Snow, soil frost and land cover relationships on the Oak Ridges Moraine, southern Ontario: implications for topographically-focused groundwater recharge.

W. J. GREENWOOD¹ AND J. M. BUTTLE²

THE OAK RIDGES MORaine (ORM) IS A KEY HYDROGEOLOGIC FEATURE IN SOUTHERN ONTARIO. PREVIOUS RESEARCH EMPHASIZED THE IMPORTANCE OF THE TIMING AND LOCATION OF WATER RECHARGE FOR GROUNDWATER MOVEMENT WITHIN THE ORM’S AQUIFERS, AND HAS SUGGESTED THAT SPATIALLY-FOCUSED RECHARGE OCCURS IN CLOSED TOPOGRAPHIC DEPRESSIONS ON THE ORM. HOWEVER, THE SIGNIFICANCE OF TOPOGRAPHICALLY-FOCUSED RECHARGE HAS NOT BEEN EMPIRICALLY DEMONSTRATED, AND THE PERMEABLE SURFICIAL DEPOSITS MANTLING MUCH OF THE ORM IMPLY THAT RAINFALL AND SNOWMELT WILL LARGELY RECHARGE VERTICALLY RATHER THAN MOVE LATERALLY DOWNSLOPE INTO TOPOGRAPHIC DEPRESSIONS. THE EXCEPTION TO THIS CONCEPTUAL MODEL MAY OCCUR DURING WINTER AND SPRING, WHEN DEVELOPMENT OF CONCRETE SOIL FROST ENCOURAGES LATERAL WATER FLUXES INTO DEPRESSIONS. THE POTENTIAL FOR THIS PROCESS WAS EXAMINED FOR CLOSED DEPRESSIONS UNDER FOREST AND AGRICULTURAL LAND COVER WITH SIMILAR SOIL AND SURFICIAL GEOLOGY CONDITIONS. AIR TEMPERATURES, PRECIPITATION, SNOW DEPTH AND WATER EQUIVALENT, SOIL WATER CONTENTS AND SOIL FREEZING (USING THERMOCOUPLE ARRAYS AND FROST TUBES) WERE MONITORED DURING THE 2012-13 WINTER AND SPRING. PRELIMINARY RESULTS SHOW THAT WHILE BOTH AGRICULTURAL AND FOREST LAND COVERS EXPERIENCED SOIL FREEZING, CONCRETE FROST DID NOT DEVELOP UNDER FOREST COVER DUE TO LOWER SOIL WATER CONTENTS. CONVERSELY, CONCRETE FROST OCCURRED FREQUENTLY DURING WINTER AND SPRING IN AGRICULTURAL FIELDS DUE TO THEIR WETTER SOILS PRIOR TO FREEZE-UP, LEADING TO WATER PONDING IN TOPOGRAPHIC DEPRESSIONS DURING RAIN-ON-SNOW AND SNOWMELT. PONDS DRAINED WITHIN A FEW DAYS OF FORMATION, IMPLYING THAT EPISODIC AND SPATIALLY-FOCUSED GROUNDWATER RECHARGE IS A SIGNIFICANT HYDROLOGIC PROCESS DURING WINTER AND SPRING UNDER AGRICULTURAL LAND COVER ON THE ORM.

Keywords: Groundwater recharge, soil freezing, soil water content, concrete frost, topographic depressions, snow cover, Oak Ridges Moraine, land cover.

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INTRODUCTION

The Oak Ridges Moraine (ORM) is a key hydrogeologic feature in southern Ontario, its aquifer systems supplying potable water to some of the more than 6 million Canadians living in the region, as well as important aquatic ecosystem services via groundwater discharge to the numerous streams draining the moraine (Gerber and Howard, 2002). Previous research has emphasized the importance of the timing and location of water recharge for groundwater movement within the ORM’s aquifers, and has suggested that spatially-focused recharge occurs in closed topographic depressions on the ORM (Bates and Metcalfe, 2006). However, the significance of topographically-focused recharge has not been empirically demonstrated, and the permeable surficial deposits mantling much of the moraine imply that rainfall and snowmelt will largely recharge vertically rather than move laterally downslope into topographic depressions. Recent work in the area of the Ganaraska Forest, a plantation forest occupying a portion of the ORM crest, has shown that the near-surface infiltration capacities of compacted agricultural soils exceed the most intense rainfalls for the region, suggesting that overland flow is not likely for this area (Greenwood and Buttle, in press).

