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Urbanization drives geographically heterogeneous freshwater salinization in the northeastern United States

Ryan Utz[1] | Samantha Bidlack[1] | Burch Fisher[2] | Sujay Kaushal[3]

[1]Falk School of Sustainability, Chatham Univ., 6035 Ridge Road, Gibsonia, PA 15044, USA

[2]Earth Research Institute, Univ. of California, Santa Barbara, CA 93106, USA

[3]Dep. of Geology & Earth System Science Interdisciplinary Center, Univ, of Maryland, College Park 20740, USA

Correspondence
Ryan M. Utz, Falk School of Sustainability, Chatham Univ., 6035 Ridge Road, Gibsonia, PA 15044, USA.
Email: rutz@chatham.edu

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Abstract

Rising trends in freshwater salinity, collectively termed the Freshwater Salinization Syndrome (FSS), constitute a global environmental concern. Given that the FSS has been observed in diverse settings, key questions regarding the causes, trend magnitudes, and consequences remain. Prior work hypothesized that FSS is driven by state factors, such as human-centered land use change, geology, and climate. Here, we identify the fundamental overriding factors driving FSS within the northeastern United States and quantify the diversity of FSS severity within the region. Specifically, we analyzed decadal-scale trends in specific conductance (a salinity proxy) for 333 lotic sites over four decades. Next, we quantified potential variables driving the rising or falling trends, including impervious surface cover (ISC), winter temperature and precipitation, watershed size, and ambient conductance. Temperature and ISC were considered the most likely candidates for predicting FSS severity because road salts have previously emerged as the fundamental regional driver. Most (62.5%) sites exhibited patterns of significantly increasing conductance; thus, the overall regional state reflects advancing FSS. However, others exhibited an absence of change (28.8%) or decreasing values (8.7%), and slope magnitude did change with latitude. Linear modeling demonstrated that two variables—ISC and watershed size—constitute the best predictors of long-term conductance trends and that an intercept not significantly different than zero suggests that the FSS does not reign in the absence of urbanization. We also detected areas with consistently decreasing trends despite moderate ISC. Therefore, within the region, advancing urbanization causes the typical condition of advancing FSS, but heterogeneity also exists.

1 | INTRODUCTION

Rising salinity in freshwaters represents an emerging problem for water quality across regional and global scales, with risks to ecosystems, agriculture, human health, and infrastructure (Cañedo-Argüelles et al., 2013; Hintz et al., 2022; Kaushal et al., 2005, 2018, 2021; Thorslund et al., 2021). Trends of rising salinization and associated complex interactions with ecosystems, engineered water systems, and social consequences have led to the conceptual framework known as Freshwater Salinization Syndrome (FSS) (Kaushal et al., 2018, 2019, 2021). Heterogeneity in FSS-associated impacts varies across many state attributes, such as climate, geology, flowpaths, human and activities (Kaushal et al., 2018, 2021). However, where surface water salinity increases, many

Abbreviations: AIC, Akaike information criterion; FSS, Freshwater Salinization Syndrome; ISC, impervious surface cover; MK, Mann–Kendall.

impacts to municipal drinking water quality can drive human health impacts and reduce the ability of aquatic ecosystems to support biodiverse ecosystems (Cañedo-Argüelles, 2020; Castillo et al., 2018; Szklarek et al., 2022).

Settings where FSS has been detected in lotic waters are geologically and climatically disparate, suggesting that multiple factors can drive the phenomenon. For example, FSS is commonly detected in warm, arid, and semi-arid climates where droughts are common (Ginatullina et al., 2017; Rengasamy, 2006). In semi-xeric regions, increasing salinity in both headwater streams and large rivers driven by concentrating salts in groundwaters due to irrigation appears to be common (Cañedo-Argüelles et al., 2016; Jolly, 1997; Jolly et al., 2001). Similar trends have been detected in cold dryland climates, such as Central Asia (Ginatullina et al., 2017; Liu et al., 2020). Freshwater Salinization Syndrome and widespread alkalinization also commonly occur in temperate and mesic regions. Kaushal et al. (2013) demonstrated widespread rising surface water alkalinity in the United States due to decades of acidic precipitation and the proliferation of impervious surfaces in urban areas. Kaushal et al. (2018) estimated that more than 37% of the drainage area in the contiguous United States has been affected by salinization, particularly in midwestern and northeastern states, where some streams exhibit exponentially rising trends (Jackson & Jobbágy, 2005). Such patterns have been consistently observed in inquiries applying disparate methodologies and spatiotemporal scales (Dugan et al., 2017; Evans et al., 2018; Jackson & Jobbágy, 2005; Kaushal et al., 2005).

Despite rising salinity trends observed in rural settings, salinization is often associated with urbanization due to multiple diverse sources of chemicals associated with urban land use but especially road salts (Steele & Aitkenhead-Peterson, 2011). Urbanization and associated impervious surfaces increase the volume and speed of runoff entering bodies of water but also shift the chemical composition of storm flow and groundwater (Miller et al., 2014). Road salts, a common road deicer used across cold regions of the United States, directly and acutely elevate salinity when salts dissolved in surface runoff contribute to groundwater (Evans & Frick, 2001; Kaushal et al., 2018). The annual salt load applied to U.S. roadways has increased from 0.15 million t in the 1940s to 15–18 million t in modern times (Dugan et al., 2017; Jackson & Jobbágy, 2005). However, surface waters in many regions lacking urban growth and/or in warmer climates where road salts are rarely applied also exhibit rising salinity (Kaushal et al., 2013, 2018). Regions where the FSS appears to be afflicting surface waters but where urbanization is limited and/or road salts are sparingly or rarely applied include Mediterranean climate regions of southeastern Australia, the North American southwest, western Europe, and central China (Dugan et al., 2017; Kaushal et al., 2019). Specific examples include the Angara River in Russia, the Songhua River in China, the Tombigbee River in the southern United States, the Rhine River in France, and the Ajichay River in Iran (Kaushal et al., 2019).

Core Ideas

- Freshwater salinization in streams and rivers is primarily driven by urbanization in the northeastern United States
- Geographic heterogeneity in freshwater salinization intensity also exists within the region.
- Salinization intensity was not aligned with gradients that should reflect road salt application intensity.
- Surface water conductance in some regions, such as western Pennsylvania, may be declining.

One region where rapid advancement of the FSS has been attributed to urbanization is the northeastern United States (Stets et al., 2018, 2020). Within this region, dense human population coupled with an advanced and expansive road network create a strong potential for road salt–driven FSS, and several investigations conducted at broad spatial scales offer affirming evidence of the link. For example, Moore et al. (2020) compared streams draining urban areas of the eastern United States spanning regions with cold to warm climates and found that freshwater systems in the coldest climates exhibited the strongest FSS trends, a pattern the authors attributed to road salt applications. Baker et al. (2019) demonstrated that FSS intensity near the southern extent of cold winters of the eastern United States (the state of Maryland) was strongest in the most urbanized sites and that severe winter storms resulted in elevated conductivity over medium-term temporal scales. However, most studies investigating drivers of FSS in the region have either compared sites along watershed urban gradients within metropolitan areas (Baker et al., 2019) or intensively monitored a single or small number of sites at fine temporal scales (Godwin et al., 2003; Perera et al., 2009). Considering the repeated observation of pervasive FSS among disparate geoclimatic settings that include warm regions, identifying the primary driver(s) of salinization requires comprehensive consideration of regional waterways.

Given the diverse suite of potential FSS drivers coupled with a rich source of water quality monitoring data available in the northeastern United States, we sought to quantify within-region patterns of lotic salinization and to determine if urbanization represents the primary driver across diverse watershed settings. Our data are derived from over 300 sites with long-term (≥20 yr) records of specific conductance (water temperature–corrected conductance at 25 ˚C, hereafter conductance) derived from grab samples or sonde readings, used here as a proxy for salinity because conductance is directly proportional to total ion concentrations and is comparatively easy to measure (Kaushal et al., 2018). Once the FSS status of each site was quantified we applied a model selection technique to assess what best predicts FSS intensity among the following variables: total impervious surface cover (ISC), winter temperature and precipitation, ambient conductance, and watershed size using the slope of long-term salinization as the independent variable. We hypothesized that watershed ISC, a proxy for urbanization, would dominate as a driver for FSS intensity and that urbanized watersheds in colder climates within the region would exhibit the highest FSS rates because of the impact from road salts.

2 | MATERIALS AND METHODS

2.1 | Study area

We focused on the northeastern United States due to consistently observed evidence of increasing salinity in streams within the region (Daley et al., 2009; Evans & Frick, 2001; Kaushal et al., 2005, 2018, 2019). Surface water conductance was collected from sites located in the following U.S. states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, Pennsylvania, Rhode Island, and Vermont. The study area climate is characterized by strong seasonal variability in temperature with local heterogeneity caused by proximity to geographic features such as the Atlantic Ocean in the east, the Great Lakes in the northwest, and the Appalachian Mountains. Average annual precipitation ranges from 79 to 152 cm (Vose et al., 2012), but it is common for inland areas to experience more extreme precipitation events due to orographic lift, especially during winter. Average annual temperatures range from −6 to 18 ˚C (Vose et al., 2012), with average winter temperatures ranging from −10 to 4 ˚C (NRCC, 2022).

