Pennsylvania Legacy Well Integrity and Emissions Study: Part 1

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Abstract

Oil and gas development in Pennsylvania has been ongoing for over 150 years, with the most recent phase of exploration and production activities targeting shale gas plays, including the prolific Marcellus and Utica shales. Regulatory standards for the industry have evolved significantly during this period as a function of both advances in technology and a relatively recent focus on environmental protection. Much of the contemporary dialog relating to oil and gas development and environmental protection has been directed toward operating well integrity, surface impacts, and human health; with little research focusing on the final stage of a well's life, which involves proper decommissioning, i.e., well plugging. Materials and techniques historically used for well plugging are inadequate by today's standards. Additionally, because oil and gas development had been taking place for nearly a century prior to permitting requirements enacted in 1955, an estimated 100,000 to 560,000 abandoned wells are yet to be accounted for in the state. In cases where no viable responsible party can be identified for an oil or gas well, the Department of Environmental Protection's (DEP) Bureau of Oil & Gas Planning and Program Management assumes responsibility for well plugging.

This study has provided insight relating to greenhouse gas contributions and methane flux to the subsurface from legacy well sites. A better understanding of variables that influence legacy well integrity and other well inventory shortcomings has been revealed, and such information is informative in the evaluation of hydraulic fracturing communication risks. Perhaps most importantly, DEP's unfunded plugging liability has been quantified using data gathered during the study. This information can be utilized to explore different funding models, and adjust regulatory program activities considerate of environmental and safety risks.

Introduction/Background

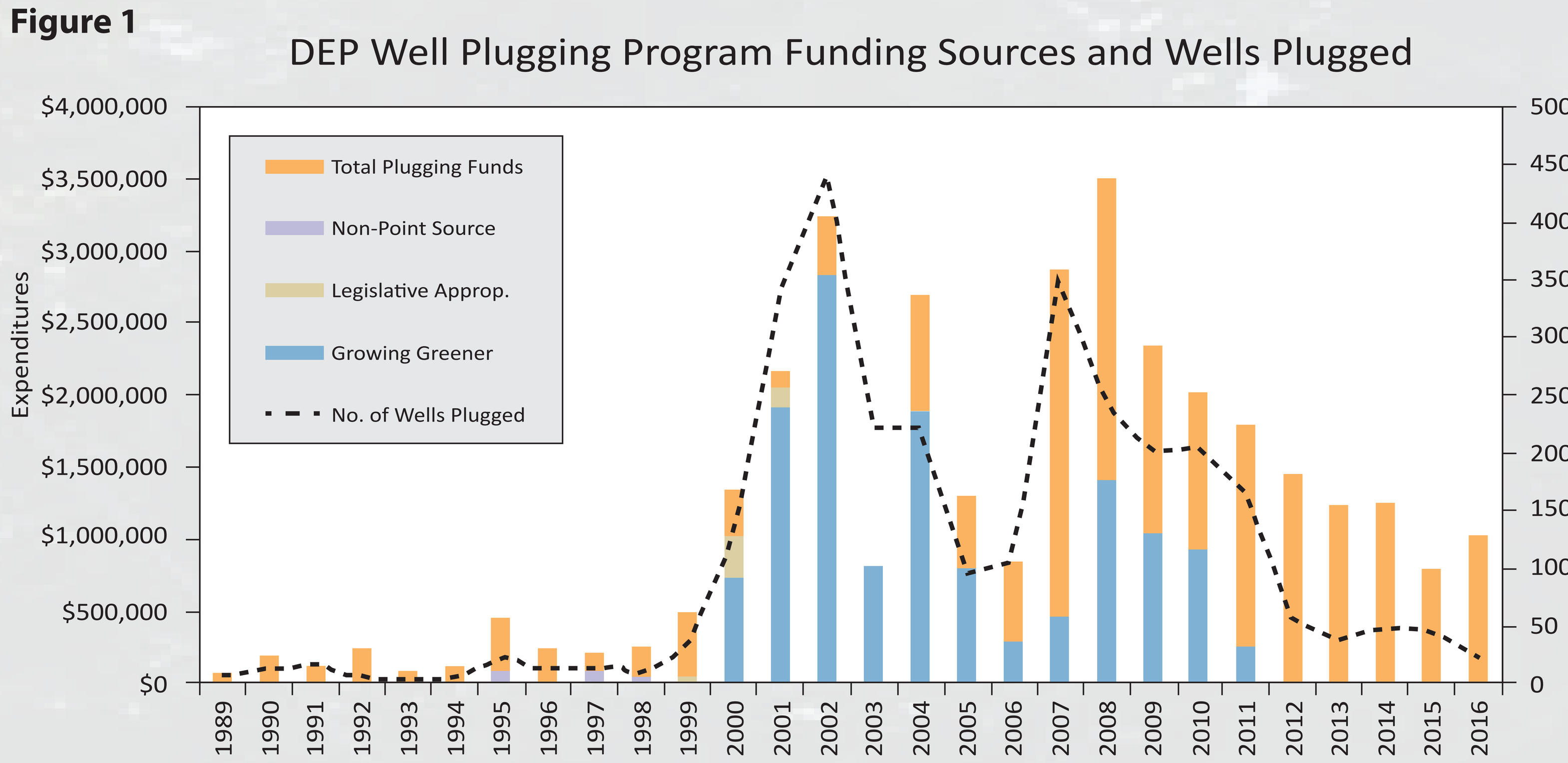
Pennsylvania is the birthplace of commercial hydrocarbon production. Appalachian basin oil reservoirs near Titusville were first exploited by Colonel Edwin Drake in 1859. The unique geology in this part of the state resulted in oil deposits that were so shallow they contributed to seeps along the aptly named Oil Creek. Since that time, hundreds of thousands of wells have been completed through portions of western, north-central, and northeastern Pennsylvania. Research has shown that somewhere between 300,000 and 760,000 wells may have been drilled in the state (Dilmore et al., 2015; Kang et al., (2014); Kang et al., 2016), with the most recent work by Kang et al. (2016) suggesting that 480,000 to 760,000 may be a reasonable estimate.

The relatively recent era of shale gas production in Pennsylvania has been transformative by anyone's standards. The state has become a leader in natural gas production, (DEP, 2017; EIA, 2017) second only to Texas domestically; and the diversity of operators has expanded, resulting in acreage being developed by global exploration and production companies alongside independent operators who continue to conduct infill drilling in previously discovered plays. The overprint of modern exploration and production activities atop a long and varied legacy substrate raises compelling challenges for both regulators and their industry counterparts. This intersection of past and present industrial activity is magnified in the coal measures of southwestern Pennsylvania, where legacy room-and-pillar mining, present-day longwall mining, and oil and gas activity all coalesce. As with any long-lived industrial activity, it is critical to adequately decommission legacy infrastructure in order to maintain safety and environmental protection standards in the present-day operating environment. For oil and gas wells, decommissioning involves proper plugging and abandonment.

