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Modelling enhanced infiltration of snowmelt ions into frozen soil

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Abstract:

A model is proposed in which the cumulative load of an ion infiltrating into frozen unsaturated soil can be estimated as a function of meltwater ion concentration and infiltration rate. Assumptions of the model are that the meltwater solution released to the soil surface is conservative, fully mixed within each time step, and that mass and energy are conserved. Infiltration and meltwater concentration are estimated using relationships developed by Gray and Stein respectively. The model suggests that the relationship between ion concentration and volume of infiltration is non-linear with a positive covariance. Infiltration of snowmelt ions is therefore a function of the products of the mean concentration in the meltwater and the cumulative volume of water that infiltrates, plus the covariance between instantaneous values of ion concentration and infiltration rate. This covariance effect is termed *enhanced infiltration*. Meteorological observations and soil parameters from four sites in western Canada were used to assess the sensitivity of the model to conditions at a prairie site, a boreal forest site, a mountain forest site, and a shrub tundra site. Model results showed the greatest cumulative infiltration of ion load for the Prairie site; the general ranking was Prairie > Mountain Forest > Boreal Forest > Tundra. However, the greatest impact of enhanced infiltration was found for the Tundra site. At this site, enhanced infiltration caused up to 50% more ion load to infiltrate within the initial third of the melt period compared to infiltration estimates not accounting for this effect. Over the whole melt period, enhanced infiltration caused 55–160% more ion load to infiltrate than estimates based solely on the mean depth of infiltration and ion concentration. Sensitivity analysis showed that enhanced infiltration varies most strongly with initial snow water equivalent, average melt rate over the whole melt period, and snowpack ion elution concentration factor (CF).

KEY WORDS enhanced infiltration; frozen soil; snow chemistry; meltwater chemistry; frozen soil infiltration; flow paths; soil chemistry

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INTRODUCTION

The seasonal snowcover accumulates ions as wet and dry deposition over the winter, releasing them rapidly at the time of spring snowmelt. This is a major event in terrestrial and aquatic ecosystems (Jones, 1999) that has been related to episodic acidification of lakes and streams (Davies *et al*., 1987; Ikuta *et al*., 1999; Schindler, 1999) and to changes in soil chemistry and microbiology (Abrahams *et al*., 1989). Ion fractionation and preferential elution of ions in snowpacks take place during melt, resulting in a two- to sevenfold enrichment of major ions in the initial meltwater and characteristic sequences of peak ion concentration in meltwater (Johannessen and Henriksen, 1978; Tranter, 1991). As melting proceeds, meltwater ion concentrations decrease exponentially; up to 80% of the solute within a snowpack may be eluted within the initial third of the melt period. This leads to a change in the proportional ion composition of the snowpack and meltwater during snowmelt.

In land surfaces typical of many cold regions, meltwater at the base of the snowpack can be partitioned into ponded water, basal ice, overland flow, organic layer storage, organic interflow, and/or infiltration to frozen mineral soils (Figure 1). Partitioning depends on factors such as soil temperature, available pore space, macropores, hillslope gradient, depressional storage availability, hydraulic conductivity of the frozen organic layer, and the infiltrability of the frozen mineral soil. Infiltrated water can be stored as soil moisture (frozen or liquid), drained as mineral interflow, or percolate deeper to become part of the groundwater system. Surface and organic layer flows and storage are termed *infiltration excess*, and primarily end up as rapid runoff, even where there is a well-developed organic layer (Carey and Woo, 2001; Quinton and Pomeroy, 2006). Water that infiltrates can often remain stored in the soil for long periods and then eventually contribute to evaporation or relatively slow groundwater or interflow contributions to streamflow. Soil interflow, during infiltration of snowmelt water, can become highly concentrated and when mixed with infiltration excess water can dramatically change surface water chemistry (Peters and Driscoll, 1987). Thus, partitioning of the snowmelt chemical load via infiltration is important in determining the aquatic or terrestrial sink for ions and the timing of ion delivery to water bodies.

Previous studies have shown that both the depth of infiltration into unsaturated frozen soils and the rate of

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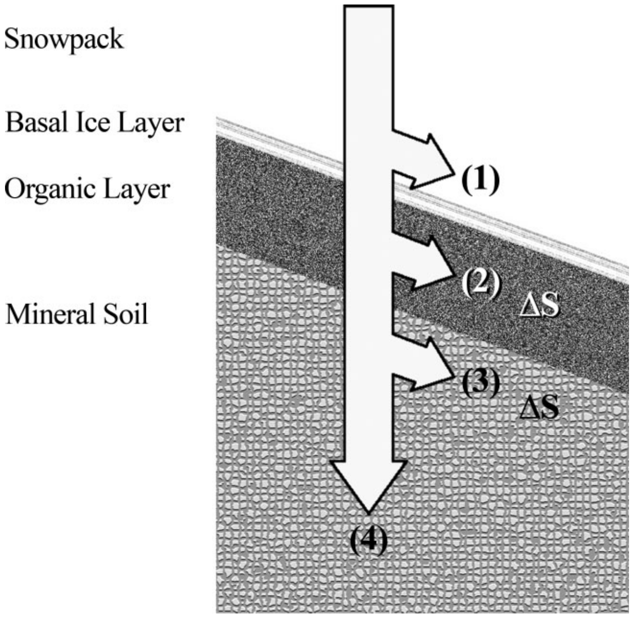

