

Rinsing of Saline Water from Road Salt in a Sandy Soil by Infiltrating Rainfall: Experiments, Simulations, and Implications

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Abstract Saline melt water from road salt applications that has percolated into a fine sandy soil in winter is rinsed out of the soil by infiltrating rainwater in the following warmer seasons. This sequence of saturated and unsaturated flow processes associated with saline water transport in a fine sandy soil was studied by simulation and exploratory laboratory experiments. Experiments in soil columns of 300- μm sand revealed that two rinses of pure water, each of one pore volume, were sufficient to reduce the salt concentration by 99% of its original value in the soil column. Simulated time variations of salt concentration in the effluent from the column agreed with experimental results. Based on simulated and experimental results, a sandy soil must become saturated to experience pore water flow in order to efficiently rinse saline snowmelt water. Depending on the saturated hydraulic conductivity and the soil depth, days, weeks, or months of freshwater infiltration in summer are needed to rinse saline melt water from an

unsaturated sandy soil after road salt applications in winter. This explains findings of significant salt concentrations in surface and shallow groundwater during summer months, long after road salt application and infiltration has ceased.

Keywords Infiltration · Percolation · Pore water · Porous media · Rainfall · Rinsing · Road salt · Solute transport · Unsaturated soil · Rainwater · Hydraulic conductivity

Notation (Units)

C	Concentration of salt (g cm^{-3})
C_c	Specific moisture capacity (cm^{-1})
D_m	Molecular diffusion coefficient of salt ($\text{cm}^2 \text{s}^{-1}$)
d_s	Grain diameter (cm)
D_{zz}	Dispersion coefficient ($\text{cm}^2 \text{s}^{-1}$)
g	Gravitational acceleration (9.8 m s^{-2})
K_e	Effective hydraulic conductivity (cm s^{-1})
K_s	Hydraulic conductivity at saturation (cm s^{-1})

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l	The constant (=0.5)
L	Soil depth (cm)
m	The constant
n	The constant (=2.68)
p	Pressure (N m^{-2})
S_e	Effective water saturation
S_s	Specific storage coefficient (cm^{-1})
t	Time (hour)
t^+	Normalized time
t_{dry}	Time required for effective hydraulic conductivity to reduce to less than 10% of the value at saturation (hours)
t_s	Time required to become saturated (hours)
t_r	Time required to reduce the total amount of salt in the soil to less than 1% of its initial value from a soil initially at saturation (hours)
t_{total}	Time required to remove salt from a soil initially at field capacity (hours)
u	Velocity of pore water flow (cm s^{-1})
z	Vertical coordinate (cm)
α	The constant (=0.145)
β	The constant ($\beta = 0$ for saturated soil and $\beta = 1$ for unsaturated soil)
θ	Water content
θ_r	Residual water content
θ_s	Water content at saturation
ρ	Fluid (water) density (g cm^{-3})
Ψ	Pressure head (suction) (cm)

1 Introduction

Road salt (commonly NaCl) is used during winter months in populated cold climate regions to improve winter road safety by lowering the freezing point of water and prevent the formation of ice (i.e., anti-icing; Lord 1989) or melt any ice and snow that develops on the pavement. Sodium chloride (NaCl) and calcium chloride (CaCl_2) are commonly used for road salt applications (Marsalek 2003). These salts are highly soluble and conservative, and Cl^- , Na^+ , and Ca^{++} ions are easily transported by water through the environment and to sensitive water bodies. Saline water runs off from roads where road salt has been applied, and accumulates and/or infiltrates near the top of the frozen soil during winter. During warmer temperatures in spring, the soil thaws, the saline water percolates, and some amount of saline water (up to the field capacity) is left in the pores of the

unsaturated soil. Infiltrating rainfall in warmer spring and summer weather can rinse accumulated saline water stored in the pores of the soil. Cl^- , Na^+ , and Ca^{++} ions are thus transported to groundwater or back to surface water by interflow and can be found in surface waters unexpectedly during summer months and in shallow groundwater near roadways year around.

An overview of the road salt problem in the USA was given by Mullaney et al. (2009) from the USGS. A local situation in Madison and Dane County, WI, is described in an annual report by Public Health Madison and Dane County (2014), and the effects of road salt on shallow aquifers in Ohio by Kunze and Sroka (2004). Mitigation measures to reduce groundwater and surface water pollution emphasize foremost the reduction and better planning of road salt applications. The effectiveness of highway drainage systems to prevent groundwater pollution by road salt was explored by Church et al. (1996). The transport of road salt from upland areas to streams has been modeled (Jin et al. 2011), and increasing chloride concentrations in groundwater and surface water of urban environments have been attributed to road salt applications (Bowen and Hinton 1998; Fong 2000; Lofgren 2001; Godwin et al. 2003; Marsalek 2003; Thunquist 2004; Kaushal et al. 2005; Andrews et al. 2005; Kelly et al. 2008; Novotny et al. 2008; Novotny and Stefan 2009a, b; Gardner and Royer 2010).

Increases in salt concentration in freshwater environments can impact water quality, water use, and ecosystems (Jones and Jeffrey 1992; Ramakrishna and Viraraghocan 2005). Saline water moves to the bottom of freshwater lakes and reservoirs, resulting in increased duration of benthic summer hypoxia (Ellis et al. 1997; Novotny and Stefan 2012). This can significantly increase the release of phosphate from lake sediments (Mortimer 1972). Chloride-rich water can also worsen the effects of other pollutants in the water, such as hydrocarbons and trace metals, which commonly contaminate road runoff (Marsalek 2003). Long-term changes in soil chemistry due to road salt applications also affect microbial nitrogen transformation processes in soils (Green et al. 2008). Long-term road salt use and retention can be contributing to a gradual increase in baseline chloride concentrations in at-risk mussel habitat (Gillis 2011). Furthermore, salt in water decreases biodiversity and reduces survival of certain aquatic animals (Environment Canada Health Canada 1999). The concentration of chloride commonly occurring in salted road runoff often exceeds the ambient water quality

criteria indicating acute and chronic toxicity, which are 860 and 230 mg/L of chloride, respectively (U.S. EPA 1988). Information on runoff and infiltration of road salt in melt water is needed for water quality management in cold climate areas experiencing urbanization and increased road density.

A chloride budget for the Twin Cities metropolitan area of Minneapolis/St. Paul was developed by Novotny et al. (2009b). Of the chloride applied annually as road salt (NaCl) in the metropolitan watershed, less than 30% was exported in surface water by the Mississippi River and more than 70% was retained in the watershed. Salt concentrations were higher than expected in urban tributaries in the summer months (Novotny et al. 2009b) because of temporary salt retention by soils and in lotic surface water bodies (lakes and stormwater detention ponds) and shallow groundwater. Chloride concentrations in many urban water bodies, including shallow groundwater, were found to be considerably higher than the presettlement background levels of less than 3 mg/L. Significant increases in chloride concentrations in surface waters were also observed in southern Ontario, Canada, during nonwinter months from May to October (Todd and Kaltenecker 2012). Shallow groundwater discharge may dilute chloride concentrations in urban streams in winter but enrich them in summer (Bischoff et al. 2006; Ledford et al. 2016).

