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Shenandoah Accumulated Wastewater Mapper: A Screening Tool to Understand Human and Wildlife Exposure to Toxicants and Pathogens Associated with the Incidental Reuse of Treated Wastewater

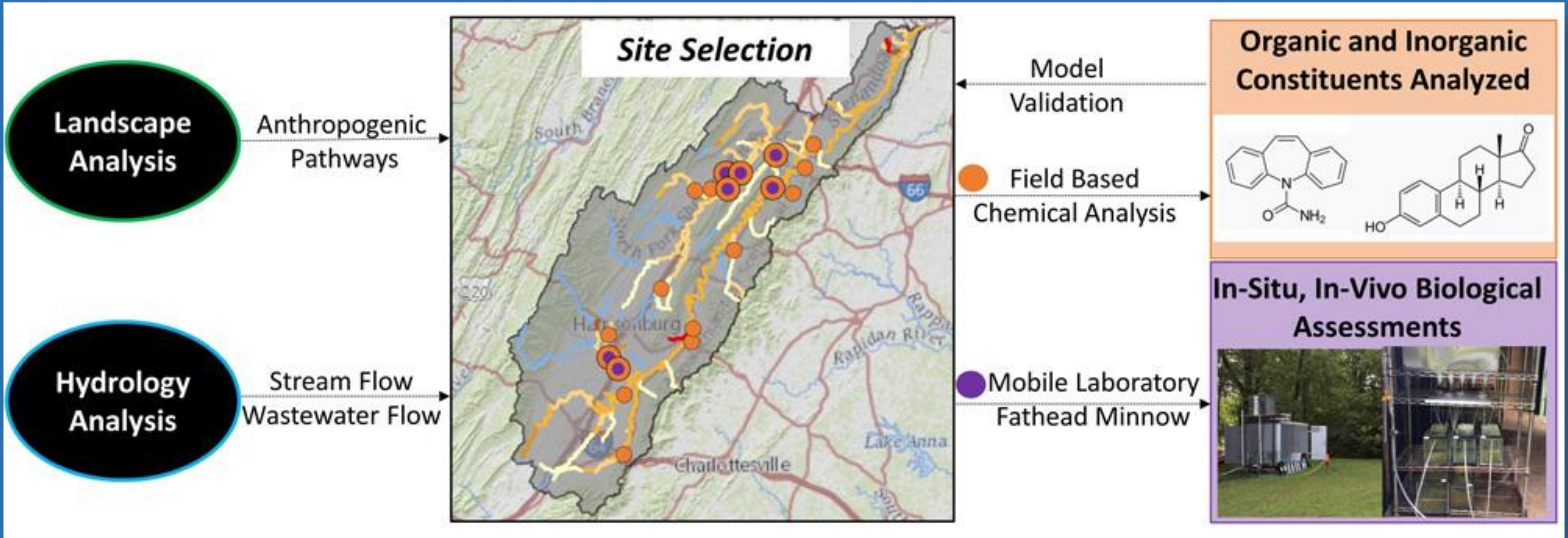
Jennifer L. Rapp, Larry Barber

https://va.water.usgs.gov/webmap/shenmap/

Barber, Rapp, Keefe, Kandel, Rice, Westerhoff, and Vajda, 2019.
Integrated Assessment of Wastewater Reuse, Exposure Risk, and Fish Endocrine Disruption in the Shenandoah River Watershed, ES&T.

Funded through: USGS Environmental Health & Water Mission Areas
Chesapeake Bay Endocrine Disrupting Compound (EDC) Project

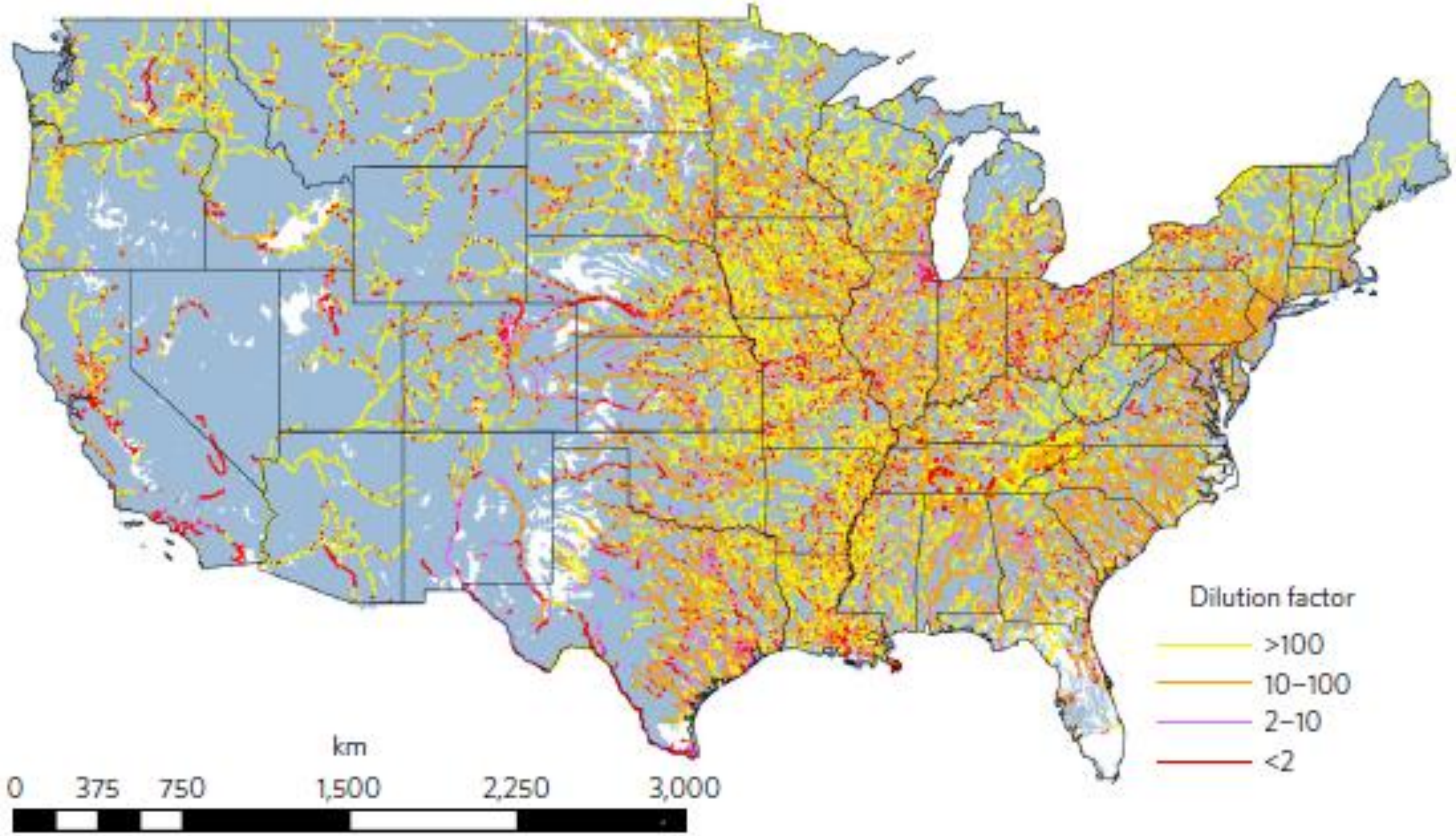
Background | Wastewater Modeling and Mapper tool | Field Studies | On-going work



Rice artwork from Barber et al., 2019

Wastewater Reuse is Critical Water Resource

15,800 WWTPs in US - 14,600 discharge to surface water



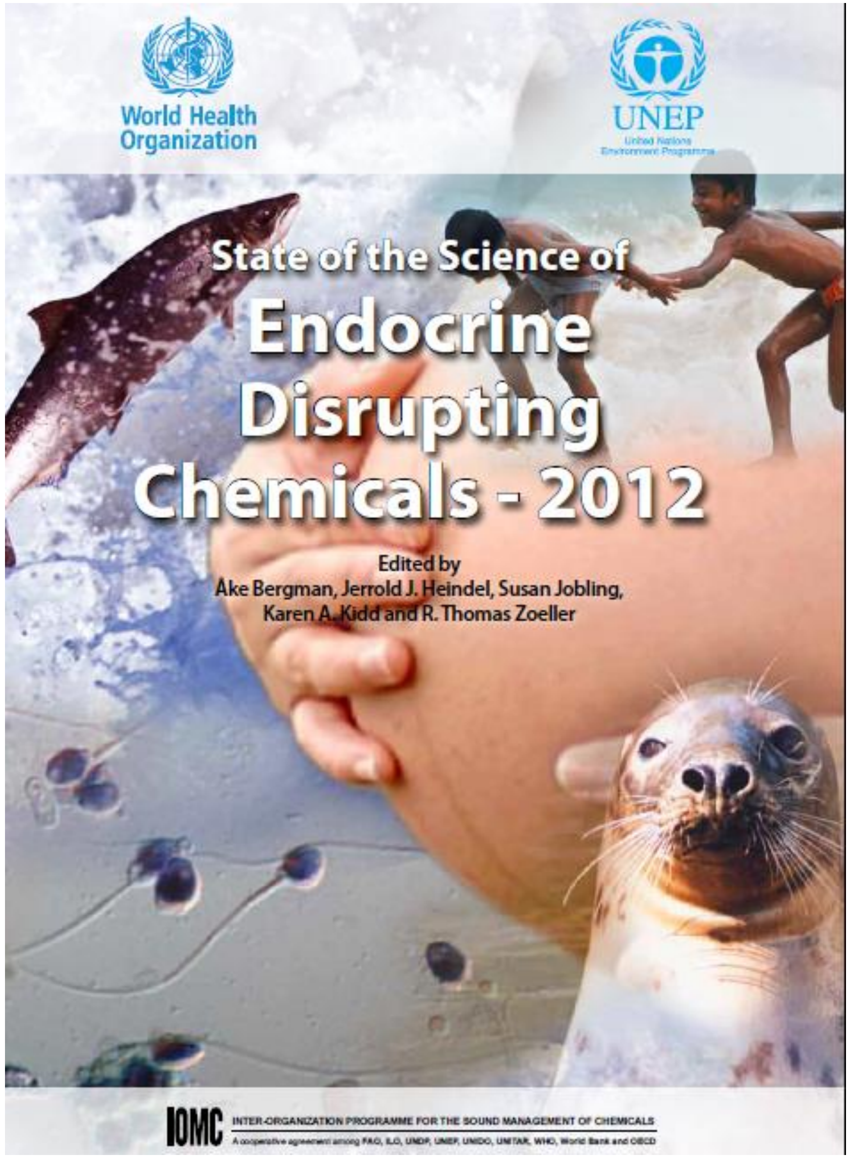
Types of reuse:
- Direct
- Indirect
- De Facto

