

Relating Road Salt to Exceedances of the Water Quality Standard for Chloride in New Hampshire Streams

PHILIP R. TROWBRIDGE,^{*,†}
 J. STEVE KAHL,^{‡,¶} DARI A. SASSAN,^{‡,¶}
 DOUGLAS L. HEATH,[§] AND
 EDWARD M. WALSH[†]

*New Hampshire Department of Environmental Services,
 P.O. Box 95, Concord, New Hampshire 03302-0095, Plymouth
 State University, Center for the Environment, Plymouth, New
 Hampshire 03264, and United States Environmental
 Protection Agency, Boston, Massachusetts 02109*

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Six watersheds in New Hampshire were studied to determine the effects of road salt on stream water quality. Specific conductance in streams was monitored every 15 min for one year using dataloggers. Chloride concentrations were calculated from specific conductance using empirical relationships. Stream chloride concentrations were directly correlated with development in the watersheds and were inversely related to streamflow. Exceedances of the EPA water quality standard for chloride were detected in the four watersheds with the most development. The number of exceedances during a year was linearly related to the annual average concentration of chloride. Exceedances of the water quality standard were not predicted for streams with annual average concentrations less than 102 mg L⁻¹. Chloride was imported into three of the watersheds at rates ranging from 45 to 98 Mg Cl km⁻² yr⁻¹. Ninety-one percent of the chloride imported was road salt for deicing roadways and parking lots. A simple, mass balance equation was shown to predict annual average chloride concentrations from streamflow and chloride import rates to the watershed. This equation, combined with the apparent threshold for exceedances of the water quality standard, can be used for screening-level TMDLs for road salt in impaired watersheds.

Introduction

In cold climates, road salt (sodium chloride) is the principal chemical used for deicing roadways and parking lots to improve public safety during the winter months. Road salt depresses the freezing point of water and prevents ice formation on asphalt above about -12 °C. Over 18 million megagrams (Mg) of road salt for deicing were sold in the United States in 2005, an increase from nearly zero in the

1940s when road salting began (1). Road salt dissolves in water, releasing sodium and chloride ions. Sodium and chloride ions both undergo ion exchange reactions with soils, but chloride is generally retarded less and is more quickly transported to groundwater aquifers and nearby streams (2–5).

Increasing salt use for deicing has resulted in increasing chloride concentrations in rivers and lakes in the Northeast. Godwin et al. (6) reported that chloride concentrations in the Mohawk River in New York increased from 7.7 mg L⁻¹ in 1952–1953 to 20.4 in 1990–1998, while no other ions besides sodium had increasing trends. In the Merrimack River in New Hampshire, the U.S. Geological Survey documented an order of magnitude increase in mean annual chloride concentrations from 2.9 mg L⁻¹ in 1900–1917 to 24.9 mg L⁻¹ in 1976–1995 (7). Similarly, Kaushal et al. (8) reported rapid recent increases in chloride concentrations in Baltimore County in Maryland, Hudson River Valley in New York, and the White Mountains of New Hampshire. A probabilistic survey of 145 lakes in the northeast found that median chloride concentrations doubled between 1984 and 2004 (9). The amount of chloride exported from the Quinnipiac River watershed in Connecticut has increased from less than 5400 to more than 8100 Mg Cl yr⁻¹ between 1982 and 2003 (10). Daley et al. (11) reported a significant increase in monthly flow-adjusted specific conductance, a surrogate for chloride concentrations, in the Lamprey River watershed in New Hampshire between 1978 and 2008. Increasing chloride concentrations in rivers and lakes have been attributed to land development and resulting road salt use (4, 8–15). Urbanization, in particular, has been identified as a leading factor for the increasing chloride concentrations (8, 11), and concerns have been raised about potable water supplies if urbanization continues at its present pace (8, 16).

The U.S. Environmental Protection Agency (EPA) has established water quality standards for chloride for the protection of aquatic life (17). Water bodies are considered “impaired” if these standards are violated. The water quality standard for chronic exposures is a four-day average concentration of 230 mg L⁻¹ not to be exceeded more than once every three years (17). The water quality standard for acute exposures is 860 mg L⁻¹ for a one-hour average with a similar three year recurrence interval (17).

