A Test of Two Spatial Frameworks for Representing Spatial Patterns of Wetness in a Glacial Drift Watershed


In forest ecosystems, soil water availability is an important indicator and driver of biogeochemical transformations, pedogenesis, and surface water–groundwater linkages. Given the importance of soil moisture and shallow groundwater to ecosystem processes, field measurements are critical. We investigated the spatial patterns and temporal dynamics of moisture conditions in a forested first-order watershed in northern Michigan. We measured soil volumetric water content (VWC, %) and water table levels across a range of glacial parent materials and landforms. We also assessed the utility of using two different spatial frameworks (Landscape Ecosystem classification, Topographic Wetness Index) to represent spatial patterns of soil moisture and water table levels across the watershed. At the lowest landscape position (outwash-lake plain swamp), saturation was perennial, with a median soil VWC of 53% and the water table 8 cm below ground surface. Among upland ecosystems, outwash landforms had consistently low VWC (16%) and showed no evidence of groundwater within 4 m of the surface; moraine ecosystems (till parent material) possessed mixed hydrologic conditions, with VWC ranging from 18 to 25% and water table levels 6 to 65 cm below the surface. In low-variability dry or wet areas with relatively homogenous soils, larger ecosystem classification map units provide good representations of moisture conditions. In the more heterogeneous till soils, a finer-scale spatial framework that accounts for local soil variation is optimal. A combination of both spatial frameworks is most appropriate for estimating moisture conditions in this glaciated landscape and can be used to identify biogeochemically important sites and to inform land management decisions.

Terrestrial water storage is an important intermediate in the hydrologic cycle between precipitation and receiving surface waters. Soil water storage and availability are important controls for a number of ecosystem processes (Lin, 2010; Schaeztli et al., 2009). In forest landscapes, soil water and groundwater conditions influence biogeochemical processes and nutrient cycling (Burt and Pinay, 2005; Morse et al., 2014; Seneviratne et al., 2010; Vidon et al., 2010). Spatial and temporal variability of soil water can affect carbon and nitrogen cycles by creating favorable conditions for mineralization, leaching, or greenhouse gas production through differing levels of soil saturation and connections between flow paths transporting biogeochemically important substrates (Burt and Pinay, 2005; Castellano et al., 2012; McClain et al., 2003; Oswald and Branfireun, 2014; Porporato et al., 2003). The extent of hydrologic connectivity between the landscape and surface waters is dependent on soil water and shallow groundwater levels, with continuous water tables allowing for the transfer of materials, such as dissolved organic carbon or NO$_3^-$ (Duncan et al., 2015; Lambert et al., 2014), from hillslopes through riparian zones to streams and ultimately exported from a watershed to larger water bodies (Bracken et al., 2013; Freeman et al., 2007; Jencso et al., 2009). In addition, water movement through the soil influences pedogenesis, vertically through soil profiles and laterally along hydrologic
flow paths (Bailey et al., 2014; Lohse and Dietrich, 2005). Water availability and storage can influence vegetation growth and distribution (Hwang et al., 2012; Rodriguez-Iturbe et al., 1999; Tenenbaum et al., 2006), and water stress, due to either limited water or excessively saturated soils, can reduce photosynthesis and tree growth and can lead to changes in phenology (Berthelot et al., 2014; Brzostek et al., 2014; McDowell et al., 2008).

Given the importance of soil moisture and shallow groundwater to ecosystem processes and the transport of material through soil and to surface waters, field measurements of hydrologic conditions are critical. However, field measurements of soil moisture and water table levels can be limited in spatial and temporal resolution due to resource constraints or challenges in accessing the field site throughout the year (Grabs et al., 2009). Developing a relationship between field measurements and easily generated geospatial frameworks can provide a method for estimating moisture conditions across a watershed or scaling field measurements across larger regional scales (Ali et al., 2014; Zhu et al., 2012). Assessing the relationship between terrestrial moisture conditions and landscape or regional spatial frameworks could also potentially provide a method for easily estimating critical areas of soil–ground–surface water linkages, biogeochemical cycling, pedogenesis, or vegetation distribution and productivity. These spatial frameworks could then be used to identify important sites for terrestrial–aquatic interfaces or be used for land management decision-making related to forest harvesting, restoration, or adaptation to climate change.

For this analysis we used two types of spatial frameworks, the first of which is an ecosystem classification. Ecosystem classifications have been developed for a range of landscapes to identify spatial units of recognizable ecosystems using established criteria, such as landform, climate, vegetation, and/or soil (Cleland et al., 1997; Cullum et al., 2016). Ecosystem classifications have been widely used to map plant communities and to identify areas to focus conservation efforts (Boyle et al., 2014; Cameron and Williams, 2011; Cullum et al., 2016; Ferree and Thompson, 2008; Moores et al., 1996; Zenner et al., 2010). Hierarchical ecosystem classifications have been previously developed for our northern Michigan study region (Albert, 1995; Pearsall et al., 1995) and have been used to identify forest communities (Lapin and Barnes, 1995) and bird habitat (Kashian et al., 2003) and to map wetland ecosystems (Zogg and Barnes, 1995). Ecosystem classifications are often based in part on presumed patterns of wetness rather than on measured soil moisture and water table depth; therefore, making direct measurements of hydrologic conditions across ecosystems can increase our confidence in the advisability of using ecosystem classifications as representatives of wetness. Mapping hydrologic conditions with existing ecosystem classifications potentially provides a relatively easy way to identify soil moisture status or water table levels across a range of landscapes and regions.

