

Sources of Elevated Chloride in Local Streams: Groundwater and Soils as Potential Reservoirs

Dustin W. Kincaid · Stuart E. G. Findlay

Received: 30 January 2008 / Accepted: 5 February 2009 / Published online: 3 March 2009
© Springer Science + Business Media B.V. 2009

Abstract Several recent reports document increasing concentrations of chloride in surface waters of northeastern and midwestern North America. These patterns, together with high summertime baseflow concentrations, suggest the possibility of short-term retention of winter-applied chloride within catchments. This study examined the potential of groundwater and soils to act as reservoirs of Cl within the watershed of a small rural stream in New York that has shown a doubling of Cl over the past two decades and almost constant concentrations across seasons. Groundwater samples were obtained from 20 private drinking wells distributed around the catchment to determine whether concentrations were at or greater than surface waters and so could act as a source to the stream. In 16 of the 20 wells, chloride concentrations were lower (mean of 16 samples=4.10 mg Cl/L (standard deviation=4.8)) than concurrent streamwater concentrations (mean of

eight locations sampled on two dates=28.9 (5.8)). Four wells, however, showed higher concentrations ranging from 35 to 230 mg Cl/L suggesting either point source contamination or very heterogeneous groundwater chloride sources. Soil cores from the catchment were irrigated in the laboratory with a NaCl solution for 2 weeks followed by 2 weeks irrigation with a chloride-free solution. Chloride concentrations in core leachates were lower than in the irrigation solution during the first 2 weeks indicating some retention of Cl within the cores. After cores were irrigated with chloride-free water, leachate concentrations declined but would not reach streamwater concentrations until the equivalent of 15 cm of precipitation was added to the core.

Keywords Chloride · Groundwater · Salt · Soil · Stream

D. W. Kincaid
University of Wisconsin,
Madison, WI, USA
e-mail: dustinkincaid@gmail.com

S. E. G. Findlay (✉)
Cary Institute of Ecosystem Studies,
P.O. Box AB, Millbrook, NY, USA
e-mail: findlays@ecostudies.org

Present Address:
D. W. Kincaid
C3860 Elroy Drive,
Stratford, WI 54448, USA

1 Introduction

High and often increasing sodium chloride levels in surface waters are viewed as indicators of nonpoint source pollution from road salt application and frequently reach concentrations capable of causing environmental harm or concern for human health (Kaushal et al. 2005). Increases in surface water chloride over the past 10–20 years (e.g., Kelly et al. 2008) in the absence of new road construction and

despite efforts to minimize salt application rates suggests some sort of long-term reservoir or mechanism for chloride retention in catchments. Summertime base-flow concentrations that are not markedly lower than winter values further suggest that chloride is not being exported from catchments proportionally with surface or shallow groundwater turnover. Several mechanisms for Cl retention have been proposed and tested including sorption to soils, chlorination of organic matter, or accumulation in one or more groundwater pools (c.f. Bastviken et al. 2006).

Any process contributing to chronic concentrations of Cl can have deleterious effects on the environment and water quality and are consequently a growing environmental concern. Chloride concentrations as low as 250 mg/L are recognized as harmful to freshwater life (Office of Water, Regulations, and Standards, Criteria and Standards Division 1988), and chronic inputs of Cl are thought to negatively affect plants of wetlands and uplands (Bogemans et al. 1989; Richburg et al. 2001). Moreover, maintenance of high concentrations during the more biologically active summer months may increase ecological effects. Further, water becomes salty to the human palate at 250 mg/L and high concentrations of Cl are often associated with high concentrations of sodium, which are harmful to human health (Lewis 1999). Recent studies of macroinvertebrate bioindicators in New York show negative associations between chloride and biotic indices (Riva-Murray et al. 2002) but the generally low Cl concentrations in their streams (median 15–20 mg/L) imply chloride is serving as an indicator not a direct stressor.

Until recently, rising salinity levels in surface water received little attention, despite documentation of this occurrence over several decades (Rosenberry et al. 1999; Godwin et al. 2003; Jackson and Jobbagy 2005) and multiple studies have correlated high Cl levels in catchments with high percent road cover and other impervious surfaces (Godwin et al. 2003; Kaushal et al. 2005; Peters and Turk 1981). Kaushal et al. observed winter Cl concentrations in urban northeastern US streams up to 25% of the concentration of seawater, with peak concentrations as much as 100 times greater than in streams draining forested watersheds.

