MELTWATER INFILTRATION INTO COMPLETELY-FROZEN SOILS

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Abstract

The process of infiltration into completely-frozen soils, soils whose frozen profile does not thaw to appreciable depth during snowcover ablation, is examined. Infiltration into these soils is largely a function of the air-filled porosity and inversely related to the ice/moisture content of the shallow, 0 - 300 mm soil layer. An infiltration model groups frozen soils into three classes in respect to their infiltration potential, namely: Restricted - relatively impermeable; Limited - infiltration is governed by the snowcover water equivalent; and ice/moisture content of the 0 - 300 mm soil layer at the time of melt and Unlimited - soils containing large macropores. Expressions for calculating infiltration for "Limited" and "Unlimited" (cracked) soils are presented and experimental data are provided which show that surface runoff volumes estimated by the model generally fall within about 15% of those determined from observed hydrographs, independent of snowcover water equivalent and catchment size. The work is based on field data monitored during winter in the central plains region of western Canada.

Introduction

This paper summarizes the results of a comprehensive investigation of the snowmelt infiltration characteristics of "completely-frozen" soils, soils whose frozen profile does not thaw during the period of snowcover ablation, conducted within the prairie region of the Province of Saskatchewan in western Canada. Although the objectives of this study were not directly related the role of snow in "urban hydrology", the findings have application in any cold climate region where snow and frozen soils have a significant impact on the hydrology of the environment.

Throughout a large part of the semi-arid prairie region annual snowfall, which ranges in depth between 90 and 130 mm water equivalent, comprises on average about 30% of the annual precipitation. Excluding large-scale water development projects, snow constitutes the most amenable source of fresh water available for management and meltwater from the shallow snowcovers serves many beneficial purposes as wildlife habitat, as a local supply for domestic and livestock use, and for recharging groundwater supplies. Soil water reserves and lakes. Conversely, snowmelt runoff may lead to serious flooding, soil erosion and drainage problems.

During snowcover ablation on the Prairies the single, most-important factor which has the greatest effect on the apportionment of snow water to direct runoff and soil water are the infiltration properties of the frozen soil. Between 1980 and 1988, observations of snowcover water equivalent, soil temperature and soil moisture changes during snowcover ablation were monitored
in undisturbed, cracked and subsoiled medium and fine-textured soils with surface covers of stubble (harvested grain stalks), fallow (bare ground) and grass. In total, the program included about 230 field sites centred around latitude 51° 44'N and longitude 107° 30'W. Infiltration was calculated from changes in soil density monitored with a twin probe gamma density meter. This measuring system provides non-destructive sampling of the density of a 20-mm thick soil layer between two access tubes (into which a cesium source and a scintillation detector are lowered) spaced about 300-mm C.C. By assuming the mass of the soil in the cube remains constant (no structural changes occur) changes in density of the layer can be attributed to changes in the mass of water confined within the layer. The equivalent moisture change is calculated assuming a density of water equal to 1000 kg/m³. Measurements were made at 20-mm increments of depth to 0.4 m and at 40 mm between 0.4 and 1.6 m. Repeatability tests with the equipment gave a standard error of estimate in moisture content of about ±2.5 mm in a 1-m profile. All systems were tested and calibrated to operate reliably in cold weather (to -20°C).

Density profiles were obtained in the fall prior to freeze-up and during the winter, snowmelt and post-melt periods. up to the time of seeding of annual crops. An attempt was made to obtain measurements at least once every three weeks during the winter and post-melt periods. During snowcover ablation the frequency of observation was increased with the final readings taken immediately following the disappearance of the snowcover.

At several locations soil temperature probes with automatic recorders were installed to provide measurements at depths of 25, 50, 100, 200, 400, 800 and 1600 mm. Daily maximum and minimum air temperatures were also recorded. The temperature data were used to help identify the layers of soil where overwinter moisture changes occurred. periods of midwinter melt and infiltration, the times of freeze-up, snowmelt and thaw, and to establish rates and depths of freezing and thawing.

