# AN ANALYSIS OF PALUSTRINE MITIGATION WETLANDS IN THE VIRGINIA COASTAL PLAIN

by

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## (ABSTRACT)

In recent years, the success of wetland mitigation projects and their ability to function as natural systems has been questioned. This study was conducted (i) to characterize and examine differences between mitigation and natural wetlands, (ii) to examine differences in soil morphology along a wetness gradient in mitigation and natural wetlands, and (iii) to observe changes in mitigation wetlands with time. Site characteristics, including soil properties, hydrology, and vegetation, were analyzed for three mitigation-reference wetland pairs located in the Virginia Coastal Plain. Hydrologic regimes of mitigation areas, when compared to reference areas, generally showed larger differentials between seasonal high and low watertables. Mitigation areas, dominated by herbaceous vegetation, tended to be lower in C and N levels and higher in soil pH, and much higher in bulk density than the mature forested reference wetland. Initially low levels of C and N did not increase significantly over the five-year study period. Soils in the mitigation area were more uniform and considerably less differentiated when compared to those of the reference area. Testing for Fe(II) with $\alpha,\alpha'$-dipyridyl dye solution produced mixed results, obtaining both positive and negative reactions to saturated samples. Oxidized rhizospheres, associated with active root channels in surface horizons, formed in less than ten years under the current hydrologic conditions. These features were more abundant and more prominent in areas saturated at or above the surface for longer periods of time. Overall, site differences between mitigation and reference areas are mainly due to construction practices and a lack of organic matter accumulation. Better design methods should incorporate the addition of organic amendments, with attempts to minimize soil compaction.

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## 1. INTRODUCTION

Wetlands are characterized by saturated and/or inundated soil conditions, unique soil characteristics distinct from adjacent uplands, and the ability to support water-tolerant vegetation (Mitsch and Gosselink, 1993). Wetlands contribute immensely to this country's quality of life, maintaining water quality and quantity, supporting diverse and abundant plant and animal habitats, and providing economic livelihood and recreation for millions of people. For these reasons federal, state, and local wetland policies promote the theory of "no net losses" (National Wetland Policy Forum, 1988). The concept of compensatory wetland mitigation arose from this theory and is intended to maintain and protect this nation's remaining wetlands.

By definition, wetland mitigation activities include avoidance of impacts, minimization of impacts, site restoration, or replacement of unavoidable losses (40 CFR Part 1508.20 [a - e]). Wetland mitigation may occur due to losses caused by draining and filling, urban development, or agricultural and forestry activities. In Virginia, highway construction generates numerous mitigation projects as a result of impacts to wetlands (Atkinson, 1991). For this reason, the Virginia Department of Transportation (VDOT) has expressed a need for an effective mitigation strategy (Frost et al., 1989). Recently, the success and sustainability of wetland mitigation projects has been questioned (Kusler, 1990; Nash and Cotten, 1997). Studies comparing mitigation areas to natural wetlands have examined differences in site function (Confer and Niering, 1992), soil chemical and physical properties (Bishel-Machung et al., 1996; Stolt et al., 1999) and soil morphology (Vepraskas et al., 1999; 1995). Generally, mitigation sites differed significantly in their basic physical, chemical, and morphological properties when compared to natural wetlands, which results from design methods, construction practices, and a lack of development time (Atkinson, 1991; Bishel-Machung et al., 1996; Daniels et al., 1996).

Mitigation sites are constructed to replace natural wetlands and must meet the same criteria: hydric soils, wetland hydrology, and hydrophytic vegetation (Environmental Laboratory, 1987). Hydric soils are usually indicated in the field by redoximorphic features as described by Vepraskas (1994) and NRCS (1996) and other indicators (Environmental Laboratory, 1987; Soil Survey Staff, 1994). Very few studies have examined the time frame required for the formation of redoximorphic features in mitigation wetlands (Vepraskas et al., 1999; 1995; Stolt et al., 1998).

Limited detailed research has been conducted examining the success of wetland mitigation projects and their ability to function as natural systems. More research is needed to examine the interactions between soils, hydrology, and vegetation in both natural and created wetlands. A better understanding of these systems will result in improved design techniques, construction methods, and long-term site sustainability. Therefore, the specific objectives of this study were:

1. to examine differences in soil properties between mitigation and natural wetlands;
2. to characterize the soil and hydrologic regime of mitigation wetlands and their interaction with wetland biota; and
3. to examine differences in soil morphology along a wetness gradient in mitigation and natural wetlands.

# 2. LITERATURE REVIEW

## 2.1 Introduction

The U.S. Army Corps of Engineers (Federal Register, 1982) and the Environmental Protection Agency (Federal Register, 1980) jointly define wetlands as:

> *Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.*

Section 404 of the 1972 Clean Water Act authorizes the U.S. Army Corps of Engineers (COE) to establish a permit system to regulate the dredging and filling of materials in "waters of the U.S.", which include wetlands. Federal and state agencies involved in wetlands permitting are mandated to preserve and protect wetlands, ensuring proper mitigation measures to offset wetland losses and impacts.

By definition, mitigation activities include avoidance of impacts, minimization of impacts, site restoration, or replacement of unavoidable losses (40 CFR Part 1508.20 [a - e]), in that order of application. In avoidance, wetlands impacts are averted by altering construction plans or relocating the project. Kusler (1990) defines site restoration as "returning a damaged or destroyed wetland to a former, normal or unimpaired state". Replacement of impacted wetlands is usually accomplished by constructing new wetlands. Wetland mitigation may occur due to urban expansion activities such as draining and filling, commercial development, or highway construction. Mitigation may also result from damage due to agricultural and forestry activities. In Virginia, highway construction generates numerous mitigation projects as a result of wetland impacts (Atkinson, 1991). Road construction projects are not easily altered or relocated to avoid wetland impacts. Therefore, highway departments are largely constrained to the option of wetland construction for loss compensation. For this reason, the Virginia Department of Transportation (VDOT) has expressed a need for an effective mitigation strategy (Frost et al., 1989).

Many uncertainties surround the success of constructed wetlands (Bishel-Machung et al., 1996; Nash and Cotten, 1997). Wetlands are natural systems which have evolved under specific conditions to form complex ecosystems. The interdependence of the biotic and abiotic communities is not fully understood, which makes successful replication difficult. Despite inherent difficulties, recommendations for planning and construction have been developed to promote a successful, self-sustaining system (Mitsch and Cronk, 1992; Salvesen, 1990; Whittecar and Daniels, 1999).

## 2.2 Wetland Criteria

Hydric soils, hydrophytic vegetation, and wetland hydrology are the three diagnostic environmental characteristics used to identify jurisdictional wetlands in the field (Environmental Laboratory, 1987). For a mitigation site to be considered jurisdictional it must contain sufficient indicators from all three parameters.

While vegetation and hydrology are relatively straightforward to assess in mitigation sites, determination of hydric soils is much more complicated. A hydric soil is a soil that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (Soil Survey Staff, 1994). The term growing season, when used to evaluate wetland criteria, is defined as the period of the year when soil temperature at 50 cm below the surface is above $5^{o}$ C (SCS, 1985b). The following criteria were developed by the National Technical Committee for Hydric Soils (1995) to reflect those soils that meet this definition.

*CRITERIA FOR HYDRIC SOILS*

1. *All Histosols except Folists, or*
2. *Soils in Aquic suborders, great groups, or subgroups, Albolls suborder, Aquisalids, Pachic subgroups, or Cumulic subgroups that are:*
    a. *Somewhat poorly drained with a water table equal to 0.0 foot (ft) from the surface during the growing season, or*
    b. *poorly drained or very poorly drained and have either:*

    - *(1) water table equal to 0.0 ft during the growing season if textures are coarse sand, sand, or fine sand in all layers within 20 inches (in), or for other soils*
    - *(2) water table at less than or equal to 0.5 ft from the surface during the growing season if permeability is equal to or greater than 6.0 in/hour (h) in all layers within 20 in, or*
    - *(3) water table at less than or equal to 1.0 ft from the surface during the growing season if permeability is less than 6.0 in/h in any layer within 20 in, or*

3. *Soils that are frequently ponded for long duration or very long duration during the growing season, or*
4. *Soils that are frequently flooded for long duration or very long duration during the growing season.*

The formation of a hydric soil is obviously influenced by site hydrology. Periodic or permanent saturation for sufficient duration results in anaerobic conditions. Such conditions allow for the establishment and maintenance of water-tolerant hydrophytic vegetation. Hydrophytic vegetation is defined as

> “the sum total of macrophytic plant life that occurs in areas where the frequency and duration of inundation or soil saturation produce permanently or periodically saturated soils of sufficient duration to exert a controlling influence on the plant species present” (Environmental Laboratory, 1987).

As with hydric soils, the existence of hydrophytic vegetation is strongly influenced by site hydrology. Plants lacking morphological, physiological, and reproductive adaptations cannot successfully compete in areas with prolonged saturated conditions (Mitsch and Gosselink, 1993).

Wetland hydrology is a broad term used to capture many hydrologic characteristics of an area that experiences periodic or permanent saturation at some time during the growing season. For an area to be considered a wetland, it must be inundated either permanently or periodically, or the soil must be saturated to the surface during the growing season of the prevalent vegetation. Areas which are seasonally inundated or saturated to the surface for a consecutive number of days for more than 12.5% of the growing season directly meet wetland hydrology criteria. Areas saturated to the surface between 5% and 12.5% of the growing season may or may not be wetlands. Areas saturated to the surface for less than 5% of the growing season are non-wetlands (Environmental Laboratory, 1987; Clark and Benforado, 1981).

## 2.3 Wetland Functions and Values

Wetlands play an essential role in this country's quality of life, maintaining water quality and quantity, supporting diverse and abundant plant and animal habitats, and providing economic livelihood and recreation for millions of people. Some types of wetlands minimize flooding by storing storm water, then gradually re-release the water back into the system, minimizing damaging peak flood levels (Novitzki, 1979). Wetlands also possess the ability to remove both organic and inorganic nutrients and toxins from water supplies, improving water quality (Sather and Smith, 1984). In terms of wildlife populations, wetlands provide unique habitats for fish, shellfish, mammals, and waterfowl, including many threatened and endangered species (Wharton et al., 1982). Wetlands also efficiently assist in the fulfillment of societal demand for wood and wood products (Johnson, 1979). In summary, wetlands are a diverse natural resource which provide many useful functions and values for society.

The U.S. Fish and Wildlife Service estimates that over 50% of U.S. wetlands have been destroyed during the last 200 years (Tiner, 1984). The most recent report (Dahl and Johnson, 1991) evaluated wetland trends for the period from the mid-1970's to mid-1980's. The report estimated that 51.2 million acres of wetlands existed in the 10 Southeast states in the mid-1970's. By the mid-1980's, wetland acreage was reduced to 48.9 million acres, including 44.6 million acres of freshwater wetlands and 4.3 million acres of estuarine wetlands. The net loss within the region was more than 2.3 million acres, making the average annual net loss approximately 259,000 acres. Nearly all the losses were from freshwater wetlands (Dahl and Johnson, 1991).

## 2.4 Aquic Conditions and Hydric Soils

Wetland soils are mineral and/or organic in composition. When saturated for a lengthened period of time, wet mineral soils develop certain characteristics that aid in their identification in the field. Anaerobic conditions are usually indicated by redoximorphic features as described by Vepraskas (1994) and NRCS (1996).

Anaerobic and chemically reduced soils are described as having aquic conditions for use in application of Soil Taxonomy. Soils with aquic conditions are those which currently experience continuous or periodic saturation and reduction. The occurrence of aquic conditions is indicated by redoximorphic features and can be validated, except in drained soils, by measuring saturation and reduction. For classification purposes, aquic conditions apply only to mineral soils. Most organic soils, except Folists, are assumed to be saturated and reduced (Soil Survey Staff, 1994). Three elements must be present to describe aquic conditions in soils (Vepraskas, 1994; Soil Survey Staff, 1994):

1. *<u>Soil saturation</u> – identified by zero or positive pressure in the soil water. In a state of saturation, soil water will flow from the soil matrix into a tightly sealed piezometer or tensiometer. The duration of saturation required for producing aquic conditions is site sensitive and is not specified. Depth requirements vary with subsurface horizons. Soils with argillic, kandic, oxic, spodic, or sulfuric horizons require saturation within 50 cm of the soils surface. Soils with other subsurface horizons require aquic conditions between depths of 40 to 50 cm. Three saturation types are defined:*
    - *a.) endosaturation – soil is saturated in all layers from the upper boundary of saturation to a depth of 200 cm from the mineral soil surface.*
    - *b.) episaturation – the zone of saturation, within 200 cm of the mineral soil surface, is perched on top of a relatively impermeable layer.*
    - *c.) anthric saturation – controlled saturation for wetland crops (e.g. rice and cranberries)*

2. *<u>Reduction</u> – requires the presence of Fe(II) in solution at some time during the year. The duration of reduction required for creating aquic conditions is not specified.*
3. *<u>Redoximorphic features</u> – color patterns and other features, such as nodules and clay depletions, formed by the processes of reduction, translocation, and oxidation of Fe and Mn oxides. Depth requirements for indicators of aquic conditions vary, depending on soil order, but generally coincide with the depth requirements of saturation and reduction.*

If aquic soils occur within jurisdictional wetlands, they are also classified as hydric soils (Environmental Laboratory, 1987; Soil Survey Staff, 1994). Most hydric soils have aquic conditions, but not all soils with aquic conditions are classified as hydric soils. Principal differences between hydric soils and soils with aquic conditions are the specified depths to saturation and reduction, and timing of saturation and reduction (Vepraskas and Sprecher, 1997).

To save time and effort, soil color and other field indicators are commonly used to identify hydric soils and soils with aquic conditions. Other field indicators of hydric soils and soils with aquic conditions include organic soils, histic epipedons, $H_2S$ (rotten egg smell), aquic or peraquic moisture regimes, and $Fe^{3+}$/ Fe-Mn concentrations (NRCS, 1996). Mineral soils are considered hydric if the horizon immediately below the A horizon is gleyed, has a matrix chroma of 2 or less when redoximorphic features are present, or has a matrix chroma of 1 or less when redoximorphic features are not present (Soil Survey Staff, 1994).

### 2.5 Redoximorphic Feature Identification

Soil Survey Staff (1994) describe redoximorphic features as characteristic color patterns resulting from alternating periods of saturation and drainage causing the reduction and oxidation of Fe and Mn compounds in the soil. The reduced compounds are mobile in soil solution and may be moved by water through and within the soil profile. Characteristic color patterns form as the soil solution moves through the profile and encounters zones of aeration. Oxidation occurs within these zones, resulting in the accumulation and precipitation of Fe and Mn oxides, forming redox concentrations. In the presence of microbes and organic matter, reduction occurs in the areas saturated with water, resulting in redox depletions. Redox depletions are those zones of low chroma where Fe and Mn oxides and/or clay have been removed (Soil Survey Staff, 1994).

Originally, mottles and low chroma matrix colors were used to describe saturated soil color patterns in the field. Vepraskas (1994) and the Soil Survey Staff (1994) replaced these general terms with the more specific category of "redoximorphic features" and identified special types of redoximorphic features.

1. *Redox concentrations: Evident zones of accumulated Fe/Mn oxides, in the form of:*
    1. *Nodules and concretions: Hard irregularly shaped bodies. Concretions generally form in concentric layers, whereas nodules have no organized internal structure. When formed in place, nodule and concretion boundaries are diffuse and sharp after pedoturbation;*
    2. *Masses: Soft concentrations of Fe/Mn oxides within the matrix; and*
    3. *Pore linings: Zones of accumulation that may be coating a pore surface or permeated from the matrix adjacent to the pore.*
2. *Redox depletions: Zones of low chroma (2 or less) where Fe/Mn oxides and/or clay have been removed, including:*
    1. *Iron depletions: Zones with low amounts of Fe/Mn oxides, but have a clay content similar to the surrounding matrix. These areas are often gray in color along macropores and within the matrix; and*
    2. *Clay depletions: Zones containing lower amounts of Fe/Mn oxides and clay than the surrounding matrix.*
3. *Reduced matrices: A soil matrix which has a low chroma in situ, but undergoes a change in hue or chroma within 30 minutes after the soil sample is exposed to air.*

Since they are visible, redoximorphic features are commonly used as indicators of soil wetness in the field under the assumption that they are related to current soil drainage conditions. Quantity, size, contrast, color, and other relative attributes describe redoximorphic features. Qualitative descriptors correspond to quantitative classes (Appendix A) as reported here to give a complete description of the observed features.

## 2.6 Redoximorphic Feature Formation

Oxygen diffuses 10,000 times slower through waterlogged soils than through well drained soils due to the absence of air filled pores with continuity to the surface (Gambrell and Patrick, 1978). As microbes consume oxygen faster than it can be supplied, the soil becomes anaerobic. During anaerobic respiration, organic matter is oxidized as various soil components are sequentially reduced. Facultative and/or anaerobic respiration sequentially uses $NO_3^-$, $Mn^{4+}$, $Fe^{3+}$, and $SO^{4+}$as electron acceptors after consuming all dissolved oxygen. The degree of soil reduction can be defined using measures of redox potential (Ponnamperuma, 1972). Redox potential is a measure of the tendency of a system to reduce or oxidize redox sensitive elements. It can be derived from the equation:

$$Eh = DG / nF ,$$

where $Eh$ = redox potential, $DG$ = Gibbs free energy, $n$ = the change in the number of electrons, and $F$ = the Faraday constant (Latimer, 1952). Redox potential is also related, in theory, to the relative concentrations of oxidants and reductants in a redox reaction by the Nernst Equation:

$$Eh = E^o + (RT/nF) \ln[(Ox)/(Red)]$$

where $E^o$ = potential of reference, MV; $R$ = gas constant; $T$ = temperature, K; $n$ = number of moles of electrons transferred; $F$ = Faraday constant (Bohn, 1971). If the value is positive and high (+320 to +380 mV), moderate to strong oxidizing conditions exist. Under such conditions, red, brown, and yellow colors are associated with iron oxy-hydroxides which may coat the surfaces of soil particles, while oxidized Mn may coat the soil particles black. If low and negative values are obtained (-120 to -180 mV), these elements are usually found in reduced forms. When Fe and Mn are reduced, the metal cations are water soluble. As water moves through the profile, Fe (II) and Mn (II) are transported to other horizons or leached from the soil. This removal of Fe/Mn oxides strips soil particles of the colored coatings and leaves behind natural gray colors. The critical Eh value at which redox reactions occur vary with the specific element involved (Patrick and Reddy, 1978) and other soil conditions, such as pH.

Roots growing in the soil matrix provide an energy source for microbial Fe reduction. As the root dies, bacteria consume the plant material and the root channel periodically fills with water. The bacteria first utilize the oxygen from the soil water, then proceed to reduce $NO_3^-$. After all the available $NO_3^-$ is reduced, the Fe and Mn oxide minerals composed within the channel will be reduced and translocated into the matrix, where they can be reoxidized to form redox concentrations. The root channel now lacks in Fe and Mn, and would be described as a redox depletion if the zone had a chroma of 2 or less (Vepraskas, 1994).

As explained earlier, redox concentrations are areas of Fe and Mn accumulation. Pore linings are a specific type of redox concentration which form by oxidation of Fe along macropores and can also be found around the root zone of those plants with the ability to transport oxygen to their roots under saturated conditions (Vepraskas, 1994; Vepraskas et al., 1995). The presence of oxidized rhizospheres associated with living roots provides evidence of active wetland hydrology. These oxidized root channels indicate that anaerobic conditions, due to soil saturation, occurred during the life span of the plant root. Concentrations of Fe would not form under aerobic conditions because soil Fe would remain oxidized and would not be affected by root zone oxygen depletion (Mendelssohn, 1993). Therefore, oxidized rhizospheres are a useful field indicator that can be used in place of hydrologic data. Oxidized root channels in mitigation wetlands are especially helpful in distinguishing current hydrologic conditions.

Mitigation wetlands are highly disturbed areas, making wetland delineation based upon mature soil properties difficult. The observation of oxidized rhizospheres helps to distinguish recent or active saturated conditions from relict hydrologic conditions. As with all redoximorphic features, oxidized rhizosphere formation depends on several biotic and abiotic factors. The two most important factors are the presence of soluble soil iron (Taylor et al., 1984) and the ability of plant species to create an oxidized rhizosphere (Armstrong, 1967).

Vepraskas and Bouma (1975) examined the development of redoximorphic features in artificial cores, simulating naturally occurring conditions. Redox concentrations and depletions of Fe and Mn developed within 150 days of saturation. Observations were made in initially oxidized soils, and the redoximorphic features which developed resulted from controlled moisture regimes in the laboratory. Stolt et al. (1998) investigated the time-frame required for the formation of redoximorphic features in the field. Simulated peds, some receiving treatments of additional organic matter, were buried throughout four palustrine natural/mitigation paired wetlands in Virginia. After one and two years in the wetlands, the peds were removed and sampled. Redoximorphic features were observed within the interiors and exteriors of all peds in less than two years. On the ped exterior, Fe masses were most common. Iron concentrations in the form of pore linings and Fe depletions were most prominent on ped interiors. These results suggested relatively rapid rates of hydric soil pedogenesis within mitigation wetlands for these particular features and site conditions.

Several factors affect redox potential and redoximorphic feature formation, including pH, organic matter content, microbial population, temperature, and mineral oxide contents. Critical redox potentials for most redox couples vary with pH. Alkaline soils require a very low redox potential to reduce Fe and Mn. Iron solubility is also pH dependent. As pH decreases, Fe(II) concentration in solution increases (Ponnamperuma, 1972). Soils with low amounts of Fe and/or Mn will not form prominent redox features. Such soils are mainly composed of quartz , containing few weatherable minerals that could release Fe or Mn (Vepraskas and Sprecher, 1997). Redox feature development also relies on the activity of microbes. Without an active microbial population, redox processes will not occur. Like all living organisms, microbes need an energy source. If organic matter is lacking, as is often the case in mitigation wetlands (Atkinson, 1991; Bishel-Machung, 1996), microbes will not facilitate reduction processes. Microbial populations are also influenced by soil temperature and pH. Redoximorphic feature development is therefore a dynamic process, dependent on many interrelated variables. Thus, redox feature development may be lacking in saturated soils due to a hindered reduction process. This problem may be common in mitigation wetlands, which are young soils and are usually low in organic matter and may be higher in pH than natural wetlands.

Boettinger (1997) examined the lack of redoximorphic feature development in wet saline and alkaline soils. High pH, low amounts of Fe and Mn, and low activity of microbes were cited as possible causes for a lack of development (Boettinger, 1997). Kuehl et al. (1997) discussed difficulties encountered in identifying redox features in many sandy soils due to naturally low levels of Fe, which would not readily form redoximorphic features under reducing conditions. In the same volume, Lindbo (1997) related lack of redox feature development in young, flood plain soils to high pH, low amounts of organic C and colors inherited from parent material.

## 2.7 Redoximorphic Features as Inidicators of Soil Wetness

When identifying hydric soils in the field, soil color is one of the easiest indicators to observe. Red and yellow colors are indicators of oxidized iron and zones of aeration. Gleyed (gray) colors occur where organic matter content is low and iron has been reduced and removed. Variegated redoximorphic color patterns are common in poorly drained soils and usually indicate a fluctuating water table (Buol and Rebertus, 1988). Subsoil color and redoximorphic features are primarily a function of Fe reduction, which require anaerobic conditions, an energy source, and anaerobic microbes (Bouma, 1983).

Numerous studies have related color features to measured water table regimes. Franzmeier et al. (1983) observed general relationships between water table depth and soil color patterns in some Indiana soils. Horizons with reduced matrices (chroma 2 or less) were saturated for most of the year. Horizons with redox depletions were found above or below horizons with the reduced matrices. If above, they were saturated several months of the year, and if below, they were saturated most of the year. Horizons with a dominant chroma of 3 were often saturated. Horizons with a chroma higher than 6 were never influenced by the water table if they were at least 0.2 m above the chroma 2/3 horizons (Franzmeier et al., 1983).

Coventry and Williams (1984) identified a strong relationship between soil color and contemporary water tables in northeastern Australia. Depths to redox depletions were most directly related to the depths where soils were saturated for a minimum of 5 weeks. The depth to the maximum content of ironstone gravels and to the base of the solum were most closely associated with the depth at which soils remained saturated for 10 to 15 weeks. Dominant gray colors in the C horizons were best related to soils saturated for at least 21 weeks. The observed redoximorphic features coincided with the current soil hydrologic regime.

In Indiana, Evans and Franzmeier (1986) examined the influence of geomorphology and stratigraphy on soil water and $O_2$ regimes, how soil color patterns reflected soil water and $O_2$ regimes, and the use of soil color for land use interpretation. Udalfs had deeper water tables, shorter saturation periods, higher soil water $O_2$ levels, and higher chroma colors than Aqualfs or Aquolls. Soils with reduced matrices in the B horizon were saturated and reduced, creating soil water and $O_2$ conditions consistent with the aquic moisture regime. Soils with chroma 3 or 4 had soil water and $O_2$ regimes of saturation and oxidation. These soils were observed to be occasionally saturated, but not reduced (Evans and Franzmeier, 1986).

