Do Soil Surveys and Terrain Analyses Identify Similar Priority Sites for Conservation?

M. D. Tomer* and D. E. James

ABSTRACT

Terrain analyses may help target conservation practices, but soil survey is the traditional basis for conservation planning. This study’s objective was to identify correspondence between terrain and soil survey attributes. Iowa’s South Fork (78,000 ha) and West Nishnabotna (64,000 ha) watersheds provided example datasets. Major resource concerns are soil wetness in the South Fork’s glacial terrain, and soil erosion in the West Nishnabotna’s loess hills. Slope, contributing area, curvature, and wetness (W) and erosion (E) indices, calculated from National Elevation Database (30-m) data, were each divided into two groups according to highly erodible land (HEL), hydric-soil, drainage-class, topsoil-thickness, clay, and organic matter content attributes from soil survey delineations. All groupings had different means (p < 0.001), but proportions of captured variance ranged from 0.1 to 22%. Critical values of slope and W segregated hydric, drainage, and topsoil-thickness groups with 66 to 74% accuracy in both watersheds, and slope and E segregated HEL groupings with 71 to 76% accuracy. Finer detail in terrain data appeared realistic in dissected terrain, but artificial in near-level terrain. The largest 20% of W values were about 80% hydric soils in the South Fork, and the largest 20% of E values were about 80% HEL in the West Nishnabotna. However, similar statements on E and HEL in the South Fork, and W and hydric soils in the West Nishnabotna, applied to few cells (<2%) with <70% accuracy. Therefore, targeting of conservation practices based on 30-m grid terrain analysis can be consistent with soil survey information, but to a degree that varies by landscape and resource concern.

Available data are often used to plan policy and management responses to specific environmental issues. Soil survey information is commonly used in this context. Soil surveys include information on slope, drainage class, wetlands and hydric soils, crop productivity, and other attributes that can be used to plan best management practices, or to regulate development (e.g., septic systems, wetland protection, etc.). These attributes are often related to the landscape and its hydrology as well as to soil types.

Digital terrain analyses have also been used to make interpretations relevant to land resource management and decision-making. Applied research has led to demonstration of mapping techniques for riparian management (Baker et al., 2001; Bren, 1998; Tomer et al., 2003), crop-yield mapping (Kaspar et al., 2003; Kravchenko and Bullock, 2000), and hydric soil delineations (Thompson et al., 1997).

Relationships between digitally derived terrain attributes and soil hydrology have been explored for more than 20 yr. Early work (e.g., O’Loughlin, 1981) focused on soil wetness, and recent studies have investigated soil water contents (Western et al., 1999) and water retention (Pachepsky et al., 2001). Terrain attributes may help modify pedotransfer functions (Romano and Palladino, 2002) that relate soil properties (texture, organic matter, density) to water retention characteristics and hydraulic conductivity. The influence of terrain on spatial patterns of soil moisture may be strongest during periods of surplus moisture (i.e., precipitation > evapotranspiration) (Grayson et al., 1997). Bell et al. (1994) and Merot et al. (1995) have reported that terrain attributes can be used to predict soil drainage class with reasonable accuracy, provided that geologic/geomorphic conditions are either simple, or included in the landscape modeling process. At a regional scale, geologic information can provide a basis to stratify the survey area, and then terrain data can improve predictions of soil properties within areas of similar geology and landform (McKenzie and Austin, 1993).

Soil attributes that are influenced by hydrologic processes have also been related to terrain characteristics. Moore et al. (1993) demonstrated that multiple soil attributes (A-horizon thickness, organic-matter content, NaHCO3-extractable P, pH, and texture) could be predicted (with r2 ranging from 0.41 to 0.64) and mapped using terrain parameters (slope, aspect, profile curvature, wetness and stream-power indices). Gessler et al. (2000) showed soil depths, productivity and mass of organic C in the soil profile could be predicted using slope, contributing area, and topographic wetness index (with r2 from 0.52 to 0.85). Park and Burt (2002) evaluated a broad range of soil properties on an English hillslope with podzolic soils (dominantly Fragiaquods, Haplorthods, and Dystrudepts), and found the predictive capacity of terrain features varies greatly depending on depth and the soil property of interest. These studies have typically occurred on individual hillslopes or small basins. Few studies have examined correspondence between terrain attributes and soil survey data at scales typical of public sources used for resource management planning in large watersheds. These have typically been single-issue studies, examining classes of either slope (Hammer et al., 1995) or drainage (Bell et al., 1994; Merot et al., 1995).

Conservation professionals are facing demands to show what benefits to the environment are derived from resource assessment, planning, and management activities on regional and watershed scales. Targeting investments in conservation at critical areas for nonpoint pollution control is being advocated as a way to increase those benefits. Terrain analyses may offer techniques...
to identify critical areas, but do these techniques provide results that are consistent with soil survey information? Can terrain data be used with soil survey information to improve the quality of resource analysis, and develop strategies for targeted placement of best management practices? These questions can only be answered if the correspondence between these two data sources is understood in a comprehensive context. This study explores this correspondence for publicly available datasets that could be applied toward resource planning in two Iowa watersheds.

**Map Data Sources and Issues**

Several issues need to be considered in comparing soil survey and digital terrain data, in terms of the strengths and weaknesses of mapping processes. While digital terrain analysis can aid in delineating soils (Klingebiel et al., 1987; McKenzie and Austin, 1993), the practice of soil survey is grounded in human observation and interpretation of soil patterns on the landscape (Ruhe and Walker, 1968). Most soil surveys in the USA are based on interpretations of soil scientists, who rely on field observation, and interpretation of aerial photographs and topographic maps. An understanding of the distribution of soils on the landscape is developed based on an integrated knowledge of topography, geomorphology, vegetation, and other factors. Individual surveyors make local observations and interpret this knowledge when mapping soils in the field. Field checks and correlations across survey area boundaries are used to minimize inconsistencies that naturally arise from differences in interpretation among individuals and survey teams. Soil survey delineations are intended to allow consistent and reliable land-use interpretations. Intricate soil patterns are often not delineated, resulting in map unit complexes, and distinct areas smaller than about 2 to 4 acres are seldom delineated. Buol et al. (1997) provide a good overview of soil classification and soil survey in the USA, and detailed information is also available (Soil Survey Division Staff, 1993).

