Hydraulic Fracturing of Shales:
Water Contamination Risks, Wastewater Management Strategies, and Emerging Research Challenges



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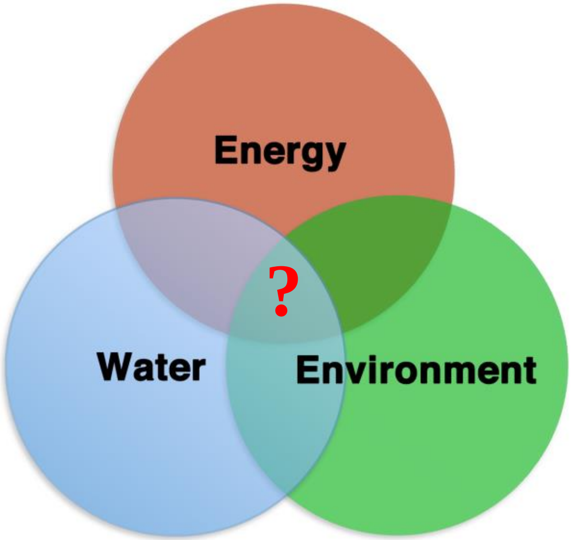
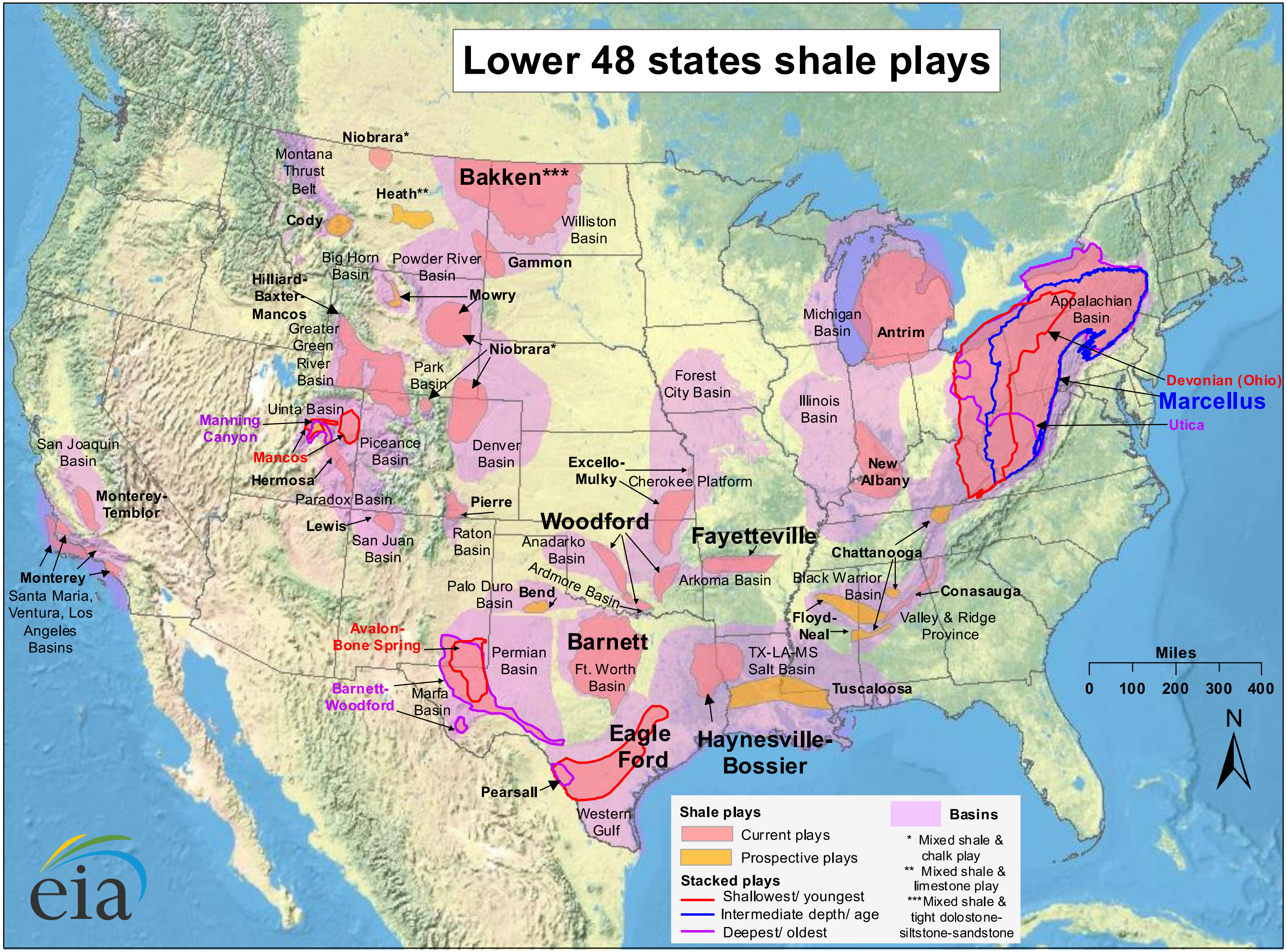
Linking Water and Energy Extraction

- *Hydraulic Fracturing*: Why are we talking about this now?
  - Scale, rate of application, incomplete knowledge

- *Life cycle of a shale well*: Identifying water risks and sustainability challenges





Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

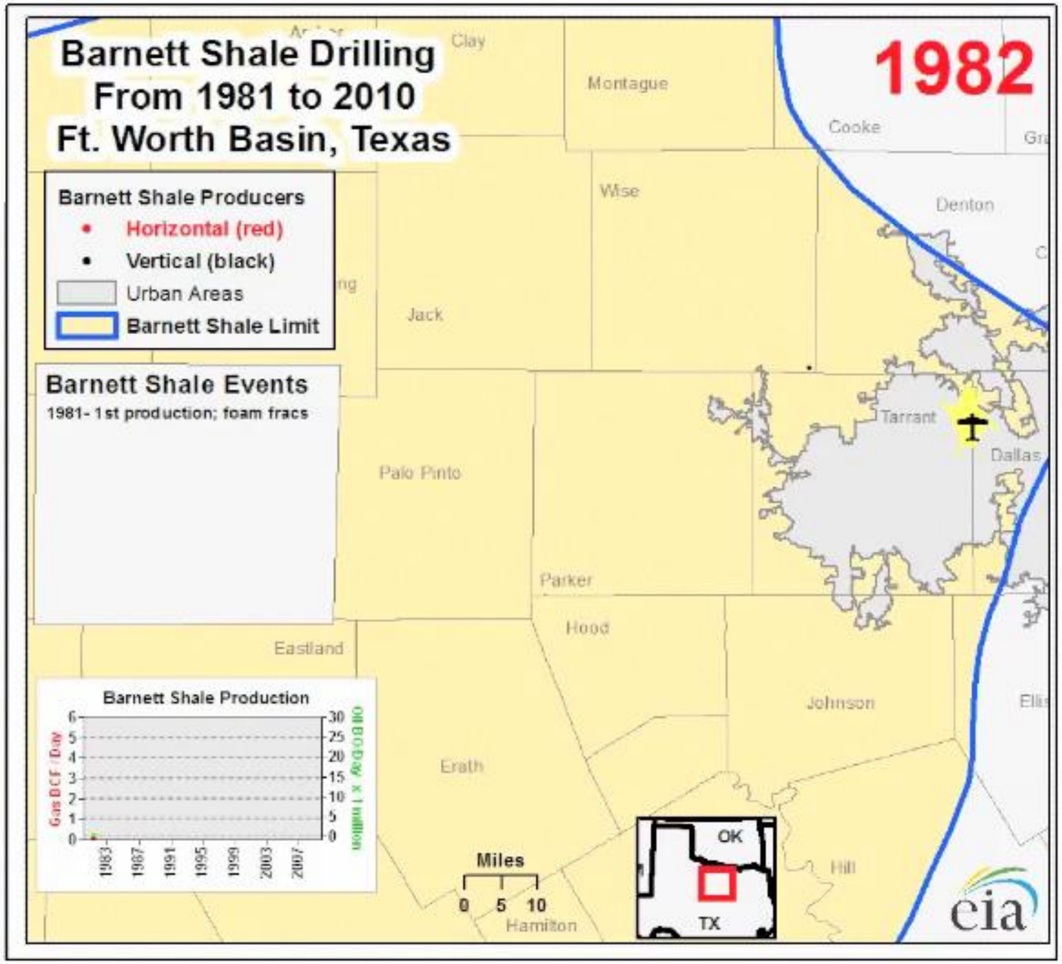
Hydraulic Fracturing: A brief history

- First test well "fracked" in 1947 by Standard Oil in Kansas using a mix of gelled gasoline (napalm) and sand
- First commercial application began in 1949, patented by Halliburton
- Many alternatives to water: N_2 foam, LPG, CO_2, etc.

What's in a name…
Fracturing via water, seems simple enough, right? Then why all the recent concern and attention?

Montgomery and Smith (2010), *JPT*

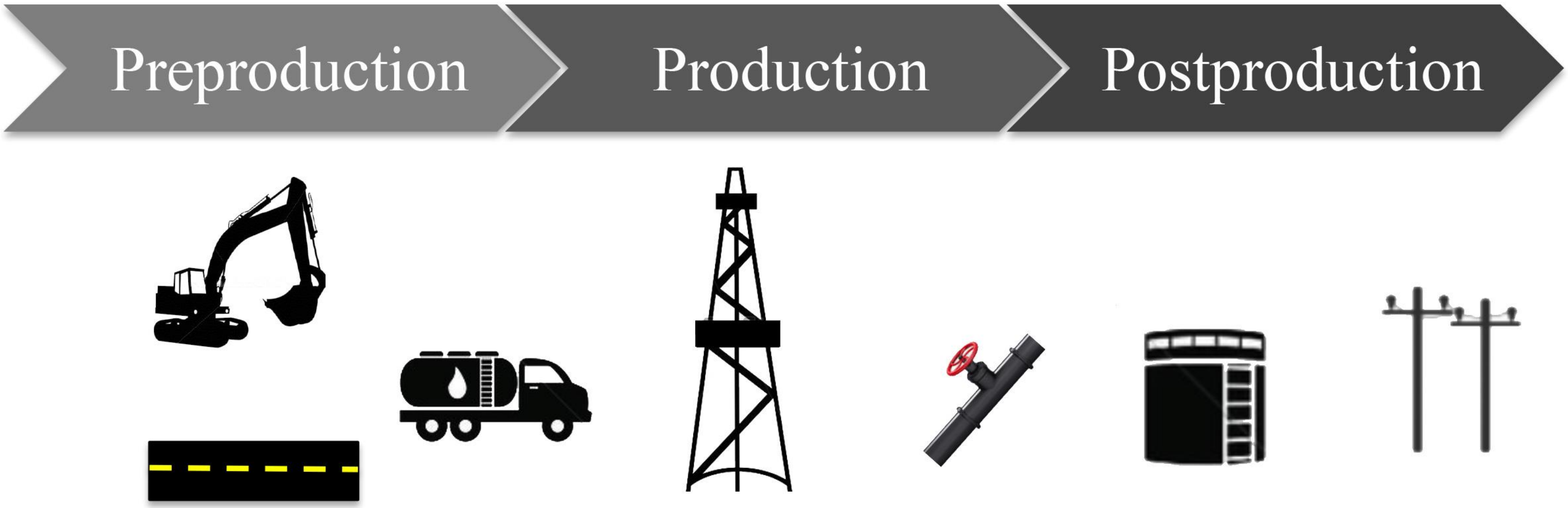
<u>Rapid deployment</u> of high-volume hydraulic fracturing coupled with horizontal drilling



Scale Matters…

Image from NASA

Life Cycle of a Shale Gas/Oil Well



Preproduction
- Wellpad construction
- Water acquisition and transport
- Chemical and equipment transport

Production
- Well completion (includes hydraulic fracturing step)
- Production infrastructure → flowback and produced brine → production

Postproduction
- Potential methane leakage
- Wastewater management
- Heating, electric power generation

Image modified from *Burton et al. (2014)*

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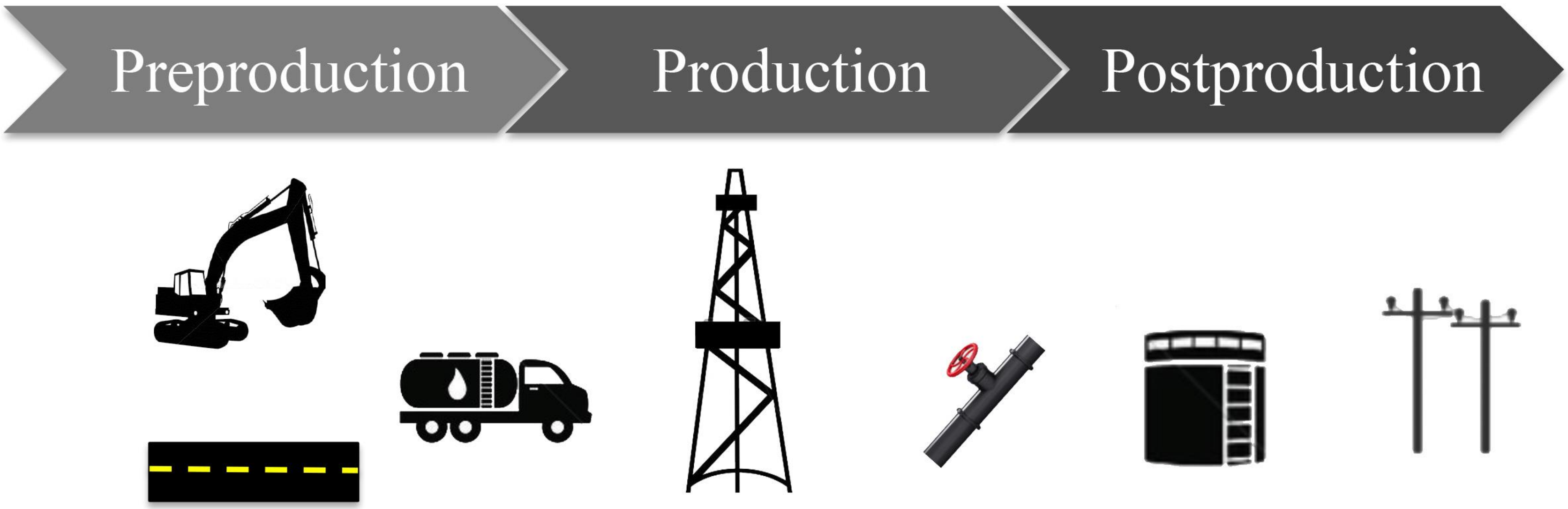

