
CASE STUDY

Monitoring Marcellus: A Case Study of a Collaborative Volunteer Monitoring Project to Document the Impact of Unconventional Shale Gas Extraction on Small Streams

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The rapid growth of the natural gas extraction industry in Pennsylvania and neighboring states has stirred concerned citizens to seek ways to collect data on water quality impacts from the extraction activities. As a response to requests from community members, the Alliance for Aquatic Resource Monitoring (ALLARM) developed a volunteer-friendly protocol in 2010 for early detection and reporting of surface water contamination by shale gas extraction activities in small streams. To date, ALLARM has trained more than 2,000 volunteers in Pennsylvania, New York, and West Virginia to monitor water quality (conductivity, barium, strontium, and total dissolved solids) and physical parameters (stream stage and visual observations) prior to, during, and after shale gas wells have been developed. This paper documents the operational models of Public Participation in Scientific Research (PPSR) used by ALLARM, describes the volunteer monitoring protocol developed, and examines three years of water quality results from hundreds of monitoring sites in Pennsylvania and New York.

The majority of watersheds monitored are small, forested, headwater streams. Results indicate that mean conductivity in streams is strongly and positively related to the percentage of development and the percentage of limestone in the watersheds. Mean conductivity is not significantly related to number or density of drilled wells, although the dataset did not lend itself to finding a signal from shale gas activities because only 20% of the watersheds had wells drilled at the time of sampling. This fact enables the use of these data as baseline data for future documentation of shale gas impacts on water quality. Volunteers have reported multiple cases of visual pollution related to shale gas activities, but have not identified water contamination events based on stream water chemistry.

The results of the volunteer dataset are compared with results from the scientific literature, affirming the credibility and usefulness of the data. Some lessons learned from this project include: The importance of strong and timely support to volunteers to ensure accurate reporting in real-time; the unique role that citizen scientists can play in a rural landscape where well sites are remote and government oversight is not practical; and the importance of customizing a PPSR operational model to fit the goals and scale of the project.

Recommendations for continued collection and analysis of data include: 1) develop and implement an intentional study design to monitor those watersheds that now have baseline data once drilling begins, 2) target watersheds whose characteristics are under-represented in this dataset, 3) consider the analysis of additional parameters and the monitoring of high risk systems, 4) develop a central, user-friendly database for volunteers to submit their own data and receive preliminary analyses, and 5) partner with other volunteer data collectors to collaborate with data analysis and interpretation.

Keywords: Volunteer monitoring; water quality; PPSR; citizen science; watershed; Marcellus Shale; shale gas; conductivity

Introduction

The context: Recent growth of natural gas extraction in the Marcellus and Utica Shale region

The Marcellus and Utica Shale are vast black shale deposits, estimated to cover approximately 100,000 square miles in

the states of New York, Pennsylvania, Ohio, Maryland, and West Virginia, creating the largest natural gas development region in the US in terms of geographic extent (US Energy Information Administration 2011). Although natural gas drilling has occurred for many years, Marcellus and

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Utica Shale gas extraction relies on two new “game changing” technological advances: Horizontal drilling and high-volume hydraulic fracturing. A vertical well is drilled to the depth of the gas reserves and then turned horizontally for thousands of feet. Hydraulic fracturing (“fracking”) is a process whereby a mixture of water, chemicals, and a particulate material (usually sand) is pumped into the well at high pressure to create fractures in the rock to release the gas (Marcellus Center for Outreach and Research 2015). The new wells that extract gas which is tightly bound in these shale formations are called “unconventional” wells.

Fracking fluids contain a variety of chemical additives (Pennsylvania Department of Environmental Protection 2010) to enhance the fracturing process. While in contact with the briny deep-rock environment, this water is contaminated further by high levels of salt and other chemicals, including chloride, bromide, barium, strontium, and naturally occurring radioactive materials (Haluszczak et al. 2013). About 10–20% of this water returns to the surface during the gas extraction phase and is called “flowback” water. These fluids can be handled through storage and reuse, or treatment and release into streams.

Although some states in the Marcellus and Utica shale region are currently moving cautiously in regard to shale

gas development, Pennsylvania has fully embraced the development of this resource. The number of unconventional drilled wells within the Marcellus and Utica Shale region in Pennsylvania has increased from 10 at the end of 2005 to more than 9,000 at the end of March, 2015, with more than 5,000 additional wells permitted (Marcellus Center for Outreach and Research 2015) (**Figure 1**).

Shale gas extraction may have an impact on local water resources, especially during the early stages of development and hydraulic fracturing. It takes 3–5 million gallons of fresh water, typically drawn from local streams, to frack a single well over the 3 to 6-week fracking period (Vengosh et al. 2014). Most well pads include 4–6 wells, creating a concern that local stream and water supply resources may be taxed severely during this development period (SRBC 2010), usually lasting about 6 months. The management of large volumes of highly contaminated water may result in spills to surface water and/or movement into ground water supplies. Experience in the state has demonstrated that spills and accidents are common (NRDC 2015; Amico et al. 2015; Drollette et al. 2015).

The act of clearing land, creating roads, and transporting large volumes of water over dirt roads to the well pad creates the opportunity for large amounts of sediment

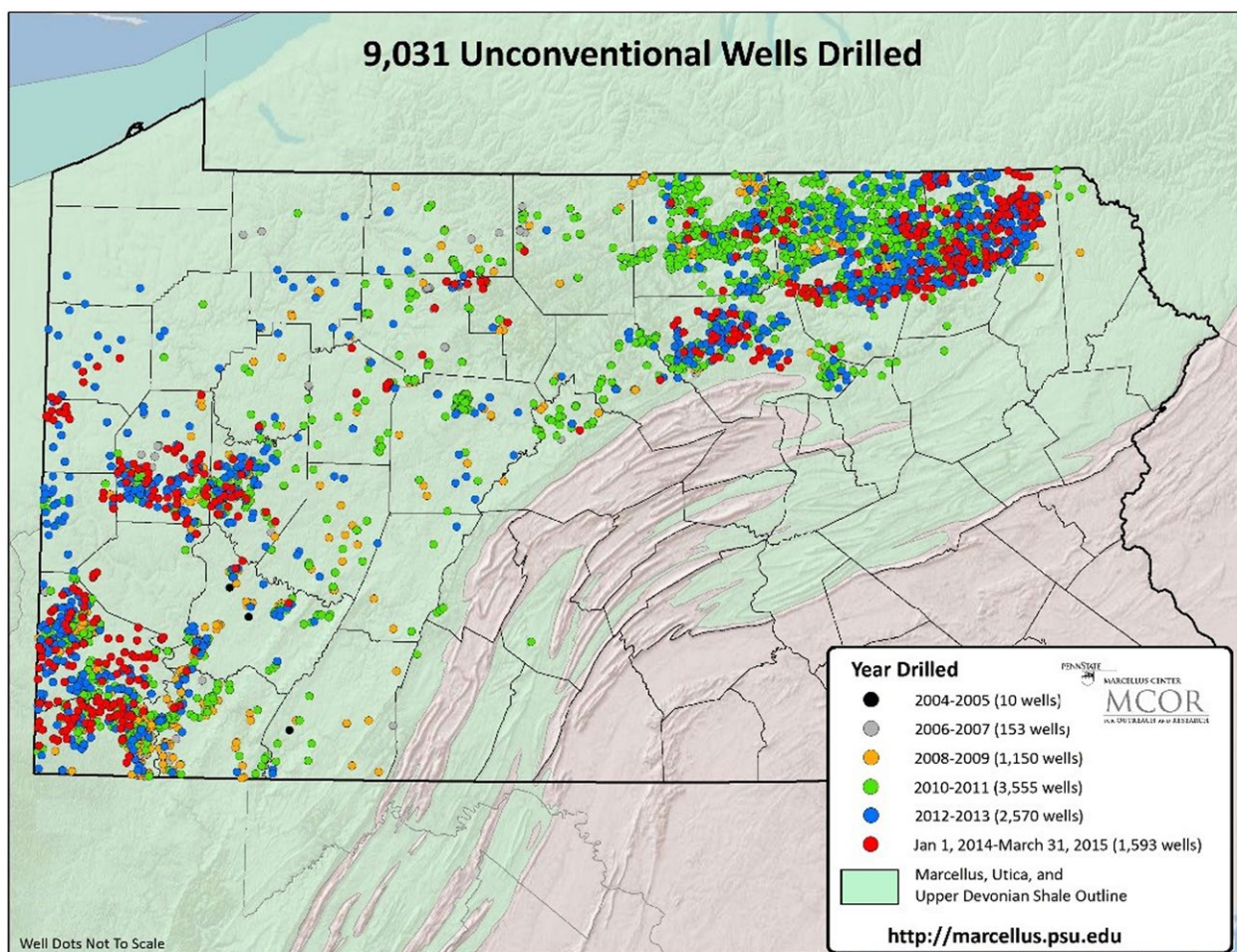


Figure 1: Map of shale gas drilling sites from 2004 to 2015. (Marcellus Center for Outreach and Research) To view the original map showing the progression of wells drilled by year, go to: <http://marcellus.psu.edu/images/PA%20Animated%20Spud%20Map%2020151231.gif>.

to mobilize and enter nearby streams. In addition, methane migration and bentonite blowouts also have been attributed to shale gas well and pipeline development. Other potential environmental effects include contamination of groundwater through poor casing of well bores (Ingraeffea et al. 2014); air pollution from transport vehicles, compressor stations, pipelines, and well pad activities (Caulton et al. 2014); and fragmentation of sensitive lands due to pipeline and infrastructure construction (Abrahams et al. 2015; Drohan et al. 2012).

