The Application of 3D Modeling to Differentiate Between Naturally Occurring Methane and Methane Migration Associated with Natural Gas Development

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Abstract:

Naturally occurring methane is found in the fresh groundwater system of northeastern Pennsylvania. However, in certain instances, natural gas drilling in the region has resulted in increased dissolved-phase methane concentrations in water supplies. The mobilization of thermogenic methane in such instances has largely been attributed to substandard gas well construction and operational practices resulting in the vertical and lateral migration of gas associated with Upper to Middle Devonian strata. This research explores how 3D modeling in the Geographic Information Systems (GIS) environment represents an effective tool for exploring the spatial relationships between water well depths and both introduced and natural occurrences of methane in fresh groundwater systems.

Ultimately, by modeling geologic structure, water and gas well construction attributes, and the distribution of shallow gas-bearing units, it is possible to gain insight regarding factors that contribute to both stray gas migration and the distribution of background methane.

Purpose/Background:

Pennsylvania has a long history of oil and gas operations dating back to 1859 with the completion of the Drake Well in Titusville. For most of that history, extraction activities have focused on the tight-gas and tight-oil sands predominantly located in the western half of the state. With advances in drilling and stimulation techniques, shale-gas plays have become an important part of the domestic energy profile. In Pennsylvania, shale-gas operations have ramped up due to the widespread occurrence of productive intervals of the Marcellus Shale, one of the largest shale-gas plays in the world.

Between 2008 and 2010, marked increases in the number of Marcellus Shale wells drilled in the state were observed (Figure 1). This trend was accompanied by an increase in the number of stray gas migration incidents investigated by DEP (Figure 2). Typically, investigations are conducted in response to a water supply complaint (Figure 3). Current DEP regulations require the operator to take a primary role in investigating the complaint if it pertains to stray gas migration, although the agency does conduct operations allowing for an independent, technical conclusion to be drawn as to whether the reported impact is attributable to local oil and gas operations or a background condition. Most of the recent stray gas incidents have taken place in the northeastern area of core development and appear associated with Upper to Middle Devonian gas-bearing units not entirely isolated during Marcellus Shale gas well construction.

Prior to Marcellus Shale development, the affected region had not been exposed to much historical oil and gas exploration and production. The area is geologically distinct in that it is largely glaciated terrain, and was subject to a more intense compressional environment compared to the other area of core Marcellus Shale development in the southwestern corner of the state. Sedimentary facies associated with the gas-bearing units are also generally more proximal in character due to the eastern disposition of clastic sources.

As exploration and production activities in the region progressed into more recent years, much effort has been focused on thorough characterization of the shallow subsurface and groundwater sampling. This has revealed, in some cases, that background thermogenic methane coincident with the fresh groundwater-bearing zone is not entirely unexpected (Figure 4). Such an observation confounds water-supply complaint investigations received following the commencement of nearby gas well drilling, oftentimes adding a layer of complexity when attempting to differentiate between the background condition and departures from that baseline. Subsurface complexities, multiple potential sources, and the spatial distribution of alleged receptors all require visualization tools to develop a robust site conceptual model.