Because the accumulation of chloride in groundwater and surface water is a cause for concern, it is necessary to develop an understanding of road salt transport and retention, especially in urban watersheds. In this study, we present an investigation of the delayed release of road salt (chloride) after percolation of saline melt water from roadways into the pore system of a sandy soil in winter and subsequent rinsing by rainfall infiltration in the warmer season. This study considers a soil column composed of fine and uniform sand; most soils in cold climate regions are more complex and varied. In addition to the total amount of road salt applied in the cold season, effects of the duration of rainfall events and the total annual rainfall infiltration in the warmer season on the balance of salt in the soil are investigated.

Salt can be rinsed from the soil by pore water flow due to infiltrating rainwater. It is important to relate infiltration from rainfall to pore water flow and transport of salt mass in order to develop a salt budget for the soil. The movement of saline water and rainwater in a soil can be classified as the flow of two miscible liquids in an unsaturated (percolation) or saturated (infiltration)

permeable porous medium. During and up to the end of a rainfall and infiltration event, the soil is likely to be saturated to some depth, but the soil is likely to be unsaturated if no precipitation has occurred. Salt transfer rates in saturated soils are likely to be large. After rainwater infiltration ceases, the soil starts to drain toward field capacity, becoming gradually more unsaturated. The retention of salt in unsaturated soils can be expected to depend on the duration and amount of rainfall infiltration.

The purpose of this study is to investigate the transport and residence time of road salt (saline water) in a fine sandy soil by exploratory experiments and transport process simulation. The effect of the total amount of infiltration from rainfall on the salt transport process is examined. This information can be used to estimate the time scale at which saline water from road salt applications will move to shallow groundwater.

2 Methods

Process simulation and laboratory experiments are used in this study. Richards' equation is used to simulate (saturated) infiltration of rainwater into an unsaturated soil with pore spaces filled by saline water to field capacity. The advection-dispersion equation is used to simulate solute transport (mass transfer of salt) driven by pore water flow into the unsaturated soil below (Fig. 1). Predicted time-variable salt concentrations in the effluent are compared with those measured in laboratory experiments where saline pore water was rinsed from unsaturated sandy soil columns.

The simulation and experiments include (1) infiltration of freshwater into a saline unsaturated soil column of uniform fine sand and (2) advective/diffusive mass transfer of salt in the saturated zone above and the unsaturated zone below. Pore water flows through this medium from above, either as a dilute solution of NaCl (saline water) during or after the road salt application season, or as (fresh) rainwater during the following warm season. The saline water is transported downwards through the pore system either by gravity flow of the saline water to field capacity or rinsed by infiltrating rainwater or chloride-free runoff water. When no saline water is added from above and the soil column has had some time to drain by gravity, the result is an unsaturated soil column with pore spaces partially filled by saline solution and air. During spring and summer,

rainwater will fall or run onto the soil surface and infiltrate. The simulation and experiments begin at this point in time. Soil moisture distribution and salinity distribution in the soil column are calculated. Water flow and salinity in the flow into and out of the column were measured in the experiments (Toledo-Cossu et al. 2014a, b). Salt transport or retention in the soil column was determined.

The experiments were conducted at the St. Anthony Falls Laboratory, University of Minnesota in Minneapolis. A translucent vertical pipe of 50.8 mm inner diameter and 155 mm length was filled with uniform 300- μm sand. The pipe diameter is adequate to make both boundary layer effects and flow along the pipe wall insignificant because the pipe diameter to grain size ratio is 169 and 102 for 300- and 500- μm sand, respectively. The columns were also dry consolidated (not compacted) to remove excess pore spaces and ensure uniform soil texture throughout the column (i.e., minimize macropores). The saturated hydraulic conductivity (K_s) was calculated from the grain size by the Creager equation (Shepherd 1989) as $K_s = 0.022$ cm/s. The pore volume was initially filled to saturation with saline water and then gravity drained to field capacity. In the experiment, the saline water was rinsed from the column by freshwater, which was supplied at constant head from the top of the column. Flow rates and salt concentrations of the effluent from the bottom of the column were measured during the freshwater infiltration. In phase 1 of the experiments, 1 pore volume of saline solution at 33.64 g/L NaCl was added to the column from the top to simulate snowmelt infiltration and subsequently drained by gravity to field capacity. In phase 2 of the experiment, the column was rinsed with approximately 1 pore volume of ultrapure (Milli-Q, 18.2 M Ω cm) freshwater repeatedly until the effluent had less than 1% of the salt water concentration first applied in phase 1. The freshwater was applied at constant head at the top of the column from where it infiltrated into the column. Effluent was collected from the bottom of the column into 35 mL bottles. The electrical conductivity ($\mu\text{S}/\text{cm}$) in the effluent samples from the column was measured with an OAKTON COND 6+ probe manufactured by Eutech Instruments and described by Toledo-Cossu et al. (2014a). Salinity of the water was determined from a nearly linear calibration curve of salt concentration (mg/L) vs. electrical conductivity with $R^2 = 0.997$ and five calibration solutions at concentrations of 0 g NaCl/L (Milli-Q ultrapure water), 8.41 g/L, 16.82 g/L,

25.23 g/L, and 33.64 g NaCl/L (saltwater stock solution). The accuracy of the instrument was regularly checked using manufacturer-supplied conductivity standards. To prevent contamination of the sensor's metal surface, the probe was rinsed with ultrapure water after every use.

To measure how much salt remained in the pores of the sand medium after the conclusion of an experimental series, all remaining liquid and sand in the column was collected and well mixed in a container. The total volume and the specific conductance of the water were measured, and the mass of salt remaining in the column was calculated.