Road deicing salts (principally NaCl) are likely the largest source of Cl to groundwater and surface water for most of the northern USA. In 2002, New York State applied approximately 9.36 Mg/lane/km/day,

averaging roughly 454,000 Mg of road salt annually (Godwin et al. 2003). Several studies have found and confirmed Cl concentrations as high as 14,000 mg/L accumulating in shallow groundwaters of the Metropolitan Toronto area, raising concern for local streams (Pilon and Howard 1987; Taylor et al. 1991).

Road salt input to streams may occur via two pathways: surface water runoff, resulting in immediate Cl inputs, and delayed, longer-term inputs via soil permeation and eventually groundwater infiltration. The first pathway is detected by a rise of Cl levels in streams during winter months and early spring snow-melt events. The original assumption was that the majority of the applied road salt would be washed out of catchments each season by precipitation events and snow melt. However, a study in the Duffin Creek-Rouge River basin in the Greater Toronto area found that only 45% of the road salt applied is removed by overland flow annually, and the remaining 55% enters temporary storage in shallow subsurface waters (Howard and Haynes 1993).

Salt entering soils and groundwater may be retained for some period, contributing to surface water Cl much later in the season. Both soil retention and accumulation in groundwater may behave as reservoirs of Cl, acting first as a sink and eventually a source of Cl in these systems. Research examining rising Cl concentrations in several New York State streams has revealed elevated Cl concentrations in summer baseflows, suggesting a constant input of Cl to the system, rather than via erratic precipitation events (Yozzo et al. 2005). If groundwater Cl concentrations were greater than surface waters, then stream recharge by shallow or regional groundwater might maintain high summer concentrations.

Soils within catchments may also function as a reservoir. Chloride is generally considered to behave conservatively in soils, moving through a system with little or no retention. Multiple studies, however, have found that significant amounts of Cl are retained in catchment areas (Lovett et al. 2005; Likens 1995, p. 26). A recent study in Sweden has shown simultaneous retention and release of Cl, suggesting much less mobility of Cl in the soil profile than previously thought (Bastviken et al. 2006).

This study examined the potential of groundwater and soils to act as reservoirs of Cl within the watershed of a small rural stream that has shown a doubling of Cl over the past two decades (Kelly et al.

2008). We address both groundwater and soils, focusing on the following questions: (1) Are there elevated concentrations of Cl in local groundwater? (2) Is there retention or release of Cl in important soil types within the watershed? (3) Does soil type have an effect on the amount of Cl retained or released?

2 Materials and Methods

2.1 Study Sites

The study was conducted in the catchment of the East Branch of the Wappinger Creek (EBWC) in Dutchess County, New York (Fig. 1). The catchment is characterized by deciduous forest (~55%) with mixed agriculture (29%) and low-density residential housing. Agriculture is largely pasture with some areas of orchards and corn fields. The Village of Millbrook, NY operates a small wastewater treatment plant that discharges to the EBWC. The general landscape is rolling hills at fairly low elevation (mostly <500 m above sea level). Subsurface geology is primarily sedimentary rocks overlain by glacial till and the predominant soils are sandy loams (details below). There are numerous small streams, ponds, and wetlands in the watershed and the vast majority have not been sampled for water chemistry. Groundwater attributes