- Wellpad construction
- ***Water acquisition*** and transport
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- Well completion (includes hydraulic fracturing step)
- Production infrastructure → ***flowback and produced brine*** → production

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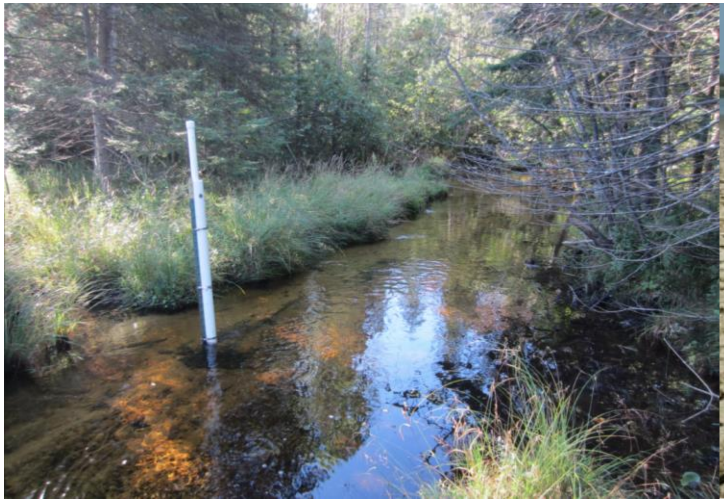
Water Acquisition and Use



Water Acquisition and Use

Table 1: High-volume well completions in the state of Michigan

Permit #	Well Name	Well No	County	Target Formation	Water Utilized (gal)
59112	SCHULTZ	1--36	SANILAC	A1 Carbonate	154,600
60041	HUBBEL	2-22 HD1	MONTMORENCY	Niagaran	220,000 (est)
60170	STATE KOEHLER & KENDALL	1-27 HD1	CHEBOYGAN	Collingwood	3,256,596
60212	KELLY ET AL	1-26 HD1	HILLSDALE	Black River	228,312
60305	STATE WILMOT	1--21	CHEBOYGAN	Collingwood	109,410
60360	STATE EXCELSIOR	1-13 HD1	KALKASKA	Collingwood	5,860,764
60380	CRONK	1-24 HD1	GLADWIN	A1 Carbonate	758,454
60389	STATE EXCELSIOR	1-25 HD1	KALKASKA	Collingwood	8,461,614
60537	MCNAIR ET AL	1-26 HD1	HILLSDALE	Black River	350,448
60452	WILEY	1-18 HD1	GLADWIN	A1 Carbonate	1,420,939
60545	STATE EXCELSIOR	2-25 HD1	KALKASKA	Collingwood	12,562,096
60546	STATE EXCELSIOR	3-25 HD1	KALKASKA	Collingwood	21,112,194
60560	STATE RICHFIELD	1-34 HD1	ROSCOMMON	Collingwood	4,811,940
60579	STATE GARFIELD	1-25 HD1	KALKASKA	Collingwood	8,461,635
60575	RILEY	1-22 HD1	OCEANA	A1 Carbonate	NA

Data accurate as of March 31, 2013

~47,000,000 L
~80,000,000 L

These wells were ~9,000 ft deep, ~1 mile long horizontals legs, ~20 frac stages

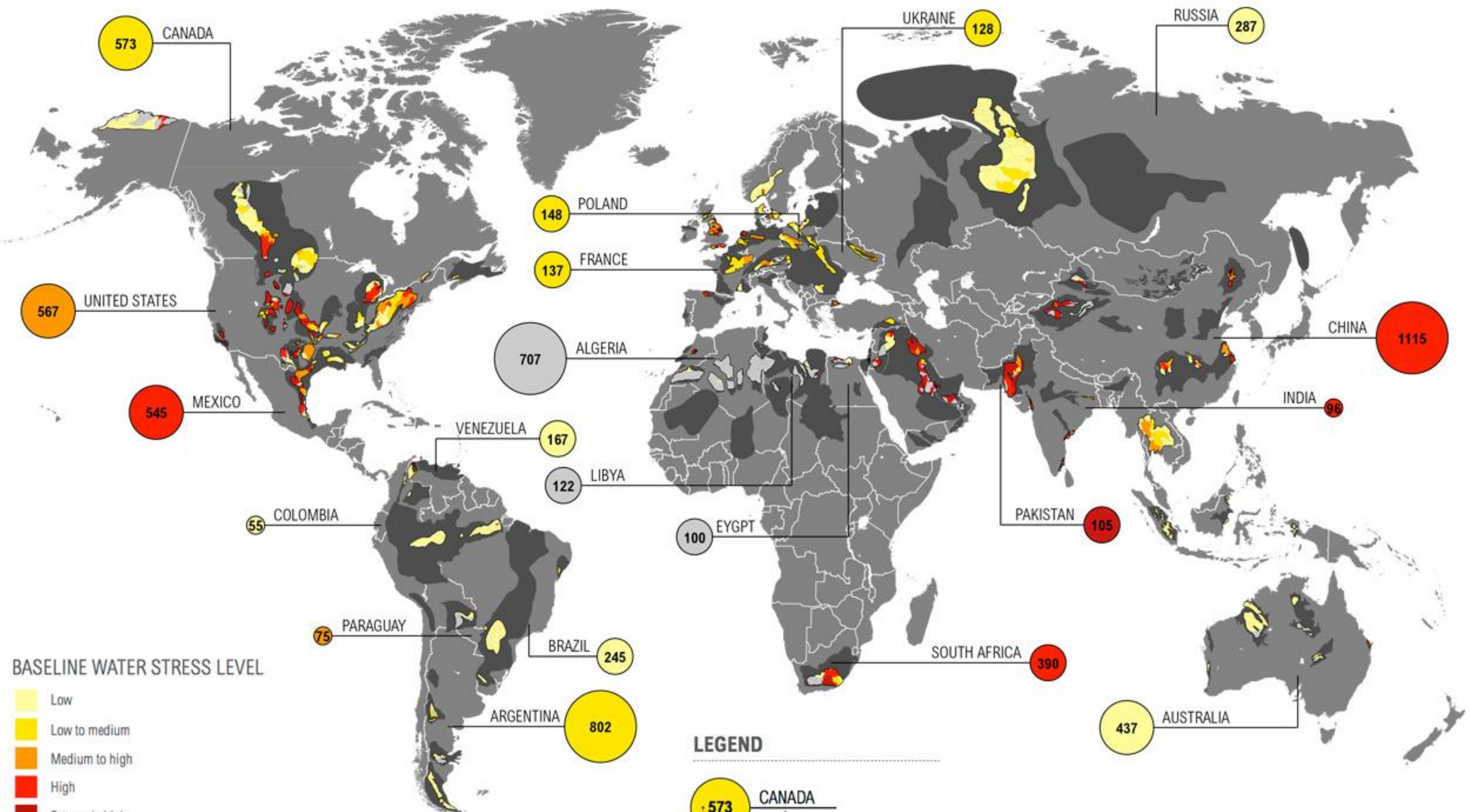
Water Use Intensity

Average use per well across major US shale plays = **14,500,000 L**

Energy source (data source)	Water for extraction (L/GJ, gallons/MMBTU)	Water for extraction and processing (L/GJ, gallons/MMBTU)	Water consumption intensity of electricity generation (L/MWh)[a]
Natural gas, conventional (42, 50)	0.7, 0.2	1.9, 6.7	See below
Natural gas, unconventional (47–49)	8.6, 2.4	15, 4.1	See below
Natural gas combined cycle (once through)	See above	See above	520
Natural gas combined cycle (closed loop)	See above	See above	850
Pulverized coal (once through) (47–49)	9.0, 2.5	27, 7.5	1,400
Pulverized coal (closed loop) (47–49)	9.0, 2.5	27, 7.5	1,900
Saudi Arabian crude (47)	79, 22	110, 32	NA
Oil shale (51)	200, 57	240, 67	NA
Oil sands (47)	NA	110, 31	NA
Nuclear (once through) (47–49)	14, 4	47, 13	1,700
Corn ethanol (unirrigated) (47, 48)	300, 83	430, 119	2,100
Corn ethanol (irrigated) (47, 48)	14,000, 3,800	14,000, 3,800	16,000
Solar photovoltaic (47–49)	0, 0	0, 0	10
Concentrated solar power[b] (47, 48)	NA	NA	3,100
Wind[a]	0, 0	0, 0	4