3 Development of a Simulation for Saline Water Transport Processes in Sandy Soil

3.1 Rainwater Infiltration into Unsaturated Sandy Soil

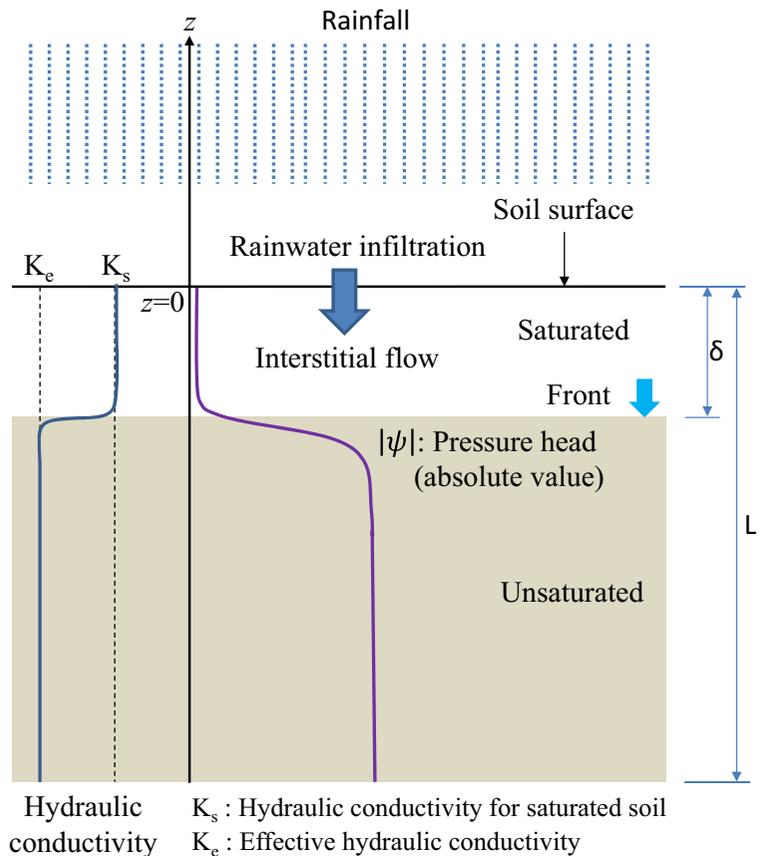
Rainfall and runoff from impervious road surfaces onto permeable soil cause rainwater to infiltrate into the soil as shown in Fig. 1. The flow field for saturated/unsaturated soil driven by rainwater can be described by Richards' equation (Richards 1931).

$$(C_c + \beta S_s) \frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial z} \left\{ K_e \frac{\partial \Psi}{\partial z} + K_e \right\} - S \quad (1)$$

where Ψ is the pressure head (suction), z is the elevation above a vertical datum ($z < 0$ below), t is time, C_c ($=d\theta/d\Psi$) is the specific moisture capacity, θ is the water content, S_s is the specific storage coefficient, K_e is the effective hydraulic conductivity; $\beta = 1$ and $C_c = 0$ for saturated soil, whereas $\beta = 0$ for unsaturated soil; and S is a sink term. The pressure head Ψ is negative ($\Psi = 0$ at atmospheric pressure) due to capillary forces when soils are unsaturated. The sink term S in Eq. (1) describes the evapotranspiration effect of plants on soil moisture. This may play an important role in the overall water budget for the soil (Baldocchi et al. 2004; Williams and Albertson 2004; Montaldo et al. 2005; Cortis and Montaldo 2013), but this study focuses exclusively on the physical transport of NaCl within a soil without vegetation or microbial activity. Thus, the sink term S is not considered here but needs further study.

Equation (2) (van Genuchten 1980) can be used to estimate the effective water saturation S_e from the suction head (Ψ) as

Fig. 1 Schematic diagram of infiltration of rainwater through unsaturated soil filled with saline water to field capacity



$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = (1 + |\alpha \Psi|^n)^{-m} \tag{2}$$

where θ is the instantaneous water content of the soil, θ_s is the water content at saturation, θ_r is the residual water content at field capacity, and α , n , and m are constants. Both α and n are specified as $\alpha = 0.145 \text{ cm}^{-1}$ and $n = 2.68$ (van Genuchten et al. 1991), because the soil considered in this study is composed of fine sand (with a hydraulic conductivity K_s from 0.001 to 0.1 cm/s). The constant m in Eq. (2) is related to the constant n by the equation

$$m = 1 - \frac{1}{n} \tag{3}$$

The effective hydraulic conductivity (K_e) is expressed as a function of the effective water saturation (S_e , van Genuchten et al. 1991) as

$$K_e = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \tag{4}$$

where K_s is the saturated hydraulic conductivity and the

power $l = 0.5$. The specific moisture capacity (C_c) can then be determined by the equation (van Genuchten et al. 1991)

$$C_c = \frac{d\theta}{d\Psi} = \frac{\alpha^n (n-1) (\theta_s - \theta_r) (-\Psi)^{n-1}}{[1 + \{\alpha(-\Psi)\}^n]^{\frac{2-n}{n}}} \tag{5}$$

3.2 Mass Transfer of Salt Through the Soil

The pore water flow rate depends on the hydraulic (piezometric) gradient and the saturated hydraulic conductivity (K_s) and is quantified by Darcy's law. The mass balance of salt in the soil is then expressed by the equation

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial z} = \frac{\partial}{\partial z} \left(D_{zz} \frac{\partial C}{\partial z} \right) \tag{6}$$

in which C is the concentration of salt, u is the Darcy velocity (Eq. 7), and D_{zz} is the dispersion coefficient (Eq. 8). The Darcy velocity of the pore water flow is

given as

$$u = -K_s d \left(\frac{p}{\rho g} + z \right) / dz \quad (7)$$

where the term in parenthesis is the piezometric head, $p(z, t)$ is the pore pressure, ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.8 m/s^2), and z is the elevation. The dispersion coefficient D_{zz} in Eq. (6) has been given by Zheng and Bennett (1995) as

$$D_{zz} = \alpha_L u + \varphi^2 D_m \quad (8)$$

in which α_L is the longitudinal dispersivity which can be approximated by the grain diameter d_s , as $\alpha_L \sim d_s$ (Qian et al. 2008), φ is the porosity, and D_m is the molecular diffusion coefficient of salt (NaCl) which was assumed to be $2.0 \times 10^{-5} \text{ cm}^2/\text{s}$.

When a soil is unsaturated, the pore water movement is by percolation, and its rate is much less than by pore water flow at saturation; the same applies to the salt transport rate. At a moisture content below field capacity, there is no significant water motion at all, and the salt flux is reduced to transport in capillary films and by molecular diffusion within the available moisture.

3.3 Numerical Solution and Boundary Conditions for the Simulation

The basic Eqs. (1) and (6) were normalized using the soil depth (L) as the length scale, and the saturated hydraulic conductivity (K_s) as the velocity scale. Infiltration of rainwater through a soil was simulated by solving the normalized Eq. (1) numerically. The normalized Eq. (6) was used to simulate the rinsing of saline water by pore water flow through the saturated soil.

To solve both Eqs. (1) and (6), the number of grids points in the z -direction was chosen as 100 with uniform spacing. Partial derivatives were approximated by a second-order finite difference formula. For time advancing, the Crank-Nicholson method was used.