Figure 1. Below a melting snowpack, meltwater is partitioned into (1) ponded water, basal ice storage, and overland flow, (2) organic layer storage and interflow, (3) infiltration to frozen mineral soils with subsequent storage or interflow, and (4) percolation to groundwater

ion elution from the snowpack depend on the depth of the snowpack and the snowmelt rate (Stein *et al.*, 1986; Tranter, 1991; Zhao and Gray, 1997). Studies of ion load and concentration in runoff from snowmelt over frozen soils have shown dramatic changes in ion retention and release that are correlated with the frozen moisture content of soils and infiltrability (Jones and Pomeroy, 2001). However, there are no known studies or theories that link the physical process of frozen soil infiltration to preferential elution of ions from melting snow. The objective of this paper is therefore to propose a solute infiltration model and assess its sensitivity to various environmental conditions in western Canada. The model describes the partitioning of snowmelt solute into infiltration excess and into infiltration to unsaturated frozen mineral soils as a function of the ion concentration in the parent snow, snow water equivalent (SWE), melt rate, soil porosity, soil temperature, and volumetric soil moisture content. The model assumes that the meltwater solute is conservative and fully mixed and that limited infiltration occurs, in which there are neither substantive macropores nor impeding basal ice layers.

MODEL

The cumulative mass of water that infiltrates into an unsaturated frozen soil, F (kg m^{-2}), is a function of heat and mass transfer processes and phase changes between water and ice in the soil (Zhao *et al.*, 1997). The variation in infiltration rate with time, $f(t)$ (kg s^{-1} m^{-2}), in frozen soils has been found to be similar to that of unfrozen soil; it decreases exponentially with time. Infiltration rate, $f(t)$, is related to F as

$$\int_0^t f(t)\mathrm{d}t = F \tag{1}$$

Zhao and Gray (1997) derived a simple parametric relationship from a physically based mass transfer scheme (Zhao *et al.*, 1997) that describes F as a function of the following conditions at the start of infiltration of meltwater: surface saturation, S_0 [mm^3 mm^{-3}], average saturation (water and ice) in the top 40 cm of soil, S_I [mm^3 mm^{-3}], estimated from average volumetric soil moisture, θ [mm^3 mm^{-3}], and soil porosity, ϕ ($S_I = \theta/\phi$), soil temperature in the top 40 cm of soil, T_I (K), and the infiltration opportunity time, t_o (h). Cumulative infiltration, F, to mineral soils of various textures can be estimated from the following parametric equation (Zhao and Gray, 1999) for frozen unsaturated mineral soils that have no impeding layer above such as basal ice and contain no substantive macropores:

$$F = \mathrm{C} \cdot \mathrm{S}_o^{2\cdot 92} \cdot (1 - \mathrm{S}_I)^{1\cdot 64} \cdot \left(\frac{273\cdot 15 - T_I}{273\cdot 15}\right)^{-0\cdot 45} \cdot t_o^{0\cdot 44} \tag{2}$$

Gray *et al.* (2001) found that F is limited by the water storage potential of the soil (available porosity) and depends on a coefficient, C, which is influenced by the vertical profile of saturation in the upper 40 cm of soil (Gray *et al.*, 2001). C was found experimentally for prairie and boreal forest soils to be 2·10 and 1·14 respectively, and these values represent the strong overwinter desiccation of prairie soils compared to less severe desiccation of forest soils. Infiltration opportunity time, t_o, can be approximated as the time required to melt the snowpack, t, which depends on the SWE [snow accumulation (kg m^{-2})] and average melt rate over the melt period, $\overline{\mathrm{M}}$ (kg m^{-2} s^{-1}). Assuming that snowmelt is continuous and storage and evaporation are small, t can be estimated as

$$\mathrm{t_o} \approx \mathrm{t} = \frac{\mathrm{SWE}}{\overline{\mathrm{M}}} \tag{3}$$

Gray *et al.* (2001) suggest more exact solutions to Equation (3) based on techniques for estimating the duration of active meltwater delivery to the soil surface under conditions when snowmelt is not continuous.

Use of Zhao and Gray's equation to estimate infiltration to mineral soils under an organic layer is appropriate when the organic layer rapidly transfers water to the mineral soil surface. This assumption is robust where the organic layer is thin or porosity is high or organic layer macropores are abundant.

Ion concentration in meltwater, $C_i(t)$ (meq m^{-3}), during an interval meltwater discharge period $t_{n-1} - t_n$ can be found from Stein *et al.*'s (1986) expression, Equation (4), which is governed by the initial ion concentration in the bulk snowpack, $C_i(0)$ (meq m^{-3}), initial SWE (kg m^{-2}), average melt rate for the whole melt period, $\overline{\mathrm{M}}$ (kg m^{-2} s^{-1}), and a dimensionless leaching

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coefficient, k.

$$C_i(t) = \frac{C_i(0)}{\overline{M}\cdot(t_n - t_{n-1})}\cdot((SWE - (\overline{M}\cdot t_{n-1}))\cdot e^{-k\cdot\overline{M}\cdot t_{n-1}} - (SWE - (\overline{M}\cdot t_n))\cdot e^{-k\overline{M}t_n}) \quad (4)$$

A concentration factor, CF [(meq m^{-3})(meq m^{-3})$^{-1}$], defined as the ratio between the ion concentration in the meltwater to that in the bulk snowpack, [$CF = C_i(t)/C_i(0)$] (Johannessen and Henriksen, 1978), is often used to illustrate the variation in meltwaters ion concentration during snowmelt. Ion enrichment is shown for CF values >1. Initial meltwaters generally show the greatest enrichment, CF_{max}, whose magnitude is mainly a function of time, $\overline{M}$, and k (Equation (4)). The rate of change in $C_i(t)$ is strongly affected by k.