In the Coastal Plain of North Carolina, Daniels et al. (1971) found pale brown and very pale brown (10YR 6/3 and 7/3) redox concentrations that were prominent in Typic Paleudults at depths saturated 25% of the time, while redox depletions developed at depths saturated for 50% of the time. In Aquults, reduced matrices occurred at depths saturated for more than 50% of the time. Faulkner and Patrick (1992) reported a strong agreement between soil profile characteristics, hydrologic regimes, and wetland status of sites in alluvial bottomlands in Louisiana and Mississippi. Overall, the quantitative data (soil redox potential and water table depth) supported the qualitative field indicators (soil profile characteristics). Schelling (1960) reported that depth to specific gray redox depletions estimated the mean wet season high water table. Simonson and Boersma (1972) found that depth to faint and distinct redox features strongly correlated with a high degree of saturation. Overall, the use of field indicators to determine moisture regimes assumes that a strong and direct correlation exists between redox potential, $O_2$ content, water table depth, and color (Megonigal et al., 1993). However, the length of saturation required at a given depth is far less certain (Genthner et al., 1998).

The application of redoximorphic features as indicators of soil wetness has been rigorously investigated in natural soils. However, very little work related to redox features and constructed wetland hydrology has been conducted to date. Constructed wetlands are man made systems, often with altered hydrology. The validity of redox features to indicate soil wetness in a constructed wetland needs to be examined further. Atkinson et al. (1998) observed redox features, including depleted matrices and oxidized rhizospheres, in 10- to 30-year-old accidental depressional wetlands resulting from surface mining activities. Soil chroma was directly influenced by the duration of inundation. Permanently flooded sites exhibited lower chroma than sites with intermittent or semi-permanent flooding conditions.

Vepraskas et al. (1999) examined soils in constructed wetlands in Illinois to see if they functioned as hydric soils and evaluated chemical and morphological changes in created wetlands to monitor hydric soil indicator development within constructed wetlands. In a constructed deep marsh, soils in and along the marsh edge were classified as hydric five years after construction. Redox potentials and well records indicated that soils in the marsh and along it's edge met the hydric soil definition throughout the study, while upland positions did not, and areas in the transition zones met the definition in some years. After five years, depleted matrices were fully developed and consistently identified as hydric soils. This study occurred at a demonstration project where the hydrologic regime could be controlled. Most mitigation wetlands are subject to seasonal flooding and dry down, which greatly impacts the timing and duration of saturation. Therefore, the rate of Fe oxidation and reduction and redox feature development would be affected.

In a constructed floodplain wetland, Vepraskas et al. (1995) found that redox depletions and pore linings could be used to identify jurisdictional wetland boundaries in constructed wetlands saturated for relatively short periods of time (7 to 14 days). Increased abundance and size of redox depletions was found to be related to soil organic matter levels greater than 3%. Redox features were not observed in areas with less than 1.5% organic matter. As discussed earlier, redoximorphic feature development is site specific, varying with organic matter content, temperature, and chemical characteristics.

## 2.8 Problems with Redoximorphic Features

Redoximorphic features have been shown to be fairly good indicators of soil wetness in natural wetlands, but there are special cases where soil saturation occurs without reduction or where soils exhibit redox features in the absence of soil saturation. Vepraskas and Wilding (1983) studied four seasonally saturated Alfisols in Texas to determine if each soil had an aquic moisture regime. Based on water table and redox potential measurements, the soils were considered to be seasonally reduced, but only two soils exhibited low (2 or less) chroma colors (Vepraskas and Wilding, 1983). Couto et al. (1985) examined oxidation-reduction processes in Oxisols of Brazil. No low chroma colors were observed to a depth of 200 cm, even though the water table was within 0.4 to 0.2 m of the soil surface at some sites for more than 90 cumulative days. Measured redox potentials (+500 to +700 mV) indicated no reduction occurred. The data suggested that reduction did not occur under saturated conditions due to a lack of an energy source for microbial activity (Couto et al., 1985).

Zampella (1994) found the correlation of redox features to soil saturation in sandy pineland soils to be highly variable. No consistent relationship between soil color and water table depth was observed along the hydrosequence. This suggested that soil features are not reliable indicators of soil saturation in somewhat poorly drained and poorly drained soils of the Lakewood catena studied. Similarly, the presence of nodules and concretions may not always indicate a current hydrologic regime. Nodules and concretions are resistant to weathering and may be relicts of wetter conditions of an earlier time or may have been transported from another location (Vepraskas, 1994). Distinguishing relict features from current redox features can be difficult in the field. Wilding et al. (1983) observed that current *in situ* nodules and concretions have gradual or diffuse boundaries with the soil matrix and have irregular surfaces. Relict nodules and concretions tend to have sharp, well defined boundaries with the matrix and smooth surfaces (Wilding et al., 1983).

Additional tools may be used in the field to help distinguish relict from contemporary redox features. The presence of Fe(II) can be verified in the field by the use of $\alpha,\alpha'$-dipyridyl dye solution (Childs, 1981), which turns the reduced soil pink, indicating the presence of Fe(II). Many recent studies include the use of the dye solution in conjunction with well records, redox potential measurements, and morphological indicators, to confirm saturated and reduced conditions. Along two catenas in Oregon, Lynn and Austin (1998) reported the presence of Fe(II) with soil saturation, low Eh readings, supported by positive reactions to the dye solution. Griffin et al. (1998) confirmed results when using the dye as an indicator of wetness and reduction in a microtoposequence on the Texas Coast Prairie. The dye is not always reliable and should only be used in combination with other indicators of soil wetness. Along a catena in Pennsylvania, Calmon et al. (1998) observed redoximorphic features, saturated conditions during the growing season, and low Eh conditions, but received negative results with the solution. More research is clearly needed to determine if it is possible to identify relict redoximorphic features using reliable field techniques.

### 2.9 Site Characterization in Mitigation Wetlands

Generally, wetland mitigation sites are very different in their basic physical, chemical, and morphological properties from natural wetlands. This clearly results from construction methods used and a lack of development time. These differences can directly affect redox feature development and hydric soil determination. Daniels et al. (1996) observed how low organic matter content greatly reduced hydric soil formation within mitigation sites and high bulk density restricted the ability of mitigation sites to support diverse wetland vegetation.

Atkinson (1991) evaluated the ability of VDOT constructed wetlands to perform wetland functions which presumably were dependent on anaerobic soil conditions. Results indicated that elevation, flooding duration, organic matter content, and active microbial populations related strongly to the development of anaerobic conditions. Constructed wetlands had lower levels of organic matter and lower microbial activity than reference wetlands. Strongly reducing conditions did not occur in many areas of the mitigation wetlands, possibly due to a short flooding duration. Amendments of native wetland topsoil were recommended to increase organic matter content, microbial activity, and to improve revegetation (Atkinson, 1991).

Bishel-Machung et al. (1996) found similar results when comparing soil properties of palustrine mitigation and reference sites in Pennsylvania. Differences in soil organic matter levels caused differences in bulk density, matrix chroma, pH and total N in both the reference and mitigation wetlands. Reference wetlands were higher in soil organic matter and percent total N than wetland creation projects. Organic matter levels in the reference wetland were significantly higher at 5 cm than at 20 cm, while mitigation wetlands had uniform organic matter levels at both depths. These differences were explained by increased surface accumulation of organic matter within the reference wetland, while mitigation wetlands in this study experienced no apparent surface accumulation. Differences in organic matter accumulation since the time of construction were found to be insignificant, however the authors acknowledged the short time period studied. Organic matter accumulation is a function of time, established vegetation, and hydrology. Variations of these factors, which were observed between reference and mitigation wetlands will impact soil organic matter levels. Bulk density, pH, and matrix chroma values were lower in the reference wetlands. A negative correlation between soil organic matter and matrix chroma was explained by the darkening effects of organic matter on soil and the role organic matter plays in the formation of iron depletions (Vepraskas, 1994). Significant differences in particle size distribution occurred between the natural and created wetlands studied, with created wetlands containing more sand and less clay. This was attributed to the fact that mitigation sites are created by excavation into the subsoil, resulting in a homogeneous soil column, showing little evidence of pedogenesis (Bishel-Machung et al., 1996).

Confer and Niering (1992) compared created palustrine/emergent wetland sites with similar natural wetlands in Connecticut. Created sites exhibited more open water, deeper surface water depths, and more fluctuations in water depths than natural wetlands. Created sites lacked hydric soil indicators, possibly as a result of low organic matter content. Vegetation within the created sites was dominated by common cattail (*Typha latifolia* L.), while natural wetlands contained a diverse mix of emergent vegetation. Wildlife activity at all sites ranged from occasional to rare, with a greater variety of species noted at the natural sites. This study supported the creation of small wetland systems to replace certain functions of natural wetlands, such as flood storage, sediment trapping, and restricted wildlife habitat. Continued monitoring was recommended to assess the long-term success of created wetland systems (Confer and Niering, 1992).

Stolt et al. (1999) reported data from 1993 through 1995 on the same wetland pairs studied here and found greater micro-relief, greater variability in particle size distribution, and significantly higher levels of organic C, N, and cation exchange capacity in reference sites. They also found similar seasonal water table fluctuations and redox potentials in both the reference and mitigation wetlands. Stolt et al. (1999) attributed many of the paired wetlands' differences to site design and construction practices.

## 2.10 Surface Horizon Development

The importance of organic matter accumulation to hydric soil development and wetland functions has already been addressed (Atkinson, 1991; Bishel-Machung et al., 1996; Vepraskas, 1994). Very few, if any, studies have been conducted to examine surface horizon development of constructed wetland sites in the middle Atlantic states. Studies have examined surface horizon development on young sites, such as glacial till and mine soils, while many other studies address the importance of organic matter additions to improve reclamation. Organic matter is extremely beneficial to soils, improving overall soil quality (Appendix B).

Crocker and Major (1955) studied the natural development of soils formed from retreating glaciers in Alaska. The degree of changes in soil properties occurred as a function of time and vegetation. With increasing time, organic C and total N content increased, bulk density and pH decreased, and $CaCO_3$ was dissolved. A majority of the changes occurred near the mineral soil surface, where the affects of climate and vegetation were most intense. Little or no changes occurred at a depth of 50 cm in 200 years. Sweeney (1979) also observed the effects of time of soil development. Ten year-old mine soils in West Virginia were found to be darker in color, have better structure, more rapid hydraulic conductivity, and a higher cation exchange capacity than younger mine soils. Soil horizon development also became more apparent with increased age. Two year-old mine soils were classified as Entisols, while 10 year-old mine soils were classified as Inceptisols. The use of unweathered rock overburden as a topsoil substitute in mine land reclamation can result in relatively rapid formation of mine soils (Haering et al., 1993). Mine soils in southwestern Virginia developed distinct A horizons within two years as a result of vegetative root growth and organic matter accumulations. Subsoil horizon development occurred more slowly, but AC transitions and C horizons were observed within eight years.

Soil forming factors work to develop and change young soils rapidly over time. With the addition of organic matter to reclaimed lands, the soil genesis processes can be accelerated, resulting in fertile, productive soils. Mine soils of southwestern Virginia were treated with varying amounts of organic amendments to observe the effects of organic matter on soil genesis (Roberts et al., 1988). Distinct A horizons, transitional AC and C horizons developed in all pedons in three years. Depth of AC horizon development was a function of organic additions. The chemical processes of leaching, dissolution, oxidation and organic matter accumulation expedited the pedogenic processes in these young mine soils.

Similar studies examining the affects of organic matter amendments to wetland mitigation soils need to be conducted. Organic matter plays an important role in the formation of redoximorphic features and hydric soils. There is a definite need for research to investigate the rate of hydric soil development as a function of organic matter versus drainage regime in both natural and mitigation wetlands.

## 2.11 Summary

Wetlands are dynamic natural systems. Hydric soil and it's associated hydrology have a large effect on the success of a wetland. Hydric soil formation is a natural physical and chemical process which requires proper hydrologic and biotic conditions to fully develop. The presence of Fe and Mn compounds and their relative amounts dramatically affect the development of redoximorphic features. Many other chemical and physical factors also influence redoximorphic feature development. Without the formation of redox features and indicators, hydric soil identification becomes more difficult. An improved understanding of soil morphology and hydrology is necessary to accurately interpret soil profile characteristics.

Little research has been conducted examining the success of wetland mitigation projects and their ability to function as natural systems. Limited organic matter levels, increased bulk density, and insufficient site hydrology seem to be the major limitations that prevent the establishment of thriving wetland systems. More research is needed to examine the interactions between soils, hydrology, and vegetation in both natural and created wetlands.  A better understanding of these systems will result is improved design techniques, construction methods, and long-term site sustainability.

# 3. MATERIALS AND METHODS

An intensive monitoring program designed to evaluate soil/hydrology/vegetation relationships in constructed wetlands was installed in 1993 by Virginia Tech's Crop and Soil Environmental Science Department (Haering et al., 1994; Stolt et al., 1999). The three wetlands used in this study (Figure 1) were selected from over 90 VDOT mitigation wetlands that were surveyed in 1992 and 1993. Selection of the study sites was based on the following criteria:

1. Location: proximity to a similar natural wetland that could be used as a control.
2. Size: greater than 0.5 hectares.
3. Wetland subclass and age: forested or scrub/shrub systems of varying ages.
4. Accessibility.

Sites selected for detailed review in this study were all forested wetland pairs of similar age located within Virginia's Coastal Plain:

| VDOT District | Site Name | Construction Date | Size |
|---|---|---|---|
| Fredericksburg | Elmwood-Baylor | 1989 | 0.63 ha |
| Richmond | Fort Lee | 1991 | 13.80 ha |
| Suffolk | Western Freeway | 1992 | 0.63 ha |

## 3.1 Site Description

### *3.1.1 Fort Lee*

The Fort Lee mitigation site is a large (13.80 ha) constructed non-tidal forested wetland adjacent to U.S. Interstate 295 North, southwest of Richmond in Prince George County, Virginia. The site lies entirely within the Coastal Plain physiographic province (Figure 2). Data recorded in Hopewell, Virginia from 1951 to 1978 report that the average growing season lasts from March 22 until November 6 based on air temperature. The average daily temperature is $15^{o}$ C and the average winter temperature is $5^{o}$ C. Annually, the county receives an average of 113 cm of precipitation, with 50% falling between April and September (SCS, 1985a).

The Fort Lee mitigation area is paired with a natural forested wetland which lies between the mitigation site and Cabin Creek, a second-order Coastal Plain stream. Plio-

Pleistocene estuarine-fill deposits underlie the entire site (Mixon et al., 1989). The Soil Survey of Prince George County, Virginia (SCS, 1985a) has mapped the reference area as map unit 14 - Kinston complex (Table 1a). These are deep, poorly drained soils formed from loamy fluvial sediments on floodplains, with slope ranging from 0 - 2%. These soils do not have a well developed subsoil due to a high water table and periodic, brief flooding events. According to the standard series criteria, from November to June the water table rises to within 30 cm of the soil surface in these soils for a brief to long duration. Flooding events are rare to common in frequency, with events most commonly occurring from November to June. Soils of the Kinston complex are so intermingled Bibb and Chastain, that they were not mapped separately. Included throughout the unit are both sandy (Bibb series) and clayey (Chastain series) poorly drained soils. Also included in the complex are small areas of well drained Emporia soils and somewhat poorly drained Slagle soils (SCS, 1985a). The Kinston series is classified as Fluvaquentic Endoaquepts and it is listed as a hydric soil (NTCHS, 1995).

The original sideslope and upland that were excavated to form the mitigation site were mapped as 25B - Slagle sandy loam, 2 - 6% slopes and 11B - Emporia fine sandy loam, 2 - 6% slopes, respectively (Table 1b and 1c). The Slagle soils are deep, somewhat poorly drained soils on side slopes, classified as Aquic Hapludults. Slagle is not classified as a hydric soil. The Emporia soils are deep, well drained soils on uplands, and are classified as Typic Hapludults; also non-hydric.

The final surface of the mitigation area was formed in 1991 by excavating the adjacent hillside down to the presumed water table level under the original uplands. Final grade elevations were based on limited winter well observations recorded by VDOT from 1990 to 1991. Twenty five cm of upland topsoil was added to achieve final grade in November 1991. The site was originally seeded in tall fescue (*Festuca arundinaceae* Schreb.) and has since been planted with forested wetland species such as red maple (*Acer rubrum* L.) and bald cypress (*Taxodium distichum* L.). The hydroperiod in the mitigation area is controlled mainly by storSWPater run-on/run-off and ground water, while in the reference area, hydroperiod is controlled by both stream overbank additions and ground water.

### *3.1.2 Elmwood-Baylor*

The Elmwood-Baylor mitigation site is a small (0.63 ha) constructed non-tidal shrub/scrub wetland located in Essex County, Virginia on State Route 17 North. Essex County is entirely within the southern Coastal Plain (Figure 3). Data recorded at Warsaw, Virginia from 1951 to 1981 indicate that the average growing season lasts from April 5 until November 1, with 208 days greater than $-2^{o}$ C. The average daily temperature is $14^{o}$ C and the average winter temperature is $4^{o}$ C. Annually, the county receives an average of 108 cm of precipitation, with 50% falling between April and September (Hoppe, 1989).

The mitigation area is paired with a natural forested wetland which follows Elmwood Creek, a second order Coastal Plain stream. The Soil Survey of Essex County, Virginia (Hoppe, 1989) indicates that the reference area as map unit 3A - Bibb sandy loam, 0 to 2% slopes, frequently flooded (Table 2a). These are very deep, poorly drained soils formed in loamy alluvium on floodplains. They are frequently flooded in late winter and early spring. According to series level criteria, the water table occurs at 15 to 30 cm from December to April. Flooding frequency during the months of December through May is common, for varying duration. The Bibb series is classified as Typic Fluvaquents and is listed as a hydric soil (NTCHS, 1995).

The original sideslope that was excavated to form the mitigation area was mapped as 19E - Rumford and Emporia, 15 - 20% slopes (Table 2b and 2c). The Rumford soils are very deep, well drained soils formed in stratified loamy and clayey, fluvial sediments on sideslopes and uplands. They are classified as Typic Hapludults. Rumford soils are nonhydric. The Emporia soils are deep, well drained soils on uplands, classified as Typic Hapludults, and are also non-hydric.

The mitigation area was formed in January, 1989 by excavating the adjacent hillside down to the presumed water table level under the original uplands. Fifteen cm of upland topsoil was added to the site after final grading. A planting design subdivided the mitigation area into four separate planting zones based on elevation. Zone 1, having the lowest elevation, received emergent species, such as Arrow Arum (*Peltandra virginica* L.). Zone 2 was planted with emergents and shrubs: rice cutgrass (*Leersia oryzoides* L.) and buttonbush (*Cephalanthus occidentalis* L.). Zone 3 was planted with emergents, shrubs and trees: soft-stem bulrush (*Scirpus validus* Vahl), highbush blueberry (*Vaccinium corymbosum* L.), and river birch (*Betula nigra* L.). Zone 4, with the highest elevation, was planted with an herbaceous wildlife seed mix. Hydroperiod at the site is controlled by surface water runoff and ground water, along with occasional overbank flooding.

### *3.1.3 Western Freeway*

The Western Freeway mitigation site is a small (0.63 ha) constructed non-tidal forested wetland located at the interchange of State Route 164 and U.S. Interstate 664 in the City of Suffolk, Virginia. Suffolk is entirely within the Coastal Plain physiographic province (Figure 4). Data recorded at Holland, Virginia from 1951 to 1975 indicate the average growing season lasts from March 29 until November 7, with 222 days greater than -2$^o$ C. The average daily temperature is 15$^o$ C and the average winter temperature is 5$^o$ C. Annually, the city receives an average of 122 cm of precipitation, with 60% falling between April and September (SCS, 1981).

The mitigation area is paired with a natural forested wetland. The Soil Survey of the City of Suffolk, Virginia (SCS, 1981) delineates the area as map unit 29 - Weston fine sandy loam (Table 3). These are deep, nearly level, poorly drained soils on broad flats formed in loamy fluvio-marine sediments. The Weston soils are classified as Typic Endoaquults and Weston is listed as a hydric soil. A seasonal high water table occurs from December to April at a depth of 2 to 46 cm below the soil surface (NTCHS, 1995) according to the official soil series criteria.

The mitigation area was formed in June, 1991, by excavating the adjacent hillside down to the presumed water table level under the original uplands. Thirty cm of upland topsoil was added to achieve final grade. A variety of wetland trees and shrubs were planted: black gum (*Nyssa sylvatica* Marsh.), green ash (*Fraxinus pennsylvanica* Marsh.), sweet pepperbush (*Clethra alnifolia* L.), river birch, highbush blueberry, and buttonbush. Hydroperiod at the site is controlled by ground water, storm water drainage, and braided overbank flow through the reference area.

## 3.2 Field Sampling

### *3.2.1 Hydrology*

At all sites, shallow (91 to 180 cm) ground water monitoring wells were installed along transects throughout the entire site by either Virginia Tech or VDOT personnel (Haering et al., 1994) from 1990 to 1993. Some wells were installed at shallower depths, and in nests to evaluate vertical gradients (Faulkner et al., 1989). Wells were installed by hand-augering to varying depths and inserting PVC well screen into the auger hole. A sand filter pack was then poured around the pipe to secure the unlined borehole and to minimize silting. Wells were surface sealed with bentonite to limit surface water from entering the well.

Beginning in April 1997, Virginia Tech personnel replaced damaged wells in the Fort Lee reference area and added additional wells and piezometers throughout the wetland. Fort Lee subsequently contained a total of 58 wells along 11 transects: 48 in the mitigation area and 10 in the reference area (Figure 2). In addition to the 58 wells at Fort Lee, USGS maintains four continuous water level indicators which record detailed diurnal ground water fluctuations.

At Elmwood-Baylor and Western Freeway, 2.5 cm diameter PVC wells were installed in April 1993. Elmwood-Baylor received a total of five wells: three in the mitigation area, two in the reference area (Figure 3). Western Freeway received a total of nine wells: six in the mitigation area, three in the reference area (Figure 4). Monthly monitoring at all sites began in June 1993 and continued for one year. As part of the current study, bi-monthly ground water monitoring resumed at Fort Lee in July 1997 and was continued through December 1998.

### *3.2.2 Soils*

At the Fort Lee site, three transects were established across a previously determined wetland saturation gradient (obtained from well records), beginning at the western side of the mitigation site extending through the reference area to Cabin Creek (Figure 5). Within each transect, five pits were excavated to 100 cm. Pit locations corresponded with existing wells and were based on well records and dominant vegetation types. Along each transect, two pits were located in very poorly drained (VPD) areas, one in the mitigation wetland and one in a similar area within the reference wetland. Two pits were located in poorly drained (PD) areas of the mitigation wetland and reference wetland, and one pit was excavated in a somewhat poorly drained (SWPD) area of the mitigation wetland. There were no SWPD areas observed within the reference wetland.

The soils were described and classified according to National Cooperative Soil Survey procedures (Soil Survey Staff, 1994) in July, 1998. Special attention was placed on the degree and extent of redoximorphic features and overall pedogenesis within each horizon. Quantitative counts were made for redoximorphic features by horizon within a 100 $cm^2$ sample area of each horizon. In horizons thinner than 10 cm, a 25 $cm^2$ sample area was used. Qualitative notes were made on the abundance, size, and color of redoximorphic features by horizon. Soil horizons were also tested for the presence of ferrous iron using α,α'-dipyridyl dye solution (Childs, 1981). Bulk subsamples and intact bulk density cores were taken from each horizon and from specific depths (0 to 5 cm, 5 to 15 cm, 40 to 50 cm, and 90 to 100 cm). These depths corresponded with sampling depths reported in previous studies (Haering et al., 1994; Daniels et al., 1996).

Sampling at Elmwood-Baylor and Western Freeway was done with an auger. Sample locations corresponded with existing groundwater wells, both in the mitigation area and reference area. Soils were described and classified according to National Cooperative Soil Survey procedures (Soil Survey Staff, 1994) in July, 1998. Special attention was given to the amount and prominence of redoximorphic features present within each horizon. Horizons were also tested for the presence of ferrous iron using α,α'-dipyridyl dye solution (Childs, 1981). In Elmwood-Baylor and Western Freeway, bulk samples were only taken from the specific depth ranges: 0 to 5 cm, 5 to 15 cm, 40 to 50 cm, and 90 to 100 cm. At Elmwood-Baylor three pedons in the reference area and two pedons in the mitigation area were described and sampled. Flooding in the Elmwood-Baylor mitigation area made sampling difficult. At Western Freeway, six mitigation area pedons were sampled, but due to the uniformity of the area only three pedons were described. In the Western Freeway reference area, severe flooding due to beaver activity limited description and sampling to one pedon.

Soil descriptions and bulk samples were originally taken from all three sites in 1993 by Virginia Tech personnel (Haering et al., 1994; Daniels et al., 1996) and will be re-evaluated in this study to compare soil properties between reference and mitigation sites. These samples were obtained with an auger while installing wells. Thus, all three sites were sampled in 1993 and then resampled in 1998 to evaluate soil development changes with time in the mitigation areas. At all sites, both the mitigation areas and the reference areas were sampled. During both sampling periods, bulk samples were taken at 0 to 5 cm, 5 to 15 cm, 40 to 50 cm, and 90 to 100 cm. Intact bulk density core samples were taken by horizon only once in Fort Lee and Western Freeway in July, 1998. Elmwood-Baylor was too wet to obtain intact bulk density core samples.

