Development and application of the Hydric Soil Technical Standard

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Abstract
The concept of hydric soils evolved over time with advances in soil science and wetland resource management. Hydric soils are identified in the field by examining morphological characteristics, including organic matter accumulation and redoximorphic features that form in response to prolonged periods of saturation and anaerobic conditions. The Hydric Soil Technical Standard (HSTS) was developed to provide a quantitative procedure for evaluating the hydric status of a soil based upon direct measurements of saturation, anaerobic conditions, and precipitation normality. In practice, the HSTS is used for (a) identifying hydric soils when a field indicator of hydric soils may not be present (e.g., naturally problematic or disturbed soils); (b) evaluating the current functional hydric status of a soil; (c) developing new field indicators of hydric soils; and (d) proposing changes to existing field indicators of hydric soils. The HSTS procedures have progressed over several decades with new approaches to soil analysis, including novel methods to document anaerobic conditions. The following review describes the development of the hydric soils concept and provides guidance for measuring each HSTS component. Practical approaches for collection and submission of HSTS data to the National Technical Committee for Hydric Soils, the group responsible for approving approaches to hydric soil identification in the United States, are also discussed. Expanding the understanding and application of the HSTS promotes technical accuracy, transparency, and efficient decision making in support of hydric soil and wetland resource management.

1 | OVERVIEW AND APPROACH

Hydric soils (or wetland soils) form as a result of prolonged soil saturation and microbial activity that induce anaerobic conditions. In the United States, hydric soils are defined as “soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part” (Soil Conservation Service, 1994). The identification of hydric soils is an important component of natural resource management and is required for wetland delineation in support of the Clean Water Act (National Research Council, 1995; Tiner, 2016) and the Food Security Act (USDA-NRCS, 1994). In a field setting,
these soils are identified using field indicators of hydric soils that are based on readily observable properties such as soil color, texture, and the presence of redboxorphic features that develop in response to anaerobic conditions (Vepraskas & Vaughan, 2016). Over the past several decades, soils research has linked the underlying biogeochemical processes occurring in wetlands with the morphological patterns unique to hydric soils (Vepraskas & Sprecher, 1997). The National Technical Committee for Hydric Soils (NTCHS) maintains the approved list of field indicators of hydric soils and oversees changes to the list using data collected during hydric soil studies (USDA-NRCS, 2018).

The NTCHS developed the Hydric Soil Technical Standard (HSTS) to provide a scientifically based and standardized approach to document that a soil is saturated and anaerobic, thus demonstrating that the definition of a hydric soil has been met. Scientists researching hydric soils to identify new field indicators of hydric soils are required to collect data using the HSTS, and to submit the results to the NTCHS in support of proposed changes to the approved list of field indicators of hydric soils. To promote a better understanding of hydric soils and the HSTS, the following review discusses (a) the evolution of the hydric soil concept; (b) field indicators of hydric soils; (c) the technical data requirements of the HSTS; and (d) practical guidance for applying the HSTS.

The biogeochemical processes underlying hydric soil formation are not specifically addressed herein, since they have been previously described in other publications (Reddy & DeLaune, 2008; Vepraskas, Polizzotto, & Faulkner, 2016). However, although this review remains focused on the HSTS, many of the data collection and analysis techniques discussed have proven useful in a variety of other contexts. Examples include the evaluation of ecological functions provided by wetlands such as water quality improvement, assessment of soil processes across landscapes and land uses in support of environmental alternatives analysis, documenting the performance of wetland restoration sites or mitigation areas in comparison with unaltered soil systems, and monitoring changes in soil characteristics in response to varying environmental conditions (e.g., climate, anthropogenic disturbances).

2 CONCEPT OF HYDRIC SOILS

Hydric soils were initially defined in the wetland classification system of Cowardin, Carter, Golet, and LaRoe (1979) in support of the National Wetlands Inventory (NWI) program that mapped the distribution of wetlands and migratory waterfowl habitat across the United States (Mausbach, 1994; Vepraskas, 2016). As part of the NWI initiative, Cowardin et al. (1979) proposed that wetlands have three components: hydric soils, hydrophytic plants, and saturated substrates (Tiner, 1997). The concept that wetland environments exhibit a combination of hydric soils, hydrophytic vegetation, and wetland hydrology is used today as the basis for wetland identification and delineation (Environmental Laboratory, 1987; National Research Council, 1995; USACE, 2012).

During the 1980s, the NTCHS was established to formalize a hydric soil definition and develop strategies to identify hydric soils using soil survey data and soil survey mapping conventions. That work resulted in publication of hydric soil lists, identifying soil series (or map units) associated with potential wetland areas to support natural resource management and the delineation of wetland habitats (Mausbach & Parker, 2001). Initially composed of the Soil Conservation Service (SCS, now the USDA-NRCS) soil scientists and two academic faculty, the NTCHS now includes six USDA-NRCS soil scientists, five university faculty members, and one representative from each of the following cooperating federal agencies: the U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, USEPA, U.S. Forest Service, and U.S. Bureau of Land Management. The membership of the NTCHS is governed by the committees operating procedures.

The hydric soil definition that emerged from NTCHS deliberations (“soils that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part”) indicated that, in order to perform the ecological functions unique to wetlands, hydric soil formation required both water and anaerobic conditions (Soil Conservation Service, 1994). Notably, the hydric soil definition does not specify a saturation depth or duration needed to induce anaerobic conditions but requires that saturation persist long enough for anaerobic conditions to develop near the soil surface (i.e., the upper part). Further, the requirement that hydric soils include those soils “formed under” saturated and anaerobic conditions emphasizes that a soil is hydric based upon the conditions under which it developed, not its current hydrologic status. As a result, a hydric soil that undergoes drainage remains a hydric soil regardless of the persistence of wetland hydrology and/or hydrophytic vegetation after alteration.

Core Ideas
- Hydric soils form in response to prolonged saturation and anaerobic conditions.
- Field indicators of hydric soils are developed for wetland identification and delineation.
- The Hydric Soil Technical Standard links measures of soil function with morphology.
- The approach requires analysis of saturation, anaerobic conditions, and precipitation normality.
- This review promotes additional hydric soil studies related to wetland soil management.
The hydric soil definition also requires that saturation and anaerobic conditions occur during the growing season. For the purposes of evaluating and identifying hydric soils, the growing season is assumed to occur when microbial activity is sufficient to remove dissolved oxygen from the soil pore water and induce anaerobic conditions (National Research Council, 1995). As a result, the term “growing season” in hydric soils is not tied to evidence of vegetative growth or an established soil temperature threshold (5 °C at a depth of 30 cm) as it is for determinations of hydrophytic vegetation and wetland hydrology, but rather to microbial activity (USACE, 2012).