Terrain analyses provide output that can be expressed as a continuous variable in a raster format, rather than classified map units that typify soil surveys. Publicly available digital elevation data are produced by interpolation of USGS quadrangle maps, and grid cells of the output raster maps are typically at a 30-m spacing. Land cover complexity, and the contour interval and age of the original quadrangle maps influence the quality of the derived digital elevation model (DEM). A set of terrain attributes can be calculated from DEM data, including slope, aspect, curvature, and upslope contributing area. Several methods can be used to calculate each of these parameters (e.g., Blaszcynski, 1997; Tarboton, 1997; Wilson and Gallant, 2000), and (obviously) results vary with the method used.

Several issues affect comparison between soil survey maps and digital terrain data, including the following. First, soil variation may follow topography that is not represented on a 30-m DEM. While dissected terrain may be well represented, areas of level terrain often lack detail. Even on flat lacustrine terrain, there are runoff and ponding patterns that can lead to considerable soil variation (Knuteson et al., 1989). These patterns might be readily interpreted on aerial photographs during soil mapping, but be indiscernible on a DEM. Second, data derived from analysis of a DEM are expressed as continuous variables, whereas soil survey data are classified variables. Statistical correlation can only be determined between two sets of continuous variables. Therefore, in this paper, the terms correspondence and association are used in quantifying relationships between classified (soil survey) and continuous (DEM) variables. Third, errors within the two data sources are difficult to quantify, particularly at a large-watershed scale. Soil surveys can (and do) identify ranges of soil variation expected within an individual map unit. However additional sampling is needed to depict spatial variation within soil map units (e.g., see Rogowski and Wolf, 1994), and sampling strategies must be selected carefully (considering underlying assumptions) for robust statistical representation (Young et al., 1998). Errors in DEM data (elevation and derived attributes) have been reviewed elsewhere (Wilson and Gallant, 2000), and can be considerable, depending on the original data and interpolation algorithms used in rasterization. Fourth, scale is a critical issue in soil survey, and in soil-landscape and terrain analysis (Wilson et al., 1996; Wilson et al., 1998). Scale determines the smallest feature that can be delineated on a map, and affects values of calculated terrain attributes (Shary et al., 2002). Soil survey and topographic quadrangle maps in the USA are frequently constructed at a 1:24,000 scale, and therefore combined use of soil survey and USGS DEM data for many locations does not involve a mixing of map scales. Map sources in this study were all originally produced at 1:24,000. In summary, these two publicly available data types should be regarded as representations of the landscape, each having strengths and flaws, but also containing information useful for resource analysis and management.

The purpose of this study was to determine the correspondence between soil survey delineations and terrain parameters, obtained from public data sources, that could be used for similar purposes in resource assessment and targeting conservation measures. The underlying hypothesis is that information from soil surveys and terrain analyses will identify similar locations as being important for managing particular soil-resource concerns. This study was an effort to clarify whether this hypothesis is equally true amongst a set of resource concerns in two Iowa landscapes, under the context of watershed-scale planning/assessment using public data. Put simply, do soil surveys highlight areas of resource-management concern that are also identified through terrain analyses? What soil properties that are identified in a soil survey are associated with terrain attributes determined at the same (nominal) mapping scale? This study addresses these questions.

**MATERIALS AND METHODS**

Two Iowa watersheds were selected for analysis (Table 1, Fig. 1). The West Nishnabotna River watershed in western
Table 1. Dominant soil types occupying key landscape positions in the two watersheds selected for analysis (National Cooperative Soil Survey, 1984, 1985).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Landscape positions</th>
<th>Dominant soil series</th>
<th>Soil classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Nishnabotna</td>
<td>interfluve/shoulders</td>
<td>Marshall</td>
<td>Typic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>backslopes</td>
<td>Exira</td>
<td>Typic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>footslopes</td>
<td>Judson</td>
<td>Typic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>drainage ways/alluvial valleys</td>
<td>Colo &amp; Zook</td>
<td>Cumulic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>drainage ways/alluvial valleys</td>
<td>Ackmore</td>
<td>Cumulic Hapludolls</td>
</tr>
<tr>
<td>South Fork</td>
<td>summits/shoulders/upper backslopes</td>
<td>Nodoway</td>
<td>Aeric Fluvaquents</td>
</tr>
<tr>
<td></td>
<td>lower backslopes/footslopes</td>
<td>Clarion</td>
<td>Typic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>depressions (potholes)</td>
<td>Nicollet</td>
<td>Aquic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>depressions (potholes)</td>
<td>Webster &amp; Canisteo</td>
<td>Typic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>alluvial valleys</td>
<td>Coland</td>
<td>Typic Calciaquolls</td>
</tr>
<tr>
<td></td>
<td>depressions (potholes)</td>
<td>Harp</td>
<td>Cumulic Hapludolls</td>
</tr>
<tr>
<td></td>
<td>alluvial valleys</td>
<td>Spillville</td>
<td>Cumulic Hapludolls</td>
</tr>
</tbody>
</table>

Iowa (64,000 ha) is dominated by deep loess, which originated as glacial-meltwater sediment in the Missouri River floodplain that was blown east during retreat of Wisconsin ice sheets (Prior, 1991). This watershed has steep slopes, and a well-defined stream network. There is little artificial drainage. The stream network is young, and gully erosion and downcutting of streams have apparently increased since settlement. Soil erosion is a key resource concern, with about 57% of the area considered highly erodible. Hydric soils occupy about 24% of the watershed. Silt loams and silty clay loams are the most common soil textures (National Cooperative Soil Survey, 1984). The watershed occupies parts of Audubon and Shelby counties, and small areas in Pottawattamie and Carroll counties.

