

## Road Salt Accumulation in Highway Snowbanks and Transport Through the Unsaturated Zone of the Oak Ridges Moraine, Southern Ontario

C.F. LABADIA<sup>1</sup> AND J.M. BUTTLE<sup>2</sup>

### ABSTRACT

Pathways and fate of road deicing salt (NaCl) applied during the 1994-95 winter were studied for a 14 km section of a major highway that crosses the Oak Ridges Moraine in southern Ontario. Total salt applications over the winter ranged from 29 to 74 kg m<sup>-1</sup> of highway, and NaCl concentrations in snowbanks adjacent to the roadway reached 9400 mg L<sup>-1</sup> during the later stages of snowcover development. This salt was released to the ground surface during snowmelt. NaCl loadings to soil from snowcover during the final melt phase were relatively uniform along the study section (3-5 kg NaCl m<sup>-1</sup> of highway). However, the snowpack at all transects retained < 50% of applied NaCl, and this shortfall probably reflected direct runoff and infiltration of saline meltwater from the road surface into the adjacent shoulder and right-of-way. Cation exchange with Ca<sup>2+</sup> in near-surface soils likely resulted in preferential retention of Na<sup>+</sup> relative to Cl<sup>-</sup>, although total storage of NaCl in upper soil horizons by winter's end was < 15% of deicing salt applications. An environmental tracer (<sup>18</sup>O) was used to trace movement of saline meltwater through the unsaturated zone underlying the highway. Average meltwater particle velocities at a site underlain by loam soils were 0.02 m d<sup>-1</sup>, and ~280 mm of water was displaced below a depth of 1.86 m over a 78 day period in the spring and summer of 1995. Na<sup>+</sup> and Cl<sup>-</sup> concentrations in water sampled in late summer 1995 at depths > 2 m exceeded 500 mg L<sup>-1</sup> and 1000 mg L<sup>-1</sup>, respectively. Approximately 75% of the net flux of NaCl below the upper soil was retained in the 0 to 2.8 m depth interval at this site, and results from

more permeable soils traversed by the highway indicate an even greater penetration of the annual NaCl application into the unsaturated zone along the moraine. This saline water likely recharges groundwater in this portion of the Oak Ridges Moraine.

Key words: Deicing salt, snowmelt, infiltration, groundwater recharge, isotopic tracers.

### INTRODUCTION

Deicing salts (e.g. NaCl) are applied to highways in Canada and the northern U.S. to maintain bare-pavement driving conditions throughout winter. Typical applications are in the order of 10s of t y<sup>-1</sup> km<sup>-1</sup> of road (e.g. Locat and Gélinas 1989, Pollack 1992). Addition of salt to snow and ice lowers the freezing point of water and creates a brine that may drain from the highway surface, thus clearing it. This salt may follow a variety of pathways after application to the road surface (Figure 1). Melted snow and ice may run off the road to the shoulder and adjacent right-of-way, where it can infiltrate into the ground. Plowing pushes saline snow and ice into snowbanks lining the highway, while road traffic on wet pavement generates salt spray which can be transported considerable distances, eventually being deposited on snowcover, structures and vegetation. Wind erosion of snowcover adjacent to the highway can also redistribute applied deicing salt.

Salts that have accumulated in snowbanks lining the highways are released to underlying soils during snowmelt. High salt levels may limit the availability

<sup>1</sup> Watershed Ecosystems Graduate Program, Trent University, Peterborough, Ontario, Canada K9J 7B8

<sup>2</sup> Department of Geography, Trent University, Peterborough, Ontario, Canada K9J 7B8

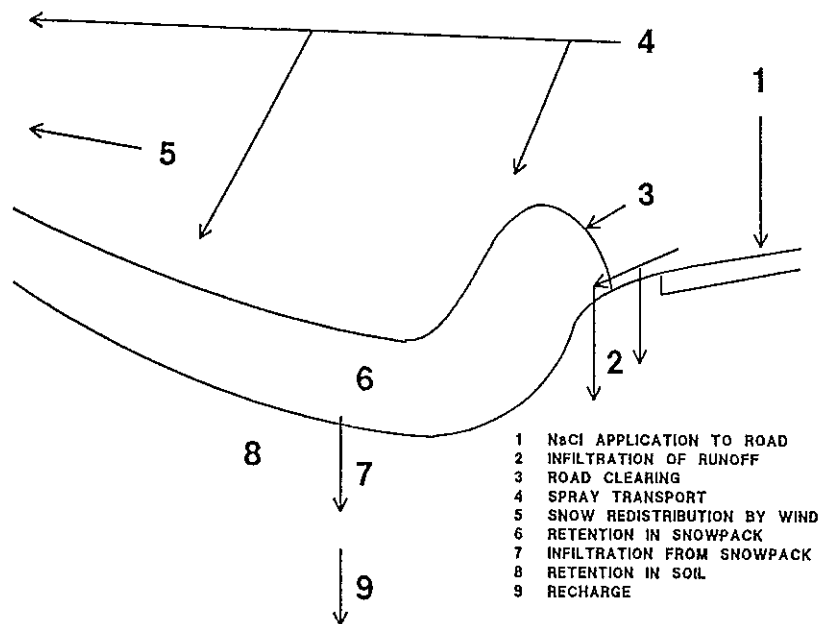


Figure 1. Pathways of deicing salt movement following application to the road surface.

of soil water to plants, while excessive exchangeable  $\text{Na}^+$  causes breakdown of soil aggregates, decreased pore size, and reduced permeability of the soil to air and water (Jones et al. 1992). Some of the infiltrating  $\text{Na}^+$  may be adsorbed on exchange sites within the soil (Villamil and Kent 1980), although the soil's adsorptive capacity can become exhausted after several years of deicing salt application (Howard and Beck 1993). Thus,  $\text{Na}^+$  can enter underlying groundwater, where it may reach levels that pose a serious threat to groundwater potability (Vitaliano 1992). The  $\text{Cl}^-$  anion is not generally retained in soils and may infiltrate into underlying groundwater or run off over the surface of frozen soils. The result is elevated  $\text{Cl}^-$  concentrations in surface and subsurface waters. For example, Kronis (1978) noted peak  $\text{Cl}^-$  concentrations of up to  $18200 \text{ mg L}^{-1}$  in initial snowmelt runoff from an urban basin in East York, Ontario. Interstitial water in the root zone of an Indiana bog impacted by deicing salt runoff had  $\text{Cl}^-$  levels of  $\sim 1200 \text{ mg L}^{-1}$  (Wilcox 1986a), while Locat and G elinas (1989) observed  $\text{Cl}^-$  concentrations in excess of  $800 \text{ mg L}^{-1}$  in a salt lens that had formed beneath a highway near Trois-Rivi eres-Ouest, Quebec as a result of road deicing. Levels in excess of the Provincial Maximum Acceptable Standard for  $\text{Cl}^-$  ( $250 \text{ mg L}^{-1}$ ) have been observed in surface and subsurface water in Ontario (Howard and Beck 1993) and in some areas in the northern U.S. (Sharp 1971). These levels upset the electrolyte balance of aquatic invertebrates and may damage roadside vegetation (de Voorde et al.

1973). Discharge of saline groundwater to wetlands may have impacts on their flora (Wilcox 1986b) and fauna (Quigley 1982). Deicing salt inputs to a small lake in south central Ontario have resulted in chemical stratification, which in turn has reduced algal productivity (Smol et al. 1983).  $\text{NaCl}$  from road salting has been found to influence trace metal partitioning between sediments and water in streams and lakes (Jones et al. 1992, Warren and Zimmerman 1994). High concentrations of deicing salts also impart a saline taste to drinking water, rendering it unfit for consumption. Thus, deicing salt applications to roads can have serious and wide-ranging environmental consequences.

