

Soil Wetness and Morphological Relations

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Introduction

Siting and designing septic systems relies on the interpretation of soil morphology and site evaluation. In much of the country one of the most critical uses of soil morphology is the determination of soil wetness conditions (water table). It is generally acknowledged that the water table fluctuates greatly over the course of the year with the highest levels (closest to the surface) occurring in the winter or early spring. This phenomenon is referred to as seasonal saturation. By rule in several states, the presence of low chroma colors (gray colors), mottles, and/or redoximorphic features in the soil is used to identify seasonal saturation. There are two potential problems with this method. First, there is no consensus on what morphology best represents short duration saturation (<14 days). Second, morphology may not be reliable if the hydrology has been altered either by development, drainage or flooding.

Where morphology is suspect, ground water level monitoring is usually undertaken. Data from monitoring wells show the water table peaks (saturated conditions) typically extend 1 to 2 feet above the level predicted by the presence of < 2 chroma colors. Since septic system drainfields may be located 1 to 1.5 feet above the low chroma colors it is conceivable that raw, untreated effluent could be discharged directly into ground water. The overall objective of this project is to compare various soil morphology (soil color) interpretations and concurrent well monitoring data to define soil morphological/water table relations in order to confirm and/or establish water table monitoring, modeling and interpretation procedures.

In 26 states soil colors or soil morphology are used in evaluating or determining seasonal high water table. For example several states use the presences of mottles to determine the water table whereas others describe specific color patterns beyond just 2 chroma colors. A few states (e.g. MA, ME, MN, MT, NH, RI, UT) are now using or will be using redoximorphic features to determine the water table or soil wetness conditions. A clear understanding of how to record and interpret these features is essential. These colors are formed due to the reduction (anaerobic conditions) and subsequent removal of iron-oxide coatings from individual mineral soil grains. The low chroma colors therefore are not only a good indicator of saturated soil conditions, but also anaerobic conditions both of which are detrimental to septic system performance.

It has long been documented that soil color patterns are related to saturated conditions in the soil (Franzmeier et al., 1983; Vepraskas and Wilding, 1983; Pickering and Veneman, 1984; Evans and Franzmeier, 1986; Veneman et al., 1998). Soil saturation alone does not change the soil color. The color pattern forms due to the microbial activity that depletes the soil of any free oxygen (O_2) causing the soil to become anaerobic. Under anaerobic conditions, and in the presence of organic carbon, ferric iron (Fe^{3+}) is microbially converted to ferrous (Fe^{2+}). This process is referred to as iron reduction. This process causes the rusty colored Fe coatings on soil particles (Fe^{3+} oxides) to dissolve off the particles and into the soil solution, resulting in the gray color (low chroma) of the mineral grains to show through.

The formation of the low chroma colors (also know as redox depletions) in soils allows the site evaluator to reliably predict the level of seasonal saturation and reduction in the soil if the site has not been hydrologically altered. Drainage ditches and subsurface tile drains are two ways in which hydrology is altered. When this occurs redox depletions may no longer be reliable indicators of the saturation and anaerobic conditions (James and Fenton, 1993; Lindbo, 1997). Features observed at hydrologically altered sites are referred to as "relict" features. However, accurate identification of

relict features must be done with knowledge of the degree of alteration (Vepraskas, 1994; Hayes and Vepraskas, 2000, He et al., 2001).

A study undertaken by M. J. Vepraskas and E. S. Stone (unpublished data) examined daily water table data collected at several wells in eastern North Carolina over a 3-year period. These results were then used to calibrate DRAINMOD (Skaggs, 1978) to develop a 32-year hydrologic simulation for the sites. Frequency and duration of saturation events were then correlated to the soil morphology from each site. Saturation durations were broken into 3 groups: 7-14 days, 14-21 days and >21 days. The DRAINMOD simulation data were used to compute the number of times per year the water table was above a given depth. Statistical analysis of the data showed that redox depletions were significantly correlated to periods of >21 days saturation ($r^2 = 0.93$). The actual percentage of redox depletions increased each time the soil was saturated for >21 days. Although these findings are important it must be noted that they are still preliminary and need to be refined with data from additional sites. However, the implication from the data is that the common or more (>2%) occurrence of redox depletions (low chroma colors) used in the rule can be correlated to a saturation event of >21 days.

