Using Geoscientific Analysis and Community Engagement to Analyze Exposures to Potential Groundwater Contamination Related to Hydrocarbon Extraction in Southwestern Pennsylvania

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1. Penn State University
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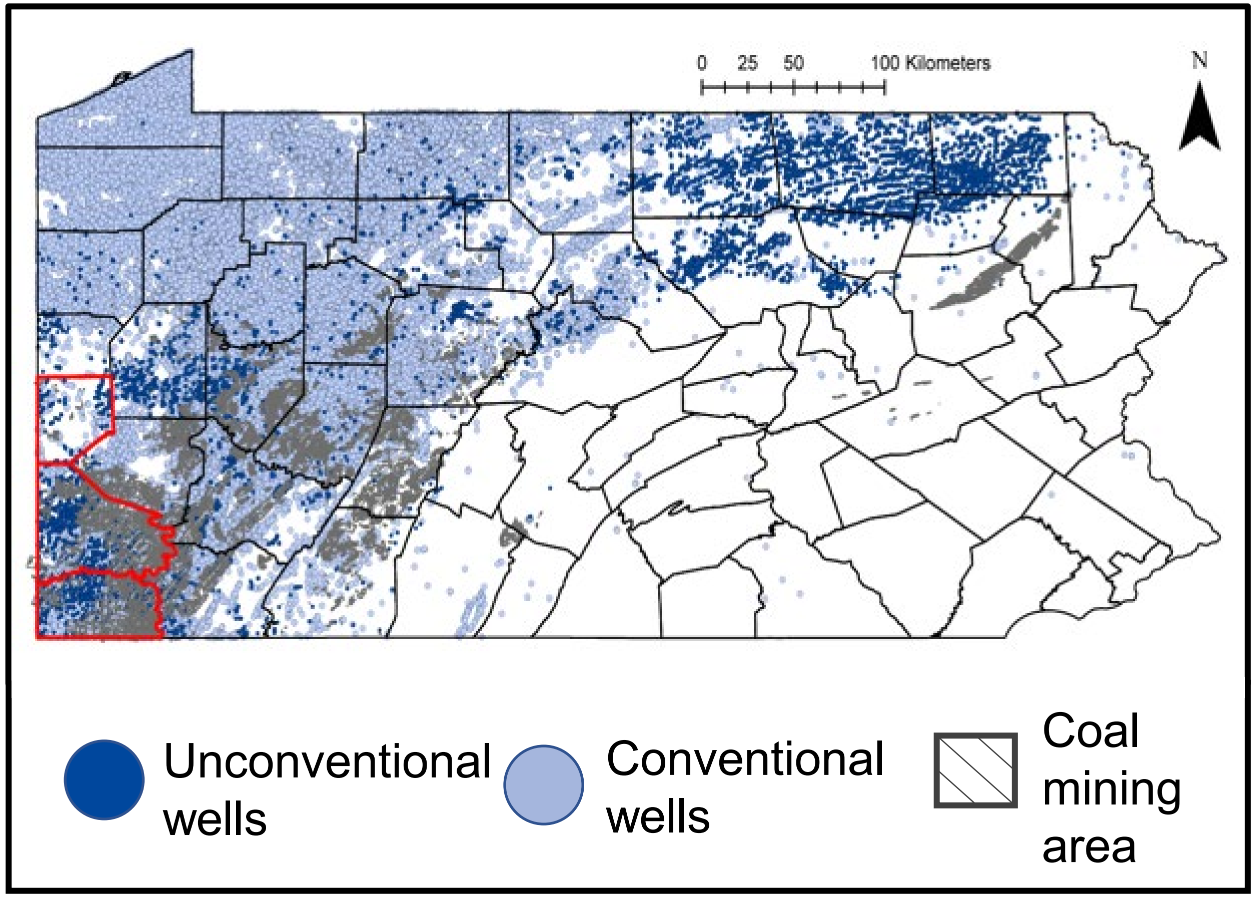
Marcellus Shale wellpad in Washington County, PA
Photo: Scott Goldsmith

Objective

- To evaluate the relationship and possible pathways amongst unconventional oil and gas development (UOGD), water contamination and public health
- Method: Integrate **community focus groups** and geoscientific analysis to better understand the energy-water-health nexus in Southwestern PA



What is a focus group?

- A qualitative research method
- A group interview of a small number of people who share similar characteristics or interests
  - NOTE: Does not have to be representative of all possible opinions on the research topic
- The objective is to gather more in-depth information on perceptions, opinions, experiences, etc.
- Research team facilitates discussion using a pre-determined set of questions
- Can be used to inform other research methods, such as quantitative analysis

Project Focus Groups

- Sessions held in summer 2022 and 2023
- Six total sessions, 3 each year, 2 total per county
- Sessions lasted ~90-150 minutes
- Participants from summer 2022 invited back to summer 2023
- Preliminary results were shared with summer 2023 participants
- All sessions were recorded, transcribed and analyzed using NVivo, a qualitative analysis software
- Emergent coding scheme, following Saldaña (2016)

Community Focus Groups

Overarching question: What UOGD-related changes have you observed to the area's water quality and public health?

	Summer 2022					Summer 2023*				
Focus Group	Participants	Male	Female	Average Age	Average Time in County (years)	Participants	Male	Female	Average Age	Average Time in County (years)
Beaver	16	3	13	54	30.2	7	3	4	55.4	35.1
Washington	14	5	9	59.9	30.5	8	3	5	64.9	45.3
Greene	6	2	4	69.1	49.5	2	1	1	69.5	32

*2023 participants also attended summer 2022 sessions.

Six Themes of Analysis

1. Observed changes to water
2. Possible contaminants and pathways of contamination
3. Health effects
4. Recommendations for improvement
5. Obstacles to knowledge
6. Sources of information

Contaminants of Concern

- Residents most concerned about possible radiation exposure
  - Very familiar with NORMS/TNORMS related to UOGD
- Mentions of chlorine/chloramine & Radon concentrated in Beaver
- Synthetics= PFAS, "fracking chemicals," non-specific "industrial chemicals"
- Radon discussed in Beaver County
- Scattered references to Barium and Strontium

Contaminant	Beaver	Washington	Greene	Total
Radiation	**12**	**14**	**0**	**26**
Synthetics	6	7	0	13
Chlorine/ Chloramine	9	1	1	11
Methane	3	1	1	5
Radon	4	0	0	4
Barium	0	2	1	3
Strontium	0	2	0	2

NOTE: #s refer to mentions of a topic

Pathways of Concern

- Residents most concerned about wastewater management practices
  - Many observed spills and leaks in the region
- Above Ground= spills, leaks, and flowback at the well pad
- Below Ground = well communication, brine migration, well water damage
- Waste Disposal & Storage= Holding ponds, drill cuttings, brine dumping

Pathway	Beaver	Washington	Greene	Total
Waste Disposal & Storage	**13**	**14**	**5**	**32**
Below Ground	3	7	5	15
Above Ground	0	3	1	4

NOTE: #s refer to mentions of a topic

Health Effects

- Residents primarily concerned about the relationship between UOGD and cancer
    - Ewing's sarcoma
    - Rare cancers
- Many were cancer survivors themselves and/or lost a close relative to cancer
- Difficulty distinguishing the causes of cancers in historically polluted landscape mentioned

Health Effect	Beaver	Washington	Greene	Total
Cancer	**5**	**7**	**4**	**16**
General sickness	3	3	1	7
Burning Eyes or Skin	1	3	0	4
Kidney Issues	1	2	0	3

NOTE: #s refer to mentions of a topic

Representative Quote

In Bobtown we have lots of kids, unfortunately, at different times who've had cancer, childhood cancers, again and all very rare diseases, and different types. So they're, "Oh, you're one in a million. You're one in a million." But how many people can hit the power ball on one particular street, or one tiny community, that has a little over 300 houses.

Greene county participant

Focus Group Key Takeaway

Communities are most concerned about potential radiation exposure from UOGD wastewater management, which may increase risks of cancer

Geoscientific Identification of Contamination

Sam Shaheen, Tao Wen, **Susan Brantley**, Jennifer Baka

Methods of investigation

- Field work to figure out what happens on a case by case basis (uses sampling, chemical analysis, isotopic analysis, history, data gathering from all concerned, etc.)
- Geostatistical analyses to figure out prevalence and identify causes of problems

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Vidic, Brantley et al., 2013 (Science)

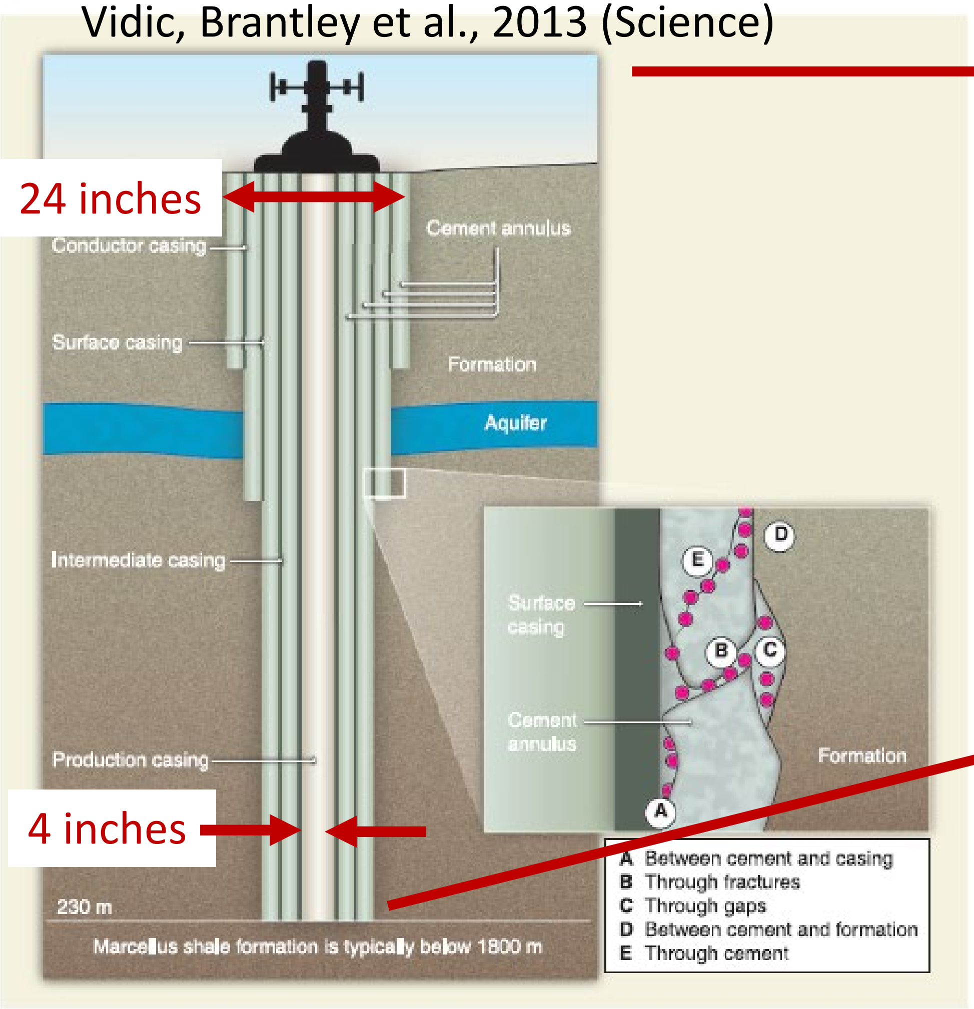
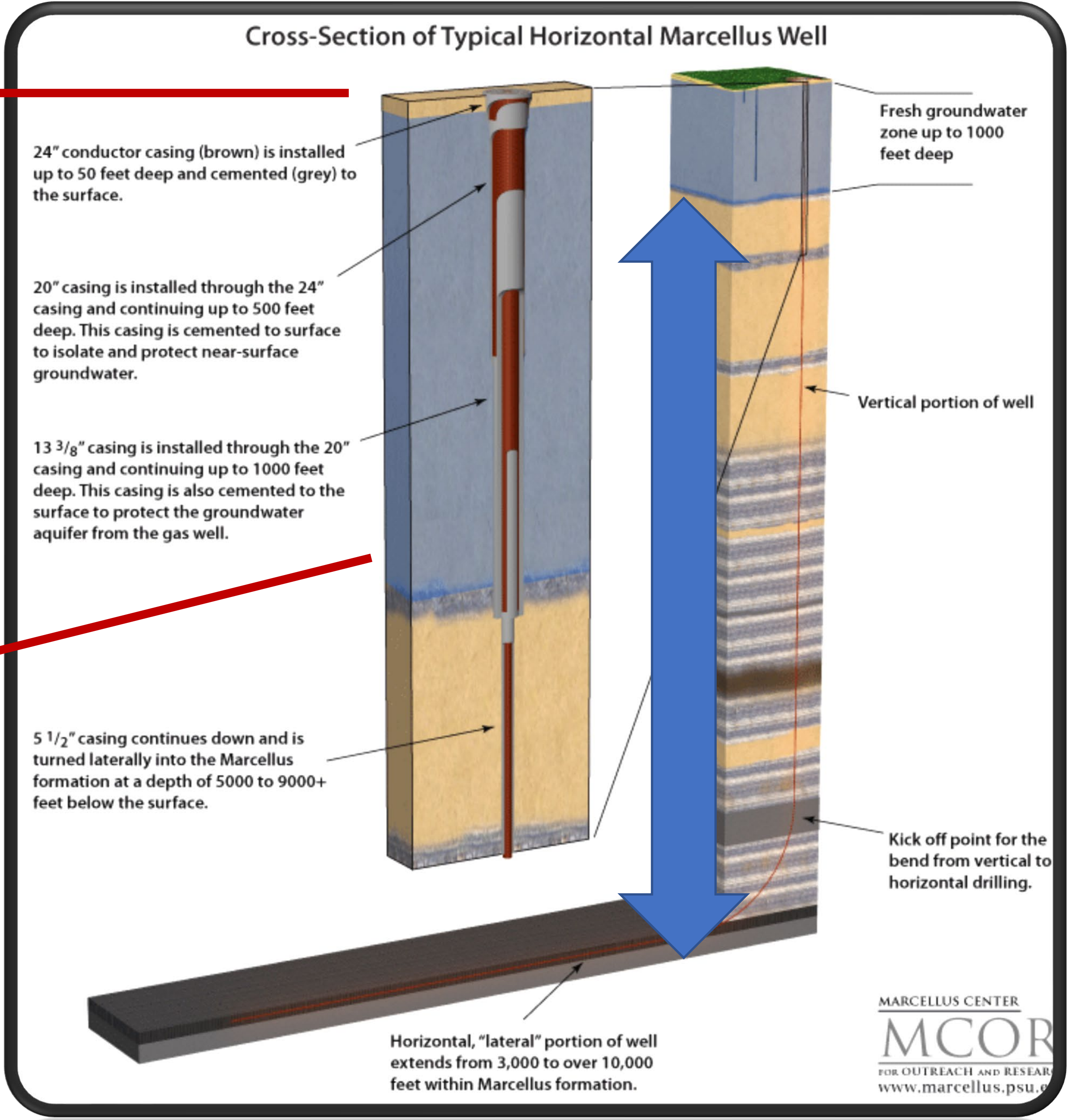
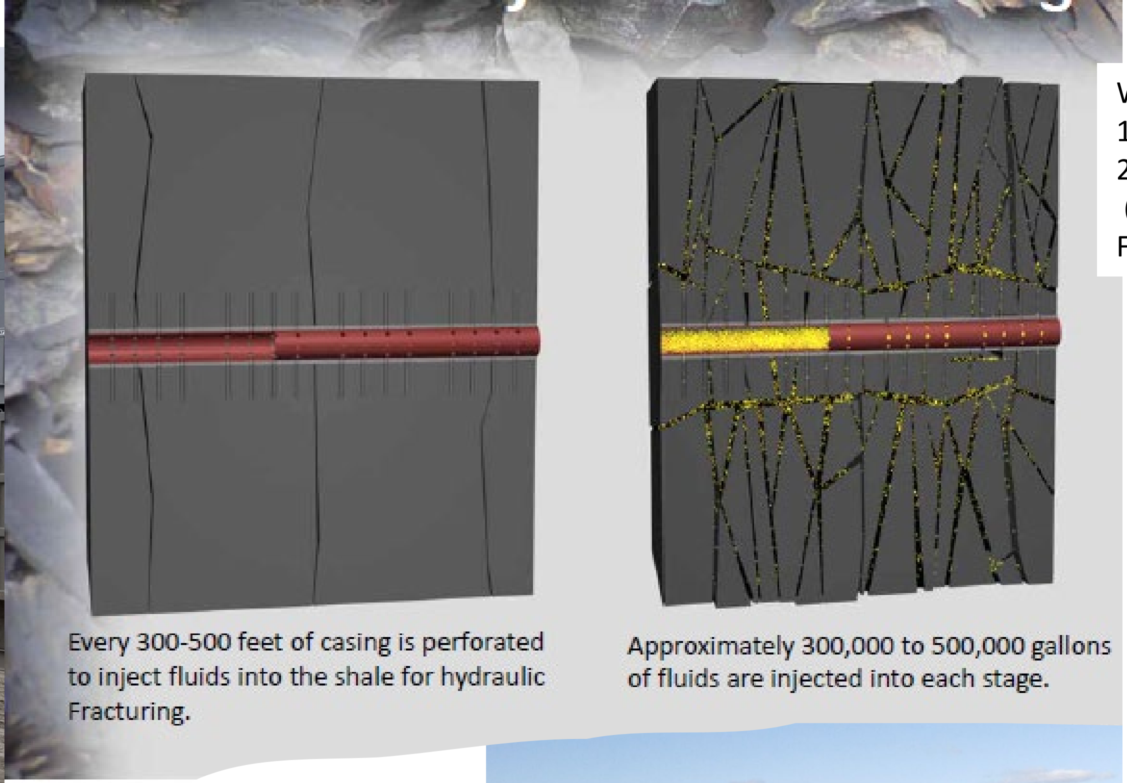
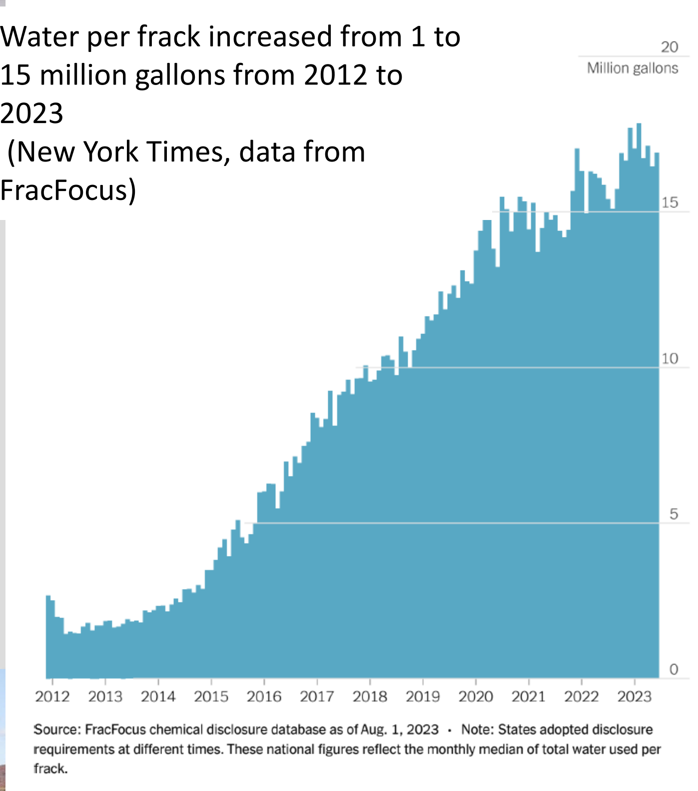


Fig. 3. Typical Marcellus well construction. (i) The conductor casing string forms the outermost barrier closest to the surface to keep the upper portion of the well from collapsing and it typically extends less than 12 m (40 ft) from the surface; (ii) the surface casing and the cement sheath surrounding it that extend to a minimum of 15 m below the lowest freshwater zone is the first layer of defense in protecting aquifers; (iii) the annulus between the intermediate casing and the surface casing is filled with cement or a brine solution; and (iv) the production string extends down to the production zone (900 to 2800 m), and cement is also placed in the annulus between the intermediate and production casing. Potential flaws in the cement annulus (Inset, "A" to "E") represent key pathways for gas migration from upper gas-bearing formations or from the target formation.







