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Characterization of redoximorphic features of forested wetland soils by simple hydro-physicochemical attributes in Northern Virginia, USA

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Abstract We assessed hydro-physicochemical (HP) settings and soil color attributes including redoximorphic features (RMFs) at four forested wetlands in Northern Virginia, USA, to identify whether four simply measurable HP attributes—inundation/saturation frequency, bulk density, soil moisture, and percent sand—can provide an explanatory framework for characterizing and classifying soil color attributes related to hydric soil field indicators. Study plots (n = 16) were grouped by site for initial characterizations and comparisons of HP (n = 4) and color attributes (n = 11); each attribute was additionally characterized and compared between three HP-based clusters formulated through k-means clustering analysis. Whereas only one HP attribute (inundation/saturation frequency) significantly differed between sites, all HP attributes but percent sand differed between HP-based clusters ($p < 0.05$), with PCA Dimensions 1 and 2 explaining over 80% of variability in plot HP attributes. Moreover, more sets of color attributes were significantly different when plots were grouped by HP-based cluster (n = 5: frequency of concentrations, non-matrix color count, hue, chroma, and depth to concentrations) compared to by site (n = 3: value, frequency of depleted matrices, depth to depletions) ($p < 0.10$). Simply measurable HP attributes are thus closely associated with certain soil RMF and color characteristics beyond site identity, potentially serving as a suite of measurements that can be adopted to assess and monitor redoximorphic features indicative of wetland soils.

Keywords Wetland soils · Soil color · Redoximorphic features (RMFs) · Hydric soils · Hydro-physicochemistry · Wetland monitoring

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Introduction

The establishment of various national policies to conserve wetland functions—notably, the United States (US) "no net loss" policy of 1990 (Page and Wilcher 1990)—has led to a suite of monitoring protocols for identifying, monitoring, constructing, and conserving wetland sites (Berkowitz 2012; Tiner 2017). A subset of such protocols is specifically focused on *hydric soils*, defined by the US Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS) as "soil[s] that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop

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anaerobic conditions in the upper part" (Federal Register 1994; USDA–NRCS 2018).

Unseen in upland environments, colors and color patterns called *redoximorphic features* (RMFs) materialize in such anaerobic soil environments due to microbially-mediated redox reactions that reduce, translocate, and oxidize soil iron (Fe) and manganese (Mn), and are thus inherently useful in establishing and utilizing field indicators of hydric soil presence. Using the Munsell Soil Color Chart (MSCC) to characterize soil *hues*, *values*, and *chromas* (Munsell 1905), observers can identify three key RMF types (Fig. 1) relevant to the hydric soil field indicators published by the USDA–NRCS: (1) redox depletions, or low-chroma [≤ 2] and high-value [≤ 4] areas where Fe–Mn oxides have been removed; (2) reduced matrices, or blue, green, or gray low-chroma areas containing reduced aqueous iron (Fe^{2+}); and redox concentrations, or orange, red, or brown accumulations of Fe–Mn oxides (Daniels and Gamble 1967; Simonson and Boersma 1972; Moore 1974; Guthrie and Hajek 1979; Richardson and Hole 1979; Franzmeier et al. 1983; Evans and Franzmeier 1988; Vepraskas 2015; USDA–NRCS 2018). Beyond soil color observations, visual measurement of ferrous iron can be possible using a α,α'-dipyridyl dye reagent, often utilized for in-situ soil observation for RMFs at the profile scale (Berkowitz et al. 2017).

As the underlying processes responsible for RMF formation are inexorably linked to the frequency, duration, and intensity of soil saturation and reduction, RMF characterizations can be used as signals of past and present wetland development. For example, high-chroma Fe concentrations have been correlated to seasonal high-water table (SHWT) depths, and low-chroma depleted/reduced matrices have been correlated to saturation durations (Veneman et al. 1998; Jacobs et al. 2002). Contemporary hydric soil research has sought to clarify and quantify the complex relationships between RMF development and environmental conditions, allowing links between field observations of RMFs and longer-term site hydrology and wetland ecosystem development (Megonigal et al. 1993; He et al. 2003; Vepraskas et al. 2006; Vepraskas and Caldwell 2008). In particular, the USDA–NRCS manual of field indicators for hydric soils is the official procedural guide for identifying if soil morphological features legally indicate the presence of a hydric soil, where indicators are differentiated between sandy soils and loamy/clayey soils (USDA–NRCS 2018).

While this binary classification of soils as *hydric* or *nonhydric* required for regulatory decision-making has been informed by research confirming the link between reducing conditions and the presence of specific color patterns by depth, thickness, abundance, and contrast, it has arguably failed to classify the diverse visual cues of soil biogeochemistry into *hydricity* classes. Furthermore, the capacity to not only apply field indicators precisely and confidently, but also to appropriately generalize observed color patterns at a plot throughout the wetland site, relies on technical understanding and/or training that may not be intuitive for land and watershed managers, citizen scientists, or general ecologists who are not well-versed in the indicator details or relationships between soil biogeochemistry and water—landscape processes. A more simplified framework may enhance the

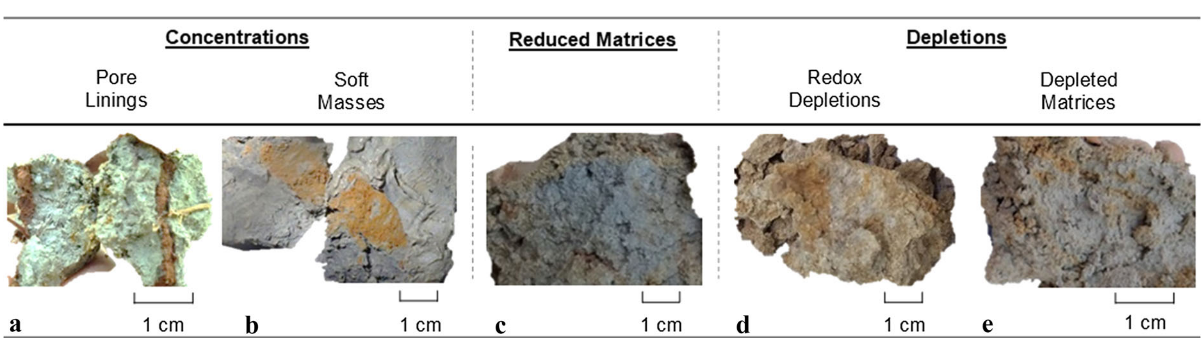

Fig. 1 Examples of each of the three main types of iron redoximorphic features from this study's field work: concentrations, including **a** pore linings and **b** soft masses; **c** reduced matrices; and depletions, which includes **d** non-matrix redox depletions and **e** depleted matrices

capacity for these stakeholders to participate in hydric soil assessment.

Individual hydrologic variables are often inadequate for simply relating RMFs to hydrology, as a combination of various hydrological and soil physicochemical attributes like soil texture, pH, redox potentials, and historic rainfall and water table levels influence RMF formation (Genthner et al. 1998; Jacobs et al. 2002; He et al. 2003; Vepraskas 2015); however, multiple indicators of hydrologic and soil physicochemical settings may be apt for the genesis of RMF color classes. Certain hydro-physicochemical (HP) soil attributes are not only ubiquitously and simply measured for various applications of soil and ecological research (Bestelmeyer et al. 2009; Kachergis et al. 2011), but also hold evidenced relationships to wetland development, including RMFs. In particular, soil texture and moisture relate to redox potential (Megonigal et al. 1993) and wetland functions like denitrification (Palta et al. 2016); soil moisture, despite its variability that may be unrelated to water table depth, has been linked to wetland vegetation prevalence index (Bollman et al. 2012) and RMF abundance (Raymond et al. 2013); wetland surface inundation and bulk density can reflect wetland hydrology and influence wetland development (Campbell et al. 2002; Palta et al. 2017); and lower bulk densities are known to encourage water infiltration necessary for producing reducing conditions and/or relate to soil organic matter contents that can be increased by the slowed decomposition of reduced soils (Adams 1973; Martens and Frankenberger 1992; Ehrich 2010).

