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SOIL MOTTLING AS AN INDICATOR OF SEASONAL HIGH WATER TABLE IN MASSACHUSETTS FLOODPLAIN SOILS

A Thesis Presented

by

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DEDICATION

Dr. William Rosenau was a high spirited and inspirational man who led many students, including myself, through this increasingly impersonal educational process with dignity and humor. I hope his memory will last longer than this department in light of the current fiscal crisis.

I would also like to dedicate this work to my two great-grandmothers, Mae Ellinger and Frances Burns and my two sisters, Carolyn Mae and Frances Chase-Dunn.

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My father has helped me most of all by giving me the thirst for knowledge, the curiosity to ask questions and the courage to explore the world around me.

ABSTRACT

SOIL MOTTLING AS AN INDICATOR OF SEASONAL HIGH WATER TABLE IN MASSACHUSETTS FLOODPLAIN SOILS

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Characterization of soil moisture regimes is often based solely upon morphologic interpretation and not on actual measurements. The accuracy and consistency of morphologic information to describe the duration and frequency of saturation within individual soil horizons was studied in 20 Connecticut River floodplain soils. The saturation level at each site was recorded at approximately 2 week intervals for 2 years in perforated PVC observation wells. The dominant Munsell chroma of each horizon was compared to the number of weeks the horizon was saturated during the growing season. An exponential model only explained 20% of the data due to recently deposited soil horizons with parent materials of low chroma. Another chroma-based index did not have a linear relationship with the number of weeks of saturation. Multiple stepwise regression using chroma, organic carbon, extractable manganese contents and particle size analysis provided better prediction (R^2 =0.956) of the number of weeks of saturation, however, the standard error of the constant was greater than a week (1.27).

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CHAPTER 1

INTRODUCTION

Wetlands are areas that are flooded or wet for a significant period of the growing season (Mitsch and Gosselink, 1986). The value of wetlands is being realized for their ability to purify wastewaters, store flood waters and to provide sanctuary for wildlife, waterfowl and plants (Adamus and Stockwell, 1983). Despite these findings, growth pressures have forced development of these "marginal" lands. Wetland boundaries sometimes are difficult to define, yet major land-use decisions are based upon the determination.

Presently, criteria for wetland delineation are based upon the occurrence of hydrophytic vegetation, hydric soils or wetland hydrology either combined (Federal Interagency Committee for Wetland Delineation, 1989), or separately. Massachusetts, for example, bases its delineation solely on the presence of vegetation, whereas Connecticut uses soils to identify wetlands.

Even though the hydrology of wetlands is their best defining characteristic, the soils and vegetation may be important indicators of seasonal wetness. Hydric soils of New England have been defined and characterized by Tiner and Veneman (1987). A national list of hydric soils by series is available as well (USDA-SCS, 1987). Wetland plant species are listed by Magee (1981). Long term monitoring of water tables is a time consuming, expensive process and is often avoided by using indirect wetland indicators such as plants and soils. The hydrology of the site also can be ascertained by a field visit .

during the wet season or by looking for high water marks on leaf litter or on vegetation because of the ephemeral nature of wetland hydrology. Water table level measurements determined from deep observation wells also may not necessarily represent the moisture conditions of the entire pedon above the level of saturation.

In this age of conservation and overabundant litigation, it is advantageous for any development project to identify wetland boundaries by accurately estimating or measuring the level and the seasonal fluctuation of the water table. High water tables affect development of rural and suburban areas due to potential problems including onsite septic systems and flooding basements (Vepraskas et al., 1974). The assessment of onsite sewage disposal suitability often includes determination of the groundwater level since treatment efficiency of the effluent through the soil is negatively impacted by the presence of the water table (Veneman, 1982).

To expedite the determination of wetland boundaries, soils are often observed along transects where the transition from upland to wetland occurs. The interpretation of the color, texture, moisture content and many other properties of these samples can be misleading and misinterpreted if only a single observation is made of a site's hydrology. The duration and frequency of seasonal high water tables is difficult to discern from this one site visit as well. Standardization of regional site assessment procedures might improve the ability to estimate high water table levels of using soil morphologic and plant information from just one field visit.

Soil development in floodplains frequently is interupted due to additions or erosion of soil resulting in weakly expressed morphology. It is the working hypothesis of this study that the transfer of identification methodology from upland situations often is difficult because of the limited morphological development in floodplain soils.

Assessment of the soil moisture regime and the way in which soil is affected, morphologically and physically, by the presence of the water table is the focus of this study. Field measurements of soil moisture parameters, such as redox potential, dissolved oxygen, and ferrous iron content of soil water were made to more accurately describe the relationship between seasonal wetness status and morphology. The primary objective of this study was to quantify soil redoximorphic features and to compare these with measured water table levels. A water table prediction model was formulated based on these soil morphologic indices as well as other soil characterization data.

CHAPTER 2

OBJECTIVES

The overall objective of this study was to improve our ability to predict soil moisture regimes in floodplain soils using soil morphological features. Specific objectives were:

i) to determine the soil moisture regime in selected Massachusetts floodplain soils by making field measurements of water table levels, redox potentials, dissolved oxygen and ferrous iron content of the soil water,

ii) to quantitatively and qualitatively describe soil morphological features and to elucidate possible relationships between them and the measured physical parameters, and

iii) to formulate a water table level prediction model utilizing the morphologic and chemical parameters measured in this study.

CHAPTER 3

LITERATURE REVIEW

The Mottling Phenomenon

Individual soil horizons have characteristic colors which can be interpreted to evaluate the degree of pedogenesis and chemical weathering. Soil color can vary considerably within a single soil horizon. The most abundant color of the horizon is the matrix color while patches of different colors are referred to as mottles (Soil Survey Staff, 1981). Dissolution, leaching and precipitation processes lead to the formation of blotches and patches within soil horizons. Presently, mottling phenomena due to alternating cycles of reducing and oxidizing soil conditions are referred to as redoximorphic features. The fact that mottles exist, shows heterogeneity of properties and conditions in the soil over small distances. The overall bleaching or graying of the matrix of a soil horizon is called gleying (Tiner and Veneman, 1987).

Mottles can be described with a high degree of detail, even microscopically (Brewer, 1976). Commonly, only the distribution, size, contrast and color of mottles are listed in most soil descriptions. Less frequently, the shape of mottles, such as tongued, threadlike or spotted or their locations are reported. Cutans are thin coatings of material. They can be grouped according to the particular structure on or in which they occur such as grain, ped, channel, plane and void cutans. The substance which forms a cutan also appears in its name (Table 1). The prefixes neo- and quasi-

Table 1. Cutan constituents and colors (adapted from Brewer, 1976 and Veneman et al., 1976).

CUTAN	MAIN CONSTITUENT	COLOR
ferran	iron	red
argillan	clay	gray to brown
mangan	manganese	black (purplish)
organo-argillan	organic matter and clay	black
sesquan	sesquioxides	red to yellow
alban	absence of oxidized iron or other materials	gray

denote the subcutanic relationship between the deposit and a structure or a surface. A neoferran occurs in contact with a pore or ped surface, whereas a quasiferran fades into the matrix at a distance away from the structure or surface. Cutans can also be described in associations. For example, a channel neoalban-quasiferran is an alban which is in contact with a pore and occurs with a ferran located at some distance from the pore.

Oxidized iron is responsible for red, orange and brown soil colors, whereas reduced iron occurs either in gray, blue-gray, or green-gray colors, or leaches away leaving the parent material colors exposed. Studies done on the morphology, minerology and forms of iron in mottles and cutans have revealed that the above assumptions generally are true, however, accurate sampling and identification of such morphological features without contamination is always difficult (Richardson and Hole, 1979; Blume and Schwertmann, 1969; Brown, 1954).

Iron Chemistry of Hydromorphic Soils

Redoximorphic features caused by seasonal soil wetness are the result of iron and manganese transformations. Iron may become reduced and mobile in a soil system due to weathering of minerals and by decay of organic matter. The influx of drainage waters can also import dissolved iron. The reweathering of secondary minerals formed in soil also can be a source of mobile iron. Soil parent materials and secondary minerals vary in iron content as well as in the ratio of the forms of reduced ferrous iron [Fe(II)] and oxidized ferric iron

[Fe(III)] (Table 2). These different minerals have varied rates of weathering and stabilities.

Mineral weathering leads to the transformation, diffusion, or leaching of iron and manganese while the remaining structures are altered to new minerals or substances. Recrystallization of minerals occurs along with the formation of amorphous, non-crystalline or poorly crystalline compounds. Munch et al. (1978) found that the smaller the amount of amorphous soil iron, the more intense the transformation was from crystalline to non-crystalline forms. Iron content of soils may vary considerably over distances of only a few centimeters (Bloomfield, 1952).

Waterlogging of soils and subsequent gleying is believed to increase the rate of weathering (Crompton, 1952). Conversely, wet soil conditions also may inhibit the recrystallization of iron oxides by retarding breakdown of organic compounds (Blume and Schwertmann, 1969). Bloomfield (1952) speculated that iron oxide mottles form as a secondary process after gleying. Fairly rapid aging and crystallization of pedogenic iron oxides occurs in the mottles of surface-water gley soils possibly due to the fluctuation between reduced and oxidized conditions (Thomasson and Bullock, 1975). Cook (1984) reported that in sediments, the chemical oxidation of Fe(II), which had a half life of less than 3 h, yielded Fe(III) hydroxide. The lower the degree of crystallinity, the more these pedogenic Fe(III) oxides may be transformed.

Some major iron minerals considered to have formed pedogenically have been identified but more work needs to be done to confirm and

Table 2. Chemical composition and range in ferric (Fe(III)) and ferrous (Fe(II)) iron content in selected minerals (* - determined by Stucki, 1981; + - present in variable or unspecified amount) (after Duda and Rejl, 1989).

MINERAL	COMPOSITION	Fe(II) (%)	Fe(III) (%)
ankerite	$CaFe(CO_3)_2$	39.06	
biotite*	$K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH)_2$	11.44	2.5
chamosite	$(Fe,Mg)_5Al(Si_3Al)O_{10}(OH,O)_8$	+	+
chapmanite	$Fe_2Sb(SiO_4)_2.OH$		36.73
chlorite	$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$	+	+
goethite	$FeOOH$		89.86
hematite	Fe_2O_3		+
ilmenite	$FeTiO_3$	47.34	
jarosite	$KFe_3(SO_4)_2(OH)_6$	47.83	
lepidocrocite	$FeOOH$		89.86
limonite	$FeOOH.nH_2O$		89.86
magnetite	Fe_3O_4	31.03	68.97
nontronite*	$Na_{0.33}Fe_2(Si,Al)_4O_{10}.nH_2O$		24.0
peridotite*	mafic rock	4.12	1.1
pyrite	FeS_2	+	
pyrrhotite	FeS	+	
siderite	$FeCO_3$	62.01	
symplesite	$Fe_3(AsO_4)_2.8H_2O$	36.56	
thuringite	$(Fe,Mg)_6(Si,Al)_4O_{10}(OH)_8$	+	+
vermiculite*	$(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2.4H_2O$	1.29	5.28
vivianite	$Fe_3(PO_4)_2.8H_2O$	42.96	

extend the information available. Brown (1954) identified lepidocrocite and goethite in soil and suggested that the rate of oxidation in the soil environment determines which mineral is formed, slow oxidation favoring the formation of lepidocrocite. Thomasson and Bullock (1975) found lepidocrocite and goethite common in mottled horizons but lacking in relatively less mottled horizons of the same profiles. Siderite, vivianite, sulfides and "green rust" are reported to be the major compounds in which Fe(II) occurs, "green rust" being a mixed Fe(II)-Fe(III) hydroxy compound (Schwertmann and Taylor, 1989).

Bloomfield (1952) sketched out a regenerative process by which ferric oxides, reduced by plant decomposition products from the surface soil layers, are solubilized and move down through the profile in the ferrous iron form. "The ferrous iron would be immobilized to some extent by sorption of ferric oxide in the lower layers... Subsequent reoxidation of the sorbed ferrous iron would occur comparatively readily once the conditions became slightly aerobic... Once reoxidized, the ferrous iron would provide a fresh medium for further fixation." Crompton (1952) suggested a means of iron pan formation where reduction and dissolution of iron in perched water on the upper surface of a flow restricting layer or an iron pan could be followed by iron diffusion downwards through the pan with reoxidation in the better aerated conditions on the lower side of the pan. This process could be occuring in the formation of concretions and nodules as well. Schwertmann and Fanning (1976) reported that the center part of concretions contain more manganese than the outer portions. They postulated that under reduced conditions manganese comes into solution sooner than iron, and is available for accumulation in concretions first; consequently, the supply of manganese is also depleted first. The iron being more ubiquitous, continues to accumulate. Cyclic reoxidation of hydromorphic soils seems to be important in concretion formation since concretions generally are not found in permanently saturated horizons (Schwertmann and Fanning, 1976).

Amorphous soil components are thought to be the source of iron that diffuses, leaches or concentrates into mottles. Research has focused on the ability of wet soils to produce quantities of ferrous iron which is seen as important in hydric soil formation. Mobilization of iron usually requires that iron be reduced into a soluble form [Fe(II)]. Blume and Schwertmann (1969), however, asserted that iron migration also occurs passively when attached to clay particles. This iron is in reduced or oxidized ionic form on the exchange complex or as an oxide attached to the clay mineral.

Lateral movement of iron in ground water was found to occur independently of clay movement in a Stagnogley (Blume and Schwertmann, 1969). A Pseudogley soil exhibited a distinct iron to clay maximum in the lower topsoil indicating lateral additions of iron which corresponded to iron depletion in neighboring profiles. Richardson and Hole (1979) reported on poorly drained sites where the iron in solution was transported from the pedon by ground water.

Lake sediments are essentially permanently saturated soils. In freshwater lakes, Cook (1984) found that 90% of the ferrous iron flux to the water column originated at the sediment/water interface, the rest came from the sediment pore waters. Iron was concentrated deeper in the sediments and less concentrated in the water column with increasing distance from the sediment/water interface, suggesting that ferrous iron is consumed or transported away from the sediments in this system. Cook also stated that the sediment pore water Fe(II) concentration appeared to be governed by the precipitation of FeS, $FeCO_3$, diffusion and rate of formation. The latter probably being the result of organic matter oxidation with Fe(III) acting as a direct or indirect electron acceptor.

In calcareous Ohio soils, ferrous iron was detected when the redox potential (Eh) was less then 400 mV (Ransom and Smeck, 1986). Ferrous iron was significantly correlated to Eh and negatively correlated to dissolved oxygen content. Ransom and Smeck (1986) found a lack of correlation between Eh and DO, but a significant negative correlation between Eh and ferrous iron content of the soil solution and between DO and ferrous iron. They also discussed the extreme variability in iron concentrations and noted how the soil Eh and pH hovered close to the transition between ferrous and ferric iron indicating that iron reactions can be driven simultaneously in either direction in different parts of the same soil depending on local soil conditions.

Microbiology of Iron Reduction

Chemical reduction occurs when oxygen is not present to act as an electron acceptor in the soil system. Alternative electron acceptors include, in decreasing order of energy yield, nitrate, ferric iron, sulfate, and carbon dioxide. Ferric iron [Fe(III)] can change to ferrous iron [(Fe(II)] when it gains an electron. This process is enhanced by the activities of microbes and plants. The reduction-oxidation (redox) conditions of the soil along with pH, organic matter content, soil temperature, and other parameters dictate the type of reactions and speciation of iron as well as manganese within the soil.

Biological reduction of iron in soils has been disputed. Bloomfield (1952) reported that sterile reduced plant extracts gave "gleying effects which were comparable in speed and extent with those obtained in sugar fermentations" and concluded that direct microbial action is not an essential requirement for the production of gley soils. Many other investigators (Ignatieff, 1941; Bromfield, 1954; Ottow, 1973; Cook, 1984) believe that the reduction of iron in waterlogged soils is largely a biological process.

Iron reducing microorganisms have been listed or reported by Bromfield (1954), Alexander (1977), Nealson (1983), Atlas and Bartha (1987), Ehrlich (1981), Jones (1986), and Lovely, et al.(1987). Only recently, however, has an anaerobic respiring bacteria, GS-15, been identified and isolated by Lovely et al. (1987) to reduce both iron and manganese at the membrane level. A distinction should be made between biological iron reduction that occurs due to anaerobic respiration where an organism gets rid of electrons to the ferric ion purposefully and "accidental" reduction caused by the proximity of ferric ions to electron cycling by fermentative organisms. The latter being similar to the reduction caused by nonbiological organic matter degradation found by Bloomfield (1952).

