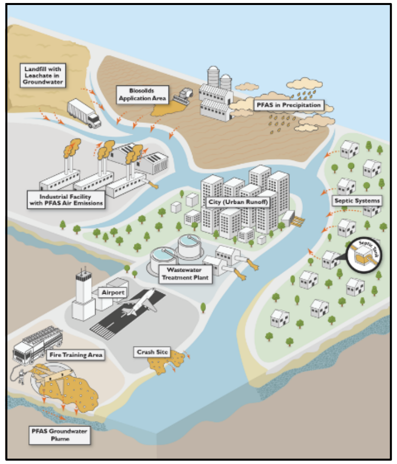
PFAS in Stormwater: Characteristics, Tools, and Potential Management Strategies

Battelle Denver 2024

June 2024



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Project ER23-3741

Roadmap – This Talk

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1. SERDP PFAS Stormwater Project
2. PFAS Environmental Criteria
3. PFAS Stormwater Source Characteristics
4. Potential Regulatory Approaches for PFAS In Stormwater

Project ER23-3741

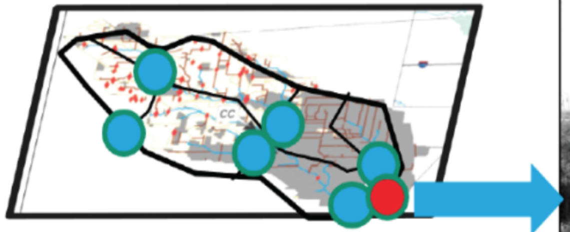
About Us

Understanding the Spatial/Temporal Nature of AFFF PFAS Loadings in Stormwater to Develop Targeted Stormwater Treatment Technologies

ER23-3741

1

One Year of Detailed Intra- and Inter- Stormwater Event Sampling…

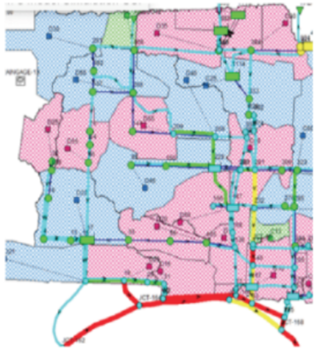


Spatial Grab Sampling of Small AFFF Site Drainage Sub-basins

Intra-Event Runoff + PFAS Sampling at AFFF Site Discharge Point Using Automatic Samplers

+

Simple Rainfall / Runoff / Stormwater Loading Models



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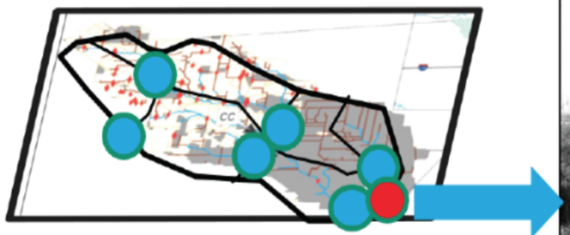

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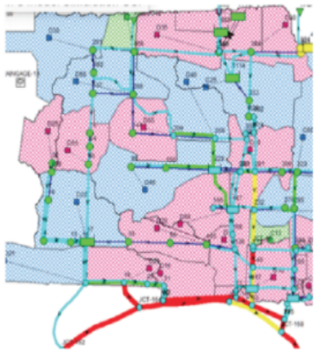
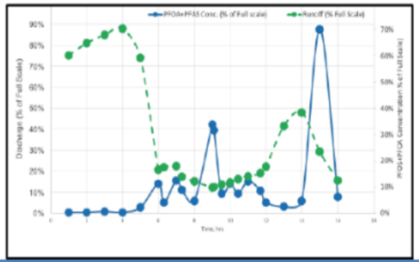


2

To Answer These Questions…

- Is there a concentrated first flush volume for PFAS at AFFF sites?
- What is the annual stormwater load vs dry weather load?
- Is there any partitioning to the air/water interface, either in conveyance systems or in settling basins?
- What is relative loading of PFAS
  - in dissolved phase
  - on colloids and fine-grained suspended solids (SS)
  - on settleable SS



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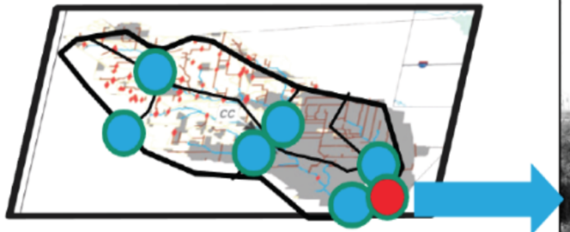

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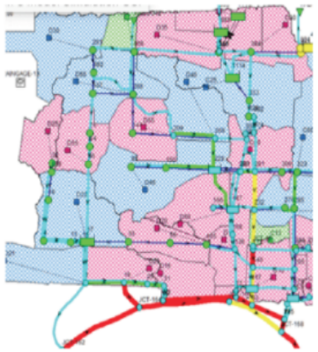

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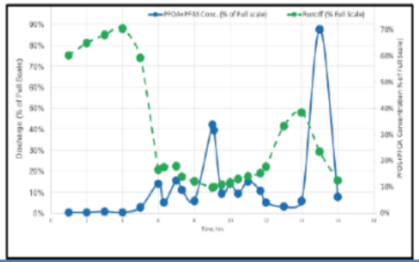


3 Learn Which SW Treatment Options Work for PFAS

- **Settling?**
- **Skimming?**
- **Source control?**
- **Separation?**
- **Sorption?**
- **Foaming?**

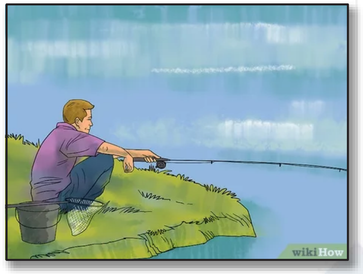
1. PFAS Environmental Criteria

Three General Exposure Pathways for PFAS in Stormwater

Examples for PFOS

1. *Protection of aquatic species (USEPA draft chronic)* → *8,400 ng/L*

2. *Drinking water ingestion (MCL)* → *4 ng/L*



3. *Human consumption of fish/seafood (SFRWQCB ESL for GW)* → *0.0047 ng/L*

G. Garvey, GSI

2. PFAS Stormwater Source Characteristics

Concentration of PFOS in Stormwater from 9 Sites

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PFOS Concentration in Stormwater (ng/L)

Event Number	Hobart Airport	RAAF Base East Sale	RAAF Base Darwin	AFFF Site With Retention Pond	USGS Wright-Patterson	Ponded AFFF Site Stormwater	San Diego Intl. Airport	San Jose Intl. Airport	San Francisco In. Airport	Summary Stats (ng/L)
1	4,400	255,000	10	500	250	80,000	553	1,900	249	
2		31,200	380				1,100			
3		33,300	80				355			
4		18,000	40							
Min		18,000	10				355			10
Geomean	**4,400**	**46,731**	**59**	**500**	**250**	**80,000**	**544**	**1,900**	**249**	**1,466**
Max		255,000	380				1,100			255,000

J. Gamlin, N. Johnson, H. Javed, GSI.

2. PFAS Stormwater Source Characteristics
Flow (Annual Runoff) from Hypothetical AFFF Sites

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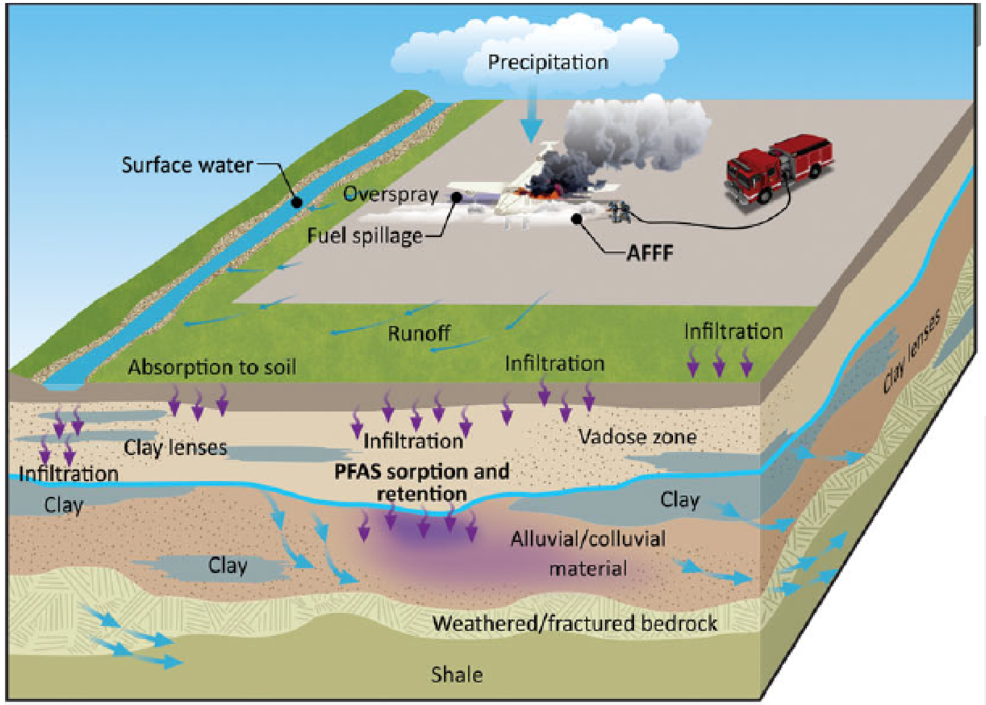
How to Estimate Runoff from an AFFF Site?