Atmospheric pressure was applied at the soil surface; hence, the boundary condition was set to be $|\Psi| = 0$ at $z = 0$ for Eq. (1). A no-flow boundary, $(\partial\Psi/\partial z = 0)$, was imposed at the bottom of the soil domain ($z = -L$) as long as the bottom layer was unsaturated at field capacity and could therefore be considered as an impermeable layer. The initial pressure head was assumed to be $\Psi = \Psi_0$ everywhere inside the unsaturated soil.

The pressure head (i.e., soil suction) for an unsaturated soil can be -10 to -100 cm depending on the effective water saturation (Ahmed et al. 2014). The effect of the initial pressure head Ψ_0 on the normalized time ($t^+ = t K_s/L$) required for a soil column composed of sand to be saturated from the surface to the given depth (δ) was simulated and is shown in Fig. 2. t^+ increases quickly for $\Psi_0 > -20 \text{ cm}$, gradually for $-20 \geq \Psi_0 > -40 \text{ cm}$, and becomes almost independent of Ψ_0 when $\Psi_0 \leq -40 \text{ cm}$. The initial pressure head was, therefore, assumed to be $\Psi_0 = -40 \text{ cm}$ ($p_0 \approx -4 \text{ kPa}$) throughout the subsequent simulations. This pressure head corresponds to $S_e = 5\%$ according to Eq. (2).

The initial condition was an unsaturated soil column at field capacity. The bottom of the column was open to drainage. When rainwater was applied, there was no outflow from the column until the soil saturation front reached the bottom of the column. For Eq. (6), the salt concentration was set to be C_0 everywhere inside the soil initially ($C = C_0$ at $t = 0$). The boundary condition at the soil surface ($z = 0$) was $C = 0$ as soon as freshwater (rainwater) was applied at the top of the column. The gradient of salt concentration was set to be zero, $(\partial C/\partial z = 0)$, at the bottom of the soil column.

3.4 Existing Transport Models for Solutes in Soils

A review of models and case histories of solute transport in unsaturated soils was given by Rumynin (2011). Chapter 2 is particularly useful. Among other publications, an introduction can also be found in Bunsri et al. (2011). For use in agriculture, models of the transport of nutrients and moisture and heat in soil are of great interest. The increase in soil salinity due to irrigation and water evaporation has been a significant problem in agriculture. Modeling of the transport of herbicides and insecticides is also of interest.

Existing simulation models of transport in porous media are more powerful than what is needed in our study of dissolved NaCl transport. For example, the HYDRUS 1D program (Simunek et al. 2005, 2013) solves the Richards' equation for unsaturated water flow, and an advection-dispersion equation for solute transport, as we do. However, in the HYDRUS code, the flow region can be composed of nonuniform soils, while our experiments and simulations are for a fine sandy soil only. The water flow part of the HYDRUS model can deal with time-varying head and flux boundaries. Soil surface boundary conditions may change during the

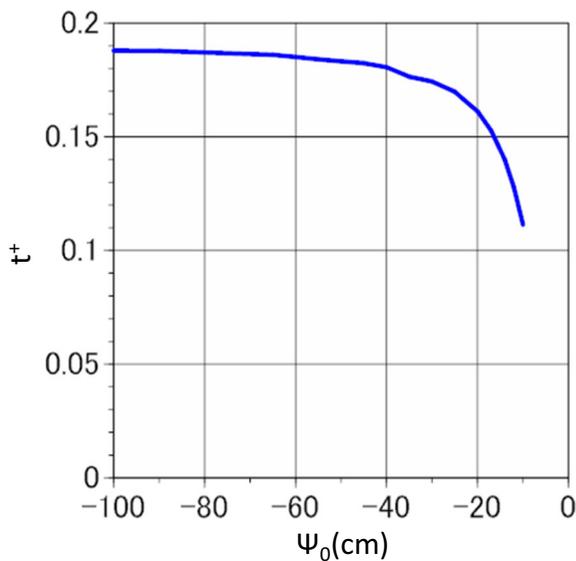


Fig. 2 Effect of initial pressure head (Ψ_0) on time required ($t^+ = t K_s/L$) for the soil to become saturated from the surface (depth δ)

simulation from prescribed flux to prescribed head. The code can handle both prescribed concentration and flux boundary conditions. The dispersion coefficient includes the effects of tortuosity and molecular diffusion. The HYDRUS code also includes hysteresis by empirical functions.

Because our needs are much less than what the HYDRUS code offers, we chose to formulate our own simulation. As in the HYDRUS code, unsaturated soil properties are described using van Genuchten (1980) and Brooks and Corey (1964). The increase in soil salinity due to irrigation and evaporation is related to our problem of saline water transport. But we are interested only in the downward movement of one solute (NaCl) under the effect of rinsing water. We do not have to consider significant interaction with plants. NaCl is a highly conservative and highly soluble substance not susceptible to much adsorption on soils (true for Cl^- , less for Na^+).

4 Experimental Results and Simulation Comparison

4.1 Rinsing Experiments

Figure 3 shows an example of the temporal variation of the effluent flow rate as simulated by Eqs. (1) and (6) for experiments RUN1 and RUN2. The soil column was

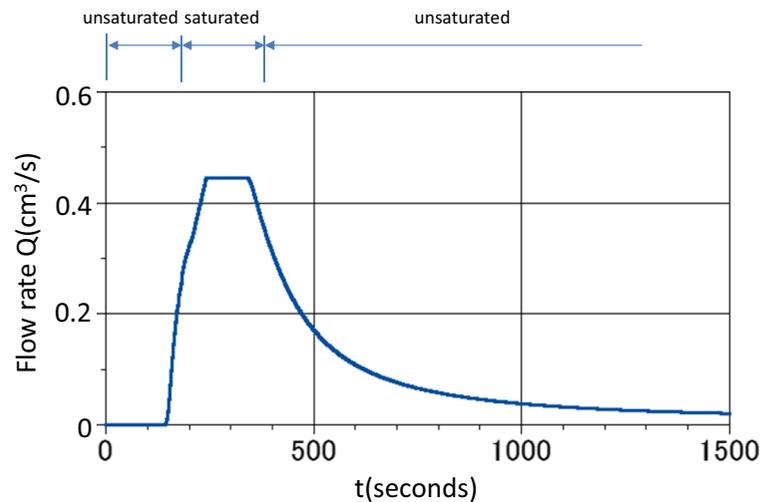
unsaturated to field capacity at the beginning of the rinsing experiment and the simulated flow rate increased as the effective water saturation in the column increased. The flow rate became constant after the soil column reached full saturation, as to be expected. A short time after the rinse water addition at the top of the sand column was terminated, the effluent flow rate from the column began to decrease. When it reached zero, the soil column was considered to be again unsaturated and at field capacity. A decreasing effluent flow rate corresponds to decreasing effective water saturation.

