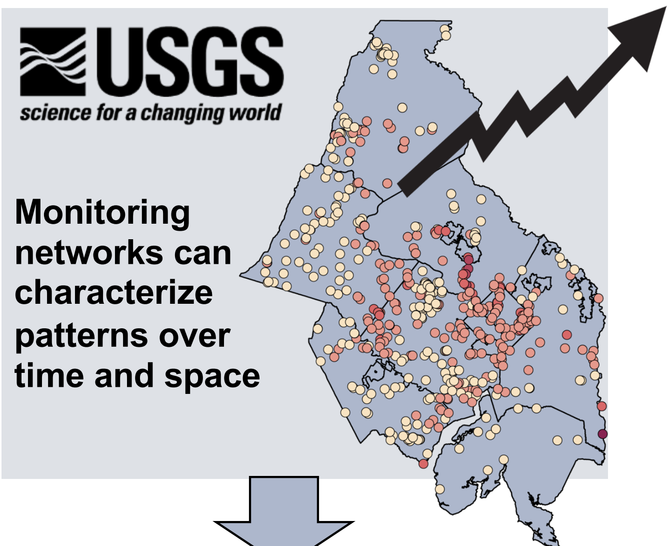
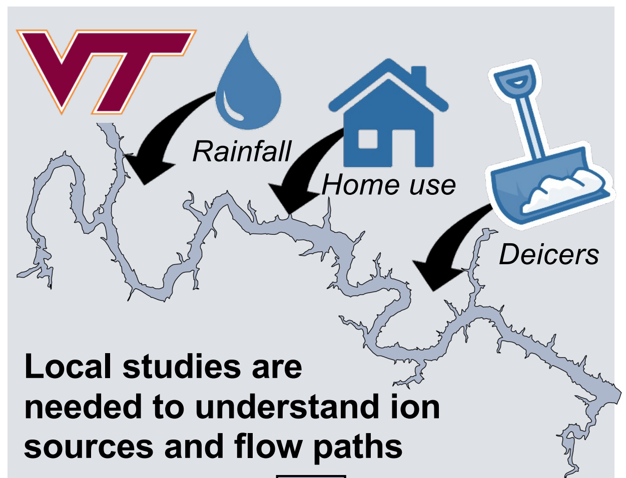
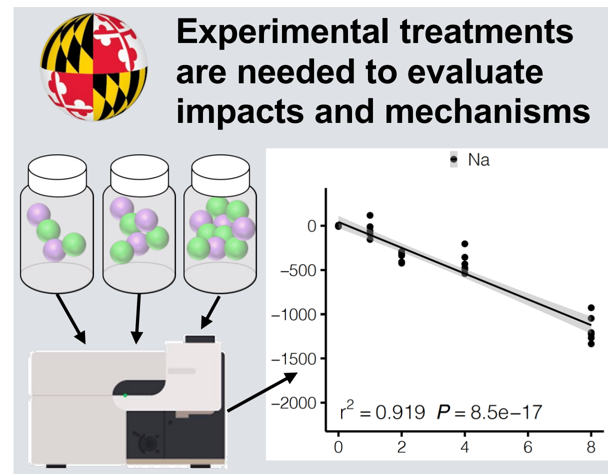
Establishing a Science Partnership to Support Understanding of the Freshwater Salinization Gradient in the Metropolitan Washington, D.C. Region

A collaborative scientific partnership is needed to address a complex, regional issue…







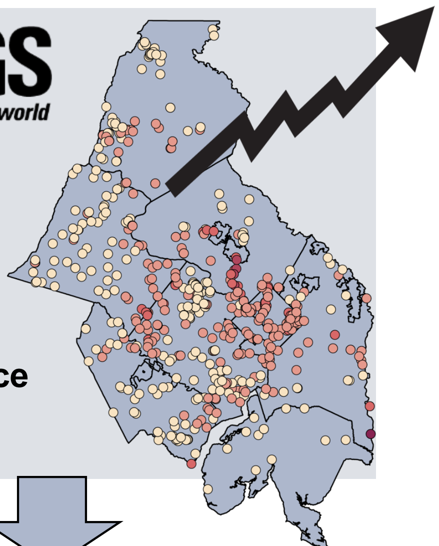
Synthesizing this knowledge is needed to understand and manage FSS in the MWCOG region

Establishing a Science Partnership to Support Understanding of the Freshwater Salinization Gradient in the Metropolitan Washington, D.C. Region

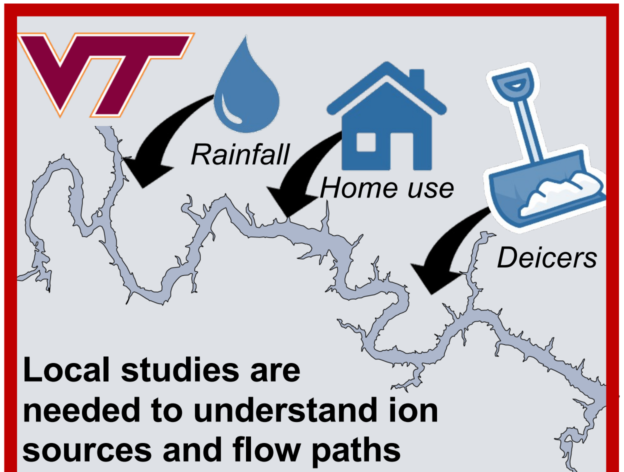
With contributions from Shantanu Bhide, Melissa Stacy and Diver Marin!

A collaborative scientific partnership is needed to address a complex, regional issue…

USGS science for a changing world

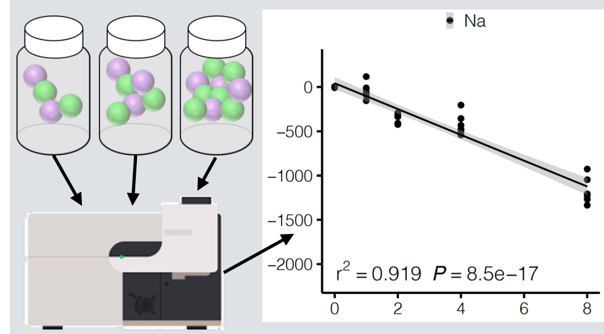


Monitoring networks can characterize patterns over time and space



Local studies are needed to understand ion sources and flow paths

Experimental treatments are needed to evaluate impacts and mechanisms



Synthesizing this knowledge is needed to understand and manage FSS in the MWCOG region

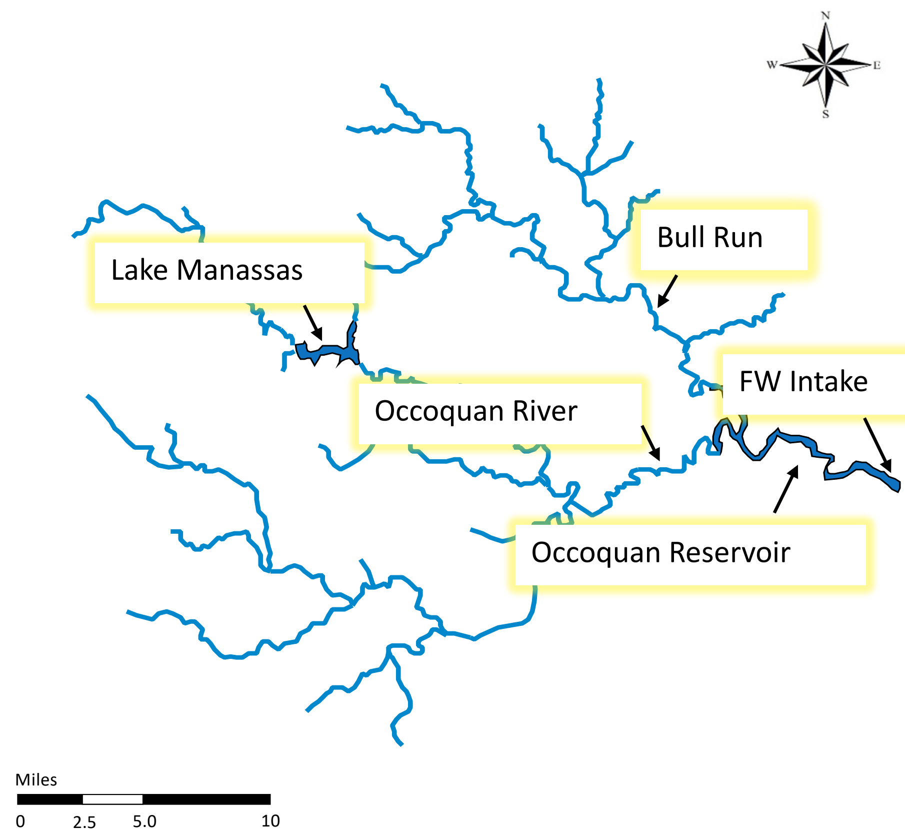
Modeling Efforts in the Occoquan Watershed

- Brief description of the **Occoquan Watershed**
- **Mechanistic** transit time model of **hourly** specific conductance measurements on Flatlick Branch—basic concept, preliminary results, potential applications and scale-up
- **Statistical** model of **annual** salt concentrations in streams, based on Transportation Analysis Zone (TAZ) population data—basic concept, preliminary results, potential applications and scale-up

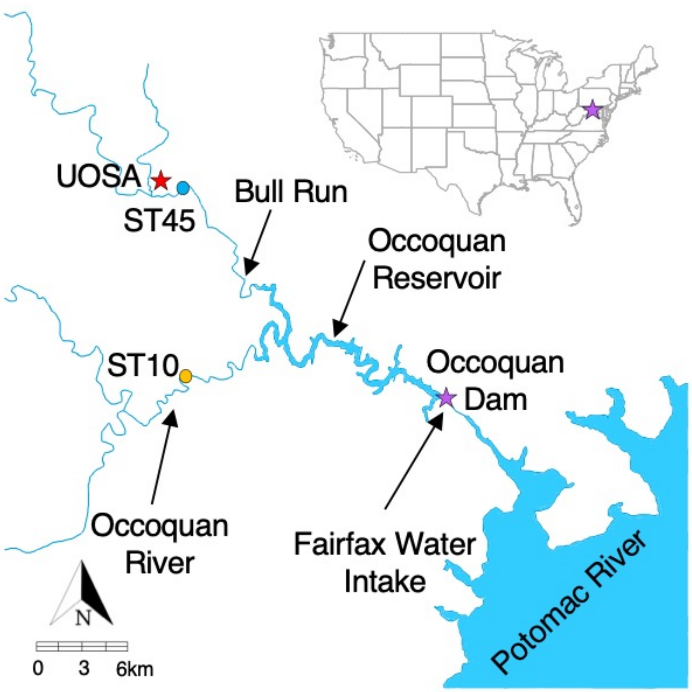
Brief Introduction to the Occoquan Watershed

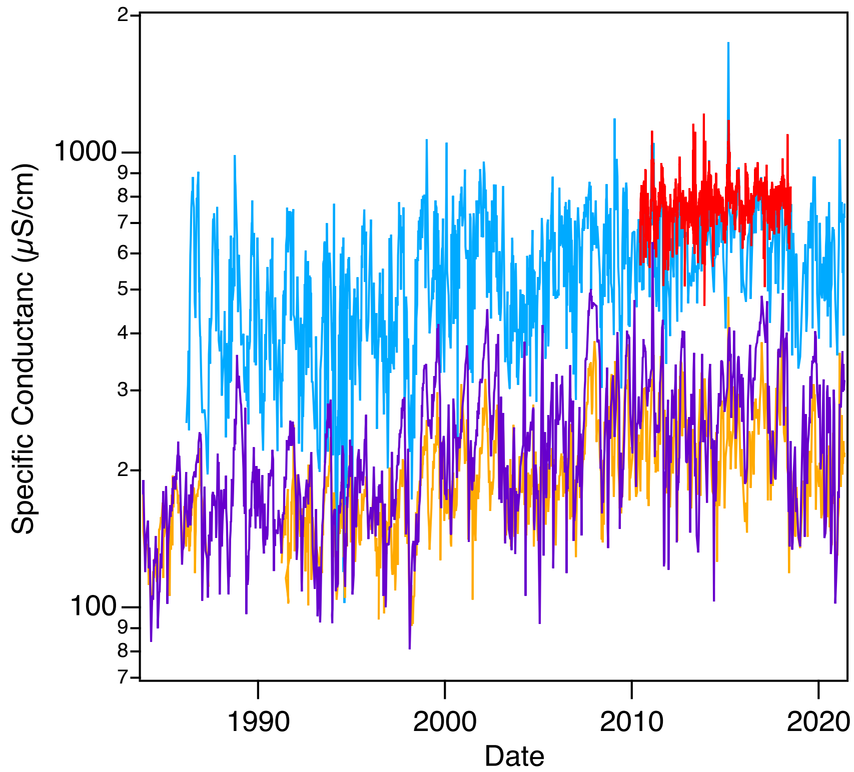
Occoquan Watershed

- Watershed drains ~370,000 acres (586 square miles) of mixed urban, agriculture, and forest land-use
- Home to 574,000 people (as of 2020, 6-fold increase since 1970s); could reach 750,000 by 2040
- Drains to the Occoquan Reservoir, which provides the raw water supply for up to 1 million people in Northern Virginia
- One of the nation's first deliberate indirect potable reuse activities for surface water augmentation