Results and Discussion

When dealing with a seasonally-frozen soil, the temperature regime (or depth of frost penetration) at the time of snowmelt affects its infiltration properties. If the depth of frost is small, the energy content of the infiltrating meltwater may be sufficient to raise the temperature of the entire frozen layer to 0°C, thus returning the infiltration characteristics of the soil to those of its unfrozen state. Komorov and Makarova (1973) suggest that a soil frozen to a depth of 150 mm or less absorbs meltwater as does an unfrozen soil. and once a soil is frozen to a depth of 600 mm. freezing to greater depth has no further effect on the infiltration of meltwater. Thus it is appropriate to define a "completely-frozen" soil as one that does not thaw during snowcover ablation.

Factors Affecting Infiltration Into Frozen Soils

The major factors influencing snowmelt infiltration into a frozen soil include the hydrophysical and thermal properties of the soil, the soil moisture and temperature regimes, the quantity and rate of release of water from the snowpack, and the energy content of the infiltrating water. In a completely-frozen soil meltwater always infiltrates against a freezing temperature and its ability to penetrate the soil is strongly related to the volume of air-filled
pores (effective porosity). Figure 1 (after Granger et al. 1984) shows the soil temperature at the wetting front plotted against effective porosity and confirms the movement of water against low temperatures in soils with large effective porosities, as reported by Steenhuis et al. (1977). Both Komarov and Makarova (1973) and Steenhuis et al. (1977) suggest however that in frozen soils the effects of soil temperature at the time of melt on infiltration may be secondary to those of effective porosity, which is inversely related to the ice content. They stress that the entry to and movement of water in frozen soils occurs mainly through large non-capillary pores.

An inverse relationship between soil moisture content and infiltration in frozen soils has been postulated by numerous investigators (see Willis et al., 1961; Kuzik and Bezmenov, 1963; Motovilov, 1979; Granger et al., 1984). This relationship is demonstrated in Fig. 2 which shows snowmelt infiltration plotted against the average moisture/ice content of the 0-300 mm layer ($\theta_p$) for completely-frozen, medium and fine-textured soils of the Canadian Prairies. The limit of saturation of the wetted depth ($L$) enveloping the data can be approximated as:

$$L = 0.6 + 0.4 \theta_p$$

in which $L$ and $\theta_p$ are expressed as a degree of pore saturation in mm$^3$/mm$^3$. Thus, the degree of pore saturation that the shallow surface layer of soil reaches during snowcover ablation increases with increasing initial moisture content. These data, combined with the observation that the average depth infiltrating meltwater penetrates into a frozen soil during snowcover ablation is of the order of 260 mm (standard deviation = 100 mm), can be used to demonstrate the low infiltration characteristics of these soils. For example, a "normal" soil with a porosity of 50% at an initial moisture content of 20% by volume (dry to medium wetness) would likely infiltrate on average

Figure 1. Soil temperature immediately below the wetting front plotted against the effective porosity of the wetted zone.

Figure 2. Infiltration plotted against the "premelt" moisture content of the 0-300 mm soil layer of completely-frozen soils.
less than about 47 mm of meltwater ($[0.5(0.6 + 0.4*0.4) - 0.2] * 260 - 46.8$), or the water equivalent of a snowcover having a depth of 18.8 cm and a density of 250 kg/m$^3$.

Enhancement of the meltwater intake properties of completely-frozen soils by macropores is demonstrated in Fig. 3 which shows changes in soil-moisture due to snowmelt infiltration into a heavy lacustrine clay in uncracked and cracked condition. Note. the moisture changes in the soil crack are calculated from measurements taken with the opening located between the source and detector of a twin probe system. Comparing the data it can be observed:

1. Uncracked soil (Fig. 3a): The amount of infiltration is limited. approximately 26 mm of meltwater infiltrated to a depth of 375 mm. The snowcover water equivalent at the site was 78 mm.

2. Soil Crack: The amount of infiltration is substantially greater than into the uncracked soil. The increase in soil moisture in the fracture was 94 mm which is substantially greater than the snowcover water equivalent of 78 mm. This is attributed to interflow in inter-connecting cracks and surface runoff from the undisturbed soil between the fractures entering the opening directly.