As summarized in Table 1, experimental results reveal that two rinses of freshwater, with one pore volume each, were enough to reduce the salt concentration in the effluent from the pores of the unsaturated soil column by 99%. This suggests that accumulation of salt in sandy soils is unlikely as long as sufficient rinsing water is available from freshwater rainfall infiltration. Because the amount of infiltrating rainwater depends on rainfall duration and intensity, saline water from road salt applications during the winter can be retained in the soil for long periods when there is not enough freshwater infiltration from rainfall after the winter.

In order to compare simulated and experimental results, the data from RUN1 and RUN2 in Table 1 are normalized using the saturated hydraulic conductivity ($K_s = 0.022$ cm/s), and the column depth of 155 mm, and plotted in Fig. 4. The simulated normalized salt concentration in the effluent water is constant until normalized time $t^+ = 0.5$; it then decreases with time and, finally, approaches zero. Saline water has almost been entirely removed from the soil at $t^+ = 2.0$. As shown in Fig. 4, the simulated results adequately represent the experimental rinsing process.

The simulation assumes a homogeneous and uniform soil column, and the sodium chloride solution is considered to be nonreactive. Adsorption to soil particles is small and was assumed negligible. Experiments were later conducted to confirm the correctness of this assumption. Based on the experimental results shown in Table 1, a small concentration of salt remained in the effluent after rinse 1 and rinse 2 (measured electrical conductivities were nonzero). Thus, a small amount of salt was trapped within pore water in the column, subject to delayed release. Even though this process is not considered in the simulation, the simulated results correspond well with the experimental data.

Fig. 3 Simulated variation of effluent flow rate with time in experiments RUN1 and RUN2



4.2 Direct Measurement of Salt Retention in the Rinsed Soil Column

The soil column was dismantled after two rinsing experiments, and the salt concentration in the remaining pore water was measured. It was found that the salt mass in the residual pore water of the dismantled sandy soil column was 0.075, 1.21, and 0.017 g, respectively (Table 2). The total salt mass in the saline water added to the column before the rinsing experiments was 22.9, 59.1, and 34.1 g, respectively. The residual salt content in the pore water was therefore 0.05–2.04% of the original salt amount that was added to the pore space of the soil.

5 Simulation of Transport Processes

5.1 Infiltration of Rainwater Through Unsaturated Soil

Profiles of the pressure head $|\Psi|$ and effective hydraulic conductivity (K_e) in the soil are shown in Fig. 5 for dimensionless time $t^+ = 0.10$. The absolute value of pressure head increases and the normalized effective hydraulic conductivity (K_e/K_s) decreases around $z/L = -0.35$, which corresponds to the saturated/unsaturated interface. The effective hydraulic conductivity (K_e) is equal to the saturated hydraulic conductivity (K_s) for the saturated soil but is 3 or 4 orders smaller than K_s when the soil is unsaturated (e.g., $S_e = 5\%$, Eq. (2)). Thus, the water is transported through unsaturated soil at much slower rate than through saturated soil.

Figure 6 illustrates simulated profiles (normalized over the length of the soil column) of effective water saturation (S_e) for normalized times $t^+ = t K_s/L = 0.05, 0.10, \text{ and } 0.20$. Onset of infiltration is at $t^+ = 0$ and the initial effective water saturation is $S_e = 5\%$. Rainwater infiltrates into the unsaturated soil, and the saturated zone extends downward with time.

The depth of the saturated zone (δ) is defined as the distance from the soil surface ($z = 0$) to the point where $S_e = 0.99$. During infiltration, t_s is the time required for the soil to become completely saturated (depth δ). The saturation zone extends more quickly (smaller t_s) when the initial effective water saturation (S_e) is larger. Figure 7 illustrates t_s as a function of K_s for an initial effective water saturation $S_e = 5\%$. The saturated zone extends more quickly with increased K_s , which is expected. For low hydraulic conductivity soils ($K_s < 0.001 \text{ cm/s}$), t_s can be more than 40 h when the saturated zone penetration depth (δ) is greater than 6 m. Figure 7 is useful to estimate how long it takes for the soil to become saturated by infiltrating rainwater or chloride-free surface runoff water depending on both the soil depth and hydraulic conductivity.

5.2 Drainage of Soil After Rainfall

After the rainwater infiltration has stopped, the soil starts to drain to field capacity. Figure 8 illustrates the time variation of the effective water saturation profile after rainwater has ceased to infiltrate. Although pore water continues to move downward, the maximum effective water saturation (S_e) decreases due to a lack of water

Table 1 Experimental data of incremental effluent measurements

Phase 1		Phase 2			
Volume in sample bottle (mL)	Electrical conductance in bottle (mS/cm)	Volume in sample bottle (mL)	Rinse 1 Electrical conductance in bottle (mS/cm)	Volume in sample bottle (mL)	Rinse 2 Electrical conductance in bottle (mS/cm)
RUN1					
35	0.46	35	53.3	35	1.23
35	0.22	35	54.4	35	0.45
35	11.0	35	43.7	35	0.41
35	48.6	35	7.28	35	0.27
35	54.5	35	1.28	35	0.20
35	54.0	35	0.77	35	0.18
9	55.0	5	0.73	10.5	0.19
RUN2					
35	1.27	35	53.5	35	1.18
35	0.43	35	53.2	35	0.47
35	12.6	35	43.9	35	0.45
35	49.6	35	7.54	35	0.25
35	54.4	35	1.51	35	0.19
35	54.1	35	0.79	35	0.15
7	55.1	11.25	0.74		

supply and increase in depth over which S_e extends. As expected, the effective hydraulic conductivity (K_e/K_s) becomes smaller with time.

Figure 9 is a specific example of Fig. 8 for $L = 2$ m, $K_s = 0.1$ cm/s, and effective water saturation $S_e = 100\%$ throughout the upper $z = 0.60$ m depth. This clearly illustrates how much time is required for pore water to

