Salinity Management Assessment

BUREAU OF WATER SUPPLY

NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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1 EXECUTIVE SUMMARY

The New York City (NYC) Water Supply System provides drinking water to almost half the state's population, which includes over 8.5 million people in New York City and one million people in upstate counties.

Freshwater salinization originates from diverse anthropogenic and geologic sources. It affects water supplies directly through a measurable increase in sodium and chloride levels, and indirectly by increasing stress and/or mortality of freshwater organisms, thereby resulting in ecosystems losing their ability to provide clean water.[1] The issue is raising alarms, with a recent study warning that freshwater salinization could become an "existential threat" to freshwater supplies[2] if no action is taken. Numerous studies identify road salt as a primary driver of freshwater salinization in the U.S., along with additional anthropogenic sources like wastewater treatment plants (WWTPs) and agriculture.

In early 2021, the New York City Department of Environmental Protection (DEP) commissioned an internal Salinity Task Force (Task Force) to examine, measure, and understand salinity in the NYC watersheds and water supply, and develop recommendations to monitor and reduce salinity. The Task Force is comprised of Bureau of Water Supply (BWS) staff with expertise in water and wastewater operations, scientific analysis, watershed programs, water quality, and public policy.

By analyzing data going back to 1985, the Task Force found a sustained increase in chloride concentrations in all NYC reservoirs. The West of Hudson (WOH) watersheds have relatively low levels of chloride. This is not unexpected given the lower population, road, and parcel densities. The highest and most concerning increases are in the reservoirs located in the East of Hudson (EOH) watershed, particularly the Croton watershed. All Croton reservoirs flow into New Croton Reservoir and, therefore, Figure 1 is a useful representation of chloride levels in the EOH watersheds.

The analysis shows a range of increases among the EOH reservoirs, but all can be connected to anthropogenic causes: the use of road deicers in winter and WWTPs. Further analysis projects the estimated chloride concentrations in New Croton Reservoir to exceed the New York State (NYS) Sanitary Code maximum contaminant level of 250 mg/L by the year 2108.

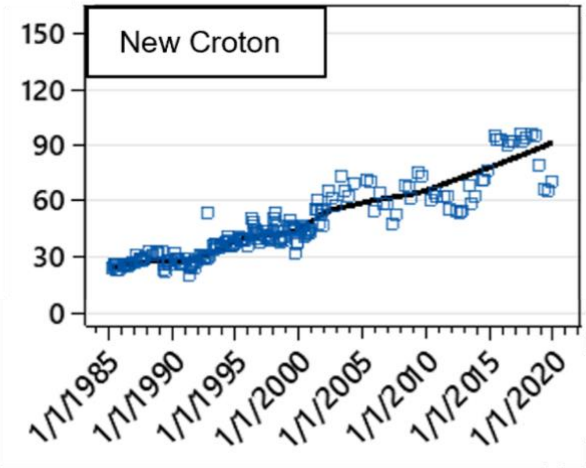

Figure 1: Temporal (1985-2019) chloride trend for New Croton Reservoir. Lines are LOWESS curves fitted through approximately monthly and quarterly data using a 30% smoothing factor.

Recommendations vary geographically as the severity of freshwater salinization is significantly different between the EOH and WOH watersheds. Given the substantial EOH chloride increases, the Task Force focused on the need to develop materials to communicate chloride trends to support policy initiatives and educate policy makers and the general public. Additional research is also recommended to understand the role that increased salinity may have on infrastructure and develop a chloride budget to understand relative contributions by source. Finally, BWS will closely track federal and state regulations for any reductions in sodium and chloride regulatory recommendations or limits.

2 INTRODUCTION

Freshwater salinization originates from diverse anthropogenic and geologic sources including road salts, human-accelerated weathering, sewage, urban construction, fertilizer, mine drainage, resource extraction, water softeners, saltwater intrusion, and climate change.[3] It affects surface water and groundwater supplies directly through a measurable increase in sodium and chloride levels, and indirectly by increasing stress and mortality of freshwater organisms, resulting in ecosystems losing their ability to provide clean water.[4]

This is an emerging issue for the New York City Water Supply System (Figure 2), which provides drinking water to almost half of New York State's population, including over 8.5 million people in New York City and one million people in upstate counties. It is comprised of three separate yet interconnected systems; the Catskill and Delaware systems are located primarily in the Catskill Mountain region, west of the Hudson River, and the Croton System is located in the lower Hudson Valley, east of the Hudson River. The City's drinking water is supplied from a network of 19 reservoirs and three controlled lakes. The total watershed area for the system is nearly 2,000 square miles, extending over 125 miles north and west of New York City.

Due to the very high quality of the Catskill/Delaware portion of the City's water supply system, it has met the criteria for waivers from the filtration requirements of the federal Surface Water Treatment from January 1993 to the present. The waiver is referred to as the Filtration Avoidance Determination (FAD).[5] The FAD requires implementation of NYC's extensive Watershed Protection Program, which limits sources of contamination, and maintains and enhances the high-quality of these surface water sources. The unfiltered nature of the NYC water supply leaves it vulnerable to ecosystem changes that can arise from freshwater salinization.

Three of the four Delaware watershed reservoirs are also located in the headwaters of the Delaware River Basin, the source water for millions of residents in New York, Pennsylvania, New Jersey, and Delaware. Management of water in the Delaware River Basin is of critical importance to the four states as well as New York City.

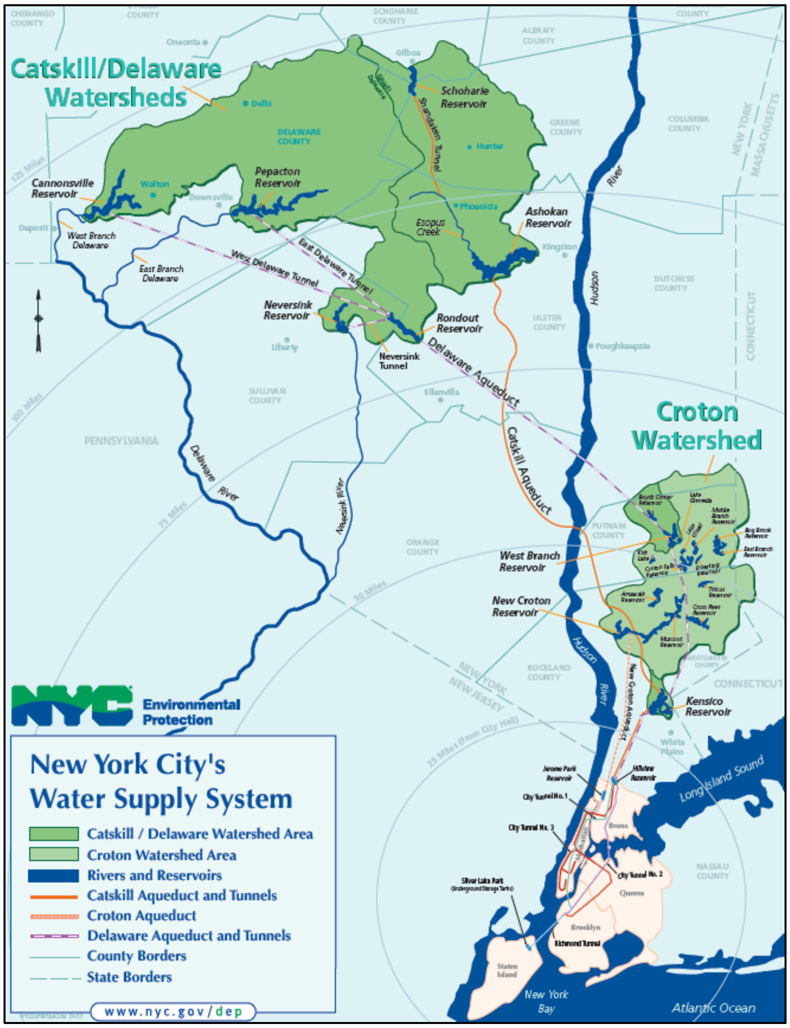

Figure 2: NYC Water Supply System.

2.1 Purpose and Need

Salinity is increasing in the NYC water supply, raising concerns of freshwater salinization as an emerging condition affecting the surface water supply for nearly 10 million New York residents. Groundwater chloride contamination is another important facet of freshwater salinization. Aquifers can retain salts for long periods of time and affect the baseflow of streams and reservoirs for decades.[6] Even if anthropogenic salt inputs are completely stopped, it can take some watersheds decades for chloride to flush out of the groundwater system.[7] [8]

Separately, salinity is not exclusively an issue that threatens surface and groundwater supplies, but also a factor that DEP considers in its operation of the NYC water supply system. For example, communities that draw their water from the Delaware River and Hudson River will need to contend with advancing salt fronts in the tidal portions of the rivers. This is of concern to NYC and especially downstream basin communities as part of the management of the Delaware River. Ambient chloride levels are also rising in the lower basin watersheds leading all users of the Delaware to take stock of their role and potential interventions to change those trends, including NYC's role in the upper part of the basin.[9]

2.2 Process

In 2021, DEP formed a Task Force, comprised of BWS staff with expertise in water and wastewater operations, scientific analysis, watershed programs, water quality, and public policy to develop a Salinity Management Assessment. This initiative was intended as a first step to better identify the drivers of increasing salinity in the City's water supply, and propose recommendations to address such drivers.

The Task Force established goals and objectives, conducted a literature review, and prepared an analysis based on over 30 years of data to evaluate freshwater salinization within the NYC water supply. The team also reviewed historical actions taken by DEP and convened a workshop to finalize recommendations and next steps. The Task Force recognizes the connected nature of water resources and incorporated this perspective into this document. Additionally, the Task Force examined case studies of salinity management in watersheds as well as inter-municipal management of dicing approaches and practices.

2.3 Problem Statement

Increasing freshwater salinization is an international and national trend that affects surface and groundwater resources.[10] NYC's watersheds are located in regions subject to various causes of freshwater salinization, including winter salt application for deicing, WWTP discharges, and agricultural practices.[11] [12]

2.4 Goals

The Task Force aims to examine, measure, and identify potential drivers of freshwater salinization in the NYC watersheds and water supply, and to make recommendations for next steps.

2.5 Objectives

- Conduct a literature review of peer-reviewed journals, federal and state reports and policies, think tank white papers, and best management practices.
- Develop a methodology and complete and maintain a trend analysis for salinity levels at the sub-basin level, including reservoirs and streams for WOH and EOH.
- Identify potential drivers of freshwater salinization.
- Create strategies to reduce salinity in the WOH and EOH water supply.

3 LITERATURE REVIEW

The widespread freshwater salinization threatens biodiversity and the services that ecosystems provide, [13] and therefore is of particular concern to DEP. The following discussion evaluates the various causes of freshwater salination and provides a screening analysis to identify those causes that may be active in the NYC watersheds. The review includes peer-reviewed journals, federal and state reports and policies, think tank white papers, and best management practices.

The potential effects of freshwater salinization are broad. This literature review focuses on environmental, health, and infrastructure impacts specific to the NYC water supply and research typically measures freshwater salinity via the concentrations of either sodium or chloride. The final section of the review focuses on alternatives and best practices related specifically to road salt application.