HP attributes have previously provided the basis for distinguishing "soil condition groups," or HP-based clusters of study areas (Schoenholtza et al. 2000; Ahn and Peralta 2012; Dee and Ahn 2012; Peralta et al. 2013), but relevance for soil RMF and color attributes was not addressed. Studies that have previously distinguished patterns of RMFs have not employed simply measurable HP attributes as a basis for such classifications (Wheeler et al. 1999; Pruitt 2001). Investigating the use of such HP attributes for classifying and characterizing RMFs may highlight the method's capacity to unleash additional information about the development of soil colors and patterns that could be challenging to uncover using the USDA–NRCS procedures.

The goal of this study was to determine if simply measurable and accessible hydro-physicochemical attributes—inundation/saturation frequency, gravimetric soil moisture, bulk density, and soil texture as percent sand—can serve as the genesis for classifying and characterizing soil color and RMF attributes for identifying both hydric and future potential hydric soils. Toward this aim, we assessed the efficacy of using HP-based clusters, in comparison to site identity, in classifying RMF color patterns in four forested wetlands of Northern Virginia, USA by (1) analyzing and comparing plot-scale HP and soil color / RMF attributes between wetland sites to identify the capacity for site identity to distinguish classes of color and RMF patterns; and, in contrast, (2) analyzing and comparing HP and soil color / RMF attributes between HP-based clusters of study plots.

Materials and methods

Study area

To investigate forested wetlands at a regional scale, field research was conducted from spring 2018 to fall 2019 at four freshwater wetlands within the Coastal Plain and Piedmont physiographic regions of Northern Virginia, USA. Average temperatures were 13.5 °C (−13.9 – 35.0 °C) in 2018 and 14.0 °C (−18.9 – 37.8 °C) in 2019; total precipitation was 169.5 cm in 2018 and 103.7 cm in 2019, with 2018 being the wettest year of the decade by 50-plus cm (Menne et al. 2012).

Sites within the Coastal Plain physiographic region include Elizabeth Hartwell–Mason Neck Wildlife Refuge (MN) in Fairfax County and Julie J. Metz–Neabsco Creek Wetland Bank (JJM) in Prince William County; sites within the Piedmont physiographic region include Banshee Reeks Nature Preserve (BR) and Algonkian Regional Park (ARP) in Loudoun County (Fig. 2). While Coastal Plains soils are generally sandier than Piedmont soils (Markewich et al. 1990), all investigated soils would be classified as *loamy/clayey* rather than *sandy* per hydric soil field indicators (USDA–NRCS 2018; USDA–NRCS Soil Survey Staff 2020).

MN (38°38′38" N, 77°09′57" W) includes a hardwood forest and forested wetland with rolling microtopography consisting of high points

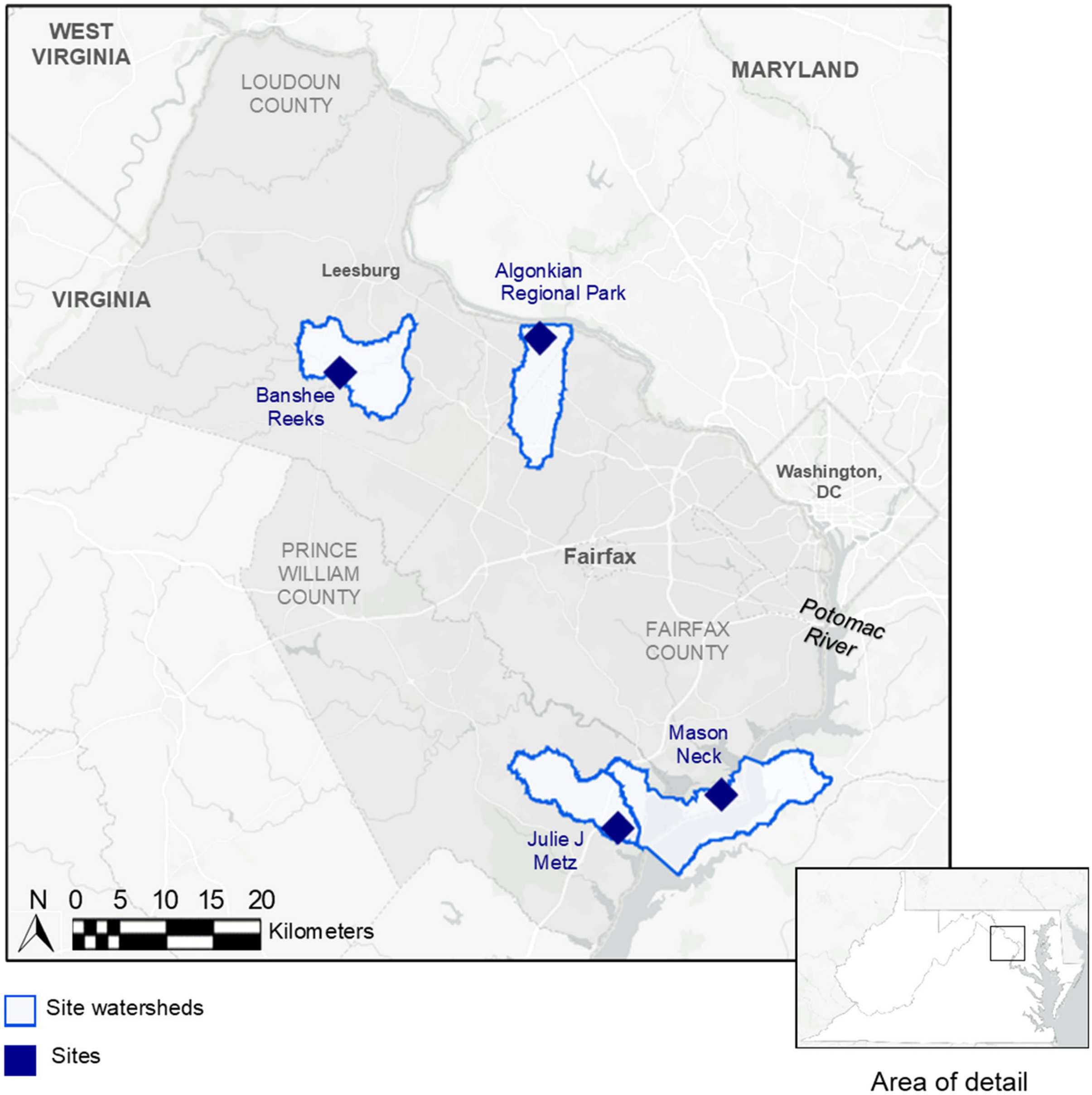

Fig. 2 Regional map displaying the four study sites and their subwatersheds in Northern Virginia, USA