From *Jackson et al. (2014)*

Location of World's Shale Plays, Volume of Technically Recoverable Shale Gas in the 20 Countries with the Largest Resources, and the Level of Baseline Water Stress



BASELINE WATER STRESS LEVEL

- Low
- Low to medium
- Medium to high
- High
- Extremely high
- Arid & low water use

SHALE BASIN

LEGEND

573 CANADA
- Country name
- Average Baseline Water Stress Level
- Technically recoverable shale gas resources (trillion cubic meters)

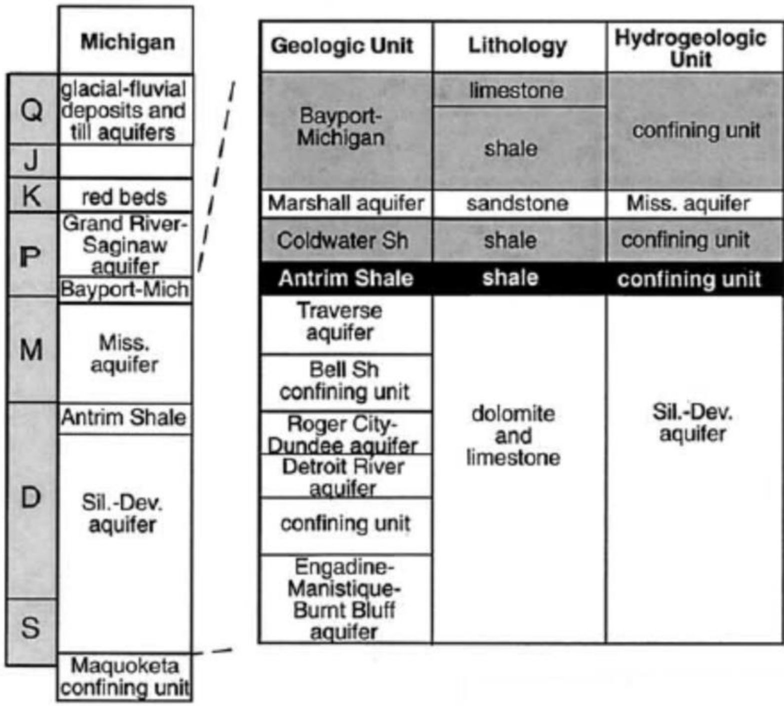
Water stress at shale plays around the world. 20 labeled countries have the world's largest technically recoverable shale gas resources. Circle color indicates average water stress level across a country's shale plays—circle size indicates overall volume of recoverable shale resources.

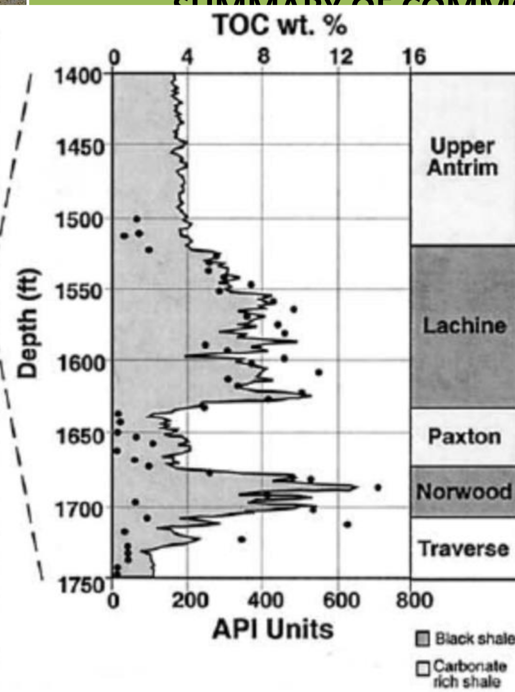
www.wri.org/water-for-shale

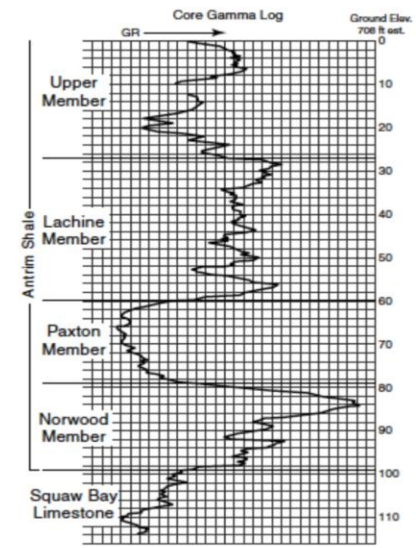
WORLD RESOURCES INSTITUTE

Flowback and Produced Water

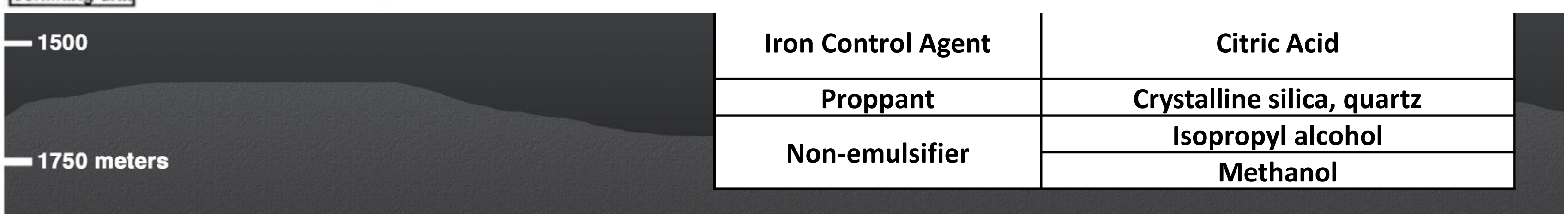
Flowback water – What's in it?