An exception to this conceptual model may occur during Winter and Spring, when development of soil frost encourages overland flow of water inputs by limiting infiltration. Several workers have observed this phenomenon in the cold prairie region of Canada (Hayashi et al., 2003; Berthold et al., 2004) and the northern United States (Hubbard and Linder, 1986; Delin et al., 2000). Hayashi et al. (2003) observed ponding of snowmelt water in enclosed topographic depressions in an active agricultural field after the already-low conductivity of its clay-rich till soils was significantly reduced by the development of soil frost throughout the Winter. Soil thawing and subsequent pond drainage resulted in a greater recharge rate directly below the depressions compared to that in the surrounding area. Delin et al. (2000) found the same process to be important in two topographic depressions in a central Minnesota cornfield, where recharge below depressions was approximately 60% greater than that in upland areas. This focusing of recharge was largely attributed to overland flow during Spring melt, showing the importance of this process for soils of similar texture to those on the ORM.

Despite the fact that such frost-induced, topographically-focused recharge is well documented, the phenomenon has only been observed in open areas with agricultural land use and not in areas under forest cover. This may be due to the general differences in microclimate and hydrology that exist between open and forested areas. All things being equal, open areas tend to develop soil frost more extensively than forested areas due to greater night-time radiative cooling (Shanley and Chalmers, 1999). Furthermore, soils in open areas are typically wetter prior to freezing and are therefore more likely to develop concrete frost, which is partially saturated soil that freezes so that pores are filled with ice (Fahey and Lang, 1975; Hardy et al., 2001). Concrete frost has a very low permeability and greatly reduces infiltration, promoting overland flow (Granger et al., 1984; Johnsson and Lundin, 1991; Hardy et al., 2001). Zhao and Gray (1999) reported that many researchers have shown Spring infiltration rates to be inversely proportional to the soil moisture content prior to freezing.

The potential land cover dependence of the focused groundwater recharge (FGR) phenomenon suggested by previous work may be an important consideration for groundwater modeling efforts on the ORM, which have based recharge estimates on surficial geology while treating the hydrologic role of land cover at relatively coarse spatial scales. The purpose of this study is to elucidate the roles of topography and land cover in promoting FGR along the ORM by testing the following hypotheses:

1. FGR will not occur in closed topographic depressions in forested landscapes, but may occur in depressions in non-forested areas along the ORM.

2. The potential for FGR in non-forested depressions results from the development of concrete frost in open soils and surface runoff during snowmelt.
STUDY AREA AND METHODS

Study area
The study was conducted in and around the Ganaraska Forest (GF; 44°5’N, 78°30’W), the largest block of continuous forest (44.5 km²) in southern Ontario. The GF is located on the crest and flanks of the ORM and consists of mainly red pine (Pinus resinosa Ait.) plantations of various ages with open agricultural fields and pastures along its boundary. This combination of land covers and surficial geology facilitates comparison of the potential for FGR between open and forested land covers on permeable ORM deposits. The ORM is an interlobate kame moraine that was deposited in patches from meltwater flowing in contact with moving or decaying glacier ice (Natural Resources Canada, 2002). Maximum elevation in the GF is 384 m.a.s.l., 309 m above that of Lake Ontario to the south. The moraine consists of sand and gravel hills and high ridges comprising a complex interlaying of gravels, sands, silts, clays, and minor diamictons (unsorted sand and/or coarser particles dispersed through a mud matrix – Allaby and Allaby, 2003) up to 150 m thick, underlain by a stony sandy silt to silty sand diamicton (Barnett et al., 1998). Hydraulic conductivities of moraine crest deposits range from $10^{-6}$ to $10^{-3}$ m s$^{-1}$ (Gerber and Howard, 2002), with conductivities of $\sim 10^{-4}$ and $\sim 10^{-3}$ m s$^{-1}$ in agricultural fields and forest stands, respectively (Greenwood and Buttle, in press).