- Municipal and industrial wastewater treatment plants (WWTPs)
- Maintains in-stream flows and water supplies
- Source of endocrine disrupting compounds (EDCs)

Rice and Westerhoff, 2017, Nature Geoscience

Endocrine Disruption is Issue of Global Concern

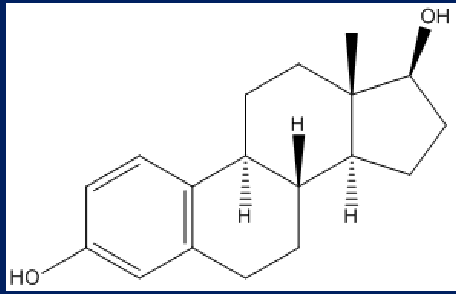
Human/wildlife health depends on endocrine system for normal development



17β-Estradiol (E2)

biogenic sex hormone

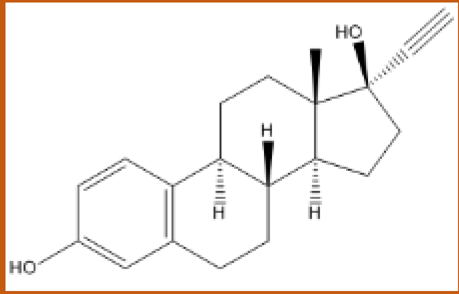
155 million women ~5,600 *kg/yr*



17α-Ethynylestradiol (EE2)

oral contraceptive

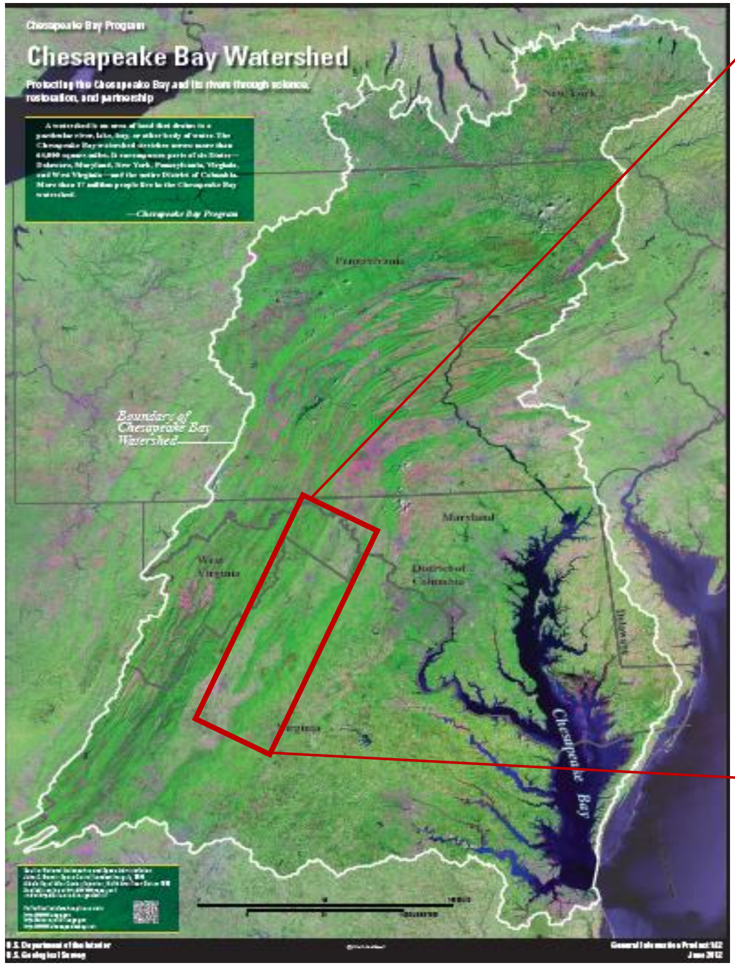
12 million women ~120 *kg/yr*

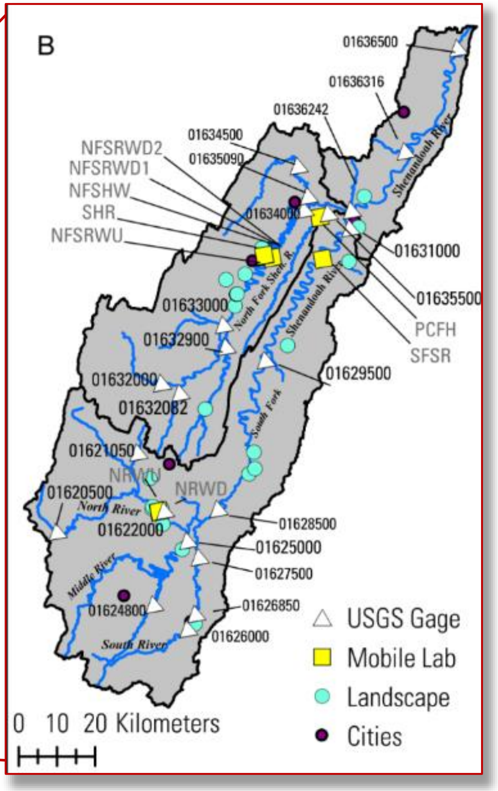


Endocrine Disruption in the Chesapeake Bay

Widespread intersex in wild smallmouth bass

(*Blazer et al, 2007, 2012; Kolpin et al, 2013; Iwanowicz et al. 2018*)



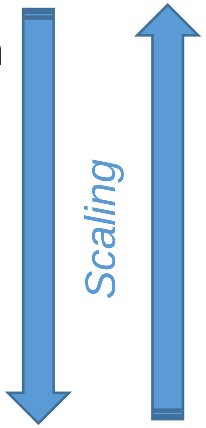


Watershed

River reach

Organism

Molecular



Transdisciplinary Science

- **Chemical Sampling of River Water**
- **Mobile Laboratory Fish Exposure Studies**
- **Modeling to Quantify Wastewater Cumulative Impacts**

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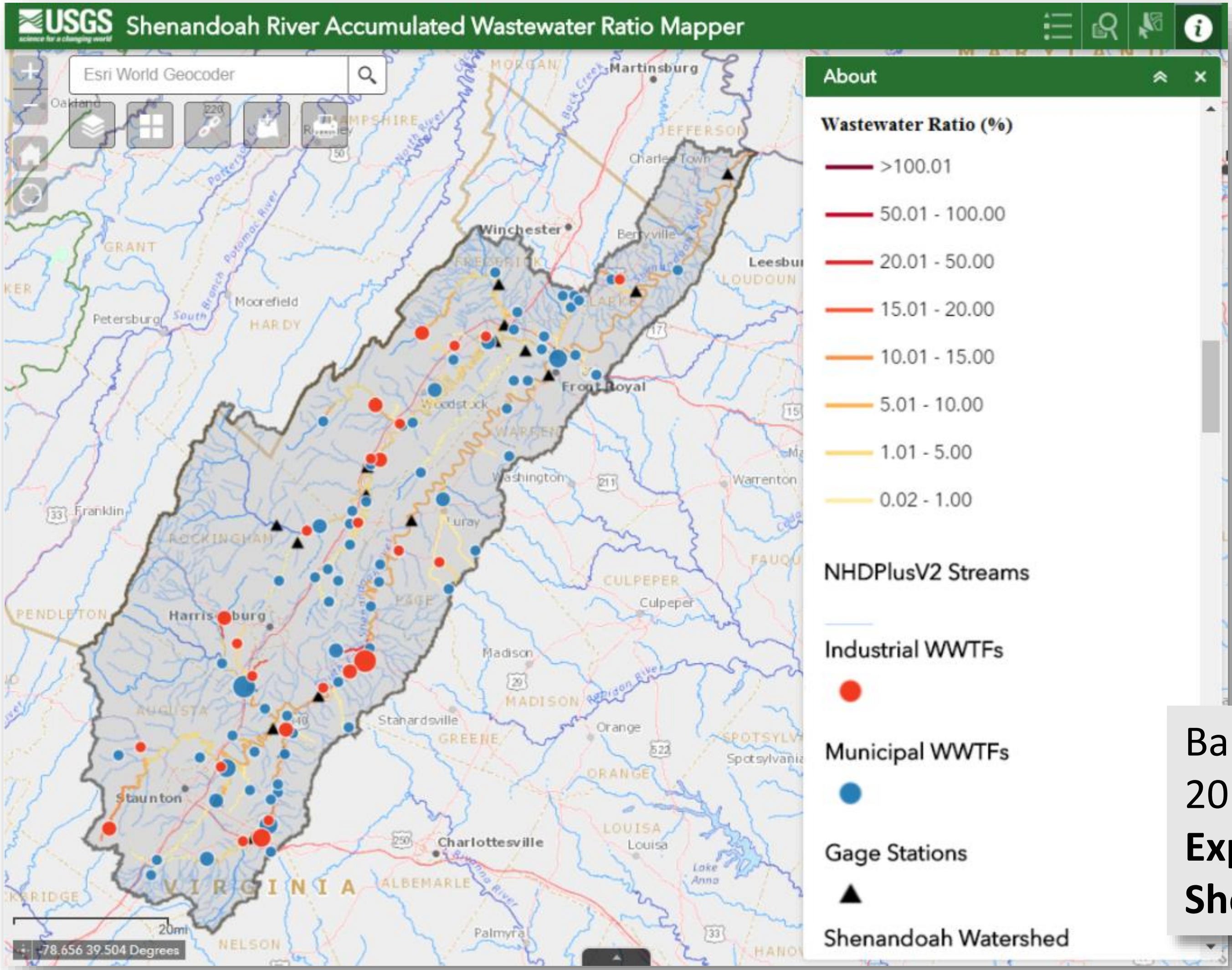
Shenandoah Accumulated Wastewater Mapper

Chintamani Kandel, Jennifer Rapp, Larry Barber

https://va.water.usgs.gov/webmap/shenmap/



Quantifies point source contributions of wastewater for fish habitat analyses and water quality studies.