The total land area of the states included in our analysis is 468,788 km^2 with heterogeneous land cover, including upland forest (51%), agriculture (13%), water (13%), wetlands (9%), development (9%), wetland forests (6%), shrub/scrub (4%), and grassland/barren land (<1%) (MRLCC, 2022). Although forests dominate the total regional land cover, these states rank among the most populous regions in the United States, with 145 individuals per square kilometer (United States Census Bureau, 2021). Localized rapid population growth led to 6,829.8 km^2 of upland forest land cover transition to developed (+3,035.5 km^2) or shrub (+2,929.3 km^2) land cover between 1996 and 2010 (MRLCC, 2022).

2.2 | Site selection

Conductance data were accessed from the Water Quality Portal, an online database maintained by the National Water Quality Monitoring Council (NWQMC, 2022). The Water Quality Portal aggregates water quality data collected from multiple U.S. state and federal agencies. Conductance (μS cm^{-1} at 25 ˚C) observations collected by partnering agencies consist of either grab samples or sonde readings collected in situ but not automated readings gathered by permanently deployed sensors. Data were collected using the following filters (selected options as listed on the portal provided in italics): states inclusive of the 10 listed above, site type = *Stream (NWIS, STEWARDS, STORET)*, sample media = *Water (NWIS, STEWARDS, STORET)*, characteristic = *Specific conductance (NWIS, STORET)*, a date range between 1 Jan.1980 and 12 Jan. 2021, and minimum results per site = 100. Sites with records that spanned <10 yr were omitted from further analyses. The final pool of sites consisted of 333 waterways with a median sample size of 250 observations (Figure 1a).

Outlier conductance observations beyond ±3 SD of the mean for each site were excluded because they likely represented conditions recorded during high flows, when precipitation or snowmelt events resulted in very anomalously high or low conductance values. Although conductance and the associated concentration of ion concentrations are typically dynamic during and after high flow events (Ulloa-Cedamanos et al., 2021), our fundamental aim was to characterize long-term trends in baseflow conductance values given that the data represented grab samples. Furthermore, the temporal resolution of the data disallowed consideration of event-based conductance dynamics. Omitting observations ±3 SD beyond the mean typically resulted in minimal data loss per site: the median proportion of omitted data was 7.8×10^{-3}, and no data were excluded from the records of 61 sites (18.3%) (Figure 1b).

The temporal coverage data varied among sites, but most records represent a period post-2000. The median year of record for nearly two-thirds of sites (65.8%) was later than the year 2000 (Figure 1c). Although a minority of records were centered on measurements dating back several decades, our fundamental aim was to quantify a broad spatial range of conductance trends by implementing loose criteria for inclusion in our site pool. Furthermore, nonlinear, decadal-scale changes to conductance trends associated with the FSS are uncommon, and most salinizing waterways exhibit a trend of linear increase beyond the record that we limited data to (Baker et al., 2019; Kaushal et al., 2018, 2021). Therefore, although most sites reflect trends over the past two decades, a minority correspond to older records.

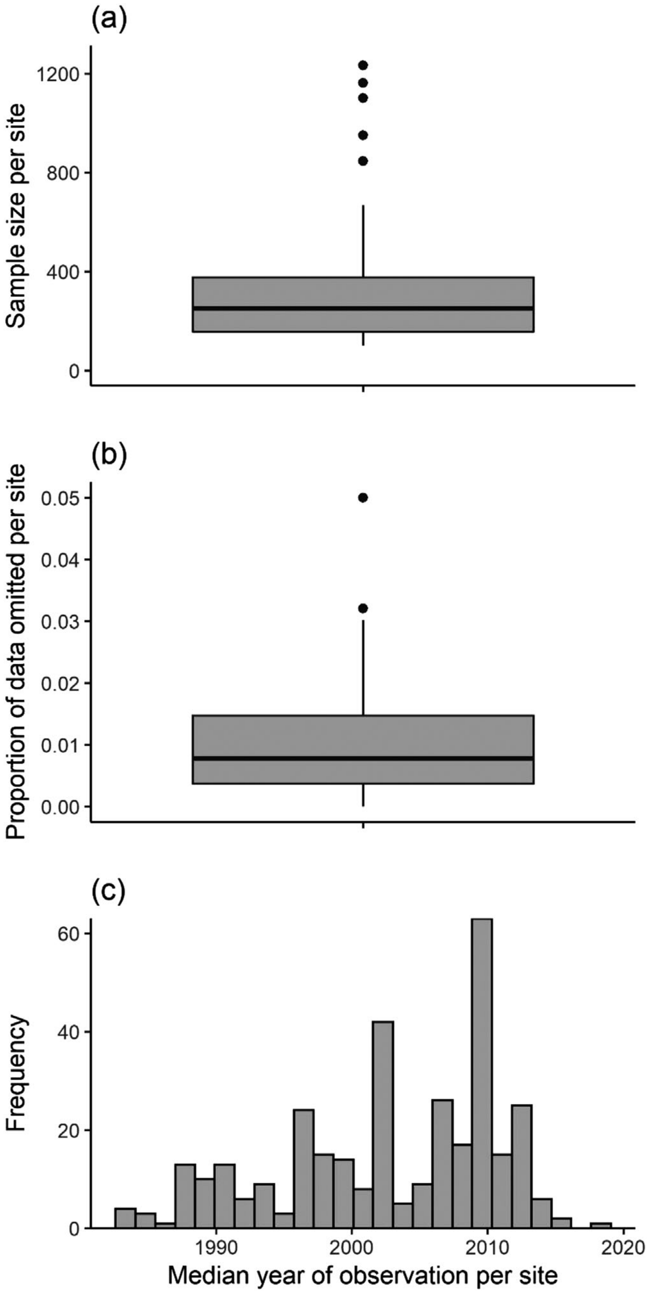

FIGURE 1 Attributes of the sites selected for conductance analysis, including (a) the sample size per site, (b) the proportion of data excluded from trend analysis due to outlier status, and (c) the median year among observations among sites

2.3 | Ion concentrations

Conductance represents a scale limitation when used as a proxy for salinization because it aggregates contributions from all dissolved ions and cannot distinguish specific chemical species driving trends. Although our primary focus was to quantify trends of conductance and therefore total salinity, we also considered changing ion concentration trends among our sites where sufficient data were available. We acquired data for seven ions that contribute to FSS and are typically found at high (>1 mg L^{-1}) concentrations (Kaushal et al., 2021) using the same Water Quality Portal system that provided conductance data (NWQMC, 2022). The same criteria described above for conductance (i.e., sample size >100, record between 1980 and 2021, at least a 10-yr span) were applied to ion concentrations (reported in mg L^{-1}). Data availability among study sites ions varied, with calcium, magnesium, and sulfate most widely available (Table 1). We applied the same trend analyses described below for conductance to each ion concentration and compared the statistical outcomes between each ion and conductance on a site-by-site basis, with the goal of inferring which ions were most likely contributing to observed conductance trends.

2.4 | Watershed data

To accurately extract land cover metrics relevant to each site, contributing watersheds were delineated for each site using the TopoToolbox software in MATLAB (Schwanghart & Scherler, 2014) and the 1 arc-second (~30-m resolution) USGS seamless digital elevation model across the study region (Archuleta et al., 2017). All delineated watersheds and gage locations were then verified for hydrologic fidelity with published drainage areas and, when possible, with previous drainage basin morphometry compilations (Falcone, 2011). Watershed areas in assessed sites ranged from 0.2 to >70,000 km^2 (mean, 2,584 km^2). To assess the impact urbanization has on long-term trends in conductance, ISC was used as a proxy. The National Land Cover Database was used to download ISC data for 2019 (MRLCC, 2022). Total watershed ISC was calculated using the National Land Cover Database ISC layer clipped by watershed boundaries to estimate the percent cover for each site.

Climate parameters averaged within site watershed boundaries were also calculated to determine if metrics likely associated with road salt application served as useful predictors of conductance trends. Mean temperature (˚C) and total precipitation (mm) during winter (November–March) were calculated from climate grids provided by Abatzoglou and Brown (2012) at a 4-km pixel resolution.

