Improving water content description of ice-rich permafrost soils

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ABSTRACT
The standard expression for soil gravimetric water content is on a dry basis (mass of water per unit mass of dry soil). In ice-rich soil, this method may produce extremely high values that are difficult to interpret. Alternatively, the wet-basis gravimetric water content (mass of water per unit mass of field-moist soil) may be used. Until now, this method has not been evaluated for use with ice-rich soils. We compare dry- and wet-basis gravimetric water contents, and find wet-basis to be a reliable and readily interpretable alternative to dry-basis for ice-rich mineral soils. However, it offers no clear advantage in organic soils or unfrozen mineral soils.

1 INTRODUCTION
Gravimetric water content determined on a dry-weight basis (W_d) is a standard and widely used expression for water content of soils (Reynolds and Topp 2008; Topp et al. 2008; ASTM D2216 2010). W_d values may be extremely high in ice-rich soils making interpretation and graphical representation difficult (e.g., Williams 1968; Mackay 1971; Kokelj and Burn 2003, 2005; Morse et al. 2009; O’Neill and Burn 2012). The scale required to display high W_d often masks important variation in W_d at lower values (e.g., Williams 1968, Fig. 2; Morse et al. 2009, Fig. 6; O’Neill and Burn 2012, Fig. 6). As a result, a logarithmic scale or broken axis is sometimes used. Volumetric water content (W_v) is restricted to values < 1 cm³ cm⁻³ (Reynolds and Topp 2008), and is not subject to the same difficulties of interpretation and graphical representation as W_d. However, W_v requires the undisturbed volume of soil samples to be determined, which may be difficult in ice-rich soils, when it is not possible to obtain large intact samples, or time-consuming when many samples are required (e.g., Morse et al. 2009; Kanevskiy et al. 2014). We propose that gravimetric water content expressed on a wet-basis (W_w) may be a useful alternative to W_d in ice-rich soil. The purpose of this paper is to evaluate the potential of W_w as an alternative to W_d for permafrost-affected soils. We present an illustrative dataset to compare water contents expressed as W_w, W_d, and W_v.

2 BACKGROUND

2.1 Dry-basis gravimetric water content in ice-rich soils
The most commonly reported measure of water content in ice-rich soils is W_d, the mass of water per unit mass of oven-dried soil (Reynolds and Topp 2008):

\[ W_d = \frac{m_w}{m_{ds}} \]  

where \( m_w \) is the mass of water (g) and \( m_{ds} \) is the mass of oven-dried soil (g). In unfrozen soils, water contents are constrained by available pore space. As \( W_d \) in these soils is typically less than 1 g g⁻¹, this is also commonly expressed as percent water content (Scott 2000). However, in soils containing excess ice, more water is present than in the saturated pore space of the thawed soil (French 2007), so any increase in water content must result in a reduced volumetric proportion of soil solids, and both \( m_w \) and \( m_{ds} \) change with the water content, i.e., as \( m_w \) increases, \( m_{ds} \) decreases. High values (> 3 g g⁻¹) are common in the literature (e.g., Mackay 1971; Kokelj and Burn 2003, 2005), and extremely high values (> 100 g g⁻¹) have also been reported (e.g., Morse et al. 2009; O’Neill and Burn 2012).

2.2 Volumetric water content in ice-rich soils
Another standard expression for water content is the volumetric water content (W_v), the volume of water per
unit volume of undisturbed soil (Reynolds and Topp 2008):

\[ W_v = \frac{m_w}{V_t \rho_w} \quad \text{(2)} \]

for liquid water or:

\[ W_v = \frac{m_w}{V_t \rho_i} \quad \text{(3)} \]

for ice, where \( V_t \) is the total sample volume (cm\(^3\)), \( \rho_w \) is the density of water (1.0 g cm\(^{-3}\)), and \( \rho_i \) is the density of ice (0.91 g cm\(^{-3}\)). \( W_v \) is a measure of the volumetric proportion of soil that is water or ice, and as such cannot be greater than 1 cm\(^3\) cm\(^{-3}\), eliminating the possibility of extremely high values that may make the use of \( W_d \) problematic. \( W_v \) then enables simpler interpretation and graphical representation.

