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Technical Memorandum: Hydrology Issues with Hydraulic Fracturing in Pennsylvania

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SUMMARY

Hydraulic fracturing (HF) of the Marcellus shale in Pennsylvania creates many problems regarding the water resources of the State, including water quality and quantity issue as well as to surface and groundwater. The worst impacts estimated to a reasonable degree of scientific certainty are:

- Fracking requires more than five million gallons of water, much of which remains underground. Diverting this water from streams or pumping from aquifers connected to streams or springs can severely deplete those water sources.
- Fracking fluid spilled on land can flow across the ground surface or through shallow groundwater to nearby lands, including into the very small first order streams which are predominant in mountain headwaters. The contamination could devastate these streams due to their small size. Fracking fluid would also damage larger streams either if spills enter them directly or by accumulating in smaller tributaries.
- Natural gas can discharge from three different sources -the deep shale, a natural gas well bore, or shallow microbial sources - to shallow groundwater or to streams and springs. Fracking can mobilize gas from either source which can cause short-term or long-term methane contamination on streams and springs. The effect would be much worse on small first-order streams.
- Natural gas can flow to shallow groundwater or surface water sources along well bores, faulty well casings, fractures through the earth’s mantle, and through the shallow groundwater.
- The high pressure required for fracking can cause fracking fluid to leak from the well bores into surrounding formations. From those sources, the fluid can follow natural pathways or abandoned wells to shallow groundwater, streams and springs. If following natural pathways, the methane could contaminate larger streams in fault-controlled valleys.
- Fracking also releases brine which can follow natural or artificial pathways to shallow groundwater. Brine contains extremely high concentrations of salt and naturally

occurring radioactive materials. The injection of fracking fluid may displace brine into pathways that will start it flowing to the near surface. Increasing salt loads to pristine streams could ruin their water quality as a coldwater fishery.

- Fracking forces fracking fluid to flow outside of the shale, whether through out-of-formation fractures or through just making a contact with more permeable formations above the shale, starts the movement of fluid to shallow groundwater through natural pathways. The potential time frame is decades to centuries, so fracking anywhere could be creating a time bomb that potentially affects the lands being fracked and nearby land for centuries into the future.

Contaminants released by fracking can flow from fracking sites through groundwater or surface water onto land near or even distant from the fracking property. Fracking can release contaminants, gas, fracking fluid, or brine, to flow upward toward the shallow groundwater and springs and streams. Transport along these pathways may occur quickly, meaning less than a year, or could require decades or more and last for centuries. Ground surface spills will allow fracking fluid, flowback, or produced water (brine) to flow onto and pollute nearby streams. Well bore leaks will allow fracking fluid or gas to flow through fractures and porous aquifers to shallow groundwater. The fracking process will cause gas pockets separate from the target shale to be mobilized and commence flowing to nearby land. Monitoring will not prevent damages, and current monitoring is not sufficient to assess damages when they occur.

INTRODUCTION

This technical memorandum qualitatively estimates, to a reasonable degree of scientific certainty, the risk to ground- and surface waters in Pennsylvania (PA) caused by unconventional natural gas development involving hydraulic fracturing (HF). This review considers issues regarding the injection of toxic HF fluid into the ground and the movement of those fluids to both deep and shallow aquifers and to springs and streams. The review also considers the potential for leaks from pits and impoundments and for spills to reach and contaminate water resources. Additionally, the review considers the risks to recreation and ecosystems that could result from the withdrawal of water for fracking operations. The discussion includes time scale factors, in that transport times for contaminants often exceed the life of the gas wells and certainly the life of any monitoring being required by the State. These risks are discussed with respect to their violation of State regulations and the Environmental Rights Amendment to the State Constitution. Water resources considered herein include surface and groundwater, with an important connection being where groundwater discharges to surface water as springs or seeps.

WATER WITHDRAWALS

The process of drilling and fracking a natural gas (NG) well requires a large volume of water, with the vast majority being for the fracking process (Jiang et al. 2013; Haluszczak et al. 2013). Fracking involves pumping water with many chemicals and proppants (fracking fluid, or slickwater) into shale under high pressure in an attempt to break the shale and increase its permeability. The study which has examined the largest number of HF operations (Jiang et al. 2013) found an average of 20,000 m^3 (5.2 million gallons) per fracked well with an average 35% becoming flowback, which is about 1.8 mil gallons returning to the surface and needing to be treated (Jiang et al. 2013).

Obtaining that water may place a large demand on local water resources. Diversions either directly from streams or from groundwater closely connected to streams can decrease streamflow substantially. Small headwaters streams can be affected by even small withdrawals. Well pumpage for fracking water, could divert groundwater that supports springs and seeps that provide stream baseflow.

