Establishing a Stream Salinization Monitoring Framework in the Susquehanna River Basin: Phase II

Publication No. 342

December 2024

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SUSQUEHANNA RIVER BASIN COMMISSION
NY ▪ PA ▪ MD ▪ USA

INTRODUCTION

Salt pollution and human-accelerated salinization of fresh water is increasing across North America, in what is commonly being referred to in the literature as freshwater salinization syndrome (Kaushal et al., 2018). Some estimates speculate that as many as 90% of the drainage areas in the United States have been impacted. The syndrome is caused by salt pollution (e.g., road deicers, irrigation runoff, sewage, potash), accelerated weathering and soil cation exchange, mining and resource extraction, and the presence of easily weathered minerals used in agriculture (lime) and urbanization (concrete) (Kaushal et al., 2018). Unless regulated and managed, the freshwater salinization can have significant impacts on ecosystem services such as safe drinking water, contaminant retention, and biodiversity.

The Susquehanna River Basin Commission (Commission) has a wealth of data throughout the basin that may be very useful in documenting increased salinization within the basin and monitoring its potential impacts on stream biota. Phase I of this study focused on historic data compilation and new data collection at 10 sites with historically high chloride concentrations and two reference sites. Phase III is underway and will focus more on data analysis including focus on long-term macroinvertebrate analysis at two sites with macroinvertebrate data and data collection post-salt spreading events. This report will present an overview of the Phase II findings.

SITE SELECTION PROCESS

Previously determined percentile ranks for chloride concentrations observed at sampling sites over long periods of time were first sorted. Then highly ranked chloride data (95th or higher percentile) were paired with available specific conductance data and evaluated in order to select sites where a majority of the conductance is driven by chloride and not some other ion or combination of ions. Priority was given to sites along transportation corridors as well as where continuous monitoring was already occurring as part of the Commission’s Continuous Instream Monitoring (CIM) network. Leveraging existing ongoing data collection as well as historical data was key to making this project happen within budget constraints. Two experiment sites (Baldwin, APAL) and one reference site (EBFC) were removed for Phase II due to low SpC and Cl levels throughout study period. Results of the decision matrix for sites selected are shown in Table 1 and the sites are shown with land use classes in Figure 1.

*Table 1. Results from Site Selection Decision Matrix (Reference Sites In Red) (Sites in Phase I only marked with *)*

Site	Drainage Area (mi²)	Type	Period of Record	R^2 Chl-SpC	# of Discrete Pairs	Max Cl Discrete (mg/L)	% Cl Below Detection
Moose Creek (Moose)	3.34	CIM - along transportation corridors	2011-2024	0.9452	66	152	0
Cayuta Creek (CAYT 1.7)	139.97	Long-term Dataset	1986-2024	0.9106	143	153	0
Apalachin Creek (APAL)*	42.87	CIM - along transportation corridors	2010-2023	0.8191	42	77.5	0
Baldwin Creek (Baldwin)*	35.53	CIM - along transportation corridors	2010-2023	0.685	45	54.3	2.22
Paxton Creek (PAXT 8.4)	11.18	Urban	1985-2024	0.658	21	274	0
South Branch Tunkhannock Creek (SBTK)	70.3	CIM - along transportation corridors	2010-2024	0.6212	65	96.8	0
Sing Sing Creek (SING 0.9)	35.7	CIM - along transportation corridors	2000-2024	0.524	62	105	0
Deer Creek (Deer 44.2)	12.72	Long-term Dataset	1986-2024	0.4876	149	122	0
Beaver Creek (BEAV 1.9)	23.8	Urban	2016-2024	0.4256	26	148	0
Conodoguinet Creek (CONO35)	386.0	Urban	2018-2024	0.2416^	8	28.4	0
Trout Run (TROT)	32.78	CIM - Reference	2010-2024	NA	53	5.8	47
East Branch Fishing Creek (EBFC)*	12.55	CIM - Reference	2012-2023	NA	51	28.9	35

^One outlier point removed from analysis

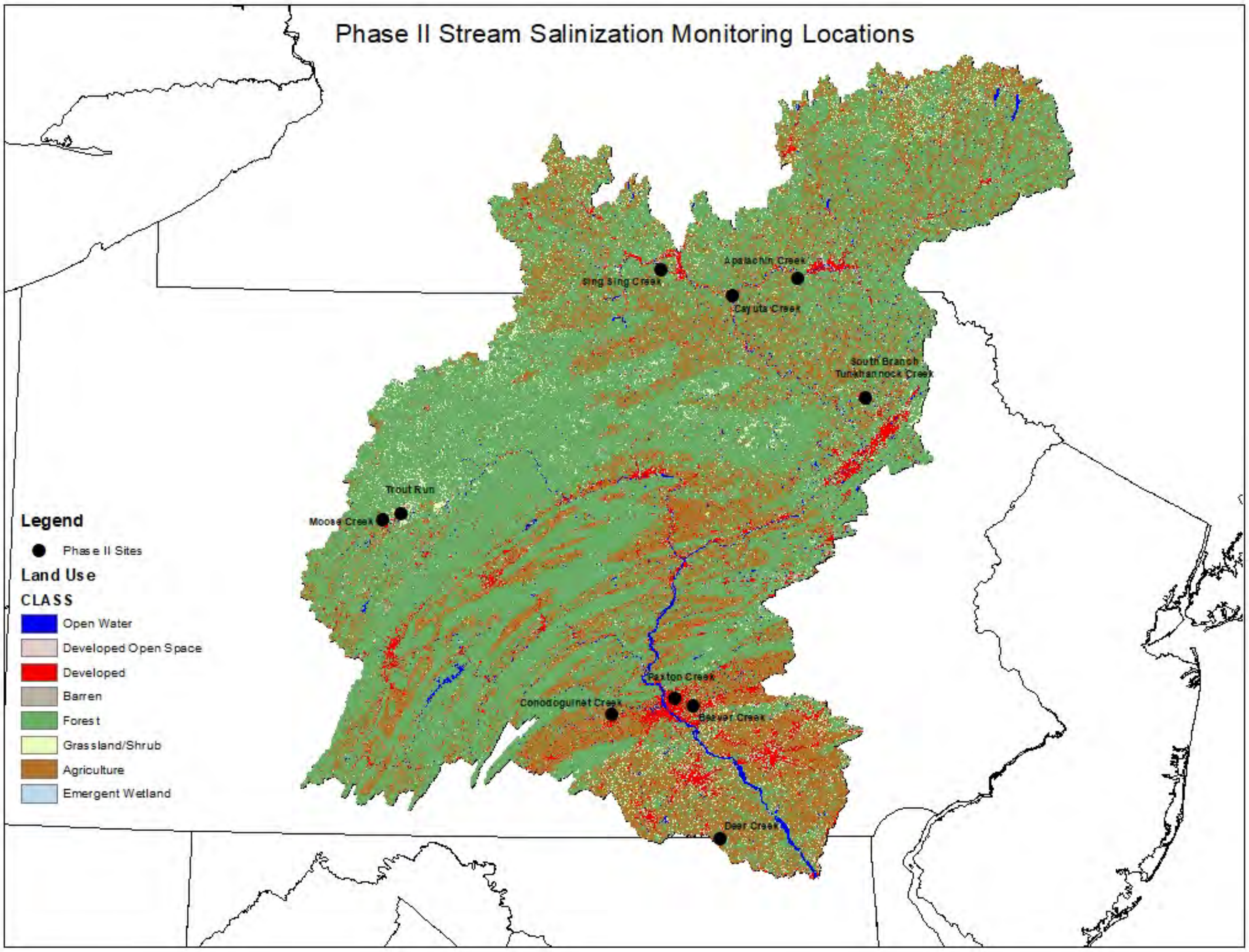

Figure 1. Map of Phase II Salinization Sample Sites with Land Use

SAMPLING METHODS

Sites were sampled monthly from October 2023 – May 2024 during primarily ambient conditions, with an additional winter storm sampling effort when conditions warranted. Most months, only parameters representing the "Development" category in the Susquehanna River Water Quality Index (Berry et al., 2020) were analyzed, including sodium, chloride, and sulfate. Three times per year, all major ions were analyzed in order to create Maucha plots to compare ion composition temporally and spatially. Water samples were collected using standard methods, including depth integrated sampling across the width of the stream, composited into a churn, and mixed well before filling bottles that were sent to Pace Laboratory for analysis. Field measurements were taken each sampling round using an YSI multi-meter and recorded for cross-checking with data collected from associated CIM sites.