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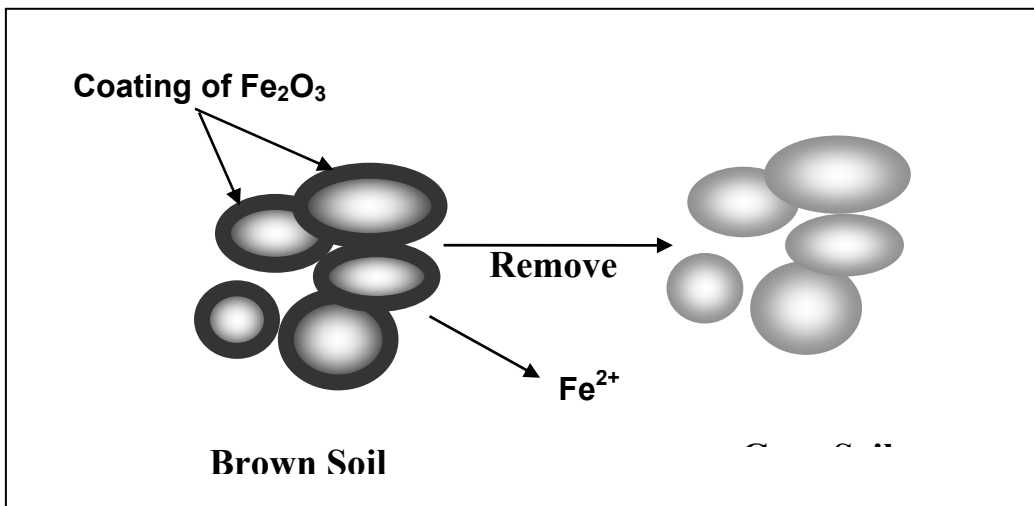
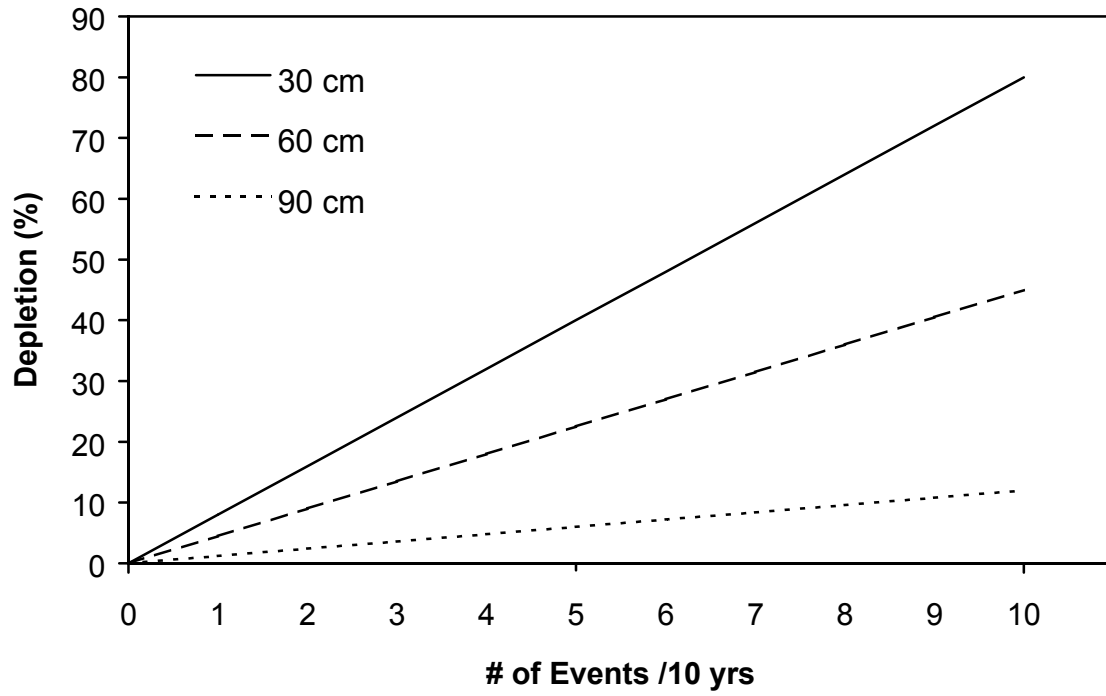


Figure 1. Schematic of the formation of a redox deletion (low chroma mottle). Fe-oxide coatings are dissolved off the gray soil mineral particles as Fe³⁺ is reduced to Fe²⁺ in saturated and anaerobic soil. The Fe²⁺ is soluble in water and is removed as soil water flows away.

Figure 2. Relation between frequency and abundance of redox deletions for saturation events > 21 days.



Literature review of color, redoximorphic features and hydrology.

