

Features

**COMMUNITY-BASED RISK ASSESSMENT OF
WATER CONTAMINATION FROM HIGH-VOLUME
HORIZONTAL HYDRAULIC FRACTURING**

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ABSTRACT

The risk of contaminating surface and groundwater as a result of shale gas extraction using high-volume horizontal hydraulic fracturing (fracking) has not been assessed using conventional risk assessment methodologies. Baseline (pre-fracking) data on relevant water quality indicators, needed for meaningful risk assessment, are largely lacking. To fill this gap, the nonprofit Community Science Institute (CSI) partners with community volunteers who perform regular sampling of more than 50 streams in the Marcellus and Utica Shale regions of upstate New York; samples are analyzed for parameters associated with HVHFF. Similar baseline data on regional groundwater comes from CSI's testing of private drinking water wells. Analytic results for groundwater (with permission) and surface water are made publicly available in an interactive, searchable database. Baseline concentrations of potential contaminants from shale gas operations are found to be low, suggesting that early community-based monitoring is an effective foundation for assessing later contamination due to fracking.

Keywords: high-volume horizontal hydraulic fracturing, groundwater contamination, certified baseline testing, volunteer stream monitoring partnerships, fracking

The risk of contaminating surface water and groundwater as a result of shale gas extraction activities utilizing high-volume horizontal hydraulic fracturing (HVHFF) technology has not yet been assessed [1]. An abundance of evidence suggests that contamination can and does occur, including academic studies [2, 3], agency reports [4], accidents [5,6], regulatory violations [7, 8], interviews with sick homeowners near gas well pads [9, 10], and out-of-court settlements with confidentiality agreements between homeowners and gas companies [11]. There is also evidence to suggest that contamination may occur along natural subsurface pathways and not necessarily as a consequence of HVHFF [12]; however, probability bounds analysis points to disposal of HVHFF waste as the greatest risk to water [13]. Despite abundant indications of adverse effects on human health and the environment, conventional risk assessment methodologies have not yet been applied to the shale gas industry, and this has resulted in a void in public health protection on the part of the state and federal governments [14]. Here we explore one possible reason for this void: a lack of government data on water quality. We describe how rural homeowners and communities in New York's Southern Tier region are attempting to fill data gaps and create baselines for risk assessment purposes before HVHFF is approved in New York.

The nonprofit Community Science Institute (CSI) was founded in 2000 and has operated a state-certified water quality testing laboratory in Ithaca, New York, since 2003 (New York State Department of Health–Environmental Laboratory Approval Program (NYSDOH-ELAP) ID# 11790). With financial support from local governments in Tompkins County, CSI partners with seven groups of volunteers who perform synoptic sampling of Cayuga Lake tributary streams— that is, volunteers collect samples at specified locations within a few hours of one another, allowing comparison of water quality values throughout the area sampled. These volunteers collect approximately 350 samples a year and transport them to the CSI lab, where they are analyzed for bacteria, phosphorus and nitrogen nutrients, suspended sediment, minerals, and other parameters. Results are made publicly available in an interactive, searchable data archive at www.communityscience.org/database, which currently contains over 35,000 certified water quality data items. We have been recruiting, training, and providing technical support for community groups to conduct long-term baseline stream monitoring in New York's gas-rich Southern Tier region since 2010. Further, with the prospect of HVHFF in New York, CSI began offering pre-drilling baseline testing of private drinking water wells in 2009. The existence of pre-drilling data should make it possible to detect whether groundwater and surface water are impacted by HVHFF and to begin the essential task of conducting formal risk assessments using methodologies that are widely accepted in the public and private sectors [15-17].

METHODS

For the Cayuga Lake watershed, surface water samples (from Six Mile Creek and its tributaries) were analyzed for parameters including a set of gas well “signature chemicals.” For the Upper Susquehanna River Basin, samples from Catatonk Creek and Cayuta Creek were analyzed for “red flag” indicators of water quality. Finally, samples of untreated groundwater, collected by CSI from private wells across the Utica and Marcellus Shale regions within New York, were analyzed for gas well “signature chemicals.”

Streams in Cayuga Lake Watershed

Trained groups of volunteers perform synoptic sampling of Cayuga Lake tributary streams independently of each other up to five times per year under base-flow and stormwater conditions (Figure 1). Data collection began between 2002 and 2009, depending on when a monitoring group was established for a tributary of Cayuga Lake. Each group collects grab samples at four to 23 fixed locations, depending on the size of the watershed. Volunteer teams deliver samples to the CSI lab in Ithaca with chain-of-custody documentation. Certified analyses are performed within prescribed holding times and using methods approved by NYSDOH-ELAP. Certified results are posted in CSI’s online searchable data archive at www.communityscience.org/database. While focused primarily on impacts from agriculture and residential development, such as nutrients and pathogenic bacteria, Cayuga Lake watershed monitoring also includes a number of parameters that overlap with gas well “signature chemicals”: pH, alkalinity, total hardness, turbidity, total suspended solids, chloride, and specific conductance. Monitoring of Cayuga Lake tributaries is guided by a Quality Assurance Project Plan (approved by the New York State Department of Environmental Conservation [NYSDEC]).

Expanded monitoring of gas well “signature chemicals” in the Cayuga Lake watershed began in 2012, with financial support from the Tompkins County Legislature. Volunteer teams collect additional samples once a year at a subset of their regular synoptic monitoring locations for certified laboratory analyses of barium, strontium, gross alpha and gross beta radioactivity, total dissolved solids, chemical oxygen demand, sulfate, and methylene blue active substances (MBAS) (anionic surfactants). The list of “signature chemicals” recommended by CSI to screen for gas well impacts on surface water quality is similar to that for groundwater quality (as listed in Table 7 below) and is based on general knowledge of HVHFF technology and on analyses reported in the NYSDEC’s 2011 draft Supplemental Generic Environmental Impact Statement of the frequencies and concentrations of chemicals in flowback from gas wells in Pennsylvania and West Virginia [18]. A moderate degree of redundancy is included, such that screening for several of the major characteristics of flowback

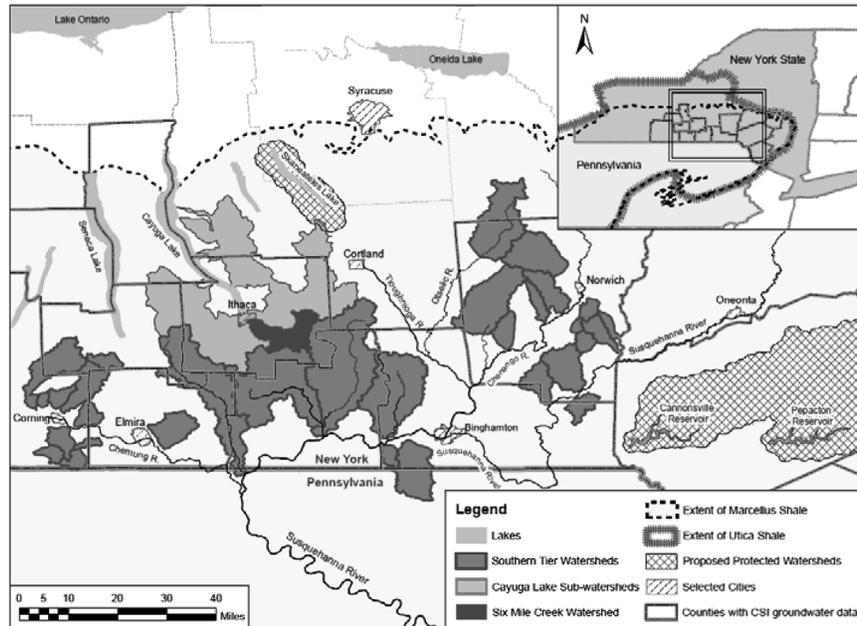


Figure 1. Map showing CSI-volunteer baseline water quality monitoring activities in the Marcellus and Utica Shale regions. Shaded areas are watersheds where volunteers monitor streams in the Finger Lakes and Upper Susquehanna River regions. The 13 counties where CSI has collected groundwater data from private drinking water wells and where clients have given permission to incorporate their results into CSI's regional groundwater baseline are shown in outline. The crosshatched areas—so-called Proposed Protected Watersheds—are areas feeding unfiltered drinking water systems in Syracuse and New York City where the New York State Department of Environmental Conservation proposes to exclude high-volume hydraulic fracturing per Section 6.1.5.4 in its 2011 draft Supplemental Generic Environmental Impact Statement, which states that “high volume hydraulic fracturing operations within the NYC and Syracuse watersheds pose the risk of causing significant adverse impacts to water resources” [18].

is based on two or more related tests. Streams are not tested for methane and volatile organic compounds (VOCs) as concentrations are expected to be low and difficult to detect due to volatilization.