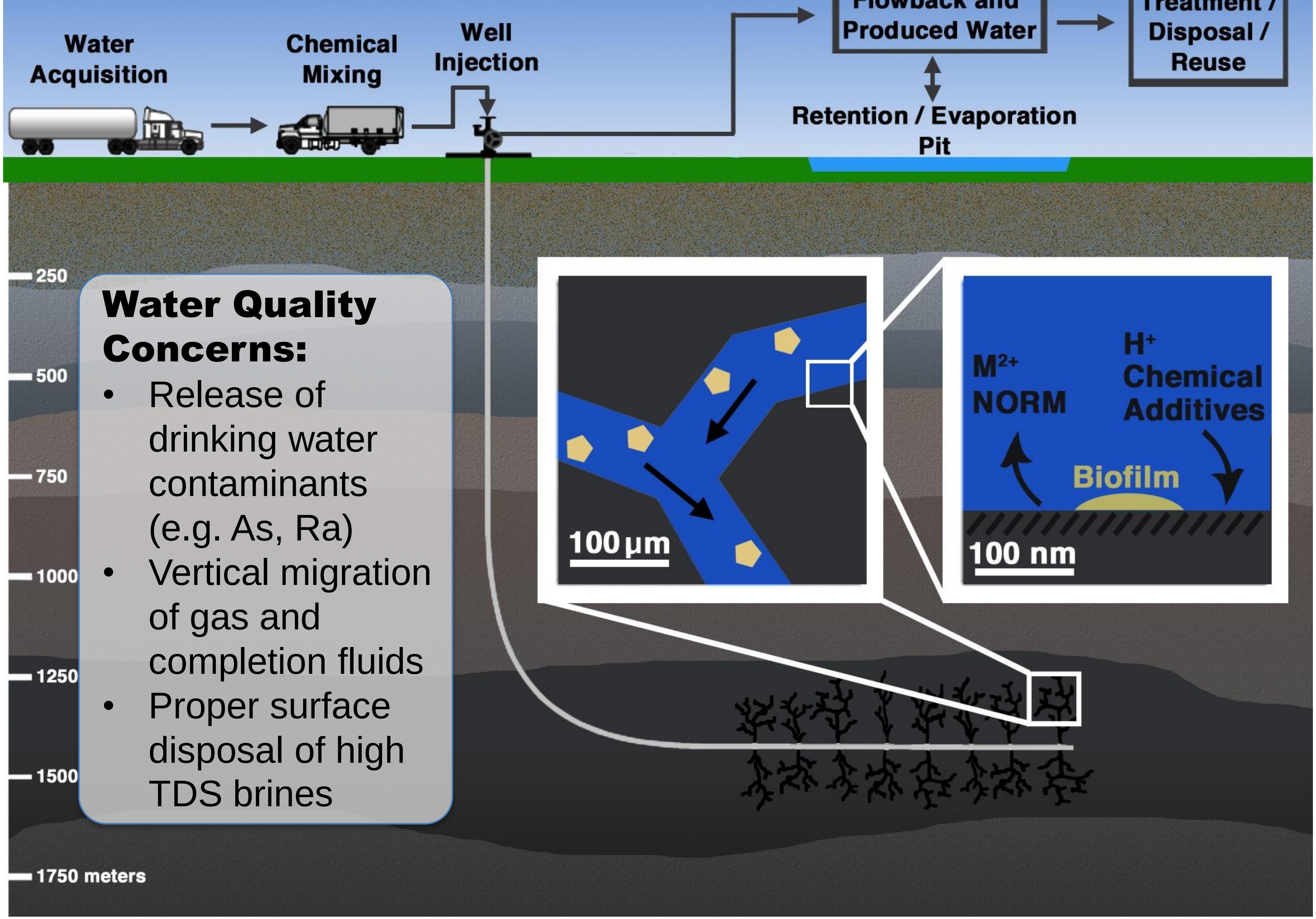
McIntosh et al. (2002),; Curtis (2002)



SUMMARY OF COMMON CHEMICALS

Iron Control Agent	Citric Acid
Proppant	Crystalline silica, quartz
Non-emulsifier	Isopropyl alcohol
	Methanol

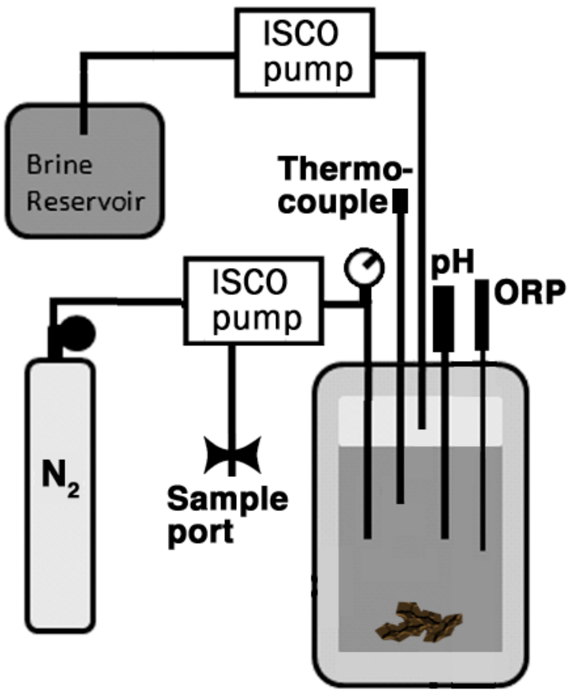
Flowback water – What's in it?



Water Quality Concerns:

- Release of drinking water contaminants (e.g. As, Ra)
- Vertical migration of gas and completion fluids
- Proper surface disposal of high TDS brines

Flowback Water Quality:
Toxic Element Leaching From Shales in Contact with Hydraulic Fracturing Fluids



Goal: Investigate toxic metal and radionuclide leaching from shales as a function of:

- **Shale composition**
- **System conditions (T, P)**
- **Chemical additives**

Table2: Fluid Composition	
Chemical Additive	**[mol/L]**
Hydrochloric Acid	0.03
Choline chloride	0.01
Citric Acid	0.00064
Ammonium Persulfate	0.00095

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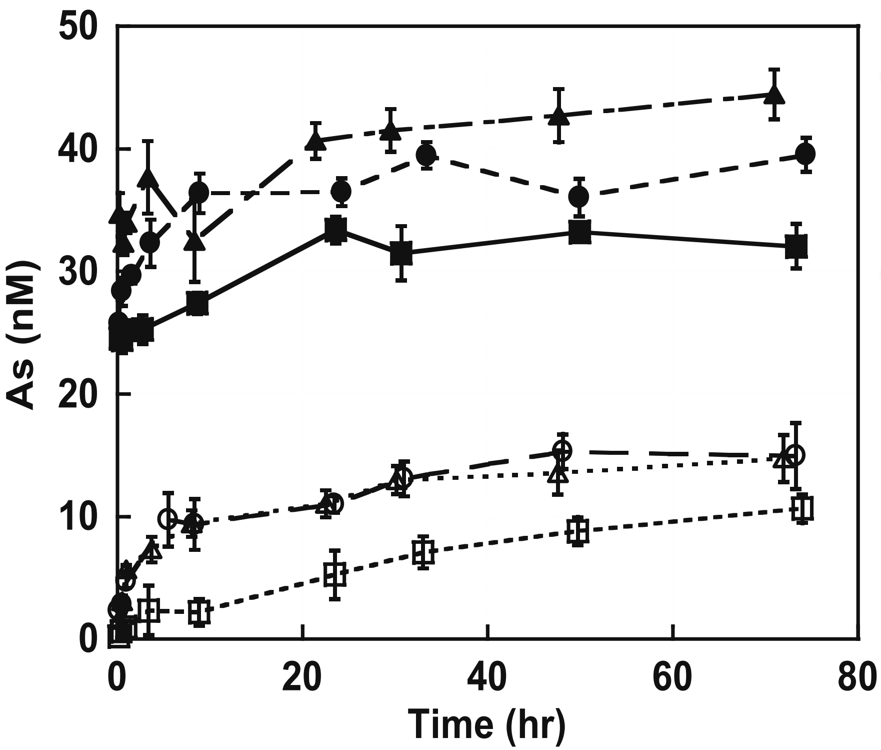