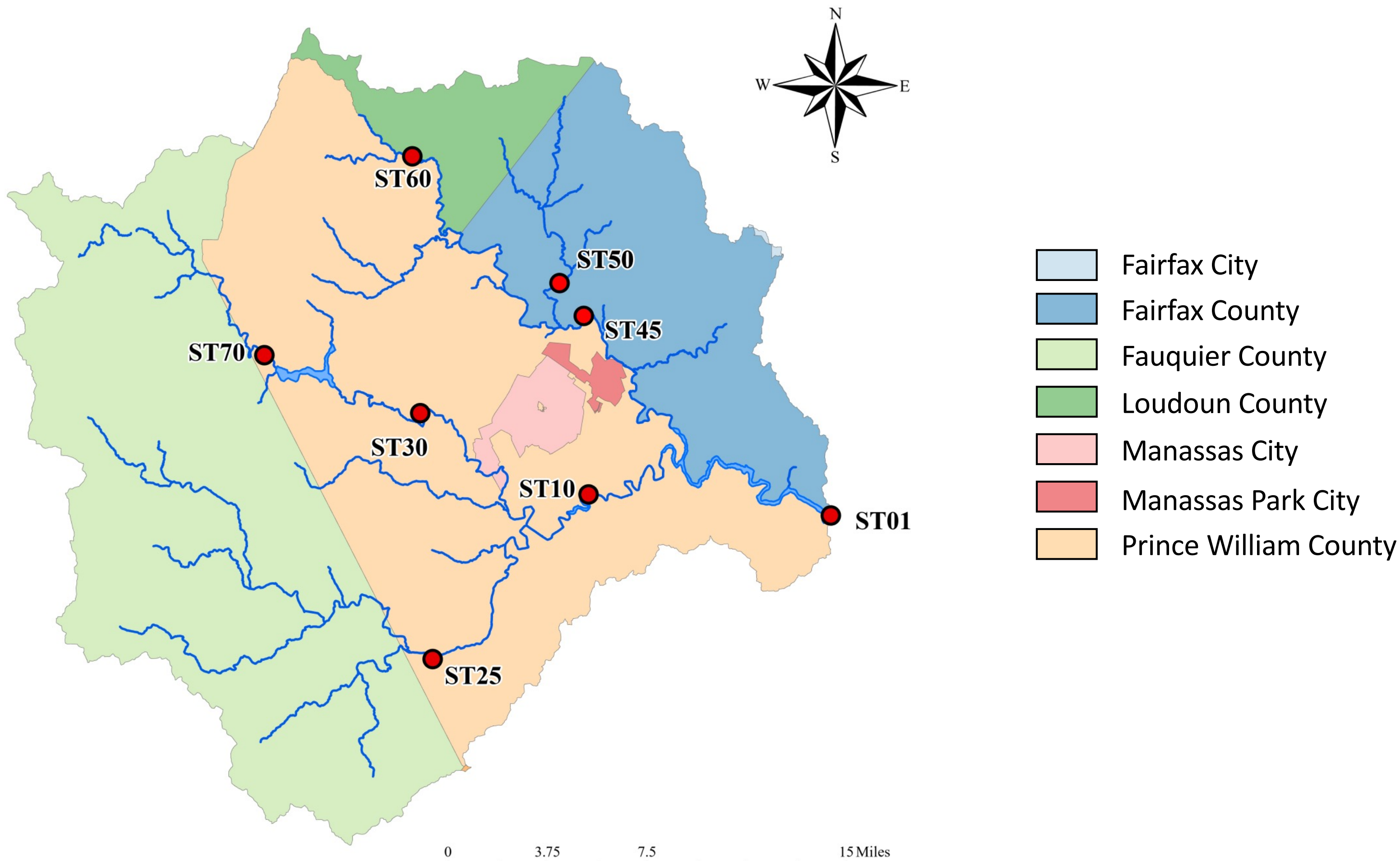
Rising Salinity in the Occoquan Reservoir



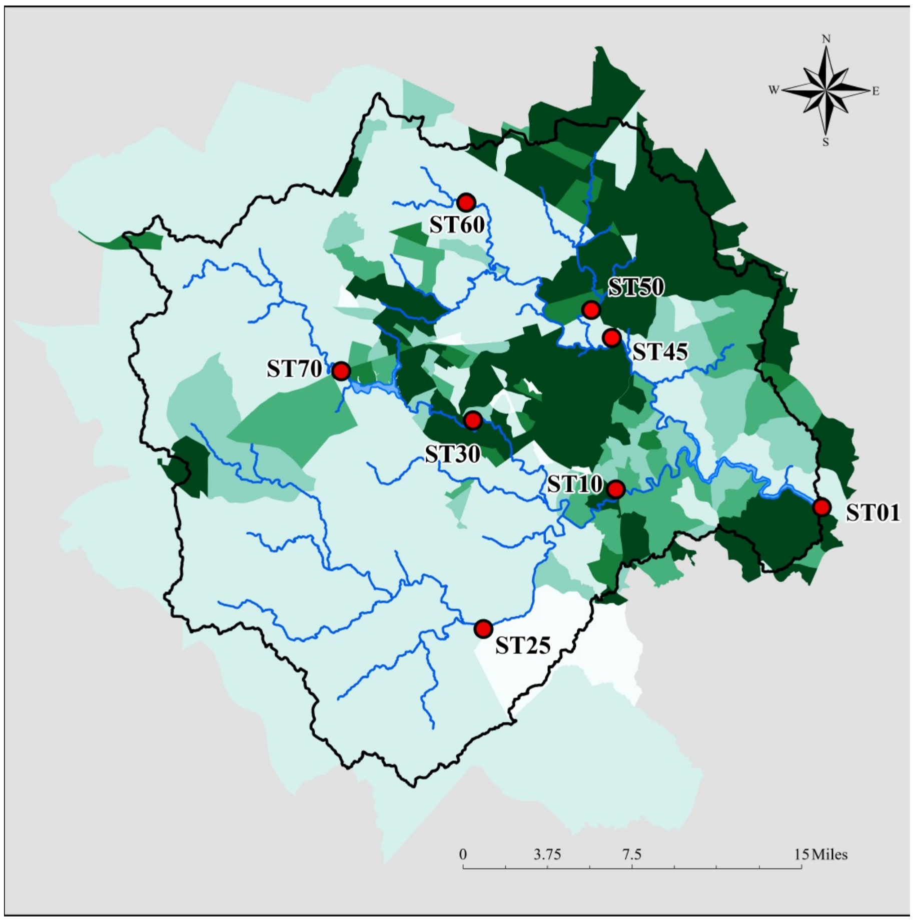


Bhide. S.V., Grant, S.B.; et al. (2021) Addressing the contribution of indirect potable reuse to inland freshwater salinization. *Nature Sustainability*.
https://doi.org/10.1038/s41893-021-00713-7

Cross-Jurisdictional Challenges



2005: Population Density in the Occoquan Watershed by Transportation Analysis Zone (TAZ)*

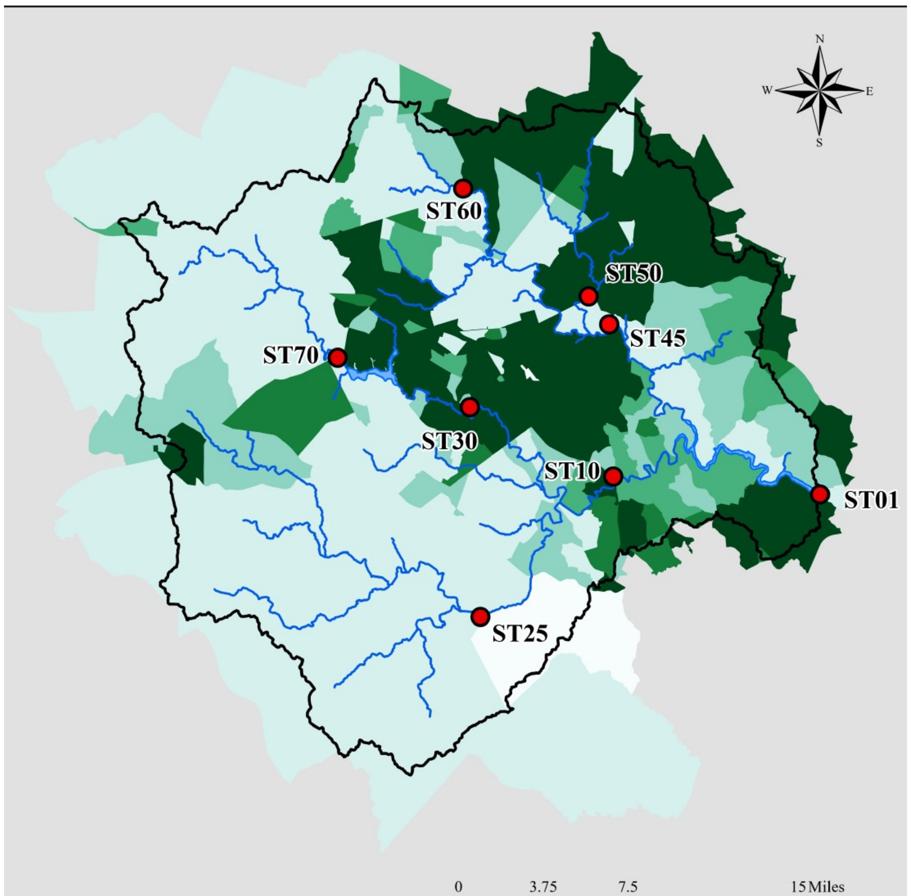


Legend (people per square mile)

- 1 - 300
- 301 - 600
- 601 - 900
- 901 - 1200
- >1201

*Prepared by Melissa Stacy (population density for each TAZ calculated by adding population from household population, "group quarters," and employment population and dividing by the area of the TAZ in square miles)

2020: Population Density in the Occoquan Watershed by Transportation Analysis Zone (TAZ)*

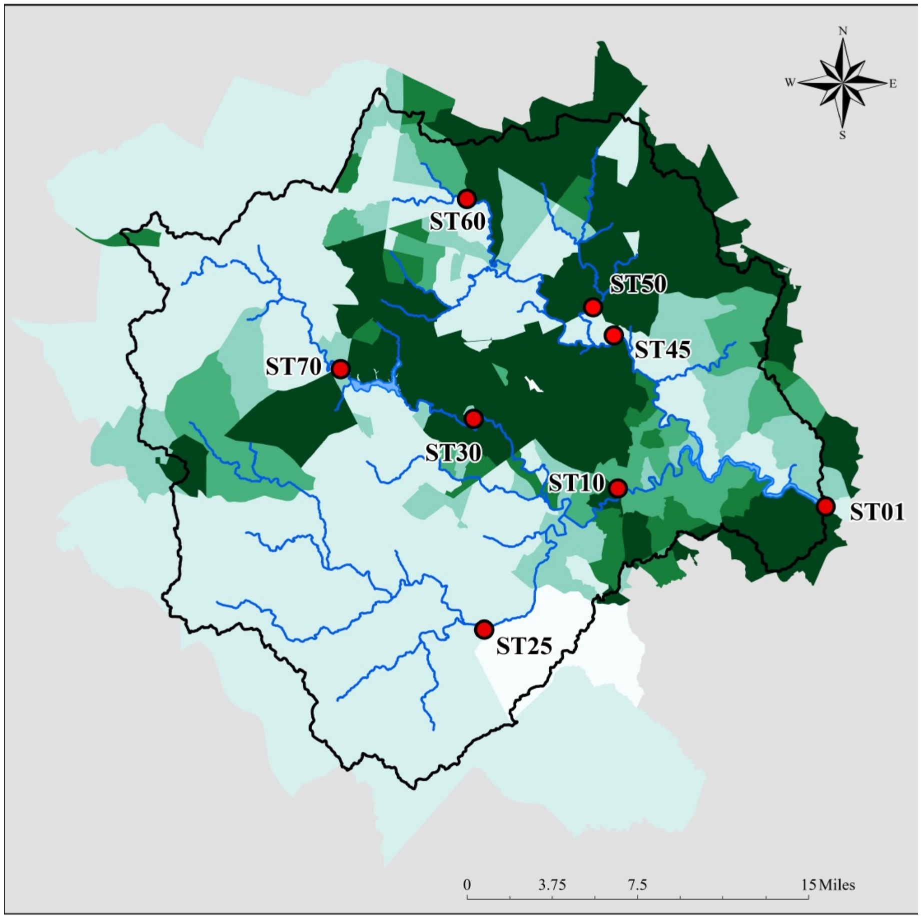


Legend (people per square mile)

- 1 - 300
- 301 - 600
- 601 - 900
- 901 - 1200
- >1201

*Prepared by Melissa Stacy (population density for each TAZ calculated by adding population from household population, "group quarters," and employment population and dividing by the area of the TAZ in square miles)

2035 (Projected): Population Density in the Occoquan Watershed by Transportation Analysis Zone (TAZ)*



Legend (people per square mile)

