Synoptic Literature Review of Shallow Groundwater Related to On-Site Sewage Facilities

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with

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CONTENTS

EXECUTIVE SUMMARY

The ability to predict the occurrence of shallow groundwater is the principal question dealt with in this review. Soil colors and mottling patterns have been the classic predictor for many years. The reliability of this indicator for evaluating soil suitability for on-site systems, however, is in question.

Mottles take time to form, and for the most part the period required for their formation far exceeds any reasonable safety factor for consideration of groundwater impacts on on-site sewage facilities (OSSFs). When identified, mottles are a very reliable indication of seasonal wetness. But their absence does not imply the lack of a seasonal water table. Mottles in some soils take months to form, and there are many soils with long-duration seasonal wetness with no mottles or other color indication of that wetness.

More robust indicators must be developed if on-site evaluation of shallow groundwater is to be effective. Climate, landscape position, and internal soil morphology could be used to develop regional models for the occurrence of unsuitably wet soils. The advent of Geographic Information Systems and digital topographic data enable the development of cost-effective and reliable maps that could be used on a county level. The data for developing simple but effective models is available, and equivalent models have been developed in other parts of the country. More refined and precise models could be developed by quanitifying soil-water-landscape relationships at a few key sites across the state. Maps of unsuitable soils, while subject to significant error, would be considerably more consistent and accurate and much less contentious than the present system which involves professional judgements that are often difficult even for the most experienced soil scientists, let alone the majority of those who must make such judgements without equivalent training.

INTRODUCTION

"The presence of groundwater shall be determined by a site evaluator." [1] This cut and dried statement, the sum total of the regulatory mandate, belies the complexity inherent in predicting the occurrence of groundwater at an on-site sewage facility (OSSF). There is just no simple way to make a reliable prediction at any one site. And yet the presence of groundwater, even if only seasonal, must be assessed with some degree of reliability to insure public safety. Raw sewage that passes through saturated soil is not completely treated, and thus the potential for public exposure is great when this sewage passes from saturated soils directly to the surface or into groundwater (Reuter et al., 1998; Bicki and Brown, 1990; Harris, 1996).

Although not stated in the regulations, the common assumption is that soil color or drainage mottles can be used as reliable indicators of seasonal wetness. This report will review that supposition and its weaknesses, and explore additional factors that can be used to predict seasonal soil wetness. This review is not intended to be an in-depth review of soil hydrology; rather it looks at those factors of most interest for on-site evaluations of unsuitable soils with respect to shallow groundwater. "Unsuitable" in this review means that the soil cannot accept untreated sewage without a properly engineered design. In addition, we look at the movement and survival of pathogens in saturated soils.

Few people have problems recognizing marshes or other wetlands with near-permanent wetness. By the same token, soils in the dry West Texas deserts are seldom mistakenly identified as wet soils. But s*easonal* wetness is much harder to recognize, and is at the root of our problems in the on-site evaluation of groundwater. Because we usually only have opportunity to view a site within a narrow window of time, we must make inferences about the presence of a water table if we do not observe one while on site, and while there are some very powerful tools available to help us make these inferences, we have to recognize that inferences automatically lead to errors. The only absolutely positive way to assess the risk of groundwater in areas of seasonal wetness would be to make on-site measurements over at least a 5-year period, a luxury no one

[1] TAC§285.30(f)

can afford. Because we are going to make some mistakes, we need to understand what kinds of errors are inherent in on-site evaluation, so that we can learn to minimize those errors that are most harmful to the public health.

WETLANDS, HYDRIC SOILS, AND SOIL EVALUATION FOR OSSFS.

Most of the literature dealing with indicators of soil wetness has been associated with wetlands, especially in the last 15 years. Soils that meet wetland criteria are referred to as hydric soils. Hydric soils cannot be directly correlated with unsuitable soils for OSSFs. All hydric soils are definitely unsuitable with respect to soil saturation, but not all soils that are too wet for standard OSSFs are hydric soils. Hydric soils require at least a two-week saturation and reduction period to be considered hydric (Environmental Laboratory, 1987). So while we must rely on the wetland literature for much of what we know about soil color patterns and drainage status, it is important to recognize the key differences between hydric soils and unsuitably wet soils with respect to OSSFs, differences that are primarily related to the duration of wetness.

THE FORMATION OF SOIL DRAINAGE COLORS.

Some terms need to be defined at the outset. A soil is ***saturated*** when all of its pores are filled with water. A saturated soil may eventually become ***anaerobic***, that is, lacking in oxygen, and may then become ***reduced*** with respect to particular chemical species. The ***redox potential*** is a measure of how reduced a soil is, expressed in voltage units as ***Eh***. A soil is unsuitable when it is saturated, irrespective of whether it becomes reduced or not.

Groundwater is the saturated portion below the capillary fringe and the top of the groundwater is the ***water table***. The ***capillary fringe*** is located above the water table. The capillary fringe is saturated but the water is held in place by capillary forces and cannot be measured with piezometers.

Soil color is described in terms of the matrix or background colors (Soil Survey Staff, 1993). Iron stains on this background are referred to as ***mottles***, or the newer term "***redoximorphic concentrations***". In this review, we use the older term "mottles", and refer the reader to Vepraskas (1995) for more details on the newer terminology.

Iron is the primary coloring agent in mineral soils[2]. Iron has two redox states: oxidized or ferric, and reduced or ferrous. Iron in a well drained soil tends to be in an oxidized state, while iron in a waterlogged or poorly drained soil tends to be reduced or ferrous. Oxidized iron is usually red or yellow, whereas reduced iron is usually gray or black. Colors and quantified with the Munsell soil color charts (1994 Revised Edition. Munsell Corp. 617 Little Britain Road New Windsor, NY 12553-6148.: 800-622-2384). Colors on these charts with chromas of 2 or less are considered to be gray.

At least in principal, then, the color of a mineral soil should be a good predictor of its drainage status, with reddish soils being well drained, and gray soils poorly drained. This is indeed the basic model, and in general works well, but requires many exceptions and caveats in order to be used as a predictive model for our purposes. In spite of these caveats, gray soils should always be viewed with caution, and assumed to be unsuitable until proven otherwise.

Iron mottles form in soils because of redox heterogeneity within the soil. Soils with seasonal wetness in particular will have considerable variability on a microsite scale within the soil (Dobermann and Mutscher, 1989). As the soil wets, for example, significant areas will lag as dry zones, and as a soil dries, large patches may remain wet for extended periods. Few seasonally wet soils will be either all reddish or all gray, but will have significant mottling or staining reflective of the variation in drainage and redox status in the soil. One might thus observe reddish soils with gray mottles, or gray soils with reddish mottles. Most of the remaining discussion on drainage colors will focus on mottles, but the reader is advised that the same principles apply to soils with gray matrix colors, or other redoximorphic features[3].

A reddish mottle of oxidized iron is a still sign of saturation and reduction because iron cannot concentrate as a mottle unless it first goes through a reduced phase. This is because oxidized or ferric iron is a solid in the pH range of most soils, and is therefore not mobile (Sposito, 1989). Ferrous or reduced iron is mobile in the soil solution, and

[2] Calcium carbonate, other salts, and organic matter can mask the color of iron in soils. Very little iron is required to color a soil, often less than 1 percent.

[3] Nodules, concretions, and depletion zones are the other principal redox features found in soils. Vepraskas (1994) provides a good review of all the features.

when it comes in contact with oxidized zones, it will precipitate out as the solid oxidized form, creating a mottle.

Saturation alone is not sufficient to change oxidized iron to reduced iron. The process of reduction in soils is a sequential one, where all of the oxygen must be removed before other elements are reduced (Maussbach and Richardson, 1994). The reduction process is microbially driven, and follows the sequence outlined in Table 1.

Table 1.Reduction Sequence for Common Soil Solutes at pH 7.

Reaction	***E*$_h$**
$O_2 + 4H^+ + 4\ e^- \leftrightarrow 2H^2O$	0.816V
$NO_3^- + 2H^+ + 2e^- \leftrightarrow NO_2^- + H_2O$	0.421V
$MnO_2 + 4H^+ + 2e^- \leftrightarrow Mn^{2+} + 2H_2O$	0.396V
$Fe(OH)_3 + 3H^+ + e^- \leftrightarrow Fe^{2+} + 3H_2O$	-0.182V
$SO_4^{2-} + 10H^+ + 8e^- \leftrightarrow H_2S + 4H_2O$	-0.215V
$CO_2 + 8H^+ + 8e^- \leftrightarrow CH_4 + 2H_2O$	-0..244

From Schlesinger, 1991.

PROBLEMS WITH MOTTLES AS PREDICTORS.

Time.

Time required for formation is the first and most fundamental problem associated with soil mottles. In one sense, time itself is not really a factor - is the *summation* of all of the other factors, which interact in varying degrees to retard or accelerate the formation of mottles. Because these factors are all interrelated, one cannot ascribe a discrete time function to any single variable. Likewise, it is not possible

to ascribe either frequency or duration of hydrologic events to mottle character (i.e., thickness, percent cover, prominence, etc), other than that the more prominent and thick any given mottle is, the longer the saturation and reduction period is relative to other similar soils.

The length of saturation and reduction required to form an iron mottle varies widely in the literature, with periods ranging from at least 1 week under the most optimal conditions (Vepraskas et al., 1995) to over four months continuous saturation and reduction (see under Redox Potential, below). Even if all mottles formed in the minimum time period of a week or two, soil drainage mottles would still not be fully reliable indicators of wetness problems with respect to on-site systems. What about soils wet for more than a day or two, but less than 2 weeks?

It was not the purpose of this review to establish the minimum time a soil needs to be saturated before it unsuitable, but one week of soil saturation clearly seems to be too long[4]. And there are many, many soils where much longer periods of saturation and reduction are required to form observable mottles. When present, mottles *may* be good indicators of soil saturation, but the *lack* of mottling does *not* imply the lack of saturation that may impact an on-site system. Over reliance on mottling as the sole indicator of soil wetness can result in the danger of falsely identifying a soil as suitable when in fact it experiences significant periods of wetness.

<u>Amount of Iron</u>**.**

It is a simple truism to state that lack of iron will result in the lack of iron mottling, but this simple fact is often overlooked. The review of the literature did not uncover any minimal values of free iron that might be required.

On the other hand, red soils with abundant iron often pose some special problems with respect to formation of mottles or gray matrix colors. Mokma and Sprecher (1994b) found that the red soils with abundant hematite they studied in Michigan were not as gray as would have been predicted.

<u>Amount and State of Organic Matter.</u>

The reduction process is microbially mediated. Without a source of carbon, microbes are ineffective, and the reduction process requires orders of magnitude increases in time for iron reduction. Daniels and Buol (1992) found it necessary to have 10 mg/l of dissolved organic carbon in solution for reduction to occur, while Vepraskas and others (1996) found that redox features did not form in soils with less than 1.5% organic matter.

Some soils have more than sufficient carbon in soil organic matter (SOM), but the SOM may be bound so tightly to clay that it is not available as a microbial energy source.

[4] This assumes one week of saturation *after* the end of a rainfall or flooding event.

This is particularly true of many of the very clayey wet Vertisols that make up much of the Gulf Coastal plain (Jacob et al. 1997).

Redox Potential and pH.

Iron cannot be reduced unless the redox potential is low enough. As is evident in Table 1, the reduction process is a sequential one, and one species is not generally reduced until all of the species with higher redox potential are reduced. Thus, iron will not be reduced in a soil until all of the O_2, NO^-_3, and Mn^{2+} species are reduced. This is a very significant fact because it means that a soil could remain saturated for long periods of time without ever having a redox potential low enough to reduce iron. Abundant nitrate, for example, could buffer Eh at a high enough level that iron would not be reduced.

pH is a corollary factor to the redox potential. Figure 1 shows the relationship between Eh and pH. The slope of the lines in this figure indicate that higher pH soils will require a lower Eh than a lower pH soil to reduce iron, all other things being equal. This means that an alkaline soil will require a much longer saturation and reduction period to form mottles than a correspondingly lower pH soil. Tentative results from high pH red soils on the Lower Brazos bottom, for example, suggest that up to four to six months

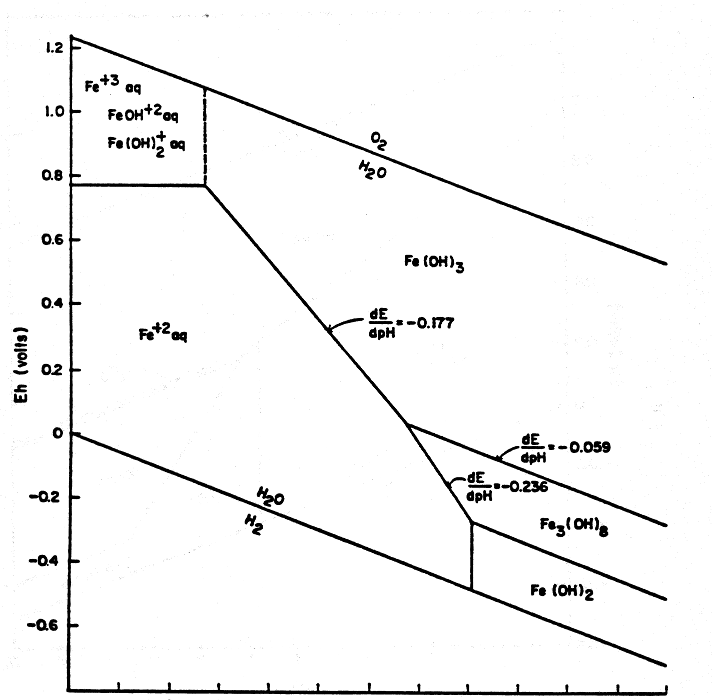

Figure 1. Stability areas of Fe species with respect Eh and pH. From Mausbach and Richadson, 1994.

saturation may be required before observable mottles form (Wes Miller, NRCS hydric soil specialist, personal communication).

THE QUESTION OF MOTTLE CONTEMPORANEITY

Once a mottle forms, how long does it last? Available evidence suggests that if thick enough, mottles could last many thousands of years in some soils, given the right conditions and lack of bioturbation or other disturbances.

We are obviously not interested in whether a soil was saturated in the distant past. We want to know the state of the soil today: is it wet enough now to be considered unsuitable with respect to a standard on-site septic system?

Many of the soil surfaces along the Texas Gulf Coast are extremely ancient. Outside of the floodplains, the vast majority of the surfaces there are in excess of 30,000 years in age (McGowen et al., 1976). The potential for ancient or relic mottles not related to current wetness conditions is clearly very high, and relic mottling features in the soils of this area are well documented (Tucker et al., 1994).