The Susquehanna River Basin Commission (SRBC) regulates freshwater withdrawals on land within the Susquehanna River basin. The SRBC requires the fracking company to maintain passby flows in the streams (SRBC 2002). Passby flow requirements help keep stream flow from dropping below critical flow rates which are based on the maintenance of a given amount of habitat. For coldwater streams in Pennsylvania with drainage area less than 100 square miles, the loss in habitat may be 5, 7.5, 10, or 15% for exceptional value, high quality, coldwater fishery class B, and CWF class C or D, respectively (SRBC 2002). Frequent diversions could increase the duration and frequency a stream flows at minimally sufficient flows. Allowing the flow to drop to a passby flow rate more frequently than occurs naturally disrupts the natural flow regime and generally decreases the habitat quality in the stream (Vannote et al. 1980).

Groundwater diversions are also subject to SRBC regulation and approval, but the SRBC method will not protect streamflow. The SRBC will require passby flows for groundwater withdrawals that "based on an analysis of the 120-day drawdown without recharge, impact streamflow, or for which a reversal of the hydraulic gradient adjacent to a stream (within the course of a 48-hour pumping test) is indicated" (SRBC 2002, p 2). Presumably this means that the groundwater diversion will be limited in the same way the surface water withdrawal is. This requirement is not protective because of lag time; it is not possible to know the flow as much as 120 days into the future so it is not possible to adequately curtail pumping.

CONTAMINANT TRANSPORT PATHWAYS

There are two primary pathways for contaminants to reach streams and springs –across the ground surface and through groundwater. The source of the leaks can be spills on the surface, the storage of fracking fluids in pits, leaks from the well, or leaks from the shale layer itself (Darrah et al. 2014). Spills on the surface can flow across the ground surface or through shallow groundwater into streams or springs. An excellent recent example of leaks from a surface pit recently occurred in Tioga County (http://www.pennlive.com/midstate/index.ssf/2014/10/dep_seeks_45m_fine_over_contam.html). Leaks from the well or directly from the target shale formation can flow along the well casing, through improperly abandoned wells, or through natural fracture/fault pathways to adjacent lands.

Setbacks from springs and streams can help protect those features by increasing the flow pathway length for a contaminant to reach the spring or stream. Pennsylvania has very small setback requirements, with the PA Department of Environmental Protection (PADEP) requiring just 200 feet from any drinking water supply and 100 feet from any stream or wetland greater than one acre in size, with waivers being available (Penn State University, 2011). The PA Department of Conservation and Natural Resources (PADCNR) requires setbacks from state parks, streams and wetlands to be just 600, 200, and 300 feet (PADCNR 2013, p 17). Waivers from the PADCNR setback requirements are easily obtained (PADCNR 2013, p 51). Of thirty-five waivers for gas wells, fifteen were for setbacks from wetlands because they claimed the wetlands were low quality and the waiver protected more valuable pristine forest. Overall, PADEP's and DCNR's setbacks from various features are insufficient to prevent spills from flowing to water sources either through surface or subsurface pathways or to prevent fracking from occurring directly beneath the water source.

Ground Surface Paths

Contamination can reach surface water near a gas well by flowing across the ground surface through small drainages to streams downhill from the source. The potential for spills or leaks to follow such a path is clear, but there is little specific research. In a substantial review paper concerning the impact of shale gas on regional water quality (Vidic et al. 2013), the authors cited just one report from grey literature (Considine et al. 2012) regarding spills and one journal article from the early 1980s regarding spills transporting through shallow groundwater (Harrison 1983).

As noted above, Pennsylvania requires very short setbacks for wells to be fracked from water supplies and streams. Spills during runoff events, a time that they would be more likely or at least likely to move existing contamination, would easily flow the short distance to streams. The effect they would have on those streams depends on the chemical and load that actually reaches the stream. Higher-order streams are at greatest risk because they are downstream of more potential sites.

Underground Paths

The most complex sources and transport pathways for contaminants from HF to reach shallow groundwater and surface water occur underground. At least three different substances released by HF can reach shallow groundwater – natural gas (either or both shallow biogenic and deep thermogenic gas), formation brine, and fracking fluid. These contaminants can follow pathways through natural faults and fractures, through abandoned wells or poorly constructed gas well, or a combination of both. This section presents gas and liquid transport separately because the pathways and timescales are different.