The authors have compiled and studied DEP regulatory records regarding acute integrity failures associated with the legacy well population and concluded in 2013 that 38% of confirmed stray gas migration cases (n = 133) in the state between 1987 and 2013 could be attributed to legacy well sources. Additionally, 3% of these cases took place as a result of present-day hydraulic fracturing activities establishing a hydraulic connection with a legacy-well conduit, thus allowing pressure and fluid transmission to the shallow subsurface. The prominence and effects of stray gas migration in Pennsylvania have most recently been summarized in Neboga et. al. (2014), and historically in other publications (Harrison, 1983; Harrison, 1985; Walker, 1984; Baldassare and Laughrey; 1997; Breen et al., 2007; DEP, 2009; Révész et al., 2010).

The state's plugging program, which is almost exclusively subsidized by surcharges on drilling permits that range from $150 (oil wells) to $250 (gas wells), has been unable to make substantial progress in its efforts to properly decommission wells that have no associated responsible party outside of the years when external grant monies were available (Figure 1). In comparison, federal and other funding sources aimed at addressing legacy mining and other industrial impacts dwarf the funding allocated for managing abandoned wells in the state. A January 2017 analysis of remediation projects initiated in 2016 by the mining, water, and cleanup programs revealed project budgets totaling $44 million, $2.9 million, and $5.8 million; respectively. No non-emergency plugging program contracts were issued during this period due to depleted fund levels.

Figure 1



DEP plugging program funding sources, expenditures, and wells plugged between 1989 to 2016. Since inception, the plugging program has plugged 3,066 wells. Plugging program expenditures between 1989 and 2002 have been compiled by reviewing historical records, whereas expenditures between 2003 and 2016 were extracted from the agency's fiscal management database.

Using inflation-adjusted, plugging cost information (based on 2015 dollars) summarized between 1988 and 2013 and assuming that between 8,000 and 200,000 legacy wells may require plugging at some point in time, DEP has estimated that somewhere between $340 million and $8.4 billion are needed to address this significant environmental challenge. Recent well inventory estimates by Kang et. al. (2016) could increase the upper end of this range nearly threefold.

Environmental and safety impacts are not the only concern DEP faces in association with the legacy well population. The agency has only recently taken steps to transition its recordkeeping practices to the digital age and, as a result, database errors and locational inaccuracies exist and pose very real liabilities for the state. For example, not having accurate status information and uncertainty relating to the physical location of an abandoned well makes it difficult to manage and mitigate risk.

This research summarizes the results of DEP's legacy well integrity and emissions study and the repercussions of the findings, from the perspective of both environmental impact and risk management relating to current oil and gas and other natural resource development, namely coal. Results are used to explore relevant environmental problems, including greenhouse gas contributions and water resource impacts. Multivariate statistical analysis is applied to deduce study variable relationships and explore how these relationships may be used to help assess future costs to administer the plugging program and focus regulatory initiatives. Finally, plugging program cost forecasting has been updated and informed through the assessment of field data, and program funding models are proposed.

Methodology

Well Selection

Wells located in DEP's northwest (Northwest Region) and southwest (Southwest Region) operational areas were chosen for inclusion in the study. Sample populations were developed using criteria relating to well status and location. Wells were randomly selected for field measurements from these populations, although several additional limiting criteria were applied prior to selection, as described in the next paragraph. The criteria applied are not expected to introduce biases relating to well conditions, thus preserving the random character of the study samples.

First, counties with a relatively large number of wells were selected from the Northwest and Southwest Regions. Selected Northwest Region counties include McKean, Venango, and Warren. Selected Southwest Region counties include Allegheny, Greene, Washington, Indiana, and Armstrong. Within these counties, wells primarily located on public lands were proposed for ease of access. However, wells located on both public and private lands were also targeted in the Southwest Region due to there being relatively few wells on public lands in this operational area. Wells located within one-quarter mile of roads, and generally on grades of less than 10% were ultimately chosen for field verification to facilitate inspection efficiencies. The study population was further reduced to wells which had a locational discrepancy of less than 50 feet between DEP's eFACTS (2015) and the Department of Conservation and Natural Resources' (DCNR) WIS (2015) databases. Oil, gas, combination (oil and gas), and wells of undetermined type in both regions were all considered for the study.

Sample size was defined based on a 95% confidence level ($\alpha = 0.05$) and a confidence interval of ± 15% in order to maximize statistical significance given available resources. Table 1 presents the sample size for each well grouping.

Table 1

		Initial Study Design		Field Located	
Well Status	Region	N	n	N	n
Abandoned/Orphan	NW	378	38	378	24
	SW	211	36	211	24
Industry Plugged	NW	1,267	40	1,267	32
	SW	66	26	66	14
DEP Plugged	NW	189	35	189	34
	SW	125	32	125	8
	Total:	2,236	207	2,236	136

Study population (N) and sample sizes (n) for well groupings. Samples were randomly selected (α = 0.05, CI = ± 15%). Since 72 wells could not be successfully identified in the field, a second sample representing field located wells has been determined to evaluate uncertainty for characteristics that require field observation.

Equipment and Field Measurements

DEP made attempts to locate each selected well in the field and collect measurements of methane concentrations/flow rates at the well location. Methane concentrations were collected using Altair 5 gas meters (detection limits: 0% - 100% combustible gas by volume, resolution: 1% lower explosive limit (LEL)) at the well casing and near the ground surface to examine for concentrated and diffuse fugitive methane emissions. Flow rate measurements were collected at locations where connecting to casing, tubing, or vents was possible. Alicat Whisper flowmeters (detection limits: 2.4 – 480 cubic feet per day (cfpd), accuracy ± (0.8% of reading + 0.2% of full scale)) or Dwyer digital manometers (detection limits: 0 – 19 inches of water column (in. w.c.), accuracy: ± 0.5%) were used to estimate fugitive methane flux in cubic feet per day (cfpd). Forward Looking Infrared (FLIR) cameras were employed to provide qualitative visualizations of fugitive methane emissions at select well sites. Garmin Montana 650t Portable Global Positioning System (GPS) units were used to locate wells and assemble updated coordinates for well locations. General observations relating to site conditions, such as evidence of distressed vegetation, condition of well casing, and well status were also recorded.