2.5 | Statistical analyses

The Mann–Kendall (MK) trend test from the R package *Kendall* (McLeod 2011) was used to quantify long-term trends in surface water conductance and ion concentrations (where available) at each site. The MK test is a nonparametric test commonly used for determining monotonic trends in environmental data that are not normally distributed or uniform. Because MK tests require a regular time series to detect

TABLE 1 Ions tested for long-term trends in concentrations, the corresponding label applied to retrieve data from the water quality portal (NWQMC, 2022) and the site sample size (including the proportion of conductance sites represented) for each assessed ion

Ion	Characteristics label	Sample size (proportion of conductance sites)
Ca^{+}	*Calcium (NWIS, STEWARDS, STORET)*	205 (0.61)
Cl^{-}	*Chloride (NWIS, STEWARDS, STORET)*	158 (0.47)
HCO_3^{-}	*Bicarbonate (NWIS, STORET)*	33 (0.10)
K^{+}	*Potassium (NWIS, STEWARDS, STORET)*	114 (0.34)
Mg^{2+}	*Magnesium (NWIS, STEWARDS, STORET)*	206 (0.62)
Na^{+}	*Sodium (NWIS, STEWARDS, STORET)*	137 (0.41)
SO_4^{-}	*Sulfate (NWIS, STEWARDS, STORET)*	204 (0.61)

long-term trends, monthly averages for specific conductivity were calculated for each site and then modeled using the *tseries* R package (Trapletti et al., 2021). The seasonal MK test detects whether a significant trend ($p < .05$) is present and produces the test statistic (tau) to estimate whether the overall trend is increasing or decreasing while accounting for seasonal signals (McLeod, 2011). Because seasonal MK tests partition seasonal signals from other patterns, interannual trends represent temporal scales without seasonal signals. Sen slopes are often used in combination with MK tests to quantify coefficients for long-term trends in time series. We therefore calculated Sen slopes to convey the directionality and magnitude of long-term (i.e., interannual) conductance trends for each site using the R package *trend* package (Pohlert, 2020). Sen slopes reported in our analyses represent units of conductance (μS cm^{-1} at 25 °C) per month.

Once Sen slopes predicting changes in conductance had been calculated, we applied a multiple linear regression framework to identify watershed metrics that influence conductance Sen slopes among sites. The Sen slopes were treated as dependent variables and watershed metrics as candidate independent variables. All slopes, regardless of statistical significance, were included in the analyses described here. Watershed metrics included percent ISC (for the year 2019), watershed size, average winter precipitation, and average winter temperature. We also included ambient conductance, calculated as the mean of all observed values, as a variable to discern if sites with the lowest values were most vulnerable to FSS. A correlation matrix among candidate variables was quantified to ensure that any highly correlated variables were excluded in the model selection procedure (Table 2). Several large rivers in our site network support more than one site. Therefore, to reduce the influence of large river sites, we averaged the Sen slope estimates and all ancillary variables among all sites on rivers with the same name prior to the analyses outlined below. The reduced sample size consisted of 278 sites: 242 lotic ecosystems with a single monitoring station and 36 with two or more stations aggregated. A forward step analysis in an Akaike information criterion (AIC) (Akaike, 1973) was used to analyze which independent variables were most influential in predicting variability of Sen slopes. We subsequently analyzed the model with the lowest AIC values using an additive multiple linear regression model. All variables were checked for normality and homogeneity of variance assumptions prior to AIC analysis. Because watershed ISC was right-skewed with a minority of large outliers, we ln-transformed the variable prior to analysis.

3 | RESULTS

Conductance is rising throughout lotic waters of the northeastern United States (Figure 2). Among all study sites, 62.5% (n = 208) were found to be statistically increasing, whereas 8.7% (n = 29) were statistically decreasing (see Figures 3 and 4 for examples). The remaining 28.8% (n = 96) exhibited no statistically significant trend (Figure 4). The mean Sen slope (±95% confidence interval) among sites was 0.356 ± 0.085 μS cm^{-1} mo^{-1}.

Conductance patterns, both directionality and magnitude, differed substantially throughout the region (Figure 5). Among states, lotic systems in eastern Massachusetts exhibited the strongest instances of FSS. Waterways in this area flow through the Boston metropolitan region, the most northerly major urban area in our study region. However, states with the most urbanized watersheds in our study did not perfectly correspond with those exhibiting the highest Sen slopes. Urbanized sites near the northernmost extent of our study area (northern Vermont) did not exhibit strong salinization rates, whereas watersheds in heavily urbanized Connecticut also exhibited more moderately elevated Sen slopes than would be expected (Figures 5 and 6). Watersheds in western Pennsylvania consistently exhibit negative or

TABLE 2 Correlation matrix of watershed variables used in candidate models predicting Sen slopes

Variable	Average winter temperature	Average winter precipitation	Drainage area	Mean conductance
	°C	cm	km^2	$\mu S\ cm^{-1}$ at 25 °C
Average winter precipitation, cm	0.17			
Drainage area, km^2	−0.11	−0.18		
Mean conductance, $\mu S\ cm^{-1}$ at 25 °C	0.20	0.00	−0.02	
ISC (2019), %	0.47	0.25	−0.10	0.51

Note. ISC, impervious surface cover.

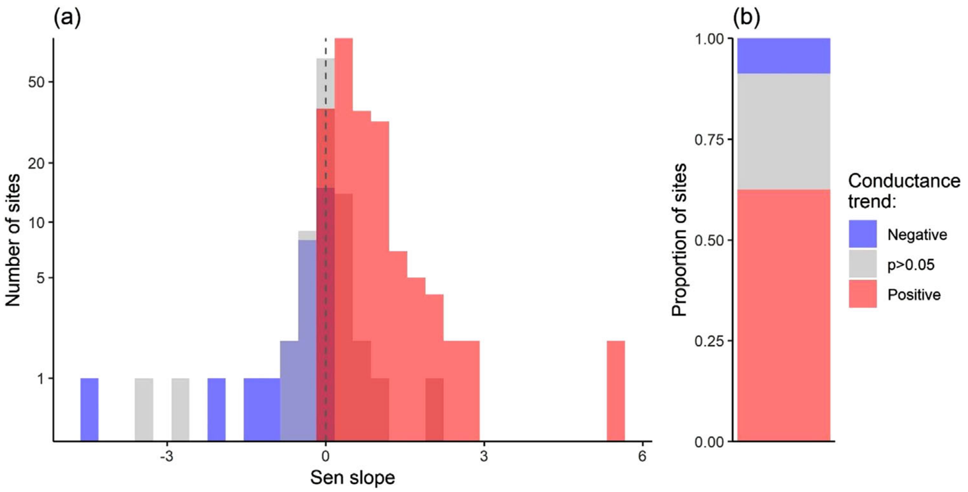

FIGURE 2 (a) Distribution of Sen slopes for all sites and (b) the proportion of sites that were statistically significantly increasing ($p < .05$ and increasing slope, red), decreasing ($p < .05$ and decreasing slope, blue), or no significant trend detected ($p > .05$, gray)

TABLE 3 Forward-step model selection parameters for models predicting Sen slopes

Model	*t* values	*p* values	Slopes (±1 SE)	R^2	AIC
ISC (2019), %	8.54	<.0001	0.31 ± 0.04	.23	−317.85
Watershed size, km^2	−2.52	.0123	$-1.81 \pm 0.72 \times 10^{-5}$		
ISC (2019), %	8.75	<.0001	0.32 ± 0.04	.21	−314.21
Intercept only	–	–	–	–	−253.63

Note. AIC, Akaike information criterion.

near-zero Sen slopes, even where sites include moderate ISC cover (Figure 5). Ambient conductance values varied significantly among states as well (Figure 5), but areas with the lowest ambient conductance did not exhibit the highest Sen slopes.

Model selection using AIC indicated that ISC and watershed size best predict Sen slopes among sites. Correlation among candidate independent variables was low to moderate, with r values ranging from 0 to .51 (Table 2). The model with the lowest AIC value consisted of ISC and watershed size as independent variables (Table 3). Both ISC and watershed size exhibited statistically significant ($\alpha < .05$) slopes in the multiple linear regression model ($F_{2,275} = 42.2$; $p < .0001$) (Figure 7). Sen slopes were positively related to ISC but declined along a gradient of watershed size. The 95% confidence interval of the model intercept overlapped with zero ($-5.5\times10^{-2} \pm 1.3\times10^{-1}$), indicating that watersheds lacking ISC would not be expected to exhibit nonzero Sen slopes.

Trends among seven ion concentrations suggested that chemicals associated with road salts, especially sodium and