Natural Gas Pathways

Many studies have highlighted the increase in CH_4 concentration within one kilometer of fracked wells, with the CH_4 being identified as thermogenic (Darrah et al. 2014; Jackson et al. 2013; Osborn et al. 2011). Others have noted the presence of increased CH_4 in valley locations along faults and lineaments (Molofsky et al. 2013; Fountain and Jacobi 2000). Darrah et al. (2014) listed the following scenarios that can lead to higher methane concentrations in shallow groundwater:

(i) in situ microbial methane production;

(ii) natural in situ presence or tectonically driven migration over geological time of gas-rich brine from an underlying source formation or gas-bearing formation of intermediate depth (e.g., Lock Haven/Catskill Fm. Or Strawn Fm.);

(iii) exsolution of hydrocarbon gas already present in shallow aquifers following scenario 1 or 2, driven by vibrations or water level fluctuations from drilling activities;

(iv) leakage from the target or intermediate-depth formations through a poorly cemented well annulus;

(v) leakage from the target formation through faulty well casings (e.g., poorly joined or corroded casings);

(vi) migration of hydrocarbon gas from the target or overlying formations along natural deformation features (e.g., faults, joints, or fractures) or those initiated by drilling (e.g., faults or fractures created, reopened, or intersected by drilling or hydraulic fracturing activities);

(vii) migration of target or intermediate-depth gases through abandoned or legacy wells

Scenarios one and two are not anthropogenic, but fracking could enhance the second scenario (Gassiat et al. 2013; Myers 2012). Warner et al. (2012) and Llewellyn (2014) provide evidence for the type of brine movement discussed in scenario 2. Drilling or vibrations caused by fracking can release dissolved gas or change its transport through shallow groundwater so that it affects water wells.

The third scenario is a mechanism by which fracking releases gas into shallow groundwater through which it can flow significant distances. The fourth and fifth scenario describes the potential movement of gas from depth along the well, due to faulty construction, to shallow groundwater. The sixth scenario is the movement of gas from the target formation through natural pathways, such as faults or fractures, to shallow groundwater. Where there are abandoned wells, scenario 7 is an obvious potential scenario, although it includes transport through bedrock to the abandoned well. Regardless of the mechanism causing methane to reach shallow groundwater, either as dissolved or buoyant gas, it can flow to nearby wells, streams and springs.

Darrah et al. (2014) studied seven locations in Pennsylvania and one in Texas and found based on the amount of noble gases in the sample that scenario 6 is unlikely because the gases in the shallow groundwater did not resemble those that have followed a natural pathway from the shale to the shallow groundwater. The paper rules out transport of gas freshly liberated from the target shale through natural fractures because the diagnostic gas isotope ratios do not reflect the changes through fractionation that would occur as the gas migrates through the water-saturated crust. Their conclusion ignores the fact that transport from the well bore to shallow wells passes through Catskill sandstone in which most of the shallow wells were completed, which is up to 5600 feet thick (Taylor 1984). Their conclusion also ignores the fact that the gas would be transported through the same formations whether from depth, the layer of the shale, or for up to a kilometer through shallow aquifers which are similar bedrock types. Darrah et al.'s conclusions also require that the gas undergo the same transformation in weeks as gas would have undergone in millions of years of brine transport to shallow groundwater. Leaks from deep formations occurred at a storage facility in Tioga County reached shallow groundwater, which suggests the transport of gas through pathways not accepted by Darrah et al. (Breen et al. 2007).

Other studies have documented the rate at which gas released by HF can move through the groundwater. Gas tracers released during HF were found at production wells 750 feet away from the source within days (Hammock et al 2014). They also found evidence of gas migration to a sandstone layer 3000 feet above the Marcellus shale (Id., Figure 33). A model study based on conditions found at the southwest Pennsylvania site used in Hammock et al. estimated that gas can flow from a well bore leak through a sandstone rock matrix to a well 170 m away in times ranging from 89 days to 17 years depending on conditions (Zhang et al 2014). Darrah et al. (2014) found several gas wells within one kilometer of fracked wells that experienced large increases in gas concentration between annual sampling events which suggests that gas transport of up to a kilometer occurred in a time period of less than a year.

Additional evidence of gas movement along faults through the earth's crust to shallow groundwater may be seen through studies concerning CO_2 sequestration. Shipton et al. (2004) found that fluids (liquid and gas) can move vertically through low permeability faults, including those otherwise considered to be sealed with calcite. Critically, gas migration is extremely heterogeneous with large fluxes occurring through high-permeability pathways resulting in large gas loads hitting very small areas (Annunnziatellis et al. 2008). The distribution of methane seeping through a fault is much more variable than the distribution of either helium or carbon dioxide following the same general pathway (Annunziatellis et al. 2008). These authors described the extreme variability in gas flow as the "'spot' nature of gas migration along spatially restricted channels" (Annunziatelis et al. 2008, p 363). Even along a single fault, the flux is highly variable and intersecting joints or faults add variability in an additional direction. The spot nature of gas flow is probably responsible for highly variable readings in domestic water wells even in small areas and for the fact that the concentration in some wells may decrease while in others it remains steady or increases.