There are at least two important considerations here. The first is that most of the areas where relic mottling has been identified are in soils that underlie some very flat surfaces that by definition are very poorly drained, particularly on the upper coast. So even if some mottles can be positively identified as relic in these soils, it is still very likely that wetness is a problem, given the topography of the area. It is important to remember these mottles have been identified as relic with respect to wetland hydrology, not suitability for an OSSF.

Second, any mottles identified in the near surface, i.e., the upper 10 –15 inches, can automatically be assumed to be contemporaneous, even in a soil of great age, because bioturbation turns the surface soil over periodically.

Much research has gone into determining which mottling patterns are relic and which are contemporaneous. The reader is referred to Vepraskas (1995) and Hurt et al. (1998) for an excellent review of mottling patterns and their significance. In general, mottles that are associated with active surfaces in the soil can be considered to be contemporaneous. Thus, oxidized iron linings on soil structural faces or along soil pores can generally be considered recent, whereas masses not associated with any current surface may often be regarded as relic. Richardson and Daniels (1993) review the significance of various redoximorphic patters in soils in terms of the duration and frequency of saturation and reduction events.

For the purposes of soil suitability for OSSFs, all mottles should probably be considered contemporaneous until proven otherwise. Following this logic, it is possible that some dry sites could be identified as wet, but the implications of this error are much less than the opposite error, identifying wet sites as dry (see below).

SUMMARY ON USE OF MOTTLES AS WETNESS INDICATORS.

Mottles, if not relic, are an excellent indicator of soil wetness conditions. Contemporaneous mottling can be relied upon almost absolutely as indicators of seasonal wetness. And because most relic mottles occur in level-sloped soils of great age, their relic nature can to a certain extent be ignored[5].

Because soil drainage mottles are such good indicators of soil wetness, it is natural to assume that their absence implies a lack of soil wetness. This assumption is the most dangerous aspect of using mottles as sole indicators. Drainage mottles take time to form, and we miss a great many wet soils if we rely on mottles alone. Many studies have demonstrated the existence of soils with significant wetness periods that do not exhibit concomitant gray colors or mottling patterns (Evans and Franzmeier, 1986; Griffin et al., 1992; James and Fenton, 1993; Mokma and Sprecher, 1994a; Pettry et al., 1995; Pickering and Veneman, 1984; Simonson and Boersma, 1972; Vepraskas et al., 1999; Wakely et al., 1996).

Because the use of mottles in on-site investigations is going to identify only the wettest soils, the presence of mottling and/or gray matrix colors clearly do not constitute a safe threshold for identification of unsuitable soils. Table 1 shows the expected utility of a given prediction for given states of wetness. Identifying a dry site as wet has some negative utility, mainly the inconvenience imposed upon the owner who must

[5] Care would have to be exercised in attributing soil wetness to the *depth* at which the relic mottles occurred. While it is true that relic mottles are in a great many cases associated with level surfaces that experience saturation, the saturation may or may not occur at the level of the relic mottling.

unnecessarily invest in an engineered system, but the error associated with misidentifying a wet site as dry has much graver implications in that raw sewage could potentially surface or enter groundwater. We must of course strive to eliminate all errors, but minimizing one of the errors in Table 1 will tend to maximize the other error. It should be obvious where we should concentrate our efforts at error minimization. Over-reliance on soil mottling will maximize the error in the upper right hand quadrant, the worst possible error for public safety.

Table 2. Expected utility for false and correct predictions

		Predicted State	
		WET	DRY
Actual State	WET	+ +	=
	DRY	—	+

Key: + positive result, - negative results.
Shaded areas are zones of error.

OTHER INDICATORS OF SOIL WETNESS

If mottles are not sufficiently precise indicators of soil wetness, what else is left? It turns out that no other single indicator can be used in isolation reliably, but there are several indicators that when used as a package could provide powerful predictive abilities. These indicators include climate, and landscape position, internal soil morphology other than mottles, and soil surveys.

CLIMATE AND LANDSCAPE

Wetter soils occur in wetter climates and in wetter landscape positions. A simple truism, but one that could be built into a powerful predictive model. We intuitively know that wet soils will only occur in the wettest, most concave parts of the landscape in West Texas, but that unsuitably wet soils can occur in many more areas in East Texas. The question is whether or not this intuition can be quantified into a model usable in a regulatory context.

Considerable research has gone into building predictive models of soil water states based on landscape position (e.g., Moore et al., 1991, 1993; Thompson et al., 1997; Bell et al., 1994; Dietrich et al., 1992; and Zheng et al. 1996), and the relationship between topographic or landscape elements and soil drainage is well established. Landscape elements have been fairly well quantified (e.g., Hall and Olson, 1991 and Fig. 2). Landscapes can be conceptually divided into water gathering or water shedding positions. Areas of convergent flow are water

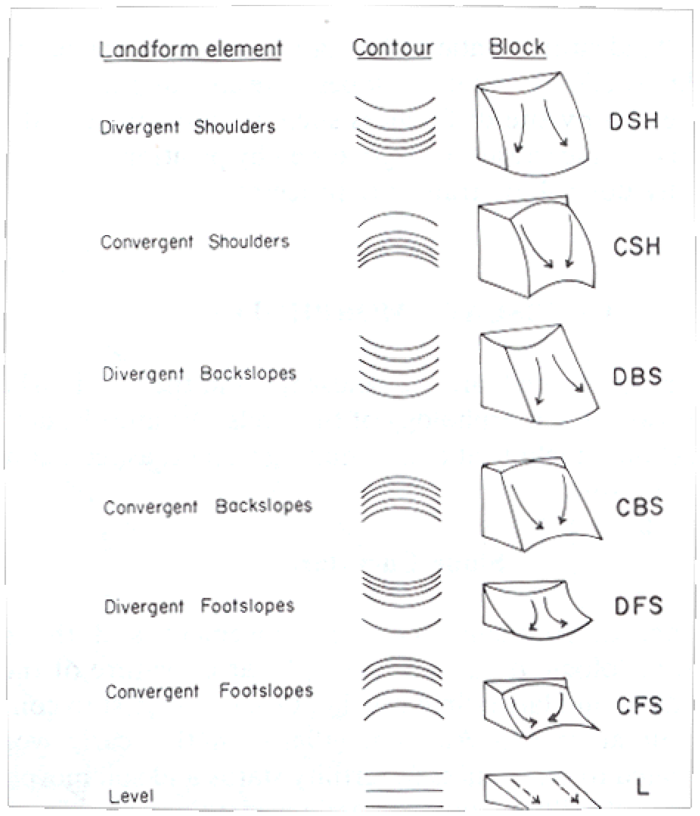

Figure 2. Slope shapes and water convergence/divergence from Hall and Olson, 1991.

gathering positions and are obviously going to be zones of high probability for seasonal soil saturation (e.g., Kahn and Fenton, 1994), at least in climates ranging from sub-humid to humid.

The availability of Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) has opened up interesting new possibilities for developing large-scale drainage status maps. 30-m DEMs are available for the entire state of Texas, with 10- resolution in the works (http://www.tnris.state.tx.us/DigitalData/ DEMs/dems.htm). Zhang et al. (1996) developed a powerful predictive large-scale map with digital elevation data using a topographic index that combined upslope or drainage area and slope angle for each pixel. Bell et al.(1994) used a GIS combined with a soil landscape model to develop a landscape map of soil drainage classes on a watershed scale. These examples clearly demonstrate the feasibility of developing such models rather cheaply on a wide scale for mapping unsuitable soils for on-site septic systems. No intensive data would be required to develop initial maps for specific regions in Texas, but some intensive data would be needed in a few locations across the state to help quantify landscape and climate interactions.

In the absence digital models and maps, it is still possible to intuitively develop some coarse but robust models. We know for example that flat areas on the Upper Gulf Coast are subject to seasonal saturation. It is not necessary to see soil mottling to be assured of this fact. (In fact, many of the highly alkaline soils on the Gulf Coast will not form mottles even with extended periods of saturation (see Jacob et al., 1965)).

We could probably extend this observation that to say that flat surfaces east of I-35 and I-37 will be saturated in most years. Certainly some sloping areas in East Texas will also be saturated. In my (Jacob) experience, planar slopes of up to 3-4% will also be unsuitable in most areas east of I-45. Areas of convergent flow are probably unsuitably wet much farther to the west of I-35. There is probably sufficient local expertise between soil surveyors and on-site evaluators to develop some initial rough models that would take care of at least the very wettest areas. Site-specific, intensive studies could help quantify these relationships.

INTERNAL SOIL MORPHOLOGY – CLAY PANS

Internal soil morphology, apart from soil mottling, can also be used as a powerful predictive tool. This morphology includes texture, structure, and restrictive layers. The effects of texture and structure are covered elsewhere- clays impede drainage, texture may improve it. Claypans are one important hydrologic feature, however, that are not well recognized in the on-site community.

Clay pans are an abrupt change in texture from an overlying to an underlying layer. Quite simply, the clay slows infiltrating water to such an extent that it stands on the clay pan. Saturated conditions frequently occur over clay pans; how thick the saturated layer is and how often it forms depends on the local climate, landscape position (amount of receiving water), depth of the overlying horizon, and amount of clay in the clay pan.

The clay pan is recognized taxonomically as an abrupt texture change (ATC) (Soil Survey Staff, 1999), and is also recognized in the on-site evaluation regulations as a restrictive layer [TAC§285.30(e)]. The ATC is not precisely defined in the regulations other than the implication that it is a clayey subsoil. The definition in Soil Taxonomy is much more precise: if the clay content of the overlying horizon is less than 20%, then the clay content must double within 3 inches or less; if the clay content of the overlying material is greater than 20%, then there must be an absolute increase in clay content of 20% within 3 inches.

From the Soil Taxonomy definition, it is possible to have an ATC even with a loamy subsoil. In the right climate and landscape position, even a loamy “clay” pan can have a profound hydrologic impact, by backing up water and creating saturated conditions.

Consider the following profile: 50 inches of loamy sand over a clay loam, with no mottling, in East Texas. Most site evaluators would automatically classify this as a suitable soil. But this soil will definitely stand water over the clay loam, well above 50 inches, certainly within less than 2 feet below any standard trench. Clay pans clearly need greater attention from site evaluators.

SOIL SURVEYS

Soil surveys cover most of the state and are woefully underutilized by the site evaluator. The soil surveys were never intended for detailed site-specific studies, but they have a wealth of information on specific soils, and are precise enough to make some first approximations with respect to on-site evaluations.

Specific water table information is usually provided for every soil in a published soil survey. Detailed studies were performed in only a few cases in the development of this information, and so while some of it may be unreliable, it is still an excellent database for referral, and will at least give a credible ranking of local soils in terms of wetness, and the seasonality of the wetness.

Soil series are based on Soil Taxonomy (Soil Survey Staff, 1999). The elements of interest from the point of view of shallow groundwater evaluation are “aquic conditions” and the “aquic moisture regime” . Aquic conditions refer to “continuous or periodic saturation and reduction”. An aquic moisture regime is a “reducing regime that is free of dissolved oxygen.” Neither of these elements specifies a time period, but the aquic moisture regime obviously implies a sufficient period to attain reducing conditions. Any time the formative element “aquic” is used in a taxonomic name of a soil series, wetness is a significant problem. For example, *Vertic Alb**aqu**alf* has the “aqu” element at the suborder level, while ***Aquic*** *Udifluvent* has the formative element at the subgroup level. Whatever level it occurs at should raise a red flag for the site evaluator. As with the definition of hydric soils, the aquic component is not all encompassing for unsuitable soils with respect to an OSSF. All soils with an aquic component are unsuitable, but there may be some unsuitably wet soils that are not considered aquic. The aquic taxa, however, are probably more closely matched with unsuitable soils than hydric soils. In terms of the minimum wetness, hydric is wetter than aquic which is wetter than OSSF unsuitable.

One possible regulatory alternative is to make any soil mapped with any aquic qualifiers as unsuitable by default. A variance could be obtained, but only if documented by a certified professional soil scientist. An examination of the Harris County Soil Survey (Soil Survey Staff, 1976) reveals that 84% of the county would be considered unsuitable with respect to moisture by this method, a figure not at all unreasonable given what we know about the flat, wet landscapes of the Upper Gulf Coast.

PUTTING IT ALL TOGETHER:
Summary and Recommendations

We have some excellent tools available for evaluating shallow water tables, but none are reliable enough to stand alone. Soil mottles are good indicators as far as they go, but have some serious limitations for recognizing soils on the drier end. Climate and landscape are powerful predictors, but would require intensive data acquisition by themselves to be powerful models. Clay pans and other internal soil morphologies provide important information, but are very limited as stand alone factors. Soil surveys have a wealth of information, but their use must be tempered with the knowledge that most of the information is not site specific.

This review should make clear that the site evaluator must use a robust procedure when making soil and site evaluations with respect to groundwater. H/She must use all the tools at their disposal to put together a reasonably accurate picture of soil wetness conditions. A highly trained professional earth scientist can use the available tools with a great deal of reliability. The vast majority of those called upon to determine soil suitability, however, do not have this kind of training, and the reliability of the evaluations is sometimes questionable. We increasingly aware of county-level disputes over regulatory determinations that are perceived as arbitrary. A more consistent system is urgently needed.

The advent of inexpensive geographic information systems that can be run on desktop computers makes possible the development of comprehensive models and maps with real predictive power. Just using existing data [soil surveys (soils with clay pans, soils with aquic conditions), digital elevation models (to quantify slope shapes), floodplains, and climate], maps could be developed immediately that would be a great improvement over the current situation. A county-level map of unsuitable sites would make locating an OSSF on the map the most difficult part of site evaluation. Because even the most accurate maps are subject to some error, a mechanism for variances would need to be established. We propose that such variances only be granted upon the endorsement of a certified professional soil scientist or equivalent professional. A program to develop a pilot county map should be undertaken immediately.

Installation of soil monitoring sites at selected locations across the state would allow for more quantitative assessments of the relationships of soil wetness to specific landscape positions in specific climatic zones. This kind of quantitative information would allow for very precise models at a relatively low cost, and should be considered immediately for densely populated areas with high densities of OSSFs.

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Bouma, J., 1983, Hydrology and soil genesis of soils with aquic moisture regimes, in Wilding, L. P., and others, eds., Pedogenesis and soil taxonomy. I. Concepts and interactions: Elsevier, Amsterdam, p. 253 – 281.

Bouma, J., Dekker, L. W., and Haans, J. C. F. M., 1980, Measurement of depth to water table in a heavy clay soil: Soil Science, v. 130, p. 264 – 269.

Buol, S. W., and Rebertus, R. A., 1988, Soil formation under hydromorphic conditions, in, Hook, D. D., and others, eds., The ecology and management of wetlands, v. 1: Ecology of wetlands: Timber Press, Portland, Oregon, p. 253 – 262.