3.1 Causes

Freshwater salinization is an emerging water quality problem across the globe, and increases are primarily due to human activities including, but not limited to, urbanization, weathering of impervious surfaces, agricultural fertilizers, hydrologic alterations, irrigation, evaporative concentration, energy production, WWTP discharges, land clearing, landfills, and application of road salts. [14] [15] [16] [17] [18] [19]

Globally, research on freshwater salinization is centered in North America, Australia, and Europe.[20] Figure 3 illustrates the findings of Cunillera-Montcusi, et. al., which focused on the causes of freshwater salinization based on publications from 2017-2021, with North America leading overall research on this issue. A review of recent studies indicate that winter deicing is the primary cause of freshwater salinization in North America.[21]

The studies categorized as unknown drivers in Figure 3 are published papers that primarily focus on salinity as a secondary variable or characteristic. There were 34 publications included in this category across a wide variety of subjects, and all of them focused on the effects of freshwater salinization rather than its causes. Studies targeting systems with already high salinities due to natural causes are included in the category ‘natural salinity’.

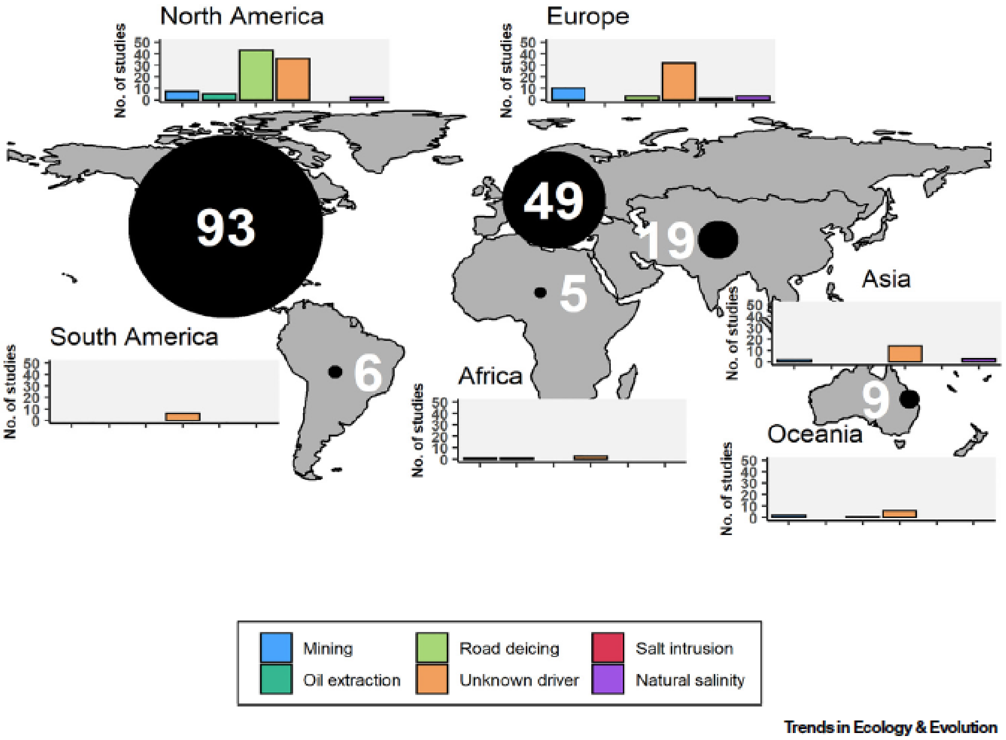

Figure 3: Global studies on salinization from 2017 to 2021. Circle size and white numbers correspond to the total number of studies conducted on each continent. [22]

In addition to Cunillera-Montcusí, et. al., numerous other studies identify road salt as a primary driver of freshwater salinization in the U.S. Road salt use has doubled since 1975 (Figure 4),[23] and additional studies show that since 1990 this accounts for 31% of the salt consumed each year.[24] While this trend corresponds to an increase in paved roads, it is critical to note that winter maintenance practices are also applied to parking lots, sidewalks, driveways, and service roads, too.[25]

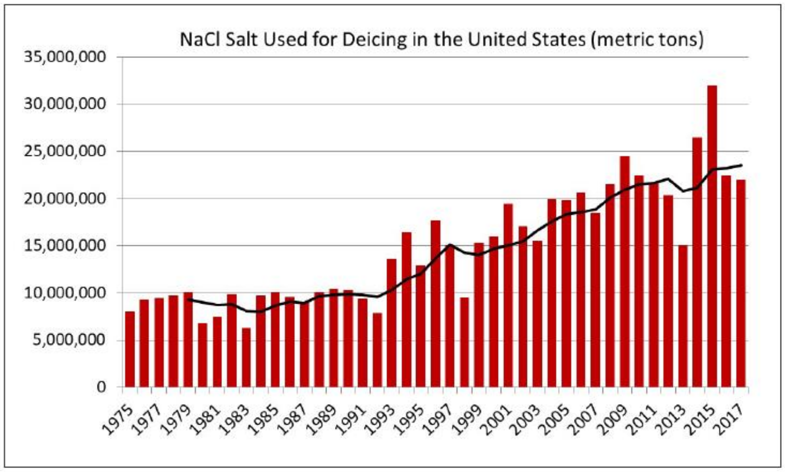

Figure 4: USGS, 2017, Salt statistics, in Kelly, T.D., and Matos, G.R., comps. Historical Statistics for Mineral and Material Commodoties in the United States: USGS Data Series 140.

Further analysis establishes that other anthropogenic sources of salinity could be associated with WWTP discharges and agricultural practices as described by Granto, et. al.[26] The predominant source of chloride in wastewater is from residential, commercial, and industrial sources including food waste, detergents, chlorine-based cleansers, and water softeners (especially in regions with drinking water that naturally contains a higher salt content).[27] Chlorine is also used to disinfect wastewater before discharging it to local recieving waterbodies.[28] [29] Additional chloride sources include industrial sources such as landfills and agricultural practices that include fertilizers, irrigation, and animal waste.[30]

3.2 Effects

This portion of the literature review outlines the environmental and public health effects of freshwater salinization, along with alternatives and best practices related to road salt application.

As noted above, freshwater salinization results from the culmination of several activities. Regardless of the cause, salinization of freshwater has numerous negative effects on the environment, ecology, and public health. For example:

- Acidification of streams.[31]
- Allowing for new saltwater tolerant species to establish communities.[32]
- Interference with the natural mixing of the lakes and reservoirs.[33]
- Mobilization of toxic metals through ion exchange.[34]

With regard to the NYC water supply, the implications of freshwater salinization intersect with the overall health of the watershed ecosystem that provides safe, clean water to almost half of New York State’s population.

3.2.1 Environment

Environmental transport and the ecological effects of salinity were explored as part of the literature review.

The process by which anthropogenic salinization affects freshwater sources is dynamic, and affects the ecosystem via individual organisms, the aquatic community, and ultimately, the entire ecosystem. Introducing anthropogenic sources of salinity in freshwater habitats affects the community’s ability to adapt and creates opportunities for new species to take over. The aquatic community must regulate its internal chemistry or it will become stressed and die.[35] [36]

The U.S. government acknowledges the potential for impacts to the environment, and the EPA sets both chronic and acute ambient water quality guidelines for chloride in the environment with respect to aquatic health. The chronic value is defined as a four-day average exceeding 230 milligrams per liter (mg/L) more than once every three years and the acute condition occurs when a one hour average exceeds 860 mg/L more than once every three years.[37] However, governmental limits and guidelines may not adequately protect the aquatic environment or freshwater sources of water supply over time, especially in the area of biodiversity degradation, including zooplankton loss and increases in algae.[38]

The difference between a recommendation and a regulation is enforceability. Recommendations are guidance levels with which compliance is encouraged, but not mandatory. By contrast, regulated mandatory levels are enforceable and exceedances of a regulated standard may prompt an enforcement action by the regulating body.

First, an understanding of how salts move through surface and groundwater is necessary to underpin how these inputs affect ecological health. When sodium and chloride are deposited in a drainage basin in the form of road salt or agricultural waste for example, a portion enters surface water through stormwater runoff, while the remainder infiltrates into soil, then into groundwater, and eventually to surface water (Figure 5). For example, in a drainage basin near Toronto, 45% of road salt is removed by overland flow annually, while 55% enters groundwater.[39] The rate at which sodium moves through the hydrologic cycle depends in part on soil and aquifer characteristics. In contrast, chloride moves more readily through the hydrologic cycle, but soil, organic matter, vegetation, and groundwater can all retain chloride for years.[40] [41] [42] [43]

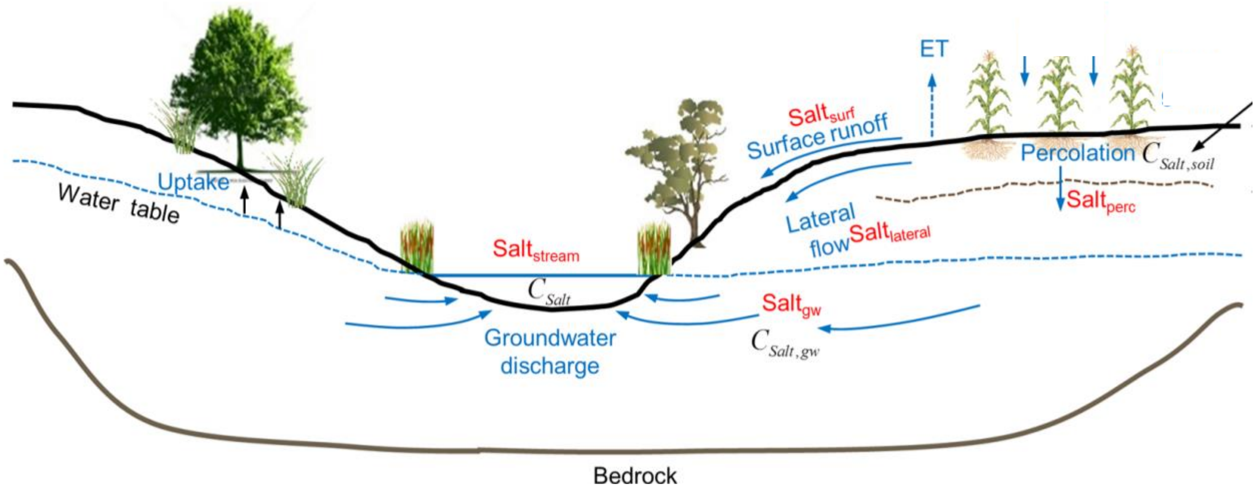

Figure 5: Salt transport through the environment. [44]

As a result, concentrations of sodium and chloride in surface water do not necessarily reflect the timing of inputs from seasonal road salt applications or pulses following precipitation events. For example, an analysis of multi-year samples taken from a watershed in Dutchess County, NY, found that concentrations of chloride increased across several years both in the winter and summer.[45] A similar study reported elevated chloride concentrations in several New York State streams during summer baseflows, suggesting accumulation of chloride in groundwater and then release to surface water.[46] Results on the timing of this lag vary: sodium concentrations did not decrease in a Rhode Island watershed 10 years after use was reduced or after decades-long population decline.[47] [48] Conversely, much shorter retention times are also possible depending on the size, geology and development of the watershed. For example, one modeling study predicted chloride retention of only up to six months in a small, urban watershed in New York State.[49] Accumulation in soil and groundwater may result in a dynamic cycle, where soil and groundwater first act as a net sink for sodium and chloride and then eventually a net source.