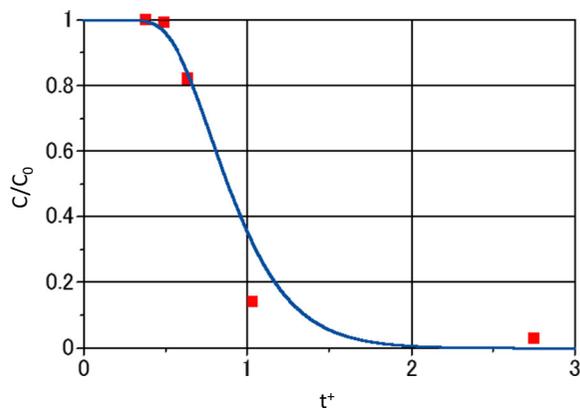


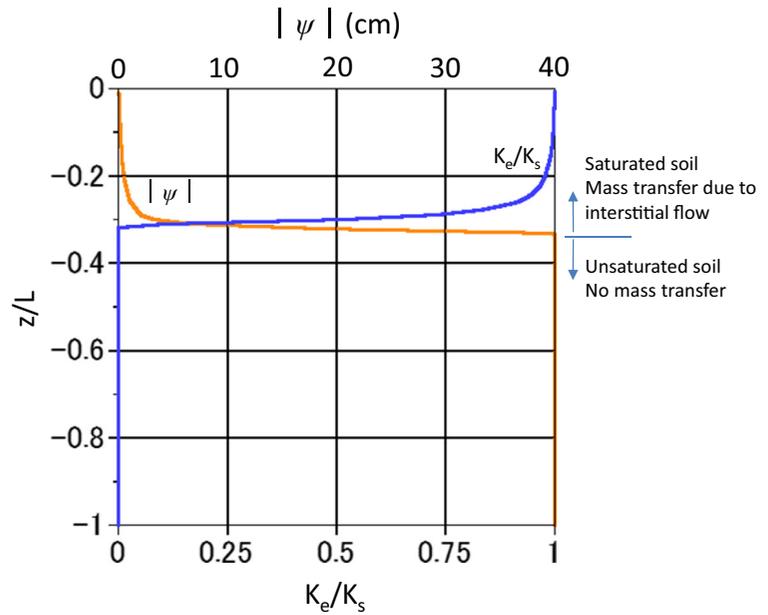
Fig. 4 Simulated salt concentration (C/C_0) in the effluent water during rinsing of the soil column with freshwater (blue line). Dimensionless time $t^+ = t K_s/L$. Experimental data are also shown (red squares)

move through the soil while draining toward field capacity. The dry time, t_{dry} , is the time required for the effective hydraulic conductivity (K_e) to reduce to less than 10% of saturation (K_s) due to progressive drainage of the soil column as shown in Fig. 10. As expected, t_{dry} increases with lower K_s and larger soil depth (L). For $K_s > 0.01$ cm/s, t_{dry} is less than 5 h for soil depths (L) less than 3 m. This suggests that this soil (uniform sand) drains quickly to field capacity after water infiltration has ceased and this applies to both rainwater and snow-melt (saline) water.

Table 2 Residual salt in the pore water of the soil column after the experiments

Experiment series (run)	Volume of pore water (mL)	Electrical conductance (mS/cm)	Salt concentration in pore water (g/L)	Salt mass in pore water (g)
1	570	0.076	0.043	0.075
2	275	0.522	0.331	1.21
3	1322	0.036	0.023	0.017

Fig. 5 Profile of the pressure head $|\psi|$ (absolute value) and effective hydraulic conductivity (K_e) in the soil column at normalized time $t^+ = t K_s/L = 0.10$



5.3 Removal of Salt from Soils

When the soil is unsaturated at field capacity, pore water flow is absent (Fig. 3), and saline water stays in the pores of the soil. The soil becomes permeable to pore water flow when it is saturated above field capacity. Assuming pore water flow is present with a hydraulic

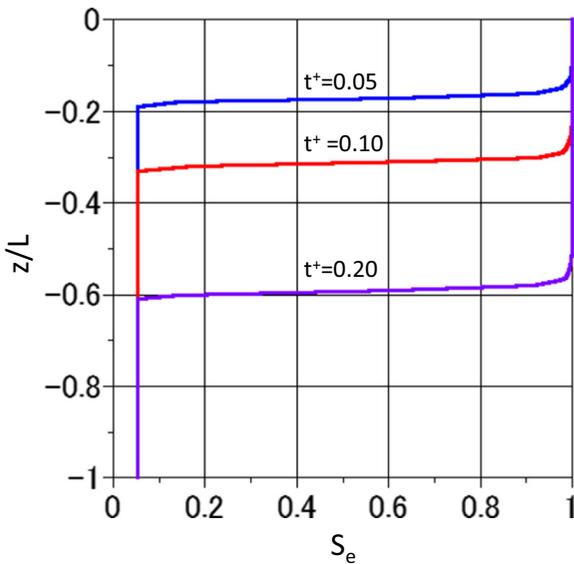


Fig. 6 Simulated effective water saturation (S_e) profiles in the soil column during infiltration at three normalized times $t^+ = t K_s/L$. (z) = depth, (L) = column height. Onset of infiltration is at time $t^+ = 0$ and initial effective saturation of the soil $S_e = 5\%$

gradient of $d(p/\rho g + z)/dz = -1$, transfer of salt mass in the soil can be simulated by Eq. (6).

The time required for a soil column at field capacity to become saturated with water (t_s) is illustrated in Fig. 11 as a function of K_s for $L = 1, 2$, and 5 m. Characterizing the salt transport during infiltration of freshwater, t_r is the time required to reduce the total amount (concentration) of salt in an unsaturated soil, initially saturated with saline water, to less than 1% of its initial concentration by the process of rainwater infiltration. Figure 12 shows the dependence of t_r on saturated hydraulic conductivity (K_s) for soil depths $L = 1, 2$,

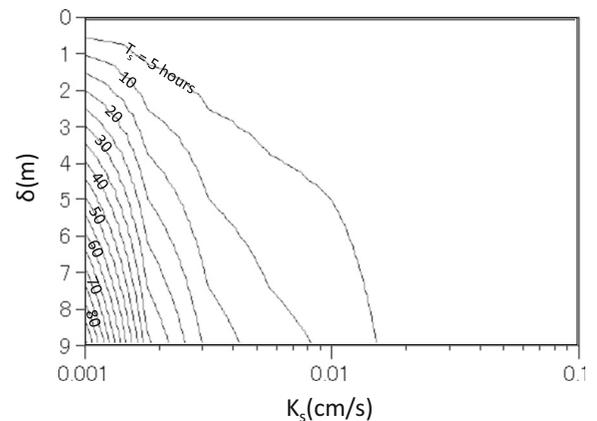


Fig. 7 Dependence of time to reach saturation (t_s) on the saturated zone penetration depth (δ) and hydraulic conductivity at saturation (K_s). Initial effective water saturation $S_e = 5\%$