A HOBO unit was deployed at sites that were not part of the CIM Network in October 2022. These standalone units continuously measured temperature and specific conductance. Data from HOBO units were downloaded every 4-6 months, and the unit was redeployed immediately. At BEAV 1.9, the HOBO became buried under sediment after the bank it was attached to collapsed during a storm over summer 2023. The HOBO was recovered 6/24/24 and redeployed the same day. Data from the period when the logger was buried in sediment were discarded as they did not reflect conditions in the surface water channel.

Flow records for calculating loads were largely synthesized from reference gage and drainage area ratio methods, but instantaneous flow measurements were taken at each site up to three times per year for additional checks on accuracy of estimated flows.

PRELIMINARY RESULTS

CIM Data and Chloride Estimations

Chloride concentration data alone are important, but calculating loads and yields by incorporating flow allows another level of interpretation by accounting for streamflow and drainage area. Mean concentrations across all experimental sites ranged from 23-129 mg/L, with a single sample maximum of 274 mg/L. Maximum yields (lbs/day/mi^2) across all experimental sites ranged from 1,265-45,837. Max yields occurred consistently in winter-early spring (Table 2). Alternatively, one reference site was sampled and had a mean chloride concentration of 1 mg/L and yields under 30 lbs/day/mi^2.

Table 2. Summary of Discrete Chloride Concentrations, Loads and Yields Across Phase II Sites, August 2022-May 2024

Experimental Sites	**Mean (Max) Cl (mg/L)**	**Mean Load (lbs/day)**	**Mean Yield (lbs/day/mi^2)**	**Max Daily Yield**	**Month of Max Yield**
Moose	26.8 (63.9)	3,260.1	976.1	2,737.0	April
Cayuta	23.1 (47.1)	24,758.5	176.9	1,264.6	January (storm)
Paxton	128.8 (274)	21,297.2	1904.8	21,337.3	February
South Branch Tunkhannock	39.4 (70.2)	28,989.7	412.4	21,76.5	January (storm)
Sing Sing	65.0 (89.2)	19,887.9	557.0	3,703.6	January (storm)
Deer	48.6 (62.2)	5,900.0	463.8	3,603.5	January (storm)
Beaver	60.2 (148)	19,454.8	817.4	5,365.4	January (storm)
Conodoguinet	34.5 (135)	61,908.3	162.6	45,836.9	January (storm)
Reference Site					
Trout Run	0.99 (1.4)	247.3	7.5	29.4	March

At sites where conductivity is highly correlated with chloride concentrations, it is possible to use continuous records of conductivity to examine the magnitude and duration of chloride concentrations after road salting events or other runoff episodes. Using continuous data from the CIM Network or recorded by a standalone HOBO unit, continuous estimates of chloride were created. Two examples of chloride concentration estimation are at Moose Creek and Deer Creek (Steffy, 2023).

Moose Creek

Moose Creek is a small forested watershed that receives significant road runoff from Interstate 80, west of Clearfield, PA. Estimate calculations from CIM records show Moose Creek often has a chloride concentration hovering around 50 mg/L, which already falls in the 95th percentile across the basin, but can experience peaks of over 200 mg/L primarily in the winter months (Figure 2).

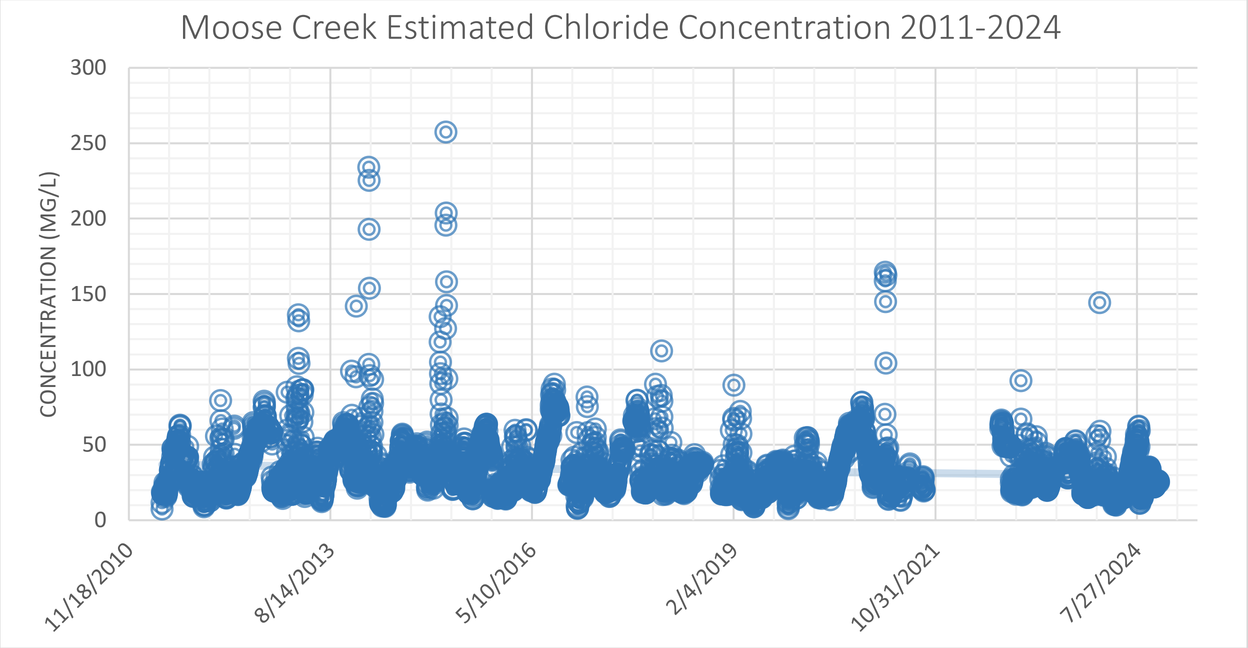

Figure 2. Continuous Estimated Chloride Concentrations at Moose Creek, 2011-2024

Other CIM sites such as South Branch Tunkhannock Creek in the greater Scranton area, and Sing Sing Creek, along Route 17 in the southern tier of New York State, show similar patterns across the last decade such as winter spikes, but the estimated concentrations of chloride are not as high.

Deer Creek

An example of a site where a HOBO was deployed in 2022 in order to provide a continuous record with which to document spikes in conductivity/chloride from road salt is Deer Creek along the Pennsylvania/Maryland border in Harford County, MD. Deer Creek empties into the Susquehanna River approximately 25 miles south east of the site, which sits near cropland and pasture in a rural area in northern Maryland. Continuous data from October 2022 – November 2024 show high consistent estimated chloride concentrations across all seasons (Figure 3). Highest spikes occurred during the winter of 2023 (March) and a targeted storm sample in January 2024. However, summer of 2024 saw smaller spikes in estimated chloride which may point to chloride being stored on the landscape or in soil and released into the stream during rain events long after the initial winter salt application.