Streams in Upper Susquehanna River Basin

CSI initiated a “red flag” volunteer stream monitoring program in 2010, training and partnering with groups of volunteers in several Southern Tier counties where HVHFF is most likely to take place if approved in New York

(Figure 1). Groups of 15 to 30 of these volunteers monitor local streams that together drain 250 to 400 square miles. Each group is organized in teams of two to six, and each team takes responsibility for monitoring a specific set of stream locations once a month for five red-flag indicators of water quality: temperature, pH, dissolved oxygen, specific conductance, and total hardness. Teams are required to calibrate their portable test kits and meters prior to each monitoring event, using standards provided by the CSI lab, and to perform at least one set of duplicate tests for each red-flag indicator. Teams submit original field data sheets to CSI in hard copy. Results that meet data quality criteria for accuracy and precision (Table 1) are entered in the open searchable data archive on the CSI website. For added quality control, red-flag groups are asked to split all samples with CSI's certified lab during the first two months of their monitoring program, and one sample per team per quarter thereafter. Groups are encouraged to seek funding from local sources and to contract with CSI or a local certified lab to conduct expanded baseline testing of gas well "signature chemicals" at as many stream locations as possible at least once a year, similar to the expanded baseline testing in the Cayuga Lake watershed made possible by the Tompkins County Legislature.

Stream water quality data presented for comparison with CSI data (see Tables 2, 3, and 4) were extracted from the U.S. Geological Survey's (USGS's) National Water Information System (NWIS) and the U.S. Environmental Protection Agency's (EPA's) STORET (STORage and RETrieval) Data Warehouse. All data were filtered to extract only base flow sampling events. The NWIS data available for Six Mile Creek were from three sites on the main stem and two sites on tributaries. STORET data were for four sites in the Catatonk Creek watershed and five sites in the Cayuta Creek watershed.

Groundwater in the Marcellus and Utica Shale Regions

CSI's certified lab offers fee-for-service baseline testing of private residential wells for gas well "signature chemicals" in groundwater. Baseline testing provides a form of insurance for homeowners in the event their water supply is contaminated and the contamination can reasonably be traced to nearby shale gas extraction activities. Clients are advised that the recommended baseline is designed as a broad screen that attempts to balance cost against the probability of identifying a "chemical signature" of gas well contamination, and that more extensive testing for specific carcinogenic, neurotoxic, teratogenic, endocrine-disrupting, and radioactive chemicals is indicated if post-drilling changes in results for some, but not necessarily all, "signature chemicals" provide reasonable evidence that contamination has occurred. Residential groundwater well samples are collected by CSI staff onsite, at a point that precedes any treatment system, such as a filter or a water softener, with chain-of-custody documentation to the CSI lab and subcontract labs.

Table 1. CSI Acceptance Criteria^a for “Red-Flag” Stream Monitoring Results Reported by Volunteer Teams on Hard-Copy Field Data Sheets

	Temperature (°C)	pH ^b	Dissolved oxygen ^c (mg/L)	Specific conductance ^d (µS/cm)	Total hardness ^e (mg CaCO ₃ /L)
Precision— acceptance of reported duplicates	± 1°C	± 0.5 pH Units	Greater of ± 20% or 0.4 mg/L ^c	± 10%	Greater of ± 20% or 8 mg/L ^e
Accuracy— acceptance of reported standards	Calibration ^f	± 0.5 pH Units	No calibration necessary ^c	± 1%	± 20% ^e
Splits—comparison with certified lab	N/A	N/A ^b	N/A ^c	± 20% ^d	± 20% ^e

^aRed-flag teams of two to five volunteers typically monitor five or fewer stream locations once a month. For quality control, teams are required to perform one standard and/or one duplicate, depending on the analyte. Quality controls are performed once per monitoring event. Red-flag teams are required to split samples with CSI at the rate of one location per quarter, or four splits per year, for certified analyses of specific conductance and total hardness. In the first months of a new red-flag monitoring program, volunteer teams are required to split one sample from every location in order to establish baselines for specific conductance and total hardness and to facilitate trouble-shooting by CSI staff if the team is having difficulty performing the tests.

^bpH is measured streamside using a wide range pH test kit accurate to 0.5 pH units over the pH range 3.0 to 10.5, LaMotte code 5858, or a hand-held meter, Hanna Instruments model HI98103. The CSI lab provides volunteer teams with an unlimited supply of pH 7.0 standard. Split samples are analyzed if requested by volunteers and if split is received by lab for analysis within 48 hours of sample collection as the frequency of spontaneous changes in pH is observed to increase after 48 hours.

^cDissolved oxygen is measured using test kit, LaMotte code 5860-01, based on the modified Winkler method approved by EPA. Test is accurate if performed correctly. Measurement range for titrator is 0.2-10.0 mg/L and is readily extended to higher concentrations by continuing to add titrant until the endpoint is reached. Limit of quantitation (sensitivity) is 0.4 mg/L or two times the smallest unit of measurement on the titrator. Results are considered reportable to the limit of quantitation, assuming quality control criteria are met, consistent with certified lab protocol. At low concentrations, precision is acceptable if duplicates agree within the limit of quantitation, 0.4 mg/L. Split samples are analyzed if requested by volunteers and if split is fixed streamside and received by lab within 8 hours of sample collection, as per EPA protocol.

^dSpecific conductance is measured using Hanna Instruments hand-held meter model HI 98303, range 1 to 1,999 µS/cm. CSI lab provides volunteer teams with an unlimited supply of 353 µS/cm specific conductance standard. Volunteer teams may hold stream samples at 4°C and perform the specific conductance test up to 28 days after sample collection, as per certified lab holding time.

^eTotal Hardness is measured using LaMotte kit 4482-DR-LT-01. Measurement range for titrator is 4 to 200 mg/L as calcium carbonate equivalents (CCE) and is readily extended to higher concentrations by continuing to add titrant until the endpoint is reached. Limit of quantitation (sensitivity) is taken to be 8 mg/L CCE, or two times the smallest unit of measurement on the titrator. Results are reportable to the limit of quantitation, assuming quality control criteria are met, consistent with certified lab protocol. At low concentrations, precision is acceptable if duplicates agree within the limit of quantitation, or 8 mg/L CCE. The CSI lab provides teams with an unlimited supply of 100 mg/L CCE or 20 mg/L CCE total hardness standard, depending on sampling sites. Teams may hold samples at 4°C and perform the total hardness test up to 14 days after sample collection, as per certified lab holding time.

^fVolunteers are instructed to calibrate their thermometers based on the temperature of boiling water equal to 100°C at sea level.

