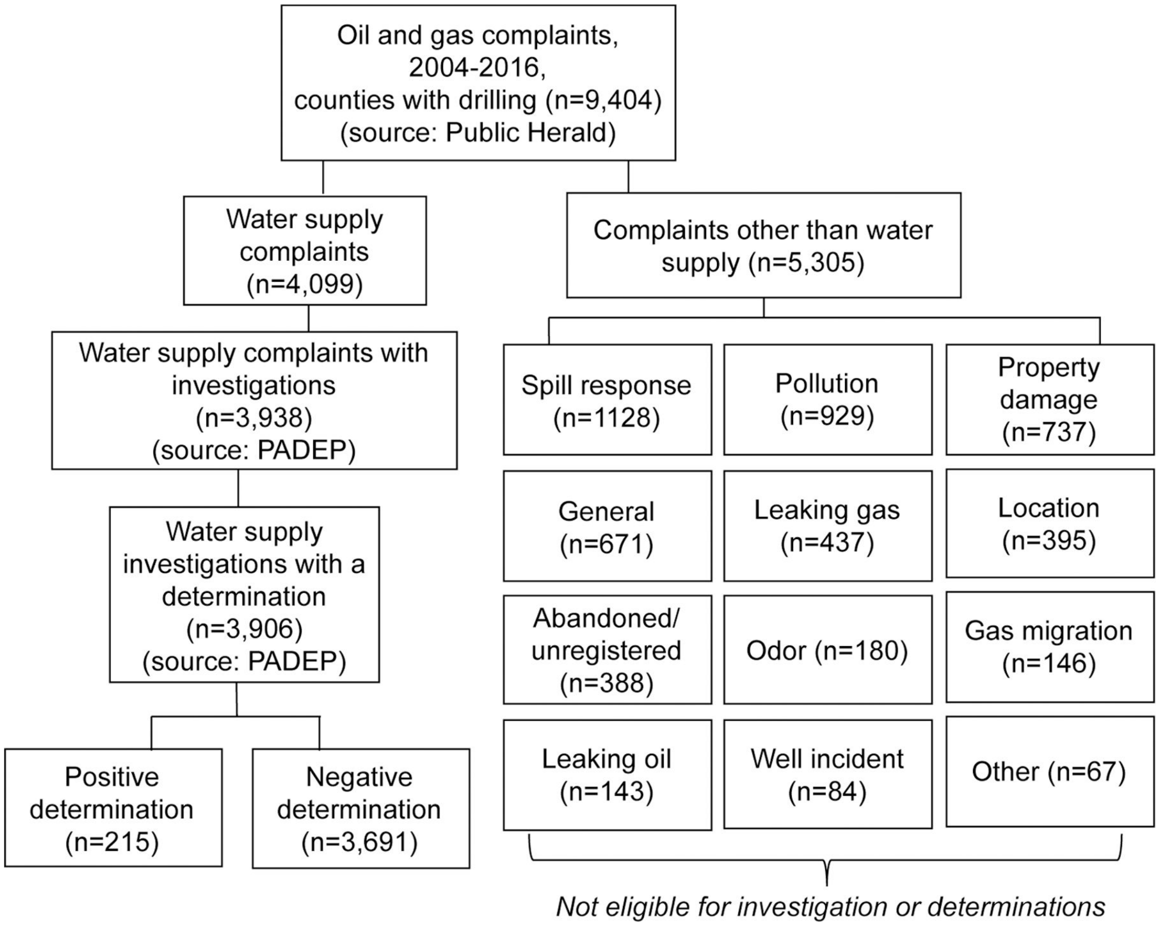

Figure 2. Flow chart of complaint and determination data acquisition and categorization.
Overview of the aggregated sources of oil and gas complaints and determinations data. Endpoints used in analyses are all oil and gas complaints (9,404), number of positive water supply determinations (215), and proportion of completed water supply investigations (denominator, 3,906) yielding a positive determination (numerator).
PA: Pennsylvania, PADEP: Pennsylvania Department of Environmental Protection