Provides a flexible framework to identify reaches with high likelihood of EDCs.

Ongoing work includes expanding the wastewater mapper as a prototype of an endocrine disrupting compound (EDC) concentration model for all rivers in the Potomac River Watershed.

Results demonstrated good agreement with the Consumer Product Model, iSTREEM.

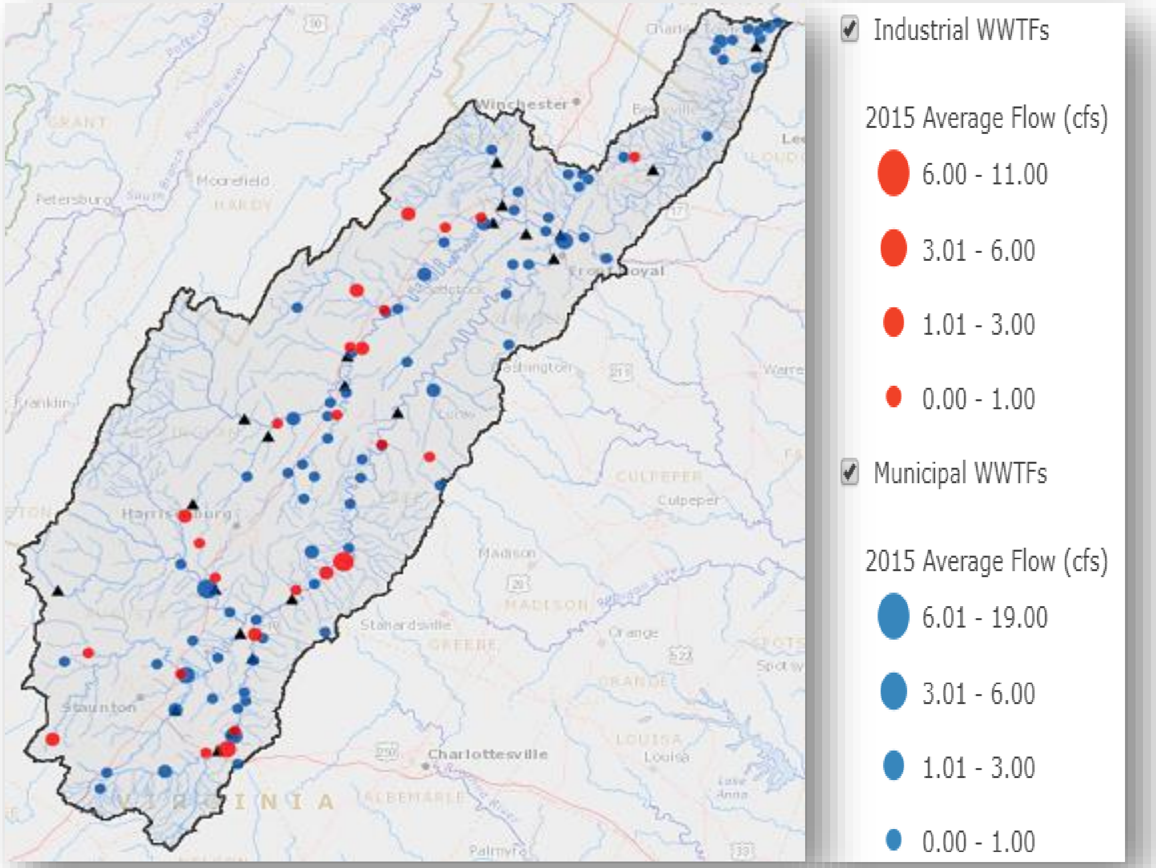
Barber, Rapp, Keefe, Kandel, Rice, Westerhoff, and Vajda, 2019. **Integrated Assessment of Wastewater Reuse, Exposure Risk, and Fish Endocrine Disruption in the Shenandoah River Watershed,** ES&T.

Municipal and Industrial Wastewater Treatment Facilities

Chintamani Kandel, Jennifer Rapp, Larry Barber

https://va.water.usgs.gov/webmap/shenmap/

	Municipal (cfs)	Industrial (cfs)	Total (cfs)
Number of sites	81	25	--
Volume discharged (Facility Capacity)	110 cfs	48 cfs	158 cfs
Volume discharged (Average Annual 2015)	**55 cfs**	**29 cfs**	**84 cfs**



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Accumulated Wastewater Ratio (ACCWW %)

Data Preprocessing and Input Preparation

Combine NHDPlus V2 streamflow and WWTP discharge

Accumulated wastewater ratio (ACCWW)

Incoming WWTP discharge + upstream WWTP discharge

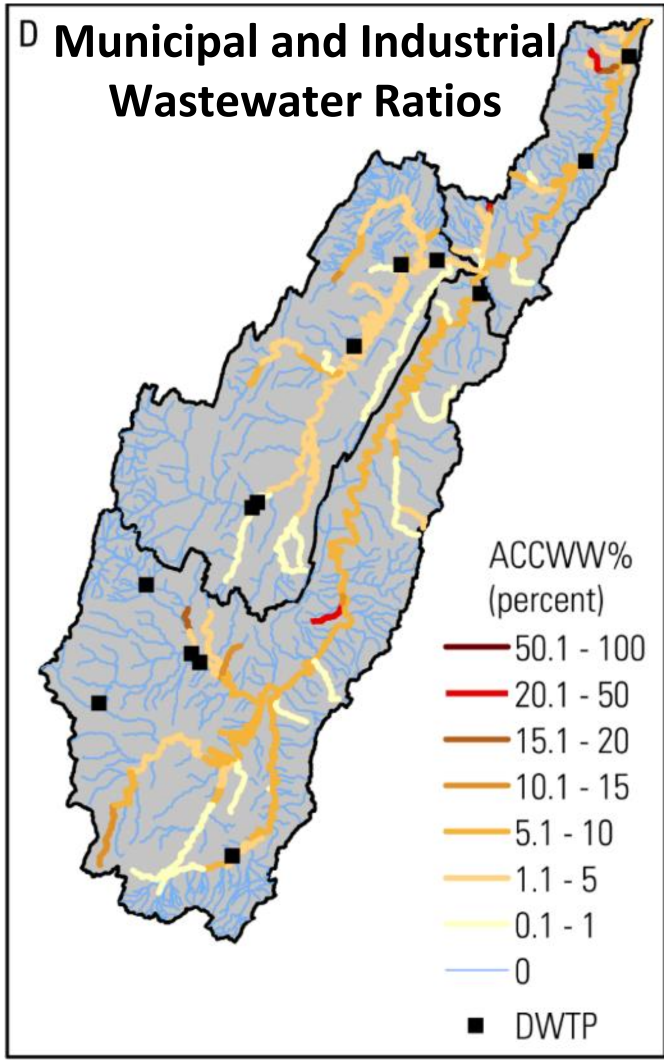
ACCWW for each river segment (%)

$$\frac{\text{ACCWW}}{\text{Streamflow}} * 100$$

Quantify the proportion of streamflow comprised of municipal and industrial WWTP effluent and predict the potential risk for endocrine disruption effects in fish.

420 of 1754 stream segments have WWTP influence

August flow conditions



Kandel, Rapp, and Barber, 2017 Shenandoah River Accumulated Wastewater Ratio Mapper.

https://va.water.usgs.gov/webmap/shenmap/

Predicting Concentrations of Selected EDCs and Estradiol Potency Factors

Two step process:

1) WWTP Load

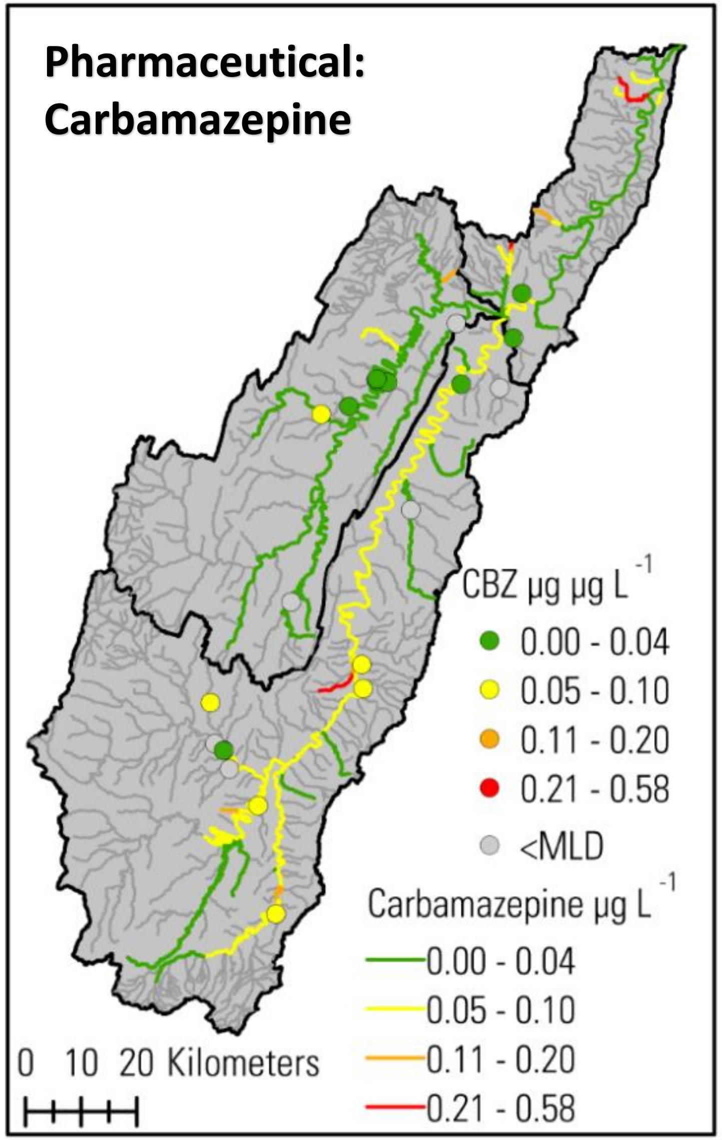
- **Per capita consumption**
- **Population served**
- **Human (animal) metabolism**
- **Treatment type**