### *3.2.3 Vegetation*

Vegetation at Fort Lee was sampled in September 1998. Sampling locations throughout the wetland occurred along the three transects immediately around the sampled soil pits. Since it was dominated by herbaceous plants, the mitigation area was sampled using a 1 $m^2$ quadrat, randomly located near each soil pit. Percent composition was determined for each species present within the quadrat. Laboratory subsamples were then taken from a 0.37 $m^2$ quadrat. All standing vegetation, both living and dead, was clipped and removed. Organic layers were then separated and collected according to stratification. The L layer or leaf layer consists of relatively unaltered plant and animal remains. Just below the L layer is the F layer, a zone consisting of partially decomposed organic material. Below the F layer is an H layer which consists of highly decomposed, amorphous organic matter (Pritchett and Fisher, 1987). H layers were not found in the mitigation area.

Vegetation in the Fort Lee reference area is dominated by mature hardwoods. Sampling in the reference area consisted of point sampling of mature trees and quadrat sampling of the litter layers. As in the mitigation area, the sample quadrat was randomly located near each soil pit. The 0.37 $m^2$ subsample area was used to separate and collect litter layers. H layers were not found in the reference area. A point sampling method was used to sample mature trees. Every tree within a 12 m radius of each soil pit was identified and measured. Trees with a diameter at breast height smaller than 13 cm were not included in the sample. Dominant species in the shrub and herbaceous layers were also identified.

All vegetation and litter samples were returned to the lab and dried. Dry weights were recorded and corrected for mineral material included in the sample. Estimates of site productivity were calculated and expressed as kg $ha^{-1}$ for herbaceous biomass and woody plant density in $m^2$ $ha^{-1}$ for live woody basal area.

## 3.3 Laboratory Methods

Bulk samples from each depth or horizon were returned to the laboratory, air-dried, and ground to pass a 2 mm sieve. Soil texture was determined by a modified pipette method (Gee and Bauder, 1986) following the removal of organic matter by oxidation with $H_2O_2$ (Kunze and Dixon, 1986). Subsamples were analyzed for total C by the dry combustion method (Nelson and Sommers, 1982) and Total Kjeldahl Nitrogen using a block digestor method (Bremner and Mulvaney, 1982). Bulk density was determined from intact cores (Blake and Hartge, 1986).

## 3.4 Statistical Analysis

After completion of sampling and laboratory analyses, data were collected and entered into a spreadsheet. Parameters included in this data set were pH, TKN, and percent carbon. Statistical analyses were conducted by parameter to determine whether significant differences existed in soil parameters:

1. between mitigation areas and reference areas at a given soil depth,
2. between soil depths at a given location;
3. over time at a given depth and location.

Data were analyzed using JMP Start Statistics (Sall and Lehman, 1996). Nonparametric contrasts were utilized due to small sample sizes and apparent presence of moderate outliers in some data sets. For contrasts between mitigation and reference areas and contrasts over time, the Wilcoxon Rank Sum Test (Hollander and Wolfe, 1973) was used. The Wilcoxon Rank Sum Test is the nonparametric equivalent of the two-sample t-test and is more appropriate when small sample sizes are involved. Differences were considered significant where $P \leq 0.05$. For contrasts with depth, means of differences found to be significant were separated by Fisher’s protected Least Significant Difference (LSD) comparison (Sall and Lehman, 1996). The P-values for the tests are given in the text where the contrasts are discussed and in the Appendix.

# 4. RESULTS

## 4.1 Wetland Properties

### *4.1.1 Elmwood-Baylor*

Herbaceous vegetation and woody shrubs dominated the mitigation area. Common herbaceous species included rice cutgrass, cattails (*Typha latifolia* L.), arrow arum (*Peltandra virginica* L.), and soft rush (*Juncus effusus* L.). Woody shrubs included black willow (*Salix nigra* Marsh.), river birch, and hazel alder (*Alnus serrulata* Ait.). The reference area supported mature trees, shrubs, and herbaceous vegetation. The herbaceous layer included sensitive fern (*Onoclea sensibilis* L.), arrow arum, and smartweed (*Polygonum hydropiper* L.). Hazel alder, buttonbush and other woody species dominated the shrub layer. River birch, red maple, and tulip poplar (*Liriodendron tulipifera* L.) were dominant trees in the reference area.

Selected pedon descriptions (Table 4) from the mitigation area indicate that the soils were more uniform and considerably less differentiated when compared to those of the reference area. Reference area soils contained multiple horizons, varying in texture and/or color, while mitigation soils exhibited only a replaced surface A horizon over a massive C horizon. In the reference area a brown, loamy sand A horizon generally extended to a depth of 10 cm, with a gray loamy sand A horizon extending to 23 cm. Reference area Cg horizons were gray and varied from sandy loam to loam texture. By contrast, in the mitigation area a bluish gray sandy loam surface horizon extended to 20 cm. Underlying loam C horizons varied widely in color, from strong brown to gray. Subsoil structure in both the reference and mitigation area was described as massive due to the saturated conditions at the time of description. Bulk density cores were not taken due to saturated conditions. Observations of rooting in the mitigation area found many coarse roots in the surface horizon and few fine roots in the upper C horizon. In the reference area, many fine and few coarse roots were observed in the surface horizons. A greater number of fine roots were observed in the mitigation area due to the flood-tolerant, herbaceous nature of the vegetation. Larger tree and shrub roots appeared confined to surface horizons of the reference area, presumably to avoid permanently saturated zones lower in the profile.

A detailed, quantitative analysis of redox features was conducted for Fort Lee, while observations from Elmwood-Baylor and Western Freeway were primarily qualitative. At Elmwood-Baylor, redoximorphic features in general, and specifically oxidized rhizospheres were more abundant in the reference area. In the A horizon many, fine dark brown pore linings were observed and faint brown Fe masses were observed throughout the C horizons. Black Mn masses and light yellowish brown Fe accumulations were commonly observed in the uppermost C horizon in the mitigation area soils. Soils in the mitigation area were flooded for larger portions of the growing season (Figure 6), resulting in the total saturation of soil pores, which may explains why no oxidized rhizospheres were observed.

In the reference area, the presence of $Fe^{+2}$ was detected by $\alpha,\alpha'$-dipyridyl (Childs, 1981) throughout the three pedons described. In the mitigation area, only deeper gleyed soil horizons displayed the presence of $Fe^{+2}$ in the two pedons described, while $Fe^{+2}$ was not detected in horizons with high chroma. Water table levels were above the surface in the mitigation area and 30 cm below the surface in the reference area when sampled in July, 1998. Soil horizons in the mitigation area were therefore observed to be saturated, but not reduced. Such saturation without reduction could be a result of low levels of organic matter and/or the absence of anaerobic microbes. Atkinson's (1991) results indicated that elevation, flooding duration, organic matter content, and an active microbe population related strongly to the development of anaerobic conditions. Constructed wetlands had lower levels of organic matter, lower microbial activity, and lacked reducing conditions compared to reference wetlands in his study. In a report to VDOT on mitigation wetlands in Virginia, Daniels et al. (1996) observed higher redox potentials in mitigation areas than those in paired reference areas, particularly during the winter months. They attributed the lack of a strong reducing environment under saturated conditions to a lack of organic matter and limited microbial activity.

Soil chemical properties in the mitigation wetland differed (Table 5) from those of the reference in many ways. Soil pH in the mitigation area was higher than that in the reference area at all subsurface depths. In the reference area, soil pH did not vary significantly with depth, while the 0 to 5 cm layer in the mitigation area was much lower in pH than the underlying horizons.

Soils in the mitigation area were examined for changes with time by comparing samples taken from the same well locations and depths in 1993 and 1998 (Table 6). No significant changes in soil pH were noted over the five year study period at any depth. Overall, %N levels were higher in the reference area than in the mitigation area, but were only highly significant at a depth of 5 to 15 cm ($p = 0.012$). In both the reference area and mitigation area, %N levels generally decreased with depth. A decrease in %N between 1993 and 1998 was observed in the mitigation area at 40 to 50 cm ($p = 0.027$) and 90 to 100 cm ($p = 0.024$). Percent C levels were also higher in the reference area than in the mitigation area for all subsurface depths. Carbon levels generally decreased with depth in both the reference and mitigation area. No significant changes in %C occurred in the mitigation soil at any depth over the five year study. Therefore, these soils do not appear to be accumulating C as would be expected.

### *4.1.2 Western Freeway*

Although dominated by shrubs and herbaceous vegetation, this site contained a more diverse mix of species in the mitigation area than the other two sites. The herbaceous layer included soft rush, morning glory (*Ipomoea purpurea* L.), and jewelweed (*Impatiens capanensis* Meerb.). The shrub layer included red maple, sweet gum (*Liquidambar styraciflua* L.), American sycamore (*Plantanus occidentalis* L.), black willow, buttonbush, and wax myrtle (*Myrica cerifera* L.). Red maple, sweet gum, and willow oak (*Quercus phellos* L.) dominated the reference area tree layer. Common shrub species included sweetbay magnolia (*Magnolia virginiana* L.) and sweet pepper bush. The herbaceous layer was dominated by lizards tail (*Saururus cernuus* L.) and false nettle (*Boehmeria cylindrica* L.).

As with Elmwood-Baylor, selected pedon descriptions (Table 7) of the mitigation area at Western Freeway indicate that the soils were more uniform and considerably less differentiated when compared to those of the reference area. Matrix colors of chroma 2 or less were observed throughout all pedons in the reference area. A dark grayish brown to very dark grayish brown sandy loam A horizon extended to a depth of 40 cm. Many fine roots were located in this surface horizon. Few faint strong brown oxidized rhizospheres were associated with fine root channels. Below the surface horizon a dark grayish brown silt loam Btg horizon extended to 70 cm. Few fine roots were observed in the Btg horizon. No redox features were observed below the surface horizons in these reference area soils. Sandy C horizons ranged from very dark grayish brown to light brownish gray and roots were not visible. In comparison, pedons from the mitigation area were less developed with a dark grayish brown loamy sand A horizon extending to 46 cm. Fine roots commonly occurred in the surface horizon. Few faint strong brown Fe masses and oxidized rhizospheres were associated with fine root channels. Underlying sandy loam C horizons varied in color from light yellowish brown to light gray. Roots were not observed in C horizons, but many, distinct dark yellowish brown and yellowish brown Fe masses were observed here. All surface horizons, in both the mitigation area and reference area, were described as having weak granular structure. Subsurface horizons were described as massive due to saturated conditions and the mixing and grinding of soil materials by the auger. Bulk density could only be measured at the 0 to 5 cm depth in the reference area due to standing water. Surface bulk density in the reference area was 0.81 g $cm^{-3}$ compared with 1.24 g $cm^{-3}$ in the mitigation area. A higher surface bulk density in the mitigation area is a result of compaction during site construction and low levels of organic matter. As expected, bulk density increased with depth in the mitigation area, ranging from 1.51 g $cm^{-3}$ (5 to 15 cm) to 1.63 g $cm^{-3}$ (40 to 50 cm) with depth due to lower levels of organic matter and less aggregation.

In the reference area, the presence of $Fe^{+2}$ was detected (Childs, 1981) in the loamy horizons of the pedons described. Sandy horizons appeared reduced and saturated but did not respond to the $\alpha,\alpha'$-dipyridyl. In the mitigation area, $Fe^{+2}$ was observed in only the surface horizons of the three pedons described. Water table levels were above the surface in the reference area and 120 cm below the surface in the mitigation area at the time of description. Hydrographs recorded in 1993 do not reflect the current hydrology of the site due to recent beaver activity which caused ponding of the reference area (Figure 7).

Soils in the mitigation wetland differed (Table 5 and 6) from those of the reference in many chemical parameters. Soil pH in the mitigation area was higher than that in the reference area at all subsurface depths. In the reference area, soil pH generally decreased with depth, while the 5 to 15 cm layer in the mitigation area was much higher in pH than the other horizons. Soil pH decreased from 5.40 to 4.97 at a depth of 90 to 100 cm ($p = 0.007$) over the five year study period. Percent N levels were significantly higher in the reference area than in the mitigation area at all depths. In both the reference area and mitigation area, %N levels generally decreased with depth. A decrease in %N between 1993 and 1998 was observed in the mitigation area at all depths. Percent C levels were also higher in the reference area than in the mitigation area at all depths. Carbon levels generally decreased with depth in the mitigation area. In the reference area, higher C levels were observed at the 5 to 15 cm depth than at the surface. No significant changes in %C occurred in the mitigation soil at any depth between the 1993 and 1998 sampling dates (Table 6).

### *4.1.3 Fort Lee*

The vegetation at Fort Lee exhibited similar character and species composition as Elmwood-Baylor and Western Freeway. The mitigation area was dominated by herbaceous vegetation, while the reference area supported a mature forested wetland with a multi-storied canopy structure. The vegetation at Fort Lee is described in greater detail below and in the Appendix.

Pedon descriptions (Table 8a – 8f) in the mitigation area display the same trends described earlier for Elmwood-Baylor and Western Freeway. Matrix colors of chroma 2 or less were observed throughout all pedons in the reference area. Very dark grayish brown, sandy loam A horizons extended to about 14 cm with an average bulk density of 0.71 g $cm^{-3}$. An underlying grayish brown sandy loam AC horizon extended to about 70 cm with an average bulk density of 1.42 g $cm^{-3}$, and an underlying light gray sandy C horizon extended to 150 cm. Roots were commonly observed to a depth of 70 cm. Roots varied in size and amount, generally with many fine roots at the surface and few coarse roots deeper in the profile.

Soil physical properties and rooting density of the mitigation area soils varied with drainage class, and the subsoil in VPD areas was coarser in texture and brighter in color when compared to SWPD and PD areas. Matrix colors most likely do not reflect the current hydrologic regime, but are a result of the previous upland to wetland transition soil morphology. Very poorly drained areas of the mitigation area were SWPD areas of the original catena, with associated coarser textures and brighter colors. Today, soils closer to the reference wetland are SWPD due to site design and construction, but these soils exhibit finer textures and gray matrix colors. As a result of upland topsoil application during construction, mitigation area soils contained a uniform A horizon throughout the site. The A horizon was an olive brown sandy loam which extended to 20 cm with an average bulk density of 1.71 g $cm^{-3}$. As drainage improved, rooting increased. Within a 100 $cm^2$ sample area, an average of 25 fine roots were counted in VPD areas, 26 fine roots were found in PD areas, and 31 fine roots were observed in SWPD areas. Below the surface, a brownish yellow sandy C horizon extended to about 80 cm. In VPD areas this horizon had an average bulk density of 1.52 g $cm^{-3}$, with an average of 8 fine roots per 100 $cm^2$. In PD and SWPD areas this horizon was light gray and highly compacted.

Soil in PD areas had an average bulk density of 1.73 g $cm^{-3}$, with an average of 3 fine roots per 100 $cm^2$, while SWPD areas had an average bulk density of 1.82 g $cm^{-3}$, with an average of 2 very fine roots per 100 $cm^2$. This upper 2C horizon was so heavily compacted during site construction that it could be considered *densic material* by Soil Taxonomy. Densic materials are non-cemented earthy materials whose bulk density or organization prohibit roots to enter, except in cracks (Soil Survey Staff, 1999). Where densic materials were present, root growth occurred only in cracks. A deeper non-densic 2C horizon existed from about 80 cm to 150 cm. This deeper 2C horizon was light yellowish brown to brownish yellow and sandy, with no roots.

In the reference area, reaction of $Fe^{+2}$ to $\alpha$,$\alpha$'-dipyridyl generally corresponded with water table depth in the six pedons described. Positive reactions were obtained from horizons below the water table, although two negative reactions were also observed below the water table. In the mitigation area, $Fe^{+2}$ detection in the nine pedons studied varied. Six horizons in four pedons produced a positive reaction. These horizons were saturated or well below the water table, but many saturated horizons did not produce a positive reaction. Water table levels occurred at an average depth of 60 cm below the surface in the reference area and 90 cm below the surface in the mitigation area at the time of description. A more detailed discussion of site hydrology is given below.

Comparisons between soil chemical properties of reference and mitigation wetlands at Fort Lee (Table 5) revealed similar trends described earlier for Elmwood-Baylor and Western Freeway. No data were collected at Fort Lee for the 0 to 5 cm depth class in 1993. However, soil pH in the mitigation area was higher than that in the reference area at the 5 to 15 cm ($p < 0.0001$) and 40 to 50 cm ($p = 0.0001$) depths. In the reference area, soil pH generally decreased with depth, while soil pH in the mitigation area was constant with depth.

Percent N levels were higher in the reference area than in the mitigation area at depths of 5 to 15 cm and 40 to 50 cm. In both the reference area and mitigation area, %N levels generally decreased with depth. Percent C levels were higher in the reference area than in the mitigation area at all depths in 1998. Carbon levels decreased with depth in both the reference area and mitigation area. Between 1993 and 1998 (Table 6), a decrease in soil C occurred in the mitigation area at the 90 to 100 cm depth ($p = 0.067$), although not highly significant. Soil pH increased at the 5 to 15 cm depth ($p = 0.024$) and decreased at the 40 to 50 cm depth ($p = 0.021$) and a significant decrease in soil N was observed in the mitigation area at all depths between 1993 and 1998.

### 4.2 Hydrologic Gradients

Initial investigations of the Fort Lee mitigation area revealed an obvious wetness gradient created during site construction. Well readings (Figure 8a) taken from July 1997 to January 1999 confirmed and detailed the wetness gradient. Moving east across the mitigation area, the site progressed from VPD to SWPD soils. The SWPD soils of the mitigation area occur along a highly compacted and elevated ridge created during construction. Soils of the VPD region were saturated within 30 cm of the soil surface for 164 days (68% of the growing season) and saturated at or above the surface for 98 days (40% of the growing season). Soils of the PD region were saturated within 30 cm of the soil surface for 123 days (51% of the growing season) and saturated from 0 to 15 cm for

98 days (40% of the growing season). Soils of the SWPD ridge were never ponded, but saturated within 30 cm for 70 consecutive days (30% of the growing season).

A similar wetness gradient existed in the reference area (Figure 8b), but was much more complex spatially. Regions further away from Cabin Creek were PD and saturated from 0 to 15 cm for 57 days (25% of the growing season), while soils contiguous to Cabin Creek tended to be VPD and were saturated at or above the soil surface for 70 days (30% of the growing season). Very poorly drained areas were saturated within 30 cm of the soil surface for 85 days (35% of the growing season), while PD areas were saturated within 30 cm of the soil surface for 70 days (30% of the growing season). Somewhat poorly drained soils were not found in the reference area due to the hydrologic characteristics of the area.

Mitigation and reference areas exhibited similar patterns in water table fluctuations during the monitoring period (Figure 9a & 9b). Water tables were highest from November through May as a result of increased precipitation and decreased evapotranspiration.

### 4.3 Observations of Redoximorphic Features at Fort Lee

The occurrence of redoximorphic features was evaluated by drainage class. As discussed earlier, redox feature descriptions are largely qualitative since it is difficult to obtain accurate and repeatable quantitative estimates of relative occurrence, size, and distinctness. In a given horizon in a given pedon, redox features will vary from point to point laterally due to short range changes in rooting, organic matter, texture, and internal drainage. This study attempted to make quantitative counts of redox features, specifically oxidized rhizospheres, noting location and size of features. The overall discussion below is drawn from a combination of quantitative data and qualitative synthesis of the features observed across and within the many pedons studied.

Numerous redoximorphic features were observed and counted, including Fe accumulations/depletions and Mn accumulations, but a greater emphasis was place on oxidized rhizospheres due to the disturbed state of the mitigation area. Oxidized rhizospheres are presumably active features indicative of current hydrologic conditions, whereas Fe and Mn accumulations/depletions could be relict features from a previous hydrologic regime. Oxidized rhizospheres were located mainly in surface horizons where roots were concentrated. They were associated with active root channels both on and within ped faces. In the PD and VPD areas, black Mn masses 0.5 to 1.0 cm in diameter were observed within peds starting at a depth of 40 cm. Strong brown Fe masses were also noted in PD and VPD areas and were generally 0.25 to 1.0 cm in diameter, associated with small pockets of sand. The Fe masses occurred higher in the profile, generally occurring between 10 and 30 cm. In SWPD areas no Mn masses were observed. Yellowish red to strong brown Fe masses were associated with ped faces. These features started at a depth of 20 cm and continued throughout the profile.

Mitigation area soils in the VPD areas contained a greater quantity of active redox features (Figure 10 and Table 9a) in the surface horizon than those soils in upslope, drier areas. Fewer active oxidized rhizospheres occurred in the SWPD soils and where present, were faint. Within a 100 $cm^2$ area of the surface horizon, 62% of roots formed oxidized rhizospheres in the VPD areas as compared with 31% in the SWPD areas. Redox feature prominence decreased as the degree of soil saturation decreased. Prominent features were observed in VPD areas, distinct features were observed in PD areas, and faint features were observed in SWPD areas. Oxidized rhizospheres in the PD areas were more abundant than those in the SWPD areas, but less prominent than those in the VPD areas. Forty seven percent of roots in the PD areas contained oxidized rhizospheres as compared to 31% in the SWPD areas. The oxidized rhizospheres of the PD areas were described as distinct, while those of the VPD areas were described as prominent. Among the three transects within the mitigation area, the northern-most transect was coarser in texture than the other two transects and oxidized rhizospheres in this transect were not as prominent, but still followed the general trend of occurrence discussed above.

In the reference area, redox features did not reflect the saturation gradient as distinctively as soils of the mitigation area (Figure 10 and Table 9b). Oxidized rhizospheres in both VPD and PD areas were faint. Poorly drained areas contained fewer oxidized rhizospheres in surface horizons than VPD areas, as expected. Sixty five percent of roots in VPD areas contained oxidized rhizospheres as compared with 37% in the PD areas. Oxidized rhizospheres (0.25 to 0.5 cm) were associated with active root channels in surface horizons, while larger Fe masses (1.0 to 2.0 cm) were associated with pore linings above the water table.

### 4.4 Fort Lee Vegetation

Vegetation standing biomass (Table 10) was estimated for each drainage class along each transect in both the reference area and mitigation area. Stand density in the reference area was estimated by measuring basal area. In PD areas, basal area was 67.65 $m^2$ $ha^{-1}$ as compared to 183.45 $m^2$ $ha^{-1}$ in VPD areas. These high estimates reflect bias in sampling a number of large trees within small plots, resulting in an over-sampling relative to the number of trees in the entire stand.

All sites in the reference area were dominated by a mix of red maple, sweet gum, and swamp chestnut oak (*Quercus michauxii* Nutt.). In the shrub layer, the wetland was dominated by sweetbay magnolia and sweet pepperbush. Very poorly drained sites also contained switch cane (*Arundinaria gigantea* Walt.), while PD sites contained extensive greenbriar (*Smilax rotundifolia* L.). Where present, the herbaceous layer was dominated by lizards tail in VPD areas and cardinal flower (*Lobelia cardinalis* L.) in PD areas. All species found in the reference area were facultative-upland or wetter.

Very poorly drained areas in the mitigation site were dominated by common cattail and supported an average of 4234 kg $ha^{-1}$ of standing biomass. Poorly drained areas contained a mix of common cattail, woolgrass (*Scirpus cyperinus* L.), and tall fescue and standing biomass averaged 4028 kg $ha^{-1}$. Moderately well drained areas were dominated by tall fescue and annual lespedeza (*Lespedeza striata* L.) and produced an average of 2521 kg $ha^{-1}$ of standing biomass. Dominant vegetation types in the SWPD areas do not agree with the well records which show saturated conditions within 30 cm of the surface for 30% of the growing season. These areas are capable of supporting more water-tolerant species, but may lack such types of vegetation due to low levels of organic matter and high redox potentials. Standing biomass did not significantly vary with drainage class ($p = 0.739$). Vegetation growing in VPD areas had a wetland indicator status of facultative-wet or wetter. Vegetation in the PD areas ranged from facultative-wet to facultative-upland status and in SWPD areas straight facultative to upland species dominated. Wetland vegetation indicators of the SWPD areas ranged from facultative to upland.

Litter layers (L – leaf, F – fermentation) were collected and weighed for sites in both the reference and mitigation area (Table 11). L layers in VPD areas of the mitigation wetland averaged 1381 kg $ha^{-1}$, while L layers VPD sites of the reference area averaged 1821 kg $ha^{-1}$. This difference was not significant ($p$ = 1.00). L layers in PD sites of the mitigation wetland averaged 1202 kg $ha^{-1}$ and did not differ ($P$ = 0.825) from the average L layer in the reference area of 1139 kg $ha^{-1}$. L layers in the SWPD sites averaged 1785 kg $ha^{-1}$. Leaf (L) layers did not vary by drainage class within the mitigation area ($p$ = 0.276) or the reference area ($p$ = 0.383).

F layers in VPD sites of the mitigation area averaged 5463 kg $ha^{-1}$ (1.56% ash), while VPD sites in the reference area averaged 8271 kg $ha^{-1}$ (0.76% ash). This difference was also not significant ($p$ = 0.663). Poorly drained sites in the mitigation area averaged 2664 kg $ha^{-1}$ (2.53% ash) and were not different ($p$ = 0.149) from the average F layer in the reference area (4691 kg $ha^{-1}$ – 2.78% ash). F layer weights did not vary across drainage class in either the mitigation ($p$ = 0.773) or the reference ($p$ = 0.663) area.