Because the extraction activities are occurring over a very large and remote geographic area in Pennsylvania and because spill events can be quite ephemeral, the documentation of these impacts is extremely challenging (Brantley et al. 2014). In this knowledge landscape of scarce data and controversial environmental threats (Bowen et al. 2015; Entekin et al. 2011; Vidic et al. 2013), the unprecedented rapid growth of the shale gas extraction industry in Pennsylvania has motivated concerned citizens to seek ways to help fill data gaps and contribute to sound evidence for public policy decisions. As a response to requests from community members, the Alliance for Aquatic Resource Monitoring (ALLARM) developed a volunteer-friendly protocol for early detection and reporting of surface water contamination by shale gas extraction activities in 2010 (Wilderman and Monismith 2012).

This paper is presented as a case study, summarizing the ALLARM Shale Gas Volunteer Monitoring Protocol and the results of the first phase of data analysis associated with this shale gas monitoring effort. The goal of the paper is to demonstrate how a regional collaborative Public Participation in Scientific Research (PPSR) project can generate sound and useful scientific outcomes to help assess impact from gas extraction activities. Lessons

learned in building community capacity to collect data in a timely fashion from a large, multi-state region are also shared.

The history of ALLARM in the context of operational models for Public Participation in Scientific Research (PPSR)

Founded in 1986 as a project of Dickinson College, ALLARM provides technical and programmatic support to train community members to use science as a tool to carry out stream assessments and to use collected data for watershed education, protection, and restoration. In addition to three full time professional staff and a faculty science advisor, ALLARM also employs 12–15 Dickinson College students, giving them the opportunity to engage in issues faced by communities, to play a role in the development and dissemination of community-based resources, and to further develop their skill sets in community-based participatory research.

Throughout ALLARM’s history, the program has used several operational models, as defined in the Center for the Advancement of Informal Science Education (CAISE) Inquiry Report (Bonney et al. 2009; Shirk et al. 2012; Wilderman 2007), to successfully train and engage volunteer monitors to investigate and answer questions about the myriad of issues facing Pennsylvania’s water quality (Table 1).

From 1986–2004, ALLARM used a **contributory** model to engage volunteers in the collection of data to help document the impact of acid deposition on streams in Pennsylvania (Table 1). In response to volunteers’ growing interest in monitoring other impacts of concern in their watersheds, ALLARM developed a watershed-based technical assistance program in 1996, using a **co-created** model, where volunteers establish the research question

Steps in Scientific Process	Contributory		Collaborative		Co-created	
	CAISE report	ALLARM acid rain project	CAISE report	ALLARM shale gas project	CAISE report	ALLARM watershed projects
Choose or define question(s) for study				X	X	X
Gather information and resources				X	X	X
Develop explanations (hypotheses)					X	X
Design data collection methodologies			(X)		X	X
Collect samples and/or record data	X	X	X	X	X	X
Analyze samples		X	X	X	X	X
Analyze data	(X)		X	X	X	X
Interpret data and draw conclusions			(X)	X	X	X
Disseminate conclusions/translate results into action	(X)	(X)	(X)	X	X	X
Discuss results and ask new questions				X	X	X

Table 1: A comparison of the general characteristics of three different models for Public Participation in Scientific Research (PPSR) from Bonney et al. (2009) with the characteristics of the ALLARM projects that fall into similar models. The Xs denote citizen participation; the parentheses around the Xs denote that some projects categorized in this model may include volunteers in this step, while others may not. The table is arranged in order of increasing community participation in the scientific process in the three models, from left to right.

and are then mentored through all stages of the scientific process, including development of study design, data collection, data analysis and interpretation, and data communication (Table 1). A toolkit containing all tools necessary for the implementation of these watershed-based programs is publically available online (ALLARM 2015a). To date, this program has resulted in more than 25,000 square miles of watershed assessments and more than 3,500 community volunteers engaged in watershed protection and restoration.

In 2009, during a period of unprecedented growth of unconventional gas wells being drilled in Pennsylvania, residents, community organizations, non-profits, and local governments turned to ALLARM to explore the possibility of developing monitoring capacity to document possible impacts of the drilling operations. In response to these requests, ALLARM, in consultation with the Delaware Riverkeeper Network and Pennsylvania Trout Unlimited, created a shale gas monitoring protocol that allows volunteers to conduct baseline monitoring and analysis for early detection of pollution related to shale gas extraction activities (Zerbe and Wilderman 2010). This program is conducted using a **collaborative** or hybrid model of PPSR, with the community setting the research agenda and collecting the data. Volunteers work collaboratively with scientists on developing the study design and on data analysis, interpretation, and dissemination (Table 1). Since the beginning of the shale gas monitoring program in June 2010, ALLARM has worked with partners in New York, Pennsylvania, and West Virginia and has conducted 61 workshops in 37 counties and trained more than 2,000 individuals. To date, volunteers have monitored more than 600 sites in Pennsylvania and New York and have collected more than 6,000 data points.

A timeline of ALLARM's three major projects over the past 29 years is shown in Figure 2, and the geographic extent of those projects is shown in Figure 3.

Methods: ALLARM's Shale Gas Volunteer Monitoring Study Design and Protocol

The study design wheel in Figure 4 shows the steps that ALLARM follows in developing a study design plan for volunteer monitoring programs.

When working with groups in a co-created model, ALLARM staff mentor volunteers through every step in the study design process to create a customized plan to address their specific questions. This process can take up to six months, depending on the scope of the project, ability of the group to reach a consensus, and its availability to meet on a consistent basis.

ALLARM spent one year developing the Shale Gas Volunteer Monitoring Program, which required ALLARM to not only identify the parameters influenced by flowback pollution, but also to develop new and cost-effective monitoring methods. Whereas watershed groups using the co-created model typically choose parameters and protocols from a list of methods already developed and field-tested by ALLARM, the Shale Gas Program required ALLARM to research, test, and compare monitoring methods and equipment in order to choose the best option for volunteers. Only steps 6 and 10 (noted in red in Figure 4) require volunteer participation; ALLARM facilitates conversations to complete those customized steps during the first training workshop.

This more prescriptive study design is characteristic of a collaborative model and is appropriate for the shale gas monitoring project, where volunteers extend over a large geographic area, have shared monitoring goals, and require standard protocols to produce comparable results.

Step 1: Major objectives of the project

The goals of the ALLARM Shale Gas Monitoring Program are: 1) early detection and reporting of contamination by flowback (produced) water in small streams and 2) visual documentation of environmental impacts associated with