With model hydraulic fracturing fluid

Increasing P, T

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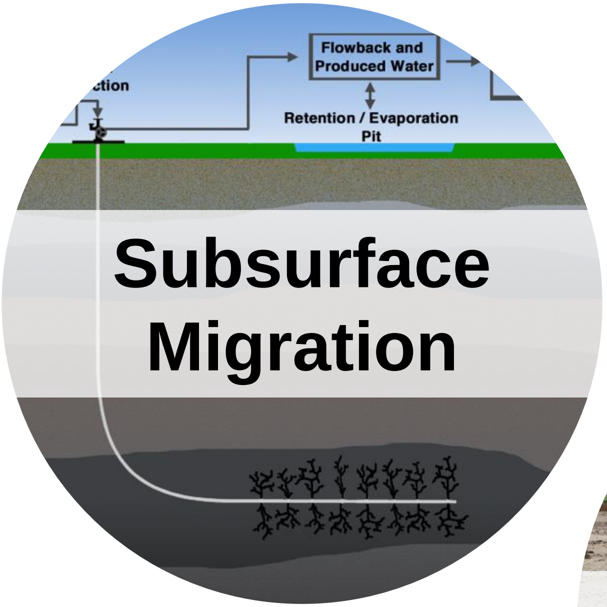
Fan *et al.* (in prep)

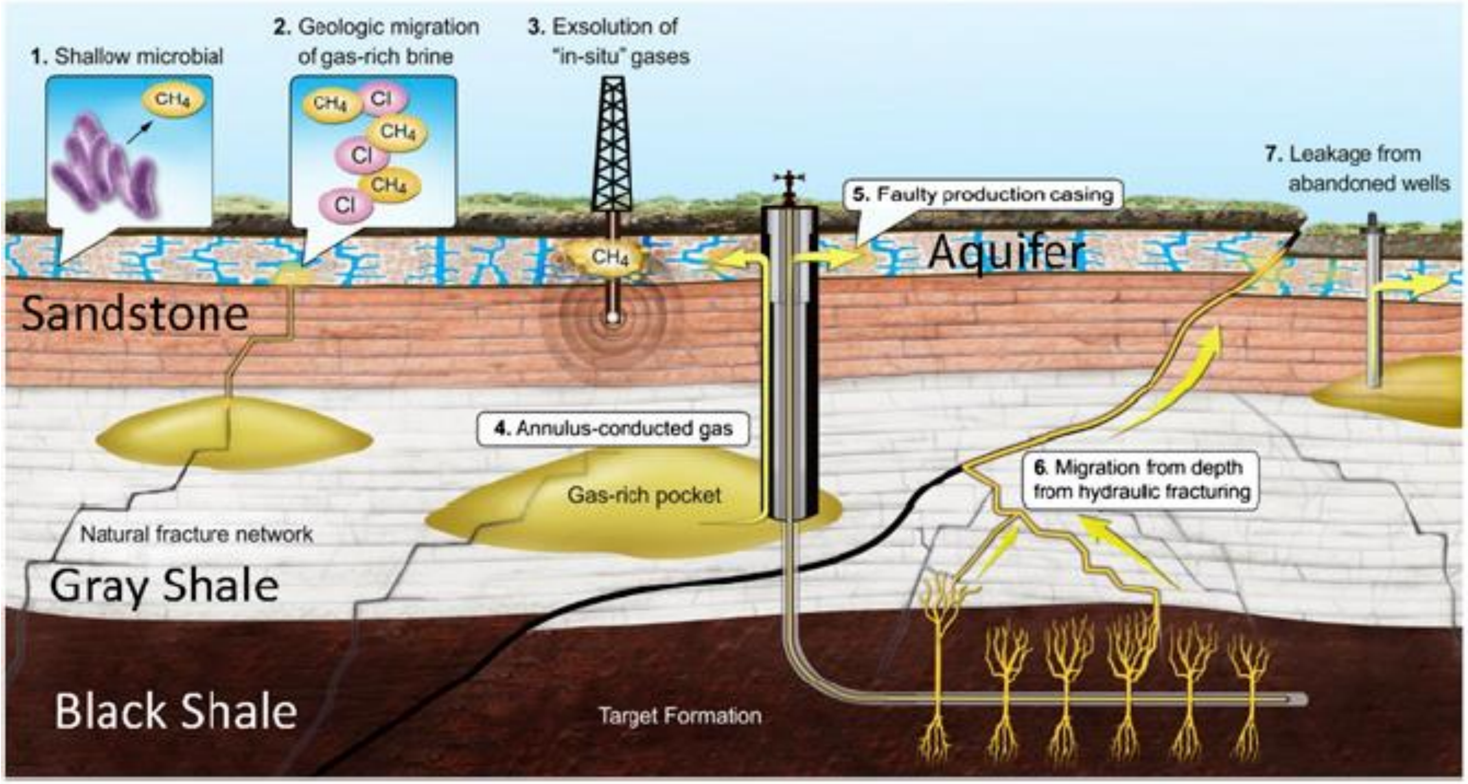
Water Contamination Risks



Gas Leakage Risk

Challenges: Estimating leakage rates, confirming methane sources

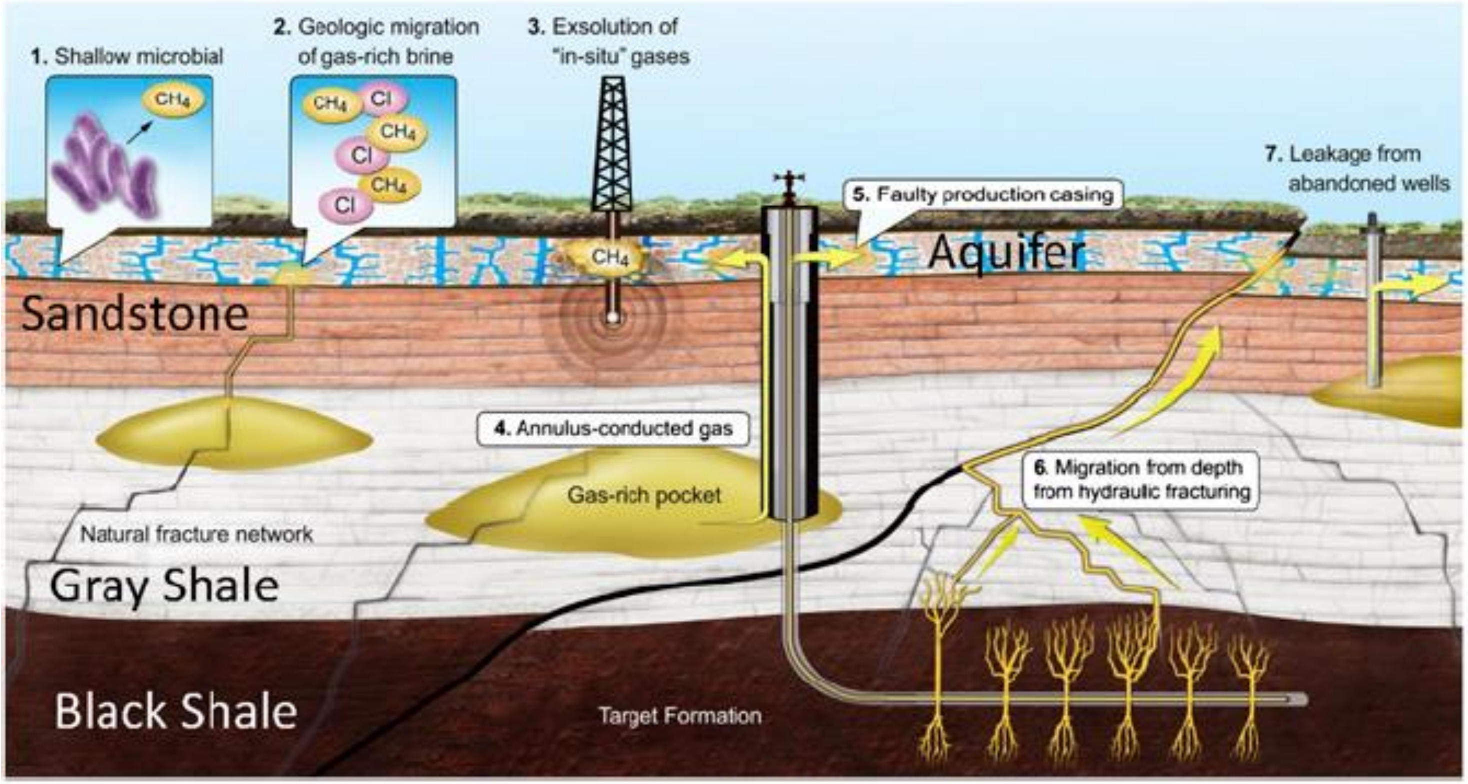
- **Casing failure** most common leakage pathway



