Risks of Shale Gas Exploration and Hydraulic Fracturing to Water Resources in the United States

Avner Vengosh, Robert B. Jackson, Nathaniel Warner, Thomas H. Darrah

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Duke University

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Short term

- Stray gas contamination;
- Surface water contamination via disposal of inadequately treated wastewater;
- Spills;

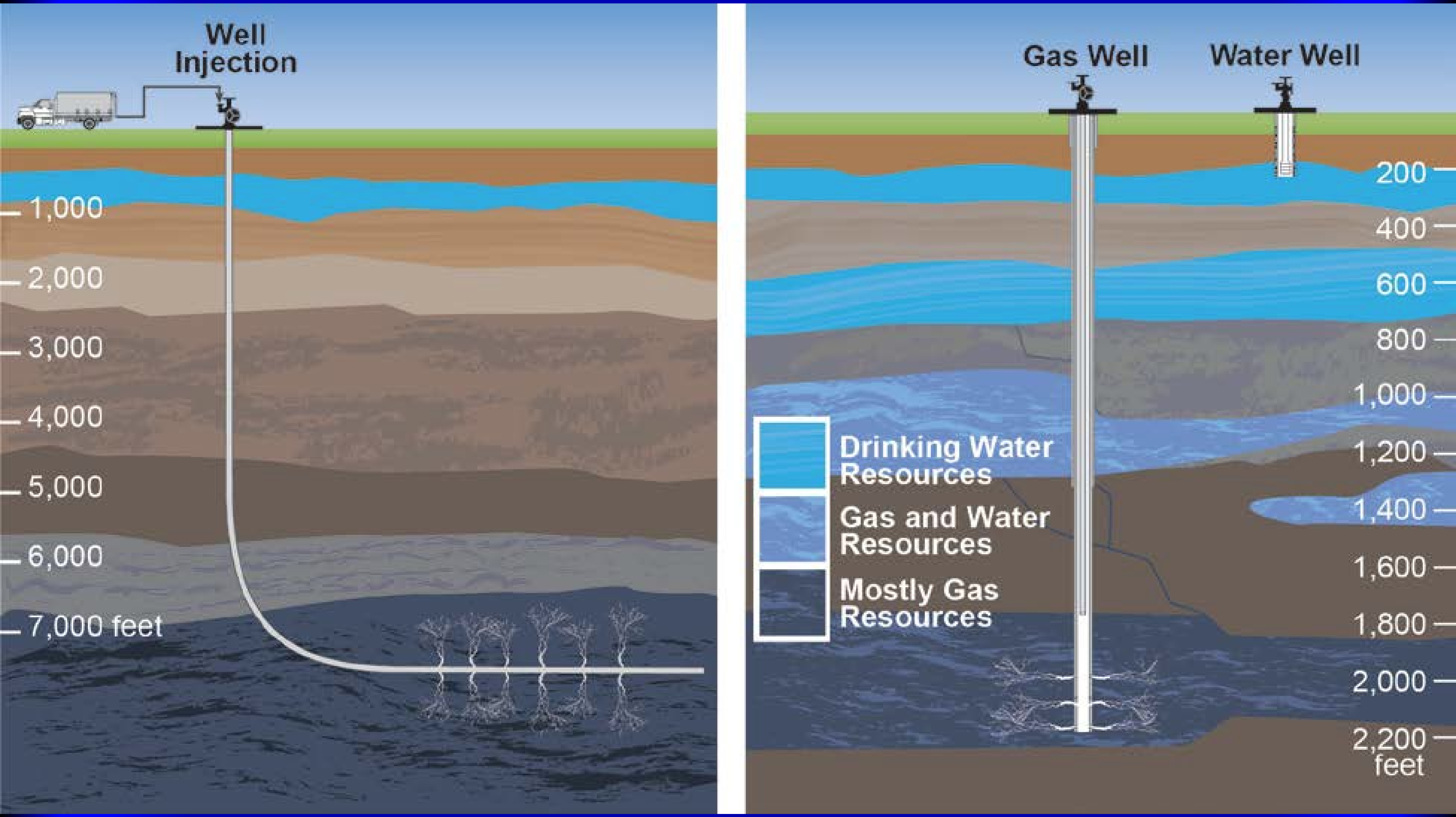
Long term

- Water availability in water scarce areas;
- Groundwater contamination through natural fracture networks;
- Groundwater contamination through abandoned and improperly sealed conventional oil and gas wells;
- Accumulation of residual contaminants and radiation in areas of wastewater disposal and spills;

Stray gas contamination

The risks:

- Occurrence of elevated levels of methane and in shallow drinking water wells can pose a potential flammability or explosion hazard to homes near shale gas drilling sites;
- Shut-down of private drinking water wells, need for alternative water resources;
- Houses and property devaluation;



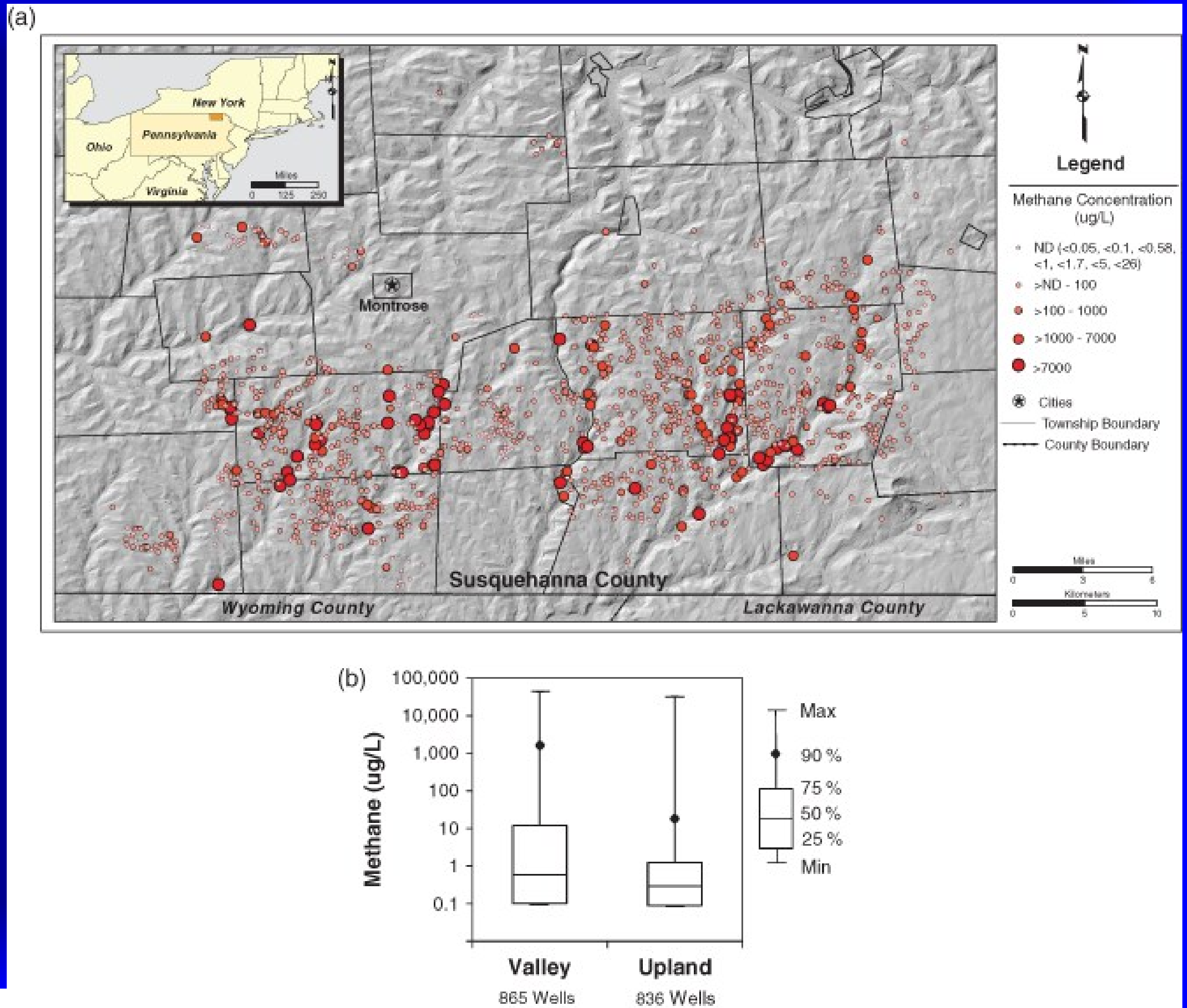
Source: EPA Progress Report 2012

The debate on stray gas contamination

No risk:
Methane is ubiquitous in groundwater, with higher concentrations observed in valleys vs. upland; methane concentrations are best correlated to topographic and hydrogeologic features, rather than shale-gas extraction (Molofsky et al., 2013).

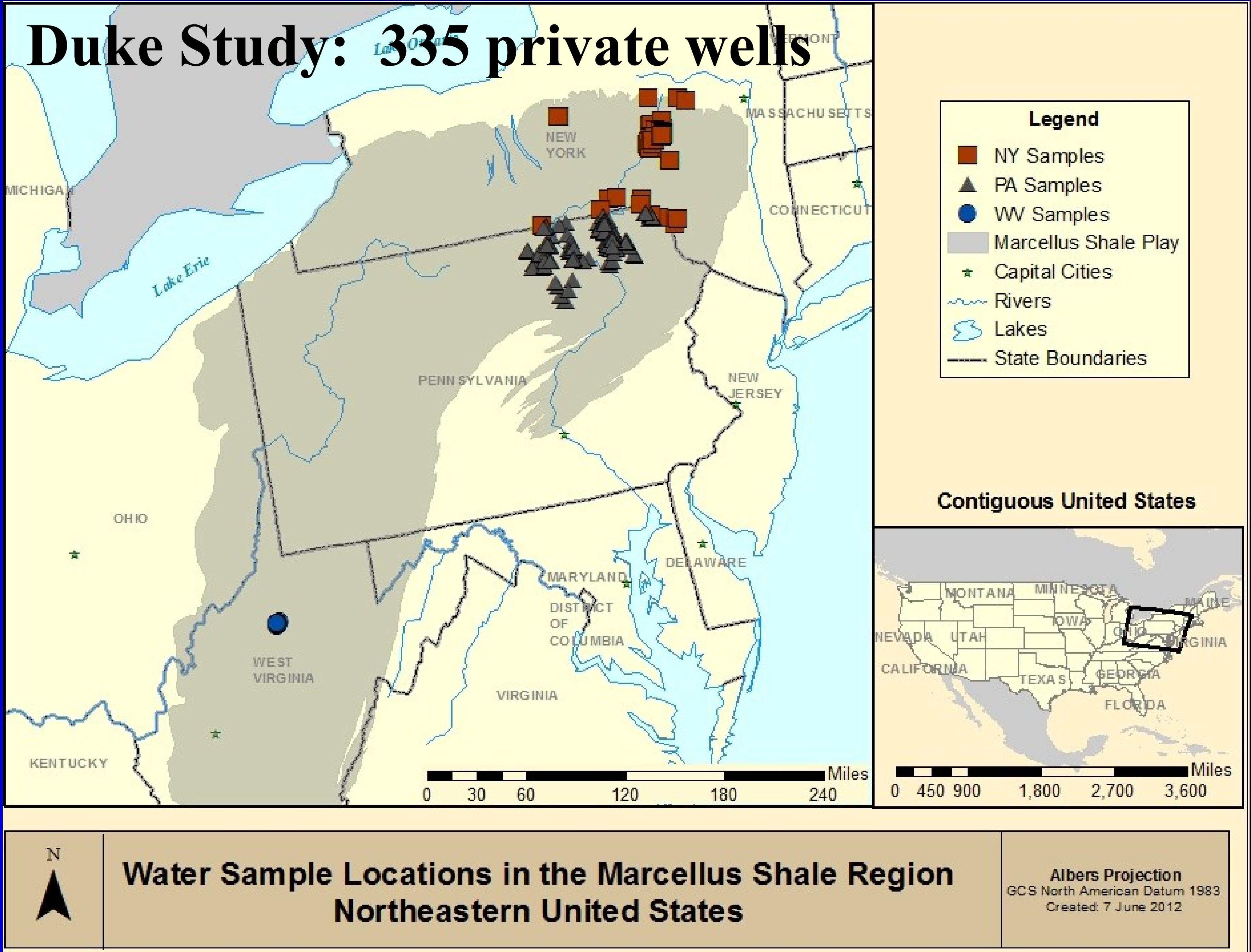
High risk in a subset of wells near shale gas sites :
Evidence for stray gas contamination in a subset of wells less than a km from shale gas sites in northeastern PA (Osborn et al., 2011; Darrah et al., 2012).

Methane is ubiquitous in PA groundwater



Molofsky et al., 2013; *Groundwater*, 3 333–349

Duke Study: 335 private wells



Proceedings of National Academy of Sciences, May 17, 2011

Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing

Stephen G. Osborn[a], Avner Vengosh[b], Nathaniel R. Warner[b], and Robert B. Jackson[a,b,c,1]

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Edited* by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved April 14, 2011 (received for review January 13, 2011)

Directional drilling and hydraulic-fracturing technologies are dramatically increasing natural-gas extraction. In aquifers overlying the Marcellus and Utica shale formations of northeastern Pennsylvania and upstate New York, we document systematic evidence for methane contamination of drinking water associated with shale-gas extraction. In active gas-extraction areas (one or more gas wells within 1 km), average and maximum methane concentrations in drinking-water wells increased with proximity to the nearest gas well and were 19.2 and 64 mg CH_4 L^{-1} ($n = 26$), a potential explosion hazard; in contrast, dissolved methane samples in neighboring nonextraction sites (no gas wells within 1 km) within similar geologic formations and hydrogeologic regimes averaged only 1.1 mg L^{-1} ($P < 0.05$; $n = 34$). Average $\delta^{13}C$-CH_4 values of dissolved methane in shallow groundwater were significantly less negative for active than for nonactive sites ($-37 \pm 7‰$ and $-54 \pm 11‰$, respectively; $P < 0.0001$). These $\delta^{13}C$-CH_4 data, coupled with the ratios of methane-to-higher-chain hydrocarbons, and $\delta^{2}H$-CH_4 values, are consistent with deeper thermogenic methane sources such as the Marcellus and Utica shales at the active sites and matched gas geochemistry from gas wells nearby. In contrast, lower-concentration samples from shallow groundwater at nonactive sites had isotopic signatures reflecting a more biogenic or mixed biogenic/thermogenic methane source. We found no evidence for contamination of drinking-water samples with deep saline brines or fracturing fluids. We conclude that greater stewardship, data, and—possibly—regulation are needed to ensure the sustainable future of shale-gas extraction and to improve public confidence in its use.

groundwater | organic-rich shale | isotopes | formation waters | water chemistry

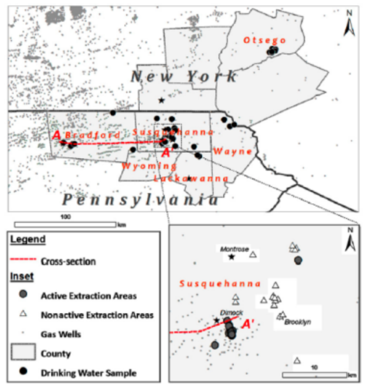

Fig. 1. Map of drilling operations and well-water sampling locations in Pennsylvania and New York. The star represents the location of Binghamton, New York. (*Inset*) A close-up in Susquehanna County, Pennsylvania, showing areas of active (closed circles) or nonactive (open triangles) extraction. A drinking-water well is classified as being in an active extraction area if a gas well is within 1 km (see *Methods*). Note that drilling has already spread to the area around Brooklyn, Pennsylvania, primarily a nonactive location at the time of our sampling (see inset). The stars in the inset represent the towns of Dimock, Brooklyn, and Montrose, Pennsylvania.

Increases in natural-gas extraction are being driven by rising energy demands, mandates for cleaner burning fuels, and the economics of energy use (1–5). Directional drilling and hydraulic-fracturing technologies are allowing expanded natural-gas extraction from organic-rich shales in the United States and elsewhere (2, 3). Accompanying the benefits of such extraction (6, 7) are public concerns about drinking-water contamination from drilling and hydraulic fracturing that are ubiquitous but lack a strong scientific foundation. In this paper, we evaluate the potential impacts associated with gas-well drilling and fracturing on shallow groundwater systems of the Catskill and Lockhaven formations that overlie the Marcellus Shale in Pennsylvania and the Genesee Group that overlies the Utica Shale in New York (Figs. 1 and 2 and Fig. S1). Our results show evidence for methane contamination of shallow drinking-water systems in at least three areas of the region and suggest important environmental risks accompanying shale-gas exploration worldwide.

The drilling of organic-rich shales, typically of Upper Devonian to Ordovician age, in Pennsylvania, New York, and elsewhere in the Appalachian Basin is spreading rapidly, raising concerns for impacts on water resources (8, 9). In Susquehanna County, Pennsylvania alone, approved gas-well permits in the Marcellus formation increased 27-fold from 2007 to 2009 (10).

Concerns for impacts to groundwater resources are based on (*i*) fluid (water and gas) flow and discharge to shallow aquifers due to the high pressure of the injected fracturing fluids in the gas wells (10); (*ii*) the toxicity and radioactivity of produced water from a mixture of fracturing fluids and deep saline formation waters that may discharge to the environment (11); (*iii*) the potential explosion and asphyxiation hazard of natural gas; and (*iv*) the large number of private wells in rural areas that rely on shallow groundwater for household and agricultural use—up to one million wells in Pennsylvania alone—that are typically unregulated and untested (8, 9, 12). In this study, we analyzed groundwater from 68 private water wells from 36- to 190-m deep in

Author contributions: S.G.O., A.V., and R.B.J. designed research; S.G.O. and N.R.W. performed research; A.V. contributed new reagents/analytic tools; S.G.O., A.V., N.R.W., and R.B.J. analyzed data; and S.G.O., A.V., N.R.W., and R.B.J. wrote the paper.

The authors declare no conflict of interest.