In unfrozen soils, \( W_v \) may be determined by several well-established indirect methods, but these methods either do not perform well or are impractical in frozen soils. Time domain-reflectometry and ground-penetrating radar assess the dielectric permittivity of the soil, whereas capacitance and impedance methods assess the soil’s function as a capacitor or resistor in an electrical circuit, respectively. These electromagnetic properties usually differ by more than an order of magnitude between liquid water and air or soil solids, and are used to infer \( W_v \) on this basis (Reynolds and Topp 2008; Topp et al. 2008). However, because these electromagnetic properties are not sufficiently dissimilar between ice and air or soil solids, commercially available methods based on electromagnetic properties cannot determine ice content in frozen soils (Patterson and Smith 1981). Neutron scattering detects the hydrogen concentration of the soil and relates it to the volumetric water content (Reynolds and Topp 2008). This method can discriminate ice (e.g., Williat 1979), but requires site-specific calibration, expensive equipment, and special training and licensing to work with the necessary radioactive materials.

By far the most common direct method to determine \( W_v \) is the thermogravimetric method (Reynolds and Topp 2008). In this method the weight of a sample of known undisturbed volume is measured before and after oven-drying. The mass of water is then related to the volumetric water content through its density, as in Eqs. 2 and 3. This method is possible in ice-rich soils, but it may be difficult to determine the volume of extracted permafrost samples in a field setting (Figure 1a). Furthermore, the thermogravimetric method requires destructive sampling of large samples which may preclude the use of samples for other analyses.

New methods of determining \( W_v \) specifically tailored to ice-rich soils have recently been developed. For example, computerized tomography (CT) scanning (Calmels and Allard 2008) employs medical equipment and software to determine \( W_v \) while leaving the extracted permafrost cores available for other analyses. However, this method requires expensive, specialized equipment and the cores must stay frozen during transport to a lab for imaging. Photogrammetric methods for determination of extra-pore ice volume have also been applied in conjunction with thermogravimetric methods to produce \( W_v \) estimates (Kanevskiy et al. 2013, 2014). This requires photographs of intact cores or exposures (Figure 1b), which are often difficult to obtain for ice-rich soil. Furthermore, this method relies on estimates of the specific gravity of soil solids, which can have a considerable range of values in soils with significant amounts of organic matter (Hao et al. 2008).

2.3 Wet-basis gravimetric water content

Current methods used to determine and express water content in ice-rich soils have significant limitations for routine, inexpensive use in field studies. Wet-basis gravimetric water content (\( W_w \)) may be a useful alternative to \( W_d \) and \( W_v \) in ice-rich soils, but its performance has not been evaluated.

\( W_w \) is an adaptation of the standard expression for \( W_d \) (Eq. 1) where the mass of the field-moist soil is used in place of the dry soil:

\[ W_w = \frac{m_w}{(m_{ds} + m_w)} = \frac{m_w}{m_{ws}}. \quad \text{(4)} \]

where \( m_{ws} \) is the mass of field-moist soil (g). Similar to \( W_d \) (Eq. 1), for soils with excess ice, a change in \( m_w \) will lead to a change in \( m_{ws} \). However, unlike the expression for \( W_d \), these two variables converge at high water contents. For this reason, an incremental change in water content in a soil containing excess ice will produce a smaller change in \( W_w \) than in \( W_d \). Moreover, as \( m_w > m_{ws} \) is not possible, \( W_w \) is restricted to values between 0 and 1 g g\(^{-1}\), which
Table 1. The number of samples included for gravimetric water content determination, with the number of samples used for both gravimetric and volumetric water content determination (i.e., samples with known undisturbed volume) shown in parentheses. Note than 166 additional samples from the Yellowknife region were included for gravimetric water content determination, but data on the organic or mineral nature of the samples were not available.

<table>
<thead>
<tr>
<th>Site</th>
<th>Active Layer</th>
<th>Permafrost</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mineral</td>
<td>Organic</td>
<td>Mineral</td>
</tr>
<tr>
<td>Mackenzie Delta (Forested)</td>
<td>133 (88)</td>
<td>4 (3)</td>
<td>79 (30)</td>
</tr>
<tr>
<td>Mackenzie Delta (Tundra)</td>
<td>100 (0)</td>
<td>34 (4)</td>
<td>423 (18)</td>
</tr>
<tr>
<td>Mackenzie Delta Region Uplands (Forested)</td>
<td>29 (29)</td>
<td>15 (13)</td>
<td>66 (38)</td>
</tr>
<tr>
<td>Mackenzie Delta Region Uplands (Tundra)</td>
<td>64 (58)</td>
<td>37 (40)</td>
<td>72 (34)</td>
</tr>
<tr>
<td>Peel Plateau</td>
<td>31 (31)</td>
<td>11 (11)</td>
<td>0</td>
</tr>
<tr>
<td>Yellowknife Region</td>
<td>61 (0)</td>
<td>252 (0)</td>
<td>39 (0)</td>
</tr>
<tr>
<td>Mayo Region</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>418 (206)</td>
<td>353 (71)</td>
<td>679 (120)</td>
</tr>
</tbody>
</table>