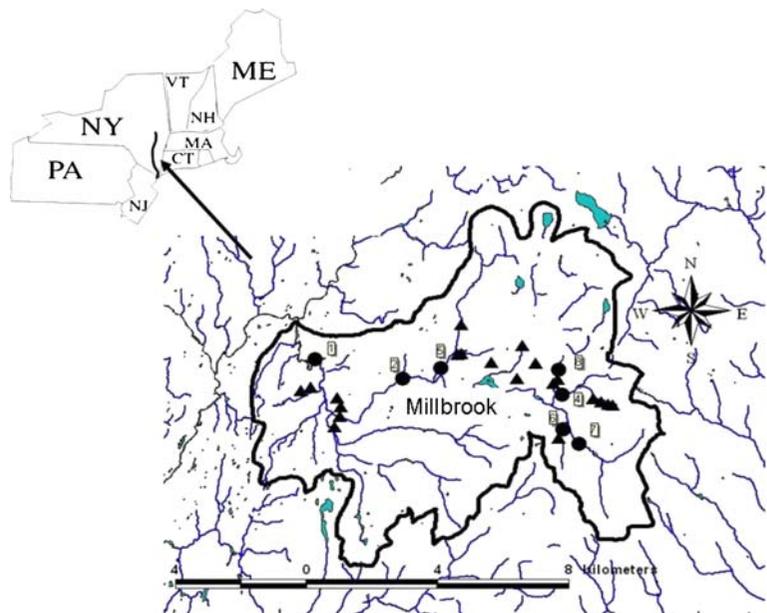
and hydrogeology have been described for areas near the Village of Millbrook's public water supply. The saturated zone is about 2.5 m thick and overlays a layer of glacial lake clay deposits. The catchment area is 8,655 ha and the EBWC is third order at the point of discharge to the mainstem Wappinger Creek. Mean annual discharge is about 1 m³/s ranging from a high of 2.5 in January to summer baseflow of 0.3–0.5 m³/s. The Institute of Ecosystem Studies has monitored water quality in the East Branch for 20 years providing a good context for a more intensive study of chloride distributions (see Kelly et al. 2008). Monthly mean chloride concentrations at the monitoring site range from 24–30 mg/L with slightly lower concentrations in the high discharge months of March through July.

The climate of the area is temperate with an annual mean temperature of slightly under 10°C and 3 months (December–February) with mean temperatures below freezing. Annual precipitation averages about 100 cm and is fairly evenly distributed throughout the year. Precipitation as snow or freezing rain is common during winter with perhaps half or more of the total precipitation during December–March in frozen form.

2.2 Surface and Groundwater Sampling

Surface water samples were obtained from the EBWC on 15 June 2006 and 18 July 2006. Eight sites within

Fig. 1 Watershed of the East Branch of the Wappinger Creek in southeastern New York State. *Triangles* are groundwater wells and *circles* are surface water locations. *Numbers in boxes* identify surface water sample locations shown in Fig. 2. The *heavy black line* shows the approximate watershed boundary. Stream flow direction is generally from east to west. The *arrow* shows location of the study watershed in the northeastern USA



the EBWC catchment were sampled (Fig. 1), including locations above and below the Village of Millbrook wastewater treatment plant. Water samples were collected by hand from well-mixed areas of the stream using 125 mL polyethylene bottles.

Samples were unfiltered and stored cold until analysis of Cl by an ion specific electrode [Thermo-Electron (Orion) 9717BN Chloride Electrode]. The probe was calibrated each time samples were analyzed.

Groundwater samples from private drinking water wells ($n=20$) were obtained throughout the EBWC catchment over a 2-week period in midlate summer of 2006. Since most of these were collected by the property owner, we do not know the precise well location but all parcels adjoined the EBWC or one of its tributaries (Fig. 1). Samples were collected immediately after the pressure tank where possible or from commonly used faucets as necessary. Owners were asked to confirm that there was not a water softener before the point of sample collection. The wells were of unknown depths, ages, and recharge rates.

2.3 Soil Retention Experiment

To examine the potential for Cl retention in common local soils, we obtained cores from six sites and four different soil series representing two of the most common and two of the most distinct soil classes in the catchment including a common riparian soil [i.e., Fluvaquents–Udifluvents (Ff)] (Table 1). Soil cores ($n=20$, height=15 cm) were collected in polyvinyl chloride (PVC) cylinders with an inner cross-sectional area of 20 cm² to capture the soil organic layer. Samples for characterization of soil organic matter and initial water and chloride content were collected at each site where soil cores were obtained. The PVC

cylinders containing the undisturbed soil cores were stored in a refrigerator for 5 days and thereafter in a temperature controlled (10°C) chamber. Cores were fitted with a bottom cap including a small hole so all soils could drain freely. A small square of screen and approximately 1 cm of gravel that had been previously soaked and rinsed were placed in the bottom PVC end cap. Rubber stoppers were placed loosely on the top of the cylinders to limit evaporation.