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Soils are judged by onsite evaluators for their ability to accept and sustain a working OSWS. Accurate assessment of the water table regime is necessary for design purposes. This assessment is performed in three general ways (i) direct observation of soil morphology, in particular, shallowest depth to redox depletion occurrence; (ii) direct observation of soil water tables via a well(s); and (iii) predictions of water tables through computerized hydrologic models such as DRAINMOD using historical climatic data. This review will encompass the current knowledge of formation redoximorphic feature and their relationship to measured and predicted soil water tables.

Soil Morphology

Soil morphology is the physical composition of the soil which includes its texture, structure, color, and consistence; its biological, chemical, and mineral properties of the horizontal layers, and the thickness and arrangement of these layers (Soil Survey staff, 1999). The layers, or horizons, are almost parallel to the ground surface, having distinct characteristics as a function of soil forming processes. The layers are distinguished from adjacent horizons by a change in any morphological feature such as a change in texture or color. Morphology is best examined in the field where all the horizons can be exposed along a vertical face, which extends into the parent material (generally 2 m deep).

Morphology is relatively constant over time and thus observable at any given point within a year. Morphological features such as soil color and specifically redoximorphic features in soil can be a function of the chemical reactions within a given horizon.

Soil Color

Soil color, the most obvious and easily observed soil characteristic, is the morphological feature of concern with respect to OSWSs. Soil color has three quantifiable variables: hue, value, and chroma. Hue is the dominant color related to the wavelength of light (red, brown, or yellow). Value is a measure of degree of light reflected of a color (lightness or darkness). Chroma is a measure of the purity or strength of the dominant wavelength of light reflected (color intensity).

Since the description of soil color is subjective, a standardized measurement system, in the form of the Munsell Color Charts (www.munsell.com). Each chart contains 29 to 42 color chips enabling the user to best fit the soil color to a particular chip. All chips on a given page have the same spectral color, or hue. Every chip corresponds to a given color. Soil held next to the chips enable a visual match to give the proper Munsell notation. For example a notation of 10 YR 5/6 is a soil with a color of 10YR hue, value of 5, and a chroma of 6. The color is light brownish yellow.

Soil color is controlled by several components. In general, humified organic matter coating mineral grains controls dark colors in surface horizons. The red to yellow colors of the subsoil are due to iron oxide coatings on mineral grains. Even in low amounts, these iron oxides have high pigmenting power (Schwertmann and Taylor, 1977). Since organic matter usually decreases with depth, subsoil color is controlled either by parent material and/or iron oxides. However, organic matter in addition to iron and aluminum compounds controls subsurface horizon color in spodic horizons.

Soil color can also be a function of its redox status. Oxidation of iron occurs during periods of aeration. Hydrolysis and oxidation reactions release reduced (Fe^{2+}) iron bound in primary silicate minerals. Iron (Fe^{3+}) that is released precipitates as iron oxides (Fe_2O_3) due to its low solubility

(Schwertmann and Taylor, 1977). The precipitated iron oxides are then uniformly distributed throughout the matrix in aerated soils, or can be segregated into concentrations and depletions in soils with a fluctuating water table.

Matrix color is the dominant color in the soil. Mottling is spots or blotches of color in the soil that differ from the matrix color. The pattern may relate to the aeration or drainage of the soil. Well drained soils usually have uniform bright colors. Soils with a fluctuating water table have a mottled pattern of gray, yellow, and/or orange colors. Mottling is a generic term for redoximorphic features.

Redoximorphic Features

Evidence of wetness in soils is marked by redoximorphic features as a result of redox reactions of C, Mn, Fe, and S in seasonally saturated soil (Vepraskas, 2000). These features form from the reduction, movement, and reoxidation of these compounds. The reaction of each element is related to its own feature of soil wetness; (i) organic-C based features, (ii) Mn-based features, (iii) Fe-based features, and (iv) S-based features. Examples of the C-based features is the accumulation of organic material over the whole surface layer, providing evidence of oxygen depletion, and hindered organic matter oxidation due to the soil being saturated. Mn-based features manifest themselves as black masses and gray depletions. The Fe-based features occur as red masses or gray depletions. Finally the S-feature is apparent by the smell of rotten eggs.

Iron based redoximorphic features are morphological features formed from oxidation-reduction reactions (Soil Survey Staff, 1999; Vepraskas, 2000). They are formed by changes in redox conditions in seasonally saturated soil. They are identified in the field by their loss (depletion) or gain (concentration) of pigmentation compared with the matrix color. This pigmentation is due to the reduction, translocation and oxidation of Fe oxides. The concentrations usually have high chroma (6 or higher in Munsell notation), while depletions have low chroma colors (≤ 2 or ≥ 3). These features generally form near organic matter (Vepraskas, 2000). Factors that affect redox reactions can include type and amount of organic matter, slope and water movement, and temperature.