Interpreting the growing season for the purposes of examining hydric soils differs from approaches used to evaluate hydrophytic vegetation and wetland hydrology because studies have demonstrated that microbial communities remain active in many soils throughout the year (Megonigal, Faulkner, & Patrick, 1996) and can even induce anaerobic conditions in soils that remain below 5 °C year round (Ping, Moore, & Clark, 1987). Direct assessments of microbial activity related to growing season determinations are generally not conducted in hydric soils studies because microbial communities are robust and adapted to local conditions. However, indirect evidence that microbial oxygen consumption is inducing anaerobic conditions can be derived from measurements that demonstrate the absence of dissolved oxygen in soil water, observations of a reduced matrix (i.e., ferrous iron in soil solution; USDA-NRCS 2018), positive reactions of α,α′-dipyridyl dye, or other means to infer that microbial activity is occurring.

### 3 | FIELD INDICATORS OF HYDRIC SOILS

Beginning as early as 1983, the SCS began conducting a series of field tests evaluating soil morphology at the perceived wetland–upland boundary based upon changes in plant communities, shifts in topography, and expert opinion (Hurt & Brown, 1995). Researchers documented the soil properties that could be readily seen, felt, or smelled that occurred in hydric soils, but which were absent in nonhydric soils. These properties included the presence of hydrogen sulfide odor, stratified layers resulting from repeated sediment deposition events induced by flooding, accumulation of organic material near the soil surface, and a variety of morphological features related to the dissolution, translocation, and re-precipitation of iron/manganese oxides occurring in response to cycles of aerobic–anaerobic conditions (Hurt & Puckett, 1992). These studies resulted in the development of a set of guidelines first published in 1992 as “Field Indicators of Hydric Soils in the United States,” which combine specific soil textures, color patterns, and other morphological features with depth requirements indicating that anaerobic conditions have occurred near the soil surface. The guidance document has undergone multiple updates since its inception to incorporate new field indicators of hydric soils or alter existing indicators based on new data. The document was most recently published as version 8.2 (USDA-NRCS, 2018), and future updates are anticipated as the science surrounding hydric soil identification continues to improve. As an example, hydric soil field indicator S5—Sandy Redox states the following:

“S5—Sandy Redox. For use in all LRRs [Land Resource Regions], except for Q, V, W, X, and Y. A layer starting at a depth ≤15 cm (6 inches) from the soil surface that is at least 10 cm (4 inches) thick and has a matrix with 60 percent or more chroma of 2 or less and 2 percent or more distinct or prominent redox concentrations occurring as soft masses and/or pore linings.”

The field indicators of hydric soils are developed for three different textural groups indicated by the alphanumeric designation (e.g., S5) associated with each hydric soil indicator:

- “A” (i.e., all soil types) indicators are applicable in soil layers (or a combination of layers) composed of organic materials or any mineral soil textures.
- “S” (i.e., sandy soil) indicators are only applicable in mineral soil layers composed sands and loamy sands; specific soil textures include sand, fine sand, very fine sand, very fine sand, loamy coarse sand, loamy sand, and loamy fine sand.
- “F” (i.e., fine soil) indicators are only applicable in mineral soil layers composed of loamy very fine sand and finer soil materials (i.e., all mineral soil textures not addressed by the “S” indicators).

This system accounts for the different water holding capacities, capillary fringe potentials (e.g., clay vs. sands), and other factors that vary with soil texture. It also allows for the application and use of multiple field indicators of hydric soils within soil profiles composed of varying soil textures. For example, a soil may exhibit an A indicator in the organic surface layer, an S indicator in the underlying sandy soil layer, and an F indicator in a fine textured subsoil layer. The numbers associated with the alphanumeric designations reflect the order in which the field indicators were developed and adopted (i.e., S5 was the fifth indicator developed for application in sandy soils). The hydric soil indicator names provide insight into the general characteristic(s) of the indicator, where the field indicator of hydric soils S5—Sandy Redox requires a sandy soil texture and the presence of redoximorphic features.

The geographic area where a given field indicator of hydric soils can be applied is defined using Land Resource Regions.
(LRRs) and Major Land Resource Areas (MLRAs) (USDA-NRCS, 2006). For example, the field indicator S5–Sandy Redox can be applied in all areas of the United States except in the Pacific basin (LRR Q), the Hawaiian Islands (LRR V), and Alaska (LRRs W, X, and Y). This approach recognizes the differences in pedogenic processes and morphology related to varying climate, parent materials, and other factors. For example, in tropical regions (e.g., south Florida, Pacific basin) where hot temperatures and a year round growing season limit the accumulation of organic materials in many soils, only the presence of muck is required to meet a field indicator of hydric soils (A8–Muck Presence; USDA-NRCS, 2018). However, thicker organic matter layers are required in soils forming in colder climates with shorter growing seasons where organic matter accumulates more easily. As a result, a minimum of 2 cm of muck is required in the Midwest region (via application of field indicator A10–2 cm Muck) and ≥20 cm is required in Alaska.

Each field indicator of hydric soils has unique technical criteria specifying the soil colors (e.g., chroma ≤2), percentages of matrix colors (e.g., ≥60%), redoximorphic features (e.g., ≥2%), and soil layer depths (e.g., ≤15 cm) required for application and hydric soil identification. Additionally, user notes (not shown) accompany each field indicator of hydric soil to aid practitioners during application. The guidance document “Field Indicators of Hydric Soils in the United States” (USDA-NRCS, 2018) is a concise booklet that includes pictures, technical definitions, and background information regarding hydric soil identification (available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/use/hydric/).

The 10 regional supplements to the U.S. Army Corps of Engineers wetland delineation manual (USACE, 2012), Vasilas and Berkowitz (2016), and a variety of field-oriented publications provide additional resources for applying the field indicators of hydric soils.

Importantly, the presence of a field indicator of hydric soils is considered proof that a soil meets the hydric soil definition, as the soil properties outlined in each field indicator provide evidence that the soil formed under conditions of flooding, ponding, or saturation long enough during the growing season to develop anaerobic conditions in the upper part.

## 4 THE HYDRIC SOILS TECHNICAL STANDARD

The field indicators of hydric soils are useful for both identifying hydric soils and determining their boundaries as part of wetland delineations. The field indicators have undergone several revisions as available information on hydric soils continued to expand (Environmental Laboratory, 1987; USDA-NRCS, 2018). In order to make such changes, the NTCHS established a standardized approach for evaluating soils using quantitative measurements of soil saturation or inundation and anaerobic conditions in the upper part as stipulated in the hydric soils definition (NTCHS, 2015). The required measurements are collectively referred to as the Hydric Soil Technical Standard (HSTS).