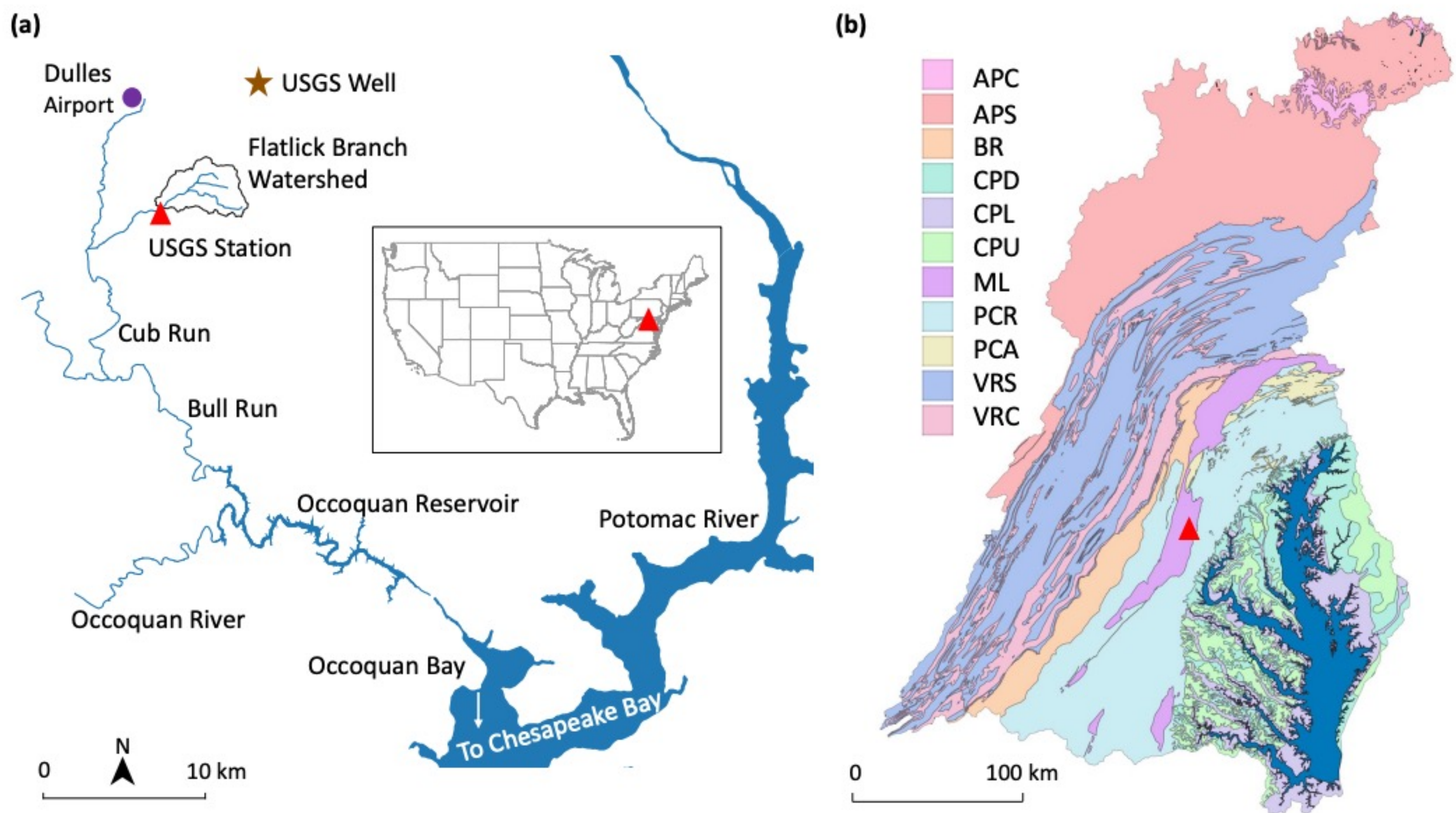
- 1 - 300
- 301 - 600
- 601 - 900
- 901 - 1200
- >1201

*Prepared by Melissa Stacy (population density for each TAZ calculated by adding population from household population, "group quarters," and employment population and dividing by the area of the TAZ in square miles)

Mechanistic transit time model of **hourly** specific conductance measurements on Flatlick Branch

Bhide. S.V., Grant, S.B.; **Kaushal, S.S**., McGuire, K., Gomez-Velez, J., Hotchkiss, E.R., Rippy, M.A., Vikesland, P. Saxena, S., Schenk, T., **Curtis, S**., **Webber, J., Jastram, J., Sekellick, A.** (202X) Stream Water Age Drives Patterns of Inland Freshwater Salinization. *Science Advances, in review*.

Flatlick Branch Tributary to Bull Run



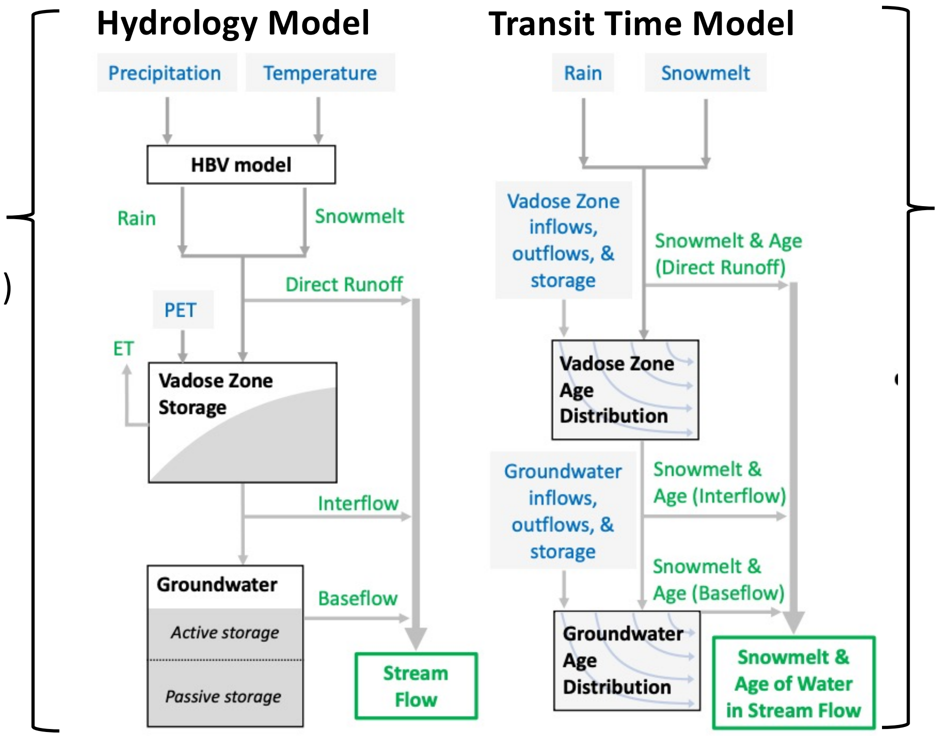
Hypothesis: salt sources and physical processes that control stream salinity in a complex urban watershed can be revealed by combining high-frequency measurements of in-stream specific conductance with high-frequency (model generated) estimates of **stream water age**.

Stream Water Age: elapsed time an average water parcel, starting out as rainfall or snow melt, spends moving along surface and subsurface flow paths before reaching a stream.

Transit Time Model framework

Inputs (hourly)

1. Precipitation (Dulles)
2. Air temp (Dulles)
3. PET (NASA LSM)

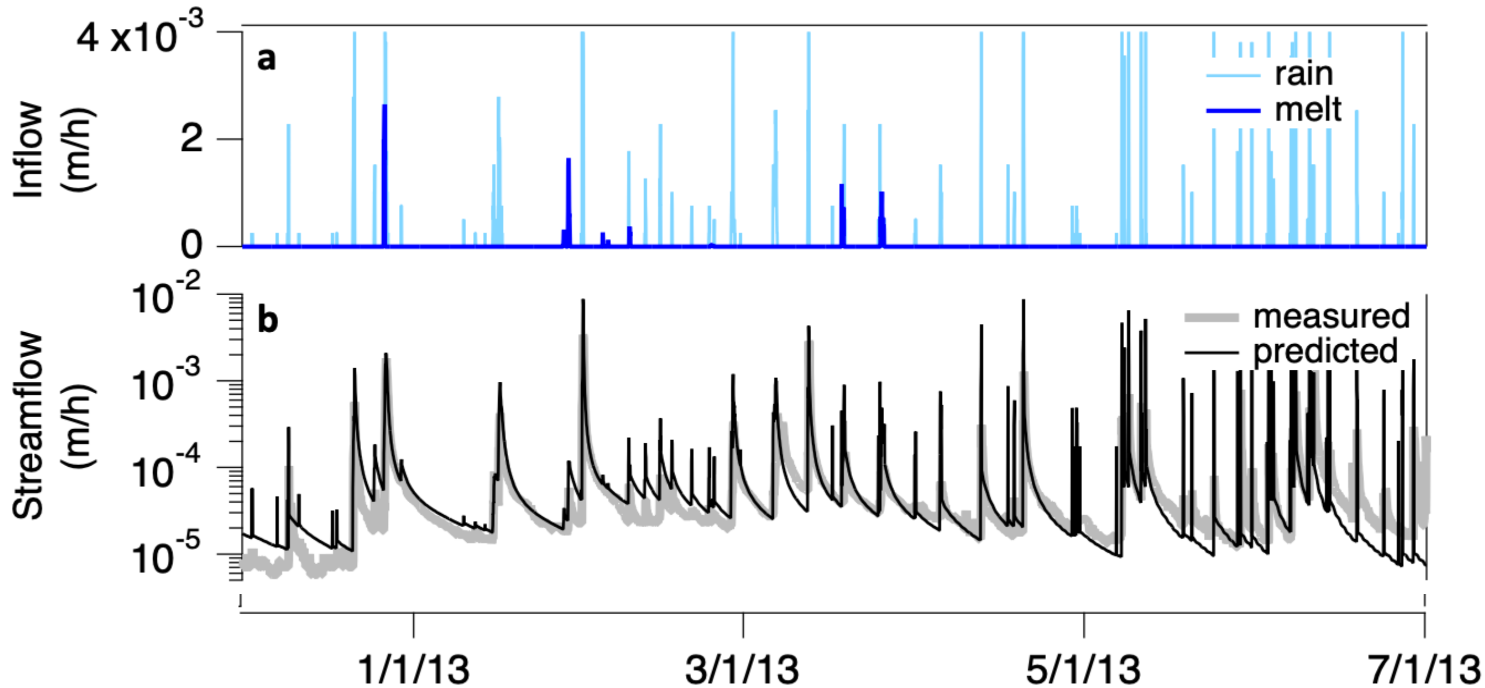


Outputs (hourly)

1. Streamflow
2. Snowmelt fraction
3. Stream water age

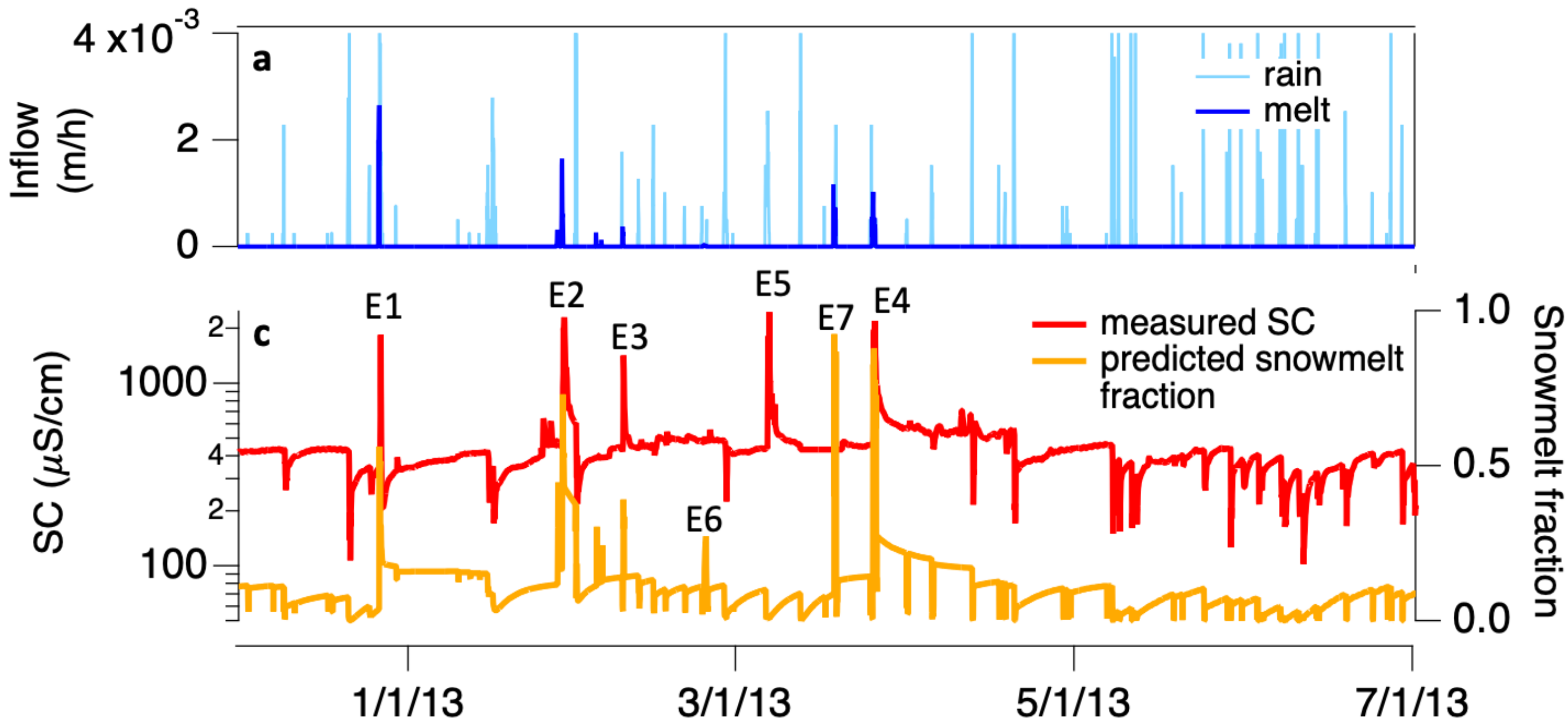
Bhide. S.V., Grant, S.B.; **Kaushal, S.S.**, McGuire, K., Gomez-Velez, J., Hotchkiss, E.R., Rippy, M.A., Vikesland, P. Saxena, S., Schenk, T., **Curtis, S.**, **Webber, J., Jastram, J., Sekellick, A.** (202X) Stream Water Age Drives Patterns of Inland Freshwater Salinization. *Science Advances, in review*.