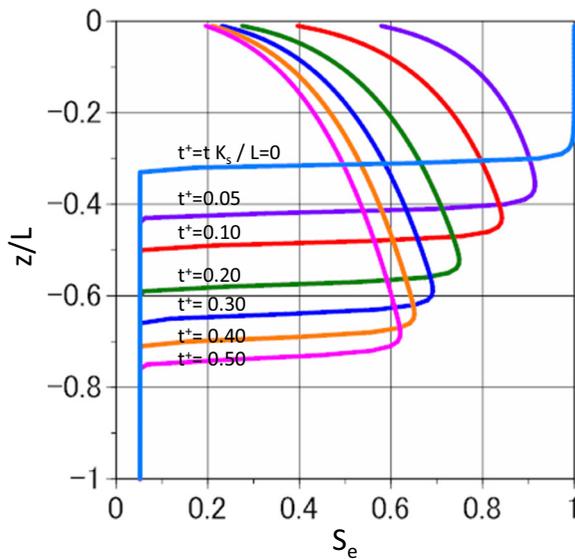


Fig. 8 Effective water saturation profiles (S_e) as a function of normalized depth in the soil column (z/L) that is draining by gravity. Normalized time ($t^+ = t K_s / L$) is shown for each profile. Rainwater has stopped to infiltrate into the soil column at time $t^+ = 0$

and 5 m. The time t_r increases as soil depth increases and as saturated hydraulic conductivity decreases. Comparing Figs. 11 to 12, it is evident that t_r is significantly longer than t_s for all values of L and K_s , demonstrating

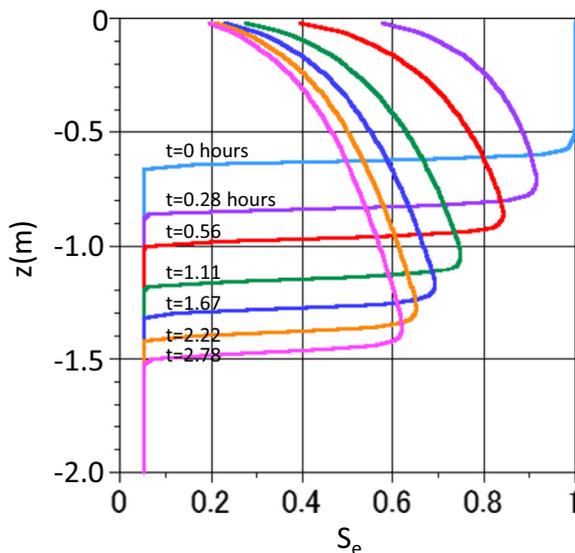


Fig. 9 Example of simulated effective water saturation profiles (S_e) as a function of depth in the soil column (z) when a saturated sandy soil column drains by gravity. Hydraulic conductivity at saturation $K_s = 0.1$ cm/s and height of the soil column $L = 2$ m

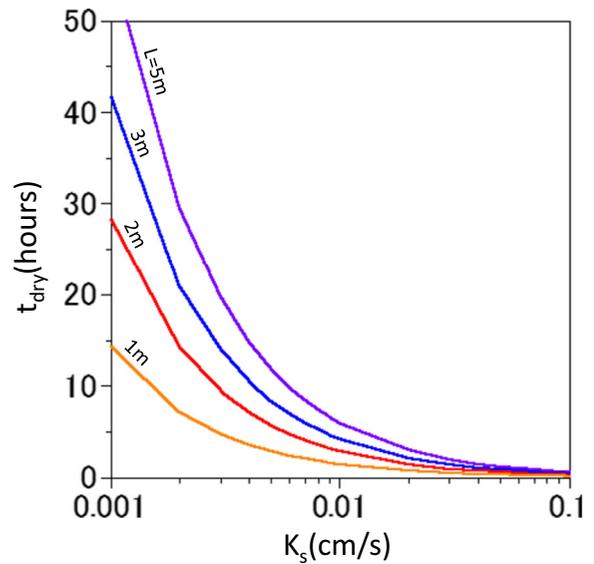


Fig. 10 Dependence of simulated draining time (t_{dry}) of a saturated soil column on hydraulic conductivity at saturation (K_s) for soil columns of height $L = 1, 2, 3,$ and 5 m

that the release of salt from soil requires more time than simply saturating the soil.

The total time required (t_{total}) to rinse saline water from a soil consists of the time required to saturate the soil (t_s) and the time required to reduce the saline water concentration by 99% (t_r) with infiltrated freshwater ($t_{total} = t_s + t_r$). This total time (t_{total}) is given in Fig. 13 as a function of the soil depth (L) and hydraulic conductivity at saturation (K_s). As to be expected, t_{total} increases as the soil depth increases and hydraulic conductivity at saturation decreases (Fig. 13). Because $t_r > t_s$, t_{total} is mostly dependent on t_r .

6 Implications of Salt Transport Through Soils

6.1 Significance of Total Amount and Duration of Precipitation for the Removal of Road Salt from Sandy Soil

Melt water from road salt carries salt onto and into nearby soils. Soils near roadways in cold climate regions are often saline after winter. Spring and summer rainfall and the associated surface runoff composed of freshwater begin to rinse the accumulated salt from the soil into nearby surface waters by interflow or to shallow aquifers. The freshwater infiltration required to completely

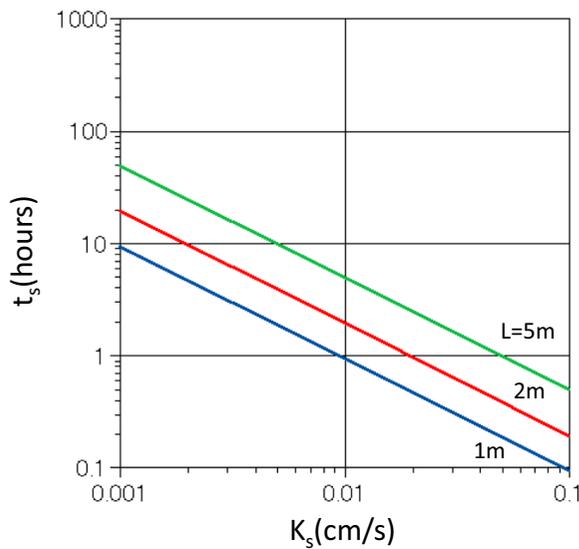


Fig. 11 Simulated time required (t_s) to fill soil columns of height $L = 1, 2,$ and 5 m with salt or freshwater from field capacity to saturation as a function of hydraulic conductivity at saturation (K_s)

rinse salt from the soil is a function of the soil porosity and soil depth. Results presented here are for a soil composed of fine and uniform sand that will be different from natural soils. Though important, evaporation from the surface of the soil or evapotranspiration by plants from the soil was not considered. In addition, the roles

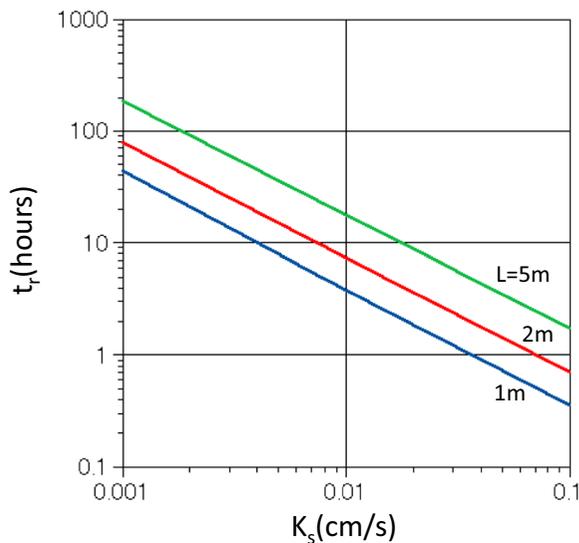


Fig. 12 Simulated time required (t_r) to reduce salt concentration by 99% of saline water by freshwater rinsing in soil columns of height $L = 1, 2,$ and 5 m, and at saturation ($S_e = 100\%$) before rinsing as a function of hydraulic conductivity at saturation (K_s)