General Characteristics (High Uncertainty):

- Median area: about 1.5 acres (0.5 ha) (criteria ~100,000 ng/kg PFOS)
- Wide range of soil types
- Median slope: 0.2%

	Average % of Land Cover (n= 16 Sites)
Concrete	27%
Grass	43%
Bare Ground	30%

Kulkarni et al., in preparation.



Graphic: Leeson et al., 2021.

2. PFAS Stormwater Source Characteristics
Modeling **Runoff** from Hypothetical AFFF Sites

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USDA

United States Department of Agriculture

Natural Resources Conservation Service

Conservation Engineering Division

Technical Release 55

June 1986

Urban Hydrology for Small Watersheds

TR-55

Table 2-2a Runoff curve numbers for urban areas [1/]

Cover description: Cover type and hydrologic condition	Average percent impervious area [2/]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3/]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98

"Curve Number Method" accounts for:

- Catchment area
- Land cover
- Soil type
- Storm Size

2. PFAS Stormwater Source Characteristics
Modeling Annual Runoff from Hypothetical AFFF Sites

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Table 2-2a Runoff curve numbers for urban areas [1/]

But this model estimates runoff from individual 24-hour storms…

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2. PFAS Stormwater Source Characteristics
Modeling Annual Runoff from Hypnotical AFFF Sites

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Curve Number Approach to Estimate Monthly and Annual Direct Runoff

Andrew J. Guswa, A.M.ASCE[1]; Perrine Hamel[2]; and Katherine Meyer[3]

Solving Eq. (9) results in the following expression for the mean runoff:

$$\langle Q^{new} \rangle = (\alpha - S)\exp\left(-\frac{\lambda S}{\alpha}\right) + \frac{S^2}{\alpha}\exp\left(\frac{(1-\lambda)S}{\alpha}\right)E_1\left(\frac{S}{\alpha}\right) \tag{10}$$

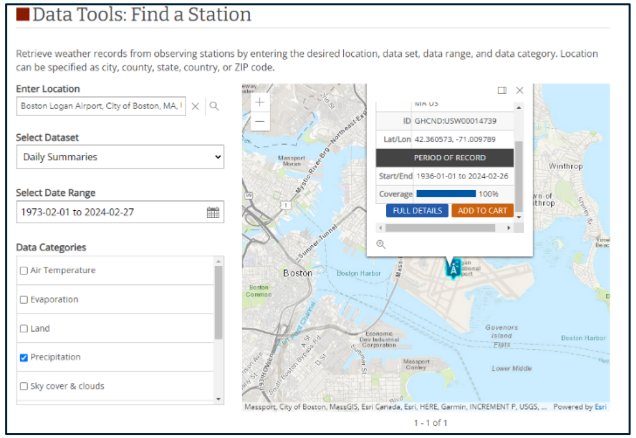
where $E_1(x)$ = exponential integral (Abramowitz and Stegun 1972)

$$E_1(x) = \int_x^\infty \frac{\exp(-u)}{u}\,du \tag{11}$$

Cumulative runoff over the period of interest is

$$Q_N^{new} = \langle Q^{new} \rangle \eta N \tag{12}$$

But Guswa's method requires long daily rainfall data…



Site 10 Houston IAH

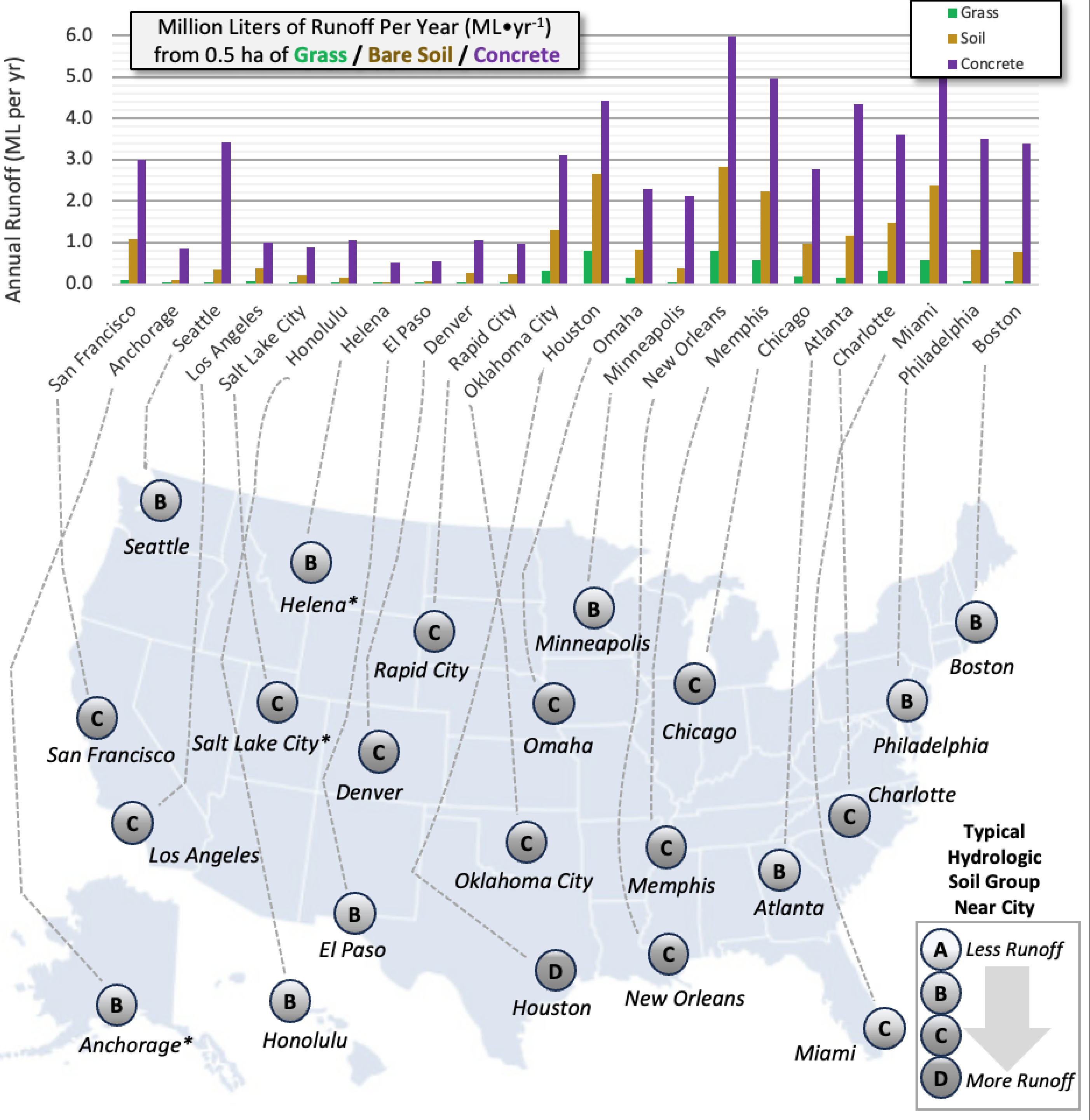
STATION	NAME	DATE	PRCP	SNOW	SNWD
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-01	1.16	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-02	0.07	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-03	0.20	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-04	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-05	0.61	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-06	0.29	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-07	0.16	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-08	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-09	0.01	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-10	0.41	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-11	0.58	2.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-12	0.00	0.0	1.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-13	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-14	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-15	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-16	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-17	0.00	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-18	0.12	0.0	0.0
USW00012960	HOUSTON INTERCONTINENTAL AIRPORT, TX US	1973-01-19	0.00	0.0	0.0