The second watershed was the South Fork of the Iowa River, which covers about 78,000 ha including tributaries of Tipton and Beaver Creeks. The watershed lies in Hardin and Hamilton counties, with small areas in Franklin and Wright counties. It is representative of the Des Moines Lobe, the dominant landform region of north-central Iowa. The terrain is young (about 10^4 yr since last glacial retreat), therefore natural stream incision and development of alluvial valleys.

Fig. 1. Maps of the West Nishnabotna and South Fork watersheds, showing the distributions of highly erodible land (HEL) and hydric soils identified from soil survey information. Non-shaded areas are neither hydric nor highly erodible.
has only occurred in lower parts of the watershed. Upper areas of the watershed are occupied by till plains and marginal moraines, with many internally drained “prairie potholes.” Post-glacial erosion, hydrology of shallow ground water, and soil development on landscapes typical of the Des Moines Lobe were discussed by Burras and Scholtes (1987) and Steinwand and Fenton (1995). Soil wetness is a major concern for land management and agricultural production, with hydric soils occupying about 54% of the watershed. Artificial subsurface (tile) drainage is prevalent, and nearly all potholes have been drained to a network of ditches that convey water to natural stream channels. Most soils are loam-textured, and HEL occupies about 13% of the watershed area. (National Cooperative Soil Survey, 1985, 1986). These two watersheds were selected because they are fairly simple in their physiography and parent material, but differ in topographic features, extent of stream dissection, and major resource concerns, namely soil erosion in the West Nishnabotna and soil wetness in the South Fork watershed.

Soil survey data for these two watersheds were extracted from the Iowa Soil Properties and Interpretations Database (Iowa State University Cooperative Extension Service, 1996). The database is linked to a state-wide raster coverage with a 30-m grid matching the elevation data. Rasterization of the soil survey polygons makes comparison with the terrain data straightforward, but map-unit boundaries are generalized according to a 30-m grid. Land-use interpretation data were extracted, including hydric soils, drainage class, and HEL. Surface soil properties, including topsoil thickness, organic matter content, and clay content, were also extracted for analysis.

Digital elevation data were extracted from the National Elevation Database (available with metadata from the U.S. Geological Survey, 2001). The data were processed by a pit-filling routine (Tarboton, 2002), which allows overland flow routing to be determined to the watershed’s outlet from any grid-cell location. This process is designed to remove presumed errors from the elevation data, although pits may represent the actual landscape in glacial terrain. The pit filling affected 7.1% of the South Fork watershed, most of which (3.9%) occurred as four or more contiguous grid cells (glacial depressions could be indicated by these larger filled areas). Pit filling only affected 3.1% of the West Nishnabotna; 0.7% was in contiguous areas, largely coinciding with ponds and reservoirs. Several terrain attributes were calculated from the processed elevation data using TauDEM software (Tarboton, 2002), including slope (β, expressed in degrees) and specific upslope contributing area (A_i), which is total upslope contributing area divided by the 30-m cell width (m^2 m^-1). Slope calculations were based on steepest descent to a neighboring cell. Upslope contributing areas were calculated using an ‘infinite’ (actually 360°) direction method described by Tarboton (1997), which proportionally assigns flow-area contributions to two adjacent downslope grid cells, according to the aspect of the steepest of eight triangular facets, formed among the centroids of two adjacent grid cells and its eight neighbors. The method provides realistic flow divergence on convex landforms, compared with other methods (Tarboton, 1997). A surface curvature value (C_s) was calculated using the following equation proposed by Blaszczynski (1997)

\[ C_s = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{z_i - z_{i+1}}{d_i} \right) \]  

[1]

in which n is the number of surrounding grid-cells used in the calculation (e.g., 24 for a 5 by 5 search window), z_i is the elevation of the central cell, z_{i+1} the elevation of the i-th surrounding grid cell, and d_i, the distance from the central to the i-th cell. This curvature value gives an average rate of elevation change between a grid cell and its neighbors (on a distance-weighted basis). It is positive for convex landforms, negative for concave landforms, and near zero for planar surfaces. Park et al. (2001) recently applied Eq. [1] to help classify landforms. In this application, Eq. [1] was applied using ARC macro language in ARCMAP software (ESRI, 2002).

Compound terrain indices for topographic wetness (Moore et al., 1991) and erosion (Moore and Wilson, 1992) indices were then calculated by

\[ W = \ln \left( \frac{A_i}{\tan \beta} \right) \]  

[2]

\[ E = \left( \frac{A_i}{22.13} \right)^{0.4} \sin \beta^{0.896} \]  

[3]

in which W is the topographic wetness index and E is the erosion index. Zero slopes were assigned a value of 0.0001 (for tanβ) to calculate a value for W. This reassignment influenced 3.7% of the grid cells in the West Nishnabotna watershed (3.1% originating from pit filling), but 12.5% of the grid cells in the South Fork (7.1% originating from pit filling). In the succeeding discussion, we denote slope as S, expressed as a percentage following soil survey convention. (note S = 100(tanβ)). Calculations for Eq. [2] and [3] were performed using ARCMAP’s internal map calculator.