The cores were irrigated every 5 days with 2.5 cm (52 mL) of artificial rain (i.e., eight total irrigations). The amount of artificial rain corresponds to the weekly mean precipitation for spring and early summer. The chemical composition corresponds to local precipitation chemistry (Lovett and Hubbell 1991).

Cores were subjected sequentially to two different irrigation treatments. For the first four irrigation events, enough NaCl was added to the artificial rain to bring the concentration to 643 mg/L Cl. The concentration corresponds to an approximation of the maximum amount of Cl present in highway runoff after a deicing event in the catchment of the EBWC. For the final four irrigation events, no NaCl was added to the artificial rain. After each irrigation, the resulting leachate was collected for 1 h with the majority of leachate draining within the first 5 min. The amount of leachate was determined by weight and the samples were stored in a refrigerator until measurement of Cl.

One day after the final irrigation event, wet mass was determined for each core. Water content and loss on ignition (LOI) were determined for the reference samples that had been stored in a refrigerator during the incubation period. Initial chloride concentration of reference samples was determined using a sodium bicarbonate extraction.

Table 1 Soil core sample descriptions

Soil core	Soil series	Musym	Area of watershed (%)	Texture	Mean H ₂ O content (%)	Mean OM (%)
1–9	Hoosic	HsA	1.8	Gra L	24.4	9.9
10–13	Dutchess–Cardigan	DwC	11.8	Sil L/L	25.0	7.7
14–17	Nassau–Cardigan	NwD	23.0	Sil L/L	29.4	10.6
18–20	Fluvaquents–Udifluvents	Ff	0.8	Sil L	43.23	15.07

Soil series classifications are according to Dutchess County Soil and Water Conservation District (1991). Musym is the map unit symbol used to classify the soils in the soil survey

2.4 Analytical Procedures

The concentration of Cl in the soil leachate and all surface and groundwater samples was determined using a ThermoElectron (Orion) 9717BN Chloride Electrode. Before each set of analyses, the probe was calibrated with solutions of known Cl concentrations, prepared using NaCl and Nanopure™ water. An aliquot of the leachate or water sample (25 mL) was mixed with a stabilizing solution [5 M NaNO₃ (0.5 mL)] following the manufacturer's recommendation.

The water content was determined by drying a small portion of each reference soil sample to constant weight at 65°C. Duplicate analyses were conducted for each reference sample. Small subsamples (4–7 g) were then combusted for 4 h at 450°C to determine organic content as LOI.

The dry mass of the undisturbed soil cores was estimated by weighing the wet soil 1 day after the final irrigation and using the water content obtained from the reference samples to estimate the dry mass of the undisturbed soil.

Chloride retention in the incubated soil cores for irrigation events was calculated as:

$$Cl_{\text{ret}}(\text{mg}) = [\text{vol.}(\text{L}) \times \text{conc.}(\text{mg}/\text{L})]_{\text{IN}} - [\text{vol.}(\text{L}) \times \text{conc.}(\text{mg}/\text{L})]_{\text{OUT}} \quad (1)$$

This was calculated for each irrigation event and then summed over the NaCl addition and no-salt periods of the experiment. A one-way analysis of variance (ANOVA) was used to evaluate whether total Cl retention per gram of dry soil varied by soil type.

3 Results and Discussion

3.1 Surface Water and Groundwater

Surface water chloride concentrations in the EBWC ranged from 20 to 35 mg/L with generally higher values in the south and west (further down the drainage (Fig. 2). The mean concentrations for the two dates were indistinguishable (31.4±5.7 and 26.4±5.2 (mean, standard deviation, *n*=8)) for mid-June and mid-July, respectively. There was no significant increase in ambient Cl concentrations in a

