Source water quality in a changing climate: The case of disinfection byproduct precursors

KIRIN E. FURST, PhD

Assistant Professor, Dewberry Department of Civil, Environmental & Infrastructure Engineering, George Mason University

Potomac DWSPP Annual Meeting, November 1st, 2023

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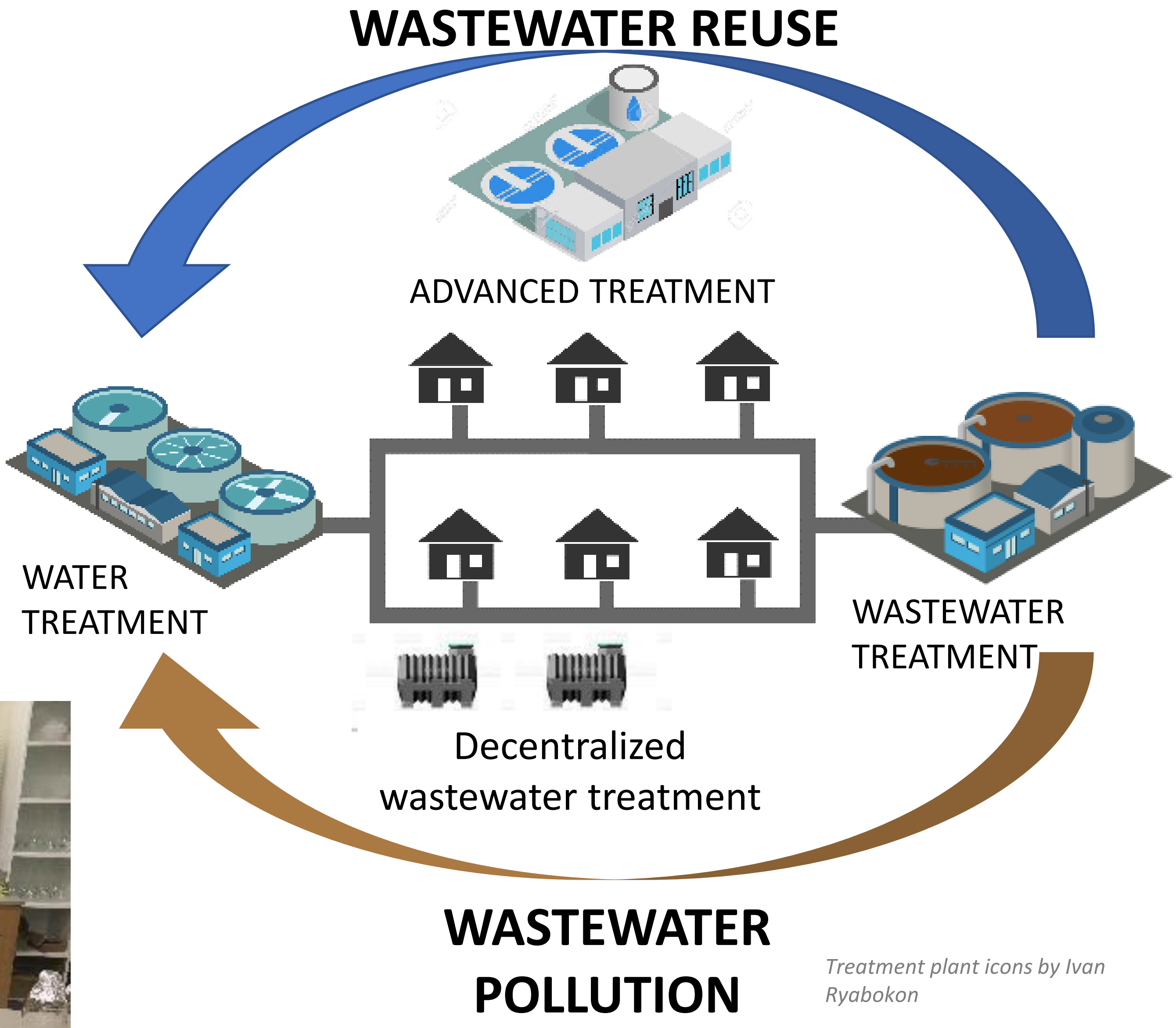
GMU Water Quality Engineering Lab

PI: Kirin Emlet Furst

- Organic contaminant fate and transport in the engineered water cycle
- Resilient treatment systems



Treatment plant icons by Ivan Ryabokon

Potential impacts of changing climate on DBP precursors in the Potomac River Basin

1. What are DBPs (disinfection byproducts)?
2. Climate effects on DBP precursors
3. Drought and *de facto* reuse
4. *De facto* reuse case study*
5. Septic systems and *de facto* reuse in NOVA

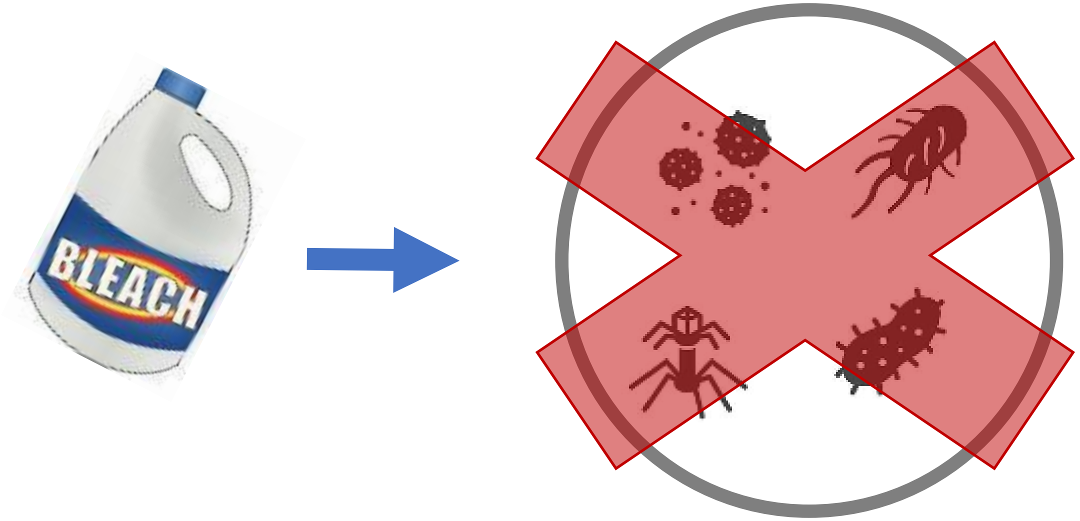
https://www.potomacriver.org/potomac-basin-facts/

Disinfection of drinking water

- Goal is to protect against waterborne pathogens (disease-causing bacteria, viruses, protozoa, etc.)
- Common disinfectants
  - Chlorine (e.g., bleach)
  - Chloramine (monochloramine, NH_2Cl) – used by many Mid-Atlantic utilities

https://en.wikipedia.org/wiki/Vibrio_cholerae

Vibrio cholerae (Cholera)



Art credit: anttohoho

www.iccsafe.org

Naegleria fowleri, "brain-eating amoeba"

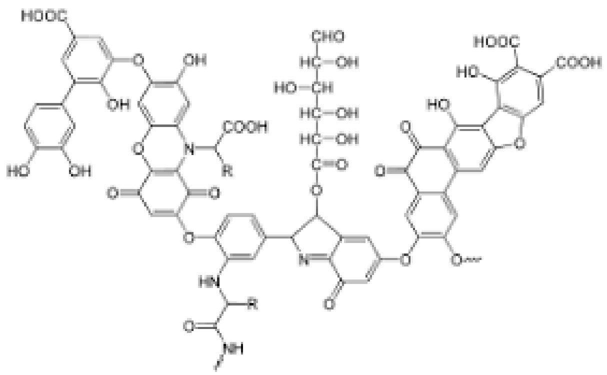
Disinfection byproducts

disinfectants + organic matter → disinfection byproducts (DBPs)

+ salts (bromide, iodide)