The association of microbial activities to iron reduction has been observed previously. Bromfield (1954) found Bacillus circulans and B. polymyxa to be the major iron reducing bacteria in soil based on iron reducing activity in various media. Ottow (1973) reported Clostridia as the main bacteria responsible for iron reduction in soils because it has properties that suit it well to hydromorphic soil conditions. Ottow questioned the role of Bacillus circulans and Pseudomonas aeruginosa in gleyed soils because of their "complex nutritional requirements" and therefore could be "reducing iron during the first stage after flooding in a seasonal wetland" (Ottow, 1973).

Munch et al. (1978) found iron reducing, nitrogen fixing, saccarolytic clostridia (Clostridium butyricum S22a), but cautioned that "an increase in redox potential of flooded soils is just the result of active, metabolizing reducing microorganisms but cannot account for a true mechanism of reductive tranformations in soil." They also noted the importance of microbial attachment to the oxide surface. Additionally, non-crystalline ferric iron seemed reactive in preference to other forms probably due to a thermodynamic advantage. Jones et al. (1984) isolated Vibrio as an actively Fe(III) reducing facultative anaerobe along with another facultative autotroph. A dissimilatory iron reducing bacteria, GS-15, reduced amorphous ferric oxide to make extracellular magnetite (Lovely et al., 1987).

The presence of nitrate is known to suppress ferric iron reduction (Jones, 1983). Proposed mechanisms include: 1) direct involvement of nitrate reductase in ferric iron reduction, 2) diversion of electrons from a ferri-reductase system which precedes cytochrome b to nitrate reductase in the presence of nitrate, and 3) reoxidation of ferrous iron by nitrite formed in the presence of nitrate.

Microbial reduction of amorphous Fe(III) oxyhydroxide produced ten times more Fe(II) than reduction of hematite (Lovely and Phillips, 1986a). Lowered substrate availability inhibited methane production in the Fe(III) supplemented sediments, therefore iron reduction in sediments could outcompete methanogenic food chains for sediment organic matter even though Jones *et al*. (1984) reported that reduction of ferric iron accounted for only a small proportion (<1%) of the reducing equivalents found in the available organic matter. Lovely and Phillips (1986b) measured many forms of ferric iron sources for microbial reduction and found that oxalate extractability was not a good indicator of availability for microbial reduction. Poorly reducible forms are also extracted with oxalate such as mixed Fe(II)/Fe(III) compounds.

Iron reduction also occurs when nitrate does not interfere. In this case, the iron is reduced by some other ferrireductase. Microbial reduction of Fe(III) can occur by:

$$\text{Energy} \xrightarrow[\text{dehydrogenase}]{\text{substrate}} e^- + H^+ + \text{ATP} + \text{end product}$$

$$Fe(OH)_3 + 3H^+ + e^- \longrightarrow Fe^{+2} + 3H_2O$$

$$2Fe(OH)_3 + Fe^{+2} + 2OH^- \longrightarrow Fe_3(OH)_8$$

The last iron oxide above was described as "a gray-green mixed oxide of gley" (Erhlich, 1981).

Microbes that gain energy from iron reduction are chemoautotrophs, such as GS-15. Another chemoautotroph, Thiobacillus thiooxidans aerobically reduces iron with sulfur as the electron donor; T. ferrioxidans reduces iron only anaerobically while Sulfolobus acidocaldarius reduces it microaerophilically (requiring a low concentration of oxygen when grown under aerobic conditions but prefers anaerobic conditions) (Ehrlich, 1981).

Many environmental conditions are important in controlling how and when iron is reduced in wet soils. Solely inorganic chemical reduction in waterlogged soils probably occurs in extreme conditions of very high temperature, low pH and Eh. Environmental factors limiting microbial processes are just beginning to be considered and measured.

Soil reduction by microbes should be extensive only during the growing season when the soil temperature is above the "biological zero" of 4°C. Soils which are saturated only in the winter season often will not exhibit strong mottling. Ransom and Smeck (1986) measured ferrous iron in the soil solution only during the summer months when the soil temperature was above 8°C. Carter and Ciolkosz (1980) presented data collected from a soil with a mesic temperature regime in Pennsylvania where the portion of the year experiencing soil temperatures of <4°C is 3 to 4 months long, whereas the portion experiencing <8°C is 5 to 6 months long. The growing season needs to be measured and defined when studying the activity of iron reducing microbes.

Soil moisture content is limiting to microbes in both extremes. Too little water creates stress by limiting membrane absorption of water and cell dessication occurs disrupting metabolic activities. When a dry soil experiences rapid wetting, the sudden rehydration can cause microbial cells to burst due to high osmotic potential. During the previous dry period, the cell had to increase its internal osmotic potential to extract water from the soil matrix. In a drying soil, this water is held under increasing tension.

Too much water is only a direct problem for xerophilic organisms. Obligate aerobic organisms will be in trouble when saturated conditions lead to oxygen depletion forcing soil microbial populations to change or adapt to the anaerobic conditions.

Another form of water stress is limited microbial movement through soil pores. Matric potential influences the movement of unicellular organisms by affecting the amount and continuity of water-filled pores (Griffin, 1981). Attachment of microbial cells to soil mineral particles could be water controlled as well, and it has been asserted that microbes need this contact to solubilize ferric iron from oxides (geothite and hematite) and also from silicates (glauconite) in order for reduction to occur (Robert and Berthelin, 1986).

Soil aeration conditions within the same horizon may vary drastically over short distances or short time periods. For example, soil next to an air-filled pore could be oxidized, whereas inside the soil ped the pores are saturated and the soil can be chemically reduced. Air and water replace one another quite readily in a macropore so that aeration conditions may change quickly and both aerobic and facultative anaerobic iron reducing microbes may exist simultaneously.

The reduction of iron in soils lags behind the onset of saturation conditions (Maltby, 1986). Iron reduction generally occurs for a shorter time than the period of saturation because other ions, such as NO_3^+ and Mn^{+4}, are reduced first. Aerated rain or ground water may result in oxidizing soil conditions even though the soil may be saturated. The reverse is also true, that reducing conditions can extend beyond the period of saturation if the soil holds capillary water and maintains reduced sites within an otherwise drained soil.

A consideration of the iron cycle in natural environments may help in understanding the conditions needed to produce mottling in soils. Both Nealson (1983) and Ehrlich (1981) diagrammed known iron transformations. Numerous oxidation and reduction transformations occur despite the fact that most of the iron present on the earth's surface is in the oxidized form, mainly within minerals. Microbial iron reduction is a major path of iron into the hydrologic cycles and the biosphere.

Jones (1986) studied the iron content of freshwater lakes and graphed iron cycles over the seasons and compared this to the hydrologic and temperature variations. Initiation of Fe(II) formation occurred when the water table was highest and temperatures were rising. The peak of the Fe(II) concentrations occurred in the late summer, after the soil had been saturated for most of the growing season. A cyclic relationship was also found to exist in coastal areas between the two organisms Desulfovibrio desulfuricans and Thiobacillus ferroxidans (Silver et al., 1986). Under submerged conditions, anaerobiosis occurred and the H_2S produced by D. desulfuricans converted jarosite to pyrite; $KFe_3(SO_4)_2(OH)_6$ ---> FeS_2. After the water receded and aerobiosis occurred, T. ferroxidans transformed pyrite back into jarosite.

Relations to Soil Color

As described in the previous section, microbially catalyzed chemical reactions in saturated and reduced soil conditions commonly produce soluble iron compounds. The soluble reduced iron can leach away from the matrix source and either be removed totally from the area or precipitate (i.e., along pores) when oxidation occurs. Removal of iron compounds exposes the color of minerals in the soil matrix. The leached matrix and sometimes the ferrous iron compounds have gray, low chroma colors (Munsell Color, 1975), whereas the oxidized iron compounds such as hematite and goethite, generally have high chroma colors (see Table 3). Horizons entirely reduced may produce gleying, whereas horizons which are only reduced in spots appear mottled.

Soil color is created by any material present as matrix or coatings in the soil. Iron containing minerals have many colors. Comparing Tables 2 and 3, there is no consistent relationship between forms of iron in minerals and their colors. It is possible that a site specific study of the minerology of soil could reveal a correlation of this type.

Table 3. Range in natural colors of selected soil minerals (after Duda and Rejl, 1989). Streak colors determined by abrading mineral on a ceramic plate and observing the color of the finely crushed particles.

MINERAL	COLOR (STREAK)
ankerite	white, gray, yellow, brown (white)
biotite	dark brown, brown-green, brown-black (gray, white)
chamosite	gray, gray-green, brown, green-black (gray-green)
chapmanite	green-yellow, yellow, olive-green (same as color)
chlorite	green, brown, white, reddish (white, gray-green)
goethite	brown, black (yellow)
hematite	reddish brown, gray-black, black (red, reddish brown)
ilmenite	black (black-brown)
jarosite	yellow, brown, brownish black, ochre yellow (yellow)
lepidocrocite	red (dark yellow, brown)
limonite	yellow, brown, black, iridescent (brown, yellowish brown)
magnetite	black (black)
nontronite	green-yellow, brown-green, olive green (white)
pyrite	yellow, brass-yellow, varigated (green-black)
pyrrhotine	yellowish brown, bronze (gray-black)
siderite	white, yellowish brown, black, gray (white, yellowish)
symplesite	grass green, indigo blue (blue-white)
thuringite	olive-green, green-brown, dark brown (green-gray)
vermiculite	yellow-brown, green-brown (greenish)
vivianite	white, blue-green, indigo blue, black-blue (white, blue)

Daniels et al. (1961) measured ferrous iron content of sediments of various hues and chromas. The sediments with grayer hues contained more Fe(II) than the other. Overall the lower (0 and 1) chroma sediments contained more ferrous iron than the high (2, 3 and 4) chroma soils. The small number of soils sampled in their study was insufficient to conclude whether or not different chromas within one hue had significantly different iron contents.

Soil Morphologic Indicators

Redoximorphic features are often described, catagorized and their relative extent measured to form predictions of the soil-moisture status of a pedon. As early as the 1950's, wet soils were identified by their gleyed morphology (gray or low chroma) along with the assumption that the process of mottling was biological (Simonson, 1951; Bloomfield, 1949). Even though mottling has long been noted as useful in determining the moisture regime, detailed studies describing the distinctive morphology and mottled patterns in individual soils along with actual measurements of the frequency and duration of water table fluctuations have been limited, especially in New England.

Elsewhere, soil mottling has been successfully correlated to soil drainage classes within the USDA-SCS soil classification system at the subgroup level (Fanning et al., 1973). Richardson and Hole (1979) reported that mottling increased when progressing from well-drained to very poorly drained soils in a glacial moraine. Well-drained sites had no mottling, somewhat poorly drained sites showed considerable amounts of mottling, whereas very poorly drained sites were gleyed. Soil moisture regimes and associated morphology also have been studied by Vepraskas and Wilding (1983a), Childs and Clayden (1986), and Franzmeier (1986). Soil drainage class describes only one aspect of soil-water interactions in the field. Hydraulic conductivity along with duration and level of saturation are soil-water properties that have been measured in an attempt to correlate drainage to mottling (Evans and Franzmeier, 1986).

It is important to note that hydric soil morphology does correlate to a large extent to wet conditions. Veneman _et_ _al_. (1976) diagrammed the degree of wetness to the amount of low chroma mottling. They showed the current classification criteria of low (<2) chroma mottling and matrix (along with other mottling phenomena such as relative amounts of ferrans, mangans, neoalbans and quasiferrans) related to varying degrees of wetness.

Mottles with chromas of 2 or less are assumed to indicate saturation of the soil with water during some period of the year (Vepraskas _et_ _al_., 1974). The association of low chroma soil colors with ferrous iron content is true only in soils which have a supply of iron to reduce and the color of the parent material doesn't interfere with the color determination. Color interference occurs when the parent material is too red or brightly colored to show an accumulation of gray coatings of ferrous iron and clay. In the reverse situation, gray or light-colored parent materials appear weathered before they have undergone actual pedogenesis (Tiner and Veneman, 1987). Accurate sampling of mottled features to measure the iron distribution is a difficult process as noted before by Bloomfield (1952) and Richardson and Hole (1979).

Simonson and Boersma (1972) concluded from work in soils of the Pacific Northwest, that the depths of faint and distinct mottling were strongly correlated with the degree of waterlogging. They agreed that hues of 2.5Y and 5Y in conjunction with low chroma matrices and mottles in subsoil horizons have long been recognized as a reliable identification of waterlogging in soils--with inference of reducing conditions and removal or translocation of iron oxides in the profile. They found chroma to be a separate function of the percent time saturated for each individual soil series studied.

Vepraskas and Wilding (1983a) found color chromas of peds to decrease with increasing time of reduction rather than the period of saturation. The studied soils were saturated for long periods of time with only a low amount of reduction probably due to aerated rain water entering the soil. They recommended revisions in the current aquic moisture regime criteria of Alfisols to include dominant chromas of 3 on ped exteriors when accompanied by a mottled ped interior with matrix chromas of 4 or more. Vepraskas and Wilding (1983b) also recommended the use of albic neoskeletans as another diagnostic criterion for water saturation, even though these had moist color chromas of 4 or less. Measurements of the redox and water table conditions were compared to the abundance of albic neoskeletans which were found to be related to the duration of reducing conditions but not to the duration of saturation.

Soils with a wider range in moisture content and redox potential appear to be most strongly developed in terms of chroma and structure (Macyk _et_ _al_., 1978). A common mottling pattern which occurs in sandy-loam soils is where short rains fill macropores but leave ped interiors oxidized resulting in channel albans with sesquioxidic nodules in ped interiors (Veneman and Bodine, 1982). The reverse situation can occur in more saturated soils where macropores are drained first after a rain and aeration of the pore linings results in the formation of channel neoferrans.

Vepraskas and Bouma (1976) related soil mottling to saturated conditions. They found that mottling can occur in soils which are not saturated throughout the entire horizon. The reduced conditions necessary for mottling occured only in ped interiors, whereas the macropores were reoxidized relatively rapidly after saturation and mobilized iron, which then precipitated along the pores forming channel neoferrans.

Many studies have reported the occurrence of mottling in soil drainage sequences and catenas (Glentworth and Dion, 1949; Thorp and Gamble, 197 Vepraskas _et_ _al_., 1974; Veneman _et_ _al_.; Gile, 1958; Hanna _et_ _al_., 1975; Richardson and Hole, 1979; Zobeck and Ritchie, 1984a; Evans and Franzmeier, 1988). Topography often dictates mottling patterns in soils by controlling the drainage conditions imposed by the slope. A gradual progression of increased mottling and gleying with increased moisture content of soils can be expected downslope. This relationship is clear in some sequences and more complicated in others. Clear examples of this increase in mottling in the lower midslope and downslope have been described by Gile (1958), Hanna *et al*. (1975), Richardson and Hole (1979), and Veneman and Bodine (1982). On one drumlin catena the mottling zone was thicker at the top, possibly where free draining water from the summit was encountering a fragipan but then follows the expected progression (Veneman and Bodine, 1982). More difficult to explain in terms of slope position are the sequences described in other cases (Zobeck and Ritchie, 1984a; Evans and Franzmeier, 1988). Zobeck and Ritchie (1984a) described a mottled layer of uniform thickness down the entire slope with some thickening of the mottled layer downslope. Mottling also occurred in upland depressions with slow drainage. The mottling increased towards the depressions and tapered off towards the steeper fall face where aeration and permeability increased.

Ruhe (1969) measured and correlated other soil properties with slope position or gradient. Organic carbon was found to have a preferential accumulation in the wetter part of the landscape. Particle size distributions also correlated well with slope position and gradient. Percent very fine sand was found to increase linearly with slope gradient.