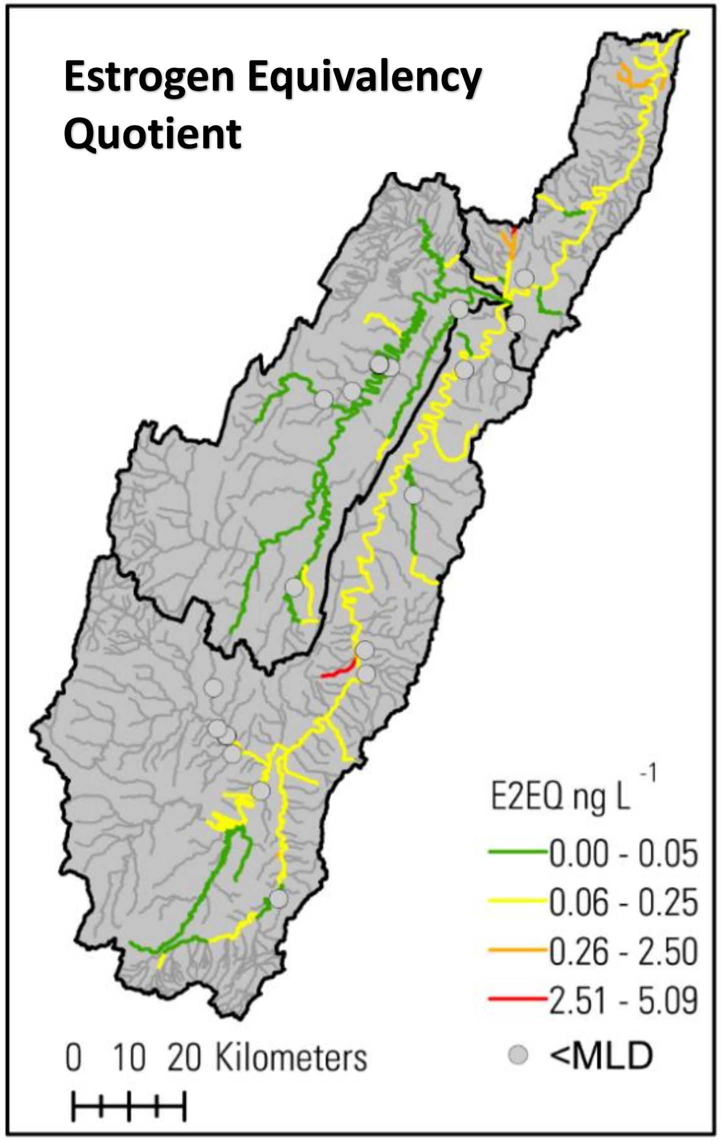
Load (ug/day) =

Effluent Concentration * Q_{WWTP}

2) River reach accumulated load

- **In-stream loss rates**
- **Stream velocity for travel time**





Streamflow Exceedance is directly linked to ACCWW%

North River near Burketown (Orange)

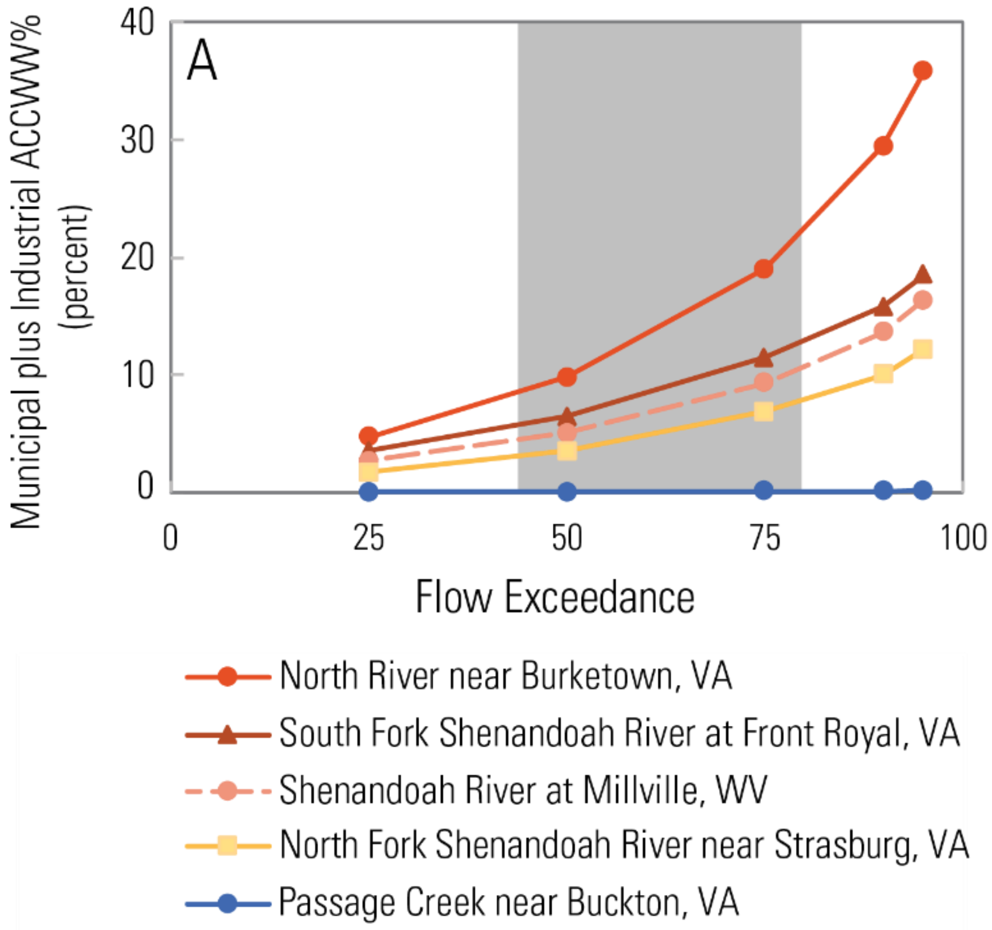
- Flow = 75% Exceedance and WWRatio = 17% in 2014

North Fork near Strasburg (yellow)

- Flow = 75% - 50% Exceedance WWRatio = 2% - 5% in 2014-2016

- Flow exceedance supports conclusions about biological effects from the Mobile Lab study.

ACCWW% at Stream gages during the Mobile Lab study and across the entire flow regime.



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Mobile Laboratory Assessment of Endocrine Disruption

South Fork Shenandoah River

Lab

Flow to lab

Flow from lab

Power to lab

Male/Female
Fathead Minnows

- Photoperiod
- Aeration
- Temperature
- Diet

- 21-d exposures
- Continuous flow
- Water sampling day 0, 7, 14, 21
- Fish sampling day 0, 7, 21

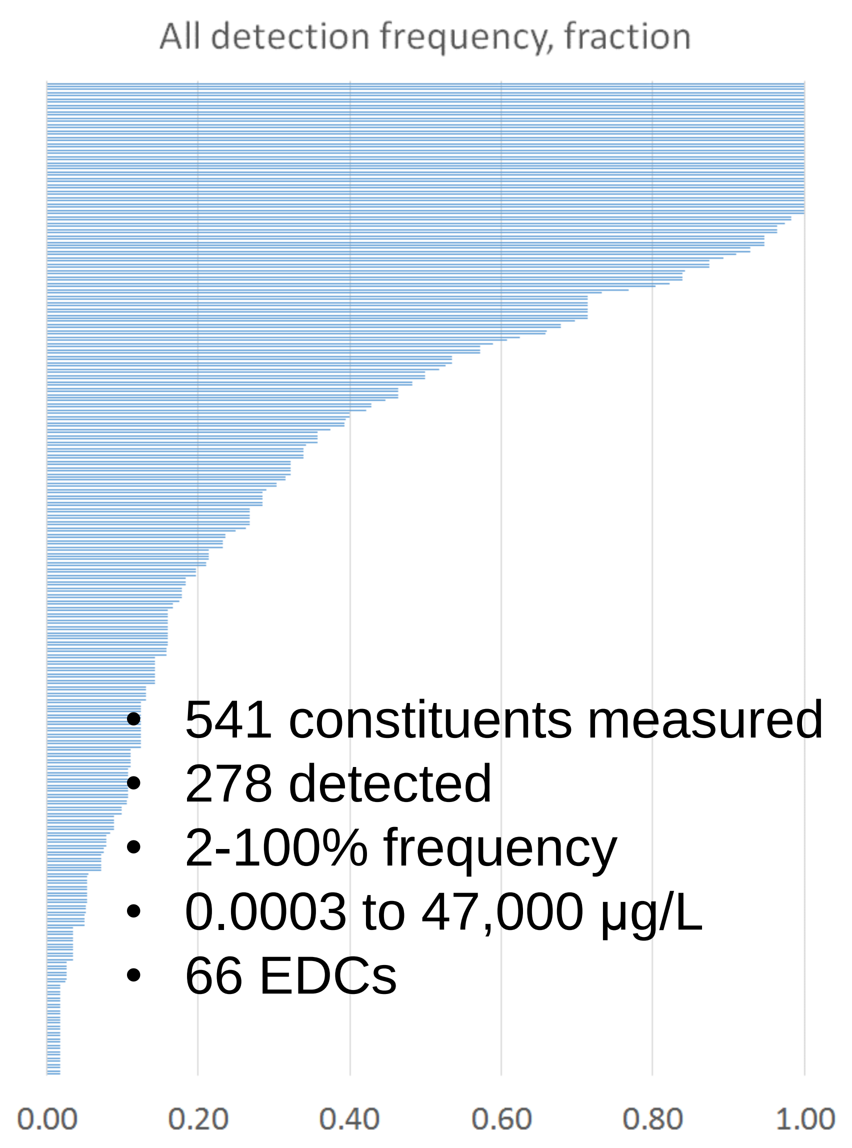
River Waters are Complex Chemical Mixtures

20 Methods in 6 laboratories

- Field constituents
- Nutrients
- Major ions
- Trace elements
- Pesticides
- Pharmaceuticals
- Personal care products
- Hormones
- Phytoestrogens
- Perfluoroalkyl substances
- Disinfection byproducts

