Unconventional oil and gas development (UOGD) and potential impacts to water resources and children's health

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Unconventional oil and gas development (UOGD)

- UOGD combines horizontal drilling and hydraulic fracturing (HF) to access oil/gas in tight rock formations
  - **HF**: injecting thousands of gallons of water and chemicals into the well to blow open channels in the rock formations, allowing the natural gas/oil to rise to the surface

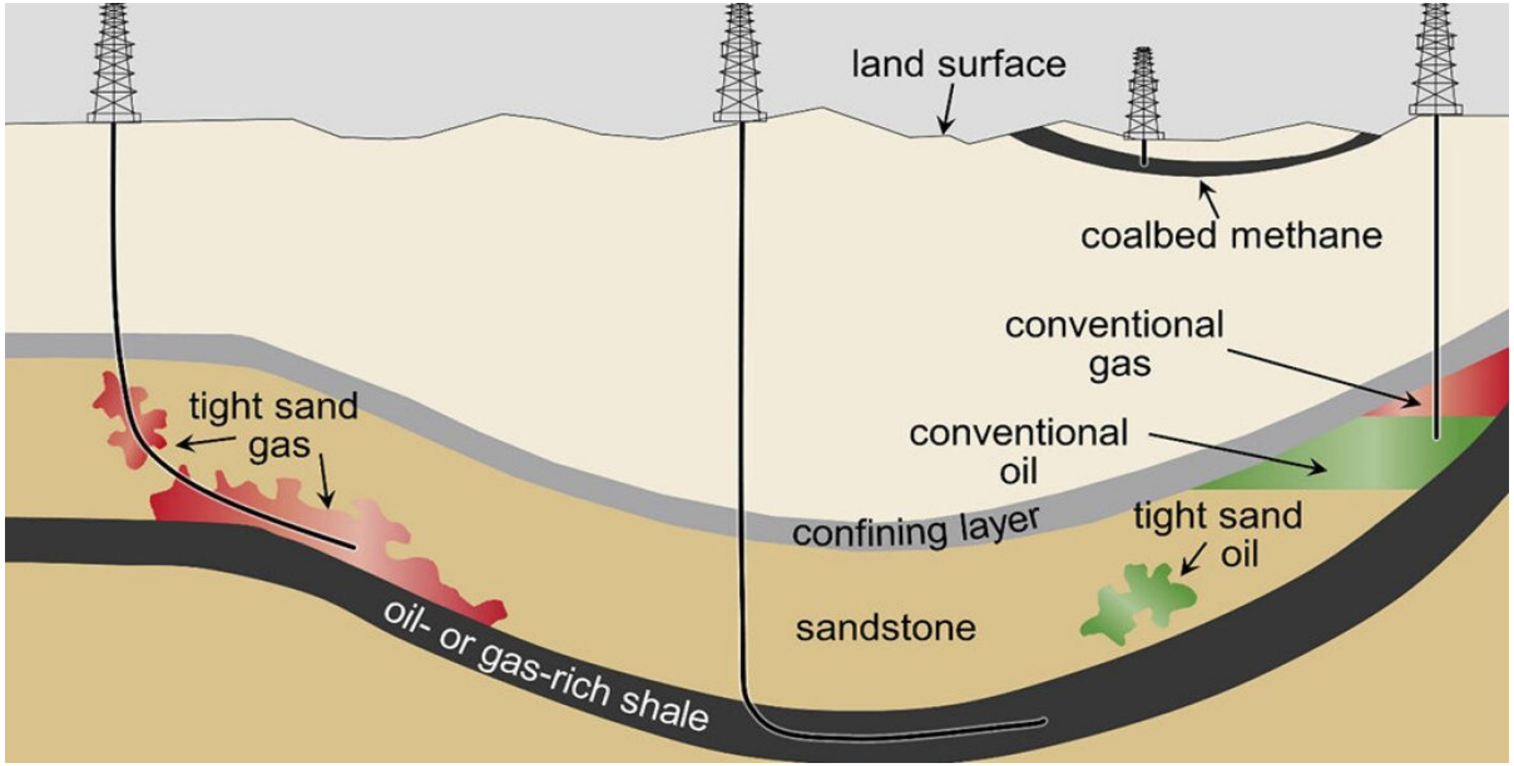

Image from USEPA

Potential hazards from UOGD

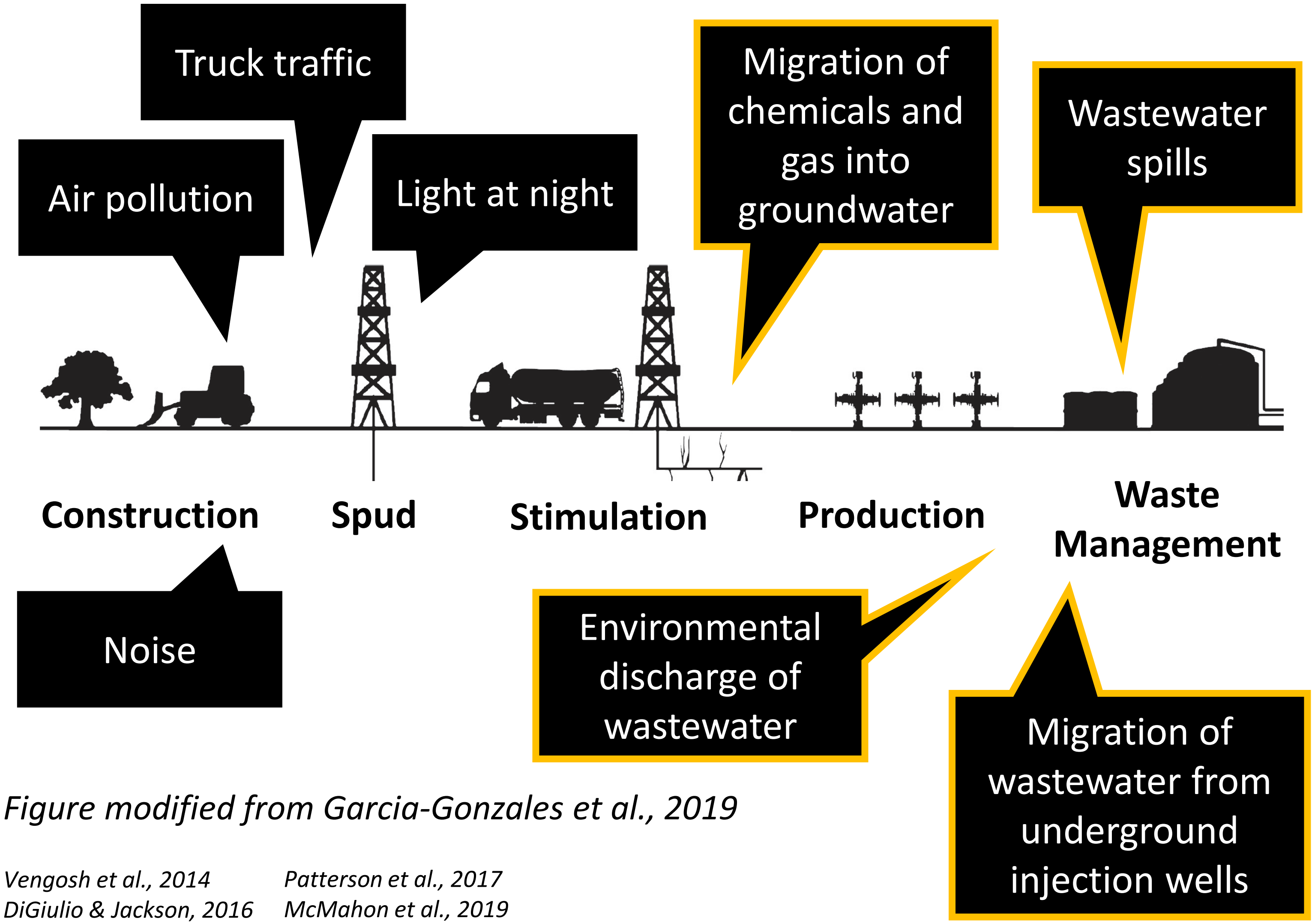

Figure modified from Garcia-Gonzales et al., 2019

Vengosh et al., 2014
DiGiulio & Jackson, 2016
Orem et al., 2017
Lauer et al., 2016
Maloney et al., 2017
Brantley et al., 2014
Patterson et al., 2017
McMahon et al., 2019
Siegel et al., 2015
Drollette et al., 2015
Barth-Naftilan et al., 2018
Claire Botner et al., 2018

UOGD impacts water resources

- Documented impacts include:
  - Spills or improper disposal of wastewater
  - Releases of hydrocarbons into groundwater
- Multiple groundwater monitoring studies conducted in the heavily-drilled Appalachian Basin
  - Few focused on health-relevant compounds

Vengosh et al., 2014
DiGiulio & Jackson, 2016
Orem et al., 2017
Lauer et al., 2016
Maloney et al., 2017
Brantley et al., 2014
Patterson et al., 2017
McMahon et al., 2019
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Claire Botner et al., 2018

Threats to human health from chemicals used or produced by UOGD

- UOG fracturing fluids and wastewater contain toxic, carcinogenic, and endocrine-disrupting compounds
- Many more compounds have not been tested for health effects