Potential groundwater contamination by road deicing salts is particularly important in the context of the Oak Ridges Moraine (ORM), a large glacial deposit (interlobate kame moraine) in southern Ontario that runs from north of Toronto eastward to the Trent River (Figure 2). The moraine consists of a complex interlayering of sands and gravels up to 100 m thick underlain by fine sandy till and clay tills, with a maximum total thickness of  $\sim 210 \text{ m}$ . The ORM is a major aquifer complex and one of the most heavily-used groundwater sources in Canada, supplying much of the potable water for the Greater Toronto Area. It forms a major recharge zone for a series of aquifers extending southward to Lake Ontario, and is also the headwater source of numerous streams. Shallow aquifers may discharge groundwater only a short distance ( $< 1 \text{ km}$ ) downflow of the ORM; however, some aquifers are quite extensive and

their exact discharge zones are unknown.

The ORM is crossed by a number of major highways and minor roads, and application of deicing salts to these routes provides a linear source of chemicals which have the potential to enter underlying groundwater. This flux of deicing salts from roads to groundwater beneath the ORM may increase with the completion of a major highway (Highway 407) which is currently under construction and will traverse part of the moraine. Groundwater susceptibility to contamination by road deicing salts applied on the ORM has been demonstrated by Howard and Beck (1986; 1993). Nevertheless, the hydrostratigraphic complexity of the various formations that make up the moraine has impeded our ability to understand and predict the effect of deicing salt application upon groundwater quality in aquifers recharged on the ORM. In addition, efforts to model infiltration of these salts and their impact on groundwater quality are hampered by the absence of information on deicing salt loadings to soils adjacent to highways on the ORM and the fluxes of water and salts through the unsaturated zone to groundwater beneath the moraine.

This paper examines the fate of deicing salt applied to a major highway crossing the ORM. In particular, it assesses (1) the ability of roadside snowcover to retain and release deicing salt to the underlying soil; (2) the retention of deicing salt in the dominant soil types that mantle the moraine; and (3) the flux of water and deicing salt within the unsaturated zone underlying the highway right-of-way.

## STUDY AREA AND METHODS

A 14 km section of Highway 115 (from 44° 4'N, 78° 37'W to 44° 9'N, 78° 29'W) was selected for study (Figure 2). Six transects covering the major soil types found on the crest of the ORM were selected (Figure 2, Table 1). Transects spanned the right-of-way areas on either side of this divided 4-lane highway and the median section that separates the northbound and southbound lanes. The elevation of the ORM traversed by the highway ranges from 365 m a.s.l. 1 km southwest of transect 6, to 295 m a.s.l. at transect 4, to 315 m a.s.l. at transect 1. Depth to the water table (based on Ontario Ministry of Environment and Energy well records) varies from ~9 m between transects 3 and 4 to ~38 m at transect 6. Mean annual precipitation in the area is ~800 mm, while mean annual snowfall (October to May) is ~160 cm.

### 1. Climatic conditions and deicing salt application

Climate data were obtained from the Environment Canada station at the Peterborough Airport (14 km northeast of transect 1). These data were assumed to represent conditions in the study area, and included daily maximum, minimum and mean temperatures, rainfall, snowfall, and depth of snow-on-ground. Salt application data for the 1994/95 winter were obtained from the Ministry of Transportation for Ontario (MTO) patrol yard at Pontypool, ON, which was responsible for road clearance of the study section of Highway 115. Data were converted to the daily deicing salt load applied to each transect ( $\text{kg m}^{-1}$  of roadway). MTO estimates the error associated with these application rates at  $\pm 5\%$ .

### 2. Salt Retention in Near-Surface Soil

Soil samples were collected along the transects during the period November 13 - December 13, 1994 and on March 30, 1995 in order to estimate pre- and post-winter salt levels held in near-surface soil. The upper soil was assumed to have the greatest potential to retain inputs of deicing salts, since it generally has greater organic matter contents, finer textures, and presumably larger cation and anion exchange capacities than the sands and gravels found at depth. Vertical soil cores (0.2 m length) were obtained using EMT conduit. The conduit was cleaned to remove any impurities prior to sampling. Cores were taken at 3 m intervals along the sampling transect north and south of the highway. In the median section a sample was collected 1 m from the edge of each shoulder in addition to the center of the median (usually in the central ditch). Cores were sealed in plastic prior to analysis.

Samples were air-dried, homogenized and passed through a 2 mm sieve to separate the gravel and fine earth fractions. The combined dry weight of these fractions was used to determine bulk density. Extractable  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations were determined on a 20 g subsample of the fine earth fraction that had been resaturated in 100 mL of distilled, deionized water (Bower and Wilcox 1965). This extract was shaken for 30 minutes on a wrist-action shaker and analysed for  $\text{Na}^+$  and  $\text{Cl}^-$  using specific ion electrodes. The load of  $\text{Na}^+$  and  $\text{Cl}^-$  held in a soil volume of  $1 \text{ m}^2$  surface area  $\times$  0.2 m depth was determined from the product of concentrations on the fine earth fraction ( $\text{g kg}^{-1}$  of soil) and bulk density ( $\text{kg m}^{-3}$ ) for a given sample.

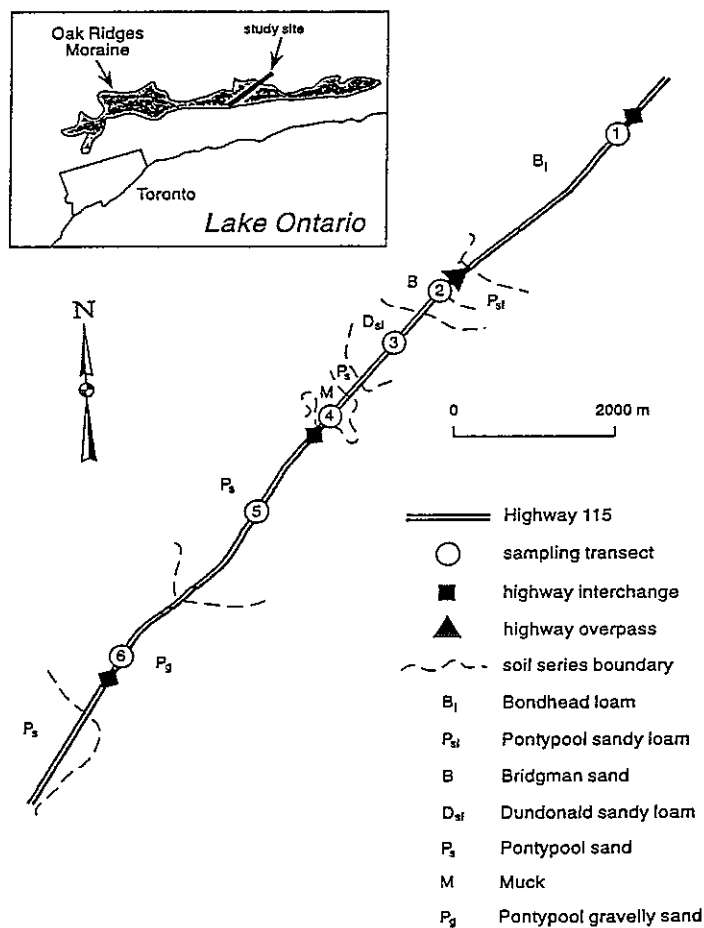


Figure 2. Soil series and study transects along Highway 115 where it crosses the Oak Ridges Moraine. Soil series are described in Table 1.

Table 1. Soil types traversed by the study section of Highway 115. Descriptions from Webber et al. (1946).