Results and Analysis

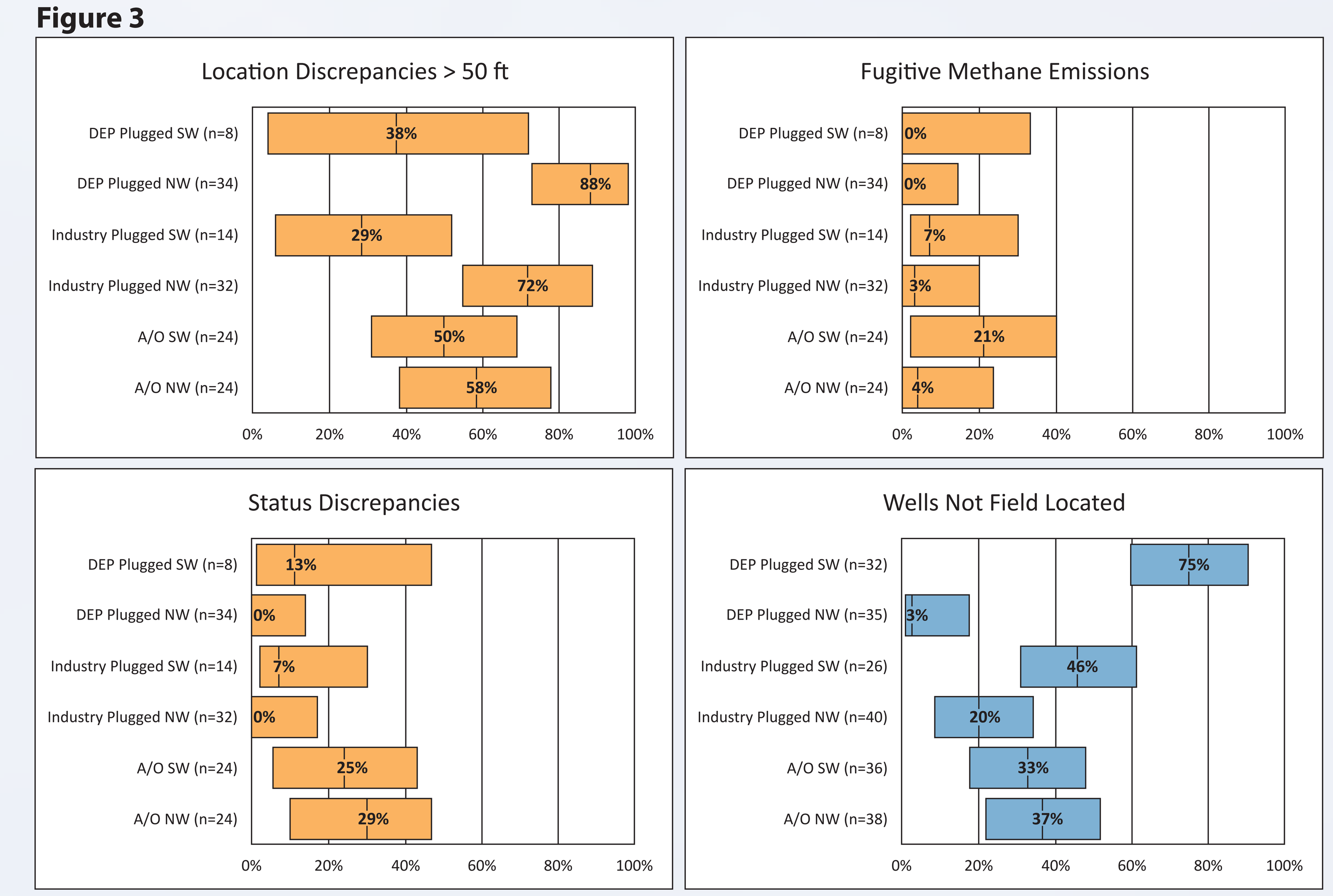
Summary of Observations

The characteristics of the sites visited were highly variable (Figure 2). Data were compiled and analyzed for general trends, including the ability to locate previously identified wells in the field, locational discrepancies between coordinates in DEP's database and actual field coordinates, discrepancies between well status as reported in DEP's database and as observed in the field, and the frequency of fugitive methane emissions. Confidence intervals have been updated to account for wells that could not be successfully located in the field. Results are summarized in Figure 3.

Figure 2

Field images captured at three locations investigated as part of the study. Site characteristics and surface infrastructure at legacy well sites can be highly variable. In some cases, no evidence of a former well could be identified.

Figure 3



Summary of field observations. Observation frequencies and confidence intervals (α = 0.05) for final sample sizes (n) depicted using data labels (%) and blue or orange-shaded bars, respectively.

Cluster Analysis

Field observations and other variables pertinent for characterizing the selected well locations were tabulated. The intent was to understand whether certain variables might be useful in explaining the results of the field study. For example, a large percentage of the wells in the Southwest Region could not be located in the field, and the authors surmised that this observation might, at least in part, be influenced by site characteristics. The variables describing site characteristics and field observations deemed potentially useful for this analysis are summarized in Table 2. Variable types, i.e., continuous or categorical, are also indicated.

Table 2

Attribute	Type	Mean	Median	Range	Standard Deviation
Latitude	Continuous	41.09711	41.51181	2.11071	0.69272
Longitude	Continuous	-79.48574	-79.44348	2.14859	0.59196
Locational Offset (feet)	Categorical (5)				
Spud Date	Categorical (4)				
Gas Presence	Categorical (2)				
Gas Flow (cfpd)	Categorical (2)				
Well Status	Categorical (5)				
Status Discrepancy	Categorical (2)				
Coal Area	Categorical (2)				
Mined Out	Categorical (2)				
Storage Well Density, per square mile	Continuous	0.1	0.0	2.1	0.3
Conventional Well Density, per square mile	Continuous	18.9	17.9	47.9	13.7
Unconventional Well Density, per square mile	Continuous	0.4	0.0	5.2	0.8
Population Density, per square mile	Continuous	245.4	34.8	4,634.4	650.2
Land Cover	Categorical (12)				
Well Type	Categorical (3)				
Public Land	Categorical (2)				
Slope Mean, degrees	Continuous	23.0	21.8	53.5	11.2
Slove Standard Deviation, degrees	Continuous	12.6	12.3	26.8	5.0
Pools Intersected by Well	Continuous	1.1	1.0	2.0	0.5

The number in parentheses for categorical variables indicates the number of categories.