From *Darrah et al. (2014)*

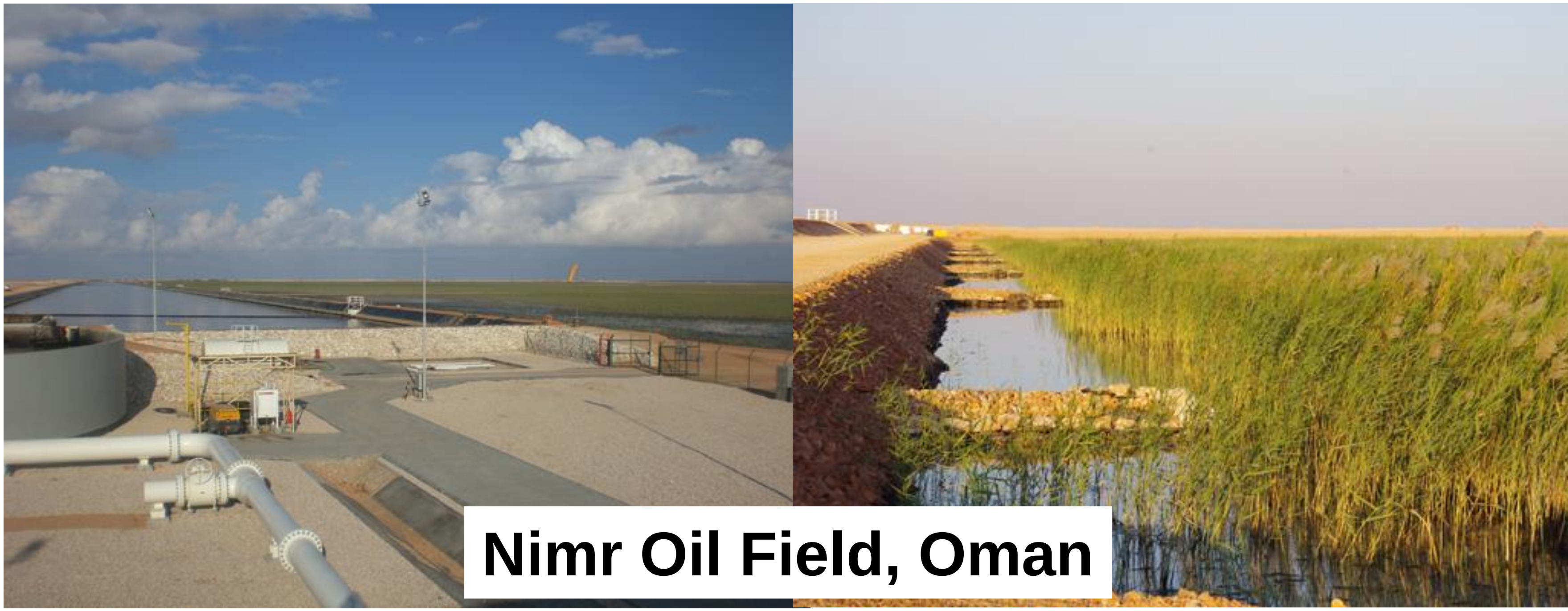
Geochemical Fingerprinting

- Evaluate noble gas and isotopic signatures of produced brine and natural gas → fingerprint gas/water to track *migration* of gas in the subsurface, *mixing* of injected fluids with native brines



From *Darrah et al. (2014)*

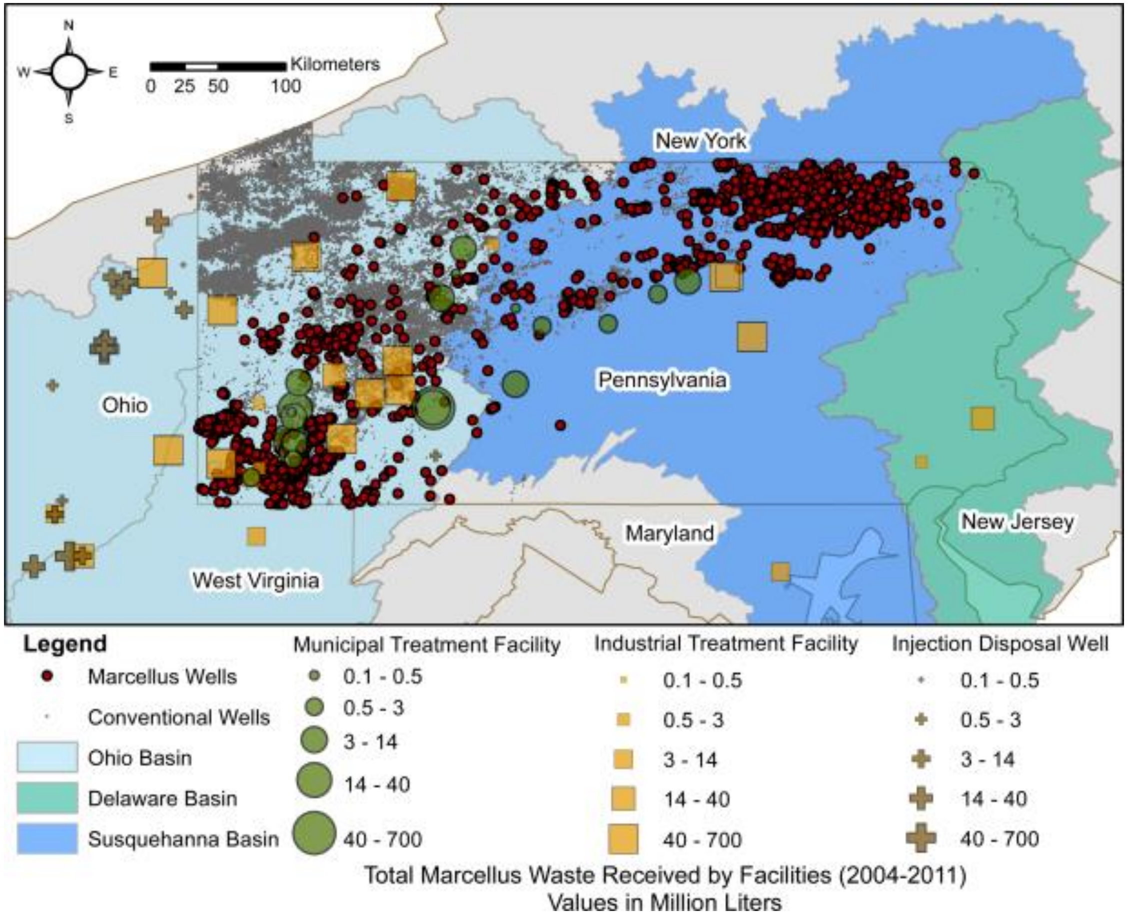
Wastewater Management



Deep well injection comprises >95% of oil and gas wastewater disposal in the U.S.[1]

