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SOIL TEMPERATURE AND FALL FREEZE-THAW EFFECTS ON INFILTRATION AND SOIL MOISTURE MOVEMENT

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Abstract

The quantity of spring snowmelt infiltration and runoff depends on the antecedent soil moisture conditions at the time of soil freezing. Determining the soil moisture status at any particular time during the freezing process requires an understanding of vertical distribution of liquid and frozen water content within the soil profile. This study investigated the effects of soil freezing and thawing during the fall, on early snowmelt infiltration and water movement. Time domain reflectometry with 35-mm mini-probes was used to determine the liquid water content. Total moisture content was determined using the neutron scattering method. The difference between the two measurements allowed the partitioning of soil water into liquid and frozen water content. Comparison between the two methods was made, and an equation was derived to account for the effect of change in soil temperature on the accuracy of TDR measurements. Results showed that as the freezing front progressed downwards, liquid water migrated towards the frozen soil layer from below. A combination of time domain reflectometry and neutron scattering methods could be used to quantify the frozen and unfrozen soil water content within the soil profile as the freezing progress with time.

Keywords: infiltration, soil moisture, soil freezing, TDR mini-probes, soil temperature.

INTRODUCTION

Soil freezing and thawing processes play a major role in the studies of soil water movement in seasonally frozen soils. The quantity and distribution of soil moisture during the fall, when soil begins to freeze, influences the freeze-thaw behavior of the soil during the spring snowmelt (Luo et al. 2002). Understanding the soil moisture distribution during the fall and early winter requires measurement of both the frozen and unfrozen (liquid) parts of the total soil moisture because the soil is partly frozen.

There are various methods for measuring soil moisture. They range from classical methods such as neutron scattering (NS), electrical conductivity, and thermogravimetric; to modern sensor methods such as time domain reflectometry (TDR), frequency domain reflectometry (FDR), water content reflectometer (WCR), and capacitance methods (Seyfried 2001; Warrick 2001; Evett 2000 and 2003a; Evett et al. 2002). Despite the innovations of these methods which are non-destructive with high precision, both the old and the new methods encounter particular problems related to physics of the methods i.e. accuracy and precision of the measurements, coverage and volume of measurements, and varying soil conditions (Warrik 2001; Evett 2000). A study by Seyfried and Murdock (2001) showed that sensitivity of soil water measurement instruments differ with temperature, and the temperature effects also vary with water content and the type of soil. Soil moisture measurements in partly frozen soils in particular pose a challenge to many methods due to the existence of water in both liquid and frozen conditions. Evett (2003b) noted that the decrease in permittivity of water as it freezes hinder accurate measurement of frozen water content in the soil.

The TDR method measures liquid water content in the soil. The measurements involve measuring travel time of electromagnetic wave (EM) along wave guides of known length placed in the soil. The measured travel time is related to the dielectric constant of the medium in which the wave is moving. The dielectric constant K_a is then related to volumetric water content (θ_v), since change in θ is directly related to the change in K_a (Evett 2000). This is attributed to significant difference between the dielectric constant of water and that of other soil materials (K_{water} = 78.5 at 25°C, K_{air} = 1, and K_{soil} = 3 – 7 depending on soil composition and texture), (Warrik 2001; Tardif 2002; Evett 2003b). As the soil freezes, the dielectric constant of frozen water changes significantly from that of unfrozen water. This allows for the unfrozen part of water content to be determined.