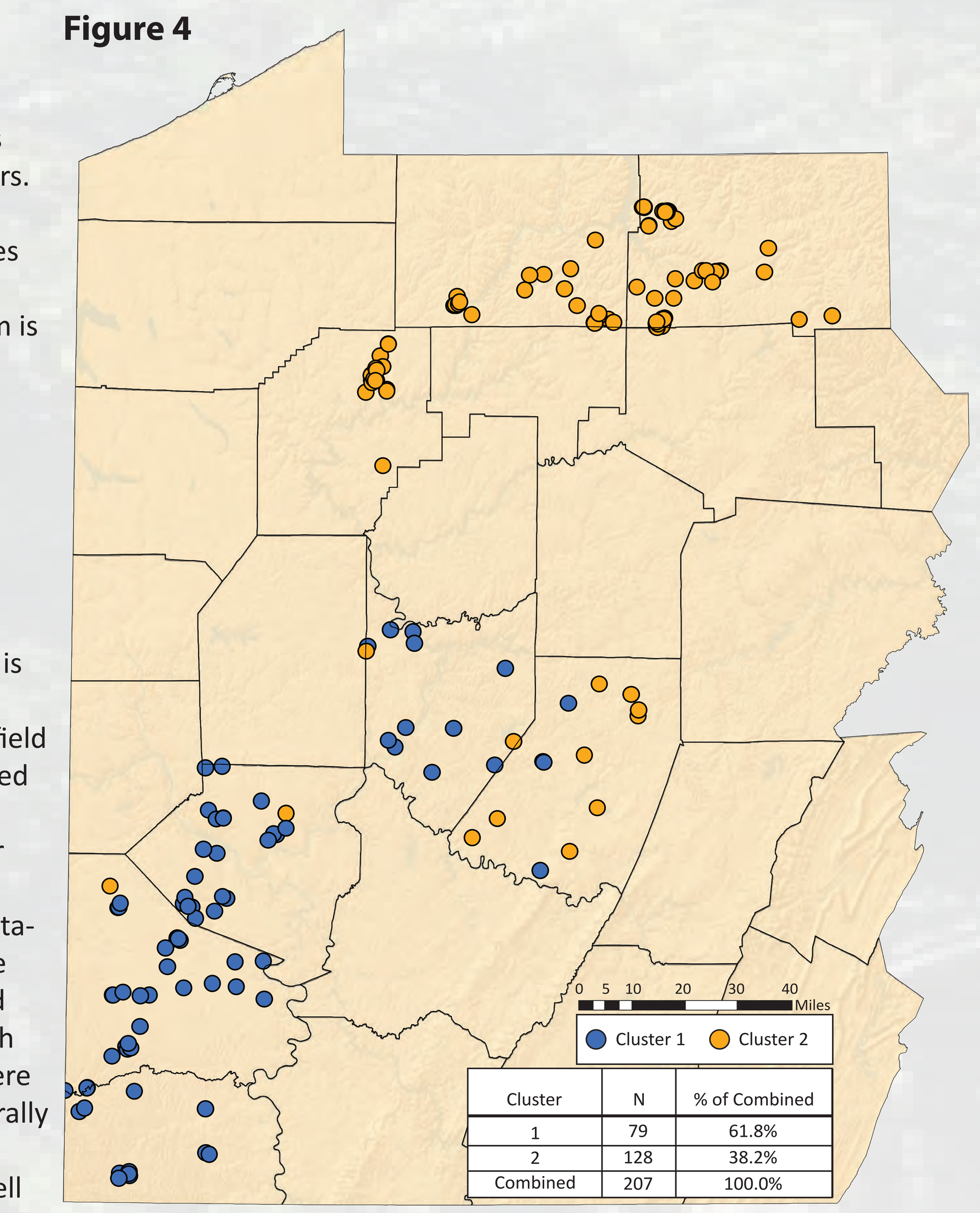
Coordinates are in NAD 83, and are taken from DEP's eFACTS (2015) database or DCNR's WIS (2015) database, if unavailable in eFACTS. Locational offset is the distance between the coordinates reported in the database and actual field coordinates. Spud date, Well Status, Coal Area, and Well Type are taken from eFACTS. Well densities were calculated from data available in eFACTS. Gas Flow is categorized as either ≥ 5 cfpd, or < 5 cfpd. Population Density is taken from 2015 municipal data (US Census Bureau, 2015). Land Cover is 2011 data (USGS, 2011). Slope was calculated within a 300-foot buffer around each well. Slope units are degrees from horizontal. Pools Intersected by Well is the total count of oil and gas pools mapped at the well location (Carter et al., 2015).

IBM SPSS Statistics 21.0 was used to evaluate the dataset. The two-step clustering algorithm was applied. Cluster analysis is an exploratory tool used to subdivide a dataset into smaller, more discrete groupings based on similarities between the variables comprising the groupings, or clusters. The two-step algorithm is capable of assessing both categorical and continuous variables. The method assumes that all variables are independent and that continuous variables are normally distributed. The two-step algorithm is favorable, as it can be executed to identify the optimal number of clusters, thus removing any user bias.

Two clusters were identified using the two-step clustering technique. The spatial distribution of these clusters is depicted in Figure 4.

The spatial discreteness of the clusters suggests a strong influence on grouping relating to location. Of significance is the large percentage of wells in cluster 1, which occupies DEP's Southwest Region, that could not be located in the field (54%). This geographical area is also generally characterized by more developed land, higher population densities, and different terrain, i.e., both higher mean slopes and greater variation in slope (standard deviation) at distances of 300-radial feet beyond the well locations tabulated in DEP's database. Utica and Marcellus shale development is also more prevalent in cluster 1 areas, whereas gas sand and oil sand development is more common in cluster 2 areas. Although more of the wells randomly selected for the field study were able to be located in the Northwest Region, which is generally represented by cluster 2, the offset distance calculated by comparing the actual position of the well in the field to well locational information tabulated in DEP's database is much greater than the offset noted for cluster 1.

Figure 4



Spatial and frequency distribution of clusters 1 and 2, which were identified using the two-step clustering algorithm executed to optimize the number of groupings. A strong regional component is noted.