Soil Series	Map Symbol	Sampling Transect	Description of surface and subsoil
Bondhead loam	B <sub>1</sub>	1	Grey brown loam over light brown loam over brownish clayey loam over grey stony loam; few stones.
Pontypool sandy loam	P <sub>st</sub>		Light brownish sandy loam and yellow brown sand over dark brown loam underlain by grey coarse calcareous sand; some stones.
Bridgman sand	B	2	Loose yellow or grey sand; occasional stones.
Dundonald sandy loam	D <sub>st</sub>	3	Grey brown sandy loam over yellowish sandy loam over brown loam underlain by compact stony calcareous loam; stonefree.
Muck	M	4	Black organic material of various depths in different stages of decomposition.
Pontypool sand	P <sub>s</sub>	5	Light grey brown sand and yellow sand over grey coarse calcareous sand and stony sand; some boulders.
Pontypool gravelly sand	P <sub>g</sub>	6	Light grey brown coarse sand with large quantities of gravel and cobbles underlain by grey coarse gravelly sand; some boulders.

### 3. Deicing Salt Storage and Loss From Snowcover

Snowcover in the highway right-of-way at each transect was sampled weekly from January 20 (Year Day [YD] 20) to March 16 (YD 75) during the main period of continuous snowcover in 1994-95. Depth-integrated samples were obtained at 2 m intervals along both sides of the right-of-way and the median section using a snow tube. The tube was cleaned after sampling each transect to prevent cross-contamination, and samples within each transect were collected in the direction of the expected increase in  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations in snowcover. Snow depth at each sampling site was recorded, and samples were placed in plastic bags for transport to the laboratory. Sampling sites along the north and south portions of each transect were positioned with respect to their distance from the limit of the right-of-way. Sample locations in the median portion of the transect were determined with respect to the asphalt/shoulder boundary on the northern side of the median. The same sites were sampled in each weekly snow survey.

Samples were weighed in the laboratory to determine snow water equivalent (SWE). They were then allowed to melt overnight and equilibrate with room temperature prior to determination of  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations using specific ion electrodes. Selected snowpack samples were analyzed for the environmental isotope oxygen-18 ( $^{18}\text{O}$ ) by mass spectrometry at the University of Waterloo Environmental Isotope Laboratory.  $^{18}\text{O}$  contents were reported as the relative deviation of the isotopic ratio  $^{18}\text{O}/^{16}\text{O}$  ( $\delta^{18}\text{O}$ ) from that of SMOW (Standard Mean Ocean Water).

### 4. Salt Transport and Retention in the Unsaturated Zone

Deep soil cores were obtained in Spring and Fall 1995 using thin-walled aluminum core tubing. Overburden was sampled continuously in the Spring by driving successively longer lengths of tubing into the ground using a post-pounder. Tubes were driven as deep as possible until stones prevented further progress or saturated layers prevented extraction of the soil core. Fall cores were driven to depth with a mobile drill rig. This allowed deeper cores to be obtained; however, the stoniness at transect 6 prevented sampling in both Spring and Fall. Cores were sealed and stored horizontally at  $5^\circ\text{C}$  prior to analysis.

Soil water extraction was performed using the procedure developed by Munch and Killey (1985). Cores were sectioned at 0.06 m intervals, weighed, inserted into a holding device, and spun in a

centrifuge at 13200 G for 15 minutes to extract pore water. Soil water was analysed for  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\delta^{18}\text{O}$ . At least 15 mL of water was required for chemical and isotopic analyses, often making it necessary to combine two or more samples of extracted pore water from successive 0.06 m cores to reach this total. This was particularly true in drier cores. Following centrifugation, soil cores were weighed, oven-dried overnight at  $105^\circ\text{C}$  and reweighed. Gravimetric water loss was added to the extracted water volume to obtain volumetric moisture content ( $\theta$ ).

Mean water particle velocities and soil water fluxes in the unsaturated zone were determined using the isotope tracer method (Saxena 1984, Bengtsson et al. 1987), which has been used successfully to estimate recharge in a number of areas, including Sweden (Saxena 1984) and Israel (Gvirtzman and Margaritz 1986). It is based on the rate of vertical displacement of the centre of gravity of a tracer as it percolates through the unsaturated zone below the root zone (Sami and Buttle 1991). The tracer is transported through the unsaturated zone with the infiltrating soil water. It has been shown that: (a) soil water cannot bypass the tagged layer in either direction in the vertical; and (b) downward displacement of the tagged layer is like a moving piston, shunting soil water below the tagged layer deeper into the unsaturated zone (Zimmermann et al. 1967, Saxena 1984).

The environmental isotope  $^{18}\text{O}$  was used to trace soil water movement.  $^{18}\text{O}$  is a naturally-occurring conservative tracer that is applied to the ground surface over extensive areas during rainfall and snowmelt. Isotope concentrations in precipitation are temperature-dependent, such that the  $^{18}\text{O}$  signature of precipitation may be seasonally tagged in areas experiencing a marked seasonal temperature cycle. Therefore snowmelt water tends to have lower levels of  $^{18}\text{O}$  (more negative values of  $\delta^{18}\text{O}$ ) than summer and fall rains, and can be readily distinguished from previous inputs stored in the unsaturated zone (Figure 3a). Measurement of the downward displacement of this layer of snowmelt water provides direct information on the rate of soil water movement (Saxena 1984).

The isotopic tracer method assumes that the centre of gravity of soil water of snowmelt origin is at depth  $z_1$  shortly after spring melt (Figure 3b), and is found at depth  $z_2$  after the time interval  $\Delta t$  has elapsed. Mean soil water particle velocities can be calculated by:

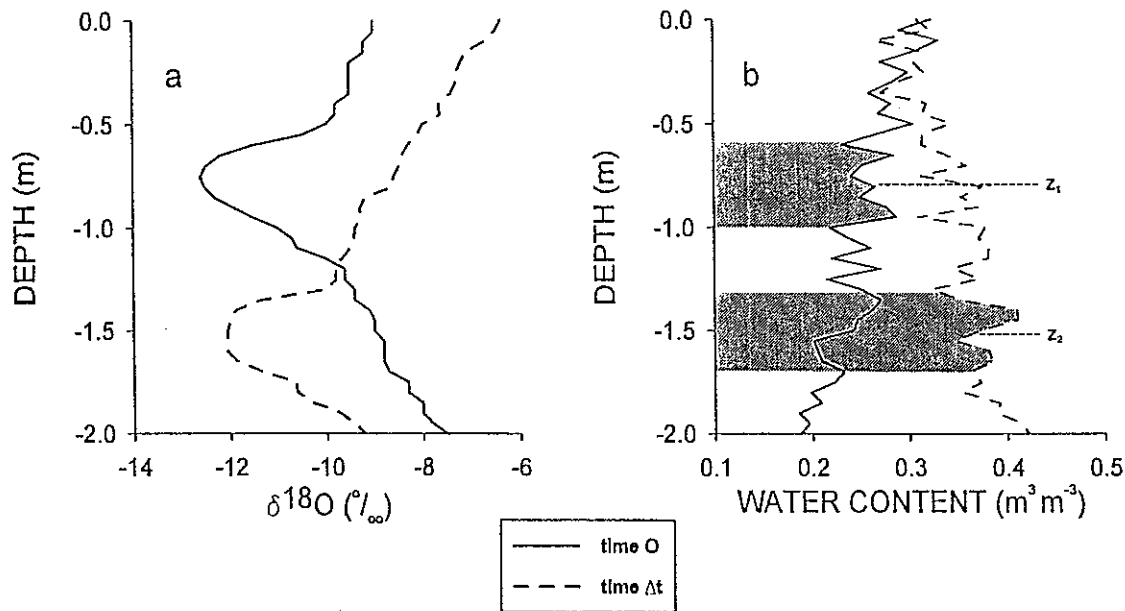


Figure 3. Hypothetical profiles of  $\delta^{18}\text{O}$  levels in soil water (a) and soil water content (b) in the unsaturated zone measured at time = 0 and time =  $\Delta t$ . Soil water with a  $\delta^{18}\text{O} < -11\text{‰}$  is assumed to be of snowmelt origin, and is indicated by shading in (b). Position of the centre of gravity of the snowmelt water at time = 0 and time =  $\Delta t$  is indicated by  $z_1$  and  $z_2$ , respectively.