Biological Effects

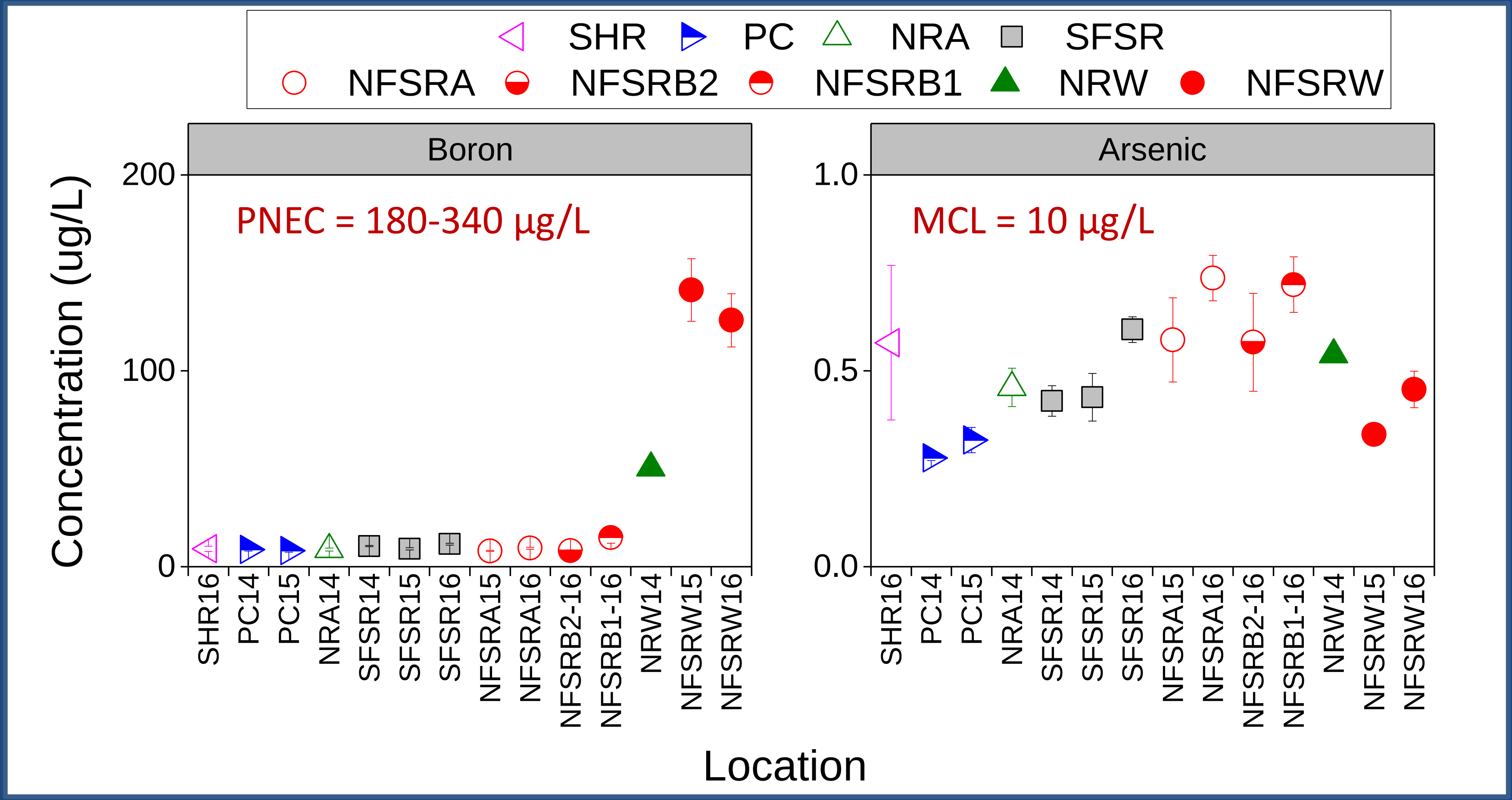
Chemical structure
Concentration
Mode of action
Exposure pathways
Target organism



- 541 constituents measured
- 278 detected
- 2-100% frequency
- 0.0003 to 47,000 µg/L
- 66 EDCs

Trace Element Tracers of Contaminant Sources

Boron - conservative indicator of “down-the-drain” chemicals
Arsenic - reactive indicator of pesticide use
Maximum contaminant level (MCL)/predicted no effect concentration (PNEC)



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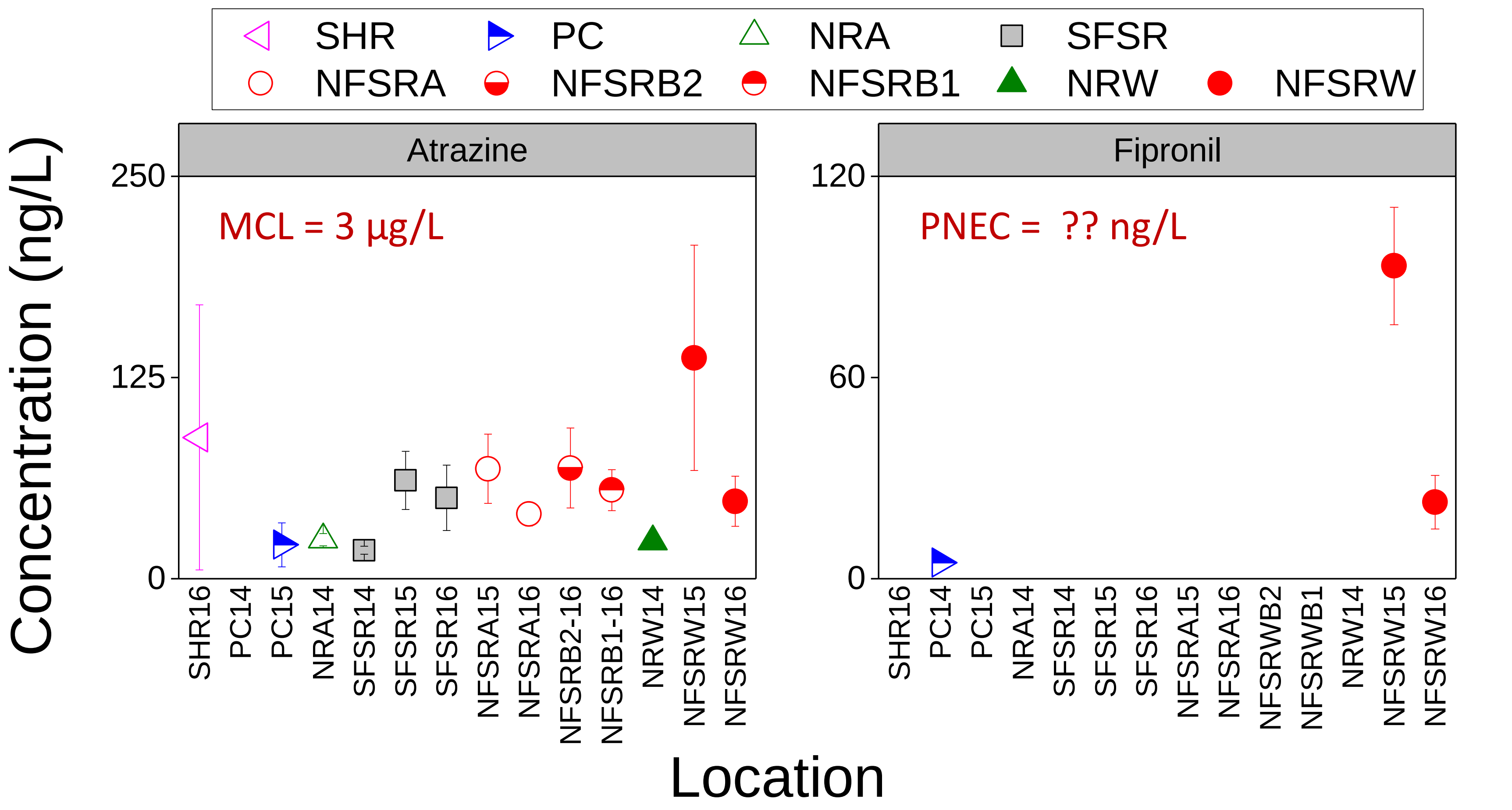
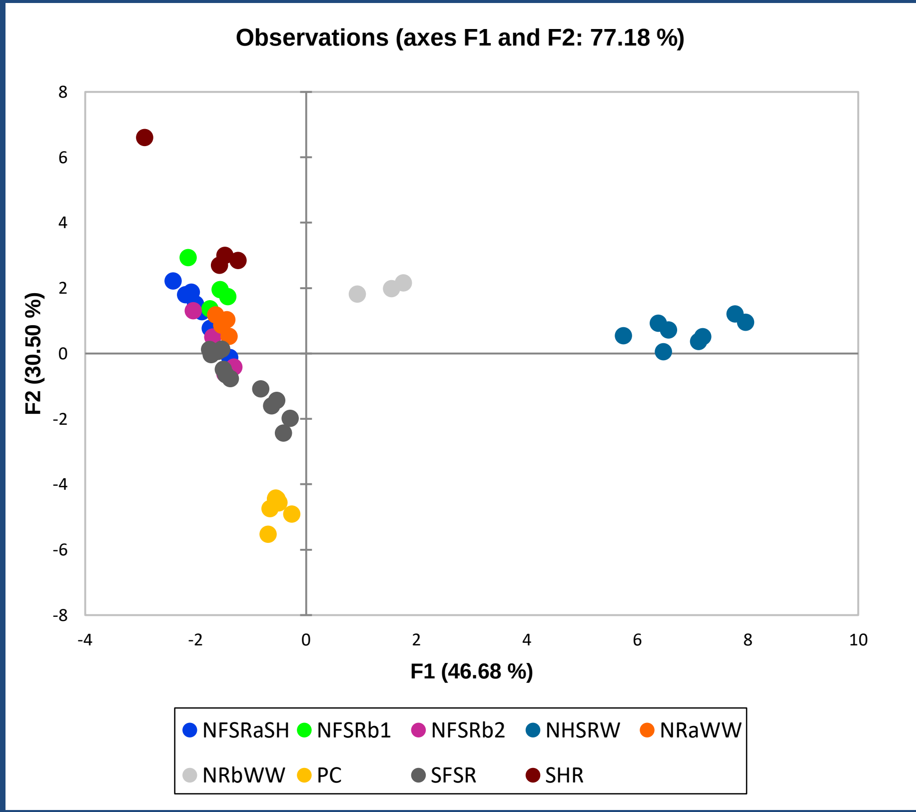
Pesticides from Agriculture and WWTPs