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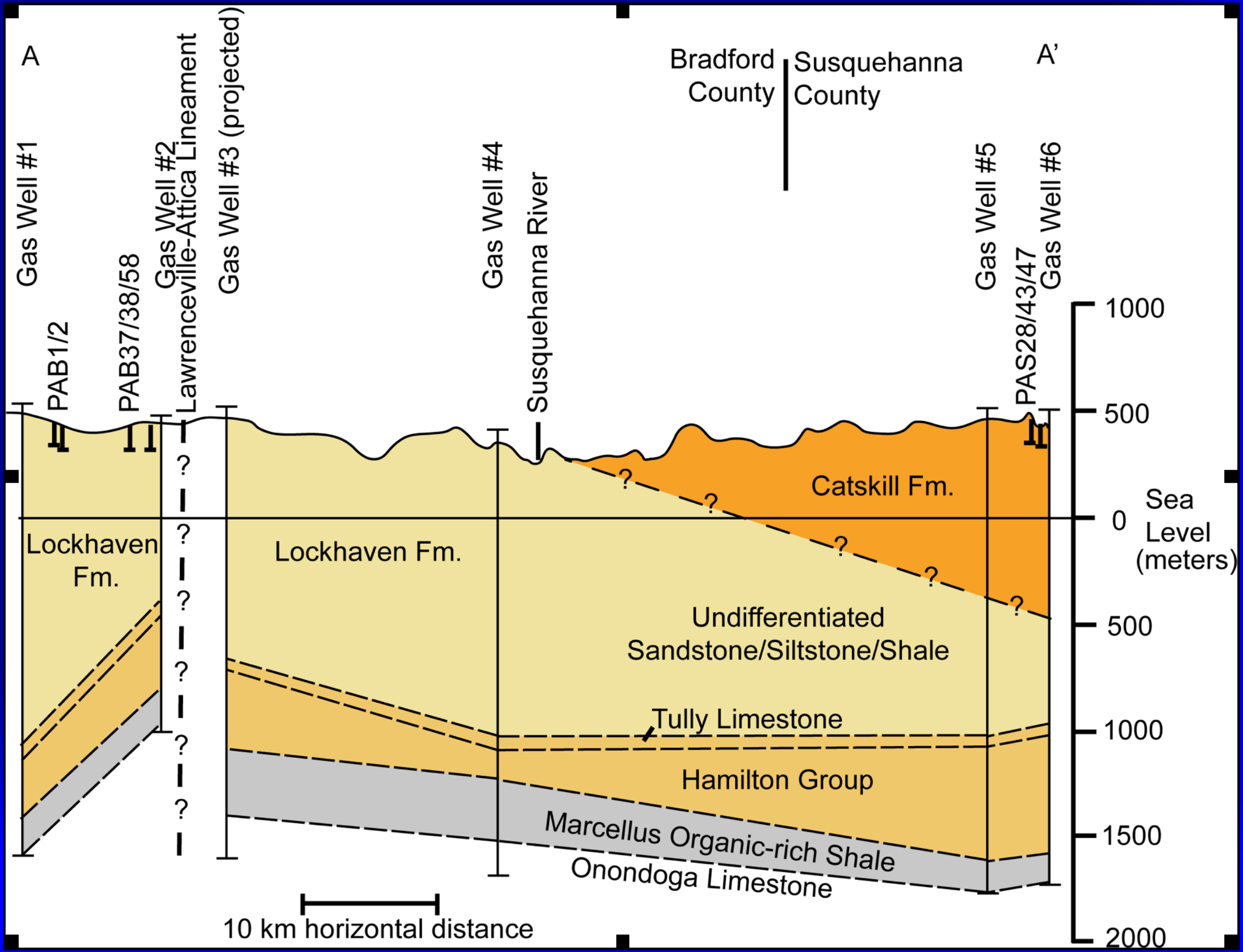
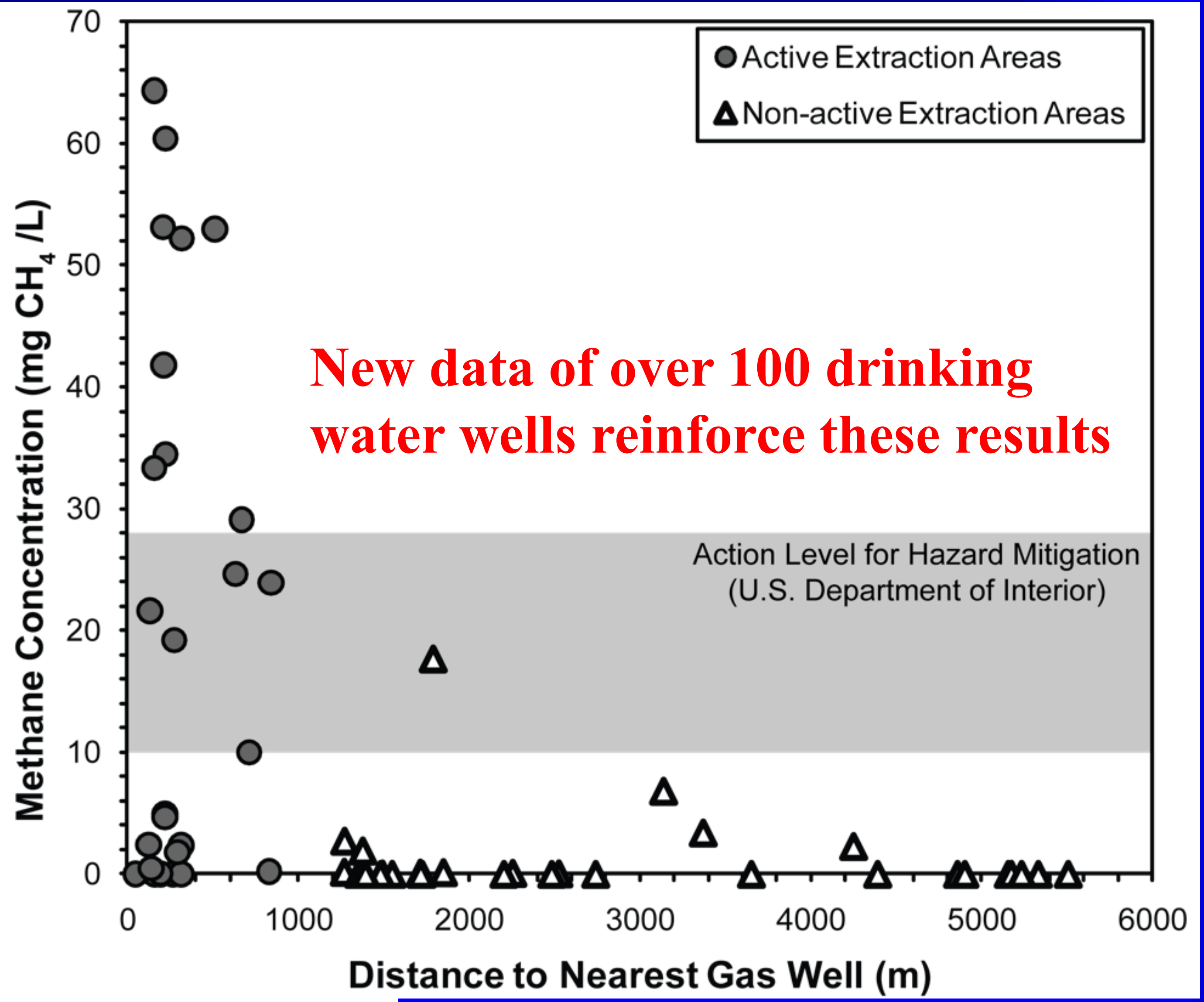
Hydro-geological cross section



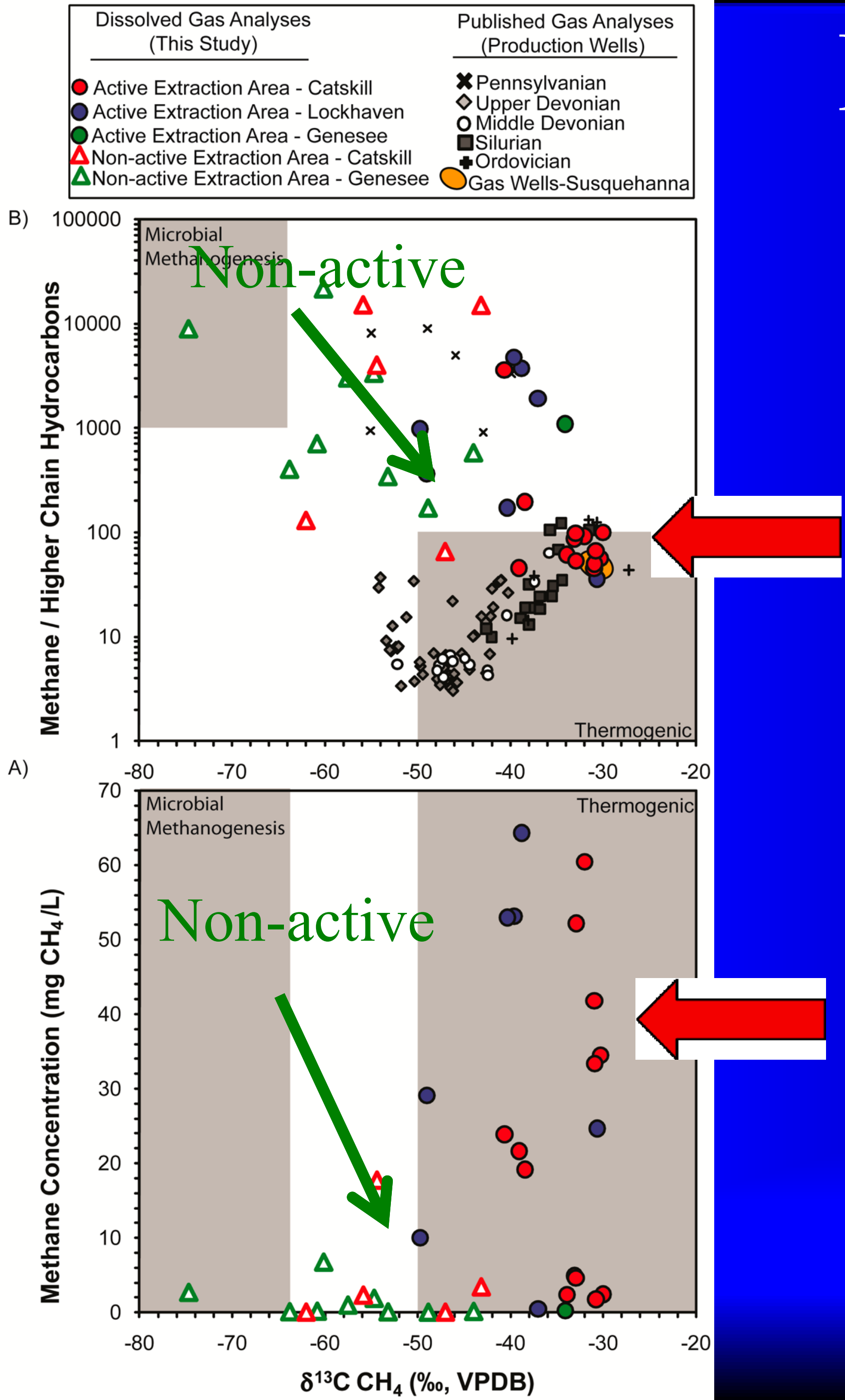
Definition of active versus non-active wells:

Private wells located <1km from a shale gas had typically higher methane



(Osborn et al., 2011; *PNAS*, 108,8172-8176)

Methane sources?



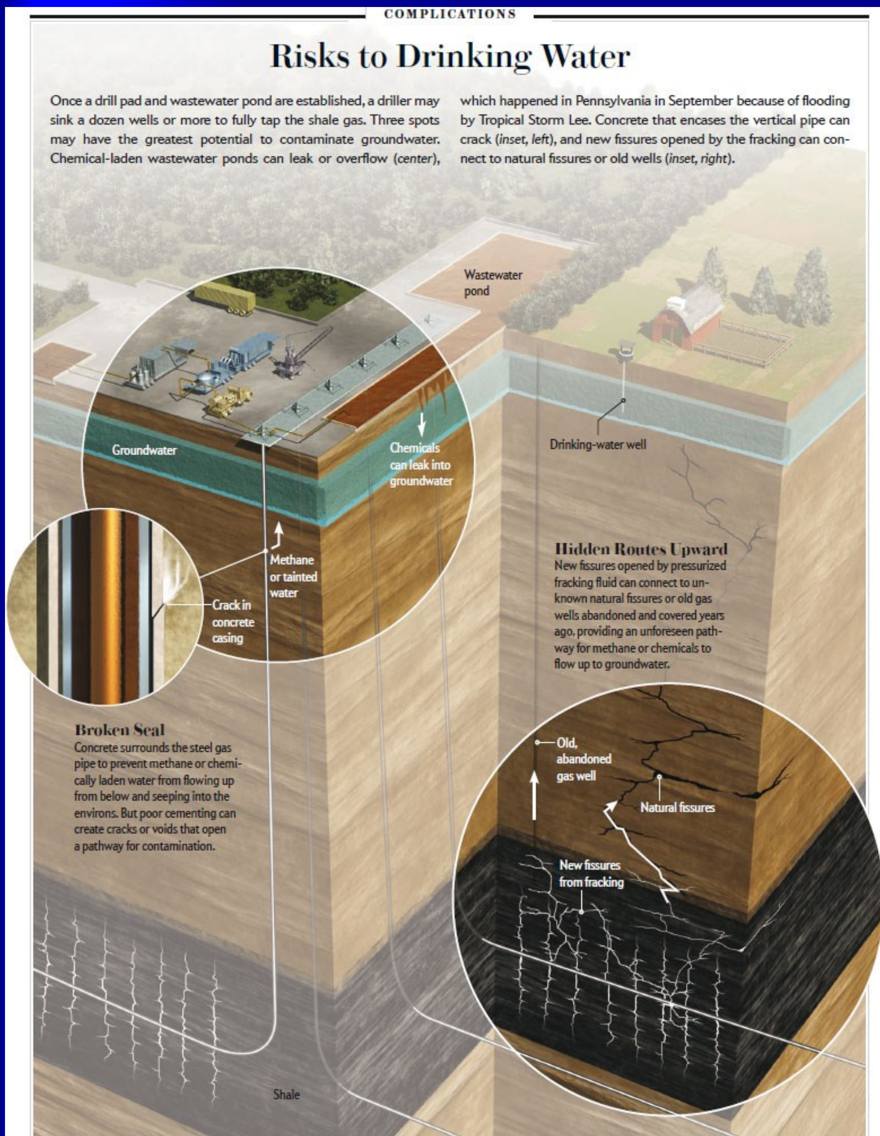
Active

Active

A distinction between active wells with a thermogenic isotopic fingerprint and non-active wells with a mixed composition

(Osborn et al., 2011; *PNAS*, 108,8172-8176)

Possible mechanisms for leakage of stay gas to water resources


COMPLICATIONS

Risks to Drinking Water

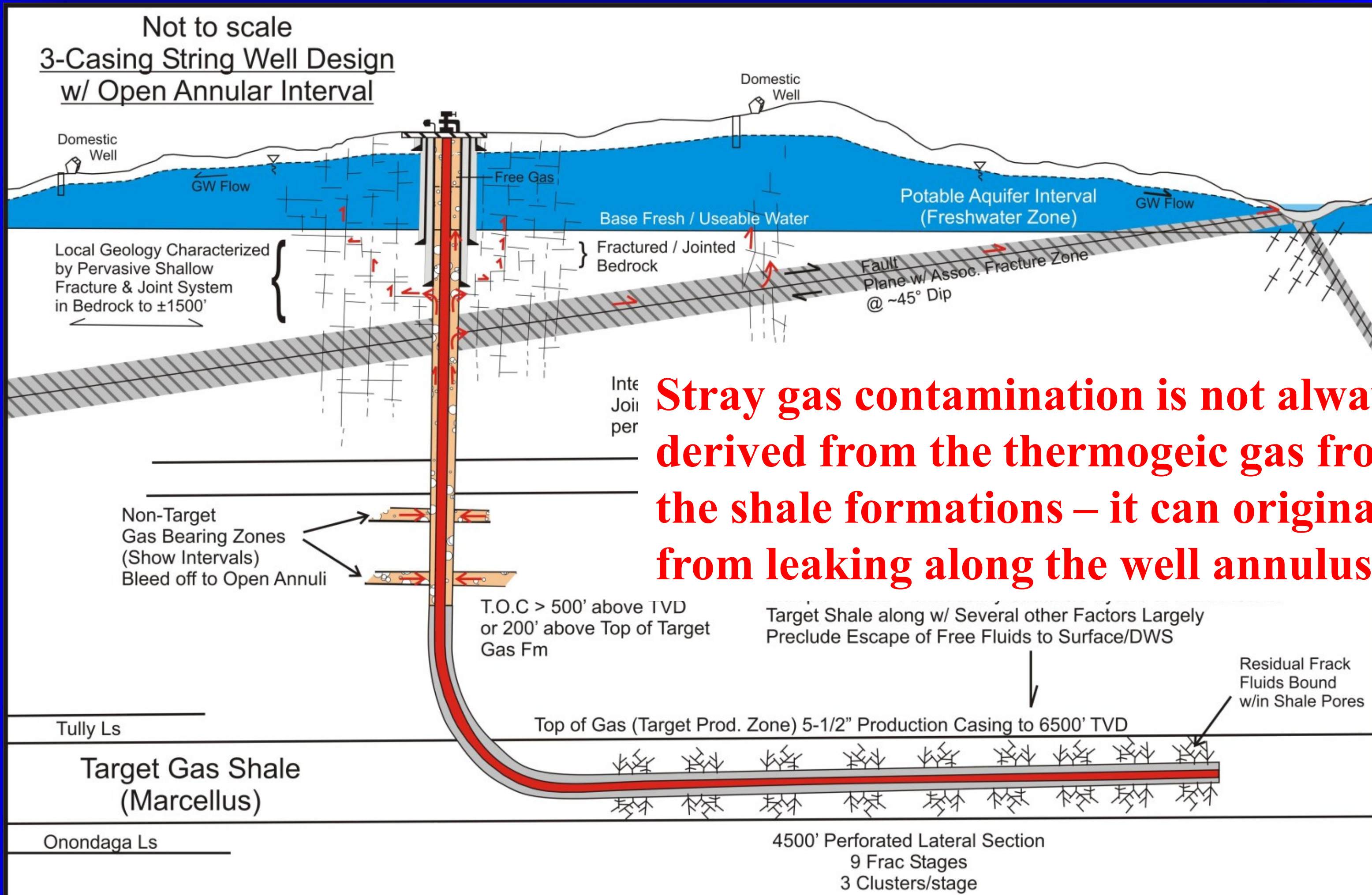
Once a drill pad and wastewater pond are established, a driller may sink a dozen wells or more to fully tap the shale gas. Three spots may have the greatest potential to contaminate groundwater. Chemical-laden wastewater ponds can leak or overflow (*center*), which happened in Pennsylvania in September because of flooding by Tropical Storm Lee. Concrete that encases the vertical pipe can crack (*inset, left*), and new fissures opened by the fracking can connect to natural fissures or old wells (*inset, right*).