Different types of these redox features include redox concentrations (Fe masses, Fe pore linings), redox depletions (Fe depletions), and reduced matrix (gray matrix). Gray colors usually indicate a lack of iron on particle surface. Redox features are generally widespread features, permanent unless destroyed by reduction or mixing, and need Fe to form. In some cases, gray colors may mean there was never any iron present (Vepraskas, 1999, 2000).

Redox concentrations are defined as an apparent accumulation of oxidized iron (Soil Survey Staff, 1999). They are noted by a higher iron oxide content and chroma than the surrounding matrix. They form by iron moving, oxidizing and precipitating. Typical mineral composition of concentrations includes goethite, ferrihydrite, and lepidocrocite (Schwertmann and Taylor, 1989), producing red, orange, yellow, and brown colors. There are three types of redox concentrations: iron masses, iron in pore linings, and nodules and concretions. Iron masses are soft, non-cemented, easily crushed accumulations of iron oxides within peds, away from cracks or root channels. The size of these masses depends on the size of the structural aggregate.

Pore linings are iron accumulations around ped surfaces, cracks, and root channels. These can occur at any depth that rooting occurs within the profile, and do not need live roots to form. Oxidized rhizospheres have iron oxidized around an active root bringing oxygen into a saturated environment. Nodules and concretions are usually round, cemented iron that is not easily crushed. They are not a

reliable indicator of current redox processes because of the uncertainty of their origin (Vepraskas, 2000). They are thought to have either formed in place or been deposited.

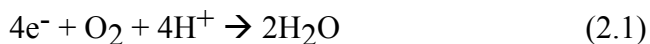
Redox depletions are zones of iron loss. They are defined as bodies of low chroma ≤ 2 and value of 4 or more, where Fe, Mn, and perhaps clay have been stripped from the area (Soil Survey Staff 1999; Vepraskas, 1999). Depletions can occur as ≥ 3 chroma depletions (Vepraskas and Wilding, 1983, Franzmeier, et. al., 1983). These depletions are not interpreted as indicators of the SHWT. They do indicate the partial removal of iron oxide coatings off mineral grains, however, not as complete as iron removal on the ≤ 2 depletions. Depletions can occur along pore linings, root channels, ped surfaces, or ped interiors. Evidence of iron reduction is readily identifiable in the field. In many cases, the iron has been reduced for substantial periods.

An entire horizon can be a redox depletion, called a gray matrix. Once exposed, iron within the gray (reduced) matrix will begin to oxidize within 30 minutes of exposure (Vepraskas, 2000). Gley colored depletions matrices are a sign of permanent saturation. Colors found in the Munsell Color Chart "Gley Pages" can be bluish, greenish, or purplish tints of gray colors, probably due to iron associated with a carbonate, phosphate, or sulfate anion (Schwertmann and Taylor, 1989).

Redox chemistry and morphology

Redox reactions are the most significant chemical reactions in soils with fluctuating water tables. These reactions control soil color, organic matter content, and soil water chemistry, particularly levels of nitrate, iron, and sulphur. In subsoil environments decaying roots and dissolved organic C typically provide the labile organic matter necessary for biochemical reduction with temperatures above biological zero, 5° C (Menongial, et. al. 1993, Menongial, 1996).

Oxidation is a loss of electrons while reduction is a gain of electrons during a chemical reaction involving electron transfer. If oxygen is present, electrons produced in organic matter decomposition are accepted by O₂ to make water.



When all oxygen is depleted, the soil becomes anaerobic.

Redox potential is theoretically based on the quantity of e⁻ available in the soil solution, which is measured as potential electron activity (pe) which can be converted into redox potential Eh (mv):

$$Eh = .059 pe \quad (2.2)$$

Recent soil hydromorphology studies employ redox electrodes with monitoring wells to assess soil redox potential by measuring Eh (Hayes, 1998, Karthenasis, et. al., 2003, D'Amore, et. al., 2004). Field measurements of voltage are converted to Eh by adding a correction factor of 200 mv. The presence of reduced iron in soil solution is determined by the use of an Eh-pH diagram (Vepraskas, 2000) as calculated by:

$$Eh = 1235 - 177pH \quad (pH < 7.5) \quad (2.3)$$

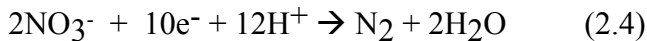
Magnitude and sign of voltage must be recorded and pH of soil solution must be known. Redox potential measurements are highly variable; therefore measurements should include at least 5

separate probes at a given depth in the soil and should be no more than 6 inches apart within the same horizon. Potentials range from +1 volt to -1 volt (+1000 mv to -1000 mv). Aerated soils tend to have higher Eh values (1000 to 500mv) while soils with reduced iron have lower potentials (around 500mv, depending on pH to -400mv). Salt bridges were used to connect the reference electrode to the soil as outlined by Pickering and Veneman (1983).