Research related to overall ecosystem function and the cascading or intersecting effects of freshwater salinization is less understood. Regardless of the time scale, increasing salinity in wetlands, streams, lakes, and reservoirs is believed to cause compounding detrimental effects on ecosystem function in both aquatic and wetland environments.[50] Increases in salinity can reduce populations and diversity of algae and zooplankton – a critical component of the freshwater ecosystem – allowing large populations of harmful or nuisance algae to cause blooms.[51] A cascading effect then moves up the food chain to larger species,[52] [53] and can cause decreases in the growth, reproductive capacity, and survival of sensitive amphibians.[54] [55] This is of considerable concern to DEP given that the City's water supply is largely unfiltered.

Figure 6 illustrates ecosystem, community, and species changes as road salt concentrations increase.[56] Notably, however, there is insufficient research to understand the full scope of ecological effects of freshwater salinization – most research is focused on specific species and fails to evaluate potential impacts on the larger food web, ecology, or watershed.[57]

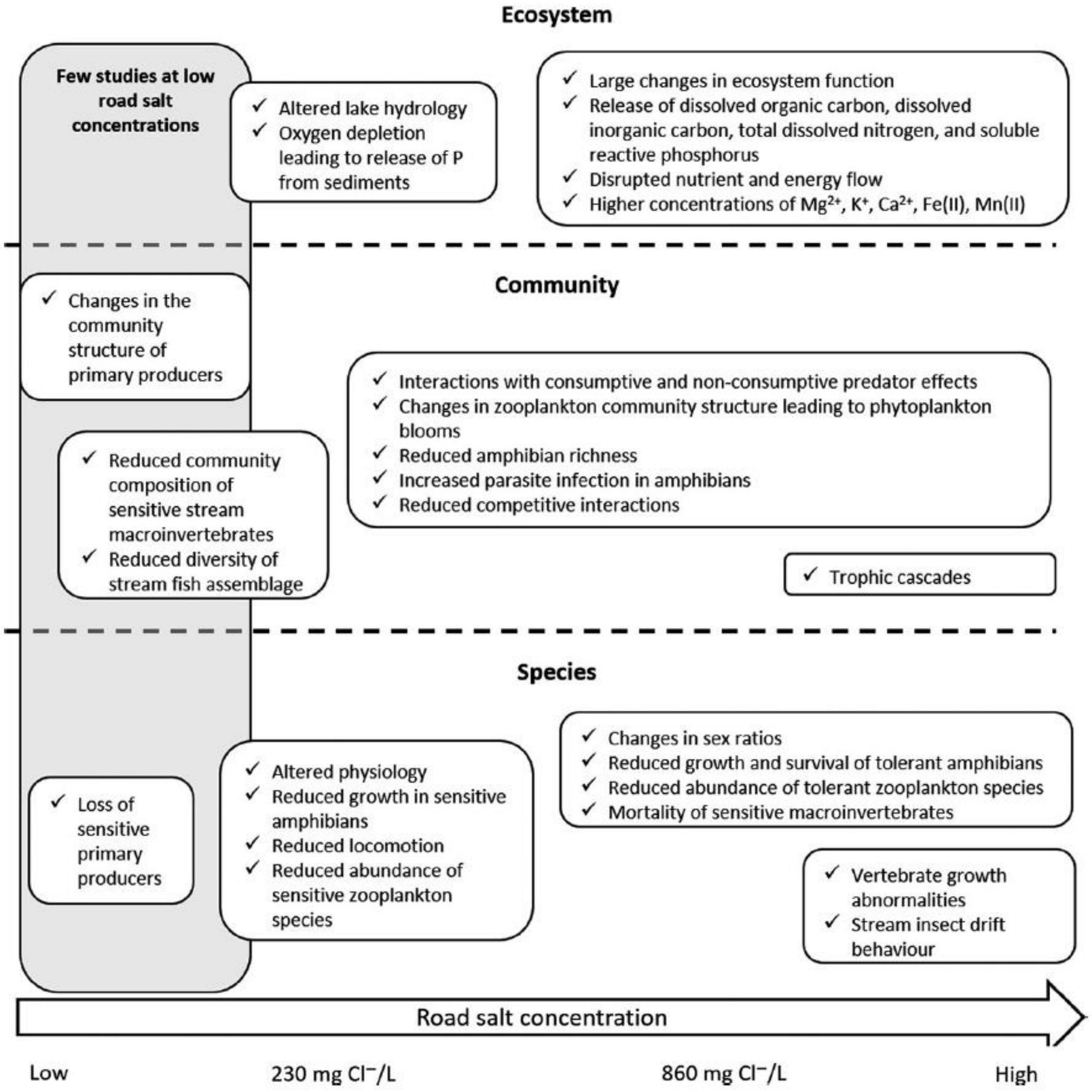

Figure 6: Species, community, and ecosystem effects of road salt salinization in fresh waters [58]

Finally, increased salinization can cause fundamental changes to stratification patterns of lakes, leading to sediment nutrient release and disrupted energy flow which can exacerbate eutrophication processes.[59] It can accumulate at the bottom of a freshwater lake or reservoir and inhibit turnover, the natural cycling of water caused by temperature changes.[60] This is a critical issue for surface water supplies because of its potential to cause harmful algal blooms and taste and odor issues.

3.2.2 Public Health

Freshwater salinization intersects with public health in several ways. Winter road deicers serve an important role in public safety by reducing the number of accidents, but water sources with high levels of salts may contribute to hypertension.

To that end, the U.S. Environmental Protection Agency's recommendation for sodium in drinking water is 20 mg/L, a figure based on the needs of individuals on very low (500 mg/day) sodium diets.[61] However, sodium levels are not federally regulated for surface drinking water sources. New York State does have a drinking water regulation for sodium: less than 20 mg/L.[62] As previously noted the difference between a recommendation and a regulation is enforceability.

New York State also regulates chloride in surface drinking water sources, and the regulated standard is 250 mg/L.[63] Additionally, EPA lists chloride on its table of secondary drinking water standards. These secondary drinking water standards are secondary maximum contaminant level (SMCL).[64] EPA's SMCL for chloride is also 250 mg/L.[65]

3.2.2.1 Lead

Modern water treatment involves using chemical additives for disinfection, coagulating solids, and inhibiting corrosion. The finished water provided by the utility must travel through public and private infrastructure to reach the end users. One challenge for water utilities is the release of lead from service line pipes into the water along the journey from the treatment operation to the kitchen sink. Anthropogenic increases in chloride can mobilize heavy metals such as lead,[66] [67] that can be found in older lead pipes on private property and in private homes.

Fortunately, NYC's source water is delivered from upstate reservoirs through lead-free aqueducts and water mains. While the use of lead in household plumbing has been banned for decades, some older homes may still have lead pipes and fixtures. To prevent lead from leaching from household plumbing, DEP treats the City's water supply by adjusting the pH and by adding orthophosphate, a common food additive, which forms a protective barrier on plumbing and is the most effective for lead reduction.[68]

3.2.2.2 Hypertension

A large body of evidence suggests that excessive sodium intake contributes to age-related increases in blood pressure and hypertension.[69] High blood pressure is associated with an increased risk of developing coronary heart disease, stroke, congestive heart failure, renal insufficiency, and peripheral vascular diseases. However, high blood pressure is a multifaceted disorder, and it is not possible to draw significant conclusions regarding sodium in drinking water and hypertension based on the current research.

3.2.2.3 Traffic Safety

Public safety is the primary driver for road salt application.[70] Snow and ice-covered roads pose a considerable threat to traffic safety.[71] Winter weather produces hazardous driving conditions which increase traffic deaths, injuries, and property damage. Road salt is used to increase traction on roads, parking lots, and walkways.

The use of road salt improves safety by lowering the freezing point of water so that ice and snow can be removed and reduces the frequency and severity of winter road accidents. A 1992 study found that the rate for all traffic accidents before salt spreading is about eight times higher than after.72 Furthermore, this study also noted that the severity of traffic accidents is approximately 30% higher before road salt application. Overall, the use of road salt reduced traffic accident costs by 85% and reduced the average cost of an accident by 30%.[73]

3.2.2.3.1 Best Practices

Given the road safety benefits of using road salt, a variety of products are available with various costs and levels of effectiveness. There are roughly a half-dozen to a dozen different types of chemicals and other treatments used for ice control in the greater New York area. The New York State Department of Transportation and many local municipalities use seven types of treatments depending on the snow/ice conditions, air temperature and pavement temperature. Table 1 below illustrates the relative financial costs and benefits of each.[74]

Product	**Relative Direct Cost**	**Effective Lower Limit (degrees F)**	**Corrosive?**	**Aquatic Toxicity**	**Other Environmental Impacts**
Road Salt or Rock Salt	Low	15	Yes	Moderate	Roadside tree damage
Potassium Chloride	Moderate	12	Yes	High	Potassium fertilization
Magnesium Chloride	Moderate	5	Yes	High	Magnesium addition to soil
Calcium Chloride	Moderate	-25	Very	Moderate	Calcium addition to soil
Calcium Magnesium Acetate (CMA)	High	-17	No	Indirect	Decreased aquatic oxygen
Potassium Acetate (KA)	High	-15	No	Indirect	Decreased aquatic oxygen
Sand	Low		No	Indirect	Sedimentation

Table 1: Comparison of Common Deicing Products[75]

Calcium magnesium acetate (CMA) and potassium acetate (KA) are the two most widely used treatments listed above. CMA is relatively harmless to plants and animals, and non-corrosive to metals and concrete, and is also effective as an anti-icer when applied prior to snow events.[76] KA is used as a base for commercial chloride-free liquid deicers. Its advantages include low corrosion, relatively high performance and low environmental impact. The downside to both is the cost: per ton, these chemicals are 10 to 15 times higher than the cost of traditional road salt.

Some deicers are less-commonly-used agricultural products like corn steepwater, cheese and pickle brine, fermentation byproducts (from beer and wine) and de-sugared molasses (from sugar beets). These are alternatives that also lower the freezing point of chloride-based salts and increase the amount of time salts remain on pavement, improve sunlight absorption, and reduce corrosivity of salt solutions. However, these deicers can release high levels of organic material into freshwater lakes and reservoirs, depleting oxygen, stimulating algae blooms, and killing fish.[77]

Best practices (listed below) are identified where the product type and method of application intersect and can limit the tons of road salt used each year:[78]

- Anti-icing using a low-proportion salt brine solution, which prevents snow and ice from bonding to the road surface. Anti-icing uses fewer chemicals and prevents snow and ice from bonding to the road surface; as a result, it makes it easier to achieve road maintenance goals, provides cost savings, and imposes less impact on the environment.
- Pre-wetting salt before roadway application can reduce infiltration to aquifers by 5% and allows it to bond better to the road, which minimizes spray and kick-up of salt grains.
- Calibrating equipment and utilizing variable application rates for salt distribution is an effective way to optimize application to ensure efficient deicing with less total salt used.
- Proper salt storage and operating protocols that include secondary containment, enclosures, and regular inspections to minimize salt loss and pollution.
- Creating networks of data on road and weather conditions between transportation officials and weather forecast providers can reduce the total road salt applied through targeted application.
- Pavement temperature sensors determine whether precipitation will bond to the roadway and if so, how much salt is needed to maintain safe driving conditions. Road and vehicle cameras can inform treatment requirements and defend operators.
- Improving plow types by using live-edge flexible plow blades that conform to uneven surfaces reduce the amount of road salt needed to maintain safe driving conditions.
- Several states adjust levels of service to conditions. For example, Vermont Agency of Transportation emphasizes “safe roads at safe speeds” over bare roads in winter. New Hampshire, Ohio, and Colorado similarly assign levels of service to roads based on traffic volume.
- No salt or low salt areas are located near sensitive freshwater bodies and well fields.