Hidden Routes Upward
New fissures opened by pressurized fracking fluid can connect to unknown natural fissures or old gas wells abandoned and covered years ago, providing an unforeseen pathway for methane or chemicals to flow up to groundwater.

Broken Seal
Concrete surrounds the steel gas pipe to prevent methane or chemically laden water from flowing up from below and seeping into the environs. But poor cementing can create cracks or voids that open a pathway for contamination.

Figure from Scientific American Magazine, Nov 2011

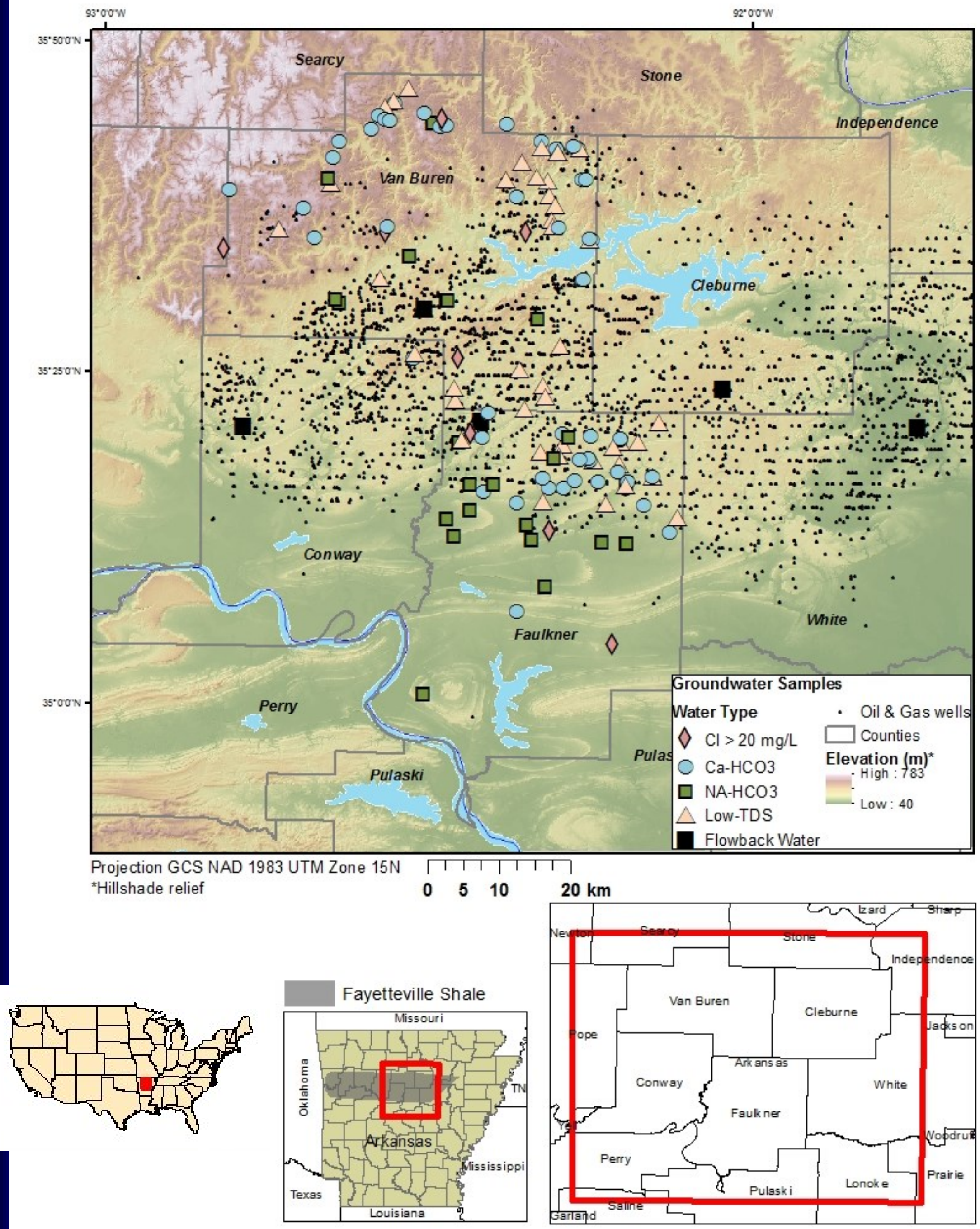
Possible mechanisms for leakage of stay gas to water resources



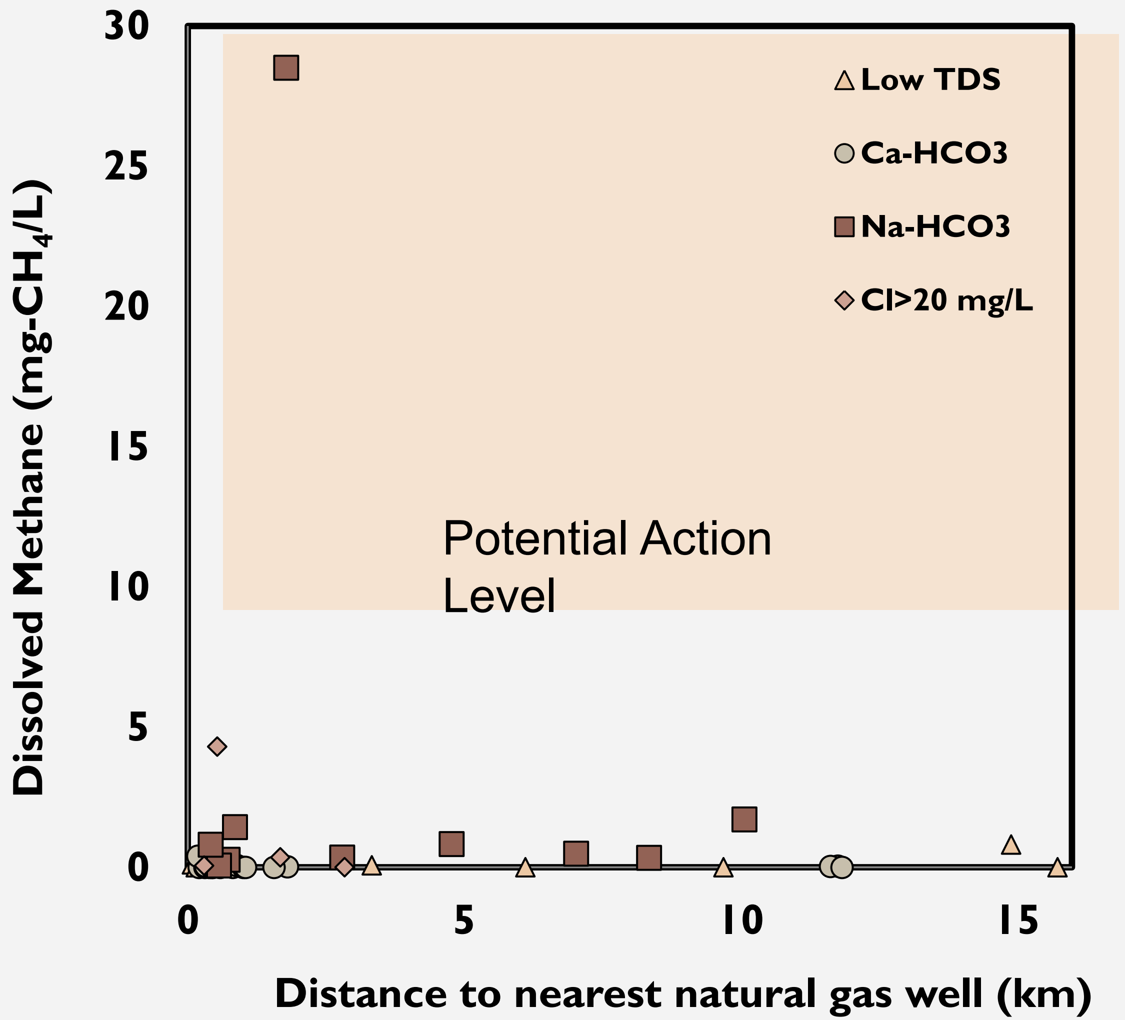
Stray gas contamination is not always derived from the thermogeic gas from the shale formations – it can originated from leaking along the well annulus

From Penoyer, (2011), Natural Resource Stewardship & Science

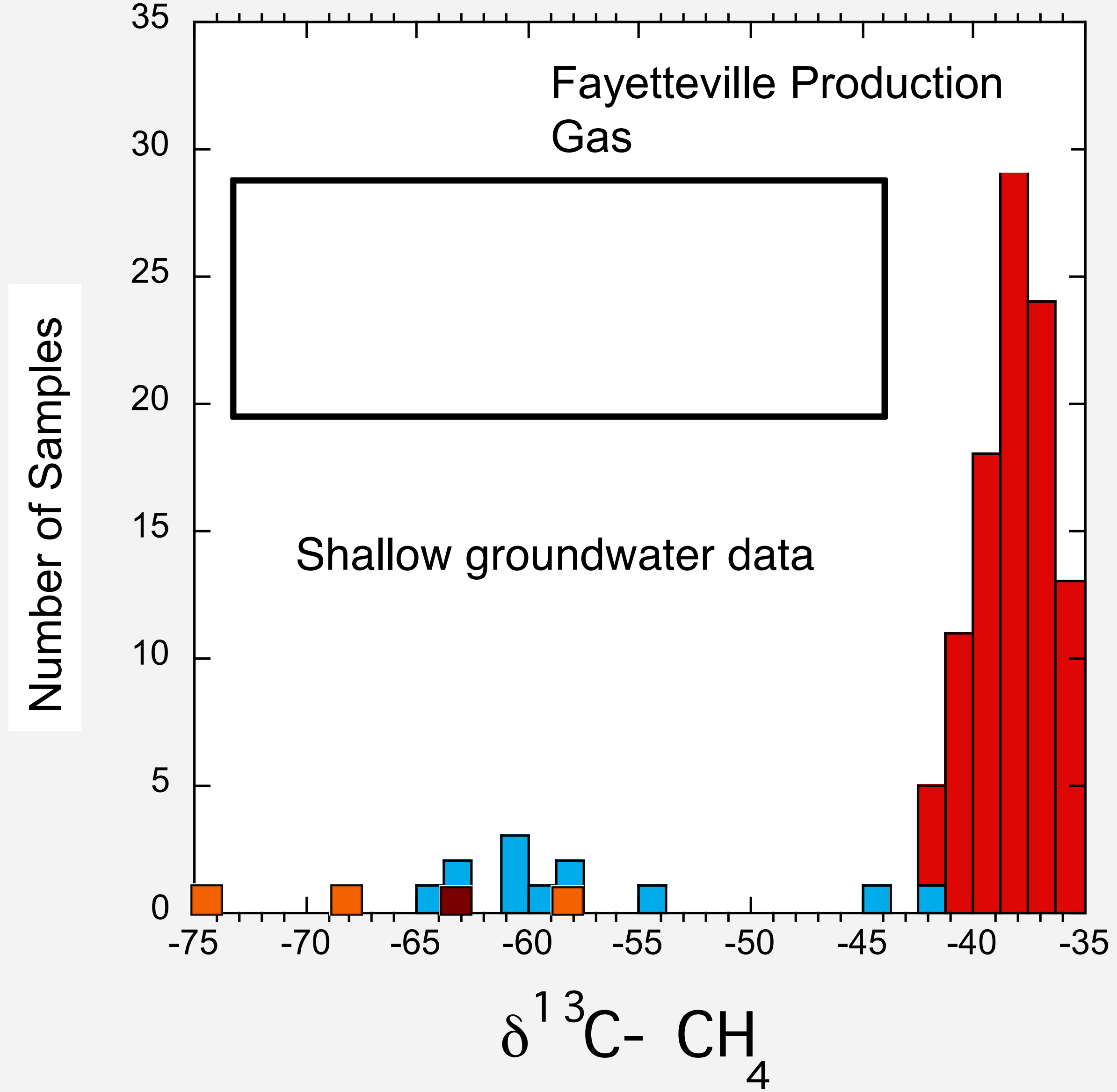
GROUNDWATER IN FAYETTEVILLE SHALE NORTH-CENTRAL ARKANSAS



Warner et *al., (2013); Applied Geochemistry*, May 2013



Warner et *al., (2013); Applied Geochemistry*, May 2013



Warner et *al., (2013); Applied Geochemistry*, May 2013

Stray gas contamination- conclusions

- Methane is indeed ubiquitous in groundwater in some areas overlying shale plays (e.g., Marcellus);
- Geochemical and isotopic evidence for stray gas contamination in a subset of wells near shale gas drilling sites in northeastern PA but not in AK;
- Stray gas contamination can result from leaking of natural gas along the well annulus from shallower formations and/or the the target formation through poorly constructed or failing well casings.

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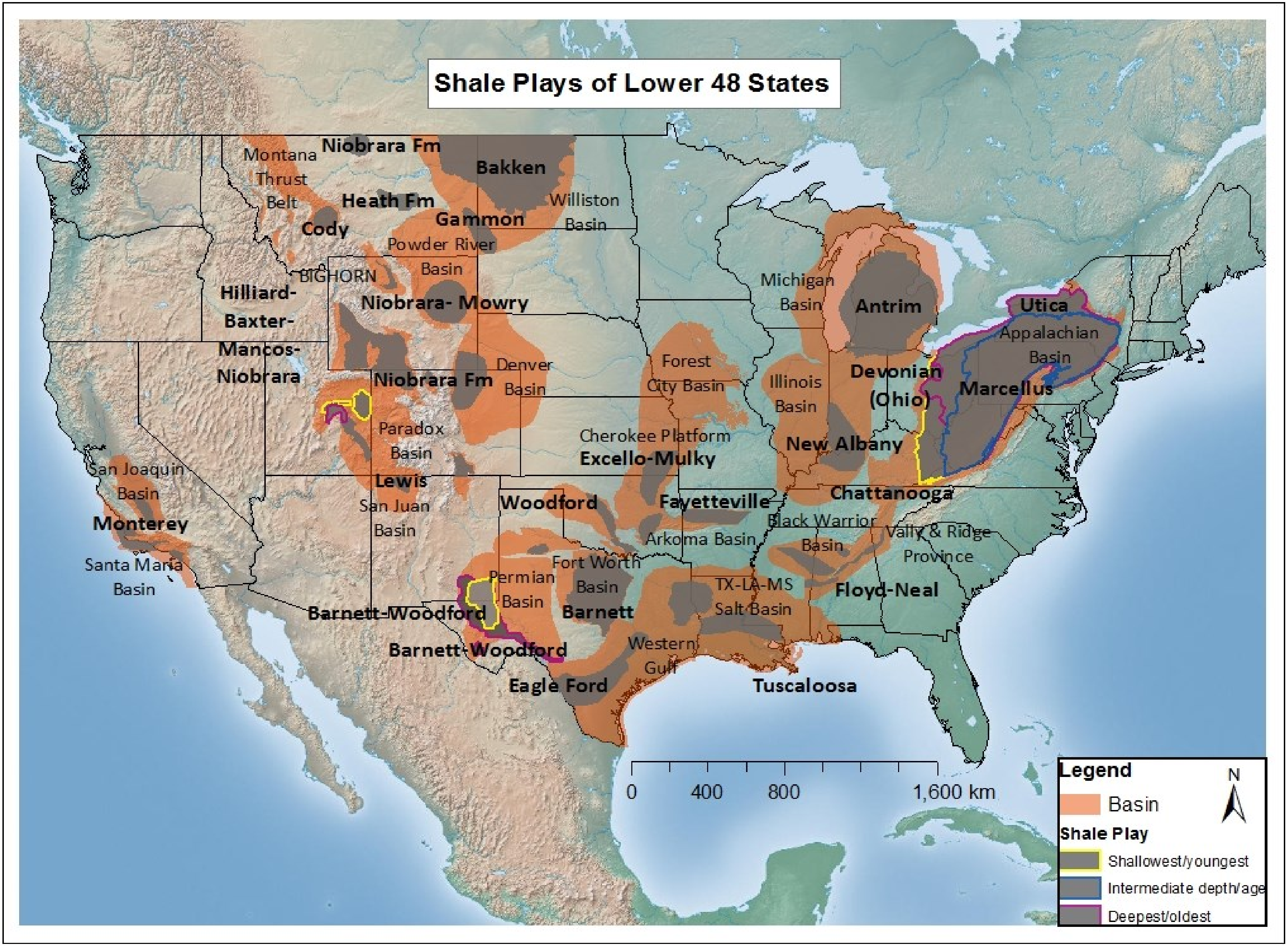
Disposal of inadequately treated shale gas wastewater: contamination of waterways


Shale Plays of Lower 48 States
Montana Thrust Belt
Niobrara Fm
Bakken
Heath Fm
Williston Basin
Gammon
Cody
Powder River Basin
BIGHORN
Hilliard-Baxter-Mancos-Niobrara
Niobrara- Mowry
Denver Basin
Niobrara Fm
Paradox Basin
Lewis
San Juan Basin
San Joaquin Basin
Monterey
Santa Maria Basin
Michigan Basin
Antrim
Utica
Appalachian Basin
Marcellus
Devonian (Ohio)
Forest City Basin
Illinois Basin
Cherokee Platform
Excello-Mulky
New Albany
Chattanooga
Woodford
Fayetteville
Black Warrior Basin
Arkoma Basin
Vally & Ridge Province
Fort Worth Basin
Permian Basin
Barnett
TX-LA-MS Salt Basin
Floyd-Neal
Barnett-Woodford
Barnett-Woodford
Western Gulf
Eagle Ford
Tuscaloosa
0 400 800 1,600 km
N
Legend
Basin
Shale Play
Shallowest/youngest
Intermediate depth/age
Deepest/oldest

Shale gas water footprint

- Hydraulic fracturing requires large quantities of fracturing fluid
  - Marcellus: 12–19 million liter (ML) per well;
  - Oklahoma: 11.3 ML
- Marcellus shale gas well generates on average 5.2 ML of wastewater (12% drilling fluids, 32% flowback; 55% brine)
- Total Marcellus wastewater production in 2011 was 3144 ML (3.14×10^6 m^3) relative to ~800 ML from conventional oil and gas wells. 1200 ML was disposed at treatment facilities.

Sources: Lutz et al., *(2013) WRR*, 49, 647–656

What's in shale gas wastewater?