Despite the widespread use of road salt as a deicer and evidence in the literature of increasing chloride concentrations, few water quality impairments related to chloride have been reported, and only a handful of total maximum daily load (TMDL) studies have been completed in the United States. Two complications are responsible for this. First, the one-hour and four-day averaging times in the water quality standards make it difficult to detect exceedances of the water quality standard using grab samples. Instead, high frequency measurements of chloride with dataloggers are needed. This requirement has prevented many watershed monitoring groups and municipalities from detecting exceedances and placing water bodies on the state’s impaired waters list. Second, with sporadic exceedances, it is difficult to predict how much salt imports to a watershed must be reduced to meet water quality standards. Most of the chloride TMDLs that have been approved by EPA rely on flow duration curves (18–21) which are difficult to interpret in terms of salt loading reductions.

Our objective was to develop simple, but accurate, methods which watershed groups, municipalities, and states could use to determine chloride impairments and to complete screening-level TMDLs to reduce salt imports. We ap-

* Corresponding author phone: (603)271-8872; fax: (603)271-7894; e-mail: Philip.Trowbridge@des.nh.gov.

† New Hampshire Department of Environmental Services.

‡ Plymouth State University.

¶ Present address: Department of Natural Resources and the Environment, University of New Hampshire, Durham, New Hampshire 03824.

§ Present address: New Hampshire Office of Energy and Planning, Concord, New Hampshire 03301.

§ United States Environmental Protection Agency.

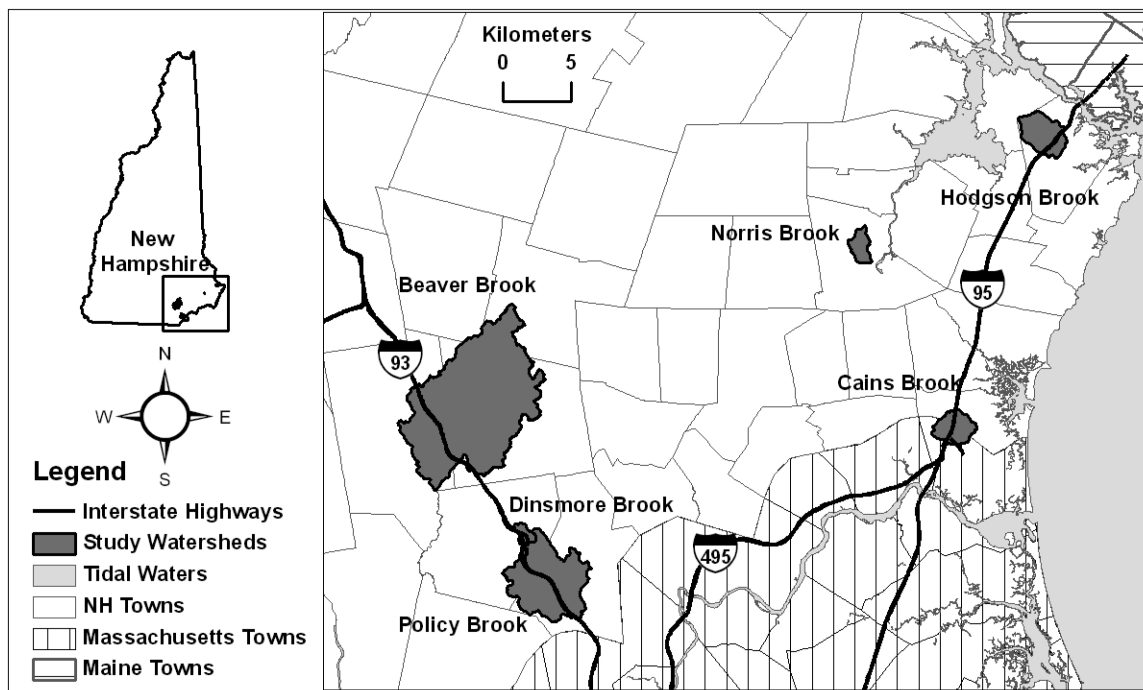


FIGURE 1. Watersheds in southern New Hampshire that were monitored for chloride concentrations using dataloggers. Beaver Brook, Dinsmore Brook, and Policy Brook are in the I-93 corridor. Hodgson Brook, Cains Brook, and Norris Brook are in the seacoast region of New Hampshire near I-95.

proached this objective in three stages. First, we used high frequency observations of chloride concentrations in streams to understand relationships between land use, streamflow, and chloride concentrations. Second, we sought to derive relationships between exceedances of water quality standards detected by high frequency measurements and easier measurements of annual average chloride concentrations. Third, we tested a mass-balance approach to relate annual average chloride concentrations to chloride imports to the watershed and streamflow.