Gerrard (1981) discussed some concepts surrounding geomorphic units of slopes with respect to soil color in West Africa. Upland soils were reddish brown in color because they contained iron compounds such as non-hydrated iron oxides. Middle and lower slope positions had soils which contained hydrated iron oxides such as limonite and goethite. The color changes were gradual from reddish-brown to orange-brown and yellow-brown to brownish-yellow. On the lowest slopes where iron was reduced, bluish gray, greenish gray, and neutral gray colors appeared. When water tables fluctuated mottling occurred. High chroma mottling in low chroma matrices indicated fluctuating water tables and oxidation and reduction occurred in cycles. Gerrard (1981) noted that gray mottles which were elongated downslope were an indication of throughflow. Water table position, shape of land surface and shape of bedrock all impacted the morphology of soils along a slope. In the British Isles, well-drained fine loamy brown soils occurred on steep slopes with more gleyed brown soils and surface-water gleyed soils occuring on the gentler slopes (Gerrard, 1981).

Crown and Hoffman (1970) concluded from work in Gleysols in Ontario that the shape of mottles might be useful in a quantitative appraisal of the moisture status of soils. They found that horizontal banding of mottles occurred in soils through which there had been the highest frequency of water table fluctuation through a relatively narrow depth range. Vertical streaking of mottles occurred in soils through which the water table fluctuated only once during four months of observation. Mottles in horizons almost permanently saturated were large nebulous features while those in horizons rarely saturated were generally smaller and had more distinct boundaries.

There are problems in determining the moisture regime from redoximorphic features. If the initial parent material has a very high or very low chroma then mottling can be obscured as discussed previously. Climatic or geomorphic changes in the past could result in a drainage condition different from that at present. These relict redoximorphic features remain in the soil and can easily be misinterpreted as representative of present drainage conditions. Confirmation of drainage condition estimates using soil colors should include an assessment of the present topographic position.

Variability in soil morphology may often result from differential wetting and drying cycles in the unsaturated zone and infiltration through macropores or preferential flow paths. Incomplete saturation and short duration are factors which account for the large variation in iron reduction hence in soil morphology. Ignatieff (1941) discussed saturated peat creating an air-resistant layer preserving anaerobic conditions and preventing oxidation of ferrous iron in a gleyed horizon. Ferrous iron can persist in a layer of soil at a fairly low moisture content if the upper layers of soil prevent the free passage of air. Ransom and Smeck (1986) used a ferrous iron indicator test developed by Childs (1981) and found extreme variability in the ferrous and ferric iron concentrations among samples. They attributed the variation to iron reduction in micro-environments within the soil.

Topography controls drainage of soils by increasing the amount of throughflow water, decreasing the depth to saturation downslope, and increasing the flow rate of water (and therefore aeration) with increasing gradients. Glentworth and Dion (1949) diagrammed soil drainage associations to slope position and found excessively drained soils at the summit with "freely, deep freely, slightly poorly, poorly and very poorly drained soils" proceeding downslope, respectively.

The hydrology of hillslopes can be assessed by studying the water flow pathways and processes such as piping, saturated and unsaturated throughflow in soil, and percolation to groundwater. Distance from the summit and slope drainage are linearly related to the amount of flow accumulated from upslope. Slope gradient determines the rate of flow and a saturated layer (formed, for instance, above an impeding horizon) will thicken downslope (Whipkey and Kirkby, 1978). Flow velocities were measured by Thorp and Gamble (1972) down a slope through a Crosby silt loam where the maximum distance traveled underground was 6.1 meters over a 3-week period. Steep slopes contained soils of larger particle sizes and were more permeable so that subsurface flow velocities were increased proportionately with increasing gradient (Whipkey and Kirkby, 1978).

Patric and Lyford (1980) reported on small pool formation and overland flow from well to poorly drained soils in the Harvard Forest in Petersham, Massachusetts. Soils downslope always saturated first at the onset of rain. The duration of soil saturation was closely related to slope position, suggesting that the drainage of upslope soils was inhibited whenever soils downslope were fully charged with water (Patric and Lyford, 1980).

A nine unit topographic model devised by Conacher and Dalrymple (1977) is modified here to demonstrate the various conditions that slope position can enforce upon the soil moisture content and water movement.

- Summits are characterized by slow horizontal drainage and vertical drainage determined by the parent material (often glacial till, outwash, or bedrock in Massachusetts). In the case of low permeable parent materials or fragipans, mottling could be present in summit soils.

- At the seepage face, lateral drainage velocity may increase as does aeration and so does the amount of water passing through the soil.

- The fall face and transportational midslope is where erosion dominates. In humid temperate climates, these slopes are usually not characterized by mass movements but considerable soil removal may thin the pedon to where the bedrock is closer to the soil surface. This can funnel water through a smaller amount of soil and cause saturation to occur. These waters can be quite highly aerated, so this may retard mottle formation even if saturation occurs.

- The footslope and toeslope are zones of accumulation of debris as well as water from upslope positions. Water tables may rise up to shallower depths and create saturated reduced conditions more easily than summit and seepage slope positions.

- The present floodplain exists downslope of the latest terrace deposit and contains backmarshes and sloughs, natural levees, and the river channel. Backmarshes and sloughs are submerged longest and soils here can be saturated and reduced for long periods of time, whereas the levee is only submerged seasonally. The levee positions are occupied by soils with better drainage than other soils of the floodplain because of the higher position on the landscape and coarser parent materials. The water table level of the floodplain is hydrologically connected to the river stage. Prediction models based on river stage have shown a stronger relationship to water table levels in wells which were located closer to the river (Grossman, 1981).

Floodplain hydrology is characterized by slow lateral movement of water until it reaches the river channel. On gentler slopes, slow drainage may produce peaty soils which hold large amounts of water and impede lateral subsurface flow because of their low permeability (Bay, 1969). Where gradients vary over a slope, flow is slower in a concavity where flow lines converge and causes the saturated subsurface flow layer to thicken and may bring it to the surface (Whipkey and Kirkby, 1978). Dunne and Black (1970) mapped the upslope movement of saturated conditions during a rain event in moderately to poorly drained soils in the head of a valley. This upslope migration of saturation also was observed by Patric and Lyford (1980) in their study of the Harvard Forest. Metzler and Damman (1985) found that inundation periods are poorly predicted by flood duration curves if the area is not freely drained.

Prediction of Soil-Water Regimes

The water table is the level at which the soil pores are totally filled with water held at zero water potential or zero tension. Many soils have a substantial variation in the size distribution of pores and exhibit a capillary fringe which lies well above the free water table. Within this zone the smaller pores hold the water with a greater tension and allow saturation of some pores to occur at levels above the actual free water table. This can also be a zone where both reducing and oxidizing conditions are present at the same time. The use of tensiometers would help describe the unsaturated water content of the soil above the water table.

Ustic, udic and aquic moisture regimes are defined in Soil Taxonomy (Soil Survey Staff, 1990). The moisture regime is ustic when the soil moisture control section is moist for more than half of the year (183 d) but less than 3/4 of a year (274 d). The udic regime is used when the control section is moist for greater than 3/4 of a year. Moisture regime determinations must be made when the soil temperature is greater than 5^{o}C. The aquic moisture regime has been called a soil-water regime (Eswaran and Cook, 1985) or reducing regime since it doesn't apply to a control section and the only criterion is that the soil be saturated for long enough to develop anoxic conditions.

The aquic regime is used at the suborder and subgroup level in Soil Taxonomy. An aeric subgroup is provided which can be used to express an intergrade of wetness between an aquic and non-aquic suborder. For example, a Typic Fragiaquept would be wetter than an Aeric Fragiaquept which, in turn, is wetter than an Aquic Fragiochrept. Eswaran and Cook (1985) discuss how these conditions are used throughout different orders of Soil Taxonomy since the definition of aquic and peraquic moisture regimes is not uniformly applied at all levels of the system.

Quantification of mottling to determine moisture status has been attempted in a variety of ways. Concentrations of iron oxides and other substances that form mottles were measured by Vepraskas et al. (1974) and Richardson and Hole (1979). Relative distribution of mottles [many (>20%), common (2-20%), few (<2%)] as defined in the Soil Survey Manual (1981) can give useful information as well.

Evans and Franzmeier (1988) reported that a morphologic index based on hue and chroma was directly related to the dissolved oxygen concentration, whereas with length of saturation there was an inverse relationship. A longer period of inundation resulted in a lower index.

Simonson and Boersma (1972) plotted chroma against percent time saturated and found a curvilinear relationship with the least saturated horizons having lower chromas than the wetter horizons. This inconsistency demonstrated the heterogeneity of the soil morphology which should be used cautiously as a wetness indicator. This study included only three soil pedons with four horizons each. Munsell values were found to have a linear relationship with the lowest value corresponding to the drier horizons. The depths at which faint or distinct mottling occurred were found to be strongly correlated to a high percent of waterlogging during the months of January through June.

Coleman and Fenton (1982) related the depth to a buried geomorphic surface to the average depth to the water table on stable loess divides in Iowa. They showed that depth to a slowly permeable buried geomorphic surface (Y) was related to depth to the water table (X) on flat divides by $Y = -83.32 + 0.85X$, and on sloping divides by $Y = 20.03 + 61X$. Multiple regression equations added month (A) and temperature (B) to the analysis resulting in $Y = 109.04 + 60.06A + 3.21A^2 + 0.84X - 5.60B + 0.67AB$ for the flat divides and $Y = 201.69 - 58.81A + 3.20A^2 + 0.62X - 4.91B + 0.60AB$ for the sloping divides.

In the Netherlands, Van der Sluis and De Gruijter (1985) used frequency distributions from a time series set of data where HW3 was defined as the mean of the three highest water table depths and LW3 was the mean of the three lowest depths from twice monthly measurements. The MHW and MLW were the mean values of HW3's and LW3's over a sequence of years. They attempt to narrow these down to mean spring water table depths, MSW, where $MSW = 5.4 + 1.02MHW + 0.19(MLW-MHW)$ and condense this further to $MSW = MHW + 15$ for I, II, and IV water table classes (the wetter of the Dutch system) and $MSW = MHW + 25$ for III, V, VI and VII classes.

Flood frequency analysis might aid in determining the total period of saturation that occurs in soils along with duration of saturation. Flood frequency determinations are highly dependent upon the length of record and accuracy of information about a given site. The duration of flooding events can be measured but when predicting duration, the surface and internal drainage characteristics of each site need to be evaluated. Closed back sloughs with drainage prevented by dams of debris are very common in the floodplain of meandering rivers. The slope and vegetation of the site also affect the surface drainage. Hydraulic conductivities of each flood deposit need to be determined before internal drainage rates can be predicted.

Other models predicting water table depths, use data of previous water table measurements but since adequate monitoring periods can be quite long, 3 years or more according to Zobeck and Ritchie (1984b), it is desirable to use a model based solely on parameters which can be measured with a few field visits. Boersma et al. (1972) developed the model $h_n = h_{n-1} + 100q/r - 100P/S$, where $q = dr/100$, water table height (h), day number (n, 1-365), pore space drained during a decline in the water table (r), rate of water table decline (d), rainfall rate (P) and pore space available for storage (S).

Nelson et al. (1973) developed a model using basically all meterologic parameters such as months of the year, cumulative rainfall, antecedent rainfall for 30 days, relative humidity at lam, 7am, 7pm, days since last reading of rainfall and water table level.

Water balance equations have been considered as well. Marshall (1973) related the precipitation (P) to underground drainage (U), evapotranspiration (E), lateral runoff of surface and shallow seepage water (L) and change in soil storage (S) where: $P = U + E + L + S$.

MacIntosh and Van der Hulst (1978) discovered a large variability of water table depths within drainage classes. Mean high and low water table depths (MHWT and MLWT) were calculated from five catenas with four drainage classes (20 soils) monitored for five years. Use of MHWT and MLWT did not provide any indication of the duration that a particular horizon remained saturated with water.

Many researchers have worked on how moisture affects soil formation and morphology but little actual data of substantial duration (water table measurements) and accuracy (soil mottling distributions) have been collected at the same sites. Soil reduction is the process by which hydrology and soil morphology are connected. The complexities of this process are acknowledged here while noting that soil reduction is barely understood at this time. Microbial activities and soil physical properties and chemical characteristics are just beginning to be understood. Progress in the research of wet soils can possibly be made when variables are held constant in an isolated subsystem in order to test an individual parameter. The results of this approach are tentatively applied back to the larger wet soil system which is exposed to many changing environments.

CHAPTER 4

MATERIALS AND METHODS

Soil moisture regimes at 20 sites in the Connecticut River floodplain in Massachusetts (Figure 1) were determined by measuring the ground water elevations and soil temperatures every two weeks. Selected sites were monitored in more detail for redox potential, ferrous iron content of pore water, dissolved oxygen and other parameters. The monitoring sites were selected as part of a previous study funded by the U. S. Fish and Wildlife Service (Veneman and Tiner, 1990).

Site Descriptions

Study sites were located in the Connecticut River Valley in Western Massachusetts extending from the northern most well site (site XVI) in Northfield to the southern most well site (site XII) near the Holyoke Mountain Range. The Connecticut River controls the water regime at all sites and affects soil formation through periodic flooding resulting in the removal or deposition of soil material. This unique control of the soil formation at these sites is a dominant factor.

Sites X, XI, and XII are located on the oxbow south of the downtown area of the city of Northampton (Figure 1). Sites X and XI are in Manhan Meadow which lies east of site XII located in the Pynchon Meadow. All of these sites are forested. Complete vegetation

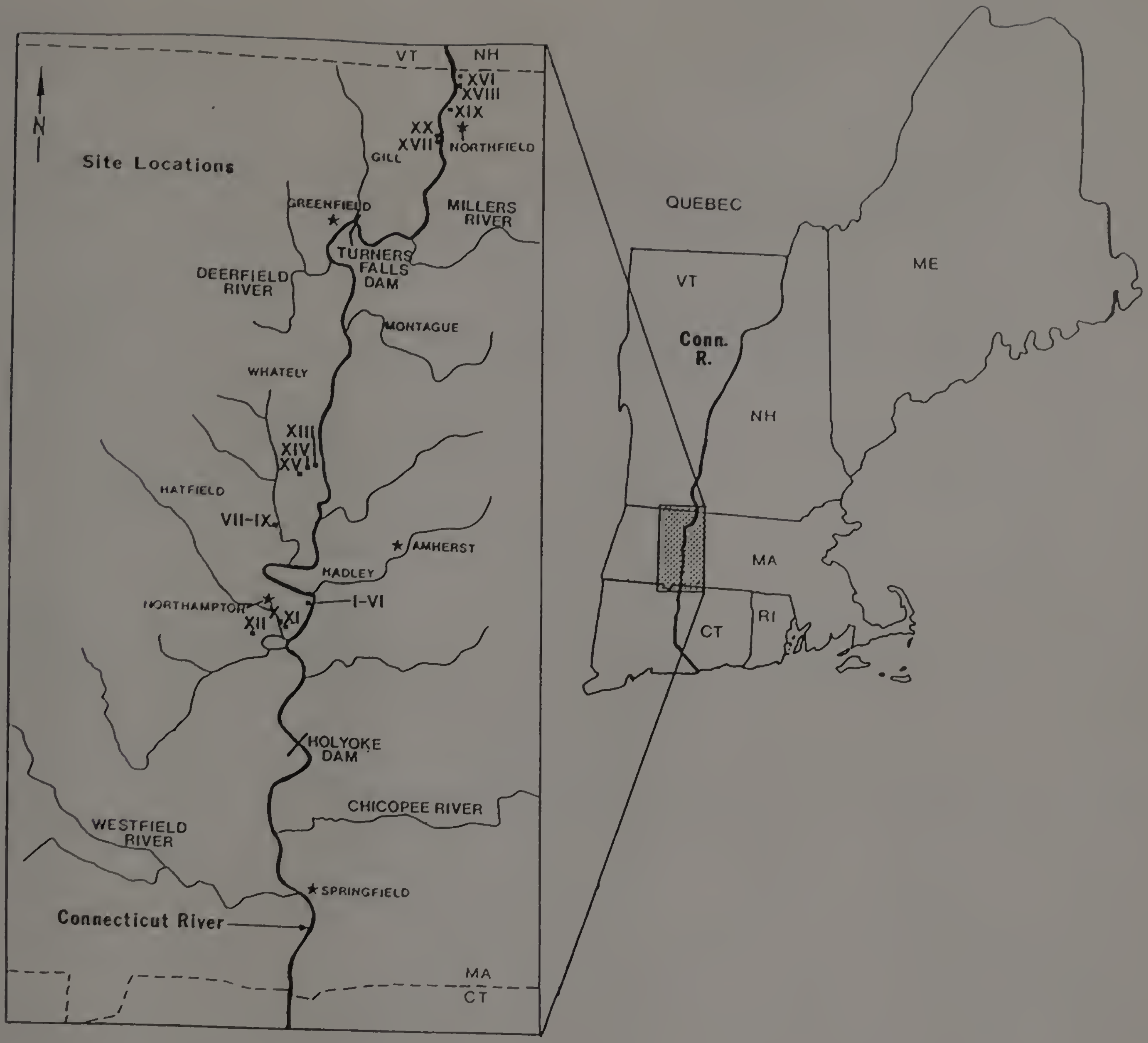


Figure 1. Locations of well sites in the Connecticut River Valley. Major tributaries and dams are included.

identification and descriptions of every site have been performed by Veneman and Tiner (1990).