Fracking ('well completion')

Table 1. Common chemical additives for hydraulic fracturing.

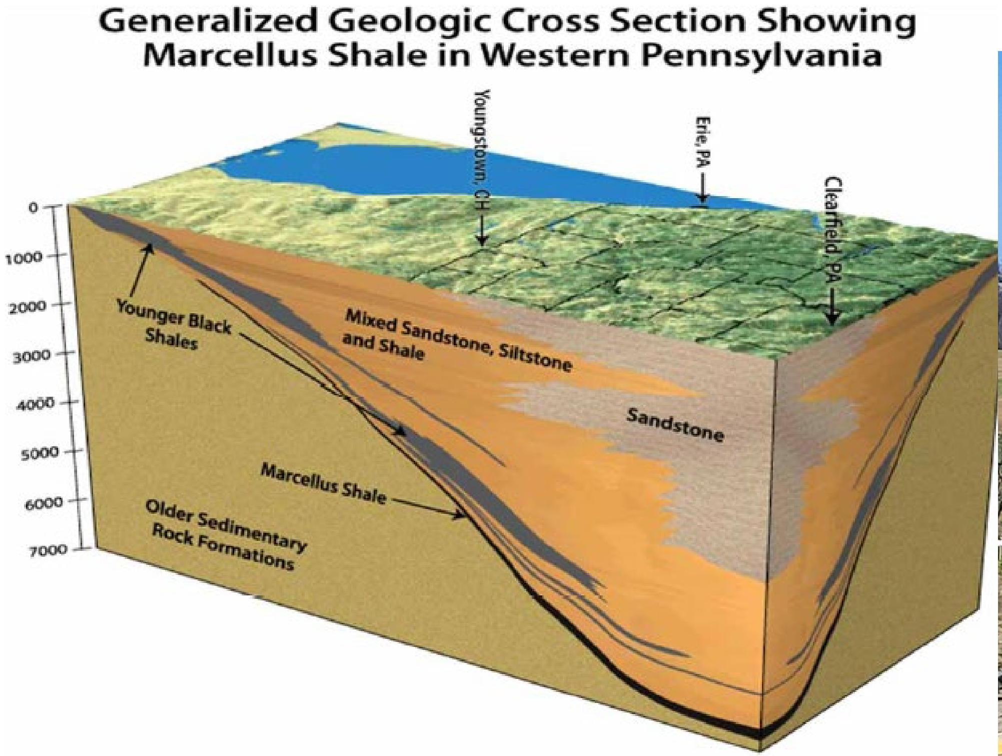
Additive type	Example compounds
Acid	Hydrochloric acid
Friction reducer	Polyacrylamide, petroleum distillate
Corrosion inhibitor	Isopropanol, acetaldehyde
Iron control	Citric acid, thioglycolic acid
Biocide	Glutaraldehyde, 2,2-dibromo-3-nitrilopropionamide (DBNPA)
Gelling agent	Guar/xantham gum or hydroxyethyl cellulose
Crosslinker	Borate salts
Breaker	Ammonium persulfate, magnesium peroxide
Oxygen scavenger	Ammonium bisulfite
pH adjustment	Potassium or sodium hydroxide or carbonate
Proppant	Silica quartz sand
Scale inhibitor	Ethylene glycol
Surfactant	Ethanol, isopropyl alcohol, 2-butoxyethanol

Many chemical compounds are included in the frack water, including poisons, at very very low concentrations (0.5 to 2% of mixture). **In PA and many other states not all chemicals must be reported publicly**.

At least 17 compounds, including benzene, have been associated with cancers such as leukemia.

Vidic, Brantley, et al. Science 2013

In Appalachian Basin, 10-20% of the injected frack water returns to the surface either as flowback water (soon after fracturing) or production water (after gas production commences).

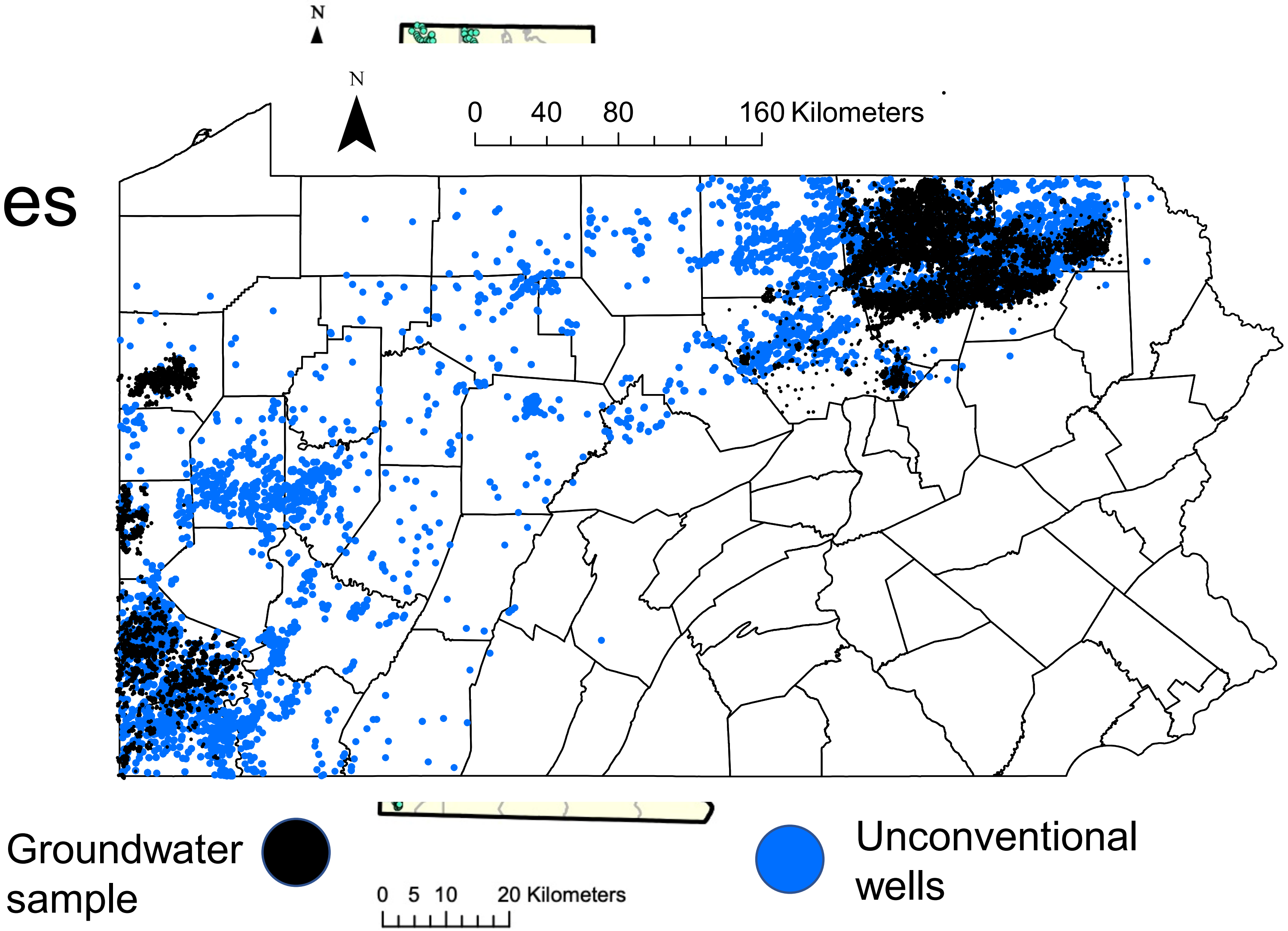


Perhaps 1/2 the fluid returns during lifetime of well … and one wellpad with 6 wells might drain brine from a square mile of shale (Pers. Comm. T. Engelder, Penn State)

The Shale Network dataset

SWPA dataset:
~7000 groundwater analyses from Washington, Greene, and Beaver counties

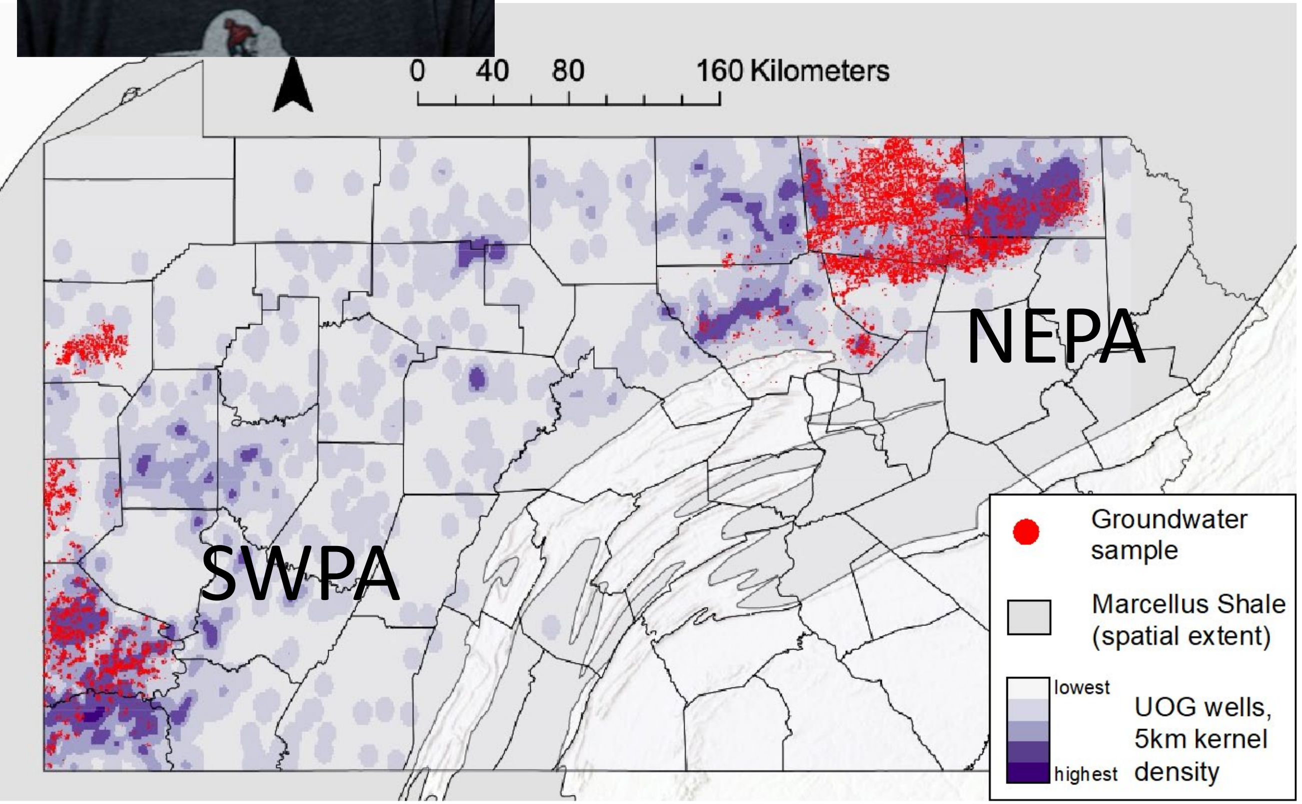
Statewide dataset:
~29000 groundwater samples from shale gas regions of PA

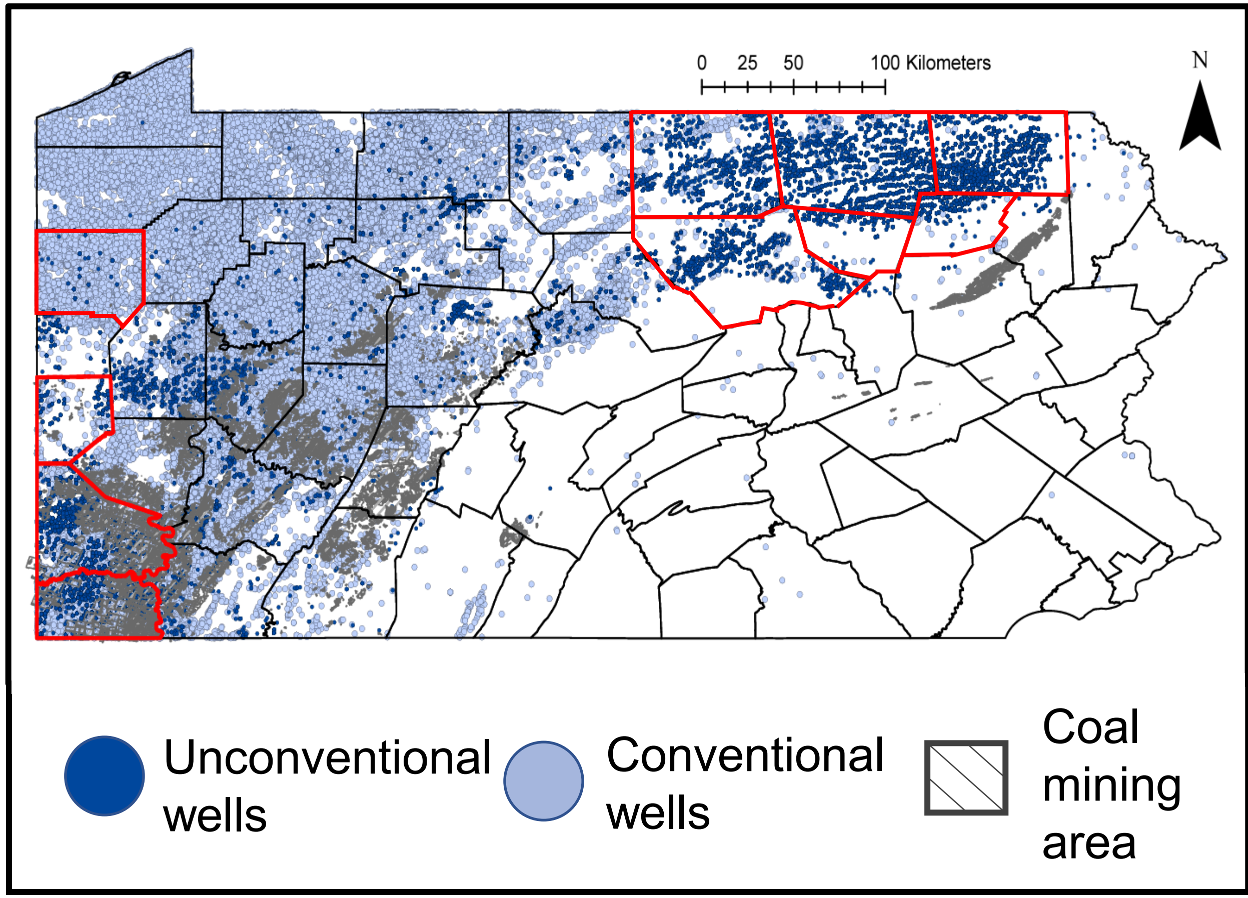


Is UOGD affecting groundwater in water wells and if so…how?

>28,500 samples from Marcellus shale regions of PA

Work by Sam Shaheen, PhD candidate, Penn State





Shaheen et al., submitted to ERL

Some Species in Marcellus Shale Production Water

Statewide Average	
TDS	106,390 mg/L
TSS	352 mg/L
oil and grease	74 mg/L
Chemical O_2 demand	15,358 mg/L
pH	6.56
SO_4	71 mg/L
Cl	57,447 mg/L
Br	511 mg/L
Na	24,123 mg/L
Ca	7,220 mg/L
Ba	2,224 mg/L
Sr	1,695 mg/L
Ra-total (pCi/L)	4093
U-total (pCi/L)	43

7X saltier than seawater

Organics can contain benzene, toluene, TCE

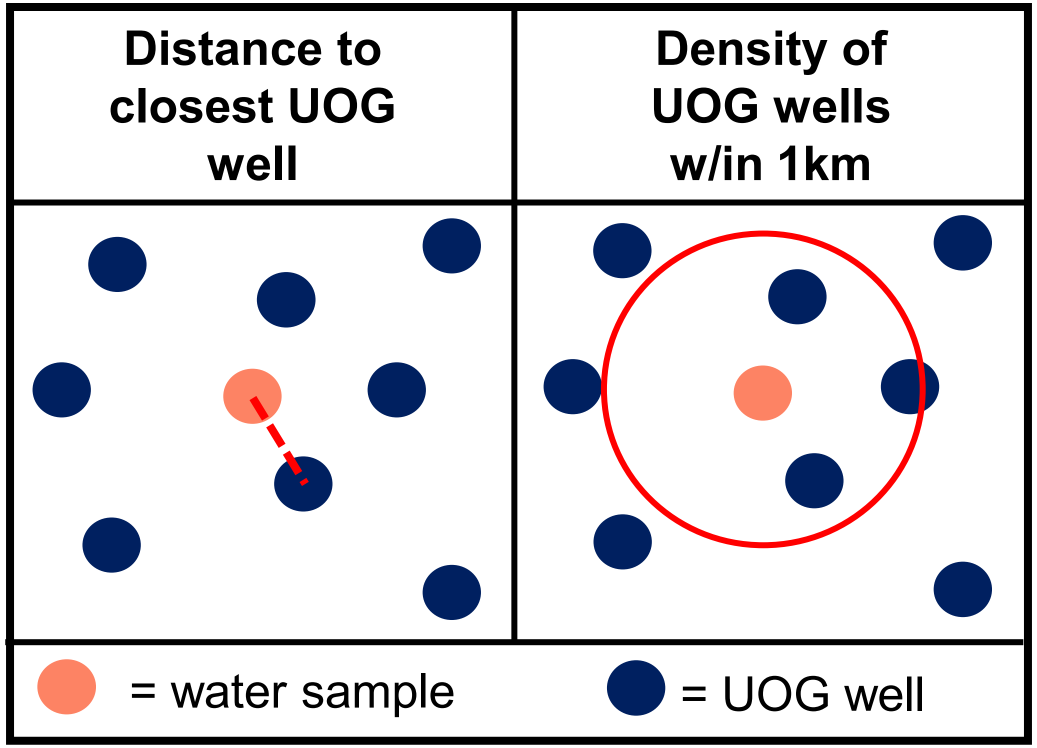
The Marcellus production water, which contains organic compounds from fracking and shale, is mostly sodium (Na) + chloride (Cl) brine. It has "fingerprint species" barium (Ba), strontium (Sr), and bromide (Br), and toxic elements such as thallium and arsenic.