Materials and Methods

Study Area. The six watersheds for this study were Policy Brook, Dinsmore Brook, Beaver Brook, Hodgson Brook, Cains Brook, and Norris Brook in southern New Hampshire (Figure 1). The first three of these watersheds are in the Interstate 93 corridor. The latter three are in the seacoast region of New Hampshire near Interstate 95. The watersheds ranged in size from 1.42 to 78.55 km². Land use in the watersheds was calculated from the National Land Cover data set (c. 2001).

Water Quality Measurements. Measurements of specific conductance at the outlets of the six watersheds were recorded every 15 min for one year using programmable, automated dataloggers (In Situ Troll 9500, YSI 600 XLM, YSI 600 LS, or Hydrolab Datasonde 4A). The watersheds in the I-93 corridor were monitored between October 1, 2006 and September 30, 2007. The seacoast watersheds were monitored between October 1, 2008 and September 30, 2009.

The dataloggers were secured to cabled cinder blocks and deployed on the stream bottom with the sensor end facing upstream. Dataloggers were retrieved at 3 to 6 week intervals, downloaded, and checked for problems. The calibration for specific conductance was checked at the beginning and ending of each deployment using 100 $\mu\text{S cm}^{-1}$ and 2000 $\mu\text{S cm}^{-1}$ standards. The calibration was considered acceptable, and the data were retained if the probe read within 20% of both standards.

Chloride concentrations were estimated from specific conductance measurements using a regression equation

developed for these streams. The regression was derived from 649 paired measurements of chloride and specific conductance collected by the New Hampshire Department of Environmental Services (NHDES), EPA, and the New Hampshire Department of Transportation (NHDT) between 2002 and 2006: Chloride (in mg L^{-1}) = $0.307 \cdot \text{Specific Conductance (in } \mu\text{S cm}^{-1}) - 22.00$ ($r^2 = 0.97$, $n = 649$, $p < 0.01$).

To confirm the datalogger results, chloride concentrations at the outlet stations were also measured in grab samples of water that were collected every three to six weeks for laboratory analysis. The samples were collected in 125 mL plastic bottles, stored on ice, and analyzed using Lachat Method 10-117-07-1-A or using a Thermo-Orion Star Series ISE meter by ASTM Method D512(c) in the NHDES Laboratory in Concord, New Hampshire.

All of the water quality data were quality assured using trip blanks, field duplicate measurements, pre- and post-deployment calibration checks for dataloggers, and inspection of time series. For datalogger records, a yearly time series was considered complete if >90% of the 35,040 possible observations in a year were collected.

The complete datalogger time series of chloride concentrations in the streams were used to determine the number and timing of exceedances of the acute and chronic water quality standards. The time series for chloride concentrations were processed to calculate one-hour and four-day rolling averages, which were compared to the appropriate standard. To avoid double counting from overlapping rolling averages, independent periods of exceedance were determined. Each independent period of exceedance was identified by the beginning of the time block of the first overlapping exceedance and the end of the time block of the last overlapping exceedance. The duration of each independent period of exceedance was calculated and then divided by one hour or four days and rounded down to the nearest integer to obtain the number of independent exceedances of the water quality standard during the period. All of the exceedances in the year were summed.

Stream Flow Measurements. Stream flow at the outlets of the I-93 watersheds was measured between October 1,

2006 and September 30, 2007 by the U.S. Geological Survey using temporary streamgages. Stream flow data were collected at 15 min increments to coincide with the water quality measurements. Streamgage structures were 30 cm by 46 cm by 61 cm aluminum boxes mounted on the upstream-side of culverts with 5 cm steel conduit carrying submersible stage-transducers into the stream. Continuous, 15-min stream stages were measured by submersible transducers and the data were stored by an electronic datalogger. Stage sensing equipment had an accuracy of ± 3 mm. USGS procedures for field work and computation of discharge records were followed (22, 23).

Chloride Imports to Study Watersheds. Chloride imports (i.e., the total mass of chloride applied to the watershed surface) were estimated for the period October 1, 2006 to September 30, 2007 in the three I-93 watersheds to coincide with the water quality measurements in these watersheds.