Callebaut, F., Gabriels, D., Minjauw, W., and de Boodt, M., 1982, Redox potential, oxygen diffusion rate, and soil gas composition in relation to water table level in two soils: Soil Science, v. 134, n. 3, p. 149 - 156.

The study measured redox potential, soil gas composition, and oxygen diffusion rate at different groundwater levels to compare the changes in the measurements. They also proposed to design a way to use tensiometer readings to determine the aeration status of the soil by relating the oxygen diffusion rate with the soil water pressure head. The study found that an exact relationship between oxygen diffusion rate and soil water pressure head or soil water content can not be expected because the oxygen diffusion rate is strongly affected by the aeration zone depth and by the soil structure. However, they did determine calculations for using soil water pressure head in sandy loams or loamy sands to find the aeration profile. They also concluded that redox potentials better reflected soil aeration at low oxygen concentrations, and this method would be better suited to saturated or very near saturated conditions.

Chen, C. C., Dixon, J. B., and Turner, F. T., 1980, Iron coatings on rice roots: mineralogy and quantity influencing factors: Soil Science Society of America Journal, v. 44, p. 635 – 639.

Both studies done in Texas. See Mendelssohn, I. A., 1993 for annotated bibliography.

Chen, C. C., Dixon, J. B., and Turner, F. T., 1980, Iron coatings on rice roots: morphology and models of development: Soil Science Society of America Journal, v. 44, p. 1113 – 1119.

Childs, C. W., 1981, Field test for ferrous iron and ferric-organic complexes (on exchange sites or in water-soluble forms) in soils: Australian Journal of Soil Research, v. 19, p. 178 – 180.

Clothier, B. E., Pollock, J. A., and Scotter, D. R., 1978, Mottling in soil profiles containing a coarse-textured horizon: Soil Science Society of America Journal, v. 42, p. 761 – 763.

Cogger, C. G., and Kennedy, P. E. 1992. Seasonally saturated soils in the Puget lowland. I. Saturation, reduction, and color patterns. Soil Science 153:421-433.

The depth and duration of seasonal saturation affect land use and management decisions. Soil chromas less than or equal to 2 were used to indicate the depth of seasonal saturation, but in many soils this relationship is not valid. This study was conducted to determine the relationships among seasonal saturation, soil colour patterns, and soil redox in soils derived from glacial till, alluvium, and volcanic mudflow material in the Puget Sound lowland of Washington, USA. Soil profiles were described at key positions on landscapes typical of each parent material. Water tables, soil redox potentials, groundwater dissolved oxygen (DO), and soil moisture tensions were measured in selected soil horizons and the results compared with soil colour patterns. Seasonal high water tables could be predicted using chroma 2 colours on the glacial till and volcanic mudflow landscapes. Soil colours did not indicate current redox conditions in the alluvial sites, although they could be used to predict seasonal high water tables on the overwash plain landscape. The duration of DO levels less than 5 mg/litre could be related to soil redox status. Soil horizons with DO less than 5 mg/litre for more than 80% of the time they were saturated had low soil redox potentials and were reduced for at least part of the year. Soil horizons with DO less than 5 mg/litre for 60-80% of the time were reduced only in microsites. Other soil horizons remained oxidized throughout the year.

Cogger, C. G., Kennedy, P. E., Carlson, D. 1992. Seasonally saturated soils in the Puget Lowland II. Measuring and interpreting redox potentials. Soil Science 154: 50-58.

Redox potential measurements can aid the understanding of the relationships between saturation and colour patterns in seasonally saturated soils. Their value is limited, however, because there are no widely accepted methods to measure and interpret field redox potentials. This study was made to determine which measurement and interpretation methods are most appropriate for field use in seasonally saturated soils. Redox electrodes were constructed by soldering Pt wire onto a Cu lead, encasing the junction in an acrylic tube, and sealing with epoxy. Redox potentials were measured at

three sites in Washington using permanently installed soil electrodes and at one site using temporarily installed groundwater electrodes. Redox potentials were also measured in laboratory soil cores to compare the effects of microsite environments vs. electrode differences on apparent redox variability. Finally, exchangeable Fe(II) was measured in extracts from soil core samples at different redox potentials to estimate the redox environment needed for the onset of Fe reduction and soil mottling in the sample soils. Properly constructed soil electrodes responded to changes in the redox environment and were reliable for at least 1 year. Variability among electrodes was often large in changing or intermediate redox environments and was due primarily to microsite differences in the soil. Groundwater redox measurements were of little value, because the shallow groundwater in the soils studied was generally oxidizing, even when the soil was reduced. Groundwater dissolved O<sub(2)> combined with soil redox measurements give the most complete picture of the soil-groundwater redox environment. In the soils of this study, exchangeable Fe(II) was present at less than or equal to +200 mV (pH 6-7) indicating conditions suitable for Fe reduction and mottling.

Collins, J. F., and Buol, S. W., 1970, Effects of fluctuations in the Eh-pH environment on iron and/or manganese equlibria: Soil Science, v. 110, p. 111- 118.

Developed a composite Eh-pH stability diagram. The diagram shows that at low Eh measurements, iron and manganese precipitate at higher pH level than at high Eh (more positive) measurements.

Comerford, NB, A. Jerez, A.A. Freitas, and J. Montgomery. 1996. Soil water table, reducing conditions, and hydrologic regime in a Florida flatwood landscape. Soil Science 161:194-199

Cypress/pine flatwoods are a dominant landscape of the lower coastal plain of the southeastern U.S. It is clear that the cypress swamps are wetlands, but it is not clear that the intervening pine ecosystems would meet hydrologic criteria of a wetland definition. Hydrology, as defined by the periodicity of the fluctuating water table and its effect on the redox environment of the soil, will determine whether these areas are wetlands. The objectives of this study were (i) to evaluate the relationship between water table depth and redox environment for a typical pine flatwoods/cypress swamp landscape and (ii) to use this relationship to contrast the amount of the study area that would fit a specific wetland hydrology definition where that definition was based on either water table depth or the development of a reduced environment in the soil surface. One hundred twenty water table wells were installed in a grid system over a 42-ha study site, and water table depth was measured approximately every 2 weeks. At selected locations, redox electrodes were installed at a 5-cm depth in pine planations growing on Spodosols and landscape positions that were in transition between these Spodosols and the adjoining cypress swamps. A Geographical Information System was used to calculate the area of the study site meeting different criteria related to water table depth or soil reduction. Results suggest that 20 to 56% of the study area would meet a hydrologic definitions of wetland, depending on the hydrologic criteria used. In these landscapes, water tables between 15 and 20 cm below the soil surface promoted reduced conditions in the surface. This criteria could be used for evaluating redox conditions relative to hydrophytic vegetation and soil redoximorphic features.

Crawford, C. A., 1999, Hydric properties of shrink swell soils in a riparian setting in Central Texas, unpub. Bachelor's thesis, Baylor University, Waco, Texas, 54 p.

†Daniels, R. and Buol, S. W., 1992, Water table dynamics and significance to soil genesis. pp 66-74 in Kimble, J. M., ed., Proceedings of the VIIIth International Correlation Meeting on Wetland Soils: USDA Soil Conservation Service, Washington, D. C.

A review of studies on water table dynamics in various settings. Data on dissolved organic carbon in soil water indicate that more than 10 mgL-1 of dissolved organic carbon is needed for reduction to occur.

‡Daniels, R. B., and Hammer, R. D., 1992, Soil Geomorphology: John Wiley & Sons, New York.

Daniels, R. B., Gamble, E. E., and Buol, S. W., 1973, Oxygen content in the ground water of some North Carolina aquults and udults in Bruce, R. R., et. al., eds., Field soil water regime: Special Publications 5 Soil Science Society of America, Madison, WI, p. 153 – 166.

Daniels, R. B., Gamble, E. E., and Nelson, L. A., 1971, Relations between soil morphology and water-table levels on a dissected North Carolina coastal plain surface: Soil Science Society of America Proceeding, v. 35, p. 781 – 784.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., J. McKean, and R. Bauer. 1992. Erosion thresholds and land surface morphology. Geology 20:675-679.

A detailed digital terrain model (10m data density) was developed to assess erosion potential. Elevation model developed shows areas of divergent, convergent and planar flow. Although not addressed in this paper, convergent flow areas would be zones of potential seasonal soil wetness.

Dobermann, A., and Mutscher, H. 1989. Experiments on the influence of organic matter and water regime on horizontal and vertical changes of the redox potential in flooded soil columns. Beitrage zur Tropischen Landwirtschaft und Veterinarmedizin 27:381-393.

Vertical and horizontal variations in redox potential were studied in flooded soil columns without plants. The sandy loam soil used was characterized by considerable microzonal variations of the redox potential. The standard deviations of measurements were 34-58 mV and were considerably decreased by supply of straw (s = 12-25 mV). The intensity of Eh decline after flooding decreased with increasing soil depth, which was attributed to occlusions and enrichments of oxygen. Incorporation of organic matter accelerated reduction processes. Vertical variations in Eh were compensated by mass-flow processes under moderate percolation, especially with straw. The diffusion of dissolved reducing substances in treatments without percolation affected Eh variations horizontally and, to a lesser extent, vertically. The best properties of organic amendments for amending soil redox potential are their content of water-soluble and easily transformable compounds.

Dobos, R. R., E.J. Ciolkosz, and W.J. Waltman. 1990. The effect of organic carbon, temperature, time, and redox conditions on soil color. Soil Science 150:506-512.

The effects of organic carbon content (3.2, 9.6, and 15.4 g/kg), organic carbon quality (26 and 107 g/kg nonstructural carbohydrates), temperature (5, 15, and 25 deg C), and time (7, 14, 21, and 35 wk) on colour changes in soil material (originally 7.5 YR 5/6) under alternating oxidizing and reducing conditions were observed in the laboratory. Hues of the mottle and matrix colours were strongly influenced by organic carbon content and shifted from 7.5 YR to 2.5 Y as organic carbon was added. Temperature and time influenced matrix colour and mottle hues to a lesser extent. Mottle and matric colour values were altered but did not exhibit any trends with organic carbon, temperature, or time. The chromas of the mottle and matrix colours were strongly influenced by organic carbon content. Mottle chromas ranged from 8 to 1 whereas matric chromas ranged from 6 to 3. Temperature and time influenced mottle and matrix chromas to a lesser extent. The areal extent of colour changes increased with organic carbon content, temperature, and time. The increased yellow (10YR and 2.5Y) components, higher values, and lower chroma of the colours was attributed to haematite dissolution, which allowed goethite and non-iron oxide minerals to influence the observed colours more strongly. A decrease in colour values was attributed to new precipitates on existing oxide or silicate mineral surfaces.

Elless, M. P. Rabenhorst, M. C. James, B. R. 1996. Redoximorphic features in soils of the Triassic Culpeper Basin. Soil Science 161:58-69.

The relationship between soil characteristics and the development of redoximorphic features was investigated in soils developed from red Triassic sediments in the Culpeper Basin, Maryland, USA. Eleven pedons were described and characterized. In addition, water table depths were measured biweekly over a period at each pedon during the wet season. Similarly drained, yet morphologically different pedons were observed occupying the lower backslope, footslope, and toeslope positions of both topohydrosequences. Differences in organic carbon content and soil temperature did not explain the observed morphological differences among these similarly drained soils. The nature of the parent material, appears to control the development of redoximorphic features in these soils. Lithological discontinuities were observed at the boundary between horizons with yellow and red hues (i.e. 5YR) in soils that occupy the footslope and toeslope positions. These discontinuities represent the incorporation of alluvial debris. Within pedons whose upper sola were influenced by alluvial additions and a persistent seasonally high water table, substantial development of redoximorphic features was observed. Within hydrologically-similar pedons derived mainly from Triassic residuum, redoximorphic features were weakly expressed. Hydromorphological features are formed by redox processes, but the particular expression may be affected by the nature of the parent materials.

‡Environmental Laboratory. 1987. Corps of Engineers wetlands delineation manual: Environmental Laboratory. Technical Report Y-87-1. U. S. Army Eng. Waterway Experiment Station, Viscksburg, Miss.

Manual developed by the Army Corps of Engineers to delineate wetlands in the field. Part of the manual entails determining the hydric status of soil.

Evans, C. V., and Franzmeier, D. P., 1986, Saturation, aeration, and color patterns in a toposequence of soils in north-central Indiana: Soil Science Society of America Journal, v. 50, p. 975 – 980.

This study showed that many soils have water tables higher than described in published soil surveys and in the soil interpretations records for those series. The Aqualfs, in swells, and Aquolls, in swales, contained shallower water tables, lower soil-water oxygen levels, longer periods of saturation, and lower chroma colors than the Udalfs located on the hillslope shoulder and backslope positions. The study found soils with a chroma color of 3 and possibly 4 experienced occasional saturation and some reduction. They determined the water table in soils with brownish B horizons to periodically be shallower than reported in the soil survey for durations of over 30 days. Soils fulfilling these characteristics are in Typic, Udic subgroups of Alfisols and Ultisols. They concluded soils that are saturated and oxidized are not adequately recognized in published soil surveys and soil interpretation records.

†Fanning, D. S., Hall, R. L., and Foss, J. E., 1973, Soil morphology, water tables and iron relationships in soils of the Sassafras drainage catena in Maryland in Schlicting, E., and Scwertmann, U., eds., Pseudogley and gley: International Soil Science Society Trans. Comm. V and VI (Stuttgart-Hohenheim, W. Germany, 1972), Verlag Chemie, Weihem, W. Germany, p. 71 – 79.

Faulkner, S. P., and Patrick, W. H., 1992, Redox processes and diagnostic wetland soil indicators in bottomland hardwood forests: Soil Science Society of America Journal, v. 56, p. 856 – 865.

Soils at three sites in this study fit the hydric soil requirements with soil chromas of 2 or less and mottling, but did not experience reducing conditions during the three year monitoring period. Two of these sites contain soil with an aquic suborder, and one of these contains a gleyed B (Btg1 – 10YR3/1) horizon. Based on the O2 and Eh data, these three sites were determined to be nonwetland, and the qualitative hydric soil indicators were believed to be relict features of a previous moisture regime or the color was inherited from grayer parent material. One of the transitional sites contains soil with an aquic moisture regime that is not on the hydric soil list. The chroma colors are greater than 2, and the iron and manganese concentrations are below the 7.5 cm depth required for a hydric soil.

Faulkner, S. P., Patrick, Jr., W. H., and Gambrell, R. P., 1989, Field techniques for measuring wetland soil parameters: Soil Science Society of America Journal, v. 53, p. 883 – 890.

Covers procedures to measure soil redox potential, soil oxygen content, and hydrology, and methods of detecting ferrous iron.