Hydrology Model: Predicted streamflow in the Validation Period



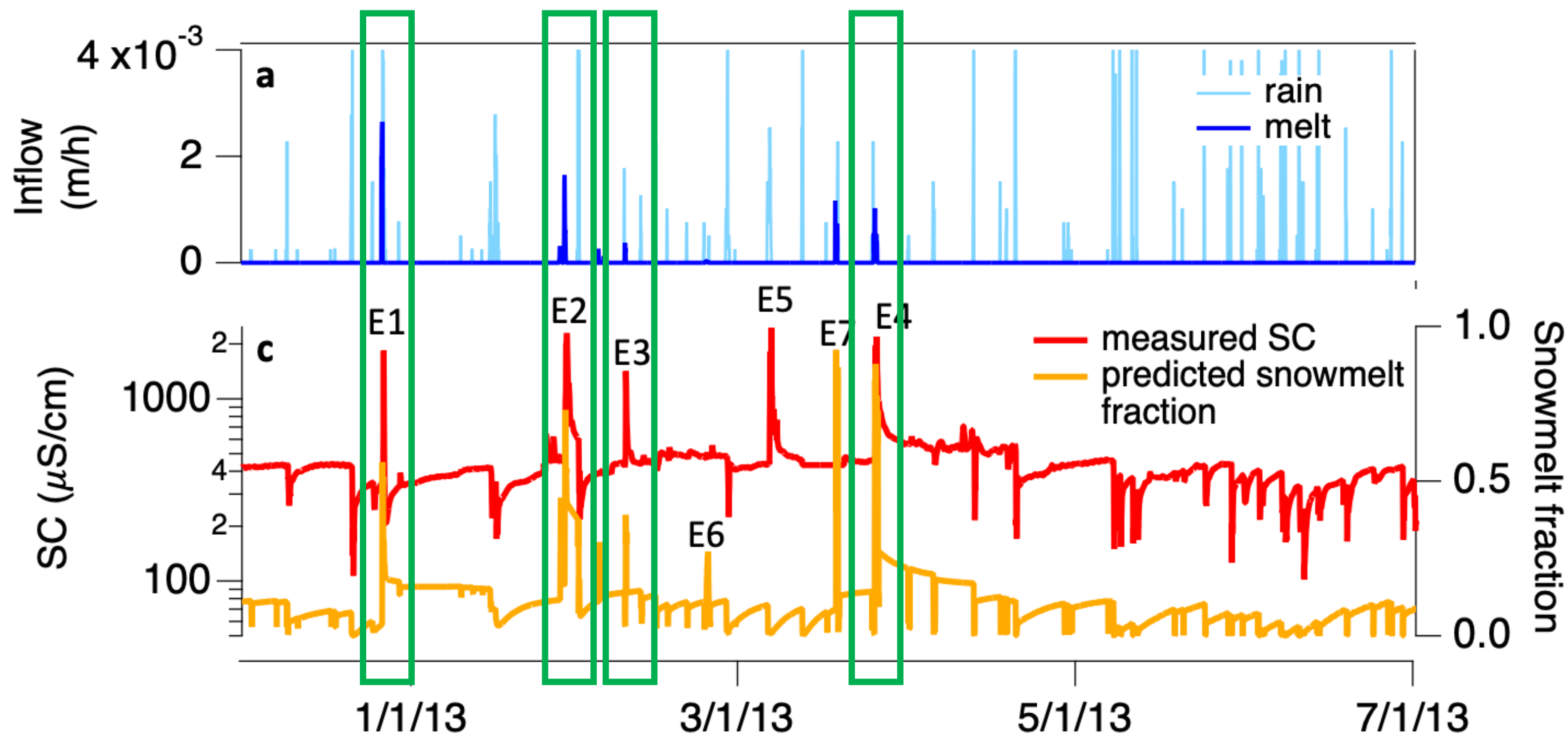
Bhide. S.V., Grant, S.B.; **Kaushal, S.S.**, McGuire, K., Gomez-Velez, J., Hotchkiss, E.R., Rippy, M.A., Vikesland, P. Saxena, S., Schenk, T., **Curtis, S.**, **Webber, J., Jastram, J., Sekellick, A.** (202X) Stream Water Age Drives Patterns of Inland Freshwater Salinization. *Science Advances, in review*.

Stream Specific Conductance & Model-Predicted Snowmelt Fraction

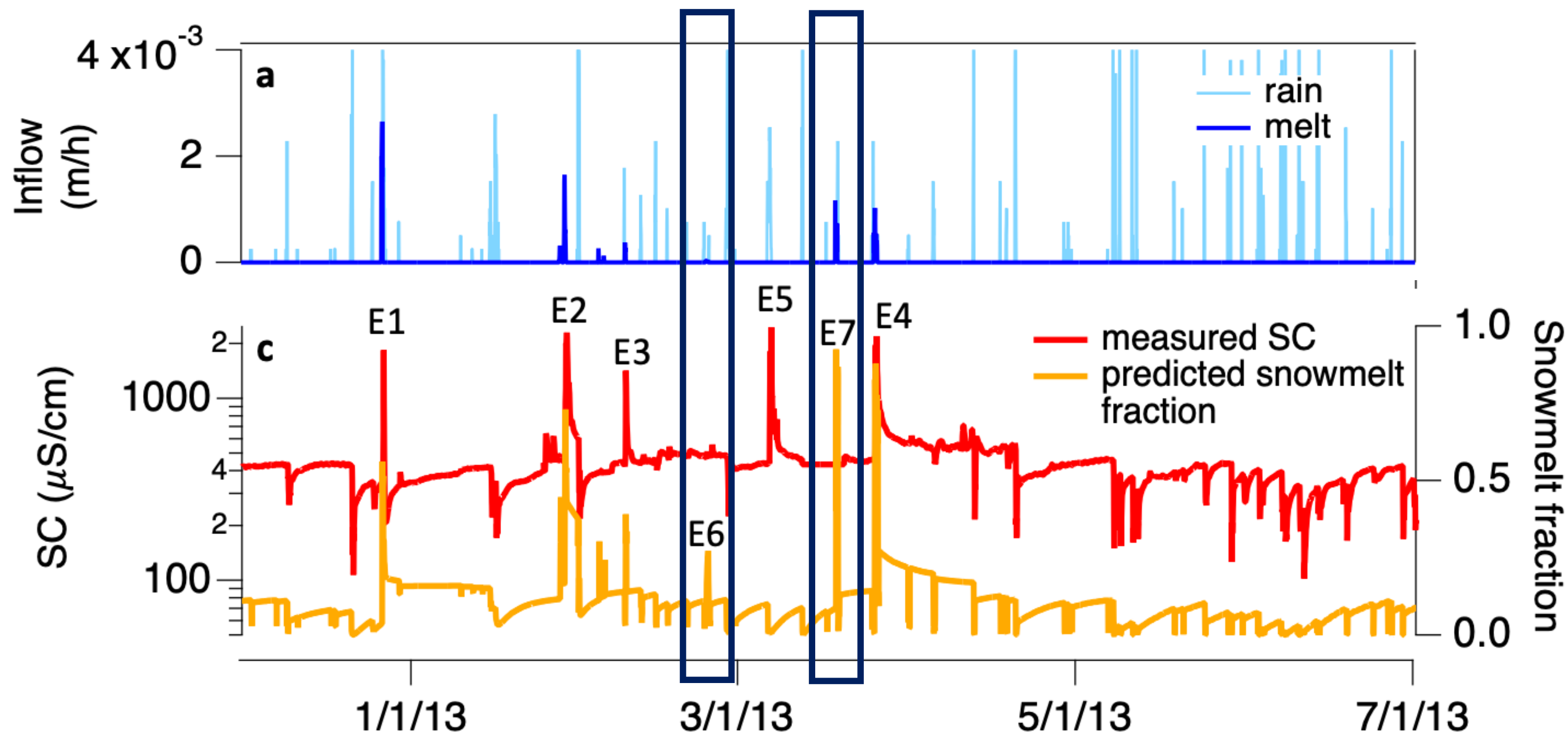


Bhide. S.V., Grant, S.B.; **Kaushal, S.S.**, McGuire, K., Gomez-Velez, J., Hotchkiss, E.R., Rippy, M.A., Vikesland, P. Saxena, S., Schenk, T., **Curtis, S.**, **Webber, J., Jastram, J., Sekellick, A.** (202X) Stream Water Age Drives Patterns of Inland Freshwater Salinization. *Science Advances, in review*.

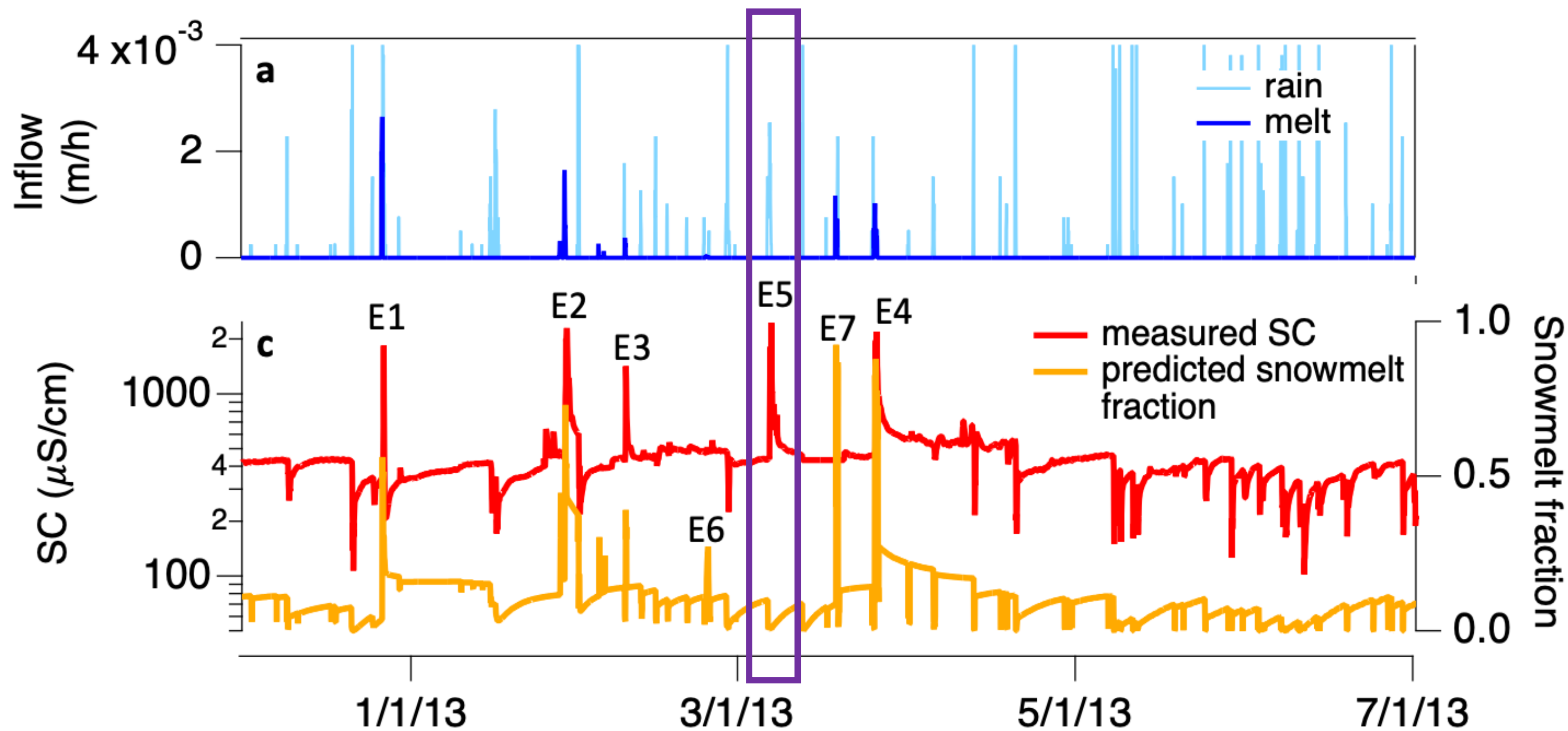
Events for which SC spikes coincide with model-predicted snow melt events