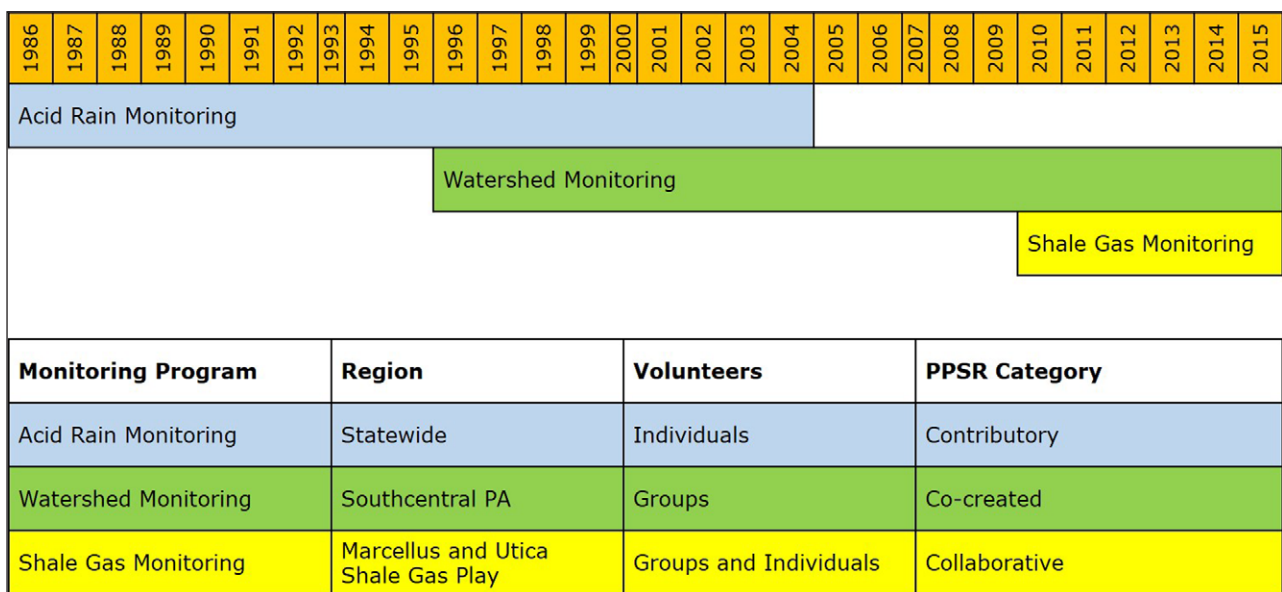


Figure 2: Timeline showing the history of ALLARM's work with volunteers, using three different models for public participation in scientific research.

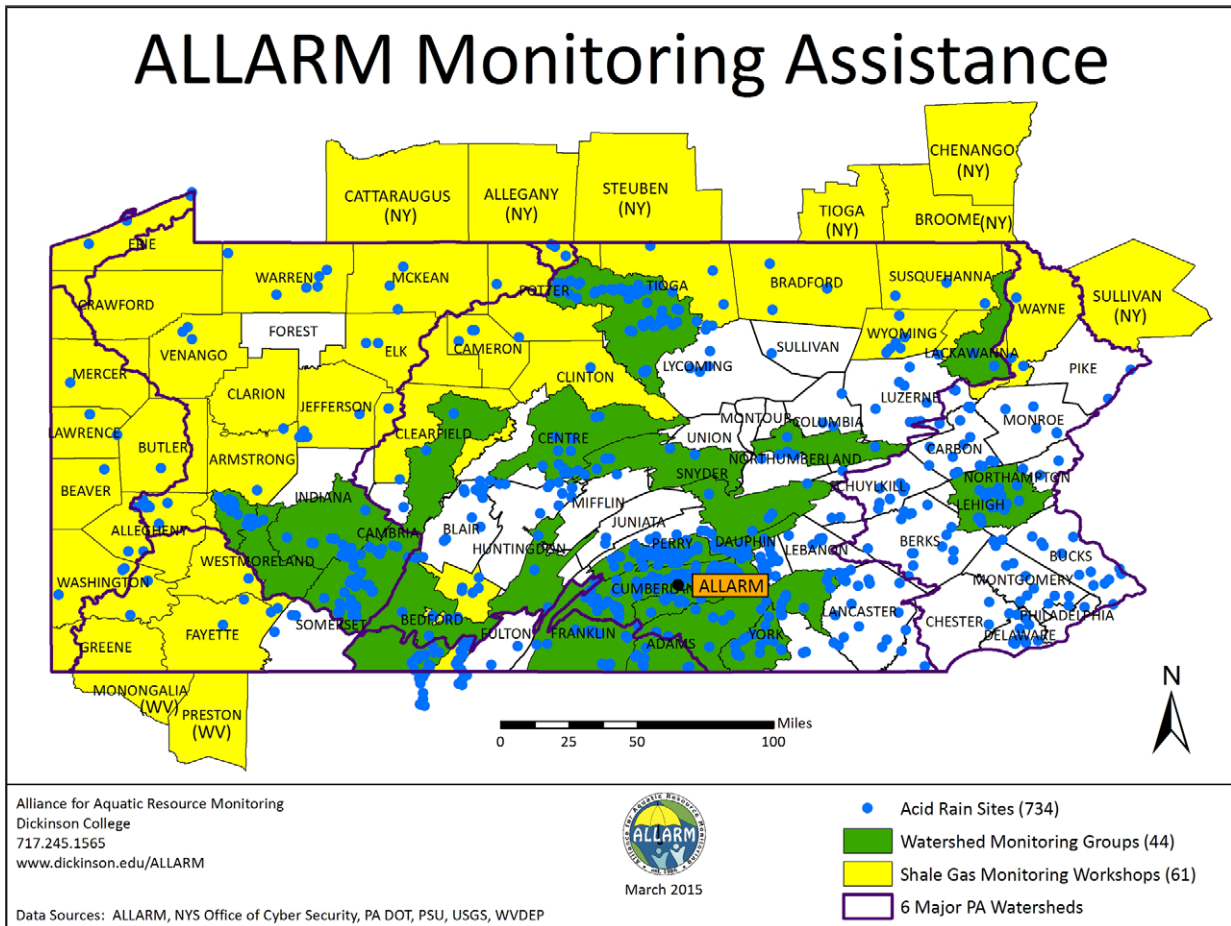


Figure 3: The geographical reach of ALLARM’s three major projects over the course of their history.

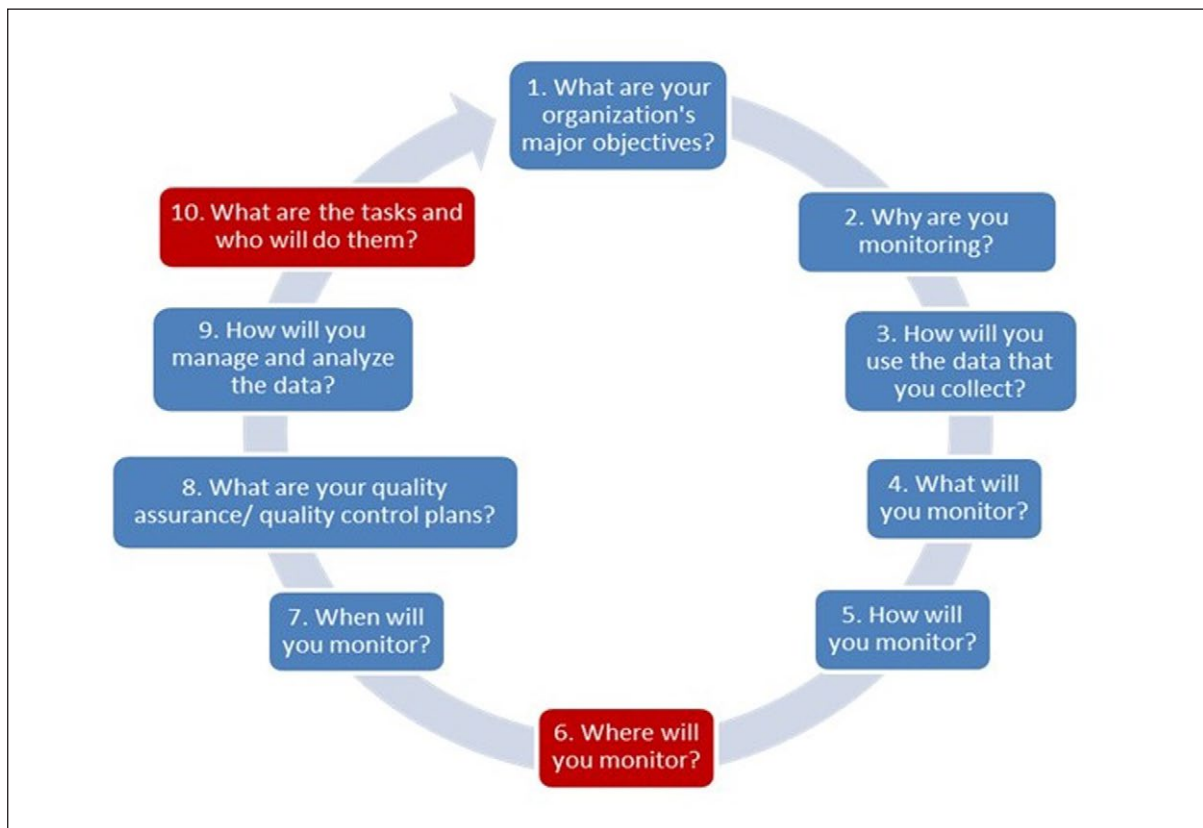


Figure 4: A study design wheel, showing the steps involved in developing a study design with volunteer monitors (from Wilderman and Monismith 2012). Modified from Dates, 1995.

the development of well sites and pipelines. The protocol is largely a “red flag” protocol, training volunteers to immediately report possible pollution incidents to the correct response agency.