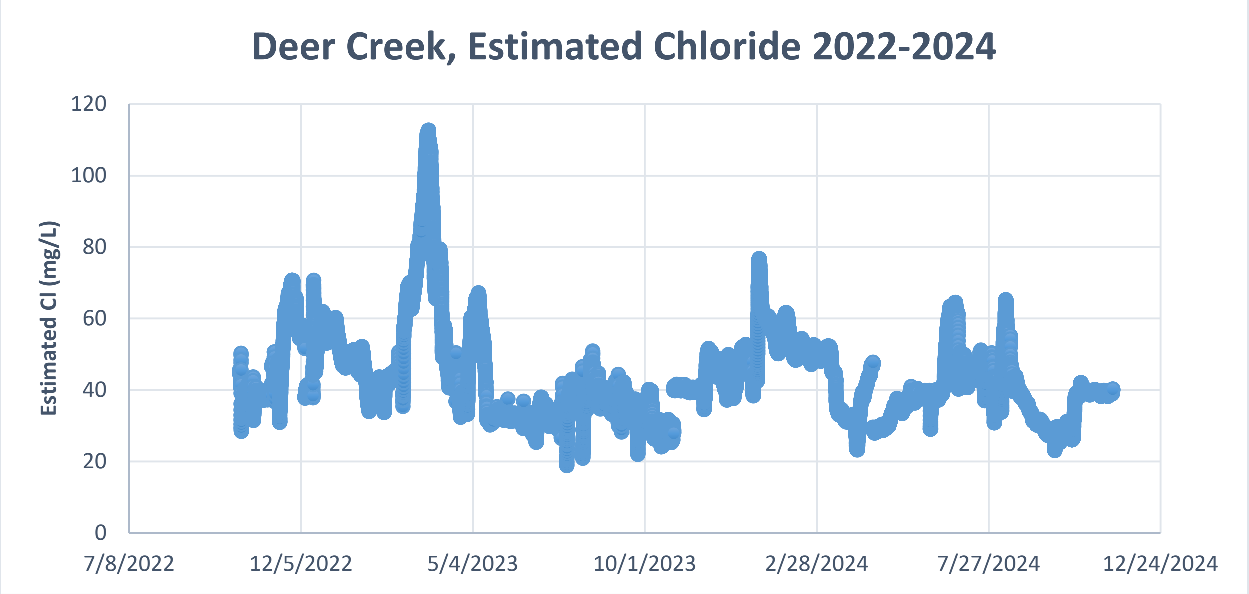

Figure 3. Continuous Estimated Chloride in Deer Creek, Derived from HOBO Conductivity Data 2022-2024

<u>Trout Run (reference site)</u>

At reference sites, estimated chloride rarely exceeded 10 mg/L over the period of record. An example is Trout Run, in Clearfield County, PA, where using CIM data back to 2010, estimated chloride concentrations rarely even exceeded 4 mg/L (Figure 4).

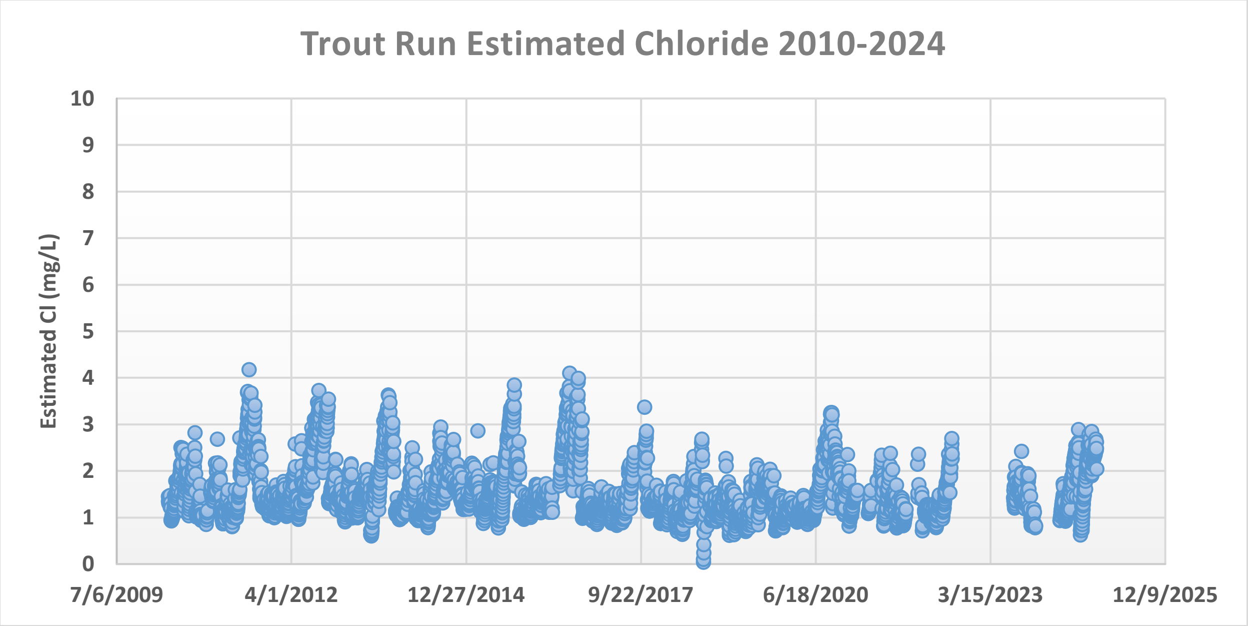

Figure 4. Estimated Chloride at Trout Run Reference Site, Derived from CIM Chloride Data, 2010-2024

Discrete Samples/Direct Measurements

Comparing the WQI Development scores for all sites for all samples collected from 2000-2023 (n ranges from 40-198) reveal a wide variation in scores. However, reference sites (EBFC and TROT) show less variation and score significantly higher than experimental sites. Unexpectedly, there was no significant difference between winter and non-winter WQI Development scores in experimental sites, which could indicate either consistent source of chloride even outside of winter months or the influence of sulfate in the calculations (sulfate is also included in WQI development category scoring)