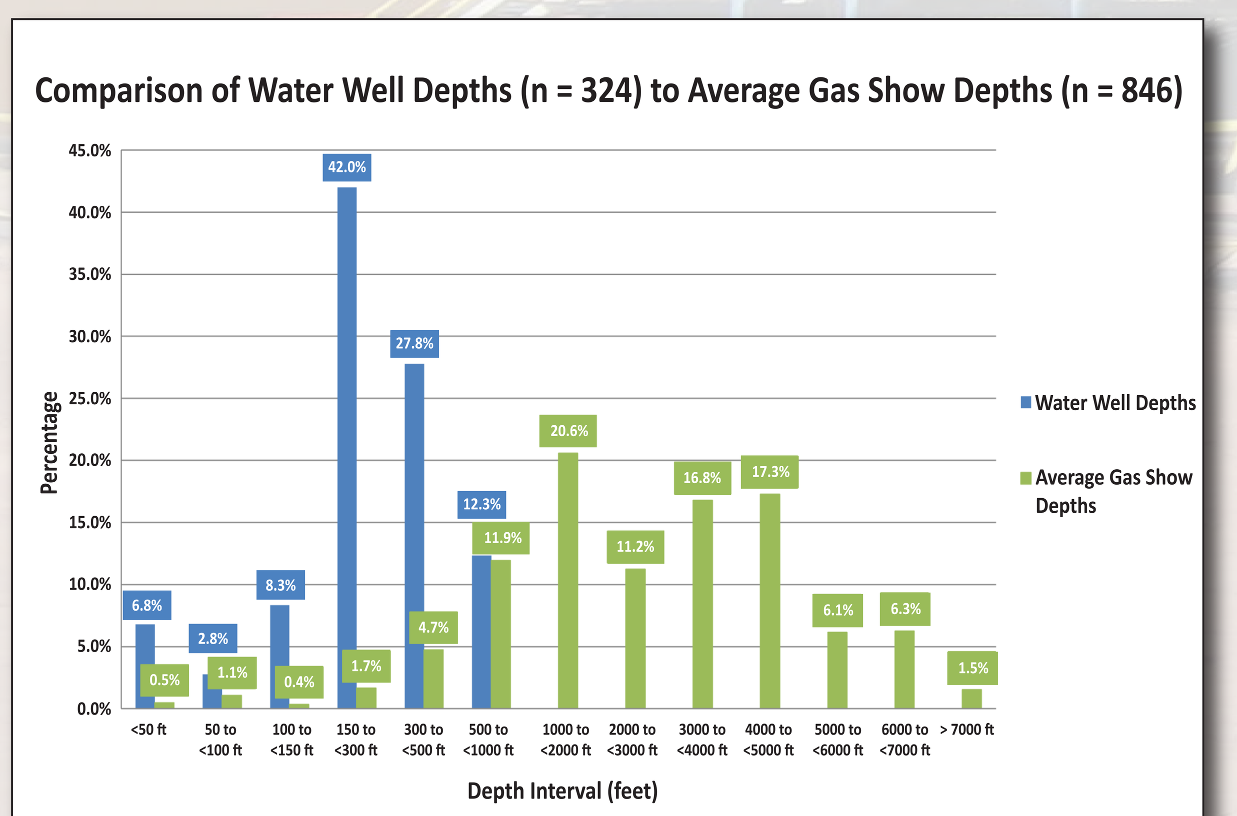


Figure 4:

Comparison of water well depth to average gas show depth based on well records submitted to DEP associated with Marcellus Shale development in Susquehanna County. Gas shows are based on operator mud logging and are only reported for vertical wellbore sections.