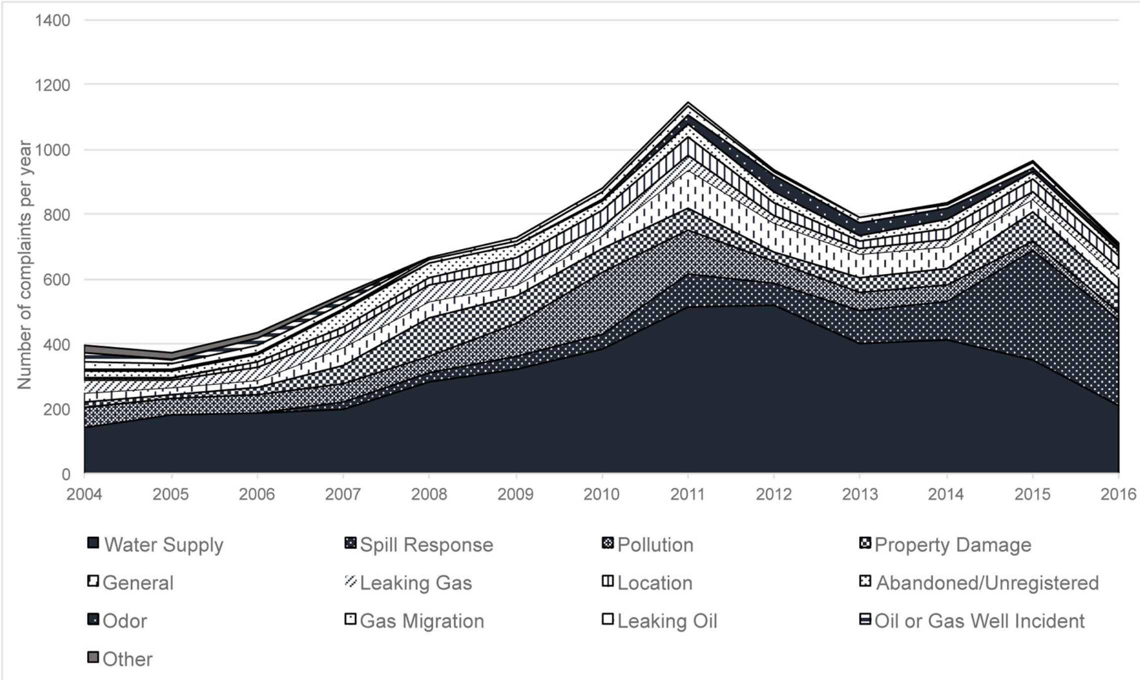

Figure 3. Number of complaints by category and year (2004–2016).

PADEP-assigned complaint categories include water supply (cumulative number 4,108), spill response (1,128), pollution (929), property damage (737), general (671), leaking gas (437), location (395), abandoned/unregistered (388), odor (180), gas migration (146), leaking oil (143), oil or gas well incident (84), and other (67) for a total of 9,404 complaints from 2004 to 2016.