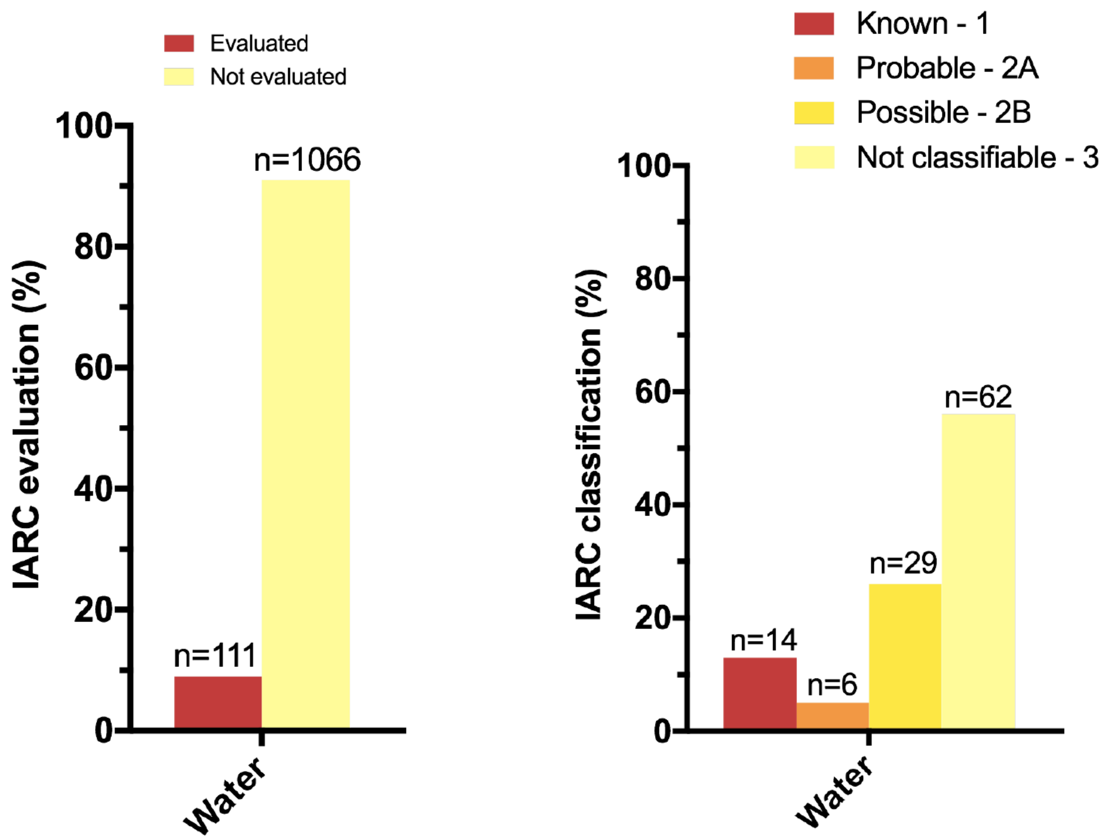


Figure from Elliott et al., 2018

Shih et al., 2015
Elliott et al., 2017, 2018
Kassotis et al., 2018
Deziel et al., 2022

Residential proximity to UOGD has been associated with multiple adverse health outcomes

Adverse perinatal outcomes (n = 20)

Cardiovascular disease, asthma, and hospitalizations (n = 11)

Other health outcomes (n = 6)

Cancer (n = 4*)

Literature Gap: UOGD uses and releases carcinogenic chemicals, but few quality studies of cancer despite major public concern

Aim: Evaluate the potential association between residential proximity to UOGD and childhood acute lymphoblastic leukemia (ALL)

Deziel et al., 2022

**Clark et al., 2022*

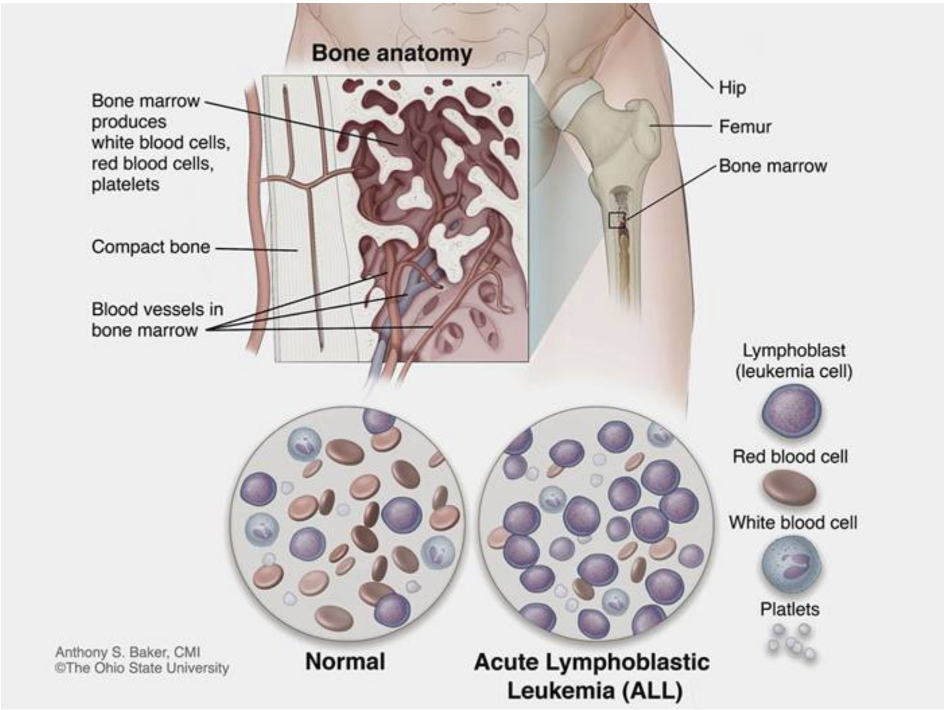
Unconventional oil and gas development exposure and risk of childhood acute lymphoblastic leukemia: A case-control study in Pennsylvania, 2009-2017

Clark et al. 2022, Env. Health Persp.

Photo Credit: Ted Auch. FracTracker Alliance.

Childhood acute lymphoblastic leukemia (ALL)

- Most common cancer subtype among children (80% of leukemias, ~25-30% of all cancers)
- Arises from immature B- and T-lymphoid immune cells as a result of multiple genetic insults, such as chromosomal translocations or alterations

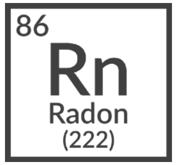


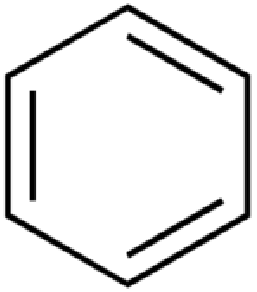
Pui, 2011
Eden, 2010
Greaves et al., 2003, 2006
Wiemels et al., 1999
Hunger et al., 2015

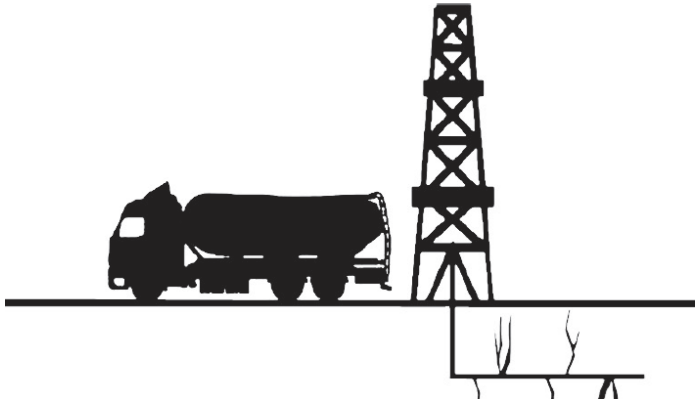
Figure from Ohio State University James Cancer Center

Childhood acute lymphoblastic leukemia (ALL)

- ALL is thought to be multifactorial, attributable to both environmental exposures and genetic susceptibility
- ALL has been linked to several environmental exposures:



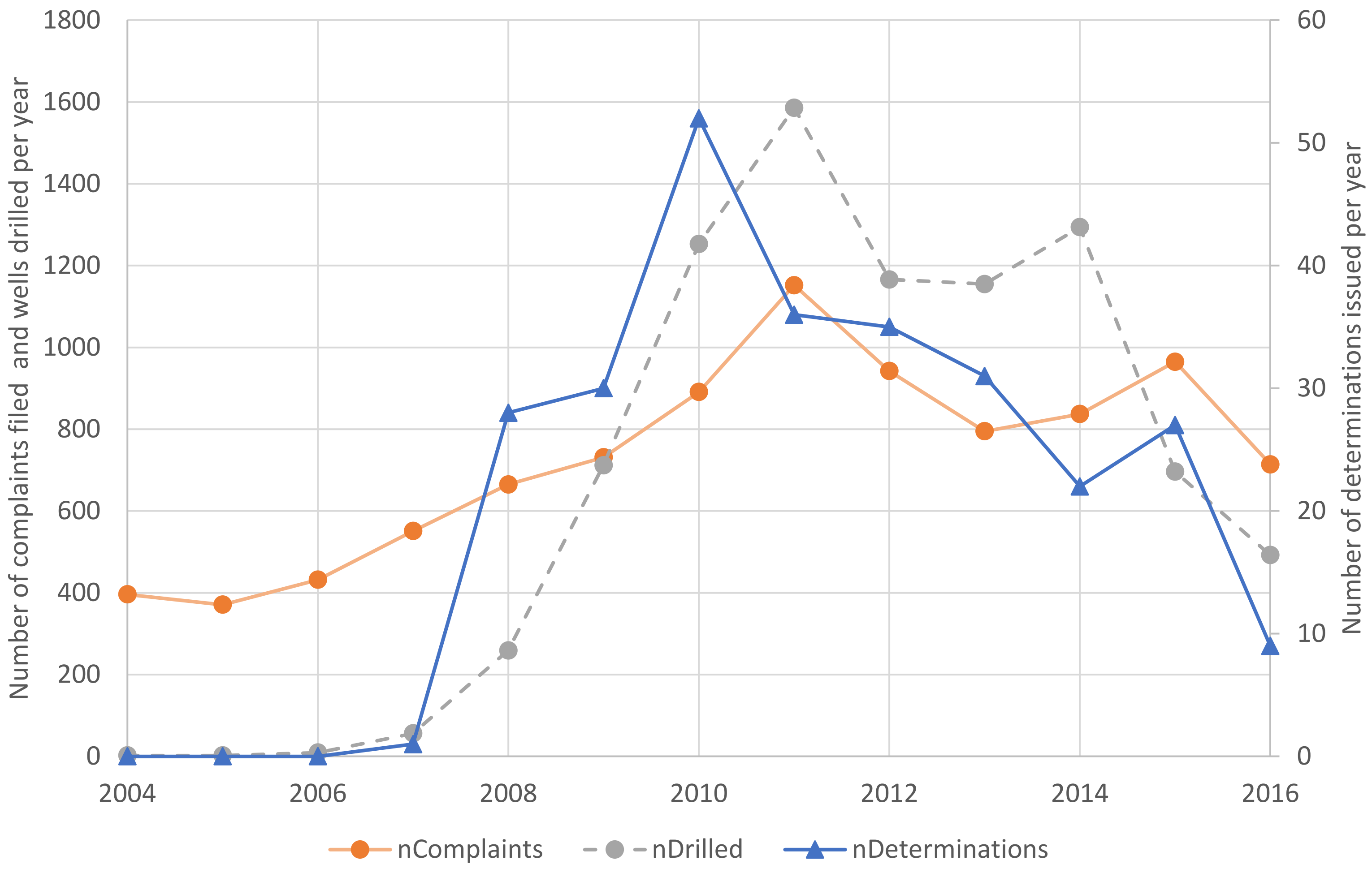




→ *At least 49 known carcinogens and 17 leukemogens associated with UOGD; many more have some evidence of carcinogenicity*