Radium (Ra) is the main contributor of radioactivity

Data from Radisav Vidic as published in Barbot et al. (2013); Rowan et al. (2011)

Regional analysis indicates chloride, barium, and strontium concentrations increase with UOGD proximity and density across SWPA (natural gas concentrations do not increase)

Tested 2 metrics:



Evaluated Kendall rank correlation between concentrations and proximity or density of UOGD

Statistically significant ($p < 0.005$) correlations identified for Cl, Ba, Sr

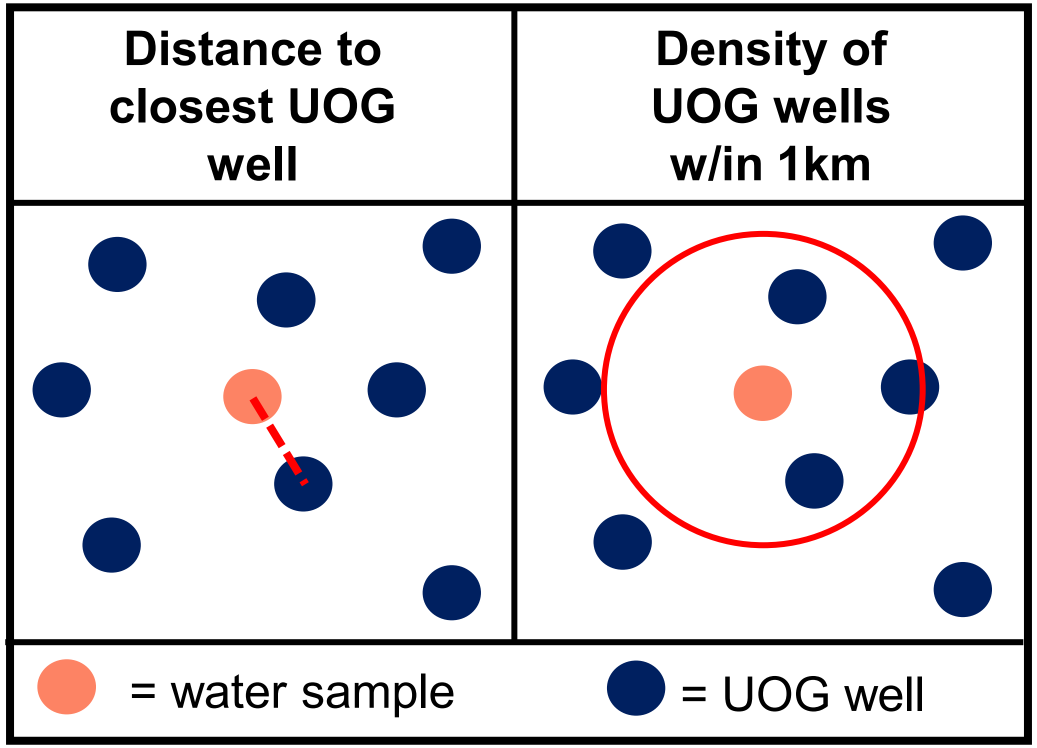
Shaheen et al., *ES&T*, 2022

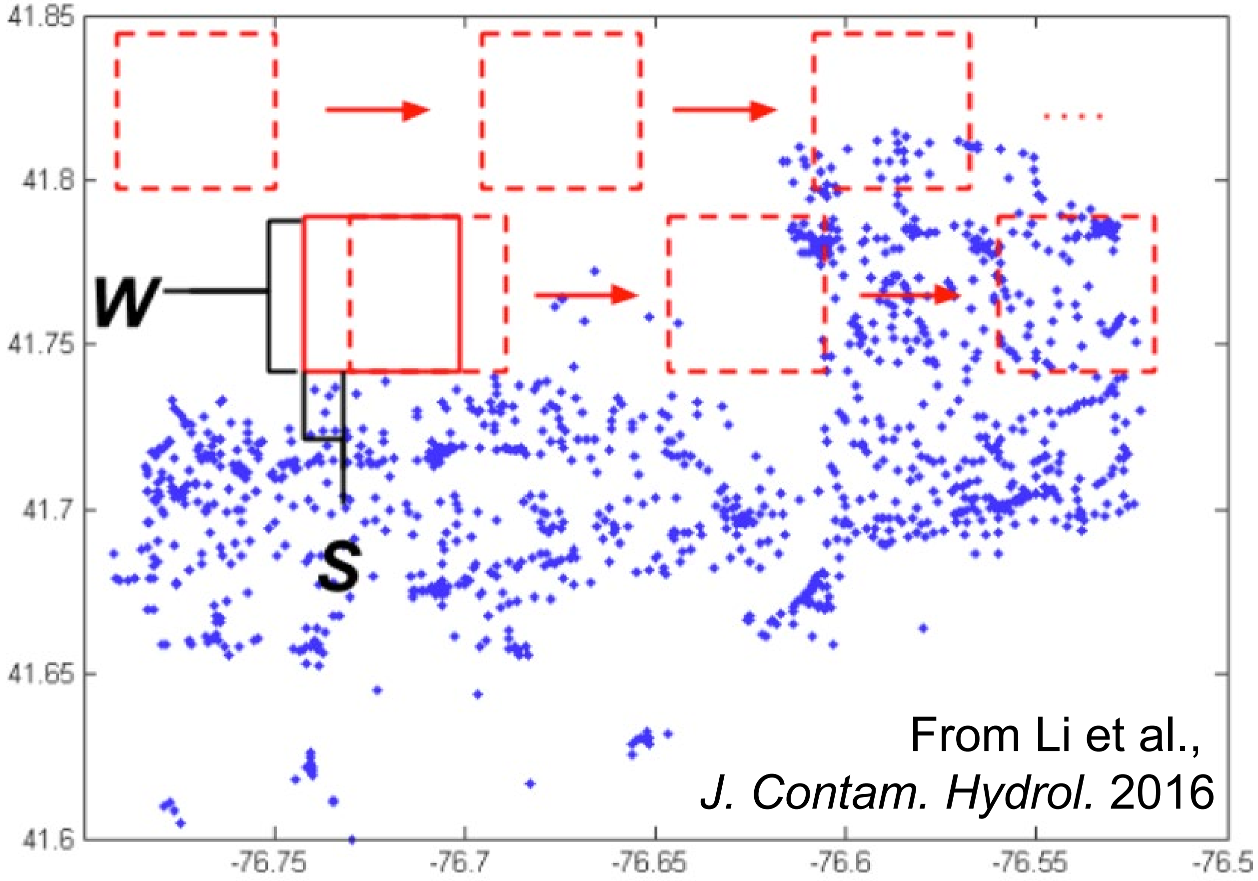
Why are there regional increases in salt concentrations in groundwater in SWPA?

Is the regional increase in salts caused by isolated problem locations?

Sliding window finds "hotspots" of strong correlation moving a 5km x 5km window across an area by 200 m increments, calculating Kendall rank

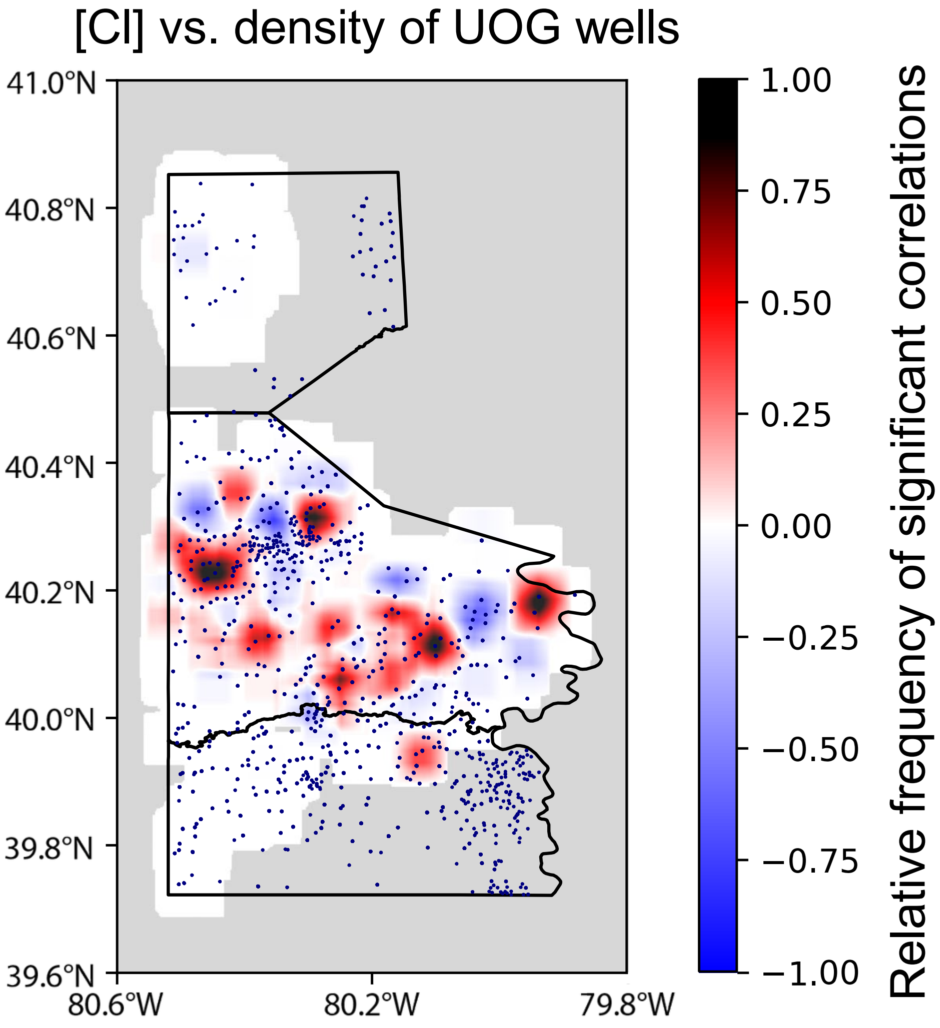
Tested 2 metrics:





From Li et al., *J. Contam. Hydrol.* 2016

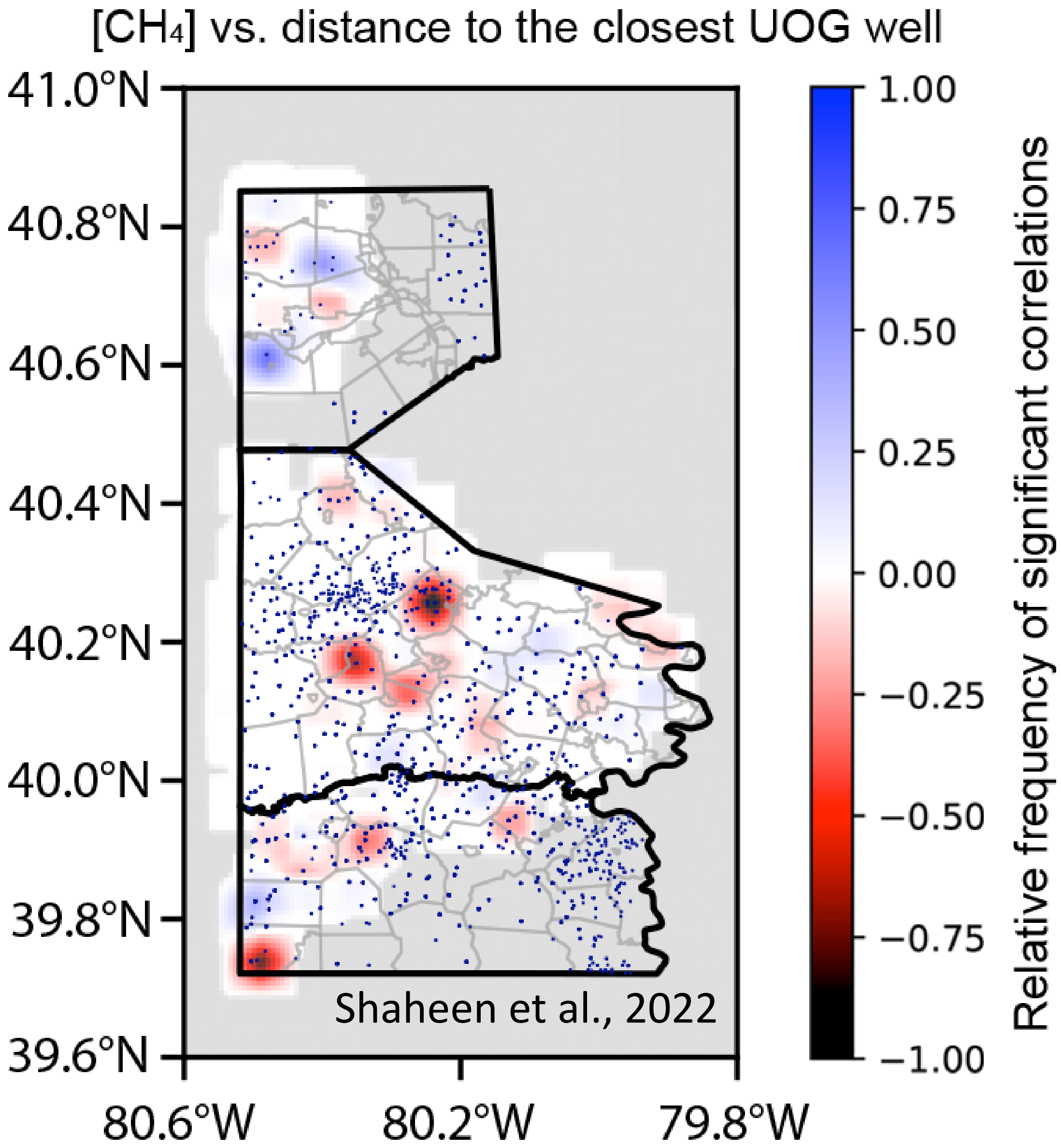
Slide from Sam Shaheen



Shaheen et al., submitted to ERL

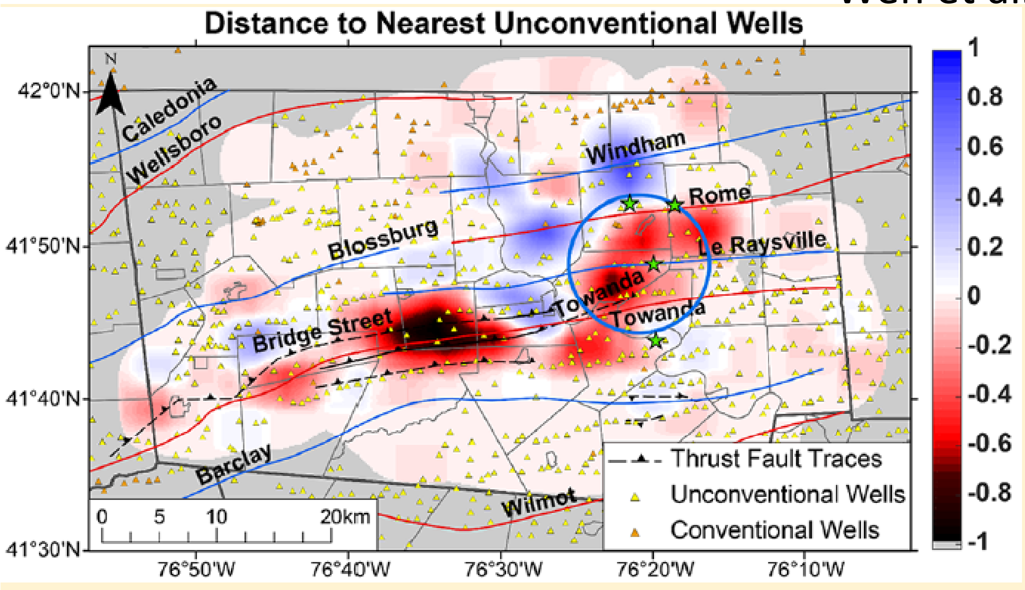
The regional salt increases in groundwater are likely explained by hotspots (identified here with the computational sliding window approach)

We also observed that only 0.13% of UOG wells may leak CH_4 in SWPA versus 0.51% in NEPA



Shaheen et al., 2022

Wen et al., 2018



North Eastern Pennsylvania (NEPA)…may leak especially where uncased/cemented wells cross dipping faults

South Western Pennsylvania (SWPA)..may leak less than NEPA because much of the intermediate-depth gas was already extracted

What causes the chloride hotspots?