Table I compares the findings of the moisture monitoring program in the same soils in uncracked and cracked condition as average amounts of snowmelt infiltration for different ranges of snowcover water equivalent. These data show infiltration into soil cracks increasing with snowcover water equivalent. however the ratio of the amount of infiltration into the opening to the amount infiltrating the uncracked soil varies only slightly with depth of snow water. The ratio-values range from 3.4 to 4.3 with a mean of 3.8.

Analyses of numerous profiles of soil moisture changes due to meltwater infiltration into uncracked and cracked, "completely-frozen" soils have indicated a strong relationship between infiltration (INF) and the depth of penetration of the wetting front (d) (Gray et al., 1986b). The curve enveloping these variables can be approximated as $\text{INF} = 0.2d$, in which INF and d are in mm.

Infiltration Model

In 1972, Popov in a study concerned with long-range forecasting of spring runoff for lowland rivers in the Soviet Union grouped soils of a watershed into two broad classes in accordance with their degree of permeability or ability to absorb water: (a) the capacity type - a soil is impermeable or its permeability is such that the infiltration rate is equal to the rate of snowmelt; and (b) the capacity - infiltration type - the conditions where surface runoff is formed by the excess of the rate of snowmelt over the rate of infiltration. More recently Granger et al. (1984) and Gray et al. (1985) employed a similar
Table I. Average amounts of snowmelt infiltration into uncracked soils and soil cracks for different ranges of snowcover water equivalent (SWE).

<table>
<thead>
<tr>
<th>SWE (mm)</th>
<th>Uncracked (mm)</th>
<th>Crack (mm)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30</td>
<td>12.4 (5)**</td>
<td>49.7 (2)</td>
<td>4.0</td>
</tr>
<tr>
<td>30-50</td>
<td>18.6 (7)</td>
<td>70.7 (2)</td>
<td>3.8</td>
</tr>
<tr>
<td>50-70</td>
<td>23.7 (11)</td>
<td>84.1 (9)</td>
<td>3.5</td>
</tr>
<tr>
<td>70-100</td>
<td>28.0 (23)</td>
<td>95.7 (5)</td>
<td>3.4</td>
</tr>
<tr>
<td>100-150</td>
<td>30.5 (17)</td>
<td>116.6 (9)</td>
<td>3.8</td>
</tr>
<tr>
<td>&gt;150</td>
<td>34.5 (9)</td>
<td>147.0 (4)</td>
<td>4.3</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

* Values for uncracked and cracked soils from all sites within Brown and Dark Brown soil zones of the Province of Saskatchewan in which soil cracking was observed. The major textural groups are clay loam and heavy clay.

** Numbers in parentheses refer to the number of samples.

classification system in the development and testing of a simple physically-based model to describe infiltration into "completely-frozen" soils. The model groups frozen soils into the following classes in respect to their infiltration potential.

Restricted: Infiltration is impeded by an ice lens on the surface or at shallow depth. The amount of meltwater infiltrating the soil is negligible and most of the snow water goes to direct runoff and evaporation. Restricted conditions usually form when:
1. A soil, wetted by "fall" rains, is frozen at a high moisture content.
2. Melt-freeze events during the winter months due to diurnal cycling in temperature result in the formation of an impermeable ice/soil layer at the soil surface.
3. A basal ice layer develops at the bottom of the snow cover during ablation due to heat flow into the ground.

Limited: Infiltration is governed primarily by the snowcover water equivalent and the frozen water content of the 0-300 mm soil layer.

Unlimited: Soils containing a high percentage of large, air-filled macropores which are capable of infiltrating most or all of the meltwater. In nature the most common macropores are the cracks which develop in colloidal soils in response to evaporation demands.

Figure 4 is a plot of infiltration against snowwater equivalent in which the three categories are demonstrated. The 1:1 line represents the "Unlimited" situation where all the snow water infiltrates. Because the data are point measurements, infiltration can exceed measured snow water due to overland flow.
to and interflow within the soil fractures. The data points on and near the abscissa, which represent the "Restricted" case, show that even with relatively large amounts of snow water, infiltration is negligible. The family of curves represent different initial "premelt" moisture conditions for soils in the "Limited" category. These curves are described by the following relationship between snowmelt infiltration (INF), snow-cover water equivalent (SWE) and the premelt moisture content ($\theta_p$) given by Gray et al. (1985):

$$\text{INF} = 5(1-\theta_p)\text{SWE}^{0.584} \quad [1]$$

in which INF and SWE are in mm and $\theta_p$ is the degree of pore saturation, $\text{mm}^3/\text{mm}^3$. Equation 1 is based on the findings of Granger et al. (1984) and measurements from 130 sites in different textured soils under various land uses (fallow, stubble and grass). It has a correlation coefficient of 0.85 and a standard error of the estimate of 5.5 mm.