The Neutron scattering (NS) technique on the other hand, measures the total (frozen and unfrozen) soil moisture. It uses a radioactive source emitting fast neutrons, and a counter for detecting slow neutrons thermalized by the hydrogen ions in the soil water (Evett 2000, 2003a). The loss in the kinetic energy of the neutrons varies depending on type of soil constituents they collide with. When neutrons collide with hydrogen atom with approximately equal weight, they are slowed to thermal energy level and deflected back to the detector with their kinetic energy reduced significantly and some being absorbed by the hydrogen molecule (Evett 2003a). The concentration of the thermalized neutrons, which relates to the number of hydrogen atoms collided with them, is then related to the total volumetric soil moisture content, since the most contribution of hydrogen in the soil is from water molecules (Evett 2003a). Calibrations are normally performed to account for other sources of hydrogen in the soil other than water, such as humus and organic matter, and other efficient nutrient thermalizers (Carbon, Nitrogen and Oxygen). The relationship between thermalized neutron counts and the volumetric moisture content depends on field calibration for each specific soil.

Studies have been made to describe the potential for the use of TDR and NS in partitioning the total moisture content into frozen and unfrozen water (Baker and Allmaras, 1990; Herkelrath and Delin 1999). However little has been documented on the freeze thaw processes during the fall as the soil starts to freeze. In addition, the accuracy of TDR soil moisture measurements at varying soil temperatures along the soil profile needs more attention. Spaans and Baker (1995) studied the use of TDR in frozen soils and found that calibration of TDR probes using water and soil in the lab does not give accurate results in the field when the soil is frozen. Tardif (2002) suggested temperature correction for soil moisture sensors depending on manufacturers' suggestions. Seyfried (2004) also showed that use of TDR probes calibrated in the lab for field measurements in partly frozen soils affect the measurement accuracy. In this paper a combination of both time domain reflectometry and neutron scattering methods was used to study infiltration and soil moisture movement in a vertical soil profile during the fall of 2005 when the soil started to freeze. Migration of the liquid moisture in relation to the frozen moisture was also explored for various ground cover conditions caused by different cropping systems. Comparison was made between TDR and NS to determine how soil temperature affects the accuracy of TDR soil moisture measurements in partly frozen soils in the field. An equation was derived that could be used to correct the TDR soil moisture measurement at different soil temperature conditions.

MATERIALS AND METHODS

TDR instrumentation

Time domain reflectometry technique was used to measure the liquid water content in a vertical soil profile. The TDR mini-probes used were calibrated in a laboratory experiment at average temperature of 25°C using water and soil columns. The 35 mm-long probes were made using stainless steel rods (3-wire configuration), 1.59 mm diameter placed in a single plane at a spacing of 6 mm centre to centre. The rods were connected to outer conductor coaxial cable type RG–58, 50Ω with different lengths 2.0, 2.5, and 3.0 m depending on the depth of the soil profile (Table 1). Procedures for making the mini-probes were similar to the 20 mm-long TDR probes made by Evett (1994). The same author also describes the advantage of a three-wire compared to a two-wire probe configuration as the narrower range of sensitivity above and below the plane of rods in the three-wire configuration, which gives a better identification of soil moisture variability with depth. The need for impedance matching transformer used in the two-wire configuration is also eliminated due to semi-coaxial nature of the three-wire configuration (Evett 1994).

Field installation

Four experimental plots were selected, each with a different cropping system. The cropping system involved no-till cultivation for oats with Berseem clover cover crop, oats alone, fallow, and prairie grasses. For each treatment, three replicates of sampling points were selected. TDR probes were installed at each sampling point at depths 0.1, 0.2, 0.4, 0.6, and 0.8 m from ground level. The probes were installed at an angle of 60° from the horizontal to minimize preferential flow in the vertical direction. The steel rods of each probe were arranged in the same plane so that each leg would be at the same distance from the ground surface. The angular installation has also been described by Dahan et al. (2003) who described angle installation of flexible TDR probes for deeper soil layers. The installation in that study however involved large diameter holes up to 200 mm, drilled at an angle of 45° from the horizontal.

For each probe location, the corresponding depths in the soil profile and horizontal distances from a vertical line are shown in Table 1.

Table 1. TDR probes on a vertical soil profile and their corresponding depths.