Predicted snow melt events with no SC spike



SC spike but no predicted snow melt

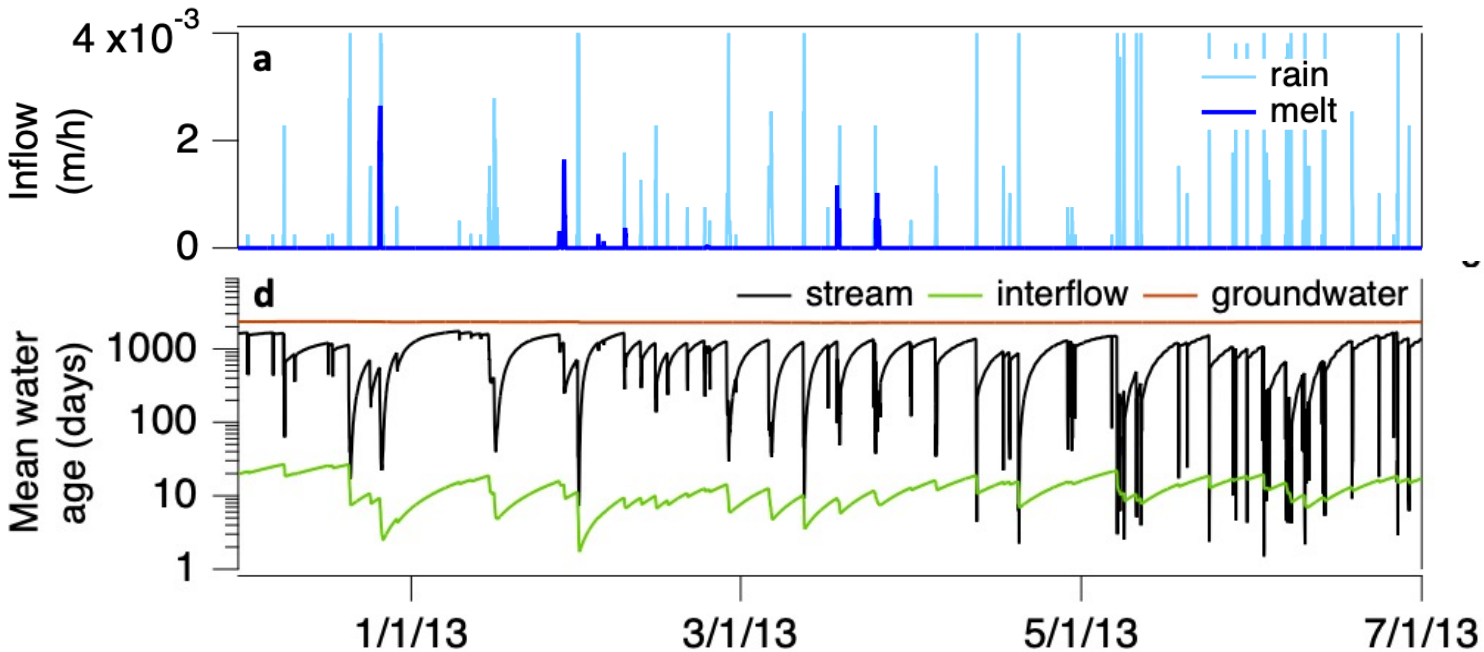


Summary statistics for the eight-year period (2010 – 2017):

- 77% of the time: model-predicted snow melt events aligned with measured spikes in specific conductance
- 15% of the time: model-predicted snow melt events occurred in the absence of measured spikes in specific conductance
- 8% of the time: measured spikes in specific conductance occurred in the absence of model-predicted snow melt

Occasional misalignment of predicted snow melt and spikes in specific conductance could reflect: (1) challenges in predicting snow melt when temperature is fluctuating around freezing; (2) deicers are not always applied in advance of a snow melt event; and (3) deicers are sometimes applied but no snowfall occurs.

Predicted Mean Water Age of Streamflow, Interflow and Groundwater



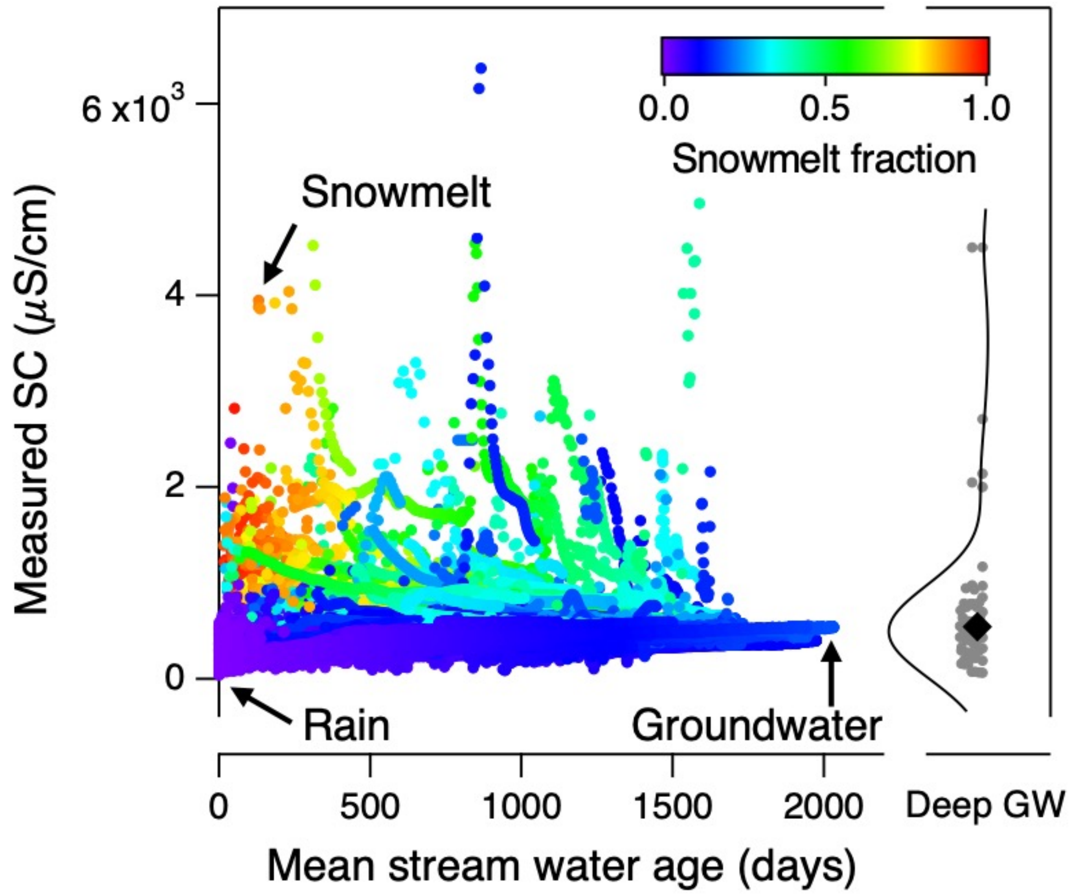
Bhide. S.V., Grant, S.B.; **Kaushal, S.S**., McGuire, K., Gomez-Velez, J., Hotchkiss, E.R., Rippy, M.A., Vikesland, P. Saxena, S., Schenk, T., **Curtis, S.**, **Webber, J., Jastram, J., Sekellick, A.** (202X) Stream Water Age Drives Patterns of Inland Freshwater Salinization. *Science Advances, in review*.

Summary of Water Age Predictions

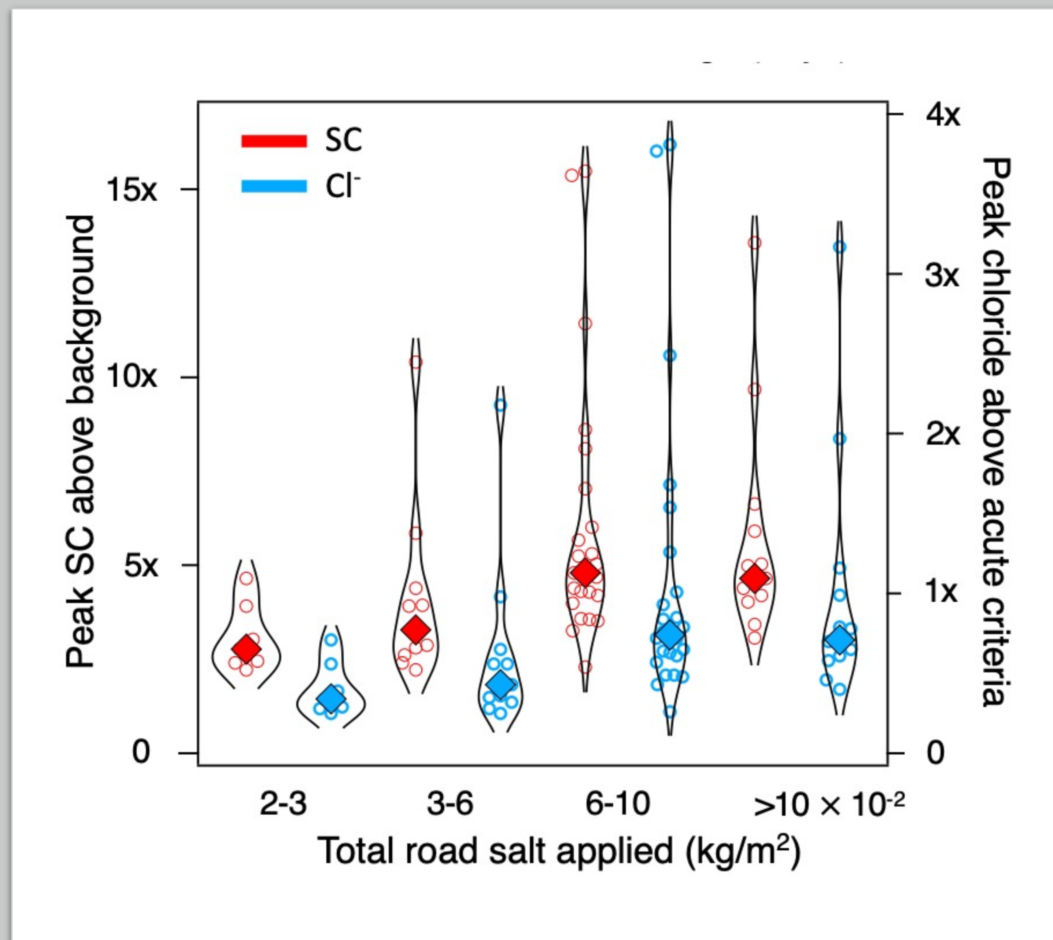
- Mean age of groundwater is steady around 6 years, calibrated relative to age-dating of groundwater in the Mesozoic Lowland hydrogeomorphic region
- Mean age of interflow (from the vadose zone) varies between ~2 (during rain events) to ~20 days (during dry periods)
- Mean age of stream flow varies between ~2 days (during heavy rain) to ~6 years (during long dry periods)

Three source end-members

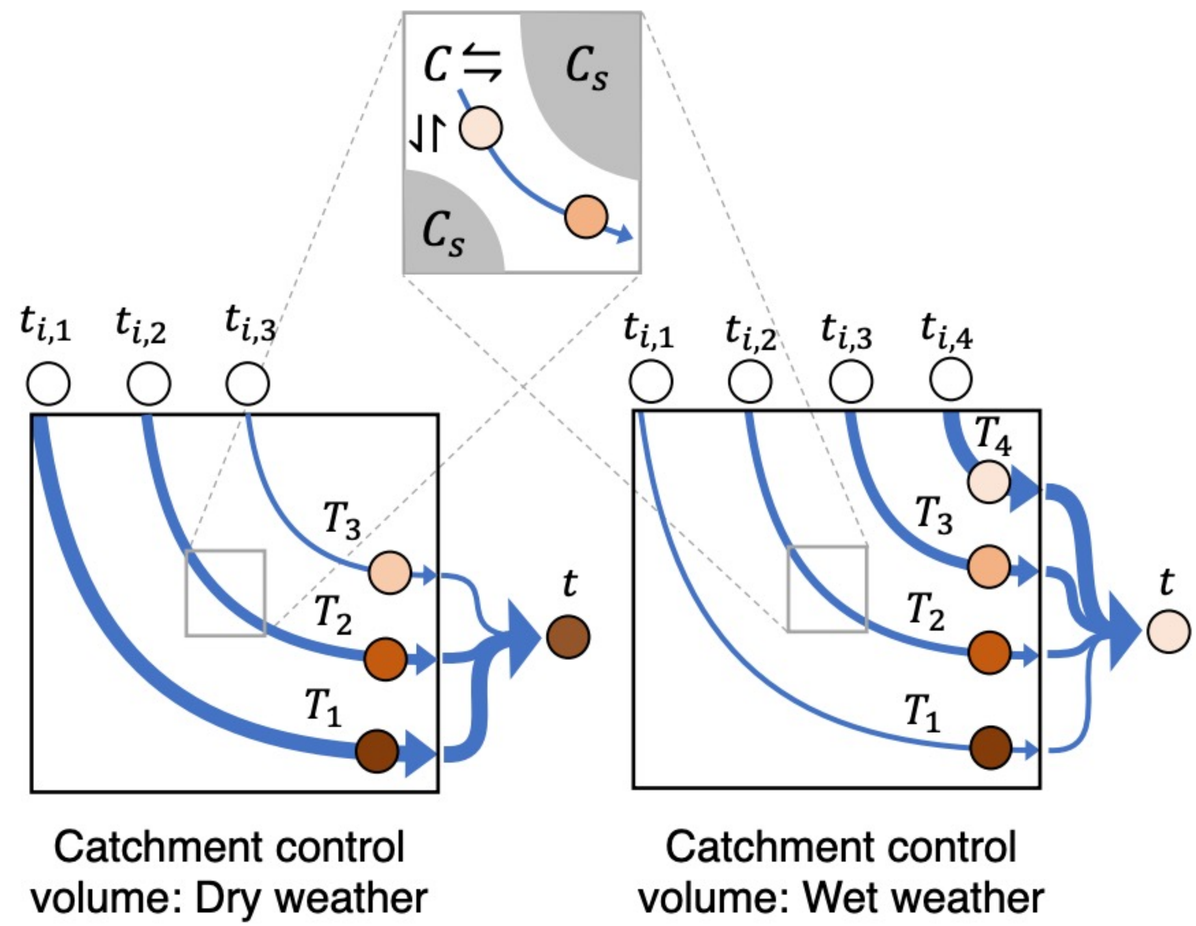
- Young low-salinity stream water from rain events;
- Young high-salinity stream water from snow melt events, or rain-on-ice events;
- Older moderate-salinity stream water from groundwater during long antecedent dry periods