$$v = \frac{(z_1 - z_2)}{\Delta t} \quad (1)$$

where  $z_1$  and  $z_2$  are the depths of the tracer's centre of gravity over the time interval  $\Delta t$ . Equation (1) gives a mean displacement rate, since the soil water may follow a variety of flow paths and the tracer may be subject to extensive dispersion (Bengtsson et al. 1987). This approach is based on the assumption that all soil water (including that held in micropores) is displaced downwards by percolating water from above (Bengtsson et al. 1987). Soil water held below depth  $z_1$  at time = 0 is displaced past depth  $z_2$  during the period  $\Delta t$  between the two measurements of soil water content and tracer profiles in the unsaturated zone. The amount of soil water  $m$  that passed the lower depth  $z_2$  during  $\Delta t$  is:

$$m = \int_{z_1}^{z_2} \theta_m(z, 0) dz \quad (2)$$

where  $\theta_m(z, 0)$  is the mobile soil water content at depth  $z$  and  $t = 0$  (at the first observation). Use of  $\theta_m$  rather than total volumetric soil water content  $\theta$  in equation (2) recognizes that a small portion of soil water is attached irreducibly to fine soil particles and does not participate in flow (Bengtsson et al. 1987). This immobile water content was not measured directly; however, Sami and Buttle (1991) suggest that a value of  $0.03 \text{ m}^3 \text{ m}^{-3}$  is reasonable for sandy soils such as those found on the ORM.

## RESULTS AND DISCUSSION

### 1. Conditions During the 1994-95 Winter

There were five phases of snowpack growth and ablation during the 1994-95 winter (Figure 4), with the longest period of continuous snowcover lasting from mid January to early March. Total winter snowfall was 137.2 cm, which was slightly below the long-term mean. Brief periods of above  $0^\circ\text{C}$  air temperatures during the winter were often associated with large rainfalls. Deicing salt was applied during each significant snowfall, and Figure 4c indicates daily NaCl application rates to transects experiencing the largest (transect 1) and smallest (transect 5) deicing salt loads over the winter (Table 2). Those transects near highway interchanges (1, 4 and 6) generally received more than twice the amount of NaCl added to the other

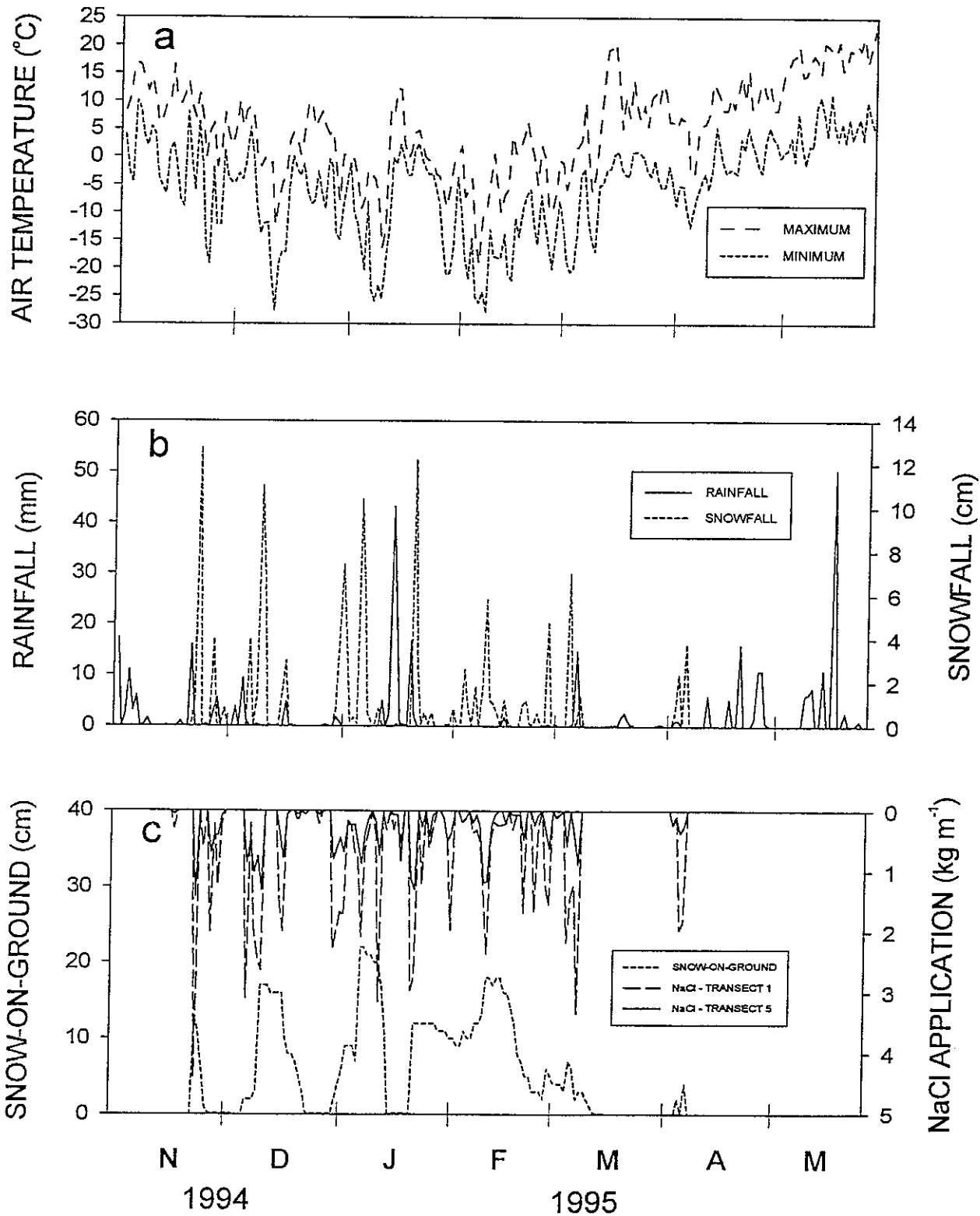


Figure 4. Daily air temperature (a); rainfall and snowfall (b); depth of snow-on-ground at the Peterborough Airport Climate Station and NaCl applications to transects 1 and 5 (d), 1994-95 winter.

**Table 2. NaCl application ( $\text{kg m}^{-1}$ ) to the study transects for the entire 1994-95 winter and for the detailed monitoring period (20 January to 16 March).**

Transect	Transect length (width of right-of-way) (m)	1994-95 winter		NaCl	20 January - 16 March			% of total winter application
		Na <sup>+</sup>	Cl <sup>-</sup>		Na <sup>+</sup>	Cl <sup>-</sup>	NaCl	
1	78	29.2	45.0	74.2	12.5	19.4	31.9	43
2	77	11.0	17.0	28.0	4.4	6.9	11.3	40
3	77	11.0	17.0	28.0	4.4	6.9	11.3	40
4	78	29.2	45.0	74.2	12.5	19.4	31.9	43
5	68	10.9	16.8	27.7	4.3	6.7	11.0	40
6	90	29.1	44.8	73.9	12.7	19.5	32.2	44

transects due to the large applications of salt to interchange ramps. There was only a weak correlation between NaCl application to the transects and the depth of snowfall, and large daily NaCl applications occurred during freezing rain episodes when snowfall was minimal. Peak daily NaCl application along Highway 115 ranged from 1.4 to 4.4  $\text{kg m}^{-1}$  of highway in response to a 13 cm snowfall in November 1994. There was a larger mass loading of Cl<sup>-</sup> to the transects relative to Na<sup>+</sup>; this is the result of the greater atomic weight of Cl<sup>-</sup>.