# 5. DISCUSSION

My comparative study results reveal several trends that were observed within all three study sites. Mitigation areas tended to be lower in C and N levels, higher in soil pH and bulk density, and coarser in texture than their paired reference areas. Both mitigation areas and reference areas exhibited a decrease in C and N levels with depth as would be expected. Horizon differentiation was much greater in the reference area and the associated mature forested wetland was much more diverse. Mitigation areas were dominated by herbaceous and shrub species, including both upland and wetland plants. All of these differences are a result of construction practices, lack of site development time, or perhaps both.

## 5.1 Site Development

Many differences between the paired natural reference areas and mitigation areas that I studied here can be attributed to a lack in development time. Mitigation areas were dominated by herbaceous and shrub species due to their young age and reflect an early stage of primary succession. Limited soil profile differentiation in mitigation site pedons was also primarily due to their young age. Lack of pedon differentiation was also a result of construction practices which break down replaced soil structure, compact the soil and increase bulk density, thereby limiting water movement and associated pedogenic processes. Mitigation sites have historically been deprived of significant additions of organic amendments after construction, which help to improve aggregation, increase levels of organic matter, and increase microbial activity (Atkinson, 1991). When wetland soil is stockpiled to be redistributed over the mitigation area, it often loses organic matter during storage and seldom in reapplied at the same depths as removed due to the mitigation ratio. Historically, VDOT has been more likely to return upland topsoil to mitigation sites than wetland mucks (Haering et al., 1994).

## 5.2 Changes Over Time

Very few changes in mitigation soil properties were detected over the five-year study period. Initially low levels of C and N in the mitigation area did not seem to rise over time, which would imply organic matter accumulation is not occurring. In some instances, soil C actually declined over the five-year period. An unchanging amount of soil C in the mitigation area would indicate that the degree of saturation is not sufficient enough to retard the rate of organic matter decomposition. Low and unchanging total N levels are also a result of limited organic matter accumulation. In forest soils, N is accumulated in the form of plant and animal residues. If soil moisture and pH conditions are well suited for decomposition, but are not wet enough to limit humus losses, mitigation wetlands will not see net accumulations of organic matter or a rise in soil C and N with time.

Due to an apparent lack of organic matter and associated acidification over time, soil pH levels in mitigation areas were higher than those in the paired reference areas. The decomposition of organic matter forms both organic and inorganic acids which, over time, dissolve and leach large amounts of base cations, lowering soil pH. The soils of the mitigation area have not undergone sufficient acid leaching to remove bases and release Fe and Al for acid hydrolysis.

Soil physical properties are also affected by the lack of organic matter and time. Matrix colors of chroma 2 or less appeared less frequently in the subsoil of mitigation sites than in reference areas. This can also be attributed to the previous hydrologic regime of the pre-construction mitigation sites. Soils in the mitigation areas were originally located in an upland-transition zone, where bright colors would be expected (Veneman et al., 1976; Vepraskas and Wilding, 1983; Evans and Franzmeier, 1986). According to Vepraskas et al. (1999), even under ideal circumstances the development of reduced matrices requires at least five years. Ideal conditions would include saturated and reducing conditions during the growing season, adequate amounts of organic matter ($\geq 1.5\%$), and an active microbial population.

My results are similar, but more detailed and specific to the Coastal Plain than those reported by other reference/mitigation comparison studies. In a comparison of reference wetlands and created wetlands in Pennsylvania, Bishel-Machung et al. (1996) found reference wetlands to be higher in soil organic matter and percent total-N than wetland creation projects. Organic matter levels in the reference wetland were significantly higher at 5 cm than at 20 cm, while mitigation wetlands had uniform organic matter levels at both depths. These differences were explained by increased surface accumulation of organic matter within the reference wetland, while mitigation wetlands experienced no apparent surface accumulation. Bishel-Machung et al. (1996) studied a broader range of wetland types, varying in landscape position and parent material, whereas my study focused on mitigation-reference pairs of palustrine wetlands in Coastal Plain sediments, minimizing some of the natural variability found in soils. Although many of my overall results were similar, my study involved direct comparisons of mitigation-reference pairs with more detailed sampling, full profile descriptions, well records, and vegetation sampling.

Confer and Niering (1992) compared five created palustrine/emergent wetland sites with natural reference wetlands in Connecticut. Created sites exhibited more open water, deeper surface water depths, and more fluctuations in water depths than natural wetlands. Created sites lacked hydric soil indicators, possibly as a result of low organic matter content. Vegetation within the created sites was dominated by common cattail, while natural wetlands contained a diverse mix of emergent vegetation. Although Confer and Niering studied primarily emergent created wetlands, their findings tend to support my observations of low levels of organic matter and lower species diversity in mitigation areas.

Stolt et al. (1999) reported on the same wetlands studied here and found greater micro-relief, greater variability in particle size distribution, and significantly higher levels of organic C, N, and cation exchange capacity in reference sites. I found similar results and expanded on related topics in my comparisons. Sharing only the same 1993 data sets for C and N, my comparative study evaluated soil chemical properties between reference and mitigation wetland pairs, and changes in mitigation soil chemical properties over time. My study included a much more detailed evaluation of soil characteristics along a wetness gradient, examining trends in the presence of redoximorphic features that were not described in detail by Stolt et al. They also found similarities between the paired wetlands in redox potentials and soil temperatures, which were not evaluated in my study.

### 5.3 Use of α,α'-Dipyridyl Solution

Testing for the presence of $Fe^{2+}$ produced varying results and associated interpretations in my study. Some horizons were gleyed and saturated, but did not react to the α,α'-dipyridyl solution. In this instance, all $Fe^{2+}$ may have been leached from the profile. Reduced Fe was also detected in horizons which were not gleyed. This could mean the Fe was being actively mobilized to some extent before gray colors appear. Childs (1981) also gives several reasons for false positives. False positive readings could be obtained if the dye solution is applied to soil that has been in contact with steel tools, if the sample has been exposed to strong sunlight after dye application, or if the sample were previously tested for carbonates using a 10% solution of hydrochloric acid. Results were mixed in recent studies using α,α'-dipyridyl solution to test for the presence of $Fe^{2+}$. Calmon et al. (1998) observed redoximorphic features, soil saturation during the growing season, and low Eh conditions suitable for Fe reduction, but received negative results with the solution. Lynn and Austin (1998) supported the presence of ferrous iron with soil saturation, low Eh readings, and a positive reaction to α,α'-dipyridyl solution. Griffin et al. (1998) confirmed results when using the dye as an indicator of wetness and reducing conditions in a microtoposequence on the Texas coast prairie. Use of the α,α'-dipyridyl dye solution alone should therefore not be recognized as a definite indicator of reduced Fe. The dye should be used to support results obtained from additional long term sampling regimes, such as piezometers, tensiometers, redox potential electrodes, and observed redoximorphic features.

My study also obtained mixed results using the dye. In reference areas at all sites, some gleyed horizons below the water table did not produce a positive reaction to the dye. This would suggest that all $Fe^{2+}$ had been removed from the given horizon. In mitigation areas at all sites, some bright colored horizons were saturated but still did not produce a positive reaction to the dye. This would suggest that some areas of mitigation wetlands are saturated but not reduced, most likely due to low levels of organic matter and limited microbial activity.

## 5.4 Redoximorphic Features at Fort Lee

My detailed study of mitigation soils at Fort Lee found that the occurrence of active redoximorphic features reflected the current hydrologic regime and that these features have apparently formed in less than 10 years. Stolt et al. (1998) investigated the time frame required for the formation of certain redoximorphic features at Fort Lee in buried weathering bags. Redoximorphic features were observed within the interiors and exteriors of simulated peds within two years. Vepraskas et al. (1995) showed that redoximorphic features could be used as indicators of wetland hydrology in soils of constructed wetlands that are ponded or flooded for short periods of time (7 to 14 days). In another study, Vepraskas et al. (1999) found hydric soil field indicators formed by Fe reduction developed over time in a constructed marsh, with full development of Fe depleted matrices occurring five years after construction. Areas experiencing longer periods of saturation during the growing season contained higher quantities of prominent redox features than better drained areas. These results are in agreement with the results of my study.

Similar results were also found along a natural catena in Oregon by Simonson and Boersma (1972). The size and abundance of Fe and Mn concentrations increased with increasing wetness. Schwertmann and Fanning (1976) found maximum amounts of Fe and Mn concretions increasing with increasing wetness in the Eder hydrosequence in Bavaria. These results indirectly support findings from this study. Although they refer to relationships in natural areas, similar relationships were observed in the mitigation area of Fort Lee. The presence of redoximorphic features, particularly oxidized rhizospheres, increased with longer periods of saturation (Figure 10). For this site, jurisdictional areas were separated from non-jurisdictional areas by having greater than 35% relative abundance of oxidized rhizospheres in the surface. Soils in SWPD areas contained less the 35%. Trends in the occurrence of redox features with local changes in wetness or texture were not as pronounced in the reference area at Fort Lee. Differences between drainage classes in the reference area were not as pronounced as in the mitigation area and soils were fairly uniform throughout the reference area. Well developed and deep A horizons coupled with very sandy textures probably worked in concert to mask prominence in surface horizon features in the Fort Lee reference area.

Coarser textured horizons in the Fort Lee mitigation area displayed fewer redox features than clayey horizons of the same drainage class. This trend could be a result of water holding capacity and the effects of finer textured materials on gas exchange and reduction reactions. Kuehl et al. (1997) discussed difficulties encountered in identifying redox features in many sandy soils due to naturally low levels of Fe, which would not readily form redoximorphic features under reducing conditions. Kuehl et al. refer specifically to albic horizons of Spodosols, which did not occur in the Fort Lee mitigation wetland.

### 5.5 Hydrologic Gradients at Fort Lee

Mitigation and reference areas of Fort Lee, Elmwood-Baylor, and Western Freeway exhibited similar patterns in seasonal water table fluctuations during the period studied, but mean seasonal water table depths were very different between the mitigation-reference pairs. Water tables were highest from November through May as a result of increased precipitation and decreased evapotranspiration. A different scenario occurred at each of the three sites. At Elmwood-Baylor, water levels in the mitigation area were generally at or above the soil surface throughout the growing season, while reference area water levels exhibited a greater fluctuations with the seasons. High water tables have contributed to the dominance of herbaceous vegetation in the mitigation area. Well records at Western Freeway show that the reference area maintained a more constant water table at or just below the surface when compared to the mitigation area, which was 10 cm above the surface in the winter months and 35 cm below the surface in the summer months. Well records do not reflect the current beaver activity at Western Freeway, which has greatly influenced site hydrology. As a result, water tables are higher year-round, with saturation to the surface in the mitigation area and inundation in the reference area. Water table levels and the overall hydrologic regime at these sites greatly influence the function and characterization of each wetland pair. Hydrology also influenced site characteristics at the Fort Lee wetland.

At Fort Lee, SWPD areas were saturated within 30 cm of the soil surface for 30% of the growing season, with seasonal high water tables never reaching the soil surface.

Poorly drained areas were saturated within 30 cm of the soil surface for 51% of the growing season, with almost 100 consecutive days between 0 and 15 cm. Very poorly drained areas were saturated within 30 cm of the soil surface for 68% of the growing season, with almost 100 consecutive days at or above the soil surface. At this site the relative occurrence of oxidized rhizospheres exhibits a direct relationship with the seasonal saturation interval and can be used as an indicator of wetland hydrology. According to the COE Wetlands Delineation Manual (Environmental Laboratory, 1987), VPD and PD areas of the Fort Lee mitigation site meet the criteria for wetland hydrology, while SWPD areas may not meet the specified criteria. The manual outlines parameters for wetland hydrology which require that an area be seasonally saturated and/or inundated to the surface for a consecutive number of days for more than 12.5% of the growing season. Areas saturated to the surface between 5% and 12.5% of the growing season my or may not be wetlands (Environmental Laboratory, 1987). Somewhat poorly drained areas may be saturated for some time during the growing season, but are never inundated to the soil surface. Failure to meet wetland criteria could prevent approval for release by the COE.

### 5.6 Fort Lee Vegetation

A detailed comparison of vegetation in both the reference and mitigation area of Fort Lee revealed many similarities. Biomass measurements did not widely vary with drainage class, possibly due to the different types and adaptations of plants found in each area and the relative youth of the young successional system. The VPD areas contained facultative-wet to obligate wetland species, while the SWPD areas were dominated by facultative to upland species despite being wet at or near the surface for 30% of the growing season. Litter and fermentation layers in the reference and mitigation area did not differ in total weight. Although the reference area supports a mature forest, both areas contained comparable amounts of accumulated litter, particularly in the L layer, indicating somewhat similar levels of primary productivity and first year decomposition. Thus, it appears that even while the vegetative community and canopy structure are quite different between the mitigation and reference areas, certain biomass turnover functions could be quite similar.  Further detailed study is currently ongoing at Fort Lee on this topic.

## 6. SUMMARY AND CONCLUSIONS

Various conclusions can be drawn from this comparative study of wetland mitigation/reference pairs which encompassed the three major aspects of wetland classification: soils, vegetation, and hydrology. In general, mitigation wetlands are dramatically different from reference wetlands in terms of soil chemical and physical properties, plant communities, and hydrologic regimes, but at the same time share many of the same functions and values.

Mitigation area soils are lower in C and N, higher in bulk density and soil pH, and coarser in texture than their adjacent reference wetlands. These differences are mainly due to construction practices and a lack of organic matter accumulation. When mitigation sites are designed and constructed, attempts should be made to reduce site compaction by ripping and chisel-plowing both the subsoil and topsoil layers. In addition, natural muck topsoils or soil amendments rich in organic matter should be applied to the surface before planting. Such amendments will provide the beneficial effects of organic matter, which act to improve aggregation, decrease bulk density, improve water holding capacity, and provide essential nutrients for plant growth.

Since organic amendments are not often used, newly planted hydrophytic vegetation must struggle to survive in nutrient deficient, compacted soils, that may also have a higher redox potential than the plants prefer. Newly established mitigation areas are often dominated by undesirable wetland species such as cattails, while reference areas are more diverse, mature forested wetland communities. Increasing the amount of microtopography will increase environmental variability and species diversity. Eventually, more desirable wetland species begin to replace the “weed” species, but this process takes time. Hydrophytic species not only need essential nutrients for successful growth, but they also need the proper hydrologic regime and associated redox conditions.

In a well planned mitigation site, the hydrologic regime can mimic that of the reference area very closely, but this requires monitoring prior to site construction to locate water table levels and very precise forward water budgeting procedures. In the Fort Lee mitigation area a wetness gradient exists, which transitions from very poorly drained to somewhat poorly drained areas. Well records from the mitigation and reference area show similar trends in water table rise and fall, with the highest water tables occurring from November through May due to increased precipitation and decreased evapotranspiration as expected. Somewhat poorly drained areas were saturated for the shortest amount of time at greater depths than very poorly and poorly drained areas, and therefore may not meet wetland hydrologic criteria. Poorly drained areas were saturated to the surface for a short time during the growing season and were saturated long enough near the surface to meet wetland hydrologic criteria. Very poorly drained areas remained saturated at or above the soil surface for the longest duration, easily meeting wetland hydrologic criteria. Varying degrees of saturation affected soil morphology within the mitigation/reference pair.

Along the observed wetness gradient at Fort Lee, oxidized rhizospheres in surface horizons were more abundant and more prominent in areas saturated at or above the surface for longer periods of time. Better drained areas had fewer oxidized rhizospheres, which were more faint. Areas of coarser textured materials possessed more faint features than finer textured materials in the same drainage class. Other features such as Fe/Mn concentrations/depletions were present, but emphasis was placed on oxidized rhizospheres in this study. Oxidized rhizospheres are associated with active root channels and have formed in less than 10 years under the current hydrologic conditions. Matrix colors in the mitigation area are dominantly relict features from a previous hydrologic regime and will require years of organic matter accumulation and soil saturation and reduction to become gleyed.

For a mitigation site to be approved for release by the COE, it must meet wetland criteria within a permitted monitoring time-frame of five to ten years in Virginia. This study suggests that the five-year deadline is premature, given the current construction methods and soil development sequences studied. More research is needed to examine the interactions between soils, hydrology, and vegetation in both natural and created wetlands over extended periods of time. A better understanding of these systems will result in improved design techniques, construction methods, and long-term site sustainability. Little is known about time requirements in the field for the development of redoximorphic features in both natural and mitigation wetlands. Better construction and design methods should incorporate the replacement of mucky surface soils and the addition of organic amendments, with attempts to limit or ameliorate soil compaction through ripping after grading.

**Table 1a.-1c.** Typifying pedon descriptions for soil series mapped at Fort Lee. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

**Table 1a.** Fort Lee Reference Area: Kinston series (SCS, 1985a).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| A1 | 0 - 10 | 10YR 4/2 | -- | -- | L | 1MGR | M2,3 | CS |
| A2 | 10 - 18 | 10YR 6/2 | 10YR 6/6 | F1D | L | 1MGR | M2 | CS |
| Cg1 | 18 - 36 | 10YR 6/1 | 10YR 5/8 | M2D | CL | 0MA - 1FSBK | F2 | CW |
| Cg2 | 36 - 102 | 10YR 6/1 | 10YR 6/6 | M2D | CL | 0MA - 1FSBK | F2 | CW |
| Cg3 | 102 - 125 | 10YR 6/1 | 10YR 5/8 | F2D | CL | 0MA - 1CSBK | -- | GW |
| Cg4 | 125 -157 | 10YR 6/1 | -- | -- | CL | 0MA | -- | -- |

**Table 1b.** Fort Lee Mitigation Area: Emporia series (SCS, 1985a).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| Ap | 0 - 20 | 10YR 4/2 | -- | -- | FSL | WFGR | M2 | AS |
| Bt1 | 20 - 36 | 10YR 5/6 | 2.5Y 6/4 | C2F | L | WFSBK | C2 | CS |
| Bt2 | 36 - 50 | 10YR 5/8 | -- | -- | L | WFSBK | F2 | GS |
| Bt3 | 50 - 71 | 10YR 5/8 | 7.5YR 5/6;<br>2.5Y 6/4 | C2D;<br>F2F | CL | WF,MSBK | F2 | GS |
| Bt4 | 71 - 101 | 10YR 5/8 | 5YR 5/6;<br>10YR 6/4 | C3D;<br>C2F | CL | WMSBK | F2 | GS |
| Bt5 | 101 - 127 | 10YR 5/6 | 10YR 7/1;<br>2.5YR 5/6 | C1F;<br>F2D | SCL | WTKPL - WFSBK | F2 | GS |
| C | 127 - 163 | 10YR 5/6 | 10YR 7/1;<br>2.5YR 5/6 | M3D;<br>C2D | SCL | 0MA | -- | -- |

**Table 1c.** Fort Lee Mitigation Area: Slagle Series (SCS, 1985a).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| Ap | 0 - 25 | 10YR 5/2 | -- | -- | SL | WFGR | C1 | AS |
| Bt1 | 25 - 41 | 10YR 6/4 | -- | -- | SL | WFSBK | F2 | CS |
| Bt2 | 41 - 53 | 10YR 5/6 | -- | -- | SL | WFSBK | F1 | CS |
| Bt3 | 53 - 66 | 10YR 5/6 | 7.5YR 5/6 | C2D | SCL | MMSBK | F1 | CS |
| Bt4 | 66 - 91 | 10YR 6/4 | 7.5YR 5/6 &<br>10YR 6/2 | M3D | SCL | WTKPL - MFSBK | F1 | GS |
| Btg | 91 - 122 | 10YR 6/1 | 7.5YR 5/6 &<br>2.5Y 6/4 | M3D | SCL | WCSBK | -- | GS |
| Cg | 122 - 165 | 10YR 6/1 | 10YR 5/6 | C3D | SL | 0MA | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 2a. - 2c.** Typifying pedon descriptions for soil series mapped at Elmwood-Baylor. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

**Table 2a.** Elmwood-Baylor Reference Area: Bibb Series (Hoppe, 1989).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| A | 0 - 10 | 10YR 4/3 | -- | -- | SL | WFGR | M2 | CS |
| Cg1 | 10 - 56 | 2.5Y 5/2 | 10YR 5/6 | C2D | L | 0MA | M2 | GS |
| Cg2 | 56 - 91 | 10YR 6/1 | -- | -- | LS | 0SG | C2 | GS |
| Cg3 | 91 - 122 | 10YR 6/1 | -- | -- | SL | 0MA | C2 | GS |
| Cg4 | 122 - 183 | 10YR 7/1 | -- | -- | SL | 0SG | C2 | -- |

**Table 2b.** Elmwood-Baylor Mitigation Area: Rumford Series (Hoppe, 1989).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| Ap | 0 - 18 | 10YR 5/3 | -- | -- | LS | WFGR | M2, F3 | CS |
| BE | 18 - 36 | 10YR 5/4 | -- | -- | LS | MFSBK | C2 | GS |
| Bt1 | 36 - 58 | 7.5YR 4/6 | -- | -- | SCL | WMSBK | F2 | CS |
| Bt2 | 58 - 79 | 7.5YR 4/6 | -- | -- | SL | WFSBK | F2 | GS |
| BC | 79 - 132 | 10YR 5/8 | -- | -- | LS | 0SG | F2 | GS |
| C | 132 - 183 | 10YR 6/8 | 10YR 8/2 | F2D | FS | 0SG | F2, F3 | -- |

**Table 2c.** Elmwood-Baylor Mitigation Area: Emporia series (Hoppe, 1989).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| A | 0 - 8 | 2.5Y 5/2 | -- | -- | SL | WFGR | M2 | CS |
| E | 8 - 23 | 10YR 5/4 | -- | -- | L | WFGR | M2; F3 | CS |
| Bt1 | 23 - 33 | 10YR 5/8 | -- | -- | CL | WFSBK | C2 | CW |
| Bt2 | 33 - 61 | 7.5YR 5/6 | 5YR 5/8;<br>10YR 5/6 | F1D;<br>C3D | CL | WFSBK | F2 | CW |
| Bt3 | 61 - 107 | 10YR 6/6 | 7.5YR 5/6;<br>5YR 5/8 | C3D;<br>F1D | SCL | WTNPL - MMSBK | F2 | GS |
| Bt4 | 107 - 122 | 10YR 5/6 | 10YR 7/2;<br>10YR 6/3 | F2D;<br>M2D | SCL | WTNPL - MMSBK | -- | GW |
| Bt5 | 122 - 183 | 10YR 5/6 | 10YR 7/1;<br>2.5YR 5/8 | M2D | CL | WVTNPL - MFSBK | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 3.** Typifying pedon descriptions for soil series mapped at Western Freeway. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Texture | Structure | Roots | Boundary |
|---|---|---|---|---|---|---|---|---|
| Ap | 0 20 | 10YR 3/1 | -- | -- | FSL | WFGR | C2 | AS |
| Btg1 | 20 - 46 | 10YR 5/2 | 10YR 6/3 | F1F | L | WC&MSBK | F2 | GW |
| Btg2 | 46 - 74 | 10YR 5/1 | 2.5Y 5/6 | C2D | L | WC&MSBK | F2 | CW |
| Bg | 74 - 99 | 10YR 6/1 | 2.5Y 4/4 | C1D | FSL | WCSBK | -- | CW |
| 2C | 99 - 130 | 10YR 5/8 | 5Y 8/1 | M3D | LS | 0SG | -- | AW |
| 2Cg | 130 - 158 | 5Y 8/1 | 5Y 6/2 | M2F | S | 0SG | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 4.** Typifying pedon descriptions for soils described at Elmwood-Baylor in July, 1998. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference Area | | | | | | | | | | | |
| A1 | 0 - 10 | 7.5YR 4/3 | 7.5YR 3/4 | M1D | Pore linings | M2 | LS | WFGR | + | CS | |
| A2 | 10 - 23 | 7.5YR 5/1 | 7.5YR 4/3 | C1F | Fe masses | F3 | LS | 0MA | + | AB | |
| Cg1 | 23 - 70 | 2.5Y 5/1 | 7.5YR 4/3 | F1F | Fe masses | -- | SL | 0MA | + | CS | WT @ 30 cm |
| Cg2 | 70 - 150 | 2.5Y 5/1 | -- | -- | -- | -- | L | 0MA | + | -- | |
| Mitigation Area | | | | | | | | | | | |
| A | 0 - 20 | 5B 6/1 | -- | -- | -- | M3 | SL | WFGR | + | AS | WT @ surface |
| 2C | 20 - 112 | 7.5YR 5/8 | 2.5Y 2.5/1;<br>2.5Y 6/3 | C1F;<br>M1D | Mn masses;<br>In matrix | F2 | L | 0MA | - | GS | |
| 2Cg | 112 - 150 | 5Y 5/1 | -- | -- | -- | -- | L | 0MA | + | -- | |

*Redox Color refers to primary depletions or concentrations.