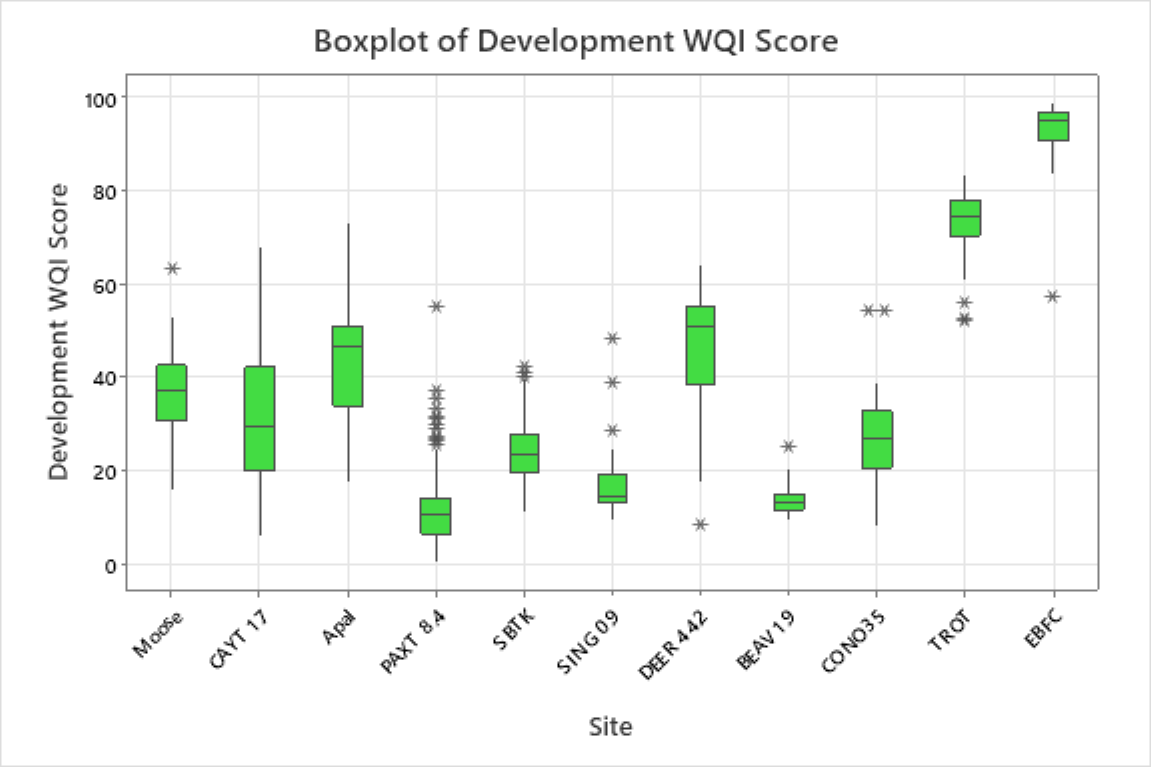

Figure 5. Boxplot of WQI Development Scores at Salinization Sites, 2000-2023

Maucha plots are symbolized ways to show the chemical composition of major ions in water. Each color represents a specific ion as shown in Figure 6. Key colors for salinization impacts are green for chloride and yellow for sodium.

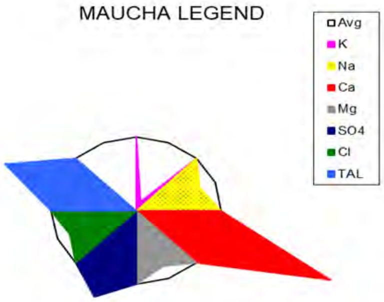

Figure 6. Legend for Maucha Plot Interpretation

Not every stream in the study reacts similarly to increased salt exposure. Below are two examples of how ions change in water samples over time and how that may be impacted by road salt. In Beaver Creek, measured chloride signals are strongest directly after a January rain event where salt or brine was applied and immediately ran off into the stream, and also the month following this event (Figure 7). Other winter samples and non-winter samples show calcium and alkalinity signals likely geological in nature as the underlying chemical signature of that stream.

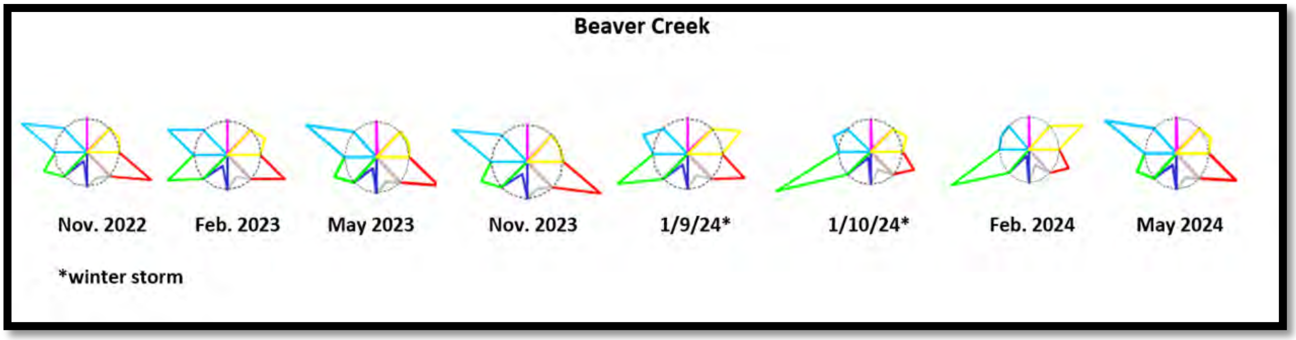

Figure 7. Time Series of Maucha Plots in Beaver Creek, 2022-2024

Moose Creek reacts much differently, as the sodium and chloride signals are quite strong regardless of season. This is likely a function of a couple of factors. First, the sandstone geology naturally leads to fewer ions in the water. However, decades of road salt runoff from Interstate 80 are impacting the chemical composition of the water. The signal is not quite as strong in summer months but they are still the dominant ions, indicating the potential of soil-bound sources of chloride leaching out during any rain event.

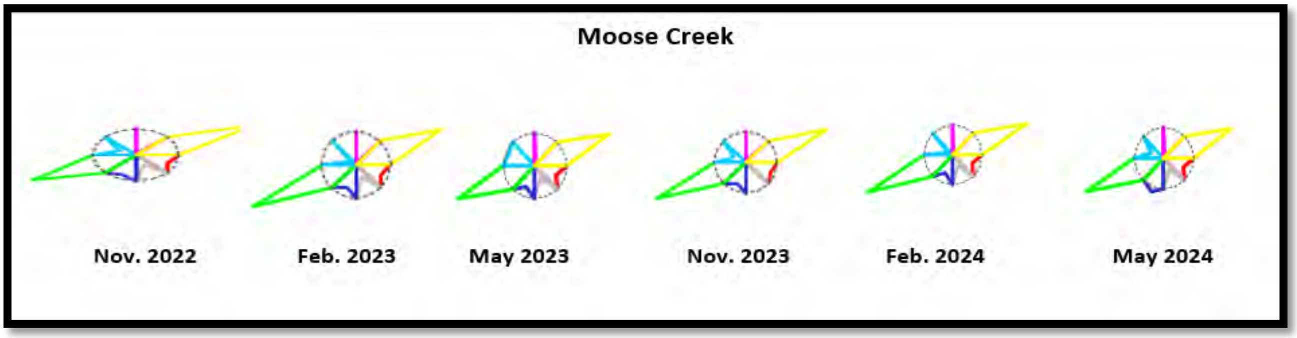

Figure 8. Time Series of Maucha Plots in Moose Creek, 2022-2024

Long-term Datasets

From 1986-2013, the Commission routinely collected water quality and macroinvertebrate samples in streams that crossed the state borders in the basin: Pennsylvania-Maryland and Pennsylvania-New York. Two of these sites, one on each border (Deer Creek and Cayuta Creek), were selected to be part of this study because of the long-term available dataset of discrete samples as well as the pattern of increasing chloride concentrations over the past three decades. Deer Creek, on the border of Maryland and Pennsylvania, in particular, shows a pattern of increasing chloride that is apparent, despite no samples being collected from 2014-2021 (Figure 9).