The chloride imports for roadway deicing were estimated from the roadway lane-kilometers (roadway length multiplied by the number of lanes) in a watershed multiplied by the average salt application rate reported by the organization responsible for deicing the road. Roadway lane-kilometers for state, municipal, and private roads were calculated from the NHDOT roads datalayer (c. 2007) clipped to the watersheds. The salt application rates for the NHDOT and municipalities were derived from the total salt usage reported by each organization during the winter divided by the total lane-kilometers maintained by each organization. The application rates for the 2006–2007 winter ranged from 1.4 to 5.4 Mg Cl lane-km⁻¹ yr⁻¹. The application rate for private roads was assumed to be the average value of the six municipal application rates (2.99 Mg Cl lane-km⁻¹ yr⁻¹).

The chloride imports for deicing parking lots were estimated by multiplying the surface area of parking lots in each watershed by the average salt application rate for municipal roads. The municipal roadway application rate was converted from a per lane-kilometer basis (2.99 Mg Cl lane-km⁻¹ yr⁻¹) to a per hectare basis (8.18 Mg Cl Ha⁻¹ yr⁻¹) by assuming that each roadway lane is 3.66 m wide. Parking lots in each watershed were delineated using GIS software (ESRI ArcView) from aerial photographs (<1 m accuracy) taken between April 22 and May 15, 2005. The delineations were confirmed by 30 visits to the watersheds to identify new parking lots, lots that had been removed, and lots that had been changed since 2005. A Garmin GPS unit was used to map lot boundaries as needed.

Domestic wastewater contains chloride from salt added to foods and household chemicals. There are no wastewater treatment facility outfalls in the watersheds, although some of the watersheds are sewered. The population in each of the watersheds that discharges domestic waste to septic systems was determined using census block data on domestic return flows from Hayes and Horn (24). The per capita chloride discharge rate for excreta and household chemicals in domestic waste was assumed to be 12.4 kg Cl per person per year following Kelly et al. (5) and Godwin et al. (6).

Another large source of chloride from households is water softeners. Water softeners contribute chloride to the watershed when the systems are back flushed and the brine is discharged to septic systems. The population served by septic systems was determined using census block data from Hayes and Horn (24). To determine the fraction of this population with water softeners, we reviewed records of private drinking water samples from towns in the I-93 corridor that were analyzed by the NHDES Laboratory between 2001 and 2005. When a sample is delivered to the laboratory, any treatment system for the drinking water is reported. Approximately 25% of the samples (356 of 1,521 unique samples) reported a treatment type indicative of a water softener (e.g., “water softener”, “salt”, “brine”). A per capita discharge rate for water

softeners of 29.2 kg Cl person⁻¹ year⁻¹ was assumed following Kelly et al. (5).

The chloride load from atmospheric deposition was calculated from the area of each watershed multiplied by the annual wet deposition rate from the closest station from the National Atmospheric Deposition Program (6.7 kg Ha⁻¹ yr⁻¹ at site MA13 in 2006).

Uncovered salt piles in the watersheds contribute to the chloride imports through losses of salt during precipitation. During the winter of 2006–2007, 17 uncovered piles of salt or salt-sand mixture were mapped in the watersheds by windshield surveys and interviews with town employees. We assumed that chloride losses from covered salt piles were negligible. For the largest pile (a 450 m³ pile with a 4:1 salt-sand mixture), a site-specific study was completed which found the chloride losses from the pile were 173 Mg Cl yr⁻¹. The chloride load in the river upstream and downstream of the pile was measured using dataloggers and streamgages for three months. The load from the salt pile was determined by the difference between the chloride load at the downstream and upstream stations, accounting for other chloride sources in the vicinity. For the smaller salt piles, the rate of salt loss was determined from the mass of salt in the pile (product of volume and salt-sand mixture) and an annual loss rate of 33% based on a study of salt pile leachate in New Brunswick (25).

Data Analysis. Summary statistics were calculated for the year-long chloride concentration time series including the number of exceedances of the chronic water quality standard. Chloride concentrations and streamflow were multiplied to calculate chloride export from watersheds. Linear regression was used to quantify the relationship between the annual average chloride concentrations and the frequency of water quality standard exceedances. Finally, annual average chloride concentrations in streams were predicted from a mass balance equation and compared to the measured concentrations for the three I-93 watersheds.