**Table 5.** Means for selected soil chemical properites sampled in 1993 (Haering et al., 1994). Means followed by different letters within columns by site are significantly different (P = 0.05, Fisher's LSD). Reference means with and * are significantly different from mitigation means at the matching depth by site (P = 0.05, Wilcoxon Rank Sum).

| Wetland | n | pH | % N | % C |
|---|---|---|---|---|
| Elmwood Baylor - Reference | | | | |
| 0-5 cm | 2 | 4.53 | 0.48a | 6.02a |
| 5-15 cm | 15 | 4.80* | 0.28*b | 4.44*a |
| 40-50 cm | 15 | 4.62* | 0.12b | 1.79*b |
| 90-100 cm | 15 | 4.69* | 0.07b | 0.92*b |
| Elmwood Baylor - Mitigation | | | | |
| 0-5 cm | 3 | 4.72a | 0.14a | 1.41a |
| 5-15 cm | 15 | 5.18b | 0.09b | 0.77b |
| 40-50 cm | 15 | 5.29b | 0.04c | 0.17c |
| 90-100 cm | 15 | 5.26b | 0.04c | 0.13c |
| Western Freeway - Reference | | | | |
| 0-5 cm | 3 | 6.05a | 0.22*a | 2.62*a |
| 5-15 cm | 15 | 5.44*ab | 0.44*b | 6.30*b |
| 40-50 cm | 15 | 5.14*ab | 0.42*b | 5.86*b |
| 90-100 cm | 15 | 5.08*b | 0.32*ab | 5.23*ab |
| Western Freeway - Mitigation | | | | |
| 0-5 cm | 6 | 5.67a | 0.14a | 1.05a |
| 5-15 cm | 15 | 6.87b | 0.09b | 1.01a |
| 40-50 cm | 15 | 6.07a | 0.07c | 0.40b |
| 90-100 cm | 15 | 5.40a | 0.05d | 0.09c |
| Fort Lee - Reference | | | | |
| 0-5 cm | no data | no data | no data | no data |
| 5-15 cm | 15 | 4.76*a | 0.18*a | 2.89*a |
| 40-50 cm | 15 | 4.86*a | 0.08*b | 0.92*b |
| 90-100 cm | 15 | 5.31b | 0.05c | 0.14* c |
| Fort Lee - Mitigation | | | | |
| 0-5 cm | no data | no data | no data | no data |
| 5-15 cm | 15 | 5.31 | 0.07a | 0.82a |
| 40-50 cm | 15 | 5.31 | 0.04b | 0.14b |
| 90-100 cm | 15 | 5.41 | 0.04b | 0.06b |

**Table 6.** Means for selected soil chemical properties of mitigation areas sampled in 1993 (Haering et al., 1994) and 1998. 1993 means followed by an * are significantly different from 1998 means at the matching depth by site (P = 0.05, Wilcoxon Rank Sum).

| Wetland | n | pH | % N | % C |
|---|---|---|---|---|
| Elmwood Baylor - 1993 | | | | |
| 0-5 cm | 3 | 4.72 | 0.14 | 1.41 |
| 5-15 cm | 15 | 5.18 | 0.09 | 0.77 |
| 40-50 cm | 15 | 5.29 | 0.04* | 0.17 |
| 90-100 cm | 15 | 5.26 | 0.04* | 0.13 |
| Elmwood Baylor - 1998 | | | | |
| 0-5 cm | 2 | 5.10 | 0.09 | 1.46 |
| 5-15 cm | 2 | 5.50 | 0.06 | 0.82 |
| 40-50 cm | 2 | 5.40 | 0.01 | 0.10 |
| 90-100 cm | 2 | 5.50 | 0.01 | 0.21 |
| Western Freeway - 1993 | | | | |
| 0-5 cm | 6 | 5.67 | 0.14* | 1.05 |
| 5-15 cm | 15 | 6.86 | 0.09* | 1.01 |
| 40-50 cm | 15 | 6.07 | 0.07* | 0.43 |
| 90-100 cm | 15 | 5.40* | 0.05* | 0.09 |
| Western Freeway - 1998 | | | | |
| 0-5 cm | 6 | 6.23 | 0.08 | 1.19 |
| 5-15 cm | 6 | 6.37 | 0.07 | 0.99 |
| 40-50 cm | 6 | 5.65 | 0.03 | 0.43 |
| 90-100 cm | 6 | 4.97 | 0.01 | 0.09 |
| Fort Lee - 1993 | | | | |
| 0-5 cm | 0 | N/A | N/A | N/A |
| 5-15 cm | 15 | 5.31* | 0.07* | 0.82 |
| 40-50 cm | 15 | 5.31* | 0.04* | 0.12 |
| 90-100 cm | 15 | 5.41 | 0.04* | 0.06* |
| Fort Lee - 1998 | | | | |
| 0-5 cm | 6 | N/A | N/A | N/A |
| 5-15 cm | 6 | 5.63 | 0.03 | 0.76 |
| 40-50 cm | 6 | 5.10 | 0.01 | 0.26 |
| 90-100 cm | 6 | 5.22 | 0.00 | 0.03 |

**Table 7.** Typifying pedon descriptions for soils described at Western Freeway in July, 1998. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

| Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference Area | | | | | | | | | | | |
| A1 | 0 - 19 | 10YR 3/2 | 7.5YR 5/8 | F1F | Pore linings | M2 | SL | WFGR | + | AS | |
| A2 | 19 - 40 | 10YR 4/2 | -- | -- | -- | F2 | SL | WFGR | + | AS | Sulfur smell |
| Btg | 40 - 70 | 2.5Y 4/2 | -- | -- | -- | F3 | SIL | 0MA | + | CS | WT @ 46 cm |
| Cg1 | 70 - 135 | 2.5Y 4/2 | -- | -- | -- | -- | S | 0SG | - | CS | |
| Cg2 | 135 - 150 | 2.5Y 6./2 | -- | -- | -- | -- | S | 0SG | - | -- | |
| Mitigation Area | | | | | | | | | | | |
| A | 0 - 46 | 2.5Y 4/2 | 7.5YR 5/8 | F1F | Fe masses | C2 | LS | WMGR | + | AS | |
| 2C1 | 46 - 70 | 2.5Y 6/4 | 10YR 6/8 | M1P | Fe masses | -- | SL | WMGR | - | GS | |
| 2C2 | 70 - 150 | 2.5Y 7/2 | 10YR 5/8 | M1D | Fe masses | -- | SL | 0MA | - | -- | WT @ 122 cm |

*Redox Color refers to primary depletions or concentrations.

**Table 8a – 8f:** Individual pedon descriptions for soils described at Fort Lee in July, 1998. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

**Table 8a.** Fort Lee Mitigation Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Somewhat Poorly (4C) | | | | | | | | | | | | |
| | A | 0 - 20 | 2.5Y 4/3 | 7.5YR 5/8 | C1F | Pore linings | C2 | SL | MMGR | - | GS | -- |
| | ACgd | 20 - 50 | 2.5Y 4/2 | 7.5YR 5/8 | C2D | Fe masses | F1 | SL | WTNPL | - | GS | -- |
| | 2C | 50 - 80 | 10YR 6/8 & 5Y 5/1 | 7.5YR 5/8 | F2D (relict) | Along ped faces | -- | SCL | 0MA | + | GS | Plastic |
| | 2Cg | 80 - 150 | 5Y 5/1 | -- | -- | -- | -- | LS | 0MA | + | -- | Sulfur smell |
| Poorly (4LD) | | | | | | | | | | | | |
| | A | 0 -25 | 2.5Y 5/4 | 10YR 5/8 | C1D | Fe masses & pore linings | C2 | LS | WMGR | - | AS | |
| | ACgd | 25 -66 | 5Y 7/2 & 7.5YR 6/8 | 10YR 5/8 | C1D | Pore linings | M2 | SL | WTNPL | - | AS | WT @ 61 cm |
| | 2C1 | 66 - 115 | 10YR 5/8 & 10YR 8/1 | -- | -- | -- | -- | LS | 0MA | - | AS | |
| | 2C2 | 115 - 150 | 10YR 5/8 | -- | -- | -- | -- | LS | 0SG | - | -- | |
| Very Poorly (4B) | | | | | | | | | | | | |
| | Oi | 4 - 0 | -- | -- | -- | -- | -- | -- | -- | -- | AS | -- |
| | A | 0 - 11 | 2.5Y 5/4 | 7.5YR 5/8 | F1F | Pore linings & Fe masses | C2 | LS | WFGR | - | AS | -- |
| | 2C1 | 11 - 80 | 10YR 6/6 | 10YR 8/1 | C2D (relict) | In matrix | F2 | SL | 0MA | - | GS | -- |
| | 2C2 | 80 - 150 | 5YR 5/8 | 5YR 4/6 | F2D (relict) | Fe masses | -- | S | 0SG | - | -- | WT @ 80 cm |

*Redox Color refers to primary depletions or concentrations.

**Table 8b.** Fort Lee Mitigation Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Somewhat Poorly (5C) | | | | | | | | | | | | |
| | A | 0 - 20 | 2.5Y 4/3 | 7.5YR 5/8 | F1F | Pore linings | C2 | SL | WFGR | - | AS | |
| | ACgd | 20 - 45 | 2.5Y 3/2 | 5YR 5/8 | F2D | Along ped faces | F1 | SL | WTNPL | - | AS | -- |
| | 2Cg | 45 - 80 | 5Y 6/1 | 5YR 5/8 | F2D (relict) | Along ped faces | -- | SL | 0MA | + | GS | Plastic |
| | 2C | 80 - 150 | 10YR 6/6 | -- | | | -- | S | 0MA | - | -- | -- |
| Poorly (5-3) | | | | | | | | | | | | |
| | A | 0 - 22 | 2.5Y 4/2 | 7.5YR 5/8 | C1D | Pore linings & Fe masses | C2 | SL | WMGR | - | AS | -- |
| | ACd | 22 - 50 | 5Y 7/2 & 10YR 6/8 | -- | -- | -- | -- | LS | WTNPL | - | AS | -- |
| | 2C | 50 - 150 | 10YR 6/8 | 10YR 3/1 | C2P (relict) | Mn masses | -- | S | 0MA | + | -- | WT @ 82 cm |
| Very Poorly (5B) | | | | | | | | | | | | |
| | A | 0 - 25 | 2.5Y 4/3 | 7.5YR 5/8 | C2P | Pore linings & Fe masses | C2 | SL | WFGR | - | AS | -- |
| | 2C1 | 25 - 70 | 10YR 6/8 | 10YR 3/1;<br>10YR 7/1;<br>7.5YR 5/8 | C1P (relict);<br>C1D (relict);<br>F2D (relict) | Mn masses;<br>Pore linings;<br>In matrix | F2 | S | 0MA | - | GS | WT @ 61 cm |
| | 2C2 | 70 - 150 | 2.5Y 6/4 | -- | -- | -- | -- | S | 0SG | - | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 8c.** Fort Lee Mitigation Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Somewhat Poorly (7C) | | | | | | | | | | | | |
| | A | 0 - 22 | 2.5Y 4/3 | 7.5YR 5/8 | C1F | Pore linings | C2 | SL | WFGR | - | AS | -- |
| | ACgd | 22 - 40 | 2.5Y 3/2 | 5YR 5/8 | C2D | Along ped faces | F1 | SL | WTNPL | - | AS | -- |
| | 2C1 | 40 - 80 | 10YR 5/6 & 5Y 6/1 | -- | -- | -- | -- | SL | 0MA | - | GS | -- |
| | 2C2 | 80 - 150 | 5Y 6/3 | 7.5YR 5/8 | C2D | Fe masses | -- | C | 0MA | - | -- | Highly plastic |
| Poorly (7-4) | | | | | | | | | | | | |
| | A | 0 -10 | 2.5Y 4/3 | 7.5YR 5/8 | F1F; F2F | Pore linings, Fe masses | C2 | SL | WFGR | - | GS | -- |
| | ACg | 10 - 40 | 10YR 4/1 | 5YR 5/8;<br>10YR 5/8 | M2D;<br>F2D | Pore linings,<br>Fe masses | F3 | SL | 0MA | - | AS | -- |
| | 2C | 40 - 60 | 10YR 5/8 | 10YR 3/1;<br>10YR 8/2 | C2P<br>F2D (relict) | Mn masses;<br>In matrix | -- | LS | 0MA | + | AS | -- |
| | 2Cg | 60 - 150 | 10YR 8/2 | 10YR 3/1 | C2P (relict) | Mn masses | -- | S | 0SG | - | -- | WT @ 77 cm |
| Very Poorly (7B) | | | | | | | | | | | | |
| | A | 0 - 25 | 2.5Y 4/3 | 7.5YR 5/8 | C2P | Pore linings & Fe masses | C2 | SL | WFGR | - | AS | -- |
| | 2C1 | 25 - 70 | 10YR 6/8 | 10YR 3/1;<br>10YR 7/1;<br>7.5YR 5/8 | C1P (relict);<br>C1D (relict);<br>F2D (relict) | Mn masses;<br>Pore linings;<br>In matrix | C2 | S | 0MA | - | GS | WT @ 61 cm |
| | 2C2 | 70 - 150 | 2.5Y 6/4 | -- | -- | -- | -- | S | 0SG | - | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 8d.** Fort Lee Reference Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Poorly (4LRA) | | | | | | | | | | | | |
| | A | 0 - 16 | 10YR 3/2 | 7.5YR 5/8 | F1F | Pore linings | M2, C3 | SL | WFGR | - | GS | -- |
| | Cg1 | 16 - 45 | 2.5Y 5/2 | 7.5YR 5/8 | F1F | Pore linings | C2, F3 | SL | 0MA | - | GS | -- |
| | Cg2 | 45 - 80 | 2.5Y 6/3 | 7.5YR 5/8 | C2F | Fe masses | F2 | LS | 0MA | - | GS | -- |
| | Cg3 | 80 - 150 | 2.5Y 7/1 | -- | -- | -- | -- | S | 0SG | + | -- | WT @ 90 cm |
| Very Poorly (Ref 5) | | | | | | | | | | | | |
| | A | 0 - 16 | 10YR 3/2 | 7.5YR 7/8 | M1F | Pore linings | C2 | SL | WMGR | - | GS | -- |
| | Cg1 | 16 - 70 | 2.5Y 5/2 | 10YR 3/1;<br>7.5YR 5/8 | F2F;<br>C1D | Mn masses;<br>Pore linings | F1 | SL | 0MA | - | GS | -- |
| | Cg2 | 70 -150 | 2.5Y 7/1 | -- | -- | -- | -- | S | 0SG | + | -- | WT @ 100 cm |

*Redox Color refers to primary depletions or concentrations.

**Table 8e.** Fort Lee Reference Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Poorly (Ref 4) | | | | | | | | | | | | |
| | A | 0 - 13 | 10YR 3/2 | -- | -- | -- | M1, 2 | LS | WFGR | - | GS | -- |
| | Cg1 | 13 - 60 | 2.5Y 5/1 | 7.5YR 5/8;<br>2.5Y 7/1 | C1F;<br>F2F | Pore linings;<br>In matrix | C2, 3 | SL | 0MA | + | AS | WT @ 47 cm |
| | Cg2 | 60 - 150 | 2.5Y 7/1 | -- | -- | -- | -- | S | 0SG | - | -- | -- |
| Very Poorly (5LRW) | | | | | | | | | | | | |
| | A | 0 - 13 | 10YR 3/2 | 7.5YR 5/8 | C1F | Pore linings & Fe masses | M1,2 | SL | WMGR | - | GS | -- |
| | Cg1 | 13 - 65 | 2.5Y 5/1 | 7.5YR 5/8 | C1D | Pore linings | C2,3 | SL | 0MA | + | AS | WT @ 45 cm |
| | Cg2 | 65 - 150 | 2.5Y 7/1 | -- | -- | -- | -- | S | 0SG | - | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 8f.** Fort Lee Reference Area Pedon Descriptions.

| Pit | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Roots | Texture | Structure | Dipyr. RXN. | Boundary | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Poorly (Ref 3A) | | | | | | | | | | | | |
| | A | 0 - 15 | 10YR 3/2 | 7.5YR 5/8 | F1F | Pore linings | M1,2 | SL | WFGR | - | GS | -- |
| | Cg1 | 15 - 60 | 2.5Y 5/1 | 7.5YR 5/8 | F1F | Pore linings | C2 | SL | 0MA | + | GS | WT @ 56 cm |
| | Cg2 | 60 - 150 | 2.5Y 7/1 | -- | -- | -- | -- | LS | 0SG | + | -- | |
| Very Poorly (Ref 3B) | | | | | | | | | | | | |
| | A | 0 - 10 | 10YR 3/2 | 7.5YR 5/8 | C2F | Pore linings | C2 | SL | WMGR | - | GS | -- |
| | Cg1 | 10 - 90 | 2.5Y 5/1 | 7.5YR 5/8 | M2D | Pore linings | C2 | SL | 0MA | + | GS | WT @ 56 cm |
| | Cg2 | 90 - 150 | 2.5Y 7/1 | -- | -- | -- | -- | S | 0SG | + | -- | -- |

*Redox Color refers to primary depletions or concentrations.

**Table 9a.** Quantitative measures of redoximorphic features in the Fort Lee mitigation area.

| Drainage Class & Sample Location | Depth (cm) | Roots | Oxidized. Rhizospheres | Percent of roots with Oxidized Rhizospheres |
|---|---|---|---|---|
| SWP – 4C | 0-20 | 21 | 10 | 47.62 |
| SWP – 4C | 20-50 | 1 | 0 | 0.00 |
| SWP – 4C | 50-80 | 0 | 0 | N/A |
| SWP – 4C | 80-150 | 0 | 0 | N/A |
| SWP – 5C | 0-20 | 33 | 7 | 21.21 |
| SWP – 5C | 20-45 | 2 | 0 | 0.00 |
| SWP – 5C | 45-80 | 0 | 0 | N/A |
| SWP – 5C | 80-150 | 0 | 0 | N/A |
| SWP – 7D | 0-22 | 40 | 10 | 25.00 |
| SWP – 7D | 22-40 | 3 | 0 | 0.00 |
| SWP – 7D | 40-80 | 0 | 0 | N/A |
| SWP – 7D | 80-150 | 0 | 0 | N/A |
| P – 4LD | 0-25 | 11 | 5 | 45.45 |
| P – 4LD | 115-150 | 0 | 0 | N/A |
| P – 4LD | 25-66 | 0 | 0 | N/A |
| P – 4LD | 66-115 | 0 | 0 | N/A |
| P – 5-3 | 0-22 | 37 | 12 | 32.43 |
| P – 5-3 | 22-50 | 0 | 0 | N/A |
| P – 5-3 | 50-150 | 0 | 0 | N/A |
| P – 7-4 | 0-10 | 30 | 10 | 33.33 |
| P – 7-4 | 10-40 | 10 | 8 | 80.00 |
| P – 7-4 | 40-60 | 0 | 0 | N/A |
| P – 7-4 | 60-150 | 0 | 0 | N/A |
| VP – 4B | 0-11 | 25 | 7 | 28.00 |
| VP – 4B | 11-80 | 3 | 0 | 0.00 |
| VP – 4B | 80-150 | 0 | 0 | N/A |
| VP – 5B | 0-25 | 26 | 20 | 76.92 |
| VP – 5B | 25-70 | 6 | 5 | 83.33 |
| VP – 5B | 70-150 | 0 | 0 | N/A |
| VP – 7B | 0-12 | 25 | 10 | 40.00 |
| VP – 7B | 12-35 | 12 | 10 | 83.33 |
| VP – 7B | 35-62 | 10 | 0 | 0.00 |
| VP – 7B | 62-150 | 0 | 0 | N/A |

**Table 9b.** Quantitative measures of redoximorphic features in the Fort Lee reference area.

| Drainage Class & Sample Location | Depth (cm) | Roots | Oxidized. Rhizospheres | Percent of roots with Oxidized Rhizospheres |
|---|---|---|---|---|
| P – 4LRA | 0-16 | 40 | 10 | 25.00 |
| P – 4LRA | 16-45 | 15 | 8 | 53.33 |
| P – 4LRA | 45-80 | 1 | 0 | 0.00 |
| P – 4LRA | 80-150 | 0 | 0 | N/A |
| P – REF3A | 0-15 | 10 | 5 | 50.00 |
| P – REF3A | 15-60 | 14 | 3 | 21.43 |
| P – REF3A | 60-150 | 0 | 0 | N/A |
| P – REF4 | 0-13 | 10 | 0 | 0.00 |
| P – REF4 | 13-60 | 18 | 6 | 33.33 |
| P – REF4 | 60-150 | 0 | 0 | N/A |
| VP – REF5 | 0-13 | 40 | 21 | 52.50 |
| VP – REF5 | 13-65 | 12 | 9 | 75.00 |
| VP – REF5 | 65-150 | 0 | 0 | N/A |
| VP – REF3B | 0-10 | 15 | 8 | 53.33 |
| VP – REF3B | 10-90 | 10 | 8 | 80.00 |
| VP – REF3B | 90-150 | 0 | 0 | N/A |
| VP – 5LRW | 0-16 | 30 | 20 | 66.67 |
| VP – 5LRW | 16-70 | 10 | 5 | 50.00 |
| VP – 5LRW | 70-150 | 0 | 0 | N/A |

**Table 10.** Woody stem (> 5 cm) basal area in the Fort Lee reference area.

| Drainage Class & Sample Location | Species | # Stems | BA | Total |
|---|---|---|---|---|
| | | | $m^2$ $ha^{-1}$ | $m^2$ $ha^{-1}$ |
| P – REF3A | American Holly (*Ilex opaca* Soland.) | 1 | 0.9 | |
| P – REF3A | Black Gum (*Nyssa sylvatica* Marsh.) | 6 | 4.2 | |
| P – REF3A | Swamp Chestnut Oak (*Quercus michauxii* Nutt.) | 4 | 1.5 | |
| P – REF3A | Swamp White Oak (*Quercus bicolor* Willd.) | 3 | 11.8 | |
| P – REF3A | Sweet Gum (*Liquidambar styraciflua* L.) | 1 | 2.8 | |
| P – REF3A | Willow Oak (*Quercus phellos* L.) | 2 | 5.9 | 27.1 |
| P – 4LRA | Black Gum (*Nyssa sylvatica* Marsh.) | 2 | 4.1 | |
| P – 4LRA | Loblolly Pine (*Pinus taeda* L.) | 1 | 0.3 | |
| P – 4LRA | Musclewood (*Carpinus caroliniana* Walt.) | 1 | 1.1 | |
| P – 4LRA | Red Maple (*Acer rubrum* L.) | 10 | 24.1 | |
| P – 4LRA | Swamp Chestnut Oak (*Quercus michauxii* Nutt.) | 12 | 21.0 | |
| P – 4LRA | Sweet Gum (*Liquidambar styraciflua* L.) | 3 | 25.1 | |
| P – 4LRA | Tulip Poplar (*Liriodendron tulipifera* L.) | 1 | 2.3 | |
| P – 4LRA | Willow Oak (*Quercus phellos* L.) | 8 | 10.1 | 88.1 |
| P – REF4 | Black Gum (*Nyssa sylvatica* Marsh.) | 3 | 6.0 | |
| P – REF4 | Loblolly Pine (*Pinus taeda* L.) | 1 | 3.1 | |
| P – REF4 | Musclewood (*Carpinus caroliniana* Walt.) | 1 | 4.3 | |
| P – REF4 | Red Maple (*Acer rubrum* L.) | 13 | 36.9 | |
| P – REF4 | Swamp Chestnut Oak (*Quercus michauxii* Nutt.) | 5 | 1.5 | |
| P – REF4 | Sweet Gum (*Liquidambar styraciflua* L.) | 3 | 10.7 | |
| P – REF4 | Tulip Poplar (*Liriodendron tulipifera* L.) | 1 | 25.5 | 88.0 |
| VP – REF3B | Black Gum (*Nyssa sylvatica* Marsh.) | 2 | 45.8 | |
| VP – REF3B | Pignut Hickory (*Carya glabra* Mill.) | 1 | 1.1 | |
| VP – REF3B | Musclewood (*Carpinus caroliniana* Walt.) | 1 | 0.5 | |
| VP – REF3B | Red Maple (*Acer rubrum* L.) | 1 | 6.8 | |
| VP – REF3B | River Birch (*Betula nigra* L.) | 1 | 7.3 | |
| VP – REF3B | Slippery Elm (*Ulmus rubra* Muhl.) | 1 | 3.5 | |
| VP – REF3B | Swamp Chestnut Oak (*Quercus michauxii* Nutt.) | 4 | 47.9 | |
| VP – REF3B | Sweet Gum (*Liquidambar styraciflua* L.) | 4 | 7.8 | |
| VP – REF3B | Tulip Poplar (*Liriodendron tulipifera* L.) | 3 | 34.9 | |
| VP – REF3B | Willow Oak (*Quercus phellos* L.) | 4 | 99.2 | 254.8 |
| VP – REF5 | Black Gum (*Nyssa sylvatica* Marsh.) | 1 | 0.8 | |
| VP – REF5 | Red Maple (*Acer rubrum* L.) | 17 | 29.3 | |
| VP – REF5 | Sweet Gum (*Liquidambar styraciflua* L.) | 18 | 72.3 | |
| VP – REF5 | Tulip Poplar (*Liriodendron tulipifera* L.) | 1 | 5.2 | |
| VP – REF5 | Willow Oak (*Quercus phellos* L.) | 2 | 11.9 | 119.5 |
| VP – 5LRW | Black Gum (*Nyssa sylvatica* Marsh.) | 2 | 3.0 | |
| VP – 5LRW | Musclewood (*Carpinus caroliniana* Walt.) | 1 | 1.8 | |
| VP – 5LRW | Red Maple (*Acer rubrum* L.) | 7 | 34.1 | |
| VP – 5LRW | Swamp Chestnut Oak (*Quercus michauxii* Nutt.) | 9 | 16.8 | |
| VP – 5LRW | Sweet Gum (*Liquidambar styraciflua* L.) | 8 | 101.0 | |
| VP – 5LRW | Tulip Poplar (*Liriodendron tulipifera* L.) | 1 | 13.6 | |
| VP – 5LRW | Willow Oak (*Quercus phellos* L.) | 1 | 5.7 | 176.0 |