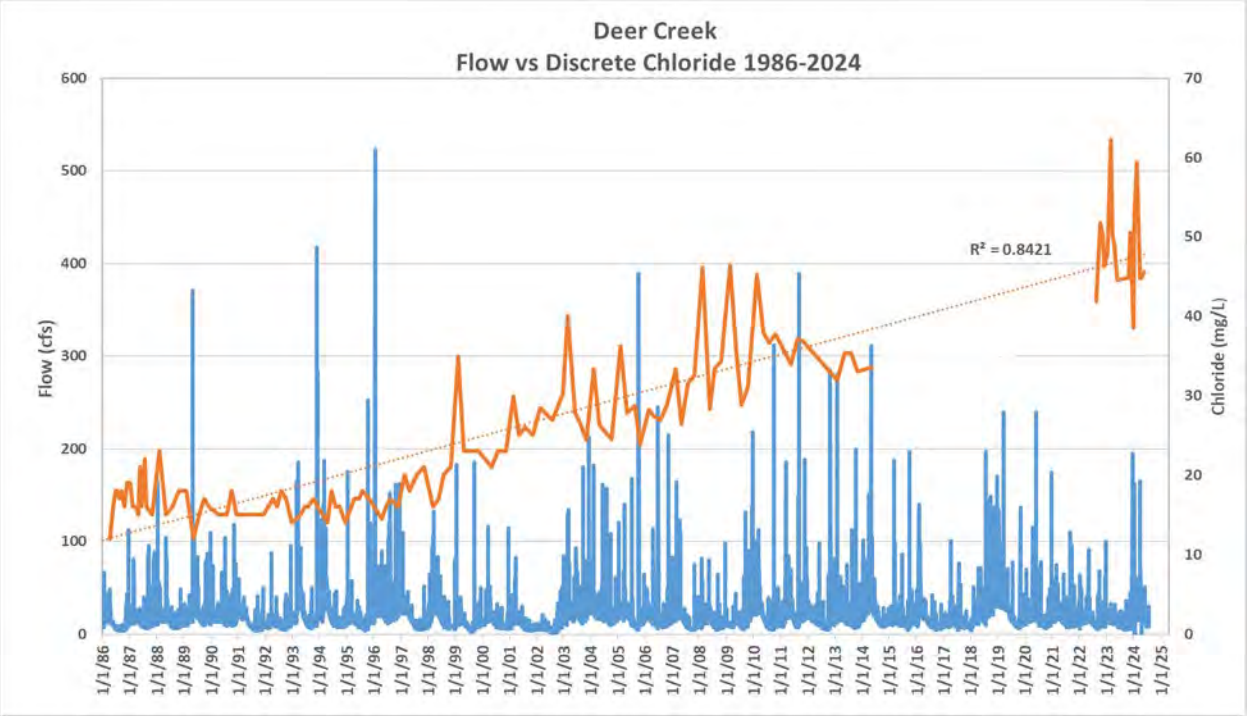

Figure 9. Long-term Record of Streamflow and Chloride at Deer Creek, 1986-2024 (Note: no samples were taken from 2014-2021)

Cayuta Creek is on the border of Pennsylvania and New York, in Sayre, PA, and has a similar long-term dataset to Deer Creek, although the increasing trend in chloride is not quite as strong (Figure 10). Cayuta Creek shows a stronger pattern of non-winter spikes in chloride which could be a result of chloride (e.g., residual salt piles) being stored on the landscape and entering the stream through runoff long after the salt was originally spread. Alternatively, there may be other significant sources of chloride besides road salt in the upstream catchment, particularly obvious in the 1980s-1990s. Overall the winter chloride concentrations are trending slightly up and the non-winter concentrations are trending down (Figure 11).

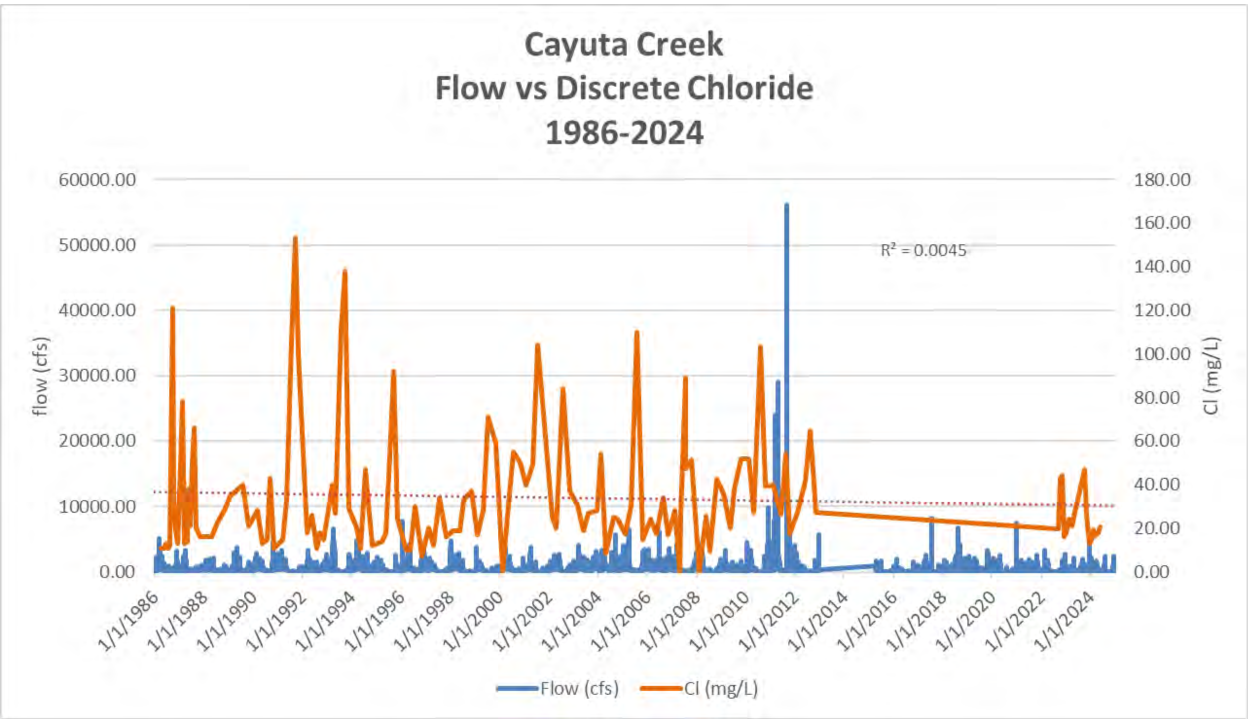

***Figure 10.** Long-term Record of Streamflow and Chloride at Cayuta Creek, 1986-2024 (Note: no samples were taken from 2014-2021)*