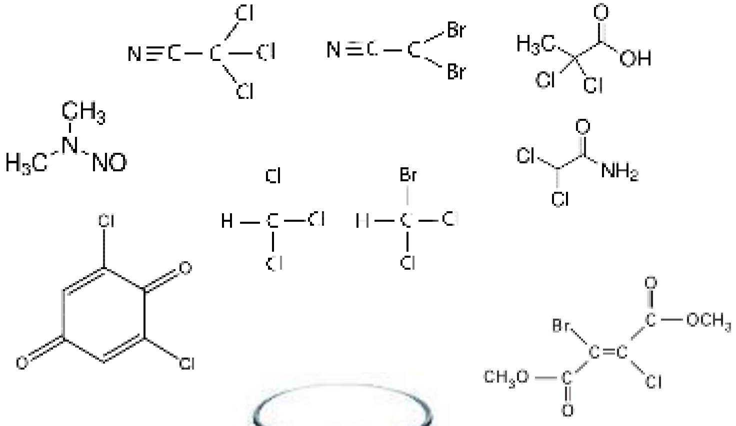
+ inorganic nitrogen

+



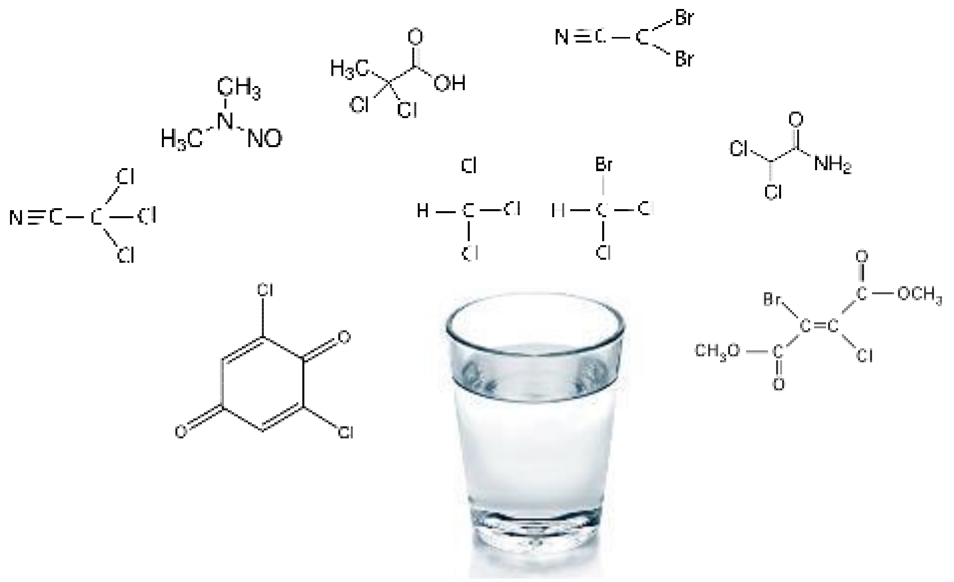
Natural organic matter example (humic acid)

→



DBP exposure linked to increased disease risk

- 700+ identified species – unknown which cause disease
- Regulated species serve as indicators



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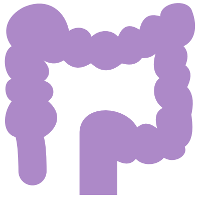
Bladder cancer

Colorectal cancer



Reproductive health effects

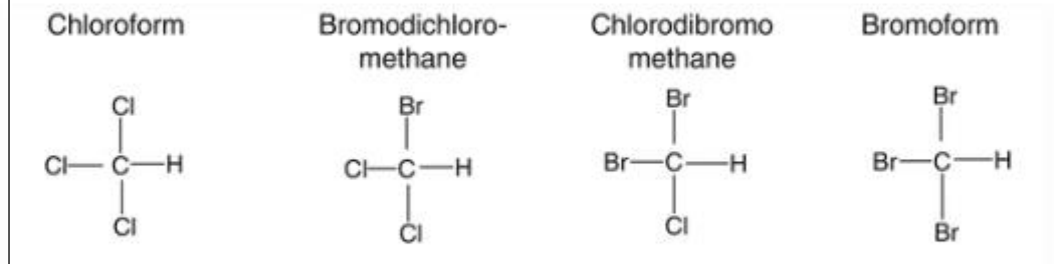
Preterm birth, low birth weight, congenital defects

Bull, R. J. *Disinfection By-Products and Human Health* **2012**.
Hrudey, S. E.; Fawell, J. *Water Sci. and Technol.* **2015**.

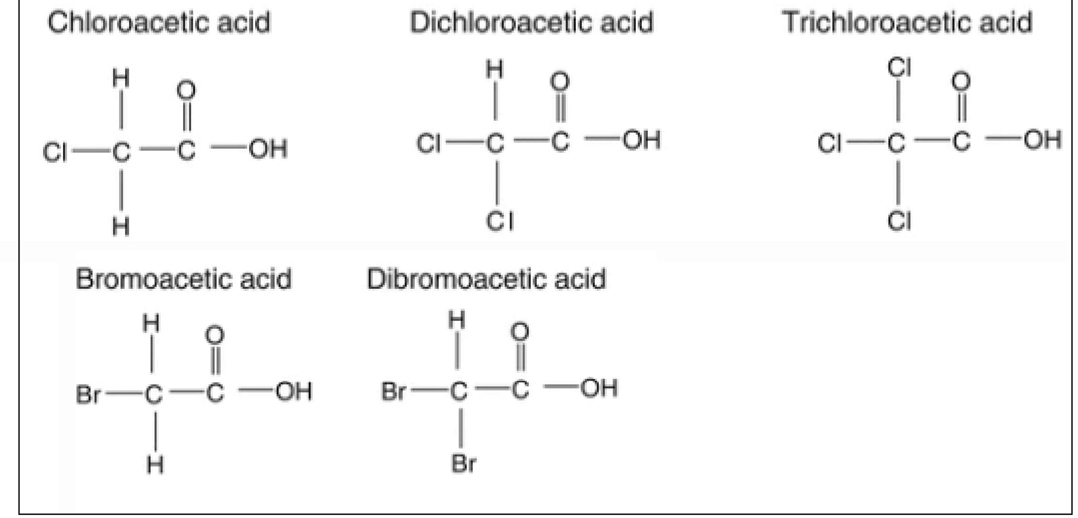
DBPs form in a complex mixture

Regulated DBPs

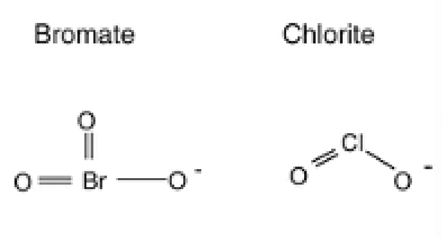
Trihalomethanes (TTHMs, THM4)



Haloacetic Acids (HAA5)



Inorganic regulated DBPs



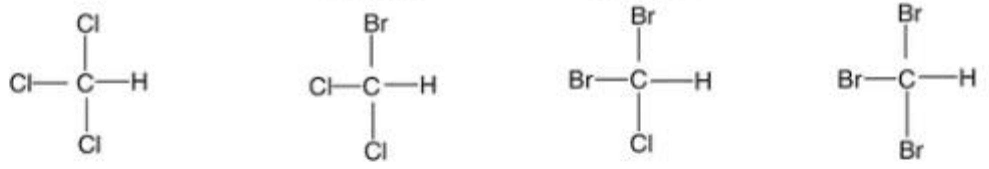
Richardson and Potigo, Drinking Water Disinfection By-products. 2011.

DBPs form in a complex mixture

Regulated DBPs

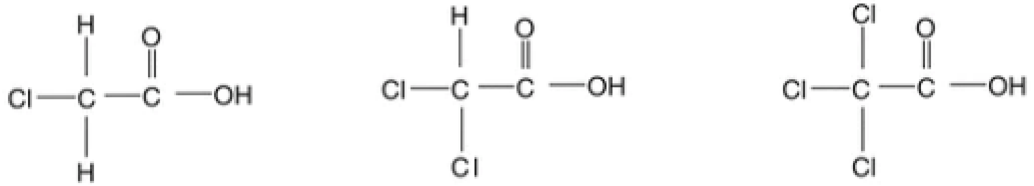
Trihalomethanes (TTHMs, THM4)

Chloroform | Bromodichloro-methane | Chlorodibromo methane | Bromoform

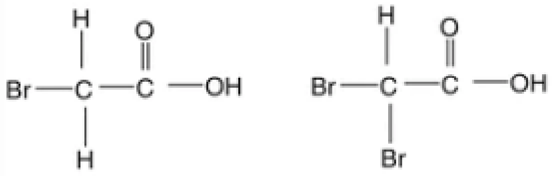


Haloacetic Acids (HAA5)

Chloroacetic acid | Dichloroacetic acid | Trichloroacetic acid



Bromoacetic acid | Dibromoacetic acid

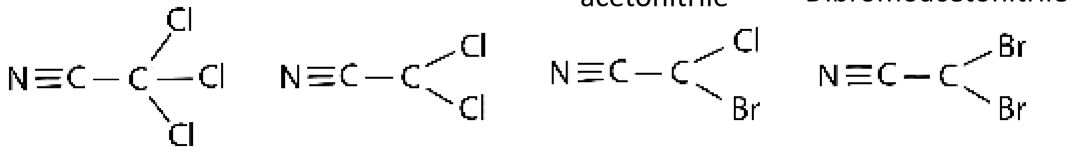


Unregulated DBPs of regulatory interest

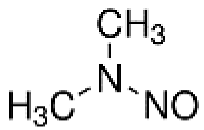
Nitrogenated (N-DBPs)

Haloacetonitriles (HANs)

Trichloroacetonitrile | Dichloroacetonitrile | Bromochloro acetonitrile | Dibromoacetonitrile



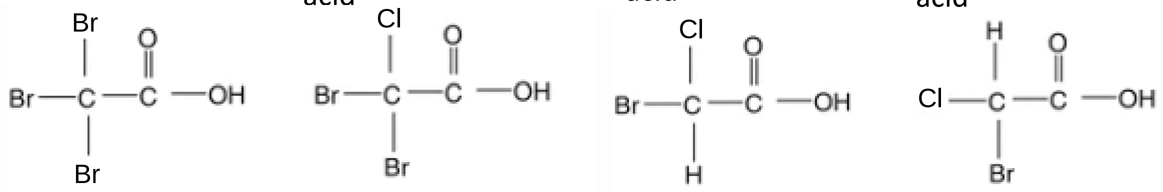
Nitrosamines



N-nitrosodimethylamine (NDMA)

Brominated haloacetic acids

Tribromoacetic acid | Dibromochloroacetic acid | Bromodichloroacetic acid | Bromochloroacetic acid



Richardson and Potigo, Drinking Water Disinfection By-products. 2011.