...may simplify the interpretation and graphical representation of \( W_w \) for ice-rich soils in comparison with \( W_d \). Whereas \( W_d \) is a standard and widely used expression, it may be readily transformed to \( W_w \) for analytical purposes. \( W_d \) is related to \( W_w \) as follows:

\[
W_d = \frac{W_w}{1 - W_w}. \tag{5}
\]

and similarly, \( W_w \) is related to \( W_d \) accordingly:

\[
W_w = \frac{W_d}{1 + W_d}. \tag{6}
\]

We suggest that \( W_w \) is a useful expression to employ in ice-rich soils in place of \( W_d \) in cases where it is not practical to determine \( W_v \). To explore this suggestion, we examined water contents from a large database \((n = 1806)\) of water contents from permafrost-affected soils. The database included 416 samples with measured undisturbed volume. We examined the water contents determined by \( W_d \), \( W_w \), and \( W_v \) for ease of interpretation and representation. We also compared \( W_d \) and \( W_w \) to \( W_v \), which we accept as a relatively easy-to-interpret measure because it is an expression of the water content not altered by the bulk density of the soil solids (see Eqs. 1–4). For this reason, nonlinear relations between \( W_d \) or \( W_w \) and \( W_v \) are less desirable than linear relations as an easily interpretable measure of water content.

Figure 2. Histograms showing the distribution of water contents expressed as (a) dry-basis gravimetric water content \((W_d, n = 1806)\), (b) wet-basis gravimetric water content \((W_w, n = 1806)\), and (c) volumetric water content \((W_v, n = 416)\). Note that \( W_w, W_v, \) and \( W_d < 1 \text{ g g}^{-1} \) are shown on the same linear x-axis scale, while \( W_d > 1 \text{ g g}^{-1} \) are shown on a logarithmic scale.
3 DATA COLLECTION

Table 1 indicates the distribution of samples from the various sites included in the database. Samples were collected from three profiles in the forested portion of the Mackenzie River delta near Inuvik, NT (68.3°N, 133.8°W), and riverbank exposures were sampled at six other locations in the upper Mackenzie Delta south of treeline (Kokelj and Burn 2005). Additionally, 33 profiles were examined in the lower Mackenzie Delta north of treeline, predominantly from within and near the Kendall Island Bird Sanctuary (69.3°N, 135.0°W; Morse et al. 2009). The uplands adjacent to the Mackenzie Delta were also sampled, including six profiles south of treeline near Inuvik (68.4°N, 133.7°W) and 12 profiles north of treeline at Illisarvik, Richards Island, NT (69.5°N, 134.6°W) and Garry Island, NT (69.5°N, 135.7°W; Mackay 1992; Kokelj and Burn 2003; O’Neill and Burn 2012). Samples were collected from 30 locations near the Dempster Highway in the Peel Plateau west of Fort McPherson, NT (67.2°N, 135.6°W), 19 profiles near Yellowknife, NT (62.5°N, 114.1°W), and 7 profiles in a peatland near Mayo, YK (63.8°N, 135.2°W) (Burn 1991; Wolfe et al. 2011; Gaanderse 2015; O’Neill et al. 2015). Most profiles were sampled to a depth of 1–3 m from the soil surface, except on the Peel Plateau, where only the active layer was sampled, and at eight profiles from the Yellowknife region which extended beyond 3 m to a maximum of 7.25 m. Taken together, these locations include a considerable variation in site conditions, including peatlands, glaciolacustrine deposits, till, and alluvium. The dataset includes samples from discontinuous and continuous permafrost zones, as well as forested and tundra biomes. $W_v$ was determined for a subset of samples in the database (Table 1, $n = 416$).

4 METHODS

Samples from different sites were not always collected by the same individuals and slightly variable sampling protocols were applied. For unfrozen samples where a measured volume of soil was extracted, volume was determined by using either a cylinder ($\sim$115 cm$^3$) or cube ($\sim$215 cm$^3$) of known volume for mineral samples and some organic samples, or by directly measuring the size of an extracted parcel of soil for other organic samples. Frozen samples were collected using Cold Regions Research and Engineering Laboratory (CRREL) core barrels with inside diameters of either 5.1 or 7.6 cm.