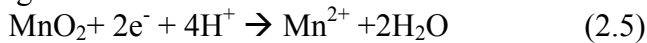
When soils become saturated, aerobic microbes utilize and deplete the remaining O₂ in the system. Aerobic microbes then die or become dormant and obligate and anaerobic bacteria dominate. During anaerobic respiration soil organic matter is oxidized, and other oxidized soil components act as electron acceptors and become reduced (Ponnamperuma, 1972, Faulkner and Patrick, 1992, and Vepraskas, 2000).

Electron acceptors in soil systems generally follow this scheme with increasing reduction:

(1) Denitrification



(2) Manganese Reduction



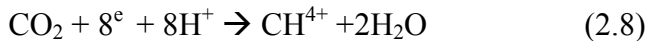
(3) Iron Reduction



(4) Sulfate Reduction



(5) Carbon Dioxide Reduction



(adapted from McBride, 1994, and Mitsch and Gosselink, 1993)

The typical reduction sequence in soils is attributed to the lack of air in soil pores. Oxygen is reduced first, making the soil anaerobic, followed by nitrate, manganese oxides, then iron oxides, sulphur and lastly carbon. Each element acts as an electron acceptor until it is fully consumed. By its virtue of position in the reduction sequence, iron reduction must occur when oxygen, nitrate, and Mn oxides have been fully exhausted. Once the soil drains and oxygen enters the pores, aerobic microbes dominate and oxygen once again becomes the primary electron acceptor.

Four conditions must be satisfied simultaneously for iron reduction (Faulkner and Patrick, 1992, Menongial et. al., 1996 Vepraskas, 1999): (i) dissolved oxygen removal; (ii) a source of soluble organic matter (electron source); (iii) active bacteria to decompose organic matter with soil temperatures above biological zero (5° C); and (iv) stagnant, waterlogged soils. Also, a source of Fe(III) is needed for its reduction. Iron reduction is decreased or stopped when any of these components are absent. When all factors are acting in concert, bacteria decomposing the soluble organic matter will reduce Fe(III) to Fe(II). If any of the steps in the above sequence do not occur, iron reduction may not occur. In some cases, soils must be saturated for 21-d for iron reduction to occur (Hayes, 1998, He et. al., 2002).

Redox feature formation

Fe-based redox features form from the reduction, movement and oxidation of iron. Iron oxides coat soil mineral (often silicate) surfaces, giving a reddish, yellow, or brownish characteristic color. When saturation occurs, oxygen diffusion into the soil is reduced by orders of magnitude, and is depleted by microbes decomposing organic matter (Menongial, et. al., 1996). The microbes then deplete any remaining NO₃⁻ and Mn, and the next element in the sequence of reduction, Fe. Iron

oxides dissolve and become colorless in solution; gray color remains because that is the color of silicate mineral grains without the Fe oxide coating. Mobile Fe^{2+} ions then move to points of oxidation, concentrate and re-oxidize upon soil drying (oxidation) or are leached from the system. Points of oxidation include entrapped oxygen within peds, root channels and cracks, or anywhere oxygen reenters the soil (Vepraskas, 2000).

Oxidized rhizospheres form in flooded soils where actively respiring plant roots bring oxygen into the rooting zone, thus causing Fe^{2+} to oxidize and precipitate as Fe^{3+} around the root channels. Pore linings can develop at any depth in the soil profile. Once the soil is saturated and reduced, the ferrous iron is mobile in soil solution. As the soil drains, the soluble iron can move to points of oxidation (Vepraskas 2000, Evans and Franzmeier, 1986). These points are either within peds (masses), caused by larger pores or voids; or along ped faces

Redox depletions of chroma greater than 2 can occur if they are formed by the same process of iron loss seen in chroma 2 depletions. Chroma 3 colors can indicate the presence of remaining Fe oxides on the particle surfaces (Vepraskas 1999), natural mineral color, low amounts (<1%), or oxygenated water. These soils can be reduced for short periods, but may be waterlogged for long periods (Vepraskas and Wilding, 1983). Chroma ≥ 3 depletions are associated with saturation, but have been found to be saturated and reduced for a lesser time period than chroma ≤ 2 depletions (Franzmeier, et. al. 1983). Presence of chroma 3 depletions are a good indicator of a water table (Daniels, et. al. 1987).