The second type of spatial framework we used is a higher-resolution topographic wetness index (TWI), where pixel-level values are calculated based on geospatial inputs. Topographic indices have commonly been correlated with soil moisture (e.g., Ali et al., 2010; Beaudette et al., 2013; James and Roulet, 2007; Liang et al., 2017; Lin et al., 2006; Tague et al., 2010) and water table (e.g., Detty and McGuire, 2010; Grabs et al., 2012; Monteith et al., 2006; Rinderer et al., 2014; Thompson and Moore 1996) measurements across many study systems. Topographic wetness indices have been related to hydropedologic unit, soil organic matter, and other soil properties (Gillin et al., 2015; Grabs et al., 2012; Laamrani et al., 2014; Lin et al., 2006; Moore et al., 1993; Murphy et al., 2011; Pei et al., 2010; Seibert et al., 2007; Zinko et al., 2006). Topographic wetness indices have also been used to map wetland occurrence (Grabs et al., 2009; Rampi et al., 2014; Rodhe and Seibert, 1999) and vegetation distribution (Hwang et al., 2012; Petrocelli et al., 2013). Although TWIs have been used for various purposes, these indices can be limited in their use at very large scales or across regions due to data limitations or model assumptions (Rinderer et al., 2014; Schaezel et al., 2009).

Although numerous studies have used TWIs to describe wetness conditions across watersheds, few have assessed ecosystem classifications against quantitative hydrologic measurements or evaluated soil moisture or groundwater across heterogeneous glacial drift landscape such as ours. This landscape provided us the opportunity to evaluate distinct spatial frameworks in settings with diverse parent materials and young topography. Identifying which spatial frameworks can be used to represent soil moisture and groundwater patterns will aid us in determining important sites for hydrologically influenced processes. The present study, conducted in a first-order watershed possessing high-resolution data amenable to testing both types of spatial frameworks, had two primary objectives. First, we measured patterns of soil moisture and water table position throughout the hydrologic year, contributing to the characterization of watershed-level water distribution and storage across the upper Great Lakes physiographic region. Second, we evaluated the utility of two types of spatial frameworks to represent spatial patterns of and variability in soil moisture and water table levels across the watershed.

Materials and Methods

Study Area

This research was conducted within the Honeysuckle Creek watershed at the University of Michigan Biological Station (UMBS) in northern Lower Michigan (45.56°, −84.72°) (Fig. 1). The regional climate is continental with strong local topographic gradients. Mean annual temperature is 5.5°C, and mean annual precipitation is 817 cm, 294 cm of which is snowfall (Nave et al., 2017b). The ~120-ha Honeysuckle Creek watershed drains a small first-order stream and several ephemeral channels occupying a variety of glacial and postglacial landforms to Burt Lake, Michigan’s fourth largest inland lake.

The UMBS landscape is characteristic of many areas in the northern Lake Michigan and eastern Lake Superior basins. Major landforms were created by the deposition and modification of glacial parent materials at the end of the Laurentian glaciation,
between 14,000 and 11,000 years before present (YBP) (Blewett and Winters, 1995; Lapin and Barnes, 1995; Spurr and Zumberge, 1956). At UMBS, coarse-textured glacial deposits 100 to 200 m thick overlay Silurian limestone and Devonian shale bedrock. The wasting ice mass deposited till as ground, interlobate, and drumlinized moraines. Much of the till was later capped by meters of outwash deposited during the final stages of glacial retreat from the region. Below an elevation of 255 m asl, these landforms were altered by large, postglacial lakes (Lake Algonquin 11,500–10,500 YBP; Lake Nipissing 5000–3000 YBP), which resulted in till and outwash features reworked into lacustrine landforms (dunes, beach ridges, lake plains; Blewett and Winters, 1995; Spurr and Zumberge, 1956). The elevation of the Honeysuckle Creek watershed ranges from 276 m at the top of an interlobate moraine to 181 m at present-day Burt Lake.

Within the watershed, soils above 245 m elevation and the northern half of the middle of the watershed (245–190 m) are Entic and Lamellic Haplorthods (Rubicon and Blue Lake series, respectively; Soil Survey Staff [1991]). These are very deep soils (>150 cm) formed in thick sandy or gravelly outwash deposits (Rubicon) or in stratified mixtures of coarse outwash and underlying glacial till (Blue Lake). Blue Lake soils possess loamy lamellae at depth (typically below 80 cm), which impede infiltration. This soil series roughly correspond with soils in the outwash and banded outwash over till Landscape Ecosystem groups (discussed below), which are sandy in texture and have glacial till restrictive material >400 cm from the surface. Soils in the southern half of the middle of the watershed are Alfic Haplorthods and Alfic Epiaquods (Cheboygan and Riggsville series, respectively), which formed in thinner deposits of finer-textured outwash and the underlying dense glacial till. In these soils, the till is laterally extensive and acts as a restrictive layer, causing perched water tables. The Cheboygan and Riggsville soil series correspond with soils in the mesic and aquic till Landscape Ecosystem types, respectively. Soils in the mesic till ecosystems have a glacial till restrictive layer between 45 and 265 cm from the surface and textures that range from medium sand to loamy sand. In the aquic till ecosystems, the glacial till restrictive layer is within 150 cm of the surface, and soil textures are predominantly loamy sand or silt loam. In riparian areas of the middle elevations of the watershed (Landscape Ecosystem riparian wetland type), Mollic Endoaquents (Brevort series) occur; these are mucky mineral soils with redoximorphic features due
Field Measurements

We measured soil moisture, as volumetric water content (VWC, %) of the upper 20 cm of soil, at a minimum biweekly from July to November 2015 and April to November 2016 across the Honeysuckle Creek watershed. We selected sample points (n = 97) from a systematic grid of 392 transect points located 10 m apart (north to south) along transects spaced every 300 m (east to west) across the watershed area. Sample points were selected from a stratified random design to span Landscape Ecosystem types and TWI values present in the watershed (discussed below). Point locations in the field were marked with a flag to allow for repeated measurements of the exact same point throughout the study period and were georeferenced with a high-resolution GPS unit (~1 m accuracy; Trimble R1 GNSS, Trimble, Inc.). Each time measurements were collected, three time domain reflectometry (Hydrosense, Campbell Scientific, Inc.) readings of soil VWC were taken at each point, 2 m from the flag at 0, 120, and 240° headings. Each set of soil moisture measurements was taken across the watershed within 1 d, and measurements were not interrupted by rain events. The time domain reflectometry probe was calibrated with volumetric soil moisture measurements of soil cores taken across a range of wetness conditions throughout the watershed ($R^2 = 0.84$).