(hummocks) and low points (hollows) with precipitation being the main hydrologic input. The occasionally to frequently saturated hollows are mapped as the hydric Gunston silt loams; the rarely saturated hummocks are mapped as the nonhydric Matapeake silt loams and Mattapex loams (Table 1; Ahn et al. 2009; US Fish and Wildlife Service 2010; USDA–NRCS Soil Survey Staff 2020). JJM (38°36′23“ N, 77°16′38” W) lies adjacent to Neabsco Creek, a tributary of the Potomac River, and has sustained wetland hydrology since its construction as a mitigation wetland in 1994 (Environmental Laboratory 1987). The wetland contains occasionally, frequently, and permanently flooded soils mapped as the hydric Featherstone mucky silty loam and Hatboro-Codorus Complex (Table 1), influenced by groundwater recharge, precipitation, and stream surface flow (USDA–NRCS Soil Survey Staff 2020). In the Piedmont, BR (39°1′31“ N, 77°35′30” W) includes occasionally to frequently saturated forested areas

Table 1 Summary of site descriptions, including landscape, hydrologic, morphologic, and soil characteristics; percent impervious surface (%ISC) was obtained from the Watershed Index Online (WSIO) and all other information was obtained from the Web Soil Survey (US EPA 2019; USDA–NRCS Soil Survey Staff 2020)

	Algonkian Regional Park (ARP)	Banshee Reeks (BR)	Julie J. Metz—Neabsco Creek (JJM)	Mason Neck (MN)
Watershed name	Sugarland Run	Big Branch—Goose Creek	Neabsco Creek	Occoquan Bay—Potomac River
% Impervious surface[a]	26.2% (urbanized, U)	0.7% (non-urbanized, N)	24.9% (urbanized, U)	0.1% (non-urbanized, N)
Physiographic region	Piedmont	Piedmont	Coastal Plain	Coastal Plain
Geologic age	Upper Triassic	Upper Triassic	Quaternary	Quaternary
Parent material	alluvium (sandstone)	Alluvium (sandstone, shale) over residuum	alluvium, marine deposits	Fluviomarine deposits (sedimentary gravel, sand)
Geomorphology	Drainageways, floodplains, terraces	Drainageways, floodplains	Terraces, floodplains	Fluviomarine terraces, interfluves, drainageways
Nonhydric soil series	Linside, Huntington silt loams	Leedsville cobbly silt loam Oatlands gravelly silt loam Manassas silt loam	Dumfries sandy loam, Lunt loam	Gunston, Matapeake silt loams Mattapex loam
Hydric soil series	Kinkora-Delanco complex Huntington silt loam	Codorus, Albano, Hatboro silt loams	Featherstone mucky silt loam Hatboro-Codorus silt loam	Elbert, Elkton silt loams
Major vegetation communities	Black walnut and oak forested floodplains; freshwater forested and emergent wetlands	Hardwood forests, riparian wetlands, and Mountain-Piedmont basic seepage swamp	Forested, scrub, and emergent wetlands	Hardwood oakhickory forest, palustrine forested wetlands

[a]%ISC = Percent impervious surface cover in the watershed; U = urbanized (%ISC > 20%) and N = non-urbanized (%ISC < 5%)

mapped as the hydric Albano silt loam plus the nonhydric Codorus and Manassas silt loams (Table 1; USDA–NRCS Soil Survey Staff 2020). Floodplains and riparian zones are influenced by subsurface flow from Goose Creek, precipitation, and surface runoff from tributaries. ARP (39°3′28“ N, 77°21′51” W) includes riparian forests and freshwater forested and emergent wetlands influenced by overland flow from the Potomac River, a groundwater connection with nearby emergent wetlands, and precipitation. Mapped soil series include Rowland silt loams and Lindside silt loams (Table 1); while neither is hydric, ARP was observed to be capable of supporting wetland vegetation before sampling began (USDA–NRCS Soil Survey Staff 2020).

Per site, four 1 $\times$ 1 m randomly selected plots were chosen to represent local wetland heterogeneity (n = 16) using ESRI ArcGIS software. Nonhydric plots within sites were included to increase variability in HP attributes and provide results applicable to sites not yet identified to be wetlands. Randomly chosen plots were modified if necessary to ensure accessibility and maintain $\geq$ 200 m between plots (Chi et al. 2018).

Field methods

To capture seasonal variations in soil color, soil profile characterizations and color measurements were obtained at each plot during spring (February–March), summer (May–July), and fall (September–October) of 2018 and 2019, yielding 96 profiles overall. Per visit, soil was collected from each plot using a 10-cm diameter soil auger (AMS) to a depth of roughly 60 cm, with subsequent profiles spaced $\geq$ 10 cm apart to avoid disturbed areas. Soil surface inundation/saturation down to 30 cm was also visually assessed and recorded per visit.

Augered soil peds were repeatedly broken into smaller pieces up to − 4 cm in diameter to ensure internal colors were identified, including redox depletions (matrix or nonmatrix), concentrations, reduced matrices, and gley colors. For each unique color observed (n = 374), the MSCC was used to determine color *hue*, *value*, and *chroma*. Conventional methods of soil profiling per the MSCC were employed, including wetting soils before color judgments and noting RMF abundance (as a percentage), size, and location (i.e., depth from surface [cm] and horizon); Schmidt and Ahn (2019) provides further discussion of the MSCC methodology. To assess HP attributes, soils were collected at three subplots per plot (n = 48) between March and August 2020, approximately 50 cm from soil profile locations. A PVC pipe with handcrafted jigsaw teeth (radius = 3.8 cm) was used to remove soil cores with minimal disturbance for lab processing.

Lab processing and calculations

Soil cores were massed (M_{s+w}) and placed in a drying oven at 98 °C for 3–6 days until a constant dry mass (M_s) was achieved. Calculations based on wet and dry masses and total core volumes (V_T, calculated as $\pi \times 3.8^2 \times 10$ cm^3) include soil bulk density (*BD*, g•cm^{-3}), equal to M_s / V_T, and (2) gravimetric soil moisture (*GSM, %*), equal to $100 \times (M_{s+w} - M_s)$ / M_s. Additionally, inundation/saturation frequencies were calculated per plot by summing binary observations of surface inundation and/or saturation across the study period and dividing by the number of plot visits (6). Soil texture for the top 30 cm was represented by percent sand, obtained from the Web Soil Survey (WSS) using plot GPS coordinates (USDA–NRCS Soil Survey Staff 2020).

Given within-site heterogeneity and sufficient spatial separation, plots were treated as independent samples for soil HP and color attributes, which were obtained by profile then summarized by plot before statistical analyses. Soil RMF and color attributes (henceforth collectively termed *color attributes*) were summarized for the top 60 cm of each plot; organic (O) horizons were excluded, as no plots met hydric field indicators relating to O horizon thickness. To prepare data for statistical analysis, each color was defined to be one of the following: (1) non-RMF matrix, (2) concentration, (3) depleted matrix, (4) non-matrix depletion, (5) reduced matrix, or (6) non-matrix reduction. Color hues, values, and chromas were reduced to three single measurements per plot by averaging only matrix colors for the A horizon. Eight additional color attributes deemed relevant to RMF characterization and hydric soil field indicators were calculated from non-averaged field data, including attributes defined at the individual color level (n = 374; e.g., contrast) or profile level (n = 96; e.g., depth to depletions) (USDA–NRCS 2018). Metrics relied on either non-matrix RMF colors (e.g., contrast), or both matrix and non-matrix RMF colors (e.g., depth to depletions). Overall, 11 color attributes were prepared for statistical analysis per plot: (1) *hue*, (2) *value*, (3) *chroma*, and RMF attributes including (4) *contrast*; (5) *non-matrix color count* (e.g., relative contribution of RMFs to all horizon colors, independent of abundance); *frequencies of* (6) *concentrations*, (7) *depleted matrices*, (8) *reduced matrices*, and (9) *gley colors*; and *depths to* (10) *depletions* and (11) *concentrations*. Contrast was converted to a numerical attribute where prominent = 3, distinct = 2, faint = 1, and n/a = 0. Hue was converted to a numerical attribute by equating 10YR with 10; hues from MSCC pages were set to be smaller (redder) or larger (yellower) than 10 in steps of 2.5.