There is evidence that water wells near fault zones will likely have more gas occurrences naturally, but it is also clear that HF should increase the occurrence of gas in these areas. Drainages in Pennsylvania have more natural gas occurrences than other areas (Molofsky et al. 2013; Fountain and Jacobi 2000). Fountain and Jacobi (2000) mapped the presence of thermogenic NG in soils as a means of detecting underlying lineaments and fracture zones, based on the assumption of a fault/fracture connection between thermogenic gas sources and the surface. It is likely that anthropogenic gas, regardless of the source (the well bore or the source shale formation), can follow faults and fractures to shallow groundwater. If HF releases gas from shale and/or increases the connection between the shale and fracture zones, it seems likely that HF will be responsible for increasing gas in the streams underlain by fracture systems (Jackson et al. 2013; Osborn et al. 2011).

Drainages in northeast Pennsylvania likely coincide with fault/fracture zones, as described by Taylor (1984):

> Wells in higher topographic positions (hilltops and hillsides) have smaller yields than those in lower topographic positions (valley, gullies, and draws). Valleys and draws often form where the rocks are most susceptible to physical or chemical weathering. Hilltops are generally underlain by more resistant rocks. Lithologic variations and weaknesses in rocks caused by bedding partings, joints, cleavage, and faults promote rapid weathering and can produce low areas in the topography. These types of geologic features often occur in high-permeability zones which yield significant amounts of water to wells. (Taylor 1984, p 29).

First order streams are mostly in “higher topographic positions” and therefore may not be fault controlled. The general plan of these streams is more sinuous than higher-order fault-controlled streams. This observation suggests the pathway to first order streams would primarily be from leaks from the wellbore into shallow groundwater through which it transports to the stream.

The previous paragraphs describe the various pathways gas can flow from a fracked well to shallow groundwater, streams, and springs on nearby land. Whether the source is gas released directly from the shale or the well bore and whether the pathway is along a faulty well bore or natural fractures, these findings point to a significant risk that NG wells with HF significantly increase the risk for gas reaching shallow groundwater near stream channels. The chance probably increases for higher order streams in fault controlled valleys.

Most studies and monitoring of gas development impacts on surface water, either streams or springs, focus on contaminants easily carried through the water, such as geochemical indicators such as chloride or suspended sediment (Olmstead et al. 2014) or fracking fluids. It is common to ignore the presence of methane in streams. Methane does degas from surface water, but until sufficient mixing occurs to cause degassing, the methane causes the dissolved oxygen in the surface water to be low which would have severe aquatic effects. Essentially, methane discharges to streams increase the dissolved methane content of the stream thereby decreasing the dissolved oxygen content for areas near the methane source. This can lead to dead zones just as anything else that depletes oxygen.

Liquid Pathways

Formation brine has been documented to naturally flow from the Marcellus (Warner et al. 2012) or other deep Appalachian basins to shallow groundwater (Llewellyn 2014). The evidence is geochemical and isotopic, and both papers surmise fracture and fault connections to the surface. Both papers warn that this flow and these connections could allow more rapid brine flow or portend the movement of HF fluid to shallow groundwater due to increased pressure or enhanced connections due to fracking. While, no studies have documented pathways that HF fluid travel from the shale to shallow groundwater, the evidence for brine following such pathways suggests it is possible. Additionally, at least two published studies have documented HF fluid reaching drinking water wells (DiGiulio et al. 2011; EPA 1987) and similar circumstances have occurred elsewhere but settlements prevent disclosure of the facts.

Model studies for years have simulated the potential for deep brine to circulate to the surface naturally (Deming and Nunn 1991; Person and Baumgartner 1995) or in conjunction with deep waste or CO2 injection (Birkholzer and Zhou 2009)). The role of fractures to allow flow through shale layers has also been known for years, with Bredehoeft et al. (1983) finding that at a field scale, the vertical conductivity of shale is up to three orders of magnitude greater than the conductivity estimated from a column in a laboratory.

Recent model studies have estimated that fluids could flow from the Marcellus, or similar shale layers in similar sedimentary basins, to shallow aquifers naturally and that the flow could be enhanced by HF to occur in less than 10,000 years depending on assumed conditions (Chesnauw et al. 2013; Gassiat et al. 2013; Kissinger et al. 2013; Myers 2012). Most modelers found conditions that would allow transport of liquids to occur due to HF within a couple hundred years for some of the conditions they simulated. Myers (2012) found that transport from the Marcellus to shallow aquifers could occur over a period from 10 to more than a thousand years, depending on the conductivity assumed to result from fracking -- his model had the horizontal gas well intersecting a vertical fault connecting the shale to the near-surface. All of the models found the most rapid transport could occur through a vertical fault system. Gassiat et al. (2013) modeled a high permeability, continuous, 10-m wide fault zone from the shale to the shallow groundwater with HF simulated as a change in permeability over a 2-km long, 150-m thick zone. Kissinger et al. (2013) simulated a continuous 30-m thick vertical fault with a vertical head drop of up to 60 m to vertically drive a plume of HF fluid introduced into the lower aquifer. After 30 years under this scenario, simulated HF fluid had reached the shallow aquifer with the injected concentration reduced by a factor of 4000. Lateral migration of contaminants occurred at rates up to 25 m/y (Lange et al. 2013). Chesnauw et al. (2013) modeled flow along a fracture pathway between a target shale zone and surface aquifer in a two-dimensional framework, 3000-m long by 3000-m deep and 1 m thick. A key factor in all of the modeling studies is that they utilized generic stratigraphic and topographic cross-sections with idealized formation properties. Another key fact is that although they considered flow through a fault, they likely underestimated the potential for preferential flow through small but highly permeable fractures even within a preferential flow zone.