Overlay map-data layers for the terrain parameters and soil-survey attributes were extracted for analysis. We determined the degree of association of terrain parameters with soil properties and land-use interpretations on a five percentage random sample of grid cells. The samples provided excellent representation of the data, but also allowed efficient computations and preparation of graphics.

Slopes were compared between the two data sources according to slope classes of A, B, C, D, E, F, and G in the soil surveys, corresponding to 0 to 2, 2 to 5, 5 to 9, 9 to 14, 14 to 18, 18 to 25, and >25%. These classes were used to group the slopes calculated from the DEMs, and a contingency (cross classification) table was built from the paired sets of slope-class data for each watershed. The results were used to calculate the percentage of agreement between soil survey and DEM-calculated slopes.

Several procedures were used to evaluate associations between the remaining soil survey and terrain data sets. First, terrain attribute data (S, A_i, C_s, W, and E) were divided into two groups according to hydric soil condition, HEL status, drainage class, topsoil thickness, surface soil clay content, and surface soil organic matter content. The criteria used to divide the two groups for each soil attribute (Table 2) followed natural breaks in distributions (not an arbitrary 50% break). For the purpose of this study, groups are different between the two watersheds (except for HEL and hydric soils) because in the West Nishnabotna there are many large areas of well-drained soils, and thinner, finer textured topsoils with less organic matter. Note that more poorly drained soils occur in the South Fork watershed due to flat terrain and a dense till substrate, not finer-textured soils. The use of two groups generalized the soil survey information, but allowed simple and comparable analyses to determine how effectively the continuous, terrain attributes can be segregated according to mapped soil-survey attributes.

Single-factor ANOVA is an appropriate technique to identify the association between continuous and classified data
sets with paired observations, and was applied to determine the proportion of variance in terrain parameters that could be accounted by the soil-attribute groupings. In using ANOVA, there is no assumption or inference that the soil survey classes have fewer errors than the terrain data. Rather, the ANOVA simply identified the types of soil-attributes and terrain parameters that are most strongly associated with one another. The null hypothesis of equal distributions between soil-attribute groups was rejected only for \( p > 0.001 \); with the large number of observations (\( > 32,000 \) grid cells), this level of significance is achieved even if 0.1% of the variance is accounted by the classification. Therefore, percentage of variance accounted better indicates the association between the two data sets than significance level. For the \( A_i \), data, this analysis was applied to the natural logarithms to correct for skewness across seven orders of magnitude. Only one compound terrain index (\( W \) or \( E \)) was analyzed for each soil-attribute grouping because both indices are calculated from the derivatives (\( \frac{\partial z}{\partial x} \) and \( \frac{\partial z}{\partial y} \)). The data were analyzed as grouped according to HEL status, whereas the \( W \) data were analyzed according to dry soil condition, drainage class, and surface soil properties. Multivariate analyses were not conducted due to correlations (colinearity) amongst the terrain attributes, which result from their common origin (all computed from a single data set, namely elevation).

We next determined how accurately the terrain parameters could predict membership in the hydric-soil, HEL, topsoil-thickness, organic matter content, and clay-content groupings. Using trial and error, we identified a critical value of each terrain parameter that segregated the soil-attribute groups with equal accuracy. For example, we identified the critical value of slope, \( S \), such that the proportion of HEL on slopes steeper than \( S \) is equal to the proportion of non-HEL occurring on slopes less than \( S \). The value of \( S \) identifies a basis for identifying HEL from slope data that is most consistent with soil survey information. The value of the equal proportions identifies how accurately HEL can be delineated using slopes calculated from a DEM extracted from the national elevation database. Repeating this analysis across the matrix of terrain parameters and soil attributes provides comparative detail on how accurately the individual terrain parameters could predict and map the soil-attribute groupings.

Map analyses were performed to compare delineations based on these critical terrain parameter values, with delineations from the soil survey. In particular, we wanted to characterize the differences in these delineations spatially, and evaluate patchiness, boundary differences, and regional patterns in each watershed. This was based on inspection of maps and patch-size statistics (percentage of uniformly classified grid cells as a function of neighborhood size).

A graphical analysis was also applied to the soil-attribute groupings. A set of curves were plotted that, for any chosen value of a terrain parameter, identified the proportion of grid cells with greater terrain-parameter values that belong to one soil-attribute group, and the proportion of grid cells with smaller values that belong to the other group. Three curves were plotted showing the terrain attribute on the \( x \)-axis, and a proportion scale (0 to 1) on the \( y \)-axis. Explaining by an example, one curve shows the cumulative distribution of \( W \) values, a second curve plots the proportion of cells with larger \( W \) values that are mapped as having hydric soils, and the third curve shows the proportion of cells with smaller \( W \) values that are mapped as non-hydric soils. The plots thereby provide information on how terrain-parameter values, across their distribution, can be used to predict soil-attribute memberships with known probability.

### RESULTS AND DISCUSSION

#### Slope Comparisons

Slope classes identified from the soil survey and from DEM calculations (Table 3) show agreement between the two data sources was 62% in the South Fork watershed, and 40% in the West Nishnabotna watershed. A random distribution would be expected to give 14% correct (1/7, given seven classes), by comparison. In both watersheds, only 14 to 15% of the sampled grid-cells were in nonadjacent classes in terms of slope classification. That is, the percentages not along a main diagonal within Table 3, nor adjacent to a main diagonal along any row or column, sum to 14 to 15% for both watersheds. This is the rate at which discrepancies between the two classified data sets exceed 3 to 7% slope, and on this basis the correspondence between the two data sources is similar in the two watersheds. In the South Fork, the distributions of slope classes are similar between the two data sets (Table 3; comparing totaled rows and columns in the of the cross-classified data for each watershed). In the West Nishnabotna, however, a bimodal distribution is apparent in the soil survey data (largest class memberships in B and D slope classes), whereas the terrain data shows large memberships in Classes B, C, and D, but the largest membership is in Class C (5–9% slopes).