Pennsylvania Legacy Well Integrity and Emissions Study: Part 2

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Significance of Findings

Hydraulic Fracturing Communication Incidents

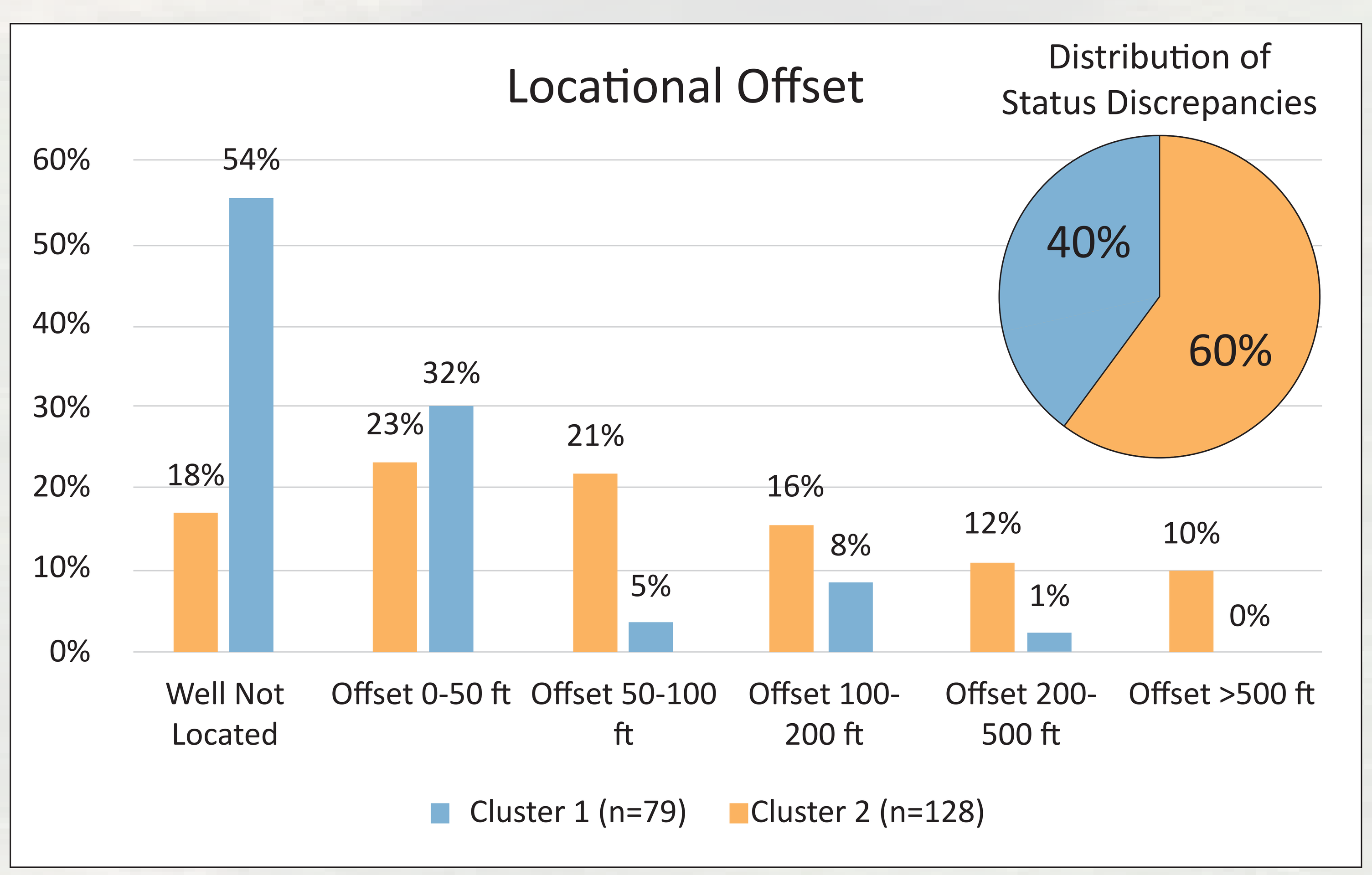
The intersection of present-day and legacy development poses documented environmental and safety risks. Specifically, legacy wells that are not properly plugged and abandoned, and penetrate deep enough to become hydraulically connected with nearby wells undergoing stimulation by hydraulic fracturing, serve as conduits that may allow the transmission of pressure and fluids to shallower portions of the subsurface and the surface (Detrow, 2012). In 2015, the AOR Committee estimated that, in areas of northwestern Pennsylvania where areas of legacy development is dense, hydraulic fracturing communication incidents occur one time for every 200 wells completed. In other parts of the state, the Area of Review Committee (2015) concluded that these incidents have not occurred nearly as often, but DEP's regulatory program had no formal way to document hydraulic fracturing communication incidents until October 2016, when a new regulation was promulgated for shale gas operators that included Area of Review provisions (The Pennsylvania Code, 2017). Prior to this rulemaking, the authors reviewed DEP internal records relating to several such incidents that had occurred in association with Marcellus shale development. The review showed that in at least two instances hydraulic fracturing communication with a legacy well resulted in stray gas migration and impacted water supplies. Both accurate locational and status information for offset wells is important for properly mitigating the risks associated with hydraulic fracturing communication incidents.

To better understand the distribution of hydraulic fracturing communication risks in the context of this study, it is important to revisit the results of the cluster analysis. Northwestern Pennsylvania, which is where most of the cluster 2 legacy wells are found, is an area of dense gas sand and oil sand development. Study wells were able to be located more often in this region, but the offset distance was considerable in many cases. The majority of the status discrepancies (9 out of 15, 60%) were also associated with cluster 2 wells. Although drilling has slowed in this region due to commodity prices, it is likely that hydraulic fracturing communication risks are elevated in association with the exploitation of shallow, sandstone reservoirs because the resource has been developed so intensively for such a long period of time. However, assessing and mitigating risk is con-founded by a prevalence of both inaccurate locational and status information for offset wells.

Cluster 1 wells, many of which are situated in areas where the Marcellus and Utica shales are being developed actively, were often unable to be located in the field at all. Additionally, 40% (6 out of 15) of the status discrepancies were associated with cluster 1 wells. Marked underground coal mining, both present day and historical, is also common in this region. The process of both longwall and room and pillar mining introduces vast regions of enhanced permeability associated with mine voids, collapsed roof materials, and the subsidence of overlying strata. These preferential pathways have the potential to magnify the severity and extent of impacts associated with hydraulic fracturing communication incidents.

Figure 5, below, illustrates the critical characteristics of clusters 1 and 2 associated with locational and status discrepancy distributions. Figure 6 depicts a shale gas development location in Robinson Township, Washington County where legacy development – both coal mining and oil and gas production – serves to elevate the risk of hydraulic fracturing communication and could potentially exacerbate the impacts were such an incident to occur.

Figure 5



Frequency distribution of locational and status discrepancies.