Elliott et al., 2018

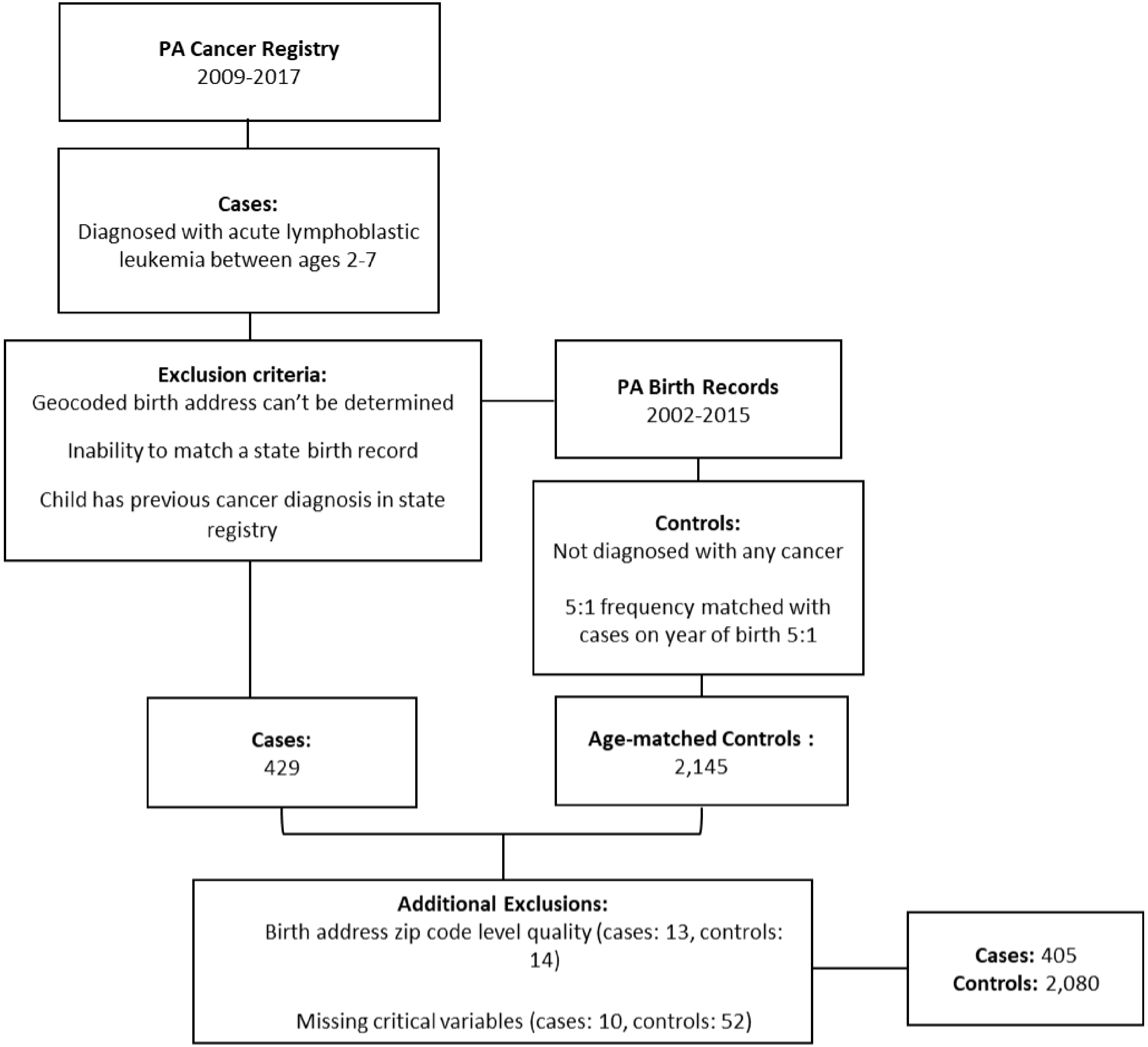
Yearly UOGD activity in PA, 2004-2016



Oil and gas complaints and unconventional wells drilled are shown on the primary axis. Positive determinations made are shown on the secondary axis.

Figure from Clark et al., 2021

Data sources and case and control selection



UOGD exposure assignment:

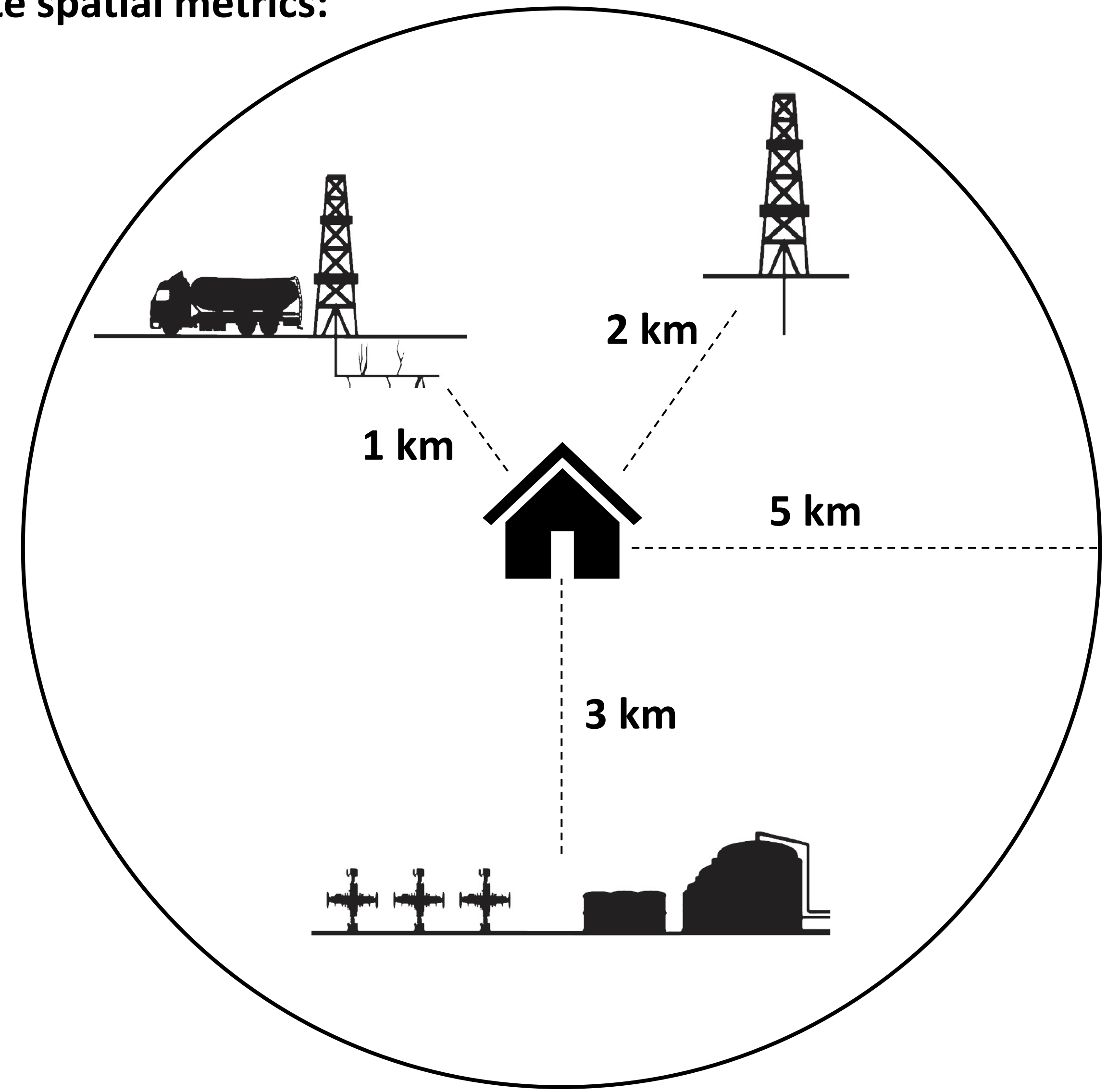
Spatial Metrics

Metric:	Aggregate exposure metric	Water-specific exposure metric [17-18]
Formula:	$ID^2W\ well\ count = \sum_{i=1}^{n} \frac{1}{d_i^2}$	$IDups = \frac{1}{u_i}$
Mathematical definition:	With distance (d) between the (i) UOG well and residence, and n the number of UOG wells	With distance (u) between the (i) UOG well hydrologically upgradient of the residence
Simple definition:	*Uses proximity and density of nearby UOG wells to estimate exposure potential*	*Uses proximity to nearest UOG well within a child's watershed area (where they might get their drinking water)*
Buffer sizes:	*2, 5, 10 km buffers*	*2, 5, 10 km buffers*

Assessing exposure to UOGD:

Aggregate Metrics

Aggregate spatial metrics:

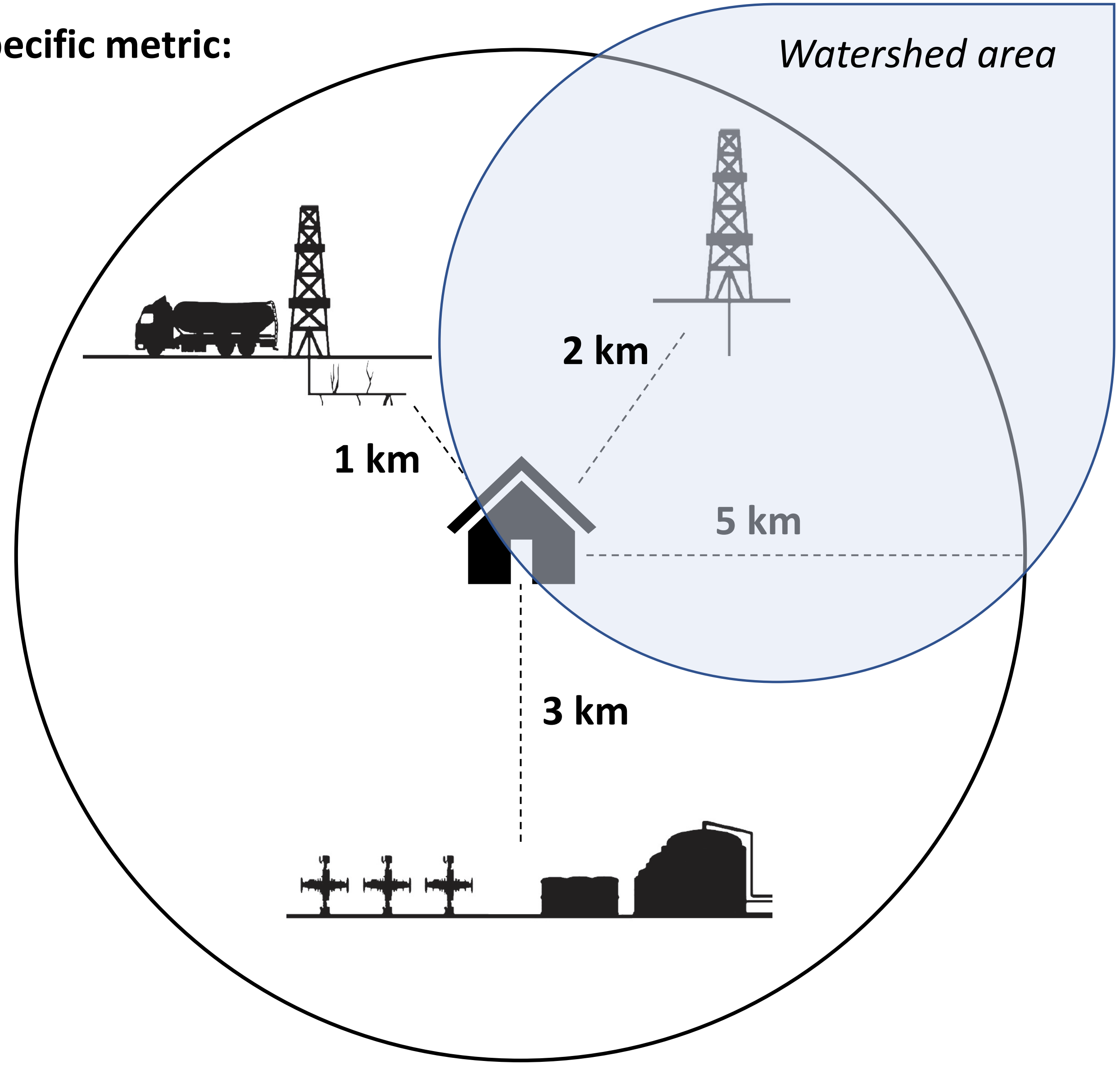


Parts of figure modified from Garcia-Gonzales et al., 2019

Assessing exposure to UOGD:

Water-specific Metric

Water-specific metric:



Soriano et al., 2020, 2021

Parts of figure modified from Garcia-Gonzales et al., 2019

Assessing exposure to UOGD:

Water-specific metric compared to drinking water samples

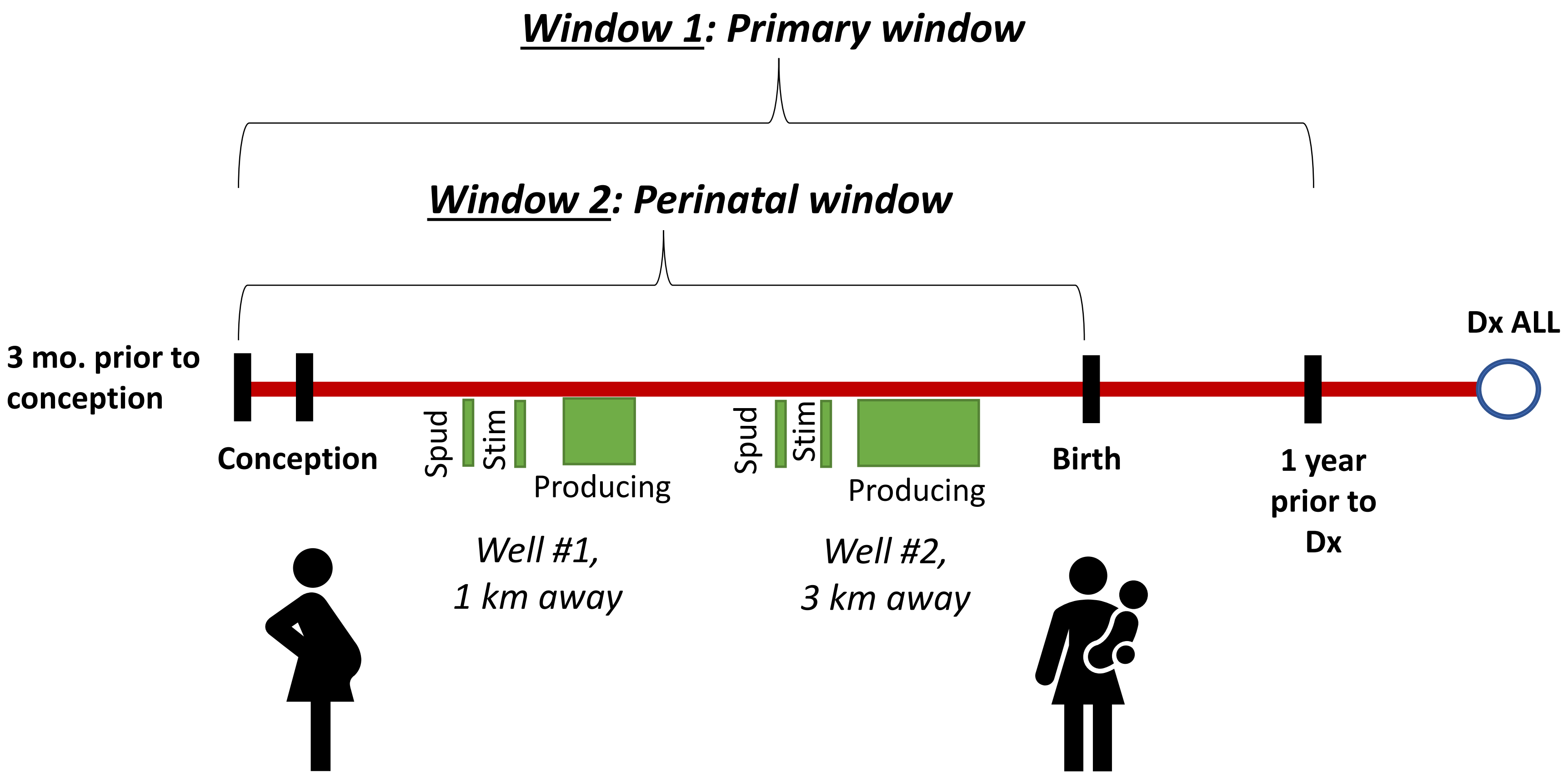
Chemical	Nearest (km) OR (95% CI)	ID_{ups} 0.5 km OR (95% CI)	ID_{ups} 1 km* OR (95% CI)	ID_{ups} 2 km* OR (95% CI)	IDW 2 km* OR (95% CI)	ID^2W 2 km* OR (95% CI)
PA						
Vinyl chloride	0.71 (0.33, 1.53)	0.92 (0.33, 2.60)	1.87 (0.71, 4.91)	1.87 (0.71, 4.91)	1.87 (0.71, 4.91)	1.47 (0.56, 3.82)
Bromomethane	0.70 (0.37, 1.32)	0.68 (0.26, 1.78)	**2.55 (1.06, 6.13)**	1.72 (0.73, 4.07)	0.97 (0.42, 2.28)	0.81 (0.34, 1.89)
1,2-Dichloroethene & benzene	**0.46 (0.23, 0.93)**	0.60 (0.21, 1.72)	1.66 (0.66, 4.14)	**2.59 (1.01, 6.67)**	**2.59 (1.01, 6.67)**	**3.29 (1.25, 8.66)**
Toluene	*0.52 (0.27, 1.03)*	0.72 (0.27, 1.92)	**2.63 (1.07, 6.45)**	1.74 (0.73, 4.19)	2.13 (0.88, 5.18)	2.13 (0.88, 5.18)
Chloroform	1.41 (0.63, 3.13)	0.96 (0.33, 2.83)	2.63 (0.32, 2.28)	0.67 (0.25, 1.79)	0.67 (0.25, 1.79)	0.86 (0.32, 2.28)
M-xylene & p-xylene	**0.28 (0.10, 0.80)**	1.04 (0.35, 3.07)	**3.36 (1.16, 9.72)**	1.50 (0.56, 4.02)	**3.36 (1.16, 9.72)**	2.53 (0.91, 7.07)
1,1-Dichloroethene & trans-1,2-dichloroethene	0.76 (0.37, 1.57)	0.63 (0.22, 1.83)	2.05 (0.75, 5.63)	2.05 (0.75, 5.63)	1.09 (0.40, 2.96)	1.58 (0.58, 4.30)
Bromochloromethane**	*0.36 (0.11, 1.19)*	0.42 (0.17, 1.06)	1.09 (0.49, 2.45)	1.09 (0.49, 2.45)	0.92 (0.41, 2.06)	1.29 (0.57, 2.91)
Trichloroethene	0.87 (0.44, 1.74)	1.18 (0.42, 3.34)	0.76 (0.29, 2.00)	0.60 (0.23, 1.58)	0.60 (0.23, 1.58)	0.60 (0.23, 1.58)
Dibromomethane	0.91 (0.49, 1.69)	0.75 (0.30, 1.88)	1.80 (0.78, 4.20)	1.25 (0.54, 2.88)	1.04 (0.45, 2.40)	1.25 (0.54, 2.88)

*Exposure is defined as a value above the median; **Detection is defined as a value above the median concentration for PA homes only. Compounds marked NA were not detected at a sufficient frequency for analysis.