The cumulative load of an ion that infiltrates into frozen unsaturated soil underneath a snowpack, F_i [meq m^{-2}], is a function of the ion concentration in the meltwater released at the base of the snowpack, $C_i(t)$, infiltration rate, $f(t)$, and water density, ρ (kg m^{-3}); thus,

$$F_i = \int_0^t C_i(t)\cdot\frac{f(t)}{\rho}dt \quad (5)$$

So, over the whole snowmelt event, F_i can be found from a combination of frozen soil infiltration and preferential elution expressions using Equations (1–5).

Enhanced infiltration

As seen in Equations (1), (2), and (4), the infiltration rate, $f(t)$, and meltwater ion concentration, $C_i(t)$, both decline rapidly with time. High concentrations during high infiltration rates result in greater cumulative ion infiltration than if concentration and infiltration were time invariant. The resulting temporal association between $C_i(t)$ and $f(t)$ is highly non-linear, and a covariance term must be added in order to use time-averaged values of ion concentration and infiltration rate in calculating chemical infiltration. Time-averaged ion concentration and infiltration are far easier and more reliable to estimate than are concentrations at some time or infiltration rates. Thus, the solution to F_i in Equation (5) can be found from the product of time, t, and the time-averaged values of ion concentration and infiltration rate, $\overline{C_i}$ and $\overline{f}/\rho$, plus the covariance between the instantaneous values of $C_i(t)$ and $f(t)$.

$$F_i = \frac{\overline{C_i}\cdot\overline{f}\cdot t}{\rho} + cov[C_i(t), f(t)] = \frac{\overline{C_i}\cdot F}{\rho} + cov[C_i(t),f(t)] \quad (6)$$

The covariance term is positive as both meltwater ion concentration and infiltration rate decrease with time. It represents the additional load of ion that infiltrates during snowmelt due to the temporal association between ion concentration and infiltration rate (Figure 2). This covariance term is labelled the *enhanced infiltration* of ion.

An exact analytical solution of Equation (5) is not straightforward because both infiltration rate and ion concentration are functions of time. Equation (5) was therefore integrated over time using 1-h increments of t in a numerical solution.

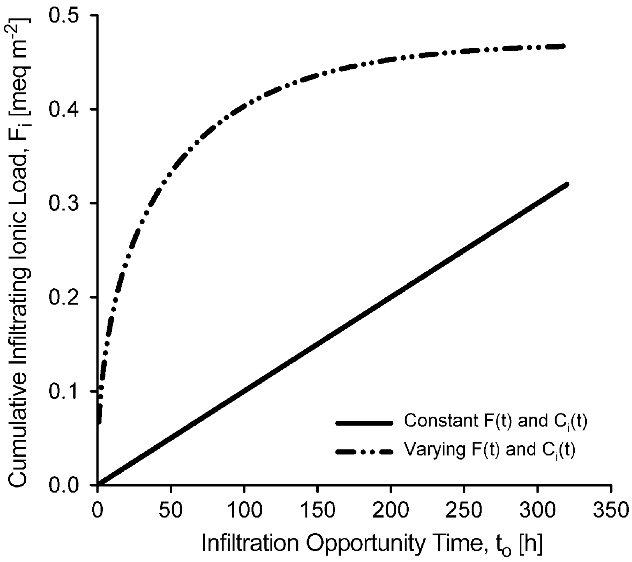

Figure 2. The cumulative load of an ion that infiltrates frozen soil if infiltration rate, $f(t)$, and ion concentration, $C_i(t)$, are held constant with time and if both parameters vary with time respectively

DEMONSTRATION SCENARIOS

Four sites, all located in western Canada, were used to demonstrate the theory presented in this paper, and to evaluate the possible magnitude of the enhancement of ion infiltration due to covariance. At all the sites, a large part of the yearly precipitation falls as snow, and soils are frozen at the time of snowmelt. Using field-based meteorology, soil and snow conditions to evaluate the model are considered an appropriate first step in assessing the importance of enhanced infiltration over a wide range of environmental conditions. The four sites are as follows:

- A *Prairie site*, located in St. Denis National Wildlife Area (52°02′N 106°06′W) in south-central Saskatchewan. This area is cultivated for cereal grains and oilseeds or left to hay and native pasture and has a gently rolling terrain with fine loamy textured soil underlain by clay-rich glacial till (van der Kamp *et al.*, 2003).
- A *Boreal Forest site*, located in Prince Albert National Park (53°53′N 106°07′W), central Saskatchewan. The site is in the southern boreal forest and has a terrain that consists of gently rolling slopes with vegetation consisting of 15- to 25-m-tall jack pine and aspen stands together with 10–12 m-tall black spruce stands (Pomeroy *et al.*, 1997). The understory consists of deciduous bushes and sphagnum moss; an organic layer overlies sandy loam textured soils, developed on thick glacial deposits.
- A *Mountain Forest site*, located in the Marmot Creek Research Basin (50°56′N 115°08′W) in the Kananaskis