Hydric soils are defined as soils “formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part” (Soil Conservation Service, 1994). As a result, the HSTS requires that three technical criteria be met: (a) anaerobic conditions; (b) soil saturation in the upper 25 cm of the soil profile for at least 14 consecutive days for most soils, or for seven consecutive days occurring for a minimum of 28 d annually for Vertisols in Louisiana and Texas; and (c) the saturation and anaerobic conditions criteria must be met following a period of normal or drier than normal precipitation when soil microbes are active.

The HSTS addresses the need for an approach coupling the hydric soil definition with the functional status of a soil using direct measures of soil saturation, flooding, or ponding in conjunction with the presence of anaerobic conditions in the upper part of the soil profile (i.e., the root zone; National Research Council, 1995). The HSTS also facilitates the development or alteration of field indicators of hydric soils by linking observed soil morphological features with the hydric soil definition via quantitative data collection. As a result, the HSTS provides a mechanism to (a) initiate new field indicators of hydric soils, (b) alter existing field indicators of hydric soils, (c) identify the presence of hydric soil conditions in areas lacking an approved field indicator of hydric soil, and (d) evaluate the current functional status of a hydric soil. For example, Berkowitz and Salle (2011) applied the HSTS to develop a new field indicator of hydric soils (S11—High Chroma Sands) in wetland areas that previously lacked a field indicator. Results of that study also used the HSTS to expand the applicable range of several existing field indicators of hydric soils (e.g., F10—Marl, S7—Dark Surface) based upon evidence that some soils in the region met the hydric soil definition yet occurred in portions of the United States where those field indicators of hydric soils had not been previously documented.

The HSTS documents whether or not a soil currently functions as a hydric soil and does not address the conditions under which the soil formed. As a result, the HSTS is not designed or intended to be used to overrule or invalidate a hydric soil determination based on the presence of one or more field indicators of hydric soils. The field indicators reflect natural processes that develop over time during soil formation and generally provide the best evidence that hydric soils are present on a site. However, the NTCHS acknowledges that some hydric soils do not display approved field indicators of hydric soils for a variety of reasons (e.g., problematic parent materials, recently deposited or disturbed soils). In such cases, the HSTS
is a valuable tool to evaluate the current hydric status of those soils.

The following provides a concise summary of the HSTS technical requirements. Later sections discuss the rationale behind each HSTS element and provide practical guidance for applying the HSTS.

### 4.1 Saturation, flooding, or ponding

As outlined in the HSTS, soil saturation must occur for at least 14 consecutive days in most soils. Vertisols in Louisiana and Texas require soil saturation for at least seven consecutive days with saturation occurring for a minimum of 28 d annually. Vertisols in these states occur on flood plains where saturation periods of 14 d in soils are not common. Soil saturation must occur within 25 cm of the soil surface in all soils to meet the requirements of the HSTS.

Saturated conditions are measured using shallow piezometers or water table wells. Saturated conditions should be documented by either automated data loggers or direct observations of the water table. At a minimum, water table measurements should be made once per week; however, daily observations are recommended. When observations are made weekly, three consecutive weeks of measurements showing that the water table is within 25 cm of the surface are needed to meet the 14-d saturation requirement. Water table monitoring should be conducted across a full field season or a minimum of one dry–wet–dry hydrologic cycle encompassing the normal wet portion of the growing season.

Although shallow groundwater wells provide sufficient evidence of soil saturation in most soils, they may not be appropriate for use in soils where restrictive layers or perched water tables occur near the soil surface. If confining layers including low-permeability clays, dense till, or other aquitards are encountered, a series of piezometers (which reflect the water pressure at the bottom of the device) installed above and below the restrictive layer (typically at depths of 25 and 100 cm) are needed to determine saturation depths in the upper portion of the soil profile and in the subsoil. Additionally, a deep (1–2 m) groundwater well (which integrates the water pressure over the perforated portion of the device) can inform patterns of saturation in systems with the potential to perch water near the soil surface.

### 4.2 Anaerobic conditions

Anaerobic conditions must occur during the period when the soils are saturated as outlined above. Notably, the depth at which anaerobic conditions must be observed varies with soil texture and measurement technique. The HSTS provides three methods to document anaerobic conditions in the soil:

1. Indicator of Reduction in Soils (IRIS) devices: a minimum of three of five IRIS devices must display 30% iron removal within a zone 15 cm or more thick. The zone of removal must begin within 15 cm of the soil surface for all soil textures.

2. α,α'-dipyridyl dye: a positive reaction to α,α'-dipyridyl dye must occur within 60% or more of a specific layer in at least two of three soil samples. The positive dye reaction must occur within a 10-cm-thick layer in the upper 30 cm for most soils, a 6.25-cm-thick layer within the upper 12.5 cm in sandy textured soils, or a 5-cm layer within the upper 10 cm in soils that inundate by flooding or ponding.

3. Oxidation–reduction potential (redox potential, Eh) measurements using Pt-tipped electrodes: a minimum of three of five platinum (Pt)-tipped electrodes must have measurements of Eh that indicate anaerobic soil conditions. Anaerobic conditions are presumed to occur when the oxidation–reduction potentials are below the line shown in Figure 1; corresponding to a threshold of Eh < 595 – 60(pH). The redox potential value indicating anaerobic conditions depends on soil pH, with Eh values below 295 and 175 mV required at soil pH values of 5.0 and 7.0 respectively. As a result, soil pH measurements must be collected in situ each time an Eh measurement is made at the location of one of the five Pt-tipped electrodes. Electrodes should be installed at 25 cm for most soils, 12.5 cm in sandy textured soils, and 10 cm in soils that inundate by flooding or ponding.

![Figure 1](https://example.com/figure1.png)
4.3 | Analysis of precipitation normality

An analysis of precipitation normality is required to determine if the saturation, flooding, or ponding and anaerobic conditions criteria of the HSTS are met following a period of normal, wetter than normal, or drier than normal precipitation. This approach avoids potential misidentification of hydric soils when data collection occurred during a wetter than normal period, or when using data collected during a drier than normal period erroneously indicates nonhydric conditions (Vepraskas, Berkowitz, & Arellano, 2019). The analysis should be based on data collected onsite or at a nearby location with similar elevation and climate. Precipitation data must be analyzed using the Direct Antecedent Rainfall Evaluation Method (DAREM), Moving Total Antecedent Rainfall Method, or Adjusted Moving Total Antecedent Rainfall Method (Sumner, Vepraskas, & Kolka, 2009). These methods evaluate the precipitation totals prior to the soil data collection period to determine if the study occurred during a period of normal, above-normal, or below-normal precipitation. Precipitation normality evaluations examine the 30th and 70th percentile averages based on long-term (e.g., 30 yr) average precipitation records (Sprecher & Warne, 2000; USDA-NRCS 1997). Additional discussion of interpreting precipitation normality data in hydric soil studies and conducting these analyses is provided in Section 5.4 below.