- **Clark et al., 2022:** Compared spatial metrics of UOG exposure to detections of organic chemicals in drinking water samples from 94 PA homes
- Generally low detection frequencies and concentrations, limited associations between metrics and chemicals, though several chemicals were more likely to be detected in homes with higher UOG exposure potential

UOGD exposure assignment:

Windows of Exposure



UOGD exposure distribution

Exposure metric and buffer size	Primary Window Cases (n=405) N (%)	Primary Window Controls (n=2080) N (%)	Perinatal Window Cases (n=405) N (%)	Perinatal Window Controls (n=2080) N (%)
Aggregate metric				
ID^2W 2 km				
Exposed	14 (3)	37 (2)	7 (2)	13 (1)
Unexposed	391 (97)	2043 (98)	398 (98)	2067 (99)
ID^2W 5 km				
Exposed	31 (8)	122 (6)	18 (4)	61 (3)
Unexposed	374 (92)	1958 (94)	387 (96)	2019 (97)
ID^2W 10 km				
Exposed	59 (15)	270 (13)	41 (10)	153 (7)
Unexposed	346 (85)	1810 (87)	364 (89)	1927 (83)
Water-specific metric				
ID_{ups} 2 km				
Exposed	6 (2)	16 (1)	3 (1)	5 (1)
Unexposed	399 (98)	2064 (99)	402 (99)	2075 (99)
ID_{ups} 5 km				
Exposed	12 (3)	43 (2)	6 (1)	21 (1)
Unexposed	393 (97)	2037 (98)	399 (99)	2059 (99)
ID_{ups} 10 km				
Exposed	18 (5)	74 (4)	12 (3)	39 (2)
Unexposed	346 (95)	1810 (96)	393 (97)	2041 (98)

Covariates and confounders considered

- **Matching variable:** year of birth
- **Biological factors** (sex, birth weight, delivery route)
- **Socioeconomic stressors** (maternal education, median household income, participation in food stamp program [WIC], CDC Social Vulnerability Index)
- **Demographic factors** (maternal race/ethnicity)
- **Environmental exposures** (air pollution, agricultural pesticide exposure)

Statistical analysis

- **Unconditional logistic regression**
  - Odds ratios (the odds of the outcome occurring given the exposure) and 95% Confidence Intervals (the range of values the odds are believed to fall within)

- **Three models:**
  - *Minimally adjusted* (adjusted for birth year only)
  - *Parsimonious* (birth year, maternal race, maternal food stamp program [WIC] participation)
  - *Most adjusted** (birth year, maternal race, WIC participation, sex, birth weight, delivery mode, agricultural pesticide exposure)

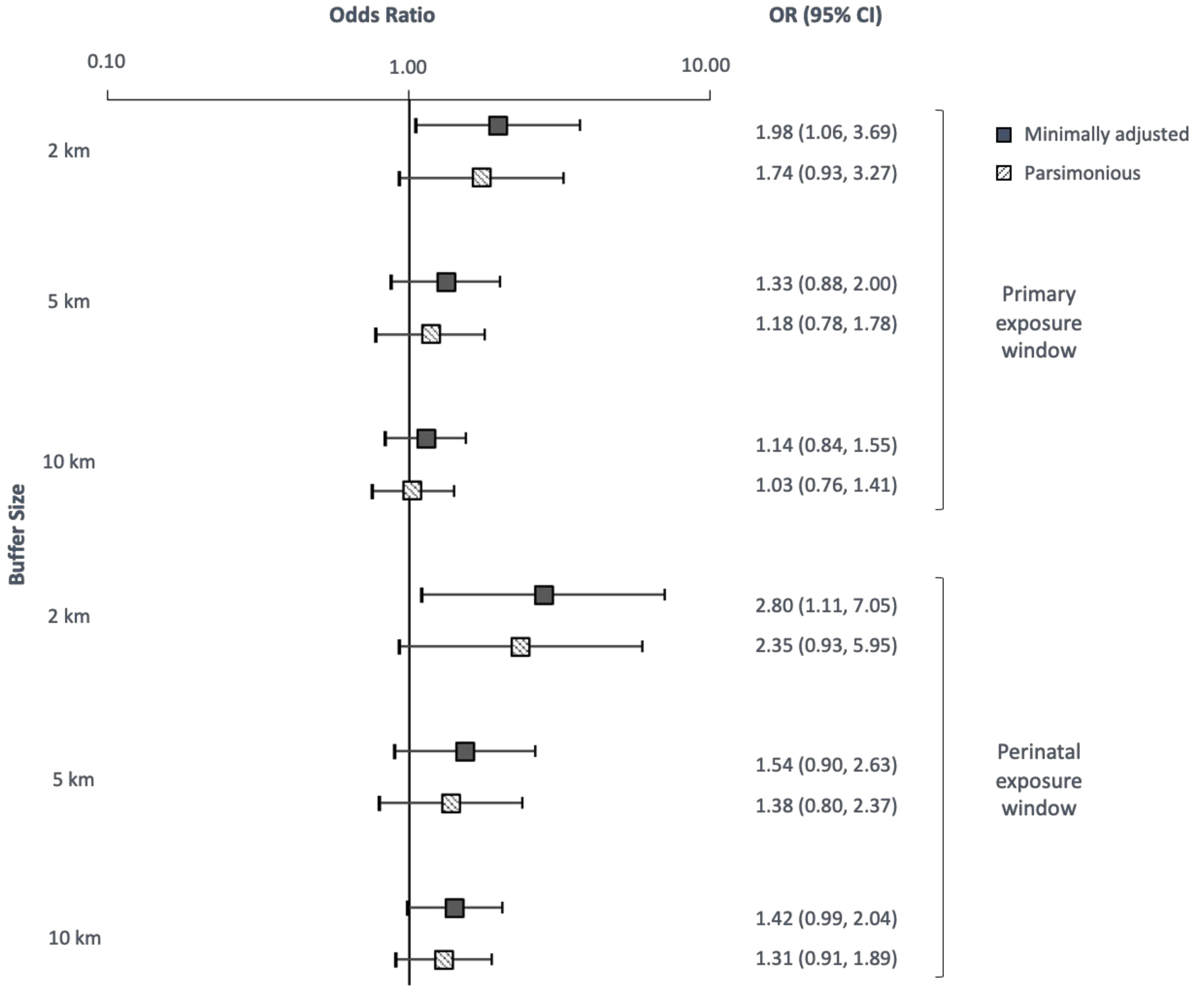
*Not shown

Population characteristics

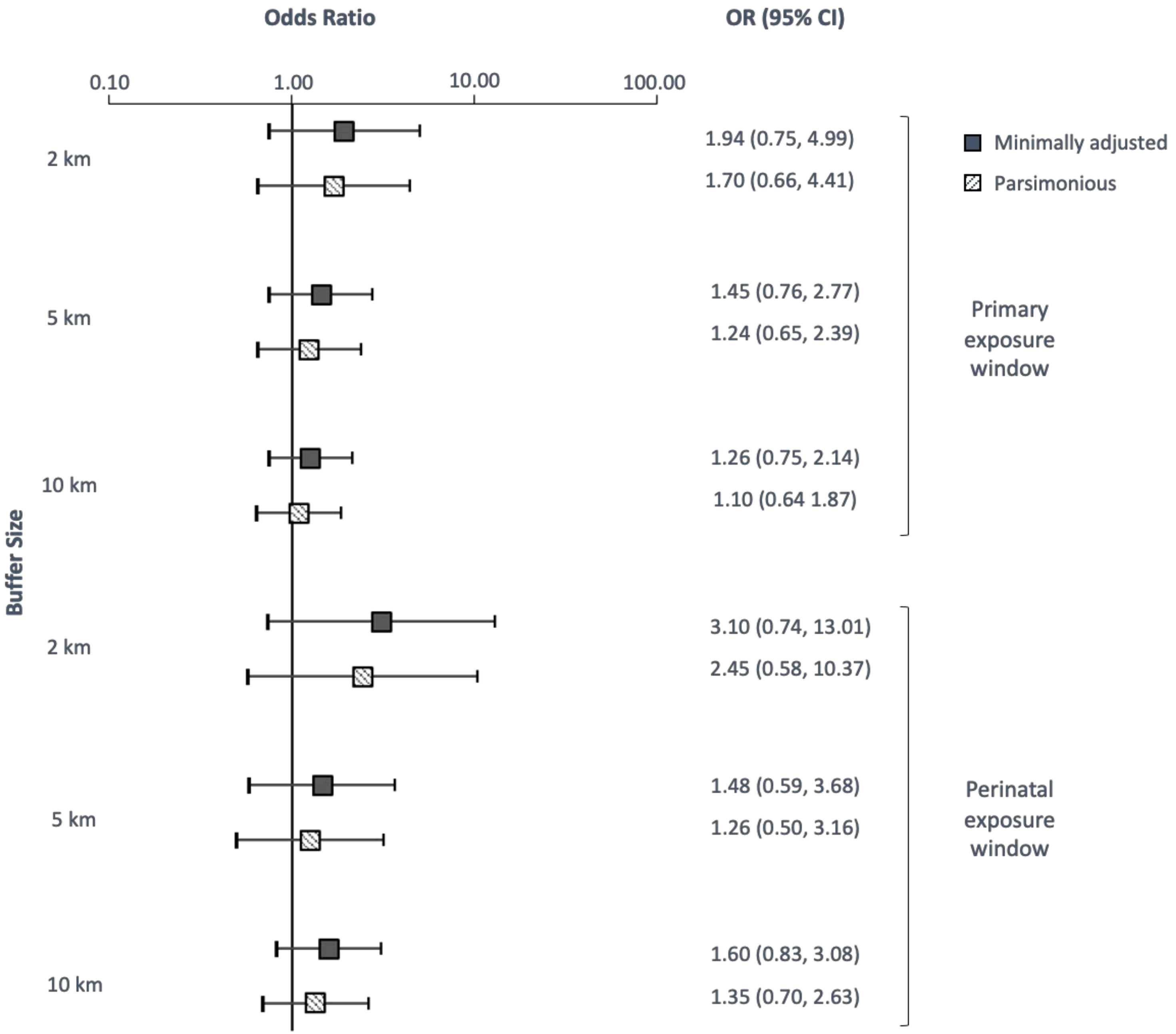
Variable	Cases (n=405) N (%)	Controls (n=2,080) N (%)	χ^2 p-value
Sex			0.57
M	222 (55)	1,108 (53)	
F	183 (45)	972 (47)	
Gestational age (weeks)			0.76
<32 weeks (Very preterm)	5 (1)	40 (2)	
32 to <37 (Preterm)	35 (9)	162 (8)	
37 to <39 (Early term)	78 (19)	436 (21)	
39-41 (Term)	258 (64)	1,275 (61)	
42+ (Post-term)	28 (7)	155 (7)	
Out of limit, missing, no physician estimate	1 (1)	12 (1)	
Birth weight			0.41
Low birth weight (<2499g)	27 (7)	172 (8)	
Normal birth weight (2500-3999g)	333 (82)	1,707 (82)	
High birth weight (>4000g)	45 (11)	201 (10)	
Delivery route			0.40
Vaginal	281 (69)	1,399 (67)	
Cesarean	124 (31)	681 (33)	
Mother's race			<0.0001
White	327 (81)	1,520 (73)	
Black	29 (7)	333 (16)	
Other	42 (10)	179 (9)	
Not reported	7 (2)	48 (2)	
Mother's ethnicity			0.90
Not Hispanic	370 (91)	1,888 (91)	
Hispanic	31 (8)	173 (8)	
Unknown	4 (1)	19 (1)	
Mother's educational attainment			0.96
High school or less	54 (13)	266 (13)	
Some college	221 (55)	1,129 (54)	
Bachelor's	84 (21)	430 (21)	
>16	46 (11)	255 (12)	
Mother uses WIC			0.18
Yes	160 (40)	749 (36)	
No	245 (60)	1,331 (64)	
Median household income ($USD)			0.88
<$26,500	96 (24)	517 (25)	
$26,500 – 53,000	191 (47)	971 (47)	
>$53,000	118 (29)	492 (28)	
	Mean (IQR)	Mean (IQR)	
Percent agricultural land (500 m[a])	13.8 (0.1-19.9)	12.5 (0-18.5)	<0.0001[b]
CDC SVI Percentile	54.0 (30.8-79.4)	53.4 (28.3-80.1)	0.70[b]
Annual PM 2.5 [ug/m^3]	11.7 (10.5-12.9)	11.7 (10.6-12.8)	0.93[b]

[a] Used as a proxy for pesticide exposure, accounting for likely extent of pesticide drift; [b] T-test p-value. IQR: Inter-quartile range; WIC: Supplemental Nutritional Program for Women, Infants, and Children; SVI: Center for Disease Control Social Vulnerability Index.