Using the information in Table I an analogous expression for infiltration into a soil crack can be developed as:

$$\text{INFC} = 8.48\text{SWE}^{0.553}.$$  \quad [2]

where INFC is the amount of infiltration per unit length of crack into a 300-mm wide column of soil in which the crack is centred (mm) and SWE is the snowcover water equivalent (mm). Field measurements of the surface features of cracks in heavy lacustrine clays showed a mean length:area ratio of 1.75 mm/m$^2$. Using this information with Eqs. 1 and 2 leads to an average "areal" infiltration into a "cracked" field as:

$$\text{INFC} = 4.53\text{SWE}^{0.553} + 2.33[(1 - \theta_p)\text{SWE}^{0.584}].$$  \quad [3]

The accuracy of Eq. 3 will change as the length:area ratio for cracks varies from the value of 1.75 mm/m$^2$ and the geometry of the soil cracks differ appreciably from those in which the measurements were obtained.

Model Verification

**Water Balance:** The performance of the infiltration model in predicting snowmelt runoff has been tested by comparing runoff volumes, calculated as the difference between snowcover water equivalent and infiltration estimated by the model (SWE - INF), against the volumes of observed streamflow from land areas ranging from 35 m$^2$ to 11.4 km$^2$ in size (Gray et al. 1985: 1986). For the smaller areas, the volumes calculated by the two methods were associated with a correlation coefficient of 0.73 and a standard error of estimate of 7.2 mm. The size of the catchment appeared to have little effect on the association.
Table II summarizes the results of the comparison on a 11.4 km² watershed. Certain features of the data and physical characteristics of the watershed validate the comparison: (a) comprehensive snow surveys employing stratified sampling procedures were conducted on the watershed to establish the snowcover water equivalent; (b) "neutron" measurements of "fall" soil moisture were available from 23 sites; (c) streamflow was carefully monitored and (d) the watershed is well-drained with very small elements of depressional storage.

The two winters, 1973/74 and 1974/75, had contrasting snowcover and "premelt" soil moisture conditions. The winter of 1973/74 was a year of near-record snowfall which produced an average snowcover water equivalent of 143 mm on the watershed. It was preceded by a warm, dry fall and the average moisture content of the 0 - 300 mm soil layer in fields cropped during the summer was of the order of 15% by volume. Fields in fallow and grass were classified as having "Limited" infiltration potential whereas those in cereal grains were designated as "Unlimited". In 1974/75, winter conditions were close to "normal". The average depth and water equivalent of the snowcover were 299 mm and 71 mm respectively, and the average "fall" soil moisture content was 27.4% by volume. All land units within the watershed were classified as having "Limited" infiltration potential.

Table II shows differences between the snowmelt runoff volume estimated from the snowcover water equivalent and the infiltration model (SWE - INF) and the observed runoff of 6.5 mm in 1973/74 and 5.8 mm in 1974/75, which represent an average overestimate in the observed value of 16%. Given that evaporation and storage losses and measurement errors have not been considered in the calculation it is believed that the agreement is reasonable.

Table II. Comparison of volumes of snowmelt runoff calculated by the infiltration model with those obtained from recorded hydrographs monitored on a 11.9 km² watershed in western Saskatchewan.