Sites I through VI are located on Rainbow Beach, a point bar of the Connecticut River, to the east of the downtown area of the city of Northampton. There are two transects, one northern (sites IV, V, and VI) and one southern (sites I, II, and III). The area here is vegetated with silver maples (*Acer saccharinum* L.) and an understory of nettles (*Laportea canadensis* L. and *Urtica dioica* L.) and sensitive ferns (*Onoclea sensibilis* L.). The understory remains herbaceous due to seasonal scouring by debris-laden flood waters that prevents any woody shrub understory to persist from year to year.

The Mill River, a small tributary of the Connecticut River, provides for the immediate drainage of sites VII, VIII and IX in the town of Hatfield. Site VII is located closest to the tributary and is vegetated with tall grass, while site VIII has alder shrubs (*Alnus rugosa* (Du Roi) Spreng.). Site IX is vegetated with taller trees (i.e. Yellow Birch (*Betula lutea* Michx. f.)) and is the most upland of these sites.

The town of Whately is the location of sites XIII, XIV, and XV. A forested drainage channel nearby runs parallel to the Connecticut River and therefore appears hydrologically less connected than any of the previously described sites. Site XIV is the wettest of the three sites while site XIII is the driest in this drainage.

Sites XVII and XX are located on an older river terrace in the town of Gill. These sites are vegetated with trees and shrubs with some ferns. Site XIX is located near the center of the town of

Northfield and is vegetated by ferns, sedges and other herbs and shrubs with only a few trees. One large Black Willow (*Salix nigra* Marsh.) is located in this meadow. Site XVIII is located next to the Pauchaug River, another tributary of the Connecticut River, just north of the downtown area of the town of Northfield. Beaver are active in this area as evidenced by chew marks on well piping. Sensitive ferns are the dominant vegetation at this site. Site XVI is on a high terrace above site XVIII and is vegetated by trees and shrubs.

Ground Water Monitoring Wells

Water tables were measured at least twice a month at observation wells constructed from 3.8 cm PVC piping, drilled along the lower 90 cm with 0.5 cm holes and covered with a polypropylene cloth (Typar by DuPont, DE) to prevent soil from entering the well. Well tops were covered with rubber corks or PVC caps equipped with pressure release holes. Maximum depth of most wells was approximately 3 m. Many sites had two wells at differing depths to account for variation in the porosity of deeper layers and any piezometric effects resulting from a deep well.

Water table levels were measured with a YSI Temperature-Level-Conductivity Meter, Model 3000 (YSI Inc., Yellow Springs, OH 45387). The conductivity of the groundwater water was used to detect when the probe was at the water's surface and the distance to the datum was measured using the cord (marked in feet). An upward displacment of the water in the PVC piping by the probe was measured to be 2.5 cm and this correction factor was be added to each depth measurement.

Meterology

Daily air temperature and rainfall data was obtained from local waste water treatment plants within 5 km of each well site. To determine the difference in seasonal variations, temperatures of air, soil, and well water were measured at selected well sites. Well water temperature commonly was determined at the bottom of the well.

Snow depth was divided by ten before adding to rain depth to account for the density difference between water and freshly packed snow. Conversions of snow to rain depth have been used as low as 5 or 6 which is based upon "ripe" (aged) snow having a density one fifth the density of water. Freshly deposited snow has a density about one tenth of water. Snow depths were recorded on the same day as deposition therefore a "fresh" snow density was used.

Soil Descriptions

Soils have been described in detail at pits located within 10 feet of the well site (Veneman and Tiner, 1990). Soil matrix, mottles and cutans have been described using terminology by Brewer (1976). The color indexing system proposed by Evans and Franzmeier (1988) was used to quantify soil color. Pertinent morphologic information was stored in computer files to allow for a statistical evaluation of the data.

Soil-Water Parameters

Dissolved oxygen (DO) concentrations of the well water at sites I-VI were measured with a YSI Model 54A oxygen meter with a Model 5739 probe affixed with a standard membrane and calibrated in the lab to an air saturated water sample at $5^{o}C$. Measurements were taken when groundwater levels were monitored. DO values were determined after the well had been purged twice.

Soil solution chemistry was examined at sites I-VI by sampling soil water using suction lysimeters installed in soil horizons where soil mottling was most prevalent or indicative of fluctuating or saturated conditions. Temperature, Eh, pH and DO were determined in the field and the samples were stored under anaerobic conditions until time of analysis for Fe(II) and Fe(III) concentrations. Iron determinations were done spectrometrically with 1,10-phenanthroline (Ransom and Smeck, 1986).

Redox electrodes (Vepraskas and Bouma, 1976) with accompanying salt bridges (Veneman and Pickering, 1983) were installed in the same horizons mentioned above. Readings were taken when water table levels were measured.

Soil Characteristics

Particle size analysis (pipette method), pH (water soluble), iron and manganese content (extracted with citrate-dithionite, oxalate, and pyrophosphate), organic carbon content (Modified Mebius method) were determined in selected soil horizons at each site using standard methodology (Soil Conservation Service, 1984).

Data Analysis

A prediction equation of the length of soil saturation was developed using multiple step-wise regression techniques. The model had the general form of:

$Y = aA + bB + cC + dD + eE + fF + gG + hH + iI + jJ + kK + Z$, where,

Y = percent year a soil horizon is saturated
A = chroma index of horizon
B = organic matter content of horizon
C = porosity (from bulk density) of horizon
D = total iron content of soil horizon
E = mean annual soil temperature
F = mean annual precipitation
G = microbial activity
H = clay content
I = ferrous iron concentration of soil solution
J = Eh of soil or solution
K = dissolved oxygen concentration of soil solution
Z = constant

Field work required for such a determination involves a one-time visit to the site for a complete soil description and anaerobic sampling of soil solution. Conversion from mean annual air temperatures to mean annual soil temperatures was done by Carter and Ciolkosz (1980). B, C, D, G, H and I were determined in the laboratory. The suitability of other models was also evaluated. For example, water level frequency, the number of observations of the water table occuring in a horizon divided by the horizon thickness, and the duration of waterlogging (in days) may be considered in a correlation model (see, for example, Moffat and Jarvis, 1988).

CHAPTER 5

RESULTS

Growing Season and Climate Data

Soil Taxonomy defines the growing season as the time of year when soil temperatures measured at 50 cm depth are at or above 5°C. Soil temperatures do not vary as much as air temperature with the seasons (Carter and Ciolkosz, 1980). The dampening effect of the soil increased with depth, consequently, well water temperatures never varied more than 5°C about the average of 9°C throughout the year.

Dates for the beginning and ending of the frost free season vary yearly resulting in a deviation of 7.1 weeks at Amherst, MA from a mean season length of 21.7 weeks at Amherst (Bradley et al., 1987). The seasons for the years 1988 to 1990 were longer than the mean reported above (Table 4) but still well within the variation observed over the past 150 years (Bradley et al., 1987). To compare the growing season defined above to the frost free season, soil and air temperatures had to be measured concurrently.

The weekly averages of daily air temperatures are shown (Figure 2) with the growing season as determined from the daily values for the first occurance of a 7-day continuous period of 2°C in the fall and 5°C in the spring. Dates when soil temperatures at 25 and 50 cm depth were at 5°C coincided with rapid seasonal changes of the weekly mean air temperatures at the Hadley Wastewater Treatment Plant. The dampening effect of temperature variation with depth mentioned above

Table 4. Growing seasons and frost free seasons for sites I-VI and X-XII based on weather data collected at the Hadley Wastewater Treatment Facility. Data from Hatfield were used for sites VII-IX and XIII-XV. Data from the Northfield Wastewater facility were used for sites XVI-XX. Field observations of spring emergence of fiddlehead ferns and fall canopy leaf turning and drop were used for vegetated season determination.

GROWING SEASON		FROST FREE SEASON		VEGETATED SEASON	
SOIL TEMPERATURE >5°C	WEEKS	AIR TEMPERATURE >0°C	WEEKS	OBSERVED FERN EMERGENCE AND LEAF DROP	WEEKS
		HADLEY			
- 10/31/88		- 10/08/88		- 10/15/88	
3/16/89 - 11/25/89	36.3	4/29/89 - 10/22/89	25.3	5/14/89 - 10/25/89	23.8
3/15/90 - 12/06/90	38.0	4/19/90 - 10/26/90	27.1	4/22/90 - 11/02/90	27.9
MEAN	37.2	MEAN	26.2	MEAN	25.9
		HATFIELD			
3/11/88 - 10/31/88	33.4	5/04/88 - 10/07/88	22.3	- 10/15/88	
3/17/89 - 11/23/89	35.7	4/26/89 - 10/10/89	23.7		
3/19/90 - 11/02/90	32.6	4/19/90 - 9/18/90	23.0		
MEAN	33.9	MEAN	23.0		
		NORTHFIELD			
3/29/88 - 11/01/88	31.0	4/25/88 - 10/20/88	25.7	- 10/23/88	
3/17/89 - 11/17/89	35.0	4/25/89 - 11/04/89	27.7	4/30/89 - 10/16/89	24.4
3/15/90 - 11/13/90	34.7	4/20/90 - 10/21/90	26.3	- 9/29/90	
MEAN	33.6	MEAN	26.6		

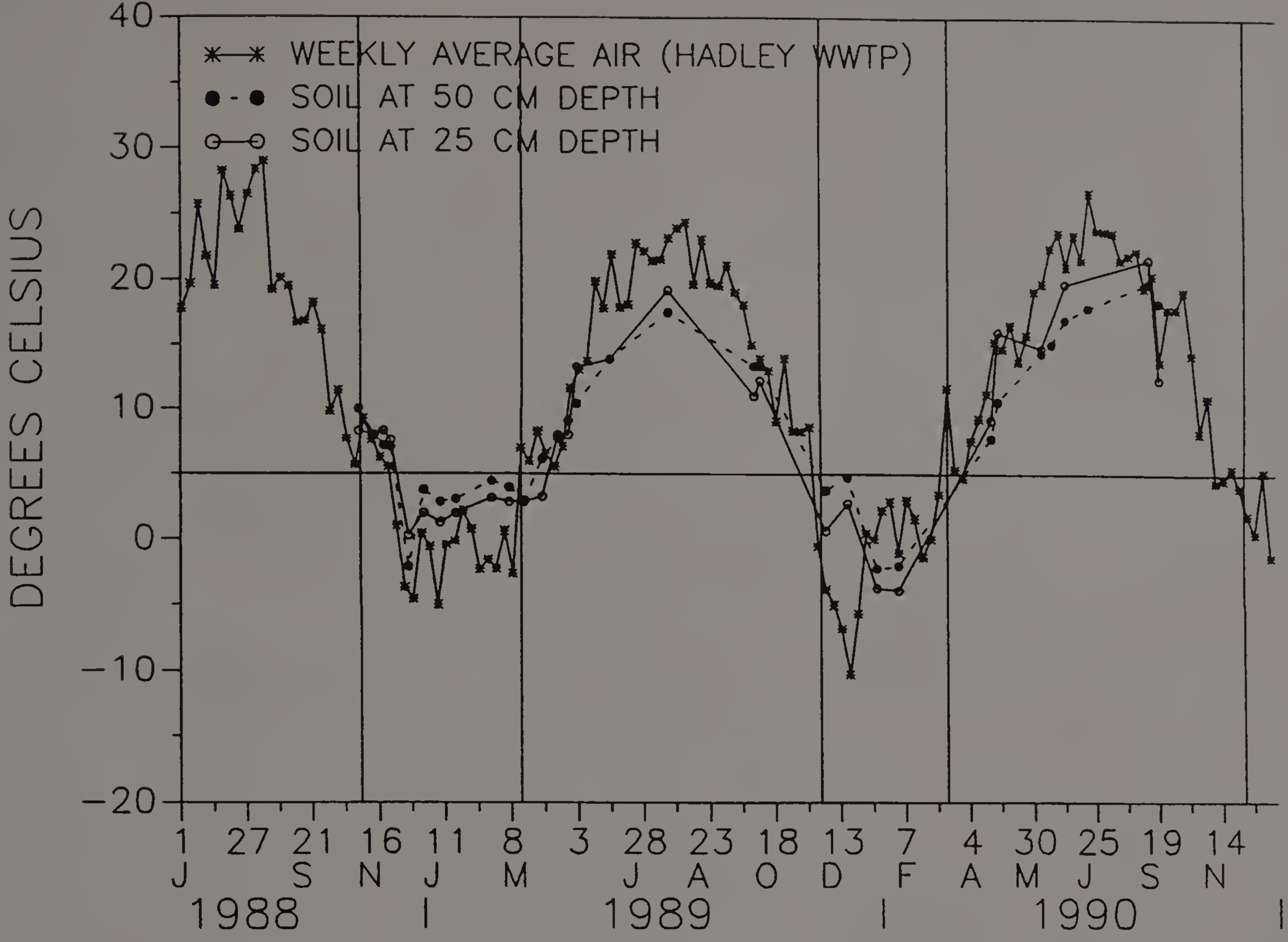


Figure 2. Comparison of dates when soil temperatures at Rainbow Beach (sites I-VI) were at 5°C at two depths, weekly air temperatures at a nearby sewage plant and the growing season (vertical lines) as defined by an air/soil temperature correlation (Figures 3 and 4).

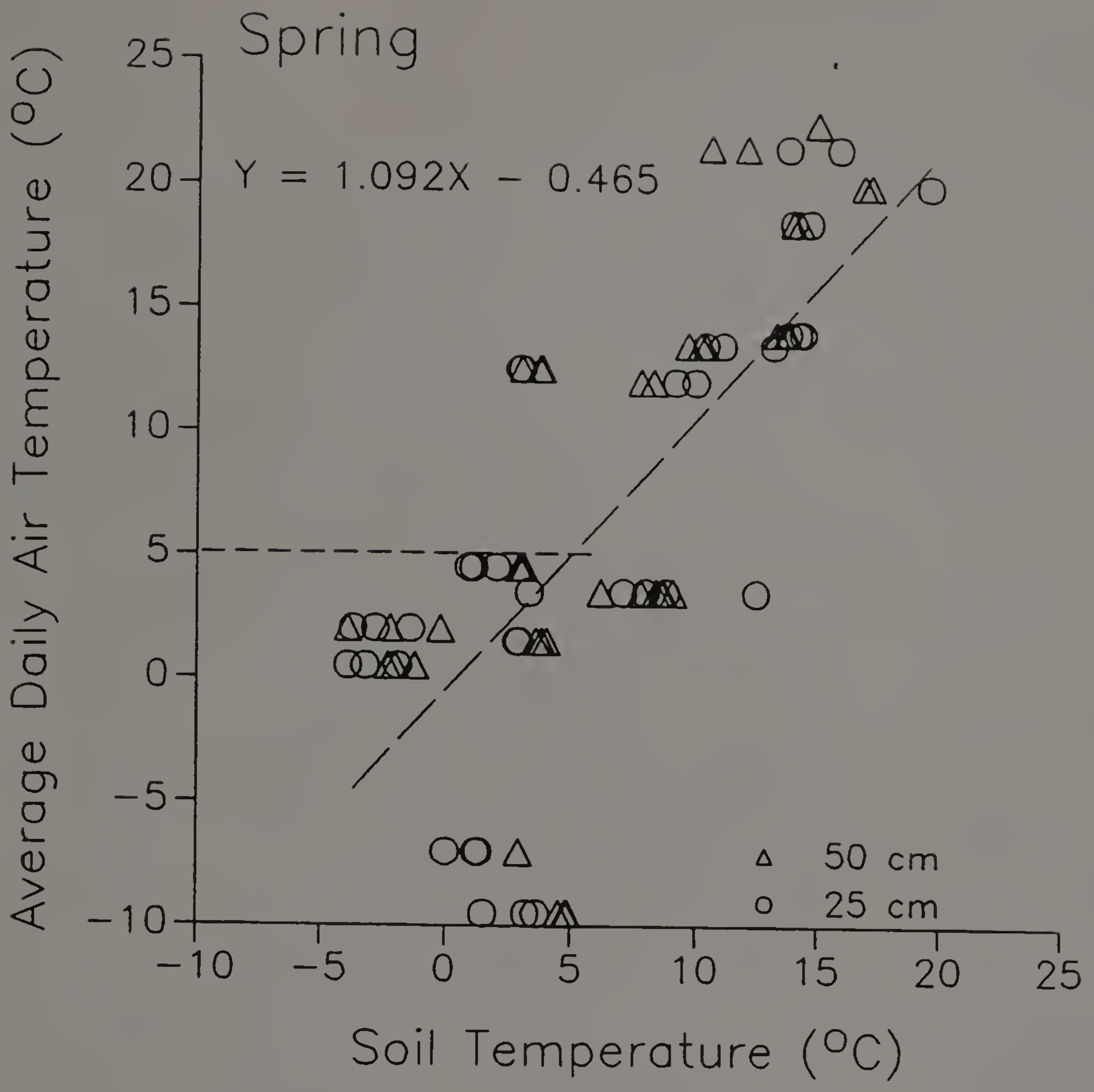


Figure 3. Correlation between soil temperatures at site III and spring (January-June) average daily air temperatures at the Hadley sewage plant. Data were collected from summer 1988 to fall 1990.