The region has a humid, mid-latitude climate (Köppen Dfb), and mean annual precipitation in the GF ranges from ~950 mm on its western edge to ~825 mm on its eastern edge (Ganaraska Region Conservation Authority, 2008), ~20% of which falls as snow. Annual evapotranspiration is ~530 mm (Brown et al., 1968). There is no marked seasonality in precipitation (Buttle, 2011), and mean daily temperatures in January and July are -7.2°C and 20.5°C, respectively. Dominant soils in the GF are brunisolic grey brown luvisols (Soil Classification Working Group, 1998; Food and Agriculture Organization (FAO) equivalent: arenosol) belonging to either the Pontypool sand or Pontypool gravelly sand series, with sandy and sandy loam textures.

Figure 1: Extent of the outcrop of the Oak Ridges Moraine in southern Ontario and the locations of the four instrumented topographic depressions.
Site selection

Four enclosed topographic depressions, two under forest cover and two in non-forested areas, were selected for study (Figure 1). Candidate depressions were identified using the Ontario provincial 10-m resolution digital elevation model (DEM), field reconnaissance, and consultation with land owners. Soil survey maps were used to confine suitable sites to the same soil series (Pontypool sand or Pontypool gravelly sand - Webber et al., 1946) in order to ensure that depressions were located on permeable moraine sediments and that inter-site differences in soil texture were controlled for as much as possible.

The two open sites (OPEN2 and OPEN5) were under active agricultural use at the time of the study, OPEN2 as pasture for cattle and OPEN5 for growing potatoes. MHW was in a private woodlot consisting of mixed hardwood species, including sugar maple (Acer saccharum Marsh.), red oak (Quercus rubra L.), and white birch (Betula papyrifera Marsh.), along with eastern white pine (Pinus strobes L.). RP was a 50 year old red pine stand in the GF managed by the Ganaraska Region Conservation Authority.

The four sites were within ~10 km of one another, there were no notable differences in aspect, and the range of elevation between sites was less than 50 m, which suggests that differences in climate were minimized. Depressions were 6100 to 22200 m² in contributing area and varied considerably in terms of depth, with the two open depressions exhibiting much more subdued topography relative to those under forest cover (Table 1).

### Table 1. Study depression characteristics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation (m.a.s.l.)</th>
<th>Contributing area (m²)</th>
<th>Maximum depth (m)</th>
<th>Land cover/use</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN2</td>
<td>44°05’22” N 78°33’44” W</td>
<td>352</td>
<td>22200</td>
<td>6</td>
</tr>
<tr>
<td>OPEN5</td>
<td>44°06’09” N 78°33’08” W</td>
<td>330</td>
<td>15400</td>
<td>4</td>
</tr>
<tr>
<td>MHW</td>
<td>44°07’12” N 78°36’41” W</td>
<td>332</td>
<td>14500</td>
<td>22</td>
</tr>
<tr>
<td>RP</td>
<td>44°04’32” N 78°28’57” W</td>
<td>305</td>
<td>6100</td>
<td>12</td>
</tr>
</tbody>
</table>