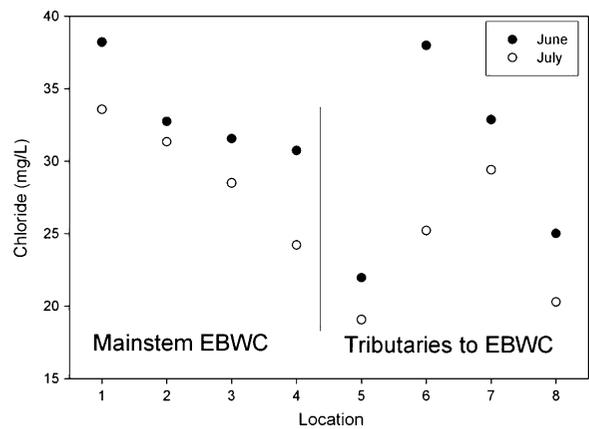


Fig. 2 Chloride concentrations of surface water samples from two dates in summer 2005 for the East Branch of the Wappinger Creek. Locations 1 through 4 are on the mainstem and 5 through 8 are tributaries. See Fig. 1 for locations on map

pairwise comparison of samples above and below the wastewater treatment plant in Millbrook ($P=0.35$).

Of the 20 groundwater samples taken from wells in the EBWC watershed, only four samples had Cl concentrations above the lowest concentration found in the surface water of the EBWC during the two samplings (Fig. 3). One sample was much higher than any of the surface waters collected and may have been the result of point-source contamination. Wells were distributed across six geological strata.

3.2 Soil Cores

Soils sampled were intended to represent large areas of the EBWC catchment as well as include a common riparian hydric soil (Table 1). The organic matter content (LOI) of the soil samples ranged from 6% to 15% of dry mass, while the water content ranged from 19% to 44% of total mass. The riparian soil had the highest water content. Initial chloride concentrations in all soil types were minimal with less than 5 mg/L in the sodium bicarbonate extracts.

Each soil core received 416 mL of artificial rain during the entire experimental period, which corresponds to 52 mL per irrigation event. The volumes of leachate leaving each core for the first irrigation event ranged from 14 to 37 mL. The volumes of leachate leaving each core for the final seven irrigations were higher, with a range of 42 to 50 mL. The initial water content of these soils ranged from 20% to 40% of

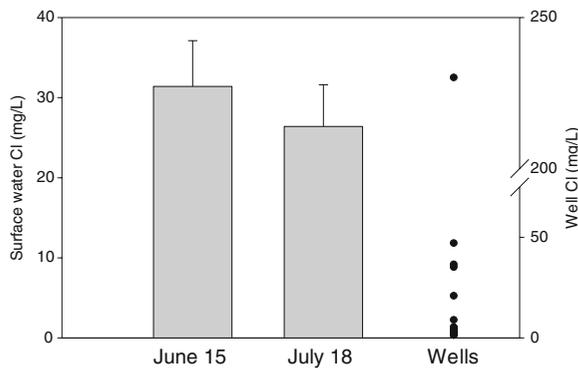


Fig. 3 Mean chloride in surface waters and wells of the catchment. The surface water means (*bars*) for each date are derived from eight sampling locations throughout the basin. Each well sample (*points*) is based on duplicates collected on a single date. Note difference in scales

total soil mass and for the upland soils, there was approximately 50–80 mL of water in the cores at the end of the experimental period. Given the frequency of irrigation, the soils were probably at field capacity for the entire experimental period.

The Cl concentration in irrigation water over the first four events was 643 mg/L and the mean leachate concentration across soils was 520 mg/L (Fig. 4). The mean percentage of Cl retention for the period encompassing the first four irrigation events for all groups was 39.9% (Table 2). The amount of Cl added to each soil core as artificial rainwater during the NaCl addition period was 134 mg Cl. The mass of Cl retained after the NaCl addition period ranged from 35 to 80 mg (Table 2). The percentage of total Cl retained after the NaCl addition period differed significantly among soil types (ANOVA, $P < 0.0003$).

After the final four irrigation events in which no additional Cl was added, Cl concentrations in the leachate ranged between 53 and 191 mg/L, with a mean of 103 mg/L (Fig. 4). At the end of the entire period, Cl retention averaged across all cores was 15% of the amount of Cl added in the first interval (Table 2). In the second interval, the soil cores released an average of 62% (range of 33–93%) of the Cl that had been retained over the course of the salt addition period. The amounts of Cl retained in the soil cores over the entire experiment differed significantly among soil types ($P < 0.0135$).