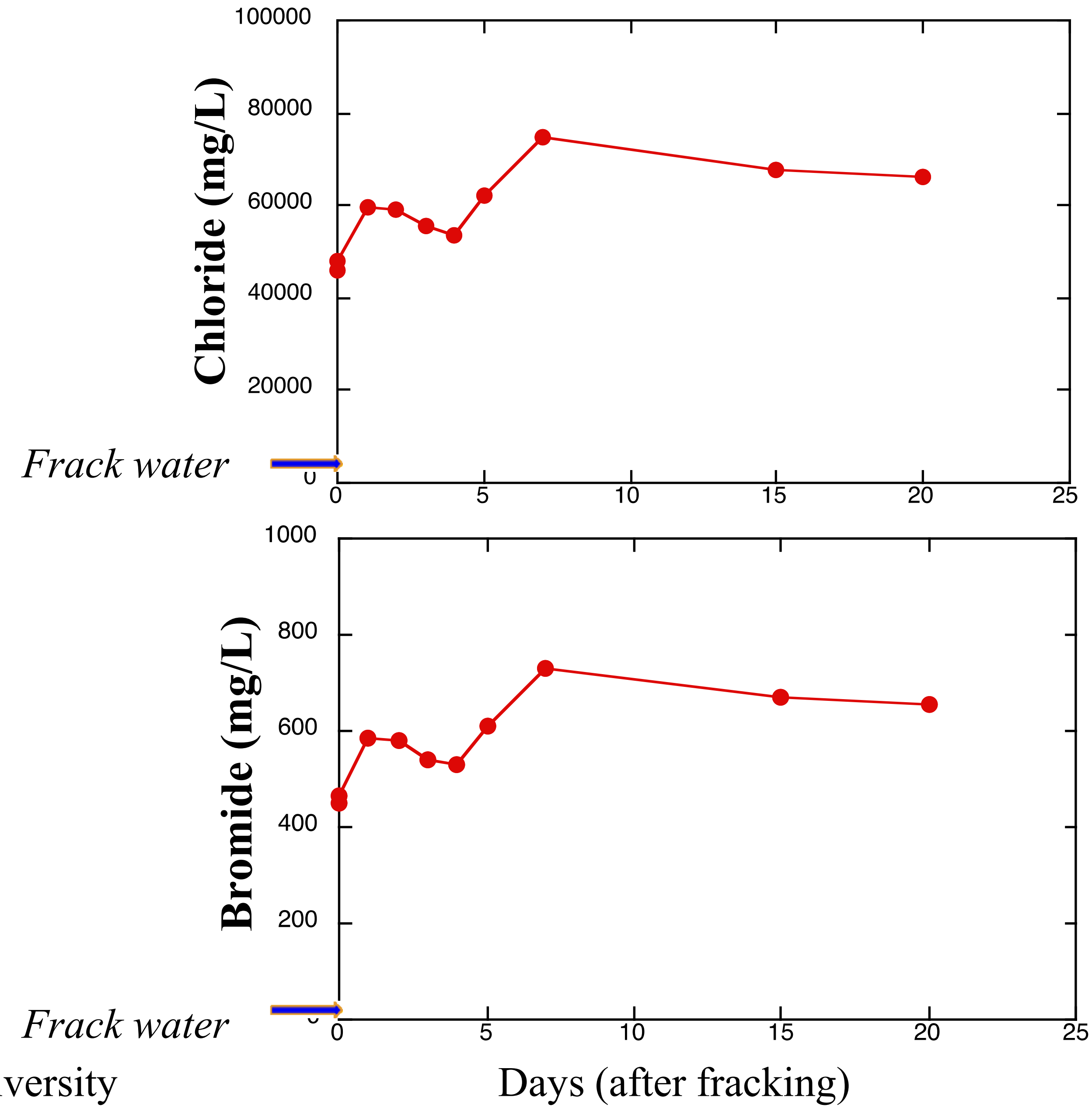
• Salinity (Marcellus brine – 250,000 mg/L ; 10 fold seawater);
High bromide, bromide presence in water enhances the formation of carcinogenic disinfection by-products (e.g., bromodichloromethane) upon chlorination of downstream potable water;

• High concentrations of toxic elements (barium, arsenic, selenium, lead);

• High concentrations of naturally occurring radioactive materials (NORMs); (**5000 pCi/L**, drinking water standard=5 pCi/L)

•Hydrocarbon residuals, oil, organics

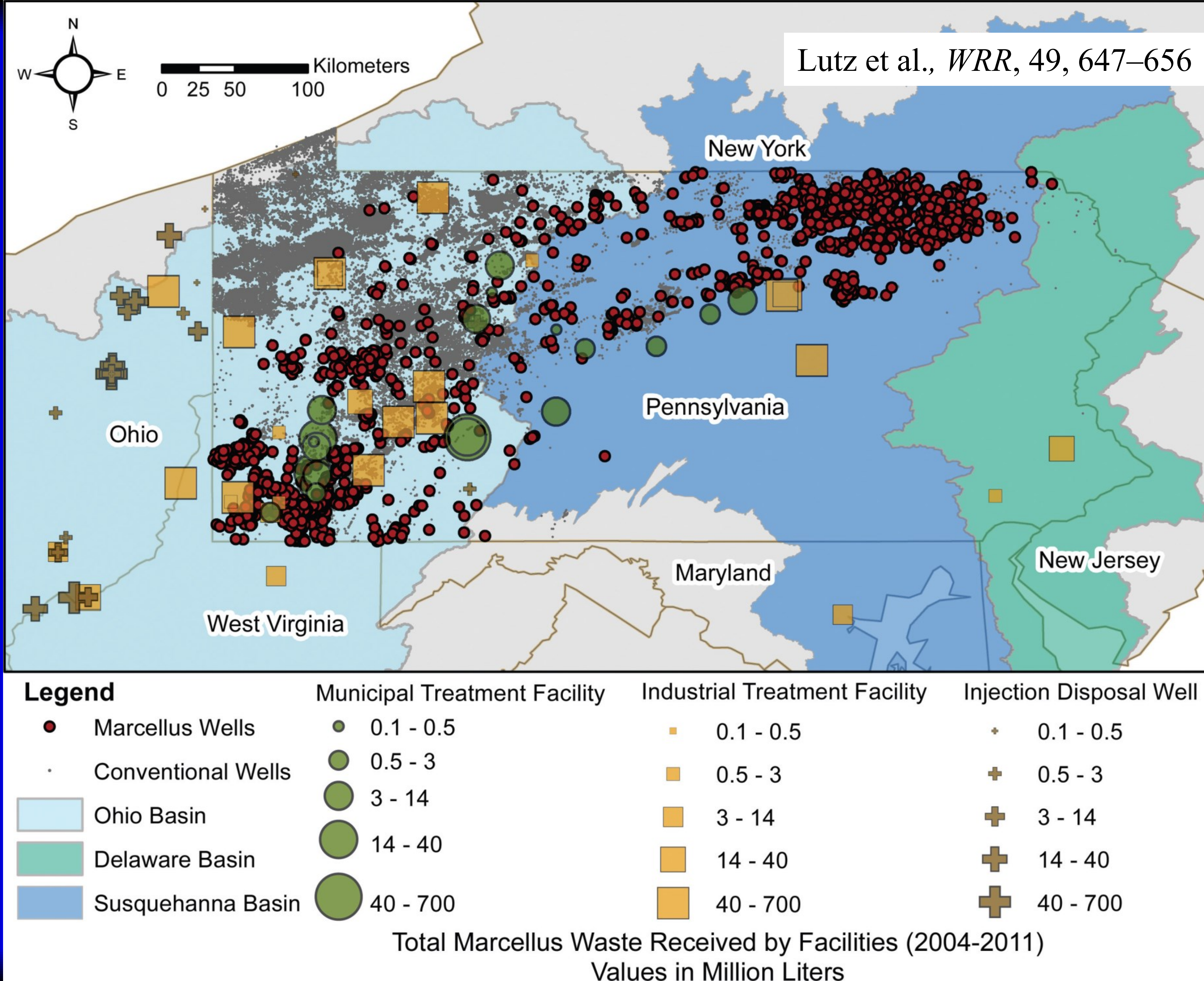
Flowback from the Marcellus gas well



Source: Duke University

Wastewater management

- Treatment at a municipal wastewater treatment facility followed by discharge to a local waterway;
- Treatment at a private industrial wastewater facility followed by discharge into a local waterway;
- Transporting to underground injection well site;
- Recycling to hydraulic fracturing (~70% in 2011 for Marcellus);
- Road spreading of brines for ice and dust control (currently not permitted in PA).

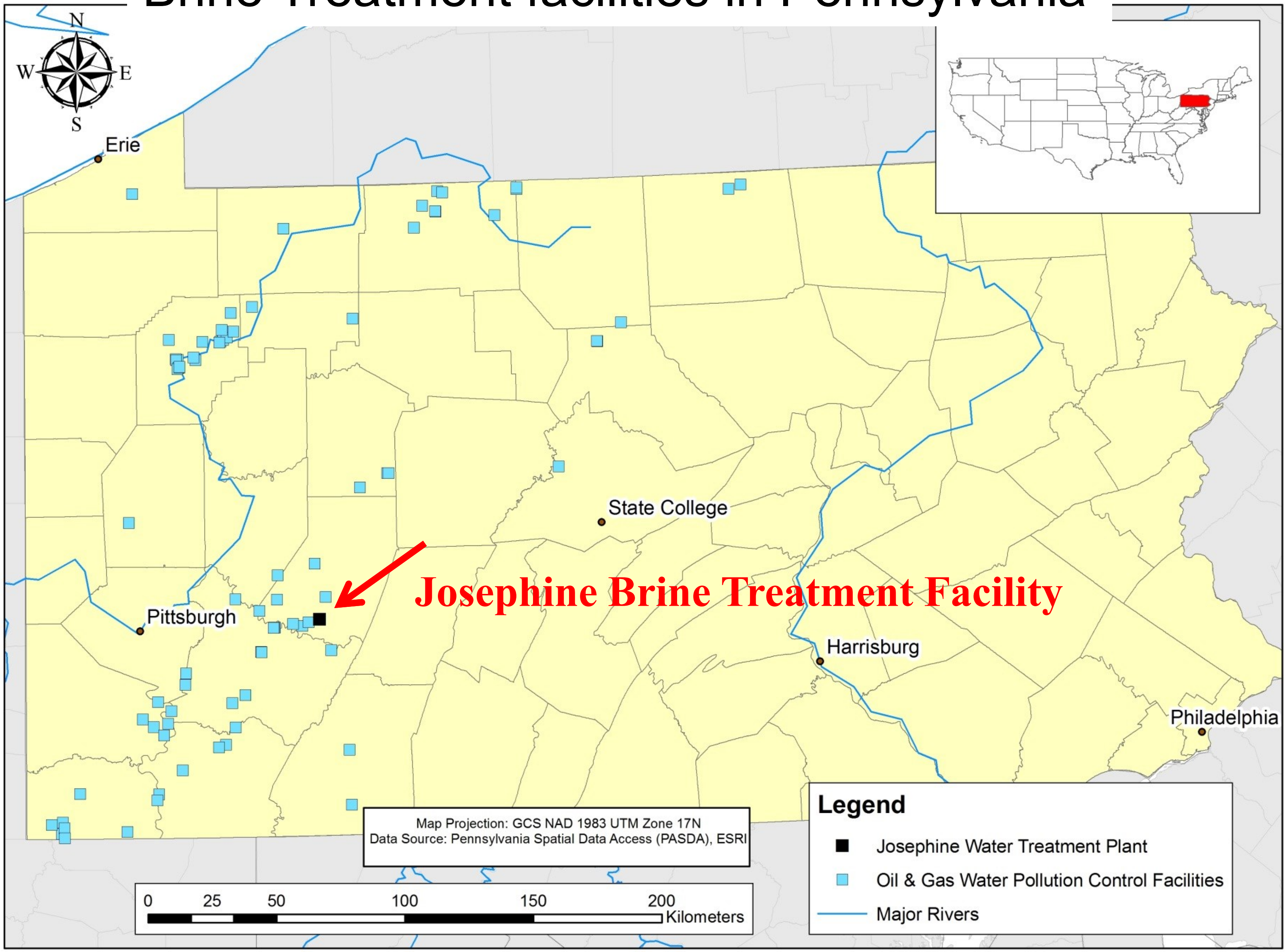

Lutz et al., *WRR*, 49, 647–656
N
W
E
S
Kilometers
0 25 50 100
New York
Pennsylvania
Ohio
West Virginia
Maryland
New Jersey
Legend
Marcellus Wells
Conventional Wells
Ohio Basin
Delaware Basin
Susquehanna Basin
Municipal Treatment Facility
0.1 - 0.5
0.5 - 3
3 - 14
14 - 40
40 - 700
Industrial Treatment Facility
0.1 - 0.5
0.5 - 3
3 - 14
14 - 40
40 - 700
Injection Disposal Well
0.1 - 0.5
0.5 - 3
3 - 14
14 - 40
40 - 700
Total Marcellus Waste Received by Facilities (2004-2011)
Values in Million Liters

Short-term risks for wastewater management options

Treatment at a municipal wastewater treatment facility	Treatment at a brine treatment facility	Transporting to deep well injection	Recycling to hydraulic fracturing
• Inadequate treatment; • Effect on domestic wastewater treatment	• Inadequate treatment for halogens; • Radioactivity in residual solids	• Induce seismicity	• Limitation by water chemistry (scaling, radioactivity, boron)

Josephine Brine Treatment Facility

Brine Treatment facilities in Pennsylvania

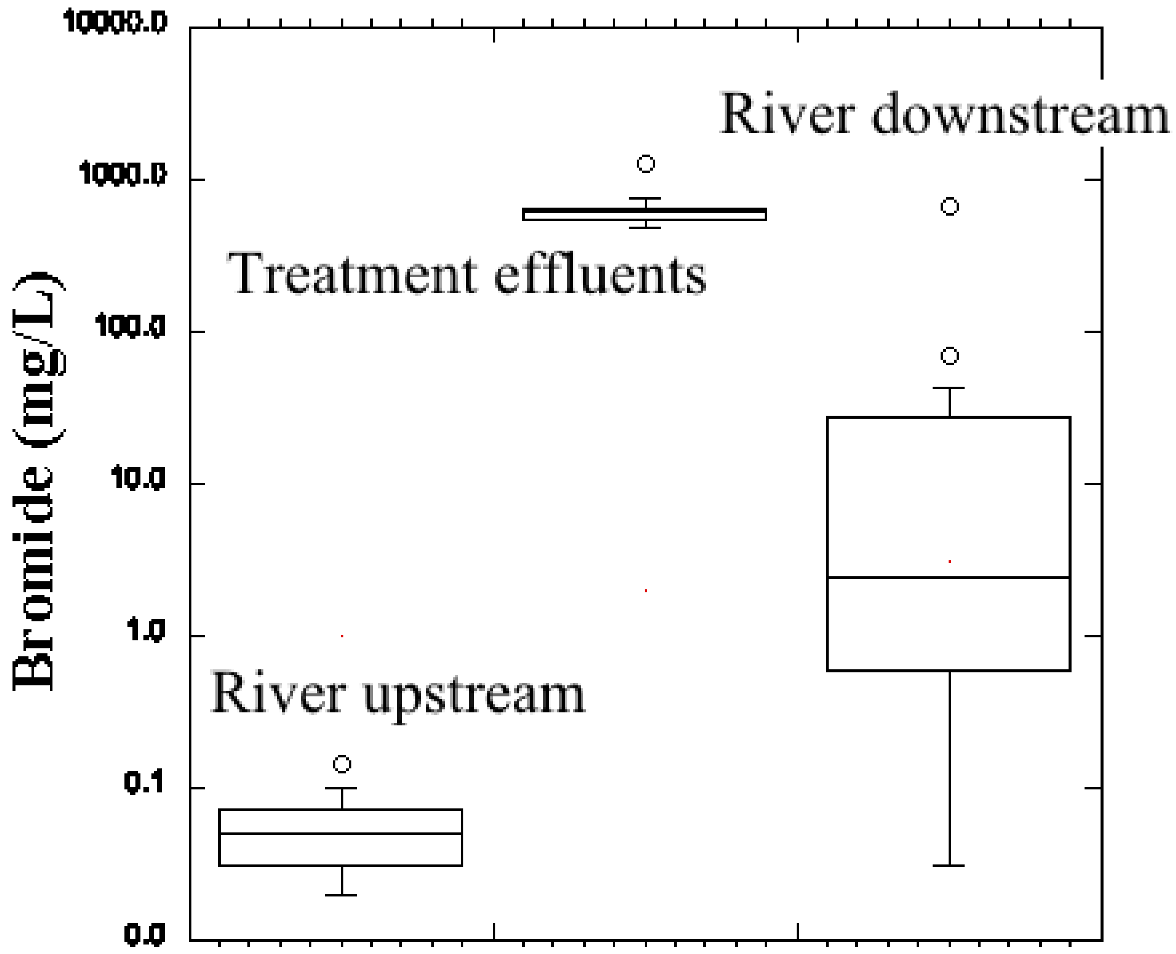


A schematic illustration of the impact of a brine treatment facility

Chloride flux (2010-2011) = $32x10^3$ and $143x10^3$ tons/year for PA

Salinity and high bromide in surface water

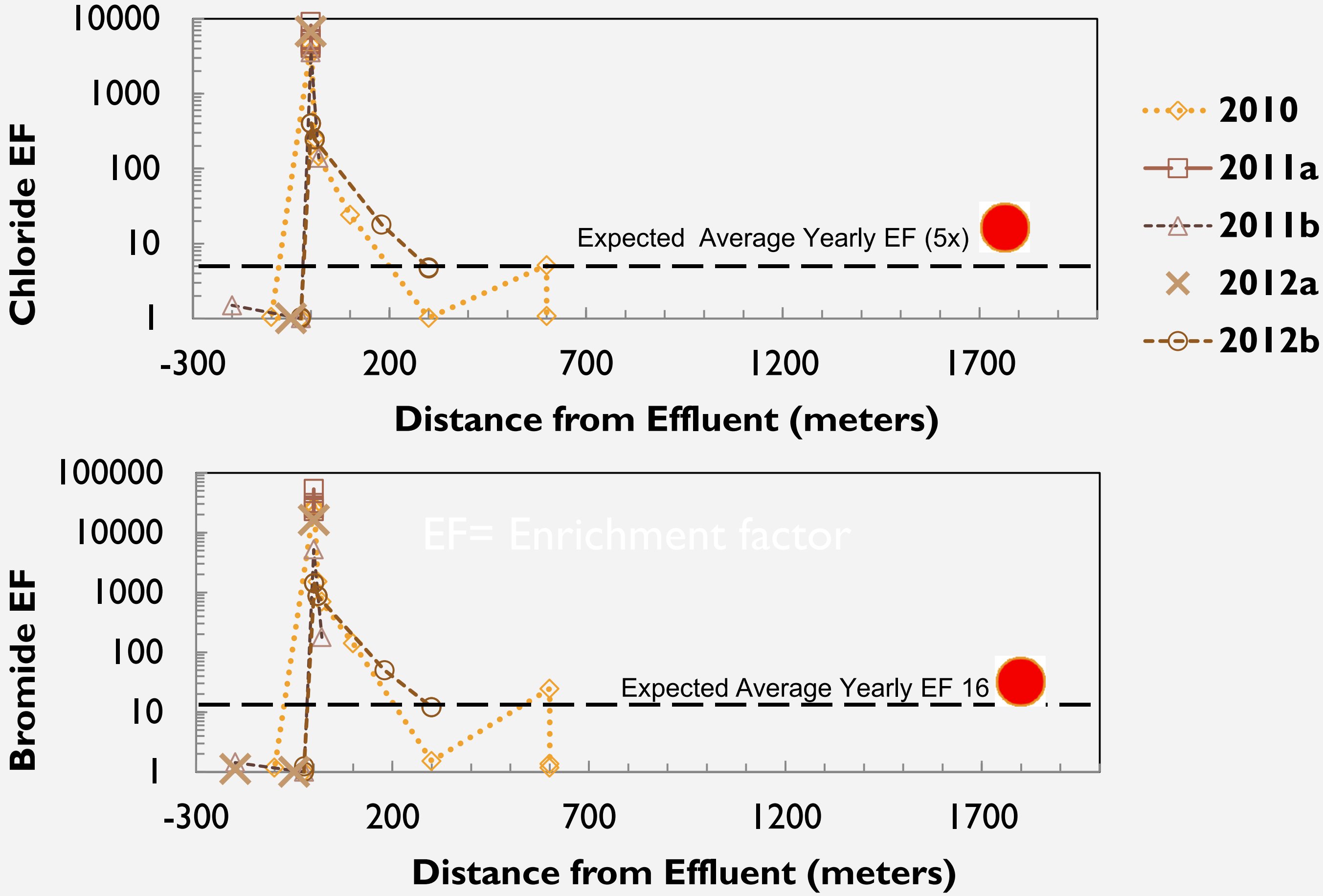
Source: Warner (2013) PhD thesis, Duke University