In addition to preparation for statistical analyses, each site's color observations were systematically simplified and summarized for general characterization. Using the aforementioned categories of color observations (n = 6), profile observations were pooled by plot to judge reproducibility of specific horizon matrix and non-matrix RMF observations; if deviations in a specific color occurred between visits (where value/chroma pairs differed by at most 1/1), ranges for hues were recorded, and half-points were awarded to reports of values and chromas. If deviations across visits altered the categorization of a color—e.g., the non-RMF matrix color 7.5YR 4/3 later being as a RMF matrix color 7.5YR 4/2—colors were not combined and instead reported for both relevant categories. Site color summaries were similarly obtained from plot color summaries and summarized by two depth intervals, 0–30 cm and 30–60 cm. Differences among plot colors where value/chroma pairs differed drastically were both retained and reported; where value/chroma deviations differed by at most 1/1, half-points were awarded to reports of values and/or chromas. RMFs with the highest chroma (concentrations) and lowest value (reduced matrices and depletions) were noted as typical site colors, with ranges in hues reported and half-points awarded for similar value/chroma pairs (difference of at most 1/1). For example, if plot visits to BR rendered matrix observations within the top 30 cm of 7.5 YR 5/4, 7.5YR 6/5, 10YR 5/5, and 7.5YR 4/3 at each plot, the maximum difference of 1/1 for the first three colors would yield a reporting of “7.5YR – 10YR 5.5/4.5”, and 7.5YR 4/3 would be reported as its own color.

Statistical analysis

Principal component analysis (PCA) and k-means clustering were conducted in R 4.0.0 software (Core Team 2013) to group study plots with the PCA being run using plot-scale HP attributes (Jolliffe and Cadima 2016). One JJM plot was removed after outlier analysis; hence, 15 plots were analyzed. The optimal number of clusters was determined using a combination of the silhouette and elbow methods in R, from which clusters of plots were grouped—herein called HP-based clusters—and described in terms of HP and color attributes using descriptive statistics (Marutho et al. 2018).

Both HP attributes (n = 4: inundation/saturation frequency [field-based], GSM and BD [lab-based], and percent sand [WSS-based]) and color attributes (n = 11) were summarized and compared between study plots initially grouped by (1) sites and subsequently grouped by (2) HP-based clusters. To assess variability in hydro-physicochemistry within each site, HP attributes were averaged as medians and compared between sites; HP attributes were analogously summarized and compared between HP-based clusters to assess the efficacy of the k-means clustering analysis to produce hydro-physicochemically distinct groups of plots. Color attributes were also averaged as medians and compared between sites and between HP-based clusters. Descriptive assessments of the resulting color classes created by the two grouping variables, site and HP-based cluster, were conducted to comment on the efficacy of using HP-based clusters, in comparison to site identity, in classifying RMF color patterns. For all analyses, nonparametric Kruskal–Wallis and post-hoc Dunn’s tests were conducted for comparisons, and α was set to 0.05 to determine significance (marginal significances, where $\alpha = 0.10$, were also noted).

Results

Hydro-physicochemical attributes by site

The initial comparison of HP attributes between sites indicated high intra-site (e.g., plot) heterogeneity. Sites were similar in their distribution of HP attributes, specifically for GSM and percent sand ($p > 0.10$); nonetheless, BD was significantly higher at BR than all other sites ($p < 0.05$) due to the inclusion of two plots—BR2 and BR4—with soils that had bulk densities above 1.5 g•cm^{-3}, exhibited no surface inundation/saturation, and were consistently perceived to be relatively dry at depths below 30 cm during the augering process. A weakly significant difference in inundation/saturation frequency between sites ($0.05 < p < 0.10$) was highlighted through the contrast between the poor drainage of all JJM plots—inundated at all 6 site visits—and other sites which included more variability, e.g. MN, which included both poorly-drained areas with inundation/saturation frequencies over 50% (MN hollows, MN2 and MN4) and well-drained areas with 0% inundation/saturation (MN hummocks, MN1 and MN3) (USDA–NRCS Soil Survey Staff 2020). GSM differed between MN hummocks (33.8% and 24.9%) and hollows (60.9% and 52.9%), highlighting the relationship between the ephemeral soil water content and surface inundation/saturation (Table 2).

Table 2 Selected hydro-physicochemical attributes across sites obtained from field observations, lab analysis, and the Web Soil Survey summarized by medians and ranges (USDA–NRCS Soil Survey Staff 2020). *GSM* gravimetric soil moisture, *BD* bulk density, *ARP* Algonkian Regional Park, *BR* Banshee Reeks, *JJM* Julie J. Metz, and *MN* Mason Neck

	ARP	BR	JJM	MN
Inundation/saturation frequency (%)*	83 (83–100)[ab]	50 (0–100)[a]	100 (100–100)[b]	50 (0–100)[a]
GSM (%)	43.9 (40.3–48.2)	28.8 (24.7–46.0)	56.7 (13.7–88.2)	43.3 (24.9–60.8)
BD (g•cm^{-3})	1.2 (1.2–1.4)	1.3 (1.2–1.8)	1.1 (0.7–1.5)	1.2 (1.0–1.3)
Sand (%)	19.3 (11.3–27.3)	32.1 (27.4–35.3)	30.1 (27.1–30.1)	24.7 (11.8–40)

*Differences are significant at $p < 0.05$ (Kruskal–Wallis)

[a, ab, b]Groups followed by the same letter are not significantly different (α = 0.05) (Dunn's test)

Characterizing and comparing soil color attributes by site

Characterizations and comparisons of color attributes at ARP, BR, JJM, and MN highlighted large variability in color patterns within and between sites, with the determination that both hydric and nonhydric soils were present at each site. Out of all study plots, eight were deemed hydric—ARP3, ARP4, BR3, JJM1, JJM3, JJM4, MN2, and MN4—while eight were deemed nonhydric—ARP1, ARP2, BR1, BR2, BR4, JJM2, MN1, and MN3 (USDA–NRCS 2018).

Table 3 summarizes typical observed colors within wetland sites, including matrix colors and observed redoximorphic features. Redox concentrations were present within both 0–30 cm and 30–60 depth intervals at all sites; in particular, red (5R) concentrations were observed at ARP, BR, and JJM. Concentrations were generally more abundant between 30 and 60 cm than between 0 and 30 cm. Below 30 cm, plots with less abundant concentrations, like MN hollows, tended to have a greater extent of redox depletions. While all sites had depleted matrices, ARP plots near an emergent wetland's edge had colors below 30 cm that were identified as either depleted or reduced matrices depending on season and year. Finally, all sites had reduced matrices and gley colors; reduced matrices were most abundant at MN, while gley colors were most abundant at BR (Table 4).