Aggregate exposure metric results



Water exposure metric results



Results & Conclusions

- Residential proximity to UOGD associated with up to 2-3 times the odds of childhood leukemia

- Water-specific metric produced estimates similar to or larger than aggregate metric, potentially providing support for water being a contributing route of exposure
  - Larger degree of uncertainty
  - Restricted exposure distribution prevented more complex analyses
  - Associations persisted after adjusting for multiple factors that may also be associated with cancer

- Relationship between buffer size used and magnitude of effect observed
  - Important to consider likely extent of transport distances for environmental exposures

Limitations & Challenges

- Sample size
  - ALL is rare, and most children in the study were not exposed to UOGD
  - Restricted exposure distribution limited the analyses we could perform
- Water-specific metric most applicable for those using private groundwater wells
  - Water contamination is highly spatially, temporally variable and challenging to capture/represent
  - Spatial metric not equivalent to environmental measurements
- Data acquisition challenges
  - Working with private health records is complex and sensitive
  - Oil and gas data quality and quantity varies by state

Strengths

- Largest case-control study of UOGD and ALL to date
- Accounted for multiple socio-economic, demographic, and environmental factors that may also be associated with cancer risk
- First to apply water-specific UOGD exposure metric in a health context
- Examined multiple buffer sizes for UOGD exposure metrics, informed by the health and environmental literature

Closing Thoughts

Tools for Assessing UOGD Exposure
Challenges for Investigating the Groundwater Pathway
UOGD & Environmental Justice
UOGD in the News
Policy Implications

Summary: Tools for assessing UOGD exposure

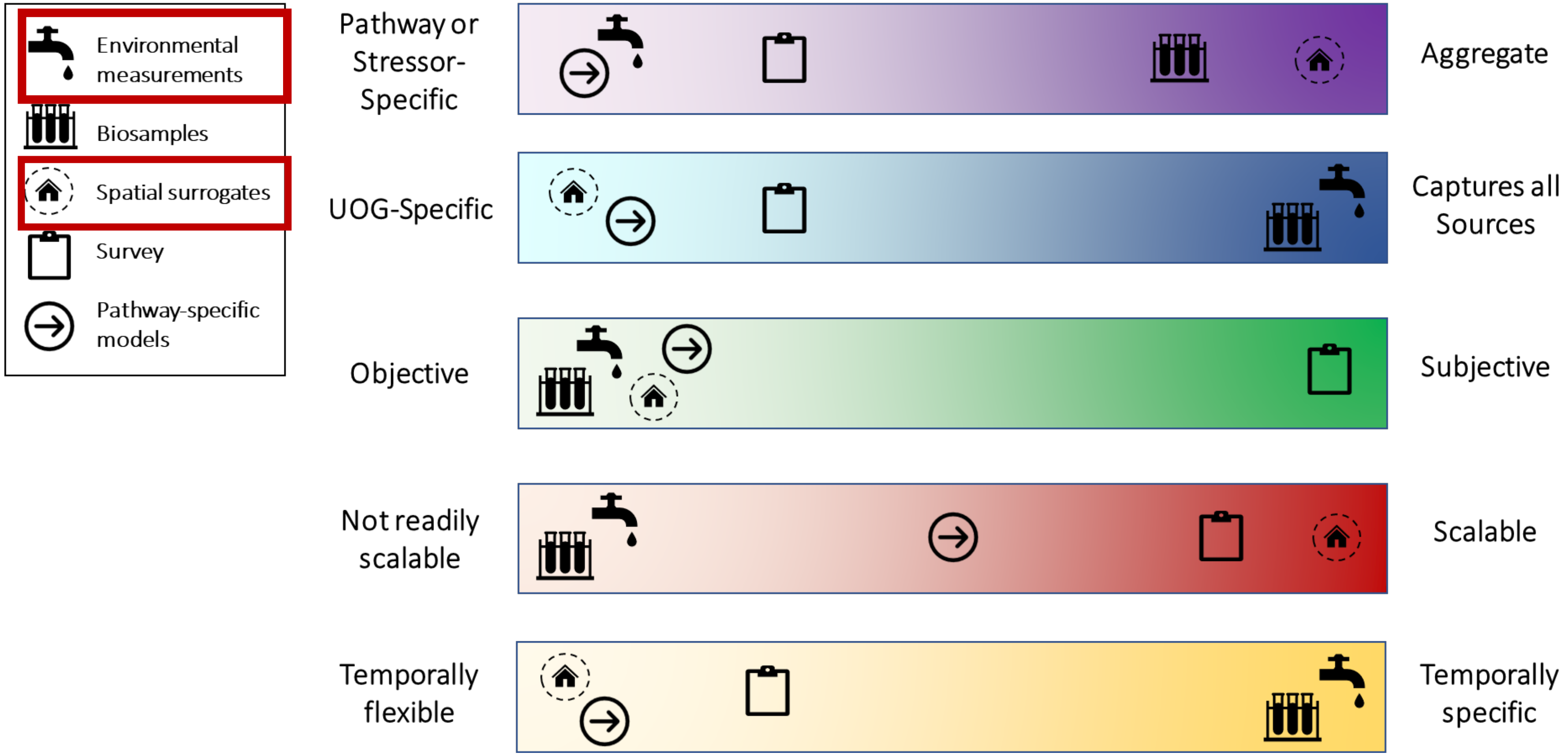


Figure from Deziel, Clark et al., 2022

Critical challenges for research investigating the groundwater pathway

- Water contamination may be transient or quickly resolved, and is thus difficult to capture
  - Timing of resource-intensive sample collection with contamination events requires timely and publicly available information on spills and other events
  - Varying physicochemical characteristics of contaminants further complicate sampling
- Difficult or even impossible to scale to large epidemiologic studies, and cannot measure contamination events occurring in the past
- Pathway specific metrics like ID_{ups} provide valuable tools for examining specific exposure pathways in a scalable, temporally flexible way

UOGD is an environmental justice issue

Are environmental health hazards distributed unequally?

Are environmental policies designed to protect everyone?

1991 First National People of Color Environmental Leadership Summit in Washington, D.C.

http://www.ejnet.org/ej/
Photo from http://ucc.org

- UOGD-related environmental health burdens are differentially distributed based on demographic and socio-economic status
  - Disproportionate exposures, occurrence of health outcomes
  - Water quality and quantity is a source of stress and anxiety for communities near UOGD, which are often the rural poor

e.g., Ogneva-Himmelberger et al. 2015
Clark et al. 2021
Silva et al. 2018
Fry et al. 2015
Cushing et al. 2020
Willow et al. 2016

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Will a push for plastics turn Appalachia into next 'Cancer Alley'?

PENNSYLVANIANS DEMAND A RESPONSE TO RARE CANCER CASES, OTHER HEALTH IMPACTS

June 26, 2019 / by Erica Jackson

New research on fracking health impacts, combined with unusually high rates of pediatric cancer, sound alarm bells in Pennsylvania

Public health in Pennsylvania ignored during fracking rush: Report

A new report outlines the alleged missteps in protecting Pennsylvanians from the health impacts of fracking.

by Nick Keppler April 14, 2022

Fractured: Harmful chemicals and unknowns haunt Pennsylvanians surrounded by fracking

We tested families in fracking country for harmful chemicals and revealed unexplained exposures, sick children, and a family's "dream life" upended.

Kristina Marusic

Wolf Administration Awards $2.5 Million Contract To University Of Pittsburgh To Research Health Effects Of Hydraulic Fracturing In Pennsylvania

12/22/2020

Pitt researchers seek participants in study on fracking and childhood cancers

MEGAN TROTTER
Pittsburgh Post-Gazette
SEP 21, 2022 10:21 AM

Policy Implications

- UOGD exempt from major water protection legislation like the Safe Drinking Water Act, Clean Water Act, and 2005 Energy Policy Act
    - Regulation happens largely at the state level
    - Variability among states

- Current setback distances as little as 150 ft
    - 500 ft in PA
    - *Observed 2-3x increased risk of ALL at up to ~6,560 ft*

- Existing setbacks are not sufficiently protective of the health of children or communities

- It should not fall on individuals to protect themselves from potential UOGD exposures, <u>it is the responsibility of policymakers to protect communities</u>

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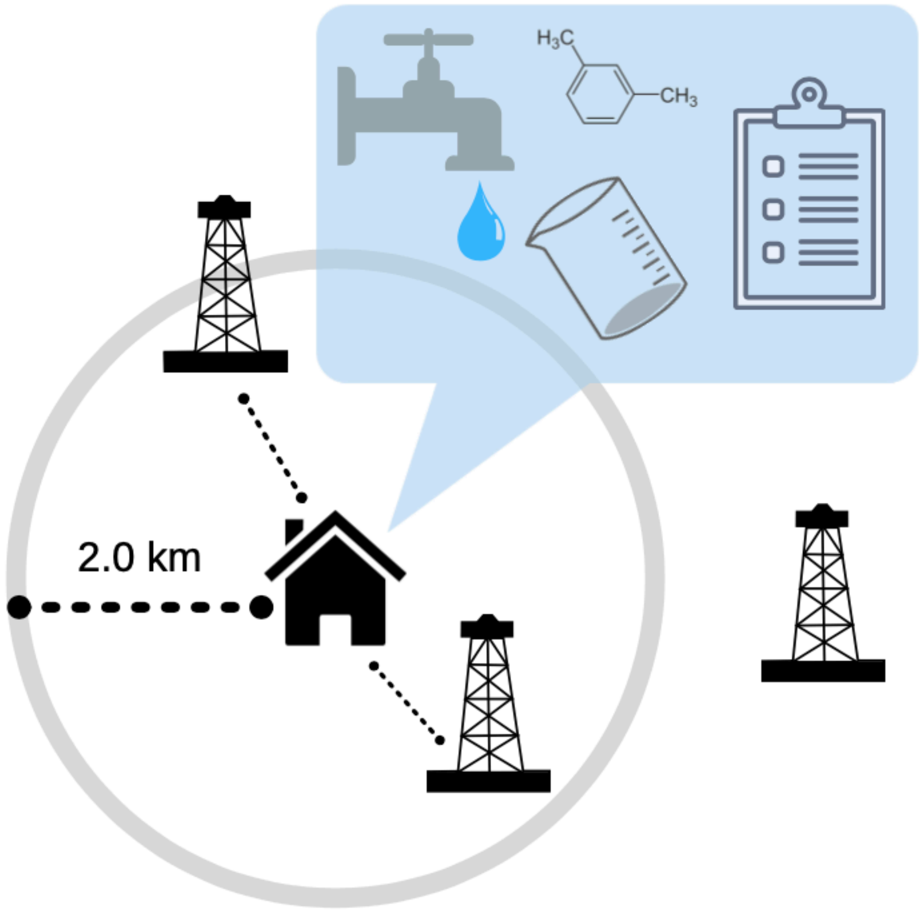
Extra slides