At least two studies (Engelder et al. 2014; Flewelling and Sharma 2013) have opined that brine and HF fluid cannot reach shallow aquifers for various reasons – stratigraphic barriers, lack of a driving force, the Marcellus is dry, imbibition removes HF fluid like a sponge, etc. Both studies have serious flaws including the fact that their “facts” are countered by many other studies in the literature. Flewelling and Sharma rely on arguments regarding permeability of the bulk formations and ignore the potential fault connections between the shale and the surface; they incorrectly claim that other studies (Myers 2012) rely on out-of-formation fracturing to provide a pathway all the way to shallow groundwater. The modeling studies cited above assume a fault connection to the top of the shale so that fracking fluid only must reach the top of the shale. Out-of-formation fractures that extend above the shale (Hammock et al. 2014; Fisher and Warpinski 2011) may short circuit the pathway making transport faster than simulated in any of the studies cited herein, but are not required for HF fluid to reach shallow groundwater. Flewelling and Sharma mistakenly assume the transport would have to be widespread across a large area when the reality is that brine migration, and transport of HF fluid, would focus flow to spatially restricted discharge zones, such as faults, that lead to springs or the shallow groundwater beneath valleys (Deming and Nunn 1991).

Engelder et al. (2014) make various arguments that are also not supported by the facts. The first is that potential transport depends on “single phase Darcy Law physics” which they claim is inappropriate when there is gas and water present; they are wrong because most of the gas occurs within the bulk matrix of the shale layers and most flow occurs in fractures and joints which are predominantly water. This may be seen even in the well log presented by Engelder et al. showing significant free water in a one-meter portion of the shale where the core likely crosses a significant fracture zone. The formations above and below the shale in the well log are also almost saturated. Transport above those zones would occur primarily through the fractures. Additionally, the large model scale employed by the models listed above renders multiphase flow considerations irrelevant, as argued for modeling CO2 sequestration as a single phase (Cihan et al. 2011).

The second is they claim that even if all of the salt in the Marcellus shale reached the shallow groundwater it would be so diluted as to be irrelevant. The fallacy in their argument is they assume the salt disperses evenly and instantaneously through shallow groundwater when reality is a high concentration flow would enter at a small fault zone intersecting the shallow aquifers, such as at Salt Springs State Park.

The third is they believe that all HF fluid not returning to the surface as flowback becomes imbibed in the shale. Imbibition is a process whereby liquid enters the micropores and becomes bound to the shale matrix, like water soaking into a sponge. Certainly, some fracking fluid becomes imbibed, so their argument might be correct if all HF fluid remains in the shale during fracking. However, much HF fluid leaves the shale during HF through out-of-formation fractures which extend as much as 1500 feet above the Marcellus shale (Hammock et al. 2014; Fisher and Warpinski 2011). Hammock et al. (2014) documented 10,286 microseismic events as much as 1900 feet above the shale from 56 HF stages for six Marcellus wells, including many events that extended above the Tully limestone, which had been considered a barrier to fracturing. The fractures do not extend to shallow groundwater, but they provide a pathway from the shale to much more permeable formations, including those that consist of sandstone or limestone. The new fractures also potentially connect with natural fractures. It simply cannot be argued, in light of such out-of-formation fracturing, that all HF fluid that does not flowback to the surface through the well remains within the shale.

Inherent in their argument is a claim that the Marcellus shale is essentially dry, which is incorrect unless one considers only the bulk matrix in which most of the methane is bound. As shown on the well log presented by Engelder et al., fracture zones with higher secondary permeability within the shale contain free water. If new fractures connect zones of secondary permeability that contain free water, fracking will have provided a pathway for Marcellus brine, the free water, to flow to the gas well, probably becoming dominant after the HF fluid remaining most closely near the well goes back up the well as flowback. Based on the rapid increase in concentrations of various constituents, including TDS, Cl, Br, Na, Ca, Sr, Ba, and Ra, in the flowback to levels several times that of seawater, Haluszczak et al. (2013) concluded the flowback was brine, not HF fluid that had dissolved rock minerals from the shale as claimed by Engelder et al. Kohl et al. (2014) use strontium isotope ratios found in flowback to isolate the source formation; the strontium signatures would not be as representative of the source formation if its presence was due only to high velocity dissolution during HF. Rowan et al. (in press, abstract, emphasis added) conclude that the "δ18O values and relationships between Na, Cl, and Br, provide evidence that the water produced after compositional stabilization is

natural formation water, whose salinity originated primarily from evaporatively concentrated paleoseawater".