We placed shallow groundwater monitoring wells in areas of the watershed where water tables were observed during soil profile observations and where surface water features indicated that shallow groundwater would likely be present. Throughout this paper we refer to shallow groundwater, which was groundwater observed within 3 m of the surface due to perching on glacial till restrictive material or consolidated sand in the outwash-lake plain swamp. Shallow wells (n = 49) were installed down to the first major parent material unconformity, which was a glacial till restrictive layer (depth, 55–220 cm) in upland ecosystems. In the outwash-lake plain swamp, wells were installed to ~160 cm through the organic soil horizons and into the sand C horizon. Slotted PVC wells (3.2–5.1 cm diameter) were deployed in 10-cm-diameter boreholes, and the void space was filled with a sand pack. Wells were not installed in locations above 240 m elevation because the deep sand outwash soils did not show indication of saturated conditions or shallow groundwater during soil observations. Water table position was measured with a flat tape water level meter (Model 101B, Solinst, Inc.) approximately weekly from June 2016 to June 2017 in all wells and from November 2015 to June 2017 in wells below 190 m elevation. Readings were corrected for the height of the standpipe such that the water table depth tape measurement was equal to the depth of water below the surface. Pressure transducers (Leveolgger, Leveolgger Jr., Solinst, Inc.) were used to take hourly water table position measurements in a subset of wells (n = 12) and were adjusted for atmospheric pressure. These measurements were then aggregated into mean daily water table positions for the subset of wells.

Soil observation, description, and sampling across the watershed were conducted for a soil characterization campaign from September 2014 to November 2016 and included field observations made with a 10-cm-diameter bucket auger (n = 54) and quantitative samples taken by with a slide hammer soil corer (n = 33) or with a McCauley gate auger (n = 41) or from a pit face (n = 13). Observations were made across ecosystem types, landforms, and elevation throughout the watershed (Fig. 2). During soil observations, we described horizon thickness and color and made field determinations of texture class, measured depth to glacial till restrictive layer or C horizon, and noted depth to water table. For the present study, field determination of soil texture class, depth to glacial till restrictive layer, and depth of water table were the soil characteristics of interest. Soil characteristics were used in the soil topographic Index (STI).

Landscape Ecosystem Classification

We used a hierarchical, multifactor ecosystem classification as the first of two spatial frameworks for assessing spatial variability in and patterns of water storage (soil VWC, water table depth) across the Honeysuckle Creek watershed. The UMBS Landscape Ecosystem classification defines and maps 125 distinct ecosystem types for the 4000-ha UMBS property based on landform, microclimate, and soil and vegetation characteristics (Lapin and Barnes, 1995; Pearsall, 1995; Pearsall et al., 1995; Zogg and Barnes, 1995). The ecosystem type map units are at the scale of tens of hectares. The Landscape Ecosystem classification nests within the US Forest Service ECOMAP ecoregional framework below the Subsection level (Cleland et al., 1997). Individual Landscape Ecosystems at UMBS approximate the Landtype phase, which is the most finely resolved spatial unit in the ECOMAP conceptual framework but which is mapped in very few places in the conterminous Unites States. Landscape Ecosystem classifications have been conducted for a variety of landscapes across the upper Midwest region (Albert et al., 2015), including the McCormick Experimental
Forest (Pregitzer and Barnes, 1984), the Sylvania Wilderness Area (Spies and Barnes, 1985), and the Huron Mountain Club Reserve Area (Simpson et al., 1990). For this analysis, the Landscape Ecosystem units (originally identified numerically) were given shorthand names that refer to the dominant parent material or landform of that ecosystem type. Due to the small spatial extent of some of the ecosystem types within the watershed and our sampling design, some ecosystem types were represented by very few ($n = 2–3$) sample points. Because we wanted to avoid these small sample numbers leveraging our statistical analyses, we grouped ecosystem types with similar parent materials. This resulted in grouping two banded outwash over till ecosystem types with loamy lamellae within 150 cm of the soil surface, resulting in the banded outwash over till group, and grouping four ecosystem types with at least 150 cm of sandy glaciofluvial or eolian parent materials, resulting in the outwash ecosystem group. After aggregating, we had six landscape ecosystem type groups, which are shown in Fig. 3: (i) outwash-lake plain swamp, (ii) riparian wetland, (iii) aquic till, (iv) mesic till, (v) banded outwash over till, and (vi) outwash (including the outwash, outwash–dune, and outwash–beach ridge ecosystems).

**Topographic Wetness Index Formulation**

The second type of spatial framework we used to assess the patterns of soil VWC and water table position were topographic wetness indices. One was based solely on topographic inputs; the second added soil properties. These use the continuous variation in elevation and soil transmissivity over space to predict wetness at finer spatial levels than the Landscape Ecosystem map units. These indices, known collectively as TWIs, were initially proposed by Beven (1986), Beven and Kirkby (1979), and Kirkby and Weyman (1974). We generated these two indices with high-resolution topographic inputs and soil properties derived from field measurements across the Honeysuckle Creek watershed. The topographic index (TI) takes the form:

$$TI = \ln \left[ \frac{a}{\tan(\beta)} \right]$$

where $a$ is the upslope area per unit contour (m), and $\beta$ is the local slope angle, both determined from a digital elevation model (DEM). We also used the soil topographic index (STI), which adds soil properties to the TI in the form:

$$STI = \ln \left[ \frac{a}{K_s D \tan(\beta)} \right]$$

where $K_s$ is the mean saturated hydraulic conductivity (m d$^{-1}$), and $D$ is the depth to the glacial till restrictive layer (m). We used both the TI and STI for this analysis to compare how the addition of soil properties to the TWI model affected the wetness index relationship to field hydrologic measurements.