Results and Discussion

Chloride Concentrations in Streams in the Study Watersheds Were Directly Correlated with Development but Were Inversely Related to Streamflow. The watersheds for Norris Brook and Beaver Brook have the lowest percent of land area classified as commercial, industrial, or transportation (3.8–5.7%) (Table 1). The annual average chloride concentrations in these watersheds were 63 and 76 mg L⁻¹, respectively. In contrast, the chloride concentrations for Cains Brook and Hodgson Brook were 201 and 309 mg L⁻¹, respectively. The percent of developed land in these watersheds was between 28 and 31%. The percent of land used for commercial, industrial, and transportation is likely an indicator of impervious, paved surfaces requiring deicing. It is expected that chloride concentrations should be highest in the watersheds where a greater surface area requires deicing treatment using road salt (10, 11, 26, 27).

The datalogger records provide detailed information on peak concentrations and changes in chloride concentrations over time. The time series for all watersheds show relatively low concentrations in the spring and early winter and high concentrations in midwinter (Figure 2). In the time series for the I-93 watersheds (Figure 2a,b,c), the highest concentrations occurred during the summer and early fall in 2007 during a period of very low rainfall. This pattern was not repeated in the seacoast watersheds which were monitored in 2009 during a year with higher summer rainfall.

A unique aspect of this study is that the complete datalogger records can be used to quantify the number of exceedances of the water quality standard during a year. The four-day chronic water quality standard (230 mg L⁻¹) was used for this analysis because there were few exceedances

TABLE 1. Land Use Characteristics and Annual Statistics for Chloride Concentrations and Exceedances of the Chronic Water Quality Standard (230 mg L^{-1}) in Study Watersheds

watershed (drainage area)	commercial, industrial, and transportation land use	period of record	chloride measured by dataloggers		
			N	ave (mg L^{-1})	number of exceedances (4-day periods)
Norris Brook (2.89 km^2)	3.8%	10/1/08–9/30/09	35,018	63.21	0
Beaver Brook (78.55 km^2)	5.7%	10/1/06–9/30/07	35,001	76.13	0
Dinsmore Brook (1.42 km^2)	8.3%	10/1/06–9/30/07	33,942	148.94	17
Policy Brook (26.36 km^2)	13.6%	10/1/06–9/30/07	34,984	180.76	27
Cains Brook (5.74 km^2)	28.1%	10/1/08–9/30/09	35,022	201.24	26
Hodgson Brook (7.94 km^2)	30.9%	10/1/08–9/30/09	35,022	308.67	67

of acute standard. Table 1 lists the number of times the chronic water quality standard was exceeded for the six watersheds during a year. No exceedances were observed in Norris Brook or Beaver Brook, the two watersheds with the lowest chloride concentrations. In Dinsmore Brook and Policy Brook, the chronic water quality standard was violated 17 and 27 times during the year, respectively. Finally, in the watersheds with the highest development, Cains Brook and Hodgson Brook, the chronic standard was violated 26 and 67 times during the year, respectively. The periods of exceedance typically lasted for one or two weeks but could persist as long as several months in the more developed watersheds.

Much of the variability in chloride concentrations within each stream can be explained by changes in streamflow. The highest chloride concentrations occurred during times of lowest stream flows. Figure 3 shows that chloride concentrations in Policy Brook were explained by changes in streamflow, regardless of the season. This finding has been documented in other studies and indicates that groundwater is the dominant source of chloride to the streams (11, 28). In winter, there was more variability in the concentration-flow relationship due to occasional rapid changes in chloride concentrations from road salt-laden stormwater discharge. There was less variability in the streamflow-chloride rela-