10000.0
1000.0
100.0
10.0
1.0
0.1
0.0
Bromide (mg/L)
River downstream
Treatment effluents
River upstream

Source: Wa

Enrichment factor of halogens in downstream river water



EF= enrichment factor relative to upstream river

Source: Warner (2013) PhD thesis, Duke University

Surface water contamination via disposal of inadequately treated wastewater - conclusions

- Local contamination of streams and rivers;
- Despite of the dilution, downstream river contains higher Br than background levels → risk of formation of carcinogenic disinfection by-products upon chlorination of downstream potable water;
- Zero discharge policy is required.

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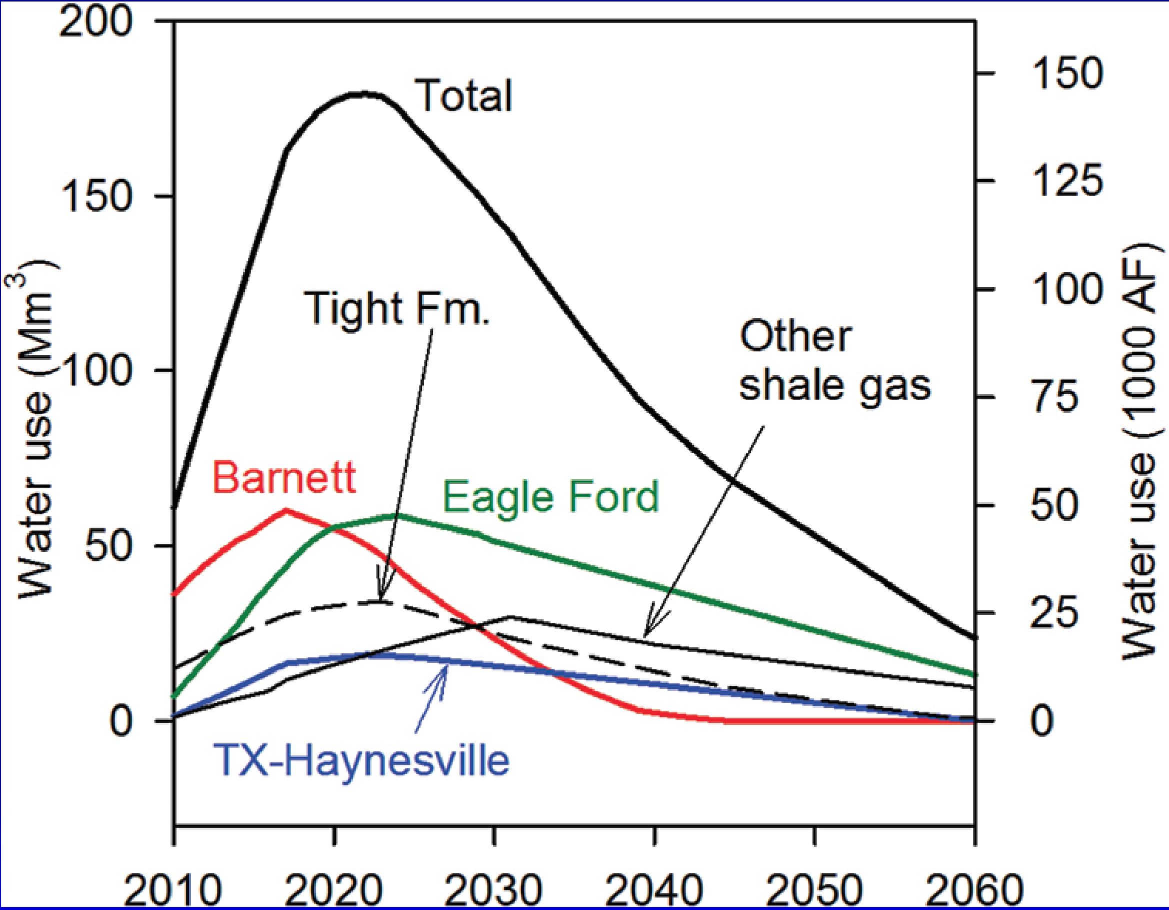
Shale gas water footprint

- Hydraulic fracturing requires large quantities of fracturing fluid
  - Marcellus: 12–19 million liter (ML) per well;
  - Oklahoma: 11.3 ML per well;
  - Barnett Shale: 10.6 ML per well;
- Total water use for shale gas:
  - Marcellus (PA): ~42-66x10^6 m^3 (2011)
  - Oklahoma State wide: 16x10^6 m^3 (2011) → 1% of statewide fresh water use
  - Barnett Shale, TX: ~30x10^6 m^3 → 7% of Dallas water use

Sources: Lutz et al., *(2013) WRR*, 49, 647–656;
Murray, (2013); *ES&T*, 47, 4918−4925;
Nicot and Scalon, (2012), *ES&T*

Shale gas water footprint



Time evolution in Texas of fracking net water use distributed among the Barnett, Tx-Haynesville, Eagle Ford, and other shale-gas plays

Sources: Nicot and Scalon, (2012), *ES&T*

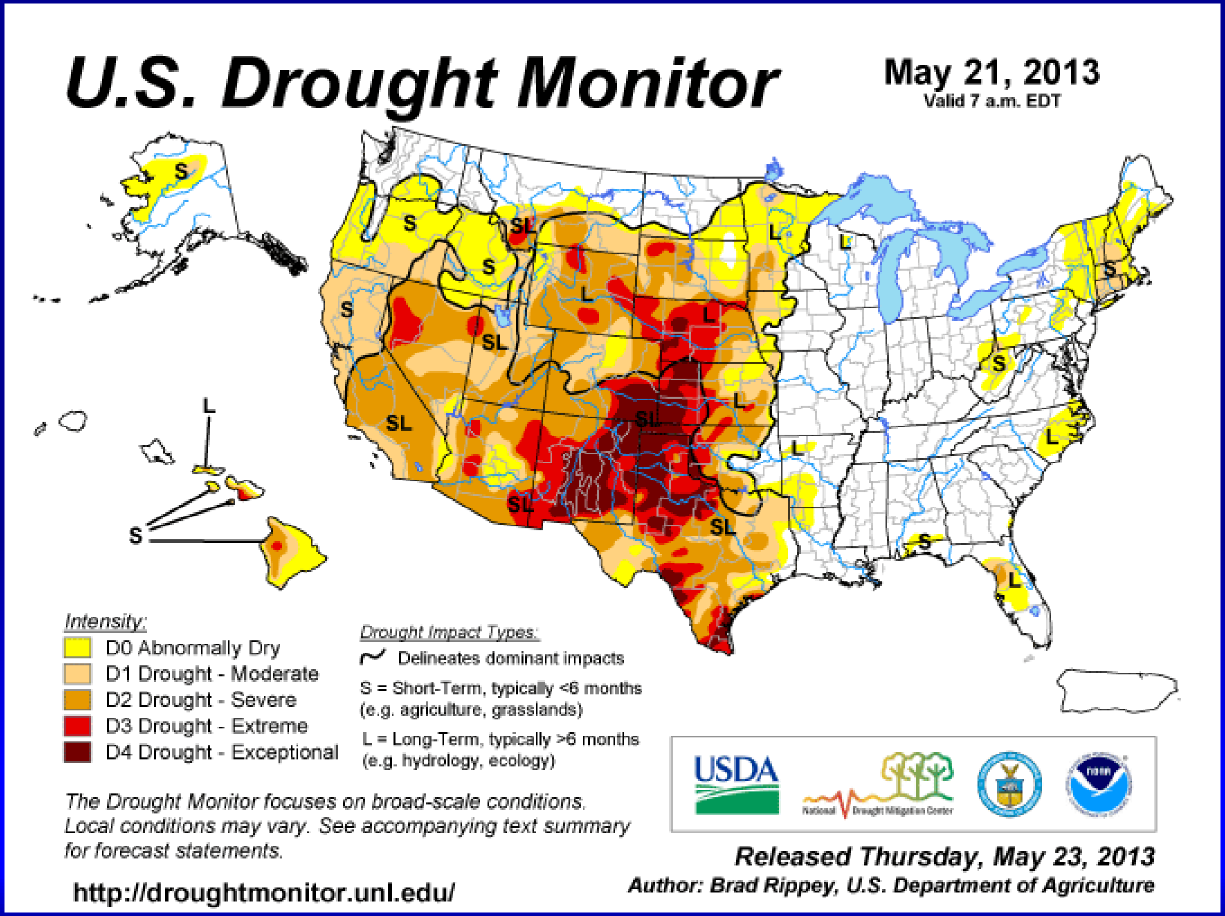
Overall water footprint

- **Shale gas water footprint – a few % of total freshwater withdrawal;**
- **Thermoelectric withdrawal (2005) – 142 Bgal/day* (196×10^9 m^3/year) ~ 40% of total freshwater withdrawal in the USA.**

*Source: Kenny et al. (2009), U.S. Geological Survey Circular 1344, 52 p.

Shale gas water footprint

Although the overall water use for shale gas and hydraulic fracturing is low in comparison to other users, in some water-scare areas, such as in TX, water use for shale gas constitutes a large fraction of groundwater resources, that could lead to potential water shortage.



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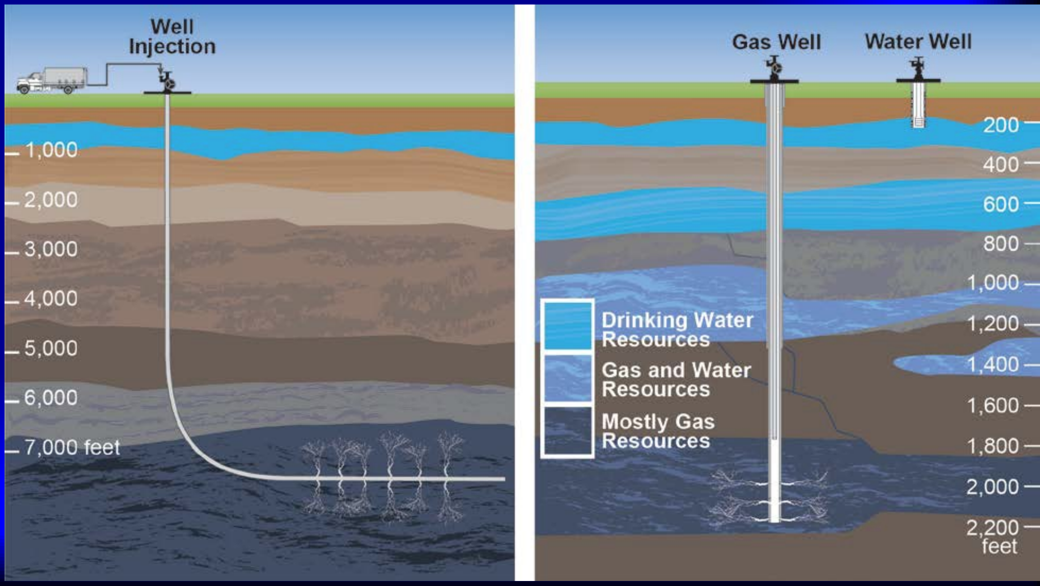
The long-term risk: Groundwater contamination through natural fracture networks

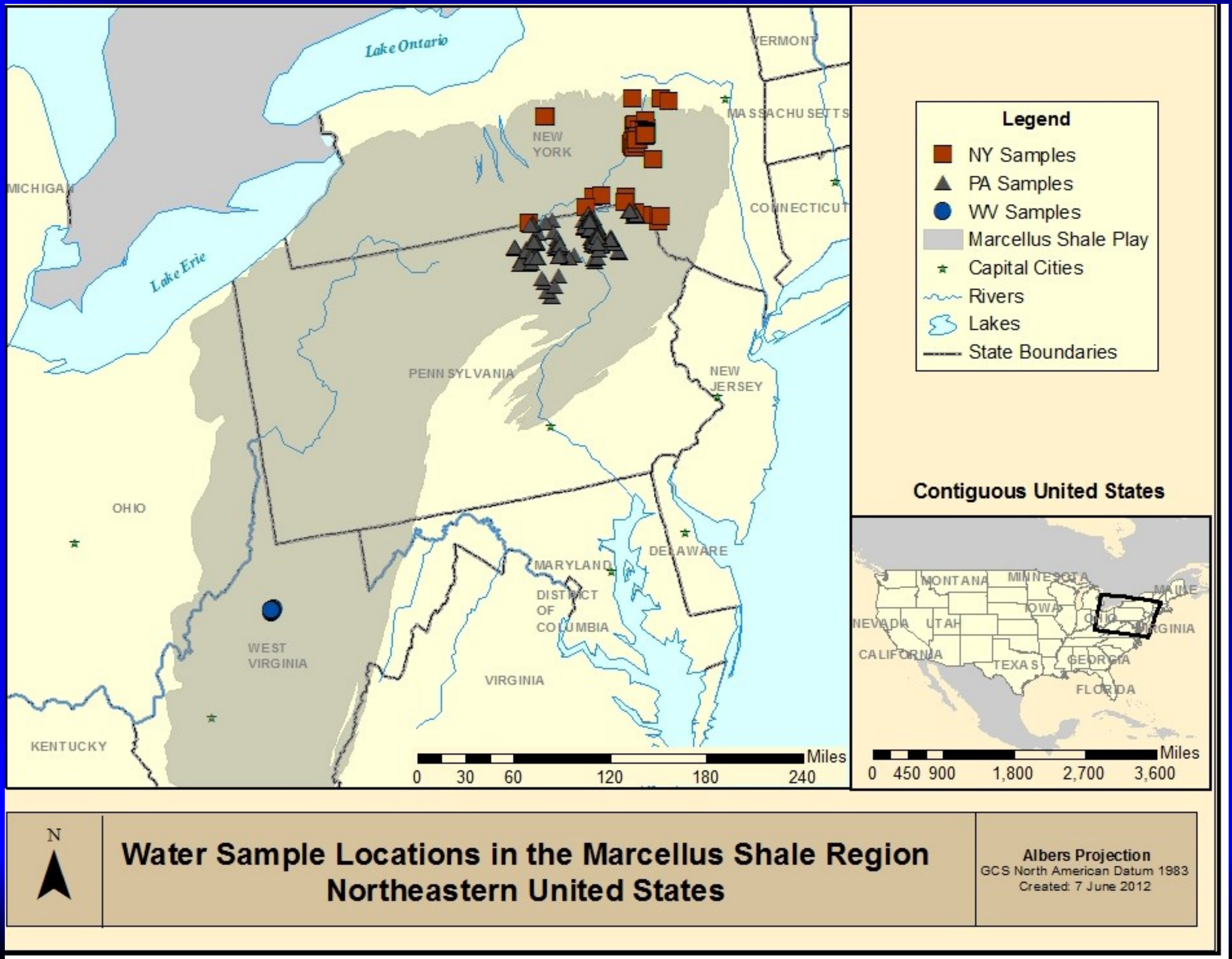
Modeling simulation: Advective transport of saline water through faults and fracture system could reach the overlying aquifers in less than 10 years

Myers (2012), *Groundwater,* 50,872- 882



Duke Study:

Evidence for hydraulic connectivity – deep brine/gas can flow to shallow aquifers in PA



Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania

Nathaniel R. Warner[a], Robert B. Jackson[a,b], Thomas H. Darrah[a], Stephen G. Osborn[c], Adrian Down[b], Kaiguang Zhao[b], Alissa White[a], and Avner Vengosh[a,1]

[a]Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC 27708; [b]Center on Global Change, Nicholas School of the Environment, Duke University, Durham, NC 27708; [c]Geological Sciences Department, California State Polytechnic University, Pomona, CA 91768

Edited by Karl K. Turekian, Yale University, North Haven, CT, and approved May 10, 2012 (received for review January 5, 2012)

The debate surrounding the safety of shale gas development in the Appalachian Basin has generated increased awareness of drinking water quality in rural communities. Concerns include the potential for migration of stray gas, metal-rich formation brines, and hydraulic fracturing and/or flowback fluids to drinking water aquifers. A critical question common to these environmental risks is the hydraulic connectivity between the shale gas formations and the overlying shallow drinking water aquifers. We present geochemical evidence from northeastern Pennsylvania showing that pathways, unrelated to recent drilling activities, exist in some locations between deep underlying formations and shallow drinking water aquifers. Integration of chemical data (Br, Cl, Na, Ba, Sr, and Li) and isotopic ratios ($^{87}Sr/^{86}Sr$, $^{2}H/H$, $^{18}O/^{16}O$, and $^{228}Ra/^{226}Ra$) from this and previous studies in 426 shallow groundwater samples and 83 northern Appalachian brine samples suggest that mixing relationships between shallow ground water and a deep formation brine causes groundwater salinization in some locations. The strong geochemical fingerprint in the salinized (Cl > 20 mg/L) groundwater sampled from the Alluvium, Catskill, and Lock Haven aquifers suggests possible migration of Marcellus brine through naturally occurring pathways. The occurrences of saline water do not correlate with the location of shale-gas wells and are consistent with reported data before rapid shale-gas development in the region; however, the presence of these fluids suggests conductive pathways and specific geostructural and/or hydrodynamic regimes in northeastern Pennsylvania that are at increased risk for contamination of shallow drinking water resources, particularly by fugitive gases, because of natural hydraulic connections to deeper formations.