We used a 0.3- by 0.3-m DEM derived from a 2015 leaf-off aerial lidar survey to delineate the Honeysuckle Creek watershed boundary and to model flow channels. We resampled the DEM to a 3-m cell size resolution for the topographic input to the wetness indices, as recommended by Buchanan et al. (2014). Depth to glacial till restrictive layer was measured in the field, and mean saturated hydraulic conductivity above the restrictive layer was estimated from field soil texture determinations using the textural triangle and $K_s$ estimates for medium bulk density soil (Schoeneberger et al., 2012). In ecosystems where no restrictive layer was observed, we set 400 cm as the depth value in the outwash upland ecosystems, because this was our maximum sampling depth capability, and 160 cm as the depth value in the outwash-lake plain swamp ecosystem, which was an average depth.
to sand C horizon taken from a combination of our soil sampling observations and drinking water well logs from adjacent property owners. Field measurements within each landscape ecosystem were averaged to provide $D$ and $K_s$ values as inputs for the STI. The TI and STI maps were generated with the maximum triangle slope calculation (Tarboton, 1997) and the multiple triangular flow direction algorithm (Seibert and McGlynn, 2007), as suggested by Buchanan et al. (2014). The TI map used for this analysis is shown in Fig. 4. Area-weighted TWI values were extracted within a 3-m buffer around soil moisture sample points and within a 10-m buffer around water table sample points to account for GPS accuracy. ArcGIS (ESRI Inc.), the System for Automated Geoscientific Analyses Geographic Information System, and the RSAGA package in R (Brenning, 2007; R Core Team, 2016) were used to generate the topographic wetness indices.

**Point Level Physical Properties**

We summarized a range of physical properties at each sampling point based on field measurements and digitized elevation and landform GIS data. These properties were: soil texture, depth to restrictive layer, drainage class, basal area, slope class, elevation, and landform. When field observations were not available at a point, we used an average of measurements made within the same landscape ecosystem type. We designated soil texture class and measured depth to glacial till restrictive layer in the field. Depth to restrictive layer measurements were grouped at 100-cm intervals for analysis, with 500 cm assigned for points where no restrictive layer was observed. We assigned soil drainage classes (excessively drained to very poorly drained; Schoeneberger et al. [2012]) based on observations of soil profile morphology (e.g., on the basis of redoximorphic features or indications of impeded or lateral drainage) and Landscape Ecosystem classifications (Pearsall et al., 1995). We calculated the basal area of live overstory vegetation from point-quarter vegetation surveys of trees with a diameter at breast height >8 cm. Slope was calculated within a 5-m buffer around each point using the high-resolution DEM and grouped by USDA–NRCS slope classes (nearly level to steep). Elevation at each point was extracted from the DEM, and then points were grouped based on the levels of significant postglacial lakes (i.e., Lake Nipissing below 190 m, Main Lake Algonquin 190–225 m, Early Lake Algonquin 225–255 m, no lakes with shorelines higher than 255 m). Major and minor landform designations were based on topography and parent material (e.g., outwash, moraine) and are the two levels of the classification hierarchy above ecosystem type (Pearsall et al., 1995).

**Data Analysis**

We performed statistical analyses of soil VWC and water table position to characterize seasonal hydrologic patterns across the Honeysuckle Creek watershed and to evaluate whether existing spatial frameworks (Landscape Ecosystem classification, TWIs) could be used to assess spatial variability and patterns of wetness. Data were examined by meteorological seasons: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). Statistical analyses were conducted with R (R Core
Team, 2016) and SigmaPlot (SYSTAT Software). Histograms and boxplots of soil VWC indicated two distinct soil hydrologic conditions, with the Terric Haplosaprists (below 190-m elevation) being permanently saturated through all seasons and the mineral soils (Haplorthods, Epiaquods, and Endoaquents) varying seasonally from dry to saturated. Given these fundamental differences in hydrology and matrix material, we separated the Terric Haplosaprists (outwash–lake plain swamp ecosystem) from all other soils in the TWI analyses. Due to non-normally distributed data that could not be transformed into normality, we used nonparametric Kruskal–Wallis one-way ANOVA on Ranks with Dunn’s Method of Comparisons to determine which static physical properties were significant predictors of median soil VWC and water table position based on $H$ statistic and $p$ value. Statistically significant $p$ values for this analysis were adjusted from $p < 0.05$ to $p = 0.0063$ by a Bonferroni correction due to repeated Kruskal–Wallis tests for each group ($n = 8$).

To address our second objective, we used two methods to evaluate the ability of the two spatial frameworks to represent spatial patterns of moisture. To evaluate the Landscape Ecosystem classification, we used Kruskal–Wallis tests to determine if soil VWC and water table position differed by ecosystem group and then if there were any seasonal differences within each ecosystem. We used daily soil VWC and water table measurements (when water was observed in wells). Due to a small number of sample points in some of the outwash ecosystem types, we compared moisture between the six ecosystem groups described above. In these tests we accepted results as statistically significant at $p < 0.0071$ due to Bonferroni correction ($n = 7$). We also assessed individual point-scale variability in measured soil VWC by comparing the mean SD of the three measurements taken at each point between landscape ecosystem types with Kruskal–Wallis tests.

We used linear regressions to test the relationship between TWI values (TI and STI) and measured soil VWC and water table position in each season. We used seasonal mean soil VWC and water table positions at each point and point-level TWI values. Non-normal data were transformed for this analysis. To assess the utility of TWIs in different soils, we grouped points by parent material (i.e., outwash, till) and tested the relationship between TWI and mean soil VWC for each season. Outwash soils (outwash >3 m deep) were compared with till soils (soils with glacial till restrictive material within 3 m of surface). All water table sample points were in till soils. We used dummy variable coding to test for significant differences between the outwash and till regression models as well as the different seasonal regression models.