Machine learning-based separation of sources of chloride

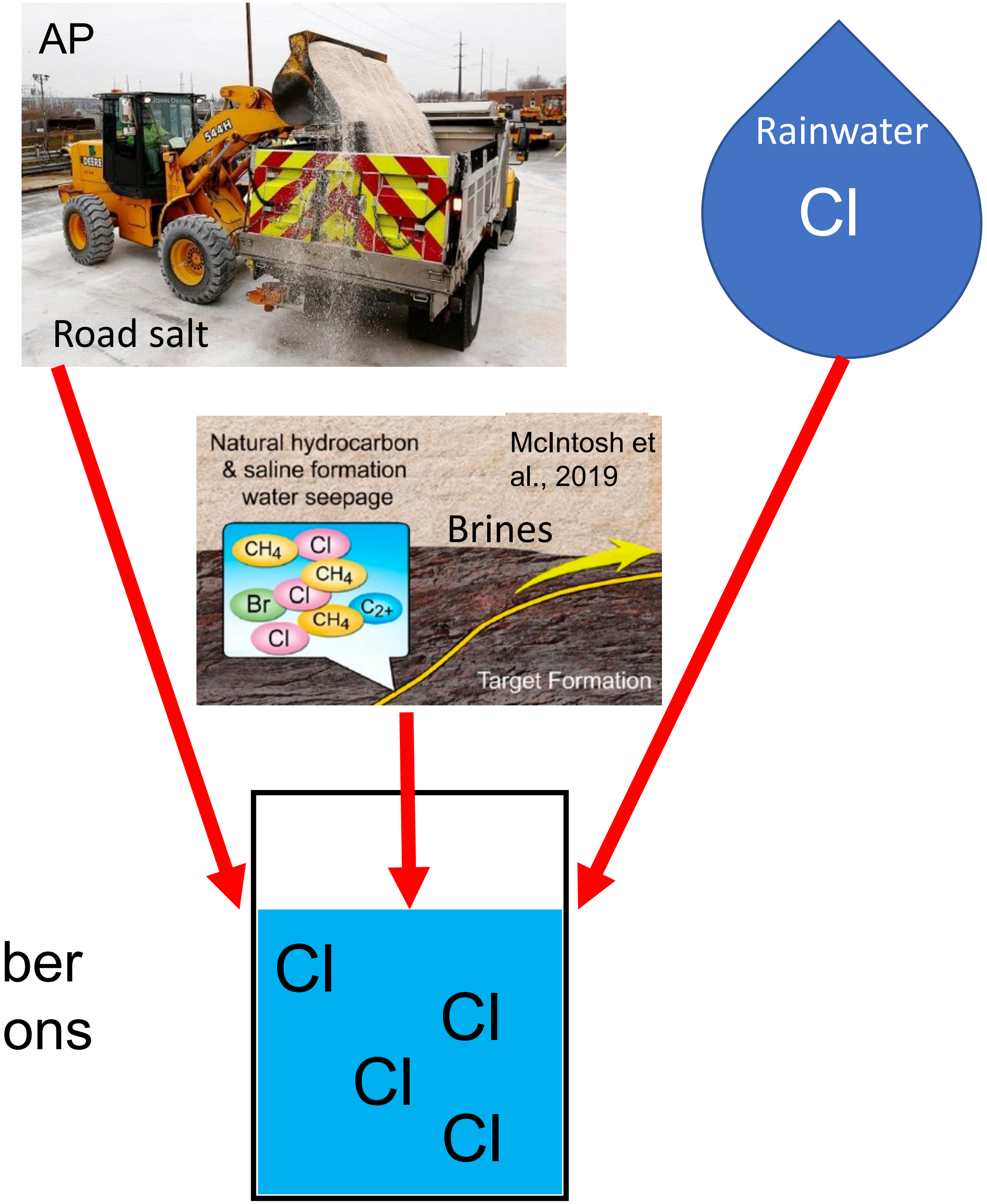
Non-negative matrix factorization

$$V = W \times H$$

Groundwater chemistry matrix

Endmember mixing proportions

Endmember compositions

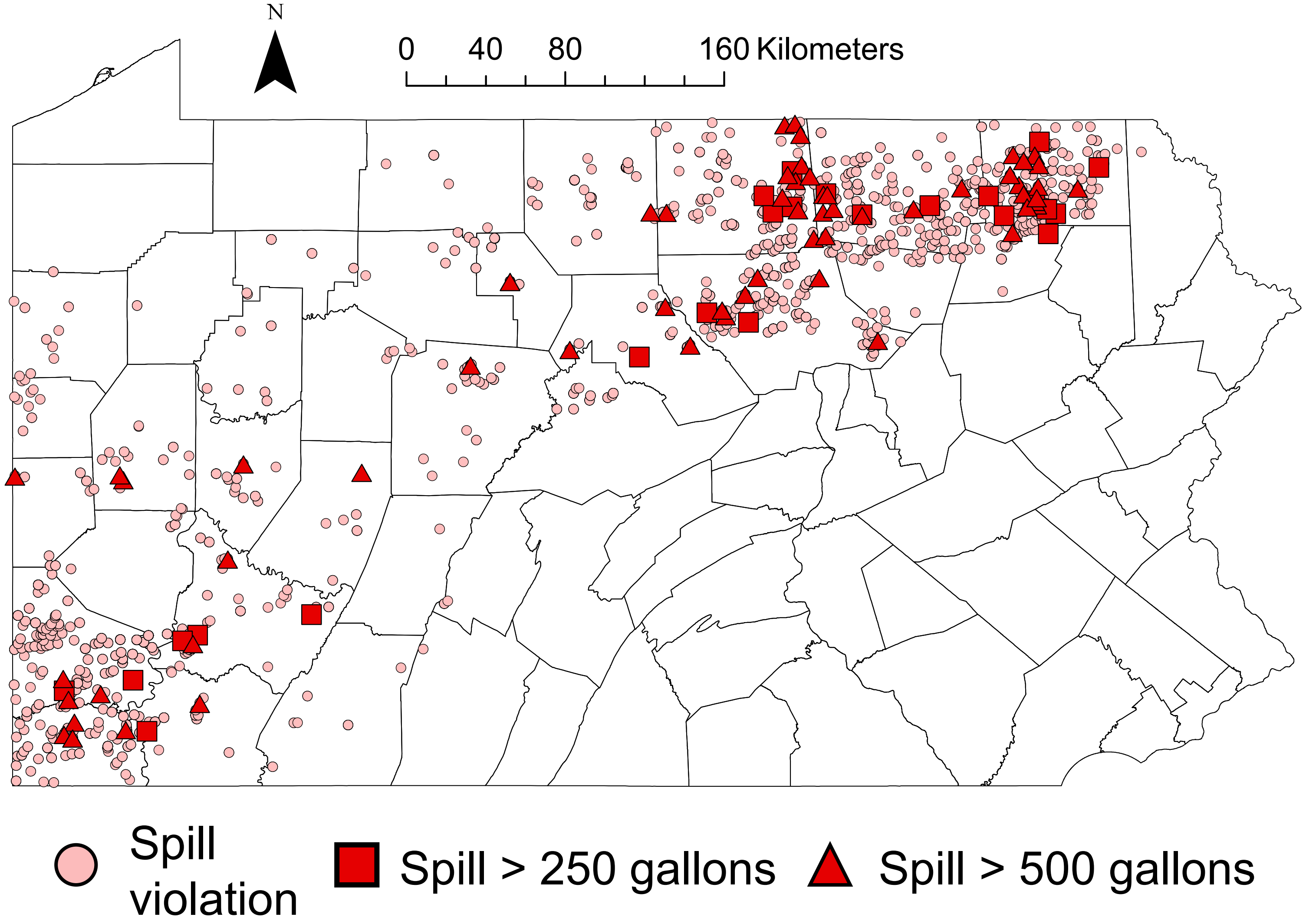


Shaheen et al., 2022

The amount of salt in a waste water **spill >250 gallons** could explain the increases in [Ba] we observe within 1km

Median **[Ba] is 23% higher** within 1km of a **>250 gallon wellpad spill** ($p < 0.05$)

Shaheen et al., submitted to ERL

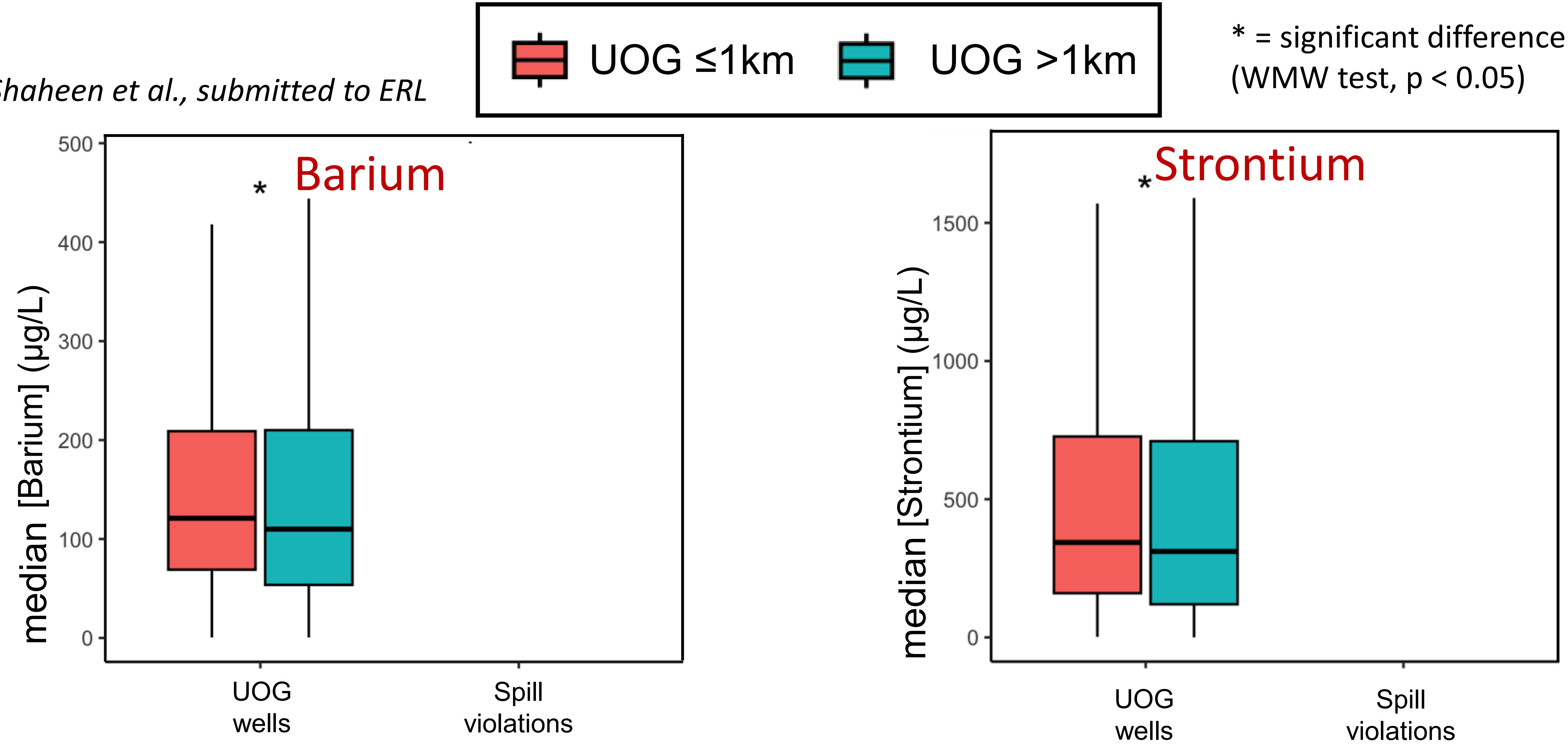


Spill volume data from Patterson et al. *ES&T*, 2017

Higher [Ba] and [Sr] within 1km gas wells statewide

Shaheen et al., submitted to ERL

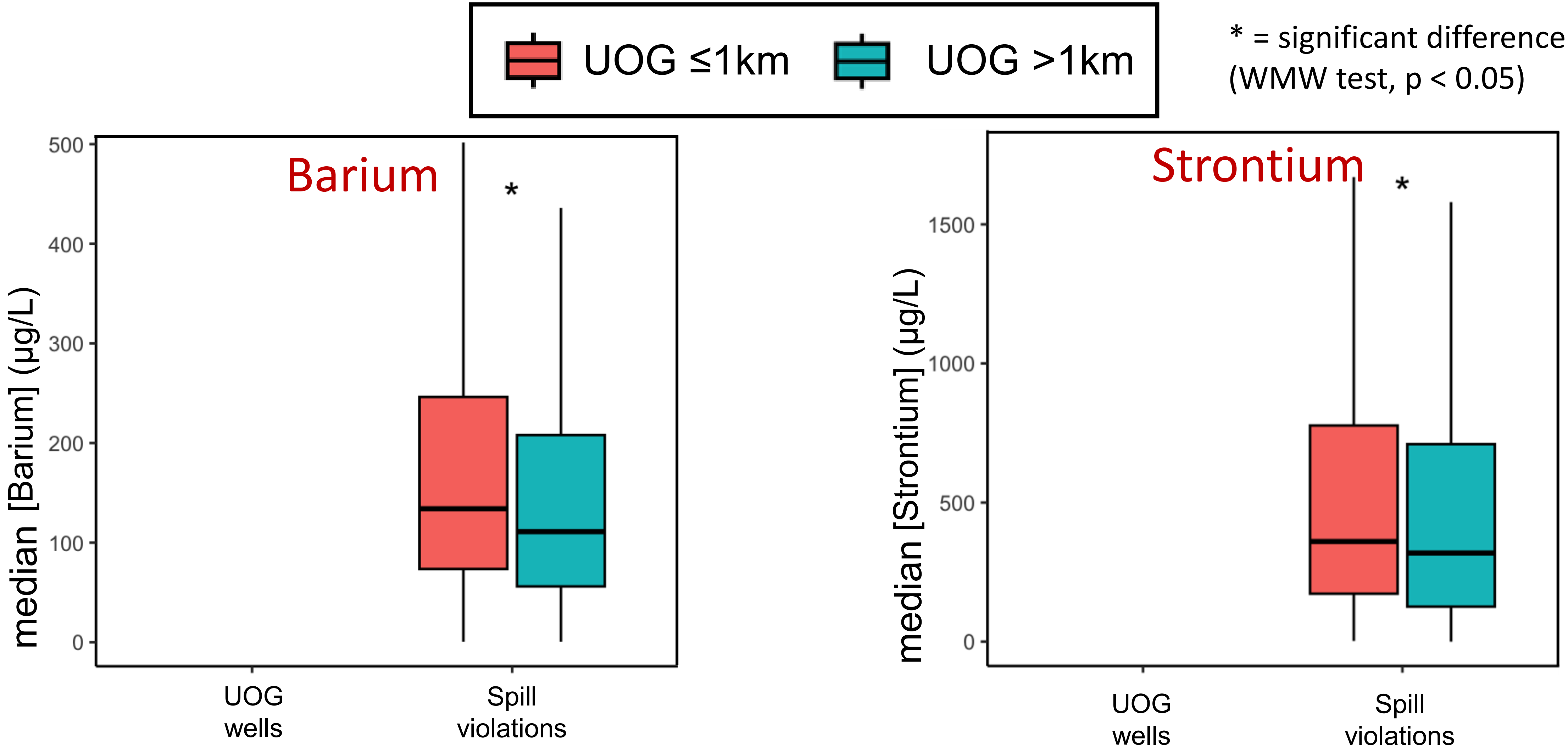
* = significant difference (WMW test, $p < 0.05$)



No significant increases found for casing or cementing violations statewide

Higher [Ba] and [Sr] within 1km of spills statewide

* = significant difference (WMW test, $p < 0.05$)

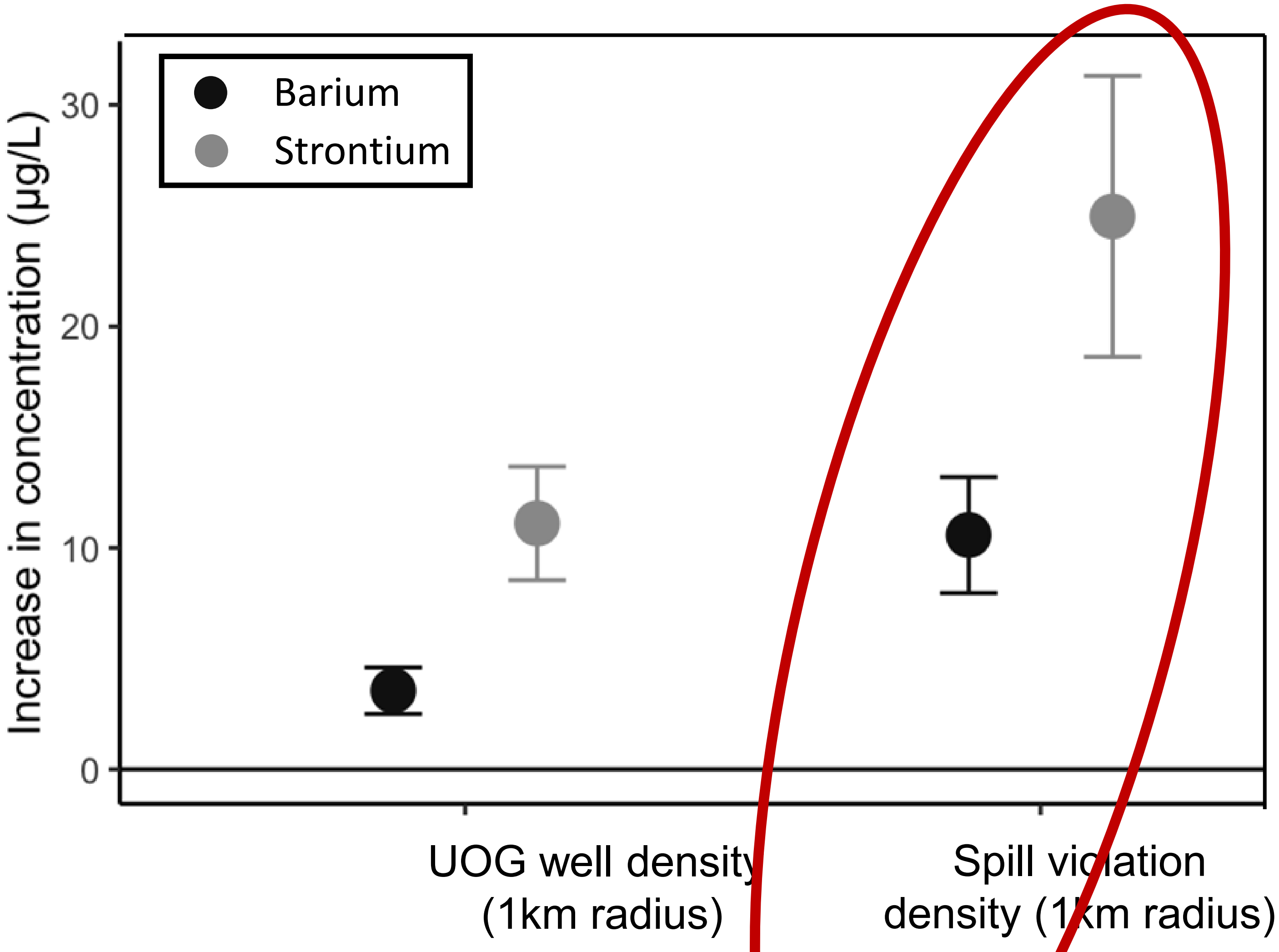


Shaheen et al., submitted to ERL

Average increase in [Ba] or [Sr] with a 1-unit increase in spill density is larger than with 1-unit increase in UOGD density…and the ratio of Ba to Sr looks like the ratio in waste waters

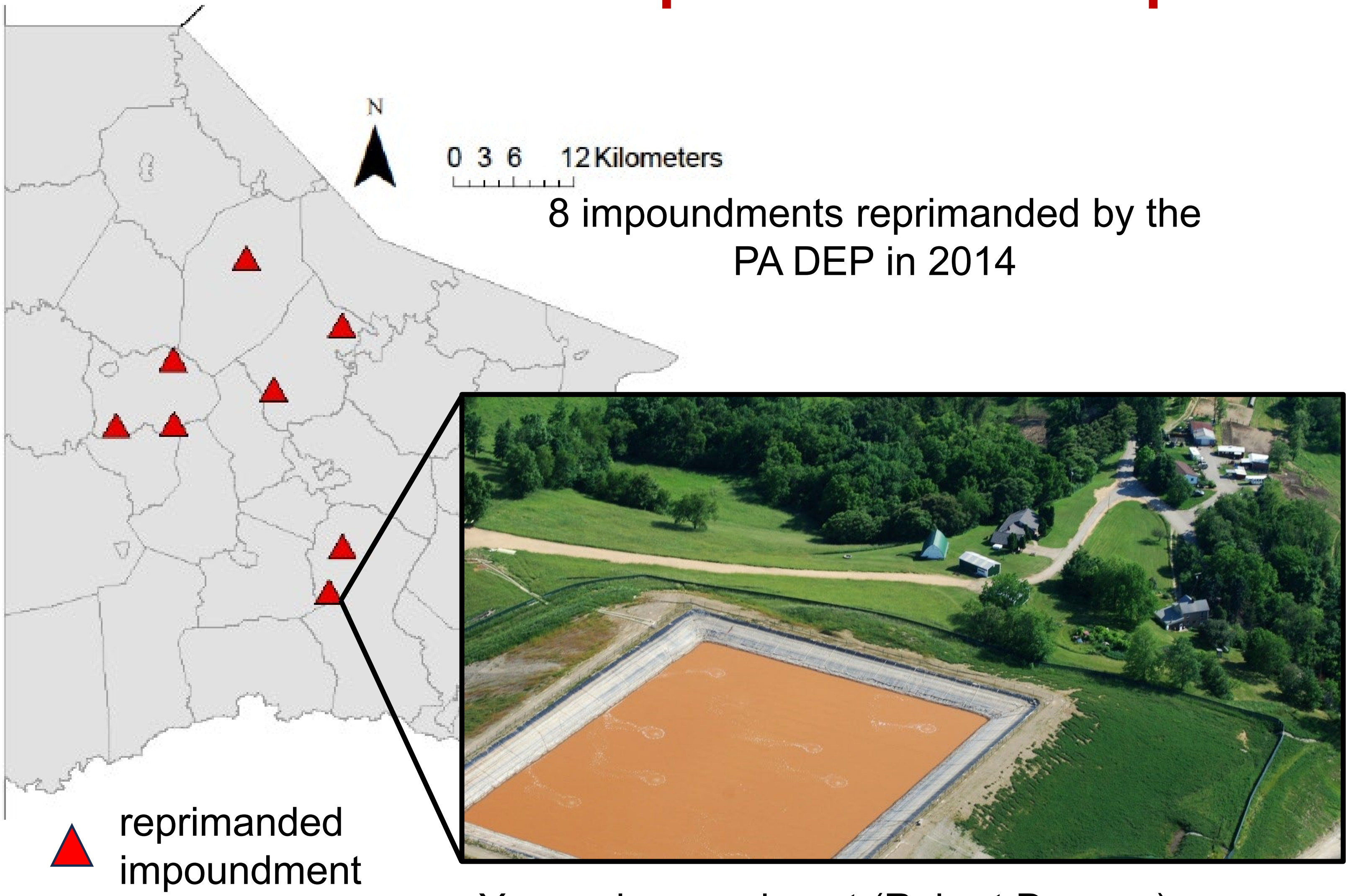
$\log C = \beta \, \#UOGD_{1km}$

Shaheen et al., submitted to ERL



	Groundwater [Ba] / [Sr]	Produced water [Ba] / [Sr]	UOG well density β_{Ba} / β_{Sr}	Spill density β_{Ba} / β_{Sr}
Ratio	**0.45**	**1.21**	**0.70**	**0.94**