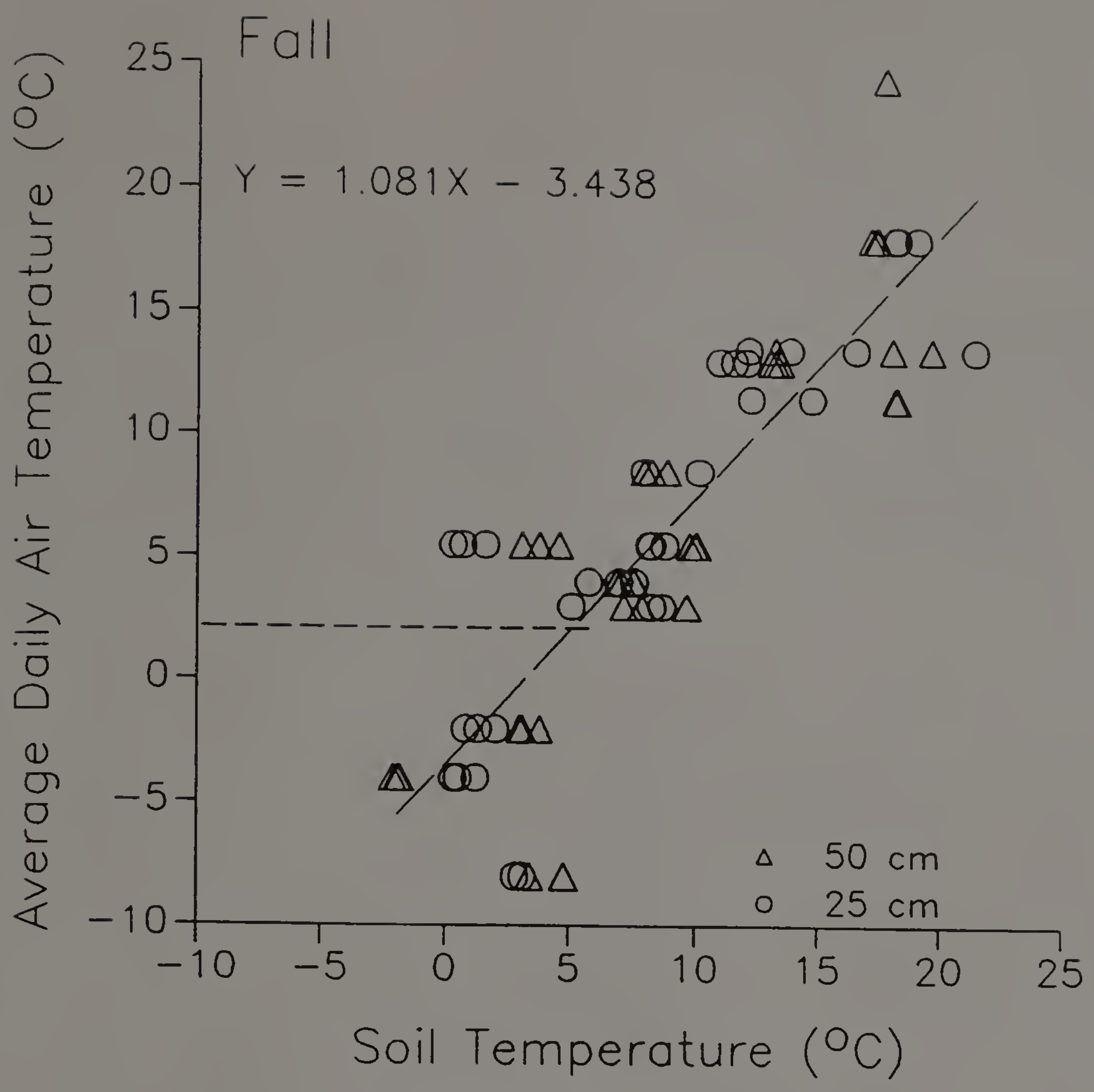


Figure 4. Correlation between soil temperatures at site III and fall (July-December) average daily air temperatures at the Hadley sewage plant. Data were collected from summer 1988 to fall 1990.

can be seen in this figure, where the 25 cm depth temperatures fluctuated more than the 50 cm depth temperatures.

Soil temperatures were measured at Rainbow Beach (sites I-VI) from fall 1988 to fall 1990. Correlations were determined between the soil temperatures on a given date at Rainbow Beach (at both 25 and 50 cm depth) and the air temperatures measured at the wastewater treatment plant. The measurements were divided into spring (January-June, Figure 3) and fall (July-December, Figure 4) seasons to determine an air temperature which corresponded to a soil temperature of 5°C. A spring air temperature of 5°C and a fall air temperature of 2°C were predicted to correspond to soil at 5 degrees. The fall data were more linear ($R^2 = 0.737$) than the spring ($R^2 = 0.521$).

A comparison between the frost free period (when air temperature is at or above 0°C) and the growing season (with air temperatures at 2 and 5°C for the fall and spring seasons) by computing the mean season length in weeks (Table 4). The season length is longer using Soil Taxonomy's growing season definition. Theoretically, season lengths should decrease northward, however, the mean frost free season for Northfield is longer than the mean for Hadley. This could be a local effect of warming from the Northfield wastewater treatment facility even though all air temperatures in this study were measured at similar plants. The mean season length as defined by the correlation to soil temperatures does decrease northward as expected. The growing seasons were longer than the frost free season by 10 weeks at Hadley and Hatfield and longer by 7 weeks at Northfield.

Field observations of the onset and finish of the growing season by the emergence of ferns and herbs in the spring and the color change and falling of leaves in the autumn. The dates of these observations coincide well with the frost free seasons except for the Northfield sites. The onset of this growing season was earlier than the beginning of the frost free season (Table 4) in all years and the end of the growing season is after the end of the frost free season for all years.

Total weekly precipitation is compared to the water table levels in Figures 6 through 15. Somewhat higher than average (120 cm, Amherst) yearly total precipitations were found at both the Hatfield and Hadley locations for both 1989 and 1990 (Hadley; 1989: 155 cm; 1990: 153 cm; Hatfield; 1989: 134 cm; 1990: 125 cm) whereas Northfield precipitations (1989: 113 cm and 1990: 122 cm) were closer to the average total from Amherst (Bradley _et_ _al_., 1987).

Local growers have noted that the 1989 and 1990 growing seasons were abnormal in many respects. Wetter springs slowed the onset of the growing season while very mild temperatures caused the late onset of winter.

Period of Saturation

The level of saturation in each soil pedon are shown in hydrographs (Figures 6-15). Spring and fall flooding occurred at sites I through VI as well as at sites X, XI and XII. All other sites were not directly flooded by the Connecticut River and show much shallower and sometimes less frequent flooding events.

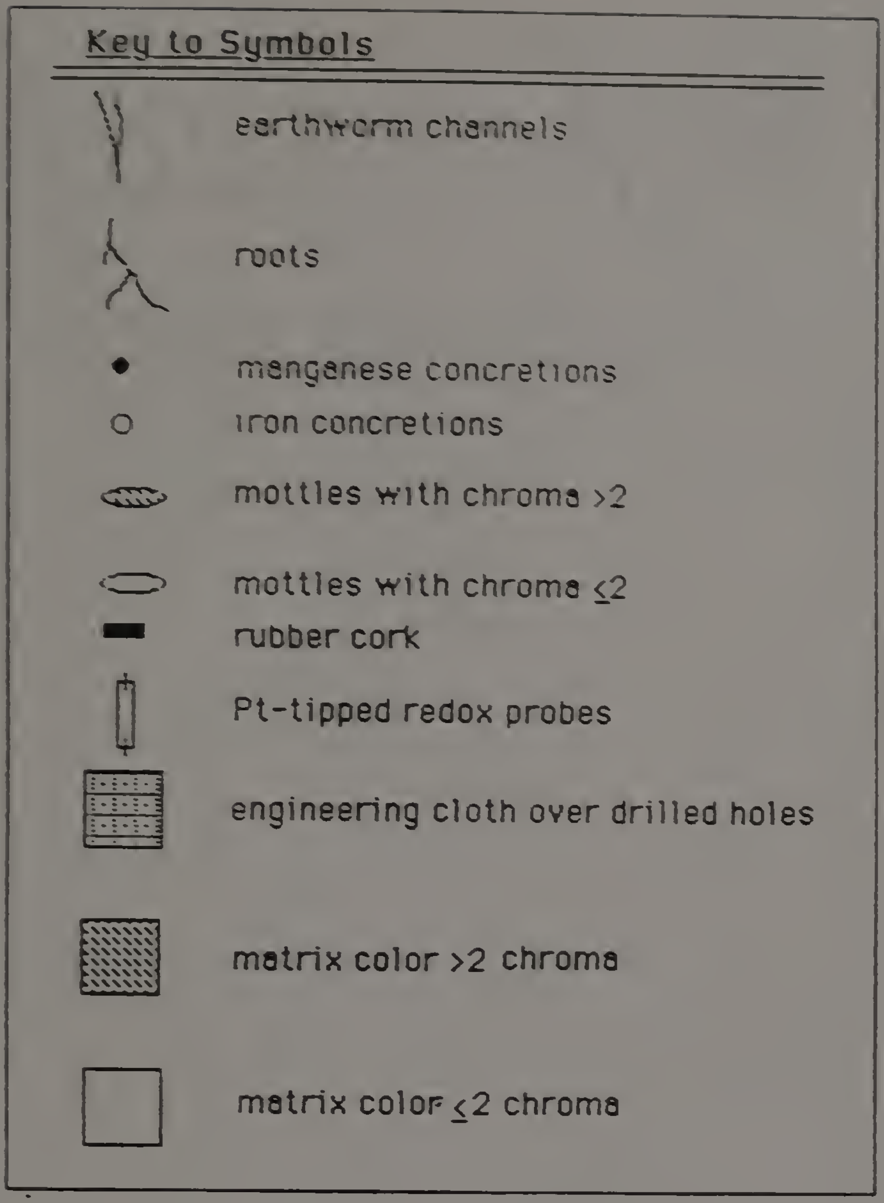


Figure 5. Key to symbols for pedons in Figures 6-15. Shading denotes high chroma colors, blank denotes low chroma colors, patches are mottles, symbols used when features were common or many in abundance.

Figure 6. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites I and VI (site descriptions in text). Flooding events are shown as water levels above the ground surface (dashed line). Weekly total precipitation (PPT) in mm for period of record. Key to symbols used in soil pedons are given in Figure 5.

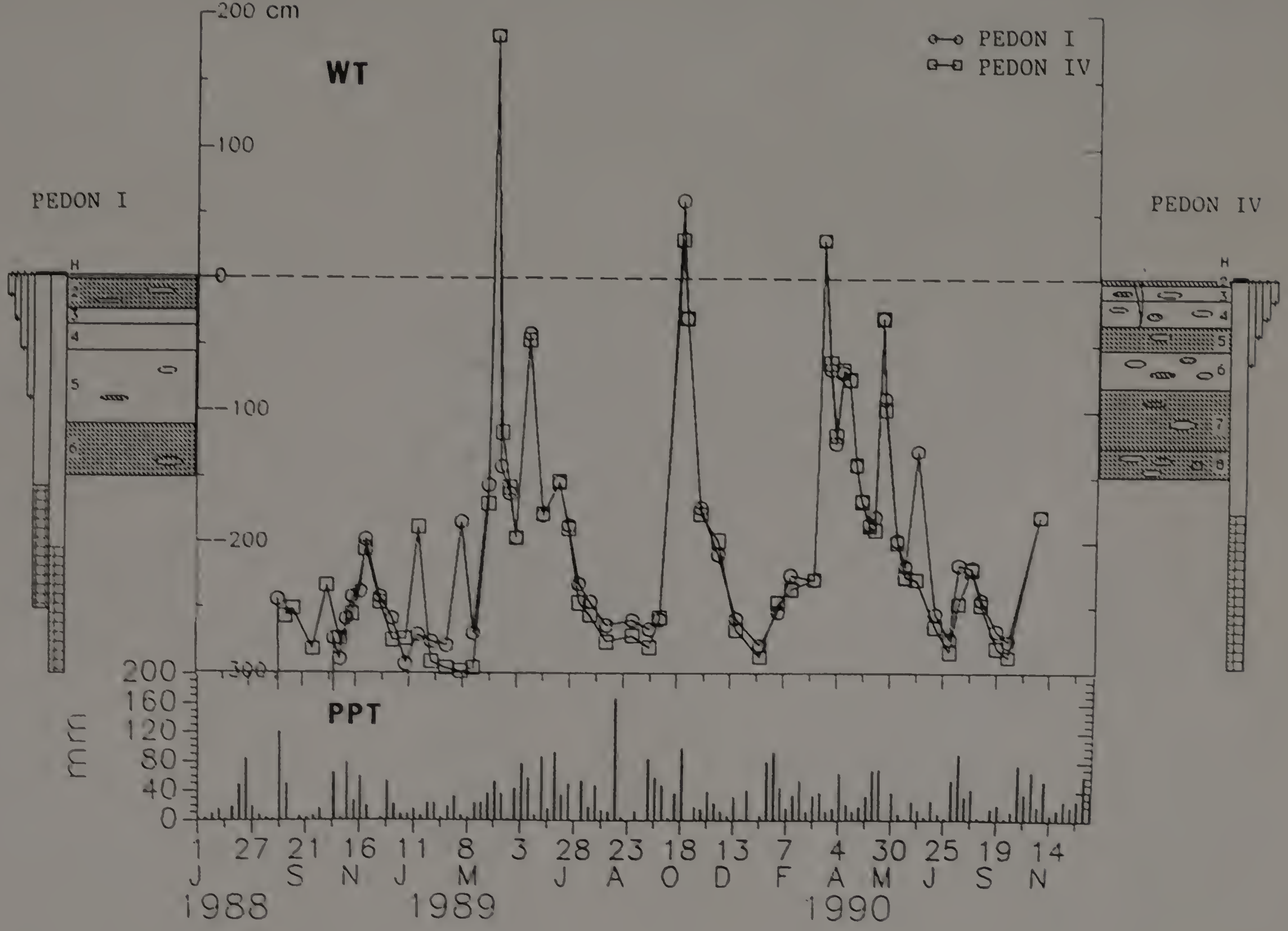

PEDON I
PEDON IV
WT
PPT
200 cm
100
0
-100
-200
-300
PEDON I
PEDON IV
H
2
3
4
5
6
7
8
mm
200
160
120
80
40
0
1 J
27
21 S
16 N
11 J
8 M
3
28 J
23 A
18 O
13 D
7 F
4 A
30 M
25 J
19 S
14 N
1988
1989
1990

Figure 7. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites II and V (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