## 2. Snowpack Formation and Ablation During the Monitoring Period

Snowfall during the period from January 20 (YD 20) to March 16 (YD 75) totalled 51.1 cm, which represented 37% of the total winter snowfall. This corresponds closely to the proportion of the total NaCl load for the 1994-95 winter applied to the transects during this period (Table 2). Figure 5 indicates temporal and spatial trends in SWE and NaCl loads held in snowcover on the north, median and south segments of transect 5. These trends were typical of those observed at the other sites. The change in SWE with distance from the highway was similar for the north and south segments: high values occurred in the highway snowbanks as a result of snow plowing; SWE then decreased and increased again at the fence line marking the edge of the right-of-way. SWE was relatively uniform across the median. Most NaCl in snowcover occurred within ~5 m of the highway for all three segments of transect 5. The rapid decrease in NaCl in snowcover with distance from the highway suggests that snow plowing and localized spray drift were the main processes by which applied salt reached the snowpack, and that spray transport beyond the limits of the transects was not significant. Both SWE and NaCl load in

snowcover increased up to YD 47; however, most of the highway snowbanks ablated between YD 47 and YD 53. This ablation occurred during a slight warming trend (Figure 4), and the disproportionately large melt rates for the snowbanks probably reflected the high NaCl concentrations in this snow. NaCl levels in roadside snowbanks exceeded 1000  $\text{mg L}^{-1}$  at all sites by YD 47, with concentrations > 9400  $\text{mg L}^{-1}$  in median snowbanks at transects 3 and 5. The result was loss of most of the salt retained in the snowcover, although there was a minor increase in NaCl levels in the snowcover after this date as a result of subsequent snowfalls and deicing salt applications.

## 3. NaCl Fluxes From the Snowpack During the Monitoring Period

Decreases in the amount of NaCl stored in snowcover between sampling dates were assumed to represent loss of deicing salt to the underlying soil. Figure 6 shows the cumulative loss of Na<sup>+</sup> and Cl<sup>-</sup> from the transects. Despite differences in the amount of applied NaCl (Table 2), the transport of salt to the soil surface was quite similar between transects. Total losses of salt from snowcover were < 50% of the applied NaCl. Given that spray losses out of the transects appear to have been minor, this suggests that (1) deicing salt levels in snowcover underestimated application rates significantly, as Vonk et al. (1991) observed for roadside snowbanks in a suburban area; and (2) runoff of saline meltwater from pavement to the adjacent shoulder and right-of-way and its subsequent infiltration was the dominant pathway by which NaCl entered the soil. Soils in the highway right-of-way remained unfrozen during the relatively mild winter of 1994-95, implying that NaCl transport in meltwater runoff along drainage ditches away from the sampling transects would have been



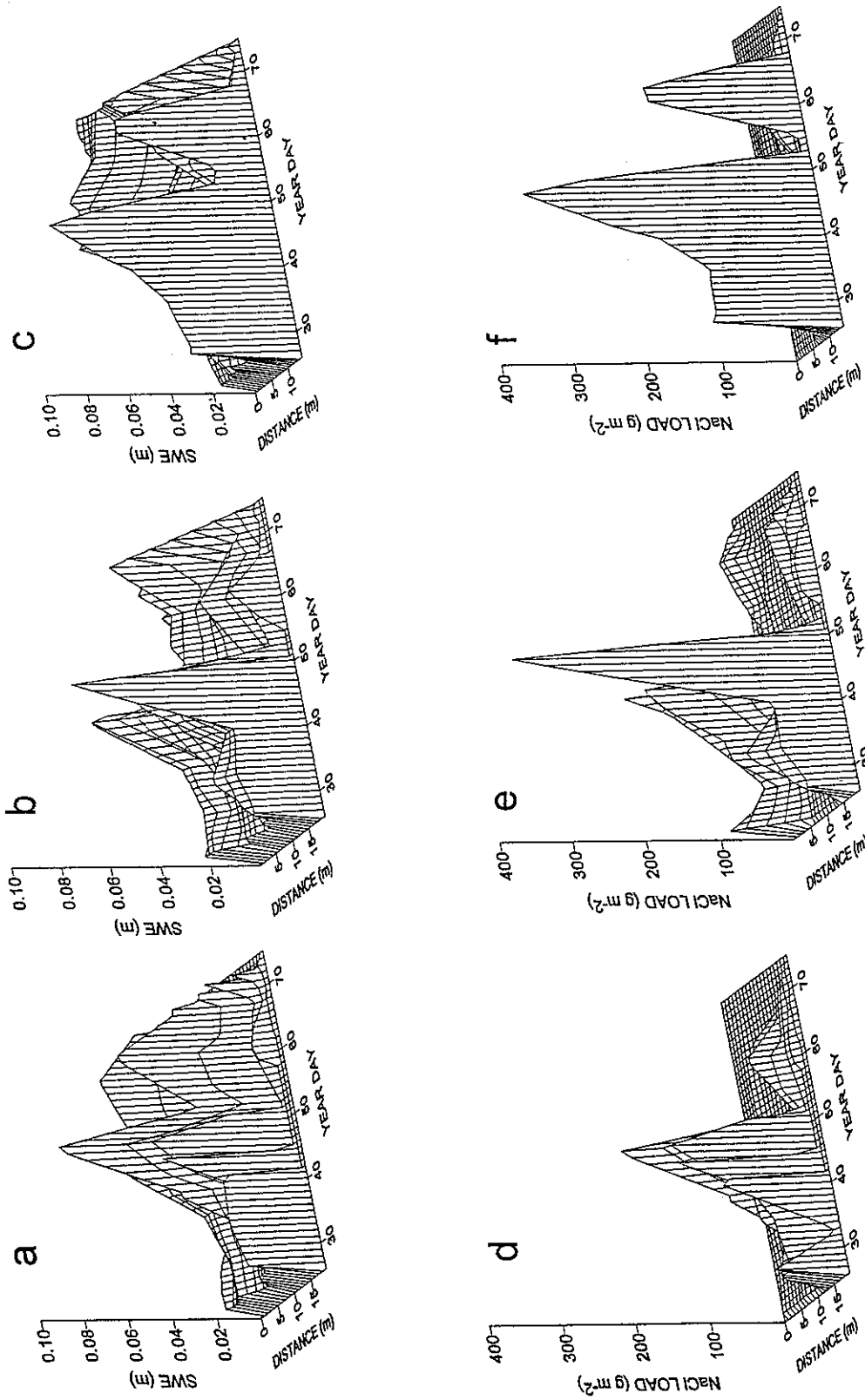


Figure 5. Evolution of snowcover and NaCl levels during the monitoring period at transect 5: changes in SWE with distance and time along the north (a), median (b) and south (c) segments of the transect; changes in NaCl load in snowcover with distance and time along the north (d), median (e) and south (f) segments of the transect.