Fiedler, S., and Fischer, W. R. 1994. Automatic longterm measurements of soil redox potentials under field conditions [German]. Zeitschrift fur Pflanzenernahrung und Bodenkunde. 157:305-308.

An inexpensive apparatus for the automatic longterm recording of soil redox potentials was developed. The apparatus was designed to cope with a high density of measuring points in both time and space. The device was used in 2 different redoximorphic soils (each with 6 horizons) over a period of 16 months (April 1992-July 1993). Readings were made at 1 hr intervals. Endurance measurements were conducted with 2-3 replicates per horizon at time intervals of 1 hr. The advantages of the system are described and it is compared to the use of a datalogger.

Genon, J. G., Hepcee, N., Delvaux, B., Dufey, J. E., Hennebert, P. A. 1994. Redox conditions and iron chemistry in highland swamps of Burundi. Plant & Soil 166:165-171.

The influence of organic C and soil redox conditions on the release of iron from Fe bearing minerals was investigated in highland swamps of Burundi. Data on pe-pH pairs distribution and oxalate dissolution suggested that Fe2+ activity was controlled by poorly crystallized Fe(III)-oxide. Levels of KCl-extractable Fe (less than or equal to 220 cmolc/kg) from the Fe(III) pool were increased by flooding. Release of Fe was positively correlated with organic matter contents although in highly organic, peaty soils with a large CEC, levels of adsorbed Fe were relatively low. It was concluded that organic matter rich (>25%) peat soils present a lower Fe toxicity hazard to rice than soils of intermediate organic matter contents (10-25%).

Gillham, R. A., 1984, The capillary fringe and its effect on water table response: Journal of Hydrology (Amsterdam), v. 67, p. 307 – 324.

Good, B. J., Faulkner, S. P., and Patrick, Jr., W. H., 1986, Evaluation of green ash root responses as a soil wetness indicator: Soil Science Society of America Journal, v. 50, p. 1570 – 1575.

Gotoh, S., and Patrick, W. H., 1974, Transformation of iron in a waterlogged soil as influenced by redox potential and pH: Soil Science Society of America Proceedings, v. 38, p. 66 – 71.

‡Greenberg, W. A., 1994, Hydrology and morphology of a toposequence of three claypan soils in Central Texas: MS thesis, Texas A&M University, College Station, 148 p.

‡Griffin, R. W., 1991, A study of aquic conditions of seasonally wet soils on the coast prairie of Texas: Ph.D. dissertation, Texas A&M University, College Station, 314 p.

†Griffin, R. W., Wilding, L. P., and Drees, L. R., 1992, Relating morphological properties to wetness conditions in the Gulf Coast Prairie of Texas. pp 126-134 In Kimble, J. M., ed., Proceedings of the VIIIth International Correlation Meeting on Wetland Soils: USDA Soil Conservation Service, Washington, D. C.

The study found soils with episaturation, but with a lack of apparent reduction, which means the soil is not epiaquic. Redoximorphic features were also found in the lower sola of soils with episaturated conditions, but where neither saturation nor reduction were found during the study.

Guertal, W. R. and G.F. Hall, 1990. Relating soil color to soil water table levels. Ohio Journal of Science. 90:118-124.

According to Soil Taxomony, soil horizons with mottles that have a Munsell chroma of 2 or less, with a moist Munsell value of 4 or more, are saturated for some period of the year during which the temperature of the horizon is above 5 deg C, if the soil is not drained. Although soil scientists have been predicting depth to the water table for many years using depth to colours with 2 chroma or less, sufficient data have not been gathered to verify this relationship. As a result, the reliability of soil interpretations has suffered. This project was conducted on a glacial till plain toposequence containing three soils representative of those common throughout northwestern Ohio. Depth to the water table was measured for two years using piezometers. During part of the year, a water table was observed within 110 cm of the soil surface for the well drained Morley soil. The moderately well drained Glynwood soil had a water table that rose to within 60 cm of the soil surface. The Blount soil, somewhat poorly drained, had a water table within 15 cm of the soil surface. The data gathered suggests that the presence of colours with 2 chroma or less, reliably predicts the depth to the water table.

Hall, G.F. and C.G. Olson. 1991. Predicting variability of soils from landscape models. In Mausbach, M.J. and L.P. Wilding (eds), Spatial variabilities of soils and landforms. Soil Sci. Soc. Am. Special Publicaion no. 28. Madison, WI.

Hammermeister, D. P., Kling, G. F., and Vomocil, J. A., 1982a, Perched water tables in western Oregon: I. some factors affecting their development and longevity: Soil Science Society of America Journal, v. 46, p. 811 - 818.

This study was conducted on hillslopes in Oregon to research perched water tables and their relationships to convex and concave hillside shape and their differences in lower and upper slope positions. The soils in the study area were Xeric Haplohumult, Ultic Haploxeroll, Aquultic Haploxeroll, and Ultic Agrixeroll with depth to the top of the boundaries ranging from 30 to 120 cm. The authors found that a perched water table did not develop at two sites, which they associated to the highly permeable soil and upper rock mantle at these localities. The study found that subsurface flow is a major contributor to the duration of perched water tables in lower slope positions (both convex and concave regions). In comparing perched water tables in a lower concave region of slope versus an upper convex region of slope, they found that the perched water tables have a longer duration in the lower concave region because of an impermeable lower B and C horizon and from subsurface flow from upslope regions of the hillslope. Also, the perched water tables developed faster in the A and B horizons in the lower region.

Hammermeister, D. P., Kling, G. F., and Vomocil, J. A., 1982b, Perched water tables on hillsides in western Oregon: II. preferential downslope movement of water and anions: Soil Science Society of America Journal, v. 46, p. 819 - 826.

This article is another study conducted at the same locality as the previous article by these authors. Maximum rates of downslope anion movement varied greatly between sites. These rates ranged from around 0.5 cm/h to 550.0 cm/h. It is also believed that these maximum rates are underestimated because the vacuum groundwater samplers probably did not sample the some of the continuous macropores, which would have faster rates. They determined that preferential flow occurred through macropores in the saturated horizons and probably occurred in unsaturated horizons. The voids interconnect the A, B, and C horizons and lower depths. These continuous macropores range in size from around 10 cm to several tenths of a millimeter.

†Hudnall, W. H. Wilding, L. P. 1992. Monitoring soil wetness conditions in Louisiana and Texas. pp135-147 In Kimble, J. M. (ed) Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): characterization, classification, and utilization of wet soils, Louisiana and Texas, October 6-21, 1990. Soil Conservation Service (SCS), Department of Agriculture, Washington, USA.

Data from ten sites in Louisiana and 14 sites in Texas, USA, were used for the following objectives: (1) to summarize the approach, conclusions, and problems associated with the proposed definition of the aquic moisture regime and criteria to be used to determine whether soils are epiquic or endoaquic saturated; (2) to discuss the processes responsible for soil redoximorphic features; (3) to show how laboratory analyses can be merged with morphological data to predict the duration and periodicity of saturation and reduction; and (4) to discuss the difficulties encountered in the measurement of these parameters.

†Hudnall, W. H., Tiarks, A. E., and Patterson, W. B., 1993, Field studies of hydric soils: system design and considerations: Agronomy Abstracts, v. 85, p. 350.

Hurt, G. W., and Brown, R. B., 1995, Development and application of hydric soil indicators in Florida: Wetlands, v. 15, n. 1, p. 74 – 81.

Just because a soil is on the hydric soil list does not necessarily mean it is hydric. A loamy soil with a water table from 0-60cm can be on the hydric soil list, but only those with a water table between 0-30cm would be hydric. Hydric soil indicators should be developed for different areas because of different environments. In Florida, α-α- dipyridyl is not useful because the soils are low in iron.

‡Hurt, G. W., Whited, P. M., and Pringle, R. F., eds., 1996, Field Indicators of Hydric Soils in the United States: U. S. Department of Agriculture, Natural Resources Conservation Service, Fort Worth.

‡Hurt, G. W., Whited, P. M., and Pringle, R. F., eds., 1998, Field indicators of hydric soils in the United States: a guide for identifying and delineating hydric soils, version 4.0: Ft. Worth, TX, U. S. Department of Agriculture, National Resources Conservation Service, 30 p.

Developed by the NRCS for identifying hydric soils in the field based on soil color, texture, and redoximorphic features.

†International Rice Research Institute, 1985, Wetland Soils: Characterization, Classification, and Utilization: Proceedings of the International Rice Research Institute, March 26-April 5, 1984, Philippines.

Jacob, J.S., R. W. Griffin, W.L. Miller, and L.P. Wilding. 1997. Aquerts and Aquertic soils: A querulous proposition. In Aquic Conditions and Hydric Soils: The Problem Soils. Soil Science Society of America Special Publication no. 50. Madison, Wi.

James, H. R. Fenton, T. E. 1993. Water tables in paired artificially drained and undrained soil catenas in Iowa. Soil Science Society of America Journal 57: 774-781.

Water table fluctuations and the influence of artificial drainage on soil morphology were studied in north-central Iowa, USA. Water table depth and duration for one artificially drained and one undrained soil sequence on paired landscapes were measured. Landscapes were composed of six soil series: Clarion (Typic Hapludolls); Nicollet (Aquic Hapludolls); Webster (Typical Haplaquolls); Canisteo (Typic Haplaquolls); Harps (Typic Calciaquolls); and Okoboji (Cumulic Haplaquolls). Morphological properties of paired soil series were compared and related to water fluctuations. Soil morphology and water table depth and duration were highly correlated for the Aquolls in the undrained traverse but not in the artificially drained traverse. Webster, Canisteo, Harps, and Okoboji in both traverses have endosaturation, contain redoximorphic features, and meet the criteria of hydric soils. In the undrained traverse, Okojobi meets the additional requirements of vegetation and hydrology, and qualifies as a wetland, while Webster, Canisteo, and Harps classify as farmed wetlands. Webster, Canisteo, Harps, and Okoboji in the artificially drained traverse met the criteria of prior converted cropland. A drained phase should be recognized for Webster, Canisteo, Harps, and Okoboji. It is suggested that all soils with water table depths modified by artificial drainage have a separate soil interpretation record and be recognized as a drained phase. This would reduce confusion in the use of data recorded on the soil interpretation record.

Johnston, C. A. Pinay, G. Arens, C. Naiman, R. J. 1995. Influence of soil properties on the biogeochemistry of a beaver meadow hydrosequence. Soil Science Society of America Journal 59:1789-1799.

Soils derived from glacio-lacustrine and fluvioglacial parent materials in northern Minnesota (USA) beaver (Castor canadensis) meadows (i.e. former beaver ponds that have drained and revegetated), were studied to: (i) describe soil morphology, (ii) analyse soil and solute chemistry, and (iii) statistically evaluate the relative influence of hydrology and soil type on solute chemistry. With decreasing depth to groundwater, soils in both hydrosequences were increasingly reducing; redox potentials were consistently negative in the Borosaprist. Differences in soil morphology associated with increasing wetness included: (i) increasing thickness of O and A horizons, (ii) decreasing thickness of the Bt horizon (glacio-lacustrine hydrosequence), and (iv) decreasing depth to redoximorphic features. In the glacio-lacustrine hydrosequence, depth to subsurface concn of oxalate-extractable Fe (more than or equal to 800 g/m3) decreased with increasing wetness. Two-way ANOVA indicated that differences in water chemistry among soils were due to moisture, parent material, and their interaction. Increasing moisture was associated with increased concn of Fe2+, Ca2+, and Mg2+ and decreased concn of SO4-S. Glacio-lacustrine soils contained higher concn of base cations (K+, Ca2+, and Mg2+) than did fluvioglacial soils, and so did their soil water. There were pronounced seasonal variations in cation concn and significant interannual differences for NH4-N, total N, and K+. Nitrate concn were consistently low and did not differ significantly among any of the groupings.

Khan, F. A., and Fenton, T. E. 1994. Saturated zones and soil morphology in a Mollisol catena of central Iowa. Soil Science Society of America Journal 58: 457-1464.

The status of water tables, groundwater hydrology and saturation zones were examined on selected Aquolls and Hapludolls in a Mollisol catena in Iowa, USA. Water table depths and precipitation were measured for a 10-yr period on 5 soils formed in glacial till or till-derived sediments. Water table depth, duration of saturation, morphological features, and recharge and discharge to groundwater varied with geomorphological position in the catena. Most soils in summit and shoulder positions (Hapludolls) were not saturated, had deeper water tables, maximum water table fluctuations and rich chromas without redoximorphic features in the B horizons. Soils on toeslopes and depressions (Aquolls) had the shallowest water tables, longest saturation times and B horizons with grey matrices, bright mottles and Fe-Mn concretions. Soils (Aquic Hapludolls) on backslope positions showed intermediate characteristics with redoximorphic features relating to the fluctuating water table depths, which were influenced by artificial tile drainage. Water table levels and calcite/dolomite ratios indicated that ephemeral recharge and discharge of groundwater occured in soils on lower landscape positions, while recharge was the dominant process in the soils of higher landscapes.

†Kimble, J. M., ed., 1992, Proceedings of the 8th International Soil Correlation Meeting (VIIIISCOM): Characterization, Classification, and Utilization of Wet Soils, USDA-SCS, National Soil Survey Center, Lincoln, Nebraska, p. 212 – 219.

Kralova, M., Masscheleyn, P. H., and Patrick, W. H., Jr. 1992. Redox potential as an indicator of electron availability for microbial activity and nitrogen transformations in aerobic soil. Zentralblatt fur Mikrobiologie 147:388-399.

The effects of soil redox potential on microbial respiration and nitrogen transformations were studied in a silt loam soil. Stirred aerated soil suspensions and soil-free water extracts simulated the behaviour of an aerobic soil and the soil solution, resp. Soil microflora in both systems differed in the amount of respirated CO<sub(2)> as well as redox potentials (Eh) under which they operated. The amount of CO<sub(2)> released was affected by temperature, pH, and the amount of water-soluble carbohydrates. Nitrogen mineralization occurred at lower redox values than nitrification. In the soil suspension, redox values of 400-500 mV favoured ammonification, while at the higher redox values (500-600 mV), nitrification predominated. In the soil-free water extract, N-mineralization occurred at redox values of 350-380 mV, and both nitrates and nitrites appeared. Increasing redox potential (400-450 mV) increased the amount of nitrates. Ammonium and nitrites remained detectable.

‡Lambert, C. C., 1998, Soils and groundwater monitoring of a seasonal wetland, West Beach, Galveston, Texas: unpub. Master's thesis, Baylor University, Waco, Texas, 135 p.

Latshaw, G. J., and Thompson, R. F., 1968, Water table study verifies soil interpretations: Journal of Soil and Water Conservation, v. 23, p. 65 – 67.