While onsite, CSI staff ask clients for voluntary written permission to incorporate their test results in CSI's data pool on groundwater quality in the Marcellus and Utica Shale regions in upstate New York. Approximately 85 percent of clients have granted permission to date. Groundwater data will be incorporated into CSI's online interactive data archive by 2013. Data will be pooled in one-mile grid squares to protect homeowners' privacy. Each grid square will link to 20 separate graphs, one for each "signature chemical" (Figure 2). The grid squares will allow chemical concentrations to be mapped, providing enough information to spot spatial trends in "signature chemicals" relative to nearby gas wells or other potential sources of contamination, while protecting homeowners' privacy. As the map in Figure 2 shows, sample wells tend to occur in loose clusters, probably because private clients often find out about CSI through word of mouth, and because CSI splits travel costs among clients whose wells we sample in the same area on the same day. Other than splitting travel costs, CSI does not offer financial incentives. Clients pay 100 percent of the cost of baseline tests themselves. Therefore, pooled groundwater results comprise a near-random sample of groundwater quality in the Marcellus and Utica Shale regions in rural Southern and Central New York.

Groundwater quality data for New York State were downloaded from NWIS from 1990 to September 2012. ArcGIS [19] was used to select groundwater sampling sites in the area of New York State underlain by the Utica and Marcellus shale gas formations. Within the shale gas formations, a subset of sites was selected that corresponds more closely with the 13 counties in upstate New York where CSI has performed baseline testing on private wells: Otsego, Tompkins, Chenango, Delaware, Steuben, Tioga, Schuyler, Broome, Chemung, Yates, Schoharie, Seneca, and Sullivan. Results were averaged if a well was sampled more than once. A geographic information system (GIS) layer representing urban centers, residential areas, and industrial zones was created as a way to evaluate the distribution of the USGS's groundwater monitoring sites.

The CSI Database: A Tool for Community-Based Risk Assessment

Placing water quality data in the public domain and facilitating its analysis and use by stakeholders is central to the Community Science Institute's nonprofit mission of empowering communities to understand local water resources and manage them sustainably. The CSI data archive at www.communityscience.org/database is an integral feature of community-based risk assessment because it makes it possible for any member of the public, free of charge, to view, search, download, and analyze surface water data developed in collaboration with our volunteer stream monitoring groups as well as groundwater data belonging to our private clients who voluntarily agree to include their test results in CSI's anonymous groundwater data pool. CSI's database structure has evolved from a

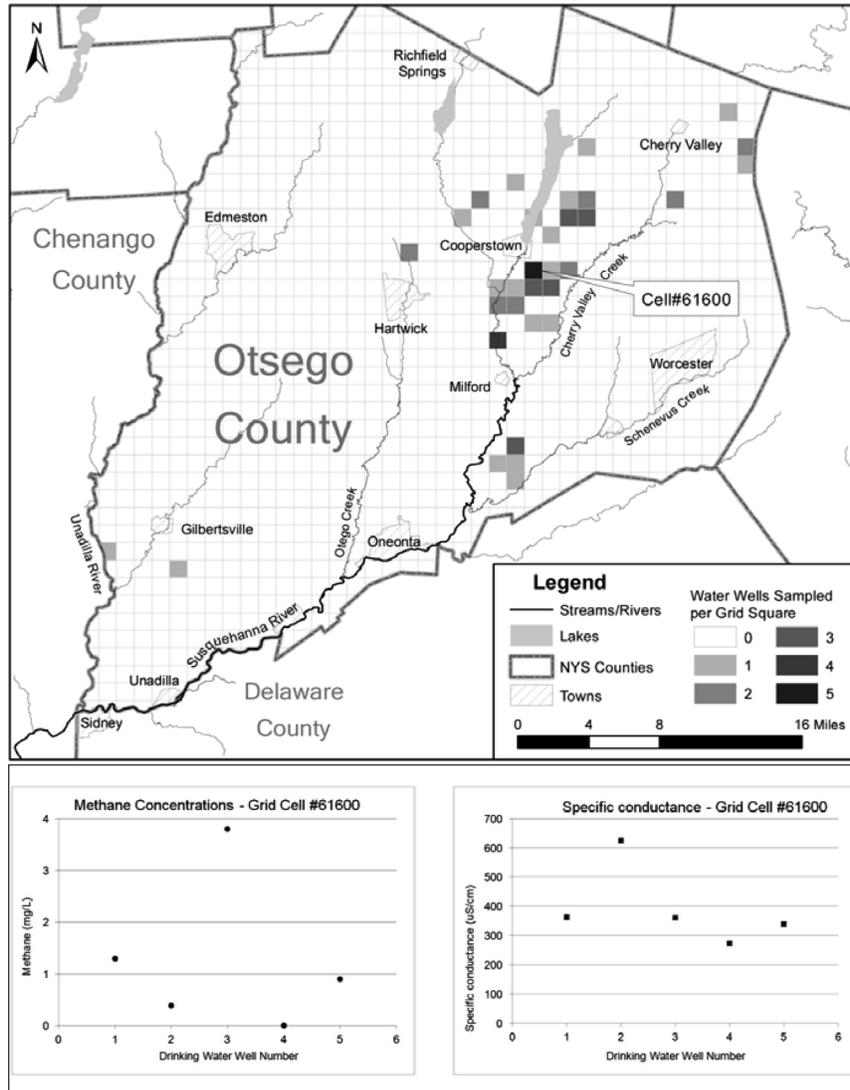


Figure 2. Example map and graphs illustrating presentation of regional groundwater baseline data planned for CSI website in 2013. The drinking water wells sampled by CSI in Otsego County are aggregated by one-mile grid square (total wells = 65). Methane and specific conductance data are graphed for one-mile grid square #61600.

Microsoft Excel-based approach, to a web-based architecture using the PHP scripting language and an SQL database back-end, and finally since 2011 to a Ruby on Rails® platform, chosen for its efficiency in building web applications. Visitors are provided with interactive tools to access over 35,000 data items linked to maps and graphs and to use a powerful querying mechanism to search the archive and export raw data. As a scalable archive, the CSI database is capable of organizing and presenting surface water and groundwater data from geographic areas of any size, including individual monitoring locations, watersheds, regions, countries, and continents. One hundred percent of the raw data produced by volunteer-CSI stream monitoring partnerships is made available to the public on the CSI website. Surface water data is searchable by region, stream, location, date, “signature chemical,” and flow conditions. Pooled groundwater data shared by private clients will be incorporated into the database by 2013. Groundwater data will be searchable by region, county, one-mile grid square and “signature chemical” (see Figure 2).

RESULTS AND CONCLUSIONS

Surface Water Monitoring in Partnership with Groups of Trained Volunteers

Streams in Cayuga Lake Watershed

Baseline stream monitoring for an expanded list of gas well “signature chemicals” is in progress at this writing (October 2012). As noted above, although CSI’s volunteer monitoring partnerships in this watershed since 2002 have focused on impacts from agriculture and residential development, there is some overlap between CSI’s traditional sampling parameters and gas well “signature chemicals.” Beginning in 2012, additional gas well “signature chemicals” are being tested once a year at a subset of Cayuga Lake watershed monitoring locations (see Methods). As a representative dataset for streams in the Cayuga Lake watershed, selected certified test results for Six Mile Creek and tributaries, downloaded through the data query interface for the CSI database at <http://www.communityscience.org/database/entries>, are summarized in Table 2 and compared to available data from the NWIS database. Median values are in good agreement considering CSI volunteers and agency staff sampled different locations on Six Mile Creek. As a preliminary estimate of variability in the CSI data set, the coefficient of variation was calculated for specific conductance under base-flow conditions for each of the 14 monitoring locations on Six Mile Creek, as follows. The data query interface in the CSI database was used to select the time period (2004-2012), monitoring region (Cayuga Lake watershed), monitoring set (Six Mile Creek), analyte (specific conductance), flow conditions (base flow), and test location (lab). The filtered data were