Cable length (m)	Vertical soil depth (mm)	Depth at 60° (mm)	Horizontal dist. (mm)	Total No. of probes
2.0	100	115	58	12
2.5	200	231	115	12
2.5	400	462	231	12
3.0	600	693	346	12
3.0	800	924	462	12
		Total number of probes		60

Table 1 shows the vertical, inclined and horizontal distance of each probe from the ground surface. The maximum vertical depth of soil profile was 0.80 m. Total probes installed were 60, out of which, on 20 probes thermocouple wires were attached (one set in each of the three replicates) for monitoring soil temperature. The temperature was monitored for the five depths of the soil profile similar to depths used for TDR measurements. A digital thermocouple thermometer with a precision of 0.1°C was used for the temperature measurements.

Probes in the field were connected using an extension cable (RG 58 coaxial cable) 17.5 m long, to a Tektronix 1502B metallic cable tester located in a warm cubicle (tractor). Information recorded by the cable tester was then downloaded into a notebook for further analysis. Data from TDR measurements were analysed to determine the quantity of liquid water as the soil continued to freeze.

Measurements using neutron moisture meter (NMM)

Considering neutron scattering method, a profiling neutron moisture meter (NMM, Troxler model 4300 depth moisture gauge) was used to measure the total volumetric moisture content. Measurements were done on the same plots in which TDR probes were installed. The sphere of influence of measurements for the NMM, in which about 98% of the counted thermalized neutrons pass to reach the detector is governed by a radius defined by equation 1 (Troxler 2001):

$$R = 280 - 0.27M \qquad (1)$$

where R is the sphere radius of influence in the soil (mm), and M is the soil moisture content (kg/m^3).

The maximum radius of influence from the centre of access tube is 280 mm when the soil is completely dry. Hence to avoid interference of TDR Probes with NS measurements, the TDR probes were installed at a distance of 500 mm from the NMM access tubes. The distance was considered far enough to avoid interference between the two methods, and close enough for comparison of the two methods. The NS access tubes in the experimental plots had already been installed in the previous experiments of long-term crop rotations. Hence the same tubes were used in this experiment. Calibration of the NMM gauge was done by measuring soil moisture at 0.2 m interval from 0.2 to 1.8 m and comparing against thermogravimetric method. Samples for the thermogravimetric method were taken at the same depth intervals within 500 mm from the access tube. A calibration equation was then derived and used for subsequent measurements.

Three sets of measurements were taken along the vertical soil profile during each time of data collection (TDR, NMM and soil temperature profiles). Data collection started in August 2005 when the soil was still unfrozen, and progressed until December 2005 when the soil had already frozen. Comparison was made between TDR and NMM data before and after soil freezing. In August 2005, ideally the TDR liquid water content was supposed to be equal to NMM total water content. Temperature measurements were used to determine how the variation in soil temperature affected the accuracy of TDR measurements as compared to the neutron moisture meter. Having established the temperature correction equation for TDR before soil freezing, measurement for both methods progressed during the fall and early winter when soil started to freeze. The decrease in the amount of liquid water content and the soil moisture migrations was monitored as the soil continued to freeze.

RESULTS AND DISCUSSIONS

Influence of soil temperature on TDR measurements

Soil moisture measurements using TDR and NS were compared in the field at varying soil temperatures before soil freezing. The aim was to determine how the variation in soil temperature affects the TDR measurement.

Readings were taken when the soil temperature was both below and above 25°C (the temperature used for laboratory calibration of the TDR probes). On 7 September 2005, the average soil temperature was 32°C on the plot with a cover crop.