Methods

Air temperature and precipitation (rain and snow) were measured during the 2012-13 Winter at a Meteorological Service of Canada (MSC) station at Tapley (44°10’14”N, 78°30’05”W), approximately 8 km northeast of OPEN5. All study depressions were located within ~10 km of this station; therefore, its records were assumed to represent meteorological conditions at each site. Regular surveys of snow depth and snow water equivalent (SWE) were conducted at each depression from snowpack initiation to the end of snowmelt. Surveys were conducted using a MSC snow sampler and employed a snow course of 20 points at each depression. Vertical profiles soil water content (SWC; PR2 profile probe) were measured regularly at 0.1, 0.2, 0.3, 0.4, 0.6, and 1.0 m depths throughout the Winter and Spring at the crest and base of each depression. At one depression in each land cover type (OPEN2 and RP) these data were supplemented by continuous measurements of the SWC profile (CS625 water content reflectometers) at 0.1, 0.3, 0.6, and 1.0 m depths. Depth of frozen soil (temperature ≤ 0°C) was also monitored at the crest and base of each depression using CRREL-Gandahl frost tubes (Ricard et al., 1976), which are an inexpensive means of obtaining the position of a soil’s freezing front (Vermette and Kanack, 2012). Frost tube data at OPEN2 and RP were supplemented by vertical profiles of soil temperature measured continuously using thermocouple arrays with measurements at 0.1, 0.3, 0.6, and 1.0 m depths.

Ponded conditions occurring in study depressions throughout the Spring and Winter were assessed using visual observation and manual measurements of pond depth taken at the base of each depression.
RESULTS AND DISCUSSION

Meteorological conditions
The first three weeks of December were relatively mild and wet, with daily average temperatures hovering around 0°C (ranging between -7 and 10°C) and rainfall on 11 of 21 days (Figures 2 and 3). Temperatures began to drop below 0°C consistently in the last week of December and remained so into the first week of January, reaching as low as -11°C. Precipitation shifted from rain to snow during this period, and a snowpack began to accumulate at all four study sites. Weather was highly variable for the remainder of January, consisting of sub-zero temperatures punctuated by short warm (> 0°C) spells. These brought temperatures of up to 7°C and were associated with rain-on-snow (ROS) events. The largest of these occurred on January 30th and consisted of ~15mm of rain falling on snow that had accumulated during the last week of January, which was the coldest portion of the study period (temperatures between -10 and -17°C). Daily mean temperatures in February were almost all below 0°C, with many at or below -10°C. The majority of the study period’s snow accumulation occurred during this month, with ~96 cm of fresh snow (almost twice the combined December and January snowfall of 50 cm). However, this snowfall was not evenly distributed throughout the month, as the majority (~73%) fell during two large events, one on February 8th and the other on February 26/27th. Rising temperatures in March continued into April, when almost all days exceeded 0°C and precipitation shifted back to rain.

Snow and soil frost
Snow cover tended to be greatest at the MHW depression, both in terms of mean depth and SWE. Maximum mean snow depth and SWE at the open depressions were only slightly less than at the MHW site, and exceeded that in the RP depression, which had the lowest peak mean depth and mean SWE of the Winter (Table 1). All sites reached their peak mean depth on February 21, while peak SWE was greatest for open sites and forested sites on March 13 and March 26, respectively. The lesser snow accumulation at the RP depression is likely due to interception of snowfall by the red pine forest canopy and subsequent sublimation. Although the forest cover at MHW may have intercepted some snowfall, the relatively small Winter interception rates associated with hardwood forests (Pomeroy et al., 1998) likely explain why this depression accumulated a snowpack similar to those at the open sites. Furthermore, MHW’s slightly greater snow cover, relative to the open sites, may partly be a result of wind scouring and redistribution of snow from open sites (McKay and Gray, 1981).

Snow cover was lost from all sites by April 16 and snowpack ablation rates appeared to be greater in open sites and MHW. This would be consistent with conditions observed in other studies, which have shown snowmelt rates to be lower at sites with coniferous cover relative to open areas and hardwood forests due to shading from solar radiation at the former (Metcalfe and Buttle, 1998).