At ARP, two plots, ARP3 and ARP4, met the indicators for hydric soils for 50% of the site visits, notably in the spring and summer of 2018 when precipitation was ample. Plots tended to have matrix hues of 7.5YR and 10YR; commonly observed value/chroma pairs were 3/4, 4/4, and 4/3. All plots, particularly those closer to the emergent wetland (ARP3 and ARP4), contained distinct to prominent concentrations, most frequently the orange-red color 7.5YR 4/8. Depletions, but not depleted matrices, were found at ARP2, ARP3, and ARP4, and were most common in the B horizons of ARP3 and ARP4. Finally, ARP4 consistently had reduced matrices (N 4/0 and N 5/0) for 50–75% of site visits.

At BR, only one plot, BR3, was officially classified as hydric. While BR1 and BR4 matrix colors were not low-chroma, the hydric BR3 as well as BR2 contained low-chroma colors including 10YR 2/1, 10GY 4(5)/1, 5GY 5/1, and N 4(5)/0. All plots but BR2 had distinct to prominent red and orange redox concentrations. While BR4 was extremely dry at each visit to a depth of > 30 cm, high-value iron depletions, identified as 7.5YR 8/1, were observed in the Bt horizon.

Three of the JJM plots, JJM1, JJM3, and JJM4, were classified as hydric. Like ARP and BR, JJM plots exhibited matrix hues of 7.5YR, 10YR, and 2.5Y. JJM2 and JJM4 included low-chroma matrices in both the A and B horizons. All plots included red- to yellow- colored redox concentrations, with prominence increasing with depth. Depletions were common among JJM2, JJM3, and JJM4 with colors like 10YR 4/1, 10YR 4/2, and 10YR 5/1. JJM1 had a uniformly reduced matrix beginning near 0 cm (observed as 5GY 6/2) and was the only plot to be fully reduced and/or depleted down to 60 cm.

Finally, MN showed similar patterns between the two hydric plots, MN2 and MN4, which showed low-chroma matrix colors including 10YR 5/2. Depletions and concentrations occurred more prominently and with greater abundance in the hollows. The hummocks (MN1 and MN3) did not include low-chroma matrix

Table 3 Summary of predominant soil color and redoximorphic ("redox") features at each site, including concentrations, depletions, and reduced matrices, for (a) the top 30 cm (0–30 cm, Horizon A) and (b) bottom 30 cm (30–60 cm, Horizon B)[a]

Site	Hydric soil indicators # plots /% of 6 visits	Depth (cm)	Non-RMF matrix colors	Redox concentrations			Redox depletions			Reduced matrices
				Color	Contrast	Abundance (%)	Color	Contrast	Abundance (%)	Color
ARP	2/50–100%	0–30	7.5YR–10YR 3.5/3	7.5YR 4.5/8	P,D	0–25	7.5YR–10YR 4.5/1.5	D, P	0 –15	N 4/0
			7.5YR–10YR 4/4	10R 3/3		0–5				
		30–60	7.5YR–10YR 4.5/3	2.5–7.5YR 4/8		10–40	10YR 4/1	D	20–50	N 5/0
			7.5YR–10YR 4/4							
BR	2/25–100%	0–30	2.5YR–10YR 5.5/4.5	2.5YR–10YR 4/8	P	0–25	0 N 5/0	Matrix	0, 70	5GY10GY 4.5/1
			7.5YR 4/3	10R 3.5/3			2.5YR–10YR 4/1.5		0, 70	
		30–60	5YR–7.5YR 5/3.5	5YR–10YR 5/8	P	15–30	7.5–10YR 4.5/1	Matrix	45–60	5GY10GY 4.5/1
				2.5YR 2.5/5	P	0–10	7.5YR 8/1	P	10–50	N 4.5/0
JJM	3/ 75–100%	0–30	2.5Y 10YR 3/4	2.5YR–7.5YR 6/8	P	10–30	2.5Y–10YR 3.5/2	P, Matrix	5–65	–
						5–15				
		30–60	7.510YR 3.5/4	5YR–10YR 5/8	P	5–35	10YR 4.5/1.5	P, Matrix	5–65	5GY 6/2
				2.5YR–5YR 3.5/6	D	5–35				
				10R 3/6		0–5				
MN	2/75–100%	0–30	2.5Y–2.5YR 5.5/4.5	2.5Y–10YR 6/5	D	5–10	2.5Y 8/1.5	P	5–30	N 5.5/0
			7.5–10YR 4.5/2.5	7.5YR–10YR 5.5/8	P	10–35	5YR–10YR 4.5/1.5			
			10YR 6/6							
		30–60	2.5Y10YR 5.5/5.5	5YR–2.5Y 5.5/8	P	5 –25	2.5Y–10YR 5.5/1.5	Matrix	0, 50–75	N 5.5/0
			10YR 4/4	2.5YR–10YR 4/6	P	5 –25	N 5.5/1		0, 60	

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[a]Redox concentrations include all types of concentrations; depletions include all colors independent of size identified where value ≥ 6 and chroma ≤ 2; and reduced matrices refer to matrices (> 50% of ped) which are reduced when present in at least one plot (see Fig. 1)

Table 4 Medians and ranges for RMF and soil color attributes compared between sites, including measured Munsell Soil Color Chart (MSCC) color aspects (hue, value, and chroma) and redoximorphic feature (RMF) characteristics including contrast, frequencies, and depths to features

Color attributes	ARP	BR	JJM	MN
Hue[d]	7.0 – 7.5YR (6.6–7.7)	10.1 – 10YR (7.7–11.5)	8.4 – 7.5YR (6.1–11.0)	8.7 – 7.5YR (6.2–11.0)
Value*	4.0 (3.6–4.1)[a]	4.5 (3.3–4.7)[ab]	4.2 (3.7–4.4)[ab]	5.1 (5.0–5.8)[b]
Chroma	3.5 (3.3–3.8)	4.2 (3.6–5.5)	3.9 (3–5)	3.7 (1.7–4.3)
Contrast	1.1 (0.2–1.5)	1.6 (0.0–2.1)	2.0 (0.7–2.3)	0.8 (0.7–1.6)
Non-matrix colors (%)	49 (22–63)	65 (0–79)	79 (29–85)	38 (30–66)
Concentrations, frequency (%)	24 (21–40)	42 (0–45)	51 (14–56)	14 (12–47)
Depleted Matrix, frequency (%)*	0 (0–0)[a]	25 (0–67)[ab]	9 (0–29)[ab]	67 (50–100)[b]
Reduced Matrix frequency (%)	14 (8–25)	10 (0–28)	9 (0–12)	19 (14–26)
Gley colors, frequency (%)	8 (0–14)	7 (0–32)	0 (0–7)	13 (5–16)
Depth to Depletions (cm)$^+$	33 (7–60)[a]	47 (14–60)[a]	14 (3–60)[a]	9 (8–21)[a]
Depth to Concentrations (cm)	18 (7–60)	18 (11–60)	7 (3–20)	30 (11–36)

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$^{+,\,*}$Attributes are marginally ($^+$; $0.05 < p < 0.10$) or significantly (*; $p < 0.05$) different between clusters

[a, ab, b, bc, c]For attributes with noted differences: groups followed by the same letter are not significantly different (α = 0.10)

[d]Hue is presented both numerically (10YR = 10) and as the nearest alphanumeric hue per the Munsell Soil Color Chart (MSCC)

colors and tended to have matrices with more yellowish hues including 2.5Y. Gley colors were found at all plots but in higher abundance at the hollows. MN2 tended to have more purplish-blue gley colors than MN4, at which neutrally colored soils were observed but were identified to be depleted rather than reduced matrices.