[1](Clark and Veil, 2009)

Marcellus Shale in Pennsylvania



Lutz et al. (2013)

Over 12,000 wells drilled

>3,500 producing wells

~10x increase in waste water disposal volume from 2004 to 2014 (now ~1.43 x 10^9 gal/yr)

7 brine disposal wells

Table 1. Summary of Marcellus Shale Produced Water Quality in Pennsylvania

	minimum	maximum	average	number of samples
TDS (mg/L)	680	345,000	106,390	129
TSS (mg/L)	4	7,600	352	156
oil and grease (mg/L)	4.6	802	74	62
COD (mg/L)	195	36,600	15,358	89
TOC (mg/L)	1.2	1530	160	55
pH	5.1	8.42	6.56	156
alkalinity (mg/L as $CaCO_3$)	7.5	577	165	144
SO_4 (mg/L)	0	763	71	113
Cl (mg/L)	64.2	196,000	57,447	154
Br (mg/L)	0.2	1,990	511	95
Na (mg/L)	69.2	117,000	24,123	157
Ca (mg/L)	37.8	41,000	7,220	159
Mg (mg/L)	17.3	2,550	632	157
Ba (mg/L)	0.24	13,800	2,224	159
Sr (mg/L)	0.59	8,460	1,695	151
Fe dissolved (mg/L)	0.1	222	40.8	134
Fe total (mg/L)	2.6	321	76	141
gross alpha[a] (pCi/L)	37.7	9,551	1,509	32
gross beta[a] (pCi/L)	75.2	597,600	43,415	32
Ra^{228} (pCi/L)	0	1,360	120	46
Ra^{226} (pCi/L)	2.75	9,280	623	46
U^{235} (pCi/L)	0	20	1	14
U^{238} (pCi/L)	0	497	42	14

[a]Data for Northeast Pennsylvania only.

Barbot *et al.* (2013)

Prior to 2011, flowback water sent to publically owned wastewater treatment plants not designed to handle high TDS fluids

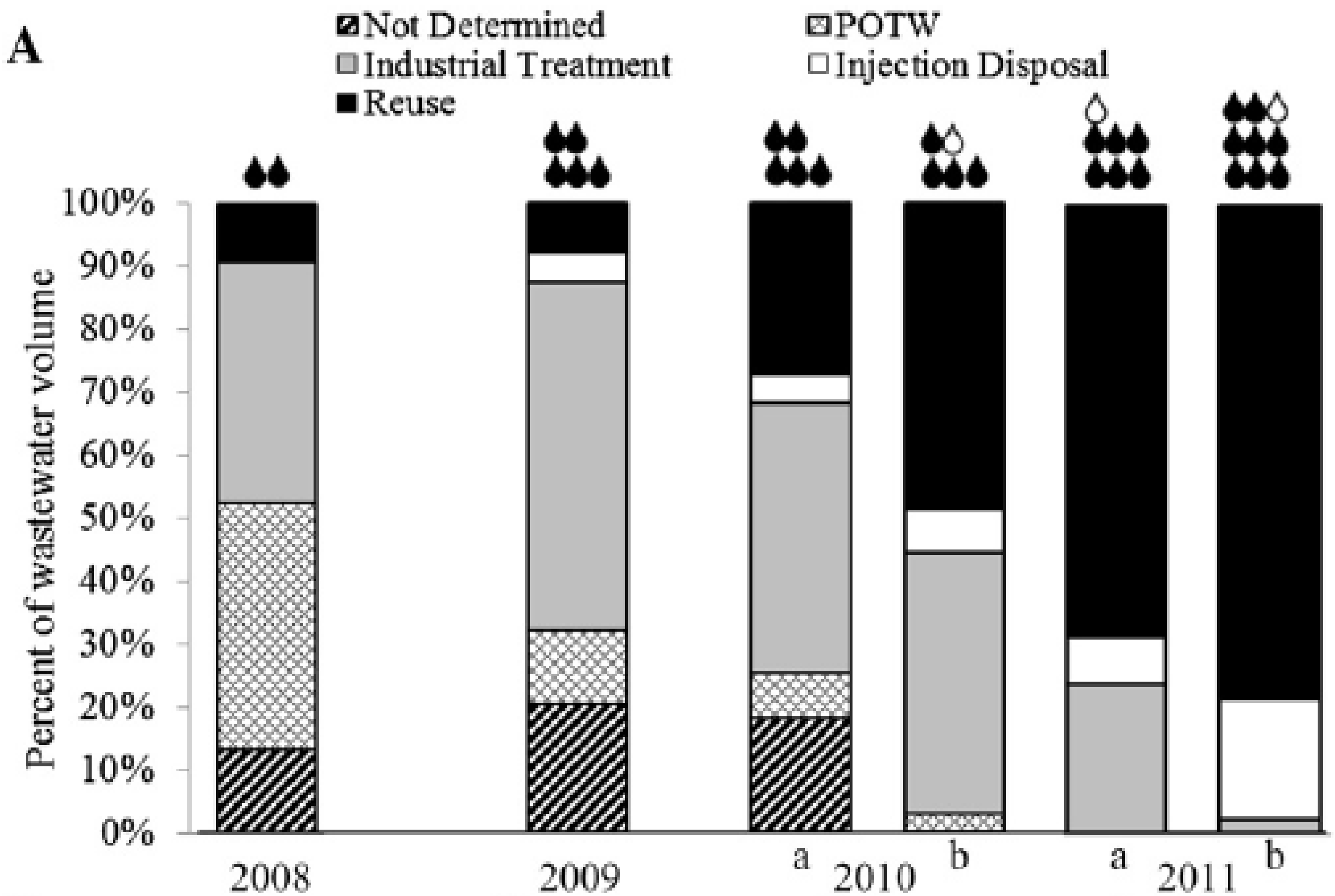
Resulted in discharge of elevated [Br-] to streams

→Drinking water facilities located downstream from discharge

→Brominated DBPs

Wilson and VanBriesen (2012)

Shift in wastewater handling in PA from treatment → Reuse



Rahm *et al.* (2013)

Emerging Research Challenges

Baseline assessment and monitoring (air and water): *what to measure? (geochemical signatures, chemical additives, well-bore integrity)*

Water use efficiency: *gray or non-potable water use, non-aqueous working fluids*

Treatment: *removing Ra, energy efficient desalination*

Wastewater disposal: *mitigating induced seismicity*