It is clear therefore that scenario 2 (Darrah et al. 2014) facilitating the movement of brine from depth to shallow groundwater could also portend the movement of HF fluid or enhanced flow of brine due to fracking. The flow could occur much faster than occurs naturally for brine because of the increased permeability due to fracking, fracking fluid pushing brine from the shale, and the added pressure due to HF injection.

A groundwater flow pathway unique to headwaters regions is shallow transport from spills or leaks of surface storage. The distance from any point on a drainage basin to a first-order stream is short, on the order of a few hundred to perhaps a thousand feet. Shallow aquifers especially on ridges are thin (Taylor 1984) and the water table follows the topography. Thus, spills would move as interflow from the source to streams relatively quickly, on the order of days. The time estimate corresponds to the time expected for the runoff from a storm to begin to significantly decrease, which corresponds to the time for the entire drainage to be contributing flow.

Shale Gas Monitoring

Pennsylvania Program

The state recognizes that small streams regardless of land ownership can be impacted by management activities, therefore Pennsylvania has at least two programs for monitoring the effect that shale gas development has on streams. The PADEP monitors some streams for several parameters diagnostic of fracking activity (Vidic et al. 2013) and PADCNR monitors streams primarily within state forests and parks (PADCNR 2014b). Both monitoring efforts recognize that shale-gas development can release high salinity materials directly or indirectly into streams (Vidic et al. 2013, PADCNR 2014b, p 110). PADEP focuses on strontium, barium, and bromide. The following paragraphs provide some critique of the PADCNR plan and its implementation to date and the following subsection outlines what monitoring should include.

Surface water sample locations were established at widespread locations throughout the shale-gas region (PADCNR 2014b, p 111). In 2011, 345 such points were established based on their proximity to existing or planned shale-gas pads (Id.). Fig. 6-5 shows the points being mostly grouped around leased tracts, with some being far from the leases, possibly for baseline surveying. Monthly sample analysis includes specific conductance, pH, TDS, TSS, bromide, chloride, barium, and strontium. Strontium has been found in other studies to be an excellent indicator of Marcellus brine in the flowback (Haluszczak et al. 2013). Semi-annual analysis includes additional metals, nutrients, and organic compounds (PADCNR 2014b, p 121). Some continuous sampling includes temperature and EC, which the report suggests can detect the influx of flowback water which often has very high TDS (PADCNR 2014b, p 122).

PADCNR's sampling of surface water is based on random locations rather than on a consideration of pathways for contaminants to reach the streams; for surface pathways they could have identified drainages from potential well sites to the streams and for groundwater pathways there could be more sampling in streams in fault-controlled drainages. The groundwater pathway to low-order streams could be from wells upgradient of the stream or from leaks in or near the surface aquifer flowing through that aquifer to the stream rather than following deep faults and fractures.

Random sampling as utilized by PADCNR would detect contamination due to fracking only by chance – if one or more sites were on a transport pathway. Random sampling is useful only for selecting sites or observations from a given population. The key is in the definition of a population, which here should be sites that lie on a potential pathway because sites away from pathways are very unlikely to become contaminated

Also, PADCNR (2014b) does not include plans to monitor groundwater, so there is no attempt to detect a contaminant plume on its way to a stream. They are also monitoring a few sites, based on stream order, with pebble counts to detect shifts in substrate due to sedimentation; this would link to all types of land management, including logging and road building, not associated with gas development. Finally, they also describe some simple longitudinal stream chemistry monitoring, with sampling done at the mouth and upstream to the headwaters at every significant inflow; this type of sampling can be used to identify the source of a contaminant or it can locate the source of groundwater inflow or losing reaches.

CONCLUSION

Contaminants released by fracking can flow from the fracking sites through groundwater or surface water to adjacent lands and water.

- Fracking can release contaminants, gas, fracking fluid, or brine, to flow upward toward the shallow groundwater and springs and streams. Transport along this pathway may occur quickly, meaning less than a year, or could require decades or more and last for centuries.
- Ground surface spills will allow fracking fluid, flowback, or produced water (brine) to flow to and pollute nearby small streams or collectively to larger streams downstream.
- Well bore leaks will allow fracking fluid or gas to flow through fractures and porous aquifers to shallow groundwater.

- The fracking process will cause gas pockets separate from the target shale to be mobilized and flow onto shallow groundwater and streams.

Monitoring will not prevent damages, and current monitoring is not sufficient to assess damages when they occur.