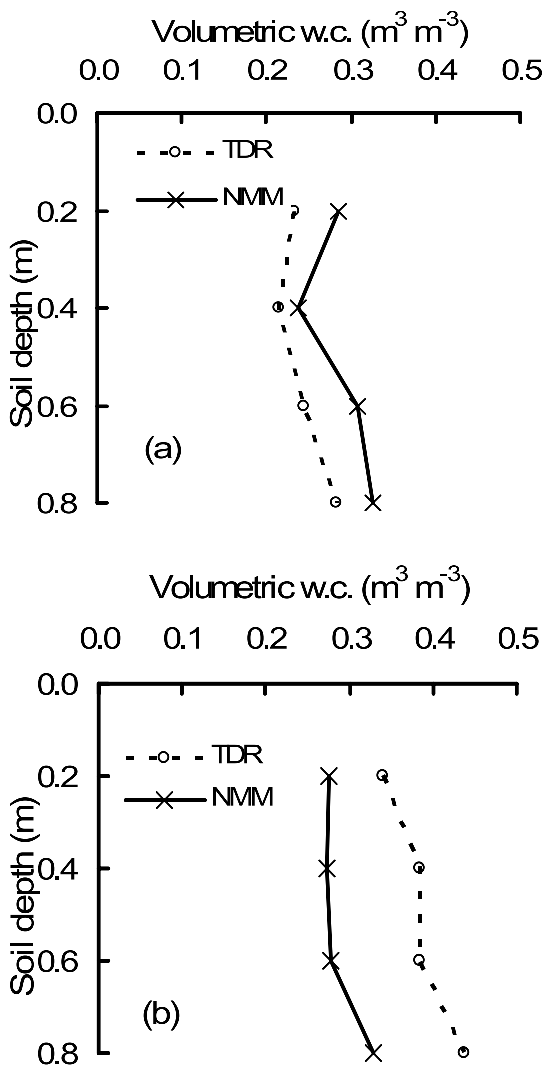

Fig. 1. Comparison of TDR and NMM soil moisture measurements before temperature corrections: (a) 32°C on 7 September 2005, and (b) 6°C on 22 November 2005

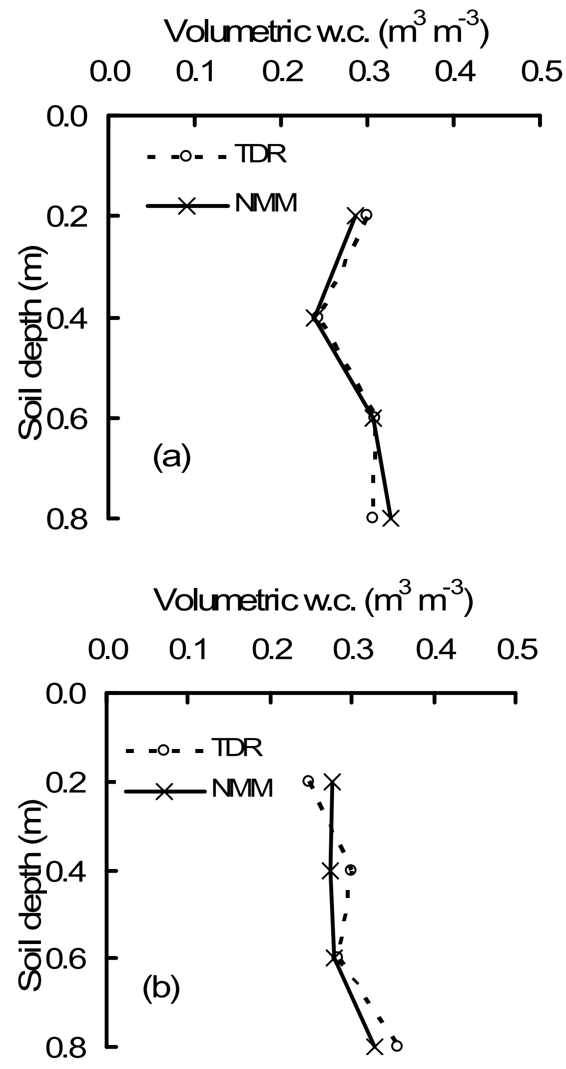

Fig. 2. Comparison of TDR and NMM soil moisture measurements below and above calibration temperature after temperature correction: (a) 7 Sept. 2005, (b) 22 November 2005.