Table 2. Comparison of Selected “Signature Chemical” Indicators of Water Quality Under Base Flow Conditions^a in Six Mile Creek and Tributary Streams as Measured by CSI’s Certified Lab in Stream Samples Collected Synoptically by Volunteers^b and by the U.S. Geological Survey (USGS)

Parameters	Data from certified CSI lab analyses of samples collected by Six Mile Creek volunteer group in 23 synoptic sampling events at 15 stream locations ^c			USGS data ^d
	Min	Max	Median (n)	Median (n)
Alkalinity (mg CaCO ₃ /L)	10.3	165	92.3 (299)	79 (14)
Barium (mg/L) ^e	0.017	0.056	0.0435 (8)	no data
Calcium hardness (mg CaCO ₃ /L)	19	89	71 (13)	no data
Chloride (mg/L)	3.5	57.8	18.6 (312)	19.7 (18)
Gross alpha radioactivity (pCi/L) ^e	0.22	1.55	0.595 (8)	no data
Gross beta radioactivity (pCi/L) ^e	0.97	3.83	1.69 (8)	no data
Total hardness (mg CaCO ₃ /L)	10.3	183	108 (312)	120.5 (18)
pH	6.75	8.85	7.5 (312)	8 (17)
Total nitrogen (mg/L) ^f	non-detect (< 0.11)	1.75	0.4 (291)	0.545 (15)
Total suspended solids (mg/L)	non-detect (< 0.625)	85	2.05 (311)	no data
Specific conductance (μS/cm)	58	450	254.5 (312)	297.5 (20)
Strontium (mg/L) ^e	0.045	0.108	0.085 (8)	no data
Sulfate (mg/L)	4.4	17.4	10.25 (139)	11.7 (18)
Total dissolved solids (mg/L) ^e	100	180	161.5 (8)	173 (17)
Turbidity (NTU)	0.38	81.2	4.48 (312)	no data

^aBase flow is defined as a flow equal to or less than two times the historic median as recorded by the USGS gauging station on Six Mile Creek at Bethel Grove for the day of a synoptic sampling event. The Six Mile Creek volunteer group performs on average three base flow and two stormwater sampling events per year.

^bA “synoptic sampling event” or “synoptic monitoring event” is defined as one in which a group of volunteers collect samples at specific locations on the same day within a few hours of each other in order to facilitate comparison of water quality values throughout the sampled drainage area. In the CSI database (www.communityscience.org/database/), “synoptic monitoring location” refers to a stream location that is always included in synoptic monitoring events for a particular monitoring set (e.g., the Six Mile Creek watershed) year after year. An “investigative monitoring location” is one which is sampled occasionally to track pollution that may be detected at synoptic locations.

^cCertified lab data from 23 base flow sampling events at 14 synoptic sampling sites plus one investigative site on the Six Mile Creek mainstem and tributary streams from 2004-2012. Results may be viewed at www.communityscience.org/database/monitoringsets/5. Raw data may be selected and downloaded at <http://www.communityscience.org/database/entries>.

^dU.S. Geologic Survey data from 16 sampling events at three sites on the Six Mile Creek main stem and six sites on Six Mile Creek tributaries from 2003-2005 (waterdata.usgs.gov/).

^eExpanded gas well baseline parameters measured one time at seven synoptic sampling sites and one investigative site as part of a base flow synoptic sampling event in 2012.

^fCSI Total Nitrogen equal to sum of total Kjeldahl nitrogen (TKN) and nitrate- + nitrite-nitrogen. According to Table 5.10 in the 2011 draft Supplemental Generic Environmental Impact Statement (dSGEIS) by the New York State Department of Environmental Conservation (NYSDEC), TKN is elevated approximately 300-fold in flowback compared to typical values in Six Mile Creek, making it a potential contributor to a “chemical signature” of gas well impacts.

downloaded to MS Excel, the mean and standard deviation were calculated, and the coefficient of variation (COV) was calculated as the ratio of the standard deviation to the mean multiplied by 100. The COV was calculated for each of the 14 synoptic sampling locations on Six Mile Creek. COVs for specific conductance at the 14 locations ranged from 13.6 percent to 31.5 percent, the mean COV was 21.4 percent, and the median COV was 20.7 percent. It is noted that the data query interface in the CSI database can be used to select and export other data sets for Six Mile Creek and analyze their variability. For example, COVs for total hardness were calculated for each of the 14 locations, and the mean COV for total hardness was found to be 22 percent. This low variability strengthens the baseline from which to assess possible impacts on specific streams and stream reaches if HVHFF activities take place in the Cayuga Lake watershed.

Streams in Upper Susquehanna River Basin

Unlike the Cayuga Lake watershed, where volunteer groups collect grab samples two to five times a year for certified analyses by the CSI lab, volunteers in the Upper Susquehanna River Basin perform monthly measurements of five red-flag parameters in the field and report their results to CSI. At this writing (October 2012), 77 red-flag volunteers are monitoring 125 locations draining 1,233 square miles in sub-watersheds of the Upper Susquehanna River basin (Figure 1). Volunteers are added continuously as word spreads and citizens contact CSI for training and technical support. Volunteer results that meet data acceptance criteria (provided in Table 1) are entered in the CSI database by CSI staff and may be searched and downloaded via the data query interface at <http://www.communityscience.org/database/entries>. Results obtained by CSI's first red-flag group, the Cayuta-Catatonk Water Watch, in the first year of their monthly monitoring program from February 2011 to February 2012, are summarized in Tables 3 and 4 and compared to data reported by state and federal agencies. Median values for pH, specific conductance and total hardness are lower than values reported by the NYSDEC and the Susquehanna River Basin Commission (SRBC). A possible explanation is that most of the agency data are collected from a single monitoring site located near the mouths of Catatonk Creek (Table 3) and Cayuta Creek (Table 4), while volunteers collected red-flag data throughout both watersheds including headwater streams. Coefficients of variation for specific conductance at 26 red-flag monitoring locations under base-flow conditions in Catatonk and Cayuta Creeks ranged from 9.8 percent to 74.6 percent with a mean COV for all locations of 33 percent and a median COV of 32.9 percent. The generally higher COVs at red-flag monitoring locations compared to Six Mile Creek locations may be due to the smaller data set, the lower accuracy of field measurements (Tables 3 and 4) compared to certified lab results (Table 2), greater temporal variation in specific conductance in Cayuta

and Catatonk Creeks compared to Six Mile Creek, or a combination of these and other factors. Nevertheless, field measurements at fixed stream locations by volunteers (Tables 3 and 4) are sufficiently consistent over time to serve as effective baselines for detecting possible HVHMF impacts on streams. Baselines established by volunteers are important in view of the paucity of agency data on streams in recent years. A search of the federal STORET database indicated that stream data had been collected at 270 agency monitoring sites between 1990 and October of 2012 in the 13 counties in upstate New York where CSI is focusing its baseline monitoring programs (Figure 1). At least three of four red-flag parameters (pH, dissolved oxygen, specific conductance, total hardness) were measured at 85 percent of STORET sites. However, the median number of sampling events per site over the 22-year period from 1990-2012 was only four. Of the 270 STORET sites in the 13-county region, only 39 have been sampled since January 1, 2010.

Groundwater in the Marcellus and Utica Shale Regions

The NWIS database was searched for gas well “signature chemicals” that might be used in a regional baseline to assess HVHMF impacts on groundwater quality. Search results indicated that only a small fraction of wells in New

Table 3. Comparison of “Red-Flag” Indicators of Water Quality Measured by Cayuta-Catatonk Water Watch (CCWW) Volunteers with Agency Data under Base Flow Conditions in Catatonk Creek

“Red-flag” indicators	Catatonk Creek—CCWW data ^a			Catatonk Creek—NYSDEC data ^b		
	Median (n)	Min	Max	Median (n)	Min	Max
pH	7.25 (48)	6.39	8.14	7.76 (46)	6.49	8.42
Dissolved oxygen (mg/L)	9.25 (58)	5.8	13.4	10.25 (22)	7.85	13.48
Specific conductance (μS/cm)	154.5 (56)	36	431	211 (46)	49	395
Total hardness (mg/L)	68 (44)	16	160	98.5 (10)	70.4	160

^aData collected by 4 volunteer teams at 11 sites throughout the Catatonk Creek watershed from Feb. 2011-Feb. 2012 (<http://www.communityscience.org/database/monitoringsets/13>).