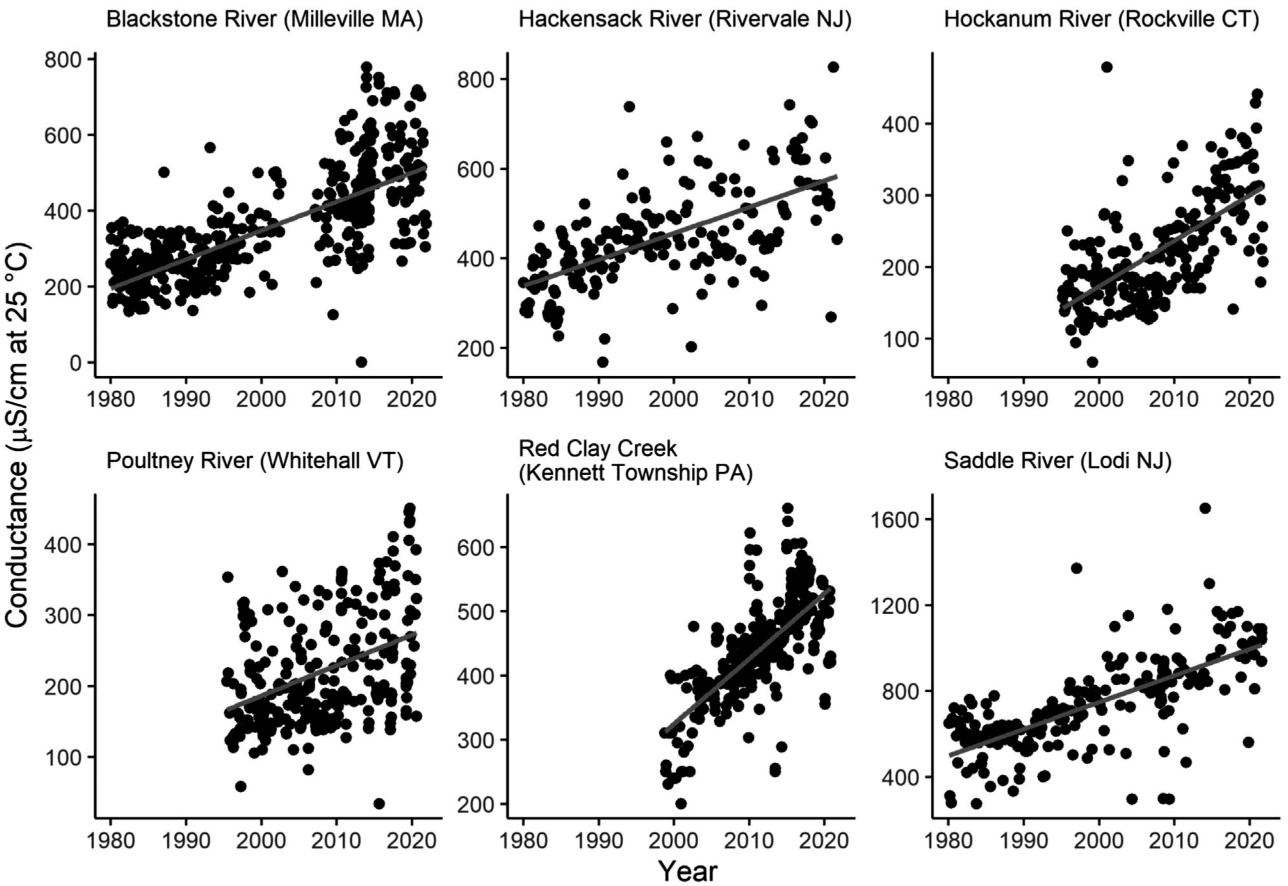

FIGURE 3 Examples of rising long-term conductance trends in the northeastern United States. All sites are statistically significantly increasing

chloride, were most aligned with conductance trends. Site-by-site statistical outcomes between conductance and ion concentrations were congruent (i.e., the same statistical outcome and trajectory was detected for both ion and conductance) for sodium and chloride among 78.8 and 80.3%, respectively (Figure 8). Potassium, calcium, and magnesium concentration trends also broadly aligned with conductance among sites (63.2, 69.8, and 66.5%, respectively). In contrast, bicarbonate and especially sulfate concentration trends were more likely to be different than those observed for conductance. Only 20.6% of sites exhibited congruent trends between sulfate concentrations and conductance, and trends in 42.6% of the sites exhibited opposing trends.

4 | DISCUSSION

Our analyses affirm urbanization as the primary driver of rising surface water conductance values, a proxy for salinity, in flowing freshwater ecosystems of the northeastern United States. Previous work investigating FSS in the region concluded that urbanization, and especially associated road salt application, drives both ambient and episodic salinization in flowing waters (Baker et al., 2019; Daley et al., 2009; Godwin et al., 2003; Moore et al., 2020). To our knowledge, results presented here represent the largest sample size and most comprehensive representation of streams spanning a rural-to-urban gradient among similar studies conducted within the region to date. The strong association between watershed ISC and conductance Sen slopes, coupled with the lack of a nonzero intercept in the regression model, strongly suggests that urbanization is the driver of FSS in the northeastern United States. Furthermore, ion concentrations associated with road salts, especially sodium and chloride, also mostly aligned with trends among sites. Although lotic systems in many other regions where road salt application is minimal or absent exhibit strong FSS patterns (Berger et al., 2019; Cañedo-Argüelles et al., 2016; Estévez et al., 2019), collective evidence firmly indicates that urbanization and associated road salt application drives FSS in the northeastern United States.

However, conductance trends among lotic ecosystems within the region also exhibit geographic heterogeneity. Site watersheds from the results presented here possess relatively similar climatic and ecological attributes, yet we detected some regional disparities in conductance trends. For example, sites in western Pennsylvania consistently exhibited marginally declining conductance despite significant

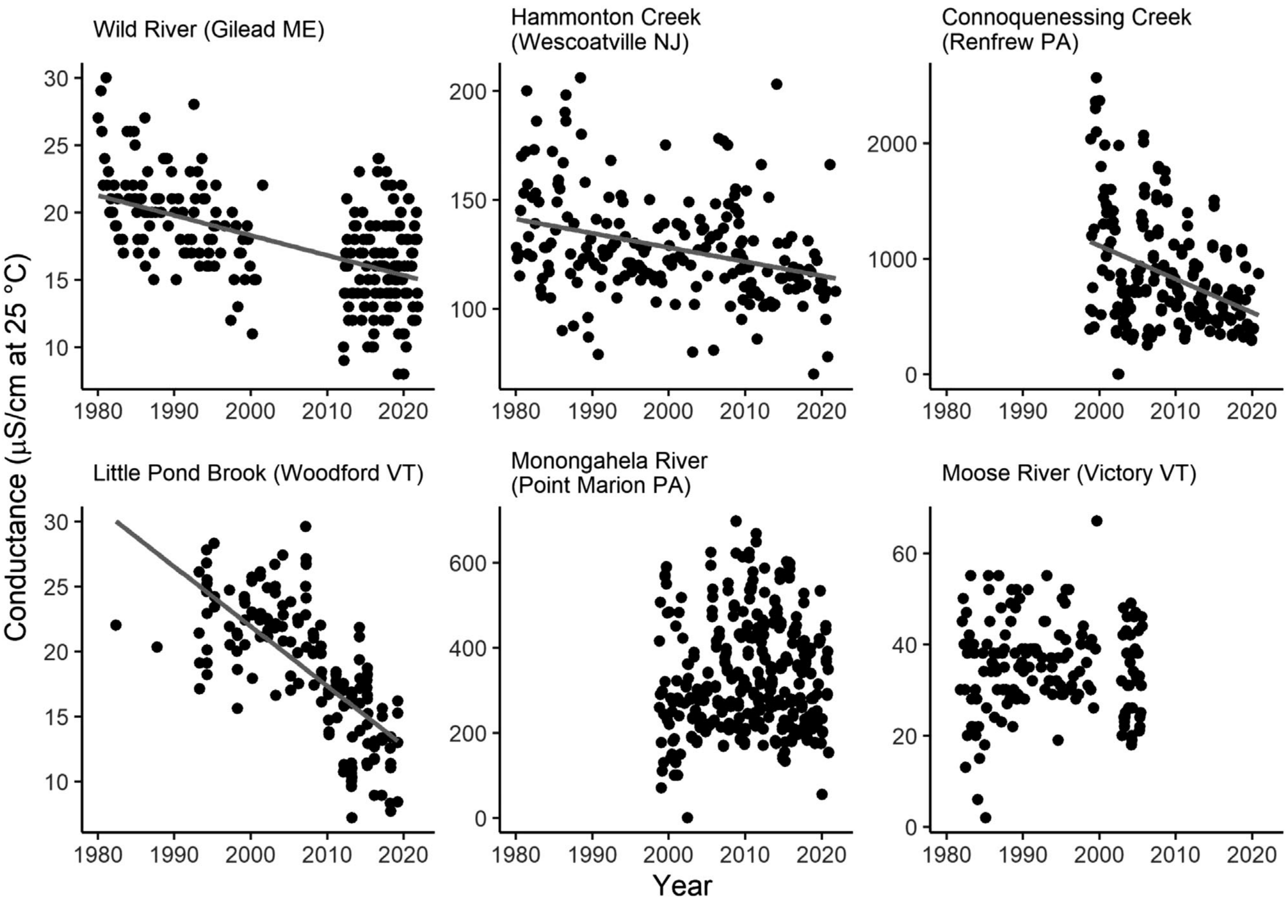

FIGURE 4 Examples of falling or stable long-term conductance trends in the northeastern United States. Sites with trendlines represent those with statistically significantly decreasing trends while those lacking lines do not exhibit rising or falling trends

urbanization among many sites, whereas the urbanized sites in northern Vermont, Connecticut, and Maryland tended to have more moderately increasing conductance trends relative to sites elsewhere with comparable degrees of urban cover. Although the link between urbanization and rising conductance can be explained by a latitudinal gradient associated with winter temperature and road salt application at larger scales (Moore et al., 2020), our findings suggest that a strong latitudinal or winter temperature gradient of increasing FSS intensity does not exist within the northeastern United States.