So we got 50 year of rain & snow from NOAA web site

2. Annual Runoff from 66 Hypothetical AFFF Sites

22 cities, three different land covers:

1. *Grass*
2. *Bare soil*
3. *Concrete*



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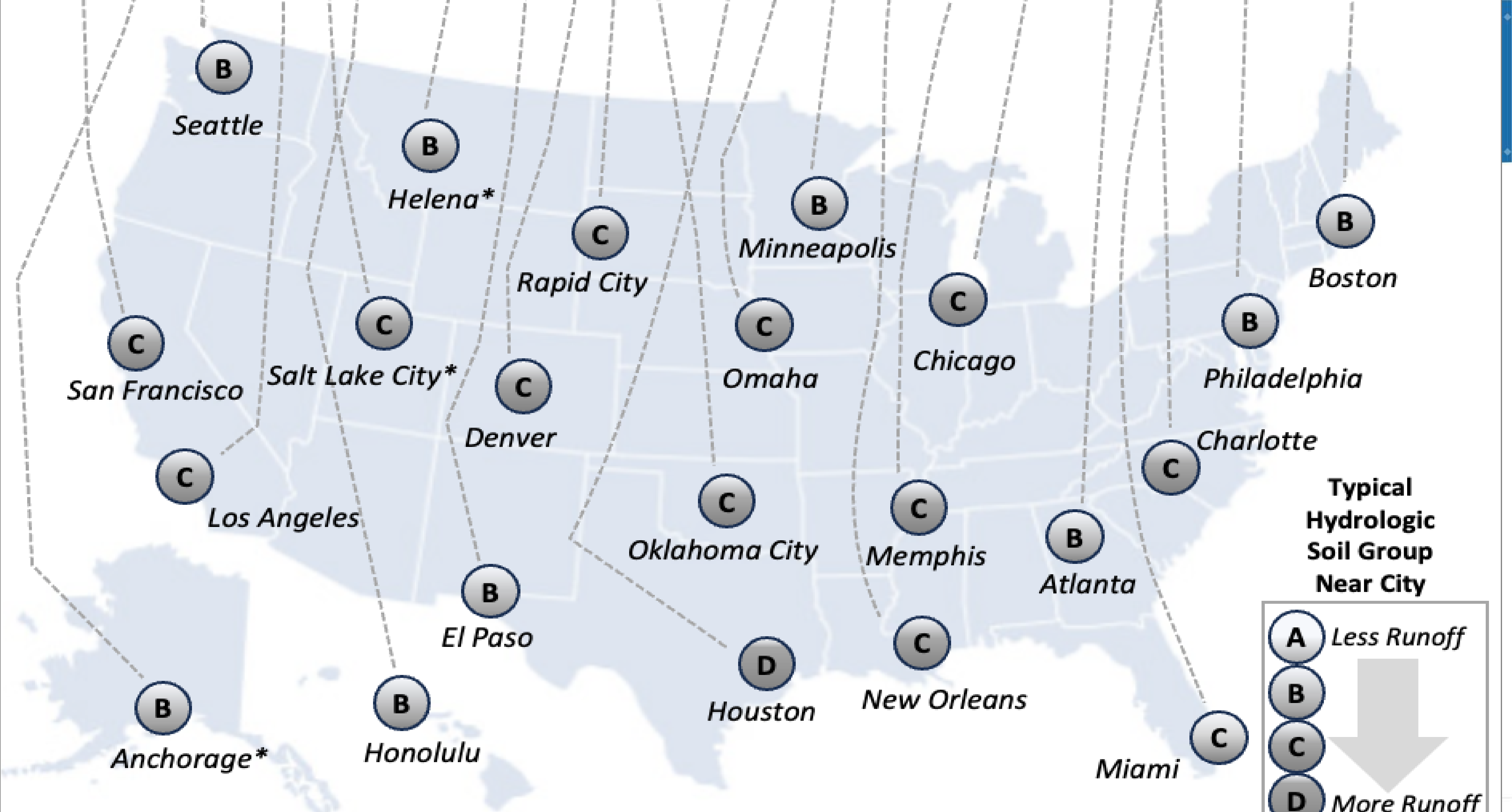
G. Grundy, M. Gupta, GSI



Soils: M. Wang, GSI

Stormwater Runoff From Hypothetical AFFF Sites in 22 Different Cities (millions liters per year)

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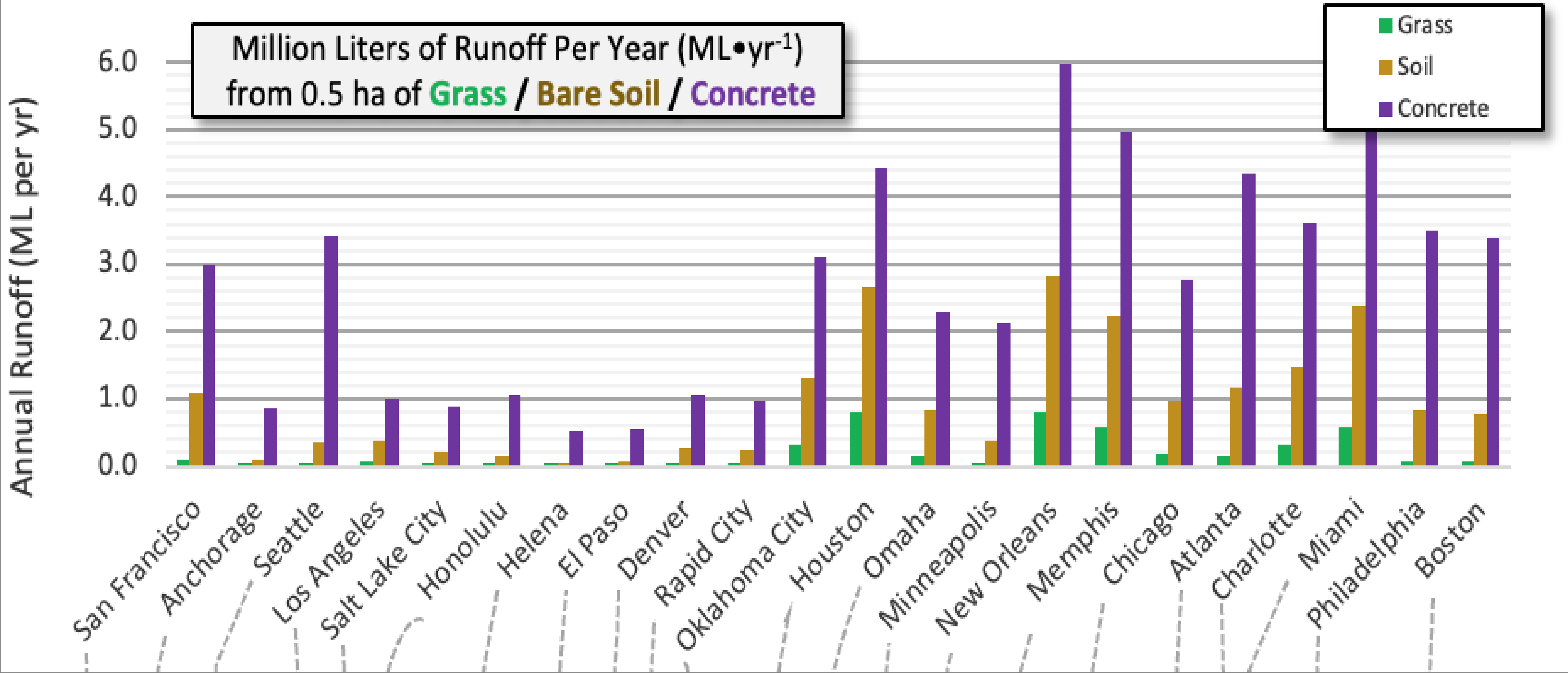

3. Modeled PFOS Mass Discharge in Stormwater from Different Hypothetical AFFF Sites

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Runoff volume (liters per year)

x PFOS concentration (ng/L)

= PFOS mass discharge (grams per yr)

Theoretical Annual PFOS Mass Discharge in Stormwater from an AFFF Site (grams per year)				
	All Grass	All Bare Soil	All Concrete	Mix
Minimum	0.00067	0.068	0.79	0.28
Median	**0.12**	**1.2**	**4.3**	**1.9**
Maximum	1.2	4.3	9.0	4.8

PFOS Mass Discharge: If Groundwater and Stormwater Got into a Fight, Who Would Win?