Assessing unconventional oil and gas exposure in the Appalachian Basin:

Comparison of exposure surrogates and residential drinking water measurements



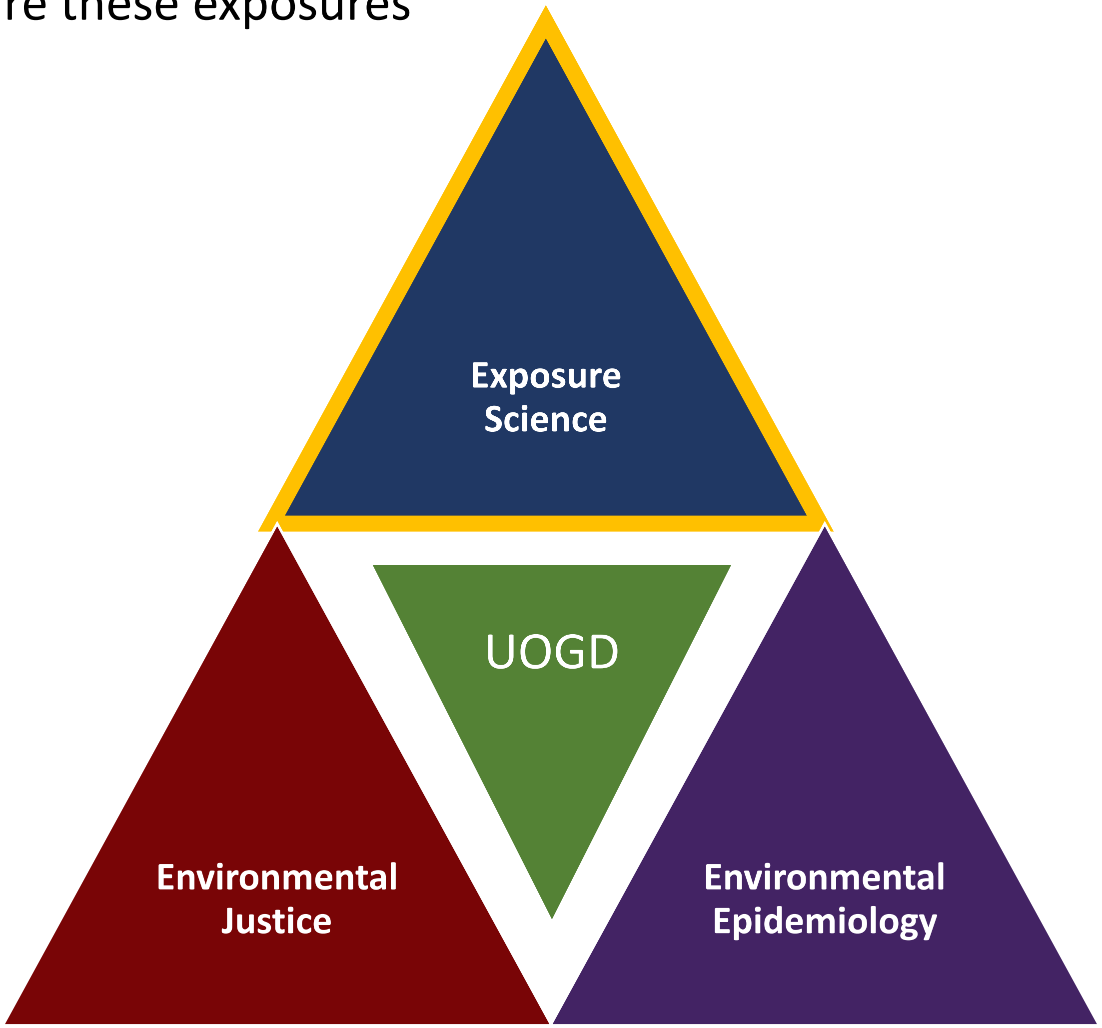
Clark et al. 2022, Env. Sci. & Technol.

Understanding exposure to UOGD

Aims:

I. Describe exposure to a range of UOGD-related health-relevant compounds in drinking water in the Appalachian Basin

II. Evaluate the whether commonly used aggregate spatial metrics capture these exposures



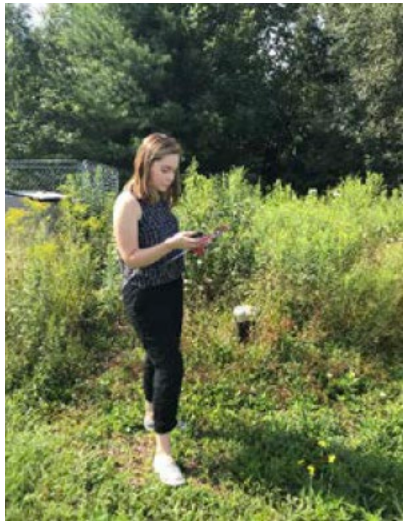
Data collection

Study population
- Adult homeowners living in Bradford County PA, Belmont and Monroe Counties OH
- Private well or spring
- English speaking

Interview
- 50-item questionnaire for the homeowner
- Information about the home, well/spring, product use, drinking water characteristics, household treatment system, demographic characteristics

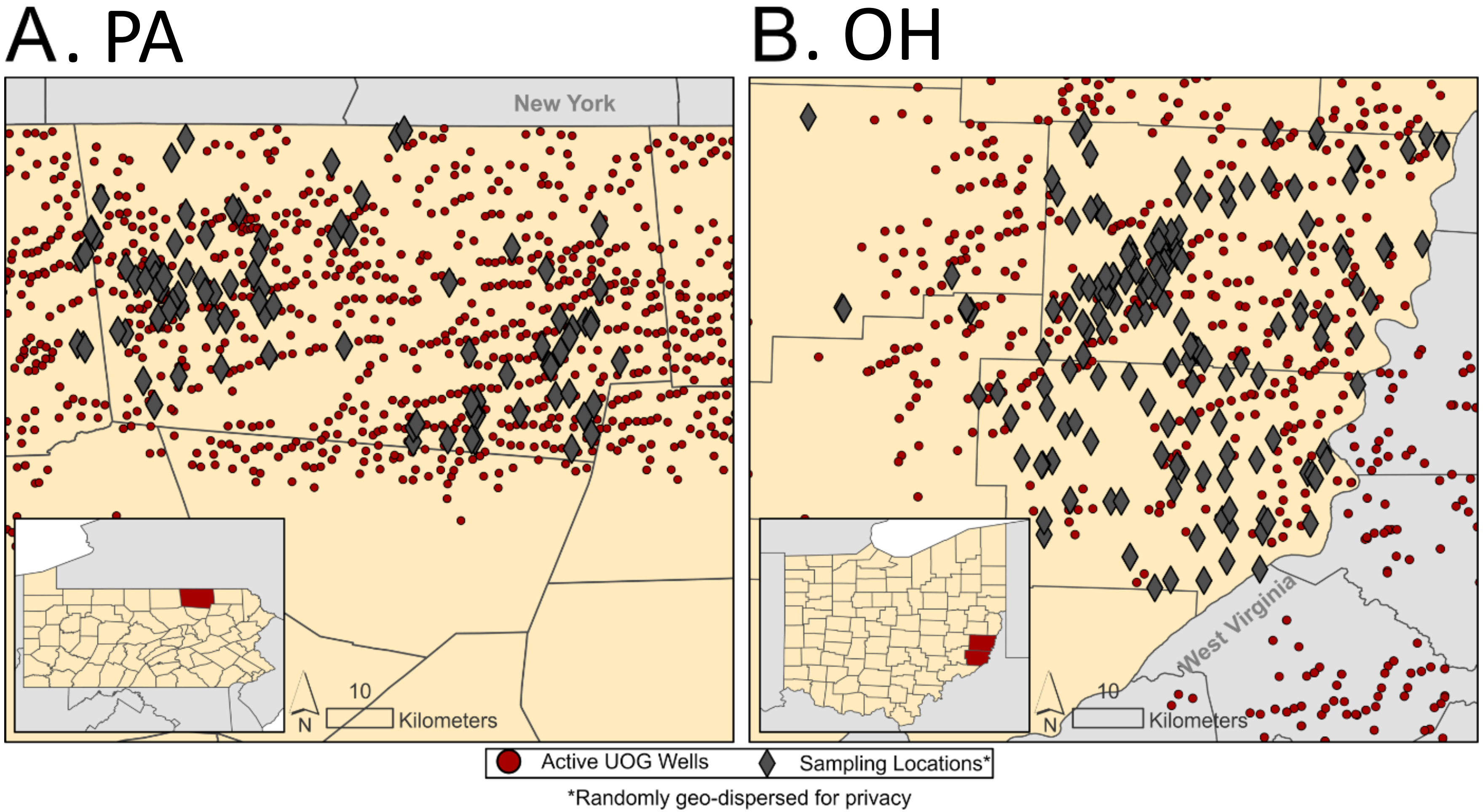
GPS collection (lat./long.)
- Coordinates taken **at door to home**

Water sample collection
- Samples analyzed for 64 organic and inorganic chemicals



Pictured: Cassandra Clark, Kristina Gutchess

Data collection



Grey diamonds represent sampling locations, red circles represent active UOG wells. Home locations randomly geo-dispersed (offset) by 0.1 km for privacy.