Overall, MSCC value ($p < 0.05$), depleted matrix frequency ($p < 0.05$), and depth to depletions ($p < 0.10$) differed between sites (Table 4), indicating that site identity is useful for informing 2 (3) color attributes when α = 0.05 (α = 0.10). While neither hue nor chroma differed between sites, median value was highest at MN (5.1) compared to ARP (4.0; $p < 0.05$). Similarly, depleted matrices were most abundant at JJM (67%) and least abundant at ARP (0%; $p < 0.05$). Differences in value were highlighted between Piedmont and Coastal Plain soils, particularly for the comparison of ARP (Piedmont) and MN (Coastal Plain) soils.

Characterizing and comparing plot hydrophysicochemistry and soil colors by HP-based cluster

As an alternative to comparing plots by site, the HP-based cluster analysis identified three distinct clusters of study plots using inundation/saturation frequency, GSM, BD, and percent sand. Dimensions 1 and 2 of the PCA explained 81.1% (50.0% and 31.1% for dimensions 1 and 2, respectively) of the total variability in HP attributes (Fig. 3). GSM had a strong and positive relationship with Dimension 1 ($p < 0.01$). Inundation/saturation frequency similarly plotted positively along Dimension 1, but with a more positive loading along Dimension 2. BD plotted negatively along Dimension 1 and positively along Dimension 2. Finally, percent sand plotted negatively along both Dimensions 1 and 2. Given the strong positive link to GSM and inundation/saturation frequency, Dimension 1 can be associated with overall water content within soil; conversely, given the negative link to percent sand, positive link to BD, and positive link to inundation, Dimension 2 can be related to soil drainage as influenced by physicochemistry including

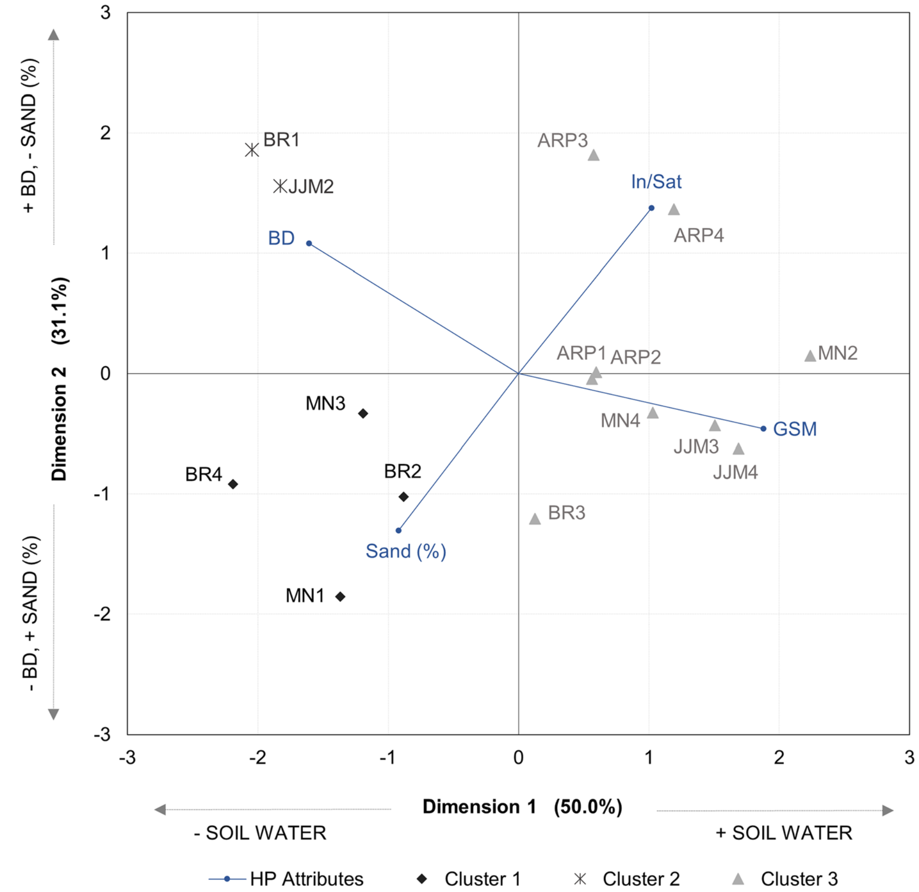

Fig. 3 Principal Component Analysis (PCA) of plots based on the following hydro-physicochemical attributes: (1) bulk density (BD), (2) inundation/saturation frequency ("In / Sat"), (3) gravimetric soil moisture (GSM), and (4) percent sand. The PCA shows Dimension 1 (50% of variance explained) on the x-axis and Dimension 2 (30% of variance explained) on the y-axis, with plots delineated by one of three clusters obtained from cluster analysis (between/total sum of squares = 64.6%) where *ARP* Algonkian Regional Park, *BR* Banshee Reeks, *JJM* Julie J. Metz, *MN* Mason Neck

texture, bulk density, and highlighted through the resulting aboveground flooding (Fig. 3).

The optimal number of HP-based clusters was identified to be three (between/total sum of squares = 64.6%), and k-means cluster analysis resulted in clusters comprising 4, 2, and 9 plots, respectively (Fig. 3; Table 5). Cluster 1 included BR2, BR4, and MN hummocks (MN1 and MN3); cluster 2 included BR1 and JJM2, which were both relatively rocky below the epipedons; finally, cluster 3 included all plots at ARP, JJM3 and JJM4, BR3, and MN hollows (MN2 and MN4). All plots identified to be hydric belonged to the third cluster of 9 plots (with the exception of JJM1, which was not included in the cluster analysis).

Except percent sand, all HP attributes differed significantly between clusters ($p < 0.05$; Table 5). Depicted in Fig. 3, cluster 1 plots shared negative loadings on both Dimension 1 and Dimension 2, plotting in the opposite direction of inundation/saturation frequency. Similarly, cluster 2 plots shared negative loadings on Dimension 1, but had positive loadings on Dimension 2 and plotted in a similar (opposite) direction as BD (GSM). In accordance with their negative loadings on Dimension 1, clusters 1 and 2 were characterized by relatively low soil moistures in comparison to cluster 3, which plotted in the positive direction on Dimension 1 ($p < 0.05$). Cluster 1 had higher GSM than cluster 2 but was composed solely of plots with 0% inundation/saturation over the study period and contained relatively high sand

Table 5 Medians and ranges for hydro-physicochemical (HP) and soil color attributes including Munsell Soil Color Chart (MSCC) color aspects and redoximorphic feature (RMF) characteristics, highlighting significant differences between three clusters created from k-means clustering on the principal component dimensions (between/total sum of squares = 64.6%)