**Table 11.** Standing biomass weights, litter layer weights, and ash content collected at Fort Lee.

| Drainage Class & Sample Location | LAYER | Ash content | Weight |
|---|---|---|---|
| | | % | kg ha$^{-1}$ |
| Reference Area | | | |
| P – REF3A | L | | 1238 |
| P – REF3A | F | 1.64 | 5248 |
| VP – REF3B | L | | 807 |
| VP – REF3B | F | | 942 |
| P – REF4 | L | | 1480 |
| P – REF4 | F | 2.57 | 3821 |
| VP – 5LRW | L | | 1911 |
| VP – 5LRW | F | 0.61 | 11087 |
| P – 4LRA | L | | 700 |
| P – 4LRA | F | 2.99 | 5005 |
| VP – REF5 | L | | 2745 |
| VP – REF5 | F | 0.80 | 12783 |
| Mitigation Area | | | |
| SWP – 7D | BIO | | 2207 |
| SWP – 7D | L | | 1480 |
| SWP – 7D | F | | |
| P – 7-4 | BIO | | 7427 |
| P – 7-4 | L | | 996 |
| P – 7-4 | F | | |
| VP – 7B | BIO | | 7427 |
| VP – 7B | L | | 2018 |
| VP – 7B | F | 1.14 | 9957 |
| SWP – 5C | BIO | | 2341 |
| SWP – 5C | L | | 1480 |
| SWP – 5C | F | | |
| P – 5-3 | BIO | | 3391 |
| P – 5-3 | L | | 1480 |
| P – 5-3 | F | 3.45 | 1859 |
| VP – 5B | BIO | | 1964 |
| VP – 5B | L | | 1023 |
| VP – 5B | F | 1.12 | 4844 |
| SWP – 4C | BIO | | 3014 |
| SWP – 4C | L | | 2395 |
| SWP – 4C | F | | |
| P – 4LD | BIO | | 1265 |
| P – 4LD | L | | 1130 |
| P – 4LD | F | 1.62 | 3471 |
| VP – 4B | BIO | | 3310 |
| VP – 4B | L | | 1103 |
| VP – 4B | F | 2.25 | 1588 |

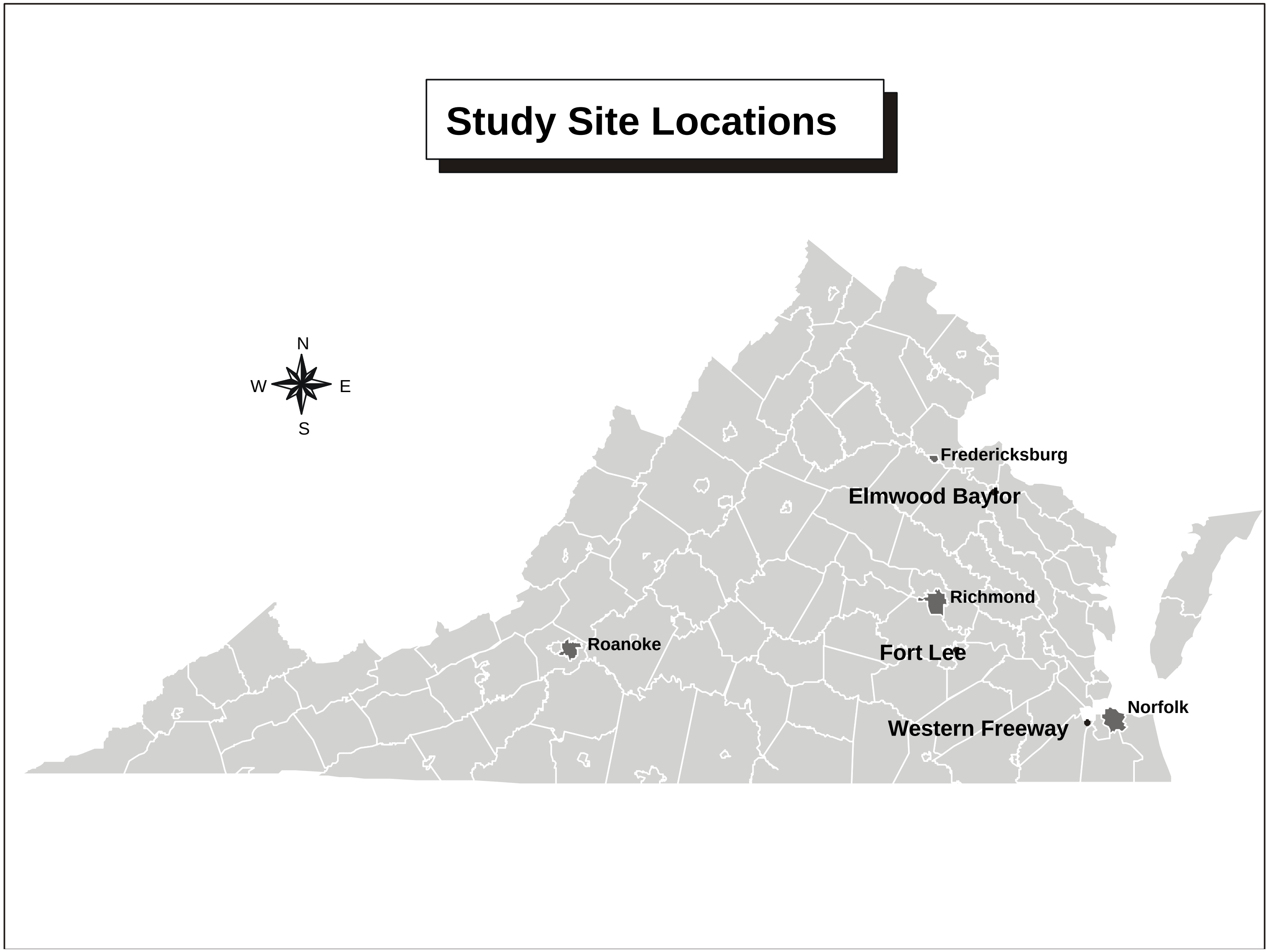

**Figure 1.** Study Site Locations.

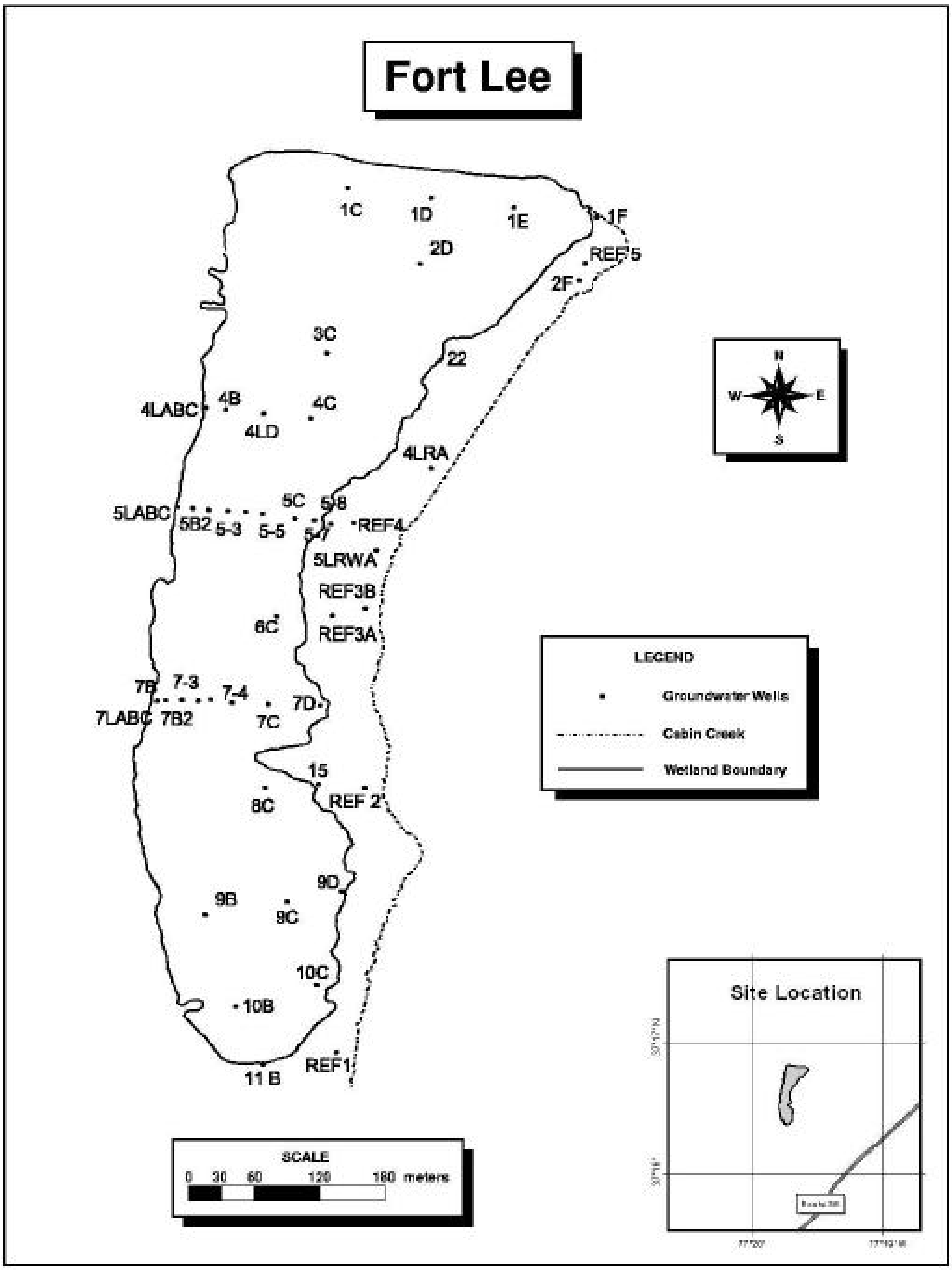

Figure 2. Fort Lee Site Map. Well locations shown.

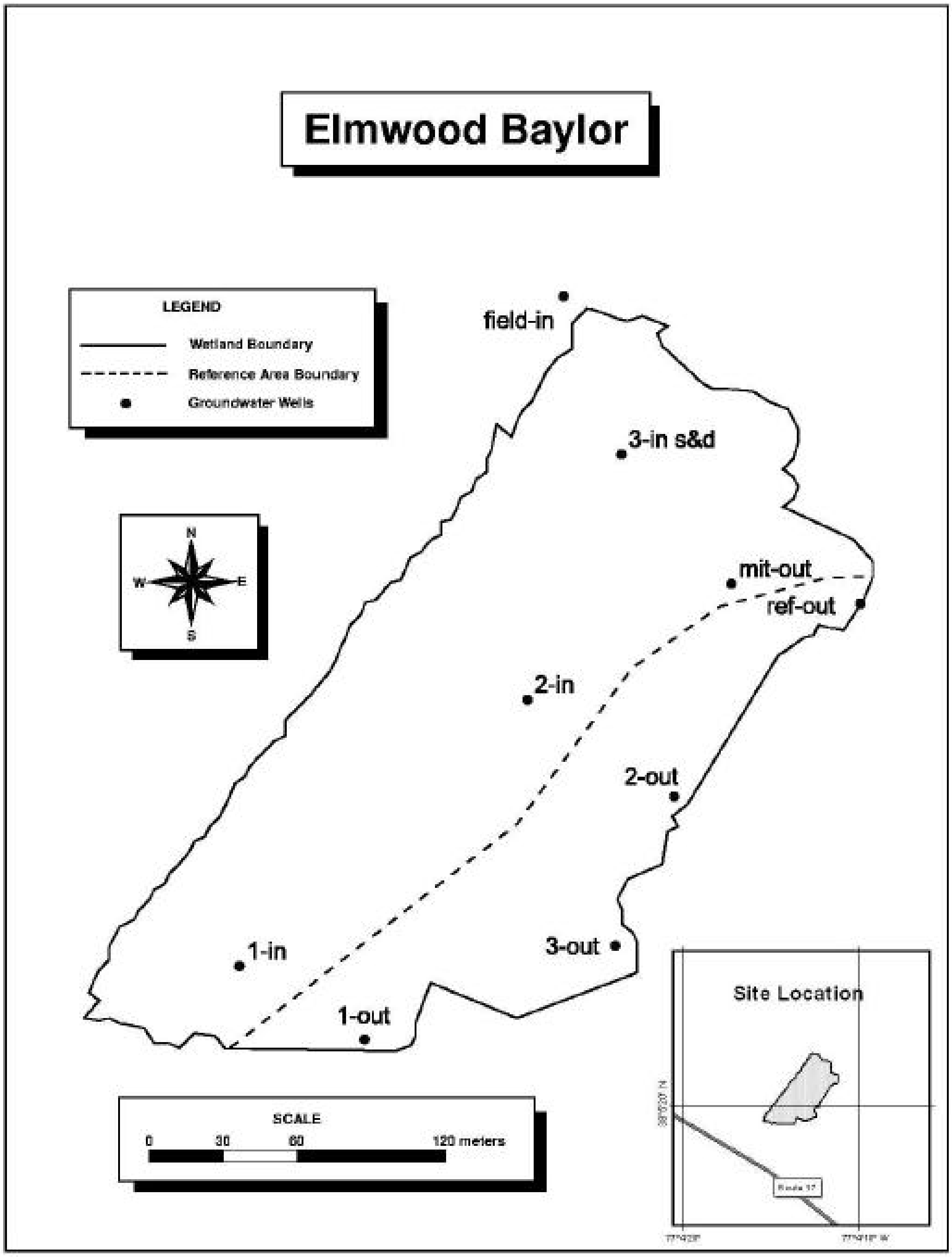

**Figure 3.** Elmwood-Baylor Site Map. Well locations shown.

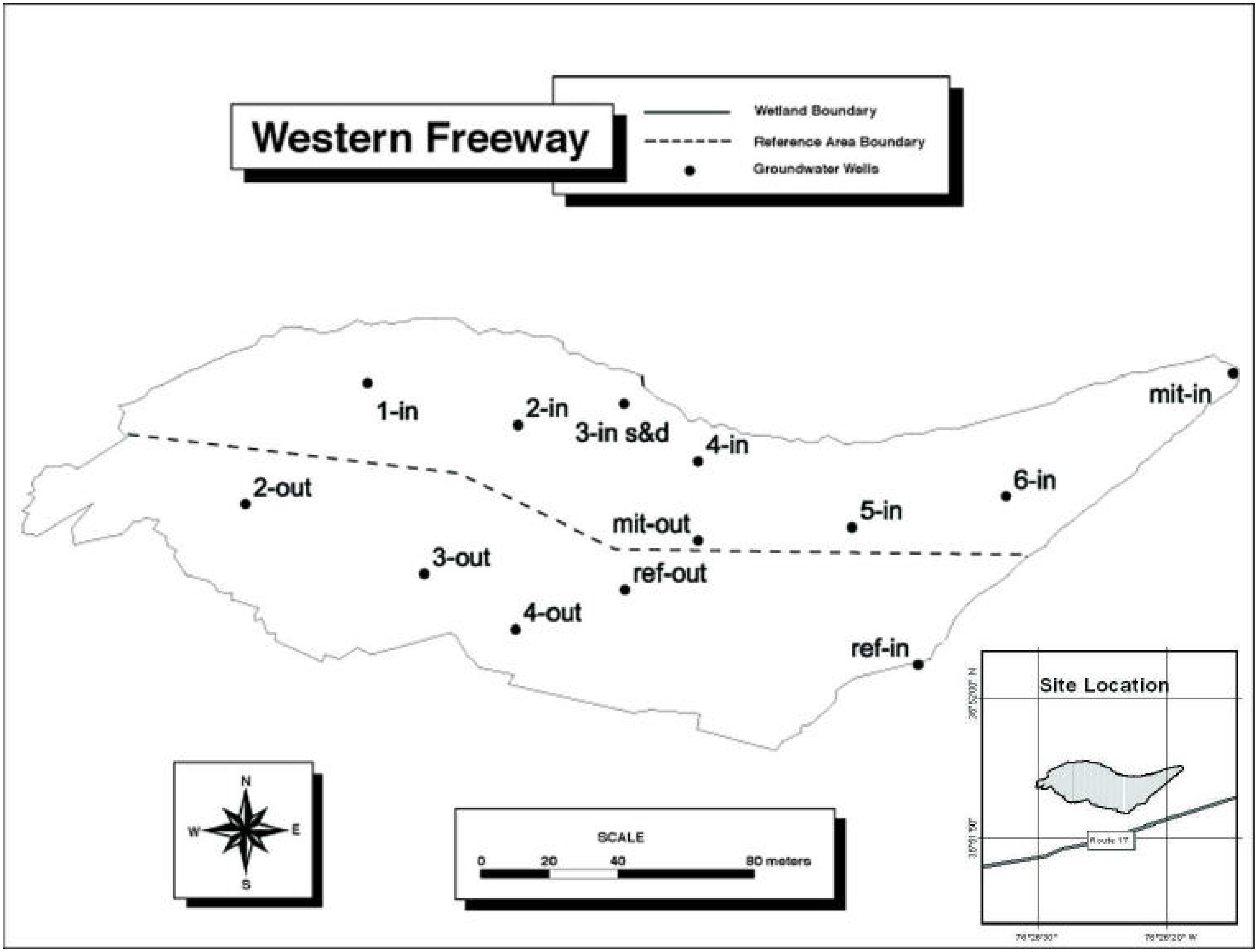

**Figure 4.** Western Freeway Site Map. Well locations shown.

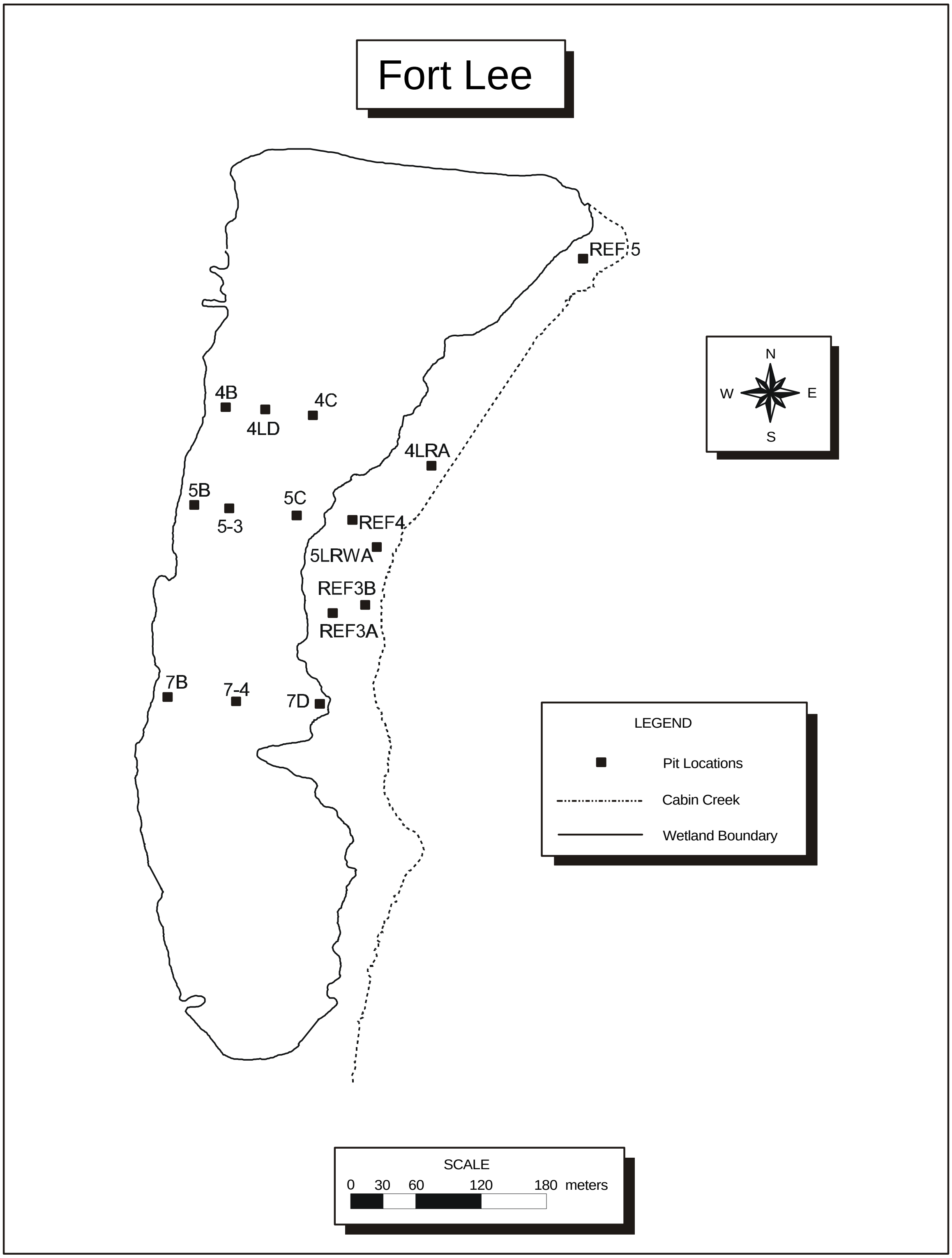

**Figure 5.** Fort Lee Pit Locations.

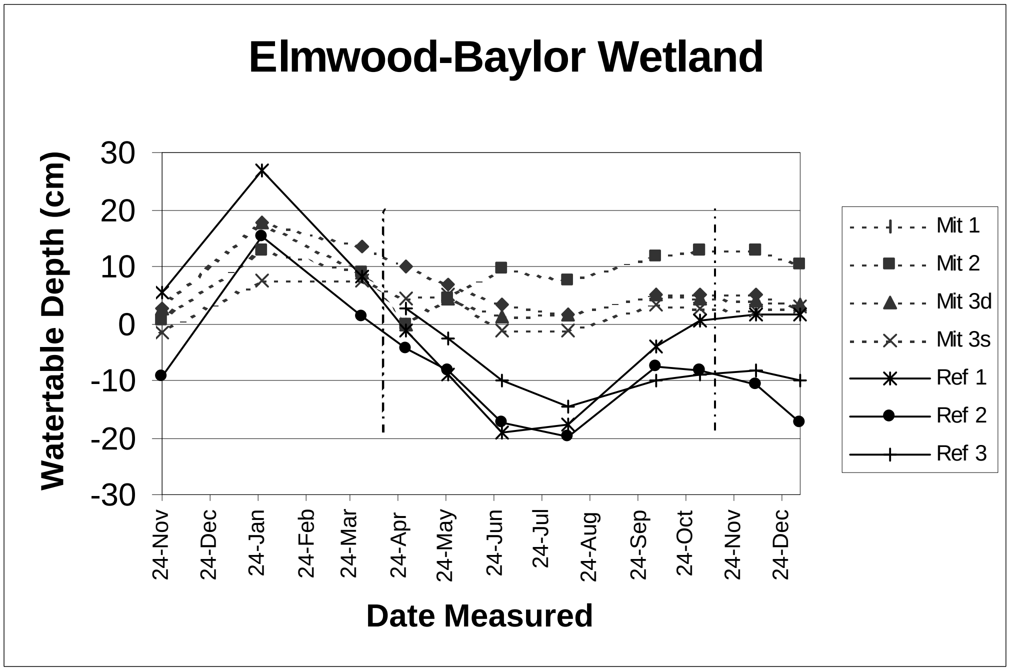

**Figure 6.** Elmwood-Baylor hydrograph. Well readings between the dashed lines occurred during the growing season.

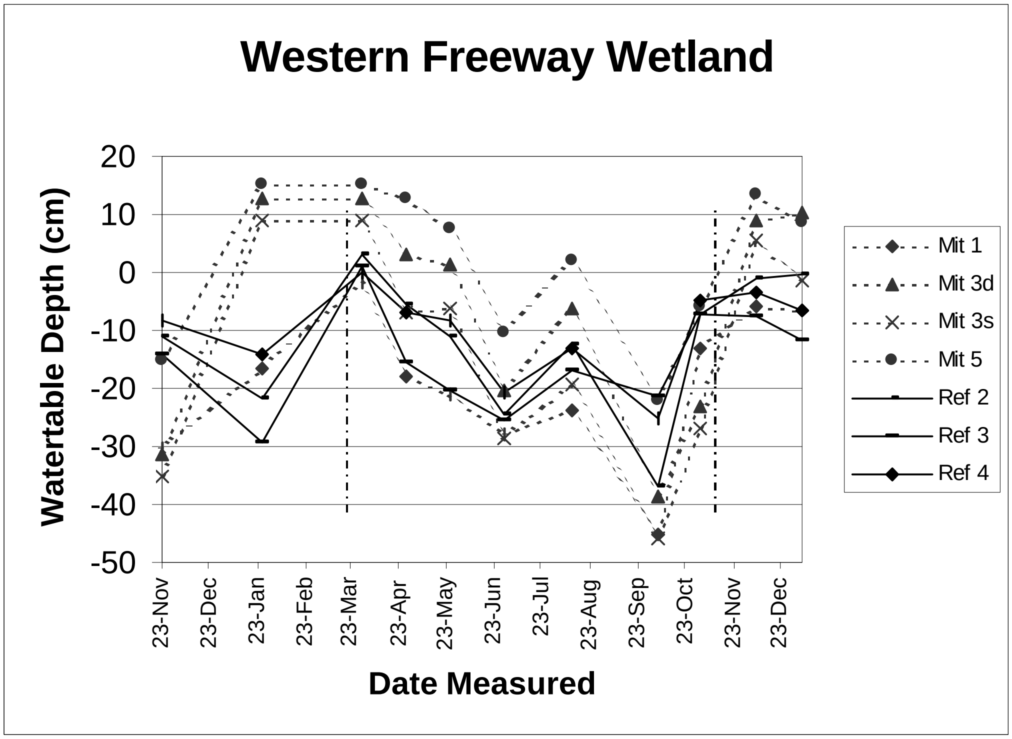

**Figure 7.** Western Freeway hydrograph. Well readings between the dashed lines occurred during the growing season.

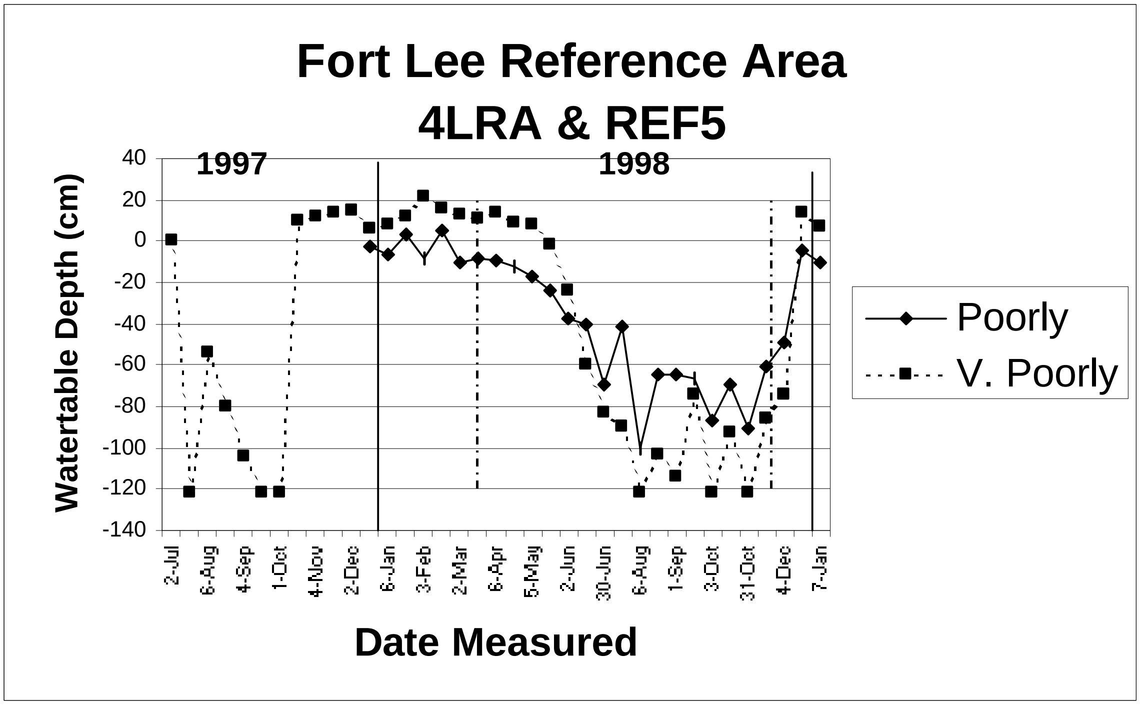

**Figure 8a.** Typical Fort Lee reference area hydrograph. Well readings between the dashed lines occurred during the growing season.