Q:1 formation water | isotopes | Marcellus Shale | water chemistry

The extraction of natural gas resources from the Marcellus Shale in the Appalachian Basin of the northeastern United States (1, 2) has increased awareness of potential contamination in shallow aquifers routinely used for drinking water. The current debate surrounding the safety of shale gas extraction (3) has focused on stray gas migration to shallow groundwater (4) and the atmosphere (5) as well as the potential for contamination from toxic substances in hydraulic fracturing fluid and/or produced brines during drilling, transport, and disposal (6–9).

The potential for shallow groundwater contamination caused by natural gas drilling is often dismissed because of the large vertical separation between the shallow drinking water wells and shale gas formations and the relatively narrow zone (up to 300 m) of seismic activity reported during the deep hydraulic fracturing of shale gas wells (10, 11). Recent findings in northeastern Pennsylvania (NE PA) demonstrated that shallow water wells in close proximity to natural gas wells (i.e., <1 km) yielded, on average, higher concentrations of methane, ethane, and propane with thermogenic isotopic signature. By comparison, water wells farther away from natural gas development had lower combustible gas concentrations and an isotopic signature consistent with a mixture between thermogenic and biogenic components (4). In contrast, when inorganic water geochemistry from active drilling areas was compared to nonactive areas and historical background values, no statistically significant differences were observed (4). Increasing reports of changes in drinking water quality have nevertheless been blamed on the accelerated rate of shale gas development.

The study area in NE PA consists of six counties (Fig. 1) that lie within the Appalachian Plateaus physiographic province in the structurally and tectonically complex transition between the highly deformed Valley and Ridge Province and the less deformed Appalachian Plateau (12, 13). The geologic setting and shallow aquifer characteristics are described and mapped in greater detail in multiple sources (4, 14–19) and in *SI Methods*. The study area contains a surficial cover composed of a mix of unconsolidated glacial till, outwash, alluvium and deltaic sediments, and postglacial deposits (the Alluvium aquifer) that are thicker in the valleys (17–19) (Fig. S1). These sediments are underlain by Upper Devonian through Pennsylvanian age sedimentary sequences that are gently folded and dip shallowly (1–3°) to the east and south (Fig. S2). The gentle folding creates alternating exposure of synclines and anticlines at the surface that are offset surface expressions of deeper deformation (12, 20). The two major bedrock aquifers are the Upper Devonian Catskill and the underlying Lock Haven Formations (14, 15, 18, 19). The average depth of drinking water wells in the study area is between 60 and 90 m (Table S1). The underlying geological formations, including the Marcellus Shale (at a depth of 1,200–2,500 m below the surface) are presented in Fig. 2, Fig. S2 *A* and *B*, and *SI Methods*.

In this study, we analyze the geochemistry of 109 newly-collected water samples and 49 wells from our previous study (4) from the three principal aquifers, Alluvium (n = 11), Catskill (n = 102), and Lock Haven (n = 45), categorizing these waters into four types based on their salinity and chemical constituents (Figs. 1 and 2, and *SI Text*). We combine these data with 268 previously-published data for wells in the Alluvium (n = 57), Catskill (n = 147), and Lock Haven (n = 64) aquifers (18, 19) for a total of 426 shallow groundwater samples. We analyzed major and trace element geochemistry and a broad spectrum of isotopic tracers ($\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$, $^{228}Ra/^{226}Ra$) in shallow

Author contributions: N.R.W., R.B.J., and A.V. designed research; N.R.W., R.B.J., S.G.O., A.D., A.W., and A.V. performed research; N.R.W., R.B.J., T.H.D., K.Z., and A.V. analyzed data; and N.R.W., R.B.J., T.H.D., and A.V. wrote the paper.

The authors declare no conflict of interest.

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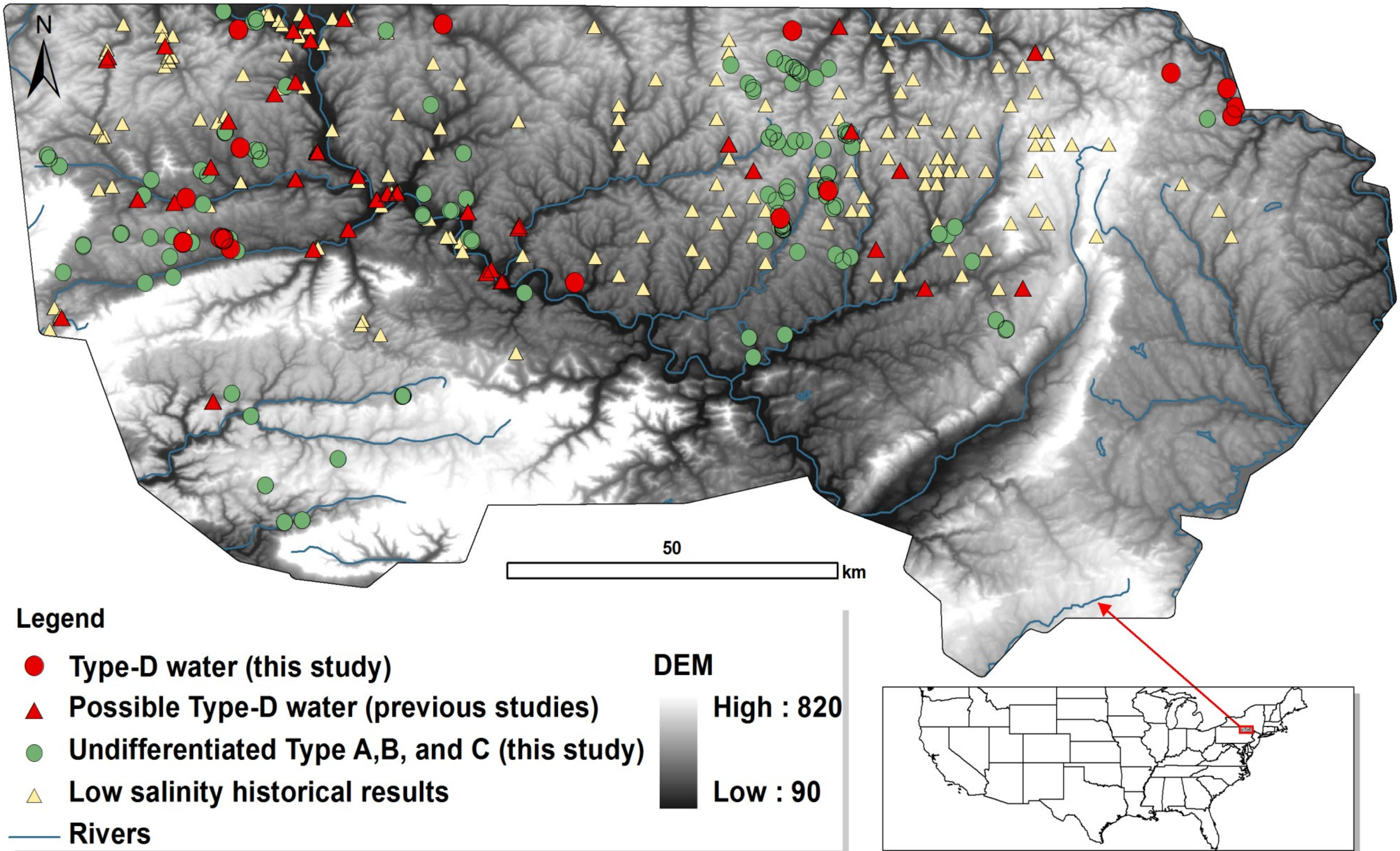
Warner et al., 2012
Proceedings of National Academy of Sciences, July 9, 2012

158 wells - new measurements

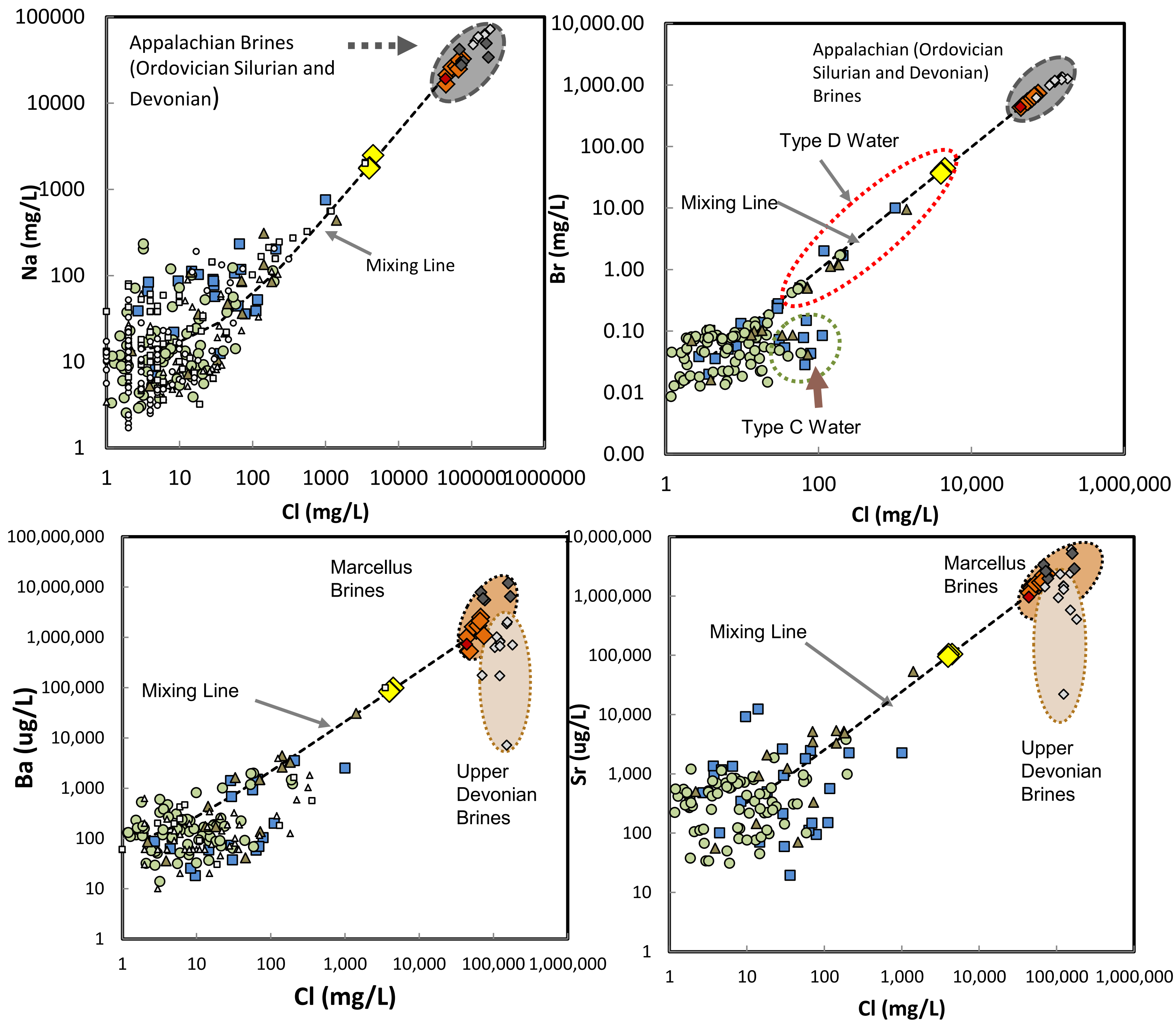
268 wells – previously published data

Occurrence of saline groundwater enriched in barium in shallow aquifers

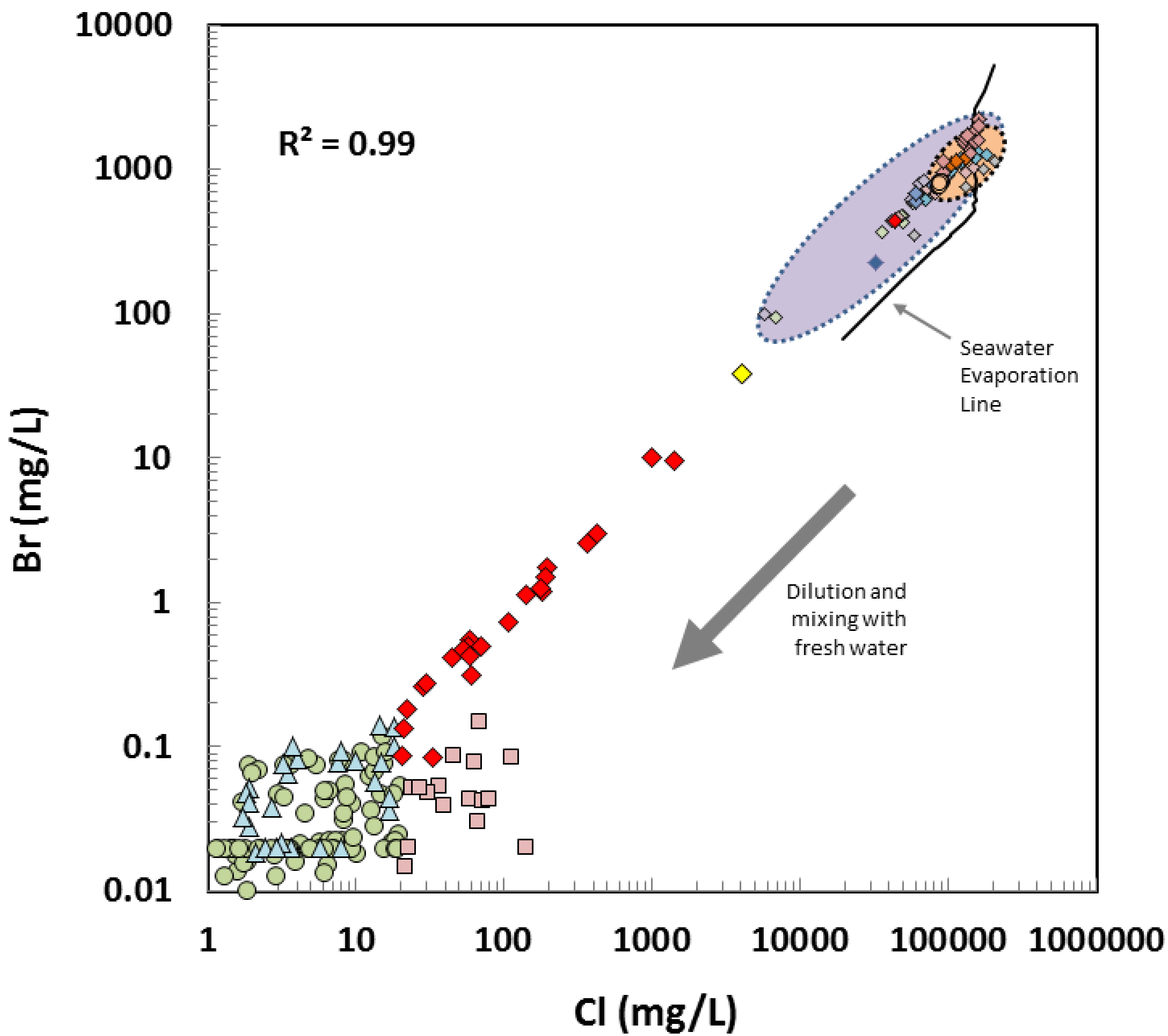


Salt Springs Park, Susquehanna County, Pennsylvania

TDS = 7,000 mg/L; CH_4 - over-saturation
Ca-Na-Cl composition; high Br/Cl



Appalachian Brines (Ordovician Silurian and Devonian)
Mixing Line
Na (mg/L)
Cl (mg/L)
100000
10000
1000
100
10
1
1
10
100
1000
10000
100000
1000000
Appalachian (Ordovician Silurian and Devonian) Brines
Type D Water
Mixing Line
Type C Water
Br (mg/L)
Cl (mg/L)
10,000.00
1,000.00
100.00
10.00
1.00
0.10
0.01
0.00
1
100
10,000
1,000,000
Marcellus Brines
Mixing Line
Upper Devonian Brines
Ba (ug/L)
Cl (mg/L)
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
1
10
100
1,000
10,000
100,000
1,000,000
Marcellus Brines
Mixing Line
Upper Devonian Brines
Sr (ug/L)
Cl (mg/L)
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
1
10
100
1,000
10,000
100,000
1,000,000



10000
1000
100
10
1
0.1
0.01
Br (mg/L)
R² = 0.99
Seawater
Evaporation
Line
Dilution and
mixing with
fresh water
1
10
100
1000
10000
100000
1000000
Cl (mg/L)

Figure 3.