Step 2: Rationale for monitoring

Marcellus Shale gas extraction activities may be a significant threat to water resources; gas extraction activities cover a vast rural area of Pennsylvania and New York where government oversight is extremely challenging and existing monitoring data are sparse (Brantley et al. 2014, Rahm and Rhia 2014). Volunteers are interested in helping to fill data gaps and to provide resources for real-time documentation of impacts.

In particular, policy on the handling and safe disposal of flowback water in Pennsylvania has dragged behind the industry’s rate of production of this wastewater. Although the preferred method of handling flowback water is reuse, many companies still have not implemented these measures. Although the Pennsylvania Department of Environmental Protection (PA DEP) standards dictate that any flowback water must be treated to have a total dissolved solids (TDS) concentration of less than or equal to 500 mg/L, only one treatment plant in Pennsylvania has been completed for this purpose (Marcellus Center for Outreach and Research 2015). If not handled properly, this water may contaminate streams and groundwater (Rozell and Reaven 2012; Drollette et al. 2015). Experience in Pennsylvania shows that safety and environmental violations are common in the industry: From 2009–2014, 4006 violations were reported by the PA DEP on 7,788 unconventional active wells (Amico et al. 2015).

Sparse data, wide geographic distribution, remote sites, limited government oversight, and questionable disposal practices of flowback water have all motivated volunteers to step up to provide real-time documentation of shale gas extraction impacts.

Step 3: Intended data use

Data use goals must be identified prior to designing protocols for monitoring so that the data quality can match the intended data use. In designing data use goals, ALLARM consulted with volunteers.

The primary use of the data by volunteers is to identify and report real-time contamination events, including water quality violations, earth disturbances, spills and discharges, and gas migration/leakages. In addition, the data are compiled and archived for use by research scientists to explore the relationship of water quality parameters such as conductivity, barium and strontium in streams, and pollution events, to watershed characteristics and drilling activity.

Steps 4 and 5: Monitoring methods

Baseline monitoring

Volunteers are trained to collect field data on water chemistry, stream stage, and visual impacts (observational monitoring) at their monitoring sites. Ideally, sites are monitored for three months to a year before the extraction activities begin. This provides baseline data with which

to compare data collected after the fracking activities have begun. Further, it establishes baseline relationships between stream stage and water chemistry and between background levels of chemicals and normal landscape conditions.

Volunteers measure conductivity and TDS at their stream sites using a LaMotte Tracer PockeTester (temperature-compensated), which measures the electrical conductivity of dissolved ions in the water; these **indicator** chemicals would increase dramatically if a flowback water contamination event occurred.

Twice a year, ideally during a low- and a high-flow event, volunteers collect a water sample to be analyzed by a certified laboratory to document background levels of barium and strontium, two **signature** parameters of flowback water contamination.

Stream stage is measured with a gage stick (hand-made by ALLARM or volunteers), calibrated to tenths of a foot, at a chosen location in the stream. Knowledge of the stream stage is critical in documenting the relationship between the concentration of conductivity/TDS and stream stage at the sampling site. Understanding this relationship helps to determine whether increases or decreases in conductivity/TDS are due simply to changes in flow or result from a possible contamination event. Stage measurements also can help to determine if changes in water level are a result from either excessive withdrawals or spills.

Monitors also perform a visual assessment each time they visit their monitoring site to document impacts to the stream such as earth disturbances, spills and discharges, and gas migration and leakages (detected as bubbling action in the stream) caused by the development of gas wells and pipelines. If volunteers observe any of these items, they are trained to take a time/date-stamped photo to submit to the appropriate environmental enforcement agency; appropriate agency contact information is included in their monitoring manual.

Monitoring during extraction activities

After drilling begins, volunteers continue to monitor the same parameters, keeping careful watch for deviations from baseline conditions.

Volunteers are given decision trees to help them determine if they have identified a pollution event and, if so, what action to take. The action protocol is described more fully in Step 9.

Step 6. Location of sites

Volunteers choose their site locations during a training workshop. The process starts with the identification of active, inactive, and proposed drilling and infrastructure sites in their geographic area of interest. Volunteers are trained to access this information from a number of online sources. They are encouraged to choose sites where no spudded (drilled) wells or pipeline construction are present but where permits have been issued for future extraction activities and/or where plans exist for pipeline construction. In those cases, volunteers can collect baseline data immediately to compare with data collected after the activity begins.

Other site location considerations include areas of special value to the community (for example, high quality stream segments, swimming and fishing holes, areas with threatened or endangered species); accessibility; resources available (mostly in terms of determining number of sites); and safety issues.

Step 7: Frequency of monitoring

The fact that volunteers are looking for leaks and spills, which are transient events, argues for a high sampling frequency. A spill or leak may impact the chemistry of a stream at any one spot for a very short period of time as it moves downstream and becomes diluted. Water chemistry is a snapshot in time of conditions; often it does not reveal much about what happened yesterday or even several hours ago. However, observational monitoring can yield other clues to recent contamination events that are longer lasting, for example, impacts on instream habitat, erosion rills on the land, or even gases bubbling from the ground.

ALLARM recommends that volunteers monitor their sites once per week, but encourages them to plan realistically, based on their resources. They are reminded to be particularly vigilant during the first six months of well development, during which time the fracking of multiple wells on the well pad takes place.

Step 8: Quality Assurance/Quality Control measures

Quality Assurance/Quality Control (QA/QC) is a fundamental component to any volunteer stream monitoring program because it assures that data-quality objectives are met. ALLARM plays a strong role in training volunteers, processing quality control samples submitted by volunteers, and following up with support for volunteer needs.

ALLARM sets up an initial all-day workshop at the request of the community. During this workshop, participants receive information on the science of shale gas extraction, safety considerations, and the meaning of the chemical and physical parameters they will measure. Then they receive hands-on training on accessing permit and drilling information; choosing monitoring sites; performing visual assessments; entering and managing data; reporting pollution events; and using field equipment for chemical and physical monitoring.

All volunteers are also required to pass a split-sample quality control test before they begin their monitoring routine and then again two times per year during their monitoring period. Monitors use the conductivity/TDS meters to test the stream water and then collect a water sample to send with their data to the ALLARM Community Aquatic Research Laboratory. At the lab, the samples are tested and results are compared to the data collected by the volunteers. If the accuracy is within acceptable limits (RPD=20%), the volunteers can continue monitoring. If the accuracy is outside the acceptable limits, ALLARM makes suggestions to the volunteers about their sampling techniques after which they resubmit samples.

As part of the overall QA/QC plan, a follow-up meeting is scheduled one month from the first workshop and every six months after that. During these meetings volunteers

share their experiences, receive updates and equipment if needed, and submit data and water samples for quality control.

All of the methods used by volunteers are clearly documented in ALLARM's Shale Gas Volunteer Monitoring Manual (Wilderman and Monismith 2012). The manual includes safety and access considerations, calibration methods, field monitoring protocols, data management and reporting procedures, and QA/QC guidelines. Detailed QA/QC procedures are also documented in ALLARM's Quality Assurance Project Plan (QAPP) (ALLARM 2015b).

In addition, ALLARM publishes a monthly email newsletter for the shale gas monitors; maintains an online toolkit, which includes training videos, information on the program, detailed equipment instructions, and other resources (ALLARM 2015c); staffs an office for inquiries; and supports bimonthly phone conferences.

ALLARM's QA/QC Program helps to ensure the quality of the data being collected and builds the confidence of the volunteers. The protocol has been vetted by the Pennsylvania Department of Environmental Protection and the Pennsylvania Fish and Boat Commission, both of which have recommended that their staff prioritize investigation of reports from volunteers trained using the ALLARM protocol.

Step 9. Data management and analysis

Methods used by volunteers in data management and analysis Because volunteers are attempting to detect impacts of gas extraction activities in real time and then to act in a timely manner, all data must be compiled and examined carefully as they are collected. Volunteers are trained to enter their data onto field datasheets (ALLARM 2015d) as well as to enter their results into an Excel spreadsheet, which automatically plots the data point on an ongoing graph so that outliers can be identified readily (**Figure 5**). Volunteers are trained in data verification techniques and bring their spreadsheets with them to the follow-up training meetings for vetting by ALLARM staff. ALLARM is currently developing an online central database with built-in data quality requirements, graphics, and feedback. This will minimize data entry errors and is expected to be launched in spring, 2016.