Best practices and alternatives have been implemented successfully in upstate and western New York, Vermont, Minnesota, Ohio, and Colorado.

3.3 Conclusions

Based on the Task Force’s review of the existing literature, salinization caused by winter deicing, WWTP discharges, and agricultural practices will be explored in the trends analysis. Mining, oil extraction, saltwater intrusion, and naturally occurring salts can be screened from further consideration given that they are not relevant to this analysis of the NYC water supply.

4 SALINITY TRENDS IN THE NYC WATERSHEDS

As discussed above, salinization caused by winter deicing, WWTP discharges, and agricultural practices are the likely primary contributors of salt to the NYC watersheds. The trends analysis utilized data collected by DEP along with publicly available data to analyze increases in salinization throughout the EOH and WOH watersheds. Chloride is the dissolution product of any chloride -containing salt solution, and is commonly used as an indicator of freshwater salinization.[79]

The analysis shows that chloride concentrations in NYC waters have increased across its nearly 2,000-square-mile watershed with the highest concentrations found in the EOH watershed in Westchester and Putnam counties.

4.1 Methodology

DEP monitors many water quality analytes in the reservoirs, reservoir releases, streams, and aqueduct keypoints[i] of the NYC Water Supply to ensure the reliable supply of clean, safe drinking water to consumers.

One routinely monitored analyte is chloride. As discussed above, chloride is commonly used as an indicator of freshwater salinization. In this report, DEP chloride data are used to show long-term chloride temporal trends and maps are provided to indicate chloride “hotspots” in the EOH and WOH systems. In addition, chloride data are compared to state and federal regulations and benchmarks. Finally, sub-basin chloride levels are regressed against sub-basin characteristics to help discern chloride sources in the NYC Water Supply.

Chloride trends over time are shown for DEP’s reservoirs and controlled lakes in both the EOH and WOH watersheds. The lines on the plots are locally-weighted scatterplot smoothing (LOWESS) curves, which are fitted to show chloride data to indicate the long term concentration trends from 1985 to 2019.[80] All available data[ii] was included – in some cases the reservoir samples used were collected at the surface, middle, and bottom depths in at least May, August, and November;[iii] for other reservoirs, monthly reservoir release data was used to show chloride trends.[iv]

In order to project future chloride levels, an estimate of the annual chloride increase was conducted using the seasonal Kendall slope estimator, a commonly used technique to estimate trend magnitude that accounts for seasonal differences and is outlier resistant.[81] Using this technique an annual rate of increase was estimated for New Croton Reservoir based on data collected from 1985-2019. The annual value was then applied to future years in a cumulative fashion to predict the year in the future when the median chloride concentration of New Croton Reservoir might exceed the New York State MCL of 250 mg/L.

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[i] Water supply intakes, reservoir elevation taps, and aqueduct sites.

[ii] Middle Branch Reservoir did not have chloride samples collected after 2010. Therefore, historic paired chloride and specific conductivity measurements were used to derive a linear regression to estimate chloride concentrations after 2010.

[iii] Pepacton, Cannonsville, Neversink, Rondout, Schoharie, Ashokan, Lake Gilead, Lake Gleneida, Kirk Lake, Middle Branch, Muscoot, New Croton Reservoirs. See figure 1.

[iv] Amawalk, Bog Brook/East Branch, Boyd Corners, Croton Falls, Cross River, Diverting, Titicus, West Branch

Next, a snapshot of recent chloride concentrations is presented to understand how current levels of chloride in the EOH reservoirs compare to federal and state guidelines and regulations. The EPA Aquatic Life Standard for acute exposure is based on a one-hour average while the standard for chronic exposure is based on a 4-day average. DEP samples are single grab samples. While grab samples are not analyzed under the EPA standards, to compare them to the standards can provide a general sense of current conditions in the NYC water supply. Chloride data were also compared to the New York State Sanitary Standard for drinking water in reservoirs that can distribute water directly into distribution.

Chloride concentrations were also evaluated with a regression analysis in an effort to identify potential causes or sources. This analysis was narrowed to sub-basins within the watersheds. More specifically, sub-basin median chloride concentrations calculated from samples collected from 2015-2019 were regressed against selected sub-basin characteristics to identify potential chloride sources.[82] Road density and impervious surface density were used as surrogates for deicers, parcel density as a surrogate for wastewater and water softener inputs, and agricultural density as a surrogate for fertilizer inputs.

Densities were further analysed by sub-basin and determined by dividing road length (km), impervious surface area (km^2), agricultural surface area (km^2), and parcel counts by the total surface area (km^2) of each sub-basin. Sub-basin land use characteristics were calculated using GIS tools and the DEP 2009 Land Use and Land Cover dataset. Annually-updated parcel boundary data was acquired from counties located within the NYC Water Supply watersheds. Road data was acquired from the New York State Department of Transportation, which was last updated in October 2020.

Finally, chloride spatial patterns for the EOH and WOH watersheds were determined using the median chloride results from 2015-2019. Spatial patterns were displayed on EOH and WOH watershed maps using different colors to represent different chloride concentration ranges.

4.2 Chloride – EOH

Chloride concentrations are increasing EOH. The analysis discusses this increase and conducts a regression analysis in an effort to determine drivers. Finally, a spatial analysis provides geographic resolution of chloride levels to identify locations of concern for future investigations.

EOH chloride concentrations from 1985-2019 are illustrated in Figure 7. Increasing chloride concentrations are apparent for all reservoirs and controlled lakes in the EOH System, with Kensico and West Branch showing lower overall concentrations and increases as they receive the majority of their water from WOH diversions. The variation in annual increase could be attributed to numerous factors such as watershed size, precipitation patterns, changes in groundwater chloride, degree of development, road deicer application rates and, in the case of West Branch (and to a lesser extent Croton Falls), changes in reservoir operations. West Branch Reservoir receives variable amounts of water from Rondout Reservoir in the City's WOH watershed, which has comparatively lower levels of chloride. After entering West Branch, water is then released via the West Branch of the Croton River to Croton Falls Reservoir, similarly reducing relative chloride levels as compared to other EOH reservoirs.

The higher rate of increase in the EOH watersheds may be due to higher road density, impervious surface area, and population with associated wastewater inputs as compared to the WOH watersheds.

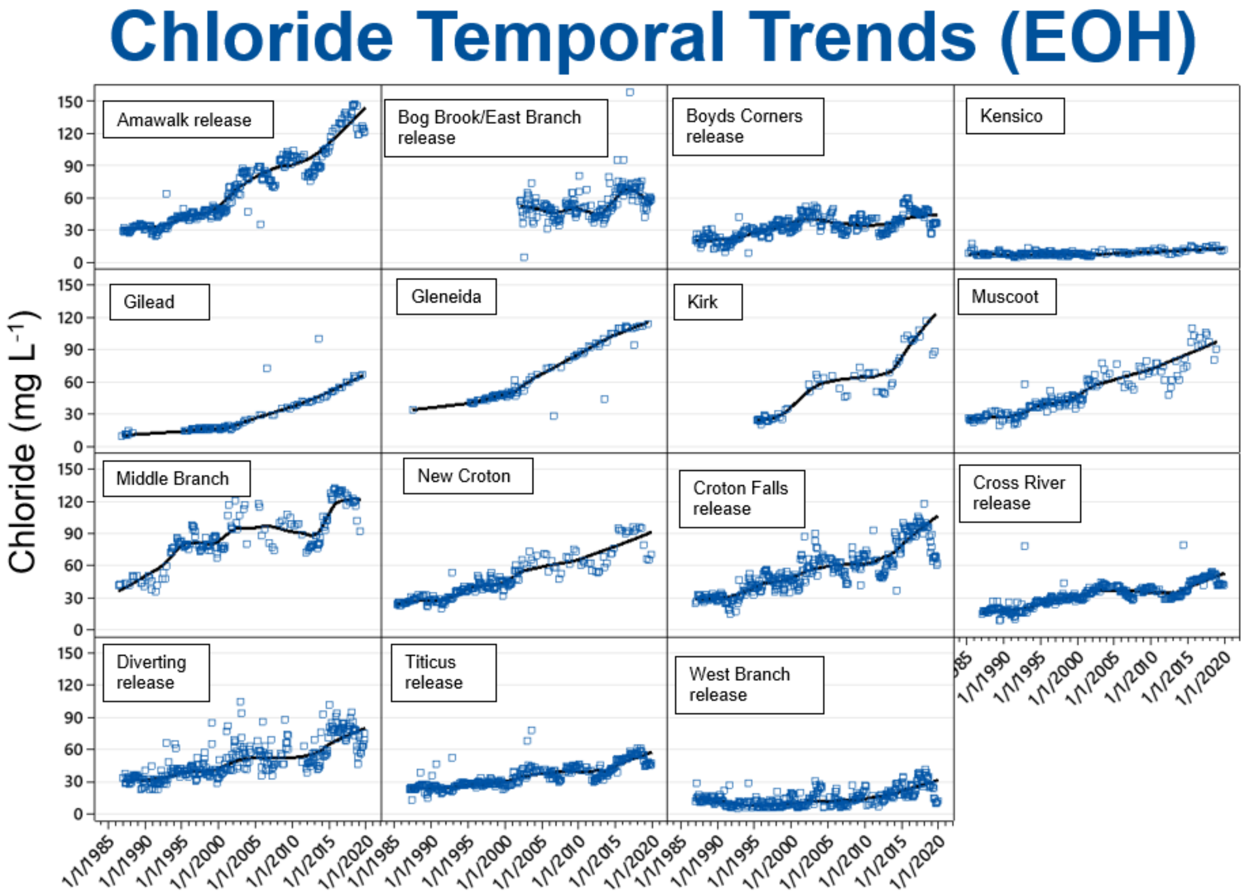

Figure 7: Temporal (1985-2019) chloride trends for East of Hudson reservoirs. Lines are LOWESS curves fitted through approximately monthly and quarterly data using a 30% smoothing factor.

Additional analysis was conducted for New Croton Reservoir to explore how chloride might increase over time. First, the yearly chloride increase was calculated and estimated to be 1.8 mg/L by applying the seasonal Kendall slope estimator. This was added to the 2019 chloride concentration of 90 mg/L (estimated by LOESS fit, Figure 7). Adding 1.8 mg/L each year in a cumulative fashion resulted in New Croton Reservoir's median chloride concentration exceeding the New York State MCL of 250 mg/L in the year 2108.