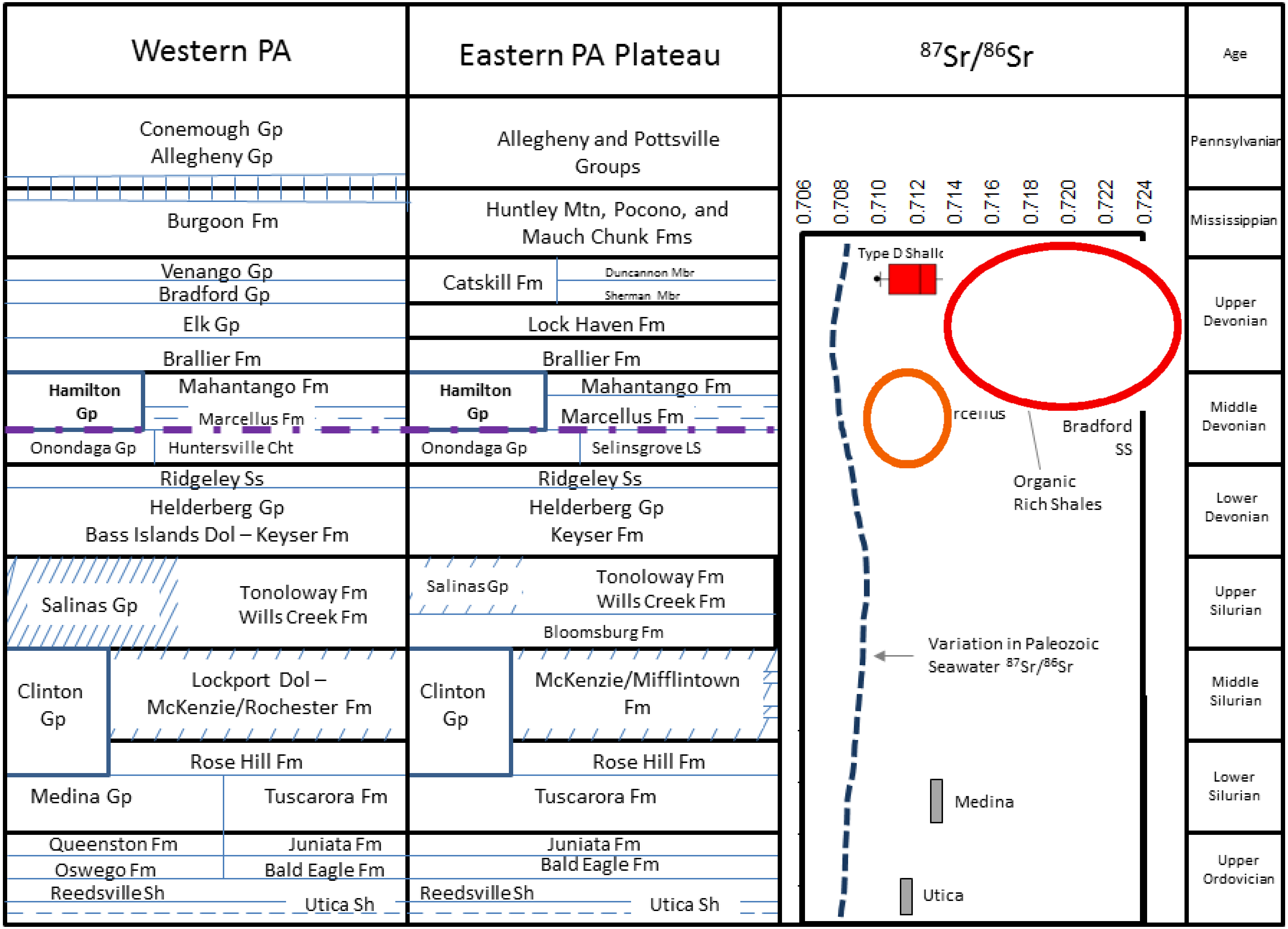

Western PA
Eastern PA Plateau
87Sr/86Sr
Age
Conemough Gp
Allegheny Gp
Allegheny and Pottsville Groups
Pennsylvanian
Burgoon Fm
Huntley Mtn, Pocono, and Mauch Chunk Fms
Mississippian
0.706
0.708
0.710
0.712
0.714
0.716
0.718
0.720
0.722
0.724
Venango Gp
Bradford Gp
Catskill Fm
Duncannon Mbr
Sherman Mbr
Type D Shalle
Upper Devonian
Elk Gp
Lock Haven Fm
Brallier Fm
Brallier Fm
Hamilton Gp
Mahantango Fm
Marcellus Fm
Hamilton Gp
Mahantango Fm
Marcellus Fm
rcellus
Bradford SS
Middle Devonian
Onondaga Gp
Huntersville Cht
Onondaga Gp
Selinsgrove LS
Organic Rich Shales
Ridgeley Ss
Helderberg Gp
Bass Islands Dol – Keyser Fm
Ridgeley Ss
Helderberg Gp
Keyser Fm
Lower Devonian
Salinas Gp
Tonoloway Fm
Wills Creek Fm
Salinas Gp
Tonoloway Fm
Wills Creek Fm
Bloomsburg Fm
Upper Silurian
Clinton Gp
Lockport Dol – McKenzie/Rochester Fm
Clinton Gp
McKenzie/Mifflintown Fm
Variation in Paleozoic Seawater 87Sr/86Sr
Middle Silurian
Rose Hill Fm
Rose Hill Fm
Medina Gp
Tuscarora Fm
Tuscarora Fm
Medina
Lower Silurian
Queenston Fm
Juniata Fm
Oswego Fm
Bald Eagle Fm
Reedsville Sh
Utica Sh
Juniata Fm
Bald Eagle Fm
Reedsville Sh
Utica Sh
Utica
Upper Ordovician

Figure 2.

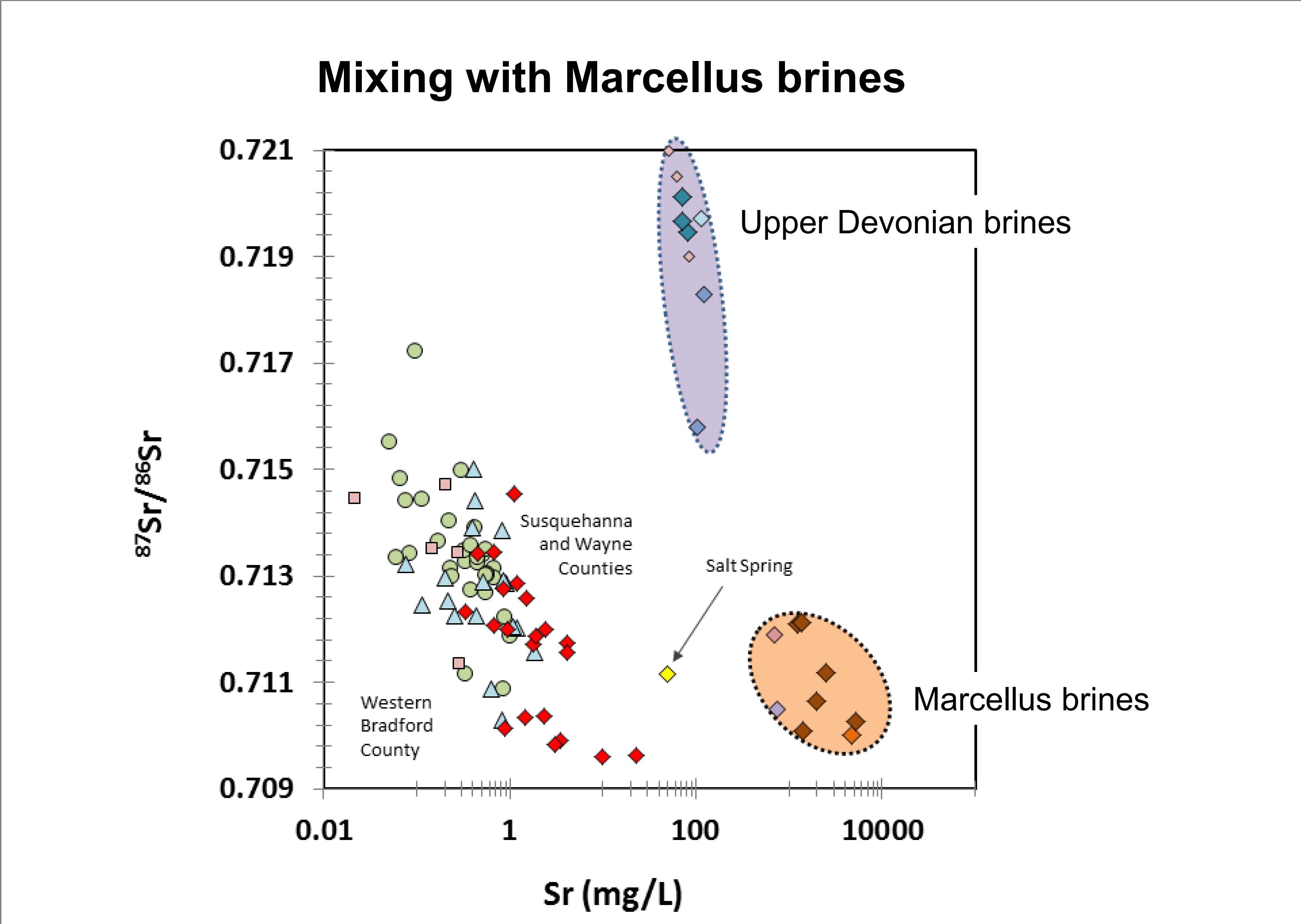
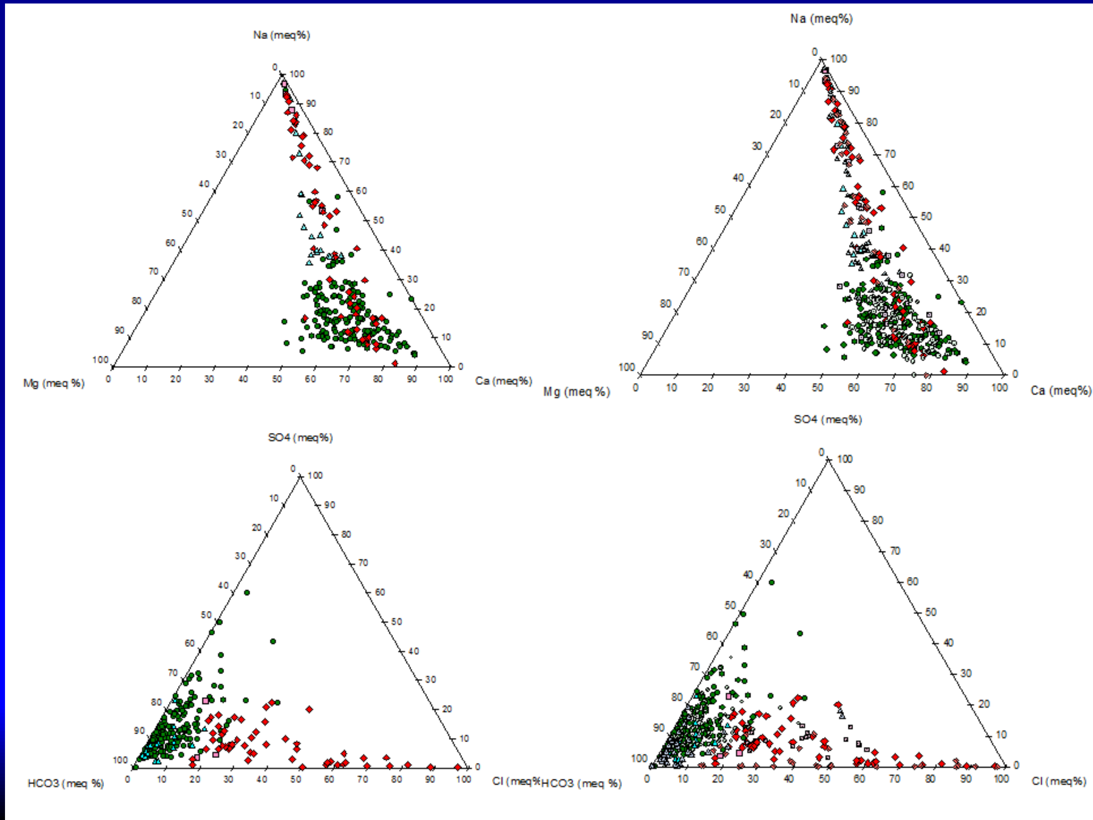

Mixing with Marcellus brines
0.721
0.719
0.717
0.715
0.713
0.711
0.709
$^{87}Sr/^{86}Sr$
Upper Devonian brines
Susquehanna
and Wayne
Counties
Salt Spring
Marcellus brines
Western
Bradford
County
0.01
1
100
10000
Sr (mg/L)

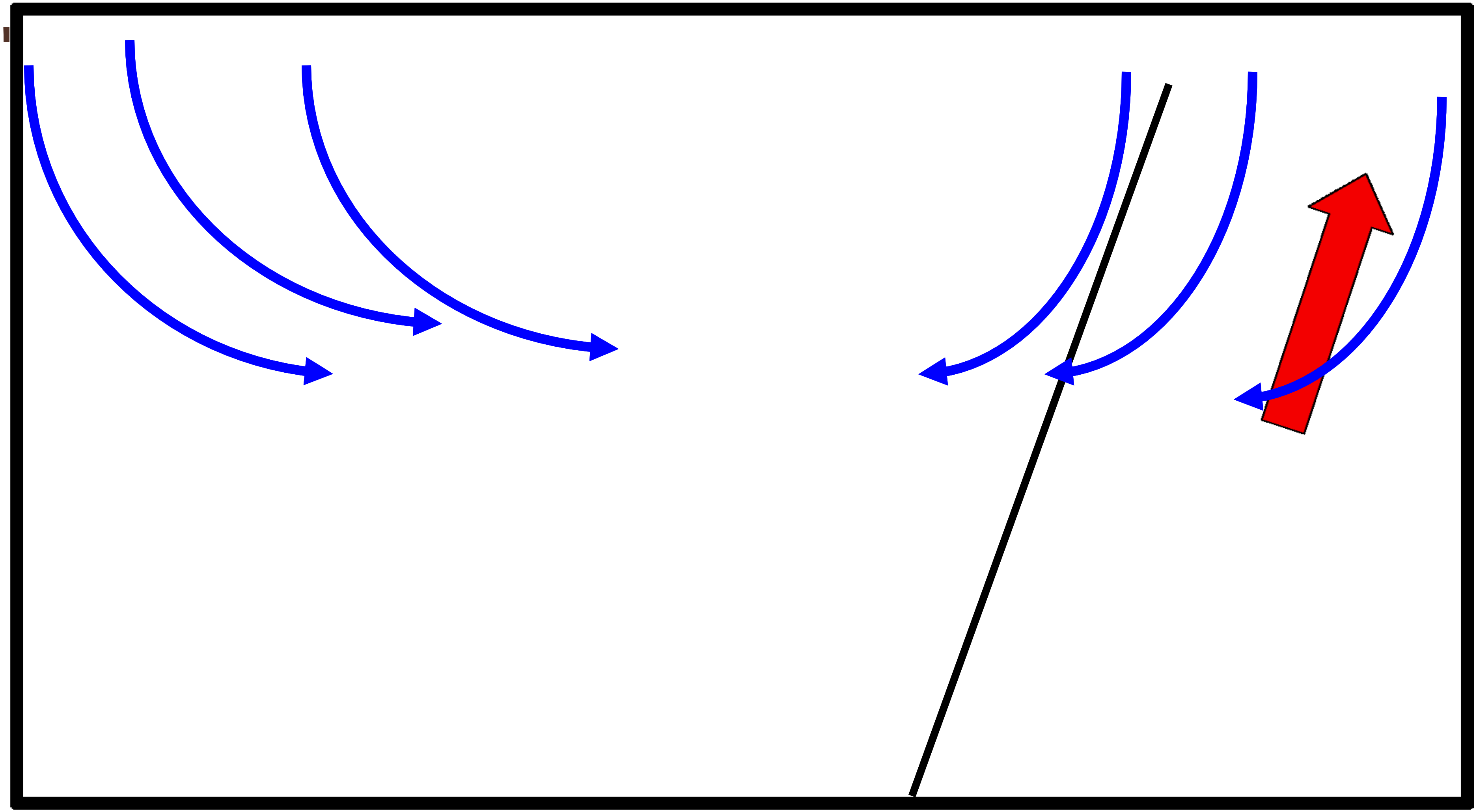
Figure 6.

No link to shale gas exploration:

- Analysis of 1980's USGS data reveals saline water of similar chemical composition (although Br data is not available)
- No geographical proximity to shale gas site (unlike the methane occurrence)



Flowpaths in a differential fractured aquifer: low-saline recharged water and upflow of deep saline groundwater through fracture zones



Risks of Shale Gas Exploration and Hydraulic Fracturing to Water Resources in the United States

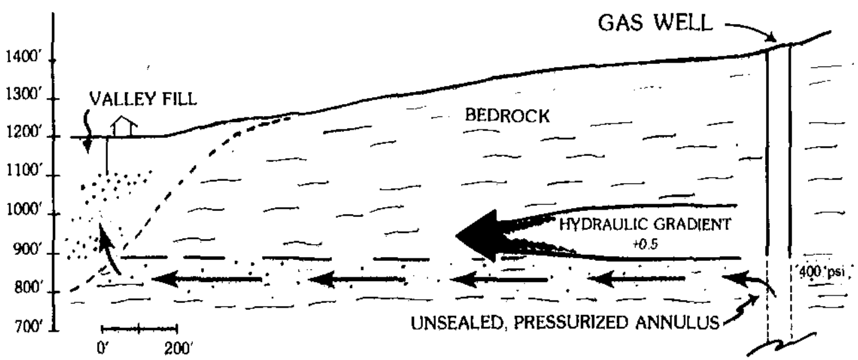
Short term

- Stray gas contamination;
- Surface water contamination via disposal of inadequately treated wastewater;
- Spills;

Long term

- Water availability in water scarce areas;
- Groundwater contamination through natural fracture networks;
- Groundwater contamination through abandoned and improperly sealed conventional oil and gas wells;
- Accumulation of residual contaminants and radiation in areas of wastewater disposal and spills;