- Herbicides (atrazine)
- Insecticides (fipronil)
- Fungicides



Exposure to Complex Contaminant Mixtures

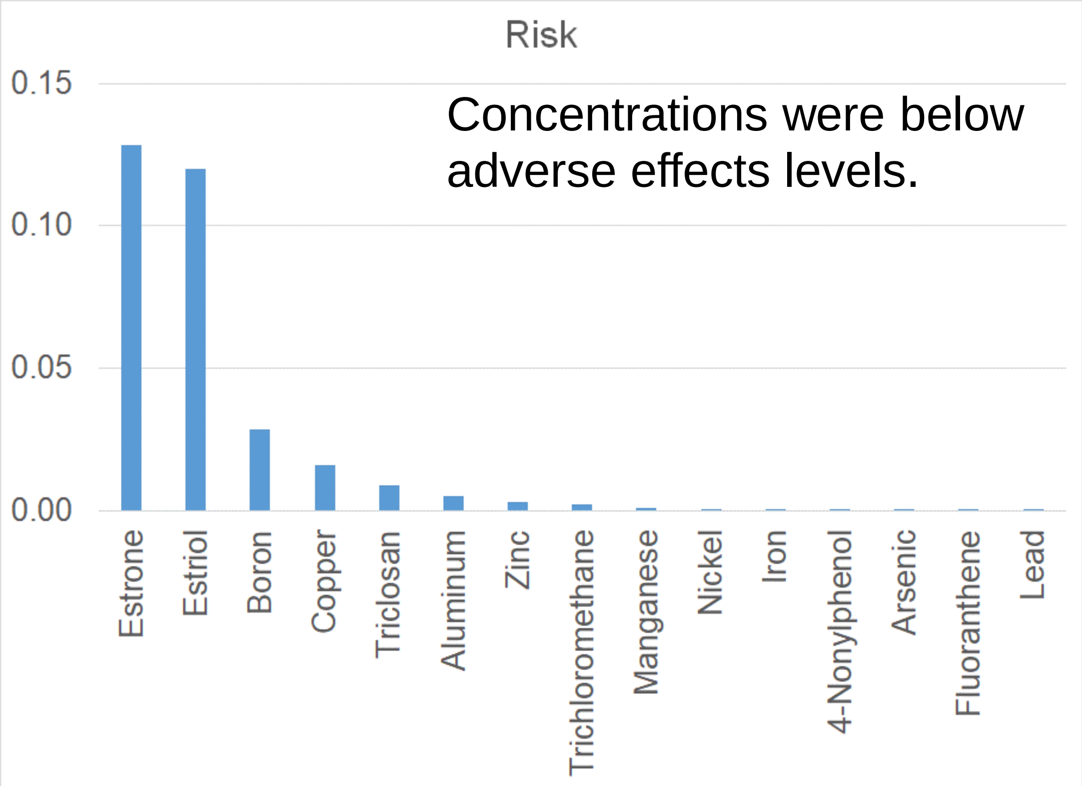
Principal component analysis (PCA) of chemical mixture data was used to classify sample sites:



Source water endmembers:

- Wastewater (factor 1),
- Mixed Use (highest factor 2), and
- Reference Site (lowest factor 2).

Ecotoxicological risk ranking for top 15 inorganic and organic constituents from acute toxicity data



Preliminary information subject to revision.
Not for citation or distribution.

Barber et al., 2019, Integrated assessment of endocrine disruption in the Shenandoah River Watershed – Exposure to complex contaminant mixtures. In preparation

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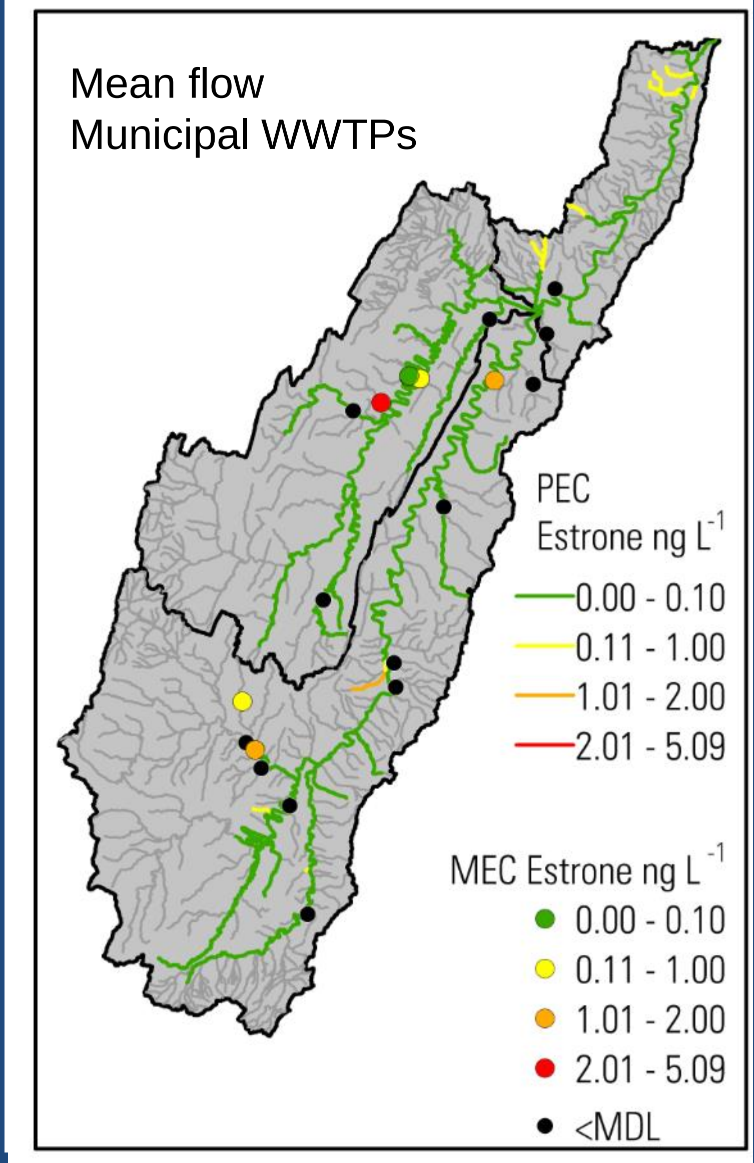
Comparing Predicted to Measured Environmental Concentrations



Predicted Environmental Concentrations (PECs)

- Determined for all stream segments
- Calculated based on mean ACCWR
- Estimates limited by chemical input data
- Low cost

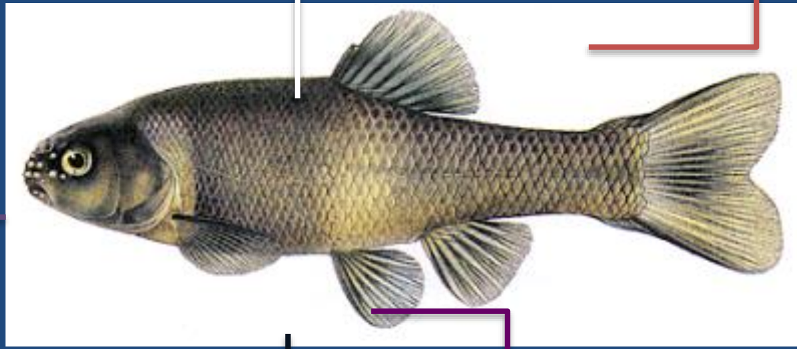
Measured Environmental Concentrations (MECs)

- Instantaneous measurements
- Mean values specific to individual sites
- “Gold standard” methods
- High cost

Constituent	NFSR MEC	NFSR PEC	SFSR MEC	SFSR PEC
Boron	9.3	8.7	12	10
Carbamazepine	0.002	0.015	0.008	0.051
Estrone	0.0008	<0.0001	0.0011	<0.0001

Concentrations in µg/L

Fish Endocrine Disruption Endpoints Collected



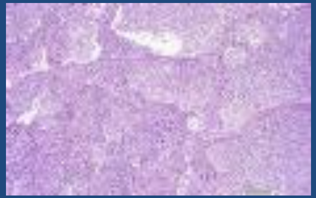
Survivorship

Plasma

Vitellogenin (Vtg)

Gonad

Histology
Vtg mRNA
Somatic index (GSI)

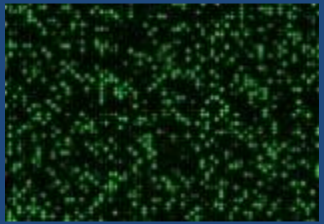


Secondary Sex Characters

Nuptial tubercle
Dorsal fat pad

Liver

Histology
Microarray
vtg mRNA
Somatic index (HIS)



Bertolatus et al., 2019, ***A transcriptomics and landscape-based approach to assess fish health impacts from exposure to complex chemical mixtures in the Shenandoah River****. In preparation.*

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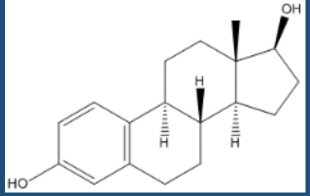
Mode-of-Action and Adverse Outcome Model

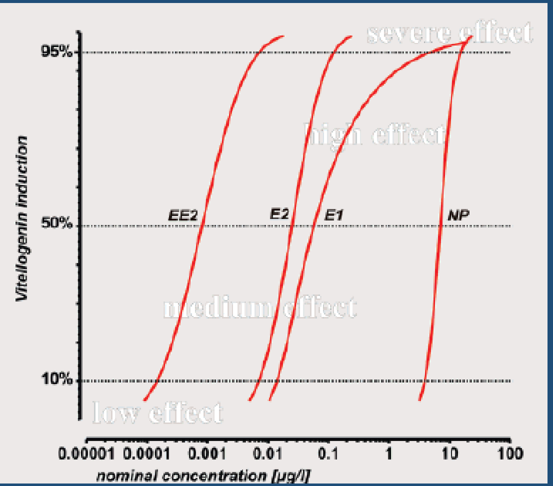
Modeling Fish Endocrine Disruption Risk

(Following Sumpter et al., 2006, Environ. Sci. Technol. 40, 5478)

Estrogen equivalency quotients (E2EQ) of four estrogen compounds were modeled, measured and compared with dose-response curves for Vitellogenin induction in male fathead minnow.