^bData are primarily from the New York State Department of Environmental Conservation (NYSDEC), Rotating Integrated Basin Studies (RIBS), site #06032102, Apr.-Nov. 2004 (http://www.epa.gov/storet/dw_home.html), with additional data from two Susquehanna River Basin Commission sites and one NYSDEC site.

Table 4. Comparison of “Red-Flag” Indicators of Water Quality Measured by Cayuta-Catatonk Water Watch (CCWW) Volunteers and Agency Data under Base Flow Conditions in Cayuta Creek

“Red-flag” indicators	Cayuta Creek—CCWW data ^a			Cayuta Creek—SRBC data ^b		
	Median (n)	Min	Max	Median (n)	Min	Max
pH	7 (118)	6	8.71	7.8 (186)	6.1	9
Dissolved oxygen (mg/L)	9.4 (135)	5.8	13.9	9.8 (164)	4.95	15.2
Specific conductance (μS/cm)	118 (134)	22	351	282 (190)	71	1165
Total hardness (mg/L)	53 (128)	12	152	120 (3)	106	148

^aData collected by 4 volunteer teams at 15 sites throughout the Cayuta Creek watershed from Feb. 2011-Feb. 2012 (<http://www.communityscience.org/database/monitoringsets/12>).

^bData are primarily from the Susquehanna River Basin Commission (SRBC), Interstate Stream Water Quality Network, Apr.-1990-Oct. 2010 (http://www.epa.gov/storet/dw_home.html). The station providing the majority of data is CAYT001.7-4176 near the mouth of Cayuta Creek. Additional data are from three SRB stations and one NYSDEC station within the Cayuta Creek watershed.

York have been characterized with respect to potential HVHFF contamination. A total of 1,995 wells in New York have been analyzed for at least one chemical in at least one of eleven “signature chemical” categories since 1990 (Table 5). However, only 208 wells have been analyzed for at least one chemical in each of eight “signature chemical” categories, and of these, only 16 are located in rural areas of the Southern Tier (Table 5). Thus, the geographic distribution of agency data on groundwater quality is skewed away from the rural areas that are most at risk of impacts from HVHFF in New York.

Available agency data were filtered and tabulated in Table 6 to facilitate comparison with CSI groundwater data on “signature chemicals” in Table 7. Median values in CSI’s regional groundwater database reported in Table 7 were generally similar to median values extracted from the USGS’s NWIS database and tabulated in Table 6. Chloride, total dissolved solids, total hardness and specific conductance values were somewhat higher in the USGS data set. These differences could be explained by random variability. Groundwater quality is known to change over short horizontal and vertical distances as a result of differences in aquifer characteristics, geochemical conditions, and residence time [20]. Indeed, we observed substantial variability among private drinking water wells, including wells in the same 1-mile grid square (Figure 2). Another possible

Table 5. Certified Measurements of CSI “Signature Chemicals” in Groundwater Wells in Urban and Rural Areas of New York State Performed by the Community Science Institute and the U.S. Geological Survey

Geographic area	Number of groundwater wells where certified measurements of gas well “signature chemicals” (SC) have been performed in New York							
	CSI				USGS			
	8 ^a of 11 SC categories ^b	11 ^a of 11 SC categories ^b	1 ^a of 11 SC categories ^b	5 ^a of 11 SC categories ^b	7 ^a of 11 SC categories ^b	8 ^a of 11 SC categories ^b		
New York total	121	110	1,995	1,260	580	208		
New York shale region	121	110	709	458	109	80		
Shale region—rural ^c	121	110	415	274	62	46		
Shale region—urban/contaminated ^c	0	0	294	184	47	34		
13-county area	121	110	245	162	48	27		
13-county area ^d —rural ^c	121	110	178	110	28	16		
13-county area ^d —urban/contaminated ^c	0	0	67	52	20	11		
Outside of shale region	0	0	1,286	802	471	128		

^aNumber of "signature chemical" categories for which certified measurements were performed on groundwater wells.

^bCSI's recommended list of 19 gas well "signature chemicals" and 52 volatile organic compounds (VOCs) were organized into eleven (11) categories of chemical characteristics with the goal of searching the NWIS database of the U.S. Geological Survey for existing groundwater quality data related to "hydrofracking." Each of the eleven "signature chemical" ("SC") categories contains one or more certified tests recommended by CSI as part of a pre-HVHF baseline designed for use in screening groundwater for possible contamination due to gas well waste. The eleven (11) CSI "signature chemical" categories used to search the NWIS database are: (1) Methane; (2) Chemical oxygen demand; (3) Methylene blue active substances (anionic surfactants); (4) Total hardness, calcium; (5) Barium, strontium; (6) Iron, manganese, arsenic; (7) Turbidity, total suspended solids; (8) Gross alpha radioactivity, gross beta radioactivity; (9) Benzene, ethylbenzene, toluene, xylene; (10) pH, alkalinity; and (11) Chloride, specific conductance, total dissolved solids. While these eleven (11) categories are considered to be broadly representative of the chemical characteristics most likely to change as a result of contamination from shale gas wells, it is recognized that they are not completely inclusive, and that there are other groundwater characteristics in the NWIS database that might be impacted by "fracking."

^cUrban/contaminated areas are defined as the union of four GIS layers: (1) U.S. Census Bureau 2010 populated places, (2) U.S. Census Bureau 2010 urban areas, (3) One-mile corridors around EPA facilities and sites subject to environmental regulation and (4) One-mile corridors around the NYSDEC remediation sites. This final GIS layer represents a rough measure of areas that have intensive residential, commercial, and industrial land use and can be distinguished from areas that are primarily rural in character.

^dThe 13-county area in upstate New York is defined as those counties where CSI has performed baseline testing on private groundwater wells: Otsego, Tompkins, Chenango, Delaware, Steuben, Tioga, Schuyler, Broome, Chemung, Yates, Schoharie, Seneca, and Sullivan.

Table 6. Levels of Gas Well "Signature Chemicals" in USGS Groundwater Monitoring Wells, 1990-2012

Gas well signature chemical (units)	USGS results for Marcellus and Utica Shale regions				USGS results for 13-county area in rural Southern Tier ^a				
	Wells tested (wells with detects) ^b	Min-max values for all wells ^c	Median values for all wells ^d	Wells tested (wells with detects) ^b	Min-max values for all wells ^c	Median values for all wells ^d	Wells tested (wells with detects) ^b	Min-max values for all wells ^c	Median values for all wells ^d
Calcium (mg Ca/L)	16 (16)	11.13-309.2	85	0 (0)	—	—	0 (0)	—	—
Alkalinity (mg CaCO ₃ /L)	0 (0)	—	—	0 (0)	—	—	0 (0)	—	—
Total hardness (mg CaCO ₃ /L)	590 (590)	0.28-87,600	219	119 (119)	1.47-1,700	137	119 (119)	1.47-1,700	137
Total dissolved solids (mg/L)	459 (459)	33-193,000	294	119 (119)	33-7,130	205	119 (119)	33-7,130	205
Total suspended solids (mg/L)	0 (0)	—	—	0 (0)	—	—	0 (0)	—	—
Turbidity (NTU)	17 (17)	0.2-230.06	15.9	0 (0)	—	—	0 (0)	—	—
pH (pH units)	566 (566)	5.8-12.4	7.6	114 (114)	5.9-9.1	8	114 (114)	5.9-9.1	8
Chloride (mg/L)	574 (574)	0.4-126,000	32.4	119 (119)	0.4-3,380	13	119 (119)	0.4-3,380	13
Specific conductance (μS/cm)	555 (555)	45-129,333	535	119 (119)	47-11,300	356	119 (119)	47-11,300	356
Chemical oxygen demand (mg/L)	4 (0)	non-detect (< 10)	non-detect (< 10)	4 (0)	non-detect (< 10)	non-detect (< 10)	4 (0)	non-detect (< 10)	non-detect (< 10)
Methane (mg/L)	172 (153)	non-detect (< 0.001)-45.4	0.003	37 (18)	non-detect (< 0.001)-38.3	non-detect (< 0.001)	37 (18)	non-detect (< 0.001)-38.3	non-detect (< 0.001)
Gross alpha radioactivity (pCi/L) ^e	98 (90)	-4-10.7	0.7	24 (16)	-0.4-10.7	1.05	24 (16)	-0.4-10.7	1.05
Gross beta radioactivity (pCi/L) ^e	98 (87)	-0.9-19.1	1.6	24 (13)	-0.5-19.1	1.05	24 (13)	-0.5-19.1	1.05