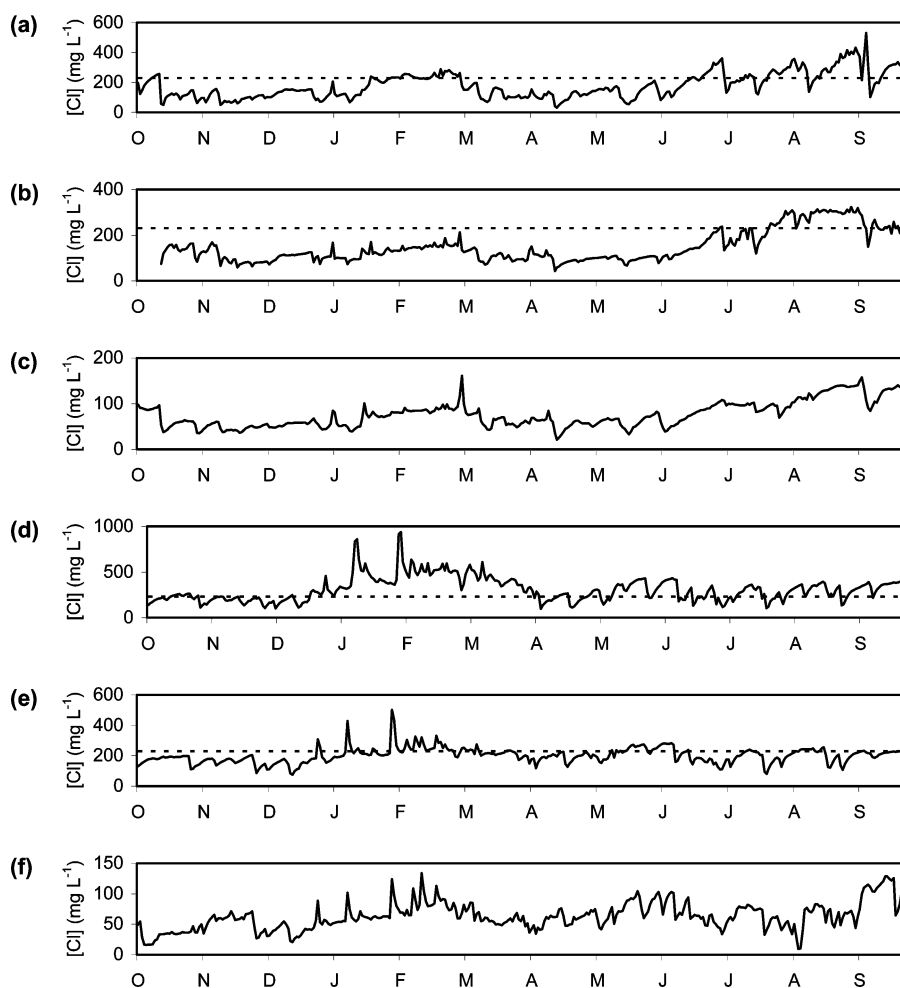


FIGURE 2. Time series of daily average chloride concentrations (mg L^{-1}) inferred from specific conductance measurements made every 15 min by dataloggers: (a) Policy Brook; (b) Dinsmore Brook; (c) Beaver Brook; (d) Hodgson Brook; (e) Cains Brook; and (f) Norris Brook. Parts a, b, and c are the I-93 watersheds and cover the period 10/1/2006 to 9/30/2006. Parts d, e, and f are the seacoast watersheds and cover the period 10/1/2008 to 9/30/2009. The x-axis is labeled with the first letter of the month. The dashed line is the chronic water quality standard (230 mg Cl L^{-1}).

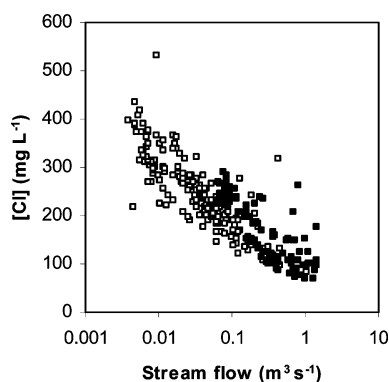


FIGURE 3. Daily average chloride concentrations (mg Cl L^{-1}) relative to streamflow ($\text{m}^3 \text{s}^{-1}$) in Policy Brook under (\square) summer conditions (7/1/07–9/30/07) and (\blacksquare) winter conditions (12/1/06–3/31/07).

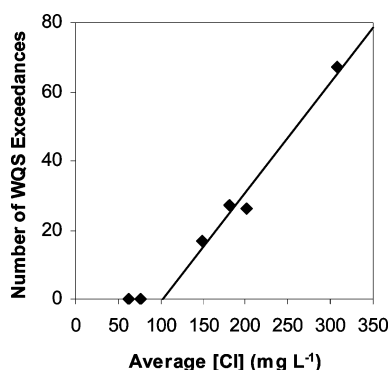


FIGURE 4. Relationship between annual average chloride concentrations in mg Cl L^{-1} and the number of exceedances of the chronic water quality standard during a year in the six study watersheds. The line is the regression of the four points with documented exceedances (number of exceedances = $0.317 \cdot [\text{Cl}] - 32.37$, $n = 4$, $r^2 = 0.96$, $p < 0.05$).

tionship in the larger watersheds, such as Beaver Brook, likely due to diversification of salt sources and longer groundwater flow paths.