E2EQ = ∑ (concentration *i* x relative potency *i*)



Estrogen	Relative E2 Potency
17-β-Estradiol (E2)	1
Estrone (E1)	0.38
17-α-Ethinylestradiol (EE2)	30
4-Nonylphenol (NP)	0.0001

Exposure
Estrone detected at ~1 ng/L

Risk
- E2EQ <1 ng/L = low
- E2EQ >1<10 ng/ L = medium
- E2EQ >10 ng/L = high

Barber, Rapp, Keefe, Kandel, Rice, Westerhoff, and Vajda, 2019. **Integrated Assessment of Wastewater Reuse, Exposure Risk, and Fish Endocrine Disruption in the Shenandoah River Watershed**, ES&T.

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Landscape *predicts* Chemistry

Chemistry *predicts* Biology

Modeling *informs* Monitoring and Management

- Widespread occurrence of complex chemical mixtures related to landscape activities.
- Fathead minnows exposures indicate minor endocrine disruption effects consistent with low levels of EDCs in water.
- Shenandoah Accumulated Wastewater Mapper Modeling results were consistent with field measurements suggesting low to moderate risk for fish endocrine disruption.
  - Accumulated WWRatios can guide water-supply permit decisions.
  - The PEC model can be used to identify hot spots for WW impacts, and could be utilized by agencies to identify biological or chemical sampling priority areas.

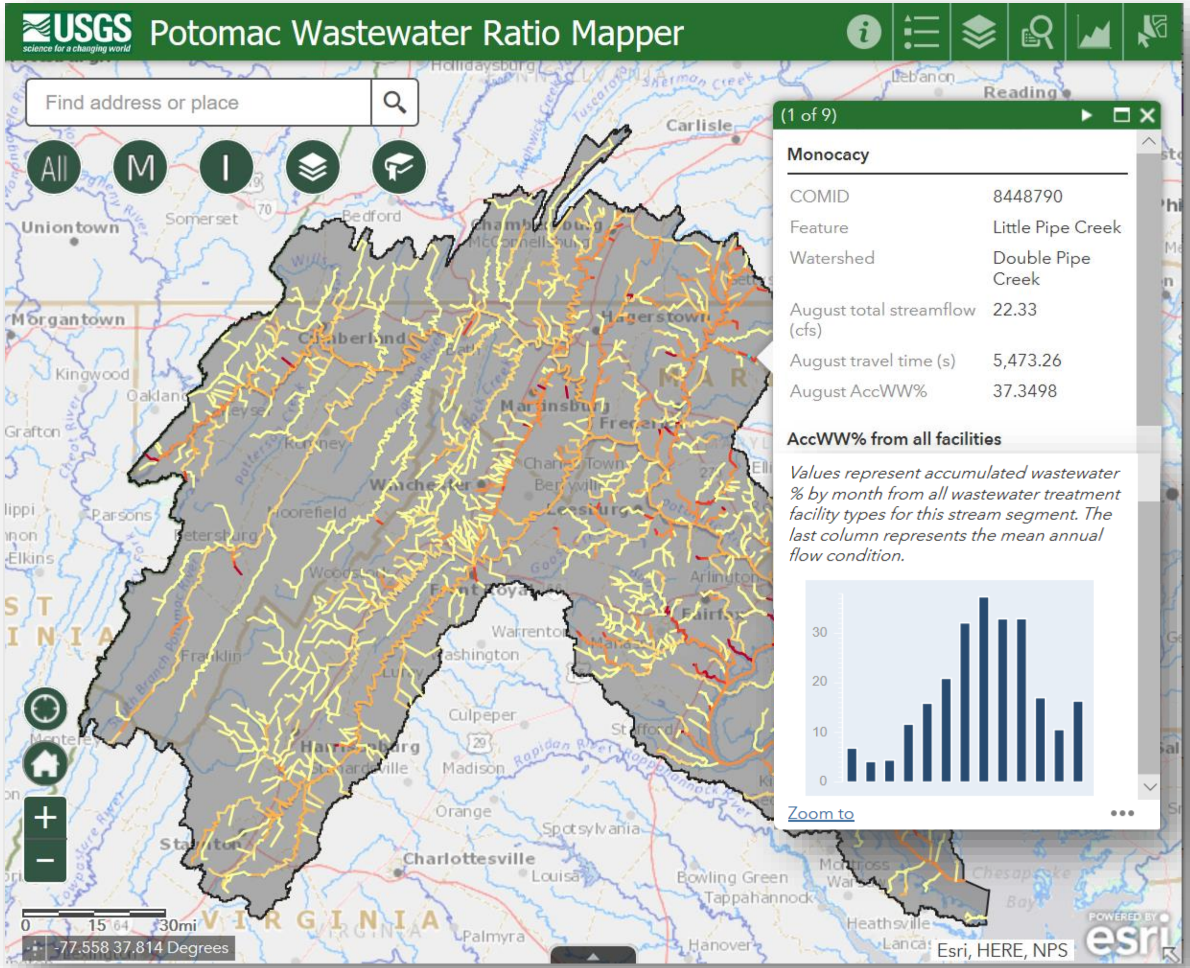
Expanding the Wastewater Mapper to the Potomac

https://va.water.usgs.gov/webmap/shenmap/

Next-Generation Tool Updates:

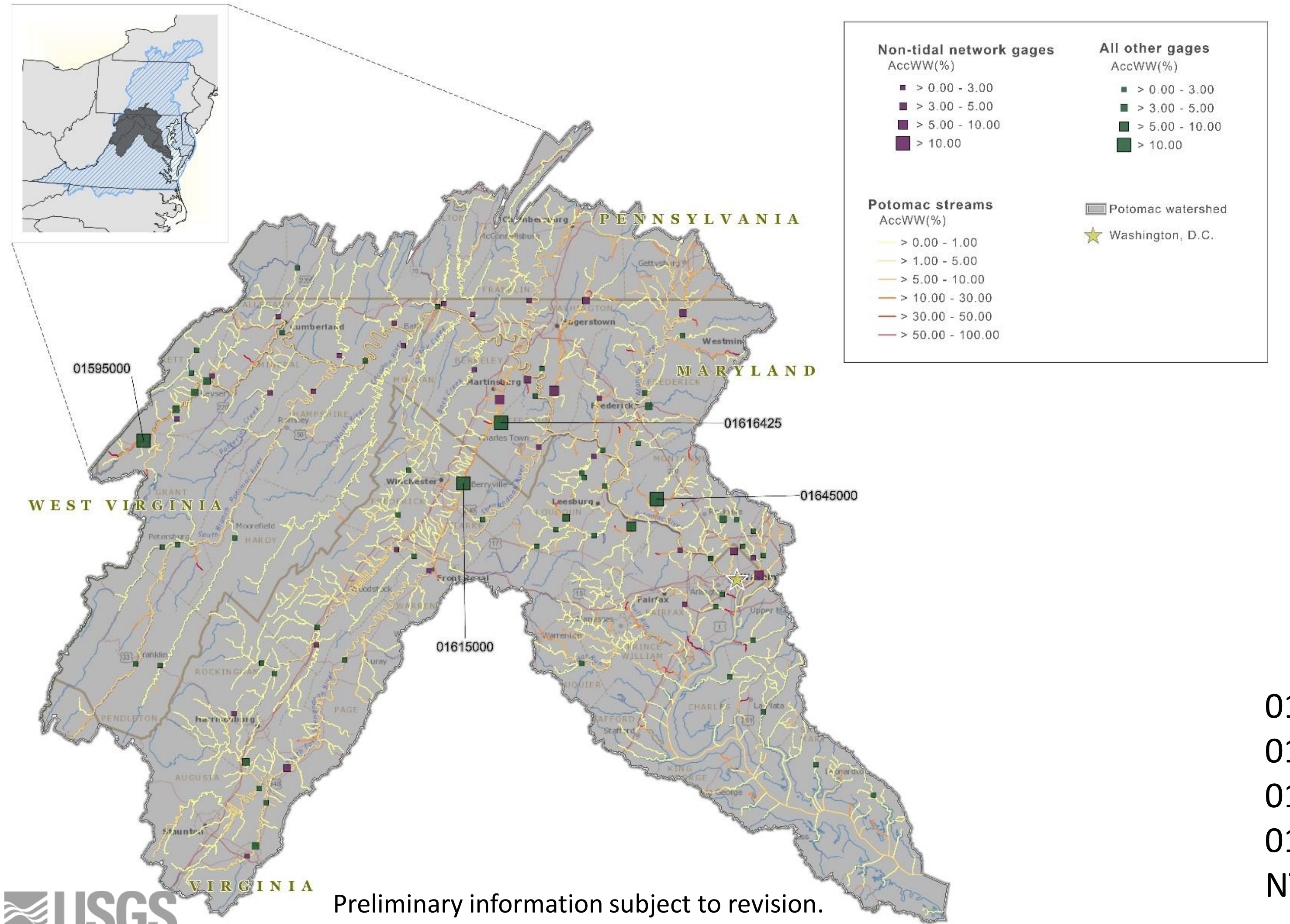
- ACCWW% and PEC for Potomac River Watershed.
- 50 Predicted Environmental Concentrations (PEC) of wastewater contaminants (and PFAS)
- Now-casting of ACCWW% predictions at USGS gages in Shenandoah.
- Incorporate Industrial discharges into the PEC models because they represent half the wastewater in the streams of Shenandoah.