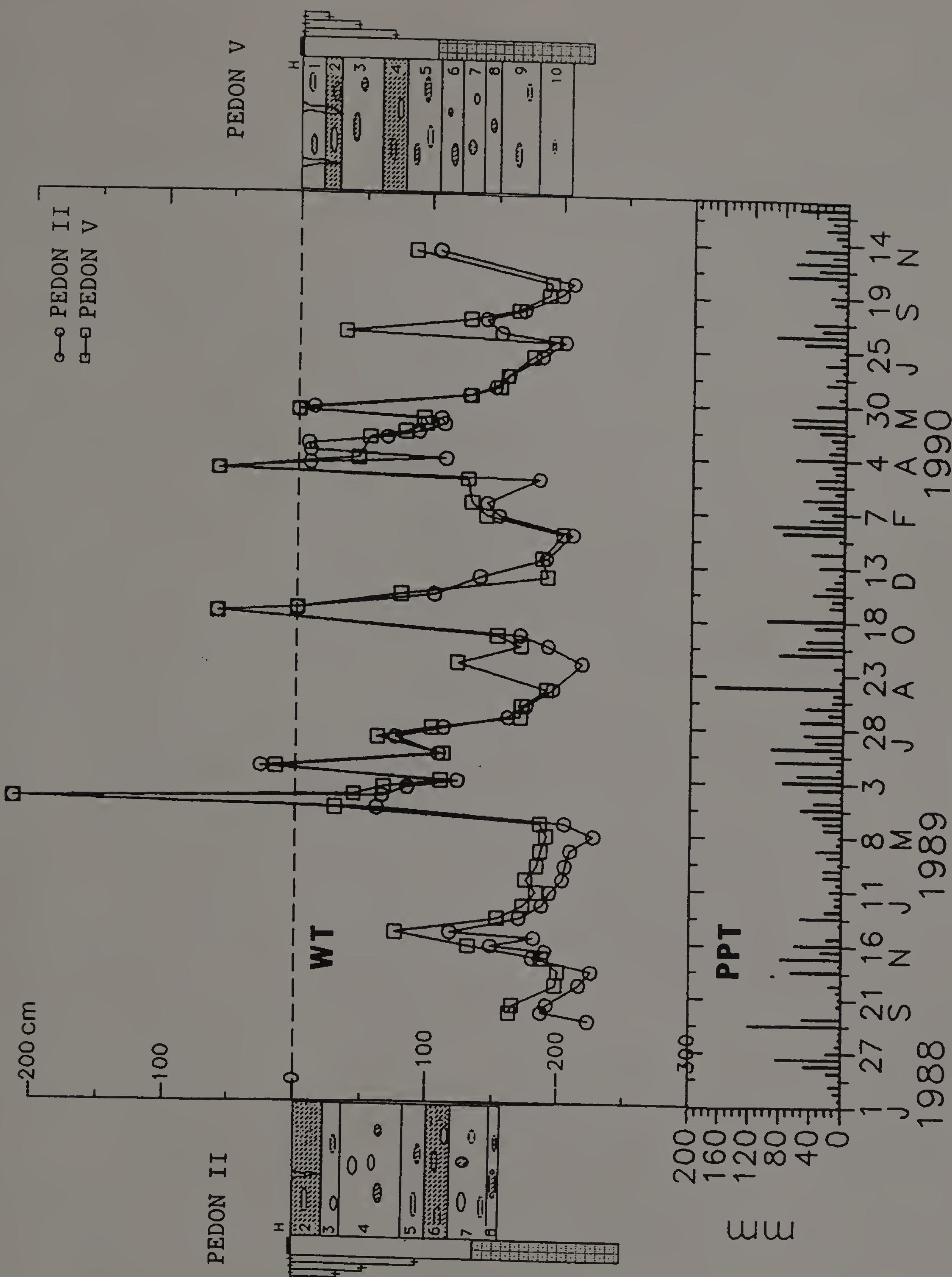

PEDON II
PEDON V
PEDON II
PEDON V
200 cm
100
0
100
200
300
WT
PPT
mm
200
160
120
80
40
0
1
27
21
16
11
8
3
28
23
18
13
7
4
30
25
19
14
J
S
N
J
M
J
A
O
D
F
A
M
J
S
N
1988
1989
1990
H
1
2
3
4
5
6
7
8
9
10

Figure 8. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (**WT**) in cm from summer 1988 to fall 1990 for sites III and VI (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (**PPT**) in mm for period of record.

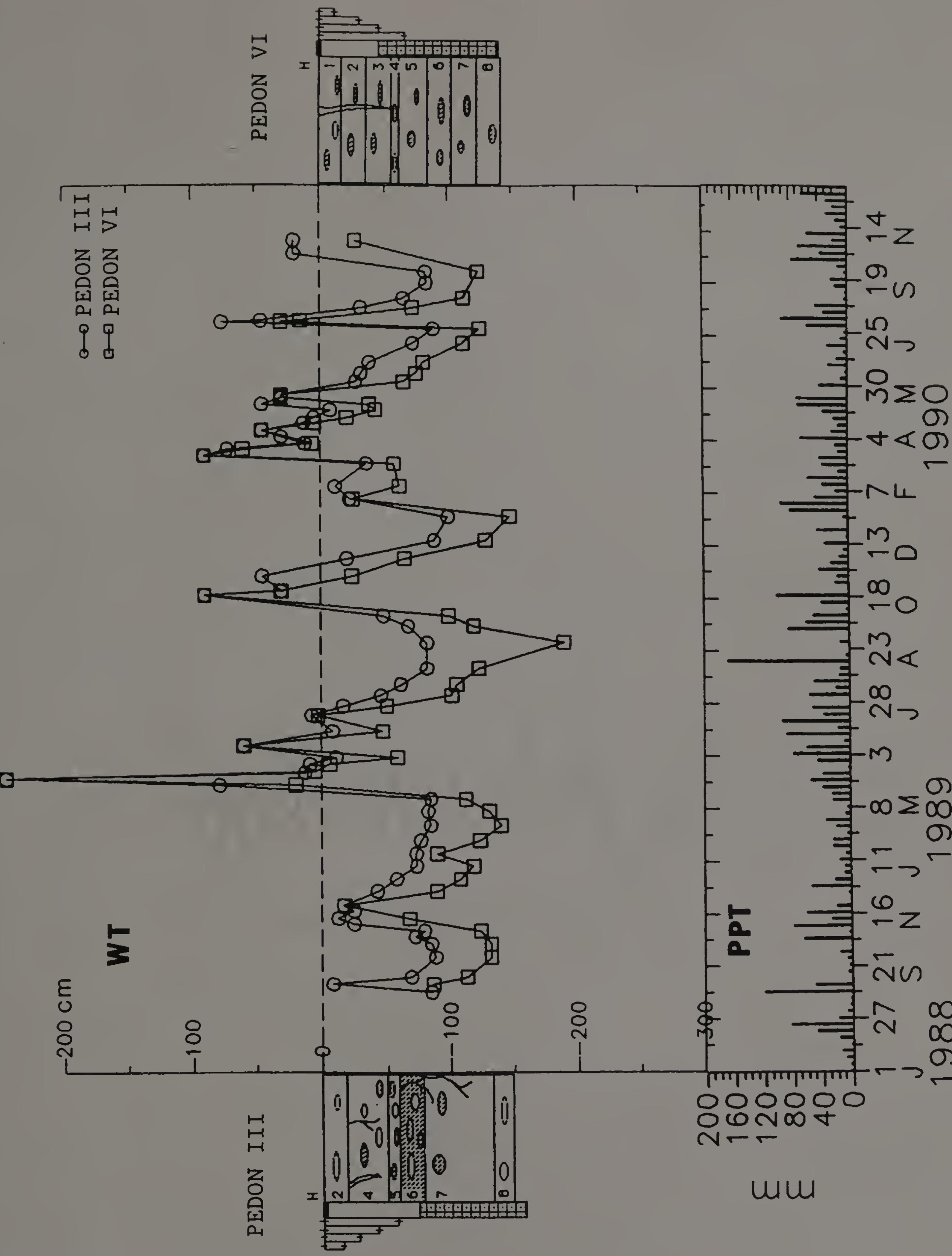
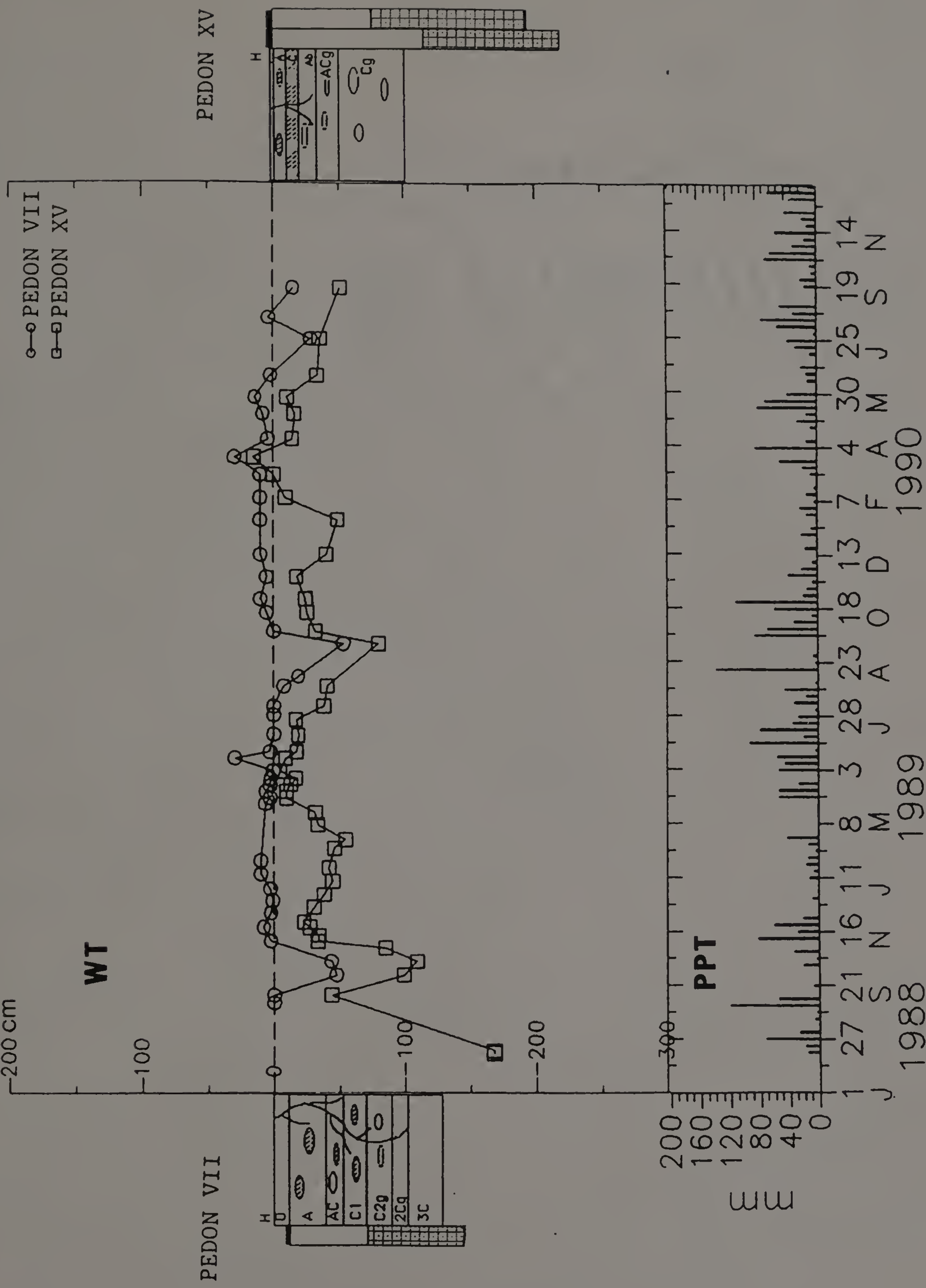

WT
PPT
PEDON III
PEDON VI
PEDON III
PEDON VI
200 cm
100
0
100
200
300
mm
200
160
120
80
40
0
H
1
2
3
4
5
6
7
8
H
2
4
5
6
7
8
1 J 1988
27
21 S
16 N
11 J
8 M 1989
3
28 J
23 A
18 O
13 D
7 F
4 A 1990
30 M
25 J
19 S
14 N

Figure 9. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (**WT**) in cm from summer 1988 to fall 1990 for sites VII and XV (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (**PPT**) in mm for period of record.



PEDON VII
PEDON XV
o—o PEDON VII
□—□ PEDON XV
WT
PPT
-200 cm
-100
0
100
200
300
mm
200
160
120
80
40
0
H
O
A
AC
C1
C2g
2Cg
3C
ACg
Cg
1
27
21
16
11
8
3
28
23
18
13
7
4
30
25
19
14
J
S
N
J
M
J
A
O
D
F
A
M
J
S
N
1988
1989
1990

Figure 10. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites VIII and IX (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

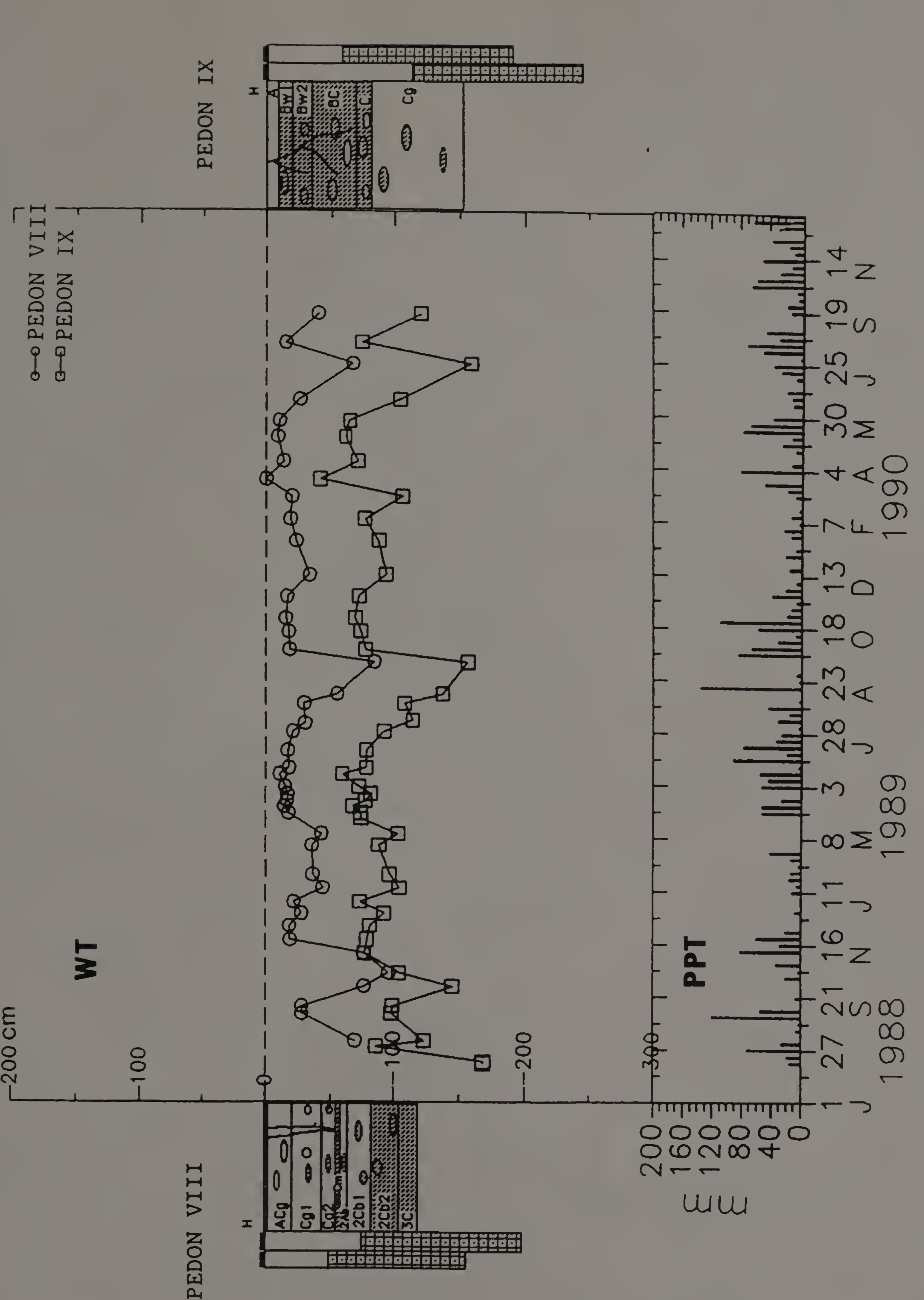

PEDON VIII
PEDON IX
o—o PEDON VIII
□—□ PEDON IX
WT
PPT
200 cm
100
0
100
200
300
mm
200
160
120
80
40
0
H
ACg
Cg1
Cg2
2Ab
2Cb1
2Cb2
3C
A
Bw1
Bw2
BC
C
Cg
J
1
27
S
21
N
16
J
11
M
8
J
3
J
28
A
23
O
18
D
13
F
7
A
4
M
30
J
25
S
19
N
14
1988
1989
1990