#### Soil-attribute Groupings

When divided according to the soil attributes, single-factor ANOVA of terrain-parameter data (Tables 4–6) identifies associations between the two data sets in both watersheds. Analysis of variance results were significant at the 0.001 confidence level for all comparisons. In both watersheds, hydric and/or poorly drained soils are

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**Table 2. Criteria used to divide terrain-attribute data (slope, contributing area, curvature, wetness index, and erosion index) into two groups according to several soil attributes.**

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>West Nishnabotna</th>
<th>South Fork</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
<td>Group 2</td>
</tr>
<tr>
<td></td>
<td>Group 1</td>
<td>Group 2</td>
</tr>
<tr>
<td>Highly erodible land (HEL)</td>
<td>HEL</td>
<td>not HEL</td>
</tr>
<tr>
<td>Hydric soils</td>
<td>hydric</td>
<td>not hydric</td>
</tr>
<tr>
<td>Drainage class</td>
<td>well</td>
<td>moderately well–very poorly</td>
</tr>
<tr>
<td>Topsoil thickness, m</td>
<td>( \leq 0.28 )</td>
<td>&gt; 0.28</td>
</tr>
<tr>
<td>Surface soil clay content, %</td>
<td>( \leq 3 )</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>Surface soil organic matter content, %</td>
<td>( \leq 5 )</td>
<td>&gt; 5</td>
</tr>
</tbody>
</table>
Table 3. Contingency table for two watersheds showing the distribution (percentage) of sampled grid cells across a cross-classification of slope classes obtained from soil survey data, against similar classes of slope calculated from terrain analysis. Percentages along main diagonals, in italic, indicate frequencies of identical slope classifications between the two data sources.

<table>
<thead>
<tr>
<th>Soil survey DEM-calculated slope† (%) slope</th>
<th>0–2%</th>
<th>2–5%</th>
<th>5–9%</th>
<th>9–14%</th>
<th>14–18%</th>
<th>18–25%</th>
<th>% of sampled grid cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. Nishnabotna A (0–2)</td>
<td>6.60</td>
<td>3.94</td>
<td>0.82</td>
<td>0.30</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>B (2–5)</td>
<td>5.60</td>
<td>11.36</td>
<td>9.89</td>
<td>3.78</td>
<td>0.59</td>
<td>0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>C (5–9)</td>
<td>0.49</td>
<td>2.82</td>
<td>5.76</td>
<td>4.26</td>
<td>2.79</td>
<td>0.53</td>
<td>0.01</td>
</tr>
<tr>
<td>D (9–14)</td>
<td>0.65</td>
<td>3.52</td>
<td>11.47</td>
<td>14.70</td>
<td>2.79</td>
<td>0.53</td>
<td>0.01</td>
</tr>
<tr>
<td>E (14–18)</td>
<td>0.08</td>
<td>0.39</td>
<td>1.53</td>
<td>3.31</td>
<td>0.56</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>F (18–25)</td>
<td>0.01</td>
<td>0.04</td>
<td>0.19</td>
<td>0.40</td>
<td>0.38</td>
<td>0.25</td>
<td>0.02</td>
</tr>
<tr>
<td>Sum</td>
<td>13.44</td>
<td>22.07</td>
<td>29.66</td>
<td>26.77</td>
<td>6.24</td>
<td>1.74</td>
<td>0.09</td>
</tr>
<tr>
<td>South Fork A (0–2)</td>
<td>49.45</td>
<td>11.09</td>
<td>1.09</td>
<td>0.18</td>
<td>0.04</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>B (2–5)</td>
<td>12.81</td>
<td>8.92</td>
<td>2.14</td>
<td>0.35</td>
<td>0.08</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>C (5–9)</td>
<td>2.67</td>
<td>4.77</td>
<td>2.99</td>
<td>0.51</td>
<td>0.08</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>D (9–14)</td>
<td>0.09</td>
<td>0.28</td>
<td>0.68</td>
<td>0.41</td>
<td>0.08</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>E (14–18)</td>
<td>0.02</td>
<td>0.07</td>
<td>0.10</td>
<td>0.14</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>F (18–25)</td>
<td>0.03</td>
<td>0.05</td>
<td>0.07</td>
<td>0.07</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>G (~25)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
<td>0.08</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>Sum</td>
<td>65.11</td>
<td>25.22</td>
<td>7.15</td>
<td>1.79</td>
<td>0.45</td>
<td>0.21</td>
<td>0.06</td>
</tr>
</tbody>
</table>

† DEM, digital elevation model.

Analysis of Variance

The above statements are all statistically valid, but soil-attribute groupings capture differing proportions of variance in the terrain parameters (Table 5). With the large sample sizes, statistical significance of the ANOVA results can result from weak association between the data types (e.g., <0.1% of variance in curvature captured by clay content grouping for the West Nishnabotna; Table 5). Slope is the terrain parameter that is most effectively captured by the soil-attribute groupings, as more than 20% of the variance in slope is accounted for by the HEL grouping in both watersheds. The surface soil property groupings (topsoil thickness, clay, and organic matter contents) also account for more of the variance in DEM-calculated slopes than in the other terrain attributes. Soil surveyors use slope information to delineate soil map units and HEL, and these results may reflect that.

Table 4. Mean values of terrain parameters for grid cells grouped according to soil survey attributes. All means are significantly different at p = 0.001.