August municipal and industrial WWTP ACCWW%

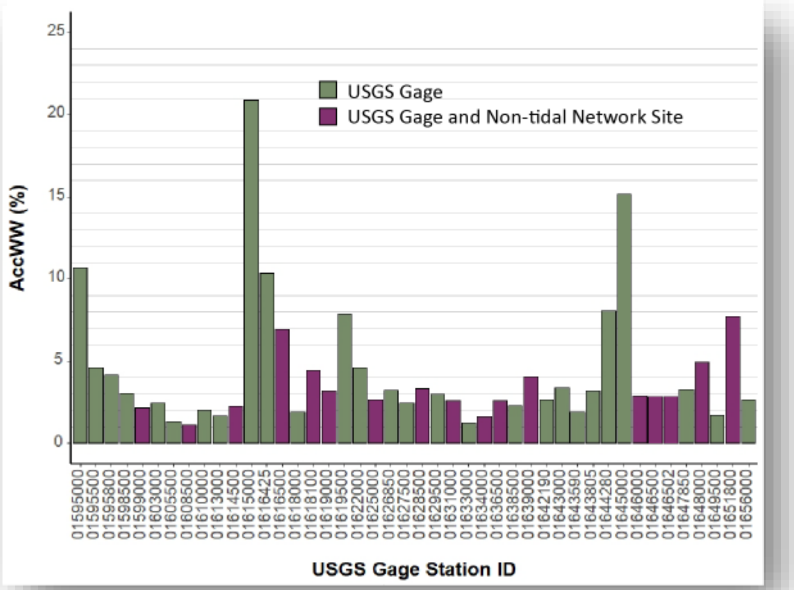


Preliminary Estimates of Accumulated Wastewater at Potomac River Watershed Gages

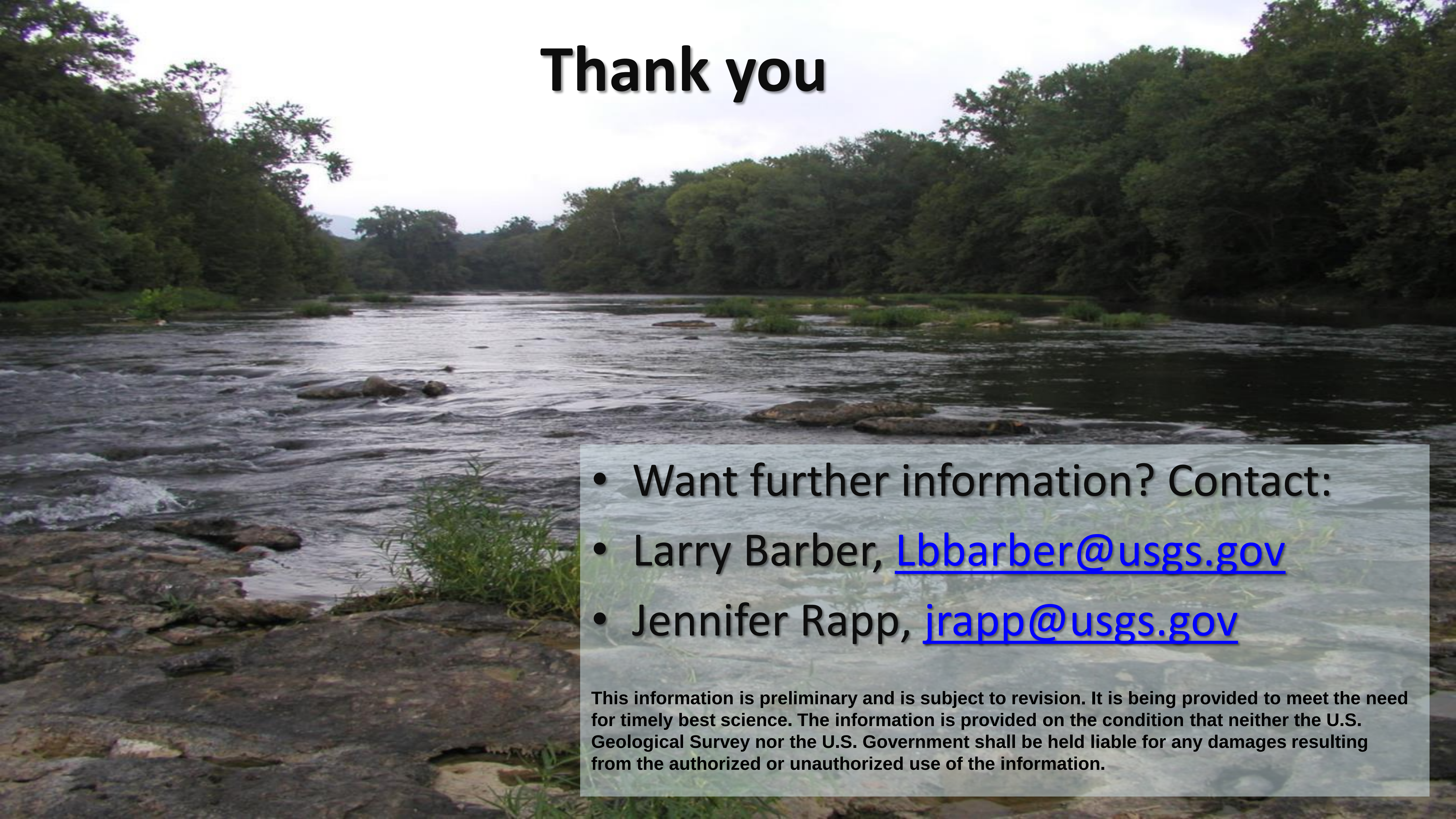
Accumulated wastewater percentages (AccWW%) under mean annual streamflow conditions using combined municipal and industrial WWTP discharge data for streams and gages.



68 out of 112 USGS gages had > 1% AccWW%



01595000 NORTH BRANCH POTOMAC AT STEYER, MD **10.7%**
01615000 OPEQUON CREEK NEAR BERRYVILLE, VA **20.9%**
01616425 HOPEWELL RUN AT LEETOWN, WV **10.3%**
01645000 SENECA CREEK AT DAWSONVILLE, MD **15.2%**
NTN Gages: **0% to 7.8 %** wastewater at mean annual flow.



Thank you

- Want further information? Contact:
- Larry Barber, Lbbarber@usgs.gov
- Jennifer Rapp, jrapp@usgs.gov

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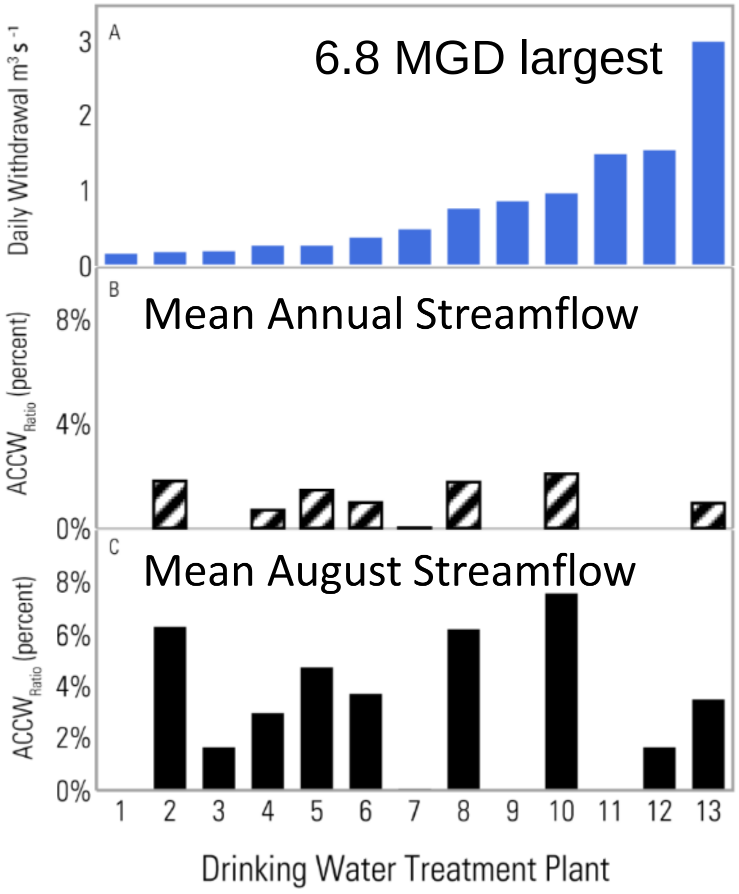
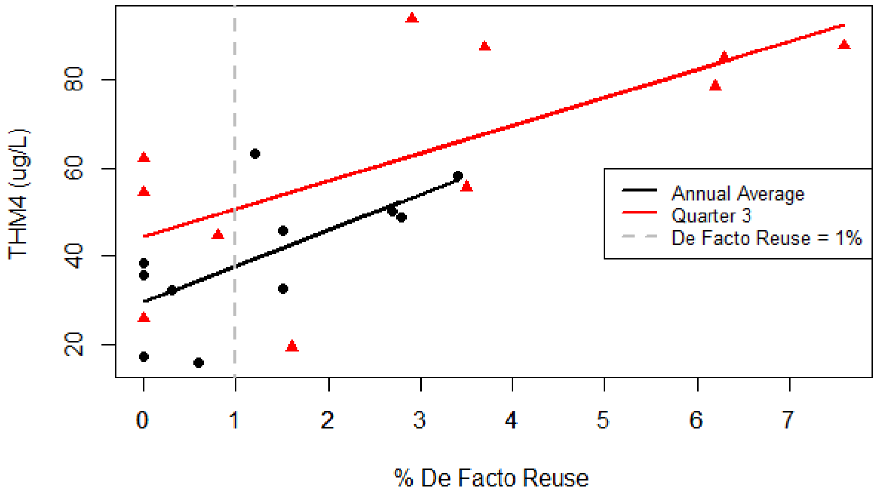
De Facto Reuse at Drinking Water Treatment Plants

13 DWTPs with surface-water intakes



National DRINCS analysis found similar ACCWWs 2.3-16% (Rice and Westerhoff 2017)

De facto wastewater reuse at DWTP intakes and measured disinfection by products.



- Strong correlation between de facto reuse and trihalomethanes (THM4).
- At >1% de facto reuse there is a **greater relative risk** that THM4 will exceed one-half the maximum contaminant levels.

Weisman et al., 2019, ***Association of de facto reuse and other stressors with disinfection by-products in drinking water systems in the Shenandoah River Watershed***, Environmental Science: Water Research & Technology.