Differences in watershed and road salt management strategies among the states and cities of our study region could contribute to the geographic heterogeneity in FSS among sites that we observed. Stormwater management policy varies significantly among U.S. states and cities (Hale 2016; Keeley et al., 2013; Lopez-Cantu & Samaras, 2018; McPhillips & Matsler, 2018), and contemporary means to mitigate storm flows include a diverse array of approaches (Raspati et al., 2017). However, structures that are in many cases at least somewhat effective at mitigating urbanization-induced flow regime changes, sedimentation, and eutrophication (Collins et al., 2010; Koch et al., 2014; Li & Davis, 2014; Yazdi et al., 2021) may not significantly reduce concentrations of less biologically reactive ion, such as those originating from road salts (Burgis et al., 2020; Scarlett et al., 2018; Snodgrass et al., 2017). Road salt management application policies among states (Hintz et al., 2022) also likely contributed to FSS variability in our results. Winter road management strategies are heterogeneous because road salts vary by chemical composition, the amount required to clear snow or ice changes with accompanying physical treatments such as sand or prewetting, and application equipment can affect efficacy (USEPA, 2010). To our knowledge, no systemic review of road salt policy among northeastern U.S. states has been conducted that could elucidate if differences in road salt management strategies contribute to the geographic heterogeneity inherent in our results.

Water quality of streams in the northeastern United States also reflect a legacy of significant shifts in regional air quality over the past century. Industrial emissions largely originating in the Midwest generated severe regional acid precipitation and nitrogen deposition during the late 20th century that drove elevated concentrations of sulfate, nitrogen, and metals in surface waters (Cronan & Schofield, 1979). Major regulations at the national scale led to a significant recovery toward pre-industrial atmospheric conditions in

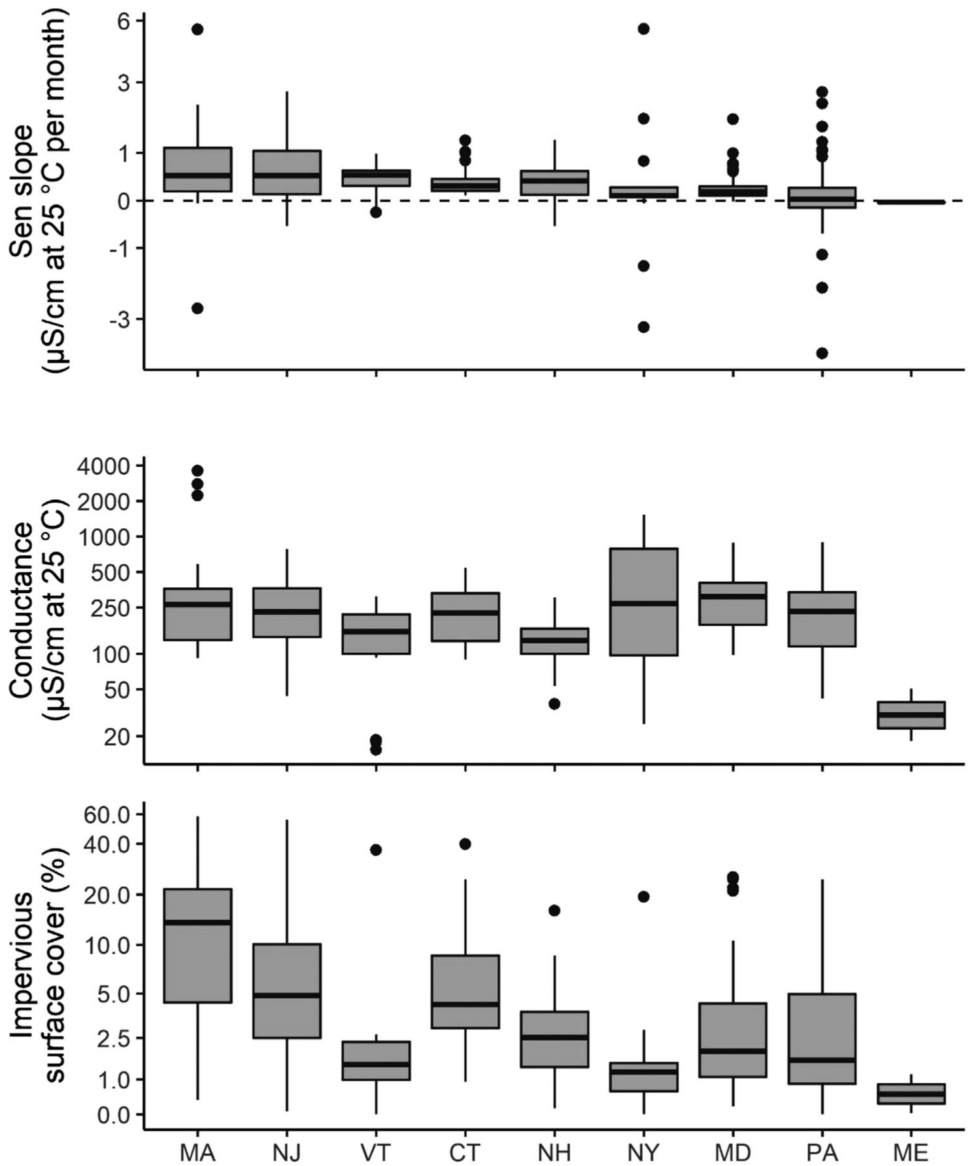

FIGURE 5 The distribution of (a) Sen slopes, (b) mean conductance values, and (c) percent impervious surface cover (2019, bottom) of each site delineated by state

subsequent decades (Aas et al., 2019; Lehmann et al., 2007). Recent surface water chemistry trends in the region also reflect the recovery from industrial atmospheric pollution because some streams in the region exhibit decreasing metal, H^+, NO_3^-, and SO_4^{2-} trends coupled with increasing dissolved organic carbon (Burns et al., 2006; SanClements et al., 2012; Siemion et al., 2018). Our finding that sulfate concentration trends are largely misaligned with conductance trends probably reflects such atmospheric dynamics. The surface waters of rural regional watersheds also can exhibit declining concentrations of ions typically associated with road salts, such as Ca^+, Na^+, Cl^-, and Mg^+, because the acidic precipitation that leached these ions from soils has exhausted stores from watershed soils (Likens & Buso, 2012). Therefore, regional surface water chemistry in urban watersheds include a complex matrix of simultaneously rising and falling ion concentrations. In some cases, such as Ca^+, drivers of both rising (road salt) and falling (soil depletion) concentrations might simultaneously shape surface water concentrations.

Our results reflect patterns detected from coarse temporal resolution data distributed across a broad spatial scale and therefore do not reflect potentially important dynamics at fine temporal scales. Ion concentrations that contribute to conductance change rapidly during spates, with event-specific magnitudes of rising or falling values depending on flow paths and seasonality (Ledford et al., 2016; Timpano et al., 2018). Interannual variability in conductance can also reflect short-term weather because anomalously strong winter storms can result in extra road salt application that results in

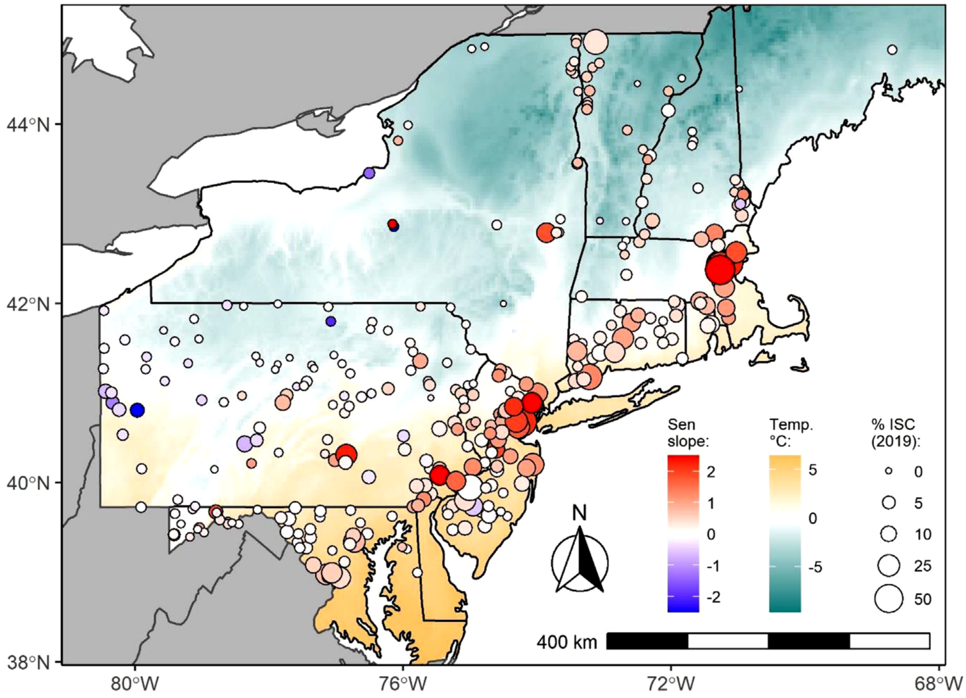

FIGURE 6 Locations, conductance Sen slopes, and watershed impervious surface cover (ISC) for all sites. Point size corresponds to the estimated 2019 watershed ISC. Color within points corresponds to the magnitude and directionality of Sen slopes; color gradient outside of points represents mean average winter (November–March) temperature