5 | APPLICATION OF THE HYDRIC SOIL TECHNICAL STANDARD

The HSTS determines if a soil currently meets the hydric soil definition based upon measurements documenting that the soil remains saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper portion of the soil profile. The monitoring approach typically utilizes paired hydric–nonhydric study sites to document differences in soil morphology, hydrology, and oxidation–reduction potential (Figure 2). The following provides practical guidance for applying the HSTS, including the collection of field data, analysis and interpretation of study results, and reporting findings to NTCHS. The rationale for selecting each HSTS component is also discussed to further the understanding of the hydric soil study process and provide insight into the origins of the field indicators of hydric soils.

To develop a new field indicator of hydric soils or alter an existing field indicator, studies should use data collected at paired hydric–nonhydric soil locations approximately within 3 m of each other (Figure 2; Berkowitz & Sallee, 2011). However, in some landscape settings such as coastal plains and broad terraces with nearly level topography, larger distances between paired study locations may be required. The paired locations approach is required to demonstrate that hydric soil conditions exist within the hydric location and remain absent.
in the nonhydric location. As a result, the paired locations should be established as close to the hydric soil boundary as possible. More than two locations should be monitored using a transect approach if the position of the hydric soil boundary is not clear. Changes in soil morphology (e.g., matrix color, abundance of redoximorphic features), breaks in topography, or shifts in plant community composition can help users locate the hydric soil boundary when establishing study locations; however, application and interpretation of HSTS data remain independent of other data typically collected as part of a wetland delineation (i.e., vegetation community composition).

A minimum of three paired hydric–nonhydric study areas are required for consideration of additions or changes to field indicators of hydric soil. Note that these should not be replicated data collection locations within a single study area, but three or more study areas designed to demonstrate that results are not confined to a single area. Since field indicators of hydric soils are approved for specific LRRs and MLRAs, the area in which the HSTS monitoring is conducted should also be carefully considered and documented. For example, placing sample sites in multiple LRRs is recommended if the intent of a study is to expand the approved region of application for an existing field indicator of hydric soils. Additionally, the application of some field indicators of hydric soils is restricted to specific landscape positions, ecosystem features, or other constraints. For example, a subset of hydric soil indicators only apply to floodplains, depressional landscape features, or soils exhibiting a unique parent material characteristic (e.g., red parent materials; Mack, Berkowitz, & Rabenhorst, 2018; USDA-NRCS, 2018). As a result, users should consider and describe the ecological setting when selecting study areas for HSTS application.

Within each paired hydric–nonhydric study area, the data required to support additions or alterations to the field indicators of hydric soils includes four components: (a) soil descriptions, (b) data documenting whether the soil meets the saturation requirements of the HSTS, (c) data documenting the soil meets the anaerobic condition criteria of the HSTS, and (d) an analysis of precipitation normality (Berkowitz & Noble, 2015). All HSTS data should be presented to the NTCHS at least 60 d prior to an annual scheduled meeting, allowing time for committee members to review and evaluate those data. The NTCHS often selects annual meeting locations based upon the availability of adequate HSTS data, or in areas with proposed changes to the field indicators of hydric soils. Therefore, early communication with NTCHS during the design and implementation of hydric soil field studies is recommended.

5.1 Soil descriptions

Soil descriptions are required when implementing hydric soil studies using the HSTS. They are necessary to show that the soil does not meet an existing field indicator of hydric soils and/or meets a proposed field indicator. Soil descriptions are also useful in identifying clayey soil layers or other aquitards that could perch water and maintain shallow water tables. Soil descriptions should include all the soil profile and landscape information necessary for an experienced soil scientist to determine whether a field indicator of hydric soils currently exists (Table 1). At a minimum, the soil properties and morphology described should include data on soil layer depth; matrix color; redoximorphic feature presence abundance, type, color, and location; soil texture; and any existing hydric soil indicators met. Vasilas and Berkowitz (2016) and Vepraskas (2013) provide guidance on describing hydric soils. An interpretation of the soil description by the investigator should also be included, highlighting which soil properties were critical in meeting, or failing to meet the relevant field indicators of hydric soils. If no field indicators of hydric soils were met, then the morphology should be used to explain which features are present or absent that prevent the use of an existing field indicator (Figure 3). For example, some hydric soils may display morphologies that preclude the application of common field indicators of hydric soils such as high chroma, or a layer may be too thin to meet depth requirements, or the soil may have formed from parent materials capable of inhibiting the development of redoximorphic features or masking those features (Berkowitz & Sallee, 2011; Mack et al., 2018).

The soil descriptions used in HSTS studies are equivalent to soils data collected as part of a wetland delineation (USACE 2012; USDA-NRCS 2018). The forms provided in the regional supplements to the U.S. Army Corps of Engineers wetland delineation manual are designed specifically for the documentation of hydric soil characteristics and are recommended for HSTS applications (Figure 3). It is important to include the soil descriptions for each paired hydric–nonhydric study site (Table 1). Landscape and soil profile pictures collected at hydric and nonhydric sample locations should also be documented (Figures 2, 4, and 5).

5.2 Applying the soil saturation criteria of the Hydric Soil Technical Standard

In hydric soil studies, a soil layer is considered saturated, flooded, or ponded if the pore water has a pressure equal to or greater than atmospheric pressure (Soil Survey Staff, 1999; Vepraskas & Sprecher, 1997). This water will flow into wells, piezometers or open boreholes. Saturation defined as such does not include the capillary fringe above the water table (i.e., the tension saturated zone) where the water is held at a pressure less than atmospheric pressure.

Water table data should be presented for each piezometer or well at each study location and summarized in tabular and
TABLE 1 Example of soil descriptions at paired hydric (H) and adjacent nonhydric (N) sites examining high chroma sandy soils in Michigan, USA. Note that the example provides data from one paired hydric–nonhydric study area. The hydric location met the proposed field indicator of hydric soil S11—High Chroma Sands and the nonhydric location failed to meet any field indicators of hydric soils. Adapted from Berkowitz and Sallee (2011)

<table>
<thead>
<tr>
<th>Site</th>
<th>Layer</th>
<th>Depth</th>
<th>Matrix color</th>
<th>% Matrix</th>
<th>Redox color</th>
<th>% Redox</th>
<th>Type &amp; location</th>
<th>Contrast</th>
<th>Texture</th>
<th>Field indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydric Site 1 (H1)</td>
<td>1</td>
<td>0–8</td>
<td>10YR 4/2</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Sandy</td>
<td>S11—High Chroma Sand</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8–20</td>
<td>10YR 4/3</td>
<td>97</td>
<td>5YR 4/6</td>
<td>3</td>
<td>PL/M</td>
<td>Prominent</td>
<td>Sandy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>20–50</td>
<td>10YR 4/3</td>
<td>95</td>
<td>7.5 YR 3/5</td>
<td>5</td>
<td>PL/M</td>
<td>Distinct</td>
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<td></td>
</tr>
<tr>
<td>Nonhydric Site 1 (N1)</td>
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<td>0–10</td>
<td>10YR 6/3</td>
<td>100</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<td>None</td>
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<tr>
<td></td>
<td>2</td>
<td>10–50</td>
<td>10YR 5/3</td>
<td>100</td>
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<td>–</td>
<td>–</td>
<td>Sandy</td>
<td></td>
</tr>
</tbody>
</table>

graphic forms indicating when the required saturation criteria (≥14 consecutive days within 25 cm) was met (Figure 6). Guidance on construction and installation of piezometers and wells in addition to automated data logger installation, monitoring, and data analysis can be found in Sprecher (2008) and USACE (2005).