3. PFOS Mass Discharge (M_d): If Groundwater and Stormwater Got into a Fight, Who Would Win?

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PFOS Mass Discharge	Modeled Stormwater PFOS M_d from 0.5 Ha Site	Groundwater PFOS M_d from 4 AFFF Sites*
Low range value:	<0.01 grams per year	2 grams per year
Middle range value:	**1.9 grams per year**	**30 grams per year**
Upper Range value:	9 grams per year	300 grams per year

**Adamson et al., 2020, 2024, Nickerson et al., 2021, Quinnan et al., 2021.*

Key Point: In general, lots of uncertainty, but maybe a little more PFOS mass discharge in groundwater than stormwater at typical sites?

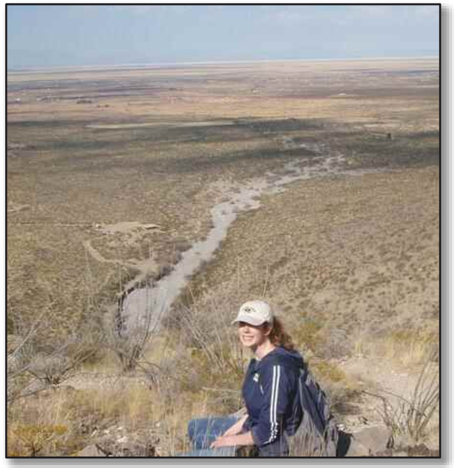
3. Which Sites are More Dominated by Groundwater vs. Stormwater?

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 53, No. 4 AMERICAN WATER RESOURCES ASSOCIATION August 2017

ANNUAL ESTIMATES OF RECHARGE, QUICK-FLOW RUNOFF, AND EVAPOTRANSPIRATION FOR THE CONTIGUOUS U.S. USING EMPIRICAL REGRESSION EQUATIONS[1]

M. Reitz, W.E. Sanford, G.B. Senay, and J. Cazenas[2]

Reitz et al., 2017



Dr. Meredith Reitz, Research Hydrologist, USGS

Key Point: This 2017 paper provides recharge and runoff at 800 meter spatial resolution across continental U.S. using USGS stream gage data.

Runoff and Recharge Maps (Reitz et al., 2019)

a) Quick-Flow Runoff (m/yr)

Median: 0.068 m/yr

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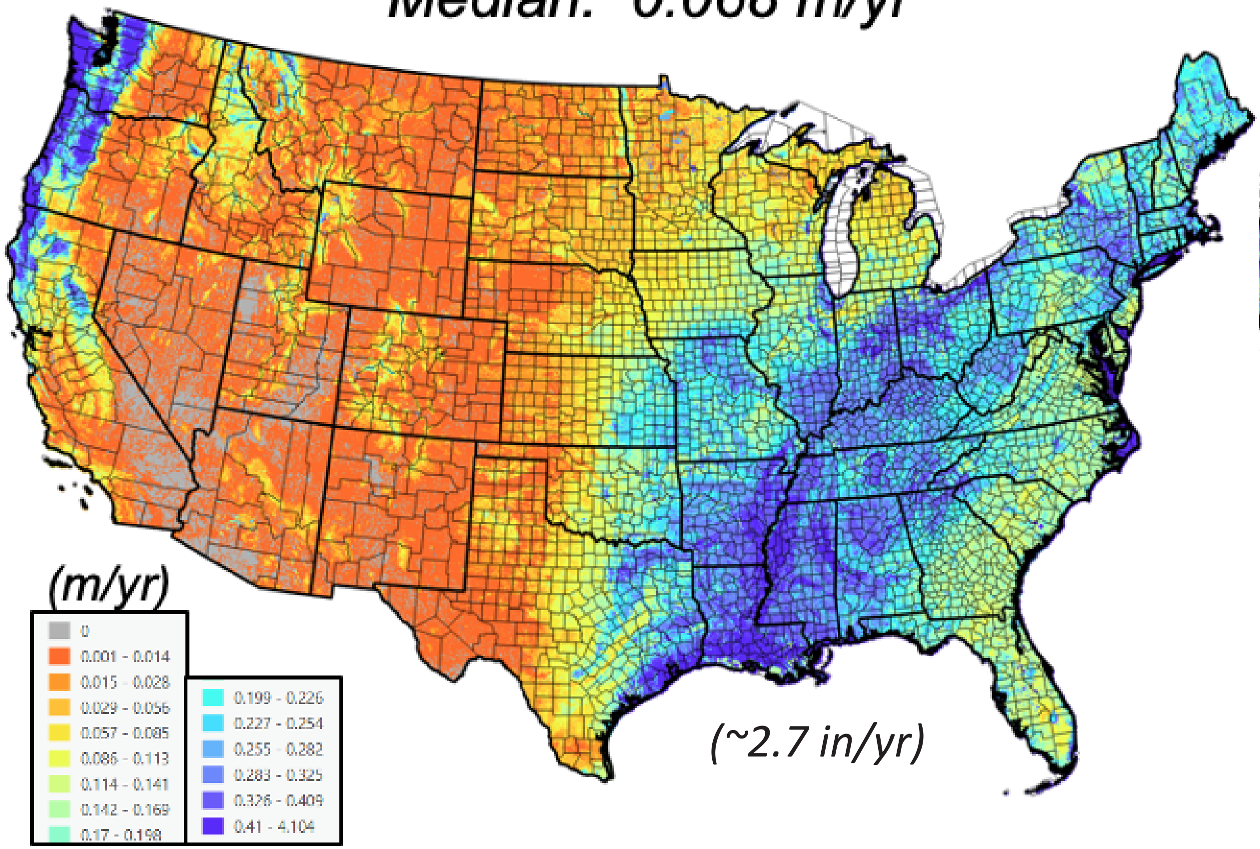
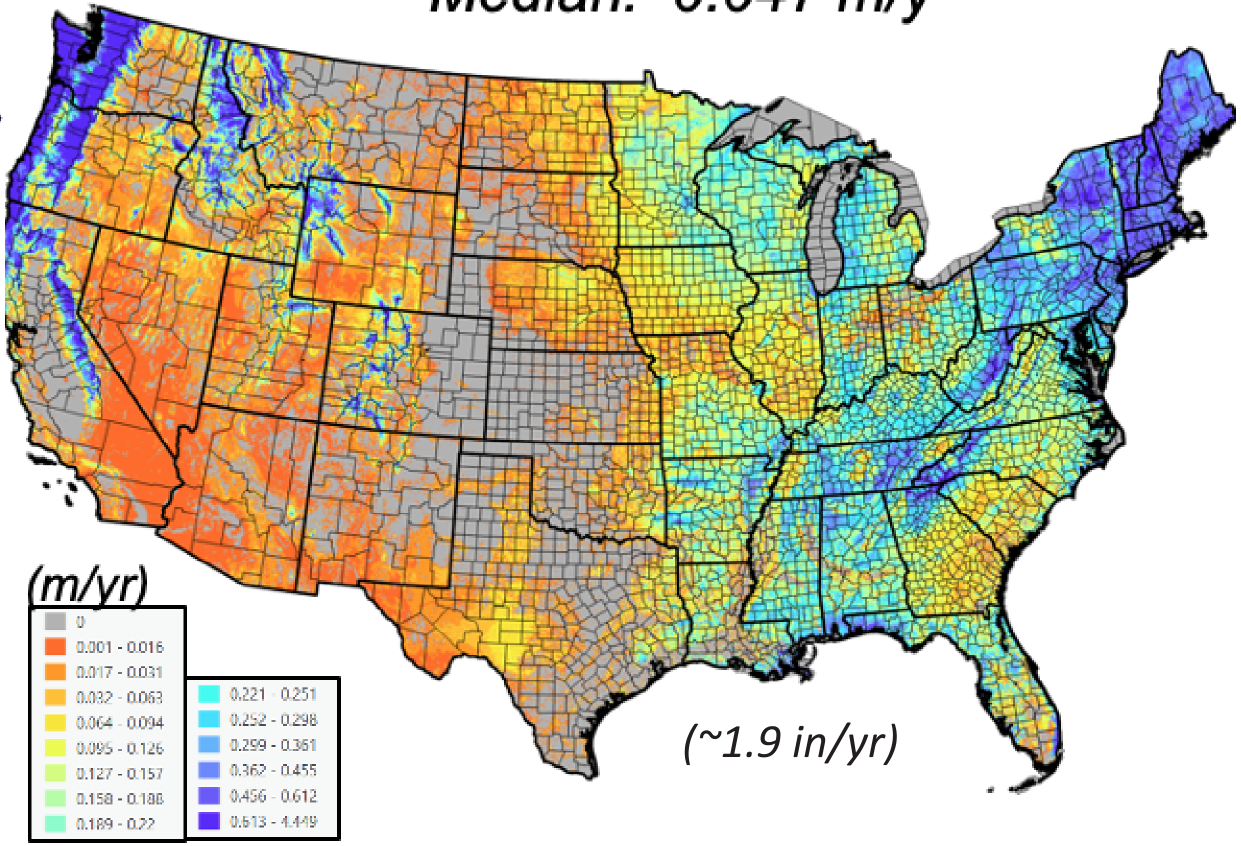
b) Effective Recharge (m/yr)