For some frozen samples the volume was determined by direct measurement of core segments following extraction. Samples were judged to be either mineral (< 50% organic matter by mass) or organic (> 50% organic matter) based on a field assessment of colour, density, and tactile feel. Samples were bagged in the field to avoid water loss during handling and transport and then weighed to determine their field-moist weight. Mineral samples were dried at 105 °C for 24–72 hours. Some samples estimated to be rich in organic matter were dried at a lower temperature (60–80 °C). $W_d$, $W_w$, and $W_v$ were determined according to equations 1–4.

Active-layer thickness was usually determined for each profile by probing during late summer. In cases where active-layer thickness from probing was not available, samples were assumed to be from the active layer if they were thawed or from the permafrost if they were frozen at the time of sampling, which was usually late summer.

5 RESULTS

The dataset includes samples for a wide range of volumetric water contents between a minimum of 0.04 cm$^3$ cm$^{-3}$ and a maximum of 0.97 cm$^3$ cm$^{-3}$. The distributions of $W_d$, $W_w$, and $W_v$ shown in Figure 2...
illustrate the difficulty involved in clearly representing $W_d$ for ice-rich soils, as the unusual scale that must be employed to display the extreme positive skew of $W_d$ without obscuring low $W_d$ is difficult to interpret in comparison to that used for $W_w$ and $W_v$. $W_w$ and $W_v$ are plotted on identical scales, as their maximum values are $<1\, \text{g g}^{-1}$ and $<1\, \text{cm}^3\text{cm}^{-3}$, respectively. There is a large proportion of high $W_d$, with 44% and 3% of $W_d > 1$ and $>10\, \text{g g}^{-1}$, respectively. $W_d$ reaches extreme values, with three samples $>1000\, \text{g g}^{-1}$.

The dry bulk density of samples ($n=416$) ranged from 0.02 to 1.73 g cm$^{-3}$, with mean and median densities of 0.76 and 0.80 g cm$^{-3}$, respectively (Figure 3). The distribution of dry bulk densities reflects the wide range of materials from very low density organic soil to dense mineral soil. The relation between $W_d$ and dry bulk density is exponential when dry density is low, particularly for mineral permafrost samples and organic samples (Figure 3a). $W_w$ also has a nonlinear relation with dry density, though to a much lesser degree than $W_d$ (Figure 3b). When density is low ($<0.2\, \text{g cm}^{-3}$) even very dry samples ($W_v < 0.2\, \text{g cm}^{-3}$) have relatively high $W_d (>1\, \text{g g}^{-1})$ and $W_w (>0.5\, \text{g g}^{-1}$), indicating that both $W_d$ and $W_w$ methods may be misleading for unsaturated, low-density soils.

Scatterplots of $W_d$ and $W_w$ against $W_v$ are presented in Figure 4. The relation between $W_d$ and $W_v$ for mineral samples (Figure 4a) appears to be linear or nearly linear for all $W_v$ below 0.6 cm$^3$ cm$^{-3}$. Above 0.6 cm$^3$ cm$^{-3}$, the relation becomes strongly nonlinear, though there is considerable spread in the data. The high values for $W_d$ when $W_v > 0.6\, \text{cm}^3\text{cm}^{-3}$ necessitate a large vertical scale. This makes it difficult to graphically evaluate $W_d$ data for $W_v < 0.6\, \text{cm}^3\text{cm}^{-3}$; and an alternative scale for this relation is presented in Figure 5. The majority of $W_d$ values for active layer samples appear to support a linear relation with $W_v$, whereas the majority of $W_d$ values from permafrost samples do not.

Considerable scatter occurs in mineral $W_w$ for $W_v > 0.5\, \text{cm}^3\text{cm}^{-3}$ (Figure 4b), although less than in mineral $W_d$ measurements (Figure 4a). For active layer mineral samples, most $W_d$ values closely resemble a 1:1 relation with $W_v$ (Figures 4a and 5), whereas $W_w$ falls slightly farther from the 1:1 line with $W_v$ (Figure 4b). For permafrost mineral samples $W_w$ is closer to a 1:1 relation with $W_v$ (Figure 4a) than is $W_d$ (Figure 4b).