The duration of saturation, flooding, or ponding associated with the HSTS (i.e., 14 consecutive days in most soils) are in accordance with findings of the National Research Council (1995), who reported that wetland saturation, flooding, or ponding should occur during a continuous period of at least 14 d during the growing season, with a minimum mean interannual frequency of 5 out of 10 yr (≥50% return interval). That report also suggested that depth requirements occur within the upper portion of the soil profile including the zone of maximum root growth, identified as <30 cm for many wetland plants. The concept of the upper root zone roughly aligns with data from early hydric soil studies, which documented hydromorphic soil features occurring within 25 cm of the soil surface (Hurt & Puckett, 1992).

5.3 Applying the anaerobic conditions criteria of the Hydric Soil Technical Standard

The HSTS requires that users document the presence or absence of anaerobic conditions within the upper part of the soil profile during the same period when soil saturation occurs as described above. Three techniques have been approved for evaluating anaerobic conditions during application of the HSTS including IRIS devices, α,α’-dipyridyl dye, and soil oxidation–reduction potential measurements using Pt-tipped electrodes. Notably, these techniques developed independently over several decades and, as a result, there are differences in how each technique is applied and how the data are interpreted. However, the three methods have shown general agreement across multiple hydric soil studies.

5.3.1 IRIS devices

The application of IRIS devices (including tubes, panels, films, etc.) to document anaerobic conditions represents a relatively new technology that has become increasingly common in recent hydric soils studies (Castenson & Rabenhorst, 2006; Rabenhorst, 2018). The IRIS devices have proven easy to install and interpret and exhibit advantages over other techniques. They are less expensive and far simpler than measurements of Eh (and associated soil pH determinations) and can be used on any soil unlike α,α’-dipyridyl dye, which only works for soils containing iron. The IRIS devices also integrate soil conditions across space and time compared with other approaches, which provide documentation for a single point in time and require several measurements to develop time series. Most IRIS device studies use polyvinyl chloride (PVC) materials or clear plastic films coated with iron hydroxide paint (combination of ferrihydrite and goethite). Under saturated and anaerobic conditions, the ferric iron-containing paint becomes chemically reduced to soluble ferrous iron. The reduced ferrous iron dissolves into the soil solution and is removed from portions of the IRIS device, leaving stripped areas on the device (Figure 7; Rabenhorst, 2010). As noted above, the HSTS requires a minimum of three of five IRIS devices display iron removal from ≥30% of a zone ≥15 cm long starting with 15 cm of the soil surface to verify anaerobic conditions (Figure 7). Rabenhorst (2008) and Berkowitz (2009) provide additional guidance on the application and analysis of IRIS devices in hydric soils studies. The IRIS devices are commercially available or can be manufactured in the laboratory (Rabenhorst & Burch, 2006; Rabenhorst, 2018). Completed IRIS device data should be presented in tabular format (Table 2), indicating the installation and removal dates of each device, how many IRIS devices were installed at each study location, the amount of oxide removal from each device, the depth at which iron removal began, and the number of devices that met the anaerobic conditions criteria.
FIGURE 3  Example of a soil description of a study location that did not meet an existing field indicator of hydric soils, but met the requirements of the Hydric Soil Technical Standard (HSTS) based upon Indicator of Reduction in Soils (IRIS) device and groundwater table monitoring data and upon precipitation data demonstrating that the study occurred during a normal or drier than normal period. Note that the dataform summarizes the results of HSTS and provides information regarding what soil components were absent, preventing the soil from meeting an existing field indicator of hydric soil. LRR is Land Resource Region, and MLRA is Major Land Resource Area.

Although there is no standard duration of IRIS device deployment, the period of deployment is typically designed to capture the normal wet portion of the growing season. The maximum period of deployment should not exceed one annual wet–dry cycle. Images of the IRIS devices provide additional information and a number of image analysis tools aid in documenting study results. These data should be incorporated with other HSTS results to communicate which sample locations meet all requirements of the HSTS (Table 3).

5.3.2  \(\alpha,\alpha'-dipyridyl\) dye

The second technique to document anaerobic conditions for HSTS application involves the use of \(\alpha,\alpha'-dipyridyl\) dye,
Soil profile and landscape setting investigated using the Hydric Soil Technical Standard (HSTS) in the Mid-Atlantic Piedmont Province of Maryland. Close-up images of the (a) shallow and (b) deep portions of the soil profile highlighting specific morphological features (redoximorphic concentrations and depletions of iron in this example). Field indicator F19—Piedmont Flood Plain Soils was developed for use in these settings which reacts with reduced, ferrous iron to form a red or pink color (Figure 8; Childs, 1981). The dye can only be used in soils containing reducible iron, and the reaction only occurs when soils are saturated, anaerobic, and sufficient ferrous iron is in soil solution at the time of dye application. The reaction of α,α′-dipyridyl dye is rapid, inexpensive, and does not require the level of effort associated with equipment installation using IRIS devices or Pt-tipped electrode studies (Vepraskas et al., 2016). However, multiple dye applications must be used to document the presence of anaerobic conditions over time. At a minimum, the soils should show a positive reaction to the dye during two applications that occur 2 wk apart, coinciding with the period of soil saturation within the 25-cm zone. Preferably, additional dye applications are made, such as three or more consecutive weekly measurements which bracket the ≥14-d period of soil saturation.