Which DBPs are the toxicity drivers?

***In vivo* toxicology evidence**

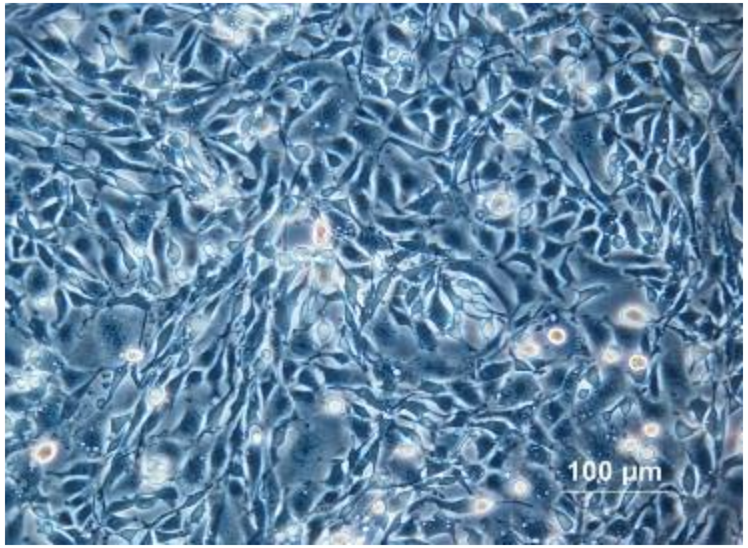
Animal (rodent) studies for <10 DBPs

***In vitro* evidence**

Database at U Illinois: 103+ DBPs

- Cytotoxicity: Reduction in cell density with chronic exposure
- Genotoxicity: Genetic damage (single cell gel electrophoresis assay)

Chinese hamster ovary (CHO) cells



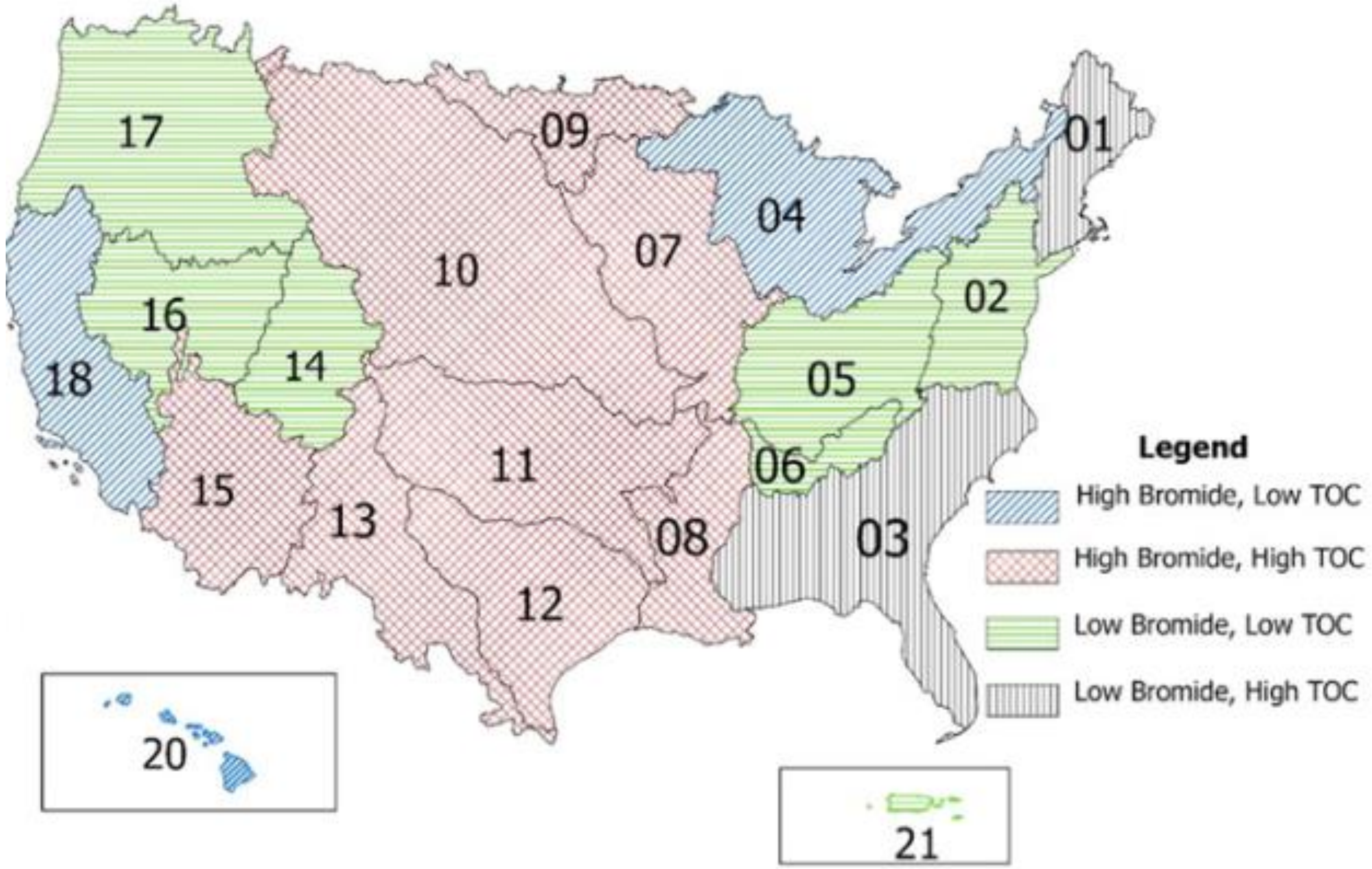
TheAtlantic.com

- N-DBPs >> C-DBPs
- I-DBPs > Br-DBPs > Cl-DBPs

Wagner & Plewa, *Environ. Sci. Tech.* 2017.

DBP precursor levels in the Potomac River Basin

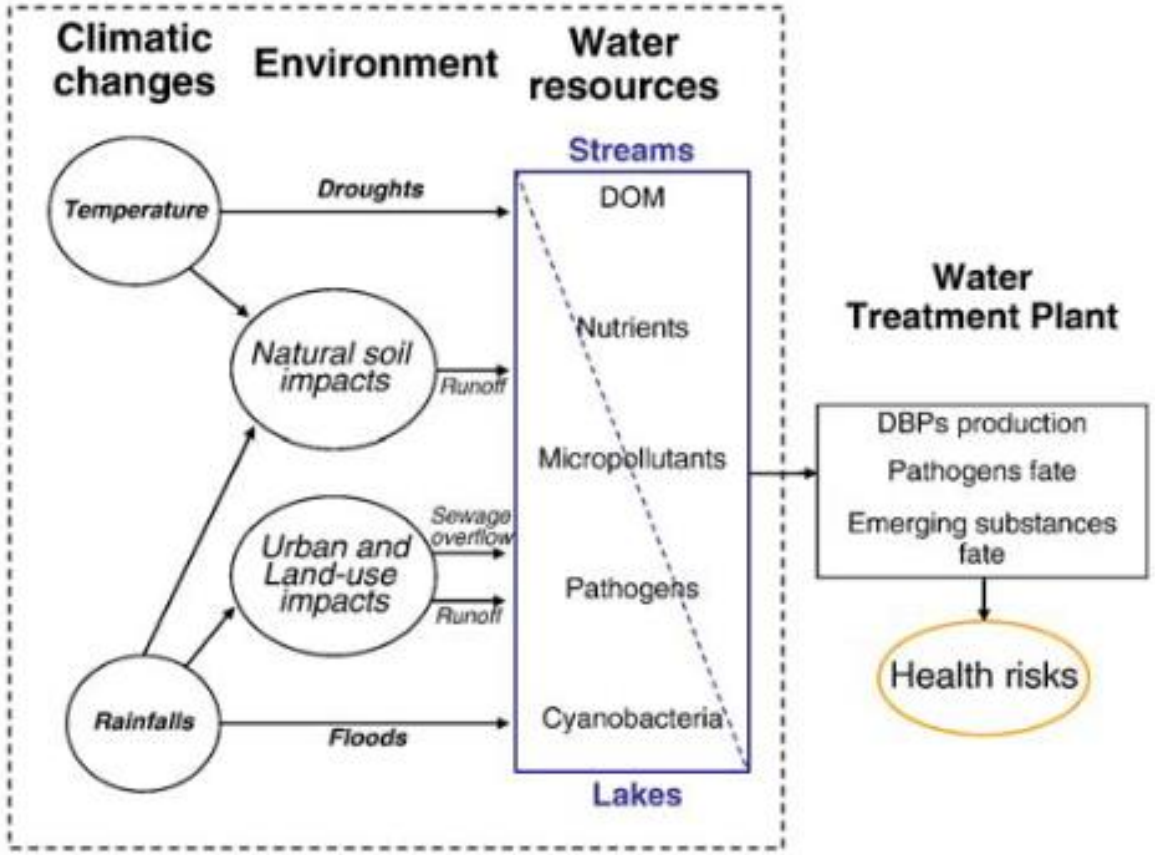
- Levels of source water TOC (Total Organic Carbon) and bromide
  - From EPA UCMR4 dataset
  - Quarterly measurements at PWS intakes during 2020-2022
- PRB enjoys relatively low TOC and bromide



Weisman, R.J., Furst K.E., Ferreira, C.M., *Environmental Engineering Science*. 2023.