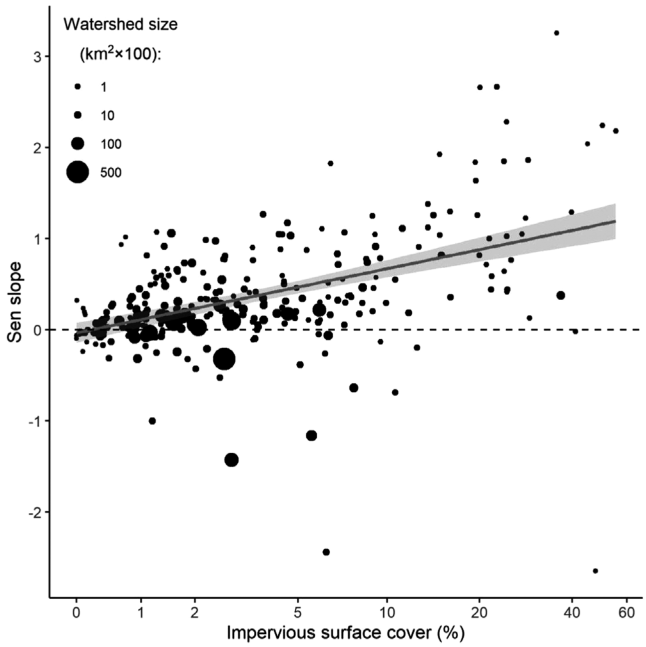

FIGURE 7 Relationship between watershed 2019 impervious surface cover and Sen slopes. Point sizes are scaled to represent watershed size

acute conductance spikes (Baker et al., 2019). Such dynamics may be more important than long-term changes of baseflow conductance values because severe, short-term changes in salinity can cause microbial mortality and subsequent

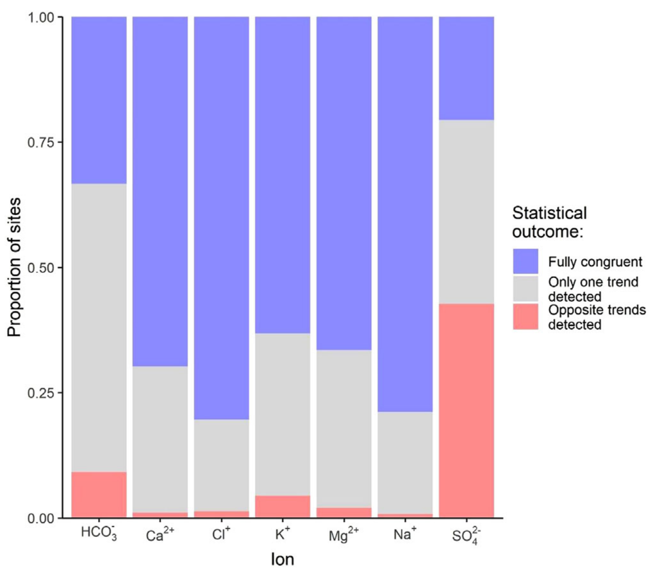

FIGURE 8 Congruence of models between conductance and individual ion concentrations for seven chemicals that commonly feature in the Freshwater Salinization Syndrome FSS. *Fully congruent* outcomes represent those where both models reported the same statistical significance, and, when trends were detected, the directionality of slopes was consistent. *Only one trend detected* reflects sites where either statistically significant conductance or ionic concentration trends were detected, but not for both. *Opposite trends detected* reflects sites where both ionic and conductance trends were detected but the directionality of slopes was reversed between parameters

reductions in metabolism (Cochero et al., 2017), which could explain why oxygen cycling diminishes for several days following floods (Utz et al., 2020). Conductance and ion concentration trends during baseflow periods immediately following spates also exhibit heterogeneous patterns structured by conditions preceding the events (Ulloa-Cedamanos et al., 2021). The data derived from grab samples or sondes represented in our results are unfit to assess conductance trends or patterns linked to spates. However, the regional patterns evident in our findings coupled with heterogeneous hydrologic responses of streams to urbanization among regions (Utz et al., 2011, 2016) highlight the strong potential for spatial heterogeneity in conductance dynamics at short temporal scales. Data streams from automated sensors set to a high temporal resolution are required to adequately assess event-driven conductance and ion concentration dynamics. Fortunately, such data streams are increasingly available (Pellerin et al., 2016).

5 | CONCLUSION

Findings presented here offer further evidence that urbanization drives FSS in the northeastern United States, but the phenomenon does exhibit geographic heterogeneity stemming from a number of potential sources. The measurement we used as a proxy for salinity (conductance) characterizes all collective dissolved ions in water and therefore cannot distinguish specific chemicals driving overall salinization in a system. Although road salts are a clear driver of FSS in cold regions, many additional anthropogenic stressors, including wastewater (Bhide et al., 2021), infrastructure weathering (Moore et al., 2017), and agricultural practices such as liming (Oberhelman & Peterson, 2020) and fertilization (Zampella et al., 2007), can simultaneously drive salinization. Furthermore, lotic ecosystems draining watersheds with FSS drivers might also exhibit falling concentrations of certain ions if other environmental stressors, such as atmospheric deposition and acidic precipitation, are ameliorating (Likens & Buso, 2012; Siemion et al., 2018). Therefore, FSS is collectively driven by multiple processes that heterogeneously affect ionic concentrations. Such heterogeneity may be expressed geographically in a region where FSS is widespread.

AUTHOR CONTRIBUTIONS

Ryan Utz: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Supervision; Visualization; Writing – original draft; Writing – review & editing. Samantha Bidlack: Conceptualization; Data curation; Formal analysis; Methodology; Writing – original draft. Burch Fisher: Data curation; Methodology; Validation; Writing – review & editing. Sujay Kaushal: Conceptualization; Writing – original draft; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Ryan Utz https://orcid.org/0000-0001-8036-2228
Burch Fisher https://orcid.org/0000-0002-9133-3059
Sujay Kaushal https://orcid.org/0000-0003-0834-9189

REFERENCES

Archuleta, C. M., Constance, E. W., Arundel, S. T., Lowe, A. J., Mantey, K. S., & Philips, L. (2017). The national map seamless digital elevation model specifications. In *United States Geological Survey, Techniques and Methods* (p. 39). https://pubs.usgs.gov/tm/11b9/tm11B9.pdf

Aas, W., Mortier, A., Bowersox, V., Cherian, R., Faluvegi, G., Fagerli, H., Hand, J., Klimont, Z., Galy-Lacaux, C., Lehmann, C. M. B., Myhre, C. L., Myhre, G., Olivié, D., Sato, K., Quaas, J., Rao, P. S. P., Schulz, M., Shindell, D., Skeie, R. B., … Xu, X. (2019). Global and regional trends of atmospheric sulfur. *Scientific Reports*, *9*, 953. https://doi.org/10.1038/s41598-018-37304-0

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, *32*, 772–780. https://doi.org/10.1002/joc.2312

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. In *Selected papers of Hirotugu Akaike* (pp. 199–213). Springer.

Baker, M. E., Schley, M. L., & Sexton, J. O. (2019). Impacts of expanding impervious surface on specific conductance in urbanizing streams. *Water Resources Research*, *55*, 6482–6498. https://doi.org/10.1029/2019WR025014

Berger, E., Frör, O., & Schäfer, R. B. (2019). Salinity impacts on river ecosystem processes: A critical mini-review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*, 20180010. https://doi.org/10.1098/rstb.2018.0010

Bhide, S. V., Grant, S. B., Parker, E. A., Rippy, M. A., Godrej, A. N., Kaushal, S., Prelewicz, G., Saji, N., Curtis, S., Vikesland, P., Maile-Moskowitz, A., Edwards, M., Lopez, K. G., Birkland, T. A., & Schenk, T. (2021). Addressing the contribution of indirect potable reuse to inland freshwater salinization. *Nature Sustainability*, *4*, 699–707. https://doi.org/10.1038/s41893-021-00713-7

Burgis, C. R., Hayes, G. M., Henderson, D. A., Zhang, W., & Smith, J. A. (2020). Green stormwater infrastructure redirects deicing salt from surface water to groundwater. *Science of the Total Environment*, *729*, 138736. https://doi.org/10.1016/j.scitotenv.2020.138736

Burns, D. A., McHale, M. R., Driscoll, C. T., & Roy, K. M. (2006). Response of surface water chemistry to reduced levels of acid precipitation: Comparison of trends in two regions of New York, USA. *Hydrological Processes*, *20*, 1611–1627. https://doi.org/10.1002/hyp.5961

Cañedo-Argüelles, M. (2020). A review of recent advances and future challenges in freshwater salinization. *Limnetica*, *39*, 185–211.