Aggregate and water-specific spatial metrics assessed

Distance to nearest UOG well

- Simple geographic distance between residence and UOG well

Inverse distance weighted well count

- $IDW\ well\ count = \sum_{i=1}^{n} \frac{1}{d_i}$
- With distance (d) between the (i) UOG well and residence, and n the number of UOG wells

Inverse distance-squared weighted well count

- $ID^2W\ well\ count = \sum_{i=1}^{n} \frac{1}{d_i^2}$
- With distance (d) between the (i) UOG well and residence, and n the number of UOG wells

(The first three metrics above are grouped by a bracket labelled "Aggregate".)

Water exposure metric, ID_{ups}

- $IDups = \frac{1}{u_i}$ [27, 28]
- With distance (u) between the (i) UOG well hydrologically upgradient of the residence

Organic chemicals (PA n=89 homes, OH n=161)

Chemical	PA >LOD (%)	PA Median (IQR) (μg/L)	OH >LOD (%)	OH Median (IQR) (μg/L)	USEPA MCL[c] (μg/L)
Bromochloromethane	97	0.52 (0.42, 0.63)	46	<LOD (<LOD, 0.08)	NS
Chloroform	76	0.09 (0.009, 0.19)	22	<LOD (<LOD, <LOD)	NS
1, 2-Dichloroethane & Benzene[a]	75	0.02 (<LOD, 0.04)	24	<LOD (<LOD, <LOD)	5
Trichloroethene	75	0.04 (0.008, 0.06)	-	-	5
Toluene	64	0.01 (<LOD, 0.03)	20	<LOD (<LOD, <LOD)	1000
Bromomethane	58	0.02 (<LOD, 0.06)	67	0.012 (<LOD, 0.04)	NS
Dibromomethane	45	<LOD (<LOD, 0.12)	-	-	NS
1,1-Dichloroethene & trans-1,2-Dichloroethene*	42	<LOD (<LOD, 0.02)	-	-	100
Vinyl chloride	26	<LOD (<LOD, 0.0004)	57	0.003 (<LOD, 0.023)	2
m-Xylene & p-Xylene[b]	24	<LOD (<LOD, <LOD)	-	-	10000

[a] Standard listed is for the chemical benzene only; [b] Standard listed is the sum of standards for total xylenes; [c] A Secondary MCL (related to taste, odor, or other aesthetic qualities) is reported for chemicals with no health-based MCL; * Out of 64 total samples for PA. Samples from 5 (5%) of PA homes were not reported due to evidence of contamination or other factors, like leaks or breakage. Twenty-five additional PA samples lack measurements of 1,1-Dichloroethene & trans-1,2-Dichloroethene only. IQR: inter-quartile range; LOQ: Limit of quantification; LOD: Limit of detection; MCL: Maximum Contaminant Level; NS: No standard.

Associations between detections of organic chemicals and metrics

Chemical	Nearest (km) OR (95% CI)	ID_{ups} 0.5 km OR (95% CI)	ID_{ups} 1 km* OR (95% CI)	ID_{ups} 2 km* OR (95% CI)	IDW 2 km* OR (95% CI)	ID^2W 2 km* OR (95% CI)
PA						
Vinyl chloride	0.71 (0.33, 1.53)	0.92 (0.33, 2.60)	1.87 (0.71, 4.91)	1.87 (0.71, 4.91)	1.87 (0.71, 4.91)	1.47 (0.56, 3.82)
Bromomethane	0.70 (0.37, 1.32)	0.68 (0.26, 1.78)	**2.55 (1.06, 6.13)**	1.72 (0.73, 4.07)	0.97 (0.42, 2.28)	0.81 (0.34, 1.89)
1,2-Dichloroethene & benzene	**0.46 (0.23, 0.93)**	0.60 (0.21, 1.72)	1.66 (0.66, 4.14)	**2.59 (1.01, 6.67)**	**2.59 (1.01, 6.67)**	**3.29 (1.25, 8.66)**
Toluene	*0.52 (0.27, 1.03)*	0.72 (0.27, 1.92)	**2.63 (1.07, 6.45)**	1.74 (0.73, 4.19)	2.13 (0.88, 5.18)	2.13 (0.88, 5.18)
Chloroform	1.41 (0.63, 3.13)	0.96 (0.33, 2.83)	2.63 (0.32, 2.28)	0.67 (0.25, 1.79)	0.67 (0.25, 1.79)	0.86 (0.32, 2.28)
M-xylene & p-xylene	**0.28 (0.10, 0.80)**	1.04 (0.35, 3.07)	**3.36 (1.16, 9.72)**	1.50 (0.56, 4.02)	**3.36 (1.16, 9.72)**	2.53 (0.91, 7.07)
1,1-Dichloroethene & trans-1,2-dichloroethene	0.76 (0.37, 1.57)	0.63 (0.22, 1.83)	2.05 (0.75, 5.63)	2.05 (0.75, 5.63)	1.09 (0.40, 2.96)	1.58 (0.58, 4.30)
Bromochloromethane**	*0.36 (0.11, 1.19)*	0.42 (0.17, 1.06)	1.09 (0.49, 2.45)	1.09 (0.49, 2.45)	0.92 (0.41, 2.06)	1.29 (0.57, 2.91)
Trichloroethene	0.87 (0.44, 1.74)	1.18 (0.42, 3.34)	0.76 (0.29, 2.00)	0.60 (0.23, 1.58)	0.60 (0.23, 1.58)	0.60 (0.23, 1.58)
Dibromomethane	0.91 (0.49, 1.69)	0.75 (0.30, 1.88)	1.80 (0.78, 4.20)	1.25 (0.54, 2.88)	1.04 (0.45, 2.40)	1.25 (0.54, 2.88)
OH						
Vinyl chloride	1.08 (0.85, 1.37)	0.71 (0.36, 1.39)	0.88 (0.44, 1.77)	0.67 (0.34, 1.33)	0.53 (0.27, 1.05)	0.66 (0.34, 1.28)
Bromomethane	0.91 (0.72, 1.17)	0.89 (0.44, 1.82)	1.99 (0.89, 4.41)	1.48 (0.70, 3.11)	1.12 (0.54, 2.31)	1.16 (0.57, 2.35)
1,2-Dichloroethene & benzene	1.18 (0.91, 1.53)	0.62 (0.27, 1.43)	0.90 (0.40, 2.04)	0.91 (0.41, 2.03)	0.77 (0.34, 1.74)	0.67 (0.30, 1.50)
Toluene	**1.54 (1.17, 2.03)**	0.33 (0.12, 0.91)	0.64 (0.26, 1.60)	0.44 (0.17, 1.15)	0.25 (0.08, 0.77)	0.30 (0.11, 0.82)
Chloroform	1.05 (0.80, 1.39)	1.95 (0.90, 4.23)	0.71 (0.30, 1.71)	0.61 (0.26, 1.47)	1.06 (0.47, 2.38)	0.92 (0.41, 2.05)
Bromochloromethane**	0.99 (0.79, 1.26)	0.97 (0.50, 1.89)	0.89 (0.44, 1.78)	1.02 (0.52, 2.00)	1.02 (0.52, 2.00)	1.45 (0.75, 2.81)

*Exposure is defined as a value above the median; **Detection is defined as a value above the median concentration for PA homes only. Compounds marked NA were not detected at a sufficient frequency for analysis.

Associations between detections of organic chemicals and metrics

- Limited associations between detections of organic chemicals and metrics, but some suggestive relationships
- **PA**: 1,2-Dichloroethane & benzene, m- & p-xylene, bromomethane, and toluene more likely to be detected in homes with higher exposure potential
- **OH**: Toluene more likely to be detected in homes with lower exposure potential

Inorganic chemicals (PA n=94 homes, OH n=161)

Chemical	PA >LOD (%)	PA Median (IQR) (μg/L)	OH >LOD (%)	OH Median (IQR) (μg/L)	USEPA MCL[c] (μg/L)
Arsenic	81	0.99 (0.36, 2.44)	8	<LOD (<LOD, <LOD)	10
Barium	100	166.03 (76.99, 399.46)	99	88.48 (50.74, 142.80)	2000
Bromide	34	<LOD (<LOD, 71.29)	53	27.00 (<LOD, 54.00)	NS
Calcium	99	34961 (20968, 42863)	100	72101 (51144, 101596)	NS
Chloride	100	5831 (3035, 16128)	99	6758 (3018, 19785)	250000[c]
Fluoride	80	82.37 (44.42, 114.2)	100	110.00 (82.00, 156.00)	4000
Iron	70	60.37 (<LOD, 139.02)	51	10.74 (<LOD, 32.70)	300[c]
Lead	96	1.27 (0.72, 2.05)	12	<LOD (<LOD, <LOD)	15
Lithium	100	23.33 (8.27, 51.95)	99	10.24 (6.79, 15.22)	NS
Magnesium	99	6767 (3526, 9845)	100	16116 (8870, 27149)	NS
Manganese	91	17.1 (0.94, 127.51)	58	1.84 (<LOD, 19.25)	50[c]
Nitrate	67	334.35 (<LOD, 1009.63)	99	560.00 (100.00, 1754.00)	10000
Potassium	100	1467.52 (1050.14, 1830.6)	100	1489.75 (1148.41, 2038.67)	NS
Sodium	100	16130 (7282, 46386)	100	23819 (16740, 52714)	NS
Strontium	100	472.04 (179.83, 1037.06)	100	526.48 (288.57, 967.63)	NS
Sulfate	100	10063 (6847, 15648)	96	30813 (20117, 50587)	250000[c]
Uranium	85	0.87 (0.24, 2.56)	16	<LOD (<LOD, <LOD)	30

IQR: inter-quartile range; LOQ: Limit of quantification; LOD: Limit of detection; MCL: Maximum Contaminant Level; NS: No standard.

Associations between concentrations of inorganic chemicals and metrics

- Most inorganic species not correlated or weakly correlated with metrics (Spearman ρ range: ±0.00-0.28)
- Direction of correlations mixed and inconsistent
- Concentrations of inorganics generally unrelated to UOGD exposure potential
- Many have alternative natural and anthropogenic sources

Strengths and Limitations

- Strengths
  - Large multi-state study of 255 homes
  - Tested for 64 organic and inorganic chemicals
  - Examined multiple commonly used metrics, including a new water-specific metric, at multiple buffer sizes

- Limitations
  - Low concentrations and limited exposure distributions restricted our analyses

Conclusions

- Organic chemicals detected infrequently and at low concentrations, though a few were positively associated with increasing UOGD exposure potential
- Several inorganic chemicals exceeded health-based standards, but were generally unrelated to UOGD exposure potential
- Aggregate metrics may be better representing non-water stressors or a combination of stressors