Potential impacts of changing climate on DBP precursors in the Potomac River Basin

- **Drought** -> less dilution of pollution
- **Extreme precipitation** -> mobilizes contaminants
- **Algal blooms** -> N-DBP precursors
- **Heat** -> changes composition of organic matter
- *Probably more!*

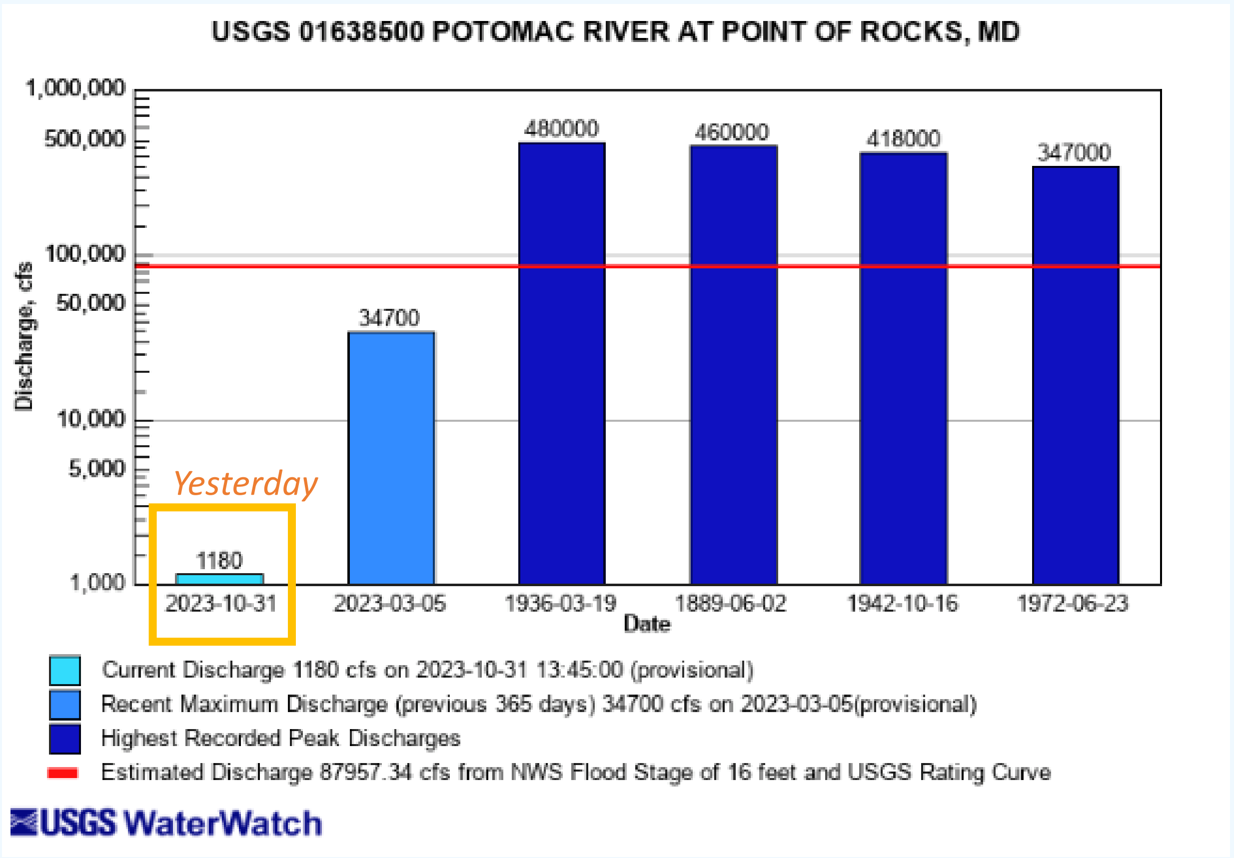


Delpla et al., *Environ. Int.* **2009.**

Michalak, A. M. *Nature,* **2016**.

Impacts of drought on water quality

- ***Drought -> less dilution of pollution***
- Municipal and industrial wastewater discharges are concentrated
  - Organic matter
  - TDS, nitrogen
  - Micropollutants



https://icprbcoop.org/basin-conditions

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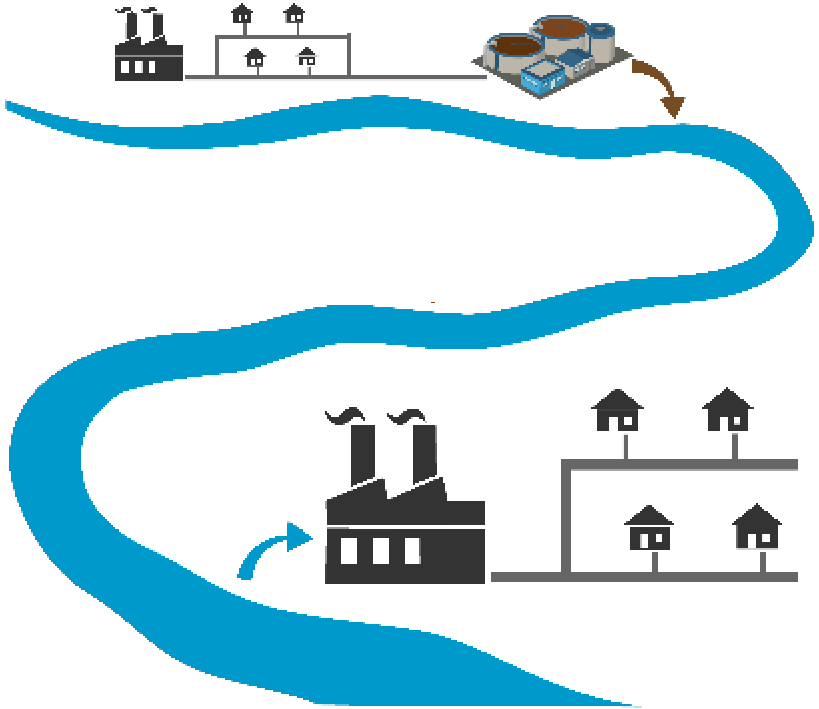
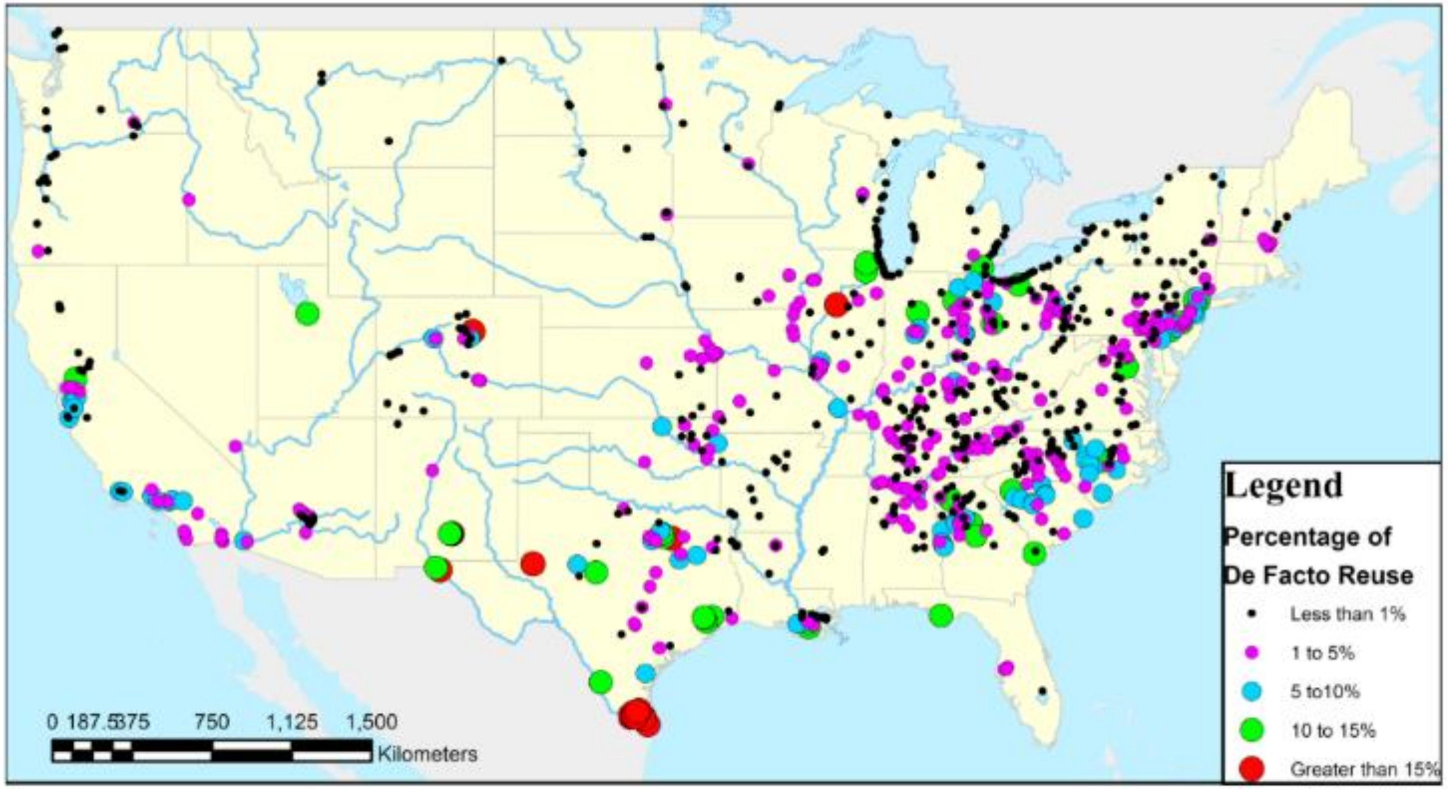
De facto **reuse:** Unintentional reuse of wastewater