‡Lindbo, D. L. Brigham-Grette, J. Veneman, P. L. M. 1994. Depositional and post-depositional features in the late Illinoian and late Wisconsinan tills of Massachusetts. pp 75-95 In Whole regolith pedology: Proceedings of a symposium, Minneapolis, Minnesota.

Morphological features in undisturbed Wisconsian (Upper Till) and Illinoian (Lower Till) aged tills in central Massachusetts, USA were investigated to relate till morphological features to soil development, hydrology and potential impact on land use. Observations at 12 exposures showed that both tills contain many morphological examples of current and inherited post-depositional weathering and water movement. It is suggested, from observations of oxidation along joints and fractures in both oxidised and unoxidised facies in the Lower Till, that water movement and redox processes are ongoing and occur several metres below the surface. An increase in amount and development of argillans and redoximorphic features within the solum developed on the oxidised Lower Till was observed and it is suggested that much of the modern soil morphology is due to pedogenesis, not inherited from the till. It was concluded that the brown matrix, oxidized mineral grains, and increased fissility in the oxidised Lower Till result from post-depositional subaerial weathering. Redox features were also observed in the Upper Till generally at textural transitions, but unweathered deeper portions of the Upper Till contain few or no argillans, although these are common in the solum developed in the Upper Till. It was concluded that standard soil survey terminology were appropriate for this study below the solum.

Lindbo, D. L., Rhoton, F. E., Bigham, J. M., Hudnall, W. H., Jones, F. S., Smeck, N. E. Tyler, D. D. 1995. Loess toposequences in the Lower Mississippi River Valley: I. Fragipan morphology and identification. Soil Science Society of America Journal 59:487-500.

Morphological differences between nonfragipan (Memphis [fine-silty, mixed, thermic Typic Hapludalf]) and fragipan (Loring [fine-silty, mixed, thermic Fraguidalf]) and Grenada [fine silty, mixed, thermic Glossic Fraguidalf] soils occurring on the same landscape in the Lower Mississippi Valley, USA, were evaluated. Five representative sites were selected based on published soil survey maps and landscape relations. Morphological characteristics associated with fragipans were present in all the Loring and Grenada pedons. The most obvious and consistent indicators of a fragipan were vertical grey seams and associated redoximorphic features. Because brittleness is subjective and a function of moisture content, it is not always a reliable indicator of fragipan occurrence. Root distribution was not a useful indicator since deep-rooted vegetation did not occur on these soils. Several Memphis pedons exhibit protofragipan development, but based primarily on the organization of grey seams, these should not be considered

Mausbach, M.J., and J.L. Richardson. 1994. Biogeochemical processes in hydric soil formation. Current Topics in Wetland Biogeochemistry. 1: 68-127.

An excellent review article detailing landscape and microsite processes.

McDaniel, P. A., and Falen, A. L. 1994. Temporal and spatial patterns of episaturation in a Fragixeralf landscape. Soil Science Society of America Journal 58:1451-1457.

Perched zones of saturation above a fragipan in a 1.4-ha field on Fragixeralf soil in northern Idaho, USA, were monitored using 64 piezometers arranged on a 15-m grid spacing. During the mild wet winter of 1991-1992, episaturation lasted from early December until May, representing 8.4-15.4 cm of water and accounting for 34-43% of seasonal precipitation. After the colder snowy winter of 1992-1993, when the snow pack began to melt in early March, >20 cm of water was present in the saturated zone above the fragipan, representing 58% of seasonal precipitation. Soil morphological characteristics and elevation were correlated with quantities of perched water present on sampling dates when potential evapotranspiration was low. For all sites the quantity of perched water was most strongly correlated with the thickness of the zone above the fragipan which exhibited redoximorphic features such as iron and manganese accumulations and mottles, while depth to fragipan was less strongly correlated.

McGowen, J.H., L.F. Brown, Jr., T.J. Evans, W.L. Fisher, and C.G. Groat. 1976. Environmental Geologic Atlas of the Texas Coastal Zone – Bay City – Freeport Area. Bureau of Economic Geology. The University of Texas. Austin.

McKeague, J. A., 1965, Relationship of water table and Eh to properties of three clay soils in the Ottawa Valley: Canadian Journal of Soil Science, v. 45, p. 49 – 62.

Megonigal, J. P. Faulkner, S. P. Patrick, W. H. 1996. The microbial activity season in southeastern hydric soils. Soil Science Society of America Journal 60:1263-1266.

The portion of the year when soils are >5 deg C at 50 cm is defined as the microbial activity season and the term growing season is reserved for plant activity. In the technical criteria for hydric soils, specific microbial activity season months were assigned to each of the soil temperature regimes. The objectives were to determine the portion of the year when southeastern US hydric soils are <5 deg C at 50 cm and to estimate rates of microbial activity during winter flooding. Thirty four bottomland hardwood forest soils in South Carolina, Louisiana, and Mississippi were <5 deg C at 50 cm during a period of 2 to 3 yr. Winter rates of soil respiration and O2 consumption (1.6 ml O2 litres\air per d) are sufficient to cause anoxia in saturated soils. Based on the available data, a 12-month microbial activity season for southeastern bottomland hardwood forests was suggested. Additional data will be necessary to determine the relationships between temperature, soil saturation, and development of redoximorphic features.

Megonigal, J. P., Patrick, Jr., W. H., and Faulkner, S. P., 1993, Wetland identification in seasonally flooded forest soils: soil morphology and redox dynamics: Soil Science Society of America Journal, v. 57, p. 140 – 149.

Mendelssohn, I. A., Kleiss, B. A., and Wakeley, J. S., 1995, Factors controlling the formation of oxidized root channels: a review: Wetlands, v. 15, n. 1, p. 37 – 46.

This article provides a good overview of studies on the formation of oxidized root channels. It concludes that the most important abiotic factor is the availability of soil iron, and the most important biotic factor is the oxidizing capacity of plant roots. The total oxidizing capacity is related to radial oxygen loss, oxygen from root metabolism, and rhizosphere bacteria. The factors that control iron plaque formation are: “1. iron concentration and form, 2. soil oxygen demand and the variables (fertility and microbial activity) that control it, 3. soil texture and organic matter content, and 4. soil pH.” Studies have found that as the iron concentration in solution increases so to does the iron deposition. There is also more iron deposition when the iron in solution is in the form of ferrous iron (Fe^{2+}). However, if the pH is 4.0 or lower iron in the ferric form (Fe^{3+}) can deposit more plaque than the ferrous form. Soil iron bound to carbonates has shown to cause more plaque formation than other iron fractions. To a certain level, a more positive soil Eh produces more plaque formation. A highly negative Eh does not produce iron plaque. As the clay content of soil increases, less plaque is formed. This relationship may be from iron remaining bound to the clay. However, it has also been noted that more iron plaque accumulates in a fine sandy loam rather that in a pure sand. Studies also show that iron plaque deposition decrease at pH’s of 5.0 and greater, but increase from about 3.0 to 4.6 (5.3 in another study). The theory is that at a higher pH there is less soluble iron in solution.

‡Mendelssohn, I. A., 1993, Factors controlling the formation of oxidized root channels: a review and annotated bibliography: U. S. Army Corps of Engineers Waterways Experiment Station, Wetlands Research Program Technical Report WRP-DE-5, Vicksburg, MS, A11 p.

‡Mitsch, W. J., and Gosselink, J. G., 1993, Wetlands, 2nd edition, Van Nostrand Reinhold, New York

Mokma, DL, and SW Sprecher. 1994a. Water table depths and color patterns in Spodosols of two hydrosequences in Northern Michigan, USA Catena 22:275-286

Relationships between soil color patterns and depth and duration of water tables were studied using piezometers in two hydrosequences of Spodosols. Color indices developed for Udalfs, Aqualfs, Aquolls and Aquepts were not helpful in relating soil color patterns in these Spodosols to water saturation. Redoximorphic features were identified with difficulty in most saturated horizons. Low Fe content in spodic horizons was a good indicator of water saturation. Landscape position was also useful in ranking length of saturation in the soils of each hydrosequence.

Mokma, DL; and SW Sprecher. 1994b. Water table depths and color patterns in soils developed from red parent materials in Michigan, USA. Catena, 22:287-298.

Relationships between soil color patterns and depth and duration of water tables were studied using piezometers in three soil hydrosequences that had developed from different colored parent materials. Correlation coefficients relating color indices and percent of time saturated were less for the hydrosequences developed from red (5YR and 7.5YR) parent materials (5YR materials are lacustrine deposits, 7.5YR materials are till) than those developed from 10YR parent materials (till). A modified color index was a better predictor of water saturation in soils developed from 5YR parent materials. The presence of hematite in the soils developed from red parent materials is thought to cause these soils to be less gray than would be predicted from landscape position and piezometer data. Iron mineralogy, at least partially, explains why hue was not as important as chroma in predicting water saturation in these hydrosequences. Iron contents in high chroma mottles were greater, whereas, those of low chroma mottles were l ess than those in matrices, suggesting Fe has moved in saturated horizons of these soils. Insufficient low chroma colors was the primary reason for misclassification of soils developed from red parent materials and is thought to be related to the presence of hematite.

Moore, I.D., P.E. Gessler, G.A. Nielson, and G.A. Peterson. 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal. 57:443-452

Soil wetness highly correlated with slope attributes.

Moore, I.D., R.B. Grayson, A.R. Ladson. 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes 5:3-30.

Topographical attributes can be used as indirect measures of the named applications. Assesses the utility of digital elevation models (DEMs) for displaying terrain characteristics. Used 30-m DEM to construct map of slope classes (%).

Pavlick, H.F. and F.D. Hole. 1977. Soilscape analysis of slightly contrasting terrains in southeastern Wisconsin. Soil Sci. Soc. Am. J. 41:407-413.

Pennock, D. J., Kessel, C. van, Farrell, R. E., and Sutherland, R. A. 1992. Landscape-scale variations in denitrification. Soil Science Society of America Journal 56:770-776.

This study was conducted to examine landscape-scale patterns of denitrification and the soil properties that control these patterns. A 110 by 110 m sampling grid was established in an irrigated field in an aridic Boroll (Brown Chernozemic) soil in Saskatchewan, Canada. The measured soil properties were correlated to the derived landform elements at the site to determine landscape-scale patterns and relationships. The soil properties occurred in one of three spatial patterns: (i) a random pattern for mineral N; (ii) a diagonal pattern for pH, soluble organic and inorganic C, and total N; and (iii) a depression-centred pattern for denitrification, bulk density, moisture, respiration, and redox potential. Statistically distinct rates of denitrification were associated with the different land-form elements: rates were lowest in the shoulder elements, intermediate in the footslope and level-convex elements, and highest in the level-concave elements. Hot spots of denitrification activity, i.e., sampling sites with denitrification rates identified statistically as outliers, were all associated with the level elements and, predominantly, the level-concave elements. For the whole data set, denitrification was most highly correlated with volumetric water content (r<sub(s)> = 0.448<sup(**)>) and soil redox potential (r<sub(s)> = -0.335<sup(**)>). In the level landform elements, volumetric water content was the soil variable most highly correlated with denitrification; in the shoulder and footslope elements, respiration and bulk density, resp., were most highly correlated. These data indicate that: (i) topography has a strong influence over in situ denitrification, and (ii) different controls are at work in the various landform elements.

‡Pettry,D.E., R.E.Switzer, R.B.Hinton. 1995 Temporal water table levels and characteristics of representative Mississippi soils. Bulletin - Mississippi Agricultural and Forestry Experiment Station(MAFES), Mississippi State University (MSU), Mississippi State, USA No. 1027, 88 pp.

Soil water table depths and precipitation were studied for 25 soil mapping units representing 23 soil series and 5 soil orders in 4 major land resource areas in Mississippi, USA, over periods of 2.5-10 years. Morphological, physical, chemical, and hydrological parameters were quantified for each soil. The soil water tables were extremely dynamic features and exhibited wide fluctuations. Generally, water tables were highest in winter and deepest in the summer and autumn. Seasonal fluctuations commonly exceeded 4 feet. Well-drained soils had a shorter period of high water levels and a longer period of low water levels than poorly-drained soils. Water table depths generally exceeded 4 feet in all drainage classes during summer and autumn, and commonly exceeded 8 feet. It was difficult to distinguish the different drainage classes on the basis of water table depths. Low chroma matrix and mottle colours and concretions often had no apparent relationships with average water table depths.

Pickering, E. W., and Veneman, P. L. M., 1984, Moisture regimes and morphological characteristics in a hydrosequence in central Massachusetts: Soil Science Society of America Journal, v. 48, p. 113 – 118.

The purpose of this study was to determine the relationship between mottling and moisture regime in sandy, poorly structured soils and to determine the effects of a fragipan on the hydrology and mottling characteristics. The soils in this study were mostly Fragiochrepts and a few Humaquepts. Soils with the highest chromas occurred in the moderately well-drained soils, which were located in the midslope position. The moderately well-drained soil contained mottling in the BC horizons, but not the upper Bw. However, groundwater monitoring determined the water table to occur in the Bw horizons at times. It was concluded that the high water table occurred during soil temperatures too low for microbial activity and thus the reduction of iron to occur. The article concluded that soil morphology appears to adequately indicate the saturated conditions of the soils except in the moderately well-drained soil.

Rabenhorst, M. C., Bell, J. C., and McDaniel, P. A (eds.), 1998, Quantifying Soil Hydromorphology, SSSA Special Publication No. 54, Soil Science Society of America, Madison

A collection of 14 refereed papers on various aspects of soil water table assessment. More geared toward the evaluation of hydric soils, but most of the papers have some relevance with respect to OSSF unsuitably wet soils.

Ransom, M. D., and Smeck, N. E., 1986, Water table characteristics and water chemistry of seasonally wet soils of southwestern Ohio: Soil Science Society of America Journal, v. 50, n. 5, p. 1281 – 1289.

Found variations in soil water pH, Eh, and Fe(II) with the seasons. Through the use of □, □' – dipyridyl and measurements of Fe(II) and Fe(III) concentrations, they concluded that iron reduction occurs primarily in microenvironments within the soil water system.

‡Rehage, J. A., 1985, Hydrology and genesis of claypan soils in East Central Texas: Ph.D. dissertation, Texas A&M University, College Station.

Rennolls-K; Carnell-R; Tee-V. 1980 A descriptive model of the relationship between rainfall and soil water table. Journal of Hydrology 47: 103-114. 1980.

Richardson, J. L., and R.B. Daniels, 1993. Stratigraphic and hydraulic influences on soil color development. Pp 109-125 In Bingham, J.M. and Ciolkosz, E.J. (esd). Soil color: proceedings of a symposium, San Antonio, Texas, Soil Science Society of America, Inc, Madison, WI, USA: 1993.