If a pollution event is observed, monitors use decision trees to guide them through the follow-up and reporting procedures (**Figure 6**) (Wilderman and Monismith 2012). If the event is related to high levels of conductivity/TDS, volunteers immediately collect a sample of water to be sent to a certified laboratory for analysis of barium and strontium concentrations. Barium and strontium are signature chemicals for contamination by flowback (produced) water and are used to determine whether high concentrations of conductivity/TDS are a result of flowback water entering the stream or can be attributed to other possible human activities such as the application of road salt.

Methods used by scientists in data management and analysis Whereas volunteers are primarily focusing on real-time pollution events, they are also interested in having their data compiled and used by research scientists to explore

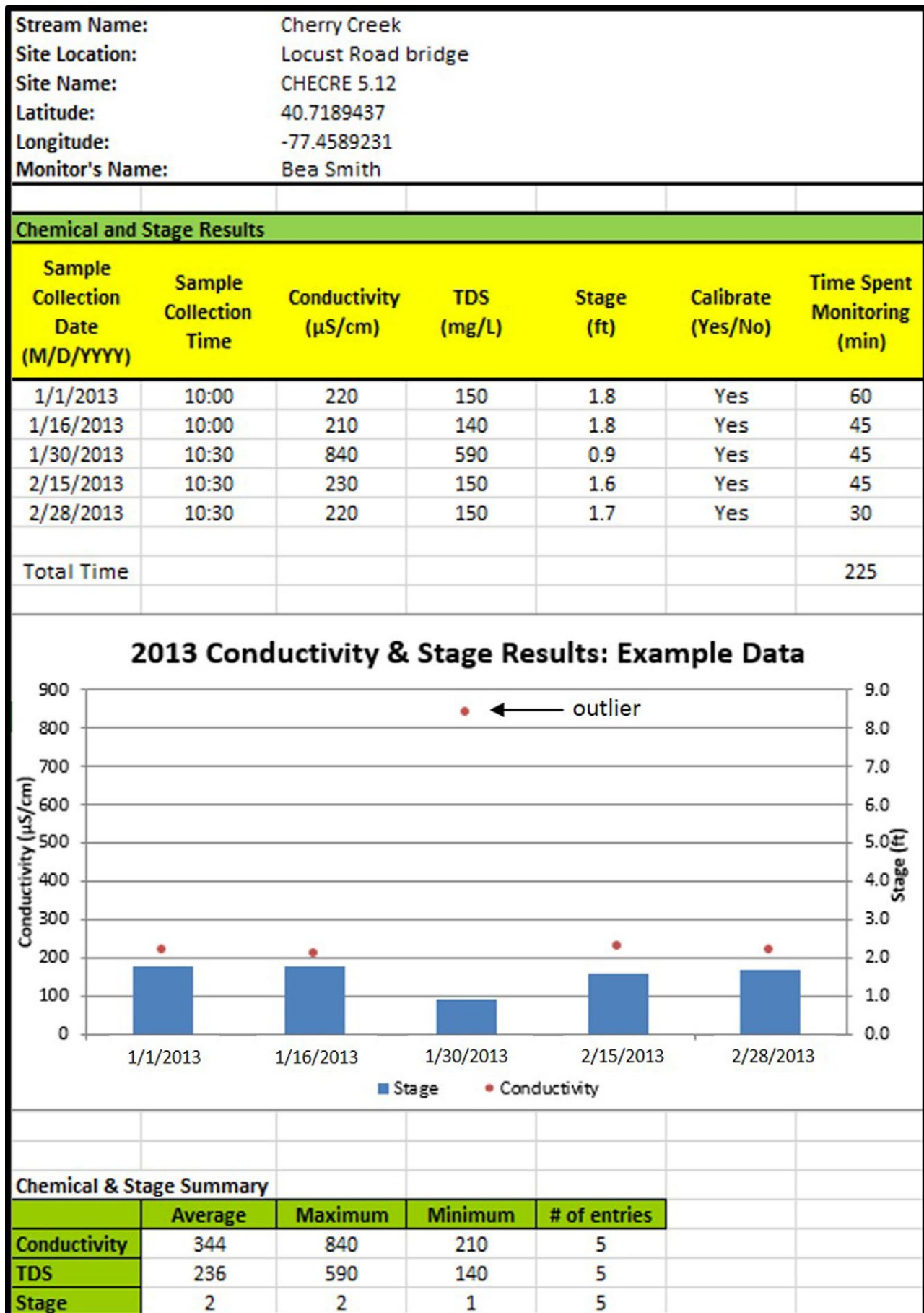


Figure 5: The Excel spreadsheet used by volunteers to compile chemical and stream stage data from a single site and to identify pollution events (outliers). This spreadsheet also has columns for visual assessment records (ALLARM 2015d).

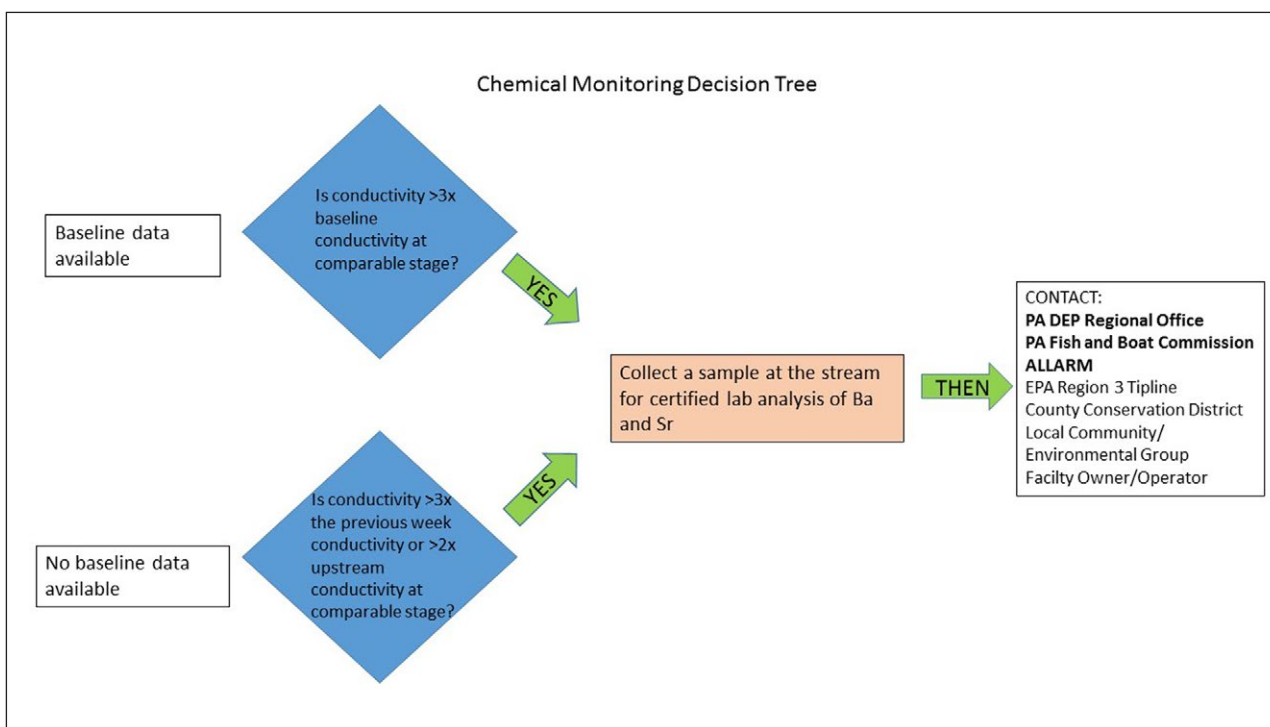


Figure 6: An example of a decision tree that volunteers follow when they identify a possible pollution event based on water chemistry. Decision trees also are available for visual assessment and pipeline observational monitoring (Wilderman and Monismith 2012).

possible patterns related to watershed characteristics and drilling activity. To that end, ALLARM scientists have completed the first phase of an analysis of compiled volunteer data from 2010–13.

To verify any contamination events reported by volunteers and to explore whether unidentified events occurred, conductivity and stream stage were plotted on a scatter graph and outliers were visually identified for each site.

Relationships between mean conductivity and watershed characteristics were explored by delineating watersheds for each site using digital elevation modeling in ArcGIS for Desktop version 10.1. Once watersheds were delineated, measurements were made to document 1) watershed size, 2) land use, 3) rock types, and 4) number and density of unconventional wells drilled at the time of sampling. Simple regression and stepwise multiple regression analyses were used to evaluate the strength of the relationships between the different characteristics of the watersheds and mean conductivity in the streams.