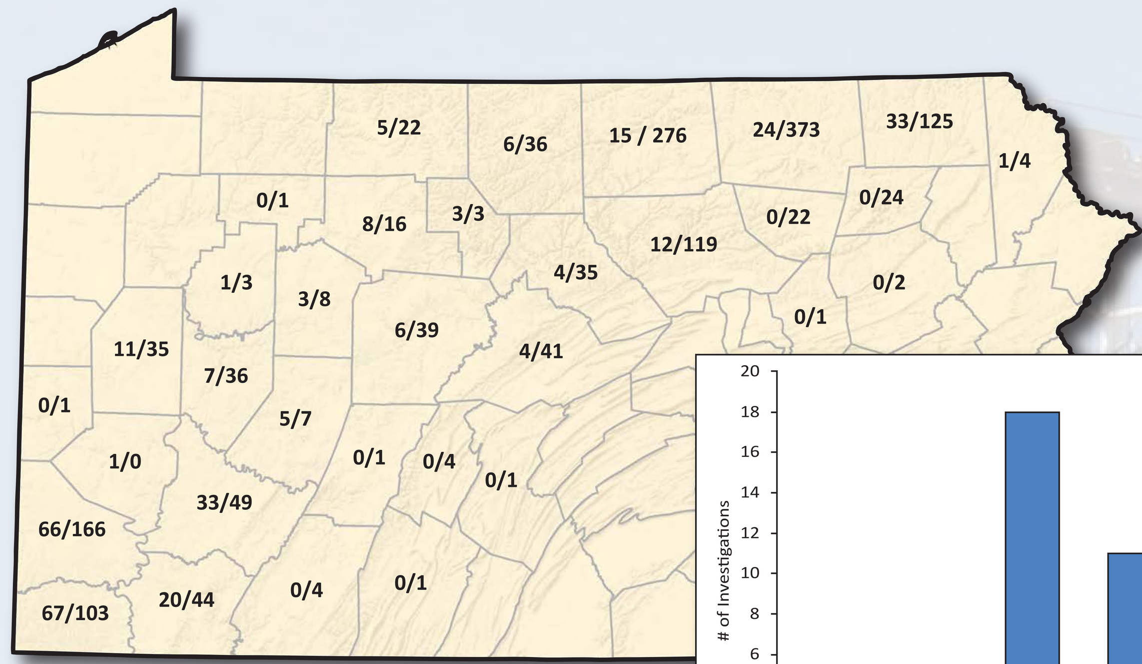


Figure 1:

Spatial distribution of unconventional wells drilled in Pennsylvania in 2008 and 2010. Totals are depicted on a county-by-county basis. Note marked increases in wells drilled in core Marcellus Shale development areas in northeastern and southwestern Pennsylvania.

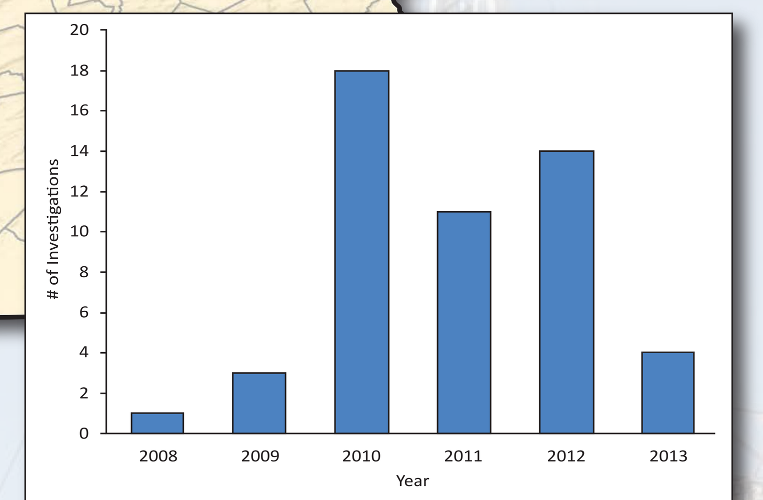


Figure 2:

Total number of stray gas cases investigated in the Eastern District since 2008.