Methylene blue active substances (MBAS) (mg/L)	0 (0)	—	—	0 (0)	—	—
Barium, unfiltered (mg/L)	276 (276)	0.00109-10.4	0.1155	73 (73)	0.00488-10.4	0.110
Iron, unfiltered (mg/L)	275 (272)	non-detect (< 0.0046)-29.171	0.138	69 (66)	non-detect (< 0.0046)-3.47	0.138
Manganese, unfiltered (mg/L)	273 (271)	non-detect (< 0.00016)-1.6	0.0351	70 (68)	non-detect (< 0.00016)-0.594	0.03265
Arsenic, unfiltered (mg/L)	219 (209)	non-detect (< 0.00006)-0.148	0.00084	50 (40)	non-detect (< 0.00006)-0.027	0.00079
Strontium, unfiltered (mg/L)	276 (276)	0.0104-53.8	0.227	73 (73)	0.0104-31.1	0.247
Benzene (mg/L)	338 (5)	non-detect (<0.00002)-0.0561	non-detect (< 0.00002)	85 (1)	non-detect (< 0.00002)-0.0003	non-detect (< 0.00002)
Ethylbenzene (mg/L)	335 (4)	non-detect (< 0.00003)-0.0076	non-detect (< 0.00003)	85 (1)	non-detect (< 0.00003)-0.0001	non-detect (< 0.00003)
Toluene (mg/L)	340 (30)	non-detect (< 0.00002)-0.023	non-detect (< 0.00002)	85 (8)	non-detect (< 0.00002)-0.001	non-detect (< 0.00002)
Xylene (mg/L)	27 (2)	non-detect (< 0.0002)-0.00475	non-detect (< 0.0002)	0 (0)	—	—

^aCounties included in this analysis: Otsego, Tompkins, Chenango, Broome, Steuben, Sullivan, Delaware, Schuyler, Tioga, Chemung, Schoharie, Seneca, Yates. Rural areas are defined as not urban/industrial areas. Urban/industrial areas are defined as U.S. Census Bureau 2010 populated places and urban areas; these GIS layers were merged with a layer comprised of 1-mile corridors around EPA facilities and sites subject to environmental regulation as well as NYSDEC remediation sites.

^bNumber of wells with concentrations above the laboratory's limit of quantitation (similar to detection).

^cMinimum values that are below the laboratory's limit of quantitation (LOQ) are reported as "non-detect" with the LOQ in parenthesis.

^dIf the laboratory reported a non-detect, the value is less than the laboratory's limit of quantitation (similar to detection). If a well was sampled more than once, the value is taken to equal the average of all samples collected from that well. The quantitation limit is indicated by "<"; for example, a chloride value of < 2 means that the measurement was less than a limit of quantitation of 2 mg/L.

^eUSGS non-detects defined as "Radiochemistry non-detect, result below sample specific critical level."

Table 7. Levels of Shale Gas Well “Signature Chemicals” in Private Groundwater Wells Measured by the Community Science Institute, 2009-2012

Gas well “signature chemical” (units)	CSI results for rural Southern Tier ^a			Drinking water regulations/guidelines	
	Number of wells tested (number of wells with detects) ^b	Min-max values for all wells ^c	Median values for all wells ^d	Federal MCL value ^e (number of CSI wells over)	NY State MCL value ^f (number of CSI wells over)
Calcium (mg Ca/L)	121 (120)	non-detect (< 1.2)-156	32.6	none	none
Alkalinity (mg CaCO ₃ /L)	122 (122)	8.13-450	140.5	none	none
Total hardness (mg CaCO ₃ /L)	121 (121)	8.8-635	107	none	none
Total dissolved solids (mg/L)	120 (114)	< 50-1090	180	none	500 ^g (3)
Total suspended solids (mg/L)	121 (5)	< 4.0-91.6	< 4.0	none	none
Turbidity (NTU)	121 (120)	< 0.01-91.8	0.83	5 (14)	5 (14)
pH (pH units)	122 (122)	5.9-8.65	7.53	none	6.5-8.5 ^g
Chloride (mg/L)	121 (82)	non-detect (< 2) 281.5	4.18	none	250 ^g (2)
Specific conductance (µS.cm)	122 (122)	40.4-1682	298.5	none	none
Chemical oxygen demand (mg/L)	121 (31)	non-detect (< 10)-26.9	non-detect (< 10)	none	none
Methane (mg/L)	122 (51)	non-detect ^h -14	non-detect ^h	none	10 ⁱ (2)
Gross alpha radioactivity (pCi/L)	121 (121)	-0.45-4.97	0.655	15 (0)	15 (0)
Gross beta radioactivity (pCi/L)	121 (121)	-0.59-40.83	1.08	15-50 ^j (0)	15-50 ^j (0)

Methylene blue active substances (MBAS) (mg/L)	122 (13)	non-detect (< 0.04)-0.054	non-detect (< 0.04)	none	0.5 ^g (0)
Barium, unfiltered (mg/L)	122 (122)	0.0019-0.895	0.0657	2 (0)	2 (0)
Iron, unfiltered (mg/L)	122 (110)	non-detect (< 0.005)-11.3	0.0885	none	0.3 ^g (26)
Manganese, unfiltered (mg/L)	122 (101)	non-detect (< 0.002)-1.52	0.045	none	0.3 ^g (2)
Arsenic, unfiltered (mg/L)	122 (44)	non-detect (< 0.0005)-0.0248	non-detect (< 0.0005)	0.01 (2)	0.01 (2)
Strontium, unfiltered (mg/L)	108 (108)	0.0006-2.07	0.217	none	none
Benzene (mg/L) ^k	114 (0)	non-detect (< 0.0005)	non-detect (< 0.0005)	0.005 (0)	POC ^l (0)
Ethylbenzene (mg/L) ^k	114 (0)	non-detect (< 0.0005)	non-detect (< 0.0005)	0.7 (0)	POC ^l (0)
Toluene (mg/L) ^k	114 (3)	non-detect (< 0.0005)-1.3	non-detect (< 0.0005)	1 (1)	POC ^l (1)
Xylene (mg/L) ^k	114 (0)	non-detect (< 0.0005)	non-detect (< 0.0005)	10 (0)	POC ^l (0)

^aCounties (number of wells included in baseline): Oisego (59), Tompkins (13), Chenango (13), Broome (10), Steuben (7), Sullivan (5), Delaware (4), Schuyler (4), Tioga (3), Chemung (2), Schoharie (1), Seneca (1), Yates (1). Private clients must give written permission for their results to be included in the regional baseline.

^bNumber of wells with concentrations above the laboratory's limit of quantitation (similar to detection).