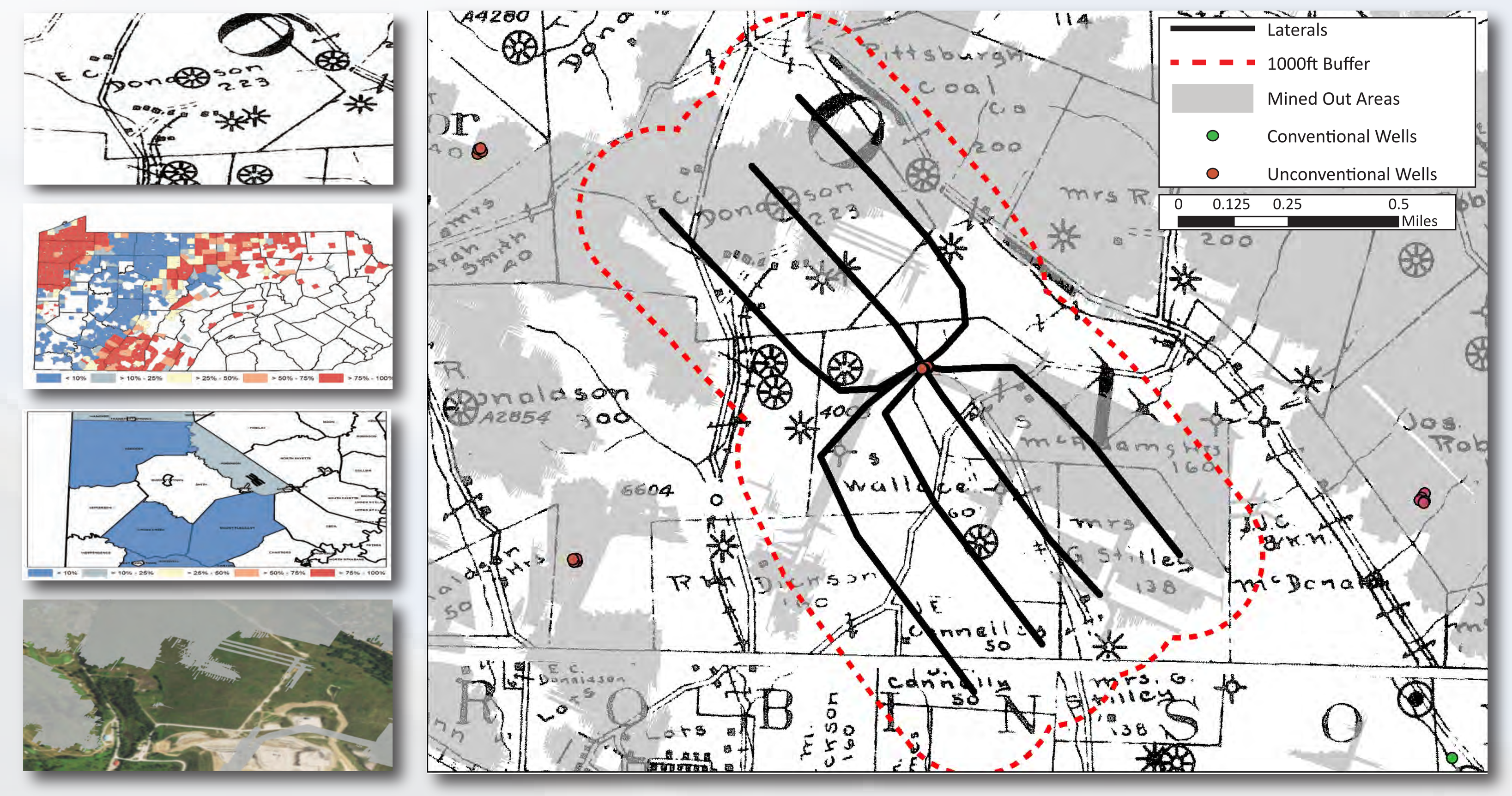
Methane Flux: Atmospheric Emissions

Of 136 wells located and inspected during the course of this study, only eight (8) were found to be emitting methane. Flow rates between 1.8 cubic feet per day (cfpd) and 1,456 cfpd were observed at five (5) of those wells. The remaining three (3) wells were emitting measurable concentrations of methane, however, quantification of flow rate was not possible either due to instrument sensitivity limitations or methane emanating from outside of the well casing or vent. Observations are tabulated in Table 3.

Methane flux to the atmosphere was calculated for the study population (see Table 1), sub-regional population, and statewide population. The sub-regional population includes wells of the same type and status as the study population, but is expanded to include all counties in each region, i.e., Northwest and Southwest Regions. For the purposes of this study, the statewide population includes the sum of the Northwest and Southwest sub-regional populations, and omits the Eastern Region. Uncertainties for each sample grouping were calculated based on a 95% confidence interval. Uncertainties for the statewide population were derived using methods suitable for combining sub-populations comprising a stratified random sample (PSU, 2017). Population sizes are tabulated in Table 4.

The estimated number of wells emitting methane was calculated for each group based on population sizes and the percent of wells found to be leaking in each sample. Well counts and the average emission rates for each group were used to determine methane flux estimates for each population. Where gas was detected, but flow rate could not be quantified, Kang et al's (2016) emission factor was applied. Results are presented in Tables 5, below.

Figure 6



Area of intersection between legacy mining and oil and gas development, and shale gas development in Robinson Township, Washington County. Note significant network of mine voids (light gray) and vast numbers of gas wells not captured in DEP's database. Historically, between 10% and 25% of the wells drilled in this municipality have penetrated within 1,500 feet of the Marcellus shale (third inset map in series).

Table 3

API No.	Region	Well Type	Status	% Gas	Observed Flow Rate (cfpd)	Emission Factor (mg/hr)[2]	Emissions Rate (MTCE /yr)
123-04922	NW	OIL	Abandoned	13%	3.4		5.87E-01
003-01262	SW	GAS	Abandoned	25%	NM	75,000	1.64E+01
003-22245	SW	UNK	Abandoned	10%	3.6		6.22E-01
063-22648	SW	GAS	Abandoned	100%	1,456		2.52E+02
063-26443	SW	GAS	Abandoned	2%	NM	75,000	1.64E+01
063-31452	SW	GAS	Abandoned	51%	NM	75,000	1.64E+01
083-54112	NW	GAS	Industry Plugged	39%	2.2		3.80E-01
063-21615	SW	GAS	Industry Plugged	10%	1.8		3.11E-01

"NM" indicates wells at which flow rates could not be measured. In these cases, emission rates were assumed to be equivalent to those reported by Kang, et al. (2016) for like well types. All flow rates have been converted to metric tons carbon equivalent per year (MTCE/yr).

Table 4

Well Status	Region	Sample Size (all)	Sample Size (field located)	Study Population	Sub-Regional Population	Statewide Population
Abandoned/Orphan	NW	38	24	378	9,923	58,997
	SW	36	24	211	939	
Industry Plugged	NW	40	32	1,267	39,374	
	SW	26	14	66	5,590	
DEP Plugged	NW	35	34	189	2,739	
	SW	32	8	125	372	
	Total:	207	136	2,236	58,997	

Population and sample sizes for emissions estimates. Statewide population only considers oil, gas, combination, and unknown well types.

Table 5

Well Status	Region	Study Population Emissions (MTCE/yr) Min	Max	Sub-Regional Population Emissions (MTCE/yr) Min	Max	Statewide Population Emissions (MTCE/yr) Min	Max
Abandoned/Orphan	NW	5.87E-01	5.33E+01	5.87E-01	1.41E+03	6.59E+04	1.03E+05
	SW	3.01E+02	5.09E+03	6.98E+02	2.29E+04		
Industry Plugged	NW	3.80E-01	9.63E+01	3.80E-01	3.04E+03		
	SW	4.10E-01	6.16E+00	3.11E-01	5.73E+02		
DEP Plugged	NW	0.00E+00	3.35E+00	0.00E+00	5.49E+01		
	SW	0.00E+00	5.03E+00	0.00E+00	1.46E+01		
	Total:	3.03E+02	5.25E+03	6.99E+02	2.80E+04		

Estimates of total methane emissions in MTCE/yr for various well populations considered in the study. Uncertainties for study population and sub-regional populations based on 95% confidence intervals (α=0.05). Kang et al.'s (2016) emission factor was applied at wells where gas was detected, but could not be quantified.