- Occurs when drinking water intakes are located downstream of wastewater discharges
- Exacerbated by dry climate

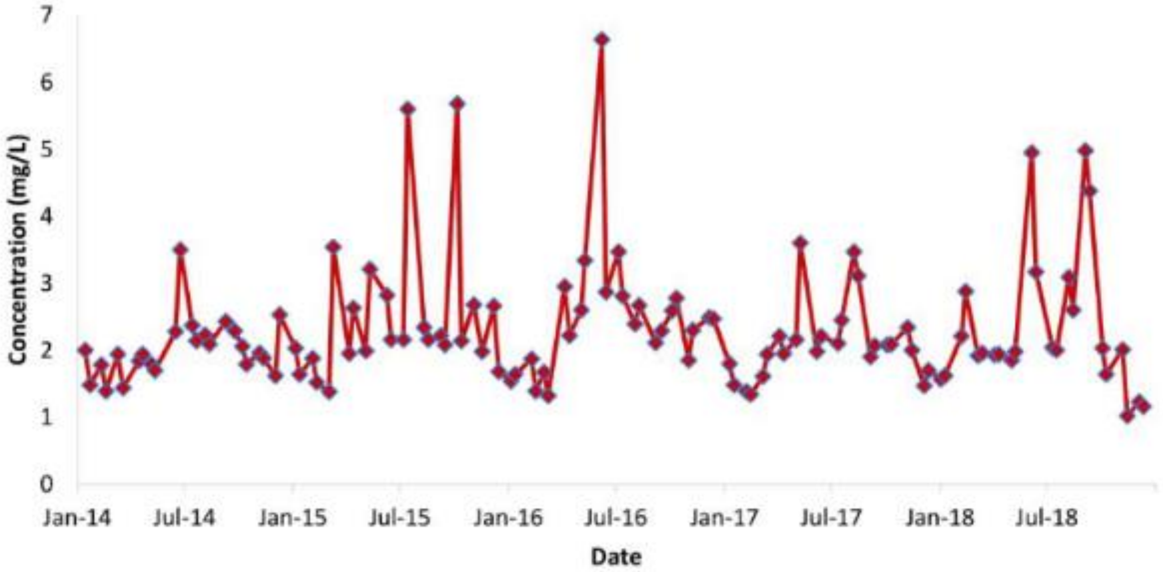




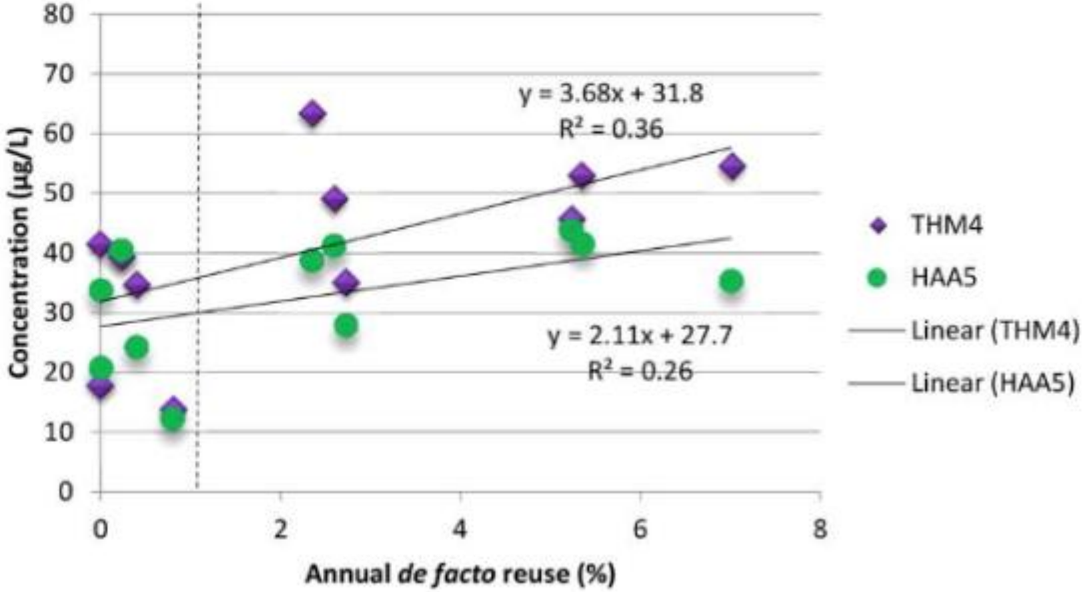
De facto reuse in US surface water supplies.
(Rice and Westerhoff, 2015.)

Percentage of *de facto* reuse affects DBP precursor levels

- % *de facto* reuse controlled by total stream discharge
- Study in Shenandoah watershed looked at variation in DBP precursors and DBPs as function of % *de facto* reuse
- Total Organic Carbon (TOC) concentration varied with percent *de facto* reuse



TOC concentration variability at a PWS intake in the Shenandoah watershed from 2014 to 2018.



De facto reuse impacts on DBP precursors

Conventional (clean) water

Wastewater

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Humic matter

Organic nitrogen

Bromide

Regulated THMs & HAAs

N-DBPs

- Haloacetonitriles (HANs), NDMA
- Increased toxicity

Br-DBPs

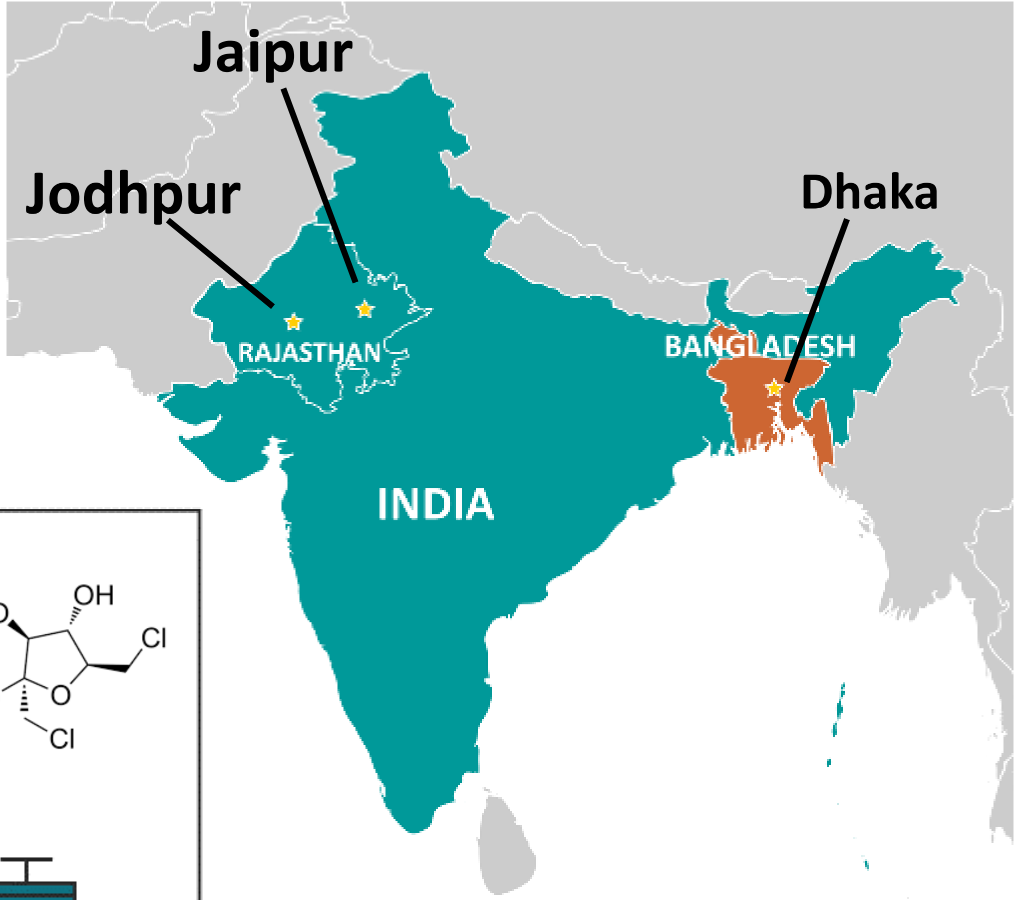
- Increased toxicity
- Br-HAAs may soon be regulated