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>Mean value of terrain parameters within each grouping†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S (m)</td>
</tr>
<tr>
<td>Hydric/not hydric</td>
<td>4.08±3</td>
</tr>
<tr>
<td>Well/poorly drained</td>
<td>6.65±0</td>
</tr>
<tr>
<td>HEL/not HEL‡</td>
<td>9.1±4.8</td>
</tr>
<tr>
<td>Topsoil &lt;0.28 m &gt;0.28 m</td>
<td>8.7±4.1</td>
</tr>
<tr>
<td>Clay &lt;32% &gt;32%</td>
<td>5.8±8.1</td>
</tr>
<tr>
<td>Organic matter &gt;3% &gt;3%</td>
<td>8.8±4.6</td>
</tr>
<tr>
<td>Hydric/not hydric</td>
<td>1.3±3.1</td>
</tr>
<tr>
<td>Mod. well/poorly drained</td>
<td>2.7±1.2</td>
</tr>
<tr>
<td>HEL/not HEL‡</td>
<td>5.2±1.6</td>
</tr>
<tr>
<td>Topsoil &lt;0.35 m &gt;0.35 m</td>
<td>3.4±1.3</td>
</tr>
<tr>
<td>Clay &lt;26% &gt;26%</td>
<td>3.3±1.3</td>
</tr>
<tr>
<td>Organic matter &gt;3% &gt;5%</td>
<td>2.8±1.3</td>
</tr>
</tbody>
</table>

† S, slope; A, contributing area; C, curvature; W, wetness index; E, erosion index.
‡ HEL, highly erodible land.
Table 5. Proportion of variance in terrain parameters accounted by grouping grid cells according to soil survey delineations based on hydric soil conditions, drainage class, topsoil thickness, clay content, and highly erodible land (see text).  

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>S</th>
<th>A_1</th>
<th>C_1</th>
<th>W</th>
<th>E</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>West Nishnabotna</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydric soils</td>
<td>15.7</td>
<td>12.9</td>
<td>13.6</td>
<td>17.1</td>
<td>9.4</td>
<td>11002</td>
</tr>
<tr>
<td>Drainage class</td>
<td>13.5</td>
<td>13.7</td>
<td>13.5</td>
<td>19.7</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Highly erodible land (HEL)</td>
<td>21.1</td>
<td>7.1</td>
<td>4.8</td>
<td>9.4</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Topsoil thickness</td>
<td>21.3</td>
<td>17.3</td>
<td>7.3</td>
<td>16.9</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Clay content</td>
<td>5.5</td>
<td>1.1</td>
<td>&lt;0.1</td>
<td>2.4</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Organic matter</td>
<td>19.6</td>
<td>7.5</td>
<td>7.0</td>
<td>13.4</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td><strong>South Fork</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydric soils</td>
<td>11.8</td>
<td>5.0</td>
<td>7.2</td>
<td>12.3</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Drainage class</td>
<td>9.0</td>
<td>4.2</td>
<td>5.3</td>
<td>12.4</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>HEL</td>
<td>22.1</td>
<td>1.3</td>
<td>2.9</td>
<td>9.8</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Topsoil thickness</td>
<td>14.1</td>
<td>4.6</td>
<td>7.8</td>
<td>11.7</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Clay content</td>
<td>13.8</td>
<td>3.1</td>
<td>5.5</td>
<td>9.8</td>
<td></td>
<td>11002</td>
</tr>
<tr>
<td>Organic matter</td>
<td>8.2</td>
<td>1.6</td>
<td>2.6</td>
<td>4.1</td>
<td></td>
<td>11002</td>
</tr>
</tbody>
</table>

† S, slope; A_1, contributing area; C_1, curvature; W, wetness index; E, erosion index. Percentage of variance (%) in parameter accounted by grouping according to soil attribute.

In interpreting Table 5, note there is significant correlation between S and C_1 (i.e., r is about 0.4 in both watersheds), because both are calculated from elevation differences among neighboring cells. Contributing area (ln A_1, that is) also exhibits some correlation with S and C_1 (0.20 < r < 0.57). Due to this colinearity, the variance in compound terrain indices (W and E) captured by the soil-attribute groupings cannot result from added proportions of variance captured by their contributing parameters, S and ln A_1. Indeed, in both watersheds, the proportion of variation in W accounted by hydric soil and drainage class groupings is greater than for S, but the increase is small. In other instances there is actually less variance in the compound terrain indices captured by the soil-attribute groupings than there was in slope. This decline is most striking for the HEL grouping, which accounts for >20% of the variance in slope, but <10% of the variance in E, in both watersheds. This could partly result from narrow drainage features with large A_1 values, which are not large enough to be represented as erodible soil map units, but that are clearly represented in the terrain data.

Table 6. Critical values of terrain parameters that segregate soil-attribute-group memberships with equal accuracy.†