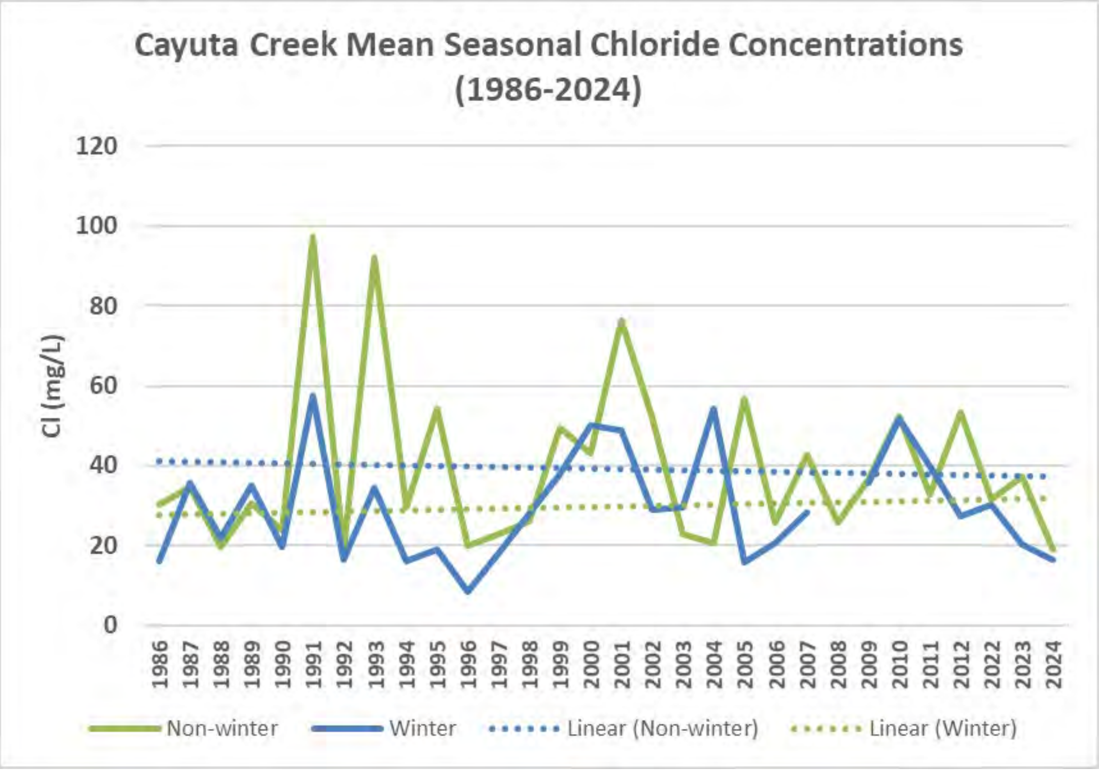

***Figure 11.** Long-term Seasonal Chloride Concentrations in Cayuta Creek*

Evaluating Shifts in Macroinvertebrate Communities

One of the goals for Phase II on the project was to take a closer look at the macroinvertebrate data from the past two decades at both Deer Creek and Cayuta Creek to evaluate if any changes in community structure can be attributed to increased salinization. Across all Phase II sites, as expected, macroinvertebrate IBI scores were strongly negatively correlated with chloride concentration (Figure 12). All macroinvertebrate samples were collected in the same index period.

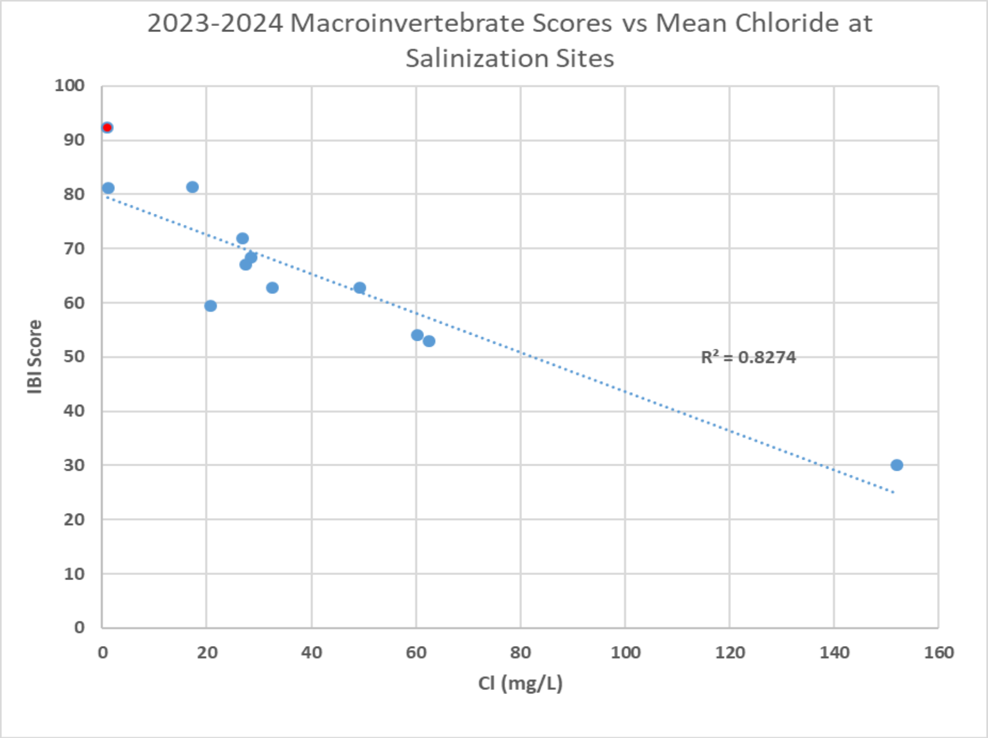

Figure 12. IBI Scores from Macroinvertebrate Samplings Versus Mean Chloride Concentrations Across Phase II Sites (Reference site (Trout Run) in red)

While low IBI scores are likely the result of a variety of stressors, sensitive taxa have been shown to decline with high chlorides, and communities will sometimes shift from mayfly-dominated to caddisfly-dominated in the presence of increasing chloride concentrations (Kefford and Papas, 2003). For the two sites with long-term datasets, an evaluation of macroinvertebrate community assemblage was completed to see if any shifts that could be linked to increasing chloride were observable. In Cayuta Creek, macroinvertebrate assemblages collected from 2000-2024 fell into three significantly different groupings. The most recent sample from 2024 was plotted with the majority of the historical samples (Figure 13), indicating no shift. Note that the 2023 sample was taken earlier in the season than the rest of the samples in the dataset and those differences are very likely related to index period. No noticeable shifts in salt-tolerant taxa were observed at Cayuta Creek over the past two decades.

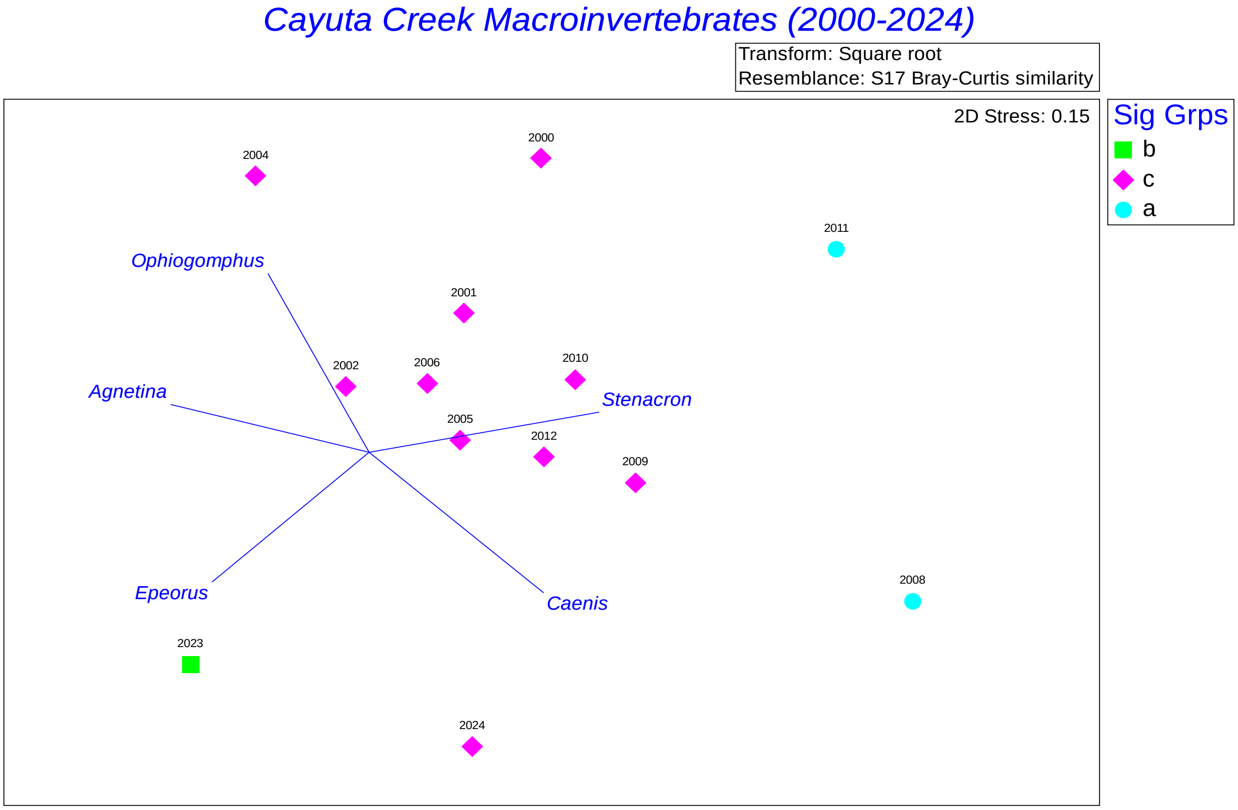

Figure 13. nMDS Plot of Macroinvertebrate Assemblage Similarity in Cayuta Creek from 2000-2024 (Each point represents a sample and the closer the points are to each other, the more similar the assemblage.)