Table I. Soil, snow, and melt properties for four demonstration sites. Parameter values were obtained from literature and field data. Initial bulk snow ion concentrations, $C_i(0)$, were all for SO_4. Melting was assumed to occur 12 h/day at the prairie and tundra sites and for 8 h/day at the forested sites. Values for k were chosen on the basis of CF_{max} values presented in previous studies (e.g. Tranter, 1991)

Parameter		Sites			
		St. Denis	Prince albert National Park	Marmot Creek	Wolf Creek
		Sask. prairie	Sask.boreal forest	Alta.mountain forest	Yukon Tundra
Soil properties	$\boldsymbol{C}$	2·10[1]	1·14[1]	1·14[6]	1·14[6]
	$\boldsymbol{S_0}$ [mm^3 mm^{-3}]	1·0[2]	1·0[2]	1·0[2]	1·0[2]
	$\boldsymbol{\phi}$	0·45[3]	0·44[3]	0·44[3]	0·44[3]
	$\boldsymbol{S_I}$ [mm^3 mm^{-3}]	0·60[4]	0·57[1]	0·68[8]	0·80[10]
	$\boldsymbol{T_I}$ [°K]	269[1]	270[1]	271[8]	272[10]
Snow properties	**SWE** [kg m^{-2}]	85[4]	50[5]	40[8]	146[9]
	$\boldsymbol{C_i}$ **(0)** [μeq m^{-3}]	12[4]	10[6]	15[8]	7·5[10]
Melt properties	$\boldsymbol{M}$ [kg m^{-2} d^{-1}]	4·5[4]	3·5[5]	1·9[8]	7·7[9]
	Melt Length [d]	19	14[5]	21	19
	$\boldsymbol{t_o}$ [h]	226·7	114·3	168·4	227·5
Case Study	$\boldsymbol{k}$	0·04	0·04	0·04	0·04
	$\boldsymbol{CF_{max}}$	4·4	3·0	2·6	6·7

[1] Zhao and Gray (1999), [2] Assumption based on Gray *et al.* (2001), [3] Clapp and Hornberger (1978), [4] Field data 2006; [5] Pomeroy *et al.* (1997), [6] Pomeroy *et al.* (1999),[7] Assumption based on Zhao and Gray (1999); [8] Field data 2005; [9] Pomeroy *et al.* (2006), and [10] Carey and Woo (2001).

River Valley of the Rocky Mountains, Alberta. The site has a ~20° inclination, facing almost due east, and a vegetation that is dominated by mature lodgepole pine with an average trunk density varying from ~0·3 to ~0·6 trunks m^{-2}. Ground cover consists mostly of grass and litter, with sparse deciduous shrubs. The mineral soil consists of sandy loam with a high content of silt and clay and is overlain by a poorly developed organic layer with a general thickness between 0·03 and 0·05 m.

- A *Tundra site*, located in Wolf Creek Research Basin, Yukon (60°32′N 135°18′W), on the northern fringe of the Coast Mountains in the zone of discontinuous permafrost (Quinton *et al*., 2005; McCartney *et al*., 2006). The soil consists of glacial till overlain by <0·14 m organic layer. The tundra is shrub tundra with vegetation dominated by *Salix* and *Alnus*.

Soil, snow, and melt properties for each site are summarized in Table I. The snowpacks initial ion concentration, $C_i(0)$, are based on sulphate concentrations. Parameter values were obtained from literature and field data collected by the authors and colleagues except for values for the leaching factor, k, which was based on previously reported CF_{max} values (e.g. Tranter, 1991). Porosity values based on the mineral soil texture at each site were used; values were obtained from Clapp and Hornberger (1978). Surface saturation, S_0, was assumed equal to 1·0 at each site due to the low infiltration rate of a frozen soil and the high likelihood of ponding above the soil (Gray *et al*., 2001).

Examples are presented to demonstrate enhanced infiltration with k held constant at 0·04 for all four sites, causing CF_{max} to vary between 2·6 and 6·7. Holding k constant throughout the melt period for various sites is possible because the parameter depends on a wide variety of factors such as snowpack flowpaths, distribution of solute in snow, melt–freeze cycles, rain on snow, and the possibility of biological activity (e.g. Tranter, 1991).

MODEL SENSITIVITY

Sensitivity of enhanced infiltration to parameters

Model results suggest that enhanced infiltration is more sensitive to changes in snow and melt properties than to changes in soil properties. The degree of ion enrichment in the meltwater, CF, and the initial SWE influence enhanced infiltration more than other parameters. To illustrate and compare enhanced infiltration, the cumulative enhanced ion infiltration due to covariance is normalized, normalized enhanced infiltration (NEI) [(meq m^{-2})(meq m^{-2})$^{-1}$], as the ratio between the cumulative enhanced infiltration and cumulative ion infiltration estimated from time-averaged ion concentration and cumulative infiltration (no covariance).

$$\mathrm{NEI} = \frac{\mathrm{cov}[\mathrm{C_i(t), f(t)}]}{\left(\dfrac{\overline{\mathrm{C}}_\mathrm{i} \cdot \mathrm{F}}{\rho}\right)} = \frac{\mathrm{F_i} - \left(\dfrac{\overline{\mathrm{C}}_\mathrm{i} \cdot \mathrm{F}}{\rho}\right)}{\left(\dfrac{\overline{\mathrm{C}}_\mathrm{i} \cdot \mathrm{F}}{\rho}\right)} \tag{7}$$