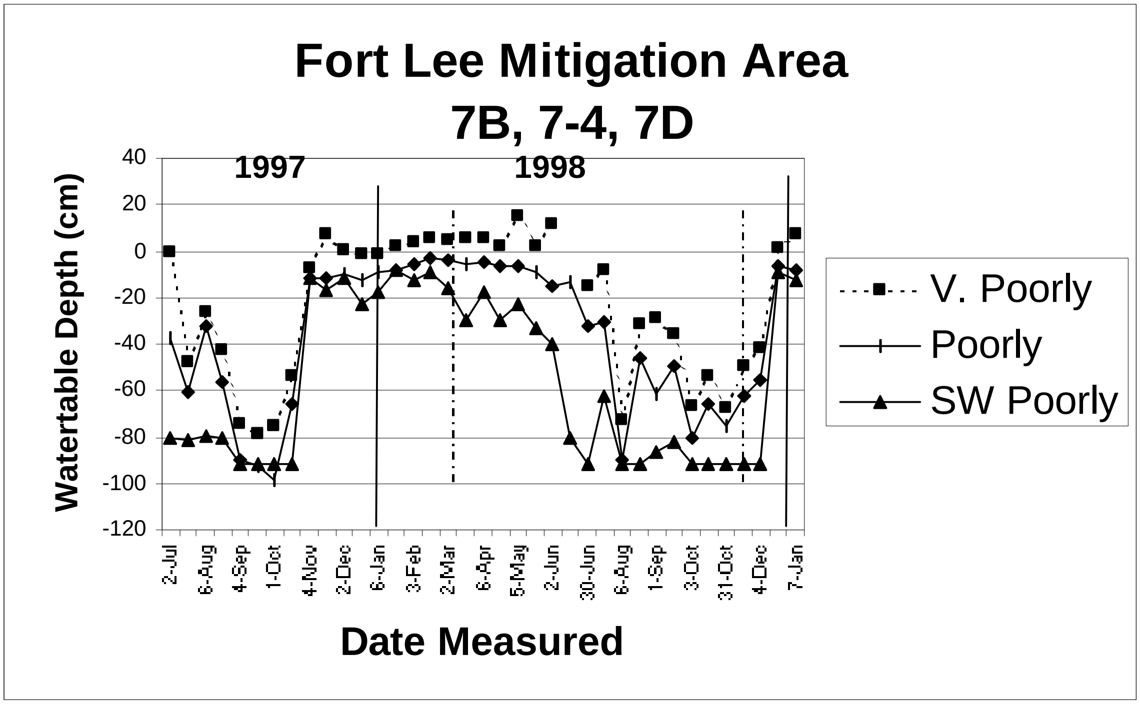

**Figure 8b.** Typical Fort Lee mitigation area hydrograph. Well readings between the dashed lines occurred during the growing season.

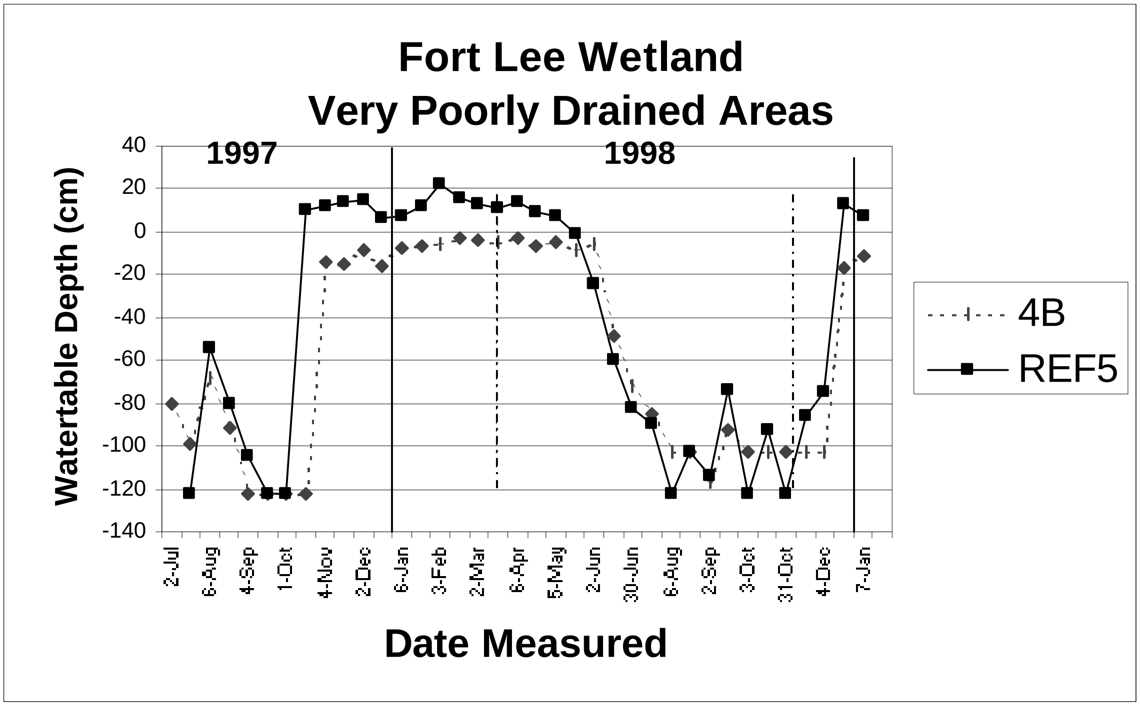

**Figure 9a.** Typical very poorly drained area hydrograph comparison. Well readings between the dashed lines occurred during the growing season.

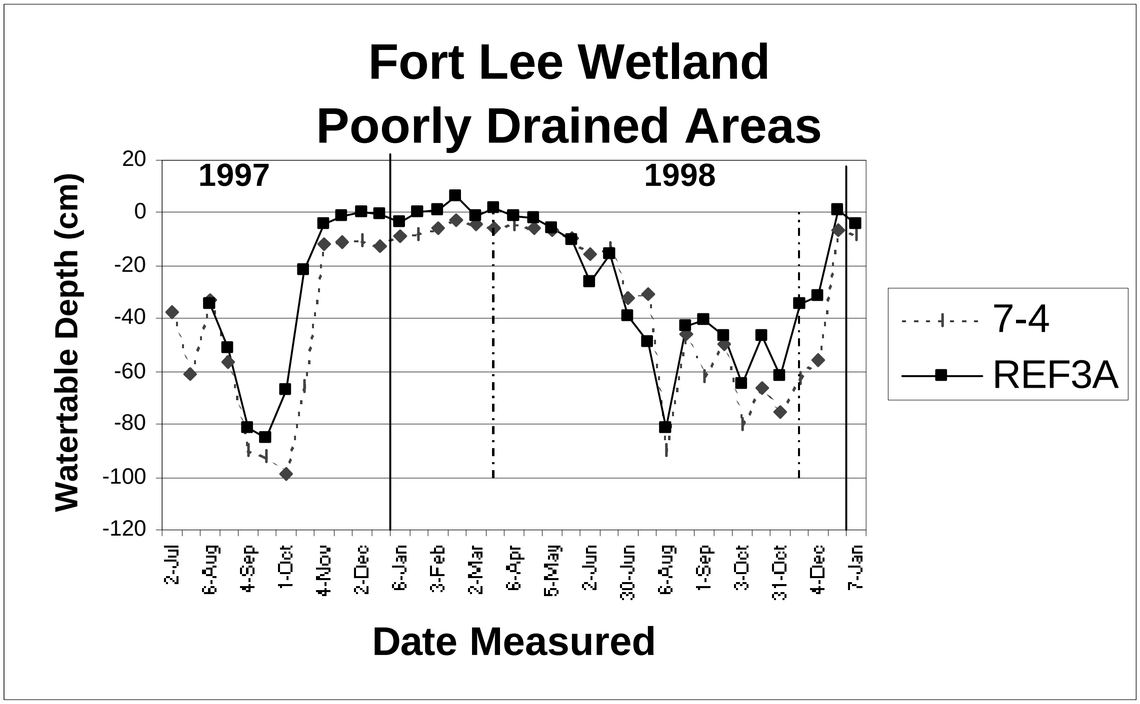

**Figure 9b.** Typical poorly drained area hydrograph comparison. Well readings between the dashed lines occurred during the growing season.

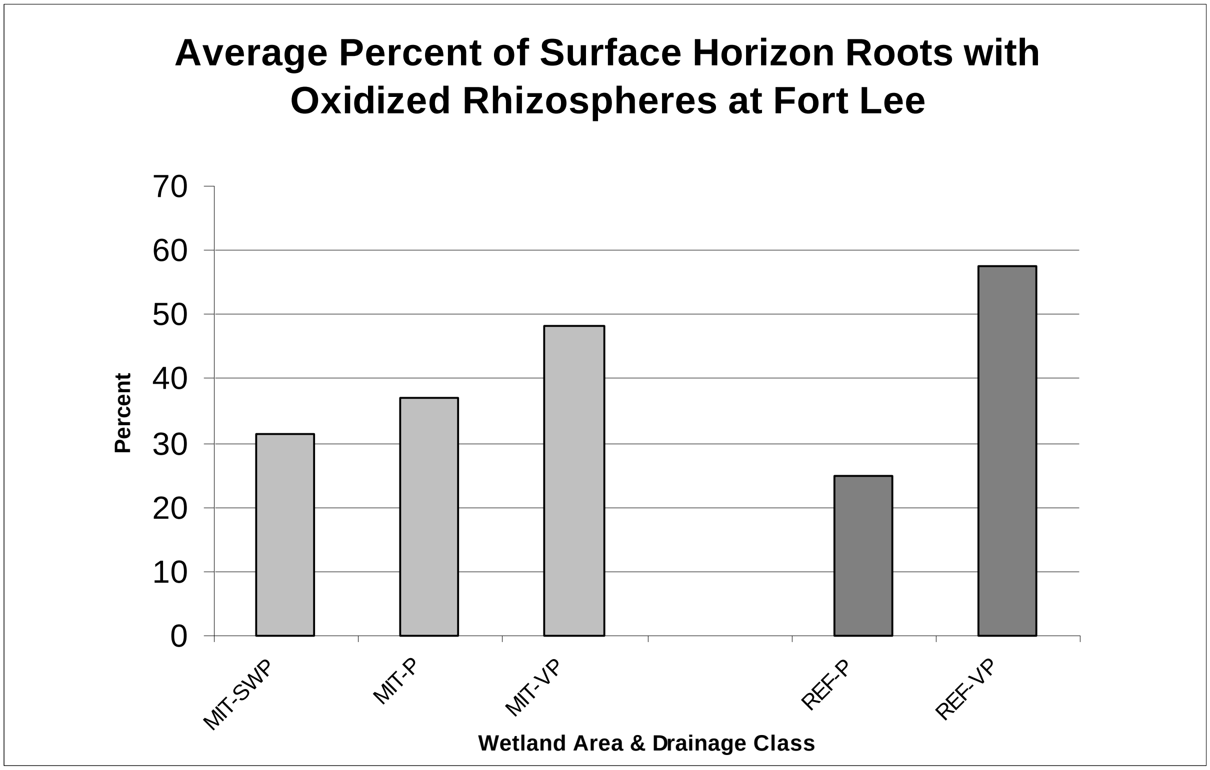

**Figure 10.** Average percent of surface horizon roots with oxidized rhizospheres at Fort Lee.

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## APPENDICIES

**Appendix A.** Redoximorphic features: quantity, size, and contrast classes (Soil Survey Staff, 1994).

| Symbol | Class | Description |
|---|---|---|
| Quantity | | |
| F | Few | < 2 % |
| C | Common | 2 – 20 % |
| M | Many | > 20 % |
| Size | | |
| 1 | Fine | < 5 mm |
| 2 | Medium | 5 – 15 mm |
| 3 | Coarse | > 15 mm |
| Contrast | | |
| F | Faint | Evident only on close examination. Faint features commonly have the same hue as the matrix color and differ by no more than 1 unit of chroma or 2 units of value. |
| D | Distinct | Readily seen but contrast only moderately with the matrix color. Distinct features have the same hue, but differ by 2 to 4 units of chroma or 3 to 4 units of value; but no more than 1 unit of chroma or 2 units of value if the hue differs by 2.5 units. |
| P | Prominent | Contrast strongly with the matrix color. Prominent features differ from the matrix by at least 5 units of hue if chroma and value are the same; at least 4 units of value or chroma if the hue is the same; or at least 1 unit of chroma or 2 units of value if the hue differs by 2.5 units. |

**Appendix B.** The beneficial properties of soil organic matter (Stevenson, 1982).

| Property | Remarks | Effect on Soil |
|---|---|---|
| Color | The typical dark colors of many soils is caused by OM. | May facilitate warming. |
| Water retention | OM can hold up to 20 times its weight in water. | May significantly improve moisture-retaining properties of sandy soils. |
| Combination with clay | Cements soil particles into aggregates. | Permits exchange of gases, stabilizes structure, increases permeability. |
| Chelation | Forms stable complexes with $Cu^{2+}$, $Mn^{2+}$, $Zn^{2+}$, and other polyvalent cations. | May enhance the availability of micronutrients to higher plants. |
| Solubility in water | Insolubility of OM is because of its association with clay. | Little OM is lost by leaching. |
| Buffer action | OM exhibits pH buffering. | Helps to maintain a uniform reaction in the soil. |
| Cation Exchange | Total acidities of isolated fractions of humus range from 300 to 1400 meq/100 g. | May increase the soil CEC. From 20 to 70 % of the CEC of many soils is due to OM. |
| Mineralization | Decomposition of OM yields $CO_2$, $NH_4^+$, $NO_3^-$, $H_2PO_4^-$, and $SO_4^-$. | A source of nutrient elements for plant growth. |
| Combines with organic molecules | Effects bioactivity, persistence and biodegradability of pesticides. | Modifies application rates of pesticides for effective control. |

**Appendix C.** P values by site for a given contrast. Contrasts were evaluated using the Wilcoxon Rank Sum Test.

| Site | pH | %N | %C |
|---|---|---|---|
| Elmwood-Baylor: Reference vs. Mitigation | | | |
| 0-5 cm | 0.5536 | 0.1386 | 0.1489 |
| 5-15 cm | 0.0006 | 0.0119 | < 0.0001 |
| 40-50 cm | < 0.0001 | 0.2416 | < 0.0001 |
| 90-100 cm | < 0.0001 | 0.1078 | < 0.0001 |
| Elmwood-Baylor: Changes with Time | | | |
| 0-5 cm | 0.3865 | 0.1386 | 0.7728 |
| 5-15 cm | 0.3323 | 0.1542 | 0.8231 |
| 40-50 cm | 0.7652 | 0.0266 | 0.2633 |
| 90-100 cm | 0.2624 | 0.0238 | 0.1175 |
| Western Freeway: Reference vs. Mitigation | | | |
| 0-5 cm | 0.5186 | 0.0243 | 0.0282 |
| 5-15 cm | < 0.0001 | < 0.0001 | < 0.0001 |
| 40-50 cm | 0.0011 | < 0.0001 | < 0.0001 |
| 90-100 cm | 0.0344 | 0.0001 | < 0.0001 |
| Western Freeway: Changes with Time | | | |
| 0-5 cm | 0.3358 | 0.0047 | 0.2980 |
| 5-15 cm | 0.2756 | 0.0066 | 0.8457 |
| 40-50 cm | 0.1725 | 0.0259 | 0.4137 |
| 90-100 cm | 0.0071 | 0.0004 | 0.5592 |
| Fort Lee: Reference vs. Mitigation | | | |
| 0-5 cm | No Data | No Data | No Data |
| 5-15 cm | < 0.0001 | < 0.0001 | < 0.0001 |
| 40-50 cm | 0.0001 | 0.0001 | < 0.0001 |
| 90-100 cm | 0.2533 | 0.5128 | 0.0011 |
| Fort Lee: Changes with Time | | | |
| 0-5 cm | No Data | No Data | No Data |
| 5-15 cm | 0.0238 | 0.0004 | 0.6853 |
| 40-50 cm | 0.0214 | 0.0008 | 0.1851 |
| 90-100 cm | 0.3300 | 0.0004 | 0.0672 |

**Appendix D.** Bulk Density at Fort Lee and Western Freeway.

| Drainage Class/Sample Location | Depth<br>cm | Average Bulk Density<br>g $cm^{-3}$ |
|---|---|---|
| Fort Lee Reference area | | |
| P – 4LRA | 0-13 | 0.79 |
| P – 4LRA | 13-50 | 1.54 |
| P – REF3A | 0-15 | 0.78 |
| P – REF3A | 15-24 | 1.29 |
| P – REF4 | 0-10 | 0.68 |
| P – REF4 | 10-40 | 1.51 |
| VP – REF3B | 0-10 | 0.78 |
| VP – REF3B | 10-24 | 1.33 |
| VP – 5LRW | 0-13 | 0.55 |
| VP – REF5 | 0-16 | 0.96 |
| VP – REF5 | 16-70 | 1.40 |
| Western Freeway Reference Area | | |
| REF4OUT | 0-5 | 0.81 |
| Fort Lee Mitigation area | | |
| MW – 4C | 0-20 | 1.50 |
| MW – 4C | 20-50 | 1.85 |
| MW – 5C | 0-20 | 1.59 |
| MW – 5C | 20-45 | 1.66 |
| MW – 5C | 45-80 | 1.99 |
| MW – 7D | 0-22 | 1.90 |
| MW – 7D | 22-40 | 1.94 |
| MW – 7D | 40-80 | 2.06 |
| P – 4LD | 0-25 | 1.84 |
| P – 4LD | 25-66 | 1.69 |
| P – 4LD | 66-115 | 1.79 |
| P – 5-3 | 0-22 | 1.64 |
| P – 5-3 | 22-50 | 1.67 |
| P – 5-3 | 50-150 | 1.47 |
| P – 7-4 | 10-40 | 1.83 |
| VP – 5B | 0-25 | 1.60 |
| VP – 5B | 25-70 | 1.26 |
| VP – 4B | 0-11 | 1.78 |
| VP – 4B | 11-80 | 1.48 |
| VP – 7B | 0-12 | 1.79 |
| VP – 7B | 12-35 | 1.83 |
| Western Freeway Mitigation Area | | |
| MIT3IN | 0-5 | 1.24 |
| MIT3IN | 5-15 | 1.51 |
| MIT3IN | 40-50 | 1.63 |

**Appendix E.** Individual pedon descriptions for Elmwood-Baylor in July, 1998. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

| Well | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Texture | Structure | Roots | Dipyr. RXN. | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3IN | | | | | | | | | | | |
| | A | 0 – 20 | 5B 6/1 | -- | -- | -- | SL | WFGR | C2 | + | WT @ surface |
| | C | 20 – 112 | 7.5YR 5/8 | 2.5Y 6/3 | M2D | Fe depletions | SL | 0MA | F1 | - | |
| | Cg | 112 – 150 | 5Y 5/1 | -- | -- | -- | SCL | 0MA | -- | + | |
| 2IN | | | | | | | | | | | |
| | A | 0 – 10 | 5GY 5/1 | 7.5YR 5/8 | C1D | Pore linings | SIL | WFGR | M2 | + | WT @ surface |
| | Cg | 10 – 98 | 5Y 6/2 | 7.5YR 5/8 | M2D | Fe masses | SICL | 0MA | F1 | + | |
| | C | 98 - 150 | 7.5YR 5/8 & 5Y 6/2 | -- | -- | -- | SICL | 0MA | -- | + | |
| 3OUT | | | | | | | | | | | |
| | A1 | 0 – 10 | 7.5YR 4/3 | 7.5YR 3/4 | M2D | Pore linings | SIL | WFGR | M2 | + | |
| | A2 | 10 – 23 | 7.5YR 5/1 | 7.5YR 4/3 | C2F | Fe masses | SIL | WFGR | F3 | + | |
| | Cg1 | 23 – 70 | 2.5Y 5/1 | 7.5YR 4/3 | C2D | Fe masses | SCL | 0MA | -- | + | WT @ 30 cm |
| | Cg2 | 70 - 150 | 2.5Y 5/1 | -- | -- | -- | SL | 0MA | -- | + | |
| 1OUT | | | | | | | | | | | |
| | A | 0 – 20 | 10YR 4/2 | -- | -- | -- | SIL | WFGR | M2 | + | |
| | Bg | 20 – 46 | 10YR 5/1 | 10YR 4/6 | F2D | Pore linings | SICL | 0MA | F3 | + | WT @ 25 cm |
| | Cg | 46 – 150 | 2.5Y 5/1 | -- | -- | -- | S | 0SG | -- | + | |

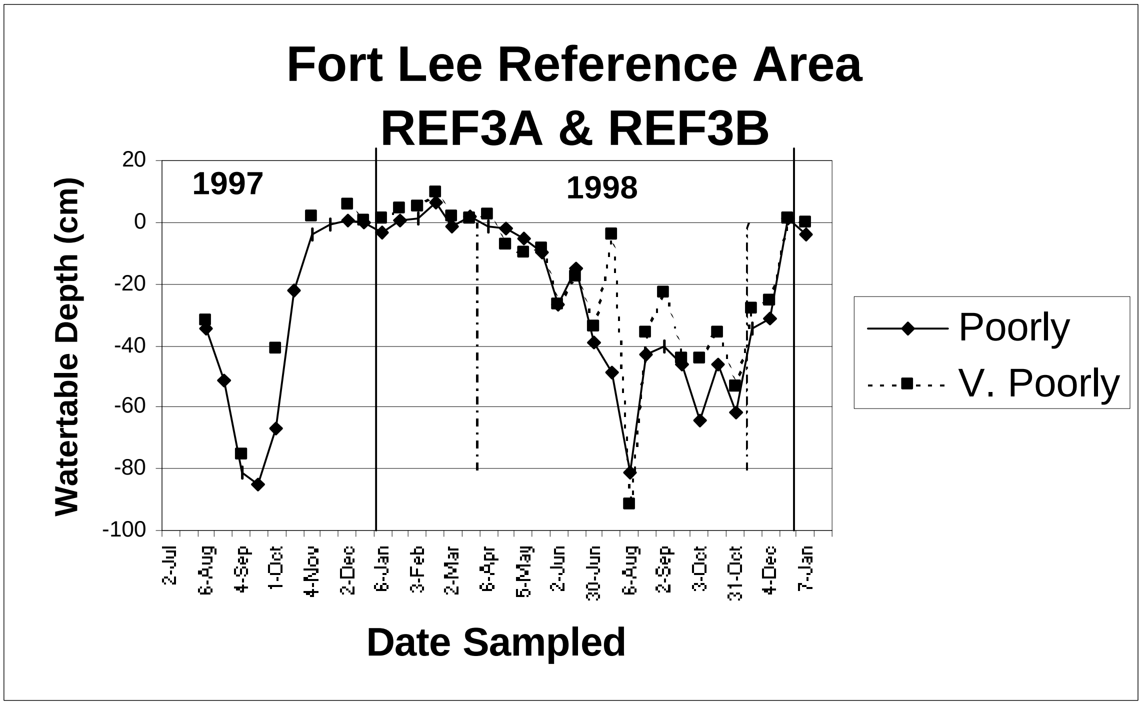
* Redox Color refers to primary depletions or concentrations.