In SWPA, [Ba] and [Sr] also increased near problem impoundments



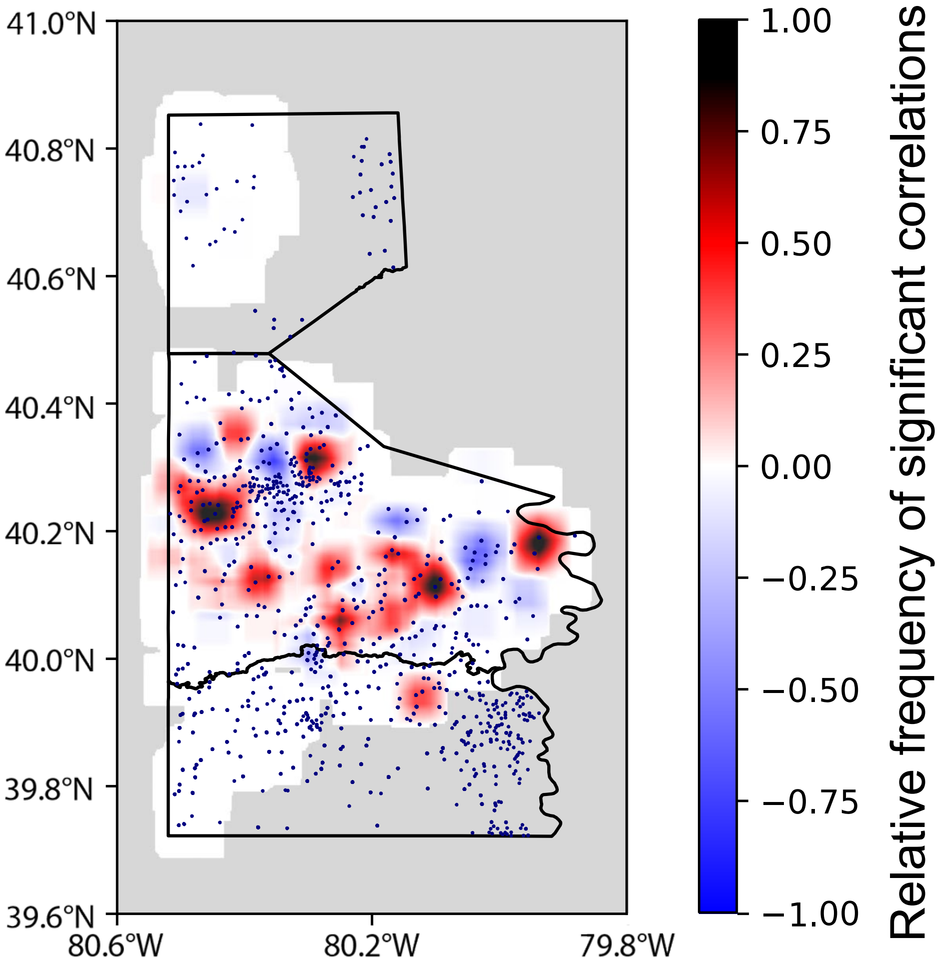
Yeager impoundment (Robert Donnan)

Median [Ba] is 34% higher within 1km of these impoundments ($p<0.001$)

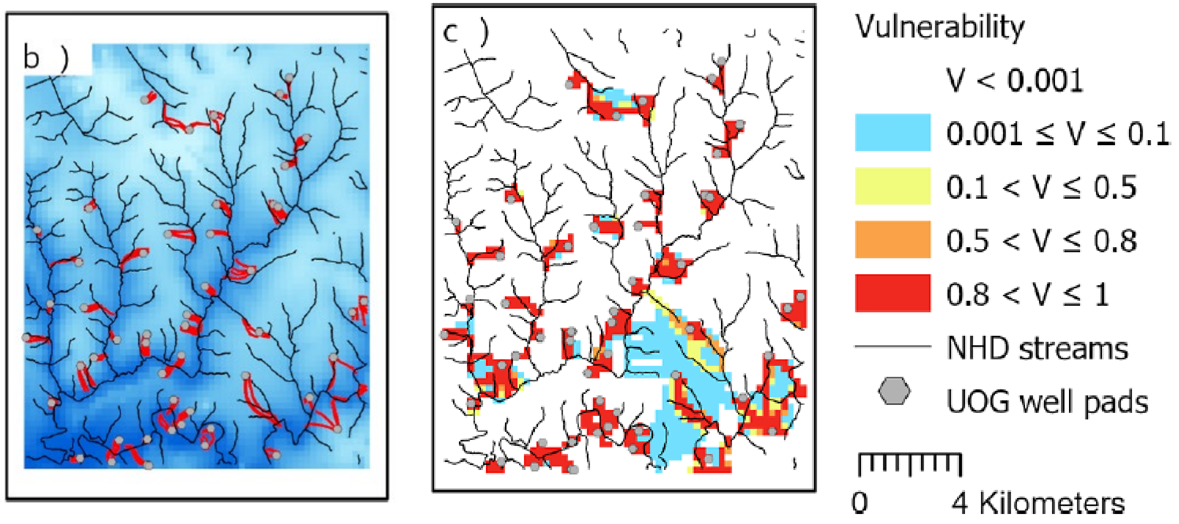
Shaheen et al., submitted to ERL

We think the regional salt increases in SWPA are caused by salts in groundwater flowing "downhill" from spills or leaking impoundments

[Cl] vs. density of UOG wells



When we compare the hotspots to groundwater flow modelling (Soriano et al. 2022) we see some general agreement



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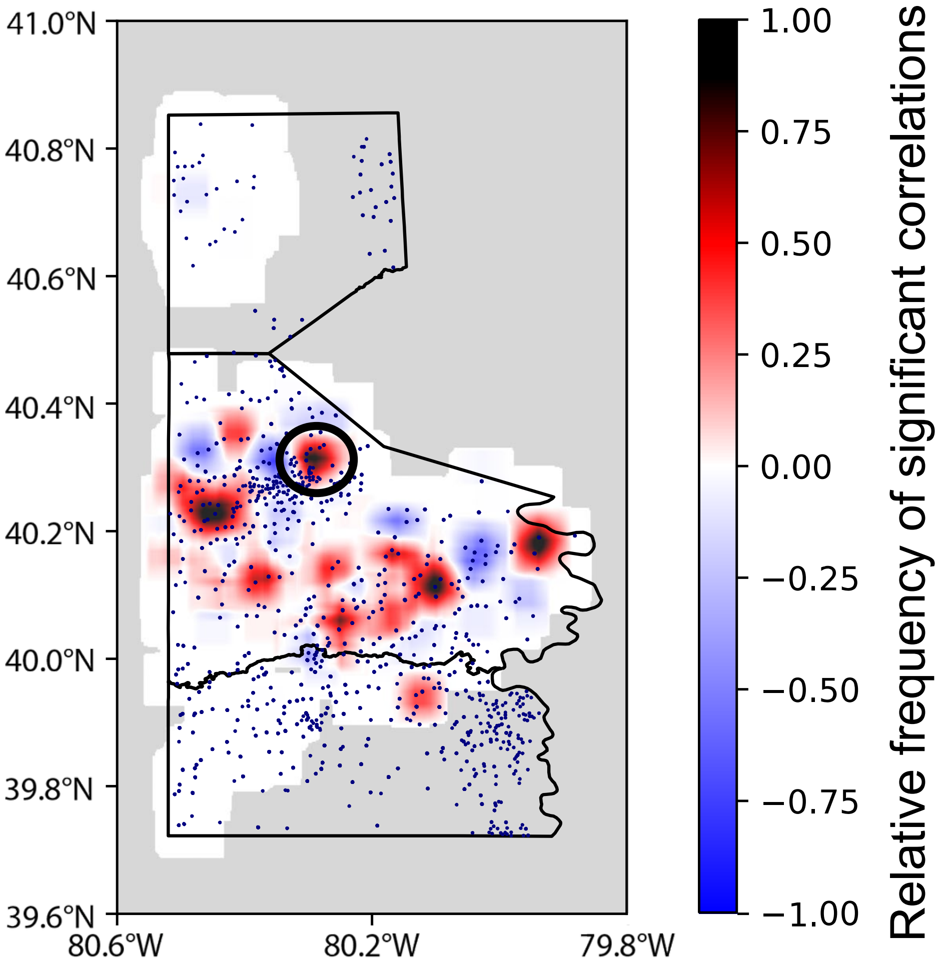


Shaheen et al., submitted to ERL

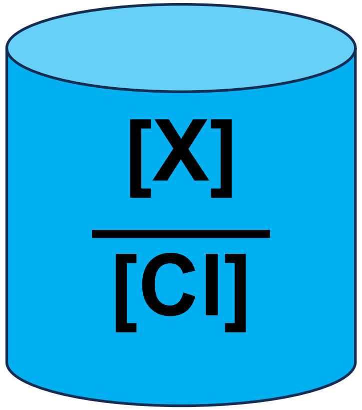
When we compare the hotspots to groundwater flow modelling (Soriano et al. 2022) we see some general agreement

One of the chloride hotspots overlaps with the Carter impoundment (where nearby residents complained of air and water contamination prior to impoundment shutdown)

Why might salt concentration be important?

Toxic element concentrations in brines are low and generally not detected in our groundwater dataset. Even at detection limit, some species can increase health risk

	Southwest PA Avg Ratio to Chloride
Radium (pCi/L)	<7:100
Barium (mg/L)	2:100
Arsenic (mg/L)	2:10,000
Thallium (mg/L)	1:10,000
Beryllium (mg/L)	1:10,000
Cadmium (mg/L)	1:10,000
Chromium (mg/L)	1:10,000

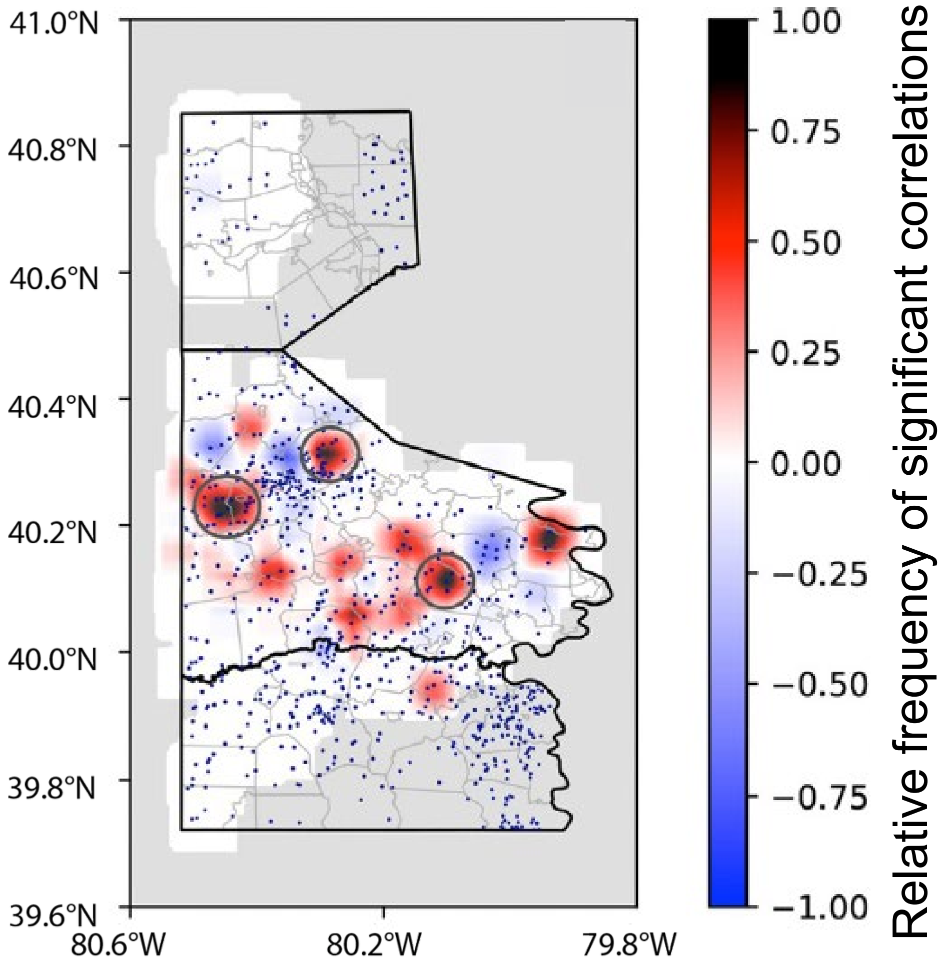


The ratio of these elements compared to chloride concentration is a way to estimate exposure

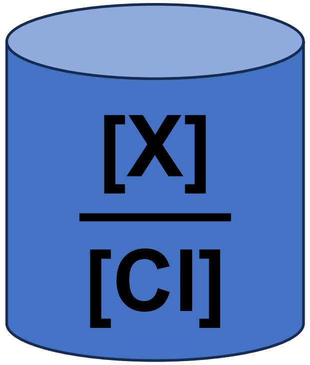
Data from Shaheen et al. (2022)

If Cl increases near UOG wells what about the toxic elements?

[Cl] vs. density of UOG wells



PA produced water



x

3.6 mg/L ↑ [Cl]

UOG well w/in 1km

[Thallium] exceeds the EPA MCL in 3 / 5 hotspots

Arsenic, beryllium, and cadmium exceed 75% of the EPA limit in at least 1 hotspot

Similar calculations for radium also show the potential for harmful [Ra] in some hotspots.

Thallium ingestion is associated with low birth weights*

Just this year, a study completed by Univ of Pittsburgh School of Public Health and funded by PA Dept of Health concluded that infants within 1 mile of 1 or more UOG wells during production phase were 20-40 g smaller at birth.

They also concluded no association between UOGD and childhood leukemia, brain, and bone cancers but children within 1 mile of 1 or more wells had 5 – 7 X the chance of lymphoma. The more intense the UOGD activity, the greater the risk (0.0012% of children under 20 versus 0.006 to 0.0084% for children within 1 mile).

No association for other environmental hazards (except a suggestion for brain tumors with uranium mill tailing sites).

Hazardous Air Pollutants reported by the industry include -- hexane, benzene, toluene, ethylbenzene, xylenes, 2,2,4-trimethylpentane and hydrogen sulfide

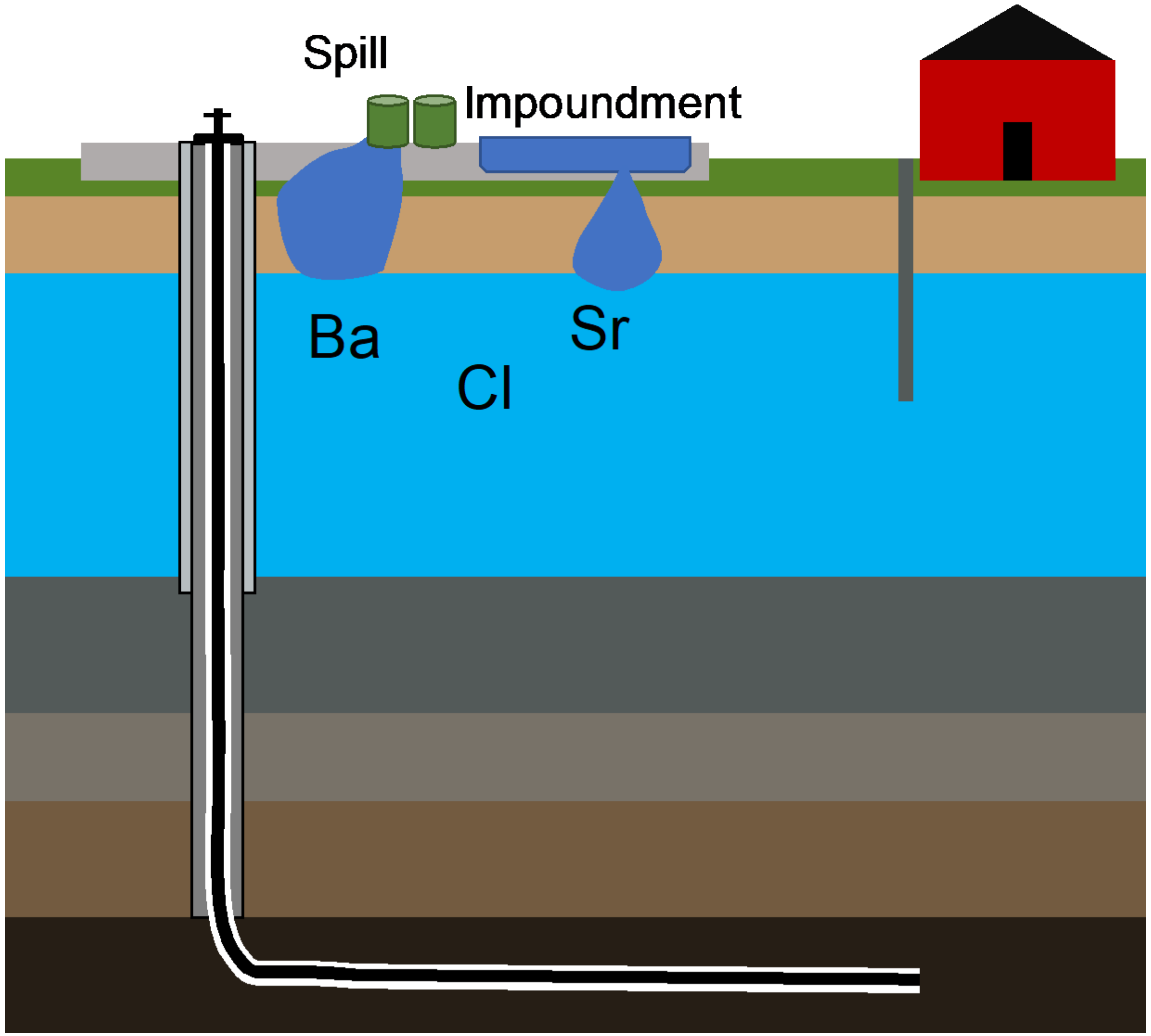
* Nuvolone et al. *Int. J. Environ. Res. Public Health*. 2021

Geospatial Conclusions

Wastewater mishandling is the likeliest mechanism to increase salts in groundwater nearby UOGD, consistent with community concerns. Salts could be accompanied by problematic species such as thallium, arsenic, and radium.

We see differences in NEPA and SWPA: hydrology & legacy extraction are both important. Households downgradient from spills and impoundment leaks are most impacted.