In Figure 8, recent chloride concentrations are presented to illustrate how the wide range of chloride concentrations in the EOH reservoirs compare to federal and state regulations. Although the median is typically below the NYS drinking water standard of 250 mg/L and the EPA aquatic life standard of 230 mg/L, there are numerous examples of individual samples that exceed these criteria.[83] Furthermore, sub-lethal effects are organism dependent and have been observed in the 100-1000 mg/L range,[84] and it is well documented that many water quality guidelines do not adequately protect the lake food webs.[85]

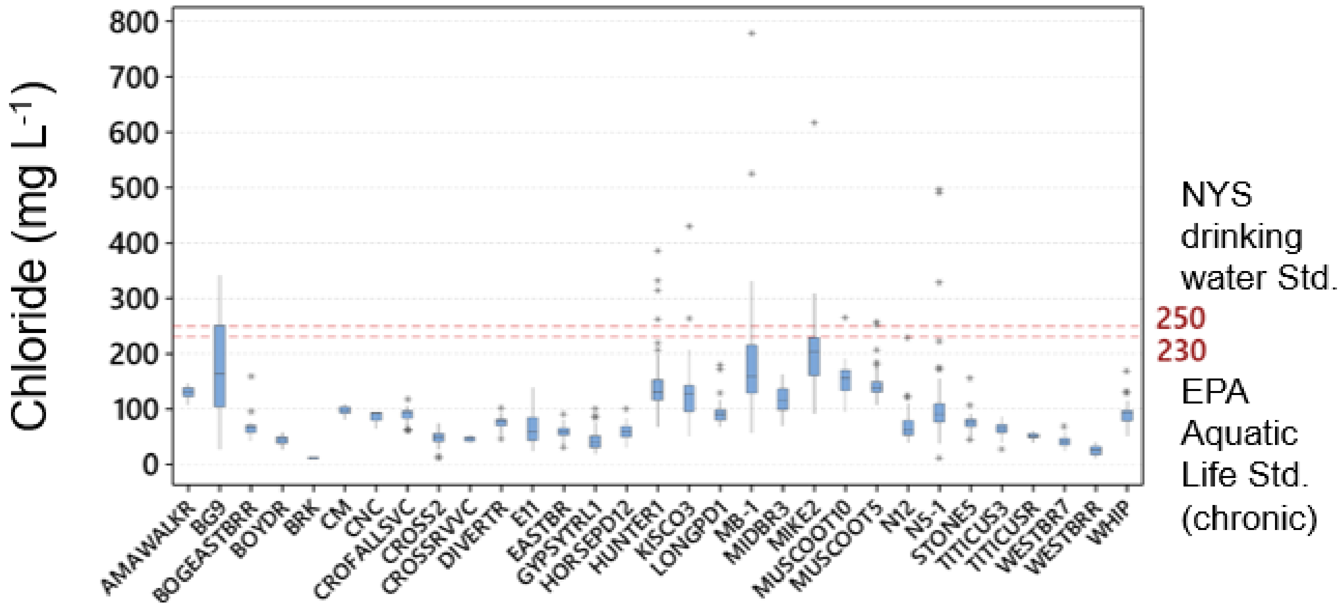

Figure 8: 2015-2019 Chloride results for EOH grab sampling locations.

In an effort to help identify potential sources of chlorides contributing to the increases above, a linear regression was performed for several source proxies (Figure 9). Results indicate moderately strong positive correlations between chloride levels and road density, impervious surface density, and parcel density. These results suggest that road deicing, impervious surface density, and wastewater/water softeners may be important chloride sources in EOH watersheds. Additional data and analysis is necessary in order to quantify the relative contributions from these potential sources. By comparison, agricultural density is relatively low in the EOH watersheds. A weak negative correlation between chloride concentration and agricultural density suggests that agricultural fertilizers are likely not a significant chloride source in the EOH watersheds.

There is an outlier in the data worth noting. Site MIKE2 is located on Michaels Brook in the Town of Carmel (Figures 9 and 10). At this site, chloride is much higher than the regressions predict, suggesting that additional chloride sources may exist within this sub-basin. Additional analysis is required, but this may be partly due to the location of the sample site which is just downstream of a wastewater treatment plant. This sub-basin is mostly sewered and the WWTP treats wastewater from portions of neighboring watersheds, which were not accounted for in this analysis. Additionally, the MIKE2 sampling location is in close proximity to a commercial area. Further research is needed to explore whether deicing application to roads and parking lots may also contribute to higher than predicted chloride levels. These findings demonstrate a moderately strong, positive relationship between chloride levels and road density, impervious surface density, and parcel density.

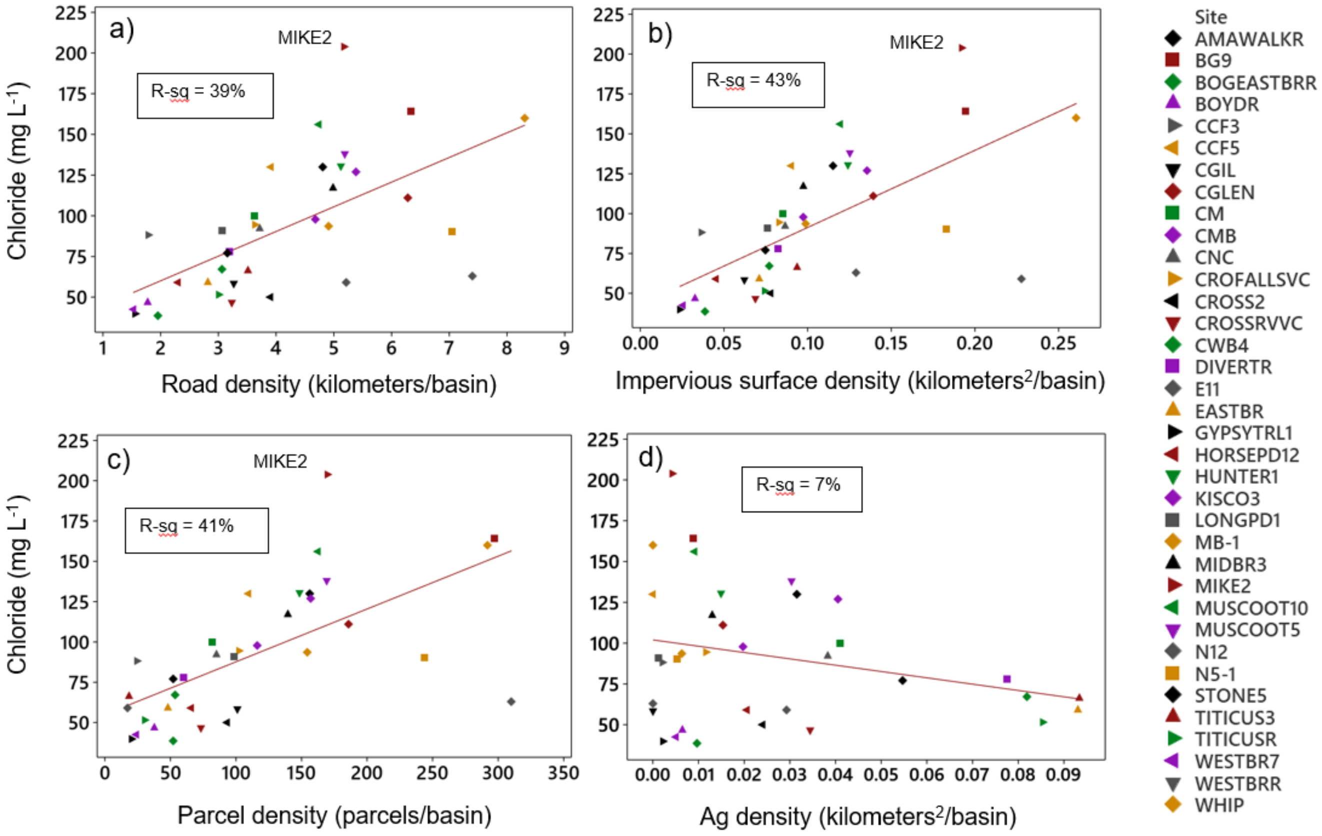

Figure 9: East of Hudson basin chloride correlations with a) road density, b) impervious surface density, c) parcel density and, d) agricultural land density. See Appendix A for key.

Next, a spatial analysis was conducted to help identify the geographic distribution of chloride across the EOH watersheds (Figure 10). Watershed sub-basins are colored according to median chloride concentrations to differentiate spatial trends in the respective water supply systems. Color gradations from yellows to oranges to reds correspond to increasing chloride concentrations. When comparing the sub-basin chloride concentrations to estimates from the USGS road salt application tool[86] (Figure 11), some overlap with roads emerges.