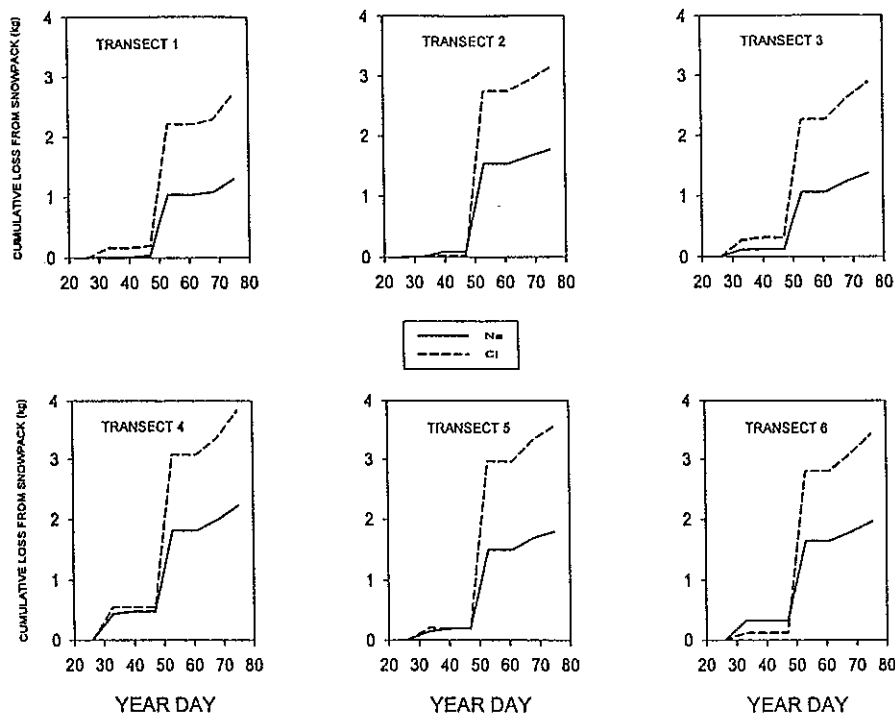


Figure 6. Cumulative total fluxes of  $\text{Na}^+$  and  $\text{Cl}^-$  to the soil surface at the transects over the monitoring period.

minimal.

Fluxes of  $\text{NaCl}$  from the snowpack to the soil surface coincided with major melt periods. Total flux of  $\text{Cl}^-$  exceeded that of  $\text{Na}^+$ , although  $\text{Na}^+$  and  $\text{Cl}^-$  losses during the initial part of the monitoring period were similar. Comparison with Figure 5 demonstrates that  $\text{NaCl}$  was lost from snowcover to the underlying soil concurrent with a general increase in SWE in the transect, and indicates that an appreciable amount of salt reached the ground surface prior to the main melt after YD 47.

#### 4. $\text{NaCl}$ Retention in Near-Surface Soil

There was a marked increase in the  $\text{Na}^+$  and  $\text{Cl}^-$  loads held in the upper 0.2 m of the soil profile in the median and the ditches adjacent to the highway following snowmelt (Figure 7). However, there was little or no change in  $\text{Na}^+$  and  $\text{Cl}^-$  loads in near-surface soil at the ends of the right-of-way, consistent with the decline in  $\text{NaCl}$  loss from the snowpack with increasing distance from the highway (Figure 5). Deicing salt retention in the upper soil at each transect was estimated by comparing pre- and post-melt levels of  $\text{NaCl}$  in the shallow soil cores taken at each of the sampling sites, and then integrating these differences along the entire transect. There was preferential retention of  $\text{Na}^+$  relative to  $\text{Cl}^-$  in the near-surface (Table 3). This is likely due to cation exchange between  $\text{Na}^+$

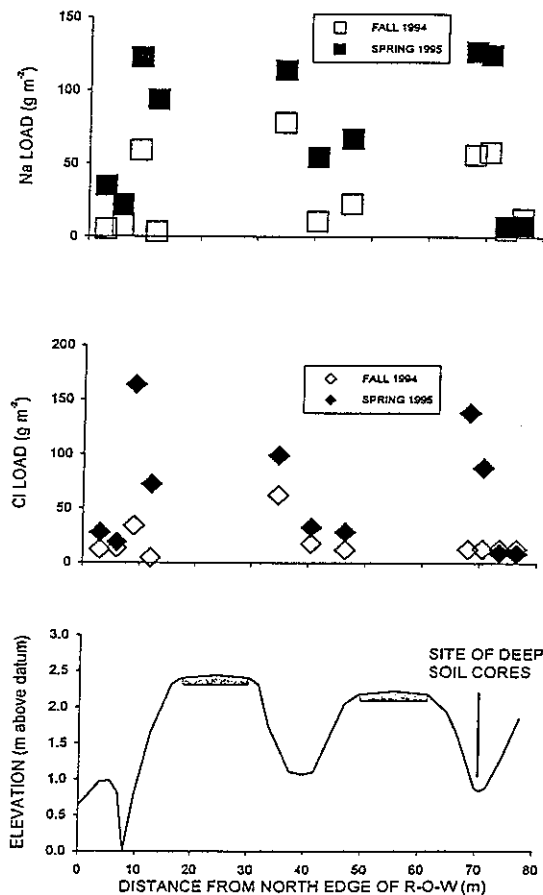
supplied in meltwater and  $\text{Ca}^{2+}$  held on exchange sites in these calcareous soils (Table 1). Howard and Beck (1993) showed that shallow domestic wells adjacent to roads near Lindsay, ON were contaminated with deicing salt transported via recharge waters. These waters were also enriched in  $\text{Ca}^{2+}$  due to cation exchange between calcium-rich sediments and  $\text{Na}^+$  dissolved in recharge. Conversely, the minor retention of  $\text{Cl}^-$  in near-surface soil reflects its behaviour as a mobile anion that undergoes limited interaction with soil particles. It is often assumed that heavy-textured soils with high cation exchange capacities will accumulate  $\text{Na}^+$  in exchange for  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$  to a greater extent than sandy soils (Villamil and Kent 1980); however, there was no association between inter-transect differences in soil texture and  $\text{Na}^+$  retention. Only a small fraction of the  $\text{NaCl}$  applied to each transect was retained in the near-surface soil (Table 3). This retention was probably only temporary, and  $\text{NaCl}$  held in the upper soil may have been released to dilute water supplied to the soil during summer and fall rainstorms and flushed deeper into the profile.

#### 5. Water and $\text{NaCl}$ Storage and Flux in the Unsaturated Zone

Deep soil cores taken at transect 1 in the drainage ditch adjacent to the southern side of the

**Table 3. Retention of NaCl in near-surface soil and net flux to the unsaturated zone ( $\text{kg m}^{-1}$  width of transect). Negative retention values indicate net loss from near-surface soil. Values in brackets represent the % of total application to the transect.**

Transect	Retention in near-surface soil		NaCl	Net flux to unsaturated zone.		
	Na <sup>+</sup>	Cl <sup>-</sup>		Na <sup>+</sup>	Cl <sup>-</sup>	NaCl
1	2.3 (8)	2.3 (5)	4.7 (6)	26.9	42.7	69.5
2	2.1 (19)	1.0 (6)	3.0 (11)	8.9	16.0	25.0
3	2.4 (22)	1.6 (9)	4.0 (14)	8.6	15.4	24.0
4	1.2 (4)	-0.2 (-0.4)	1.0 (1)	28.0	45.2	73.2
5	1.2 (11)	0.1 (1)	1.3 (5)	9.7	16.7	26.4
6	2.0 (7)	0.5 (1)	2.4 (3)	27.1	44.3	71.5



*Figure 7. Na<sup>+</sup> and Cl<sup>-</sup> loads in near-surface (0 - 0.2 m depth interval) soils measured along transect 1 in Fall 1994 and Spring 1995. Road surface location and site of the deep soil cores are indicated on the transect cross-section.*

highway (Figure 7) provided the most comprehensive picture of conditions in the unsaturated zone, and the subsequent discussion will concentrate on the results from this site. The Spring core was taken several weeks after disappearance of snowcover along Highway 115, and pronounced evaporation from the soil surface prior to core extraction resulted in very low near-surface soil water contents (Figure 8a). It was not possible to extract sufficient soil water using centrifugation to permit chemical and oxygen-18 analyses for the near-surface, and  $\delta^{18}\text{O}$ , Na<sup>+</sup> and Cl<sup>-</sup> profiles could only be constructed for depths >0.5 m. The  $\delta^{18}\text{O}$  of snowcover at transect 1 became progressively enriched over the course of the winter, ranging from -17.69‰ on YD 33 to -12.38‰ on YD 68. Assuming that the  $\delta^{18}\text{O}$  in snowcover represented the isotopic signature of snowmelt, Figure 8b suggests that meltwater had reached depths of up to 1 m on the date of coring (YD 178), since soil water immediately below this depth had  $\delta^{18}\text{O}$  values heavier than -12‰. Soil water above 1 m depth had the largest Na<sup>+</sup> and Cl<sup>-</sup> concentrations in the Spring core (Figure 8c,d), which is consistent with recharging meltwater in this portion of the unsaturated zone. NaCl levels in near-surface soil water may have been even higher than those shown in Figure 8, as indicated by the high loads of Na<sup>+</sup> and Cl<sup>-</sup> held in the 0 - 0.2 m depth interval in the drainage ditch following spring melt (Figure 7). However, this water could not be analysed for reasons noted above.