Exceedances of the Chronic Water Quality Standard for Chloride Were Linearly Related to the Annual Average Chloride Concentration. This observation means that complicated and labor-intensive datalogger records may be replaceable by simple annual average concentrations in order to estimate exceedances of the water quality standard. On Figure 4, the average chloride concentration has been plotted against the number of water quality standard exceedances for the year for the six study watersheds. No exceedances of the water quality standard were observed when annual average chloride concentrations were less than 76 mg L^{-1} . The lowest average concentration for which water quality standards were violated was 149 mg L^{-1} .

Linear regression was used to predict the annual average chloride concentration threshold below which exceedances would not occur. The regression only included the four points in Figure 4 with documented exceedances because the other two points were already lower than the threshold for exceedances. The regression was statistically significant ($r^2 = 0.96$, $p < 0.05$). The approximate threshold for any exceedances to occur during the year is an annual average concentration of 102 mg L^{-1} . The confidence interval for the threshold is 88 to 116 mg L^{-1} (one standard error). This relationship cannot be used to predict when the exceedances will occur, only that they are likely to occur, and approximately how long the exceedances will last over the course of the year.

The relationship between annual average chloride concentrations and water quality standard exceedances appears to be applicable across different watersheds in southern New Hampshire. The linear increase in exceedances shown in Figure 4 is composed of results from six different watersheds of variable size and development that were monitored in two different years with different annual and seasonal precipitation. Mullaney et al. (10) observed a similar relationship between chloride concentrations during base-flow conditions and maximum chloride concentrations in streams. Maximum concentrations greater than the chronic water quality standard were observed at sites with base-flow concentrations greater than $75\text{--}90 \text{ mg L}^{-1}$. While not exactly the same, the two relationships both illustrate that nonpeak concentrations can be used to predict peak concentrations which might exceed the water quality standard and the thresholds for exceedances of the chronic water quality standard are similar. Results from Denner et al. (29) for Vermont streams also fit the regression model. No exceedances were observed for streams with average chloride concentrations between 8.3 and 83.1 mg L^{-1} . However, the chronic standard was exceeded 65% of the year (~ 59 exceedances) for a stream with an average concentration of 292 mg L^{-1} .

Annual Average Chloride Concentrations Can Be Predicted from Chloride Import Rates and Streamflow. Chloride imports into the watershed were estimated for the I-93 watersheds: Beaver Brook, Dinsmore Brook, and Policy Brook. Due to the different drainage areas for the three study areas, comparisons between watersheds were made based on chloride imports per unit of drainage area. In these terms, the lowest chloride import rate was for Beaver Brook with $45 \text{ Mg Cl km}^{-2} \text{ yr}^{-1}$. Dinsmore Brook was in the middle with $66 \text{ Mg Cl km}^{-2} \text{ yr}^{-1}$. Policy Brook had the highest chloride import rate, $98 \text{ Mg Cl km}^{-2} \text{ yr}^{-1}$. Deicing of roadways and parking lots accounted for 91% of the imports. Parking lot deicing was the single largest source (45%) followed by municipal roads (28%), state roads (11%), domestic waste (5%), private roads (4%), losses from road salt piles (3%), water softeners (3%), and atmospheric deposition (1%). Several studies in the literature have quantified the salt imports and mass balance in watersheds similar to the I-93 watersheds. Road salt for deicing accounted for 90 to 95% of salt imports to the Mohawk River watershed in New York (6), the Wappinger Creek watershed in New York (5), the Scituate Reservoir drainage basin in Massachusetts (27), and the Shingle Creek watershed in Minnesota (18).

The range of chloride import rates for the I-93 watersheds in this study provides an opportunity to examine the effects of increasing road salt use on water quality. We have shown that annual average chloride concentrations and exceedances of the water quality standard are higher in watersheds with more development and presumably higher chloride import rates. This relationship is not merely an empirical relationship but one that can be predicted from first principles. The amount of water available to dilute the chloride imports can be represented by the runoff coefficient, the annual average streamflow divided by drainage area. If chloride is not significantly attenuated or retained in the watershed on the time scale of a year, the annual average chloride concentration should be equal to the chloride imports per unit of drainage area divided by the runoff coefficient with an appropriate unit conversion factor. The mass balance equation to predict the average chloride concentration is

$$[\text{Cl}]_{\text{ave}} = \alpha \cdot \frac{I}{R}$$

where $[\text{Cl}]_{\text{ave}}$ is the annual average chloride concentration in mg L^{-1} ; α is a units conversion factor equal to 0.0317 mg m^3