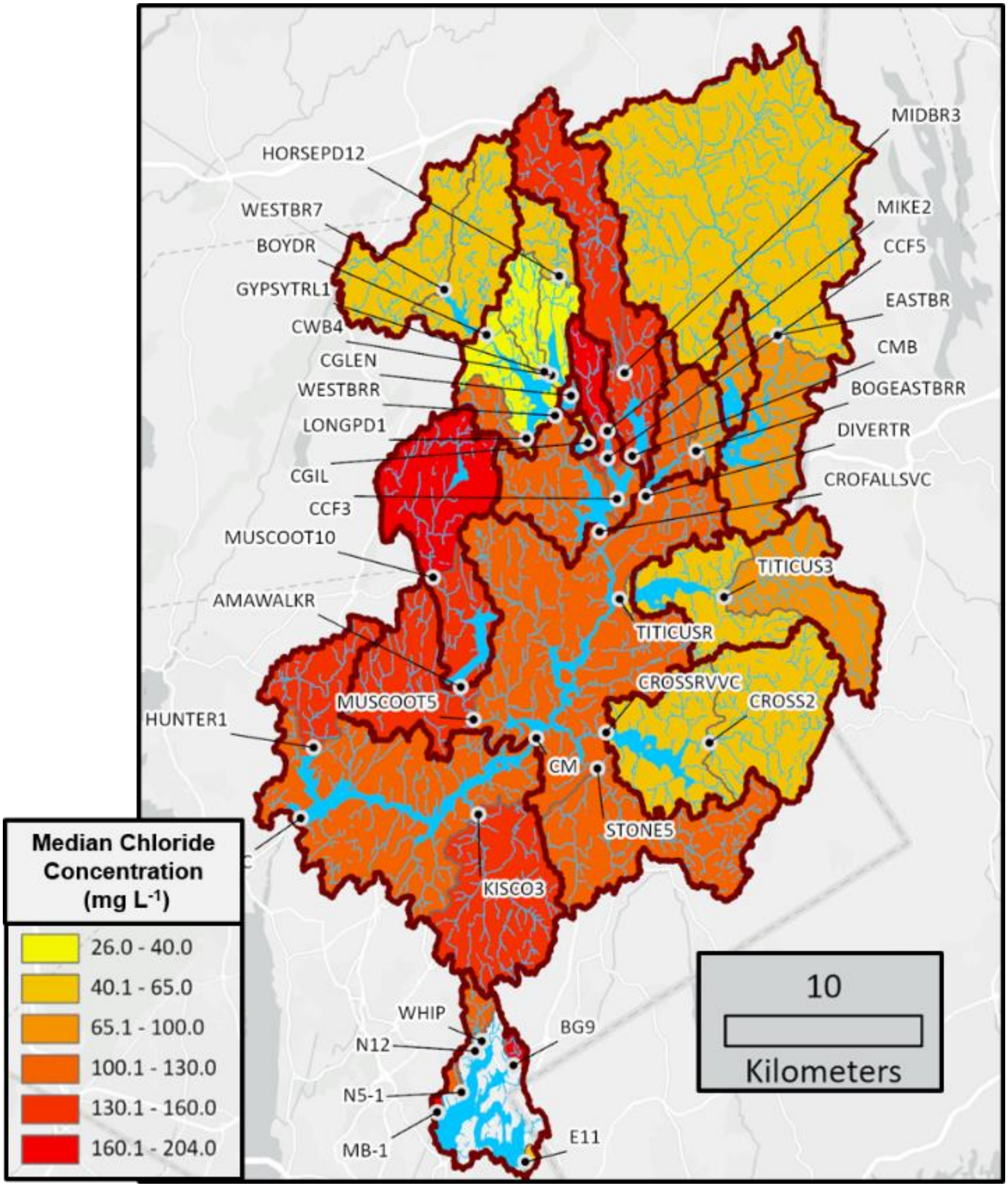

Figure 10: Spatial chloride trends for the NYC water supply EOH watersheds

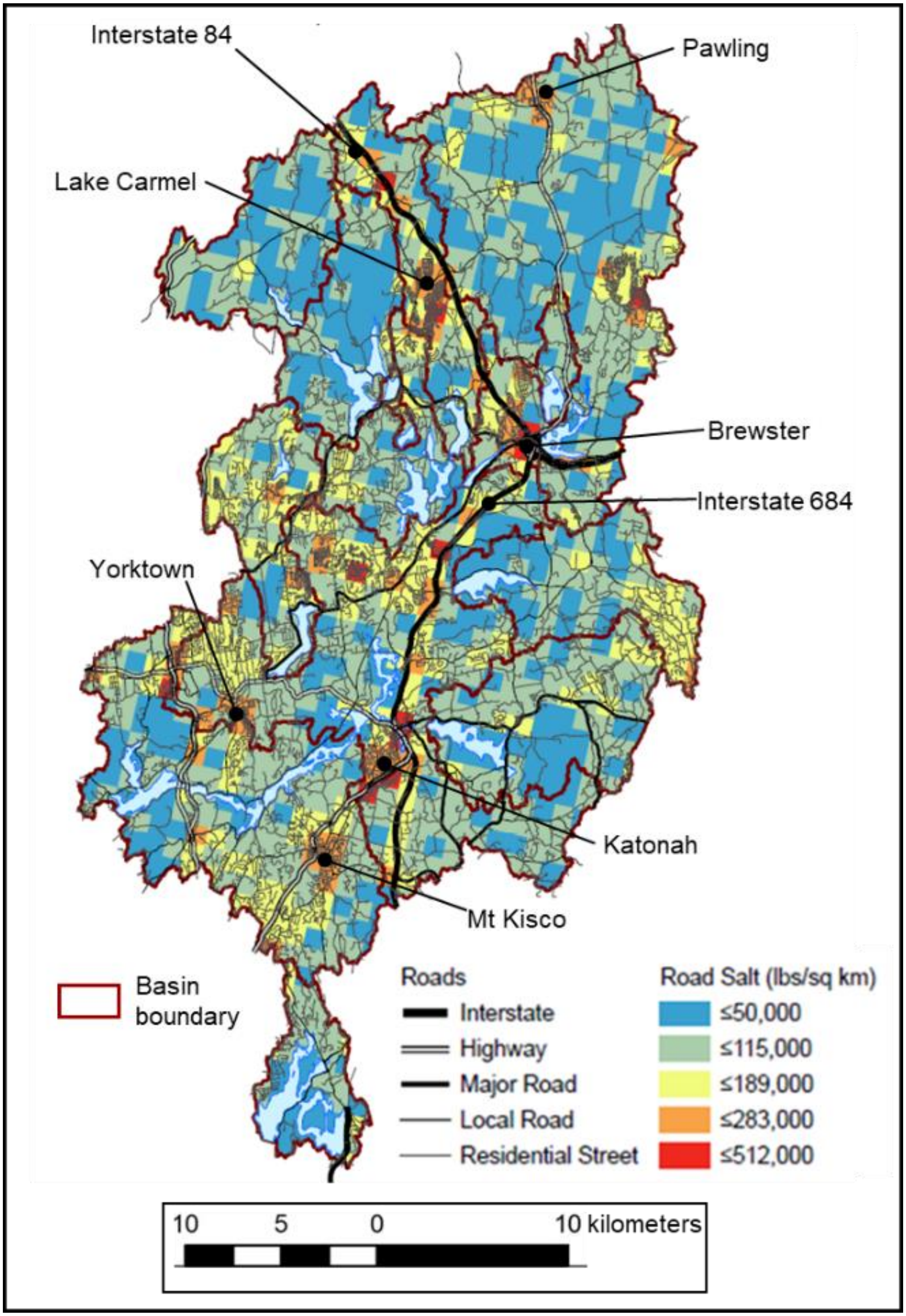

Figure 11: Estimates of road salt application in the EOH watersheds, 1992-2015.[87]

4.3 Chloride – WOH

Chloride concentrations are also increasing in all WOH reservoirs. The analysis discusses this increase and conducts a regression analysis in an effort to understand drivers. Finally, a spatial analysis provides geographic resolution of chloride levels to identify locations of concern for future investigations.

WOH chloride trends from 1985-2019 are illustrated in Figure 12. While the concentrations of chloride are lower relative to EOH values, the chloride trends for all WOH reservoirs show an overall long-term increase.

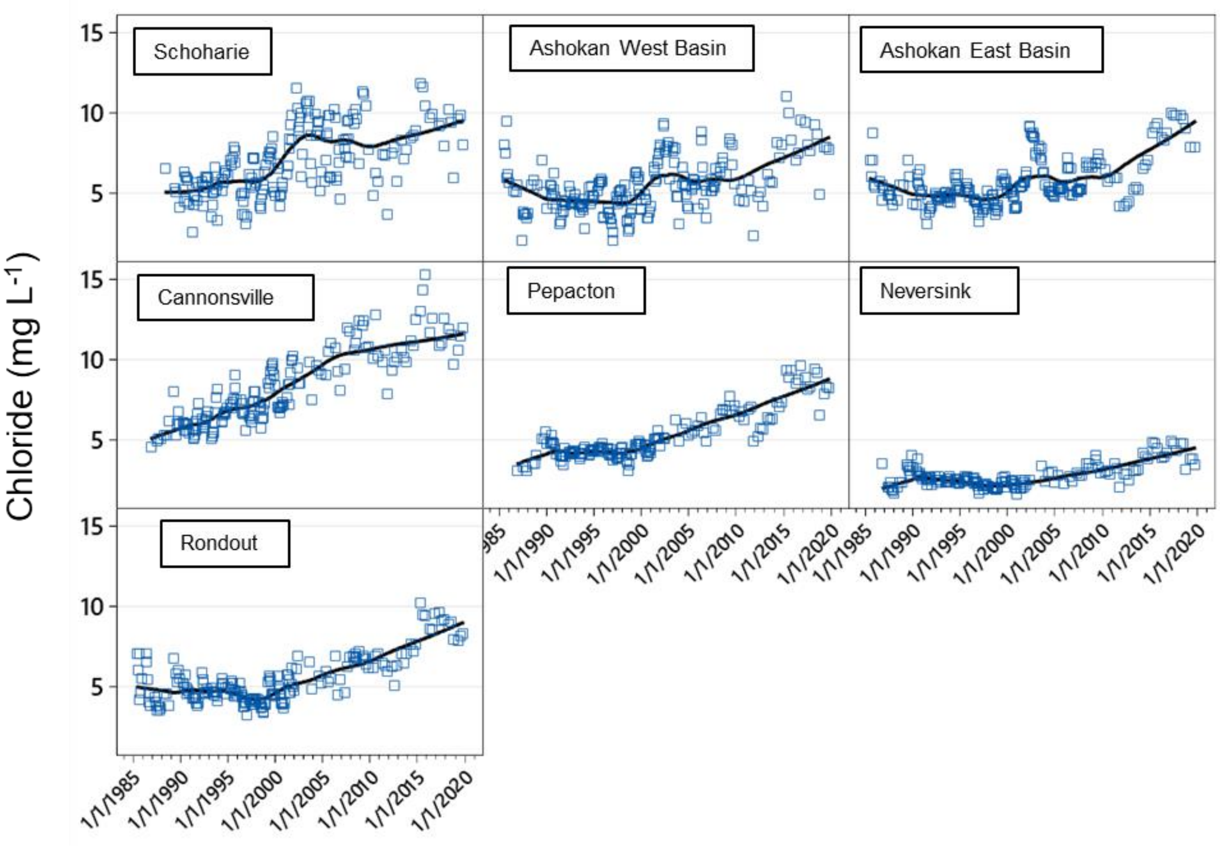

Figure 12: Temporal (1985-2019) chloride trends for West of Hudson watershed reservoirs. Lines are LOWESS curves fitted through approximately monthly data using a 30% smoothing factor.

Like the EOH analysis, WOH sub-basin chloride concentrations were correlated with the surrogates considered in our analysis (Figure 13). Similar to the EOH analysis, there is a positive relationship between chloride levels and road density, impervious surface, and parcel density. In addition, the WOH watersheds also show a positive correlation with agricultural density, indicating potential inputs from farms.

Notably, the regression analysis' estimate for chloride at site WDHOA and NK6 were much lower than observed chloride levels. WDHOA is located on the West Branch of the Delaware River in the town of Hobart. Additional analyses are needed to determine causality, but it could be related to deicer application on a nearby state road, which closely parallels the stream over much of its course.

Unknown chloride sources (e.g., industrial, salt storage inputs, etc.) are not accounted for in our analysis and may also be a factor. Similarly, the high chloride at Krammer Brook (NK6) may be explained by the relatively high road, impervious surface, and parcel density in this sub-basin.

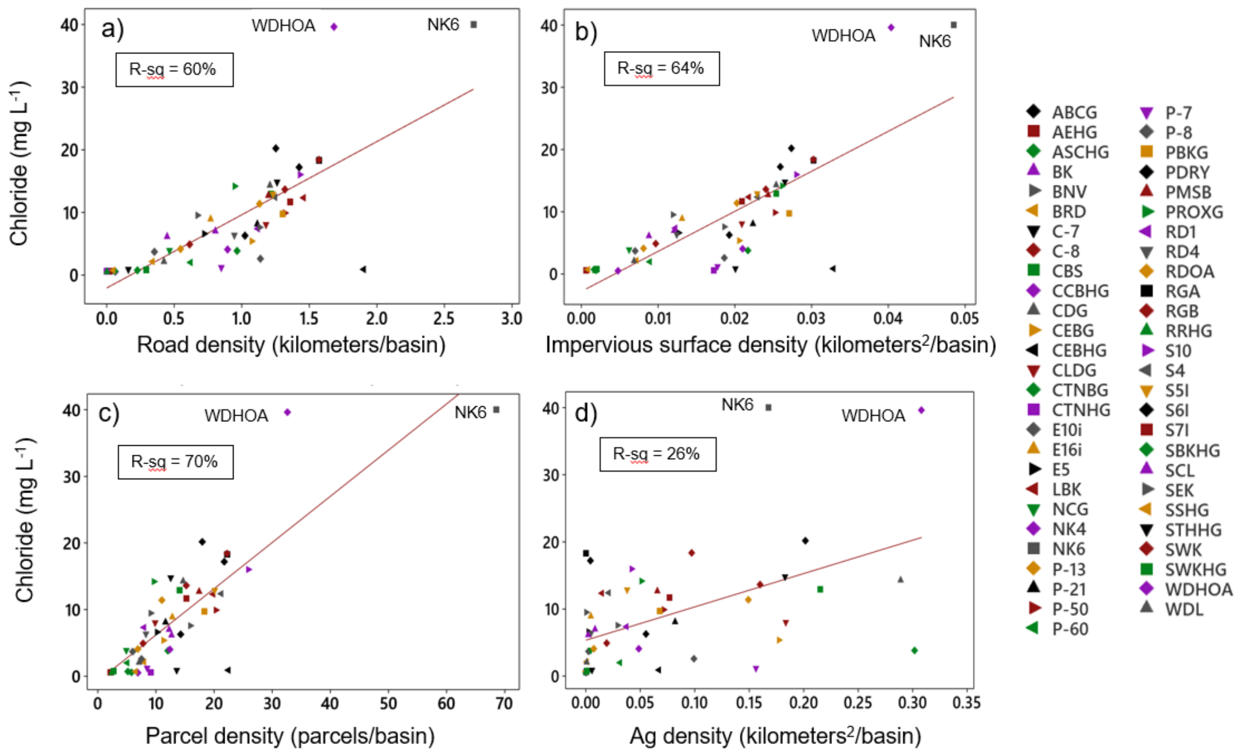

Figure 13: West of Hudson basin chloride linear regressions with a) road density, b) impervious surface density, c) parcel density and, d) agricultural land density. See Appendix A for key.