In Deer Creek, where chloride concentrations are increasing, macroinvertebrate assemblages from 2000-2024 fell into two significantly different groupings, with the two most recent samples being significantly different from all prior years (Figure 14). However, the differences were not as expected: recent samples included more mayfly taxa (*Stenonema*, *Teloganopsis*, *Ephemerella*) with low tolerance values than historical samples. Samples were collected in the same index period although the last two years were earlier in the season than most older samples. Macroinvertebrate assemblages in Deer Creek do not appear to be shifting towards more salt-tolerant taxa despite increasing chloride concentrations. In fact, recent samples included more salt-intolerant mayfly taxa than historical samples.

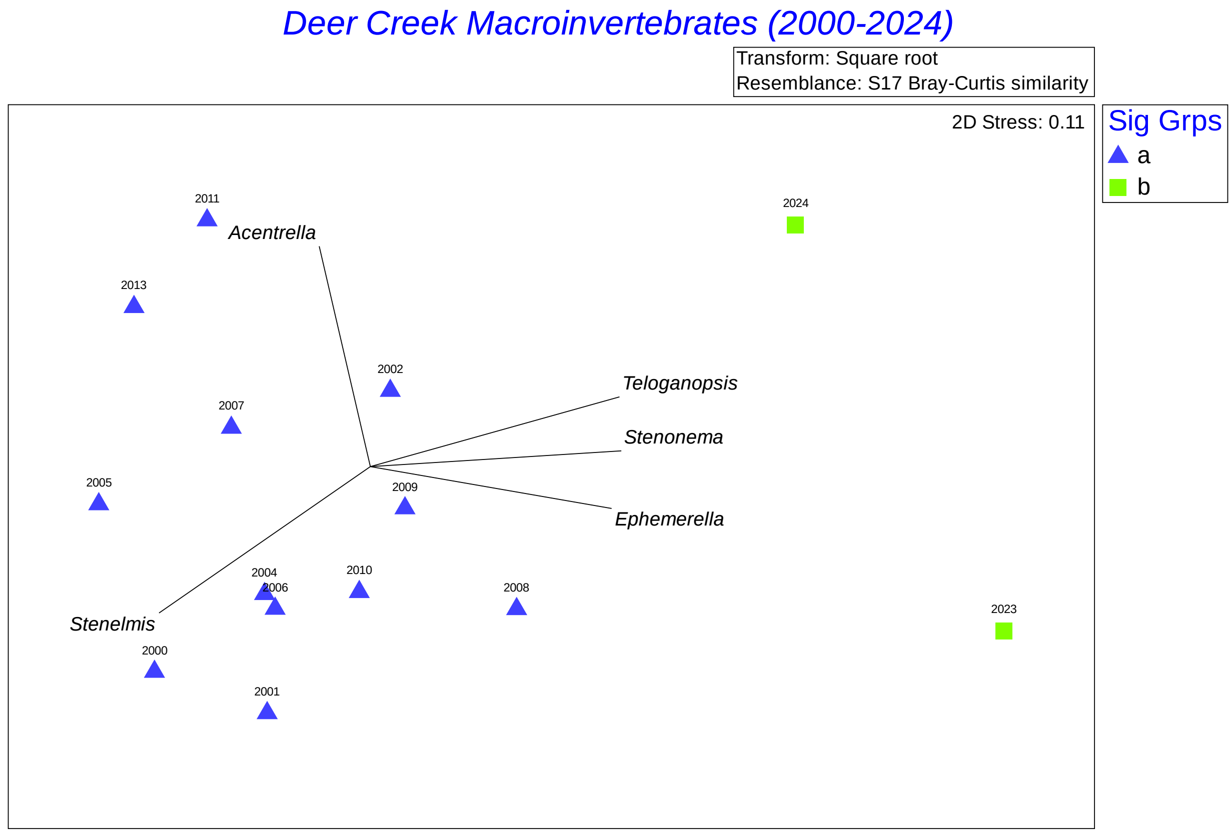

Figure 14. nMDS Plot of Macroinvertebrate Assemblage Similarity in Deer Creek from 2000-2024 (Each point represents a sample and the closer the points are to each other, the more similar the assemblage.)

Land Use and Road Salt and Brine Application Impacts

Another addition to Phase II was a deeper dive into changes in land use within the experimental watersheds and to determine if increased development was correlated with increased chloride concentrations or increased road salt application. Alternatively, if developed land use remained fairly constant, is more road salt being applied to the same amount of impervious surface. Mean chloride concentration was highly correlated with percent developed land use in the watershed (Table 3). The increase in chloride concentrations in Deer Creek that has been documented over the last nearly three decades (Figure 9) corresponds with a greater than 50% increase in developed land use in the watershed since 2006. Paxton Creek and Beaver Creek Watersheds are both greater than 30% developed, and while each has shown increasing chloride concentrations, there may be other sources of chloride besides road salting.

Table 3. Summary of Current Developed Land Use and % Change since 2006 (red font indicates reference sites)

Site	% Total Development	% Change 2006-2021	Mean Chloride (mg/l)
Paxton Creek	47.00%	12.43	143.1
Beaver Creek	30.31%	13.72	63.2
Deer Creek	11.88%	53.19	62.2
Sing Sing Creek	8.86%	30.16	60.4
Conodoguinet Creek	6.65%	46.95	26.9
South Branch Tunkhannock Creek	5.45%	3.03	29.5
Moose Creek	2.74%	-12.88	20.1
Cayuta Creek	1.94%	21.58	21.1
Apalachin Creek	1.18%	72.84	21
Baldwin Creek	1.07%	114.11	28
Trout Run	0.37%	440.62	2.1
East Branch Fishing Creek	0.01%	-71.43	1.4

Salt and brine application and how and if it is tracked varies widely across state and local jurisdictions. After numerous freedom of information requests, state departments of transportation (PADOT, NYDOT) sent some records of salt and brine application for roads proximate to salinization study sites for 2021-2024. For each year, data were recorded from the first salting event of the season (usually November) through the last salting event (usually April) of the following spring. The quantitative information obtained applied primarily to state roads and was in a variety of recorded formats (county application totals, exit to exit application rates on state highways, etc.). Consequently, GIS state road layers and watershed catchments were used to create a best judgement calculation of how much salt (in tons) and brine (in gallons) was applied to roads within the upstream catchment to each sample site. Data were not available for sites in Chemung County or Maryland. It was a challenge to create meaningful analysis from the salt application data given that any salt/brine applied on non-state roads is not included, but a few things were notable. The watersheds with the highest concentrations and loads of chloride are not always the same watersheds where the most salt is applied. The proximity of the roads to the stream is a critical piece not accounted for in this rough analysis. In general, as would be expected, the amount of salt and brine applied to state roads varies somewhat by year and the biggest watersheds receive the highest application (Table 4).