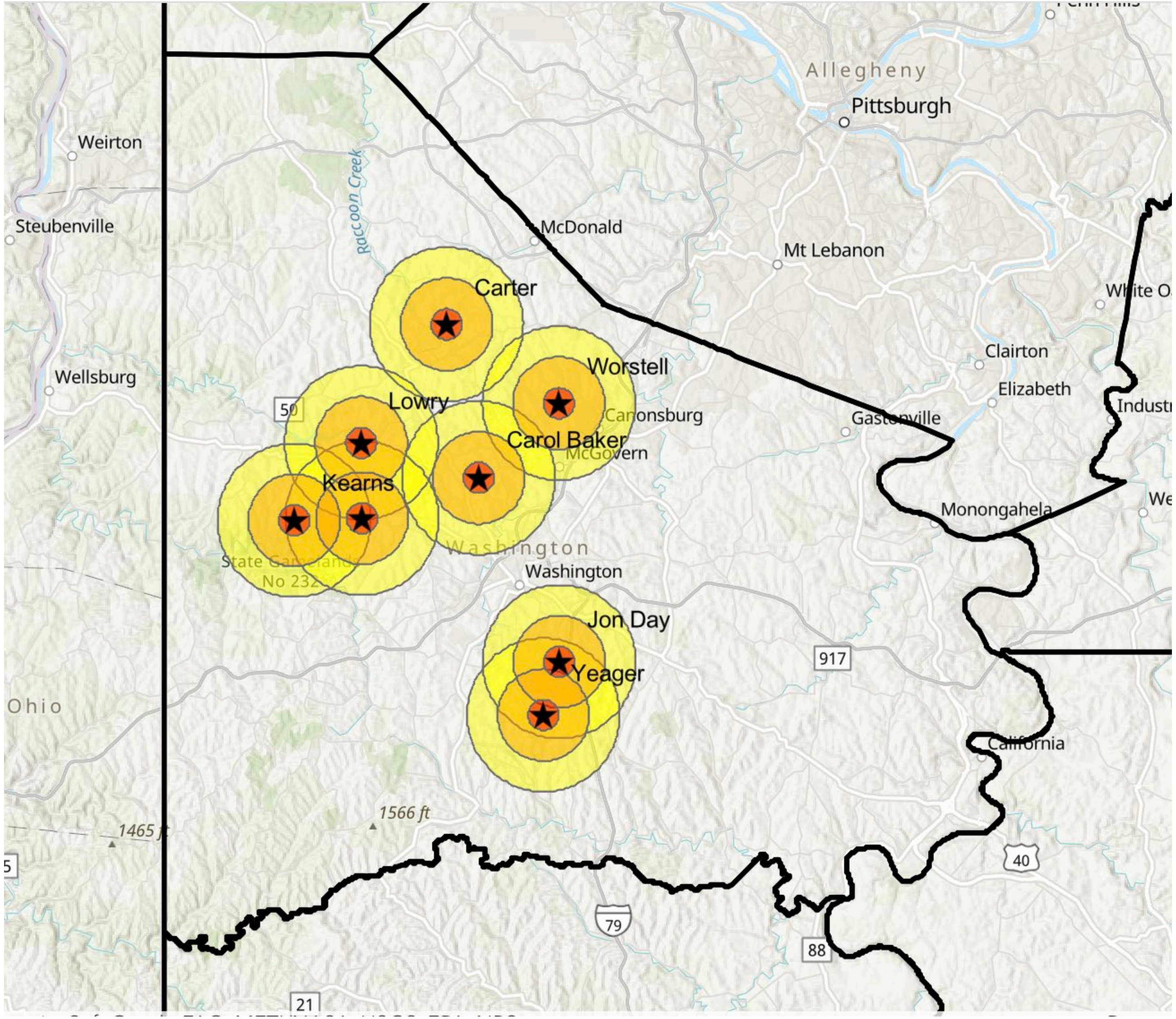
Acknowledgments: HEI Energy, Center for Coalfield Justice, Environmental Health Project, Lois Bower Bjornson, Dave Yoxtheimer, Zhong Zheng



Conclusions

- <u>Convergence</u> between focus groups and geoscientific analysis on possible pathway of concern
  - UOGD wastewater management
- <u>Divergence</u> in terms of contaminants of concern:
  - Focus groups: radiation exposure
  - Geoscientific analysis: salt species and possibly, thallium
- More follow up water testing and community outreach is needed to:
  - Test for possible contamination by radioactive species and heavy metals
  - Explain the importance of studying ‘tracer species’ such as Chloride, Bromide and Strontium
- Qualitative researchers and geoscientists can productively collaborate to integrate community knowledge and environmental science research

Targeted water sampling areas



Thank you!

- Dr. Jennifer Baka, jeb525@psu.edu
- Dr. Susan Brantley, sxb7@psu.edu

Extra slides

Targeted water sampling areas

Shut down by DEP

1. Amwell Township (Yeager)
2. Cecil Township 23 (Worstell)
3. Hopewell Township 11 (Lowry)
4. Hopewell Township (Kearns impoundments)
5. Hopewell Township 12 (Bednarski)

Forced to upgrade liners/only store freshwater

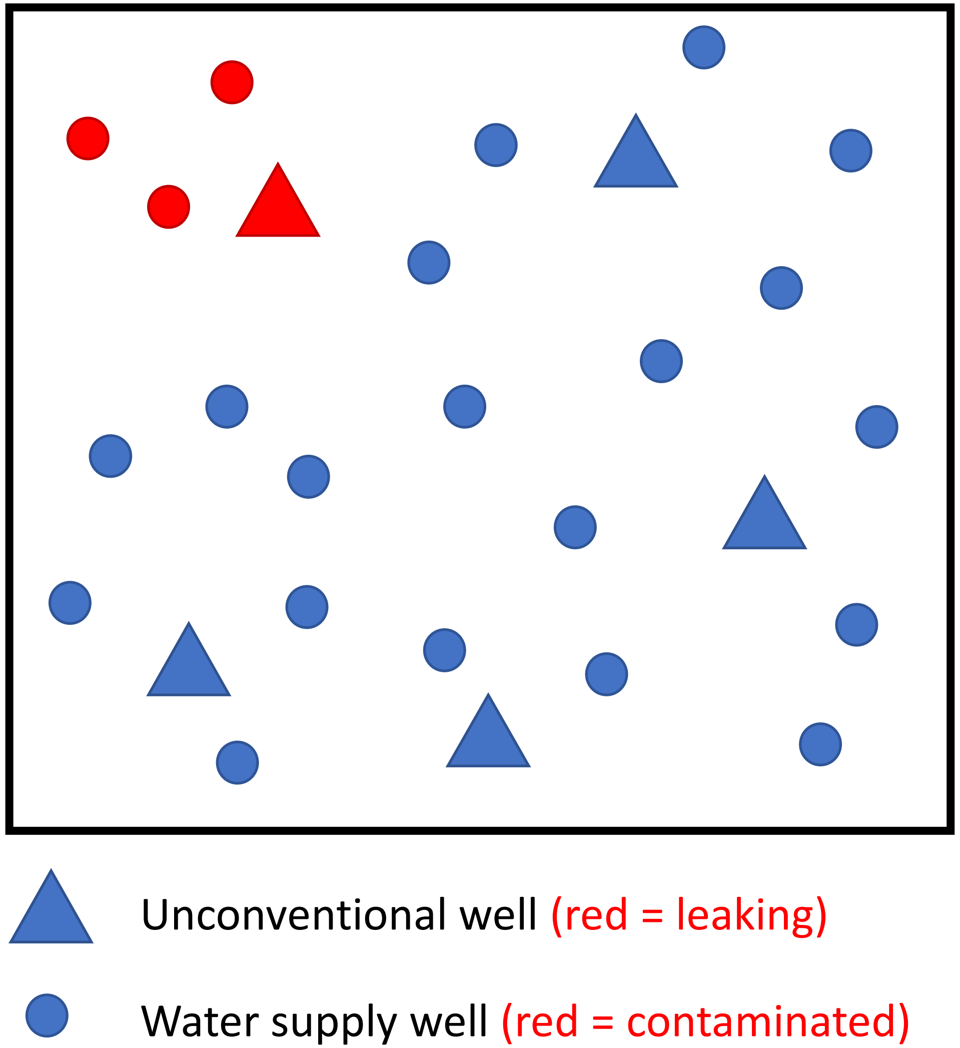
1. Amwell Township 15 (Jon Day)
2. Chartiers Township 16 (Carol Baker)
3. Mount Pleasant Township 17 (Carter)

- A qualitative research method
- A group interview of a small number of people who share similar characteristics or interests
  - NOTE: Does not have to be representative of all possible opinions on the research topic
- The objective is to gather more in-depth information on perceptions, opinions, experiences, etc.
- Research team facilitates discussion using a pre-determined set of questions
- Can be used to inform other research methods, such as quantitative analysis

Big dataset approach to investigate groundwater impacts of UOGD

Groundwater contamination generally infrequent during unconventional oil and gas development (UOGD)[1]

- Case studies of impacted water supplies can't provide a realistic estimate of contamination frequency
- Randomly collected water samples are unlikely to show evidence of contamination
- Statistical examination of impacts to groundwater is possible using large datasets[2]



1. Brantley et al., *Int. J. Coal Geo.*, 2014; 2. Li et al., *J. Contam. Hydro.*, 2016

Identifying subregions with potential contamination using the sliding window technique

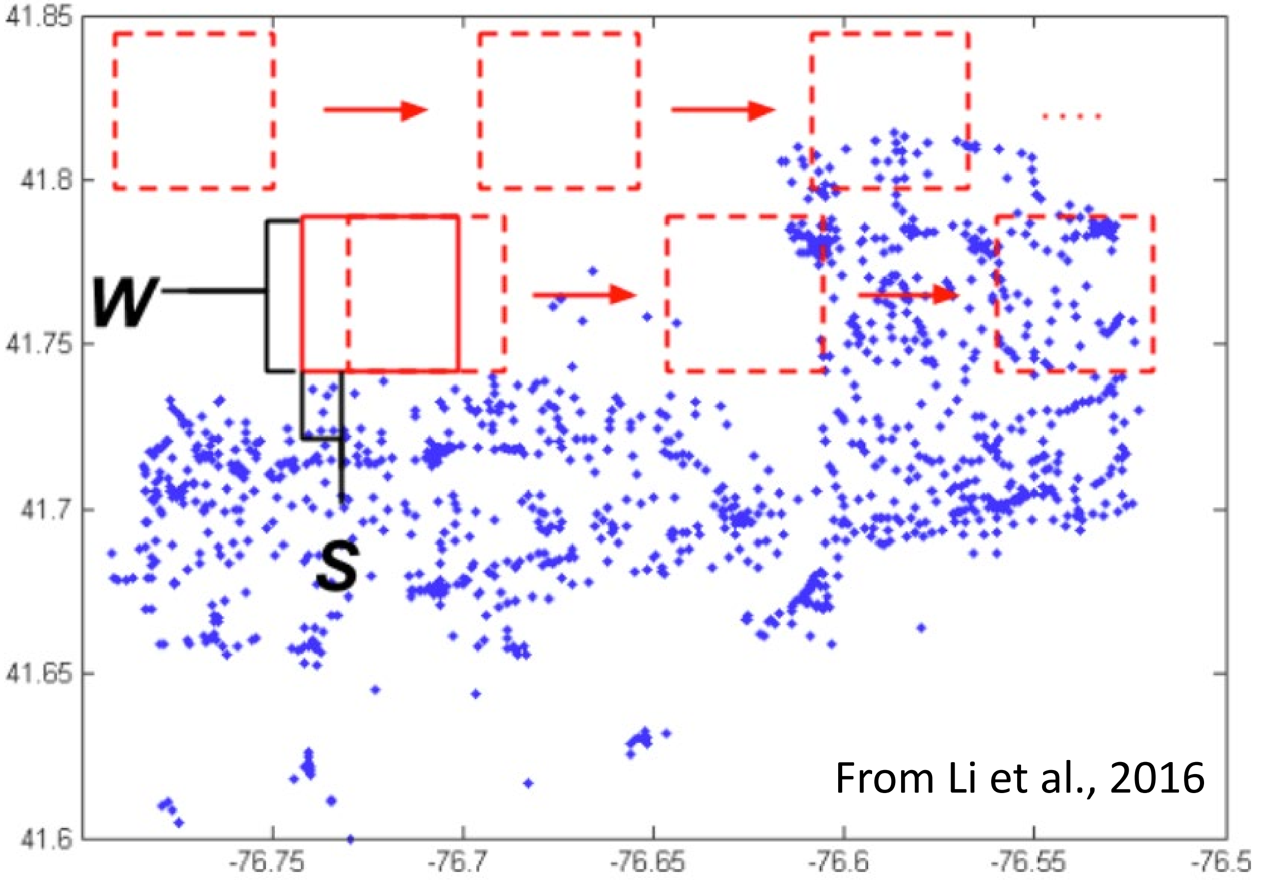
5km x 5km window stepped in 200m increments across study area

Calculate Kendall rank correlation for analyte concentrations and the distance to a feature of interest (e.g. UOG well, coal mine)

+1 or -1 for statistically significant correlations

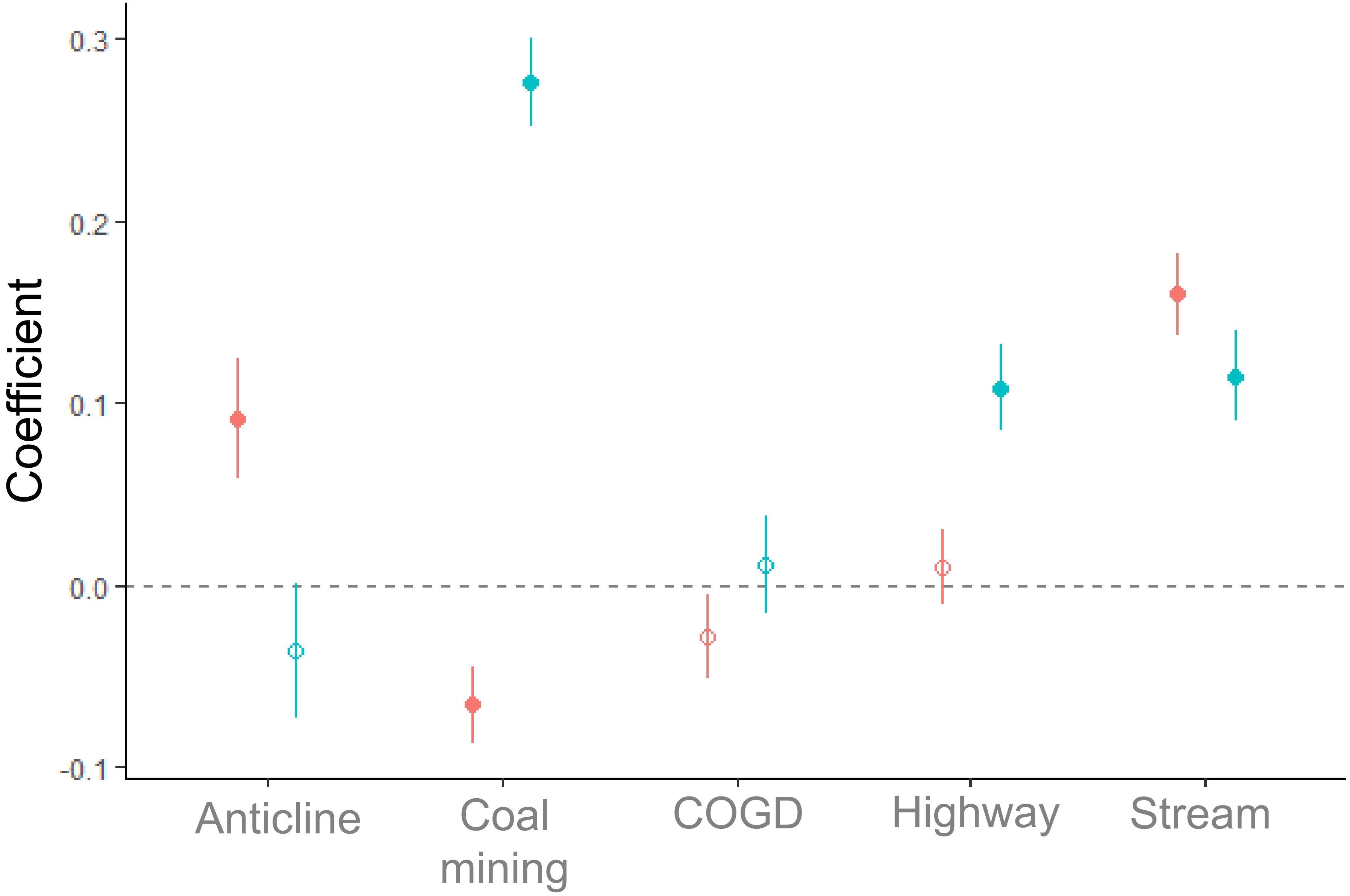
Spatially averaged significance values:

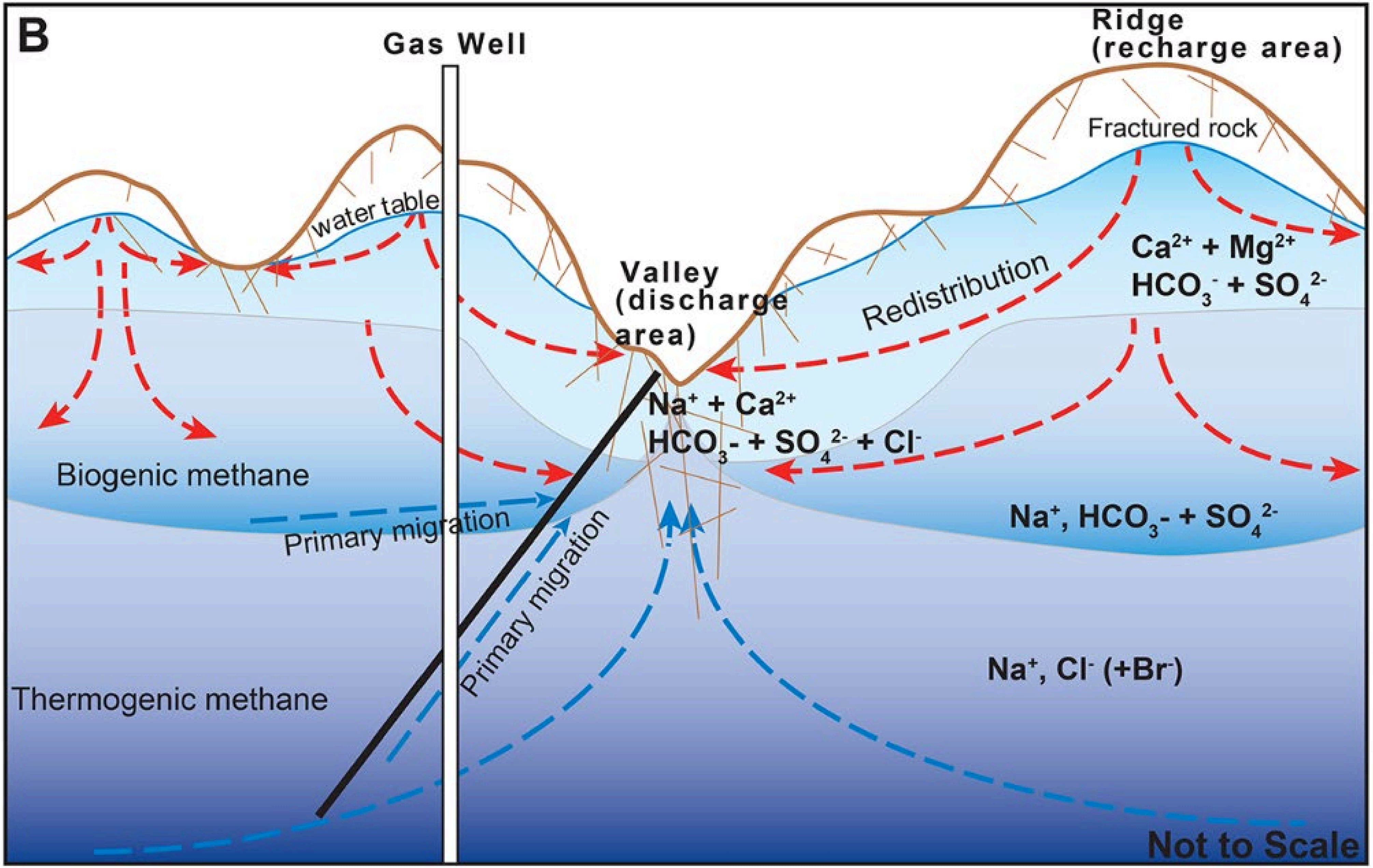
$$\frac{\text{Sum of the correlation indices of windows}}{\text{Number of windows}}$$