Figure 3 shows the influence of changes in single parameters on the cumulative ion infiltration, F_i, and NEI. A 15-mm increase in SWE resulted in an increase of the infiltration opportunity time and therefore an increase in F_i (Figure 3(a)). The change in SWE also resulted in a proportional increase in NEI of ~15% (Figure 3(b)). A 0·01 increase of k increased CF by 0·85, resulting in increasing F_i (Figure 3(c)) and a 22–27% increase in NEI (Figure 3(d)). The relative increase in

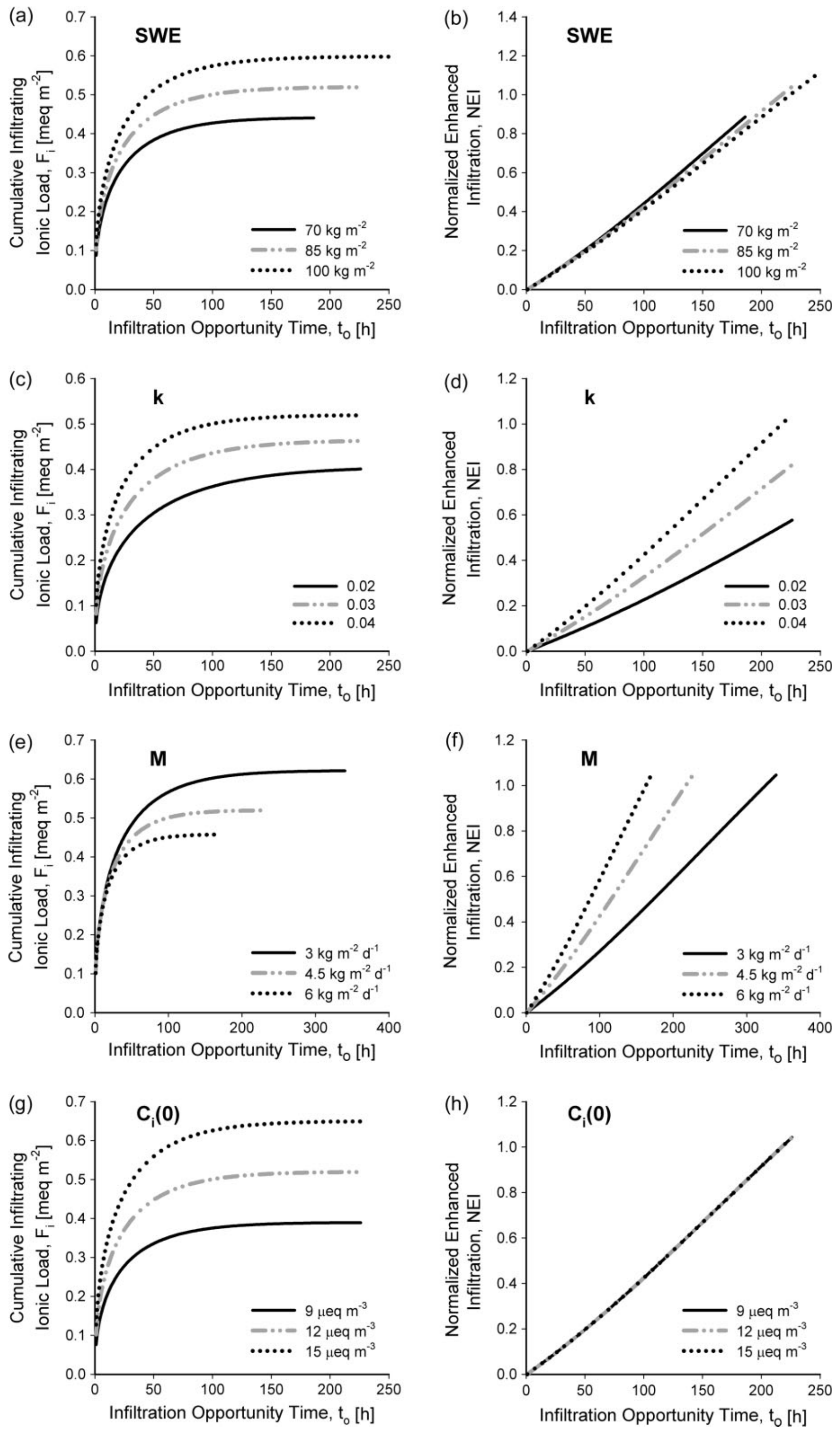

Figure 3. The influence of changes in single parameters on cumulative ion load infiltration, F_i, and normalized enhanced infiltration, NEI

F_i and NEI as k increased was not constant, but diminished with increasing k. Infiltration opportunity time was sensitive to the melt rate; increasing $\overline{M}$ resulted in decreasing F_i (Figure 3(e)). However, NEI was constant as $\overline{M}$ increased (Figure 3(f)). Increasing the initial ion concentration in the snowpack, $C_i(0)$, increased F_i (Figure 3(g)), but did not change NEI substantially ($<1\%$) (Figure 3(h)).