Median: 0.047 m/y



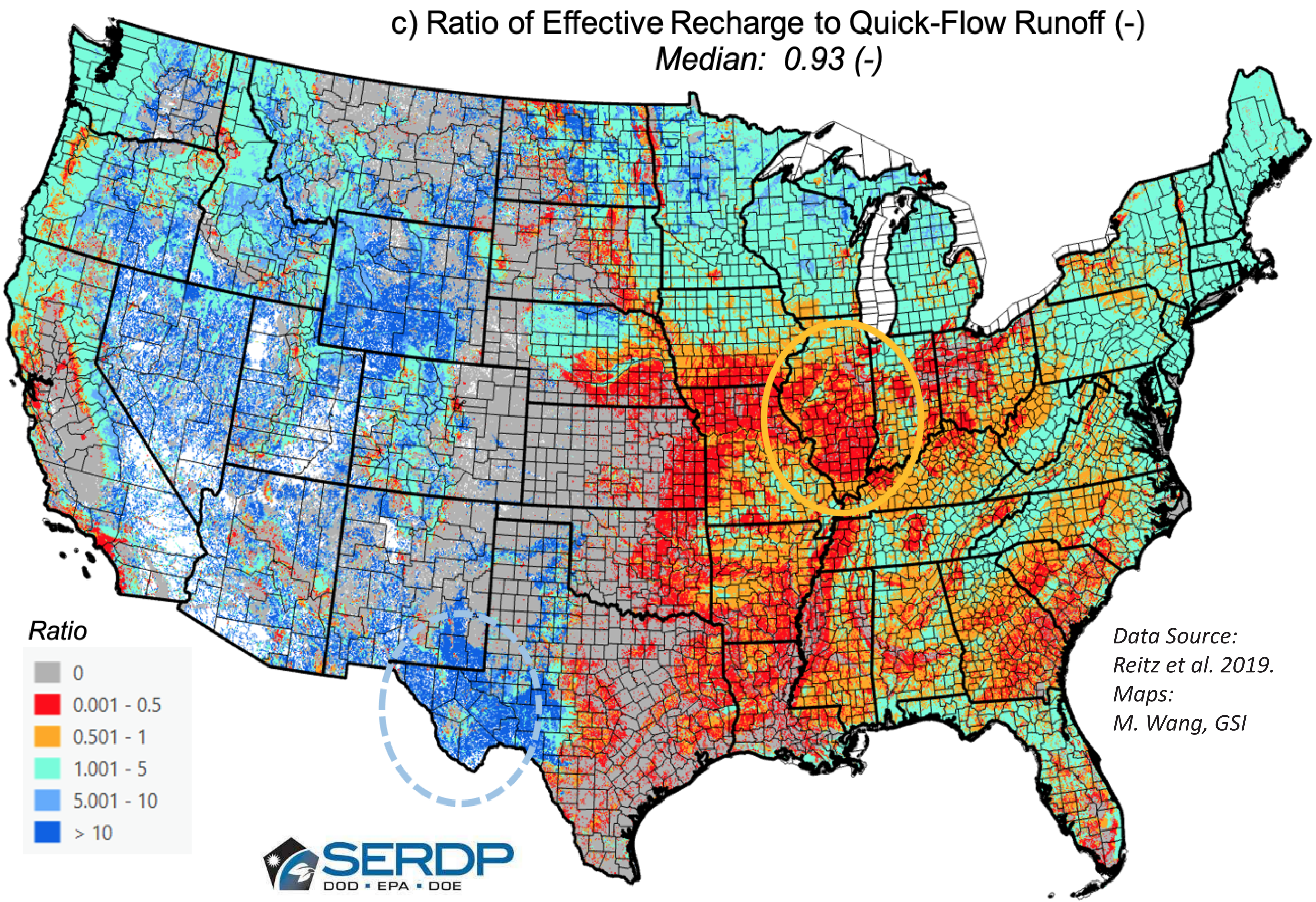


Data Source: Reitz et al. 2019.
Maps: M. Wang, GSI

Key Point:
Recharge, Runoff are one element of PFOS mass discharge calculations.

Based on hydrology only, **red/orange** areas may be more **stormwater** dominated.

Blue/green areas may be more **groundwater** dominated.



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4. Potential Regulatory Approaches

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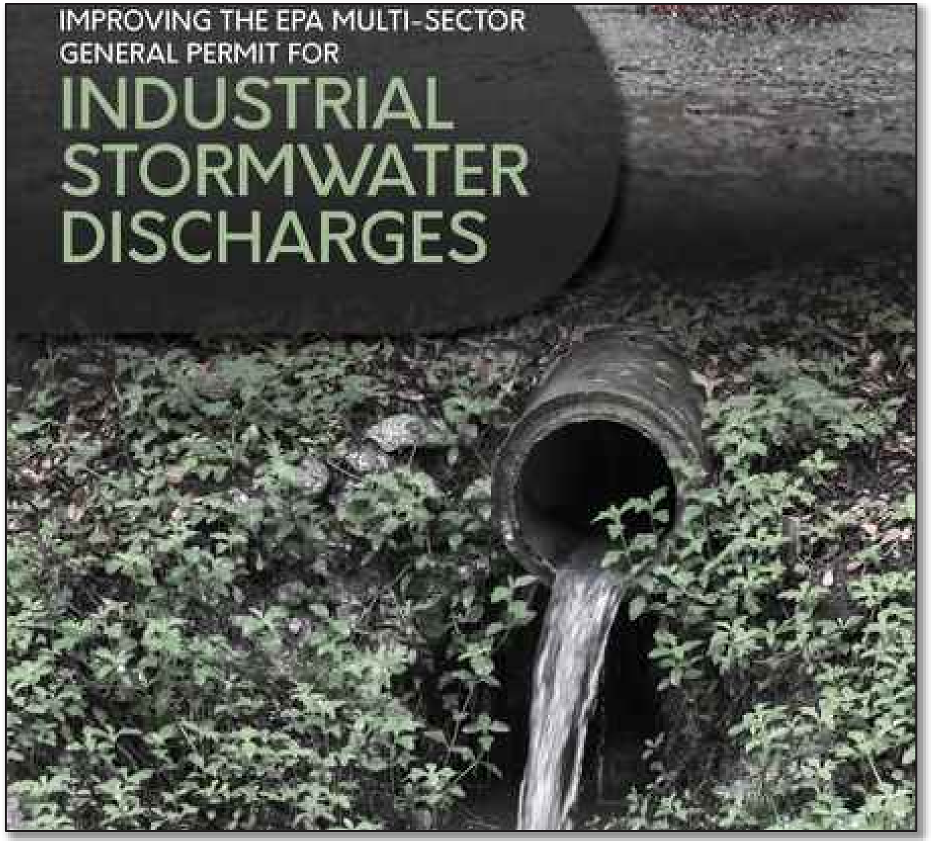
1. Expanding Existing Water Quality Regulatory Programs To Include PFAS
2. Implementation of Best Management Practices (BMPs)
3. Stormwater Mass Discharge Limits for Individual PFAS Sites
4. Watershed Mass Balance Approach



M. Lentz, C, Newell, GSI

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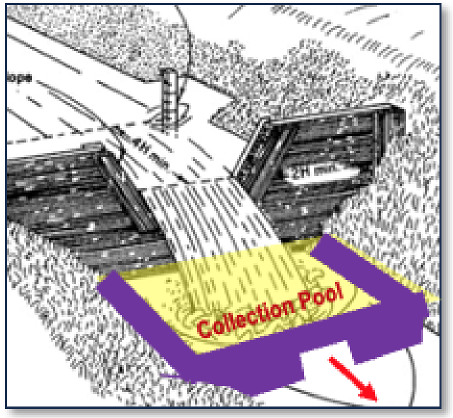

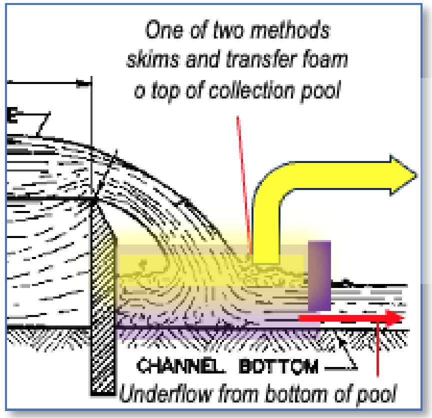

Foam is skimmed off top of water and conveyed to a foam collapse vessel.