Cañedo-Argüelles, M., Hawkins, C. P., Kefford, B. J., Schäfer, R. B., Dyack, B. J., Brucet, S., Buchwalter, D., Dunlop, J., Frör, O., Lazorchak, J., Coring, E., Fernandez, H. R., Goodfellow, W., Achem, A. L. G., Hatfield-Dodds, S., Karimov, B. K., Mensah, P., Olson, J. R., Piscart, C., … Timpano, A. J. (2016). Saving freshwater from salts. *Science*, *351*, 914–916. https://doi.org/10.1126/science.aad3488

Cañedo-Argüelles, M., Kefford, B. J., Piscart, C., Prat, N., Schäfer, R. B., & Schulz, C.-J. (2013). Salinisation of rivers: An urgent ecological issue. *Environmental Pollution*, *173*, 157–167. https://doi.org/10.1016/j.envpol.2012.10.011

Castillo, A. M., Sharpe, D. M. T., Ghalambor, C. K., & De León, L. F. (2018). Exploring the effects of salinization on trophic diversity in freshwater ecosystems: A quantitative review. *Hydrobiologia*, *807*, 1–17. https://doi.org/10.1007/s10750-017-3403-0

Cochero, J., Licursi, M., & Gómez, N. (2017). Effects of pulse and press additions of salt on biofilms of nutrient-rich streams. *Science of the Total Environment*, *579*, 1496–1503. https://doi.org/10.1016/j.scitotenv.2016.11.152

Collins, K. A., Lawrence, T. J., Stander, E. K., Jontos, R. J., Kaushal, S. S., Newcomer, T. A., Grimm, N. B., & Cole Ekberg, M. L. (2010). Opportunities and challenges for managing nitrogen in urban stormwater: A review and synthesis. *Ecological Engineering*, *36*, 1507–1519. https://doi.org/10.1016/j.ecoleng.2010.03.015

Cronan, C. S., & Schofield, C. L. (1979). Aluminum leaching response to acid precipitation: Effects on high-elevation watersheds in the northeast. *Science*, *204*, 304–306. https://doi.org/10.1126/science.204.4390.304

Daley, M. L., Potter, J. D., & McDowell, W. H. (2009). Salinization of urbanizing New Hampshire streams and groundwater: Effects of road salt and hydrologic variability. *Journal of the North American Benthological Society*, *28*, 929–940. https://doi.org/10.1899/09-052.1

Dugan, H. A., Bartlett, S. L., Burke, S. M., Doubek, J. P., Krivak-Tetley, F. E., Skaff, N. K., Summers, J. C., Farrell, K. J., McCullough, I. M., Morales-Williams, A. M., Roberts, D. C., Ouyang, Z., Scordo, F., Hanson, P. C., & Weathers, K. C. (2017). Salting our freshwater lakes. *Proceedings of the National Academy of Sciences*, *114*, 4453–4458. https://doi.org/10.1073/pnas.1620211114

Estévez, E., Rodríguez-Castillo, T., González-Ferreras, A. M., Cañedo-Argüelles, M., & Barquín, J. (2019). Drivers of spatio-temporal patterns of salinity in Spanish rivers: A nationwide assessment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*, 20180022. https://doi.org/10.1098/rstb.2018.0022

Evans, D. M., Villamagna, A. M., Green, M. B., & Campbell, J. L. (2018). Origins of stream salinization in an upland New England watershed. *Environmental Monitoring and Assessment*, *190*, 523. https://doi.org/10.1007/s10661-018-6802-4

Evans, M., & Frick, C. (2001). *The effects of road salts on aquatic ecosystems*. National Water Resources Institute Series No. 02–308. https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/193946

Falcone, J. A. (2011). *GAGES-II: Geospatial attributes of gages for evaluating streamflow*. USGS.

Ginatullina, E., Atwell, L., & Saito, L. (2017). Resilience and resistance of zooplankton communities to drought-induced salinity in freshwater and saline lakes of Central Asia. *Journal of Arid Environments*, *144*, 1–11. https://doi.org/10.1016/j.jaridenv.2017.04.010

Godwin, K. S., Hafner, S. D., & Buff, M. F. (2003). Long-term trends in sodium and chloride in the Mohawk River, New York: The effect of fifty years of road-salt application. *Environmental Pollution*, *124*, 273–281. https://doi.org/10.1016/S0269-7491(02)00481-5

Hale, R. L. (2016). Spatial and temporal variation in local stormwater infrastructure use and stormwater management paradigms over the 20th century. *Water*, *8*, 310. https://doi.org/10.3390/w8070310

Hintz, W. D., Fay, L., & Relyea, R. A. (2022). Road salts, human safety, and the rising salinity of our fresh waters. *Frontiers in Ecology and the Environment*, 20, 22–30. https://doi.org/10.1002/fee.2433

Jackson, R. B., & Jobbágy, E. G. (2005). From icy roads to salty streams. *Proceedings of the National Academy of Sciences*, *102*, 14487–14488. https://doi.org/10.1073/pnas.0507389102

Jolly, & I. (1997). The Commonwealth Scientific and Industrial Research Organisation. *Current Biology*, *7*, R126. https://doi.org/10.1016/S0960-9822(97)70976-X

Jolly, I. D., Williamson, D. R., Gilfedder, M., Walker, G. R., Morton, R., Robinson, G., Jones, H., Zhang, L., Dowling, T. I., Dyce, P., Nathan, R. J., Nandakumar, N., Clarke, R., & McNeill, V. (2001). Historical stream salinity trends and catchment salt balances in the Murray–Darling Basin, Australia. *Marine and Freshwater Research*, *52*, 53–63. https://doi.org/10.1071/mf00018

Kaushal, S. S., Groffman, P. M., Likens, G. E., Belt, K. T., Stack, W. P., Kelly, V. R., Band, L. E., & Fisher, G. T. (2005). Increased salinization of fresh water in the northeastern United States. *Proceedings of the National Academy of Sciences*, *102*, 13517–13520. https://doi.org/10.1073/pnas.0506414102

Kaushal, S. S., Likens, G. E., Utz, R. M., Pace, M. L., Grese, M., & Yepsen, M. (2013). Increased river alkalinization in the eastern U.S. *Environmental Science & Technology*, *47*, 10302–10311. https://doi.org/10.1021/es401046s

Kaushal, S. S., Likens, G. E., Pace, M. L., Haq, S., Wood, K. L., Galella, J. G., Morel, C., Doody, T. R., Wessel, B., Kortelainen, P., Räike, A., Skinner, V., Utz, R., & Jaworski, N. (2019). Novel ‘chemical cocktails’ in inland waters are a consequence of the freshwater salinization syndrome. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *374*, 20180017. https://doi.org/10.1098/rstb.2018.0017

Kaushal, S. S., Likens, G. E., Pace, M. L., Reimer, J. E., Maas, C. M., Galella, J. G., Utz, R. M., Duan, S., Kryger, J. R., Yaculak, A. M., Boger, W. L., Bailey, N. W., Haq, S., Wood, K. L., Wessel, B. M., Park, C. E., Collison, D. C., Aisin, B. Y., Aaqob, I., … Woglo, S. A. (2021). Freshwater salinization syndrome: From emerging global problem to managing risks. *Biogeochemistry*, *154*, 255–292. https://doi.org/10.1007/s10533-021-00784-w

Kaushal, S. S., Likens, G. E., Pace, M. L., Utz, R. M., Haq, S., Gorman, J., & Grese, M. (2018). Freshwater salinization syndrome on a continental scale. *Proceedings of the National Academy of Sciences*, *115*, E574–E583. https://doi.org/10.1073/pnas.1711234115

Keeley, M., Koburger, A., Dolowitz, D. P., Medearis, D., Nickel, D., & Shuster, W. (2013). Perspectives on the use of green infrastructure for stormwater management in Cleveland and Milwaukee. *Environmental Management*, *51*, 1093–1108. https://doi.org/10.1007/s00267-013-0032-x

Koch, B. J., Febria, C. M., Gevrey, M., Wainger, L. A., & Palmer, M. A. (2014). Nitrogen removal by stormwater management structures: A data synthesis. *Journal of the American Water Resources Association*, *50*, 1594–1607. https://doi.org/10.1111/jawr.12223

Lehmann, C. M. B., Bowersox, V. C., Larson, R. S., & Larson, S. M. (2007). Monitoring long-term trends in sulfate and ammonium in US precipitation: Results from the National Atmospheric Deposition Program/National Trends Network. In P. Brimblecombe, H. Hara, D. Houle, & M. Novak (Eds.), *Acid rain - Deposition to recovery* (pp. 59–66). Springer.