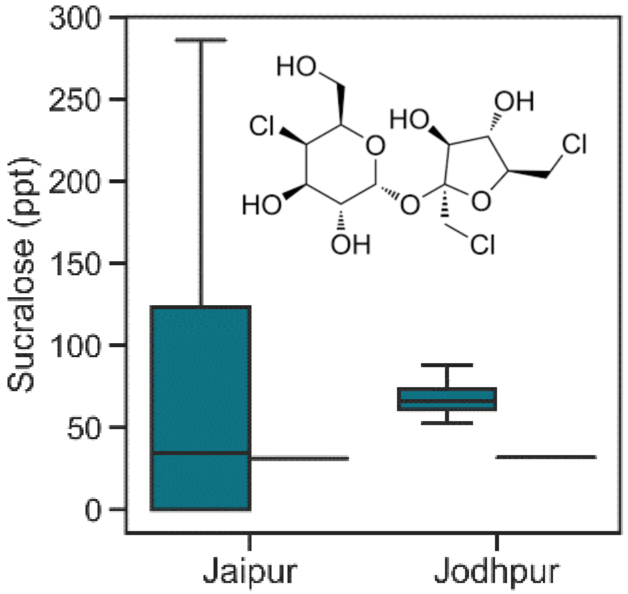
Furst, K.E., Coyte, R.M., Wood, M., Vengosh, A., Mitch, W.A., *ES&T,* 2019.

Weisman, R.J., Barber, L.B., Rapp, J.L., Ferreira, C.M. *Environ. Sci.: Water Research & Technol.* 2019

De facto reuse and DBPs – example of South Asia

- Three cities with high population density + inadequate sanitation infrastructure
- Verified *de facto* reuse in source waters using sucralose as wastewater tracer
    - Detected in every surface water, most groundwaters

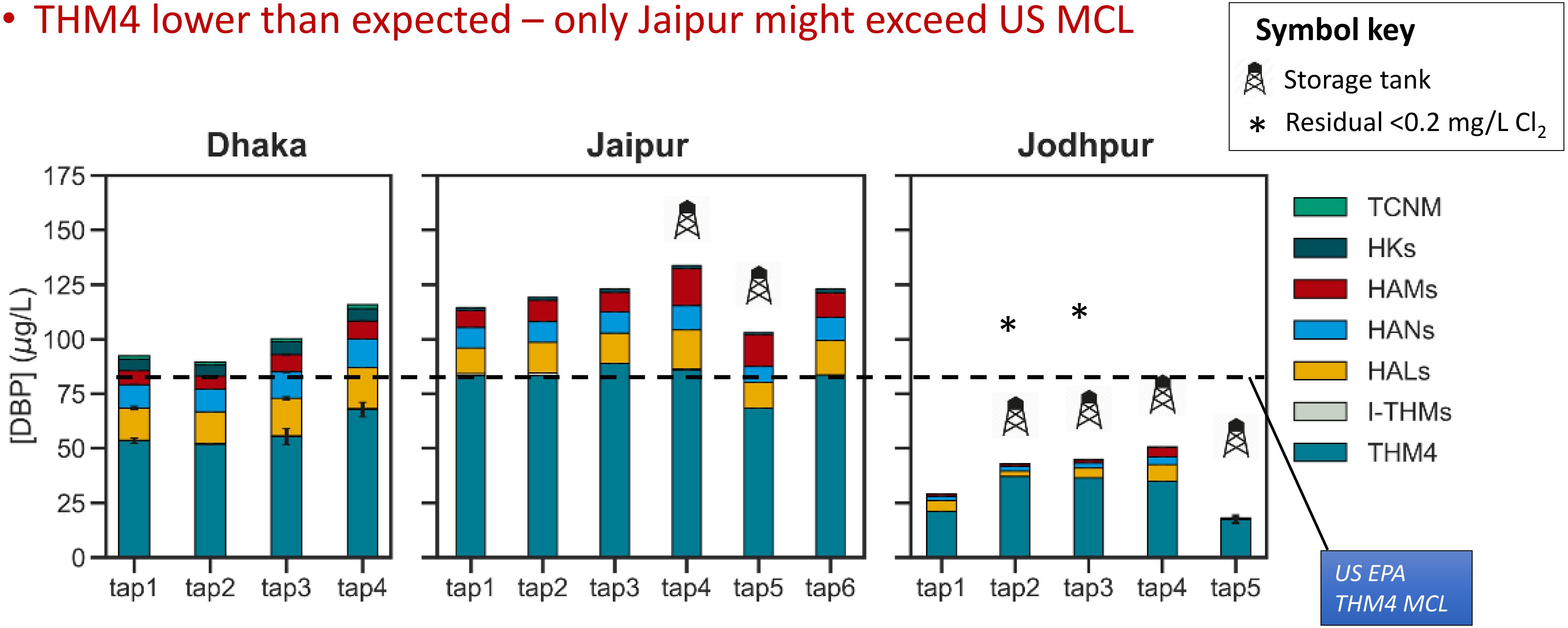




Furst et al. *ES&T,* 2019.
Furst et al. *ACS ES&T Water, 2022.*

DBP levels in three *de facto* reuse utilities

- Conventional surface water treatment + chlorination
- Samples collected from distribution system taps and storage tanks
- THM4 lower than expected – only Jaipur might exceed US MCL



Furst et al. *Environ. Sci. Technol.* 2019. Furst et al. *ACS ES&T Water, 2022.*

Toxicity is function of both **toxic-potency** and **concentration**

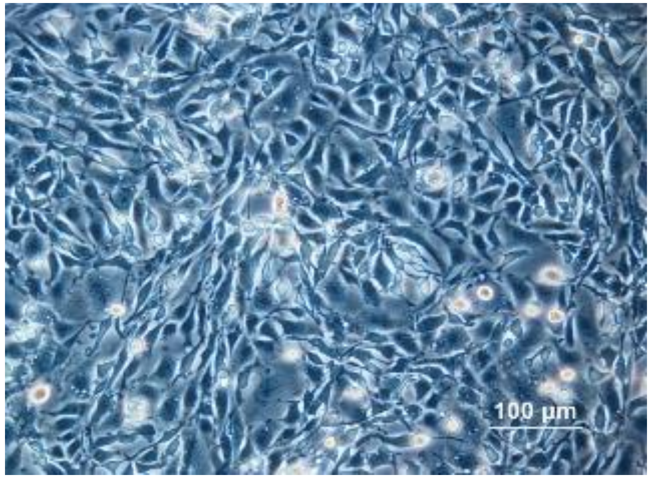
To estimate toxicity of a chemical in drinking water:

$$\sum \frac{[chemical]}{Metric\ of\ toxic\ potency}$$

- Metric of toxic potency for DBPs:

  $\boldsymbol{LC_{50}}$: The Lowest Concentration of a DBP that kills 50% of CHO cells

Chinese hamster ovary (CHO) cells



TheAtlantic.com

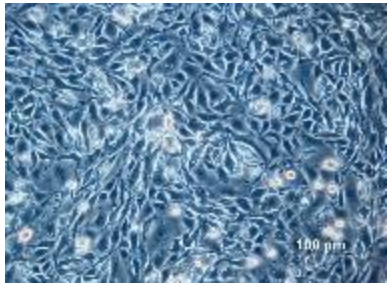
$$\sum \frac{[DBP]}{LC_{50}} =$$ Toxicity–weighted concentrations

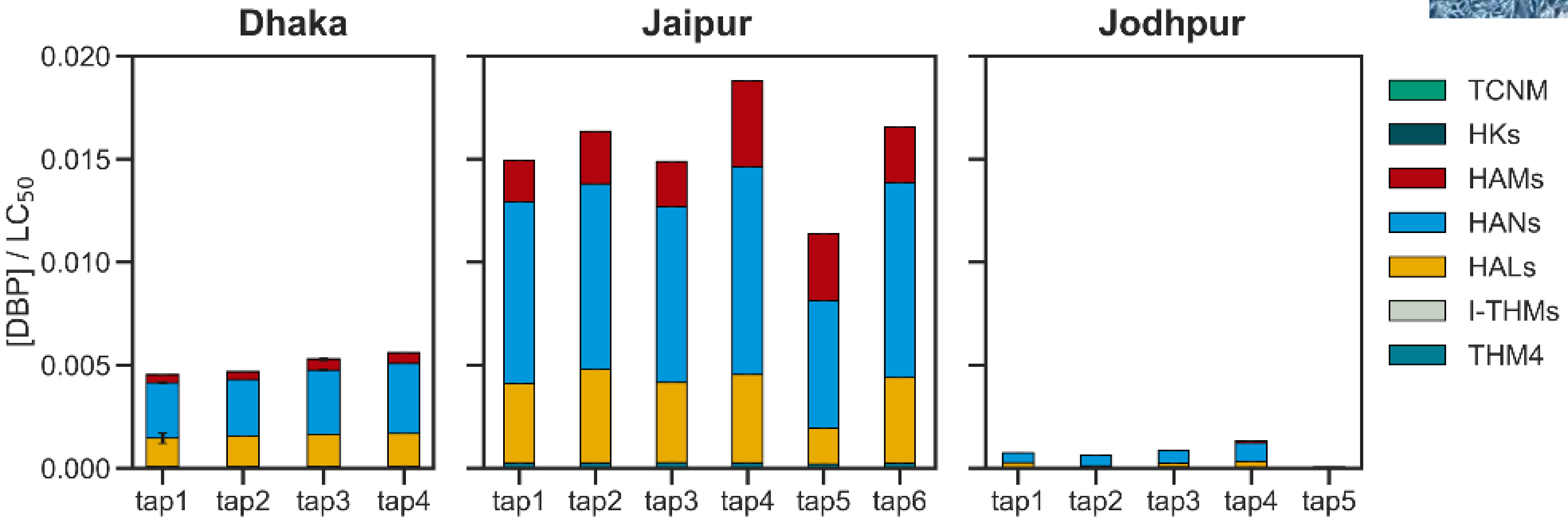
WHO. *Guidelines for Drinking Water Quality*, 4th ed. 2011.