Enhanced infiltration of ions results in reduced ion load in infiltration excess water. Infiltration excess ion load, R_i [meq m^{-2}], can be estimated as the difference between the ion load in the meltwater leaving the snowpack, P_i [meq m^{-2}], and the infiltrating ion load, F_i:

$$R_i = P_i - F_i \tag{8}$$

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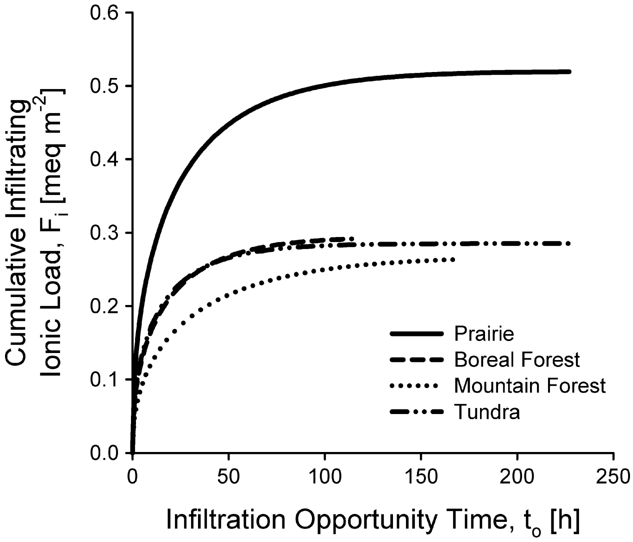

Figure 4. Cumulative ion load infiltration, F_i, as a function of time

where P_i is found from the melt rate and ion concentration in meltwater integrated over the melt period

$$P_i = \int_0^t C_i(t) \cdot \overline{M} \, dt \tag{9}$$

Subsequently, increased SWE and/or k decreases the ion load in infiltration excess water, whereas changes in $\overline{M}$ and $C_i(0)$ have little influence.

From previous studies, it is known that CF is greatly influenced by SWE and $\overline{M}$ (e.g. Bales *et al.*, 1989; Tranter, 1991). Increasing SWE and/or slow melt rates results in longer percolation times through the snowpack and greater opportunity to incorporate enriched meltwater at the surface of the snow crystals. CF is also strongly affected by the leaching coefficient, k, layering in the snowpack and preferential flow paths (Marsh and Pomeroy, 1999).

Ion infiltration and enhanced infiltration at demonstration sites

Cumulative ion infiltration, F_i, was strongly affected by the soil, snow, and melt properties at the demonstration sites (Figure 4). Two F_i groups were identified: (1) Prairie and (2) others. Largest F_i was at the Prairie, with values more than twice those of the other sites; ~0·4 meq m^{-2} higher. The high F_i was an outcome of the combination of high SWE, $C_i(0)$, and CF_{max}, together with double the mass of infiltrating water, F. This doubling of F was a result of the value of C, which was twice that of the other sites, together with the low initial soil moisture content, θ.

The values of F_i for the other sites were within 0·13 meq m^{-2} of each other. Lowest F_i was obtained for the tundra as a result of the higher SWE and $\overline{M}$ combined with the lower $C_i(0)$ and initial soil moisture content, θ. The general ranking of F_i was Prairie > Mountain Forest > Boreal Forest > Tundra.

At all the four demonstration sites, the non-linear relationship between $f(t)$ and $C_i(t)$ (Figure 5(a)) caused an initially rapid increase in enhanced infiltration, reaching a maximum in the initial third of the melt period (Figure 5(b)). As both $f(t)$ and $C_i(t)$ approached quasi-steady states with increasing time, enhanced infiltration dropped rapidly except for the Mountain Forest site, which only dropped slightly. The combination of low CF_{max} and shallow snowpack was the reason for this.

Peak enhanced infiltration ranged between 0·9 and 2·5 μeq m^{-2}, ranking Prairie > Boreal Forest > Tundra > Mountain Forest. Over the course of melt, the range of enhanced infiltration subsequently diminished to 0·2–0·9 μeq m^{-2} and the ranking position shifted for the Mountain Forest and Tundra. The timing of high ion concentration and infiltration rate caused a higher peak enhanced infiltration for the Tundra than the Mountain Forest. However, the lower $C_i(0)$ and F for the Tundra caused a greater decrease in enhanced infiltration over the course of the melt.

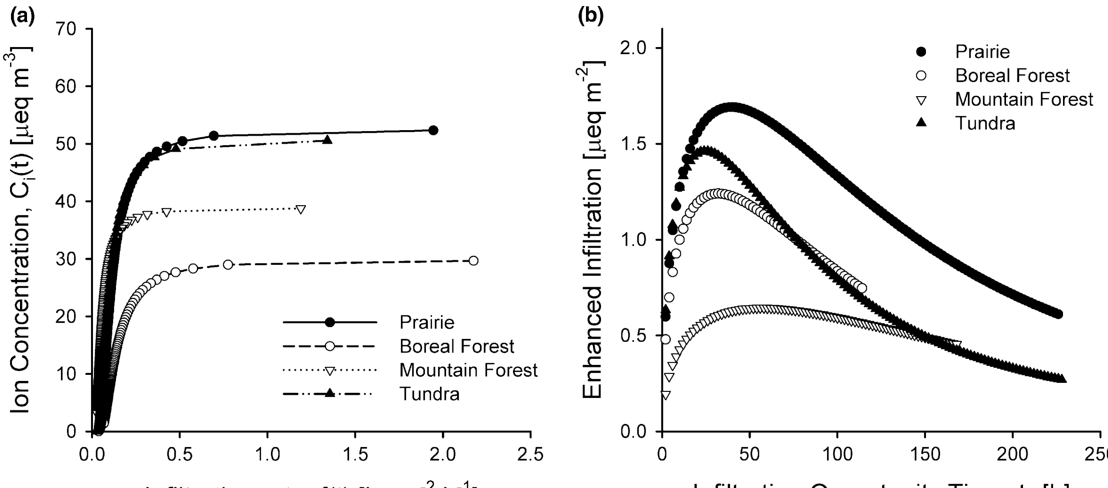

Figure 5. (a) The relationship between infiltration rate, $f(t)$, and ion concentration, $C_i(t)$. (b) Variation in enhanced infiltration of ions over the snowmelt period