Table 4. Summary of Estimated Salt and Brine Applied on State Roads in Each Watershed

Site	**Estimated 2021 Salt Total in Watershed (Tons)**	**Estimated 2021 Brine Total in Watershed (gal)**	**Estimated 2022 Salt Total in Watershed (Tons)**	**Estimated 2022 Brine Total in Watershed (gal)**	**Estimated 2023 Salt Total in Watershed (Tons)**	**Estimated 2023 Brine Total in Watershed (gal)**	**Mean Chloride (mg/L)**
SB Tunkhannock	3,149	40,915	3,063	65,661	2,231	48,079	30
Conodoguinet	2,907	49,431	1,505	40,879	2,464	41,750	27
Cayuta	14	265	718	1,764	503	415	21
Beaver	452	5,878	186	6,483	471	8,078	63
Paxton	308	4,011	127	4,424	321	5,512	143
Moose	46	1,845	44	1,976	31	1,367	20
Trout Run	*87*	*87*	*82*	*3,714*	*59*	*2,569*	*2*

When normalizing total amount of salt or brine applied between 2021-2023 by drainage area, South Branch Tunkhannock receives the most salt and brine per square mile of drainage area (Figure 15). Paxton Creek, which is the most developed watershed, has the next highest amount of salt applied for its size. Moose Creek, which is the smallest watershed but gets substantial runoff from Interstate 80, receives a larger proportion of salt and brine than many other larger watersheds, and that is reflected in the large winter spike of chloride and conductivity observed in the winter (shown in Figure 3).

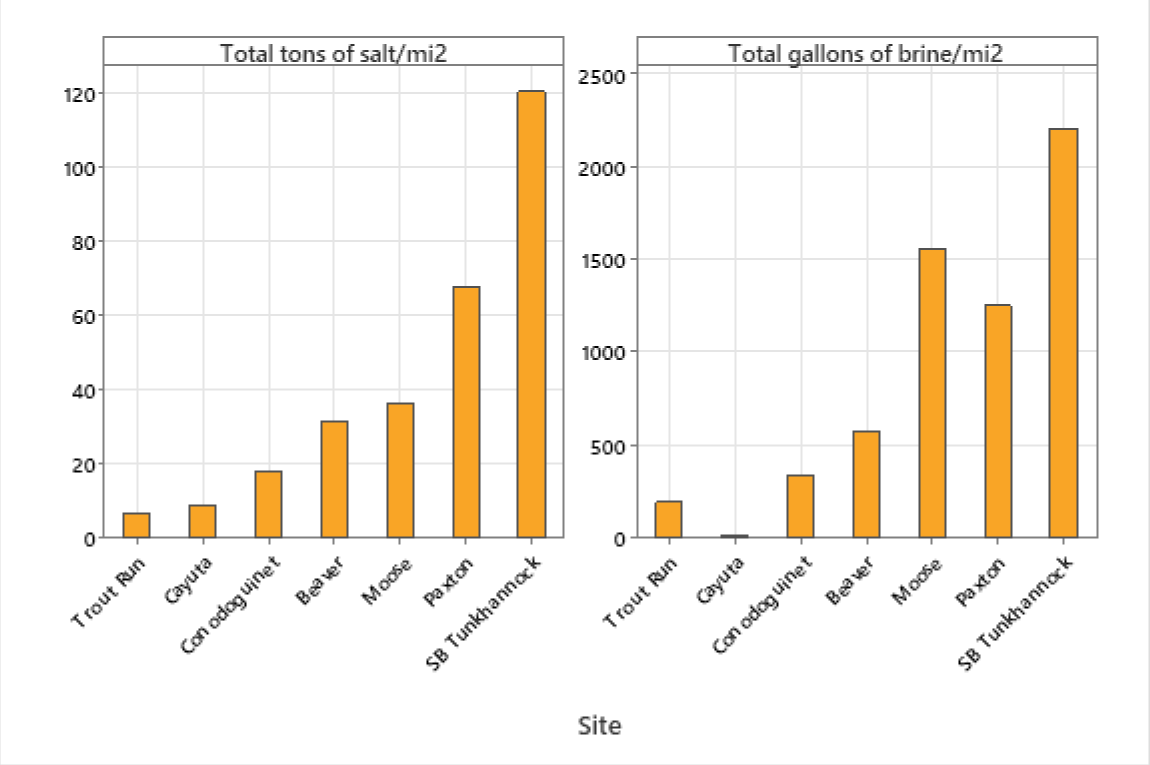

Figure 15. Normalized Salt and Brine Application Per Watershed, 2021-2023

DISCUSSION AND NEXT STEPS

The first year of this study (Phase 1) was intended to begin initial investigation into the viability and feasibility of creating a small network of sampling sites within the Susquehanna River Basin from which we can monitor chloride and specific conductance, develop a chloride estimation method from CIM data, determine chloride patterns and trends, and document and evaluate impacts of freshwater salinization. This was successfully completed through historical data mining, new data collection, and leveraging existing data to evaluate 10 streams that exhibited consistently high chloride concentrations with spikes in winter related to road salt runoff. Peaks are lasting 2-3 days in streams after significant runoff events and can occur with high frequency during winter months. Estimated concentrations of chloride occasionally briefly exceeded the drinking water standard of 250 mg/L after runoff events. Aquatic life criteria for chloride vary across states, but the current national guidelines recommend 230 mg/L as an aquatic life use threshold while some literature suggests impacts at lower concentrations (CCME, 2011; Hintz and Relyea, 2019).

Moving forward into Phase II, sites were pared down slightly to avoid redundancy (i.e., fewer sites along the same transportation corridor) and excluded where the chloride signal was not as consistent or predictable.

Phase III will sample 10 sites, including all sites in Phase II and sampling again at Baldwin Creek due to its presence along a transportation corridor and proximity to other sites (Sing Sing and Cayuta). All sites were sampled once in October or November 2024 for WQI analysis. Two additional samples will be collected at each site between December 2024 and March 2025, targeting post salting events as much as possible. One of those sample collections will be a full Maucha analysis to determine relative major ion proportions. Remaining samples will be analyzed for the Commission's "Development" categories (WQI) analysis.

Additionally, in Phase III, a focus effort will be made on capturing winter storm or runoff samples. This will allow for chloride concentrations to be directly measured in the lab along the runoff rise, peak, and fall for comparison to estimated concentrations obtained using continuous conductivity readings. We also plan to continue the analysis on impacts to biota looking at the long-term datasets and comparing communities from reference sites vs. sites with high chloride. Road salting application varies widely across state, regional, and local entities, but the Commission is attempting to obtain some level of information to how much salt is being spread. This may allow us to make inferences to what is happening instream. We appreciate the opportunity afforded by Commission internal funding to be on the cutting edge of this emerging topic in freshwater science and look forward to continuing the research.

ACKNOWLEDGEMENTS

Special thanks to Johanna Hripto for her assistance in much of the data compilation and initial analysis and to staff who assisted with field sampling efforts. Thanks to Kyle Kessler and Olivia Trombley for field sampling help, along with Monitoring & Protection Program interns Kaylyn Walters and Gerry Crispino. Thanks to Graham Markowitz for his help with reference gage selection for flow estimation.

This work was funded internally by the Susquehanna River Basin Commission and the authors thank the executive management team for their continued commitment to supporting new and timely research within the Susquehanna River Basin.

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