Colour in landscapes has been used for decades as a basic tool for assessing soil drainage. Parent material governs the types of minerals and the textural distribution of soils and sediments present in a landscape. Minerals colour the soil and often reflect the influence of texture and soil drainage, aeration, and configuration of the water table. Hydrological conditions (notably recharge, flowthrough, and discharge) influence leaching, reduction-oxidation, and the accumulation of precipitates of Fe and Ca. The water table position and fluctuation are also affected. Geomorphic setting includes climatic factors and general water circulation in open or closed drainage systems. A generalized soil mottle sequence is presented that reflects the morphological impact of alternating reducing and oxidizing conditions (redoximorphic features) proceeding from dry to very wet landscape positions: (i) unmottled peds with high chroma; (ii) low chroma colours on ped edges with little Fe removal; (iii) distinct albans or gray areas that represent Fe removal from low chroma areas on ped edges or from around root channels with a kneaded colour of 3 chroma; (iv) thick albans resulting from Fe removal around all macropores such as roots and ped faces, abundant Fe-Mn concretions in ped interiors and a kneaded colour of 2 chroma or less; and (v) zones of Fe accumulation (reddish colours or furrows) around ped faces or root channels or gley coloration in ped interiors.

‡Schlesinger, W.H. 1991. Biogeochemistry: An analysis of global change. Academic Press. San Diego.

‡Schuy, D. M., 1998, Early changes in a recently constructed riparian floodplain wetland -- Lee County, Texas: unpub. Master's thesis, Baylor University, Waco, Texas, 164 p.

Schwertmann, U. 1993. Relations between iron oxides, soil color, and soil formation. Pp 51-69 In Bingham, J.M. and Ciolkosz, E.J. (eds.) Soil color. Soil Science Society of America Special Publication, Madison, WI, USA

Iron oxides are useful field indicators of pedogenic environments for three reasons: (i) they include several minerals, (ii) these minerals have different colours, and (iii) the type of mineral formed is influenced by the environment. Therefore, recognizing the Fe-oxide mineral in the field by its colour can yield information about pedogenesis. Haematite-containing soils (usually with associated goethite) have mostly hues between 5YR and 10R, whereas goethite-containing soils with no haematite have hues between 7.5YR and 2.5Y. Orange colours with a hue of 7.5YR and a value of more than or equal to 6 are often due to lepidocrocite. Ferrihydrite can be distinguished from goethite by its more reddish hue (5-7.5YR) and from lepidocrocite by its lower value (less than or equal to 6). These mineral-specific colours, however, also vary somewhat with concentration, crystal size, degree of cementation, and possibly isomorphous substitution. Poorly crystalline goethite, lepidocrocite, and ferrihydrite may have lower values than better crystalline specimens, and cementation also leads to lower values. Small haematite crystals are bright red (2.5YR-10R), whereas the colour of larger crystals or crystal aggregates may reach into the redpurple (RP) range.

This chapter reviews the relationships between Fe oxides and soil colour and also briefly considers the occurrence and pedogenetic implications of these minerals.

Schwertmann, U., and Thalmann, H., 1976, The influence of [Fe (II)], [Si], and pH on the formation of lepidocrocite and ferrihydrite during oxidation of aqueous FeCl2 solutions: Clay Minerals, v. 11, p. 189 – 200.

Shovic, H.F. and C. Montagne. 1985. Application of a statistical soil-landscape model to an Order III wildland soil survey. Soil Sci. AM. J. 49:961-968.

Simonson, G. H., and Boersma, L., 1972, Soil morphology and water table relations: II Correlation between annual water table fluctuations and profile features: Soil Science Society of America Proceedings, v. 36, p. 649 – 653.

The depth to mottling was not a consistent indicator of the degree of waterlogging at depths above the mottled horizon. Consistent relationship was also not found between Munsell values and water table regimes for the complete drainage sequence in the study.

Smith-S-M; Beecroft-F-G. 1983. Soil morphology and water regimes in 3 Recent alluvial soils on the Taieri Plains, South Island, New Zealand. New Zealand Journal of Science 26:403-411.

An assessment of soil morphology and water regimes of 3 recent alluvial soils on the Taieri Plains, South Island, New Zealand, is described. The pattern of soil water table fluctuations follows a yearly sigmoidal cycle. With increased duration of saturation, mottles tend to decrease in size and abundance and have more diffuse boundaries. The matrix colours of the soil horizons, in conjunction with the nature of the mottles, broadly reflect the different moisture regimes at the 3 sites although the distinction between imperfectly and poorly drained soils is not clear. Moisture regimes as used by the Soil Survey of England and Wales successfully separated the soils into distinctive (quantified) classes. Soil Taxonomy separated the 2 wetter members of the sequence, but does not quantify the duration of saturation. Further research is needed to develop a system of soil moisture regime classification in New Zealand if soil survey interpretations are to be expanded.

†Sobecki, T. M. Herriman, R. C. Schultze, R. F. 1992. Hydric soils in xeric moisture regimes: an interpretations example. Pp235-239 In Kimble, J. M. (ed) Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): characterization, classification, and utilization of wet soils, Louisiana and Texas, October 6-21, 1990. Soil Conservation Service (SCS), US Department of Agriculture, Washington, USA.

The difficulty in consistent application of hydrological, vegetative, and soil criteria in assessing wetlands of the Sacramento Valley, California, USA is explained. It is thought that the thermic xeric climate retards the formation of redoximorphic features, despite abundant OM and deficient O<sub(2)>, by inhibiting anaerobic soils microorganisms. The implications for soil interpretations and soil classification are discussed.

†Soil Conservation Service, 1990, VIII International soil correlation meeting classification and management of wet soils Louisiana and Texas, USA: guidebook for Texas: Soil Management Support Services, 269 p.

‡Soil Survey Staff, 1976. Soil Survey of Harris County, TX. U.S. Dept. of Agriculture. U.S. Govt. Print. Office. Washington, D.C.

‡Soil Survey Staff, 1998, Keys to Soil Taxonomy, 8th edition, U.S. Dept. of Agriculture-Natural Resources Conservation Service, Washington, D. C. Printing Press, Washington, D.C.

Provides definitions and indicators of soil moisture regimes, aquic, ustic, udic, and oxyaquic, and rules to soil taxonomy.

‡Soil Survey Staff. 1993. Soil Survey Manual. United States Department of Agriculture Handbook No. 18. U.S. Govt. Print. Off. Washington, D. C.

‡Sposito, G. 1989. The Chemistry of soils. Oxford University Press. New York.

‡Starowitz, S. M., 1994, A Study of Aquic Conditions in a Microtoposequence of Seasonally Wet Soils on the Texas Coast Prairie, unpub. Master's Thesis, Texas A&M University, College Station, 176 p.

Studied three Alfisols in a mound, intermound, and depression topographic positions. Low oxidation-reduction potentials occurred during saturation periods, and imply iron reduction in soil in each landscape position. Fe-Mn nodules and concretions in the mound site above 50 cm were determined to be relict features of previously existing moisture conditions. Perched water tables were found in both the intermound and depression sites. These sites also had lower permeability associated with moderately fine textures in the subsoil and for the intermound, high exchangeable sodium levels. The study concluded that redoximorphic features within the perched water table region reflect current and previous reducing conditions. The piezometer and tensiometer data typically agreed on determining saturated conditions, but varied during wetting and drying cycles. Similarly, some of the replicates were significantly different from the others during wetting and drying cycles. These variations may be related to: desiccation cracks, crayfish activity, Eh errors from equipment failure, cattle disturbing the monitoring equipment, and instrumentation shifting from settling of the soil following installation.

Stolt, M. H., Ogg, C. M., and Baker, J. C. 1994. Strongly contrasting redoximorphic patterns in Virginia Valley and Ridge paleosols. Soil Science Society of America Journal 58:477-484.

Soils with bisequel morphology and classified as Typic or Plinthic Paleudults are common in the Virginia Valley and Ridge Province, USA. Horizons in the older materials have redoximorphic features that are strongly contrasting with respect to colour and distinctness of boundary. The physical and chemical properties of these horizons were examined to describe the strongly contrasting redoximorphic patterns (SCRP) and investigate their genesis. Two types of SCRP occur. In both types, redox concn have Munsell colours of 2.5YR 3/6, 4/6 or 3/2. In one case depletion features (10 YR 5/6 or 6/2) are randomly distributed throughout the horizon. These horizons are dense (bulk density of 1.75 g/cm3), which restricts water movement and promotes Fe segregation. In the other type of SCRP, most Fe concn, depletions and planar voids were oriented parallel to the soil surface. These soils have a fluctuating water table. Dithionite-extractable Fe ranged from 70 g/kg in redox concn to 4 g/kg in adjacent depletion features. Goethite occurred in both redox concn and depletion clay fractions. Haematite only occurred in the redox concn clay fractions. Depletion features had a lower coarse:fine ratio (separated at 20 micro m), more oriented clay, and 10 to 20% more clay than associated redox concn. Horizons with SCRP were dominated by nodules and masses in ped interiors and Fe depletion features along voids. Thus, Fe was primarily reduced along voids and moved into the matrix. Horizons with a fluctuating water table also contained Fe-rich pore linings. Iron is concentrated on these surfaces because these pores are the first to drain as the water table recedes.

Thompson, J. A., and Bell, J. C., 1996, Color index for identifying hydric conditions for seasonally saturated mollisols in Minnesota: Soil Science Society of America Journal, v. 60, p. 1979 – 1988.

Suggests comparing chroma changes with landscape position to better ascertain wetness of the soil. They developed a Profile Darkness Index (PDI) as an alternative to color index because of the high organic matter content in Minnesota soils.

Thompson, J. A., and Bell, J. C., 1998, Hydric conditions and hydromorphic properties within a Mollisol catena in southeastern Minnesota: Soil Science Society of America Journal, v. 62, p. 1116 – 1125.

Discusses problems with using iron based redox features in soil with high pH. Iron may not easily be reduced in the high pH soils, even though the site is saturated (and probably anaerobic) for long periods of time. Also supports the idea that subsoil color can be a poor indicator of saturated and reduced conditions.

Thompson, J.A., J.C. Bell, and C.A. Butler. 1997. Quantitative soil-landscape modelling for estimating the areal extent of hydromorphic soils. Soil Sci. Soc. AM. J. 61:971-980.

A Profile Darkness Index (PDI) was developed to assist in wetand delineations in the Mollisol regions of the Upper Midwest. Variability in slope gradient, profile curvature, and elevation above the local depression explained most of the variability of the PDI.

‡Thorp, J., and Gamble, E. E., 1972, Annual fluctuation of water levels in soils of the Miami catena, Wayne County, Indiana: Science Bulletin 5, Earlham College, Richmond, IN.

Troeh, F.R. 1964. Landform parameters correlated to soil drainage. Soil Sci. Soc. Am. J. 28:808-812.

†Tucker, R. J. Drees, L. R. Wilding, L. P. 1994. Signposts old and new:active and inactive redoximorphic features; and seasonal wetness in two Alfisols of the gulf coast region of Texas, USA. pp 149-159 In Ringrose-Voase, A. J. Humphreys, G. S. (eds). Soil micromorphology: studies in management and genesis. proceedings of the Ninth International Working Meeting on Soil Micromorphology, Townsville, Australia, July 1992. Elsevier Science Publishers, Amsterdam, Netherlands:

Two Alfisols in Texas, USA were examined to see if redoximorphic features were relict or contemporary. Relict features included: Fe-Mn nodules which had sharp boundaries to the matrix or were covered by clay coatings; mangans, skeletons and colour depletion zones which did not relate to current voids. Contemporary features included: macroscopic sand-silt coats on ped faces, nodules undergoing dissolution as shown by sand grains protruding from the nodules and diffuse boundaries to the matrix; pore linings, patches of iron and soft agglomerations of iron. Relict and contemporary features could occur in one horizon. Saturation was more pronounced where nodules were dissolving and sand silt coats were evident. nodules were dissolving in areas with little saturation which suggested that rare very wet periods may contribute more to saturation and reduction.

Veneman, P. L. M., Spokas, L. A., and Lindbo, D. L., 1998, Soil moisture and redoximorphic features: a historical perspective. Pp1-23 In Quantifying Soil Hydromorphology, Soil Science Society of America Special Publication No. 54, Madison, Wisconsin.

Provides an overview of studies pertaining to redoximorphic features, hydric soils, and aquic moisture regimes.

Veneman, P. L. M., Vepraskas, M. J., and Bouma, J., 1976, The physical significance of soil mottling in a Wisconsin toposequence: Geoderma, v. 15, p. 103 – 118.

‡Vepraskas, M. J., 1994. Redoximorphic features for identifying aquic conditions. Technical Bulletin 301: North Carolina Agricultural Research Service, North Carolina State University, Raleigh.

Explanation of types of redoximorphic features and how they form. The manual also discusses the differences in identifying relict from contemporary features.

Vepraskas, M. J., and Bouma, J., 1976, Model experiments on mottle formation simulating field conditions: Geoderma, v. 15, p. 217 – 230.

Vepraskas, M. J., and Sprecher, S. W., 1997, Aquic Conditions and Hydric Soils: The Problem Soils, SSSA Special Publication No. 50, Soil Science Society of America, Madison, 156 p.

Many of the “problem” soils are problems because they do not exhibit the color patterns one would expect given the length of measured saturation events. Required reading for on-site evaluators.

‡Vepraskas, M. J., Richardson, J. L., Tandarich, J. P., and Teets, S. J., 1995, Development of redoximorphic features in constructed wetland soils: Wetlands Research, Inc., Technical Paper No. 5, 12 p.

Found redox depletions and pore linings to start forming after a single seven day inundation event in soil with soil organic matter greater than 3%. Redox features did not form in soils with organic matter less than 1.5%.

Vepraskas, M. J., Richardson, J. L., Tandarich, J. P., and Teets, S. J., 1999, Dynamics of hydric soil formation across the edge of a created deep marsh: Wetlands, v. 19, n. 1, p. 78 – 89.

Study on hydric soil formation in the landscape positions of: in the marsh, along the edge of the marsh, in a transition zone to the upland, and in the upland. Detailed soil profile descriptions were conducted twice a year for three years. Field indicators developed by iron reduction developed in the marsh and edge of marsh positions and in some parts of the transition zone. The most consistent indicator for determining hydric soil was a depleted matrix, which develops from the reduction and removal of iron. States that even if a NRCS field indicator is not present, the soil may still be hydric. Changes in soil color were observed within three years of creation of the marsh. However, the amount and degree of color change varied with landscape position and from three to five years after marsh creation. Soils in all landscape positions contained redoximorphic features at some depth, but only soils in the marsh and edge of marsh positions reacted positively to alpha-alpha -dipyridyl dye.