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>S</th>
<th>A_1</th>
<th>C_1</th>
<th>W</th>
<th>E</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>West Nishnabotna</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydric soils</td>
<td>5.5 (71)</td>
<td>102 (68)</td>
<td>−0.0048 (69)</td>
<td>7.58 (74)</td>
<td>1.22 (71)</td>
<td></td>
</tr>
<tr>
<td>Drainage class</td>
<td>6.3 (69)</td>
<td>90 (66)</td>
<td>−0.0024 (67)</td>
<td>7.29 (71)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highly erodible land (HEL)</td>
<td>6.5 (73)</td>
<td>86 (60)</td>
<td>−0.0011 (61)</td>
<td>7.24 (71)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topsoil thickness</td>
<td>5.8 (74)</td>
<td>97 (69)</td>
<td>−0.0015 (62)</td>
<td>7.24 (71)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay content</td>
<td>6.6 (62)</td>
<td>84 (53)</td>
<td>−0.0008 (53)</td>
<td>7.15 (58)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic matter</td>
<td>6.2 (72)</td>
<td>88 (61)</td>
<td>−0.0018 (62)</td>
<td>7.26 (69)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>South Fork</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydric soils</td>
<td>1.4 (66)</td>
<td>73 (59)</td>
<td>−0.0001 (64)</td>
<td>8.66 (66)</td>
<td>0.29 (73)</td>
<td></td>
</tr>
<tr>
<td>Drainage class</td>
<td>1.2 (66)</td>
<td>78 (58)</td>
<td>−0.00022 (61)</td>
<td>8.88 (66)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highly erodible land</td>
<td>2.3 (76)</td>
<td>64 (57)</td>
<td>0.00065 (63)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topsoil thickness</td>
<td>1.5 (67)</td>
<td>69 (60)</td>
<td>0.00015 (65)</td>
<td>8.52 (67)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay content</td>
<td>1.4 (66)</td>
<td>71 (58)</td>
<td>0.00001 (62)</td>
<td>8.57 (66)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic matter</td>
<td>1.3 (60)</td>
<td>75 (56)</td>
<td>0.00010 (58)</td>
<td>8.76 (61)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Each entry in the table can be interpreted per this example that applies to the entry in the first row and column: In the West Nishnabotna watershed, 71% of hydric soils have DEM-calculated slopes <5.5%, and 71% of non-hydric soils have slopes >5.5%. Percentage of accuracy is given in parentheses.

§ S, slope; A_1, contributing area; C_1, curvature; W, wetness index; E, erosion index.

§ In the West Nishnabotna, higher clay contents in surface soils are associated with steeper, upslope, and convex areas, while the opposite is true in the South Fork.

Soil-Attribute Prediction

We next examined how accurately membership in the soil-attribute groups can be predicted using the terrain data (Table 6). We identified a critical value for each terrain parameter that could be used to assign membership in the soil-attribute groups (e.g., hydric versus non-hydric) with uniform accuracy for each group. A minimal accuracy is considered to be 50%, given all groupings are binomial. For this discussion, a 66% accuracy rate is denoted as good. Results show that S can predict membership in the hydric soil, drainage class, HEL, and topsoil thickness with good (66–76%) accuracy in both watersheds. Similarly, in both watersheds, W can predict membership in hydric soil, drainage class, and topsoil thickness groups, and E can predict HEL group membership, with good (66–74%) accuracy. Contributing area and curvature could also predict membership in some soil-attribute groupings with good (>66%) accuracy, but not in both watersheds. That is, with accuracy exceeding 66%, A_1 can predict hydric-soil, drainage-class, and topsoil-thickness group membership, and C_1 can predict hydric-soil and drainage-class group membership, but only in the West Nishnabotna watershed.

The critical values of terrain parameters that segregate soil-attribute groupings with consistent accuracy differ between watersheds. In the South Fork, all groupings other than HEL can be most accurately predicted based on a critical slope value between 1.2 and 1.5% (close to the median slope of 1.3%). A slope of 2.3% delineates HEL from non-HEL (with 76% accuracy), and a critical E of only 0.29 separates HEL and non-HEL (with 73% accuracy) in the South Fork (where the median E is 0.15). In the West Nishnabotna, critical slope values are larger, ranging from 5.5 to 6.6%, with 6.5% segregating HEL from non-HEL with 73% accuracy (the median S is 6.9%). The critical value of E in...
the West Nishnabotna is 1.22, which separates HEL and non-HEL with 71% accuracy (median $E$ is 1.30). The HEL in the South Fork, on average, is slightly steeper than the non-HEL in the West Nishnabotna (5.2 versus 4.8%; see Table 4). We did evaluate whether wind erodibility influence these comparisons, as 35% of the HEL in the South Fork watershed is susceptible to wind erosion (in wind erodibility Groups 2, 3, or 4L). However these wind-erodible HEL lands actually had greater slopes than the HEL that is not wind erodible ($p < 0.001$, based on single factor ANOVA).

Critical values of $A$, are larger in the West Nishnabotna; the more extensive geomorphic development of the stream network and alluvial valleys cause larger $A$, values in that watershed (median $A$, of 82 m$^2$ m$^{-1}$ versus 75 m$^2$ m$^{-1}$ in the South Fork). The flatter terrain of the South Fork also results in limited variation in curvature, and critical $C$, values are therefore smaller in absolute magnitude than in the West Nishnabotna (Table 6). Larger $W$ values in the South Fork are another result of the flatter terrain, and critical $W$ values range from 8.52 to 8.88 in the South Fork (median $W$ is 8.74), but only from 7.15 to 7.58 in the West Nishnabotna (median $W$ is 7.09).

Map Analyses

Maps that use critical values for $W$ and $E$ to indicate hydric soil condition and HEL status (Fig. 2) visually resemble the maps based on soil survey delineations (Fig. 1) in the following ways. General drainage patterns of the alluvial valleys are readily apparent in both sets of maps, and in both watersheds. However the hydric soils in the lower-most alluvial valleys are often associated with lower terraces, and the DEM data does not consistently delineate these. The higher terraces in these valleys can have non-hydric soils, but large wetness indices; this discrepancy was most apparent in the lower alluvial valleys of the West Nishnabotna. Areas of hydric soil on the till plains of the South Fork are also well represented, in general, by the delineation based on the critical $W$ of 8.66. In both watersheds, there are large areas of high $W$ values, where, due to low relief, topographic contours on the originating quadrangle

---

**West Nishnabotna River**

<table>
<thead>
<tr>
<th>Erosion Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1.22</td>
</tr>
<tr>
<td>&gt; 1.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wetness Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.33 - 7.58</td>
</tr>
<tr>
<td>&gt; 7.58</td>
</tr>
</tbody>
</table>