Foaming Weirs: J. Gamlin, C. Newell, GSI

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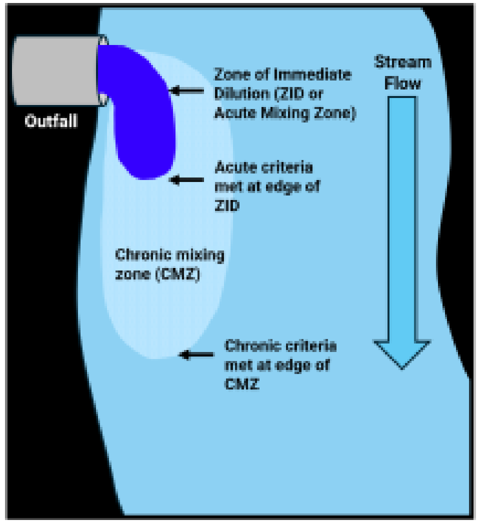

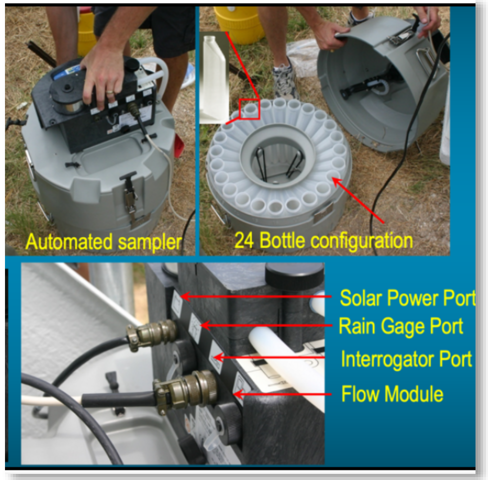

Foaming Weirs: J. Gamlin.

3. Potential Regulatory Approaches

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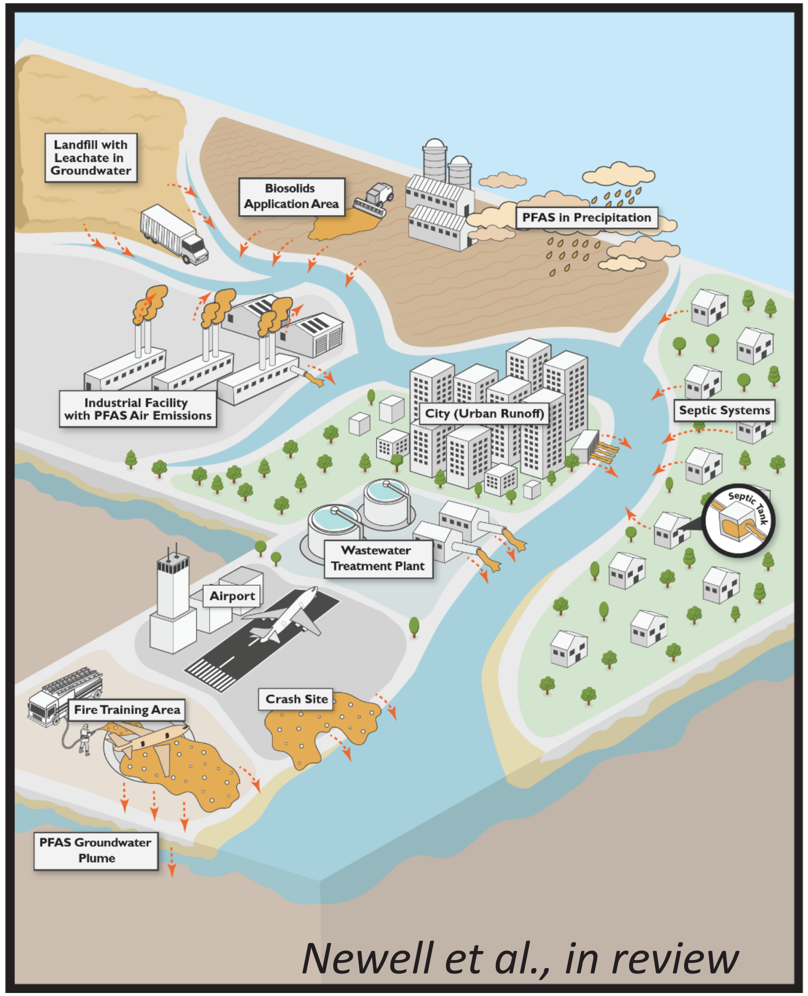
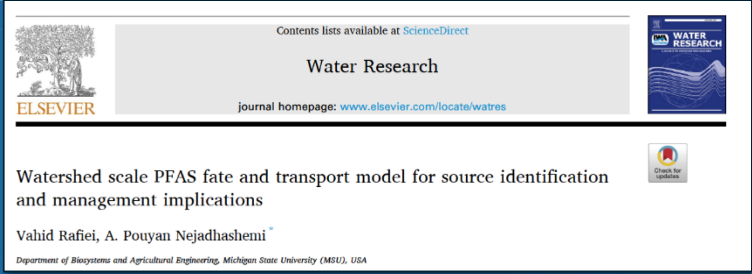
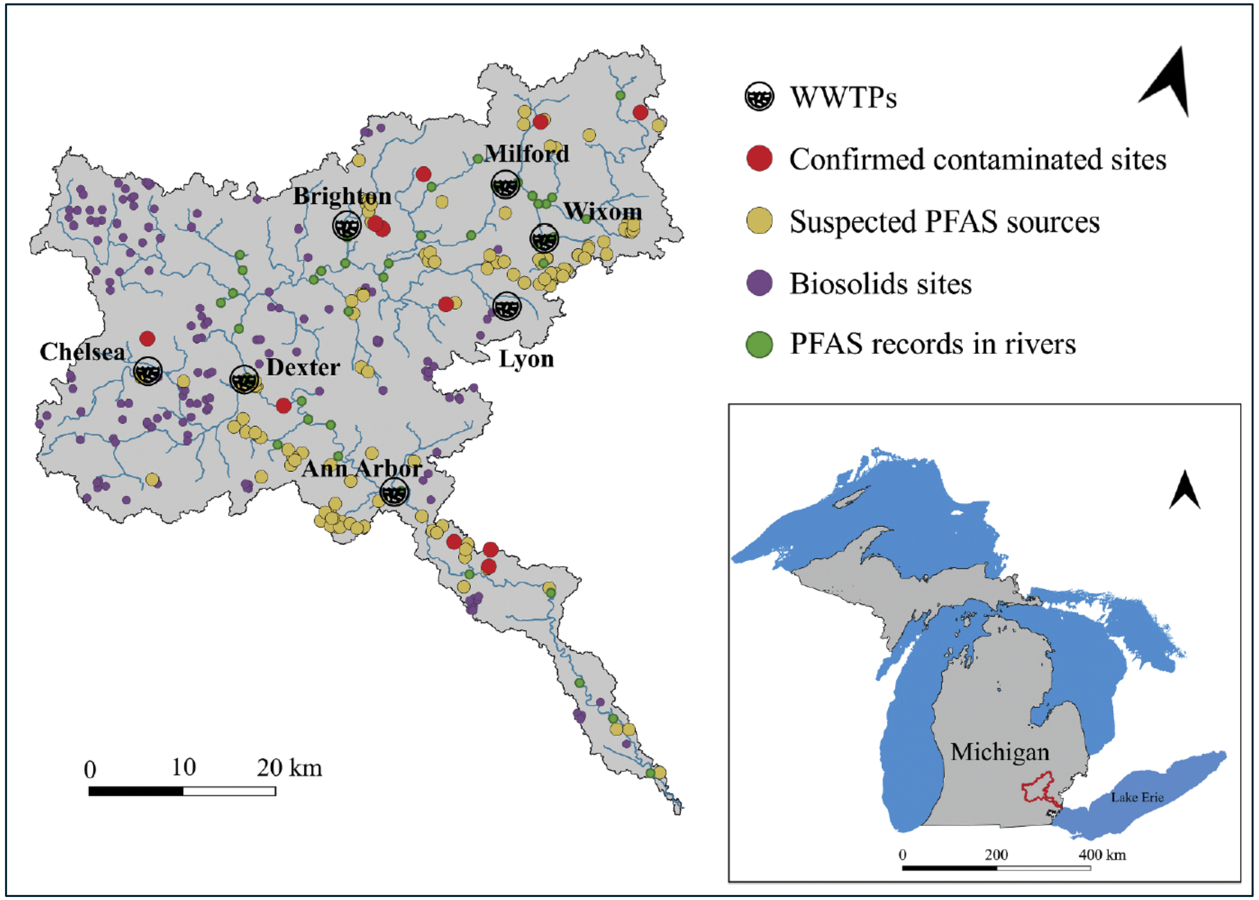
4. **Watershed Mass Balance Approach**