‡Wakeley, J. S., Sprecher, S. W., and Lynn, W. C., eds., 1996, Preliminary investigations of hydric soil hydrology and morphology in the United States: U. S. Army Corps of Engineers Wetlands Research Program, Washington, D. C., 162)

Review of the studies occurring in Alaska, Indiana, Louisiana, Minnesota, New Hampshire, North Dakota, Oregon, and Texas for the wet soils monitoring project. The research in the Texas Gulf Coast determined that 1. saturation does not always mean the conditions are anaerobic, 2. Reduced conditions are microsite specific and difficult to accurately measure by traditional means, 3. Soil color patterns may reflect relict wet conditions, and 4. Agricultural processes alter the soil hydrologic conditions. The study also found it difficult to classify soils because of the differences in aquic condition criteria and hydric status criteria.

Walker, P.H., G.F. Hall, and R. Protz. 1968. Relation between landform parameters and soil properties. Soil Sci. Soc. Am. J. 32:102-104.

Xu J. Z., and Tang, S. J. 1994. Study on redox features of calcareous purple soils after waterlogging. [Chinese]. Acta Pedologica Sinica 31:119-129.

The redox reaction of calcareous purple soils after waterlogging were studied by a simulated incubation test. Results showed that calcareous purple soils (Calcic) did not develop a strongly reducing status because of the contents of CaCO3 and active iron of soil when compared with haplic purple soils and dystric purple soils. Different organic substances had different influences on soil reduction intensity. The intensity factor (redox potential) was highly correlated with the content of reducing materials and was consistent with the growth of rice. When Eh<-100 mV and the total amount of reducing substances > 3.63 cmol/kg, soils developed strongly reducing conditions which would inhibit rice growth.

Zhang, M., and AD Karathanasis. 1997. Characterization of iron-manganese concretions in Kentucky Alfisols with perched water tables. Clays and Clay Minerals. 45:428-439.

Iron-manganese concretions are common in upper sola of Alfisols in the Inner Bluegrass Region of Kentucky. Their nature and quantities appear to be related to the fluctuation of seasonal perched water tables above clayey argillic horizons. This study was conducted to examine changes in the macro-and micromorphology, chemistry and mineralogy of concretions as a function of size, color and soil depth. Total Mn and Fe contents increased, while SiO sub(2) decreased with concretion size. Black concretions contained higher Mn, while brown concretions were higher in Fe. Crystalline Mn- and Fe-oxides fractionated with a sequential extraction procedure increased, but amorphous Mn and Fe decreased with concretion size. Goethite was the only crystalline Fe oxide mineral identified by X-ray diffraction (XRD) analysis. Manganese oxide minerals were very difficult to detect due to the diffuse nature of their XRD peaks and poor crystallinity. Examination of soil thin sections showed concretions of soil horizons overlying restrictive clayey layers to exhibit differentiated fabrics, sharp external boundaries and generally spherical shapes. Concretions found within clayey restrictive layers or above lithic interfaces usually had less structural organization, softer matrices and diffuse external boundaries due to longer term saturated conditions. Scanning electron microscopy (SEM) examinations suggested that the concretionary matrix, in spite of its density, has numerous cavities and an extensive micropore system within which dissolved plasmic Fe and Mn can diffuse and precipitate.

Zheng, D, E.R. Hunt, Jr., and S.W. Running. 1996. Comparison of available soil water capacity estimated from topography and soil series information. Landscape Ecology 11: 3-14.

Used a topographic index involving upslope drainage area and local surface slope angle to calculate available soil water capacity (ASWC). Rather coarse digital data (100m) was used to produce very useful maps.

Zobeck, T. M., and Ritchie, H., Jr., 1984, Analysis of long-term water table depth records from a hydrosequence of soils in central Ohio: Soil Science Society of America Journal, v. 47, p. 280 – 285.

Hydrology References

This section contains additional references related to hydrologic processes and monitoring related to on-site systems.

Amin, M. H. G., Chorley, R. J., Richards, K. S., Hall, L. D., Carpenter, T. A., Cislerova, M., and Vogel, T., 1997, Study of infiltration into a heterogeneous soil using magnetic resonance imaging: Hydrological Processes, vol. 11, p. 471 - 483.

This is a new method for recording and studying infiltration and wetting fronts. It requires significant expertise and calibration adjustments. Since we do not have the expertise nor the equipment and this is a new method without a proven track record, I think other methods would be more practical. JCY

‡Boulding, J. R., 1993, Subsurface characterization and monitoring techniques: a desk reference guide: Environmental Protection Agency, Office of Research and Development, Report EPA/625/R-93/003a- V. 1 &2, Washington, DC, 405 p.

This complete desk reference guide is designed to serve as a single, comprehensive source of information on existing and developing field methods as late as 1993. Guide written with the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Response, Compensation, and Liability Act (CERCLA) in mind.

Clothier, B. E., and Smettem, K. R. J., 1990, Combining laboratory and field measurements to define the hydraulic properties of soil: Soil Science Society of America Journal, vol. 54, no. 2, p. 299 - 304.

Cresswell, H. P., 1993, Evaluation of the portable pressure transducer technique for measuring field tensiometers: Australian Journal of Soil Research, vol. 31, p. 397 - 406.

See Marthaler and others (1983).

‡Daniel, D. E., and Scranton, H. B., 1997, Report of 1995 Workshop on Geosynthetic Clay Liners: National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Report EP 1.23/6:600/R-96/149, Cincinnati, 33 p

Gypsum block sensors and fiberglass mesh sensors, which both operate on a resistance basis, measure moisture content at different slopes on a landfill site with four types of soil: gray fat clay, clayey silt, silty clay, and clayey silt. Deformation and moisture data have been collected once every 2-3 weeks since plots were installed. This method of testing worked well for this particular case. However, the infrequent testing would most likely result in missed or inaccurate data for our study. It would be beneficial to perhaps combine the gypsum block sensors with another method of testing.

Faulkner, S. P., Patrick, W. H., and Gambrell, R. P., Field techniques for measuring wetland soil parameters: Soil Science Society of America Journal, v. 53, p. 883- 890.

Techniques for assessing wetland soil attributes are discussed that have been developed that allow direct field measurements of soil oxygen content, oxidation-reduction potential, water-table depth, and presence of ferrous iron. Piezometers were effectively used to measure hydraulic head. Construction techniques for each of the attribute measurements are given in this article.

Faybishenko, B. A., 1995, Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments: Water Resources Research, vol. 31, no. 10, p. 2421 – 2435.

This paper is a laboratory experimental study of entrapped air and its affect on hydraulic conductivity during infiltration events. It is not directly related to our proposed topic.

Faybishenko, B. A., 1995, Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments: Water Resources Research, v. 31, no. 10, p. 2421-2435.

Freeland, R. S., Reagan, J. C., Burns, R. T., and Ammons, J. T., 1998, Sensing perched water using ground-penetrating radar- a critical methodology examination: Applied Engineering in Agriculture, v. 14, no. 6, p. 675-681.

Freeland, R. S., Yoder, R. E., and Ammons, J. T., 1998, Mapping shallow underground features that influence site-specific agricultural production: Journal of Applied Geophysics, vol. 40, p. 19 - 27.

This study used ground-penetrating radar to look at different soil conditions including clay pan soils and perched water tables. The data are not extensive or well documented but look promising and may be applicable to our study. Ground-penetrating radar (GPR) produces non-distinct regions of increased signal scatter when scanning perched water in a shallow sandy loam soil. This article focuses on a critical verification method developed to examine the effectiveness of using the traditional procedure in manually interpreting GPR images for the detection of perched water. Project results illustrate that blind tests, human perception classification errors, help insure against possible false interpretations and reporting when using this technology. Baylor has GPR capability.

Hendry, M. J., and Wassenaar, L. I., 1999, Implications of the distribution of □D in pore waters for groundwater flow and the timing of geologic events in a thick aquitard system: Water Resources Research, vol. 35, no. 6, p. 1751 - 1760.

‡Hudnall, W. H., and Wilding, L. P., 1992, Characterization, Classification, and Utilitization of Wet Soils, Louisiana and Texas, in proceedings of the Eighth International Soil Correlation Meeting (VII ISCOM), p. 135-147.

This paper monitored soil wetness condition to revise the definition and criteria for the aquic soil moisture regime. Piezometer, tensiometers, and PT electrodes were used to measure soil moisture and redox potential every two weeks. Rainfall was recorded monthly. Tensiometers showed longer periods of saturation compared to piezometers and heterogeneity on a scale of meters was observed. The paper describes the varied responses of the different methods and references several papers that would be helpful in evaluating specific methodologies. The soils studied did not emphasize slope or landscape and occurred primarily on Pleistocene geologic units with nearly flat topography.

‡Hvorslev, M. J., 1951, Time lag and soil permeability in ground water observation: U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, Bulletin 36, 50 p.

‡Jamison, V. C., Smith, D. D., and Thornton, J. F., 1968, Soil and Water Research on a Claypan Soil, Technical Bulletin no. 1379, United States Department of Agriculture, 111 p.

A study of Midwest claypan soils that were predominantly loess overlying clay-rich till. The Studies focussed on crop management with regard to irrigation needs and erosion. None of the water studies involved piezometers or moisture measuring devices. The scale of the study was large and the timing was seasonal.

Koussis, A. D., Smith, M. E., Akylas, E., and Tombrou, M., 1998, Groundwater drainage flow in a soil layer resting on an inclined leaky bed: Water Resources Research, vol. 34, no. 11, p. 2879 - 2887.

Luthin, J. N., and Kirkham, D., 1949, Piezometer method for measuring permeability of soil in situ below a water table: Soil Science, v. 68, p. 349-358.

Piezometers were used to measure permeability. Advantages of using piezometers are that permeability can be determined, for practical purposes, to any depth, the permeability of any layer in the soil can be measured, and the method is relatively quick, accurate and simple.

‡Marino, M. A., and Luthin, J. N., 1982, Developments in Water Science: Seepage and Ground-water Flow: Elsevier Scientific Publishing Co., New York, 487 p.

Covers broad range of seepage and ground-water problems. Describes the physics of water flow through porous media and soil physical problems associated with that flow.

Marthalar, H. P., Vogelsanger, W., Richard, F., and Wierenga, P. J., 1983, A pressure transducer for field tensiometers: Soil Science Society of America Journal, v. 47, p. 624-627.

Marthaler, H. P., Vogelsanger, W., Richard, F., and Wierenga, P. J., 1983, A pressure transducer for field tensiometers: Soil Science Society of America Journal, vol. 47, p. 624 - 627.

This paper describes a method for using a pressure transducer with field tensiometers. The method uses a syringe needle inserted through a septum stopper in the upper end of the tensiometer. The advantages of this method include the ability to collect data easily and accurately with relatively low maintenance for the tensiometers. The disadvantage is that the method does not allow for continuous readings with a data logger.

‡Moore, D. W., and Miller, R. F., 1985, Soil-moisture retention in spoil during dry conditions at the Rosebud coal mine near Colstrip, Montana: U.S. Dept. Of the Interior, Geological Survey, Denver, Report I 19.76:85-295.

Soil in the upper 1-1.2 m in a sandy loam soil was sampled for various factors including moisture content. Passive gravimetric stress sensors (filter paper method) were used and areas sampled include grassy slopes, compacted road, and hillsides. Filter paper has an accuracy that is comparable to or better than the accuracy of other methods with limited ranges. This technique allows estimation of moisture holding characteristics of spoil. Although the filter paper method is useful in this study, it would not give information on continuous soil moisture changes or ground water level changes over a period of time since it only measures moisture content at the particular time that the filter paper is in the soil.

Morel-Seytoux, H. J., and Nimmo, J. R., 1999, Soil water retention and maximum capillary drive from saturation to oven dryness: Water Resources Research, vol. 35, no. 7, p. 2031 - 2041.

‡Morrison, R. D., 1983, Ground Water Monitoring Technology Procedures, Equipment and Applications: Timco Mfg., Inc., Prairie du Sac, Wisconsin, 111 p.

Provides information for use in vadose and saturated zones. Emphasis is placed upon a presentation of field proven methods which have been documented. Laboratory methods and field methods are both discussed in relationship to soil moisture content.

Nilsson, B., Jakobsen, R., and Anderson, L. J., 1995, Development and testing of active groundwater samplers: Journal of Hydrology, vol. 171, p. 223 - 238.

This paper described two types of borehole samplers that were designed to sample from specific zones within the borehole or screened interval of the well. Since the saturated zone above a textural change will be quite thin and since the shallow depths will allow well nests to be installed inexpensively, the sample system is not applicable.

Nilsson, B., Luckner, L., and Schirmer, M., 1995, Field trials of active and multi-port soil samplers in gravel-packed wells: Journal of Hydrology, vol. 171, p. 259 - 289.

Since the saturated zone above a textural change will be quite thin and since the shallow depths will allow well nests to be installed inexpensively, the sample system is not applicable.

Nyhan, J. W., and Drennon, B. J., 1990, Tensiometer data acquisition system for hydrologic studies requiring high temporal resolution: Soil Science Society of America Journal, vol. 54, p. 293 - 296.

The paper found that pressure transducers can be used effectively with tensiometers where extreme temporal and spatial variability may occur. Since we are concerned about temporal and spatial variability, the use of pressure transducers and data loggers with tensiometers will be applicable.

Parlange, M. B., Steenhuis, T. S., Timlin, D. J., Stagnitti, F., and Bryant, R. B., 1989, Subsurface flow above a fragipan horizon: Soil Science, v. 148, no. 2, p. 77 – 86.

The study looked at water movement in a shallow layer with a fragipan horizon on a moderate hillslope. The fragipan horizon contained vertical cracks, and they measured the subsurface flow above the fragipan out of a drainage system. They were able to determine physical properties of the soil above the fragipan and to develop a simple model, which should aid in interpreting hydrological observations on hillslopes with a fragipan with large cracks.

Rainwater, N. R., Yoder, R. E., Wilkerson, J. B., and Russell, B. D., 1998, Automatic sampling of perched water from vadose zone shallow wells: Applied Engineering in Agriculture, v. 14, no. 4, p. 399-406.

An automatic sampling system was used to plot the movement of perched water from vadose zone shallow wells in Tennessee. The project indicated extensive lateral movement of water in the vadose zone over a two year time frame. The sampling system worked well and was easily maintained by a field technician.

Reuter, R. J., McDaniel, P. A., Hammel, J. E., and Falen, A. L., 1998, Solute transport in seasonal perched water tables in loess-derived soilscapes: Soil Science Society of America Journal, vol. 63, p. 977 - 983.