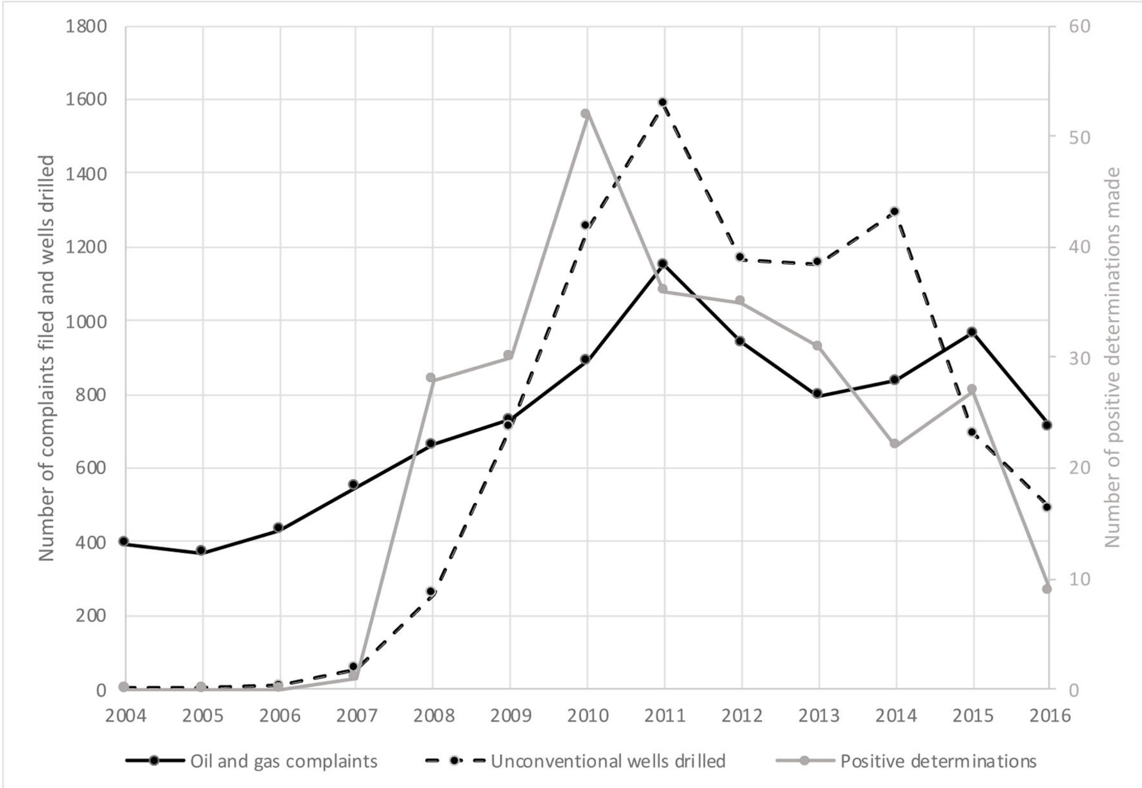

Figure 4. Yearly unconventional oil and gas activity in PA over the 2004–2016 study period.

Oil and gas complaints and unconventional wells drilled are shown on the primary axis. Positive determinations made are shown on the secondary axis.