REFERENCES

Annunziatellis A, Beaubien SE, Bigi S, Ciotoli G, Coltella M, Lombardi S(2008) Gas migration along fault systems and through the vados zone in Latera caldera (central Italy): Implications for CO2 geological storage. Int J Greenh Gas Contr 2:353-372. Doi:10.1016/j.ijggc.2008.02.003

Birkholzer JT, Q Zhou (2009) Basin-scale hydrologic impacts of CO2 storage: Regulatory and capacity implications. Int J Grnhs Gas Control

Bredehoeft JD, CE Neuzil, PCD Milly (1983) Regional Flow in the Dakota Aquifer: A Study of the Role of Confining Layers, U.S. Geological Survey Water-Supply Paper 2237.

Breen KJ, K Revesz, FH Baldassare, SD McAuley (2007) Natural gases in ground water near Tioga Junction, Tioga County, North-Central Pennsylvania – Occurrence and of isotopes to determine origin, 2005. US Geological Survey Scientific Investigations Report 2007-5085. 65 p.

Cai Z, Ofterdinger U (2014) Numerical assessment of potential impacts of hydraulically fractured Bowland Shale on overlying aquifers. Wat Resour Res doi:10.1002/2013WR014943

Chesnaux R, dal Soglio L, Wendling G (2013) Modelling the impacts of shale gas extraction on groundwater and surface water resources. Presented at GEOMontreal 2013, September 29 – October 3, 2013, Montreal, Quebec

Cihan A, Birkholzer JT, Zhou Q (2013) Pressure buildup and brine migration during CO2 storage in multilayered aquifers. Groundwater 51(2):252-267, doi: 10.1111/j.1745-6584.2012.00972.x.

Considine TJ, Watson RW, Considine NB, Martin JP (2013) Environmental regulation and compliance of Marcellus shale gas drilling. Environ Geosci 20:1-16

Darrah, T.H, A Vengosh, R.B. Jackson, N.R. Warner, and R.J.Poreda. 2014. Nobel gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. PNAS Early Edition. Doi:10;.1073/pnas.1322107111.

Deming D, Nunn JA (1991) Numerical simulations of brine migration by topographically driven recharge. Journal of Geophysical Research 96(B2):2485-2499.

DiGiulio, D. C., R. T. Wilkin, C. Miller, and G. Oberly (2011), DRAFT: Investigation of Ground Water Contamination near Pavillion, Wyoming, U.S. Environmental Prodection Agency, Office of Research and Development.

Engelder T, Cathles LM, Bryndzia LT (2014) The fate of residual treatment water in gas shale. J Unconventional Oil and Gas Resources 7:33-48

Fisher K, Warpinski N (2011) Hydraulic fracture-height growth: real data. Paper SPE presented at the Annual Technical Conference and Exhibition, Denver, Colorado. DOI:10.2118/145949 – MS.

Flewelling SA, Sharma M (2013) Constraints on upward migration of hydraulic fracturing fluid and brine. Groundwater, doi:10.1111/gwat.12095.

Fountain JC, Jacobi RD (2000) Detection of buried faults and fractures using soil gas analysis. Environ Eng Geosci 6(3):201-208

Gassiat CT, Gleeson T, Lefebvre R, McKenzie J (2013) Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential contamination of shallow aquifers over long time scales. Wat Resour Res 49:8310-8327, doi:10.1002/2013WR014287.

Haluszczak LO, Rose AW, Kump LR (2012) Geochemical evaluation of flowback brine from Marcellus gas wells in Pennsylvania, USA. Appl Geochem 28: 55-61

Hammack, R., W. Harbert, S. Sharma, B. Stewart, R. Capo, A. Wall, A. Wells, R Diehl, D. Blaushild, J. Sams, and G. Veloski. 2014. An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania, NETL-TRS-3-2014, EPAct Technical Report Series. U.S. Department of Energy, National Energy Technology Laboratory. Pittsburgh, PA. 76 p.

Harrison SS (1983) Evaluating system for ground-water contamination hazards due to gas-well drilling on the glaciated Appalachian Plateau. Ground Water 21(6):689-701

Jackson RB, Vengosh A, Darrah TH, Warner NR, Down A, Poreda RJ, Osborn SG, ZhaoK, Karr JD (2013) Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proc Natl Acad Sci, USA 110(28):11250-11255

Jiang M, CT Hendrickson, JM VanBriesen (2013) Life cycle water consumption and wastewater generation impacts of a Marcellus shale gas well. Environ Sci Technol 48:1911-1920, doi 10.1021/es4047654.