The active ingredient in α,α′-dipyridyl dye is commercially available as a coating on paper strips, or as a solid chemical that must be prepared in a laboratory setting. Liquid dye formulations utilize a solution of 0.2% α,α′-dipyridyl in 1 M ammonium acetate buffered at pH 7.0. When using coated paper strips, the paper strip may turn pink or the coating may be transferred to the soil (Figure 8). Berkowitz, VanZomeren, Currie, and Vasilas (2017) determined that both liquid and paper formulations proved effective across a range of soils and displayed similar ferrous iron detection limits (0.31 mg L⁻¹). Degradation of α,α′-dipyridyl dyes can occur with exposure to light and heat, so maintaining liquid dye and paper strips in cool, dark conditions is recommended. Prepared solutions of ferrous ammonia sulfate solution provide a simple and effective method to test the reactivity of α,α′-dipyridyl dye. The dye may also react with the metal iron in spades, augers, and some knives. These implements can contaminate the soil with metal filings, which will also produce a positive reaction. Soil in direct contact with these implements should not have dye applied to them. On the other hand, if the implements are found to react to the dye, they can also be used to test the reactivity of the α,α′-dipyridyl solution.

Positive reactions to the dye are typically visible within one minute of application but may take longer in soils with low amounts of ferrous iron. Reaction to α,α′-dipyridyl dye must be documented throughout the same period that saturation, flooding, or ponding are recorded. Results of α,α′-dipyridyl dye reaction should be documented with photographs and summarized in tabular form (Table 3). Additional guidance regarding the application of α,α′-dipyridyl dye is provided in NTCHS (2009) and Berkowitz et al. (2017).

5.3.3 Oxidation–reduction potential measurements using Pt-tipped electrodes

The third approved method for documenting anaerobic conditions during HSTS application utilizes measurements of soil oxidation-reduction potential (i.e., redox potential or Eh) via...
Advantages of using Eh measurements in hydric soil studies include the ability to track changes in soil conditions in response to environmental factors (e.g., wetting–drying cycles), the capacity to utilize automated data logging techniques, and the ability to link Eh values with specific mineral transformations (e.g., chemical reduction of iron, sulfur; Rabenhorst et al., 2009). Potential disadvantages of Eh measurements include the time and expense of construction and installation of Pt electrodes, the need to measure soil pH over time, the inherent variability associated with microsites of soil oxidation and reduction, plating or fouling of the electrode surface inducing error, and the need for additional data interpretation to differentiate aerobic and anaerobic soil conditions based upon Eh-pH phase diagrams (Vepraskas et al., 2016).

Redox potential data are interpreted using Eh-pH diagrams developed from the Nernst equation that show where the theoretical chemical reduction of specific redox active elements occur (Bohn, McNeal, & O’Connor, 1985). The Eh-pH diagram in Figure 9 displays the Eh values where the reduction of oxygen ($O_2:H_2O$) and iron [$Fe(OH)_3:Fe^{2+}$] have been estimated from the Nernst equation across the common range of soil pH values (Vepraskas et al., 2016). Also shown is the zone at a pH value of 7.0 where oxygen reduction has been found to occur in laboratory experiments as reported by McBride (1994). It is clear that oxygen reduction occurs at Eh values that are lower than those predicted by the Nernst equation. However, experimental data suggest that the reduction of iron in $Fe(OH)_3$ occurs at Eh values close to where the Nernst equation predicts (McBride, 1994).

The anaerobic conditions threshold (i.e., Eh-pH line) used to interpret redox potential measurements for the HSTS applications is also shown in Figure 9. This is a unique threshold that was defined solely for hydric soil identification. It was not developed from the Nernst equation and is not tied to a particular redox couple. The HSTS threshold has the same slope as the oxygen reduction line defined by the Nernst equation. However, the HSTS line was shifted downward to reflect Eh values that are lower than those found for oxygen reduction in experimental settings. The HSTS threshold was deliberately selected to yield a value of 175 mV at a pH of 7, corresponding with the zone where Fe reduction has been observed experimentally.

For hydric soil identification, we want to know when a soil is anaerobic. For this purpose, an HSTS threshold was needed to indicate when a soil is likely to be anaerobic with a high probability, not simply to indicate when the onset of anaerobic conditions may begin. The placement of the HSTS threshold below the range of Eh associated with the reduction of oxygen as demonstrated in experiments reflects soil conditions that can be assumed to be anaerobic with a high level of certainty. As a result, the NTCHS selected an anaerobic
The NTCHS originally considered using the theoretical threshold (derived from the Nernst equation) for the reduction of Fe(OH)$_3$ to Fe$^{2+}$ to identify anaerobic conditions in HSTS applications because the reduction and translocation of iron forms the basis for many common field indicators of hydric soils (e.g., F3—Depleted Matrix; Vepraskas & Vaughn, 2016). However, the threshold for the reduction of Fe(OH)$_3$ occurs at Eh values $\geq 644$ mV for pH values $\leq 4.0$ (Vepraskas et al., 2016). The NTCHS concluded that Eh values in that range were too high to provide a conservative and defensible threshold to document anaerobic soil conditions for the purposes of hydric soil identification.

Another alternative debated by NTCHS was the use of an anaerobic reduction threshold that maintained the slope of the conditions threshold that would ensure dissolved oxygen would be absent from the soil solution.
TABLE 3 Example of summary data from three hydric paired hydric (H)–nonhydric (N) study areas indicating whether the Hydric Soil Technical Standard (HSTS) requirements were met

<table>
<thead>
<tr>
<th>Study area</th>
<th>IRIS&lt;sup&gt;a&lt;/sup&gt; devices with ≥30% removal</th>
<th>α,α'-dipyridyl dye reaction</th>
<th>Pt electrodes displaying anaerobic conditions</th>
<th>Consecutive days of saturation, flooding or ponding</th>
<th>Anaerobic conditions</th>
<th>Saturated, flooded, or ponded conditions</th>
<th>HSTS met</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>4/5</td>
<td>Yes</td>
<td>3/5</td>
<td>26</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N1</td>
<td>1/5</td>
<td>No</td>
<td>0/5</td>
<td>5</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>H2</td>
<td>5/5</td>
<td>Yes</td>
<td>5/5</td>
<td>89</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N2</td>
<td>2/5</td>
<td>No</td>
<td>1/5</td>
<td>15</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>H3</td>
<td>3/5</td>
<td>Yes</td>
<td>4/5</td>
<td>37</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N3</td>
<td>0/5</td>
<td>No</td>
<td>0/5</td>
<td>8</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

<sup>a</sup>IRIS, Indicator of Reduction in Soils.

Figure 8 A soil exhibiting anaerobic conditions through the application of α,α'-dipyridyl dye embedded in paper test strips. Note that the positive reaction results in a red or pink color occurring over approximately 80% of the soil surface, above the 60% required to document anaerobic conditions in Hydric Soil Technical Standard (HSTS) studies.