Figure 11. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites X and XVIII (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

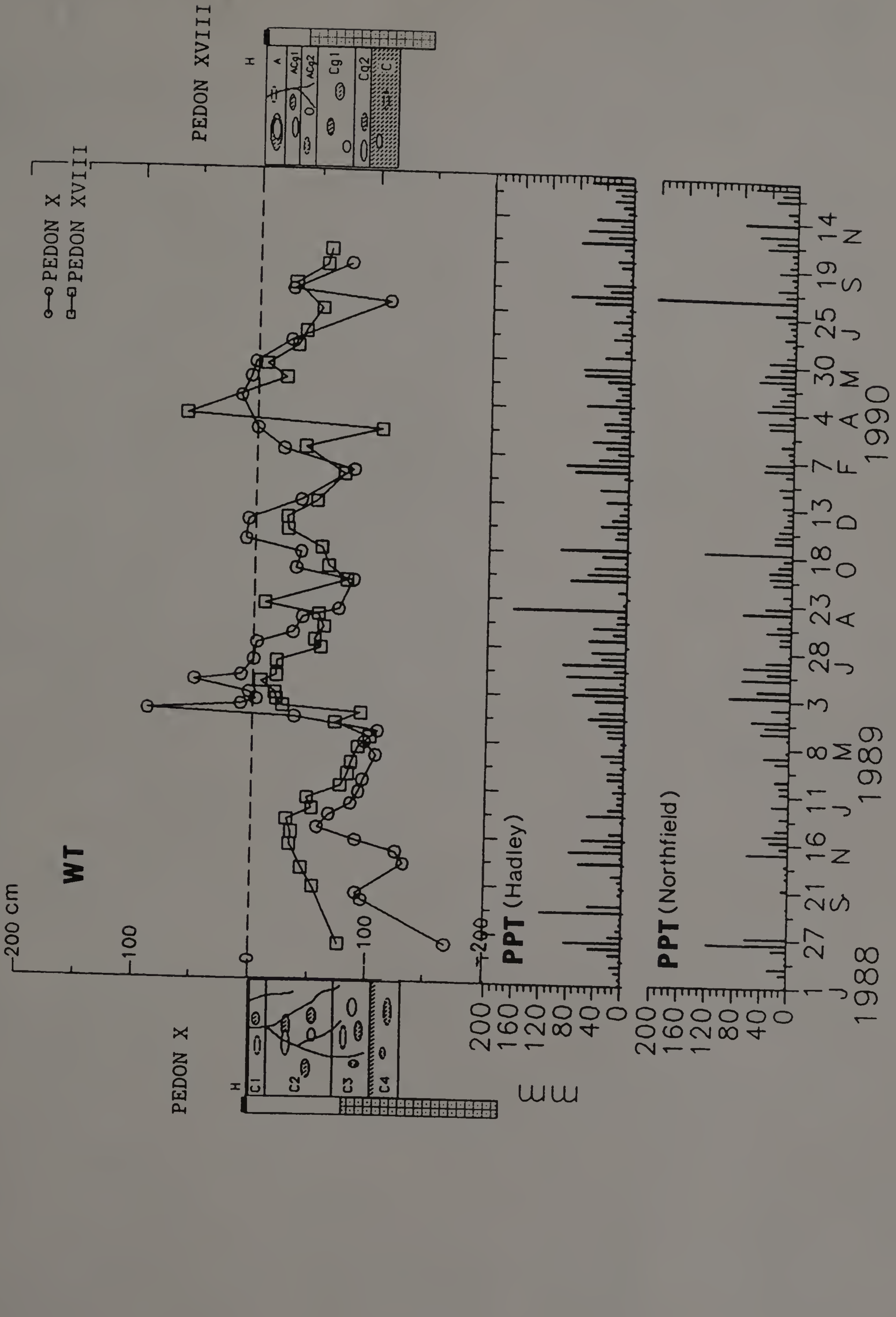

WT
200 cm
100
0
100
200
PEDON X
PEDON XVIII
H
C1
C2
C3
C4
A
ACg1
ACg2
Cg1
Cg2
C
PPT (Hadley)
PPT (Northfield)
mm
200
160
120
80
40
0
1
27
21
16
11
8
3
28
23
18
13
7
4
30
25
19
14
J
S
N
J
M
J
A
O
D
F
A
M
J
S
N
1988
1989
1990

Figure 12. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites XI and XII (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

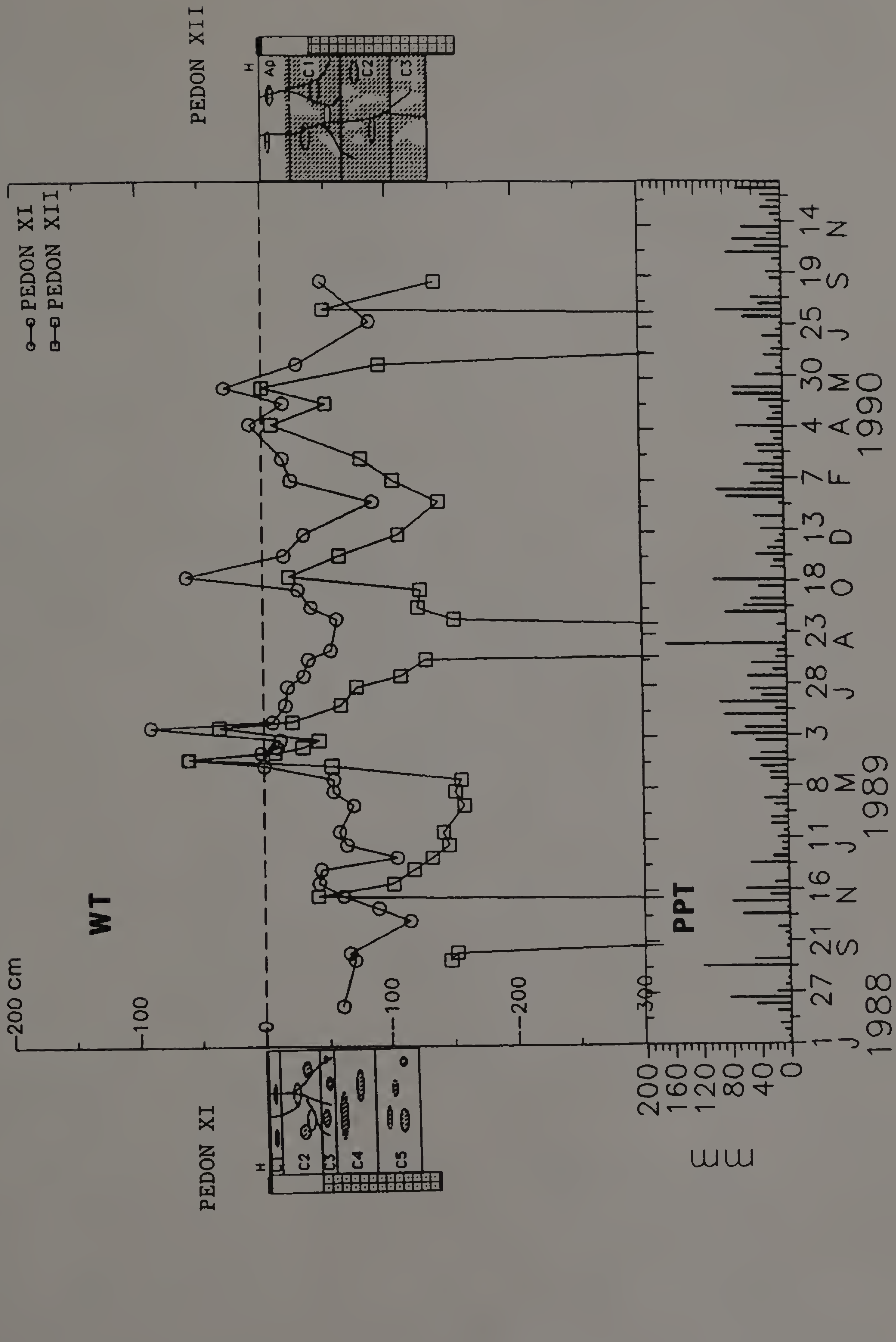

PEDON XI
PEDON XII
PEDON XI
PEDON XII
WT
PPT
200 cm
100
0
100
200
300
H
Ap
C1
C2
C3
C4
C5
mm
200
160
120
80
40
0
1 J
27
21 S
16 N
11 J
8 M
3 J
28 J
23 A
18 O
13 D
7 F
4 A
30 M
25 J
19 S
14 N
1988
1989
1990

Figure 13. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites XIII and XIV (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

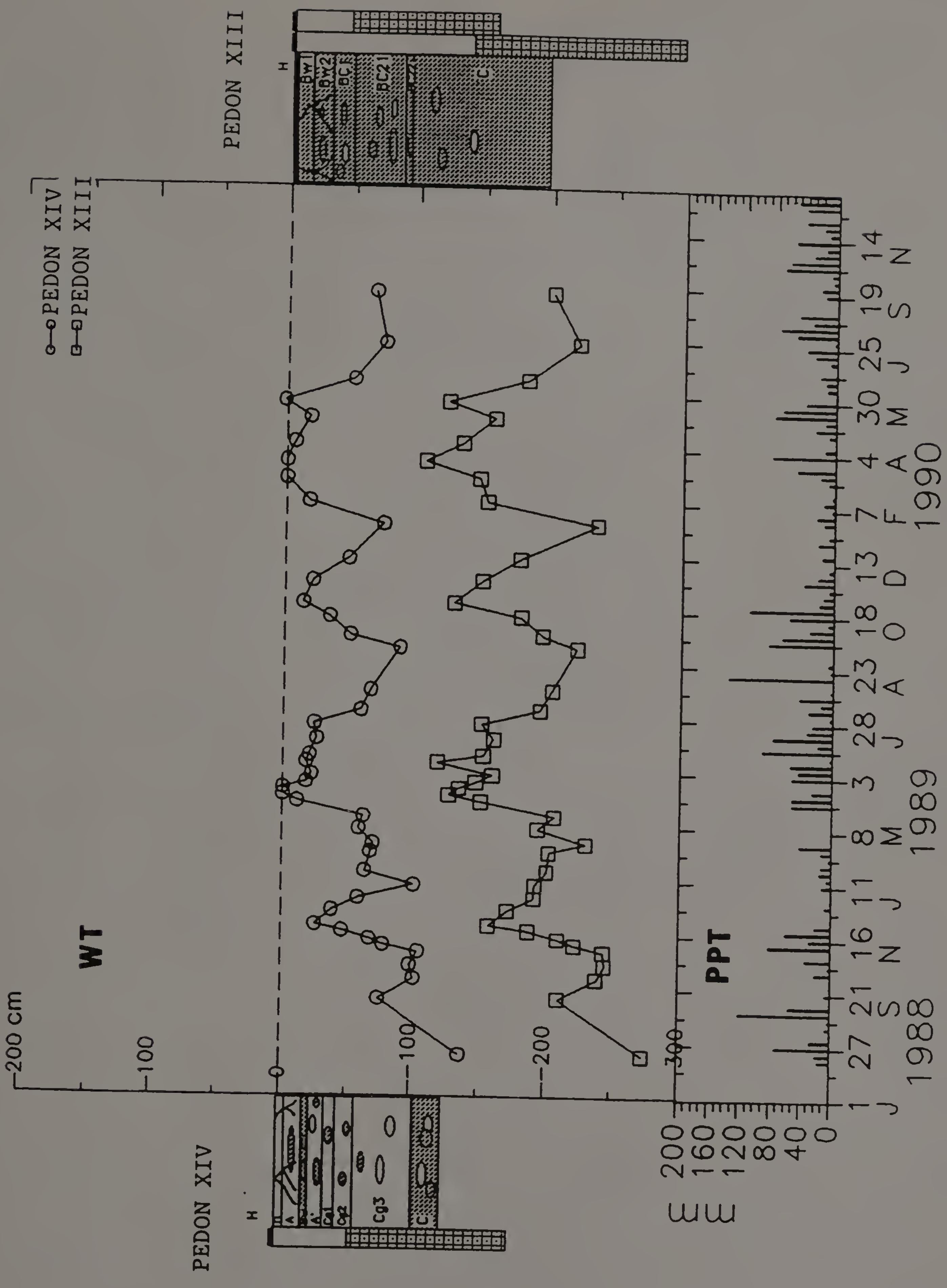

PEDON XIV
PEDON XIII
WT
PPT
-200 cm
-100
100
200
300
PEDON XIV
PEDON XIII
H
A
A'
Cg1
Cg2
Cg3
C
BW1
BW2
BC1
BC21
C
mm
200
160
120
80
40
0
1 J
27
21 S
16 N
11 J
8 M
3
28 J
23 A
18 O
13 D
7 F
4 A
30 M
25 J
19 S
14 N
1988
1989
1990

Figure 14. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites XVI and XVII (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record.