<table>
<thead>
<tr>
<th>Depression</th>
<th>Maximum mean depth (cm)</th>
<th>Date of maximum mean depth</th>
<th>Maximum mean SWE (mm)</th>
<th>Date of maximum mean SWE</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN2</td>
<td>28.6</td>
<td>February 21</td>
<td>108.8</td>
<td>March 13</td>
</tr>
<tr>
<td>OPEN5</td>
<td>28.1</td>
<td>February 21</td>
<td>109.2</td>
<td>March 13</td>
</tr>
<tr>
<td>MHW</td>
<td>33.6</td>
<td>February 21</td>
<td>120.5</td>
<td>March 26</td>
</tr>
<tr>
<td>RP</td>
<td>23.9</td>
<td>February 21</td>
<td>81.0</td>
<td>March 26</td>
</tr>
</tbody>
</table>
Figure 2: Results for the OPEN2 depression during the 2012-13 Winter and Spring: (a) precipitation and mean daily air temperature at the Tapley MSC station; (b) mean snow depth and SWE (over the entire depression), interpolated soil temperatures (°C) from the vertical thermocouple array, and the freezing front estimated from the frost tubes (green squares); and (c) interpolated SWC (m³ m⁻³) from the CS625 measurements. The red arrows in (b) indicate when ponding occurred.
Figure 3: Results for the RP depression during the 2012-13 Winter and Spring: (a) precipitation and mean daily air temperature at the Tapley MSC station; (b) mean snow depth and SWE (over the entire depression), interpolated soil temperatures (°C) from the vertical thermocouple array, and the freezing front estimated from the frost tubes (green squares); and (c) interpolated SWC (m$^3$ m$^{-3}$) from the CS625 measurements.
The onset of soil freezing was relatively simultaneous at all sites, although there were differences in soil temperature and depth of penetration of the freezing front throughout the Winter. Frost penetration at the depression base was greatest at OPEN2 despite its thicker snow cover, reaching depths of ~46 cm by mid-February (Figure 2). Frost did not penetrate quite as deep into the soil at OPEN5 and RP, which had peak frost depths in mid-February of about 39 and 36 cm, respectively. It should be noted that the frost tube at the base of the OPEN5 depression was inaccessible during mid-February due to ponding; therefore, the reported frost penetration value is based on the frost tube reading at the depression crest. Soils at MHW developed a peak frost depth roughly half that (~22 cm) of other sites. This may be due, in part, to the larger insulating snowpack at MHW, as soil frost penetration is well known to be inversely correlated to snow depth and SWE (Shanley and Chalmers, 1999; Hardy et al., 2001). Furthermore, MHW is the only site that did not lose its snowpack completely during the warm spells and ROS events in the last half of January. Most frost development at all sites occurred between January 16 and February 6. Complete loss of the insulating snowpack during this time at the other three sites likely allowed more extensive frost development relative to MHW.

Soils thawed completely at the two open sites by April 16, coinciding with the loss of the snowpack. However, frozen soil conditions in the forested sites persisted until April 24, even after the loss of the snowpack. This was likely due to reduced convective fluxes in forest sites combined with shading of the ground surface.

There was good agreement between the position of the 0°C isotherm estimated from the thermocouple array and the position of the freezing front obtained from the CRREL-Gandahl frost tubes at OPEN2 and RP (Figures 2 and 3). The frost tube estimate of the freezing front slightly lagged that given by the thermocouple data by ~4-5 days and slightly under-predicted the depth of frost by up to ~5 cm. This is consistent with the time lag of 2-4 days and the maximum depth lag of 5 cm reported by McCool and Molnau (1984). Nevertheless, the instruments provide a useful, low-cost estimate of soil frost penetration and suggest that estimates of the freezing front at OPEN5 and MHW (where supplementary thermocouple data were not available) are reasonable.

**Soil water contents, ponding, and FGR**

The major difference between open and forested sites was in terms of SWC, with much wetter near-surface soil at the two open sites prior to the onset of soil freezing. Prior to freeze-up, near-surface SWCs (0-30 cm depth) at OPEN2 and OPEN5 were in the range of 0.20-0.30 m³ m⁻³ and 0.25-0.33 m³ m⁻³, respectively, while those at RP and MHW ranged between 0.10-0.20 m³ m⁻³ (Figures 2 and 3). This is likely due to rainfall interception and soil water uptake by the forest cover at the forested sites. After the onset of soil freezing, near-surface SWCs showed a marked decrease at all sites, dropping to between 0.05 and 0.10 m³ m⁻³. These relatively low SWC values persisted throughout the main period of snow cover and frozen soil conditions, and partly reflect the effect of soil freezing on the soil’s dielectric constant and thus the SWC estimated by the PR2 profile probe and the CS625s. These instruments measure liquid water content; therefore, phase change of the soil’s pore water to ice led to a decrease in the SWC reading.