The differences among soil types in short-term chloride retention (Table 2) were associated with differences in soil organic matter and water content.

These two variables are themselves correlated ($P < 0.05$, $r^2 = 0.8$) so we cannot separate their effects. However, the correlation between chloride retention and percentage of loss on ignition accounted for slightly more of the variation in Cl retention ($r^2 = 0.53$) than the relationship between retention and water content ($r^2 = 0.49$).

The long-term increase in stream chloride concentrations and maintenance of high baseflow values suggests a reservoir of chloride somewhere within the catchment. The source could be either a point or nonpoint source in the EBWC watershed. Sewage treatment plants are a potential point source of excess Cl. However, there was no significant increase in Cl concentrations below the sewage treatment plant in Millbrook. The majority of Cl loading to the EBWC is ultimately attributed to road deicing salts (Kelly et al. 2008), but since our sampling was in midsummer, there were no road salt-contaminated surface flows to the stream. Acknowledging that most of the Cl is derived from road salt, there is likely one or more reservoirs that are retaining Cl during the period of road salt applications and gradually releasing Cl after this period.

One potential reservoir for Cl in the watershed is groundwater. Out of the 20 groundwater samples from drinking wells within the watershed, only four of them were above or within the range of ambient Cl concentrations in the stream (Fig. 3). For groundwater to be a consistent source, the concentrations would have to be above stream concentrations. These results,

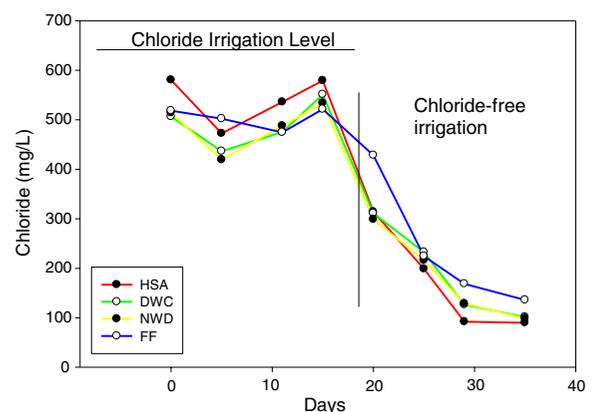


Fig. 4 Average concentration of Cl in leachate leaving the incubated soil cores after each irrigation event. The horizontal line shows the Cl concentration (643 mg Cl/L) during the first four irrigations. The second set of irrigations was free of Cl. Soil types are depicted using their map unit symbols (Table 1)

Table 2 Chloride retention in soil cores shown as mass of Cl retained as well as percent of applied Cl retained in the first and second periods of irrigation

Soil musym	Total mass Cl retained (mg)	% Cl retention period 1	% Cl retention period 1+2
Has	68.4 (3.9)	38.5 (1.4)	12.6 (2.1)
DwC	78.5 (2.6)	44.1 (2.2)	14.6 (3.9)
NwD	77.7 (13.6)	42.7 (8.0)	15.4 (3.0)
Ff	75.3 (21.7)	34.7 (7.4)	21.6 (4.2)
All groups	73.3 (3.7)	39.9 (2.0)	14.9 (1.5)

Values are averages (standard error)

however, cannot unequivocally rule out high Cl groundwater in the watershed since we do not know the depth or aquifer contributing to the various wells. If groundwater is indeed behaving as a reservoir for Cl in the system, the likely source is shallower groundwater.

Our experiment showed that a variety of common soils could in fact retain chloride over a several week period but we cannot unequivocally identify the mechanism. Residence time of chloride within the soil will probably vary greatly depending on the process responsible. Chlorination of soil organic matter (Bastviken et al. 2007) probably represents the longest-term soil sink requiring mineralization before chloride is returned to porewaters. Simple physical retention within the porewaters may be the fastest turnover pool but will depend on soil moisture, precipitation, and depth of the unsaturated zone. Any of these mechanisms, singly or in concert, may help explain the lag between winter salt application and high summertime concentrations. Our results are consistent with several other studies using similar irrigated soil core experiments (Bastviken et al. 2006; Rodstedth et al. 2003). There was net retention of Cl ranging between 26% and 60% after the four NaCl + artificial rain irrigations to the incubated soil cores. After these initial irrigation events, a minimum of 80% of the irrigation water was recovered after each event, indicating that the majority of the soil water in the cores was replaced during each event. The total amount of irrigation water applied over the course of the experiment (>400 mL/core) would have replaced the existing porewater volumes three- to tenfold depending on initial water content of the soils. Therefore, Cl retention was not simply incomplete flushing although this undoubtedly contributes to varying degrees in our experiments and in nature.