Methane Flux: Subsurface Discharges

Historically, methane discharging to groundwater and migrating vertically through the soil column, both in association with legacy wells and wells currently in production, has resulted in both environmental and safety incidents (DEP, 2009; Neboga et al., 2014). It is important to note that the number of stray gas migration incidents during the modern era of oil and gas development is small in comparison to the total number of potential source wells in the state, but methane flux to subsurface environmental media is nonetheless a significant environmental problem, and potentially a safety concern. The accumulation of methane in enclosed spaces, which can result as it exsolves from groundwater used to supply a residence or facility, or migrates through the soil column and into utility conduits or foundation cracks in structures, has contributed to several explosions and even casualties in Pennsylvania within recent years (DEP, 2009). Even in instances when accumulations of methane do not reach these critical levels, periods of elevated concentrations of methane may persist in groundwater until the source is remedied or the driving mechanism for the mobilization of gas dissipates (Neboga et al., 2014).

It is of interest that fugitive methane emissions were not often noted during inspections of the selected legacy well sites. Kang et al. (2016) found much more prevalent atmospheric methane flux in their recently completed study of legacy wells in the state. One possible reason is detection limitations and thresholds associated with DEP's measurement techniques. In cases where fugitive methane leaks were not isolated to the interior of well casing strings or other tubulars, standard gas meters were all the agency had for determining if a well was leaking. Also of significance is that Kang et al. (2016) completely enclosed the footprint of the well and portions of the ground surface beyond the outermost casing string in their study. The conceptual model is that well casings may not provide a confining pathway for vertical methane migration. In fact, the disturbed volume of unconsolidated materials and rock outside a well's casing strings may also provide a conduit for methane transport, thus increasing the likelihood that gas could escape the footprint of the wellbore more readily in the subsurface. The authors found evidence of such migration mechanisms during this study (Figure 7).

As part of this research, a risk-assessment screening tool has been developed using the statistical modeling work of Kang et al. (2016). The tool has also been used to identify and rank municipalities in Pennsylvania where further work may be proposed to better understand methane flux to the subsurface in association with the legacy well population. Predicted high-emitting wells were plotted using GIS and the percentage of them found in each municipality was calculated as a fraction of the total wells where emission estimates were made. Next, the population and water well densities were determined for each municipality that had at least one high-emitting well within its boundaries. Quartiles were determined for these datasets. This information was used to develop the scoring system presented in Figure 8, below. Figure 8 also shows the spatial distribution of the assigned scores on a municipality-by-municipality basis. The assumption is that municipalities with the highest percentages of high-emitting wells coupled with higher population and water well densities are potentially at the greatest risk for stray gas migration.

Figure 7

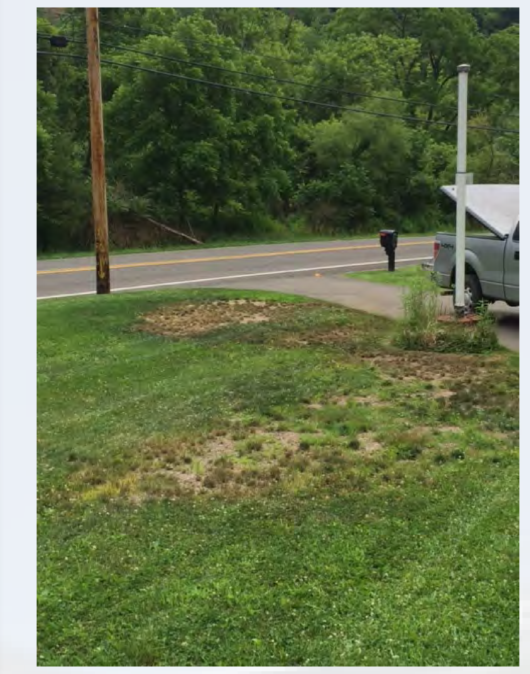
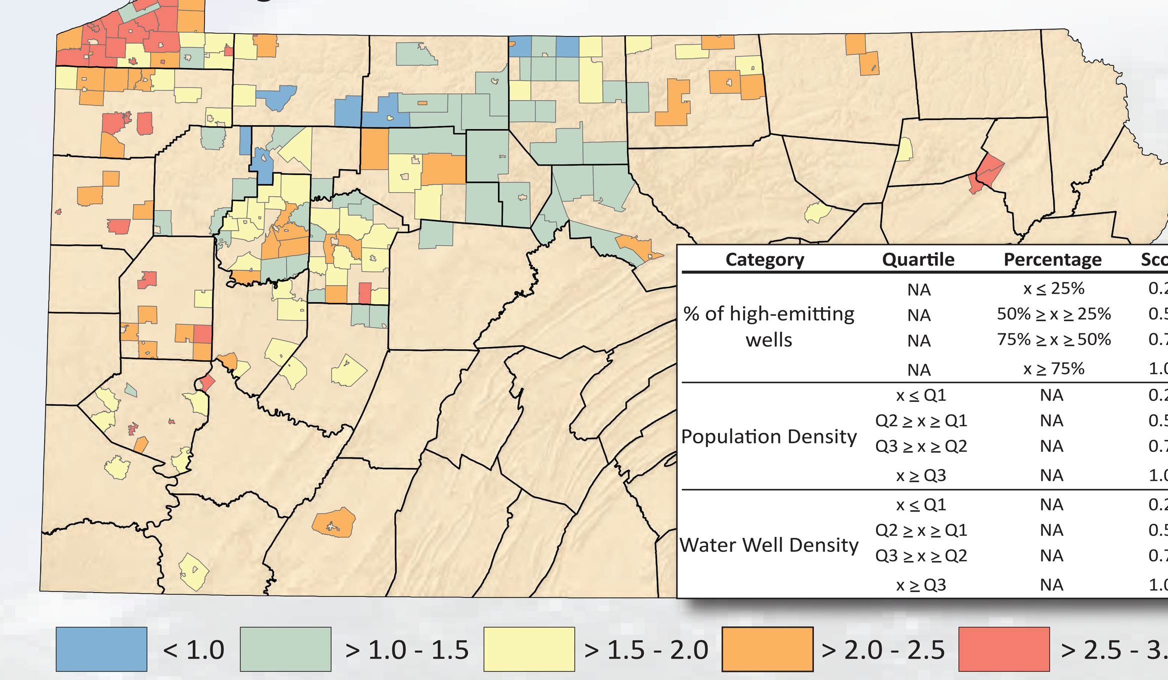


Figure 8



Category	Quartile	Percentage	Score
% of high-emitting wells	NA	x ≤ 25%	0.25
	NA	50% ≥ x ≥ 25%	0.50
	NA	75% ≥ x ≥ 50%	0.75
	NA	x ≥ 75%	1.00
Population Density	x ≤ Q1	NA	0.25
	Q2 ≥ x ≥ Q1	NA	0.50
	Q3 ≥ x ≥ Q2	NA	0.75
	x ≥ Q3	NA	1.00
Water Well Density	x ≤ Q1	NA	0.25
	Q2 ≥ x ≥ Q1	NA	0.50
	Q3 ≥ x ≥ Q2	NA	0.75
	x ≥ Q3	NA	1.00

Figure 7 on the left: Site of legacy well in Allegheny County randomly selected as part of the study. The well (location marked by white PVC riser vent pipe adjacent to driveway) had been previously vented by DEP under a plugging program contract and a passive mitigation system installed, but high levels of methane continue to manifest in the front yard of the residence, as indicated by dead vegetation in the image and also documented through field measurements.