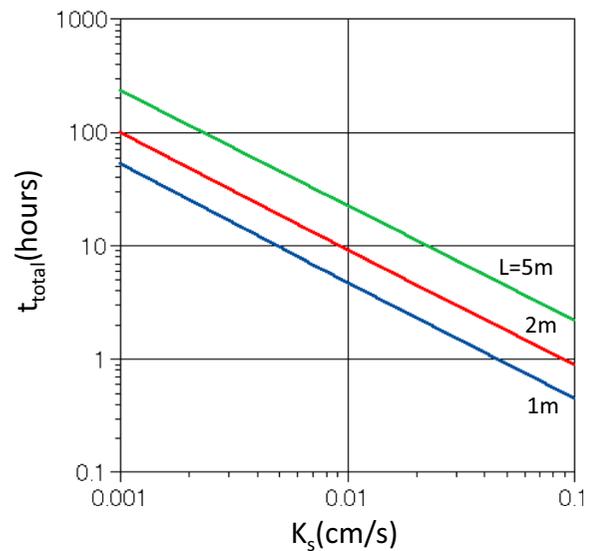


Fig. 13 Simulated total time required ($t_{total} = t_s + t_r$) to reduce salt concentration by 99% of saline water by freshwater rinsing in soil columns of height $L = 1, 2,$ and 5 m, and at field capacity before rinsing as a function of hydraulic conductivity at saturation (K_s)

of microbial communities, organic matter, and variable particle sizes need further study.

Based on the experimental results with a sandy soil column, one rinse with one pore volume of pure water can be enough to remove most of the salt from the pores of the sandy soil, but two pore volumes reduce the effluent concentration to less than 1% of the original concentration. Simulating the flow through a soil with porosity of 0.35 (a typical porosity for sandy soils can be from 0.3 to 0.4) and a soil depth of 2 m, a freshwater infiltration of 700 mm is required to rinse 99% of the road salt (NaCl) from the soil; 700 mm is about equal to the annual precipitation in the metropolitan area of Minneapolis/St. Paul, Minnesota, including snowfall. This suggests that the rinsing of soils will depend not only on the summer precipitation but also on contributions of lateral runoff. Saline water from road salt applications during winter in a soil of 2 m depth may or may not be removed in only one summer season. Some salt could remain in this soil until the next winter when road salt applications begin again.

The order of magnitude of these results is consistent with the results by Novotny et al. (2009b), that about 70% of road salt applied annually in the Twin Cities area watershed is not carried away by surface runoff to the Mississippi River but remains in the Twin Cities area watershed. It is also consistent with the field

observations of Bischoff et al. (2006) of high salt concentrations in Shingle Creek in summer and delayed release of salt due to rainwater infiltration through thick layers of soil, potentially with low saturated hydraulic conductivities.

6.2 Required Duration of Rainfall Infiltration to Remove Salt from Soils

The simulation results show that a sandy soil needs to be saturated in order to release saline water effectively. Natural soils, however, are often unsaturated soils. According to Fig. 13, about 2.5, 25, and 250 h are needed to rinse saline water from a sandy soil of 5 m depth for the hydraulic conductivity at saturation $K_s = 0.1$, 0.01, and 0.001 cm/s, respectively. An unsaturated soil with $K_s = 0.001$ cm/s requires 10 days of continuous infiltration to remove most of the saline water. An unsaturated soil with $K_s = 0.01$ cm/s, porosity of 0.3, and depth of 5 m requires 1500 mm of annual precipitation and a 1-day duration of rainfall to rinse saline water from the soil. This wide range of requirements demonstrates that both the total amount of freshwater available for infiltration from precipitation and also the duration of rainfall are important for salt release from a sandy soil.

6.3 Reappearance of Salt by Interflow into Surface Waters or Seepage to Shallow Groundwater

Saline water that is rinsed from a soil by freshwater infiltrating from the surface has two potential pathways: one is to reappear in the surface water drainage system from interflow, and the other is to percolate deeper into the ground and become part of an aquifer. The field observations of Bischoff et al. (2006) of high salt concentrations in Shingle Creek in summer are an example of the reappearance of salt that is carried by interflow through shallow groundwater back to nearby surface water.

7 Conclusions

Hydrodynamic transport processes that move chloride from road salt applications through the pores of a sandy soil column toward shallow groundwater were investigated by exploratory laboratory experiments and numerical simulation. Richards' equation for saturated-unsaturated water flow and the advection-dispersion

equation for solute transport were used in the simulations. Simulations and experiments agree that soils must become water saturated, and pore water flow is required to move saline water in the soil toward shallow groundwater. The simulations represent unsaturated and saturated flow phenomena and experimental data adequately.

Electrical conductance measurements in the effluent from PVC columns filled with 300- μ m sand showed that two rinses by infiltration of ultrapure water from above, each of approximately one pore volume, were sufficient to reduce the salt concentration by 99% from an initial concentration of 33,000 mg/L in the effluent from the soil column. Residual salt concentrations measured in the remaining pore water of sandy soil columns confirmed that over 98% of the salt had been removed by freshwater infiltration from rainwater. Simulated time variations of salt concentrations in the effluent from the column agreed well with experimental results.

Implications of this research include the amount and duration of rainfall needed to rinse salt from a sandy soil. The results indicate that, for example, one rainy season in Minneapolis/St. Paul would only rinse salt from a 2-m-deep fine sandy soil profile. Thus, deeper soil profiles would require more freshwater than supplied in 1 year, which explains why significant salt concentrations in small surface water bodies have been observed during summer months, long after winter deicing has ceased. In the long term, salt may accumulate and compound, resulting in a long-term release of salt that could potentially extend many years after road salt is no longer used for deicing.

From the results of this study, saline water is expected to move quickly through uniform granular material larger than 300 μ m with very little, if any, retention. This means that areas with sandy soils can be expected to transport salt from surface water into shallow, and potentially deep, groundwater near roadways quickly and easily. This is a significant concern for shallow and deep aquifers and may result in costly drinking water treatment requirements in the future. The percolation of salt through sediment smaller than 300 μ m, or sediment with significant organic matter content, needs to be investigated in future experiments and simulations.

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