The NEI is shown in Figure 6 as a function of the fractional infiltration opportunity time (t/t_o). NEI increased approximately linearly with fractional time at all demonstration sites. The rate of increase in NEI with time was primarily a function of $\overline{M}$, SWE, and CF_{max} differences amongst sites (Figure 3). The rate of increase was ranked as Tundra > Prairie > Boreal Forest > Mountain Forest. NEI increased from 0·36 after the initial third of the melt to 1·06 by the end of the melt for the Tundra and from 0·16 to 0·55 for the Mountain Forest. In all the cases, there was a substantial enhancement of ion infiltration by the end of melt.

The normalized infiltration excess ion load (NR_i) is defined as R_i (Equation (8)) divided by the difference between meltwater ion load, P_i, and ion infiltration, F_i, due only to time-averaged ion concentration and cumulative infiltration (no covariance), where

$$NR_i = \frac{R_i}{P_i - \left(\dfrac{\overline{C}_i \cdot F}{\rho}\right)} = \frac{P_i - F_i}{P_i - (F_i - \mathrm{cov}[C_i(t), f(t)])} = \frac{R_i}{R_i + \mathrm{cov}[C_i(t), f(t)]} \quad (10)$$

Thus, NR_i is a function of the enhanced infiltration and the infiltration excess ion load. Reductions in the infiltration excess ion load due to enhanced ion infiltration ($1 - NR_i$) give an indication of the importance of the process to runoff generation and hence its impact on aquatic chemistry. Figure 7 shows NR_i at each site as a function of the fractional infiltration opportunity time (t/t_o). NR_i values show a substantive reduction from the case of no enhanced infiltration and by the mid-point of the snowmelt period ($t/t_o = 0{\cdot}5$) indicate ion runoff reductions ranging from 11 to 57%. The trend for all sites was for decreasing NR_i with increasing time. By the end of the melt period, the reduction in NR_i ranged from 14 to 60%. The rank in terms of NR_i was Tundra > Boreal Forest ≈ Mountain Forest > Prairie reflecting the substantially larger infiltration for Prairie as previously discussed. Ranking in terms of reduction in NR_i from a value of 1 (no enhanced infiltration effect) was Boreal Forest > Prairie ≈ Tundra > Mountain Forest with the greatest reductions being roughly double the smallest reductions.

DISCUSSION AND CONCLUSION

A model is proposed in which the cumulative load of an ion that infiltrates into frozen unsaturated soil can be estimated from the ion concentration in the meltwater and infiltration rate. The model shows that the fate of the preferentially eluted ions released at the base of the snowpack during spring freshet might not be as straightforward as previously thought. That the snowmelt ion load ending up in infiltration excess water becomes reduced due to enhanced infiltration might help clarify previously unexplained changes in soil and flow path chemistry (e.g. Jones and Pomeroy, 2001).

Both eluted ion concentration and infiltration rate decline rapidly with time, but their association is nonlinear and positive. In order to use time-averaged values of ion concentration and infiltration rate in calculating the infiltrating ion load, a covariance term must be added. The covariance represents the excess of ion load that infiltrates during snowmelt and is termed the enhanced infiltration of meltwater ions into frozen soil. It is largest in the early stages of infiltration due to the association between the early timing of both high ion concentration and infiltration rate.

The model suggests that enhanced infiltration is governed by initial SWE, average melt rate, and the ion CF, which is strongly influenced by a leaching coefficient. A sensitivity analysis of these parameters showed the leaching coefficient as being the most sensitive; increasing it

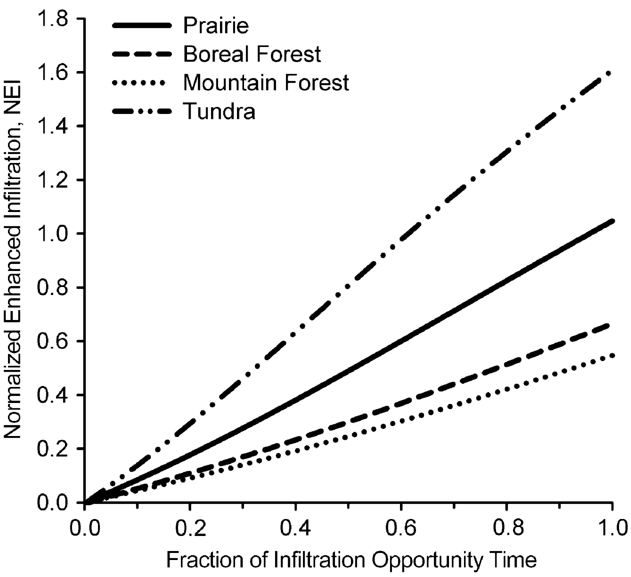

Figure 6. Variations in normalized enhanced infiltration at four demonstration sites over the course of the melt