Cause-and-Effect Relationship between Total Road Salt Applied and Stream Specific Conductance



Conceptual Model: salinity and flow paths



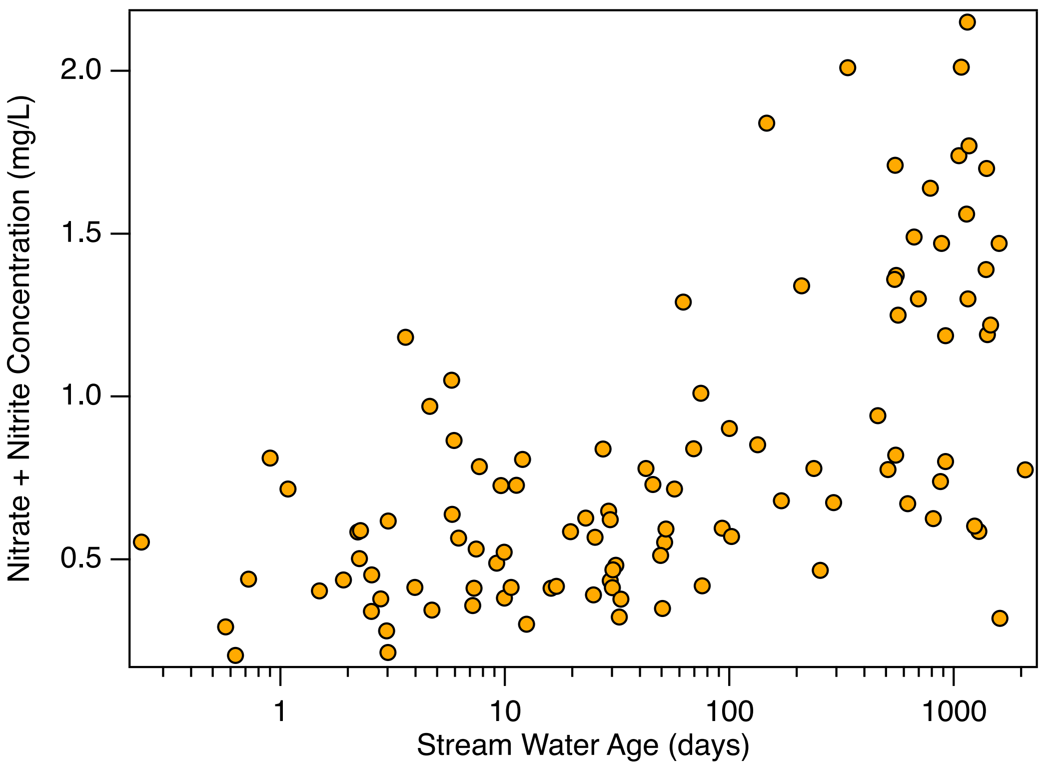
Potential uses of high-frequency (hourly) predicted stream water age

- Identify site-specific sources and physical processes responsible for patterns of inland freshwater salinization (e.g., relative contributions of rainfall runoff, deicer runoff, and groundwater)
- Identify site-specific risk factors; e.g., timescales over which deicers contaminant the vadose zone and groundwater, and corresponding clean-up times
- Leverage available data (weather stations, satellites, and in-stream specific conductance) to yield site specific information about salt sources, groundwater involvement and clean-up times
- Inform novel (e.g., real-time control) stormwater infrastructure to capture (young) high-salinity snow melt

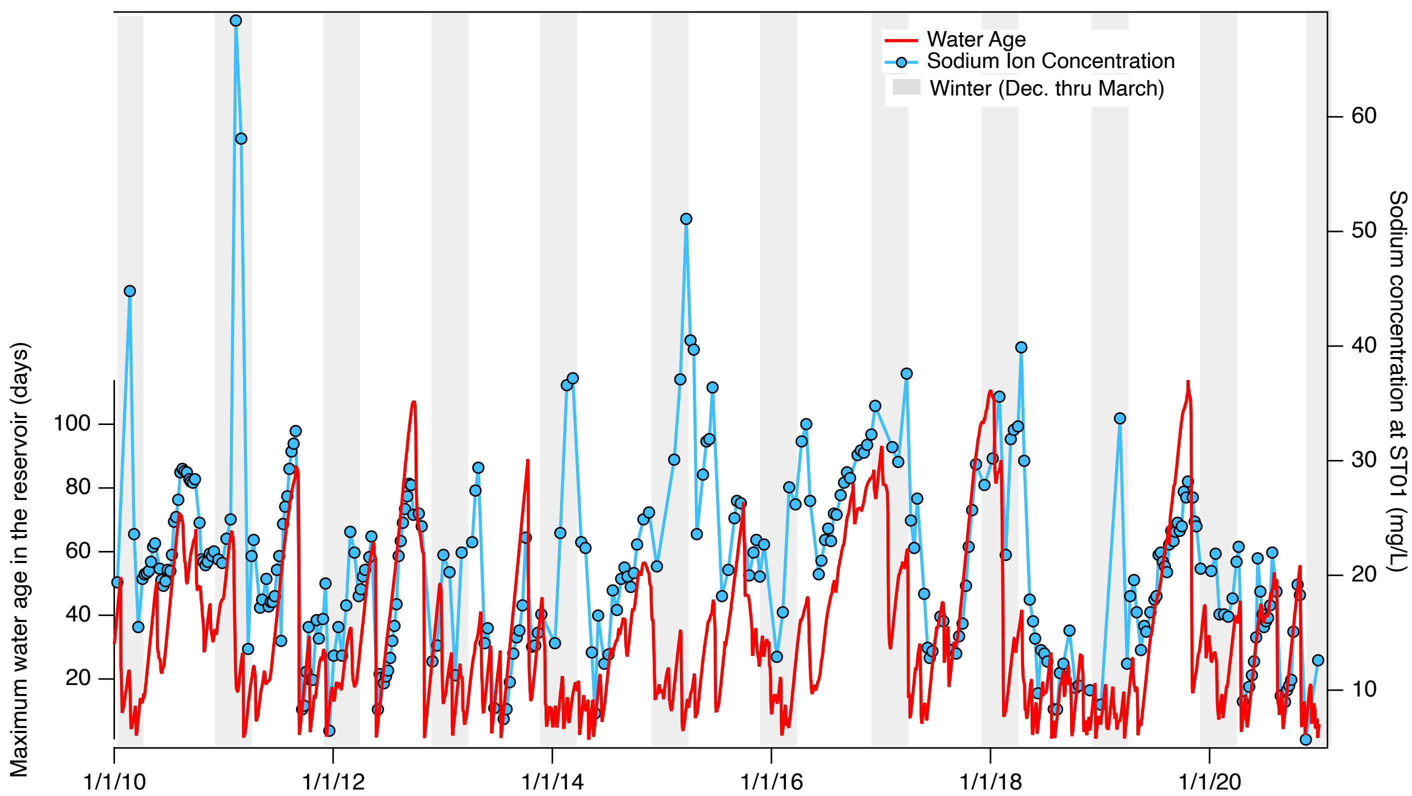
Inform sampling designs—e.g., collecting water samples targeting young or old water!

And applications not limited to stream salinity!

Oxidized nitrogen species measured in Grab Samples from Flatlick Branch (USGS data)



And not limited to streams…Maximum Water Age and Na^+ concentration in the Occoquan Reservoir

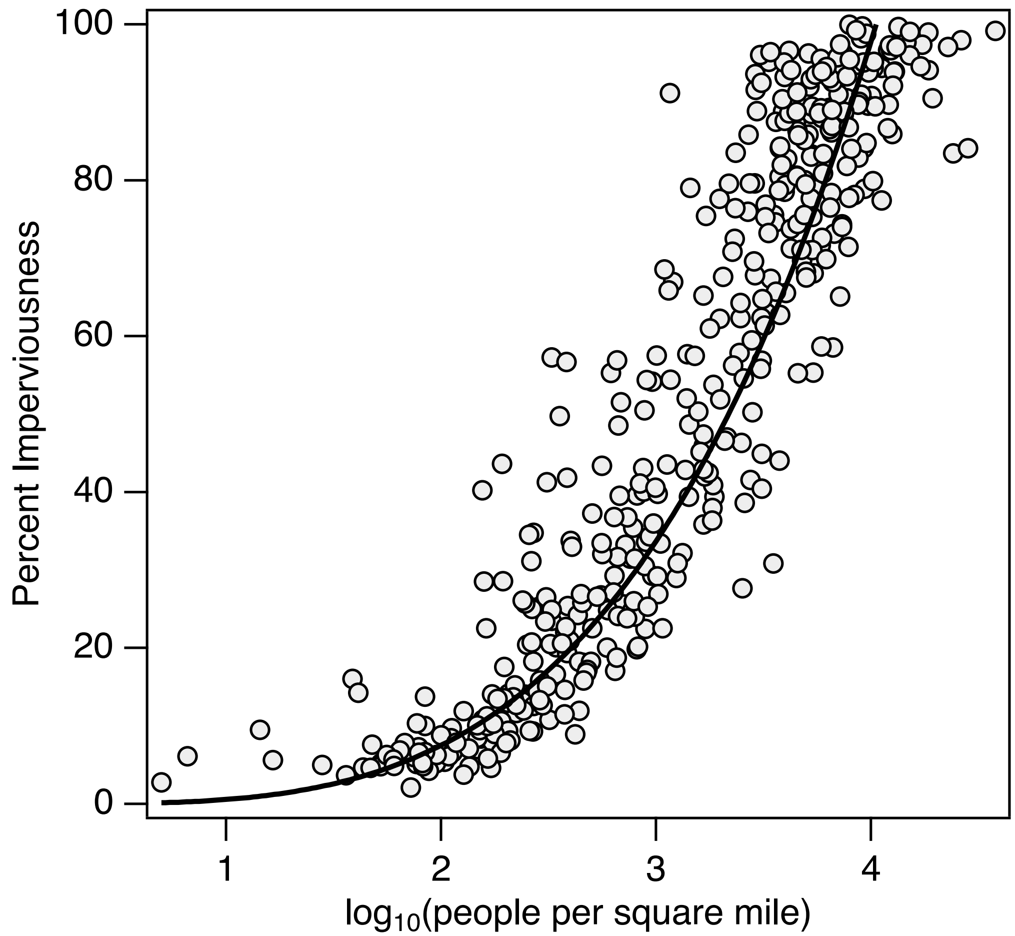


Statistical model of **annual** salt concentrations from Transportation Analysis Zone (TAZ) data