^cMinimum values that are below the laboratory's limit of quantitation (LOQ) are reported as "non-detect" with the LOQ in parenthesis.

^dIf the laboratory reported a non-detect, the value is less than the laboratory's limit of quantitation (similar to detection). The quantitation limit is indicated by "<"; for example, a chloride value of < 2 means that the measurement was less than a limit of quantitation of 2 mg/L. If a well was sampled more than once, the value is taken to equal the average of all samples collected from that well with one exception: Exceedances of federal and state standards are noted regardless of the number of times a well is sampled.

Table 7. (Cont'd.)

^eThe MCL refers to the Maximum Contaminant Level, a health-based, enforceable standard under the federal Safe Drinking Water Act (SDWA). MCLs are based on human health risk assessments and are listed on the EPA website at: <http://water.epa.gov/drink/contaminants/index.cfm#List>. MCLs are distinct from National Secondary Drinking Water Standards (NSDWS), which are not health-based and not enforceable by EPA.

^fState standards refer to levels of chemicals in drinking water that are enforced by New York State under the federal Safe Drinking Water Act (SDWA) and are listed at http://www.health.ny.gov/regulations/nycr/title_10/part_5/subpart_5-1_tables.htm. An enforceable state standard must be equally or more stringent than a federal standard. A state is not required to base its enforceable standards on human health risk assessments; however, a state may refer to its standards as MCLs. In general, state MCLs are a mixture of federal health-based MCLs and federal non-health-based National Secondary Drinking Water Standards (NSDWS). For example, New York bases several enforceable standards on NSDWS, available at <http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList>. NSDWS are not enforceable at the federal level because they are directed at cosmetic properties of drinking water such as taste and odor, not at risks to human health.

^gBased on a National Secondary Drinking Water Standard (NSDWS) that is not health-based and is not enforceable by the federal government (see <http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList>).

^hThe limit of quantitation (LOQ) for methane depends on the subcontract lab used. The lab used from 8/2009 to 6/2010 had an LOQ of 0.01 mg/L; the lab used since 6/2010 has an LOQ of 0.001 mg/L.

ⁱA guidance value, not a standard. The U.S. Department of the Interior recommends that wells containing greater than 10 mg/L of dissolved methane be vented to minimize the explosion hazard that could result from methane volatilizing (escaping) from water and building up inside a home.

^jStandard is based on an exposure limit of 4 mrems/year. This level of exposure corresponds to a concentration of 15 pCi/L to 50 pCi/L, depending on various factors. It is possible that the one well that exceeded 15 pCi/L may have resulted in an exposure greater than the federal MCL of 4 mrems/year.

^kResults for so-called BTEX chemicals are reported here. Additional 48 volatile organic compounds (VOCs) analyzed by EPA Method 524.2 are omitted from this table but will be included in CSI's online groundwater database.

^lPOCs (principal organic contaminants) have an automatic New York State MCL of 0.005 mg/L: http://www.health.ny.gov/regulations/nycr/title_10/part_5/subpart_5-1_tables.htm

explanation is that more USGS samples may have been collected in areas or regions with higher mineral content than CSI samples. Minimum values were similar in the CSI and USGS data sets, while maximum values were significantly higher in the USGS data set (compare Tables 6 and 7). The most likely explanation for the maximum values for chloride (126,000 mg/L), total dissolved solids (193,000 mg/L) and specific conductance (129,333 $\mu\text{S}/\text{cm}$) is groundwater brine resulting from salt deposits in the Syracuse area [21].

CSI's growing database indicates that groundwater quality in rural areas of New York's Southern Tier region is generally excellent with respect to gas well "signature chemicals." Results from 122 private wells with an aggregate total of 8,224 certified test results including 2,296 tests for 19 parameters related to brine, acid, metals, suspended solids, surfactants, bulk organic compounds, radioactivity, and methane, and 5,928 tests for 52 VOCs included in EPA Method 524.2, are summarized in Table 7. Twelve wells exceeded the federal standard for turbidity, one well exceeded the federal standard for arsenic and one exceeded the federal standards for both turbidity and arsenic. A fifteenth well exceeded the federal standards for turbidity and toluene; however, this was a newly drilled well, and no exceedances were observed in follow-up sampling. The remaining 107 wells showed no exceedances of federal standards for any of the 19 "signature chemicals" and 52 VOCs. Stated as a fraction of the total number of "signature chemical" results summarized in Table 7, exceedances of federal standards comprised 17 of 8,224 test results or 0.2 percent. Methane was detected in 51 of 122 wells (detection limit 0.001 or 0.01 mg/L, depending on subcontract lab); two wells had levels greater than 10 mg/L, the federal guideline for explosion hazard (Table 7). Methane concentrations may have been underestimated because containers were open during the approximately 20 seconds required to collect a sample, providing an opportunity for methane, a gas, to volatilize. Ethane, which was routinely analyzed along with methane, was not detected in any wells (detection limit 0.019 mg/L, data not shown).

It is important to note that state drinking water standards differ substantially from federal standards. In particular, New York enforces several federal National Secondary Drinking Water Standards (NSDWS), which address cosmetic, smell, and taste characteristics as MCLs, including state MCLs for iron, manganese, total dissolved solids, and methylene blue active substances (MBAS) (anionic surfactants). While the state has valid reasons for these regulations, they result in MCLs that are not based strictly on human health risk assessments. For example, the Institute of Medicine of the National Academy of Sciences has set an upper intake level (UL) for iron for adults of 45 mg/day [22], and thus an adult would have to ingest 150 liters or about 37 gallons of water per day to incur adverse health effects when the iron concentration is 0.3 mg/L, the MCL for New York State. A number of VOCs are regulated by New York as Principal Organic Contaminants (POCs) with obligatory MCLs of 0.005 mg/L even though health-based toxicity thresholds may be higher or

unknown (Table 7). For these reasons, the number of MCL exceedances under New York State regulations exceeded the number of MCL exceedances under federal regulations (Table 7).

DISCUSSION

High-volume horizontal hydraulic fracturing or HVHHF, commonly known as fracking, is a new technology that is widely believed to present substantial risks to human health and the environment. Weak regulation of fracking by federal and state governments has resulted in a dearth of data on exposure to the hazardous chemicals employed by the shale gas industry and the effects of exposure on humans and other species.

The Value of Risk Assessment

Many if not most large-scale industrial activities entail the use of hazardous chemicals and the generation of hazardous chemical waste. The role of government is to encourage entrepreneurship, innovation, and productivity while ensuring that public health and environmental resources required for diverse economic activities are protected [23]. Risk assessment, properly conducted, provides an effective tool with which to evaluate industrial activities and decide the extent to which benefits to society justify inherent risks to human health and environmental resources. Even rudimentary risk assessments offer effective decision-making tools by helping to situate risks and benefits within the broader context of economic activity and quality-of-life goals for a place or a region.

The principles of risk assessment are well known to policymakers in government agencies and, one presumes, to lawmakers and their staffs in state legislatures and Congress. Nevertheless, the authors are not aware of a single systematic risk assessment anywhere in the United States that follows protocols developed by the National Academy of Sciences and the U.S. Environmental Protection Agency [15-17, 24] and widely accepted throughout the risk assessment community to marshal available evidence and examine the risks and benefits of HVHHF-based shale gas extraction. To the contrary, the industry has been exempted from key provisions of federal environmental laws [25], and its hazardous byproducts have been arbitrarily classified as non-toxic “industrial wastewater” in New York [26], effectively privileging the industry’s growth and deflecting attention from the risks its growth entails. Risk assessment is the only available tool to evaluate the industry’s impacts within the broader context of the diverse human and environmental communities in which it operates. In the absence of action by government, it is up to citizens to gather evidence on risk. The goal of CSI-volunteer monitoring partnerships is to target data gaps at the local level where government agency data is scarce or non-existent.