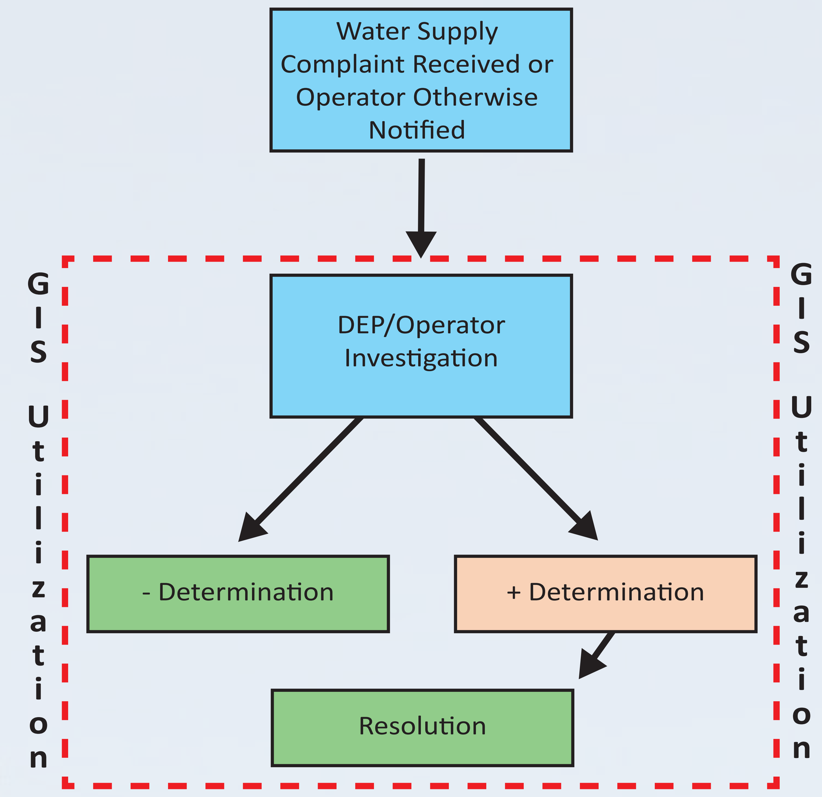


Figure 3:

Schematic illustrating water supply complaint investigations involving alleged impacts by methane. The utilization of GIS modeling and analyses throughout the process helps DEP determine potential sources and stray gas migration mechanisms.

Method:

The first part of the project involved assembling and tabulating all relevant data. Most of the data are either analog in nature or received in formats that must be modified for the purposes of modeling (Figure 5). Compiling Microsoft Excel summary tables is a useful intermediate step for ensuring consistent formatting that readily translates to the GIS environment.

The second part of the project involved importing the necessary components into the GIS and developing animations. The ArcScene and Spatial Analyst modules of ESRI's ArcGIS were critical tools for this aspect of model development.