### Results

#### Soil Moisture and Water Table Position across the Watershed

Soil moisture conditions varied widely throughout the Honeysuckle Creek watershed, with generally drier conditions at higher elevations and in glacial outwash landforms and wetter conditions in lower elevation areas underlain with glacial till. Water tables were observed from Burt Lake (181 m) up to 240 m elevation in places where glacial till was within 3 m of the ground surface. In contrast to the lower soil VWC observed across much of the watershed, soil VWC was highest in the riparian areas and in the low-lying wetland ecosystem; the water table was also closer to the surface in these portions of the watershed. Figure 5 illustrates
the spatial distribution of soil moisture and water table position at point locations across the watershed, highlighting the seasonal shifts in moisture conditions. Seasonal distributions of soil VWC and water table position indicate two fundamentally different moisture conditions between the organic soils in the outwash-lake plain swamp and the mineral soils of the other ecosystem groups (Fig. 6). Specifically, the outwash-lake plain swamp organic soils had higher median soil VWC (53%) and shallower depth to water table (8 cm below surface) than the drier mineral soils (17% VWC) with deeper water tables (22 cm below surface).

Moisture conditions also varied seasonally. In mineral soils, soil moisture was highest and the water table closest to the surface in spring, whereas organic soils were saturated in both spring and autumn, and the water table was within 7 cm of the surface. In both soil types (organic and mineral), soil moisture values were the lowest and water tables furthest from the surface in summer. Setting aside seasonal dynamics, a range of physical factors appeared to influence the soil moisture patterns that we observed across the watershed. Drainage class, soil texture, depth to restrictive layer, minor and major landforms, and elevation were all significant predictors of soil VWC in all seasons ($p < 0.0063$). These properties were also significant predictors of water table position, but only in the summer and autumn seasons; water table position in spring and winter was not related to any physical factor.
Among physical factors, slope class was the only nonsignificant predictor of soil VWC or water table position in any season. Our metric of forest biomass (live tree basal area) did not have significant predictive capacity for either soil VWC or water table position.

**Spatial Framework 1: Ecosystem Level Patterns of Wetness**

The Landscape Ecosystem classification was an effective framework to assess significant differences in soil wetness and water table position across ecosystem groups. Specifically, median soil VWC for the entire sampling period differed significantly for all ecosystem groups \( (p < 0.0071) \) except the riparian wetland and aquic till types (Table 1). Across the watershed, the wettest soil conditions in the outwash-lake plain swamp ecosystem, where soils were perennially saturated, and the driest conditions were in the outwash and banded outwash over till ecosystems where soils were around field capacity in all seasons. Regarding differences in mean soil VWC from season to season (Fig. 7), the riparian wetland and aquic till ecosystems experienced the greatest change in mean VWC across the seasons, changing by 11 to 12% VWC, whereas other ecosystems varied by only 1 to 3% VWC. In the mesic till and outwash ecosystems, soil VWC differed across all seasons, being wettest in spring and driest in summer. In the outwash-lake plain swamp, spring VWC was highest and differed only from summer VWC. In the riparian wetland, aquic till, and banded outwash over till ecosystems, spring soil VWC was higher than summer and autumn measurements.

<table>
<thead>
<tr>
<th>Landscape ecosystem group</th>
<th>Sample points (n)</th>
<th>Soil VWC All observations</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outwash-lake plain swamp</td>
<td>9</td>
<td>53 (47, 57) (^\dagger)</td>
<td>54 (51, 58)</td>
<td>51 (43, 56)</td>
<td>53 (47, 57)</td>
</tr>
<tr>
<td>Riparian wetland</td>
<td>9</td>
<td>25 (21, 33) (b)</td>
<td>35 (22, 46)</td>
<td>23 (17, 34)</td>
<td>24 (19, 35)</td>
</tr>
<tr>
<td>Aquic till</td>
<td>12</td>
<td>25 (19, 38) (b)</td>
<td>35 (30, 41)</td>
<td>24 (20, 29)</td>
<td>24 (21, 28)</td>
</tr>
<tr>
<td>Mesic till</td>
<td>13</td>
<td>18 (16, 21) (c)</td>
<td>20 (18, 29)</td>
<td>17 (15, 20)</td>
<td>19 (17, 21)</td>
</tr>
<tr>
<td>Banded outwash over till</td>
<td>20</td>
<td>17 (15, 18) (d)</td>
<td>18 (17, 19)</td>
<td>16 (14, 18)</td>
<td>18 (16, 19)</td>
</tr>
<tr>
<td>Outwash</td>
<td>33</td>
<td>16 (15, 18) (e)</td>
<td>18 (16, 18)</td>
<td>15 (14, 17)</td>
<td>17 (15, 18)</td>
</tr>
</tbody>
</table>

\(^\dagger\) Significantly different medians among ecosystem groups \( (p < 0.0071) \) are denoted with different letters for the full annual dataset.
In all ecosystems where wells were placed, median water table positions differed significantly (Table 2). Across the watershed, water table levels ranged in depth from very near to the ground surface in low topographic positions to meters deep (or even nonexistent) in upland areas (below our deepest wells). Water tables were closest to the ground surface in the outwash–lake plain swamp and riparian wetland, followed by the aquic till ecosystem; these ecosystems had median annual water levels within 25 cm of ground surface. In the mesic till ecosystem, median water table levels were greater than 50 cm below the surface, and the two wells in the outwash ecosystems had water tables more than 100 cm below ground. Although we did place two wells in outwash ecosystems, specifically the outwash–dune and heavily banded outwash ecosystems, these points were at the intersection of outwash and till areas and were not representative of most outwash areas. We did not observe water tables or evidence of saturation in the banded outwash over till ecosystem or at many points within outwash ecosystems during soil profile observations.