Figure 1a and 1b compares TDR and NMM soil moisture measurements at soil temperatures higher and lower than the probes' calibration temperature of 25°C. When the average soil temperature was 32°C, the TDR method underestimated the amount of field soil moisture. As the average temperature dropped to 6°C, TDR method overestimated the soil moisture. This is attributed to the fact that TDR measures the dielectric constant of water (K-value) that changes with temperature (Tardif, 2002). The K-value is low at higher temperatures and increases with decrease in temperature to near freezing. Hence there was a need to develop an equation for correcting the TDR measurement to give accurate measurement at any soil temperature ranges. The NMM method used for comparison was understood not being affected by temperature variations due to its principle of measuring hydrogen molecules that are not affected by temperature change in the soil. The moisture gauge used had also already been pre-calibrated in the specific soil using thermogravimetric method as explained earlier.

Temperature correction for TDR measurements

The apparent dielectric (K_a) of water varies with temperature. The K_a for water decreases from about 88 near freezing to about 70 at 50°C. The relationship between the apparent dielectric constant and temperature was obtained by plotting the values of K_a at different temperatures as shown in Figure 3 using experimental data for relative permittivity of liquid water and their corresponding temperature at 0.1 MPa pressure (Fernandez et al. 1997).

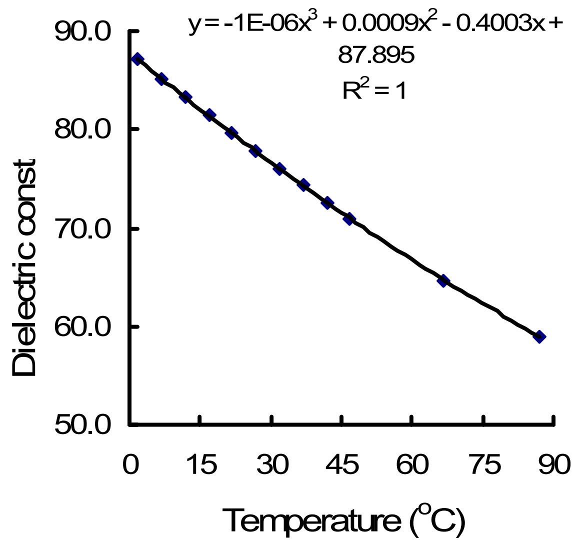

Fig. 3. Variation of dielectric constant of liquid water with temperature at 0.1 MPa pressure.

Figure 3 shows the relationship between dielectric constant of water and temperature at atmospheric pressure of 0.1 MPa. The K-values for unfrozen water decreased with increase in temperature. A three-order polynomial model (equation 2) best fitted the relationship with R^2 of 1.0.

$$K_T = 87.895 - 4.003 \times 10^{-1} T + 9 \times 10^{-4} T^2 - 1 \times 10^{-6} T^3 \quad (2)$$

where T is the temperature of water, and K_T is the apparent dielectric constant of water at the given temperature T. Using the established equation, the K-values for water could be estimated at any given temperature within the specified range of liquid state of the water.

The derived regression equation from Figure 3 was used to develop an equation that could be used to correct the dielectric constant of soil moisture, hence its water content measured in the field at soil temperature different from that of probes' laboratory calibration. Considering a standard temperature of 25°C, the equation for adjusting the field K- values was as derived follows:

$$K_{adj} = K_{field} + 0.3572(T_{soil} - 25) - 9 \times 10^{-4} (T_{soil} - 25)^2 + 1 \times 10^{-6} (T_{soil} - 25)^3 \quad (3)$$

where K_{adj} is the corrected field dielectric constant of soil, K_{field} is the measured field dielectric constant, and T_{soil} is the actual field soil temperature at specific depth (°C).