Threshold used to estimate oxygen reduction, but shifted the line downward to the lower portion of the Eh range where oxygen reduction had been shown experimentally. This would have resulted in an HSTS threshold intersecting a point of approximately 400 mV at a pH of 7.0, which corresponds with the bottom of the range where oxygen reduction has been observed in laboratory studies (McBride, 1994). The NTCHS also considered this approach problematic because the group wanted to establish a threshold that corresponded to Eh values where oxygen would be absent from the soil solution, not simply at the lower boundary of oxygen reduction where oxygen might remain in soil solution. In other words, NTCHS wanted a buffer to ensure that the Eh threshold for identifying hydric soils was clearly anaerobic and preclude the misidentification of hydric soils.

In response, the NTCHS decided the best approach would be to define an oxidation–reduction threshold that maintained the slope of the oxygen reduction line, but adjusted the line further downward to have it intersect the Fe(OH)<sub>3</sub> reduction.
### Table 4
Example of data from five replicate Pt electrodes deployed at paired hydric (H) and nonhydric (N) study locations

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Replicate electrode no.</th>
<th>Electrode reading</th>
<th>Reading after reference probe correction&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Soil pH</th>
<th>Eh required for reduction&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Anaerobic conditions met</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Jan. 2009</td>
<td>H1</td>
<td>1</td>
<td>33</td>
<td>230</td>
<td>5.51</td>
<td>264</td>
<td>Yes</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>H1</td>
<td>2</td>
<td>95</td>
<td>292</td>
<td>5.51</td>
<td>264</td>
<td>No</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>H1</td>
<td>3</td>
<td>−89</td>
<td>108</td>
<td>5.51</td>
<td>264</td>
<td>Yes</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>H1</td>
<td>4</td>
<td>154</td>
<td>351</td>
<td>5.51</td>
<td>264</td>
<td>No</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>H1</td>
<td>5</td>
<td>−15</td>
<td>182</td>
<td>5.51</td>
<td>264</td>
<td>Yes</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>N1</td>
<td>1</td>
<td>176</td>
<td>373</td>
<td>6.2</td>
<td>223</td>
<td>No</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>N1</td>
<td>2</td>
<td>302</td>
<td>499</td>
<td>6.2</td>
<td>223</td>
<td>No</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>N1</td>
<td>3</td>
<td>163</td>
<td>360</td>
<td>6.2</td>
<td>223</td>
<td>No</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>N1</td>
<td>4</td>
<td>−10</td>
<td>187</td>
<td>6.2</td>
<td>223</td>
<td>Yes</td>
</tr>
<tr>
<td>28 Jan. 2009</td>
<td>N1</td>
<td>5</td>
<td>306</td>
<td>503</td>
<td>6.2</td>
<td>223</td>
<td>No</td>
</tr>
</tbody>
</table>

Note. Three of the five electrodes installed at H1 displayed anaerobic conditions and would meet the anaerobic conditions requirement of the Hydric Soil Technical Standard (HSTS) for the date examined. Conversely, N1 would fail to meet the HSTS requirement because only one of the five electrodes displayed anaerobic conditions. Note that these data only represent a single data collection event and that multiple redox measurements are required during the period when the saturation criteria of the HSTS is met.

<sup>a</sup>Silver/silver chloride reference electrode correction factor +197.

<sup>b</sup>The Eh threshold required for reduction was $Eh < 595 - 60(pH)$.

---

The HSTS Eh-pH threshold line is purposefully conservative for use in HSTS applications in the sense that soils with Eh values below the HSTS line would clearly be anaerobic in accordance with the hydric soils definition, and not be borderline cases where oxygen could still be present in the soil solution. The NTCHS recognizes that the threshold value selected for the application of the HSTS occurs at Eh values below the theoretical zone of reduction for other redox active species including nitrogen, manganese, and (depending on the pH) some iron containing compounds. A Pt-tipped electrode study by Park and Rabenhorst (2018) highlights this, reporting that soil Eh values reached those needed for iron reduction several days before the HSTS threshold was exceeded (soil pH < 4.5). This is expected based on the relationships shown in Figure 9.

Given the complexities of Eh measurements, the reporting of data in both tables and figures will aid in data interpretation for HSTS applications (Table 4, Figure 10). Data on sampling period, replicates, uncorrected and corrected Eh measurements, soil pH values, and whether each Pt electrode is considered anaerobic should be evaluated independently and summarized in conjunction with other HSTS data (Table 3).

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**Figure 10** Example data from five replicate Pt-tipped electrodes (installed at the same depth) measuring soil oxidation-reduction potential. The dashed line represents the redox potential (Eh) threshold required for the soil to be considered anaerobic for Hydric Soil Technical Standard (HSTS) application. The Eh threshold fluctuates with changes in soil pH observed during the study. Measurements occurring above the dashed line are considered aerobic, whereas those occurring below the dashed line are considered anaerobic. Note that three of the five electrodes display anaerobic conditions (after Week 10); therefore, the site meets the anaerobic conditions requirement of the HSTS.
5.3.4 Anaerobic conditions summary

The availability of multiple approaches to evaluate anaerobic conditions has several advantages. For example, IRIS devices integrate results across the period of deployment and provide a larger reactive surface than evaluated using other methods. Chemical dye application is easy and inexpensive, providing a way to rapidly document soil conditions during site visits. Platinum electrodes add cost and require additional analysis but provide much more detailed information about particular redox interactions at a much smaller spatial scale. Although only one method is required for HSTS application, the use of multiple approaches provides supporting information to better understand oxidation–reduction dynamics and should be considered when designing hydric soil studies.

Field and laboratory studies have evaluated anaerobic conditions using multiple techniques, and determinations of anaerobic conditions made using the HSTS Eh–pH threshold have shown general agreement with determinations obtained using α-α’-dipyridyl dye and IRIS methodologies which identify Fe reduction (Jenkinson & Franzmeier, 2006; Vaughan, Miller, Navarro, & Appel, 2016). For example, Berkowitz et al. (2017) reported that three of five soils examined surpassed the Eh–pH threshold concurrently with the onset of positive α,α'-dipyridyl dye reactions. The remaining soils displayed anaerobic conditions based on Eh data several days before positive α,α'-dipyridyl dye reactions occurred, possibly due to the need for sufficient ferrous iron to accumulate in soil solution to induce a positive dye response. Further, Eh values below the HSTS Eh–pH threshold have been associated with formation of morphological features (e.g., Fe reduction and translocation, low chroma colors) that define many common field indicators of hydric soils (Berkowitz, VanZomeren, & Fresard, 2019; Vepraskas et al., 2016). However, the NTCHS recognizes that additional studies evaluating the relationship between different techniques used to document anaerobic conditions are needed.