Water table position fluctuated widely in the wells, with some wells drying up for weeks to months at a time and others maintaining water levels within a few centimeters throughout the year (Fig. 8). Generally, water table levels were closer to the surface in the spring and winter seasons and dropped during the summer and autumn seasons, with some wells even drying up during these seasons. Specific seasonal differences varied within ecosystem types. In the outwash-lake plain swamp, summer median water table position was significantly lower than in the other seasons. In the riparian wetland, winter and spring water levels were significantly higher than summer and autumn levels, with water ponding on the surface in some areas. Similarly, in the aquic till ecosystem water table positions were significantly closer to the surface in spring and winter, with the highest levels in the spring and the lowest levels in summer and autumn. In the mesic till ecosystem, water tables were highest in spring and lowest in autumn and did not significantly differ between winter and summer. Water table levels in outwash ecosystems did not differ significantly among seasons.

**Spatial Framework 2: High-Resolution Patterns of Wetness**

Within each 0.07- to 25.5-ha Landscape Ecosystem map unit in the watershed, a range of local topographic positions, fine-scale soil variation, and wetness conditions exist. Within such heterogeneous ecosystems as these, one estimate of soil VWC or water table position might not adequately characterize the range of moisture conditions observed. Ecosystem types with mixed hydrologic

**Table 2. Water table position across the full period of observation and within each season by ecosystem group. Groups consist of individual ecosystem types with similar parent materials. For each ecosystem group, the number of sample points (locations) and the median, with the 25th and 75th percentiles in parentheses, of periodic water table measurements are shown. Negative values indicate water below the ground surface.**

<table>
<thead>
<tr>
<th>Landscape ecosystem group</th>
<th>Sample points (n)</th>
<th>Water table position (cm from surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All observations</td>
<td>Spring</td>
</tr>
<tr>
<td>Outwash–lake plain swamp</td>
<td>26</td>
<td>−8 (−20, −3)†</td>
</tr>
<tr>
<td>Riparian wetland</td>
<td>3</td>
<td>−6 (−10, −1)b</td>
</tr>
<tr>
<td>Aquic till</td>
<td>11</td>
<td>−25 (−39, −17)c</td>
</tr>
<tr>
<td>Mesic till</td>
<td>7</td>
<td>−65 (−123, −37)d</td>
</tr>
<tr>
<td>Outwash</td>
<td>2</td>
<td>−139 (−155, −100)e</td>
</tr>
</tbody>
</table>

† Significantly different medians among ecosystem groups \( (p < 0.0071) \) are denoted with different letters for the full annual dataset.
conditions (riparian wetland, aquic till, mesic till) had larger standard deviations (4–7% VWC) at each triplicate sampling point than the ecosystems with consistently drier moisture conditions (2% VWC). Topographic wetness indices, with each pixel covering 9 m², were tested against field-measured moisture conditions to determine if these higher-resolution spatial frameworks could account for local variation and provide finer-scale estimates of soil VWC and water table depth, which could be especially useful in areas with mixed hydrologic conditions.

Relationships between TWIs and soil VWC revealed that soil parent material created two distinct hydrologic conditions. Across all seasons, point-level soil moisture values in outwash soils (excluding the organic soils of the outwash–lake plain swamp) were below 20% VWC, despite STI values for those points ranging from 0 to 8.2. In contrast, till soils showed increasing VWC (15–50%) with increasing STI values. Linear regressions with STI values and soil VWC were statistically significant for both the till ($p < 0.001$; $R^2 = 0.25–0.38$) and outwash soils ($p = 0.005–0.024$; $R^2 = 0.11–0.16$) with increasing STI values. Linear regressions with TI values and soil VWC were also significant for both parent materials. In addition, all seasonal VWC models were significantly different. In outwash soils, TI-based models ($p = 0.003–0.021$; $R^2 = 0.11–0.18$) were very similar to STI-based models; however, in till soils the TI-based models explained less of the variation in soil VWC ($p = 0.001–0.018$; $R^2 = 0.14–0.24$) than the STI-based models. In till soils, the STI provides better estimates of VWC than the TI. Based on dummy variable coding, model slopes were significantly lower for outwash points than till points for both TI and STI models. Although the outwash soil linear regressions were statistically significant, the very shallow slopes of the TI and STI models raises questions about the utility of TWIs in very deep and conductive soils.

Although the STI was the more statistically significant TWI form for estimating soil moisture, especially in till soils, both the STI and TI could be used to estimate water table position from ground surface when water is present (Fig. 10). Seasonal mean water table depth was estimated with both TI and STI values for all seasons using linear models ($R^2 = 0.17–0.47$ for TI models; $R^2 = 0.30–0.62$ for STI models). Summer and autumn had the strongest linear model fits ($R^2 = 0.44$ [summer] and 0.47 [autumn] for TI; $R^2 = 0.60$ [summer] and 0.62 [autumn] for STI), followed by spring ($R^2 = 0.23$ for TI; $R^2 = 0.33$ for STI) and winter ($R^2 = 0.17, p < 0.071$ for TI; $R^2 = 0.30$ for STI). Comparing the seasonal linear models, there were no significant differences between the spring and winter models or between the summer and autumn models based on dummy variable coding. This was true for both the TI- and STI-based models. Both TI and STI values were good predictors of mean water table position, but models using STI values provided a slightly better estimate of water table position.

**Discussion**

Topographic position and parent material establish three soil hydrologic regimes (dry, wet, or mixed) across the Honeysuckle Creek watershed. These hydrologic regimes include the dry...
outwash uplands, the wet outwash–lake plain swamp, and the mixed moisture areas underlain by shallow till. The dry regime is driven primarily by soils with high infiltration rates, the wet regime formed in low topographic areas receiving drainage from uplands, and the mixed moisture regime occurs in areas with both lateral transport of water and soils with a restrictive feature near the surface. Across the watershed, local soil properties have the strongest control over soil moisture conditions, whereas deeper ground water patterns are driven by both soil properties and topography. The following discussion addresses which spatial frameworks are the most appropriate to use in each of these hydrologic regimes in our study area.