Step 10: Volunteer tasks

Many responsibilities and roles come with maintaining a successful volunteer monitoring program. When volunteers are working within a group, it is important that responsibilities are shared so that volunteers are not overburdened. Some examples of leadership roles that volunteers play include program coordinator, permit watch coordinator, data management coordinator, and equipment manager.

Results of data analysis by scientists and volunteers

Identification of data patterns by scientists

Description of the dataset

Data collected between July 2010 and December 2013 were compiled into a single database for analysis. This included 4,220 observations from 280 different monitoring sites in Pennsylvania and New York. For the purposes of the scientific analysis, the dataset was reduced to 2,995 observations from 116 sites using the criteria to include only those sites with at least 8 data points distributed over at least 8 months and whose volunteers had participated and passed the ALLARM QA/QC requirements (**Table 2; Figure 7**).

Watershed attributes of study streams

Most of the volunteer monitoring sites were located in small, headwater streams. Of the 116 sites included in the analysis dataset, 58% of the watersheds were less than 10 square miles, 31% were between 10 and 50 square miles, 5% were between 50 and 80 square miles, and 6% were greater than 80 square miles (**Figure 8**). Watersheds ranged in size from 0.1 to 1,365.0 square miles.

The underlying geology of each watershed was examined using GIS with dominant lithologies classified as calcareous (limestone), claystones-mudstones-shales (shale), igneous-metamorphic, and sandstones. The monitoring sites were predominantly underlain by shale (49%) and sandstone (46%), with a few watersheds in western Pennsylvania being dominated by limestone (5%).

	Entire compiled dataset			Reduced dataset for analysis		
	Number of observations	Number of sites	Median number of observations per site	Number of observations	Number of sites	Median number of observations per site
Pennsylvania	2,653	173	10	1,879	71	24
New York	1,567	107	11	1,116	45	18
Total	4,220	280	–	2,995	116	–

Table 2: Number of observations and sites in the entire and reduced datasets.

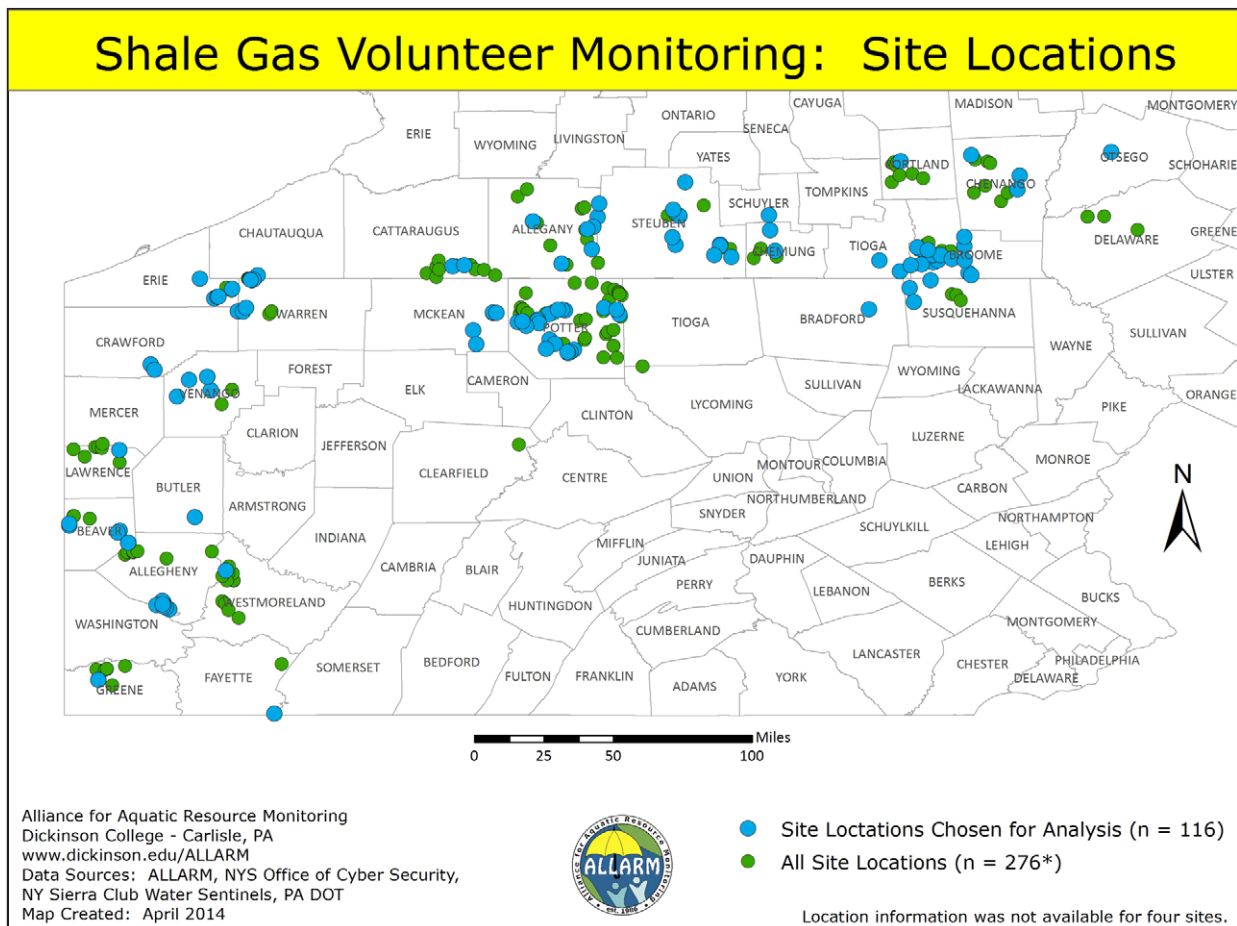


Figure 7: Map of Pennsylvania and the southern tier of New York showing all site locations for which data were compiled, with blue designating the locations of sites that fit the criteria for inclusion in the data analysis.

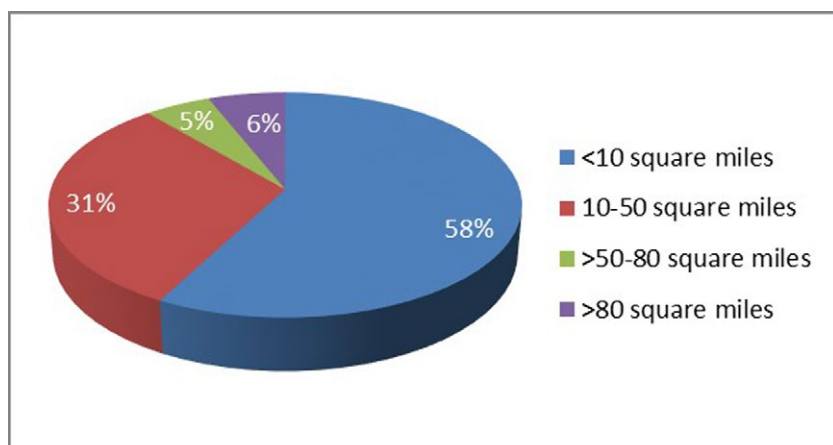


Figure 8: Distribution of watersheds in the sample set by size.

The land use coverage for each watershed was quantified by type, using data from the United States Geological Survey (USGS) NLCD 92 Land Use Cover Classes, aggregated to one digit. The distribution of the three predominant land uses within the 116 watersheds studied is shown in **Figure 9**. Most of the streams monitored were in predominantly forested watersheds.

Of the 116 watersheds sampled, only 23 have wells that were drilled prior to the end date of the monitor's sampling period. Thus, only pre-drilling data exist for the majority of watersheds monitored. Although no drilling is currently under way in New York, six of the watersheds that have drilled wells in Pennsylvania extend into New York. The number of wells drilled in each watershed ranged from 1 to 475, although only two watersheds had more than 12 shale gas wells. The density of wells varied from 0.018 to 1.788 wells per square mile.

Relationships between watershed attributes and conductivity
Relationships between watershed attributes and conductivity were considered to be statistically significant at the 99% confidence level ($P < 0.01$). There was no relationship ($R^2 = 0.0003$, $p > 0.01$) between mean conductivity and watershed size for the monitoring sites. The dataset does not include many large watersheds; however, there is a large variability in mean conductivity within the smaller watersheds, so size alone does not have much influence on conductivity values.

Mean conductivity in the small streams analyzed reflects a significant positive relationship ($R^2 = 0.6531$, $p < 0.001$)

to the percentage of limestone in the watershed, but does not reflect a significant correlation with the percentage of sandstone or shale ($R^2 = 0.0438$, $p > 0.01$ and $R^2 = 0.0027$, $p > 0.01$, respectively) (**Figure 10**).