The spatial distribution of chloride levels across the WOH System is provided in Figure 14. Overall WOH chloride concentrations are generally lower than the chloride concentrations observed in the EOH watersheds. The sub-basins with the highest chloride concentrations include the West Branch of the Delaware River, sampled at WDHOA in the town of Hobart, and Kramer Brook (sampled at NK6), a small sub-basin located in the Neversink Reservoir watershed.

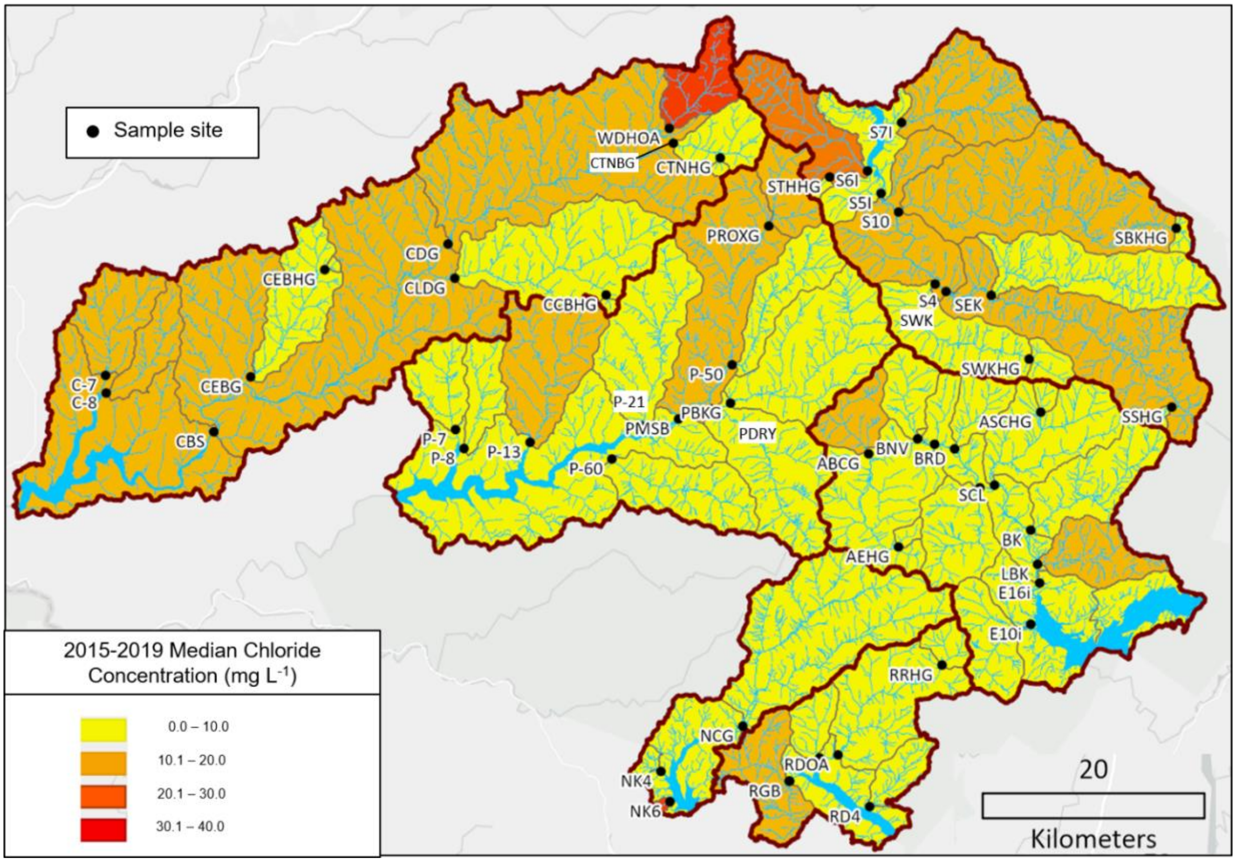

Figure 14: Spatial chloride trends for the NYC water supply WOH System.

4.4 Conclusions

Chloride is trending upward for all reservoirs in the EOH and WOH systems. EOH chloride concentrations are much higher than WOH concentrations, presumably due to the greater density of roads, impervious surface, and wastewater inputs in the the EOH System. Additional analysis is required to quantify the relative contributions from these and perhaps additional sources of chloride.

The WOH watersheds have relatively low levels of chloride. This is not unexpected given the lower population, road, and parcel densities. Further investigation into the sub-basins with higher relative chloride levels is recommended to identify best practices to limit additional increases.

5 WATERSHED PROTECTION STRATEGIES

Given the analysis above, the Task Force discussed ways to approach salinity management in the New York City watersheds (EOH and WOH) as a group and in breakout sessions. While the trend analysis demonstrates chloride increases in both regions, the acute nature of change and high chloride concentration in the EOH watershed stands out as an emerging concern for communities that rely on groundwater and, to a lesser degree, for the City water supply. Data for WOH watersheds highlight areas of concern that need to be further investigated, and upward trends may spur a reconsideration of practices at a variety of levels.

5.1 EOH

In Westchester and Putnam counties, chloride levels are increasing as documented by the above trend analysis. Key stakeholders include towns, counties, state government (primarily through New York State Department of Transportation for state roads and highways), New York State Department of Environmental Conservation, legislators, public water consumers, and numerous environmental non-governmental organizations. Of unique concern is the presence of major highways that serve the NY metro region including I-84, I-684, Taconic State Parkway, and Saw Mill River Parkway, and their proximity to reservoirs and streams.

5.1.1 Previous EOH Salt Reduction Measures

As part of the 1997 NYC Watershed Memorandum of Agreement,[v] and the FAD,[vi] DEP developed the Watershed Rules and Regulations[vii] (WR&R) to ensure a clean, wholesome water supply to NYC.

Recognizing that watershed communities were subject to new requirements, DEP supported a variety of programs and projects, including funds available to reducing the impacts from road deicing materials in various towns in the EOH watersheds. DEP provided funds to Putnam and Westchester counties to establish the Water Quality Investment Program. The Water Quality Investment Program supported numerous initiatives, and DEP authorized the use of a portion of those funds toward construction or rehabilitation of local sand and salt storage facilities. In addition, the Good Neighbor Payment Fund provided funding directly to municipalities. The funds were to be used “solely to pay for the capital costs of designing, constructing and installing public works or public improvements, or purchasing public equipment” that benefits the public at large. Two EOH municipalities used the Good Neighbor Payment Fund to comply with the sand and salt storage requirements of the WR&R.

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[v] https://archive.epa.gov/region02/water/nycshed/web/html/nycmoa.html#:~:text=The%20MOA%2C%20signed%20on%20January,and%20partnership%20programs%2C%20and%20details
[vi] https://archive.epa.gov/region02/water/nycshed/web/html/filtad.html
[vii] https://archive.epa.gov/region02/water/nycshed/web/pdf/regulations.pdf

5.1.2 Wastewater Treatment Plants

All WWTP’s in the New York City watersheds are subject to the WR&R. DEP provided funding in the 1990s to install advanced treatment to minimize the risk of introducing pathogens into source waters. Since that time, nearly all of the WWTP’s in the watershed have been upgraded to include sand filtration, disinfection, phosphorus removal, and microfiltration (or equivalent) to ensure 3-log removal of pathogens. These treatments do not remove chloride and additional field sampling is needed to understand the relative contribution of salinity resulting from WWTP’s.

5.2 WOH

In the WOH watersheds, chloride levels in streams and reservoirs are substantially lower than their EOH counterparts. This likely is due to high percentages of forest cover, including permanently protected land in the Catskill Forest Preserve and by NYC through its Land Acquisition Program, along with lower overall population and road density. Although the trend analysis demonstrates relatively low levels of chloride throughout the watershed, it is increasing at all locations. In addition, there are locations with elevated chloride that bear further study. Therefore, the Task Force recommends a preventative approach to limit further increases in salinity.

Since chloride levels are generally below 10 mg/L and most drinking water is provided by private groundwater wells, this issue is not a dominant concern in the region. However, deicing practices do comprise a significant portion of many municipal budgets, and the Catskills both supply the bulk of the NYC water and are world-renowned for recreation (trout fishing), therefore road salt is an issue of concern.

5.2.1 Previous WOH Salt Reduction Measures

As described above, the 1997 New York City Watershed Memorandum of Agreement and the FAD led to the development of the WR&R to ensure a clean, wholesome water supply to NYC. DEP has funded two programs designed to limit the amount of road salt entering streams and reservoirs in the WOH watersheds.

The Municipal Sand and Salt Storage Facilities Program was funded in 1997. The purpose of the program was to improve the storage of road deicing material (primarily sand and/or salt) to better protect water quality and to assist local governments in complying with the City’s WR&R, which required deicing material be covered. This program reimbursed municipalities for the design and construction of sand and salt sheds.

Implementation took effect over the course of approximately six years from 1998 to 2004 and had two phases. The first phase was the design and construction of 32 storage sheds in municipalities within the watershed. Phase Two provided reimbursements for up to $500,000 each for the design and construction of nine additional storage facilities outside of the watershed whose towns were partially within the watershed and served by the facility.

DEP also provided funding to Delaware County’s Department of Public Works to install a “smart technology” programmable salt dispenser control system for their trucks for approximately $10,000. There was one activity funded under the Institutional Sand and Salt Storage Program between 2009 and 2015.

5.2.2 Agriculture

As part of the FAD, the City funds the Watershed Agricultural Council to work with farm and forest landowners in the EOH and WOH watersheds. Utilizing best practices in the form of whole farm plans, best practices prevent or reduce the amount of pollution generated by non-point-sources in order to protect and enhance water quality. The primary focus of this program is nutrient management in the form of phosphorus and nitrogen. Participating farms receive a Nutrient Management Plan that summarizes the nutrient balances for each farm field, and provide recommendations on soil amendments and fertilizer inputs to reduce and balance nutrients. In addition to soil sampling results and compost analysis, a Nutrient Management Plan also includes farm maps which outline land use, soil data, field fertility, slope, flow paths, and manure spreading load and timing allowances.[88] There are currently 220 Nutrient Management Plans implemented by farms in the WOH watersheds.[89]

5.2.3 Other Considerations

An additional factor in considering salinity management in the WOH watersheds is the role that NYC's Delaware reservoirs play in the management of the Delaware River Basin. As mentioned above, the Delaware River Basin is a watershed shared by four US States – New York, Pennsylvania, New Jersey, and Delaware – and is a water supply to over 14 million people. Salinity is a constituent of concern throughout the Delaware River Basin and especially in the tidal reaches of the Delaware River where elevated chloride levels in the tidal salt front threaten the integrity of water intakes for several municipalities. These issues are exacerbated by the rise in sea level caused by global climate change which allows for intrusion of saline water further upriver where it impacts the use of the Delaware River as a drinking water supply.