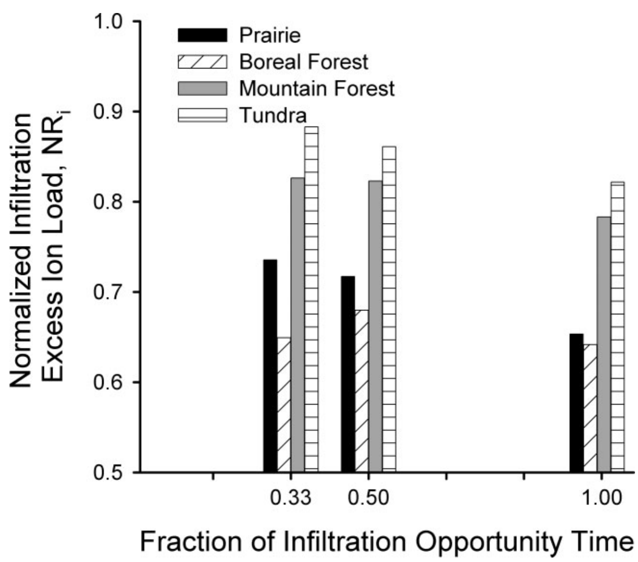

Figure 7. Normalized infiltration excess ion load, NR_i, at four sites

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by 0·01 caused an increases in cumulative enhanced infiltration of up to 25% and in cumulative ion infiltration of up to 13%.

Assessment of the sensitivity of this model to soil, snow, and melt properties showed that 16–50% more ion load infiltrates during the initial third of the melt period because of enhanced ion infiltration. For the whole melt period, 55–160% more ion load infiltrates. Conservation of mass specifies that enhanced infiltration ions are not available for infiltration excess and therefore runoff. The reduction in ion load in runoff water due to enhanced infiltration varied with site. Generally, it was reduced by 11–57% after the initial half of the melt period, increasing slightly (~3%) over the rest of the melt period.

In general, the regional demonstration of the model suggested that the cumulative infiltration of ion load was greatest for the Prairie environment and a ranking order of Prairie > Mountain Forest > Boreal Forest > Tundra. This was a result of inter-site variation in SWE, initial ion concentration, and melt rate, which all influenced the initial CF, in addition to initial soil moisture and the location coefficient, which at the Prairie site was twice that of the other sites.

The NEI, however, showed that enhanced infiltration has the greatest impact on the Tundra environment; the sites were ranked Tundra > Prairie > Boreal Forest > Mountain Forest in terms of ion infiltration enhancement. The reason for the greater influence in the Tundra environment was a combination of the reduced amount of mass infiltrating and the synchronicity between the timing of the highest ion concentration and infiltration rate. Overall, the demonstration showed that the Mountain Forest environment was influenced the least by enhanced infiltration.

The model suggests that calculations of the partitioning of snowmelt ions into infiltration and runoff need to consider enhanced infiltration effects due to temporal covariance between ion concentration and infiltration rate during melt. Future work will focus on thoroughly testing the model in field and laboratory settings.

NOMENCLATURE

C	Location coefficient [dimensionless].
$C_i(t)$	Concentration of an ion i at time t (meq m^{-3}).
$C_i(0)$	Initial ion concentration in the snowpack (meq m^{-3}).
CF	Concentration factor; $CF = C_i(t)/C_i(0)$ [(meq m^{-3})(meq m^{-3})$^{-1}$].
CF_{max}	Concentration factor of the initial meltwater [(meq m^{-3})(meq m^{-3})$^{-1}$].
$f(t)$	Infiltration rate (kg s^{-1} m^{-2}).
F	Cumulative mass of water infiltrating (kg m^{-2}).
F_i	Cumulative load of an ion that infiltrates (meq m^{-2}).
k	Leaching coefficient (dimensionless).
$\overline{M}$	Average melt rate (kg m^{-2} s^{-1}).
NEI	Normalized enhanced infiltration [(meq m^{-2})(meq m^{-2})$^{-1}$]
NR_i	Normalized infiltration excess ion load [(meq m^{-2})(meq m^{-2})$^{-1}$]
$1 - NR_i$	Reduction in infiltration excess ion load [(meq m^{-2})(meq m^{-2})$^{-1}$]
P_i	Meltwater ion load (meq m^{-2})
R_i	Infiltration excess ion load (meq m^{-2})
S_0	Soil moisture at the surface (mm^3 mm^{-3}).
S_I	Average soil saturation (water + ice) of the top 40 cm of the soil (mm^3 mm^{-3}); $S_I = \theta/\phi$.
SWE	Initial snow water equivalent (kg m^{-2}).
t	Time (s, h, or d).
t_o	Infiltration opportunity time in hours (h); estimated as $t_o = \text{SWE}/\overline{M}$.
t/t_o	Fraction of infiltration opportunity time
T_I	Average initial soil temperature within the top 40 cm of the soil (°K).
ϕ	Soil porosity (mm^3 mm^{-3}).
ρ	Density of water (kg m^{-3}).
θ	Average volumetric soil moisture (water + ice) at start of infiltration (mm^3 mm^{-3}).

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