DBP levels in three South Asian cities

$$\sum \frac{[DBP]}{LC_{50}} = \text{Toxicity–weighted concentrations}$$

Chinese hamster ovary (CHO) cells



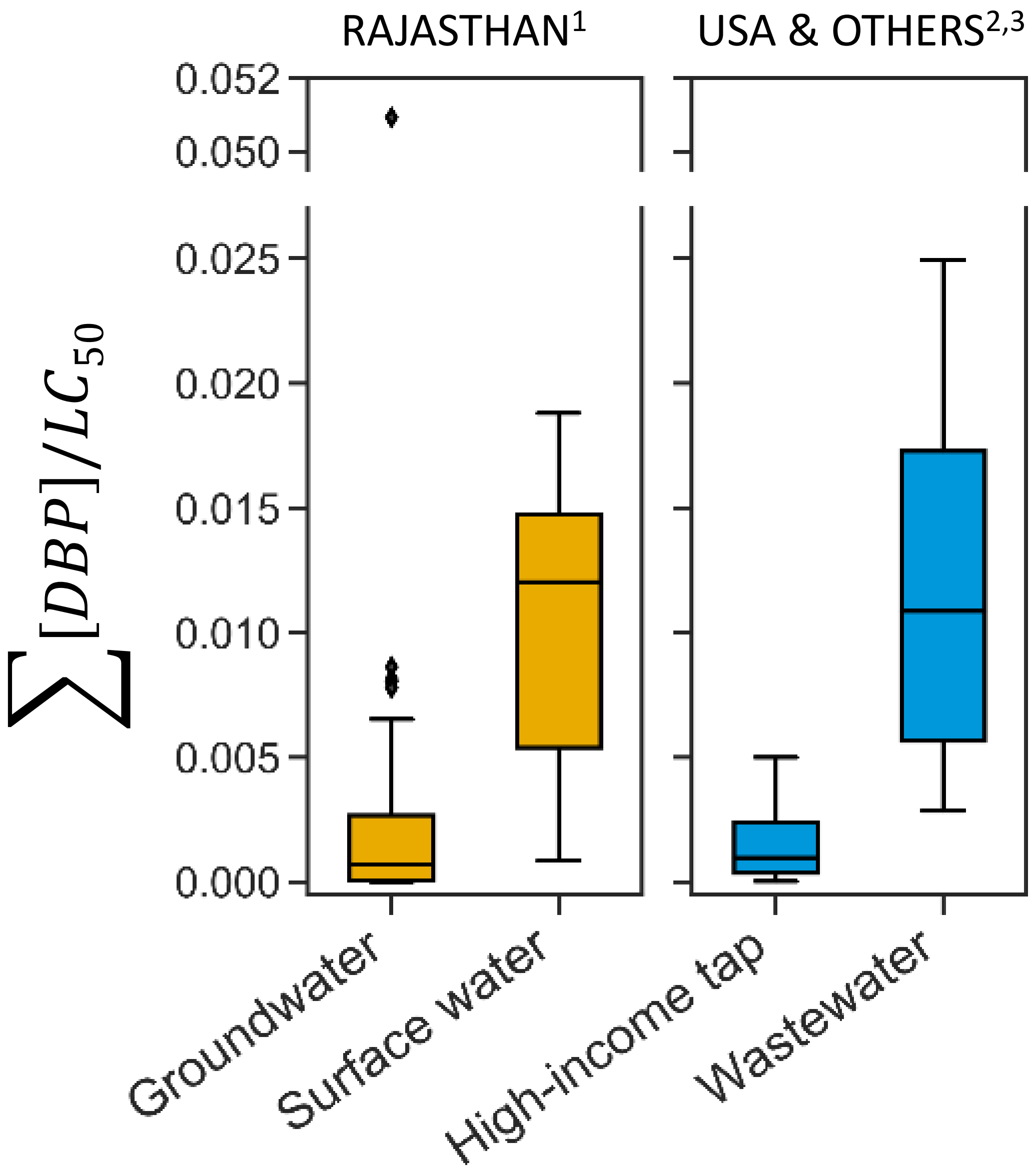


→ **HANs dominate estimated toxicity**

Furst et al. *Environ. Sci. Technol.* 2019. Furst et al. *ACS ES&T Water, 2022.*

Excessive DBP toxicity in *de facto* reuse impacted surface waters

- Compared cumulative estimated toxicity to other waters
- Treated surface water resembles disinfected wastewater
- High calculated toxicity due to nitrogen and bromine DBPs



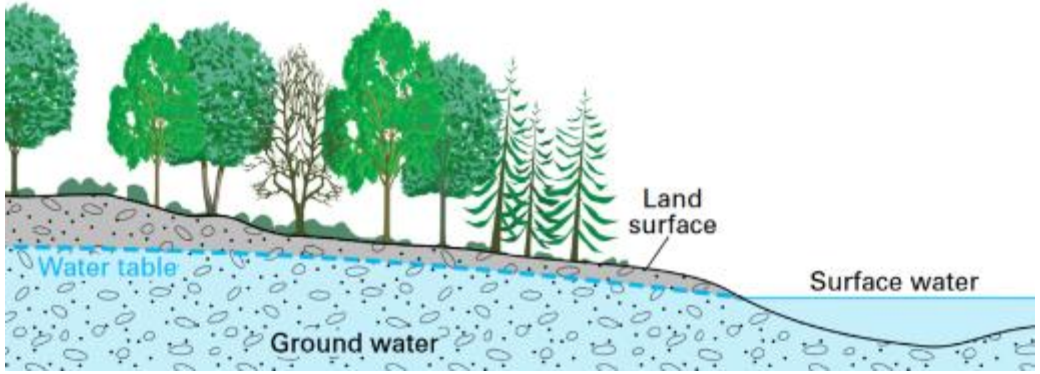
Furst, K.E., Pecson, B.M., Webber, B.D., Mitch, W.A. *Water Research,* 2018.

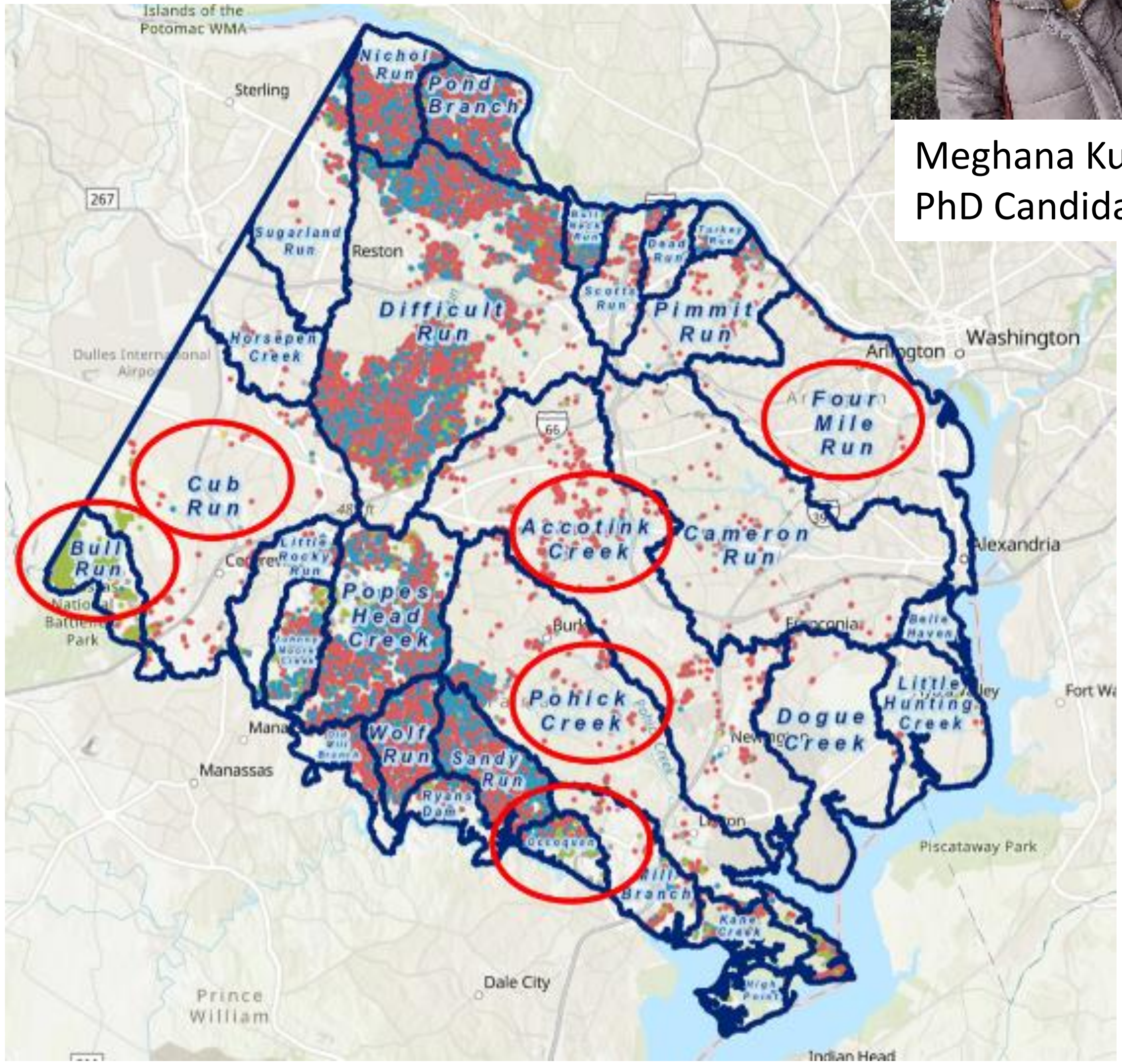
Furst, K.E., Coyte, R.M., Wood, M., Vengosh, A., Mitch, W.A., *ES&T,* 2019.