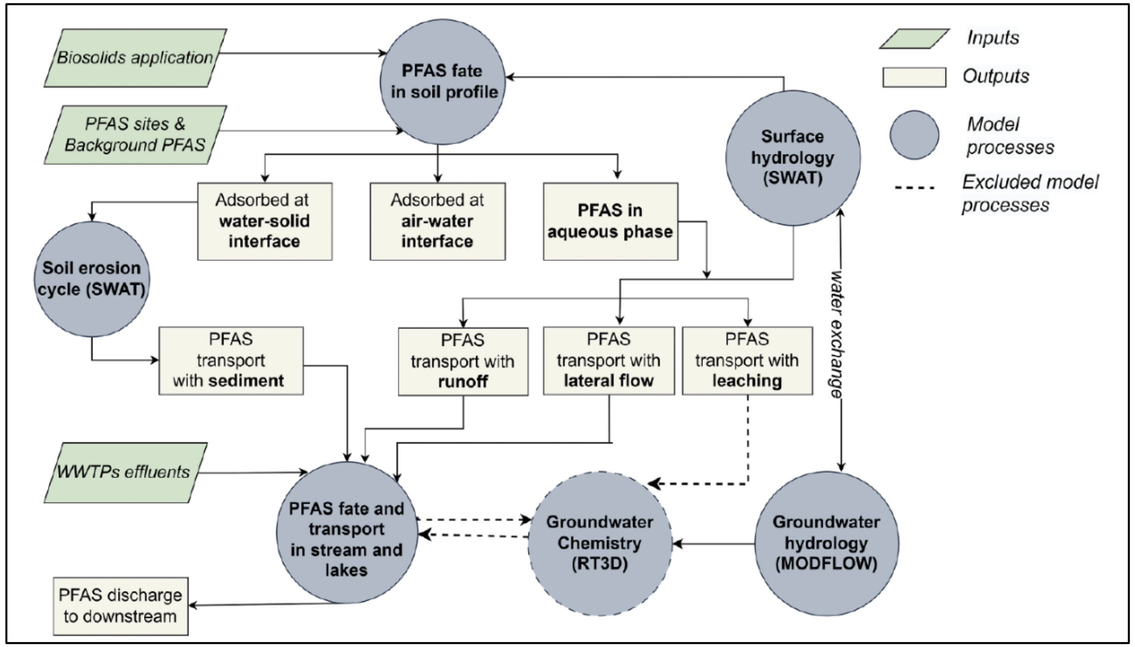


Newell et al., in review

Watershed Mass Balance Regulatory Approaches for PFAS in Groundwater?


Contents lists available at ScienceDirect
Water Research
journal homepage: www.elsevier.com/locate/watres
Watershed scale PFAS fate and transport model for source identification and management implications
Vahid Rafiei, A. Pouyan Nejadhashemi *
Department of Biosystems and Agricultural Engineering, Michigan State University (MSU), USA





Rafiei and Nejadhashemi, 2023

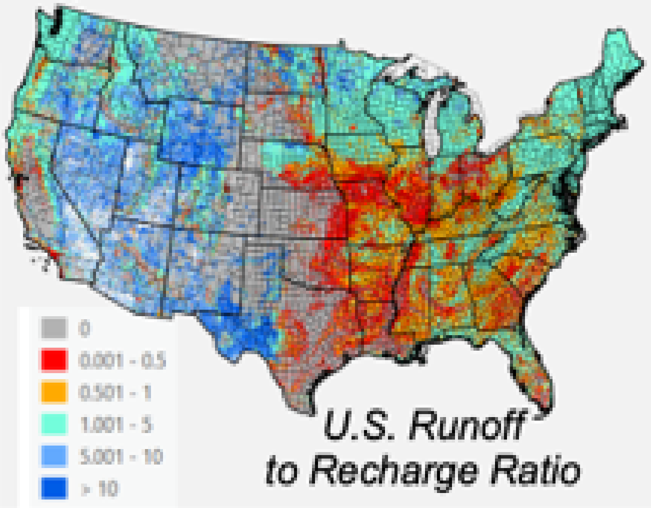
22 kg/yr PFOS at mouth of Huron River, Michigan

- 75% PFAS Sites (n=148)
- 11% Urban Sources
- 10% WWTP
- 2% Biosolids

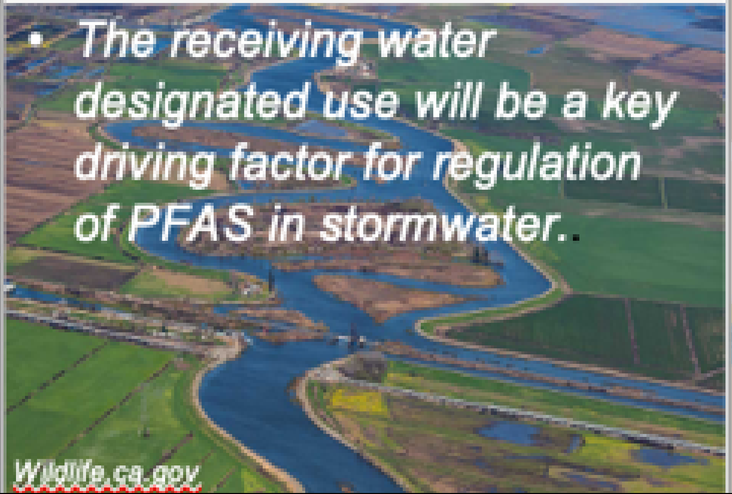
PFAS in Stormwater From Impacted Sites

- *Likely more need for monitoring, remediation of stormwater at PFAS impacted sites vs. VOC impacted sites.*

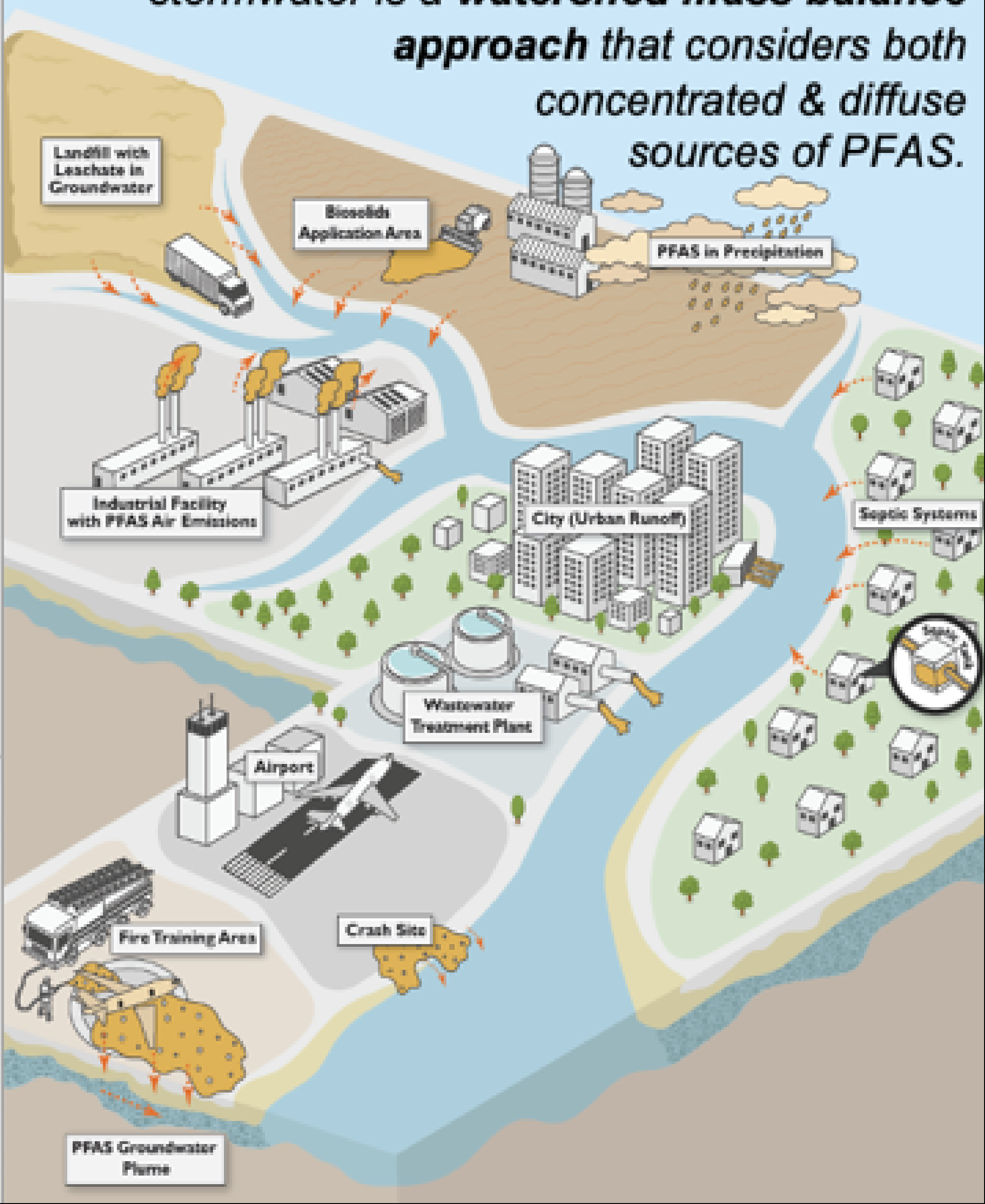
- *Average annual PFAS stormwater mass discharge at a hypothetical PFAS impacted site may be lower than annual groundwater mass discharge, but highly variable & still important at certain sites.*