Wetter near-surface soil at the open sites prior to freeze-up led to the development of concrete frost (Hardy et al., 2001). The effect of concrete frost on the infiltrability of the frozen soil was not quantified during this study; however, soil freezing at the open sites resulted in ponded conditions during ROS events in January and at the onset of snowmelt in mid-March. At OPEN2, the first pond formed during ROS on January 30, reaching a depth of ~0.25 m (Figure 2). This pond drained completely by the following day. Ponds with depths of 0.4 and 0.2 m also formed as a result of snowmelt and subsequently drained on March 13 and March 26, respectively.

Ponding at OPEN5 also began during the ROS on January 30, but did not drain as quickly as that at OPEN2. The pond at OPEN5 reached a depth of ~0.38 m and persisted into the first week of February, which saw daily average air temperatures around -10°C and freeze-over of the pond. Rapid drainage of the pond at OPEN2 and more protracted ponding at OPEN5 cannot be explained by differences in soil frost, as both sites exhibited similar near surface SWCs at the time of freezing and almost identical frost depths at the time of ponding. It is possible that differences in soil texture were responsible for the differences in pond infiltration between the two sites, and
assessment of soil properties at the sites is ongoing. Once frozen over, the pond at OPEN5 developed a Winter cover (including a snowpack) that reduced radiative and convective energy inputs that would assist in warming the pond, thawing the underlying soils, and promoting drainage (Hayashi et al., 2003). The pond persisted until the onset of snowmelt, reaching a peak depth of ~0.69 m. The pond at OPEN5 drained by April 16, coinciding with disappearance of the snowpack and complete thawing of the soil.

Pond drainage through the underlying sands and gravels produced FGR under the topographic depressions at the two open sites. This can be seen in the continuous SWC data from the base of the OPEN2 depression, which shows substantial and abrupt increases (from ~0.10 m$^3$ m$^-3$ up to 0.20-0.30 m$^3$ m$^-3$) in SWC throughout the 1 m soil profile coinciding with pond drainage (Figure 2). This reflects thawing of some of the previously frozen soil water in the profile combined with drainage of pond water through the soil.

No ponding was observed at the forested depressions during the study period, suggesting that drier near-surface soils resulted in unimpeded infiltration of water into the ORM sediments. This is consistent with studies of soil freezing in forested areas, which suggest that drier soils will develop “granular frost,” where pore spaces are not completely filled with ice and are still capable of infiltrating and conducting incoming rainfall and snowmelt (Hardy et al., 2001). The difference in infiltrability of frozen soils between forested sites and open sites in this study is exemplified by ponding during ROS and snowmelt in an open pasture directly adjacent to, and approximately 50 m from, the RP site. On one occasion, water flowed from the pond toward the RP depression, but infiltrated within ~10 m of crossing into the forest. This suggests that the role of frozen soil in promoting overland flow and FGR is dependent on land cover, as the RP site and its adjacent pasture likely did not differ in terms of soil texture.

CONCLUSIONS

Preliminary results suggest that while topographically-focused recharge can occur along the crest of the ORM during Winter and Spring, it is restricted to open areas such as agricultural fields that can develop concrete frost at the soil surface. Microclimatic and snow cover conditions in forest stands along the ORM restrict development of concrete frost and lateral transfer of rainfall and meltwater into topographic depressions. Differences in the potential for topographically-focused groundwater recharge between these land cover types have important implications for spatial variability of recharge fluxes and quality of recharging water, and should be considered by groundwater modelling efforts in this region.

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REFERENCES