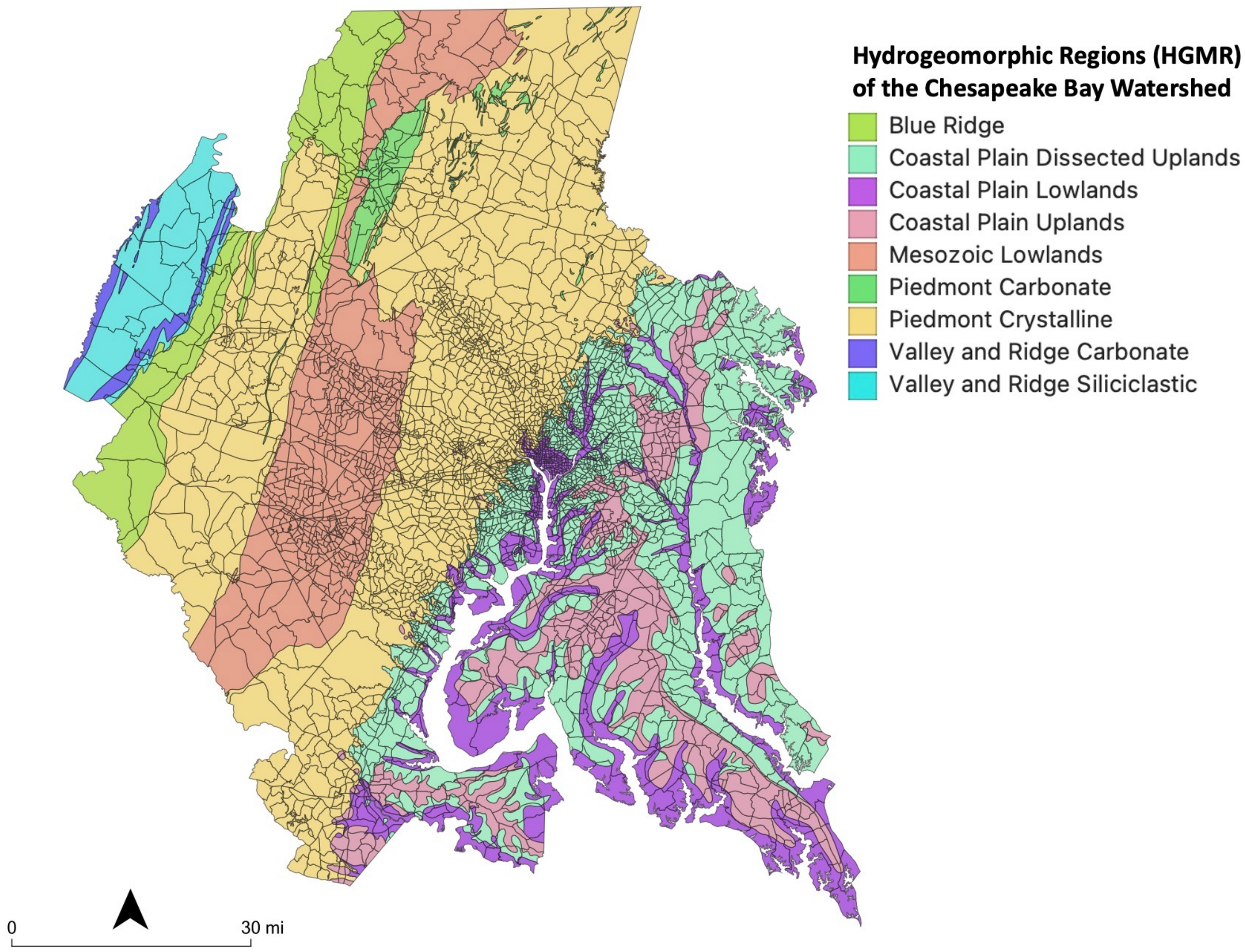
Hypothesis: TAZ estimates of population data are predictive of downstream salinity

Motivation: (1) TAZ estimates of household population, commercial population and ”group quarters” are available for the entire MWCOG region; (2) these population estimates are projected out to 2040; **(3)** TAZ population density is non-linearly correlated with percent imperviousness.

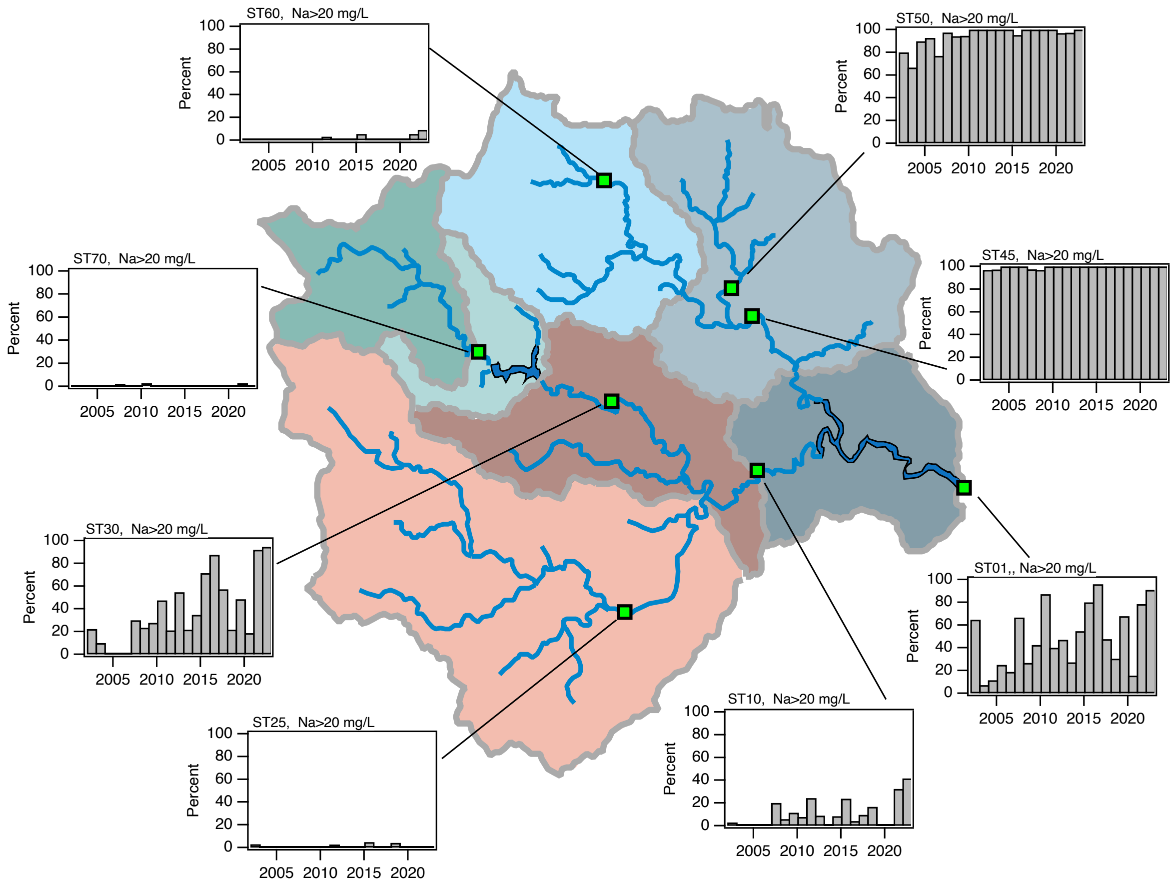
Percent imperviousness increases non-linearly with Population Density

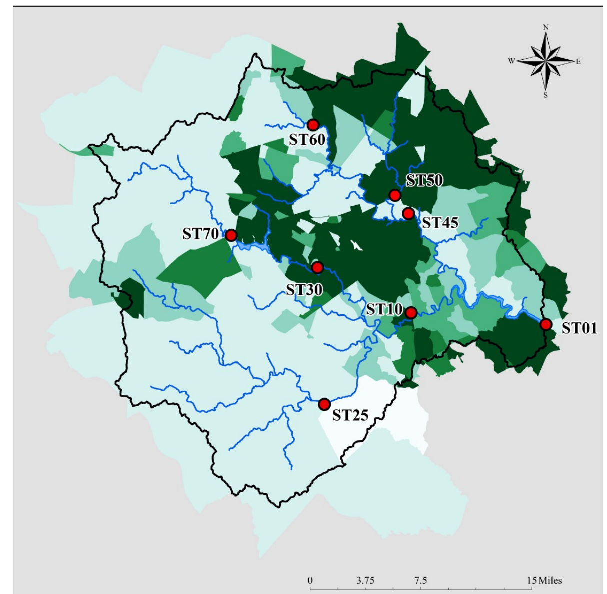


Hydrogeomorphic Regions and Transportation Analysis Zones (TAZ)



Percentage of Baseflow Samples with **Na^+ > 20** mg/L





Legend (people per square mile)

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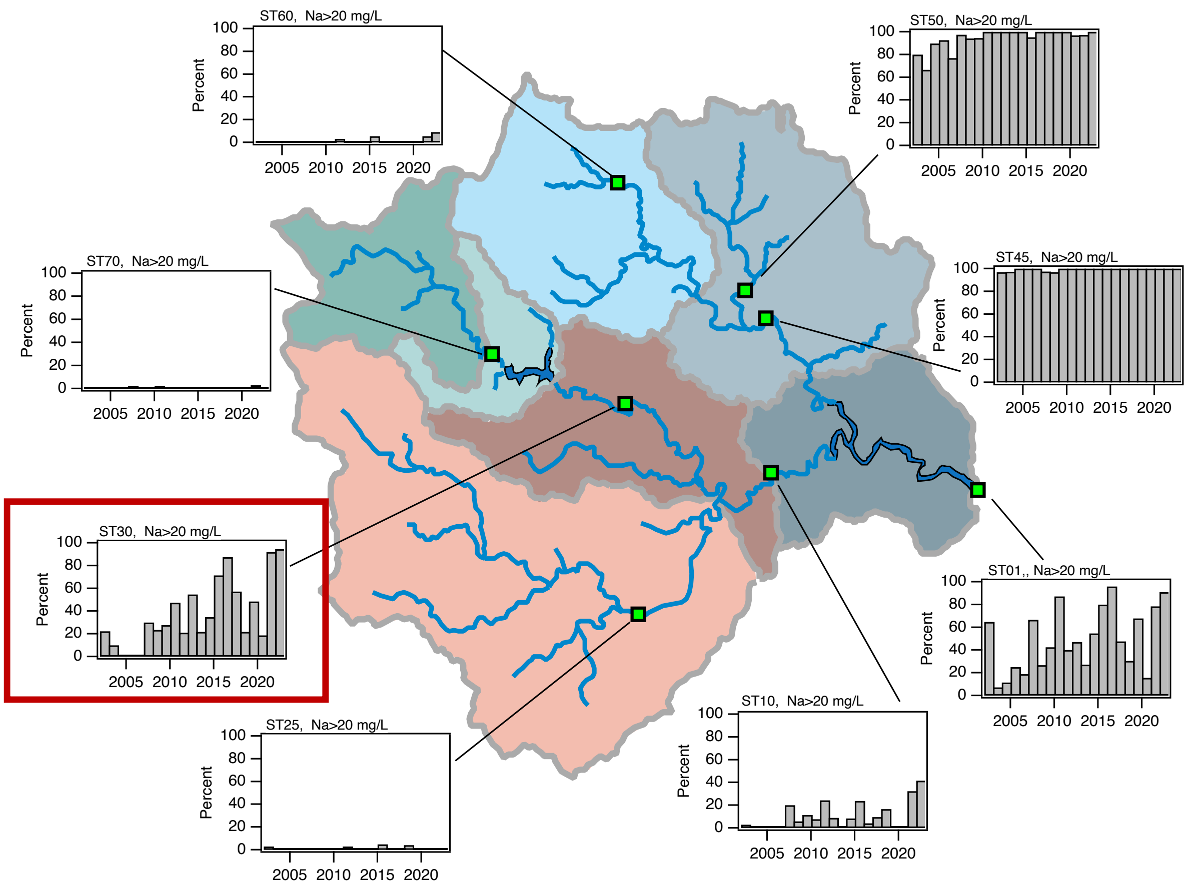
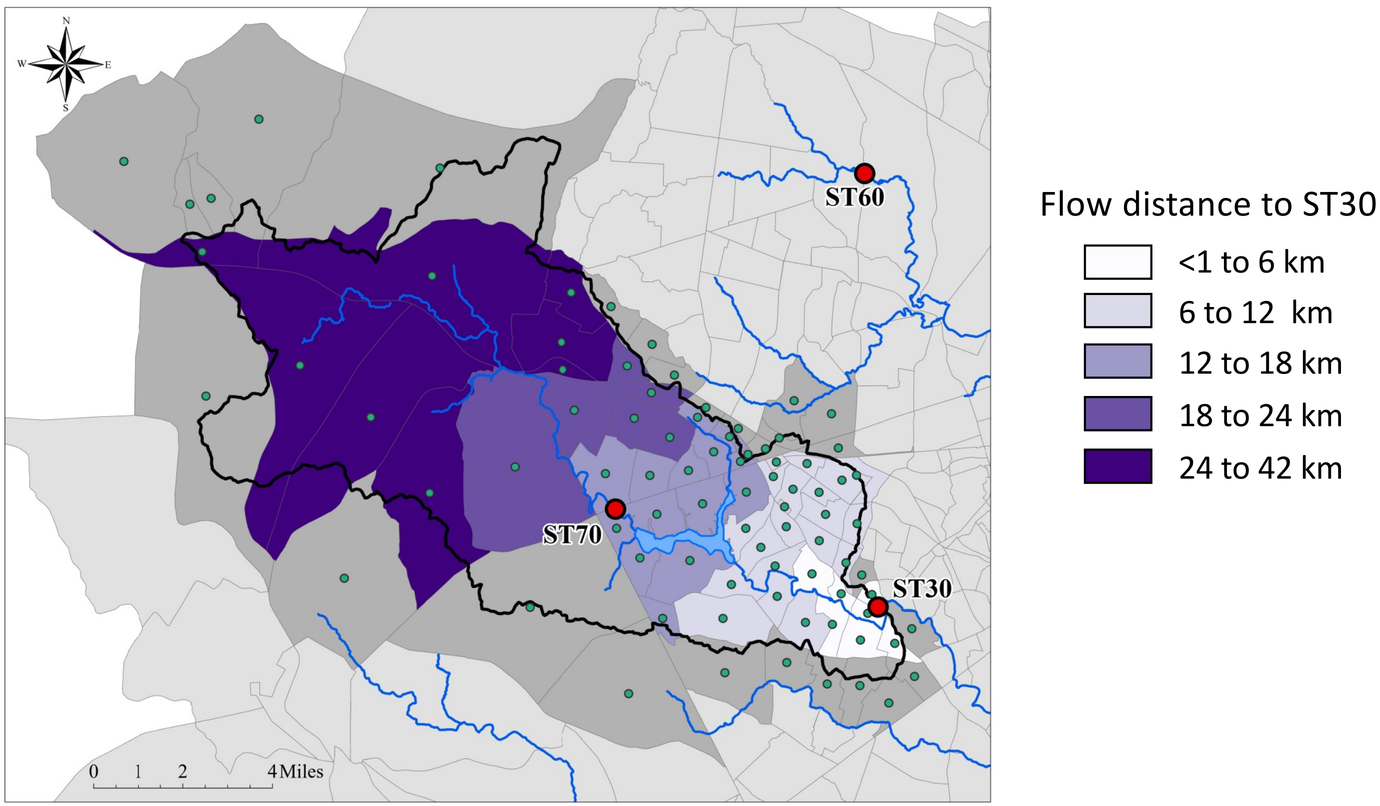
Percentage of Baseflow Samples with **Na^+ > 20** mg/L