- *The receiving water designated use will be a key driving factor for regulation of PFAS in stormwater..*



*One future approach to regulating PFAS in stormwater is a **watershed mass balance approach** that considers both concentrated & diffuse sources of PFAS.*



Spare Slides

2. PFAS Stormwater Source Characteristics
Flow (Annual Runoff) from Hypothetical AFFF Sites

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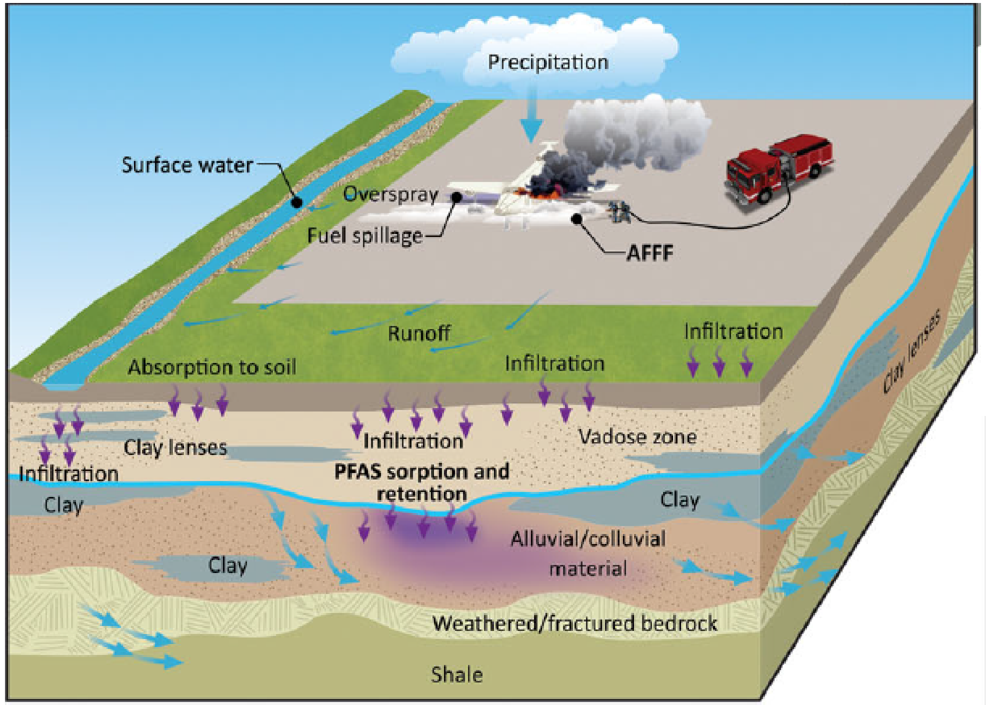
How to Estimate Runoff from an AFFF Site?

General Characteristics (High Uncertainty):

- Median area: about 1.5 acres (criteria ~100,000 ng/kg PFOS)
- Wide range of soil types
- Median slope: 0.2%

	% of 19 Sites with >90% of Land Cover	Average % of Land Cover (n= 16 Sites)
Concrete	6%	27%
Grass	19%	43%
Bare Ground	19%	30%

Kulkarni et al., in preparation.



Graphic: Leeson et al., 2021.

Wrap Up

- **PFAS vs VOC Sites:** Stormwater pathway may be a more important issue at PFAS sites?
- **Stormwater Characterization Methods**: May become more important for remediation practitioners.
- **PFAS Regulatory Criteria for Stormwater:** Orders of magnitude difference based on designated uses.
- **Site Risk Drivers for PFAS in Stormwater**: Mass discharge (mass loading) best way to evaluate risk.
- **Groundwater vs. Stormwater:** Depends on site, but early, high-level analysis SW<GW at typical PFAS site?
- **Recharge vs. Runoff:** High resolution maps show recharge to runoff ratios from sea to shining sea.
- **Potential Future Regulatory Approaches.** Four potential regulatory approaches:
    1. *Expanding existing regulatory program*
    2. *PFAS-centric Best Management Practices (BMPs)*
    3. *Single site mass discharge limits*
    4. *Watershed Mass Balance approaches.*

1. SERDP Problem Statement

The primary concern is the management of per- and polyfluoroalkyl substance (PFAS)-impacted runoff or infiltration to groundwater from historic aqueous film-forming foam (AFFF) use.

1. *Develop cost-effective active treatment technologies to treat PFAS*
2. *Handle varying flows to treat baseflow and up to 2-year storms*
3. *Technologies to prevent sediment recontamination*
4. *Methods to determine background PFAS concentrations*

Four SERDP PFAS Stormwater Projects

1. ***Tailored Carbonaceous Materials as Biofilter Amendments for PFAS Removal in Stormwater Runoff.*** PI: Dr. Wenqing Xu, Villanova University
2. ***Development of a Screening-Level Tool to Estimate PFAS Retention Lifetimes for Engineered Sorbents in Passive Stormwater Filtration Systems***. PI: Dr. Bridget Ulrich, University of Minnesota
3. ***Passive-Active Modular Stormwater Biofilter Designs to Enhance PFAS Removal in Variable Flow Conditions***. PI: Dr. Sanjay Mohanty, University of California Los Angeles
4. ***Understanding the Spatial/Temporal Nature of AFFF PFAS Loadings in Stormwater to Develop Targeted Stormwater Treatment Technologies.*** PI: Dr. Charles Newell, GSI Environmental Inc.

Reitz et al. (2017)

Reitz, Sanford, Senay, and Cazenas

TABLE 2. Summary Statistics of Water Budget Component Map Values. Here, effective recharge is the quantity that closes the water budget and represents water available to contribute to stream baseflow or to recharge the groundwater table, while total recharge includes a correction for water intercepted by riparian vegetation.

	Mean (cm/year)	Median (cm/year)	Minimum (cm/year)	Maximum (cm/year)	Standard deviation (cm/year)
Quick flow	11.9	6.78	0	410	15.7
Total recharge	15.3	7.43	0	446	20.8
Effective recharge	12.6	4.65	0	445	20.4
Evapotranspiration	54.7	52.7	1.54	404	24.3
Effective precipitation	79.3	72.2	4.87	627	45.4

3. PFAS Stormwater Source Characteristics
Relative Loading/Risk Factors for PFAS in Stormwater

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1) The amount of runoff generated from PFAS source zones.
2) The leaching of dissolved PFAS from soils, sediments, paved surfaces, or other surfaces.
3) The amount of soil erosion and subsequent sediment transport of PFAS impacted soils in stormwater.
4) Any natural or engineered "concentration reduction factors" that reduce PFAS loadings in stormwater once they are generated.