In a bivariate regression analysis of percent land use coverage and mean conductivity, developed land had a strong significant positive relationship with conductivity ($R^2 = 0.8659$, $p < 0.001$); forested land uses had a weak negative relationship with conductivity ($R^2 = 0.3779$, $p < 0.001$); and agricultural land did not have a strong influence on the variation in conductivity ($R^2 = 0.0472$, $p > 0.01$) (**Figure 11**).

There was no statistically significant relationship between mean conductivity and the number or density of wells in the watershed ($R^2 = 0.0759$, $p > 0.01$ and $R^2 = 0.1966$, $p > 0.01$ respectively). However, owing to the small sample size (23 of 116 watersheds had drilled wells), this relationship cannot be adequately tested with this dataset. Those watersheds are likely to have wells drilled in the near future.

Identification of pollution events by volunteers

In the five years of monitoring in PA (2010–2015), volunteers have not identified and reported flowback contamination events based on water chemistry. In one incident where a volunteer identified a spike in the conductivity measurement, an analysis of the signature chemicals (barium and strontium) revealed that the spike resulted from road treatment for ice control. In the dataset that was used for the scientific analysis,

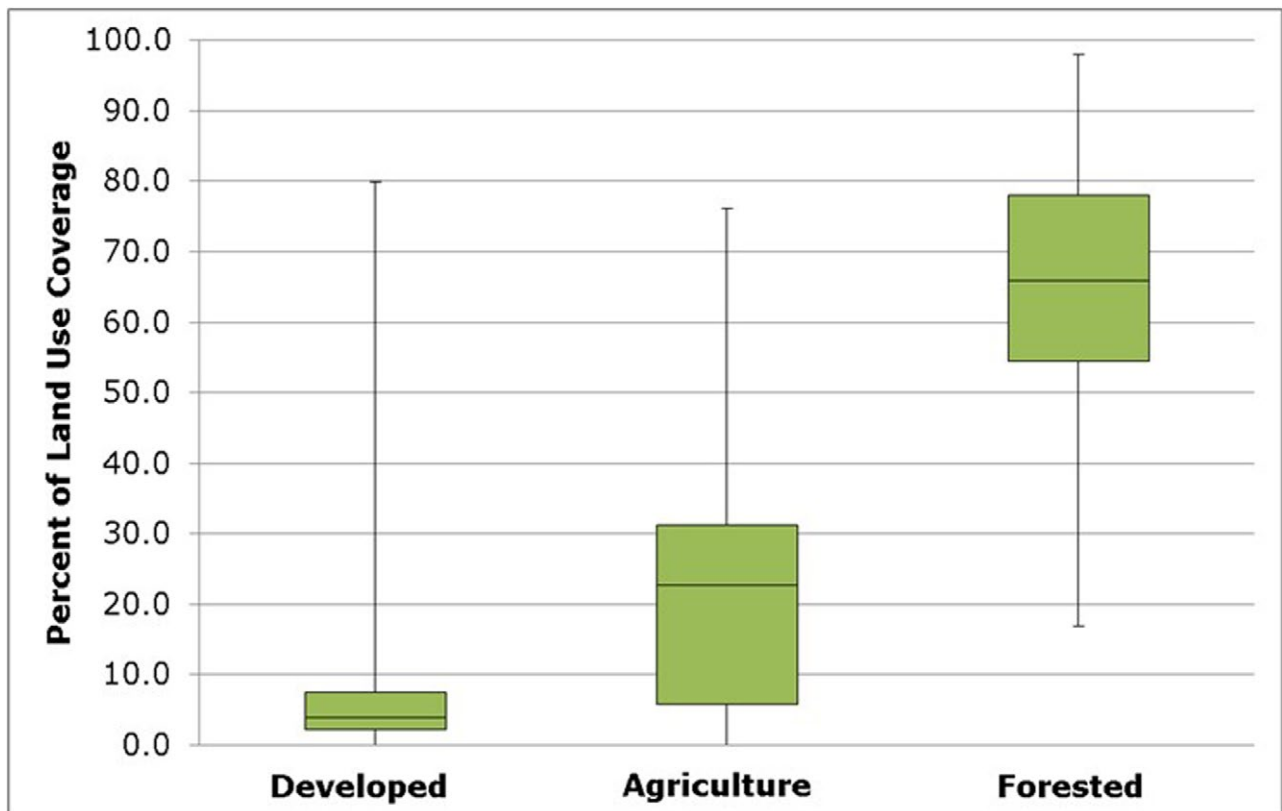


Figure 9: Box and whisker plot showing the distribution of the three major land uses within the 116 watersheds studied.

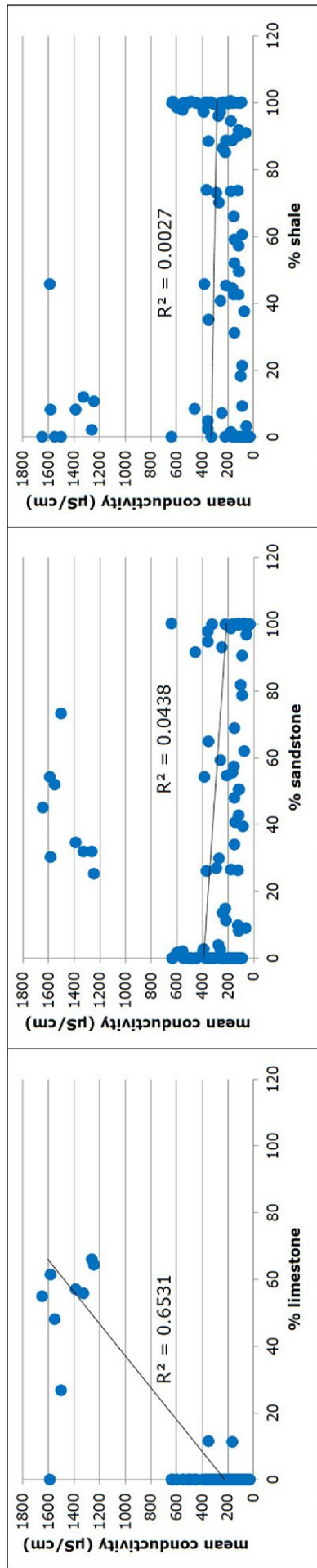


Figure 10: Plots of percent of underlying rock type in the watershed versus mean stream conductivity; n=116.

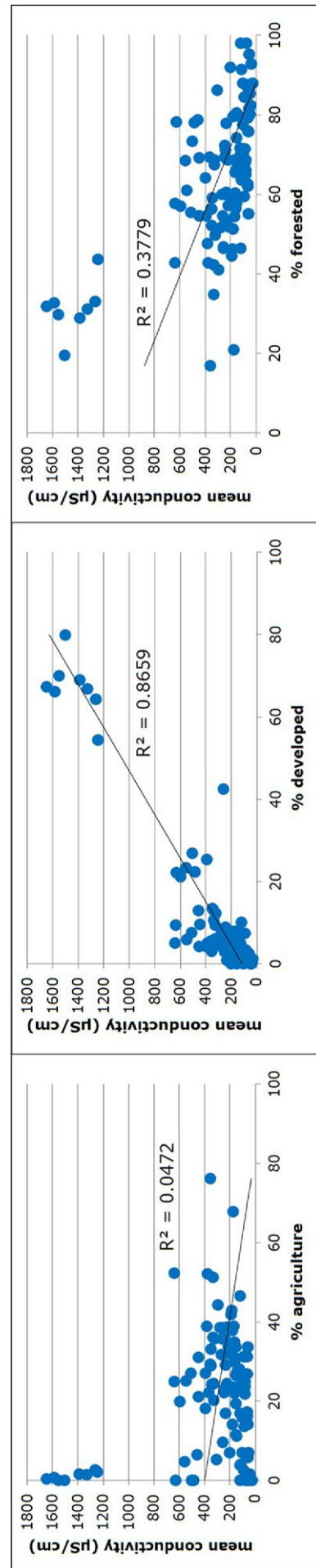


Figure 11: Plots of percent land use coverage in the watershed versus mean conductivity; n=116.

ALLARM found 7 incidents of high conductivity that (to our knowledge) were not reported or further explored by the volunteers.

On the other hand, using the visual assessment protocol, volunteers have reported 44 pollution events since the beginning of the program (Table 3). Figure 12 shows some photographs used by volunteers to document observed pollution events.

Of the reported disturbances, volunteers in the Northern Tier of Pennsylvania (Tioga and Potter counties) made the most erosion and sedimentation reports. The responsible agencies responded to the reports and took mitigation actions in a timely fashion. However, when volunteers identified gas migration, they were informed by their regional agencies that there was no way to rectify the problem.