From Li et al., 2016

C. Coefficients for fixed effects included in the model





Wen et al., 2018

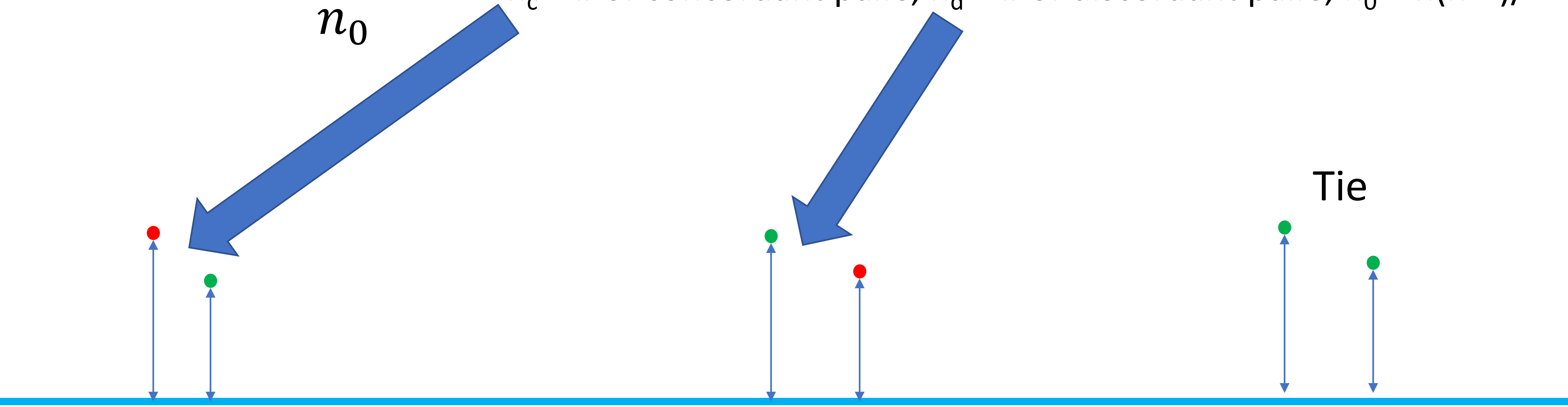
Kendall Rank Correlation

● - Sample with higher methane concentration

● - Sample with lower methane concentration

$$\tau = \frac{n_c - n_d}{n_0}$$

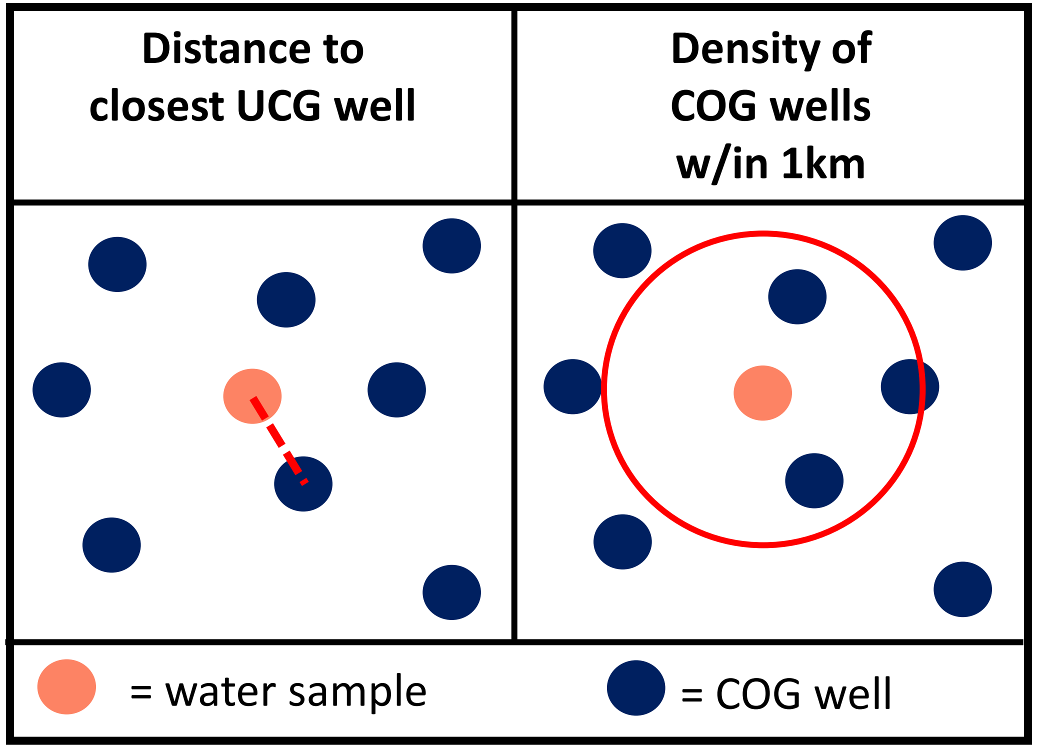
n_c = # of concordant pairs; n_d = # of discordant pairs; n_0 = n(n-1)/2



Slide by Tao Wen

Regional analysis of COGD impacts

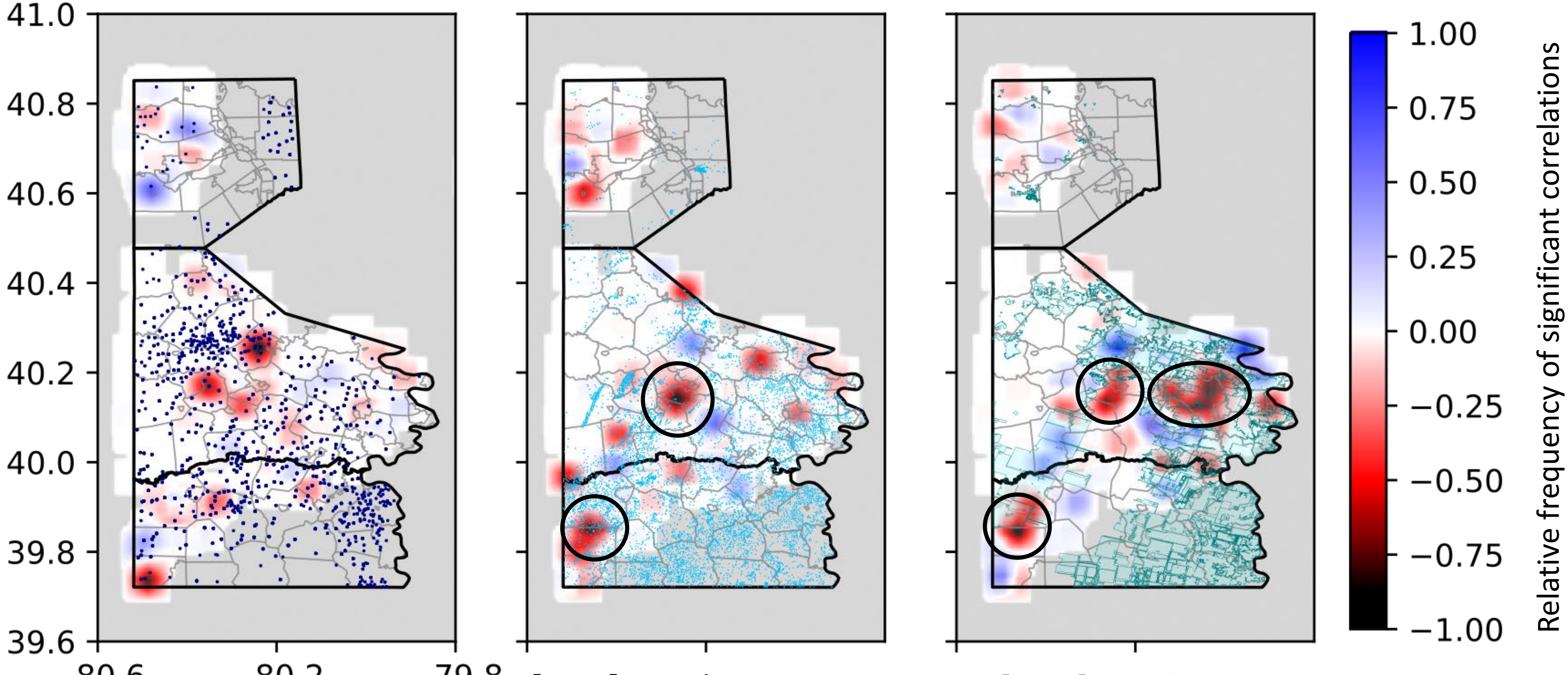
Tested 2 metrics:



Evaluate Kendall rank correlation between $[CH_4]$ or [Cl] and proximity or density of COGD

Calculation	Distance to COG wells vs.		Density of COG wells vs.	
Species	$[CH_4]$	[Cl]	$[CH_4]$	[Cl]
Kendall's τ	-0.018	-0.019	0.010	0.010
p-value	0.019	0.015	0.201	0.214

[Methane] also occasionally correlated with conventional OGD and coal mining



[CH_4] vs. distance to conventional well

[CH_4] vs. distance to coal mine

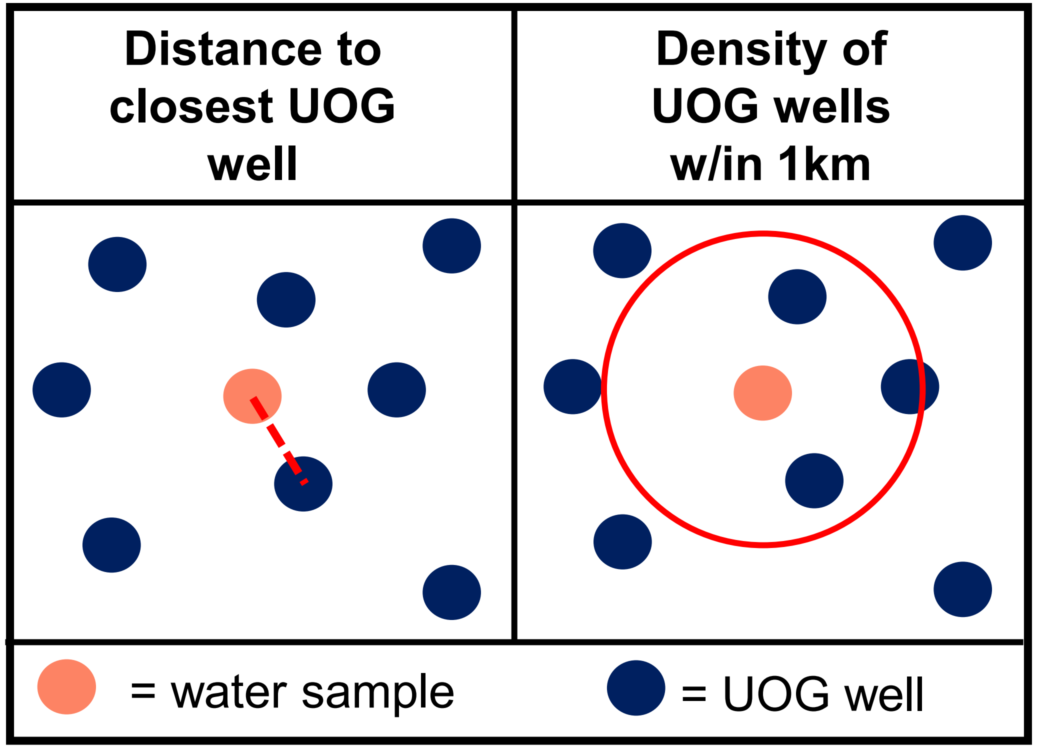
Non-negative matrix factorization (NMF) identifies Cl endmember sources in SWPA

NMF decomposes groundwater chemistry matrix to identify Cl endmember compositions & mixing proportions

Endmember	Ba / Cl	Ca / Cl	Mg / Cl	SO_4 / Cl	Na / Cl	Interpretation
1	0.0065 ± 0.0027	4.9 ± 2.0	0.6 ± 0.3	0	0.3 ± 0.3	Brine
2	0	0.1 ± 0.9	0.3 ± 0.3	0.2 ± 0.3	3.8 ± 1.8	Road salt
3	0	9.1 ± 3.9	3.3 ± 1.4	3.0 ± 1.3	0.5 ± 0.4	Rain

Regional analysis indicates chloride, barium, and strontium concentrations increase with UOGD proximity and density across SWPA (natural gas concentrations do not increase)

Tested 2 metrics:



Evaluate Kendall rank correlation between $[CH_4]$ or [Cl] and proximity or density of UOGD

Calculation	Distance to UOG wells vs.		Density of UOG wells vs.	
Species	$[CH_4]$	[Cl]	$[CH_4]$	[Cl]
Kendall's τ	-0.009	-0.036	0.011	0.033
p-value	0.219	<0.005	0.084	<0.005

Statistically significant ($p < 0.005$) correlations also identified for Ba, Sr

No significant increase in [Cl] associated with UOGD in NEPA

Shaheen et al., *ES&T*, 2022

Can we control for overlapping geogenic and anthropogenic sources?

$\log C = \beta$ #UOGD1km + $COGD_{1km}$ + $CoalMining_{1km}$ + $anticline_{1km}$ + $stream_{100m}$ + $highway_{1km}$ + Season

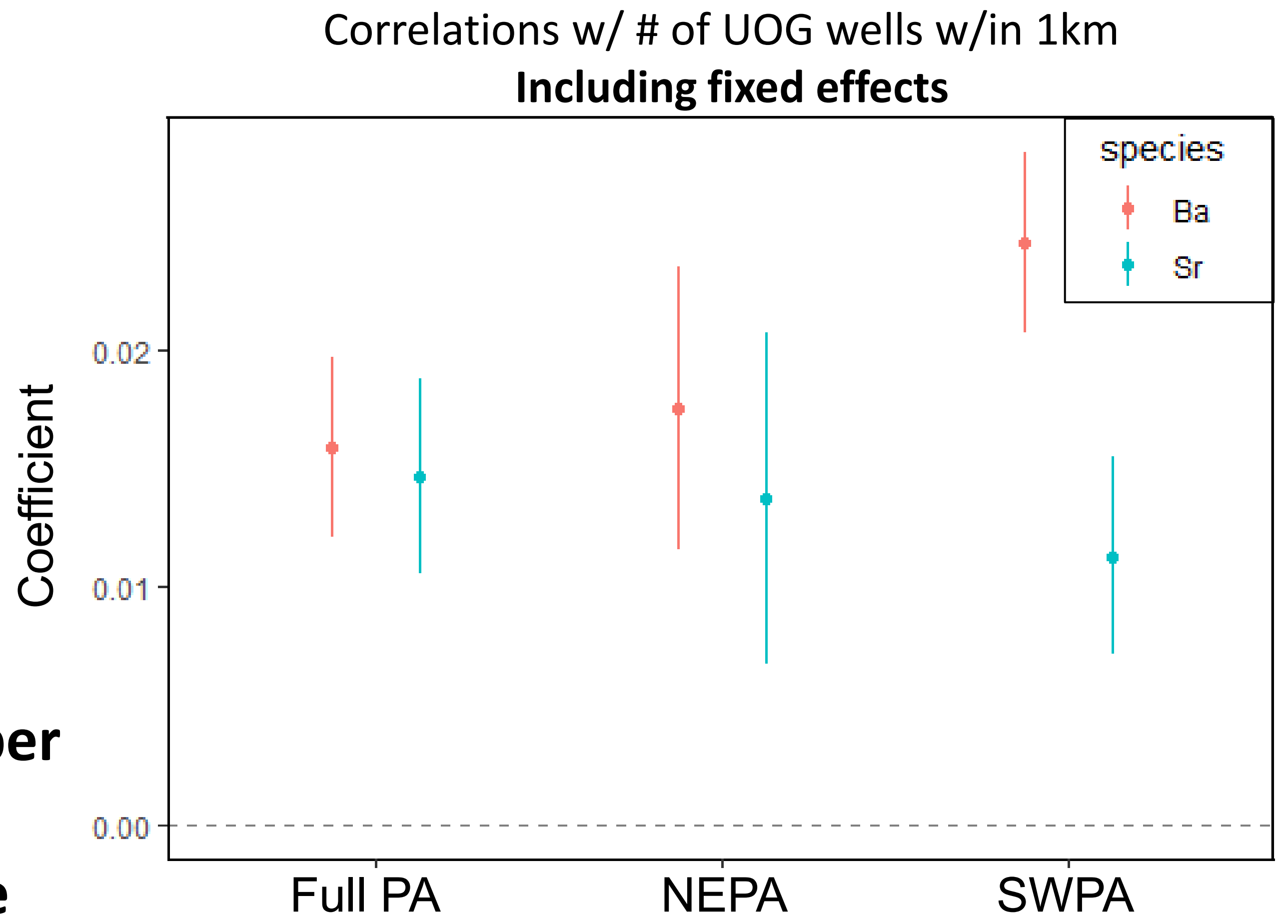
logC: Species of interest, log[Ba] or log[Sr]

β: Coefficient (% increase in logC with 1-unit increase in UOGD density)

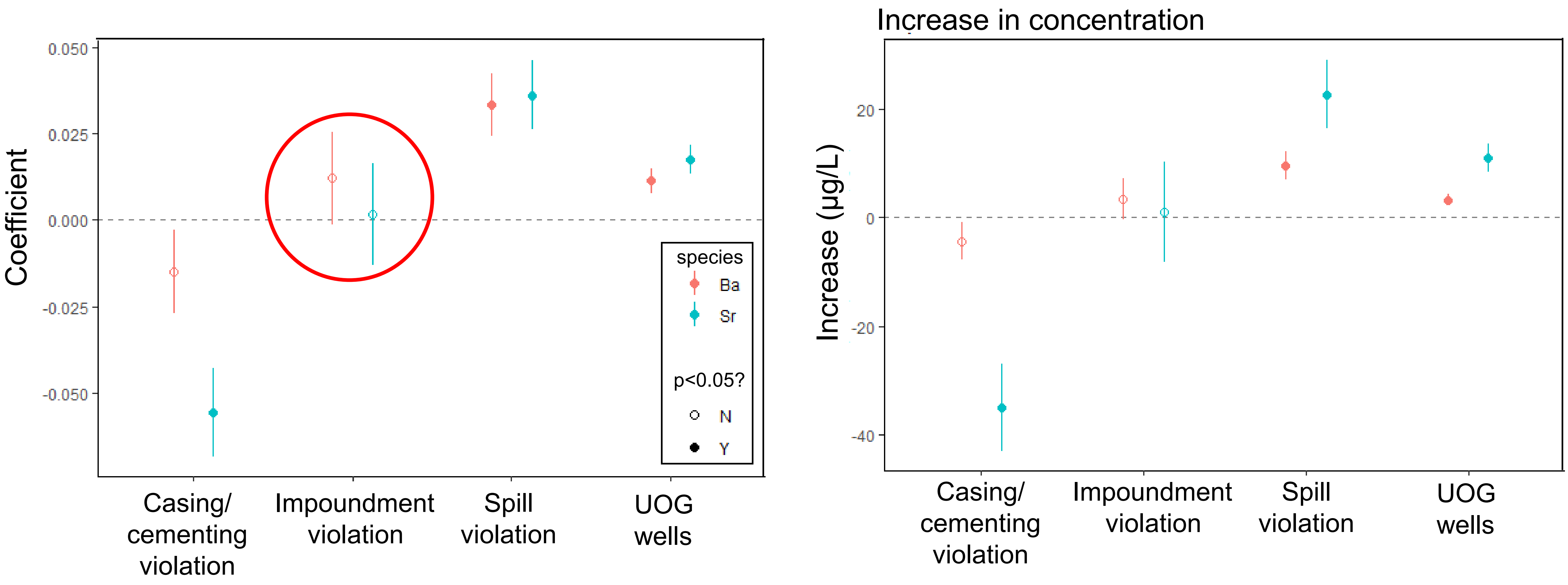
#UOGD1km: # of UOG wells within 1km

Translates to <15 µg/L increases in Ba and Sr per UOG well within 1km.