Li, L., & Davis, A. P. (2014). Urban stormwater runoff nitrogen composition and fate in bioretention systems. *Environmental Science & Technology*, *48*, 3403–3410. https://doi.org/10.1021/es4055302

Liu, X., Zhang, G., Zhang, J., Xu, Y. J., Wu, Y., Wu, Y., Sun, G., Chen, Y., & Ma, H. (2020). Effects of irrigation discharge on salinity of a large freshwater lake: A case study in Chagan Lake, northeast China. *Water*, *12*, 2112. https://doi.org/10.3390/w12082112

Ledford, S. H., Lautz, L. K., & Stella, J. C. (2016). Hydrogeologic processes impacting storage, fate, and transport of chloride from road salt in urban riparian aquifers. *Environmental Science & Technology*, *50*, 4979–4988. https://doi.org/10.1021/acs.est.6b00402

Likens, G. E., & Buso, D. C. (2012). Dilution and the elusive baseline. *Environmental Science & Technology*, *46*, 4382–4387. https://doi.org/10.1021/es3000189

Lopez-Cantu, T., & Samaras, C. (2018). Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, *13*, 074006. https://doi.org/10.1088/1748-9326/aac696

McLeod, A. I. (2011). *Kendall. R package version 2.2.0*. https://cran.r-project.org/web/packages/Kendall/index.html

McPhillips, L. E., & Matsler, A. M. (2018). Temporal evolution of green stormwater infrastructure strategies in three US cities. *Frontiers in Built Environment*, *4*, https://doi.org/10.3389/fbuil.2018.00026

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S., & Dearden, R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology*, *515*, 59–70. https://doi.org/10.1016/j.jhydrol.2014.04.011

Moore, J., Bird, D. L., Dobbis, S. K., & Woodward, G. (2017). Nonpoint source contributions drive elevated major Ion and dissolved inorganic carbon concentrations in urban watersheds. *Environmental Science & Technology Letters*, *4*, 198–204. https://doi.org/10.1021/acs.estlett.7b00096

Moore, J., Fanelli, R. M., & Sekellick, A. J. (2020). High-frequency data reveal deicing salts drive elevated specific conductance and chloride along with pervasive and frequent exceedances of the U.S. environmental Protection Agency aquatic life criteria for chloride in urban streams. *Environmental Science & Technology*, *54*, 778–789. https://doi.org/10.1021/acs.est.9b04316

Multi-Resolution Land Characteristics Consortium (MRLCC). (2022). *National land cover database*. https://www.mrlc.gov/data

Northeast Regional Climate Center (NRCC). (2022). *Monthly/seasonal climate summary tables*. http://www.nrcc.cornell.edu/regional/tables/tables.html

National Water Quality Monitoring Council (NWQMC). (2022). *Water quality data portal*. https://acwi.gov/monitoring/waterqualitydata.html

Oberhelman, A., & Peterson, E. W. (2020). Chloride source delineation in an urban-agricultural watershed: Deicing agents versus agricultural contributions. *Hydrological Processes*, *34*, 4017–4029. https://doi.org/10.1002/hyp.13861

Pellerin, B. A., Stauffer, B. A., Young, D. A., Sullivan, D. J., Bricker, S. B., Walbridge, M. R., Clyde Jr., G. A., & Shaw, D. M. (2016). Emerging tools for continuous nutrient monitoring networks: Sensors advancing science and water resources protection. *Journal of the American Water Resources Association*, *52*, 993–1008. https://doi.org/10.1111/1752-1688.12386

Perera, N., Gharabaghi, B., & Noehammer, P. (2009). Stream chloride monitoring program of city of Toronto: Implications of road salt application. *Water Quality Research Journal*, *44*, 132–140. https://doi.org/10.2166/wqrj.2009.014

Pohlert, T. (2020). *trend. R package version 1.1.4*. https://cran.r-project.org/web/packages/trend/index.html

Raspati, G. S., Azrague, K., & Jotte, L. (2017). *Review of stormwater management practices*. SINTEF.

Rengasamy, P. (2006). World salinization with emphasis on Australia. *Journal of Experimental Botany*, *57*, 1017–1023. https://doi.org/10.1093/jxb/erj108

SanClements, M. D., Oelsner, G. P., McKnight, D. M., Stoddard, J. L., & Nelson, S. J. (2012). New insights into the source of decadal increases of dissolved organic matter in acid-sensitive lakes of the northeastern United States. *Environmental Science & Technology*, *46*, 3212–3219. https://doi.org/10.1021/es204321x

Scarlett, R. D., McMillan, S. K., Bell, C. D., Clinton, S. M., Jefferson, A. J., & Rao, P. S. C. (2018). Influence of stormwater control measures on water quality at nested sites in a small suburban watershed. *Urban Water Journal*, *15*, 868–879. https://doi.org/10.1080/1573062X.2019.1579347

Schwanghart, W., & Scherler, D. (2014). TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences. *Earth Surface Dynamics*, *2*, 1–7. https://doi.org/10.5194/esurf-2-1-2014

Siemion, J., McHale, M. R., Lawrence, G. B., Burns, D. A., & Antidormi, M. (2018). Long-term changes in soil and stream chemistry across an acid deposition gradient in the northeastern United States. *Journal of Environmental Quality*, *47*, 410–418. https://doi.org/10.2134/jeq2017.08.0335

Snodgrass, J. W., Moore, J., Lev, S. M., Casey, R. E., Ownby, D. R., Flora, R. F., & Izzo, G. (2017). Influence of modern stormwater management practices on transport of road salt to surface waters. *Environmental Science & Technology*, *51*, 4165–4172. https://doi.org/10.1021/acs.est.6b03107

Steele, M. K., & Aitkenhead-Peterson, J. A. (2011). Long-term sodium and chloride surface water exports from the Dallas/Fort Worth region. *Science of the Total Environment*, *409*, 3021–3032. https://doi.org/10.1016/j.scitotenv.2011.04.015

Stets, E. G., Lee, C. J., Lytle, D. A., & Schock, M. R. (2018). Increasing chloride in rivers of the conterminous U.S. and linkages to potential corrosivity and lead action level exceedances in drinking water. *Science of the Total Environment*, *613–614*, 1498–1509. https://doi.org/10.1016/j.scitotenv.2017.07.119

Stets, E. G., Sprague, L. A., Oelsner, G. P., Johnson, H. M., Murphy, J. C., Ryberg, K., Vecchia, A. V., Zuellig, R. E., Falcone, J. A., & Riskin, M. L. (2020). Landscape drivers of dynamic change in water quality of U.S. rivers. *Environmental Science & Technology*, *54*, 4336–4343. https://doi.org/10.1021/acs.est.9b05344

Szklarek, S., Górecka, A., & Wojtal-Frankiewicz, A. (2022). The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution: A review. *Science of the Total Environment*, *805*, 150289. https://doi.org/10.1016/j.scitotenv.2021.150289

Thorslund, J., Bierkens, M. F. P., Oude Essink, G. H. P., Sutanudjaja, E. H., & van Vliet, M. T. H. (2021). Common irrigation drivers of freshwater salinisation in river basins worldwide. *Nature Communications*, *12*, 4232. https://doi.org/10.1038/s41467-021-24281-8

Timpano, A. J., Zipper, C. E., Soucek, D. J., & Schoenholtz, S. H. (2018). Seasonal pattern of anthropogenic salinization in temperate forested headwater streams. *Water Research*, *133*, 8–18. https://doi.org/10.1016/j.watres.2018.01.012

Trapletti, A., Hornik, K., & LeBaron, B. (2021). *tseries. R package version 0.10-49*. https://cran.r-project.org/web/packages/tseries/tseries.pdf

Ulloa-Cedamanos, F., Probst, A., Dos-Santos, V., Camboulive, T., Granouillac, F., & Probst, J.-L. (2021). Stream hydrochemical response to flood events in a multi-lithological karstic catchment from the Pyrenees Mountains (SW France). *Water*, *13*, 1818. https://www.mdpi.com/2073-4441/13/13/1818

United States Census Bureau. (2021). *Change in resident population of the 50 states, the District of Columbia, and Puerto Rico: 1910 to 2020*. https://www2.census.gov/programs-surveys/decennial/2020/data/apportionment/population-change-data-table.pdf

USEPA Source Water Protection Practices Bulletin. (2010). *Monitoring highway deicing to prevent contamination of drinking water* (Publication No. 816F10064). https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100N2UE.txt

Utz, R. M., Eshleman, K. N., & Hilderbrand, R. H. (2011). Variation in physicochemical responses to urbanization in streams between two Mid-Atlantic physiographic regions. *Ecological Applications*, *21*, 402–415. https://doi.org/10.1890/09-1786.1

Utz, R. M., Hopkins, K. G., Beesley, L., Booth, D. B., Hawley, R. J., Baker, M. E., Freeman, M. C., & Jones, K. L. (2016). Ecological resistance in urban streams: The role of natural and legacy attributes. *Freshwater Science*, *35*, 380–397. https://doi.org/10.1086/684839

Utz, R. M., Bookout, B. J., & Kaushal, S. S. (2020). Influence of temperature, precipitation, and cloud cover on diel dissolved oxygen ranges among headwater streams with variable watershed size and land use attributes. *Aquatic Sciences*, *82*, 1–16.

Vose, J. M., Peterson, D. L., & Patel-Weynand, T. (2012). Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the U.S. *(Gen. Technical Report No. PNW-GTR-870*). USDA, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/PNW-GTR-870

Yazdi, M. N., Scott, D., Sample, D. J., & Wang, X. (2021). Efficacy of a retention pond in treating stormwater nutrients and sediment. *Journal of Cleaner Production*, *290*, 125787. https://doi.org/10.1016/j.jclepro.2021.125787

Zampella, R. A., Procopio, N. A., Lathrop, R. G., & Dow, C. L. (2007). Relationship of land-use/land-cover patterns and surface-water quality in the Mullica River basin. *Journal of the American Water Resources Association*, *43*, 594–604. https://doi.org/10.1111/j.1752-1688.2007.00045.x

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