**South Fork - Iowa River**

<table>
<thead>
<tr>
<th>Erosion Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.29</td>
</tr>
<tr>
<td>&gt; 0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wetness Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.08 - 8.66</td>
</tr>
<tr>
<td>&gt; 8.66</td>
</tr>
</tbody>
</table>

Fig. 2. Maps of the West Nishnabotna and South Fork watersheds, showing surrogate delineations for highly erodible land (HEL) based on erosion index ($E$, defined by Eq. [3]) values, and for hydric soils based on wetness index ($W$, defined by Eq. [2]) values. These delineations have accuracies ranging from 66 to 74% (see Table 6).
maps are widely separated. These occur in the main alluvial valley in the West Nishnabotna, and on level areas of the South Fork’s till plain. With this exception, the DEM-derived maps show finer spatial patterns than the soil survey delineations. These differences were most pronounced in comparing the delineations based on critical \( W \) and hydric soils in the West Nishnabotna, and those based on the critical \( E \) and HEL in the South Fork. Only 11% of all grid cells in the West Nishnabotna were entirely neighbored by similar \( W \) values (that is, surrounded across a 5 by 5 neighborhood by \( W \) values either all greater or all \(<7.58\)). In contrast, 47% of the grid cells were entirely neighbored by cells of the same hydric status. In the South Fork, 30% of all grid cells were entirely neighbored by similar \( E \) values (either all greater or all \(<0.29\)), whereas 62% of the grid cells were entirely neighbored by cells of the same HEL status. The 5 by 5 neighborhood occupies 2.25 ha, close to the smallest delineated soil map units. Based on observation, the DEM-derived maps provide finer meaningful detail along ephemeral drainage ways where topographic drainage patterns are well represented. Finer detail in flat areas, however, were often artifacts resulting from widely spaced contours on the originating topographic maps, where the Taudem software (Tarboton, 2002) invoked default processes for flow routing across flat terrain (per the method of Garbrecht and Martz, 1997). We conclude this from examining data in the wide alluvial valleys of the West Nishnabotna, and more level till plains of the South Fork.

Hydric soils and HEL are mutually exclusive soil attributes in both the test watersheds. However this was not the case for the surrogate indicators based on terrain analysis. Only 3.5% of the grid cells in the West Nishnabotna watershed had \( W > 7.58 \), and \( E > 1.22 \). In the South Fork watershed, however, about 12% of the grid cells had \( W > 8.66 \), and \( E > 0.29 \). These combinations can occur in areas of gentle slope but significant upslope area.

**Graphical Analysis**

We finally examined how the probability of membership in a soil-attribute group varies according to any given (minimum or maximum) terrain-parameter value. Plots were developed that allow a continuous-scale map of terrain-parameter values to be interpreted in terms of probability of soil-attribute membership. Example plots of proportion hydric soil against \( W \), and of proportion HEL against \( E \) (Fig. 3), include cumulative distributions of terrain parameters across all the grid cells. We interpret that critical terrain parameter values (identified in Table 6) occur near inflections in curves such as those in Fig. 3.

The plots in Fig. 3 help answer the question posed in this paper’s title. Are critical areas identified by terrain analysis also commonly delineated by soil survey? The answer differs with resource concern and watershed. In the West Nishnabotna, about 21% of the grid cells have \( E > 2.25 \), and 79% of them are also mapped as HEL. In the South Fork, nearly 20% of the grid cells have \( W > 12 \), and 81% of these are mapped as hydric. This 80% correspondence for the top 20% of terrain attribute values provides confidence that the targeting of critical areas with terrain data can be consistent with soil survey information, and applies to the major resource concern in these two watersheds. However, in the West Nishnabotna, hydric soils cannot be identified with <69% confidence using any cutoff value of \( W \), and in the South Fork, HEL cannot be delineated with better than 59% confidence for any cutoff value of \( E \) (based on maximum value of the thick line in the upper right and lower left plots, Fig. 3), and these maximums only apply to about the upper 2% of terrain-attribute distributions in these cases.

**SUMMARY AND CONCLUSIONS**

A variety of tools and data types are available for land-resource assessment and targeted conservation planning, and there is a need to understand the compatibility between new and traditional methods. Soil survey information has been and will continue to be a broadly applied information source for conservation planning. Terrain analysis methods can also target sensitive areas for soil and water conservation practices. But, if new methods are to be applied on privately owned lands, conservation professionals will need to confirm that terrain analysis results correspond with their understanding of soil resources, embodied in soil survey information. This study shows, that for a set of soil attributes in two watersheds, several terrain parameters correspond reasonably well with soil survey delineations commonly used for land-use interpretations and conservation planning. Terrain parameters can be used to simulate these delineations in map form, in many instances with good (66–76%) accuracy. Slope \((S)\) and two compound terrain indices \((W \text{ and } E)\) could delineate groupings based...
on hydric soil condition, drainage class, HEL, and top-soil thickness with this accuracy in two test watersheds. Dominant spatial patterns were consistent in both watersheds, but fine-scale representation differed. Terrain attributes provided finer-scale detail in dissected terrain, which depicted hydrologic processes influencing erosion and soil wetness. But in areas of little relief, the 30-m DEM data do not depict subtle variation in the terrain that affect patterns of hydric soils, and artifacts of default flow-routing algorithms were apparent.

In this study, terrain-attribute delineations were consistent with soil survey in identifying critical sites to manage soil wetness in the South Fork watershed, and to address soil erosion in the West Nishnabotna watershed. But results show terrain analyses cannot be applied toward comprehensive (multiple-practice) conservation planning, assuming consistent correspondence with soil survey data for each resource concern. A separate evaluation for each resource concern is needed. This could help identify targeting criteria that are based on local data when applying terrain analyses toward resource planning.

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REFERENCES


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