This study is a consideration for salinity concerns in the NYC Watershed. It is not meant to address concerns about salinity in the Delaware River Watershed outside of the NYC Watershed. Concerns regarding salinity in the rest of the Delaware River Watershed are being addressed through the 2017 Flexible Flow Management Program (2017 FFMP) Detachment Study and Synthesis Study.[90]

5.3 Watershed Strategies: Conclusions

While planning and action is needed in EOH watersheds to begin addressing these issues, stakeholder engagement to identify common problems is key to implementing new programs and reversing freshwater salinization. Given the multitude of stakeholders and different levels of political interest, the Task Force endorses the efforts of state representatives calling for legislation that would create a regional panel to address salinity similar to legislation recently adopted in the Adirondacks.[91]

Given relatively low ambient chloride levels and the relationship of high forest cover and low road density WOH, the Task Force recommends a preventative approach to freshwater salinization. There are opportunities to explore, pilot, and demonstrate best practices and technologies for maintaining roads adjacent to reservoirs through maintenance contracts with counties.

Additional analysis should be conducted to understand salinity increases in WOH sub-basins with increased chloride levels. Additional education and outreach on chloride trends will help municipalities learn about the benefit of best practices. Deicing in close proximity to reservoirs may be of interest, especially with county and state partners.

6 OUTSTANDING QUESTIONS

Based on the literature review, trends analysis, and summary of watershed protection strategies, several outstanding questions and issue remain:

- How does increased salinity affect reservoir turnover and stratification?
- What strategies can NYC implement to protect EOH water supply while ensuring driver safety?
- How does an increase in freshwater salinity affect infrastructure?
- What metrics should be used to measure success?

7 RECOMMENDATIONS

Since the landscape and severity of the problem is vastly different on both sides of the Hudson River, separate approaches and strategies were developed through Task Force discussion. Recommendations were proposed for EOH and WOH watersheds to meet the goals and objectives of this plan. Generally, however, awareness of trends and consequences of chloride inputs needs to be better understood by all stakeholders. Some initiatives could overlap EOH and WOH, especially in the areas of education and training. There are also research and data gaps that should be identified and prioritized as described in the following sections.

7.1 EOH

While the NYC water supply is currently not in danger of approaching chloride limits, continuing trends may change this in the future. Therefore, there is a basis for a regional approach to salinity management EOH:

- Create presentations and FAQs for chloride trends in the watershed to support inform legislation efforts and to educate lawmakers and officials.policy initiatives and educate policy makers as well as the general public.
- Explore development of a chloride budget to determine chloride contributions from various sources.
- Research the role that increased salinity may have on infrastructure.
- Track federal and state regulations for reductions in sodium and chloride maximum contaminant levels.

7.2 WOH

Overall, watershed chloride levels are low in the WOH watersheds but there is an upward trend. Certain sampling points show slightly elevated levels of chloride compared to adjacent sub-basins and are worthy of further investigation. Given low chloride levels, the Task Force recommends a more preventative approach focused on implementing best practices by collaborating with county public works departments for plowing, deicing, and road maintenance activities on DEP property. Agreements between DEP and local counties to maintain DEP roads offer opportunities for further collaboration.

- Explore, identify, and implement best practices at DEP roads and WOH facilities.
    - Consider enhanced collaboration with regard to deicing best practices through DEP’s existing intermunicipal agreements with counties.
- Refine the chloride trends analysis to ensure accurate baseline data.
    - Identify data gaps to support continued trend analysis, investigate “hot spots” for the WOH basins and/or sub-basins to determine the source of chloride increases.
    - Evaluate chloride levels before and after deicing events.
- Present trend analysis at conferences.
- Gauge interest in optimizing best practices across jurisdictions.

8 ENDNOTES & APPENDECIES

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Appendix A

Site Key for NYC Water Supply Salinity Study

DEP Site	Description	Watershed
	EOH System	
AMAWALKR	Muscoot River, Amawalk Reservoir release	Amawalk Reservoir
BOGEASTBRR	East Branch Croton River, East Branch /Bog Brook release	Bog Brook/E. Branch Reservoir
BOYDR	West Branch Croton River, Boyd Corners Reservoir release	Boyd Corners Reservoir
CCF3	Site 3 on Croton Falls Reservoir middle basin	Croton Falls Reservoir
CCF5	Site 5 on Croton Falls Reservoir upper basin	Croton Falls Reservoir
CGIL	Lake Gilead	Lake Gilead
CGLEN	Lake Gleneida	Lake Gleneida
CKL	Kirk Lake	Kirk Lake
CM	Muscoot Reservoir	Muscoot Reservoir
CNC	New Croton Reservoir	New Croton Reservoir
CROFALLSVC	West Branch Croton River, Croton Falls release	Croton Falls Reservoir
CROSS2	Cross River, above Cross River reservoir	Cross River Reservoir
CROSSRVVC	Cross River, Cross River release	Cross River Reservoir
CWB4	Site 4 on West Branch Reservoir	West Branch Reservoir
DIVERTR	East Branch Croton River, Diverting Reservoir release	Diverting Reservoir
EASTBR	East Branch Croton River, near Putnam Lake	East Branch Reservoir
GYPSYTRL1	Gypsy Trail	West Branch Reservoir
HORSEPD12	Horse Pound Brook	West Branch Reservoir
HUNTER1	Hunter Brook	New Croton Reservoir
KISCO3	Kisco River	New Croton Reservoir
LONGPD1	Long Pond	West Branch Reservoir
MIDBR3	Middle Branch Croton River, above Middle Branch Reservoir	Middle Branch Reservoir
MIKE2	Michaels Brook above Croton Falls upper basin	Croton Falls Reservoir
MUSCOOT10	Muscoot River	Muscoot Reservoir
MUSCOOT5	Muscoot River, downstream of Amawalk Reservoir release	Muscoot Reservoir
STONE5	Stone River, tributary to New Croton Reservoir	New Croton Reservoir
TITICUS3	Titicus River, above Titicus Reservoir	Titicus Reservoir
TITICUSR	Titicus River, Titicus Reservoir release	Titicus Reservoir
WESTBR7	West Branch Croton River above Boyd Corners Reservoir	Boyd Corners Reservoir
WESTBRR	West Branch Croton River, West Branch Reservoir release	West Branch Reservoir
BRK	Kensico Reservoir	Kensico Reservoir
BG9	Bear Gutter Creek	Kensico Reservoir

E11	Unnamed stream	Kensico Reservoir
MB-1	Malcolm Brook	Kensico Reservoir
N12	Unnamed stream	Kensico Reservoir
N5-2	Unnamed stream	Kensico Reservoir
WHIP	Whippoorwill Creek	Kensico Reservoir
	WOH Catskill System	
EAE	Ashokan Reservoir East Basin	Ashokan Reservoir East Basin
ABCG	Birch Creek at Big Indian	Ashokan Reservoir West Basin
AEHG	Panther Mtn tributary to Esopus Creek	Ashokan Reservoir West Basin
ASCHG	Hollow Tree Brook at Lanesville	Ashokan Reservoir West Basin
BK	Beaver Kill	Ashokan Reservoir West Basin
BNV	Bushnellville Stream	Ashokan Reservoir West Basin
BRD	Broadstreet Hollow Stream	Ashokan Reservoir West Basin
E10I	Bush Kill, below Maltby Hollow Bk at West Shokan	Ashokan Reservoir West Basin
E16I	Esopus Creek at Coldbrook	Ashokan Reservoir West Basin
E5	Esopus Creek at Allaben	Ashokan Reservoir West Basin
EAW	Ashokan Reservoir West Basin	Ashokan Reservoir West Basin
LBK	Little Beaver Kill at Beechford, near Mt. Tremper	Ashokan Reservoir West Basin
WDL	Woodland Valley Stream	Ashokan Reservoir West Basin
S10	Batavia Kill, above confluence with Schoharie Creek	Schoharie Reservoir
S4	Schoharie Creek, below Lexington	Schoharie Reservoir
S5I	Schoharie Creek at Prattsville	Schoharie Reservoir
S6I	Bear Kill, near Prattsville	Schoharie Reservoir
S7I	Manor Kill at West Conesville	Schoharie Reservoir
SBKHG	Batavia Kill, near Maplecrest	Schoharie Reservoir
SCL	Stony Clove Creek	Schoharie Reservoir
SEK	East Kill, near Jewett Center	Schoharie Reservoir
SS	Schoharie Reservoir	Schoharie Reservoir
SSHG	Sugarloaf Brook, south of Tannersville	Schoharie Reservoir
STHHG	Toad Hollow Brook, near Grand Gorge	Schoharie Reservoir
SWK	West Kill, near West Kill	Schoharie Reservoir
SWKHG	West Kill, below Hunter Brook, near Spruceton	Schoharie Reservoir
	WOH Delaware System	
C-7	Trout Creek, near Trout Creek	Cannonsville Reservoir
C-8	Loomis Brook near Cleaver, NY	Cannonsville Reservoir
CBS	West Br Delaware River at Walton	Cannonsville Reservoir
CCBHG	Coulter Brook, near Bovina Center	Cannonsville Reservoir
CDG	West Br Delaware River, upstream from Delhi	Cannonsville Reservoir
CEBG	East Brook, east of Walton	Cannonsville Reservoir
CEBHG	Wolf Creek at Mundale	Cannonsville Reservoir
CLDG	Little Delaware River, near Delhi	Cannonsville Reservoir

CTNBG	Town Brook, SE of Hobart	Cannonsville Reservoir
CTNHG	Town Bk tributary, SE of Hobart	Cannonsville Reservoir
WDC	Cannonsville Reservoir	Cannonsville Reservoir
WDHOA	West Branch Delaware River	Cannonsville Reservoir
NCG	Neversink River, near Claryville	Neversink Reservoir
NK4	Aden Brook	Neversink Reservoir
NK6	Kramer Brook, Neversink watershed	Neversink Reservoir
NN	Neversink Reservoir	Neversink Reservoir
EDP	Pepacton Reservoir	Pepacton Reservoir
P-13	Tremper Kill, near Andes	Pepacton Reservoir
P-21	Platte Kill at Dunearaven	Pepacton Reservoir
P-50	Batavia Kill northeast of Arkville, NY	Pepacton Reservoir
P-60	Mill Brook, near Dunearaven	Pepacton Reservoir
P-7	Bryden Hill Brook	Pepacton Reservoir
P-8	Fall Clove southwest of Andes, NY	Pepacton Reservoir
PBKG	Bush Kill, near Arkville	Pepacton Reservoir
PDRY	Dry Brook at Arkville	Pepacton Reservoir
PMSB	East Br Del River at Margaretville	Pepacton Reservoir
PROXG	East Branch Delaware River at Roxbury	Pepacton Reservoir
RD1	Sugarloaf Brook	Rondout Reservoir
RD4	Sawkill Brook (AKA Trout Creek) near Sholam, NY	Rondout Reservoir
RDOA	Rondout Creek, near Lowes Corners	Rondout Reservoir
RGB	Chestnut Creek at Grahamsville	Rondout Reservoir
RR	Rondout Reservoir	Rondout Reservoir
RRHG	Rondout Creek, abv Red Brook at Peekamoose	Rondout Reservoir