Seasonal High Water Table Estimations

The water table is defined as the upper surface of ground water or that level in the ground where the water is at atmospheric pressure (Soil Survey Staff, 1999). A seasonal high water table is the highest level of the saturated zone, persisting in the soil continuously for at least 2 weeks within 2 meters of the soil surface (Goodwin, 1989; Barnhill, 1992). Soils that have a seasonal high water table are classified according to the depth to water table, kind of water table, and time of year when water table is highest. The normal depth range of a seasonal saturation or zone of saturation of the natural undrained soil is given to the nearest half-foot. Three kinds of seasonal high water tables are recognized within the soil (1) apparent, (2) perched and (3) artificially ponded (Soil. Survey Staff, 1999).

An apparent water table is the level at which water stands in a freshly dug, unlined borehole after adequate time for adjustments in the surrounding soil.

A perched water table is one that exists in the soil above an unsaturated zone. A water table may be inferred to be perched on the basis of general knowledge of the water levels of an area, the landscape position, the permeability of soil layers, and from other evidence. To prove that a water table is perched, the water levels in boreholes must be observed to fall when the borehole is extended.

An anthric water table occurs due to controlled artificial ponding for food and fiber production. The subsoils are not usually saturated.

The depth of the SHWT, or soil wetness condition is stated by rule .1942a in North Carolina (NCAC, 2004), the first occurrence of redox depletions, observed in the field as having a low chroma color (less than or equal to 2, {value greater than 4} in the Munsell Color Book notation). It is assumed that in periods of normal rainfall, water will rise to this level. Low chroma colors result from reduction / oxidation cycles occurring over many years (generally in terms of centuries), which makes this estimation method a reliable and conservative indicator of maximum seasonal groundwater elevation. Occasionally, the groundwater may be found at shallower soil depths. If that interval is short, aerobic soil conditions persist; consequently, no low chroma colors are formed. Black or dark

gray colors that have a chroma of 2 or less but also a value of less than 4 are not necessarily related to soil wetness, but rather an accumulation of organic matter.

Advantages to using this method include the ability to make determinations on a wide variety of soils at minimal cost at any time of the year, without prior knowledge of rainfall and hydrology. Evaluations using this approach may be an inaccurate assessment of the saturation because it does not predict how long the water table remains at a given depth, nor does it predict the frequency of saturation occurrence.

By rule, soil wetness conditions in North Carolina can be caused by seasonal high-water table, perched water table, tidal water, seasonally saturated soil or by lateral water movement determined by field observations of soil wetness indicators, and may be assessed by well monitoring, computer modeling, or a combination of both (15A NCAC 18A .1942 SOIL WETNESS CONDITIONS). Wetness conditions are determined by the indication of ≤ 2 chroma colors occurring in exactly 2% of soil volume either as depletions or matrix of a given layer. Colors of chroma 2 or less that reflect a prior drainage status or the parent material are not considered a soil wetness condition indicator.

Soils without chroma two colors can indicate wetness conditions via direct observation of saturated soils or a perched water table, or lateral water movement flowing into a bore hole, monitoring well, or open excavation above a less permeable layer. Soils with perched water tables are confirmed if saturation extends for at least three consecutive days.

Misinterpretation Possibilities

Predicting depths to a seasonal high water table within areas having sandy soils can be difficult (Veneman et al. 1998). Redox feature development may be hindered by: 1) lack of carbon source (Daniels and Buol, 1992; Vepraskas, 1999); 2) low Fe in parent material, causing the lack of contrast between matrix and redox feature; and 3) aerated or oxygenated water inhibiting reduction (Faulkner and Patrick, 1992); or (4) unstable root channels and cracks that only remain open for short periods (Vepraskas, 2000). Depletions may occur as sand grains “stripped” of iron in sandy soils. These stripped grains usually cannot be affirmatively tied to water table dynamics. The SHWT is best estimated in sandy soils with identification of redox concentrations in conjunction with depletions.

In addition, eluvial horizons typically possess low chroma matrix colors due to their low Fe content. Some coarser textured soils have a gray-colored E horizon directly below the topsoil. Incomplete breakdown of soil organic matter in the topsoil results in the formation of organic acids, which causes extensive leaching in underlying soil layers unrelated to anaerobic soil conditions (Veneman et al., 1998). The iron is stripped from the sand grains by the process of chemical complexation (podzolization) resulting in gray colors.