Even at high UOGD density, radioactive species are unlikely to exceed EPA limits



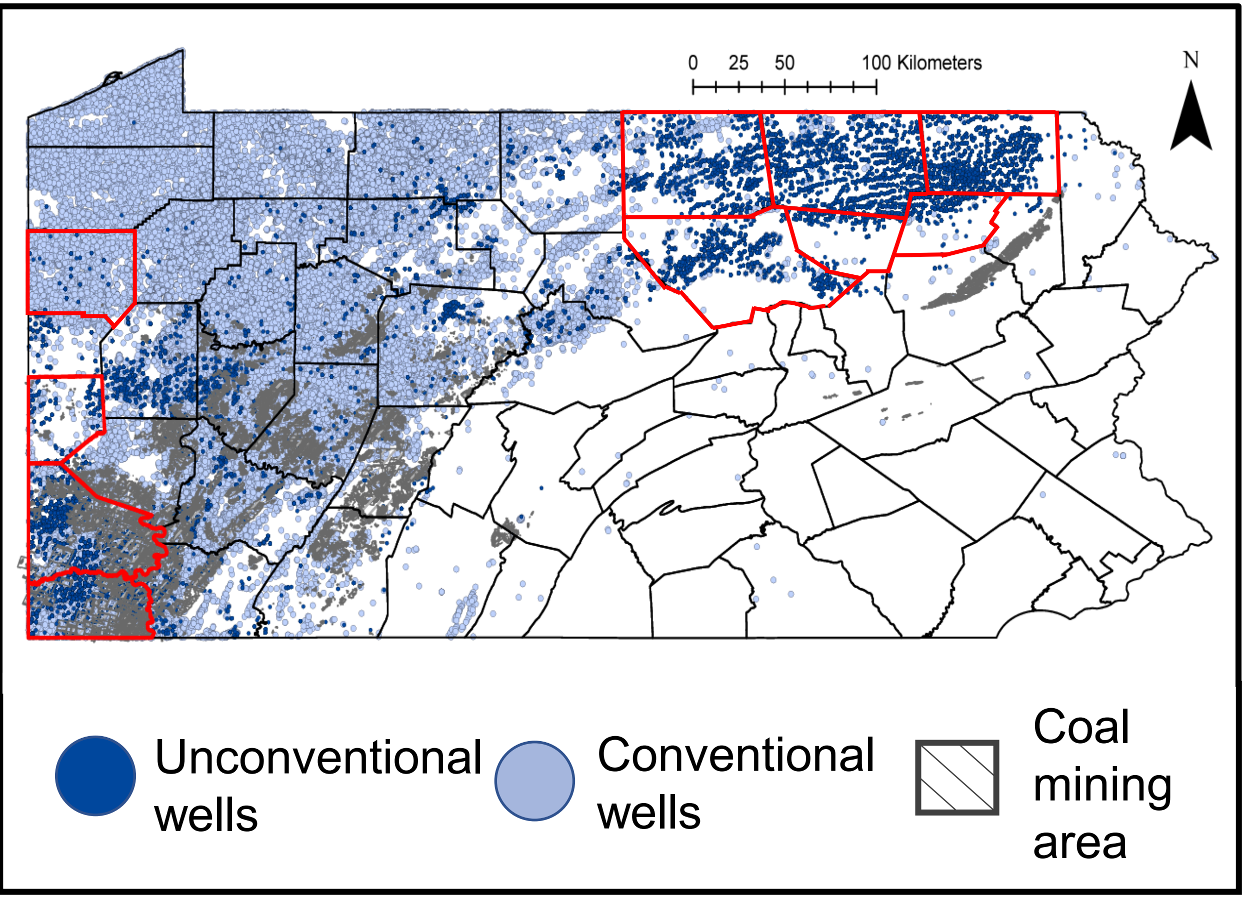
Spill density has the largest effect on brine salt concentrations on a statewide-scale

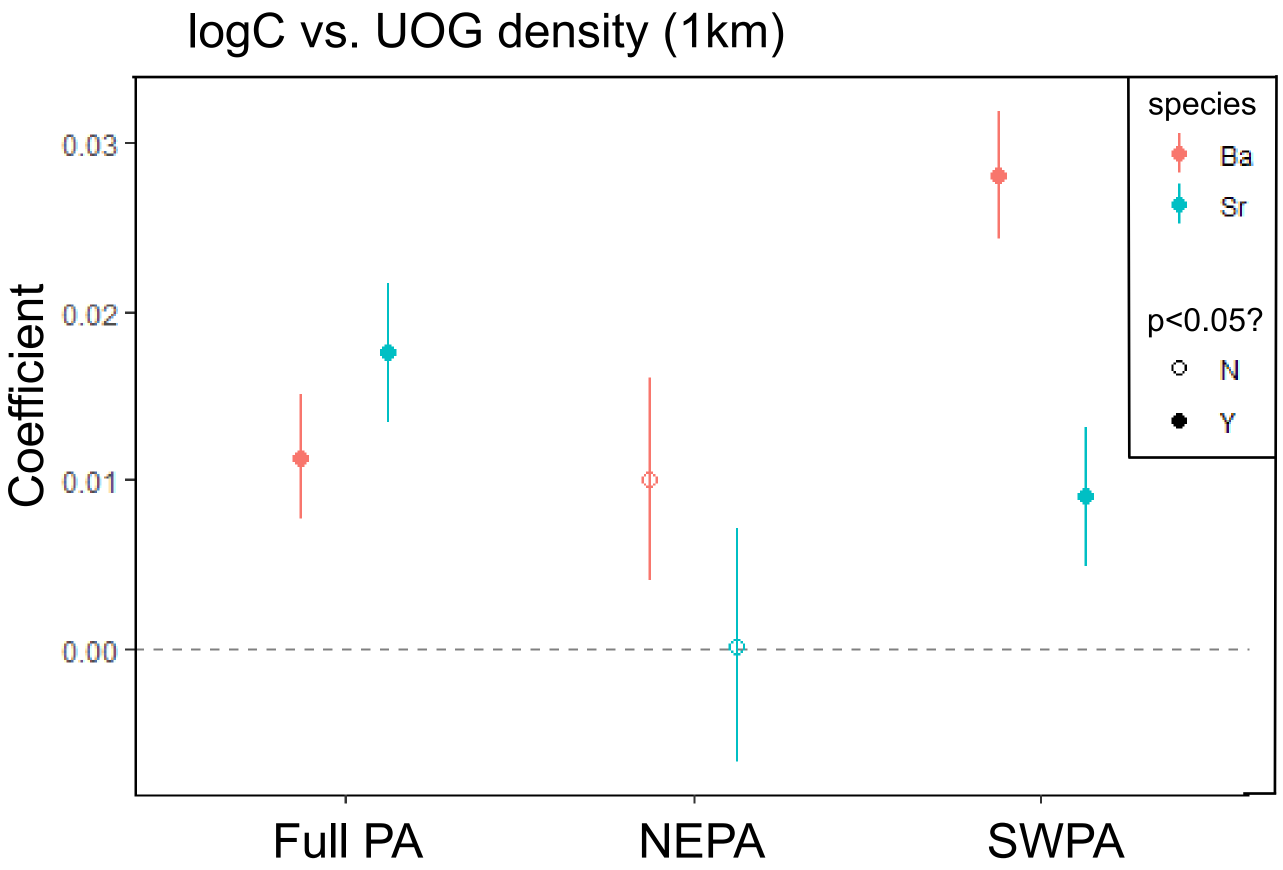


Significant ($p<0.05$) increase in Sr with impoundment density in SWPA

Brine salt increases statewide suggest impacts of wastewater leakage

>28,500 samples from Marcellus shale regions of PA

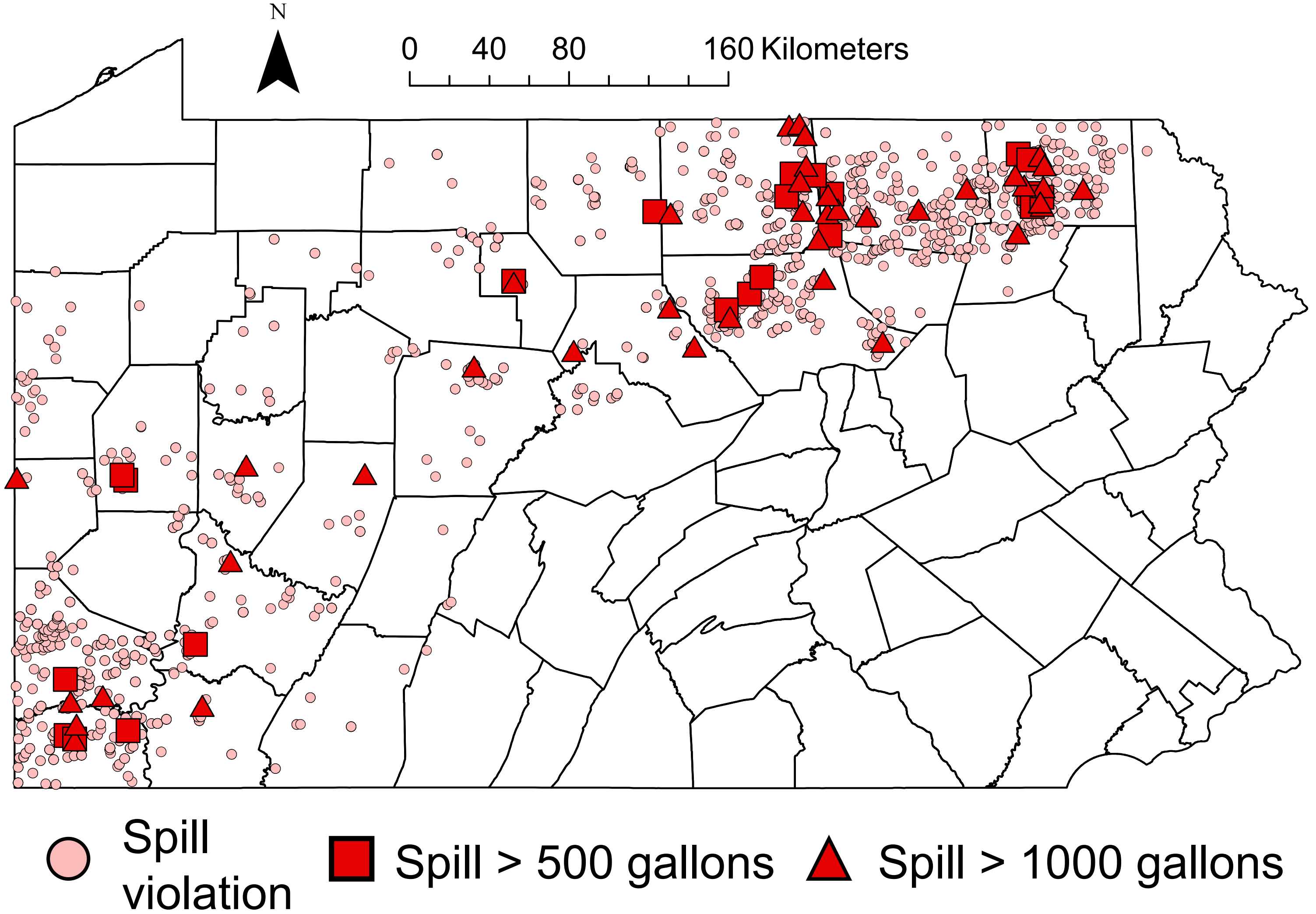




Wastewater mishandling is a likely explanation for increased salt concentrations in SWPA

Ba and **Sr** have small but **significant increases** associated with **higher volumes of produced water** at UOG wells within 3km ($p < 0.005$)

Samples **within 3km of a >500 gallon wellpad spill** have **higher median Ba** concentrations than samples >3km from a spill (MWW test, $p < 0.005$)



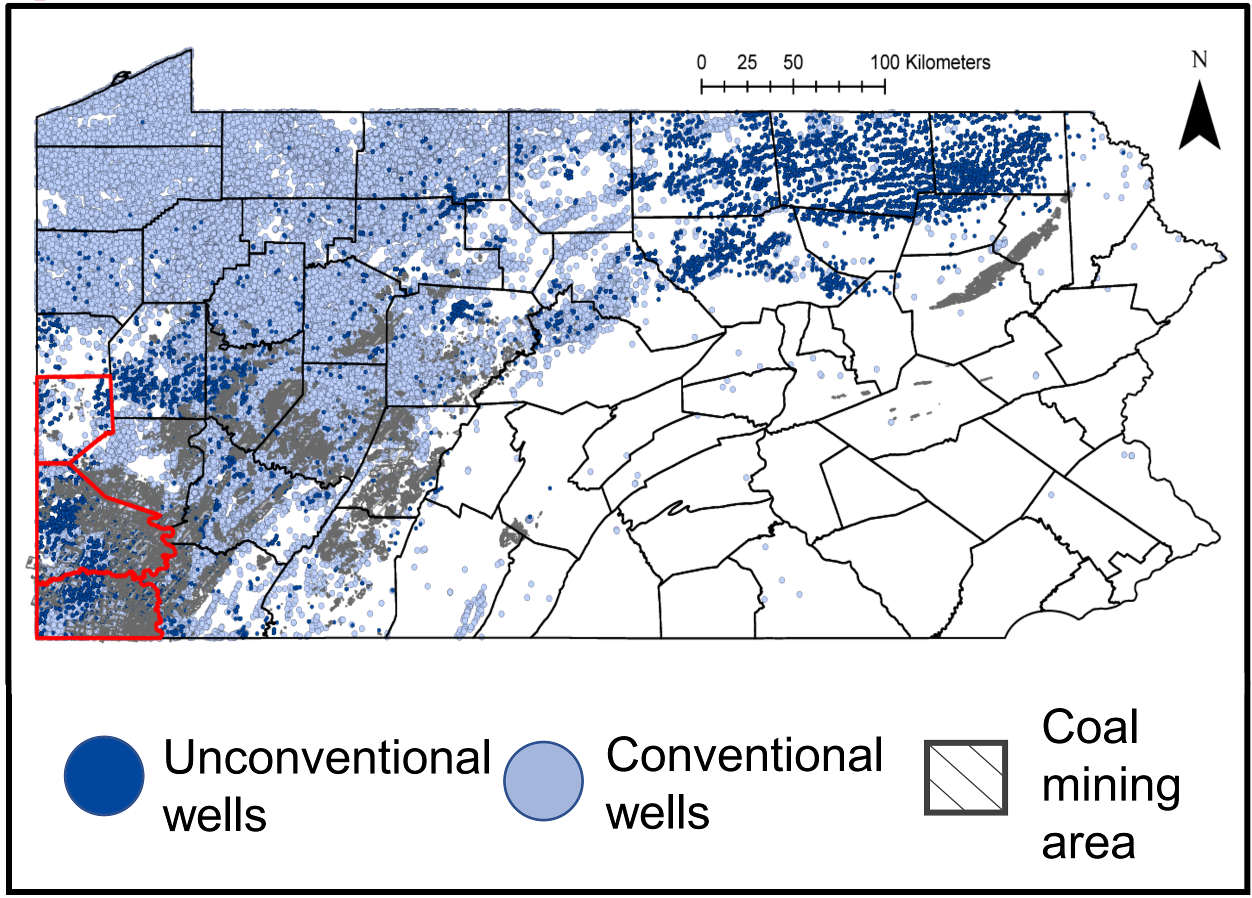
Spill volume data from Patterson et al. *ES&T*, 2017

How does SWPA compare to NEPA?

SWPA: Estimated **0.13%** of wells leaking CH_4

NEPA: Estimated **0.51%** of wells leaking CH_4 (Wen et al., 2018)

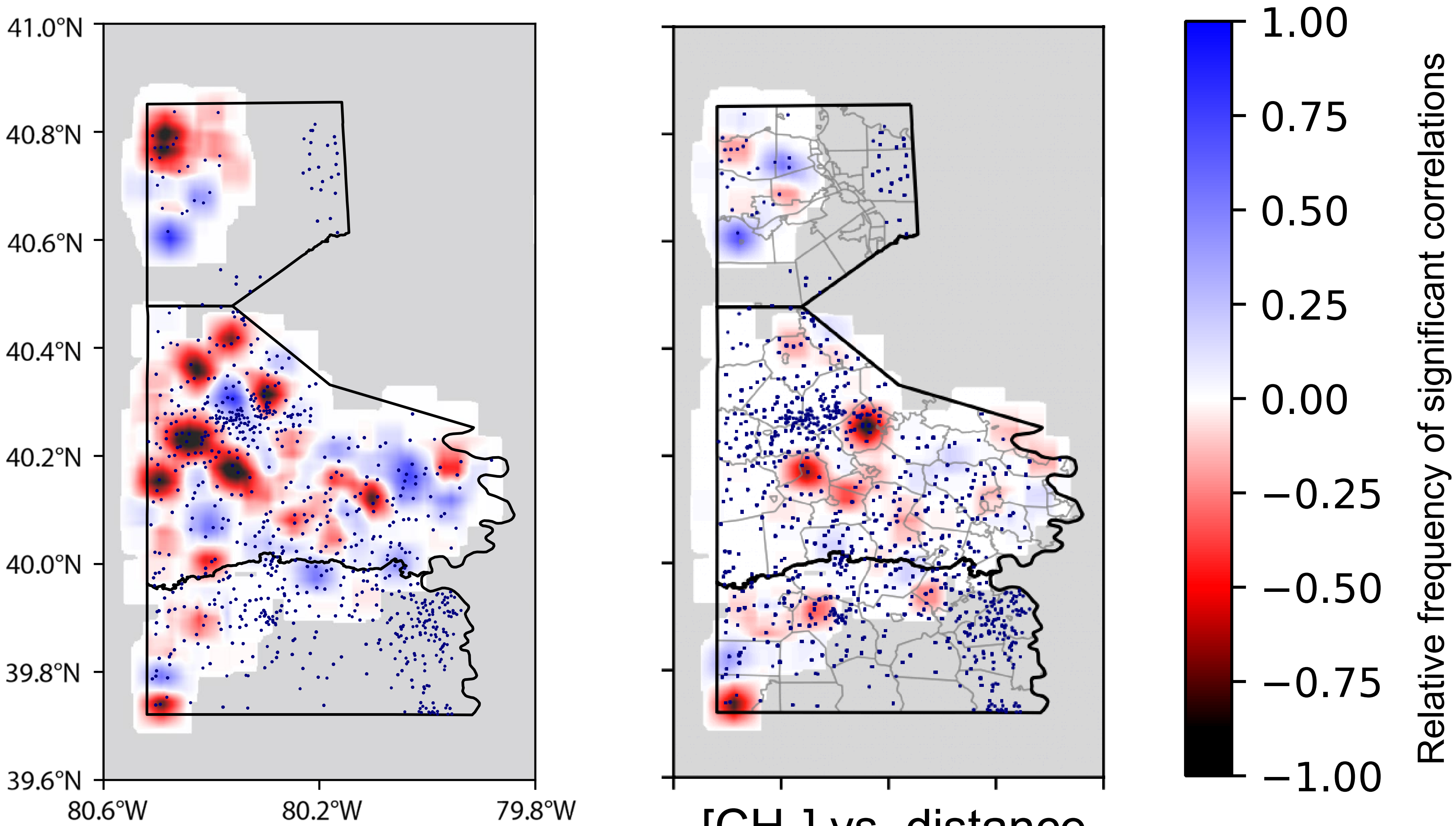
Shallower gas responsible for most methane migration incidents in PA



>100yrs of extraction via conventional oil and gas, coal mining may reduce risk of shallow gas migration in SWPA

Shaheen et al., *ES&T*, 2022

Regional effects are likely driven by “hotspots”



[Cl] vs. distance to UOG well

[CH_4] vs. distance to UOG well

Shaheen et al., *ES&T*, 2022