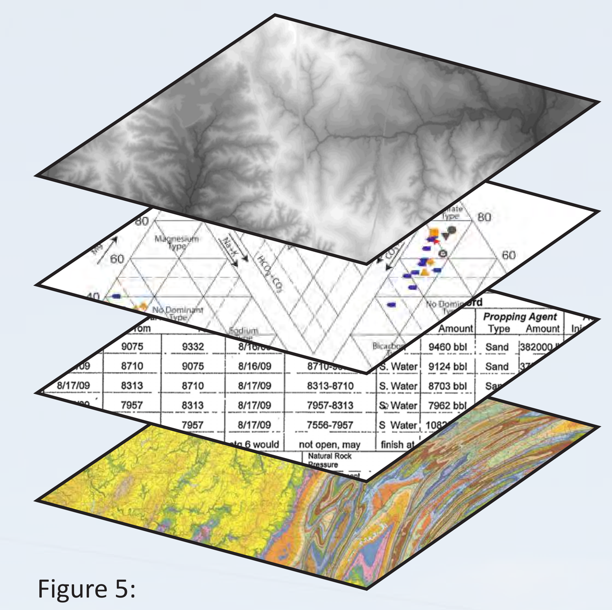
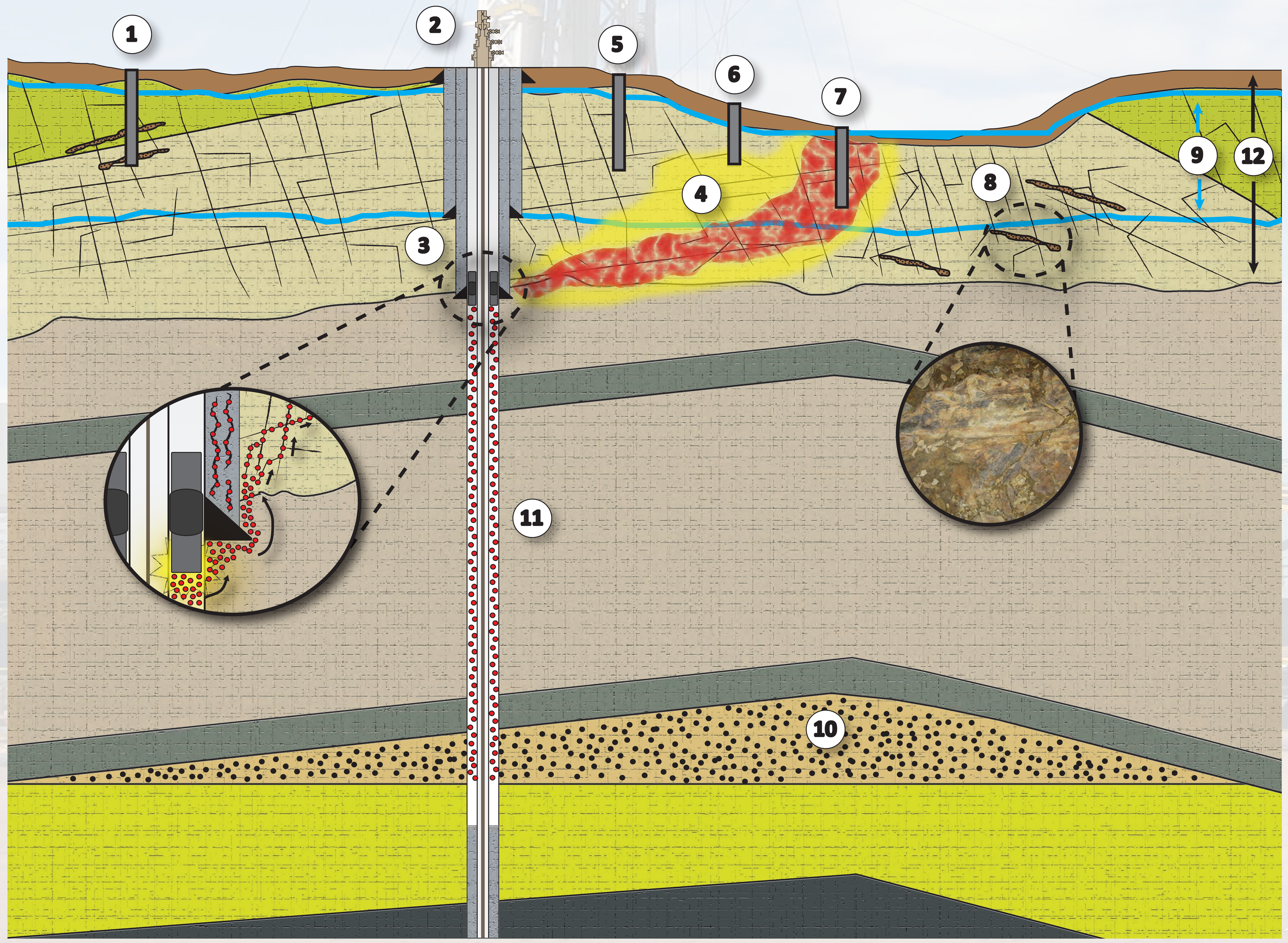


Figure 5:

Conceptual model representing inputs and sources for data used to construct 3D GIS model.