The Fall core was taken on YD 256, 78 days after the Spring core. Near-surface  $\theta$  was relatively high as a result of above-average rainfall in July and August.  $\delta^{18}\text{O}$  levels in soil water decreased with depth to 2.1 - 2.3 m. Near-surface values were typical of inputs in summer rainfall combined with isotopic enrichment as a result of evaporation. Depleted  $\delta^{18}\text{O}$  below 2 m appears to represent meltwater from the spring that had mixed with

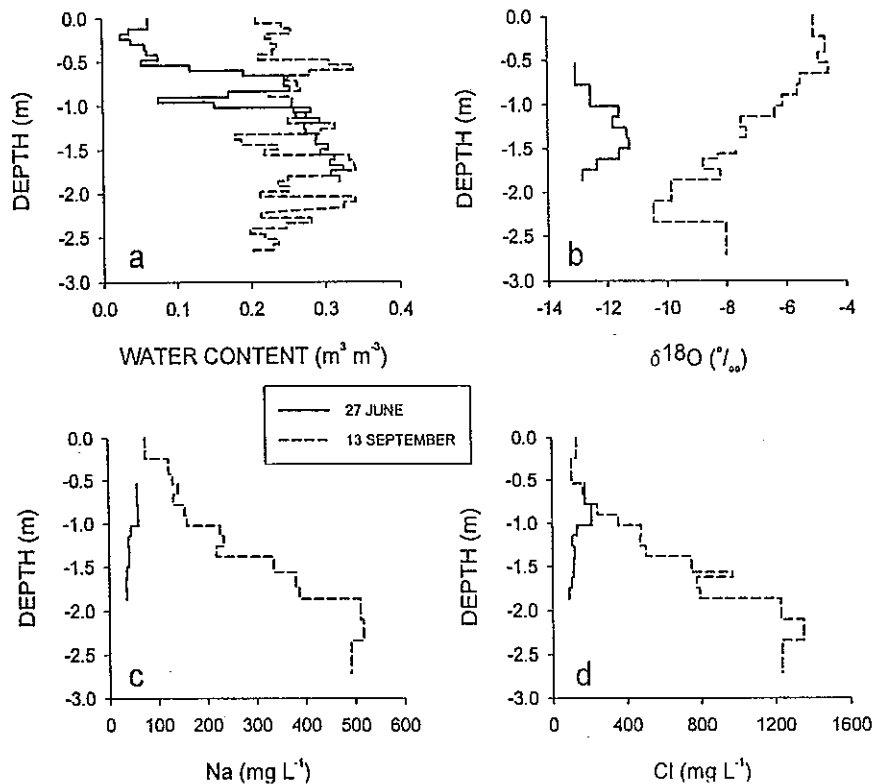


Figure 8. Profiles of soil water content (a),  $\delta^{18}\text{O}$  levels in soil water (b),  $\text{Na}^+$  (c) and  $\text{Cl}^-$  concentrations (d) in soil water extracted from cores obtained in Spring and Fall 1995, transect 1.

isotopically-enriched water supplied by spring rainfall. The resulting mixture was displaced deeper into the unsaturated zone by subsequent water inputs. This meltwater/spring rainwater contained high  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations, and the peak  $\text{Cl}^-$  levels are comparable to levels observed in pore waters and discharge from urban springs in Metropolitan Toronto, a region which has received in excess of 100,000 t of  $\text{NaCl}$  annually for several decades (Howard and Beck 1993).  $\text{NaCl}$  levels in this mixture exceeded concentrations in soil water of snowmelt origin identified in the Spring core. This may reflect the contribution of  $\text{Na}^+$  and  $\text{Cl}^-$  that was temporarily retained in the near-surface soil and was released to relatively-dilute spring rainwater as it ran off the highway into the ditch, infiltrated the soil, and mixed with snowmelt water stored in the upper unsaturated zone. This protracted release of  $\text{NaCl}$  from soils months after the last deicing salt application has been noted elsewhere (e.g. Wulkowicz and Saleem 1974, Cherkauer 1975).

The depth of the centre of gravity of meltwater held in the cores based on the  $\delta^{18}\text{O}$  profiles was estimated to be 0.66 m in Spring and 2.22 m in Fall. This produced a particle velocity of  $0.02 \text{ m d}^{-1}$  using equation (1), which is somewhat lower than

water particle velocities obtained by Sami and Buttle (1991) in a sandy soil in the Ottawa valley in southern Ontario ( $0.03$  to  $0.07 \text{ m d}^{-1}$ ). The latter study was confined to the spring snowmelt period, and the higher velocities probably reflect the effect of relatively larger water inputs to the soil surface over a much shorter period of time than was examined here. The Spring core only reached 1.86 m below ground surface; nevertheless, integration of the mobile soil water content between 0.66 and 1.86 m depths in equation (2) indicates that  $\sim 280$  mm of water was recharged below the 1.86 m depth over 78 days during 1995. This value appears reasonable in light of the estimated average annual groundwater recharge for this region of  $\sim 375$  mm based on water balance calculations (Hydrological Atlas of Canada 1978).

Fall core results indicate that 209 g of  $\text{Na}^+$  and 463 g of  $\text{Cl}^-$  were retained in soil water in the 0 - 2.8 m depth interval over a  $1 \text{ m}^2$  ground surface area. Most of this salt was likely held in the upper 0.5 m of the unsaturated zone when the Spring core was taken, and this is supported by the high deicing salt loads ( $125 - 127 \text{ g m}^{-2}$  of  $\text{Na}^+$  and  $88 - 139 \text{ g m}^{-2}$  of  $\text{Cl}^-$ ) of near-surface soil in the ditch following snowmelt (Figure 7).  $\text{NaCl}$  loadings to the ground surface at the site of the deep cores

were intermediate between the large values observed in the highway median and the negligible contributions at the edge of the right-of-way (cf. Figure 5). Transverse dispersion during infiltration and redistribution of soil water would also serve to reduce differences in salt concentrations across the transect at a given depth below the surface. Therefore the deep core results may be assumed to represent the average soil water chemistry and  $\theta$  conditions across transect 1. If unit width is assumed along the length of the transect (78 m), 16.3 kg of  $\text{Na}^+$  and 36.1 kg of  $\text{Cl}^-$  were held in the upper 2.8 m of the unsaturated zone. This represents 75% of the net flux of NaCl to the unsaturated zone by late spring 1995 (Table 3). Results from deep cores taken at other transects (not shown) suggest that NaCl applied during the 1994-95 winter moved even deeper into the unsaturated zone, probably as a result of their sandier soils and higher hydraulic conductivities relative to the Bondhead loam at transect 1. This is consistent with the findings of Locat and Gélinas (1989), who estimated that a year's worth of salt application was held in the 8 m thick unsaturated zone for sands underlying a highway in Quebec. The estimated  $\text{Cl}^-$  recharge is  $\sim 4$  orders of magnitude greater than the estimated deicing salt contributions of  $\text{Cl}^-$  to groundwater in glacial deposits in eastern Pennsylvania (Senior 1994); however, the latter area's more temperate climate means that it likely receives appreciably lower deicing salt applications relative to Highway 115.