Furst, K.E., Smith, D.W., Bhatta, L.R., Islam, M., Sultana, S., Rahman, M., Davis, J., Mitch, W.A. *ACS ES&T Water,* 2022.

Septic systems – overlooked *de facto* reuse source?

- 20,000 septic systems in Fairfax County alone
- Septic systems are designed to remove nutrients, not micropollutants, salts
- Regional soil/hydrogeology is not ideal





Septic systems color coded by type: red, conventional gravity; blue, conventional pump; green, alternative.

Meghana Kuppa
PhD Candidate

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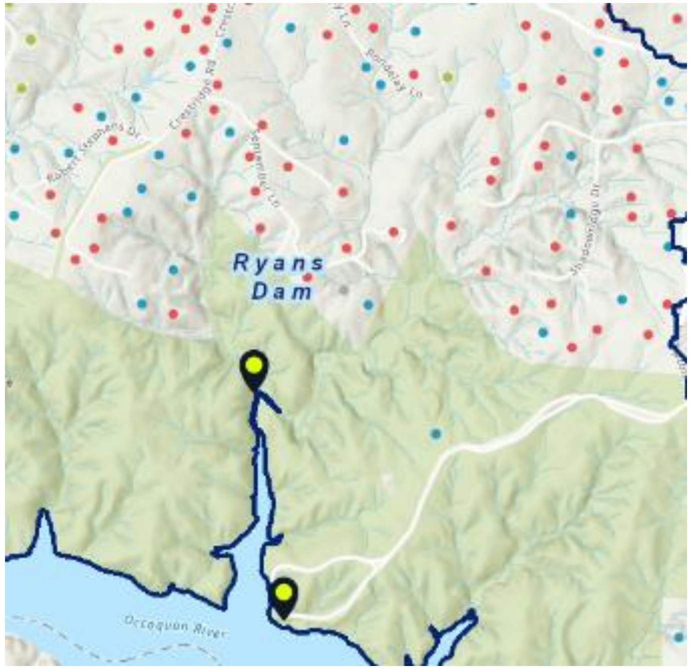
Septic system contaminant breakthrough

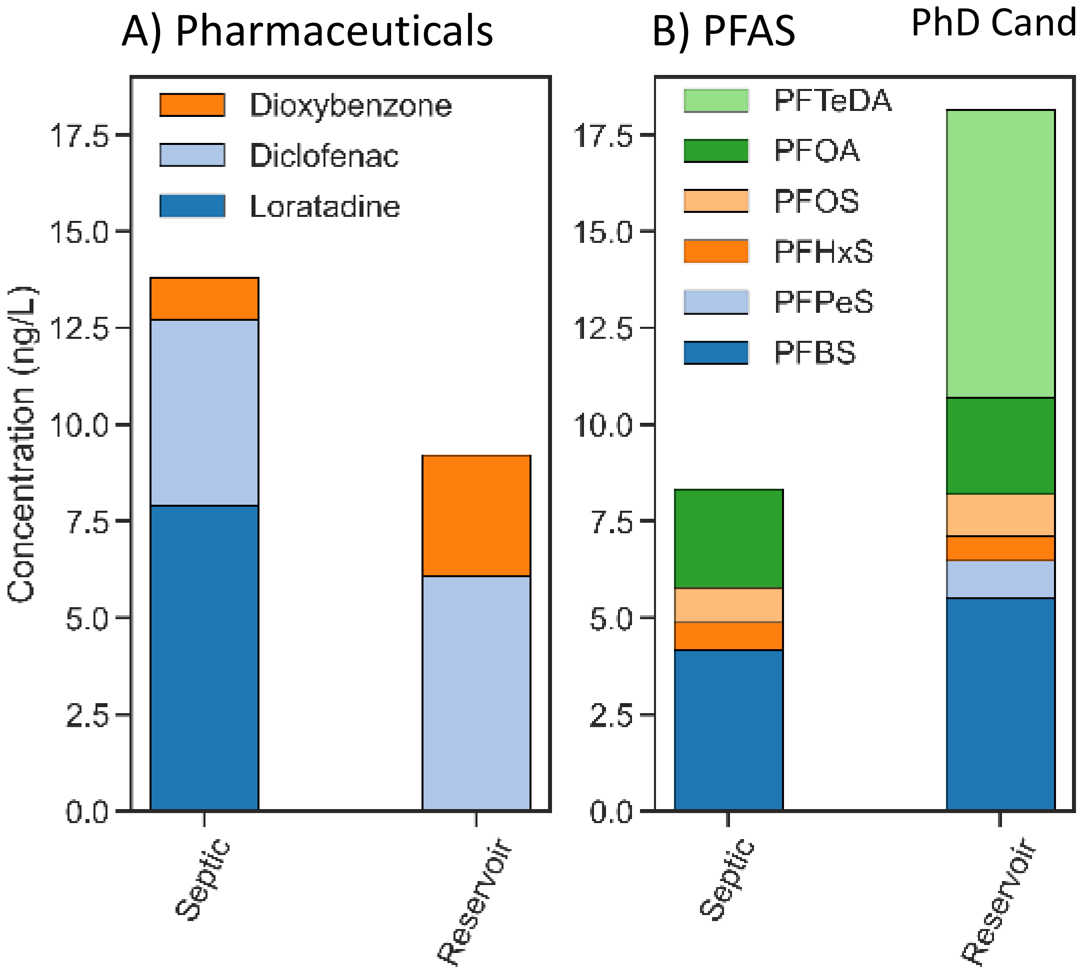
- Sampled septic-dominated stream baseflows
- Detected pharmaceuticals (indicative of wastewater impacts)
- PFAS, nitrate, relatively high DOC (>10 mg/L)

Effect of extreme precipitation? (Anticipated USGS grant)

Meghana Kuppa
PhD Candidate



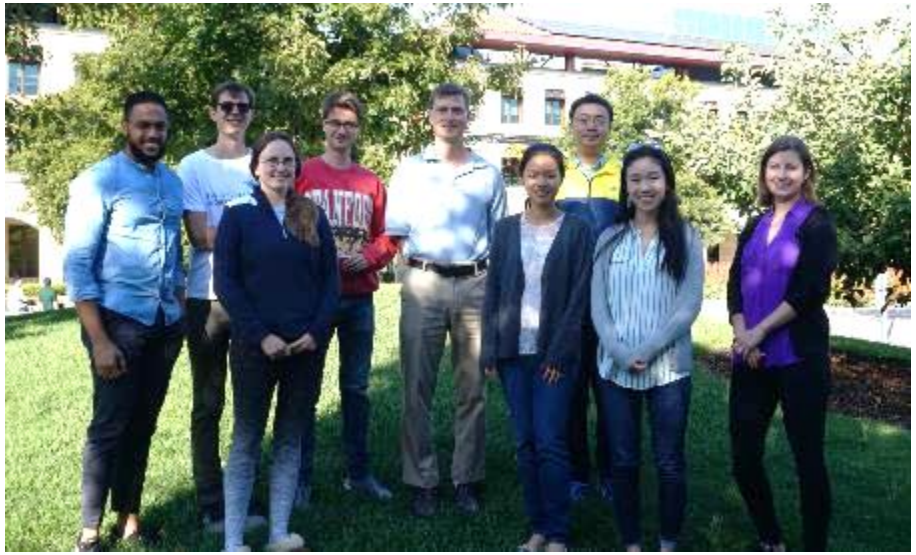
Ryan's Dam sampling sites, Occoquan watershed (2021)



Acknowledgements

National Science Foundation (ReNUWIt)

George Mason University
Center for Resilient and Sustainable Communities



The Mitch Lab

Valley Water
Santa Clara Valley Water District

Duke University | INDIA Initiative

Margaret Wood, EIT

Danny Nguyen

Linzi R. Bhatta

International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b)