Flow path distances to ST30 from the centroid of each upstream TAZ (from Andrew Sekellick)



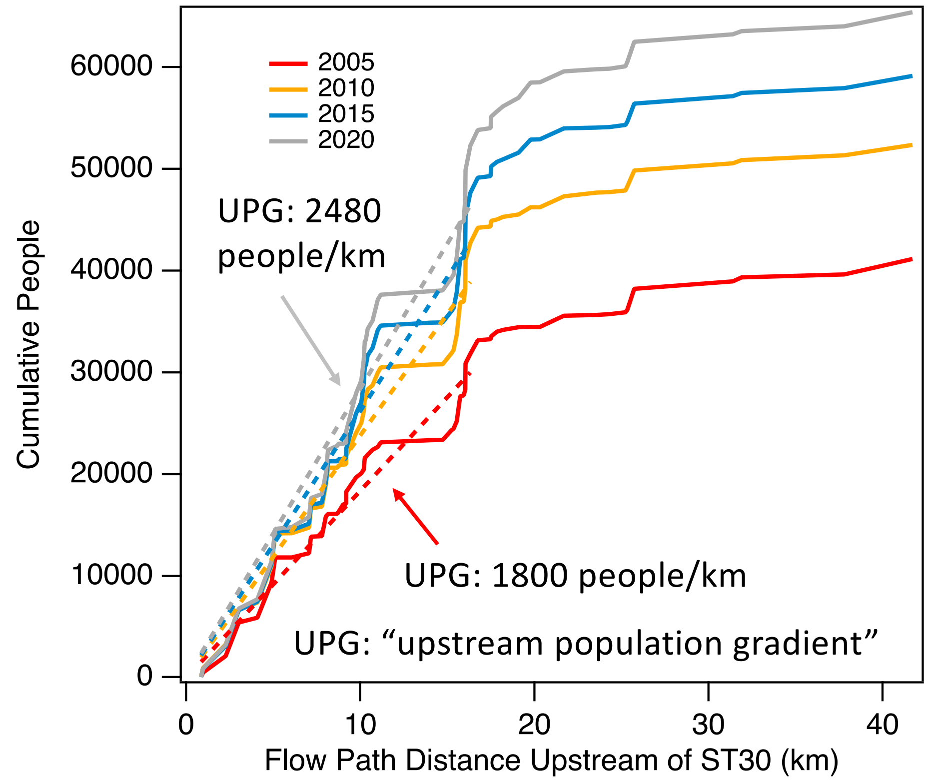
Combining the TAZ and USGS flow path data

Combining the USGS flow distance data with the TAZ population data we find:

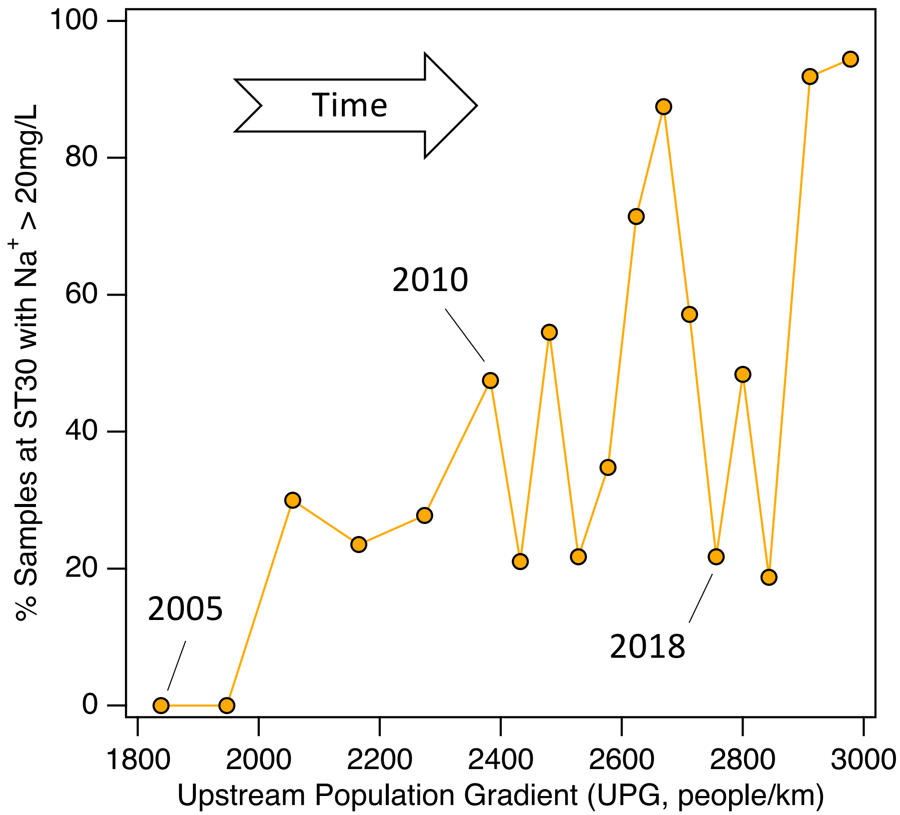
(1) The cumulative number living and working in the catchment increases linearly with upstream distance along the flow path (<20 km);

(2) The slope of the line (in units of people per km of upstream flow path) increases over time at ST30, from 1800 people/km in 2005 to 2480 people/km in 2020

(3) We refer to the slope as an **upstream population gradient (UPG)**

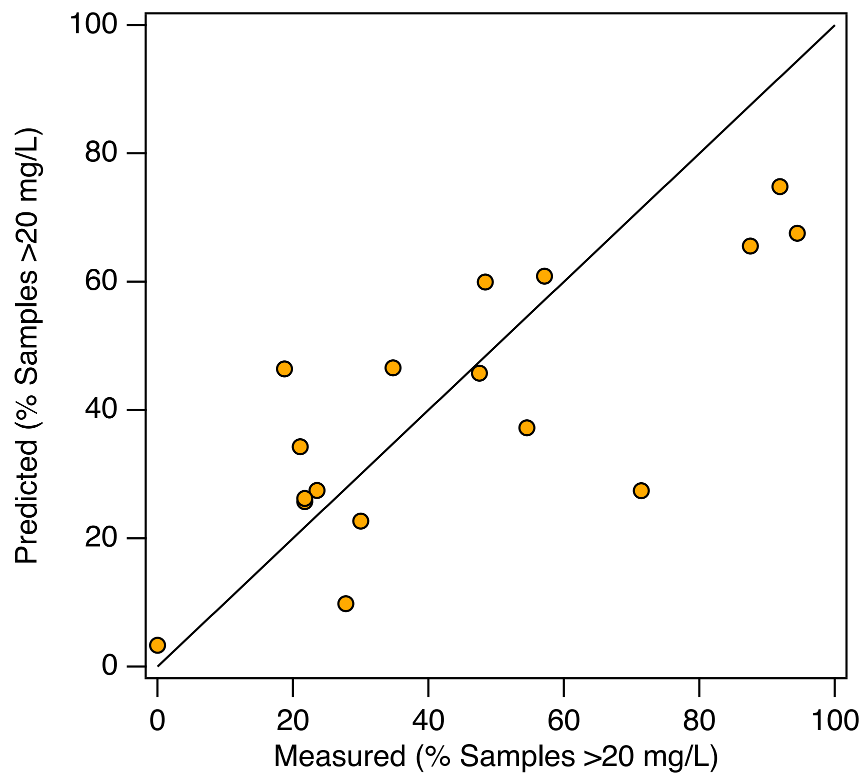


Sodium ion concentration at ST30 is correlated with Upstream Population Gradient (UPG)

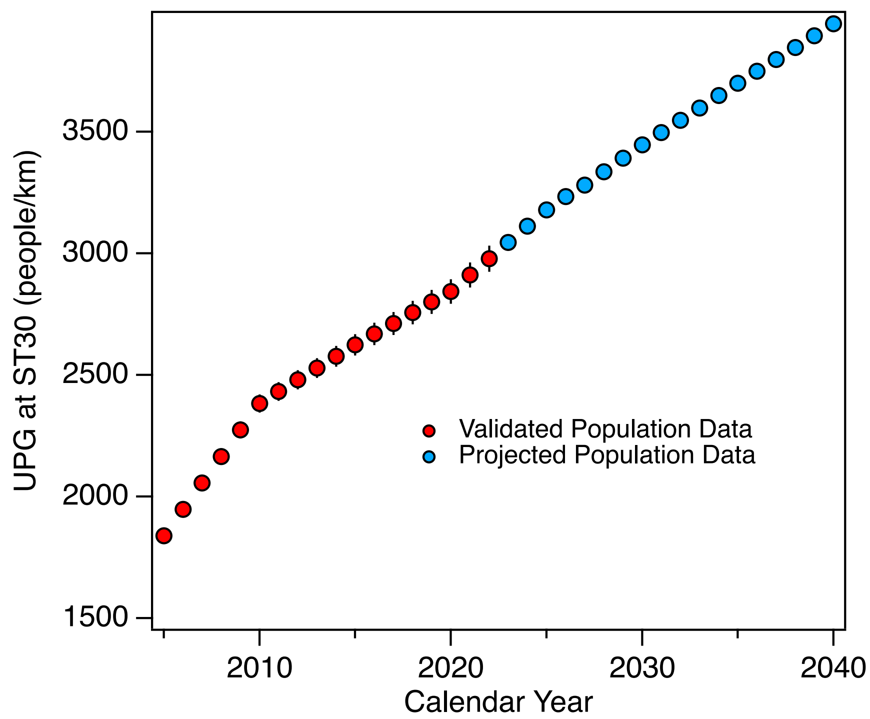


Prediction improves if we also factor in annual average flow at ST30 (R^2=0.61)

```
Call:
lm(formula = DATA$perNaSamples ~ DATA$Pop + DATA$MAF.CFS, data = DATA,
    na.action = na.exclude, family = gaussian(link = "identity"))

Residuals:
    Min      1Q  Median      3Q     Max
-32.701  -9.149  -4.629  12.666  39.347

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -118.58008   34.04950  -3.483 0.003341 **
DATA$Pop       0.07177    0.01405   5.109 0.000128 ***
DATA$MAF.CFS  -0.19151    0.06819  -2.809 0.013228 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 18.48 on 15 degrees of freedom
Multiple R-squared:  0.6515,	Adjusted R-squared:  0.605
F-statistic: 14.02 on 2 and 15 DF,  p-value: 0.0003686
```



And we can use the TAZ population forecasts to predict future changes in the UPG



Summary of Statistical Model Progress

- These preliminary results are very promising:
  - Combining TAZ population data with USGS flow path calculations, we can define an upstream population gradient (UPG)
  - At ST30 in the Occoquan Watershed, the UPG increased 1.4-fold over 15 years, from 1800 people/km in 2005 to 2480 people/km in 2020. It is projected to increase another 1.6-fold by 2040 to nearly 4000 people/km
  - Over the past 15 years (from 2005 to present), the UPG is moderately correlated with the fraction of water samples collected at ST30 with Na^+>20 mg/L (R^2=0.47). The prediction improves (R^2=0.61) if both UPG and annual average streamflow are included in the regression.
  - The UPG metric appears to be unique in the literature, but may prove generally useful as a measure of population pressure on local water quality

Next steps

- Expand this initial analysis at ST30 to all stations in the Occoquan Watershed, and allow for more potential covariates:

  Salt=function(UPG, NWS advisories, annual flow, province,…)

- Here "Salt" could be annual average sodium or chloride concentration, or the fraction of samples exceeding a threshold (which ties back to risk)
- We will calibrate the model in the Occoquan Watershed, and then validate it at other sites throughout the MWCOG region
- Vision is to eventually implement the model as an on-line interactive tool, to predict salinization (however that's defined) across the MWCOG region and allow users to test (in real time) various interventions (e.g., controlling population growth in a particular TAZ).