Low chroma colors are not always present, even though the soil has distinct periods of saturation. Many studies have demonstrated the existence of soils with significant wetness periods that do not exhibit low chroma redox features (Simonson and Boersma, 1972; Pickering and Veneman, 1984; Evans and Franzmeier, 1986; Griffin et al., 1992; James and Fenton, 1993; Mokma and Sprecher, 1994a; Wakely et al., 1996; Vepraskas et al., 1999;). Dark red-colored soils have such high iron contents that low chroma mottles are masked (Mokma and Sprecher, 1994b). Other situations, where wet soil conditions do not necessarily cause distinct low chroma colors, occur in soils with organic matter distributed throughout the soil profile, such as in frequently flooded fluvial soils (Lindbo et al., 1997).

Sometimes soils exhibit low chroma colors that do not result from seasonal anaerobic conditions. Soils can inherit low chroma colors from their geologic parent materials; or, over periods

of soil formation, have not released sufficient iron to give the soil a uniform brown appearance. The parent material may not contain enough iron to coat mineral grains (Veneman et. al., 1998).

Redox depletions in soils allow the site evaluator to reliably predict the level of seasonal saturation and reduction in the soil if the site has not been hydrologically altered. Drainage ditches and subsurface tile drains alter hydrology, and redox depletions may no longer be reliable indicators of the saturation and anaerobic conditions (Lindbo et. al., 1997, Hayes, 1998). Features observed at hydrologically altered sites are referred to as relict features. Some of these relict features are distinguished in the field by having sharp, distinct boundaries. Current redox features are indicated by a fluctuating water table, and are diffuse at the boundaries (Vepraskas, 1999).

Water table- Redox feature correlations

Relationships between SHWT's and redoximorphic features in soils (Daniels et al., 1971; Franzmeier et al., 1983; Vepraskas and Wilding, 1983; Pickering and Veneman, 1984; Evans and Franzmeier, 1986;) have been studied over the past three decades. As documented by Veneman et al. (1998) in a review of soil hydromorphology studies, correlation between SHWT depths and redoximorphic features has been shown in much of the literature. The researchers note two principal findings: i) redox concentrations along with redox depletions are more accurate than the use of a single factor in assessing SHWT's ii) significant saturation may occur without strong redoximorphic feature development.

West et al. (1998) monitored water tables for three years in a plinthite bearing clayey transect as well as a sandy catena in the Coastal Plain of southwest Georgia, and found horizons with redox concentrations were saturated 20% of the time, horizons with redox depletions were saturated 40% of the time, and horizons with reduced matrices (whole horizon reduced) were saturated 50% of the time.

Genthner et al. (1998) monitored soil transects (mostly fine-loamy soils) in the Upper Coastal Plain of Virginia and found strong correlation between SHWT depth and the depth to redox concentrations and depletions. They also found the depth to redox depletions or a reduced matrix underestimated the height of the SHWT in well-drained soils, whereas in more poorly drained soils the opposite was true. Approximately 75% of the time during the 4-yr monitoring period a piezometer identified a perched water table. This horizon had 10YR 6/4 redox depletions in a 10YR 5/8 matrix.

Weekly and biweekly water table measurements were made for ten years with an average year of rainfall in some typical soils of the North Carolina Coastal Plain: Udults, Aquults and Aquods (Daniels et al, 1987). Shallow water tables occurred in the Umbaquults, which was consistent with their morphologies. Average water level data for the Aeric and Typic Paleaquults did not drastically differ. The Typic Paleudults with chroma 3 mottles within 75cm of the soils' surface were saturated longer than the adjacent Aquic Paleudults. They also had a hydrograph similar, but drier than the Aeric Paleaquults. These Typic Paleudults were found in the middle of interstream divides where water tables fluctuate less near dissected stream edges. According to the data, chroma 3 mottles can be used as a reliable indicator for a water table presence. It was suggested that 5/3, 6/3 and 7/3 mottles (Munsell notation) be used for the criteria for placing soils in the Aquic subgroups of Paleudults and the Typic subgroups be restricted to unmottled soils or those having mottles of chroma 4 or greater above 75cm. Small differences in elevations can cause large differences in the redox processes and water tables.

Sandy Spodosols had a well-defined relationship with their morphology and water table levels. The top of Bh horizons in the spodosols was well related to the deeper average depth of water (Daniels et. al., 1987). As the mean monthly water table rose closer to the surface, so did the tops of the Bh

horizons. Soils with an abundance of morphological features of wetness generally had higher average water table depths than the better drained soils with fewer features at a greater depth.