	Cluster 1 (n = 4)	Cluster 2 (n = 2)	Cluster 3 (n = 9)
	BR2, BR4, MN1, MN3	BR1, JJM2	ARP1, ARP2, ARP3, ARP4, BR3, MN2, MN4, JJM3, JJM4
HP attributes			
Inundation/saturation frequency (%)**	0 (0–0)[a]	100 (100–100)	83 (50–100)[b]
GSM (%)**	28.7 (24.7–33.8) [a]	19.4 (13.7–25.0) [a]	48.2 (40.3–60.8)[b]
BD (g•cm^{-3})*	1.3 (1.2–1.4) [a]	1.6 (1.5–1.8) [b]	1.2 (1.0–1.4)[a]
Sand (%)	31.4 (21.2–40)[a]	28.0 (27.1–28.9)[a]	27.3 (11.3–35.3)[a]
Color attributes			
Hue[d,+]	10.1–10YR	9.3–10YR	6.9–7.5YR
	(7.6–21.0)	(7.2–11.5)	(6.1–10.3)
Value	4.9 (3.3–5.8)	4.6 (4.4–4.7)	4.0 (3.6–5.1)
Chroma [+]	4.5 (3.6–5.5)	3.5 (3.4–3.6)	3.6 (1.7–4.4)
Contrast	0.8 (0–1.3)	1.9 (1.8–1.9)	1.4 (0.2–2.1)
Non-matrix colors (%)*	38 (0–58)[a]	80 (79–81)[b]	61 (22–77)[ab]
Concentrations, frequency (%)*	13 (0–40)[a]	50 (45–56)[c]	25 (14–56)[bc]
Depleted Matrix, frequency (%)	6 (0–8)	9 (0–19)	0 (0–59)
Reduced Matrix, frequency (%)	7 (0–26)	17 (13–21)	17 (0–29)
Gley colors, frequency (%)	5 (0–11)	5 (0–10)	13 (0–32)
Depth to Depletions (cm)	40 (7–60)	18 (3–34)	14 (7–60)
Depth to Concentrations (cm)[+]	30 (23–60)[a]	8 (3–12)[b]	13 (7–60)[ab]

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[+, *]Attributes are marginally (+; 0.05 < p < 0.10) or significantly (*; $p < 0.05$) different between clusters

[a, ab, b, bc], Groups followed by the same letter are not significantly different (α = 0.05)

[d]Hue is presented both numerically (10YR = 10) and as the nearest alphanumeric hue per the MSCC

percentages. Highest soil moistures and lowest bulk densities—and thus high Dimension 1 loadings—belonged to soils in cluster 3 ($p < 0.05$; Table 5). Despite having similar inundation/saturation frequencies as cluster 3, cluster 2 soils were characterized by higher bulk densities and lower GSM ($p < 0.05$) due to the abundance of rocks and gravel below the epipedons, rendering negative loadings for Dimension 1.

At the α = 0.05 (α = 0.10) level, clusters strongly differed for two (*five*) color attributes—concentration frequency and non-matrix color count (*plus hue, chroma, and depth to concentrations*)—as opposed to the two (*three*) attributes when grouped by site—value and depleted matrix frequency (*plus depth to depletions)* (Table 4; Table 5). Notably, while value and depletion frequencies and depths were most distinct between sites, concentration frequencies and depths were most distinct between HP clusters. Furthermore, HP-based clusters of plots could be distinguished by soil chroma ($p < 0.10$) and non-matrix color counts ($p < 0.05$), which was not the case when classified by site (Table 4; Fig. 3; Table 5). Cluster 1 was characterized by lowest frequencies ($p < 0.05$) and greatest depths to concentrations ($p < 0.10$), plus lower counts of non-matrix colors ($p < 0.05$) than cluster 2. Cluster 1 had the lowest median frequency of all RMFs combined ($p < 0.10$), corroborating the HP characterization of cluster 1 with low GSM and low inundation/saturation frequency—i.e., conditions that are less likely to encourage hydric soil development. Cluster 1 also had the highest median chroma, albeit to an insignificant degree, as it consists of plots that generally showed homogeneously-colored soil matrices. Cluster 3 did not significantly differ from clusters 1 or 2 in characterizations of chromas or concentrations but exhibited the lowest minimum chroma of the clusters (< 2).

Discussion

Hydro-physicochemical classifications for study plots

This study supports conclusions of previous research that the combination of soil attributes can aid in the creation of wetland indicators (Ahn and Peralta 2012; Dee and Ahn 2012; Peralta et al. 2013). The analysis highlighted that study plots within four spatially separated wetland areas can occupy substantially different combinations of these attributes, rationalizing analysis techniques to reduce attribute variability into fewer dimensions and highlight similarities between plots with cluster analysis. The PCA provided justification for k-means clustering analysis using the four HP attributes by indicating the distinct role each variable played in explaining variability in plot loadings on Dimensions 1 and 2. As similarly observed with physicochemical attributes assessed by Wolf et al. (2011), Fig. 3 nonetheless highlights the interconnectedness of the four HP attributes; for example, GSM shared a negative relationship with bulk density, and percent sand plotted opposite to inundation/saturation frequency, indicating a strong negative correlation that is likely related to the role of soil texture in water infiltration (Jackson et al. 2014). Such interconnectedness does not imply redundancy, as the 4-variable PCA was more capable of explaining HP variability and providing distinct clusters of plots than a 3-variable PCA. In assessing a site for hydric soil development and/or future potential, using the combination of HP attributes can more effectively characterize soil conditions compared to site identity.

Soil color and RMF attributes by site

While distinct characterizations of 5 color and RMF attributes were better derived from HP-based clusters, three color attributes—value, depleted matrix frequencies, and depth to depletions—were still solidly characterized by geographic site location (Table 4; Table 5), a factor that is characterized by homogenous geomorphology and historic large-scale hydrology that are known to influence hydric soil formation (Fiedler and Sommer 2004; Li et al. 2018; Veneman et al. 1998). The disparities in color and RMF attributes distinguished by either site identity or HP-based clusters highlight the relevance of both landscape and plot-specific HP attributes in influencing RMF and color attributes, where site identity is more capable of classifying indicators of more long-term or permanent saturation and reduction conditions like depleted matrices and high values that form only with longer (e.g., ≥ 21 days) periods of reduction (Schelling 1960; Franzmeier et al. 1983; Vepraskas et al. 2004; Vepraskas and Vaughan 2016). Conversely, attributes related to high-chroma colors and concentrations are likely to be more variable across a wetland site due to variability in HP attributes: although SHWT has also been correlated to concentration depth (Gennthner et al. 1998), Fe concentrations can form depth near the topsoil with little relation to water table depth when surface soil inundation/saturation and limited oxygen diffusion produces temporary reducing conditions (Dorau et al. 2020).

Our results also highlighted the importance of physiography when characterizing RMFs and relating them to hydrology. Higher color values observed in the Coastal Plain compared to the Piedmont may be the result of finer-textured soils with better drainage but may also be related to problematic hydric soils of the Culpeper Triassic Basin, which have developed red colors due to the reddish-brown shales of the parent material and can sustain anerobic environments without high quantities of low-chroma, high-value depletions (Elless et al. 1996). A focus on the factor of physiography, specifically with inclusion of problematic hydric soils, is warranted to better discern potential differences in HP attributes as influenced by these factors.