For active layer organic samples, the relations of both $W_d$ and $W_w$ with $W_v$ appear to be linear but weak (Figures 4c and 4d). A considerable amount of the variation in $W_d$ for active layer organic samples is likely more closely related to variation in dry soil mass than to $W_v$ (c.f. Figures 3a and 3c). Linear relations between $W_d$ and $W_v$ for active layer organic samples are evident when narrow bulk density ranges are considered (data not shown), but they are not evident when the full range of samples is shown as in Figure 4c, indicating that comparisons using $W_d$ in active layer organic soils are difficult unless bulk density is known. Because of the low dry bulk density of organic samples, $m_{ws}$ is dominated by water and $W_w$ is

![Figure 4. Scatterplots of the values of dry-basis gravimetric water content ($W_d$) in plots a and c and wet-basis gravimetric water content ($W_w$) in plots b and d for different values of volumetric water content ($W_v$). Plots a and b show water contents for mineral samples, while plots c and d show water contents for organic samples. For all plots, active layer](image-url)
samples are depicted by solid red markers and permafrost samples are depicted by open blue markers. Note differences in vertical scale.

Figure 5. Scatterplot of dry-basis gravimetric water content ($W_d$) and volumetric water content ($W_v$). Active layer samples are shown as solid red triangles and permafrost samples are shown as open blue triangles. These are the same data depicted in Figure 4a, but only $W_d$ values $< 2$ g g$^{-1}$ are shown.

relatively high for all organic samples (Figure 4d), and no clear relation between $W_w$ and $W_v$ is apparent. When narrow dry bulk density ranges are considered relations are apparent, but are nonlinear (data not shown). There are too few samples in this database to reliably evaluate relations between $W_d$, $W_w$, and $W_v$ in permafrost organic samples.

6 DISCUSSION

$W_d$ is difficult to interpret in ice-rich soils. Values of $W_d > 3$ g g$^{-1}$ are common in both the published literature (Mackay 1971; Kokelj and Burn 2003, 2005; Morse et al. 2009; O’Neill and Burn 2012) and in the dataset assembled for this paper. These high $W_d$ values sometimes create difficulties in representation and interpretation of data (Figures 2a, 3a, 4a, and 4c). The extreme positive skew evident in $W_d$ measurements from this database (Figure 2a) indicates that high $W_d$ is common in ice-rich soils, and that there is a need for an easier way to express, display, and interpret gravimetric water content in ice-rich soils. $W_w$ gives a distribution of values that is more interpretable (Figures 2b and 2c) with a lower degree of nonlinearity than $W_d$ with respect to $W_v$ (Figure 4) in ice-rich mineral soils.

$W_w$ performs better than $W_d$ as a metric of water content in ice-rich mineral soils, but not in organic soils and active layer mineral soils. For most active layer mineral soils $W_d$ has a linear relation with $W_v$ (Figure 5) that is closer to a 1:1 relation with $W_v$ than is $W_w$ (Figure 4b). Both $W_d$ and $W_w$ have poor relations with $W_v$ in organic soils, much of which seems to be related to the variable dry bulk density in organic soils included in this database. This indicates that it is important to control for soil density when using gravimetric methods in organic soils, and $W_v$ should be used whenever possible (Boelter 1968). As there is no apparent advantage to using $W_w$ over $W_d$ in organic soils (frozen or unfrozen) and $W_d$ is the most widely used expression, there is no reason to recommend using $W_w$ in these soil types unless it is necessary to maintain consistency with $W_w$ used in the same analysis.

7 CONCLUSIONS

Based on analysis of the database in this paper, we recommend that $W_w$ be used in ice-rich mineral soils where interpretation of water content is difficult because of high $W_d$ values. This eliminates the problem of extremely sensitive, difficult to interpret water contents for ice-rich mineral soils. For consistency, $W_w$ may be extended to the active layer mineral soils as well, because the difference between $W_d$ and $W_w$ for these soils is typically small.

At present, there is not enough information in this database to assess the performance of $W_d$ and $W_w$ as measures of water content in organic soils. However, expression of $W_d$ in ice-rich organic soil presents similar difficulties to those encountered in ice-rich mineral soil, and further examination of this problem is warranted.

ACKNOWLEDGEMENTS

This work was conceived during a permafrost seminar at Carleton University in Ottawa, ON. Such seminars take place regularly and include researchers from Carleton University, the Geological Survey of Canada, and visiting scientists. Thanks are extended to all members of the group for stimulating discussions. For more information on this seminar, please contact Dr. Chris Burn at Carleton University (Christopher.Burn@carleton.ca). We also thank Caroline Duchesne for providing a French translation of the abstract for this paper.

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