Water table depths and oxygen levels were measured bi-weekly in forested systems on two toposequences derived from silty loess over loamy glacial till (Evans and Franzmeier, 1986). Oxygenated water perched above dense till flowed laterally to the drainageways. Udalfs on the shoulder and backslope positions had lower water tables than the more poorly drained Aquolls and Aqualfs occurring in drainageways and upland swales. However these well and moderately-well drained soils showed higher water table depths (above 1m) and durations (>30-d) than were reported in published soil surveys. These soils had three chroma depletions and matricies and four chroma clay films, which are indicators of occasional saturation with short periods of reducing conditions. The Aquolls and Aqualfs were saturated at least half the study period and had low oxygen contents (< 5mg/kg) for greater than 60% of the time. Three significant oxygen-water table regimes were proposed; (i) saturated and reduced, (ii) saturated and oxidized, and (iii) non-saturated and oxidized.

Water tables for a Mollisol catena were recorded twice a week for 4 years with an electric line meter from nested peizometers (Steinwand and Fenton, 1995). Redox features in the moderately well drained to the very poorly drained end of the transects overestimated the duration of saturation. The shallowest level at which greater than 2% redox features occurred in MWD-SWP-PD pedons on lower backslopes and footslopes were saturated less amount of time (avg. of 21% of study period) than the surface horizons of the well drained members (approximately 34% of study period). These differences could be accounted for by a lack of soluble organic matter with greater depth in the well drained member (Vepraskas and Wilding, 1983), or the presence of oxygenated water in the lower landscape positions resulting from through flow (Evans and Franzmeier, 1986; Ransom and Smeck, 1986). Water tables were maintained by a 1-meter drain of the PD-VPD soils in swales and toeslopes with overthickened mollic epipedons. The stronger gleying and accumulation of organic matter in lower landscapes were apparently relict feature that formed before artificial drainage (James and Fenton, 1993).

Duration of saturation in soils of the Goldsboro-Lynchburg-Rains catena varied slightly with distance away from an individual drainage ditch (Hayes and Vepraskas, 2000). However, within 30m of the ditch, water tables were lower and fluctuated more often and redox potential was lower (<500mv) for a shorter period than those soils away from the ditch. Reduced iron (Fe II) was discharged into the argillic horizons of soils adjacent to the ditch from upslope soils and was oxidized when water tables fell, thus creating more oxidized iron (Fe III) masses closer to the ditch.

Computer Simulated Water Tables

The hydrologic model DRAINMOD has been extensively used in the USA to analyze the long-term effects of drainage on water table fluctuations (Skaggs, 1978). DRAINMOD was originally developed for poorly drained agricultural fields. It is used to simulate and analyze water table management over a long period of climate record (e.g., 20–40 yr). The model calculates how often the soil is saturated within a given depth for a specific duration during any period in a year. DRAINMOD has been verified in extensive field experiments on a wide range of soils, crops, and climates (Skaggs, 1982; Fouss et al., 1987).

The required input data for model calibration can be acquired in a short period and the long-term simulations using historic rainfall data can be quickly obtained. Once the long-term (<30-yr) daily water table data are gathered, probability values for a specific duration of saturation can be computed for any soil depth. The major advantage of using simulation models is that the effects of annual and seasonal variability of weather can be considered in the analysis.

The relationship between long term hydrology and soil morphology was examined in a study of typical Coastal Plain soils (Norfolk catena) by He (2000; et. al., 2002). DRAINMOD was calibrated for 21 plots using short-term rainfall and measured water table data. Virtual input parameters to the model such as equivalent depth to a restrictive layer, evapotranspiration (ET), drain depth and spacing, depression storage, and drainable porosity were adjusted individually to fit measured water table data with predicted values. This relationship was quantified by an absolute standard deviation over the study period and was generally less than 20 cm. The effect of slope on drainage rates were not investigated. Soil property inputs included lateral saturated hydraulic conductivity (K) and the soil moisture characteristic. Crop inputs were the rooting depth for each plot.

This research (He, et. al., 2002) was based on three assumptions: (i) Water table levels could be predicted for individual soil plots (21 total at two sites) by treating each plot in isolation, (ii) Subsurface drainage rates were estimated by using the Hoodghout equation, using drain depth and spacing, and the depth to a restrictive layer to tabulate the drainage flux (the calibration was for a virtual drainage network); and (iii) Deep seepage rates were virtually zero and incorporated into subsurface water losses.

With calibration DRAINMOD could accurately simulate water table levels for a site with a single perimeter ditch rather than the series of parallel ditches. Input parameters such as drain depth and spacing, drainable porosity, and depth to the impermeable layer were adjusted by trial and error to minimize the difference between measured and simulated hydrographs. Simulated water table levels were very sensitive to drain spacing. The location of the impermeable layer was difficult to determine in the field. However, the values that were used for the depth to the impermeable layer did affect water table depths in the dry season. Large drainable porosity values of O horizons were used to minimize water-table fluctuations at and near the soil surface. After successful calibration, the model can compute long-term water table levels by using historic rainfall data.

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