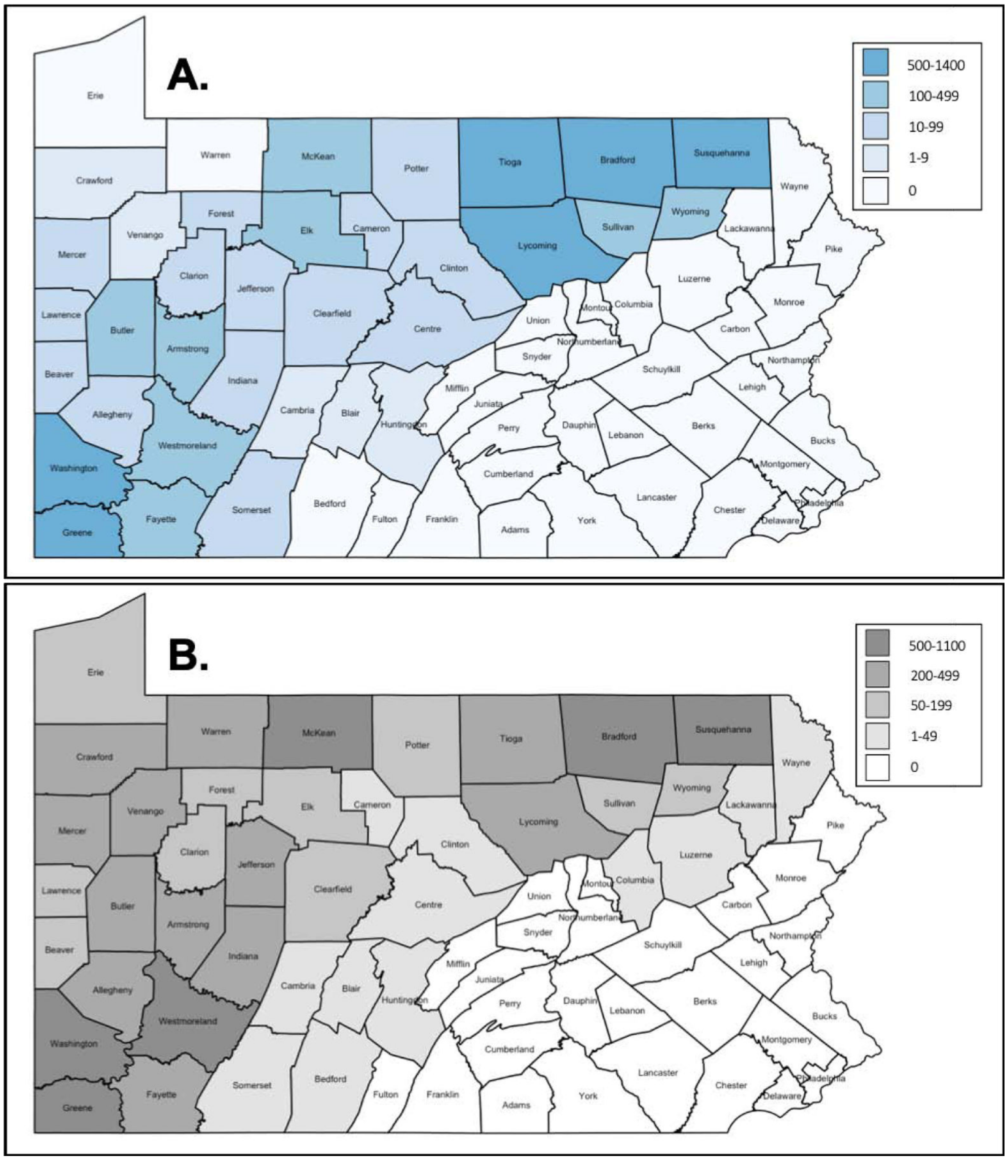

Figure 5.

Total number of unconventional oil and gas wells drilled (panel A) and complaints filed (panel B) per county over the 2004–2016 study period.

Table 1.

Social factors and oil and gas development characteristics of the study area, 2004–2016, per county-year.

Variable	Mean	Median	IQR	Range
Social Factors				
Total population (#)	122388	62761	(41373, 132958)	(4807, 1281666)
% White	94.5	95.6	(93.2, 97.4)	(59.5, 98.7)
% AAN	4.3	3.3	(1.9, 5.4)	(0.9, 33.0)
% Hispanic ethnicity	1.1	0.9	(0.6, 0.9)	(0.3, 7.5)
MHI ($USD)	39522	39754	(33152, 44161)	(27451, 63345)
% unemployed	4.0	3.9	(3.4, 4.6)	(0.7, 6.1)
% below poverty line	13.3	12.9	(11.7, 14.9)	(7.0, 20.5)
% over 25 YO with high school diploma or GED	46.2	47.4	(44.4, 49.6)	(29.8, 53.6)
Oil and gas development				
UOGD wells drilled	18.6	1	(0, 12)	(0, 323)
Conventional wells drilled	59.8	2	(0, 54)	(0, 766)
Complaints filed	20.2	12	(3, 27)	(0, 175)
PADEP positive determinations issued	0.6	0	(0, 0)	(0, 17)

IQR: Inter-quartile range, AAN: African-American/Black, Asian, Native American/Alaska Native, and other race, MHI: median household income, USD: United States dollar, GED: General Educational Development, PADEP: Pennsylvania Department of Environmental Protection.

Table 2.

Socio-economic, demographic, and drilling-related predictors of complaints and determinations.

	Number of complaints (n=9,442)		Number of positive determinations (n=215)		Proportion of water supply investigations resulting in positive determinations	
Variable	**RR**	**95% CI**	**RR**	**95% CI**	**OR**	**95% CI**
MHI per $10,000	1.47	(1.09, 1.96)	0.86	(0.18, 2.72)	0.35	(0.09, 0.96)
% Unemployed *	1.12	(0.95, 1.31)	1.19	(0.64, 2.09)	1.31	(0.74, 2.16)
% Under poverty line *	0.97	(0.89, 1.05)	0.94	(0.72, 1.19)	0.94	(0.75, 1.15)
% High school diploma *	1.18	(1.11, 1.26)	1.14	(0.96, 1.35)	0.96	(0.82, 1.12)
% AAN *	0.97	(0.92, 1.02)	0.73	(0.55, 0.93)	0.81	(0.64, 0.99)
% Hispanic *	1.08	(0.85, 1.34)	2.00	(0.89, 3.81)	1.81	(0.90, 3.23)
Unconventional drilling **	1.62	(1.43, 1.83)	2.08	(1.40, 3.04)	1.44	(1.07, 1.94)
Conventional drilling **	1.22	(1.17, 1.28)	1.37	(1.15, 1.64)	1.11	(0.95, 1.29)

RR: Rate Ratio, OR: Odds Ratio, 95% CI: Credible Interval MHI: median household income, AAN: African-American/Black, Asian, Native American/Alaska Native, and other race.

* Per 1% change per year.

** Per 50 wells drilled per year.