The K-values corrected for soil temperature were then used to determine liquid water content. A physically based Topp model (Topp et al. 1980) was used to relate K_{adj} with θ_v (equation 4).

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_{adj} - 5.5 \times 10^{-4} K_{adj}^2 + 4.3 \times 10^{-6} K_{adj}^3 \quad (4)$$

where θ_v is the volumetric soil water content.

The soil moisture measurements obtained from corrected K-values were compared with results obtained by NMM before soil freezing and they compared well (Table 2).

Table 2. TDR soil moisture measurement (wc) at soil temperatures below 25°C as compared to NMM measurements.

Soil depth (m)	Soil temperature (°C)	TDR wc uncorrected (v/v)	NMM wc (v/v)	Difference TDR-NMM (v/v)	TDR wc corrected (v/v)	Difference (Corr TDR-NMM) (v/v)
0.2	7.4	0.34	0.25	0.09	0.28	0.03
0.4	6.1	0.38	0.30	0.08	0.27	0.03
0.6	3.2	0.38	0.28	0.10	0.28	0.00
0.8	2.5	0.44	0.36	0.08	0.33	-0.03
	Average difference			0.09		0.01

Table 2 gives the soil temperature at different depths and the corresponding TDR and NMM soil moisture measurements. The uncorrected TDR measurements at temperatures lower than 25°C overestimated the actual soil moisture at an average of 9% v/v above the NMM. After applying the temperature correction equation developed, the difference was insignificant with an average difference of 1% v/v.

The corrected TDR measurements also corresponded well will the NMM for both higher and lower temperature measurements (Fig. 2).

Figure 2a and 2b compares TDR and NMM volumetric water content (w.c.) measurements after temperature correction. The two methods compared well.

After temperature correction on TDR measurements, there was no significant difference on the measured soil moisture between the two methods from August to November 2005. The total soil moisture measured by NMM was the same as liquid moisture content measured by TDR since the water was still unfrozen. Comparison of the two methods has also been done by Brendan (2003). However, that study did not account for field variation of the soil temperature.

TDR and NMM soil moisture partitioning during soil freezing

As the soil started to freeze, the difference between liquid and total soil moisture content started to emerge. During late fall and early winter in December, TDR water content became less than the NMM values. The difference between the two indicated the amount of soil moisture content in the frozen state (Fig. 4).

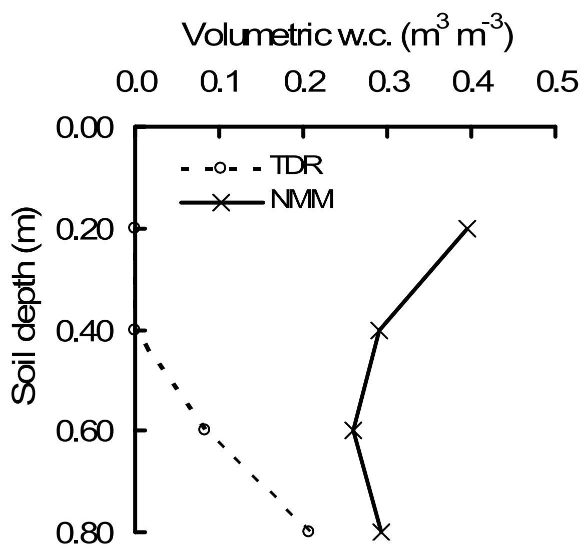

Fig. 4. Partitioning of soil moisture into unfrozen and frozen water content using TDR and NMM.

Figure 4 shows the TDR liquid (unfrozen) water content and NMM total water content. The ground had frozen to a depth of 0.4 m by 21 December 2005 on a plot which had oats alone during the summer. Below that depth the soil was partly frozen, signified by the presence of some liquid water content less than the total water content. At 0.6 m for example, the total water content was 26% and the liquid water content was 8%. The difference between the two values gave the amount of frozen water content as 18% at that depth. Baker and Allmaras (1990) demonstrated the possibility for using TDR and NMM to partition liquid and frozen water content in the soil during spring snowmelt. However the study did not cover the spring-thaw interactions in the fall as the soil freezes, and did not demonstrate how TDR measurements are affected by temperature variations.