This study of hydraulically restrictive fragipans and argillic horizons in northern Idaho focussed on the movement of solutes and the thickness of the episaturation on hillslopes. Three sites were chosen where the annual average precipitation was 610 mm, 700 mm, and 830 mm. Three transects of sampling wells were installed at each site perpendicular to slope contours with 7-9 wells per transect. The wells were sampled biweekly. The soils experienced seasonal episaturation and the authors found that redoximorphic features such as Fe and Fe-Mn concentrations tend to occur just below the boundary between the albic horizon and the restrictive horizon. The depth to perched water changed rapidly. The perched zone included not only the E horizon but extended into the BE, Bw and Ap horizons. The thickness of the perched water ranged from 14 - 69 mm. The study concluded that seasonal episaturation causes rapid downslope movement of solutes and that increasing annual precipitation increases the rates of transport. The most rapid flow of perched water occurred in the Ap and Bw horizons during periods of high precipitation. The authors referenced a study by Weyman (1973) that found water perched above restrictive horizons on sloping landscapes tends to move laterally downslope. Reuter and others (1998) also referenced two studies by Hammermeister and others (1982 a, b) that estimated transport rates up to 550 cm/hr on hillslopes in a climate with 1080 mm of average annual precipitation. Hammermeister and others attributed the high rates of preferential flow as occurring through large continuous voids in the root zone. Reuter and others (1998) also embraced the concept of soilscapes which represent the integration of the soil, hillslope, and perched water components as well as the associated processes.

‡Scanlon, B. R., Wang, F. P., and Richter, B. C., 1991, Field studies and numerical modeling of unsaturated flow in the Chihuahuan Desert, Texas: Bureau of Economic Geology, University of Texas at Austin, Report QE167.T42 no. 199, Austin, 49 p.

Study area was instrumented with neutron probe access tubes to monitor moisture content and with thermocouple psychrometers to monitor water potential. Computer code TRACRN was used to evaluate various unsaturated flow processes in this system. Numerical modeling showed between the shallow coarse material and underlying clays. Moisture content was monitored monthly. Neutron counts were recorded at approximately 0.1 m intervals from 0.3 to 1.2 m. The techniques in this test appear to be applicable to our study although more frequent testing would most likely be beneficial.

Schirmer, M., Jones, I., Teutsch, G., and Lerner, D. N., 1995, Development and testing of multiple soil samplers for groundwater: Journal of Hydrology, vol. 171, p. 239 - 257.

Since the saturated zone above a textural change will be quite thin and since the shallow depths will allow well nests to be installed inexpensively, the sample system is not applicable.

Sposito, G., 1995, Recent advances associated with soil water in the unsaturated zone: Reviews of Geophysics, Supplement, p. 1059 - 1065.

‡Steele, J. G., and others, 1983, Core versus nuclear gauge methods of determining soil bulk density and moisture content: U.S. Dept. Of Agriculture, Forest Service, Southern Forest Experiment Station, Report I 19:42/4:81-76, New Orleans.

Soil bulk density and moisture content measurements were obtained using two nuclear gauge systems and compared to those obtained from soil cores. Types of soils used include: Hiwassee sandy loam, Lakeland loamy sand, and Lloyd clay. Regression equations developed for nuclear gauges in the first phase of the study failed to predict bulk density and moisture content in the validation phase. Test results indicate that if greater confidence is placed on the standard soil core determinations, then regression equations should be developed for the nuclear gauges in each soil condition and for each soil type. The type of nuclear testing used gamma rays.

Taha, A., Gresillon, J. M., and Clothier, B. E., 1997, Modelling the link between hillslope water movement and stream flow: application to a small Mediterranean forest watershed: Journal of Hydrology, vol. 203, p. 11 - 20.

This paper found a very high hydraulic conductivity in the upper 20 cm of soil where there were abundant macropores and old water was discharged from precipitation events as the water perched in the upper soil layer. The study used a model to simulate the water table formation and there are some questionable assumptions in the model.

Timlin, D., and Pachepsky, Y., 1998, Measurement of unsaturated soil hydraulic conductivities using a ceramic cup tensiometer: Soil Science, v. 163, no. 8, p. 625 - 635.

This paper documents a method to calculate unsaturated hydraulic conductivity using a tensiometer. We are more concerned about saturated conditions but since we may use tensiometers to measure moisture content, we may be able to use this methodology. The unsaturated hydraulic conductivity may be more important than we realize but we would probably study it in a subsequent effort.

Torres, R., Dietrich, W. E., Montgomery, D. R., Anderson, S. P., and Loague, K., 1998, Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment: Water Resources Research, v. 34, no. 8, p. 1865-1879.

†Townsend, M. A., Young, D. P., and Macko, S., 1993, Migration of nitrate through the unsaturated zone in south-central Kansas, in Agricultural Research to Protect Water Quality, Conference Proceedings, p. 545 – 546, Minneapolis, Minnesota, Soil and Water Conservation Society.

This study looked at the vertical and areal distribution of NO3- below irrigated fields and the effects of clay layers in the unsaturated and saturated zones. The study used lysimeters, neutron probes, and monitoring wells. Water samples from the lysimeters and monitoring wells were analyzed for NO3- concentration and 15N isotopes. Neutron probe readings and water samples were collected weekly during the growing season. The lysimeter data show variable NO3- concentration with time and also variable concentration and volume of sample above and below clay zones in the soil profile. The perched water was thought to move downgradient rather than vertically through the clay and denitrification may occur above the clay zones. Denitrification was inferred from 15N isotope enrichment above the clay zone.

‡Van Haveren, B. P., 1986, Water Resource Measurements: American Water Works Association, Denver, 132 p.

Handbook assembled for the practicing hydrologist, water engineer, planner, and field technician which gives formulas and conversion tables for water and hydraulic data.

Weyman, D. R., 1973, Measurements of the downslope flow of water in a soil: Journal of Hydrology, vol. 20, p. 267 - 288.

This article supports our hypothesis that there may be rapid movement of water through perched zones on hillslopes and that soilscapes are a valid concept for differentiating potential problem areas associated with septic system. The thickness of the perched water zone was measured at 14 - 69 mm or 1.4 to 6.9 cm which is very thin.

Wildenschild, D., and Jensen, K. H., 1999, Laboratory investigations of effective flow behavior in unsaturated heterogeneous sands: Water Resources Research, vol. 35, no. 1, p. 17 - 27.

A laboratory dye study of unsaturated flow through heterogeneous material was conducted. There were few specific conclusions other than the fact that simple deterministic models adequately predicted the wetting front but were incapable of predicting moisture content at any point. The results also varied with scale. This study indicates we need to have redundancy in our measuring devices such as tensiometers in order to account for heterogeneity.

APPENDIX A

MOVEMENT AND SURVIVAL OF FECAL COLIFORMS IN SOIL

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Introduction

Application of domestic wastewater to land has potential for contaminating surface and groundwater with organisms of public health significance. The major indicator of pollution is the amount of fecal coliforms in the water. When soil is part of the wastewater treatment the expectation is that microorganisms remain in the treatment area until they die-off. There is potential for them to move with the water which poses problems if they survive and the water reaches the soil surface or ground water. Several factors have theoretically potential for influencing movement of bacteria in soil, active mobility by use of flagella, chemotaxis, and Brownian motion. None of these are of practical significance since they only influence movement over mm to a few cm distance in soil (Corapcioglu and Haridas, 1984;1985; Gannon et al, 1991; Reynolds et al, 1989; Stagnitti, 1999). Our review will cover the survival of fecal microorganisms in soil because time for survival influences how far they can move and cover literature on how far they actually move in soil under the influence of mass flow by water.

Survival

Several literature reviews have been conducted regarding the survival of microorganisms in soil that originate from fecal contamination. These review articles all conclude that the survival of fecal microorganisms in soil was in a time frame of days to weeks (Crane and Moore, 1986; Ellis and McCalla, 1978; Reddy et al, 1981; Sorber and Moore, 1987). Primary factors influencing survival of pathogens in soil were temperature, moisture content, and interactions with other microorganisms.

An equation has been developed describing die-off of fecal coliforms in both fresh and salt water. The time scale for die-off is in days rather than hours (Baumgartner, 1996). According to laboratory studies, Gerba (1975) reported that low temperatures and moist soil supported bacterial growth and survival, but the time for

90% die-off of fecal coliforms at soil moisture contents 5% and 23% resulted in no statistical difference (Parker and Mee ,1982). The time for 90% die-off ranged between 16 and more than 64 d depending on the soil and effluent (Parker and Mee ,1982). Die-off of fecal coliforms was determined at several locations in the field during spring and summer in Ohio with 99% die-off occurring in 8 to 15 d in the spring and 8 to 10 d in the summer (Van Donsel et al, 1967). In another study 99 % of the fecal coliforms died in soil in approximately 30 d at 41° F and less than 5 d at 37° F (Sjogren, 1994). Survival of fecal coliforms inoculated into soil at different concentrations, required approximately 4 d for 90% die-off when the inoculum was high but there was little or no die-off in 7 d when the inoculum rate was low (Klein and Casida, 1967).

Most articles on survival of fecal microorganisms in soil cover fecal coliforms but a few cover the bacterial pathogen salmonella. Populations of *Salmonella* in a soil remained high for several days when the soil was moist and the temperature was approximately 70º F (Zibilske and Weaver, 1978). When the soil was dry and the temperature was 102º F populations declined more rapidly, but were still detectable for at least 3 days. At a temperature of 60º F salmonella populations declined by 90% in 7 to 45 d depending on the soil and particular effluent used (Parker and Mee, 1982).

Movement

Several review articles have been written regarding movement of bacteria in soil and attempts have been made to model the process (Abu-Ashour et al, 1994; Corapcioglu and Haridas, 1984;1985; Hagedorn et al, 1981; Mawdsley et al, 1995; Reddy et al. 1981; Reynolds et al, 1989; Stagnitti, 1999). The general consensus of these reviews is that bacteria will move through soil and the extent of the movement will depend largely on adsorption, pore-size distribution and soil saturation. The bacteria are in the same size range as the largest clay particle therefore they would not be able to move through a well dispersed soil containing substantial clay because of the small pore sizes and filtration. Movement through unsaturated soils is minimal and not likely of public health significance. In the following section several original papers are reviewed to provide specific examples.

When bacteria were added to the top of soil in a column containing Houston Black clay they were all contained within the top 10 cm, but for Arenosa loamy sand 1% of the cells moved through 15 cm of the soil, although 26% were retained in the first 3 cm of the soil (Weaver, 1982). The Houston Black clay was very effective in filtration and adsorbing bacteria. Adding bacteria to this soil and allowing the suspension to settle resulted in 98% of the cells sedimenting out with the soil. For the Arenosa find sand only 11% of the bacteria were adsorbed onto the soil particles (Weaver, 1982). Different types of bacteria exhibit different adsorptive properties with 23 % of some strains being adsorbed while 87 % of other strains were adsorbed (Huysman and Verstraete, 1993).

Four days after introduction of bacteria into a moist soil packed into a column, bacteria remained within the top 5 cm of a 10 cm column, when water was not applied (Trevors, et at 1990). Application of water moved approximately 1 to 10% of the bacteria through the 10 cm columns. In a review of published literature Hagedorn, et al (1981) reported movement of bacteria from sewage through 0.6 to 24 m of soil. Rahe et al (1978) reported movement of fecal coliforms in two soils to distances of 15 m downslope from the point of application and at soil depths from 45 cm to 100 cm. Surface application of secondary treated domestic wastewater applied to agricultural land, resulted in populations of fecal coliforms in excess of 2,000 per g of soil at the surface and declining to background levels at 20 cm depth (Weaver et al, 1978). At another location on the same property, populations were higher at the surface and more than 1,000 per g of soil were present at the 50 cm depth. Irrigation water in southern Idaho from snow melt contained populations of fecal coliforms in excess of 200 per 100 mL and seepage water from land irrigated with this water generally contained fewer then 5 per 100 mL and often were not detectable (Smith et al, 1972).

Addition of manure to the surface of a soil resulted in movement of fecal coliforms to a 90 cm depth whenever enough rainfall occurred for water to leach through the soil (Stoddard et al, 1998). Populations of fecal coliforms in the water at the 90 cm depth exceeded 1000 per 100 mL. In another study sewage sludge was applied to the soil surface and water samples were collected from sampling tubes 180 cm below the surface (Edmonds, 1976). Fecal coliforms were detected in the leachate at 180 cm depth at a concentration of 160 per 100 mL following rainfall events. Generally fecal coliforms were not detected in a sampling well 8 m below the surface.

The importance of macropores in movement of fecal coliforms through soil was demonstrated in a comparison between four disturbed soils packed into 28 cm deep columns and four relatively undisturbed columns of the same soils (Smith et al, 1985). The number of bacteria in leachate from an "undisturbed" soil in columns was 22 to 80 % of those added depending on the particular soil and for disturbed soils only 0.2 to 7 % of the bacteria leached through the column. The rate at which water was added to the undisturbed columns influenced leaching. For some soils reducing the rate at which water moved through the soils reduced the percentage of bacteria leaching from 22 to 5 % for one soil and 59 to 8 % for another soil. In another experiment soil was placed in columns and artificial macropores were formed in some treatments and were leached with water containing fecal coliforms (Abu-Ashour et al, 1998). Columns of soil not having macropores did not have bacteria in their leachate but soil having macropores lost most of the bacteria in the leachate.

Further evidence regarding the importance of preferential flow through macropores as the route of travel of fecal coliforms through soil was achieved by taking square columns of soil and collecting leachate from specific zones on the bottoms of the columns (McMurry et al, 1998). From the results, the authors concluded that the bacteria leached from only 14 % of the column surface area. The distribution in quantity of bacteria coming from within these areas was that some contributed more than 20 % of the bacteria in the leachate while others provided less than 5 %. It was not necessary to saturate the whole column of soil with water because of preferential flow addition of only 1 cm of water per hour for 4 h was enough to cause leaching of the bacteria through the preferential paths.

Conclusion

Fecal coliforms survive in soil at significant populations for several days which is long enough time to move significant distances by mass flow in water. In addition, the populations are being replenished daily by on-site application of domestic wastewater. The fecal coliforms do not move distances in soil that are of public health significance without water as a carrier. Mass flow of water is the primary driving force moving the bacteria. The bacteria may be removed from the water by filtration and adsorption onto soil particles when the soil is dispersed. In natural settings, soil is always aggregated and structured to some extent which provides opportunity for preferential or by-pass flow to occur. Under such conditions the wastewater is not effectively treated by the soil and the fecal coliforms may travel large distances with the water to reach the soil surface or ground water.

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‡Baumgartner, D.J. 1996. Surface water pollution. p. 195-203. *In*. I.L Pepper et al. (ed.) *Pollution Science.* Academic Press, Inc. San Diego, California.

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