Soil color and RMF attributes by HP clusters

The distinct characterizations of five color and RMF attributes by HP-based clusters not only linked hydro-physicochemistry to RMFs, but also provided a classification of plot-level soil ecosystems via both hydro-physicochemistry and soil colors. The nonhydric cluster 1 plots—most homogenously colored and hosting the lowest frequency of RMFs—were matched to observed HP settings unlikely to support hydric soils, indicating that the cluster analysis was aligned with a core tenet of hydric soil science, i.e., that nonhydric plots do not exhibit substantial RMFs. Also in accordance with well-documented relationships between hydrology and soil biogeochemistry, cluster 3 soil environments—showing high soil moistures and high inundation/saturation frequencies—encouraged reducing conditions that produced less concentrations but generally more reduced matrices and depletions within the top 30 cm. Coinciding with having the highest GSM, cluster 3 represents plots where surface BD is relatively low and permeability is relatively high, such that soil inundation aboveground also coincides with high soil moisture (Table 5; $p < 0.05$). Such plots are most common in wetlands which are occasionally to frequently flooded, as was included in this study; semipermanently ponded wetlands with mineral soils may exhibit different combinations of HP attributes that yield a distinct cluster of RMF characteristics not exhibited in Fig. 3.

The usefulness of this analysis methodology is underscored through focusing on unexpected connections that can serve as the basis for scientific questions, hypotheses, and hypothesis testing. In particular, unexpected combinations of HP attributes and their links to observed RMFs were observed in cluster 2: while the nonhydric cluster 2 plots exhibited relatively low soil moistures ($p < 0.05$) and lower maximum frequencies of reductions and/or depletions in comparison to cluster 3, they had highest frequencies of inundation/saturation (Table 5). Both BR1 and JJM2 were characterized by higher bulk densities than cluster 3 plots (Table 5; $p < 0.05$), likely due to the abundance of cobbles and rocks below the epipedon, a feature that was not present above 60 cm at other plots. The epipedons of BR1 and JJM2 may have similar water holding capacities to other study plots that encourage surface inundation/saturation, the coarser textures below may promote oxygen diffusion that lowers moisture and limits the long-term potential for reducing conditions to be present (Davis 1995; Jackson et al. 2014), allowing concentrations to predominate (Table 5).

Furthermore, the plotting of nonhydric ARP1 and ARP2 with otherwise hydric plots in cluster 3 provides more variability in several color attribute indicative of hydric soils—e.g., depleted matrix frequency (0% for ARP plots; Table 4)—within cluster 3 and indicates the importance of historic land use, a factor that might outweigh HP setting and produce unexpected HP-based RMF characterizations. A previous work (Schmidt and Ahn 2021) illustrated that, compared to the other study sites, ARP tended to deviate from generally observed patterns linking hydrology and soil biogeochemistry. While the forested floodplains of ARP currently exhibit HP attributes that would indicate a high level of *hydricity*—with ARP1 and ARP2 hosting relatively low bulk densities and high GSM compared to other nonhydric plots—these plots occur on land that was nonforested farmland as late as 1957 (Loudoun County Office of Mapping and Geographic Information 2021). Such inconsistencies may explain why cluster 3 did not display significantly higher frequencies of depleted or reduced matrices than cluster 2 (Table 5; $p > 0.10$).

Implication and recommendations for further study

Linking patterns of color attributes, like chroma and concentration frequency, to plot hydro-physicochemistry has the potential to transform color indicators into accessible field estimations of soil biogeochemistry; watershed managers or planners without sufficient experience with hydric soil field indicators can rely on site history and HP attributes to characterize, assess, and track soil colors and thus hydric soil presence and/or development. This approach can be beneficial for approaching conservation planning that should view each site of interest, such as a community park or blue-green infrastructure, as a matrix of heterogeneous HP settings; furthermore, it is particularly timely as climate, landcover patterns, and stormwater management can alter hydrologic regimes, inducing more intense and frequent flooding events and modifying water flow paths and hydrologic sinks (Wissmar et al. 2004; O'Driscoll et al. 2010). Changes in flooding patterns may encourage the onset of redoximorphic feature formation that are not substantial enough to yet qualify as indicators of hydric soils. In areas prone to flooding, monitoring HP attributes and soil colors can provide a characterization of such areas that may not yet host hydric soils but nonetheless indicate the potential for hydric soil development.

The conclusions of this study are drawn from a pertinent set of sampling sites and sound statistical analyses; nonetheless, sampling and analysis constraints provide opportunities for methodological refinement. The exploratory PCA and cluster analysis provided novel insights, but a large-scale regression and/or systems model may further demonstrate the value in a multivariate link between hydro-physicochemical setting and RMF characterizations. Various environmental factors such as seasonality were not integrated into the analyses, as HP attributes like inundation/saturation frequency were evaluated at a plot- rather than profile- scale to reflect longer-term HP settings; however, as color attributes plus other included HP attributes like GSM are dynamic across seasons, an inclusion of season as a blocking variable may provide more nuanced insights if investigated. The 4 HP and 11 color attributes used within the analyses were capable of distinguishing color attributes by site and HP-based cluster, but modifications to attributes may be pertinent. For example, an analysis that retains finer details of color observations within each soil horizon—e.g., inclusion of color thicknesses as an attribute and horizons/depths as a covariate—may elucidate more sensitive patterns in color characterizations. With respect to HP attributes, a semiquantitative measure of percent sand derived from the soil texture triangle may be more accurate than Web Soil Survey data (i.e., percent sand), which was deemed sufficient for this study given the limited range in textures (i.e., from silt loam to loam) examined in this study that would not have been differentiated by reliance on hydric soil indicators' distinction of *loamy/clayey* versus *sandy* soils. Additional physicochemical attributes, such as reaction to α,α'-dipyridyl dye—an indicator of reducing conditions (Berkowitz et al. 2017)—may be appropriate to include in further assessments.

Overall, the inclusion of a greater number and diversity of HP settings, such as permanently flooded wetland areas and sandier soils, could have aided in the power of the Kruskal–Wallis comparisons by elucidating additional clusters with distinct patterns of color and RMF attributes. Several hydric field indicators rely on *depths to depleted matrices* that are as little as 10 cm—e.g., F3, "Depleted Matrix"—which was only observed for one plot with a depth of 3 cm to a depleted matrix (USDA–NRCS 2018). It is recommended that our approach be utilized for a larger study area to more fully flesh out HP attributes and HP-based clusters of terrestrial plots which may or may not be wetlands, allowing the resulting RMF characteristics to indicate their hydric soil status on a multi-class categorical scale including hydric, potentially hydric, or stable upland.

Conclusions

Our investigation has indicated that plot-specific HP attributes—e.g., seasonally observed frequencies of inundation/saturation, bulk density, soil moisture, and soil texture—can serve as the basis for classifying and distinguishing soil color characteristics that differ from those indicated through larger-scale wetland site alone. Hue, chroma, depth to concentrations, frequencies of concentrations, and number of non-matrix colors were distinguished through HP attributes, highlighting the applicability for HP-based clusters to indicate RMF characteristics related to shorter periods of soil reduction. Conversely, value, frequency of depleted matrices, and depth to depletions were distinguished through site identity, indicating the utility of landscape and site characteristics to inform RMF characteristics related to longer periods of soil reduction. While measures of the individual 11 color attributes used in this study cannot substitute for indicators of hydric soils, the capacity to characterize and distinguish RMFs and soil colors from HP attributes highlights the latter's suitability as a mechanism for identifying wetland functions and potential for future development. Furthermore, this approach highlights that the combination of information from multiple soil color measures can together depict a wetland setting capable of being explained through hydro-physicochemistry. Future research focused on a wider range of HP attributes in more field sites is warranted to further demonstrate the efficacy of a suite of simple HP attributes to be used in assessing, tracking, and indicating wetland soil development consequential to changing environmental conditions.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material Raw data will be provided if asked for.

Code availability R codes used for analysis will be provided if asked for.

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