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Exploring the Freshwater Salinization Syndrome in Suburban Headwaters: Seasonal Ion Dynamics, Metal Speciation, and Regulatory Threshold Exceedances

STEVEN T GOLDSMITH[1], LIVIA G GRAHAM[1], DR. CHARLES A. CRAVOTTA III, PHD[2] AND STEPHEN M STRADER[1]

[1]Villanova University
[2]Cravotta Geochemical Consulting

The “freshwater salinization syndrome” (FSS), which refers to long-term increases in salinity, alkalinity, major-ion, and metal concentrations in surface waters, primarily because of the accumulation of salt (NaCl) applied for deicing of roads and parking areas, has a profound effect on downstream aquatic quality and drinking water resources. Yet, little is known about the timing of delivery and variability in concentrations of the Na, Cl, and associated solutes in suburban headwater streams. Furthermore, it is unclear how dynamic changes in salinity affect metal speciation, mobility, and toxicity to freshwater aquatic organisms. We hypothesized that (1) increases in FSS solutes would result from long-term, seasonal salt application to impervious surface cover (ISC) in the upstream areas, (2) the proportions of Na^+, Cl^-, and other ionic contributions to conductivity would vary as a function of %ISC in the upstream area, and (3) increases in %ISC would result in increased percentages of metal-Cl complexation. To test these hypotheses, we performed weekly sampling during October 2024 to September 2025 at headwaters and downstream points on four suburban streams in the greater Philadelphia, Pennsylvania area. Samples were analyzed for major cations (Na^+, NH_4^+, K^+, Ca^{2+}, Mg^{2+}), anions (Cl^-, Br^-, NO_3^-, SO_4^{2-}), and select trace metals (Cr, Mn, Cu, Zn, As, and Pb). A temporal analysis of FSS solute concentrations and specific conductance was performed to assess seasonal and shorter-term responses to the relative amount of ISC in the upstream area. Aqueous speciation modeling was performed to calculate the contributions of ions to conductivity and to determine the potential influence of Cl complexation on the mobility and bioavailability of trace metals in baseflow and winter stormflow. Lastly, we explored the frequency and timing of exceedances of Cl^-, Na^+, and trace metals above aquatic life and drinking water thresholds. Study results indicate that FSS solutes and effects on aquatic systems persist year-round in areas with highest %ISC and are directly related to variations in specific conductance. These findings contribute to the understanding of FSS solute origin and are applicable to other watersheds in temperate regions where road salt is applied during winter.