**Hydrologic Regimes across the Watershed**

In the outwash ecosystems above 190 m elevation, the hydrologic regime was dry, with low soil moisture (15–18% VWC) conditions varying little spatially across the ecosystems or throughout the year. Even in the wettest season (spring, post-snowmelt), soil VWC remained at 18%, and no evidence of shallow groundwater was observed. These sandy soils continued to dry in summer as vegetation water use peaked (He et al., 2014) and remained dry throughout autumn. In this moisture regime, soil texture and the great depth of outwash material drives consistently dry surface moistures, and the limited water holding capacity and lack of restrictive material prevents shallow groundwater retention or perching on shallow restrictive layers. Furthermore, the abundance of species with deep rooting and high water use strategies, such as *P. grandidentata* and *Q. rubra*, dominate in this area and may draw down available soil water (He et al., 2013; Matheny et al., 2016).

In contrast, wet moisture conditions were observed in the outwash–lake plain swamp where median soil water remained at or above saturation and varied by only 1 to 3% VWC throughout the year, and water table levels were persistently within 10 cm of the ground surface. These wet conditions may exist because the low-lying swamp is receiving groundwater draining from higher topographic areas in the mid-elevations of the watershed (Nave et al., 2017a; Zogg and Barnes, 1995). The relatively continuous glacial till parent material in the middle elevations of the watershed (present at elevations from 245 m down to 190 m) provides a surface for shallow water to drain to the outwash–lake plain swamp throughout the year. Additionally, evapotranspiration in this mixed conifer wetland is likely lower than in the upland forests dominated by *P. grandidentata* and *Q. rubra* (Ewers et al., 2002). The low-lying landscape position coupled with low hydraulic conductivity organic soils and slow growing vegetation (e.g., *T. occidentalis*, *A. balsamea*, *T. canadensis*) allow for persistent saturation and a wet moisture regime in the outwash-lake plain swamp (Boelter, 1969; Nave et al., 2017b; Zogg and Barnes, 1995).

Ecosystem types occupying the middle elevations of the watershed possess mixed hydrologic conditions due to glacial till relatively near the surface, supporting the lateral transport of water perched on the restrictive material (the mesic till, aquic till, riparian wetland ecosystems). Here, moisture was greatest in the spring, with highest soil VWC and water table positions closest to the surface. In the middle elevations, ecosystems with deeper, more well-drained soils averaged 20% VWC, and the water table was 33 cm below the surface; in ecosystems occupying lower topographic areas with shallower soils, spring VWC was 35%, and water tables were within 25 cm of the surface or even at the surface.
in many areas. Vegetation in these ecosystems consists of a diverse assemblage of mesic species, including *A. rubra*, *A. saccharum*, *P. grandidentata*, *P. tremuloides*, and *F. americana* (Pearsall et al., 1995). Some of these species (e.g., *Acer* spp, *P. grandidentata*) differ in their transpiration rates and rooting depth, and these physiological differences could be contributing to point-to-point variation in moisture (Ewers et al., 2002; Gale and Gale, 1987). A second, not mutually exclusive, possibility is that slow lateral drainage of snow melt, finer-textured parent materials with higher water holding capacity, and thicker organic horizons keep median soil VWC around 25% and water table levels high throughout the summer and autumn, especially in the lowest topographic positions.

**Applicability of the Two Spatial Frameworks**

In the dry and wet hydrologic regimes, the Landscape Ecosystem classification map units are at a small enough scale (tens of hectares) to represent both soil moisture and shallow groundwater conditions and to provide estimates of moisture at points not directly measured. In these areas, there was little variation in soil VWC or water table position, either temporally or spatially. Variation in soil moisture within each ecosystem group was minimal in the dry uplands (<2% VWC). This consistency across the range of elevations, aspects, and slopes suggests that the excessive drainage of the deep, coarse-textured outwash soils overrides any topographic influences on soil wetness in such settings. In the outwash-lake plain swamp, variation in soil moisture content was also relatively low and was very localized in relation to surface microtopography and the thickness of the bryophyte cover. In this ecosystem, the low elevation, level topography, and large contributing area drive consistent conditions that are the opposite extreme from the xeric outwash uplands.

In the mixed hydrologic regime with heterogeneous soils that have formed in the unsorted glacial till, both soil and topography are important factors controlling moisture. Although the Landscape Ecosystem classification was able to distinguish significant differences in moisture among these ecosystems (mesic till, aquatic till, riparian wetland), within-ecosystem soil VWC varied from 15 to 46%, very local variation (i.e., among triplicate sampling points) was as high as 6% VWC, and VWC varied by over 10% seasonally. Because the till is comprised of a wider range of glacial sediments that are distributed in a nonuniform manner (i.e., as compared with water-sorted glacial deposits), the finer-scale integration of soil and topographic properties afforded by the TWIs was needed to represent the spatial patterns of wetness in areas underlain by till. Although both the TI and STI could be used to estimate soil VWC and water table position in till soils, the inclusion of soil properties in the wetness index was essential for optimal estimates of soil VWC and slightly improved estimates of water table position.