During the final four irrigation events (no NaCl), the soil cores behaved as sources and released previously applied Cl. The crucial result is that not

all of the Cl was released after the first “rinsing” event (Fig. 4). Further, the soil cores required four “rinsing” events (a cumulative water input approximately equivalent to 4 weeks of rain in the watershed) to yield more than half of the previously retained Cl. Even after these four events, the recovered leachate concentrations were above summertime ambient stream concentrations for Cl. We estimate that six additional precipitation events of 2.5 cm each would be required to bring concentrations down to 30 mg Cl/L. This quantity of precipitation falls in somewhat under 2 months in the spring and so simple soil retention can account for part of the seasonal lag in surface water chloride.

The actual range in Cl retention across soils was about threefold (Table 2) so, for whatever mechanism, there is substantial potential for variation in Cl retention across the landscape. Retention was correlated with both soil water content and organic matter but the strong association between these two soil characteristics makes it impossible to draw conclusions about the underlying mechanism.

4 Conclusions

Our results suggest soil retention and gradual release may act as the temporary reservoir and source of Cl linking wintertime salt applications with summertime surface water concentrations. The groundwaters sampled from the various drinking water wells did not consistently contain sufficient Cl to maintain summer stream Cl. However, we recognize that these two potential reservoirs are not mutually exclusive and in actuality, soil sorption or chlorination could be the first of a two-step chloride retention mechanism. If soil sorption acted as the first mode of retention, wetter conditions during spring and early summer could move the chloride into the groundwater pool. The common assumption, however, is that Cl is

highly mobile in soils (i.e., soils do not retain Cl) and therefore, Cl is often used as a tracer in soil water and groundwater. This belief is currently being questioned (Bastviken et al. 2006; Lovett et al. 2005; Oberg and Sanden 2005; Rodstedth et al. 2003). The experiment shows that soils in the EBWC may behave as a temporary reservoir of Cl.

Acknowledgments Dustin Kincaid was supported by the IES Research Experience for Undergraduates Program funded by the National Science Foundation. The Dutchess County Environmental Management Council assisted with GIS data.