Figure 8 on the right: Summary of risk-based scoring system for identifying municipalities in Pennsylvania that might be more susceptible to stray gas migration associated with methane flux to groundwater. Spatial distribution of risk depicted in accompanying map.

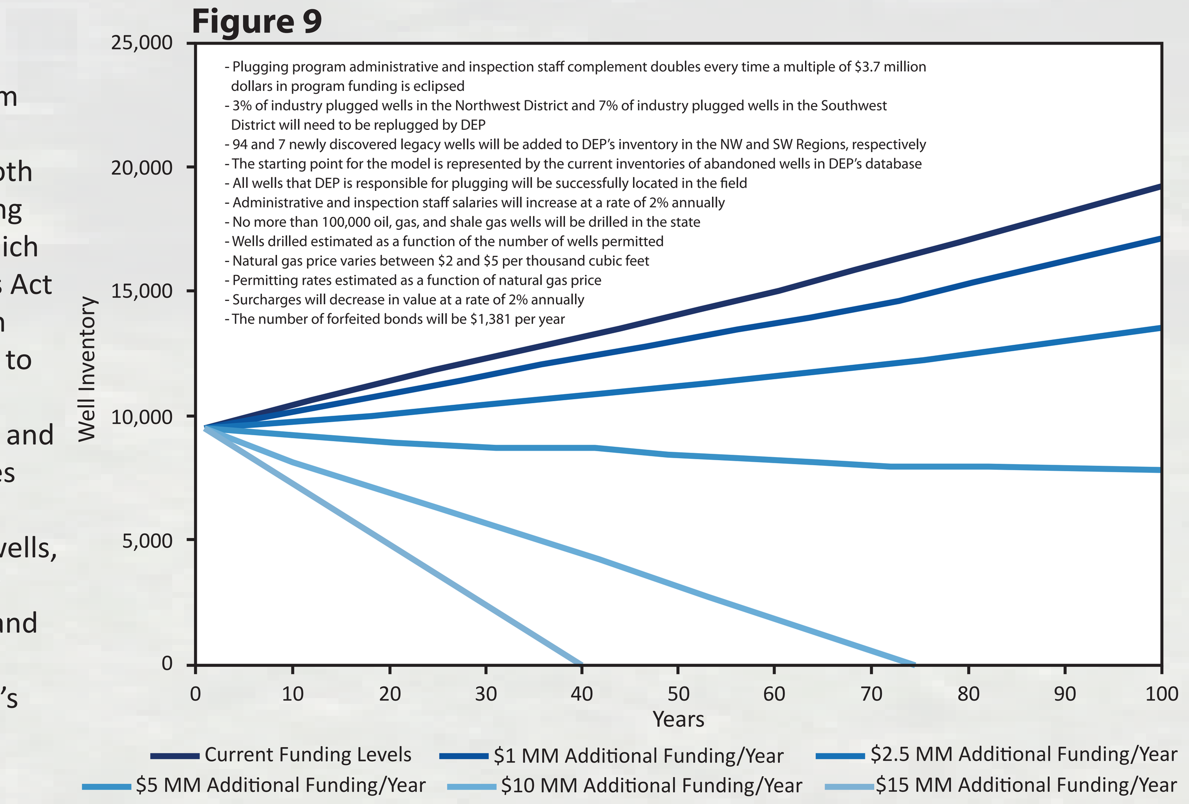
Unfunded Plugging Liability

Supplemental sources of funding are necessary to manage the legacy well population in the state. This was evident even prior to DEP's legacy well and emissions study. The magnitude of funding enhancements, however, could not be forecasted with a high degree of certainty prior to this work. It is now possible to calculate DEP's unfunded plugging liability, a critical step for informing regulatory officials, policymakers and lawmakers, the regulated community, and other stakeholders. The authors have developed a time-series modeling tool for evaluating how the legacy well population in the state will change as a function of program funding levels. Modelling runs that predict a baseline case and program funding scenarios where $1 million, $2.5 million, $5 million, $10 million, and $15 million in additional monies are available are shown (Figure 9).

Conclusions/Future Work

The environmental and regulatory program management impacts associated with Pennsylvania's legacy well population – both acute and long-term – are systemic. During the modern oil and gas regulatory era, which began with the passage of the Oil and Gas Act of 1984, the legacy well problem has been acknowledged, but the funding necessary to address it has not been provided. The concerns identified in this study are many and varied: significant data management issues relating to the maintenance of accurate spatial and status information for legacy wells, greenhouse gas contributions from legacy wells, compromised legacy well integrity and methane flux to the subsurface/stray gas migration, and gross underfunding of DEP's plugging program.

Figure 9



Plugging program funding forecast modeling exploring how legacy well inventory is projected to change if funding levels remain the same and if sources of supplemental funding equaling $1 million (MM), $2.5 MM, $5 MM, $10 MM, and $15 MM are identified. Modeling assumptions embedded in figure.

Through this work, the authors have been able to successfully characterize the scope of the problem, but developing solutions to ap-propriately manage associated environmental and public safety risks will not be possible without finding new sources of revenue for the plugging program. Further, environmen-tal and public safety risks may become elevated in certain areas of the state where shale gas development intersects with legacy development – both coal mining and oil and gas.

It is important for scientists, policymakers, lawmakers, and other stakeholders to begin focusing on the legacy well problem in Pennsylvania. The state has a long tradition of fossil fuel extraction and other industrial development, and has acknowledged the environmental legacy associated with that history in certain cases. This is evident in the amount of funding available for mining reclamation and other environmental remediation projects. Oil and gas development, specifically shale gas development in Pennsylvania, apparently will play a prominent role in providing near term domestic energy security. This new era of natural gas development can reasonably be coupled with a focused effort to address the environmental and public safety risks attributable to legacy oil and gas development in the state.

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[2] Emissions rates assumed to be equivalent to those reported by Kang, et al. (2016)

Background Imagery: Image on Part 1 poster is legacy derrick discovered at a well that was classified as plugged in DEP's database. Background image on Part 2 poster is legacy well that was previ-ously unknown and discovered in the detention pond of a new residential development during the study. Both sites are located in DEP's Southwestern Region.

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