1. Water supply well impacted by background methane due to presence of carbonaceous materials along bedding planes
2. Gas well with shut in valves at the surface permitting the build-up of annular pressure
3. External casing packer set outside production casing at depth of intermediate shoe allowing build-up of pressure at the casing seat, gas flow into the surface-by-intermediate annulus due to overpressuring and cement channeling, and flow of methane into rock fractures near the intermediate casing seat
4. Free-gas methane "plume": "red" is zone of highest gas concentration due to permeability anisotropy favoring flow along bedding planes; "yellow" zone is less concentrated and methane in this zone is in part being disseminated by the presence of vertical fractures/joint sets
5. Unaffected water supply well: shallow depth prevented deeper methane escaping gas well from impacting the aquifer at this location
6. Moderately affected water supply on the periphery of the free-phase gas "plume"
7. Heavily impacted water in valley setting where fractures are more closely spaced due to coincidence with apex of anticline; well also contains some background methane associated with carbonaceous material along bedding planes; open-hole section of water well provides vertical conduit allowing further vertical movement of methane gas
8. Area of closely spaced fractures in valley setting and image of carbonaceous material occurring along bedding planes; carbonaceous material is responsible for generating thermogenic methane in portions of the fresh groundwater interval (Wilson, 2012)
9. Fresh groundwater interval
10. Non-target gas-bearing zone
11. Annular flow of methane associated with deeper, non-target gas-bearing zone; gas is entering a portion of the production annulus that is uncemented
12. Depth interval characterized by open rock fractures

Figure 6: Site Conceptual Model

Results/Conclusion:

Visualization of the distributions of gas shows and water wells in three dimensions yields insight with regard to whether or not spatial correlations between the two datasets exist. By assuming that the used-groundwater interval is generally within 500 feet of the surface and that the base of the deepest fresh groundwater is found at approximately 1000 feet below the surface, it is possible to summarize gas show magnitude and occurrence over the fresh groundwater interval and below. It was found that even though the frequency of gas shows is higher over the shallower subsurface in the study area, gas-bearing zones tend to be less prolific based on gas unit measurements. Finally, through raster analysis in the ArcGIS environment, gas show density values were extracted and compared to the distribution of naturally occurring methane. No compelling spatial correlations were identified.

A site conceptual model (Figure 6) for the stray gas investigation site in northeastern Pennsylvania under study was also constructed in ArcScene. The model is capable of being reoriented spatially to examine various aspects of the case and different feature classes can be activated to better understand the chronology of events that led to the observed water supply impacts. Bedding orientation as well as the presence of drainage-associated lineaments appear to be the major natural controls on gas migration at the site. This conclusion was used to identify other potential source wells. Cement jobs of lesser quality and operational practices such as shutting in annular spaces both were identified as contributing to the stray gas migration incident. Further, well construction practices, including the installation of external casing packers at relatively shallow intervals with long open-hole intervals below the packer base, also appear to have been a significant causative factor.

Time-series trends with regard to water quality were also visualized to determine if any responses to remedial activities and the application of different operational practices at the site could be identified. Improvements in water quality were noted in response to the implementation of an annular venting program as well as remedial squeeze work and primary cementing operations at select gas wells.

Tools – including models – that enable some distinction to be made between natural and anthropogenic sources of methane in the fresh groundwater system provide an invaluable resource for those charged with protecting groundwater supplies and developing hydrocarbon resources responsibly, particularly in areas characterized by known concentrations of pre-existing thermogenic methane. Once constructed, models also enable different chronologies and alternate migration hypotheses to be readily explored in the context of stray gas migration case investigations. Refinement can be achieved by varying model inputs appropriately.

Although the benefits of modeling complex systems are clear, model construction is time consuming. In this case the process was also hindered by the character of the data sources, which were mostly analog and required a significant amount of data input time. Sharing the model with stakeholders has proven valuable. It has in at least one case prompted an operator to reassess how they are mud logging wells to ensure better consistency. In all cases, consistent data reporting formats will allow for more efficient model construction. Moreover, better input data will improve the quality of the model and subsequent interpretations.

Sources:

PADEP, Predrill Reports, 2010 and 2011.

PADEP, Well Records accessed using PAIRIS, 2011.

Wilson, B., 2012. Geologic and baseline groundwater evidence for naturally occuring, shallow source, thermogenic methane gas in Northeastern Pennsylvania in Abstracts of the GWPC's Stray Gas Incidence and Response Forum, Cleveland, OH.