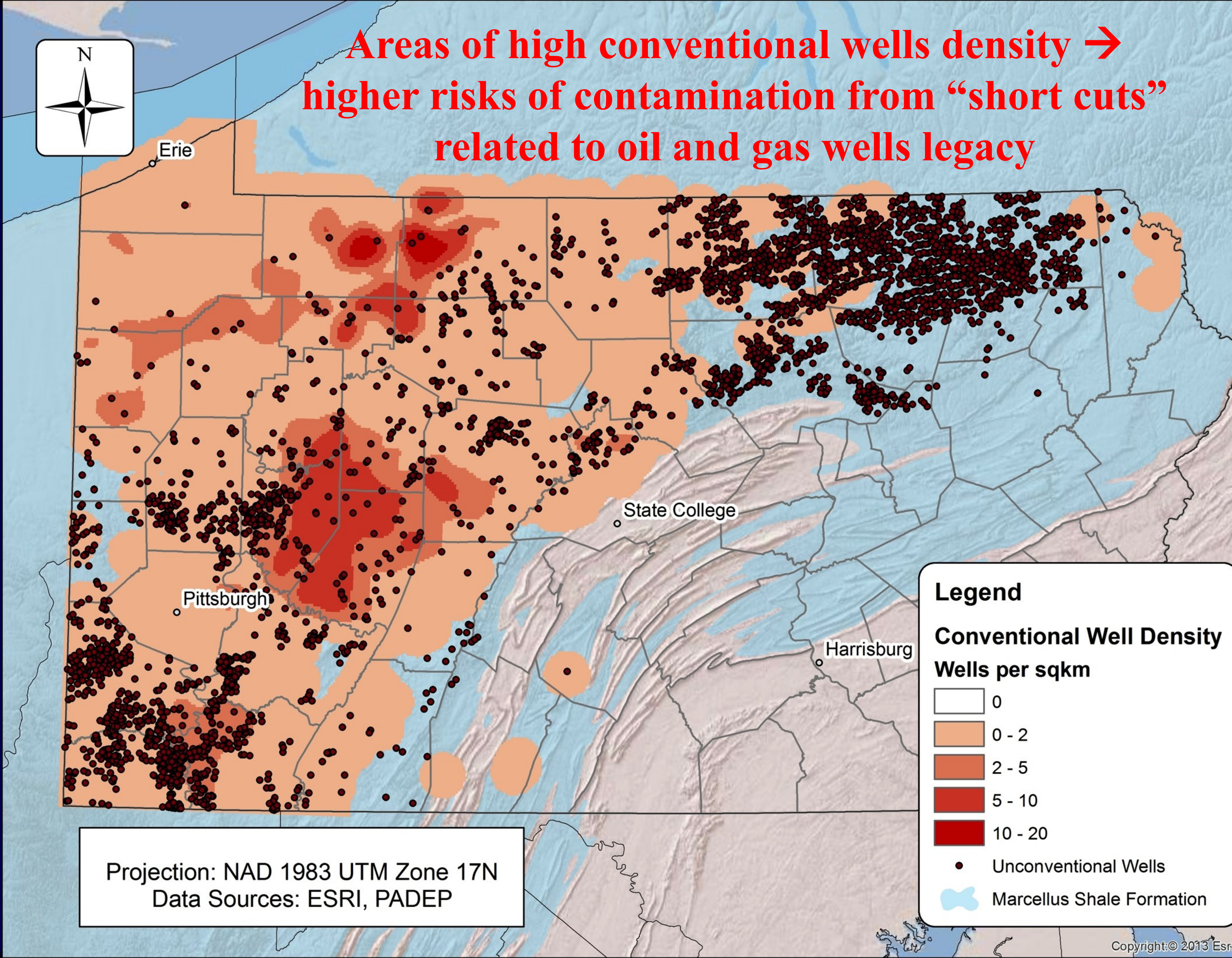
The risk: Groundwater contamination through abandoned and improperly sealed conventional oil and gas wells



Harrison, S. S. (1985) *Ground Water*, *23*, 317-324.

hydraulic gradient

Areas of high conventional wells density → higher risks of contamination from "short cuts" related to oil and gas wells legacy



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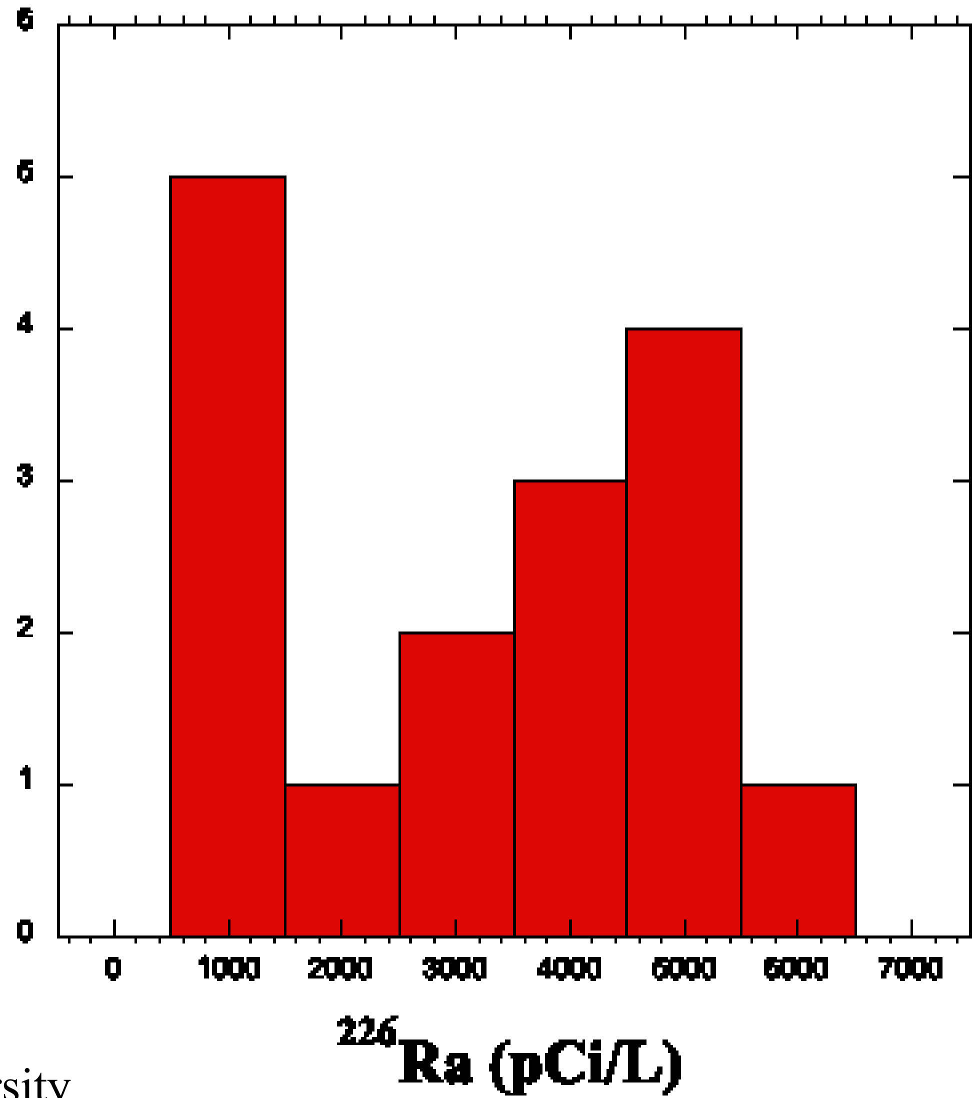
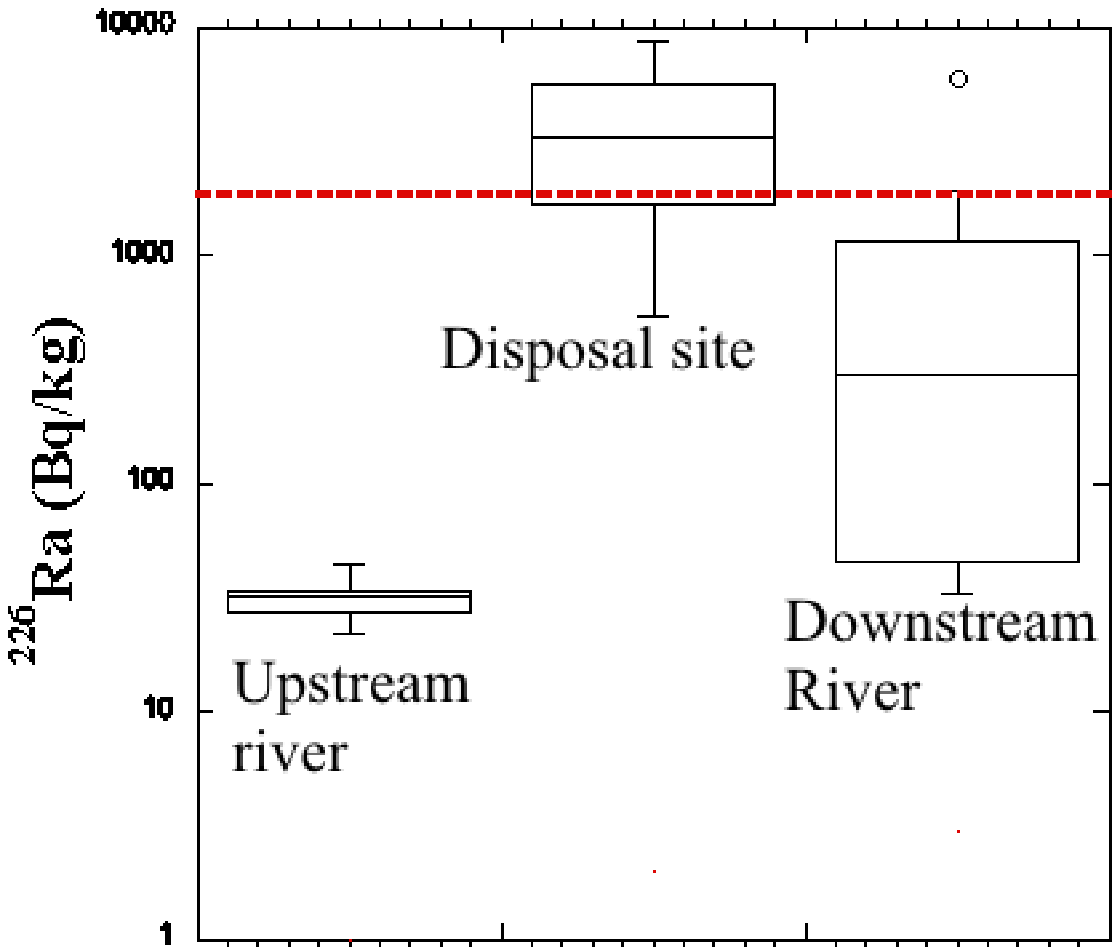
The risk: Accumulation of residual contaminants and radiation in areas of wastewater disposal and spills

Radi … uced



Source: Duke University

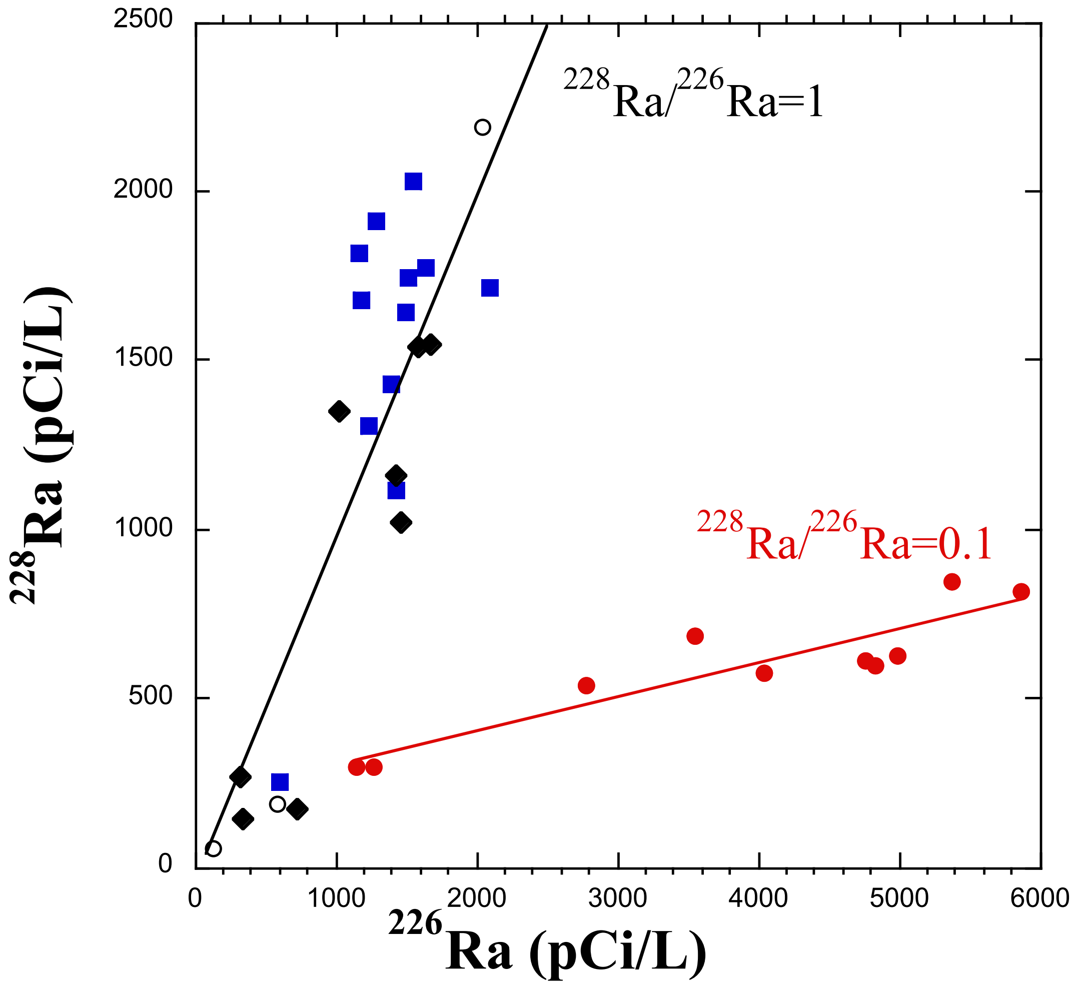


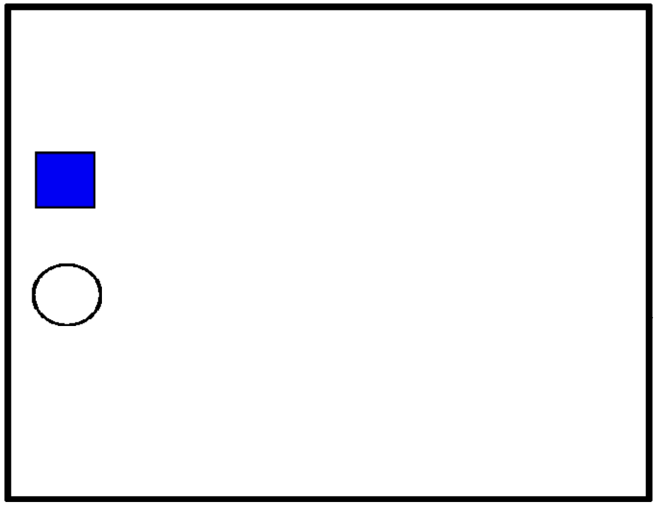
Radiation threshold (requires a licensed radioactive waste disposal facility)

Source: Warner (2013) PhD thesis, Duke University

The used of radium isotopes

Distinction between the Marcellus brines and other (conventional) oil and gas produced waters

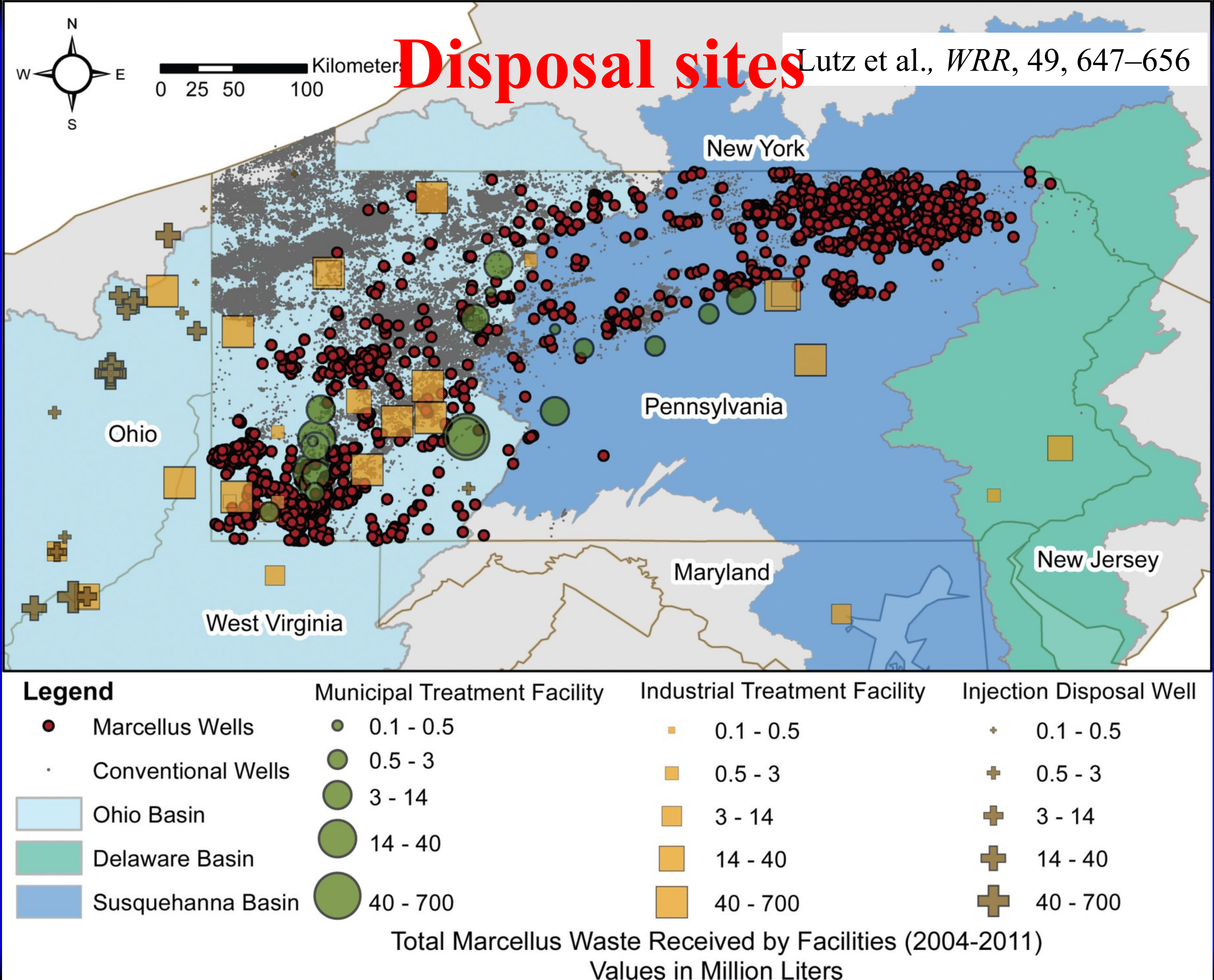




Source: Warner (2013) PhD thesis, Duke University

Disposal sites

Lutz et al., *WRR*, 49, 647–656



Final comment…

Our knowledge and actual data is limited. We are only at the beginning stage in evaluation of the overall impacts of shale gas development on water resources in the US.

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For more information: http://sites.nicholas.duke.edu/avnervengosh/