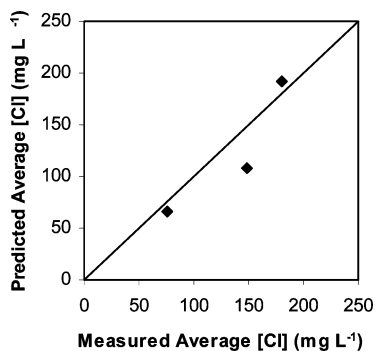


FIGURE 5. Predicted versus measured annual average chloride concentrations in Policy, Dinsmore, and Beaver Brooks. The line is the 1:1 line, not a regression through the points.

yr Mg⁻¹ L⁻¹ s⁻¹, I is the mass of chloride imported to the watershed during the year in Mg Cl km⁻² yr⁻¹; and R is the runoff coefficient in m³ s⁻¹ km⁻². Figure 5 shows that this simple equation accurately predicts the average chloride concentration for the I-93 watersheds. The points fall along the 1:1 line indicating good correspondence between the measured and predicted chloride concentrations. The sea-coast watersheds were not included in Figure 5 because chloride import rates have not been quantified for these watersheds.

Chloride fate and transport has many complicated retention and release steps (3–5). Novotny et al. (26) observed that storage of chloride in soils, aquifers, lakes, and wetlands retained the majority of the chloride imported to watersheds in Minnesota in 2000–2007. Therefore, it is unexpected that a mass balance equation that assumes no retention of chloride should predict chloride concentrations reasonably well. One explanation is that there was, in fact, relatively little chloride retention capacity remaining in the I-93 watersheds due to high and prolonged historical loading of salt. In Beaver Brook, Dinsmore Brook, and Policy Brook, the chloride export rates were 36, 59, and 51 Mg Cl km⁻² yr⁻¹, respectively, which indicate 22%, 10%, and 47% retention of chloride in these watersheds during the year.

A Screening-Level TMDL Method. Despite the complications associated with chloride retention, the mass balance equation can be coupled with the relationship between average chloride concentrations and exceedances of the water quality standard to complete screening-level TMDL studies for chlorides in watersheds. We have shown that an annual average chloride concentration of 102 mg L⁻¹ is the apparent threshold above which exceedances of the chronic water quality standard occur. Therefore, the maximum chloride imports allowable to avoid exceedances would be an annual average of 102 mg L⁻¹ multiplied by the runoff coefficient and divided by the unit conversion factor.

The published TMDLs that have been developed for the I-93 watersheds can be used to test the screening-level method. When NHDES produced the official chloride TMDLs for Policy Brook, Dinsmore Brook, and Beaver Brook (19–21), the acceptable chloride imports were calculated through a complicated algorithm based on a chloride load duration curve derived from datalogger records. This approach was used to comply with legal requirements for TMDLs from the Clean Water Act and followed an approved practice from another chloride TMDL (18). The official chloride TMDLs for Beaver Brook, Dinsmore Brook, and Policy Brook were 64, 49, and 76 Mg Cl km⁻² yr⁻¹, respectively. The screening-level TMDL method presented in this paper predicts that the TMDLs for the Beaver Brook, Dinsmore Brook, and Policy Brook watersheds should be 69, 62, and 52 Mg Cl km⁻² yr⁻¹, respectively. These screening-level estimates are close to the official values for Beaver Brook and Dinsmore Brook but not

for Policy Brook. The significant retention of chloride in the Policy Brook watershed (47%) may explain this discrepancy.

This comparison shows that the method presented in this paper can be an effective screening tool, but more detailed studies may be necessary in watersheds with unique conditions or significant chloride retention. Even with chloride retention, the method can still be used as a conservative screening tool because it tends to overestimate in-stream chloride concentrations and identify lower TMDLs than may be necessary to attain surface water quality standards. These screening-level TMDLs may be more appropriate in the long run because chloride retention is not a permanent sink. When chloride is retained in a watershed, chloride concentrations in soils, aquifers, lakes, and wetlands will increase, and the water quality standard will eventually be exceeded when the retention capacity is used up.

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Supporting Information Available

Additional information on chloride budgets for the study watersheds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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