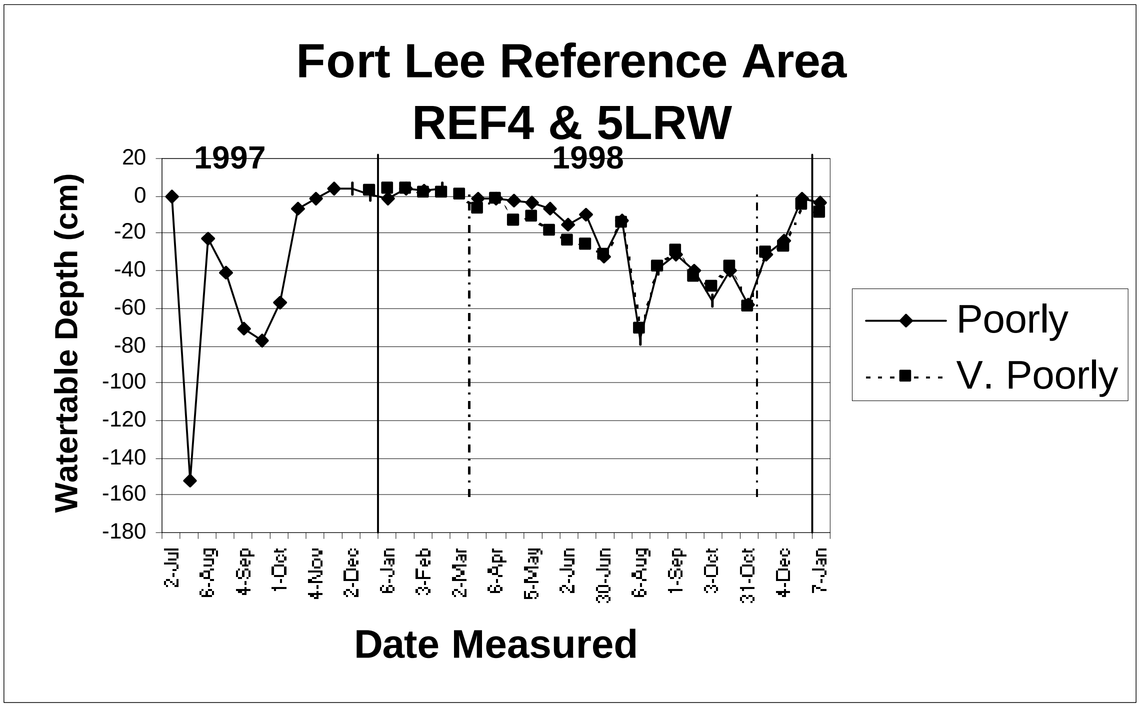
**Appendix F.** Pedon descriptions for Western Freeway in July, 1998. All abbreviations are according to the National Soil Survey Handbook (Soil Survey Staff, 1994).

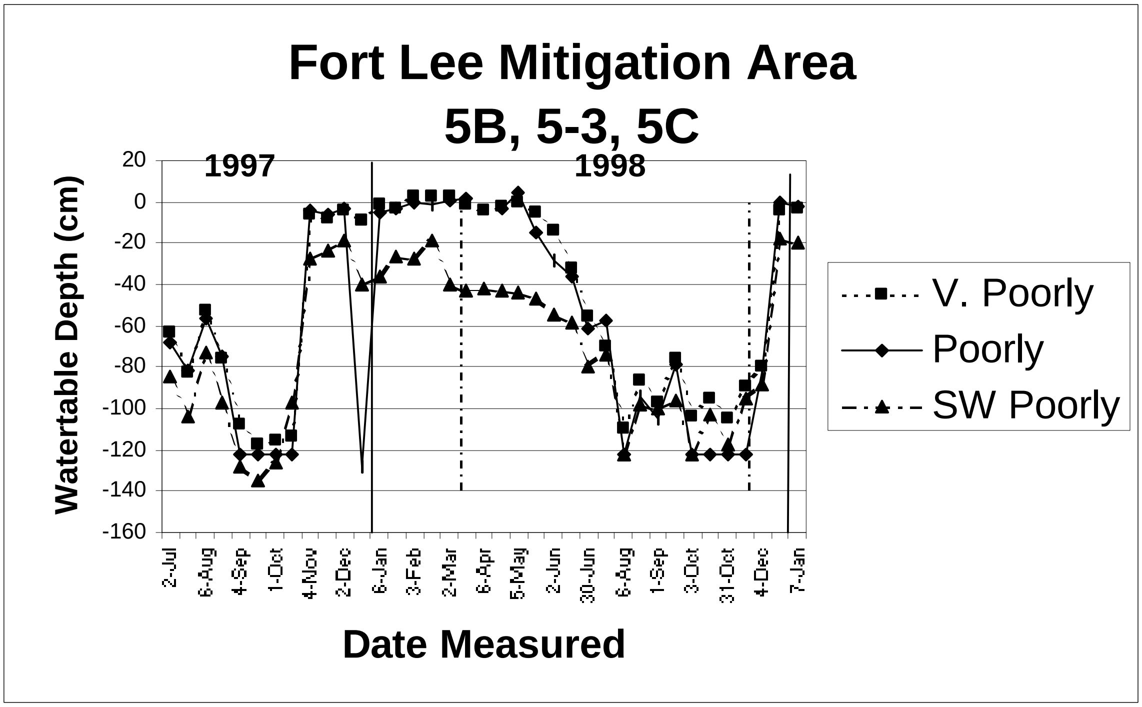
| Well | Horizon | Depth (cm) | Matrix Color | Redox Color* | Redox description | Redox Location | Texture | Structure | Roots | Dipyr. RXN. | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1IN | | | | | | | | | | | |
| | A | 0 – 36 | 2.5Y 4/2 | 7.5YR 5/8;<br>7.5YR 3/4 | F2F;<br>F2P | Fe masses;<br>Pore linings | SL | WMGR | C2 | + | WT @ 150 cm |
| | C | 36 – 90 | 2.5Y 6/4 | 10YR 6/8;<br>2.5Y 4/2 | M2P;<br>M2D | Fe masses | SCL | WFGR | -- | - | |
| | Cg | 90 – 150 | 2.5Y 7/2 | 10YR 5/8 | M2D | Fe masses | SCL | 0MA | -- | - | |
| 3IN | | | | | | | | | | | |
| | A | 0 – 37 | 2.5Y 4/2 | 7.5YR 5/8;<br>7.5YR 3/4 | M2F;<br>F2P | Fe masses;<br>Pore linings | SL | WMGR | C2 | + | WT @ 120 cm |
| | Cg | 37 – 150 | 2.5Y 7/2 | 10YR 5/8 | M2D | Fe masses | SCL | 0MA | -- | - | |
| 4IN | | | | | | | | | | | |
| | A | 0 – 46 | 2.5Y 4/2 | 7.5YR 5/8 | F1F | Fe masses | SL | WMGR | C2 | + | WT @ 120 cm |
| | C | 46 – 70 | 2.5Y 6/4 | 10YR 6/8 | M2P | Fe masses | SCL | WMGR | -- | - | |
| | Cg | 70 – 150 | 2.5Y 7/2 | 10YR 5/8 | M2D | Fe masses | SCL | 0MA | -- | - | |
| 4OUT | | | | | | | | | | | |
| | A1 | 0 – 15 | 10YR 3/2 | 7.5YR 5/8 | C1D | Pore linings | SIL | WFGR | C2 | + | WT @ 45 cm |
| | A2 | 15 – 70 | 10YR 3/2 | -- | -- | -- | SIL | WFGR | -- | + | |

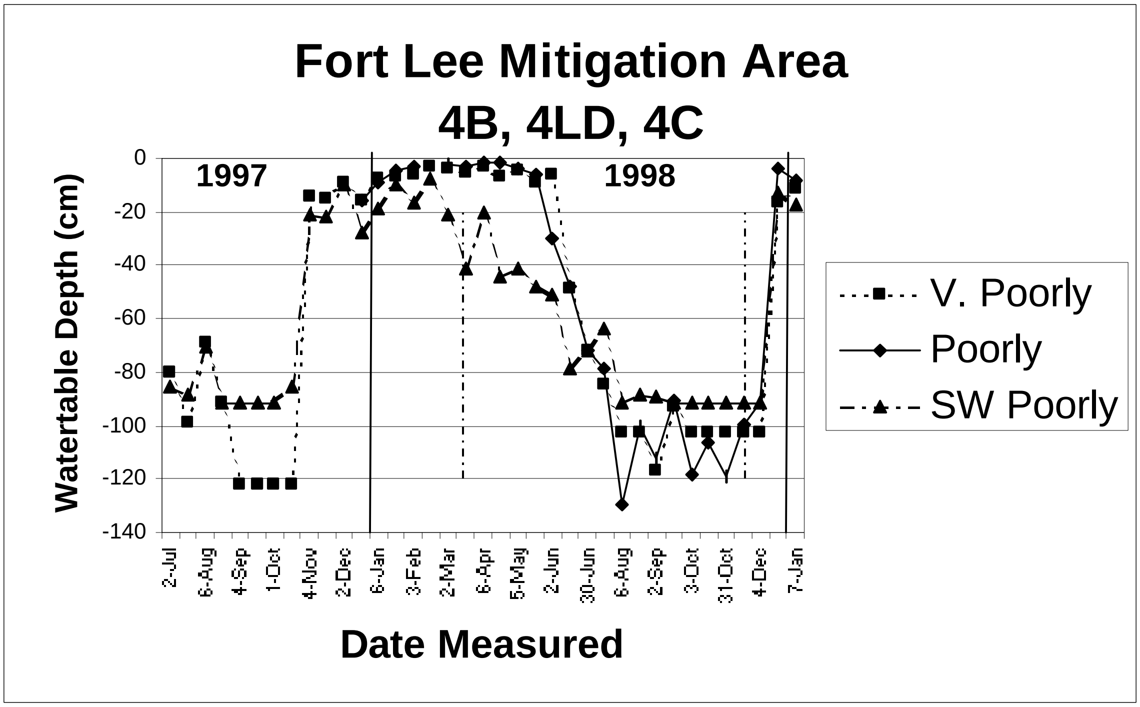
*Redox Color refers to primary depletions or concentrations.

**Appendix G.** Additional hydrographs displaying the Fort Lee wetness gradient. Well readings between the dashed lines occurred during the growing season.

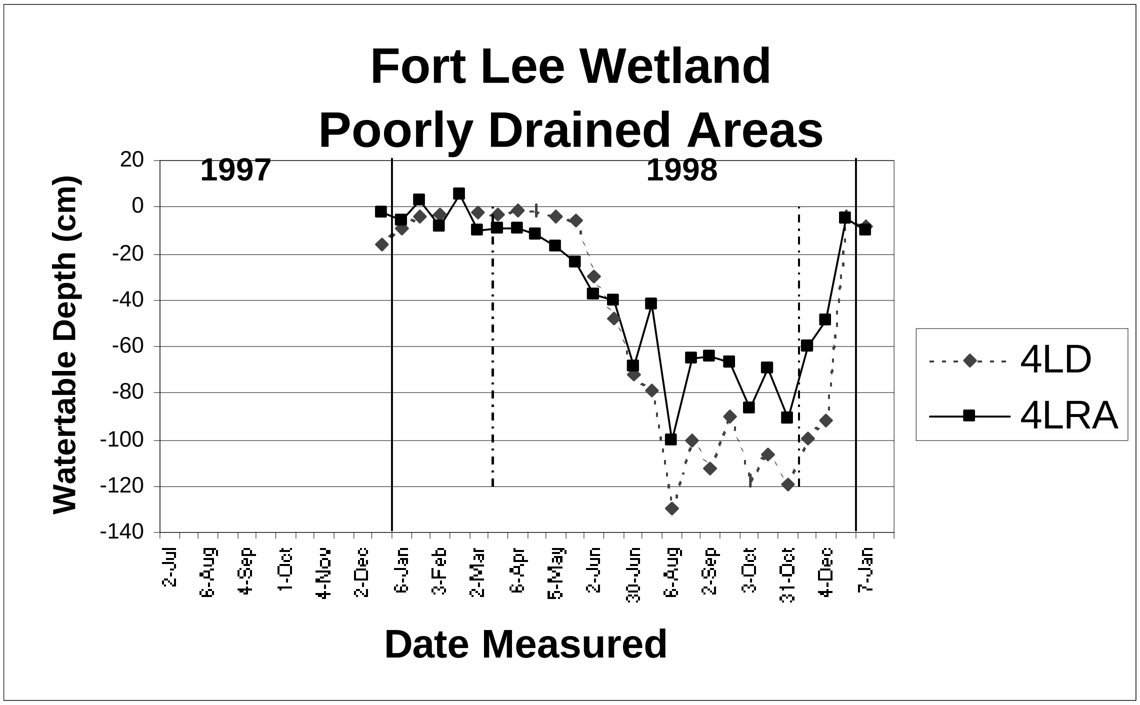


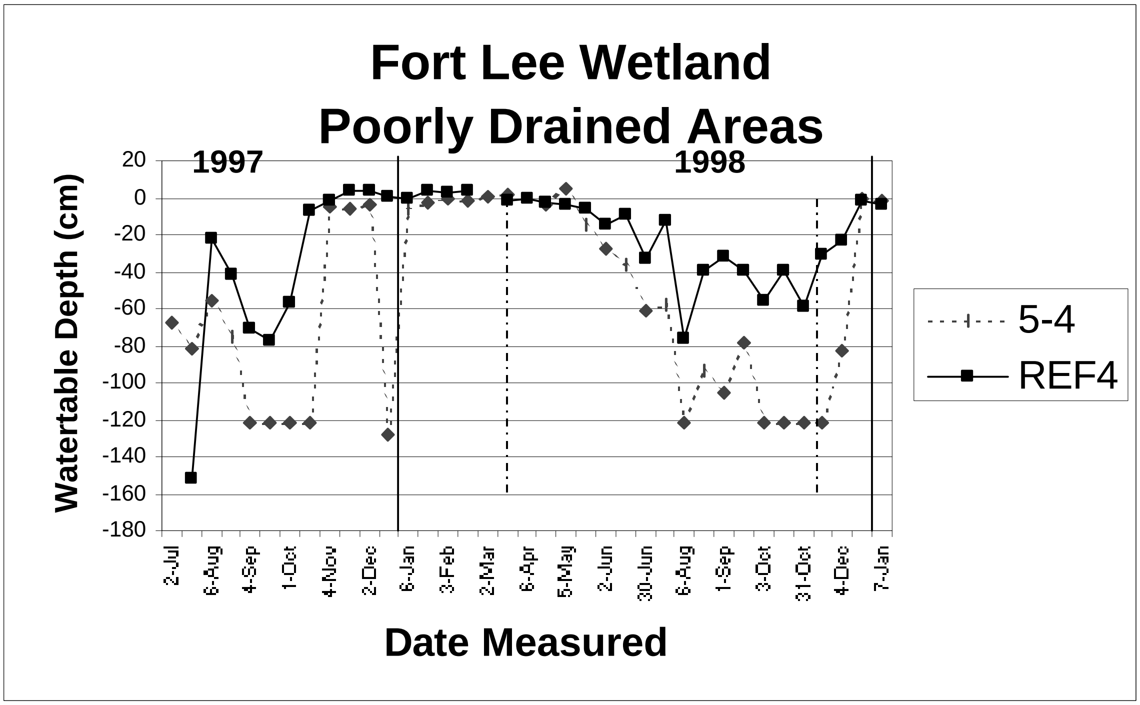


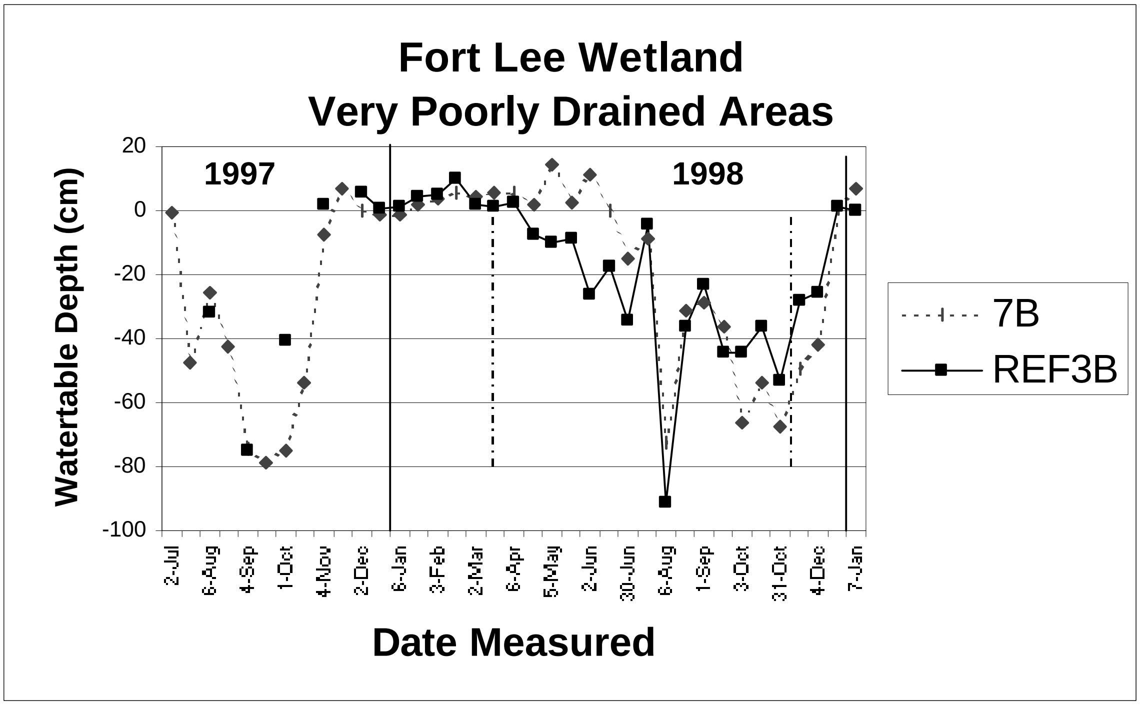

Fort Lee Mitigation Area
5B, 5-3, 5C
1997
1998
Watertable Depth (cm)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
2-Jul
6-Aug
4-Sep
1-Oct
4-Nov
2-Dec
6-Jan
3-Feb
2-Mar
6-Apr
5-May
2-Jun
30-Jun
6-Aug
1-Sep
3-Oct
31-Oct
4-Dec
7-Jan
Date Measured
V. Poorly
Poorly
SW Poorly

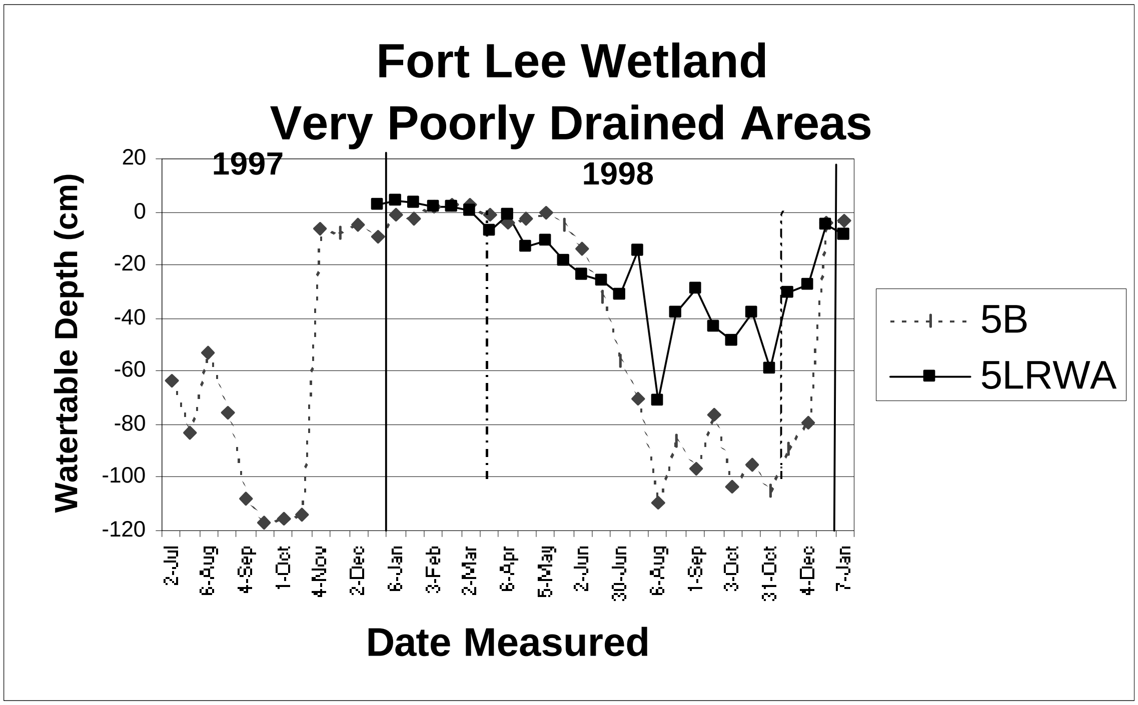

Fort Lee Mitigation Area
4B, 4LD, 4C
1997
1998
Watertable Depth (cm)
0
-20
-40
-60
-80
-100
-120
-140
2-Jul
6-Aug
4-Sep
1-Oct
4-Nov
2-Dec
6-Jan
3-Feb
2-Mar
6-Apr
5-May
2-Jun
30-Jun
6-Aug
2-Sep
3-Oct
31-Oct
4-Dec
7-Jan
Date Measured
V. Poorly
Poorly
SW Poorly

**Appendix H.** Additional mitigation-reference hydrograph comparisons by drainage class at Fort Lee. Well readings between the dashed lines occurred during the growing season.






Fort Lee Wetland
Very Poorly Drained Areas
Watertable Depth (cm)
20
0
-20
-40
-60
-80
-100
1997
1998
2-Jul
6-Aug
4-Sep
1-Oct
4-Nov
2-Dec
6-Jan
3-Feb
2-Mar
6-Apr
5-May
2-Jun
30-Jun
6-Aug
1-Sep
3-Oct
31-Oct
4-Dec
7-Jan
Date Measured
7B
REF3B


Fort Lee Wetland
Very Poorly Drained Areas
Watertable Depth (cm)
20
0
-20
-40
-60
-80
-100
-120
1997
1998
2-Jul
6-Aug
4-Sep
1-Oct
4-Nov
2-Dec
6-Jan
3-Feb
2-Mar
6-Apr
5-May
2-Jun
30-Jun
6-Aug
1-Sep
3-Oct
31-Oct
4-Dec
7-Jan
Date Measured
5B
5LRWA

## VITA

Angela R. Cummings was born on July 28, 1975 in Silver Spring, Maryland. Angela is the daughter of Craig and Robert Cummings of Pinehurst, North Carolina. She has an older sister, Melissa Cummings of Annapolis, Maryland. Angela grew up in Olney, Maryland until graduation from Sherwood High School in 1993. In the fall of 1993, she became a member of the freshmen class at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. There she pursued a degree in soil science under the advisement of Dr. William J. Edmonds. In December 1996, she completed the requirements for a Bachelor of Science degree in Crop and Soil Environmental Sciences (CSES) and began working with Dr. W. Lee Daniels on a Master of Science degree in the same discipline. As a graduate student at Virginia Tech, Angela was given the opportunity to assist in teaching several courses in the CSES department, including Basic Soils Laboratory, Soil Survey and Taxonomy, and Fundamentals of Environmental Science. She also became an ARCPACS Certified Associate Professional Soil Scientist during this time. In January 1999, Angela was hired by Canal Environmental Services as a project soil scientist, to map soils in North Carolina. Angela graduated from Virginia Polytechnic Institute and State University with a Master in Science degree in CSES in May 1999.