## CONCLUSIONS

Deicing salt application to a portion of Highway 115 crossing the Oak Ridges Moraine in southern Ontario ranged from 27 to 74 kg  $\text{m}^{-1}$  of highway during the 1994-95 winter. Most of the applied NaCl appeared to have directly run off of the road surface and infiltrated soils underlying the shoulder and adjacent right-of-way. NaCl concentrations in snowbanks beside the highway reached levels of 9400 mg  $\text{L}^{-1}$ . However, NaCl levels in snowcover dropped rapidly beyond 5 m of the highway shoulder, and less than 50% of the NaCl applied during the latter stage of snowcover development was retained in snowcover in the highway right-of-way. Salt held in the snowpack was delivered to the soil surface during snowmelt, with total loadings ranging from 3 - 5 kg NaCl  $\text{m}^{-1}$  of highway. Retention of NaCl in the near-surface soil on a

seasonal (and likely on an annual) basis was minimal in the poorly developed soils that mantle the moraine, and essentially all the applied NaCl entered the unsaturated zone. Particle velocities of saline meltwater in a loam soil were 0.02  $\text{m d}^{-1}$ , and 75% of the net annual salt application to the sampling transect was retained in the upper 2.8 m of the unsaturated zone. Higher water particle velocities and greater depths of NaCl penetration were observed at more conductive sites on the moraine. Soil water of snowmelt origin was associated with concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$  in excess of 500 mg  $\text{L}^{-1}$  and 1000 mg  $\text{L}^{-1}$ , respectively. These concentrations are likely to be reduced by dispersion and diffusion within the unsaturated zone and underlying aquifers. Nevertheless, repeated annual applications of deicing salts to Highway 115 over more than 20 years suggest that the vertical extent of NaCl-rich soil water beneath the highway right-of-way may be appreciable, and that groundwater underlying the highway is likely to receive saline recharge waters.

## ACKNOWLEDGEMENTS

This work was funded by the Ministry of Transportation for Ontario, and the assistance of Dr. W. Snodgrass and MTO staff is gratefully acknowledged. We also wish to thank Dr. K.W.F. Howard and Mr. R. Gerber for providing the drill rig and assisting with the extraction of the deep soil cores, as well as several anonymous reviewers of an earlier version of this paper.

## REFERENCES

- Bengtsson, L., R.K. Saxena and Z. Dressie. 1987. Soil water movement estimated from isotope tracers. *Hydrol. Sci. J.* 32: 497-520.
- Bower, C.A. and L.V. Wilcox. 1965. Extracts of soil to water ratios of 1:1 and 1:5. In: Black C.A. (Ed.) *Methods of Soil Analysis*, pp 935-936.
- Cherkauer, D.S. 1975. Urbanization impact on water quality during a flood in small watersheds. *Wat. Resour. Bull.* 11: 987-998.
- de Voorde, H. van, M. Nijs, and P.J. van Dijck. 1973. Effects of road salt in winter. *Environ. Poll.* 5: 213-218.
- Gvirtzman, H. and M. Margaritz. 1986. Investigation of water movement in the

- unsaturated zone under an irrigated area using environmental tritium. *Wat. Resour. Res.* 22: 635-642.
- Howard, K.W.F. and P. Beck. 1986. Hydrochemical interpretation of groundwater flow systems in Quaternary sediments of southern Ontario. *Can. J. Earth Sci.* 23: 938-947.
- Howard, K.W.F. and P. Beck. 1993. Hydrogeochemical implications of groundwater contamination by road de-icing chemicals. *Journal of Contaminant Hydrology* 12: 245-268.
- Hydrological Atlas of Canada. 1978. Fisheries and Environment Canada, Ottawa.
- Jones, P.W., B.A. Jeffrey, P.K. Watler, and H. Hutchon. 1992. Environmental impact of road salting. In: *Chemical Deicers and the Environment*, Lewis Publishers, Boca Raton, FL, pp 1-116.
- Kronis, H. 1978. Characterization and treatment of snowmelt runoff from an urban catchment. Wastewater Treatment Section, Ontario Ministry of the Environment Research Publication No. 73, 40 p.
- Locat, J. and P. Gélinas. 1989. Infiltration of de-icing road salts in aquifers: the Trois-Rivières-Ouest case, Quebec, Canada. *Can. J. Earth Sci.* 26: 2186-2193.
- Munch, J.H. and R.W.D. Killey. 1985. Equipment and methodology for sampling and testing cohesionless sediments. *Ground Wat. Mon. Rev.*, Winter 1985: 38-42.
- Pollack, S.J. 1992. Remediating highway deicing salt contamination of public and private water supplies in Massachusetts. In: *Chemical Deicers and the Environment*, Lewis Publishers, Boca Raton, FL, pp 519-538.
- Quigley, M.A. 1982. Freshwater invertebrates. *J. Wat. Poll. Con. Fed.* 54: 868-877.
- Sami, K. and J.M. Buttle. 1991. Comparison of measured and estimated unsaturated hydraulic conductivities during snowmelt. *J. Hydrol.* 123: 243-259.
- Saxena, R.K. 1984. Seasonal variations of oxygen-18 in soil moisture and estimation of recharge in esker and moraine formations. *Nord. Hydrol.* 15: 235-242.
- Senior, L.A. 1994. Geohydrology of, and nitrogen and chloride in, the glacial aquifer, Milford-Matamoras area, Pike County, Pennsylvania. USGS Water Resources Investigations Report 93-4109, 43 p.
- Sharp, R.W. 1971. Road salt as a polluting element. In: *Street Salting - Urban Water Quality Workshop Proceedings*, State University College of Forestry at Syracuse University, May 6, 1971, pp 70-73.
- Smol, J.P., S.R. Brown, and R.N. McNeely. 1983. Cultural disturbances and trophic history of a small meromictic lake from central Canada. *Hydrobiologia* 103: 125-130.
- Villamil, R.J. and F. Kent. 1980. Deicing salt migration in Vermont soils. In: *Proceedings of the 1980 - Seventh Annual Lake Champlain Basin Environmental Conference*, pp 148-161.
- Vitaliano, D.F. 1992. Environmental costs of road salting. In: *Chemical Deicers and the Environment*, Lewis Publishers, Boca Raton, FL, pp 441-461.
- Vonk, A.M., J.M. Buttle and C.H. Taylor. 1991. Chloride export in runoff from suburban areas during spring snowmelt. In: *Maksimović, Č. (Ed.) New Technologies in Urban Drainage, UDT '91*, Elsevier, London, pp 347-354.
- Warren, L.A. and A.P. Zimmerman. 1994. The influence of temperature and NaCl on cadmium, copper and zinc partitioning among suspended particulate and dissolved phases in an urban river. *Wat. Res.* 28: 1921-1931.
- Webber, L.R., F.F. Morwick and N.R. Richards. 1946. Soil Survey of Durham County. Report No. 9, Ontario Soil Survey, Guelph, ON, 68 p.
- Wilcox, D.A. 1986a. Effects of deicing salts on water chemistry in Pinhook Bog, Indiana. *Wat. Resour. Bull.* 22: 57-65.
- Wilcox, D.A. 1986b. Effects of deicing salts on vegetation in Pinhook Bog, Indiana. *Can. J. Bot.* 64: 865-874.
- Wulkowicz, G.M. and Z.A. Saleem. 1974. Chloride balance of an urban basin in the Chicago area. *Wat. Resour. Res.* 10: 974-982.
- Zimmermann, U., K.O. Münnich, and W. Roether. 1971. Downward movement of soil moisture traced by means of hydrogen isotopes. *Am. Geophys. Union, Geophysical Monograph Series* 11: 28.