References

- Bastviken, D., Sanden, P., Svensson, T., Stahlberg, C., Magounakis, M., & Oberg, C. (2006). Chloride retention and release in a boreal forest soil: Effects of soil and water residence time and nitrogen and chloride loads. *Environmental Science & Technology*, 40, 2977–2982. doi:10.1021/es0523237.
- Bastviken, D., Thomsen, F., Svensson, T., Karlsson, S., Sanden, P., et al. (2007). Chloride retention in forest soil by microbial uptake and by natural chlorination of organic matter. *Geochimica et Cosmochimica Acta*, 71, 3182–3192. doi:10.1016/j.gca.2007.04.028.
- Bogemans, J. L., Nierinck, L., & Stassart, J. M. (1989). Effect of deicing chloride salts on ion accumulation in spruce (*Picea abies* (L.) sp.). *Plant and Soil*, 113, 3–11. doi:10.1007/BF02181915.
- Dutchess County Soil and Water Conservation District (1991). *Dutchess County soil survey users guide*. Dutchess County, NY: Dutchess County Soil and Water Conservation District.
- Godwin, K. S., Hafner, S. D., & Buff, M. H. (2003). Long-term trends in sodium and chloride in the Mohawk River, New York: The effect of fifty years of road-salt application. *Environmental Pollution*, 124, 273–281. doi:10.1016/S0269-7491(02)00481-5.
- Howard, K. W. F., & Haynes, J. (1993). Groundwater contamination due to road de-icing chemicals-salt balance implications. *Geoscience Canada*, 20, 1–8.
- Jackson, R. B., & Jobbagy, E. (2005). From icy roads to salty streams. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 14487–14488. doi:10.1073/pnas.0507389102.
- Kaushal, S. S., Groffman, P. M., Likens, G. E., Belt, K. T., Stack, W. P., Kelly, V. R., et al. (2005). Increased salinization of fresh water in the northeastern United States. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 13515–13520. doi:10.1073/pnas.0506414102.
- Kelly, V. R., Lovett, G. M., Weathers, K. C., Findlay, S. E. G., Strayer, D. L., Burns, D. J., et al. (2008). Long-term sodium chloride retention in a rural watershed—legacy effects of road salt on streamwater concentration. *Environmental Science & Technology*, 42, 410–415. doi:10.1021/es071391l.
- Lewis, W. M. (1999). Studies of environmental effects of magnesium and chloride deicer in Colorado. CDOT report no. CDOT-DTD-R-99-10. Denver: Colorado Department of Transportation.
- Likens, G. E. (1995). *Biogeochemistry of a forested ecosystem*. New York: Springer.
- Lovett, G. M., & Hubbell, J. G. (1991). Effects of ozone and acid mist on foliar leaching from eastern white pine and sugar maple. *Canadian Journal of Forest Research*, 21, 794–802. doi:10.1139/x91-112.
- Lovett, G. M., Likens, G. E., Buso, D. C., Driscoll, C. T., & Bailey, S. W. (2005). The biogeochemistry of chlorine at Hubbard Brook, New Hampshire, USA. *Biogeochemistry*, 72, 191–232. doi:10.1007/s10533-004-0357-x.
- Oberg, G., & Sanden, P. (2005). Retention of chloride in soils and cycling of organic matter-bound chlorine. *Hydrological Processes*, 19, 2123–2136. doi:10.1002/hyp.5680.
- Office of Water Regulations, and Standards, Criteria and Standards Division (OWRSCSD) (1988). *Ambient water quality criteria for chloride*. Washington, DC: Environmental Protection Agency.
- Peters, N. E., & Turk, J. T. (1981). Increases in sodium and chloride in the Mohawk River, New York, from the 1950s to the 1970s attributed to road-salt. *Water Resources Bulletin*, 17, 586–597.
- Pilon, P. E., & Howard, K. W. F. (1987). Contamination of subsurface waters by road de-icing salts. *Water Pollution Research Journal of Canada*, 22, 157–171.
- Richburg, J. A., Patterson, W. A., & Lowenstein, F. (2001). Effects of road-salt and *Phragmites australis* on the vegetation of a western Massachusetts calcareous lake-basin fen. *Wetlands*, 21, 247–255. doi:10.1672/0277-5212(2001)021[0247:EORSAP]2.0.CO;2.
- Riva-Murray, K., Bode, R. W., Phillips, P. J., & Wall, G. L. (2002). Impact source determination with biomonitoring data in New York State: Concordance with environmental data. *Northeastern Naturalist*, 9, 127–162.
- Rodstedth, M., Stahlberg, C., Sanden, P., & Oberg, G. (2003). Chloride imbalances in soil lysimeters. *Chemosphere*, 52, 381–389. doi:10.1016/S0045-6535(03)00192-9.
- Rosenberry, D. O., Bukaveckas, P. A., Buso, D. C., Likens, G. E., Shapiro, A. M., & Winter, T. C. (1999). Movement of road salt to a small New Hampshire lake. *Water, Air, and Soil Pollution*, 109, 179–206. doi:10.1023/A:1005041632056.
- Taylor, L., Howard, K. W. F., & Chambers, L. (1991). The use of spring-dwelling ostracodes as bio-monitors for inorganic contamination of groundwaters along an urban-rural transect in southern Ontario. In *Proceedings of the Toronto '91 GAC-MAC Annual Conference, Toronto*.
- Yozzo, D. J., Andersen, J. L., Cianciola, M. M., Nieder, W. C., Millar, D. E., Ciparis, S., et al. (2005). Ecological profile of the Hudson River National Estuarine Research Reserve. Published under Contract to the New York State Department of Environmental Conservation [C00464].