<table>
<thead>
<tr>
<th>Winter</th>
<th>Land use</th>
<th>Area (km²)</th>
<th>SWE (mm)</th>
<th>Infiltration Class</th>
<th>q_p (mm)</th>
<th>INF (mm)</th>
<th>Runoff (mm)</th>
<th>Residual (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973/74</td>
<td>Fallow</td>
<td>4.67</td>
<td>54.2</td>
<td>Limited</td>
<td>0.31</td>
<td>24.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stubble</td>
<td>5.04</td>
<td>65.4</td>
<td>Unlimited</td>
<td>0.25</td>
<td>59.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grass</td>
<td>1.68</td>
<td>23.6</td>
<td>Limited</td>
<td>0.25</td>
<td>10.6</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>143.2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94.5</td>
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<td>42.2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.5</td>
</tr>
<tr>
<td>1974/75</td>
<td>Fallow</td>
<td>3.58</td>
<td>23.0</td>
<td>Limited</td>
<td>0.46</td>
<td>8.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stubble</td>
<td>5.04</td>
<td>30.9</td>
<td>Limited</td>
<td>0.25</td>
<td>14.8</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Grass</td>
<td>1.68</td>
<td>16.6</td>
<td>Limited</td>
<td>0.25</td>
<td>6.5</td>
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<td>70.5</td>
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<td>34.5</td>
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<td></td>
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<td>5.8</td>
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</table>

Hydrograph Simulation: Gray et al (1985; 1986) have described procedures for implementing the infiltration model into large operational streamflow forecasting systems. On "Restricted" soils snowcover runoff begins at the start of melt: for "Limited" soils the time of snowcover runoff is established by a snowmelt infiltration index equal to the infiltration potential from Eq. 1.
divided by six days. When the flux of meltwater exceeds the infiltration index, infiltration is calculated by multiplying the flux by the ratio of the infiltration potential to the snowcover water equivalent remaining at that time. Figure 5 shows the effects of the infiltration model on the performance of the U.S. National Weather Service River Forecasting System, NWSRFS (U.S. Dept. of Commerce, 1972; Anderson, 1973; Peck, 1976) and the U.S. Army Corps of Engineers Streamflow Simulation and Reservoir Regulation Model, SSARR (U.S. Corps of Engineers, 1972) in simulating snowmelt runoff from a 296 km² watershed in western Saskatchewan. The improved simulation with the modified systems over that obtained with the original systems is apparent in the closer agreement between simulated and observed hydrographs. Regarding the very small volume of runoff computed by the NWSRFS (2.6 mm compared to an observed volume of 64.1 mm), the efficiency of this model can be significantly improved by adjusting the soil moisture accounting routine so as to reduce the Upper Zone soil moisture storage capacity and by setting the Lower Zone percolation rate to a very small value. On average over five years of record the infiltration model reduced the error in the runoff volume estimated by SSARR by a factor of 2 from 34% to 15% of the observed.

![Figure 5. Effects of the infiltration model on the performance of NWSRFS and SSARR models in simulating the snowmelt runoff hydrograph from a 296 km² watershed in western Canada.](image-url)

Summary

During snowmelt, the process of infiltration into frozen soils often dominates the apportionment of snow water between direct runoff and soil water recharge in cold climate environments. This paper examines the process in completely-frozen soils, soils whose frozen profile does not thaw to appreciable depth during the period of snowcover ablation. The findings presented are based on field data monitored during winter in the central plains region of western Saskatchewan.
It is demonstrated that snowmelt infiltration into completely-frozen, medium and fine-textured soils is directly related to the air-filled porosity and inversely related to the ice/moisture content of the shallow, 0 - 300 mm soil layer. Large macropores such as soil cracks which have the capacity of absorbing large amounts of meltwater, increase the soil intake properties of frozen soils appreciably. Data are provided which show that the average amount of infiltration into a 300-mm wide column of frozen soil containing a natural crack is approximately 3.8 times that to the same soil in an uncracked condition.

An infiltration model is presented which groups completely-frozen soils into three classes in respect to their infiltration potential, namely: Restricted - relatively impermeable; Limited - infiltration is governed by the snowcover water equivalent and ice/moisture content of the 0 - 300 mm soil layer at the time of melt; and Unlimited - soils with large macropores which are capable of infiltrating large amounts of meltwater. Expressions for calculating infiltration into "Limited" and "Unlimited" (cracked) soils are given.

The performance of the model for predicting snowmelt runoff is assessed by comparing "modelled" runoff with observed streamflow. It is demonstrated that the runoff volumes estimated by the infiltration model are usually within about 15% of those obtained from observed hydrographs, independent of snowcover water equivalent and catchment size.

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