Influence of soil freezing on moisture migration

As the freezing front progressed during the late fall and early winter in December 2005, soil moisture migration in the freezing layers was found to be towards the frozen soil layer from both above and below the freezing front (Fig. 5).

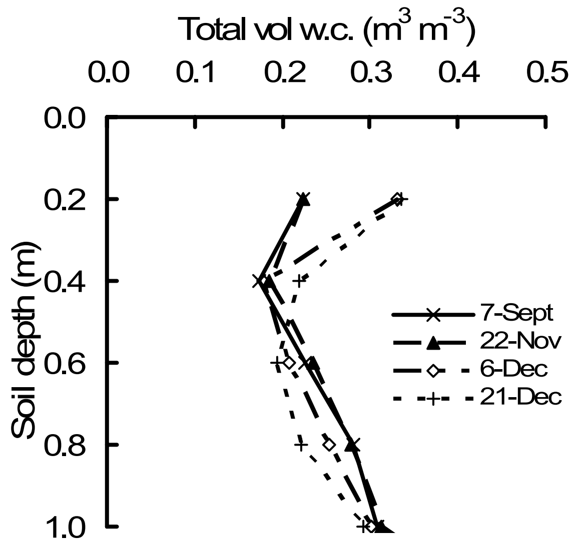

Fig. 5. Variation of total water content with depth from 7 September to 21 December 2005.

Figure 5 shows the total soil moisture variability with depth, and migration at different depths as the season changed from summer through fall to early winter. The total soil moisture increased with time in the top layers (0.2 – 0.4 m) as the winter progressed. This indicated occurrence of early snowmelt infiltration during the fall freeze-thaw processes. When the top soil was frozen (from December 6), there was no change in top soil moisture signifying no snow melt infiltration after the soil was frozen. For the deeper layers below the freezing front (0.4 m), soil moisture decreased with time and migrated towards the upper layer between 0.6 and 0.4 m. the same case was happening from above this layer for the partly unfrozen liquid water content. This implied that as the soil freezes and freezing front advance downwards the liquid and partly frozen soil moisture migrates from both above and below soil layers, towards the frozen soil layer. This process signifies that higher soil moisture is expected to be in the frozen soil layer during spring snowmelt depending on the depth that the soil has frozen. Shallower frozen soil layers will lead to lower soil moisture in the profile during the spring snowmelt.

CONCLUSION

Time domain reflectometry and Neutron scattering methods were used to measure soil moisture in partly frozen agricultural soils. Influence of soil temperature variability on the accuracy of TDR measurement was investigated. TDR method overestimated the actual field soil moisture content at lower soil temperatures below 25°C. At higher soil temperatures, the method underestimated the moisture content. A correction equation was derived and is proposed to be used for adjusting the measured field dielectric constant for soil moisture measurement to match with the actual field water contents at varying temperature conditions.

A combination of both TDR and NMM has been used to partition total soil moisture into liquid and frozen as the soil freezing progressed. Apart from determining the depth of freezing front, the two methods can be used to determine the percentage of frozen and unfrozen water at various depths of the soil profile as soil freezing progresses.

As the freezing front advance downwards, unfrozen soil moisture tends to migrate towards the frozen layer from both below and above the freezing front. The freezing characteristics of the soil during the fall as soil starts to freeze will influence the thawing response of the soil during the spring, hence its response to early snowmelt infiltration and runoff. Frozen soil layers will have more soil moisture during spring snowmelt depending on the frozen depth. Shallower frozen soil layers help to lower the amount soil moisture in the profile during the spring snowmelt. The process is expected to be advantageous in enhancing spring soil thawing, hence early farm operations.

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