Visual Assessment Results	
Type of disturbance	Number of Reports
Erosion and sedimentation	31
Methane migration	4
Spills and discharges	2
Pipeline	7
Total	44

Table 3: Compilation of visual assessment results. Compiled by Julie Vastine, Director of ALLARM, 2015.

The most common pipeline reports were bentonite blowouts, where large amounts of bentonite clay are accidentally released into the streams during pipeline crossing construction activities. These events were reported by volunteers in Pennsylvania’s Butler, Elk, and McKean counties (Northwestern Pennsylvania). One pipeline observer captured mudslides in Tioga County, Pennsylvania where the County Conservation District took the lead in addressing the situation with the company. Two other volunteers discovered flowback water contamination through visual assessment: One as a result of flowback water being discharged into an abandoned coal mine and the other as a result of a leaking flowback storage pit.

Discussion: The shale gas landscape and the role of citizen scientists

Patterns in the data

Using regression analysis, the major predictor of mean conductivity in the streams was identified to be the percentage of developed land in the watershed, with the percentage of limestone playing a significant but secondary role. High conductivity in developed watersheds are likely the result of the extensive use of road salts in urban areas, as well as high conductance metals that are typically found in urban stormwater runoff (Anning and Flynn 2014; Bannerman et al. 1993; Wilderman 2004). The influence of limestone on stream conductivity is also corroborated in the literature, where it is well documented that the solubility of limestone within watersheds, producing calcium, bicarbonate, and carbonate ions,



Figure 12: Photographs taken by volunteers to document observed disturbances and pollution events. (Photograph credits from top left, clockwise: Mountain Watershed Association (2), ALLARM, Wetzel County Action Group, PA Council of Trout Unlimited, Delaware Riverkeeper Network).

contributes significantly to increasing the conductivity of the streams (for example, Puckett and Bricker 1992; Wissmar et al. 1997).

The identification of developed lands and limestone bedrock as the primary predictors of conductivity in the volunteer-collected database is also in agreement with the results of a recent USGS study on the sources of dissolved solids in streams in the conterminous United States (Anning and Flynn 2014). In that study, researchers identified and ranked the major sources of dissolved solids in US streams, using sophisticated models and data from more than 2,500 water quality monitoring stations. Nationwide, the predominant source of dissolved solids is geologic materials, and the second most predominant source is road de-icers.

The similarity of the volunteer-collected data results to studies in the scientific literature suggests that the volunteer-collected data are credible and useful.

The unique and important role of citizen science data in the shale gas landscape: Finding the needle in the haystack

Studies have verified that shale gas extraction activities may have an impact on local streams, especially during the early stages of development and hydraulic fracturing. However, the actual documentation of pollution events has been somewhat elusive. In Pennsylvania, the extraction activities occur over a very large and remote geographic area, with little government oversight. Contamination events can be quite ephemeral, further complicating their documentation. Recent analysis of the large dataset in the Shale Network database¹ (Brantley and Vidic 2013; Vidic et al. 2013) has failed to identify pollution incidents, leading some researchers to the conclusion that sampling density requirements to detect pollution events are so high that documenting pollution events in real-time using traditional methods is unlikely. This conclusion has been corroborated by a recent USGS report (Bowen et al. 2015) discussing the inadequacy of our national databases to document impacts of shale gas extraction.

Within this context, trained local residents are able to help meet these critical data-gathering challenges. Based on a GIS analysis, 80% of volunteer-monitored streams in this study are in small, remote, forested watersheds underlain by shale and/or sandstone. These small streams are considered to be at highest risk of impact from shale gas operations (Soeder and Kappel 2009), making their continued monitoring even more critical. In fact, volunteers are the only ones who are collecting consistent data at sites along these at-risk streams in this remote landscape.

Approximately 80% of the volunteer-monitored streams are also in watersheds that have not yet experienced drilling activity. Because volunteer groups were free to choose their own sites, the large number of monitored streams in watersheds that have not yet been drilled attests to the volunteers' understanding of the critical importance of baseline data to evaluate future well activity impacts. This pre-drilling dataset is of significant value to future documentation of impacts.

During the short history of this project, volunteers have not reported flowback water contamination events

based on water chemistry and stage data. However, volunteers have *visually* documented multiple cases of pollution, such as land disturbances, spills and discharges, gas migration/leakage, and pipeline disturbance. This confirms a particularly important role for residents trained in visual assessment, especially during the construction and hydraulic fracturing stages of well development.

Volunteers do not "cry wolf": under-reporting and the need for technical assistance

The ALLARM shale gas monitoring protocol was developed as a red flag protocol within a climate of urgency in the face of rapid growth of the shale extraction industry in Pennsylvania. It was commonly believed by the industry and the regulatory agencies that volunteers would "over-report" to responsible agencies, thereby increasing the demand on limited resources. In fact, the opposite was found. Volunteers are extremely cautious about reporting violations because of the contentious nature of the situation; based on the exploration of the dataset, citizen scientists actually may have under-reported probable incidents. During the analysis of the dataset, seven incidents that appeared to be reportable outliers were found; they were not further explored by the volunteers. In discussing this with the volunteers, they expressed the strong need for additional technical support in this process, and ALLARM has had to increase individualized support, follow-up, and communication efforts to ensure that the volunteers have the confidence to report observed violations and spikes in their water quality measurements.

Customized design for PPSR: Size matters

Experience has shown that involving volunteers in every step of the scientific process results in the highest level of learning outcomes and the most successful community use of the data (Bonney et al. 2009, Wilderman et al. 2003). Since 1996, ALLARM has used a co-created model, and has customized mentoring tools to suit the needs of each of the watershed groups. For example, ALLARM trains volunteers to manage, analyze, and interpret their own data using Excel. This approach has been extremely successful in working with small, local watershed groups. ALLARM initially used the same method in the design of the shale gas protocol, but soon discovered that, given the large geographic reach of the volunteers and the number of individuals and groups, ALLARM simply could not provide the intense mentoring and support for all of the volunteers to successfully maintain and manage their own datasets. In addition, the scientific community of water resource researchers has become interested in the data as a tool to identify real-time contamination and to document cumulative impacts; therefore, making the data more widely accessible has become important. To address these issues ALLARM is in the process of developing an online central database similar to those widely used by contributory projects.

ALLARM also has implemented practices used by our contributory project colleagues to more effectively reach a large geographic area, such as the use of online resource materials, conference calls, and monthly newsletters.

Finally, ALLARM is increasing its reach by aggressively seeking partners and collaborators located throughout the shale gas region who can provide support and assistance to their local groups. These aspects of the program make it a truly hybrid or collaborative model of PPSR—using the strengths of the co-created projects by involving participants at a local level while embracing the strengths of the contributory projects to ensure the effective collection of large amounts of data over a wide geographic reach.

Conclusions

The ALLARM Shale Gas Volunteer Monitoring Program has demonstrated the value of a large volunteer-collected dataset in detecting patterns of conductivity as related to watershed characteristics. The dataset shows similar patterns to data reported in the scientific literature by professional researchers, which adds credibility and robustness to volunteer methods and data collection.

Citizen science participants also have contributed to documenting real-time contamination and impact events from the construction and development of shale gas well sites. These kinds of events are extremely difficult to document, given the expanse of rural and forested lands that are undergoing shale gas development in Pennsylvania. Therefore, any citizen science data that document and help remediate impacts are critically important.

Promoting the continuation and expansion of these monitoring activities is critical to the goal of protection of natural resources. We envision a future that involves the following activities:

1. Development and implementation of a study to monitor the watersheds that now have well-documented baseline conditions (93 sites) once wells are permitted and drilled.
2. Development and implementation of studies to intentionally target watersheds whose characteristics are currently under-represented now that we have data on watershed attributes.
3. Consideration of the possible analysis of additional parameters, including other indicator elements or isotope ratios (Brantley et al. 2014, Chapman et al. 2012), once the wells are active.
4. Development of a central, user-friendly online database for volunteers to enter their data and receive preliminary analysis.
5. Development and implementation of data analysis and interpretation workshops for volunteers to be trained to find the stories in their own data.
6. Expansion of the monitoring project in terms of increasing volunteers and incorporating more partner service providers.

Note

- ¹ The Shale Network is a project funded by the National Science Foundation (NSF-1140159) to help scientists and citizens share data about water resources that may be affected by gas exploitation in shale. Started in November 2011, the project was initiated by scientists from The Pennsylvania State University, the

University of Pittsburgh, and Dickinson College. The Shale Network database connects researchers, agencies, industry representatives, and citizen scientists by sponsoring an annual conference, during which time participants share their data results and are trained in accessing the database.

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Competing Interests

The authors declare that they have no competing interests.

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