Surface Water Monitoring by Citizen Volunteers

Through its partnerships with groups of volunteers from rural communities in Upstate New York, the Community Science Institute collects scientifically credible water quality data in an effort to evaluate risks to local streams and lakes from land uses such as agriculture, residential development and, most recently, from the burgeoning HVHFF-based shale gas industry. Results are disseminated to the general public through CSI's unique online data archive, providing factual information that can be accessed by citizens and municipal and county governments to help understand and manage water resources in their jurisdictions.

There is a growing scientific literature that seeks to understand the degree to which data collected by volunteers are valid, the purposes for which these data can or should be used, how volunteer data might be disseminated, and how to create a nexus between volunteers, planners, and regulators so that the data are put to use [27-31]. We report here on monitoring partnerships between trained groups of volunteers and CSI's certified lab that represent a workable compromise between a formal structured program with integrated quality control and a more autonomous organizational structure that promotes volunteer empowerment. Key elements of CSI-volunteer monitoring partnerships are:

- Recruitment of volunteers in groups of 15-30 people loosely defined by region.
- A series of three free training workshops spaced at least two weeks apart to give group members an opportunity to reflect on what they are learning and to foster group identity and commitment.
- Stream-side demonstrations of test kits and meters by CSI staff and hands-on practice with test kits by volunteers.
- Organization of each group into teams of two to five volunteers.
- A clear quality assurance protocol that volunteer teams can implement on their own.
- Selection of sampling sites by teams with guidance and mapping support from CSI.
- Management of the online data repository by CSI, with CSI staff entering only data that satisfy acceptance criteria (Table 1).
- Capacity for dynamic mapping and graphing of data in CSI's public database, including capacity for visitors to the CSI website to select and export raw data free of charge.

The results presented here provide evidence that surface water monitoring partnerships between groups of public-spirited citizens and CSI's certified lab are capable of generating and publicizing data for use in understanding, protecting, and managing water resources in New York State's shale gas region. Median values obtained by CSI-volunteer monitoring partnerships agreed well

with available agency data on surface water quality in the same general region, taking into account CSI's intentional focus on sampling sites located upstream and on small tributary streams as opposed to agencies' greater reliance on sampling sites located near stream mouths and agencies' inclusion of areas where contamination is suspected. Generally low coefficients of variation of data collected by volunteers at individual monitoring locations suggest that potential contamination events as well as long-term trends can be detected. The quality of volunteer data reported here is consistent with reports by other authors [29, 31].

Regional Groundwater Initiative

Groundwater monitoring is structured differently from surface water monitoring. While surface water monitoring is structured around active partnerships between CSI and volunteer groups, groundwater monitoring is based on private clients who contract with CSI's certified lab to collect and test drinking water samples from their home, then grant permission to aggregate their test results for anonymous dissemination on the CSI website. CSI's groundwater database continues to grow as more private clients request baseline tests and grant permission to pool their results. The groundwater data in CSI's archive of aggregated private client results were found to be representative of New York's shale gas region as indicated by the similarity of median values for gas well "signature chemicals" (Table 7) to groundwater data in the NWIS database (Table 6). Higher median and maximum values in the NWIS data set (Table 6) were probably due to the inclusion of groundwater data from areas with salt deposits and industrial and contaminated sites. The quality of groundwater in rural households with respect to gas well "signature chemicals" can only be described as excellent (Table 7). The most prevalent water quality issue by far was turbidity, which exceeded the federal standard of 5 NTU in 14 out of 122 private groundwater wells tested and which accounted for 14 out of 17 documented exceedances of federal health-based standards (Table 7). Methane was present in nearly half of private wells, in line with agency data [32, Table 6]. Methane concentrations ranged from barely detectable up to 14 mg/L, and the median value was 0.005 mg/L. The principal hazard associated with methane is explosion when concentrations reach 5.5 percent by volume in air, or about 55,000 ppm, and similar concentrations of methane can cause asphyxiation [33]. The U.S. Department of the Interior recommends venting wells containing methane concentrations greater than 10 ppm by weight or 0.001 percent in water in order to avoid gradual methane accumulation in air in enclosed living spaces. Methane is classified as toxicologically inert as long as oxygen is available, and animals are not affected by concentrations up to 10,000 ppm by volume in air [33, 34]; however, at concentrations greater than 50 percent or about 500,000 ppm by volume in air, nonspecific toxic effects secondary to oxygen deprivation have been noted [33]. The prevalence of methane in groundwater does not negate the

value of methane as a “signature chemical,” because concentrations would be expected to increase dramatically in the event of contamination resulting from leaks in well casings or from methane migration through subsurface fractures [12]. Ethane was not detected in any groundwater wells.

Aggregated private client groundwater results are being incorporated into CSI’s electronic database (www.communityscience.org/database) and will be made available to the general public online by 2013. Online groundwater data will be organized by region, county and 1-mile grid square (Figure 2) in contrast to surface water results, which are organized by region, “monitoring set” (e.g., the watershed of a stream such as Six Mile Creek or Catatank Creek), and monitoring location. One-mile grid squares should provide sufficient spatial information to investigate increases in post-drilling concentrations of “signature chemicals” in private drinking water wells.

Documenting HVHMF Impacts on Water

A post-fracking increase in the concentration of one or more “signature chemicals” can, in principle, be interpreted as evidence that water has been contaminated by nearby shale gas operations. The greater the number of “signature chemicals” and the higher their concentrations compared to pre-fracking baseline levels, the stronger the evidence of contamination. This application of “signature chemical” baselines should be valid both for an individual groundwater well and for a specific stream reach where pre-fracking baseline data is available. While it should be easier to detect contamination of a groundwater well that has been characterized on the basis of over 70 certified lab tests than a stream location that has been characterized on the basis of five red-flag tests performed by volunteers in the field, the guiding principle is the same: A significant change in the “chemical signature” of water quality that can be reasonably attributed to waste from the shale gas industry. Clearly the terms “significant” and “reasonable” are subject to interpretation. We anticipate that regulatory agencies and the courts will make decisions on a case-by-case basis, and that they will use a weight-of-evidence approach and take into account other factors in addition to changes in water quality, for example, proximity to a drill pad and visual evidence of a spill. Nevertheless, an increase over pre-fracking levels of “signature chemicals” is likely to constitute a strong, if not the strongest, piece of evidence that HVHMF-related contamination has occurred.

Detecting contamination by extrapolating “signature chemical” levels to groundwater wells and stream locations that lack pre-fracking data is decidedly less robust conceptually than comparing pre- and post-fracking data for the same drinking water well or the same stream location. Nevertheless, regional baselines should prove useful to agencies as part of a weight-of-evidence approach to identifying HVHMF impacts. Agencies will have to decide whether post-fracking levels of “signature chemicals” exceed regional values for groundwater, in the

case of a private well, or regional values for surface water, in the case of a stream or a stream reach, sufficiently to support a determination that the well or the stream has been degraded as a result of shale gas extraction activities.

It seems possible that despite the heterogeneity of groundwater sources in the regional baseline, some “signature chemicals” might be distributed in statistically recognizable patterns, the simplest example being a normal distribution, or bell curve. The regional baseline for a normally distributed “signature chemical” in groundwater might be used to estimate the probability that its post-fracking concentration in a private well is due to chance (that is to say, it falls within the normal distribution of the pre-fracking data set); a low probability would strengthen the case for contamination. Similarly, statistical patterns of “signature chemicals” in regional stream baselines, if present, might be used to estimate the probability that post-fracking concentrations signify contamination of a stream for which no baseline data exists. Regional surface water baselines also include a temporal component, because red-flag data are collected monthly. Temporal patterns such as seasonal variation, which can be readily analyzed by filtering and downloading red-flag data from the CSI database (<http://www.communityscience.org/database/entries>), might strengthen the case for or against HVHFF impacts.

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