5.4 Applying precipitation normality analysis for the Hydric Soil Technical Standard

Few hydric soil studies are maintained for extended periods, and many are limited in duration (i.e., 1 or 2 yr or wet–dry cycles; Vepraskas et al., 2016). Precipitation analysis places short duration study results into a larger climatic context. As a result, HSTS application requires that the saturation and anaerobic conditions criteria be met following a period of normal or drier than normal precipitation. Data meeting saturation and anaerobic conditions requirements after a wetter than normal period cannot be used to meet the HSTS, and additional monitoring is needed to document hydric soil conditions (Vepraskas et al., 2019). Alternatively, data collected with the intention to demonstrate that a soil is not currently functioning as a hydric soil must be collected during a wetter than normal or normal period during the portion of the growing season most likely to induce saturated and anaerobic conditions (USACE 2012).

Precipitation normality analysis should be based on precipitation data collected onsite or at a nearby location with similar elevation and climate. Three precipitation data analysis techniques are recommended including the DAREM, the Moving Total Antecedent Rainfall Method, and the Adjusted Moving Total Antecedent Rainfall Method (Table 5; Sumner et al., 2009). Sprecher and Warne (2000) provide a description of each method (although referring to them as the Method for Estimating Antecedent Moisture Conditions, Method of Rolling Totals, and the Combined Method, respectively), offer guidance on application, and compare and contrast the three approaches. All three methods of evaluating precipitation normality examine the 30th and 70th percentile averages based on long-term (e.g., 30 yr) average precipitation records provided in Climate Analysis for Wetlands Tables (WETS tables) developed by the USDA-NRCS National Water and Climate Center (Figure 11).

Using these techniques, the three most recent monthly precipitation totals are compared with the 30th and 70th percentile thresholds and assigned a numerical value based on drier than normal (1), normal (2), or wetter than normal (3) conditions. Numerical values are then weighted to account for temporal effects (i.e., more recent precipitation likely has a larger effect on current hydrologic conditions); then, the computed values are totaled to yield a cumulative score used to describe whether the period of precipitation was drier than normal (cumulative score = 6–9), normal (10–14), or wetter than normal (15–18).

The DAREM analysis represents the most expedient approach, has been used in a number of studies examining hydric soils, and is recommended for interpreting hydrologic data in wetlands research more broadly (USACE, 2005). Sumner et al. (2009) provides additional guidance on determining precipitation normality using DAREM, and a recent study by Vepraskas et al. (2019) suggests that the approach provides a reliable method for determining precipitation normality across a wide range of climatic and geographic conditions. However, additional data collection, interpretation, and analysis may be required in landscape settings where the DAREM approach may not reflect normal conditions with respect to either hydrology or hydraulics. For example, analysis of river stages, the Palmer drought severity index, and/or snowpack may yield valuable insight in some areas, providing additional context for short term data collection efforts investigating hydric soils.

Several precipitation normality analysis scenarios exist under which HSTS data may be unreliable or additional data collection may be required: (a) if the HSTS is met during a
TABLE 5 Example of Direct Antecedent Rainfall Evaluation Method (DAREM) analysis demonstrating precipitation normality determination for Hydric Soil Technical Standard (HSTS) determinations

<table>
<thead>
<tr>
<th>Month rank</th>
<th>Name</th>
<th>WETS 30th percentile</th>
<th>WETS 70th percentile</th>
<th>Measured precipitation</th>
<th>Condition* value</th>
<th>Month weight</th>
<th>Score</th>
<th>Precipitation condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd</td>
<td>Sept. 5.84</td>
<td>12.80</td>
<td>12.73</td>
<td>Normal</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>Dry</td>
</tr>
<tr>
<td>2nd</td>
<td>Oct. 4.34</td>
<td>10.72</td>
<td>8.13</td>
<td>Normal</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>Normal</td>
</tr>
<tr>
<td>Most recent</td>
<td>Nov. 8.05</td>
<td>15.19</td>
<td>2.26</td>
<td>Dry</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Month examined</td>
<td>Dec.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total = 9</td>
</tr>
<tr>
<td>3rd</td>
<td>Oct. 4.34</td>
<td>10.72</td>
<td>8.13</td>
<td>Normal</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>Normal</td>
</tr>
<tr>
<td>2nd</td>
<td>Nov. 8.05</td>
<td>15.19</td>
<td>2.26</td>
<td>Dry</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Most recent</td>
<td>Dec. 10.24</td>
<td>16.21</td>
<td>10.41</td>
<td>Normal</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Month examined</td>
<td>Jan.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total = 10</td>
</tr>
<tr>
<td>3rd</td>
<td>Nov. 8.05</td>
<td>15.19</td>
<td>16.76</td>
<td>Wet</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>Wet</td>
</tr>
<tr>
<td>2nd</td>
<td>Dec. 10.24</td>
<td>16.21</td>
<td>10.41</td>
<td>Normal</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Most recent</td>
<td>Jan. 11.07</td>
<td>20.45</td>
<td>22.40</td>
<td>Wet</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Month examined</td>
<td>Feb.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

Note. Based on these results, the anaerobic conditions and saturation requirements of the HSTS would need to be met during December and/or January to confirm the presence of hydric soils because those were determined to be drier than normal and normal periods of precipitation respectively. February was a wetter than normal period; as a result, data collected during that month could not be used for hydric soil identification. All precipitation data are provided in centimeters following conversion from values provided in the Climate Analysis for Wetlands (WETS) tables; all data were collected during the growing season (Figure 11; adapted from Berkowitz et al., 2014).

*Dry = 6–9, Normal = 10–14, Wet = 15–18

FIGURE 11 Example of Climate Analysis for Wetlands (WETS) data indicating the 30th and 70th percentiles for monthly precipitation. Note that the WETS tables report precipitation data in inches.
The concept of hydric soils continues to evolve as soil scientists gain a better understanding of wet soil morphology, functions, and pedogenic processes. The NTCHS makes determinations regarding the field indicators used to identify hydric soils for the purpose of wetland delineation, an important aspect of natural resource management in the United States. In support of that goal, NTCHS developed the HSTS, providing a quantitative method for determining whether or not a soil meets the definition of a hydric soil. Development or revision of field indicators of hydric soils requires data collection and analysis including (a) soil descriptions, (b) evidence of saturation and (c) anaerobic conditions as outlined in the HSTS, and (d) analysis of precipitation normality. Research investigating soil conditions through the HSTS promotes further understanding of hydric soil formation, evolution,
morphology, and processes, thus improving the identification and management of wetland resources. The HSTS is expected to undergo periodic updates as new approaches for soil analysis are developed and incorporated into the study of hydric soils. For example, new research is expanding approaches to characterize submerged soils in freshwater and tidal systems (Rabenhorst & Stolt, 2012; Erich & Drohan, 2012). Additionally, technologies for documenting in situ chemical speciation, changes in oxidation–reduction potential, and conducting accurate measurements of hydropatterns continue to improve. Approaches to precipitation normality analysis will also likely advance with new developments in climate science. These innovations can enhance hydric soils research, including the application of the HSTS and the field indicators of hydric soils.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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