**Broader Relevance of Topographic Wetness Indices**

Although not intended to be globally representative, our study area has sufficient variation in parent material and topography to
assess the ability of TWIs to represent moisture conditions across a wide range of physical factors that control wetness in glacial drift landscapes. Our analysis suggests that TWIs provide the most accurate estimates of soil moisture and water table position and are most appropriate in areas of the watershed with glacial till restrictive material within 3 m of the ground surface. Many other studies have also observed reasonably good relationships between soil moisture and groundwater level and TWIs in primarily forested study areas (8–190 ha) with shallow soils above restrictive layers or bedrock (e.g., Beaudette et al., 2013; Lin et al., 2006; Penna et al., 2009; Rinderer et al., 2014). However, in study areas with conductive soils or relatively flat topography with low hydraulic gradients, the observed relationships between TWIs and moisture conditions have been weaker, possibly because surface topography is not a strong control on groundwater under such conditions (e.g., Bachmair and Weiler, 2012; Barling et al., 1994; Case et al., 2005; Grabs et al., 2009). In glaciated areas with both till and deeper alluvial soils, Grabs et al. (2012) observed good predictions of water table depth from a TI in both till and alluvial sediment in Sweden, although the TI provided better estimates of riparian zone carbon characteristics in the till areas compared with the alluvium sediment areas. Approximately 170 km north of our study area, Monteith et al. (2006) observed a positive relationship between TI and water table depth in two glacial drift watersheds (5–6 ha), although this positive relationship was only true for wells in basal till, and they observed no relationship in ablation till areas. Our study strengthens and extends the inference of that work by indicating that dense, impermeable glacial till has a controlling influence on wetness and a functional role similar to bedrock, even in landscapes where its distribution is discrete and interrupted by other types of glacial parent materials.

In these heterogeneous glacial landscapes, we must consider landform and parent material when deciding where to use TWIs to identify moisture patterns. Where there is low hydraulic conductivity glacial till restrictive material, perched shallow water tables can form above this horizon, connecting shallow groundwater and surface soil water vertically as well as connecting these points to others along hillslopes and into riparian zones (Ali et al., 2011; Detty and McGuire, 2010). The distribution of perched water tables can activate surface and subsurface flow pathways, resulting in expanded hydrologic connectivity between the landscape and the stream network (Gburek et al., 2006; Gillin et al., 2015; Jencso et al., 2009; Tetzlaff et al., 2014). In places with deep outwash lacking some restrictive component to create a perched water table and connect surface soil and groundwater, topographic indices are likely not the most appropriate spatial framework for identifying moisture patterns. This analysis indicates that, in ecosystems where VWC and water table position do not vary much, such as ecosystems with outwash parent materials, ecosystem classifications can be used instead of TWIs to estimate moisture patterns. In the mineral outwash soils, flow paths identified by the TWIs had no relationship with moisture conditions or soil profile observations. However, in the outwash-lake plain swamp, TWI flow paths were able to identify subtle, topographically driven differences in water movement that induced spatial patterns in soil morphology and distribution of elements (Nave et al., 2017a).

Applications to Mapping, Management, and Research

Studies like the present one can be used to reveal relationships between measured moisture conditions and static factors that are important controls (e.g., topography, soil characteristics) and contribute to the body of scientific knowledge about where spatial frameworks, especially TWIs, are appropriate. In addition, the ability to map static factors provides a basis for mapping soil moisture and water table positions around the upper Midwest region either through ecosystem classifications or TWIs, which can then be used to identify forest ecosystems that should be targeted for management or further research. Using multiple levels of the Landscape Ecosystem classification system from the individual ecosystem up to the ecoregion, Nave et al. (2017b) found that physiographic and soil factors can be used to predict forest biomass production rates. Although they observed that biomass production rates varied under different moisture conditions (i.e., xeric, mesic, hydric), these moisture groups were based on field observations or estimates, not on quantifiable measurements of soil water. The insights of Nave et al. (2017b) and the results of the present study could be used to make important land management decisions that could affect terrestrial water storage and availability as well as forest productivity. Using maps of the spatial distribution of soil moisture and water tables, forest managers could select the most productive sites for timber harvesting or identify ecosystems that are vulnerable to changes in the climate and that would be critical areas to target for restoration or adaptation (Duveneck et al., 2014). In addition, although ecosystem classifications are often used to focus conservation efforts related to vegetation species (e.g., Boyle et al., 2014), they could also be used to conserve water resources.

Our quantitative moisture measurements and relation to spatial frameworks can be used to identify watersheds areas that are important sites for terrestrial–aquatic interactions and sources of materials exported to surface waters. Given our full annual period of observation, we have observed that seasonal variation is generally lower than spatial variation within all three hydrologic regimes, although, shorter-term fluctuations in wetness did occur, particularly in the mixed hydrologic regime. These peaks in soil moisture and water table level due to storm events could be important for element processing and transporting material through the watershed (Brown et al., 1999; Duncan et al., 2015; Inamadar et al., 2004; Sebestyen et al., 2014). Snowmelt and rain can cause the lateral and vertical expansion of variable source areas across the watershed and into organic rich near-surface soil horizons that are only connected to the stream at lower flows (Boyer et al., 1997; Lambert et al., 2014; Tetzlaff et al., 2014). Both TWIs and the Landscape Ecosystem classification can be used to identify the areas, such as riparian zones and topographic lows, that are likely to respond to precipitation events and to be sources of carbon or nitrate.
(Andrews et al., 2011; Duncan et al., 2013; Gannon et al., 2015) flushed from terrestrial to aquatic ecosystems. In addition to the research aspect, TWIs could be used as a tool to minimize disturbances in wet areas during forest harvesting to limit the movement of sediment and water-transported materials to aquatic ecosystems.

**Conclusions**

Our measurements of soil water and shallow groundwater through a hydrologic year provide a baseline for understanding the spatial patterns and temporal dynamics of terrestrial water in the Honesuckle Creek watershed. We have identified three dominant hydrologic regimes across the watershed and the spatial frameworks that are most appropriate to estimate moisture conditions at points we are unable to sample. Although either spatial framework (ecosystem classification or TWI) can be used to estimate water table position, a combination of both approaches is most appropriate for estimating soil VWC in this region. In areas with minimal soil moisture variation (dry or wet) with relatively homogenous overwash soils, larger ecosystem classification map units provide good estimates of moisture conditions. In areas with very heterogeneous till soils, finer-scale spatial frameworks that account for local soil variation are optimal for characterizing spatial patterns. Using spatial frameworks to map soil moisture and water table positions in the Great Lakes region can aid in identifying biogeochemically important sites, such as those at terrestrial–aquatic interfaces, or can be applied to inform forest management decisions and conservation efforts.

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P. 17 of 17