Kissinger A, Helmig R, Ebigbo A, Class H, Lange T, Sauter M, Heitfeld M, Klunker J (2013) Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system, part 2. Env Earth Sci, doi 10.1007/s12665-013-2578-6

Kohl CAK, RC Capo, BWStewart, AJ Wall, KT Schroeder, RW Hammack, GD Guthrie (in press) Strontium isotopes test long-term zonal isolation of injected and Marcellus formations water after hydraulic fracturing. Environ Sci Technol doi/10.1021/es501099k

Lange T, Sauter M, Heitfeld M, Schetelig K, Brosig K, Jahnke W, Kissinger A, Helmig R, Ebigbo A, Class H (2013) Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system part 1. Environ Earth Sci DOI 10.1007/s12665-013-2803-3.

Llewellyn GT (2014) Evidence and mechanisms for Appalachian Basin brine migration into shallow aquifers in NE Pennsylvania, USA. Hydrog J DOI 10.1007/s10040-014-1125-1

Molofsky LJ, Connor JA, Wylie AS, Wagner T, Farhat SK (2013) Evaluation of methane sources in groundwater in northeastern Pennsylvania. Groundwater 51(3):333-349, Doi:10.1111/gwat.12056

Myers T (2012) Potential contaminant pathways from hydraulically fractured shale to aquifers. Ground Water 50(6): 872-882 doi: 10.1111/j.1745-6584.2012.00933.x

Olmstead SM, Muehlenbachs LA, Shih J,Chu Z, Krupnick AJ (2013) Shale gas development impacts on surface water quality in Pennsylvania. Proc Natl Acad Sci, USA 110(13):4962-4967

Osborn SG, Vengosh A, Warner NR, Jackson RB (2011a) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Natl Acad Sci, USA 108:8172-8176

Pennsylvania Department of Conservation and Natural Resources (PADCNR) (2014a) Natural Gas Development and State Forests, Shale Gas Leasing Statistics, June 2014.

Pennsylvania Department of Conservation and Natural Resources (PADCNR) (2014b) Shale-gas Monitoring Report. http://dcnr.state.pa.us/forestry/NaturalGas/monitoringreport/index.htm

Pennsylvania Department of Conservation and Natural Resources (PADCNR) (2013) Guidelines For Administering Oil and Gas Activity on State Forest Lands. Revised 2013.

Pennsylvania Department of Conservation and Natural Resources (PADCNR) (undated) Non-Surface Disturbance Leasing of DCNR Lands, Fact Sheet.

Penn State University (2011) Penn State Extension: Marcellus Shale Gas Well Drilling: Regulations to Protect Water Supplies in Pennsylvania

Person M, L Baumgartner (1995) New evidence for long-distance fluid migration within the Earth's crust. Reviews of Geophysics, Supplement p 1083-1091.

Rowan EL, MA Engle, TI Kraemer, KT Schroeder, RW Hammack, MW Doughten (in press) Geomechanical and isotopic evolution of water produced from Middle Devonian Marcellus Shale gase wells, Appalachian Basin, Pennsylvania. AAPG Bulletin, doi: 10.1306/07071413146.

Shipton ZK, JP Evans, D Kirchner, PT Kolesar, AP Williams, J Heath (2004) Analysis of CO2 leakage through "low-permeability" faults from natural reservoirs in the Colorado Plateau, southern Utah. In: Baines, SJ, RH Worden (eds.) *Geologic Storage of Carbon Dioxide*. Geological Society, London, Special Publications 233, 43-58.

Shosky, D.J., 1987. What is an adequate screen length for monitoring wells? Opinion II. Ground Water Monitoring Review 7(1):97-101.

Susquehanna River Basin Commission (SRBC) (2002) Policy No. 2003-01, Guidelines for Using and Determining Passby Flows and Conservation Releases for Surface-Water and Ground-Water Withdrawal Approvals, November 8, 2002.

Taylor LE (1984) Groundwater Resources of the Upper Susquehanna River Basin, Pennsylvania. Pennsylvania Geological Survey, Harrisburg PA.

Thyne, G. 2008. *Review of Phase II Hydrogeologic Study*. Prepared for Garfield County, Colorado. 26 p.

U.S. Environmental Protection Agency (EPA) (1987) Report to Congress: Management of wastes from the exploration, development, and production of crude oil, natural gas, and geothermal energy, U.S. Environmental Protection Agency, Washington, DC.

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE (1980) The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37(1):130-137. Doil 10.1139/f80-017.

Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD (2013) Impact of shale gas development on regional water quality. Science 340, 1235009 (2013). DOI: 10.1126/science.1235009

Warner NR, Jackson RB, Darrah TH, Osborn SG, Down A, K. Zhao, A. White, A. Vengosh. 2012a. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of Sciences pnas.1121181109

Zhang, L., N. Anderson, R. Dilmore, D.J. Soeder, and G. Bromhal. 2014. Leakage detection of Marcellus shale natural gas at an upper Devonian gas monitoring well: A 3-D numerical modeling approach. Environmental Science and Technology 48:10795-10803, doi:10.1021/es501997p.