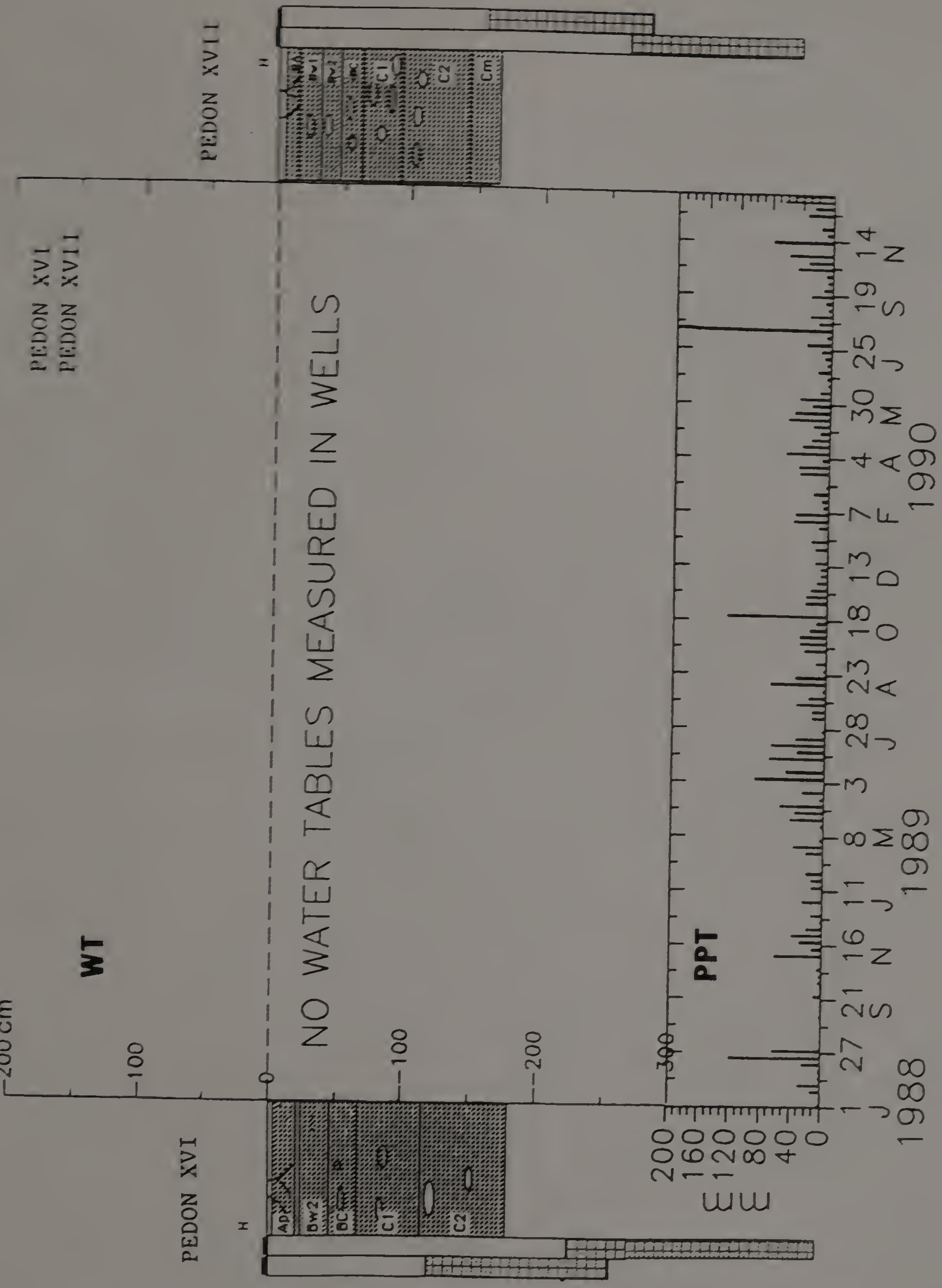
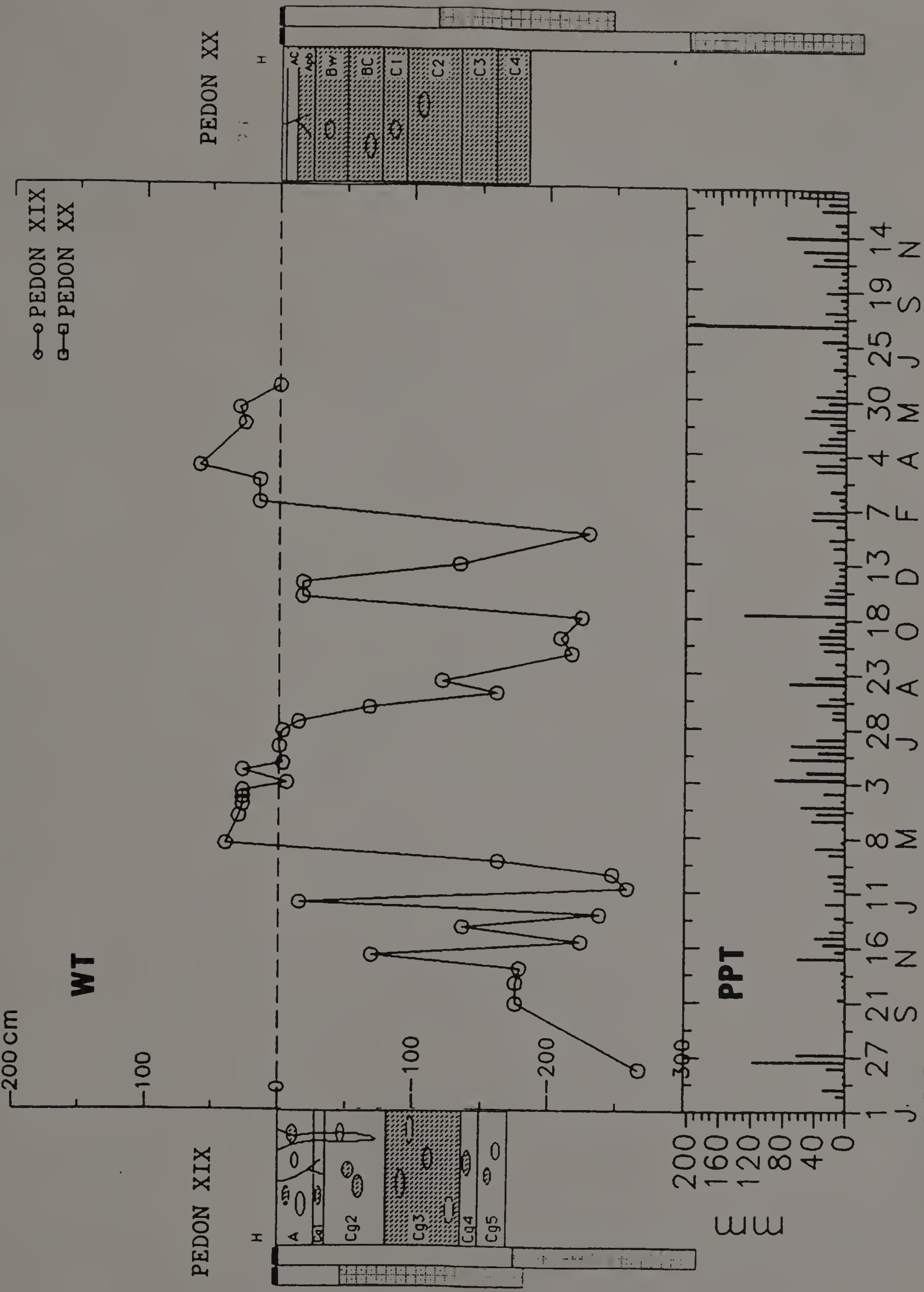

PEDON XVI
PEDON XVI
PEDON XVII
PEDON XVII
WT
200 cm
100
0
100
200
300
NO WATER TABLES MEASURED IN WELLS
PPT
mm
200
160
120
80
40
0
AP
Bw2
BC
C1
C2
Cm
1 J
1988
27
21 S
16 N
11 J
8 M
1989
3
28 J
23 A
18 O
13 D
7 F
4 A
1990
30 M
25 J
19 S
14 N

Figure 15. Soil morphologic properties, depth of installation of redox electrodes and wells, and water table levels (WT) in cm from summer 1988 to fall 1990 for sites XIX and XX (site descriptions in text; key to symbols in Figure 5). Weekly total precipitation (PPT) in mm for period of record. No water table was measured in wells at site XX.


PEDON XIX
PEDON XX
PEDON XIX
PEDON XX
WT
PPT
200 cm
100
0
100
200
300
H
A
Cg1
Cg2
Cg3
Cg4
Cg5
AC
Apb
Bw
BC
C1
C2
C3
C4
mm
200
160
120
80
40
0
1 J
27
21 S
16 N
11 J
8 M
3 J
28 J
23 A
18 O
13 D
7 F
4 A
30 M
25 J
19 S
14 N
1988
1989
1990

Frequency of Flooding Events

The frequency of flooding within the 2-year monitoring period varied from more than twice a year to no flooding (Table 5). Flooding frequency was calculated by dividing the number of flooding events of any length by 2, being the number of growing seasons studied (4 events/2 years = 200%). Longer records are required to confirm the long term flooding frequencies.

For the sites closest to the river (I-VI, X, XI and XII), the long term flooding frequency can be extrapolated from stage data for the river (Figure 16). A USGS gauging station is located upstream in the town of Montague (Figure 1). Daily average discharge data were obtained from this station for the period 1904 to 1990. Conversion of the discharge data to stage level was done with a rating curve for that station. Changes in elevation for the period of record of the gauging station in relation to the research sites should be known for this extrapolation to be meaningful. Since Rainbow Beach is a point bar where accumulation of material occurs every year making elevation changes significant. One could assume a constant rate of deposition (one cm per year, as observed in 1989 and confirmed by dated buried debris (a bicentennial beer can)) or that both the station and sites have changed elevation at the same rates. Another possibility is that more northern sites could be uplifting at a faster rate than southern sites due to isostatic rebound but this would be small. Figure 15 shows surface elevations of sites I-VI, assuming no elevation change between the station and sites, placed within the monthly river flood

Table 5. Annual flooding frequency at all sites given in percent yearly occurrence (200% = twice per year, 100% = once per year, 50% = once every two years). Frequency units are those used in Federal wetland delineation manual (Federal Interagency Committee for Wetland Delineation, 1989).

	FREQUENCY					
	ENTIRE YEAR			GROWING SEASON		
SITE	SURFACE	20cm	40cm	SURFACE	20cm	40cm
I	150	150	200	100	100	150
II	250	300	300	200	250	250
III	400	350	350	350	300*	250
IV	150	150	200	100	100	150
V	250	250	300	200	200	250
VI	300	500	450*	250	350	350
VII	200	200	150*	200	200	150*
VIII	50	250	250	50	200	200
IX	0	0	50	0	0	50
X	150	150	200	150	150	200
XI	150	200	200	150	150	150
XII	150	250	250	100	250	250
XIII	0	0	0	0	0	0
XIV	150	200	200	150	150	150
XV	50	150	200	50	150	150
XVI	0	0	0	0	0	0
XVII	0	0	0	0	0	0
XVIII	50	200	300	50	200	200
XIX	150	200	200	150	150	150
XX	0	0	0	0	0	0

* = Frequency decrease with depth because flooding event became continuous instead of remaining episodic or distinct.

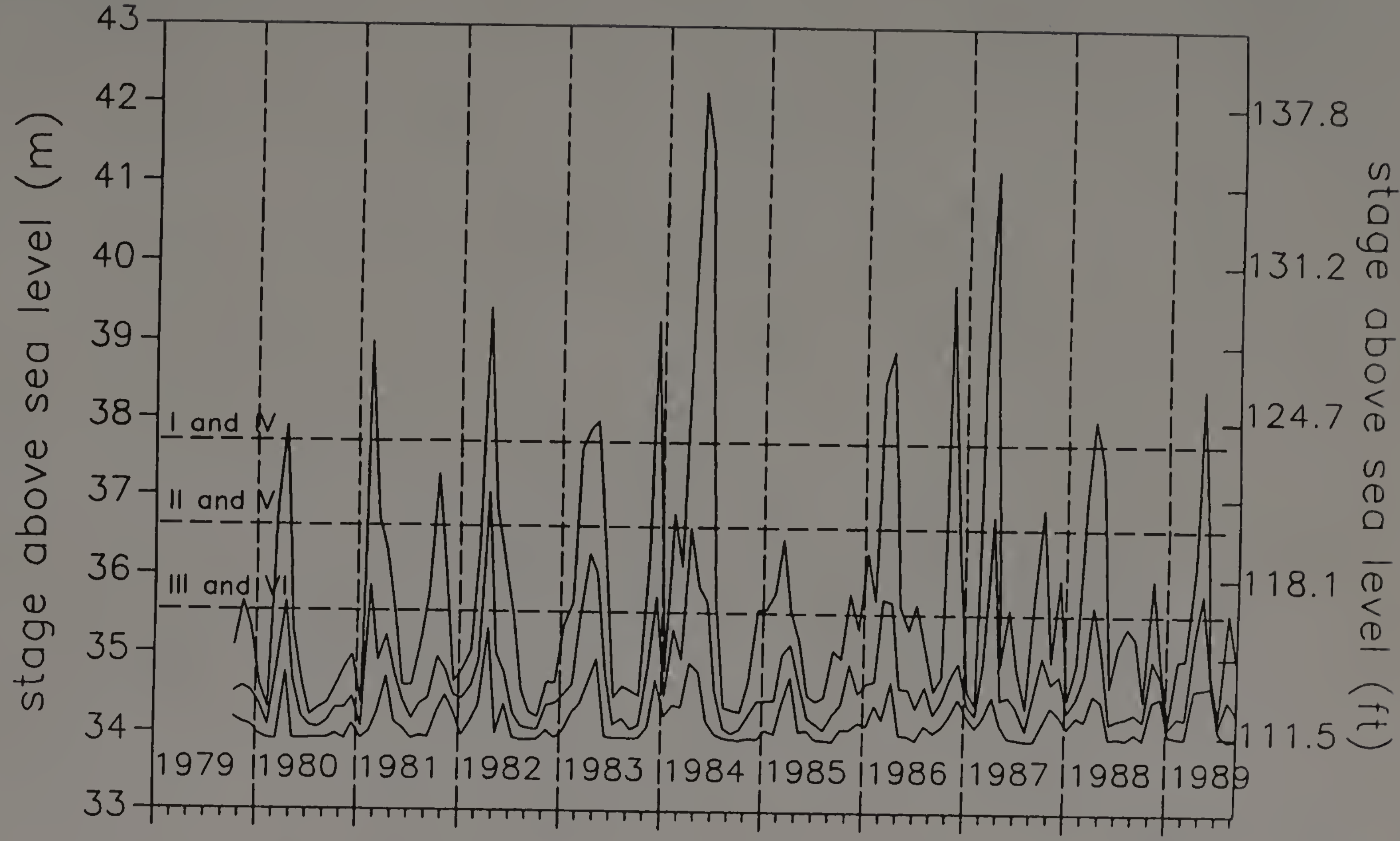


Figure 16. Connecticut river stages for 1979-1989 at the Montague City USGS gauging station. The maximum, mean and minimum stages above mean sea level given in both meters and feet. Approximate elevation of sites I through VI is indicated by the dashed lines.

stage record for a recent 10 year period. The hydrographs (Figures 6-15) in general confirm the frequencies in Table 5 for these sites.

Duration of Flooding Events

Duration was measured directly at each site. The duration in weeks of the longest continous flooding or saturation event at the surface of each pedon as well as at 20 and 40 cm depths (Table 6) was taken from the hydrographs. The duration of saturation in each horizon of each site varied dramatically from year to year along with the flooding depth and date (Figure 6). The longest flood duration was measured at site VII in Hatfield where very poor soil drainage prevented infiltration and topography prevented lateral movement of water.

The total duration (Table 7) in weeks per year or season for the entire period of observation (130 weeks) are averaged over the number of years or seasons while the durations in Table 6 are not. The values in Table 6 represent the longest duration measured for the total period of record and not the longest duration of the year or season. Therefore, the data in the two tables are not directly comparable.

Correlations to Soil Morphology

Morphologic evidence of soil saturation classified the twenty pedons in this study as either hydric or nonhydric (Table 8). The technical critiera use the frequency and duration of saturation to define a soil as hydric. The technical criteria for hydric soils as

Table 6. Duration in weeks of the longest continuous flooding or saturation events recorded at sites I-XX. The length of the longest event that occurred during the entire period of record (130 weeks or 2.5 years) was tabulated. The value was not average over the number of years or seasons as in Table 7.

LONGEST CONTINUOUS DURATION

	ENTIRE YEAR			GROWING SEASON		
SITE	SURFACE	20cm	40cm	SURFACE	20cm	40cm
I	0.9	1.3	1.8	0.9	1.3	1.8
II	1.8	2.2	3.1	1.8	2.2	3.1
III	7.0	13.2	22.0	7.0	11.9	19.4
IV	0.9	1.3	1.8	0.9	1.3	1.8
V	1.8	2.2	3.1	1.8	2.2	3.1
VI	6.2	6.6	9.9	6.2	6.6	9.9
VII	37.8	58.1	58.5	17.2	37.0	37.0
VIII	0.9	17.6	40.5	0.9	15.4	18.9
IX	0	0	0	0	0	0
X	11.9	15.8	19.4	11.9	15.8	17.6
XI	4.0	11.1	21.4	4.0	10.4	18.9
XII	1.3	2.6	7.5	1.3	2.6	7.5
XIII	0	0	0	0	0	0
XIV	2.6	15.8	18.5	2.6	14.5	15.8
XV	4.8	17.2	38.7	4.8	15.0	26.6
XVI	0	0	0	0	0	0
XVII	0	0	0	0	0	0
XVIII	5.3	11.9	15.0	5.3	11.9	15.0
XIX	16.7	18.5	19.4	15.8	17.6	18.5
XX	0	0	0	0	0	0

Table 7. Total duration in weeks per year of flooding or saturation events recorded at sites I-XX. The total durations were averaged over the number of years of the period of record (130 weeks or 2.5 years).

TOTAL DURATION

	ENTIRE YEAR			GROWING SEASON		
SITE	SURFACE	20cm	40cm	SURFACE	20cm	40cm
I	0.9	1.4	1.6	0.5	0.9	1.1
II	2.1	3.9	5.3	1.4	3.2	4.6
III	13.7	18.5	22.6	12.4	16.7	19.7
IV	0.9	1.4	1.6	0.5	0.9	1.1
V	2.1	3.7	4.6	1.4	3.0	3.9
VI	7.3	9.8	12.3	6.4	8.7	10.8
VII	32.2	44.6	45.9	20.6	33.1	34.4
VIII	0.4	17.4	35.4	0.4	15.5	23.8
IX	0	0	0	0	0	0
X	11.4	14.2	19.9	10.8	13.3	17.8
XI	5.7	14.9	20.8	5.0	12.4	17.6
XII	1.2	4.3	6.8	0.7	3.6	6.8
XIII	0	0	0	0	0	0
XIV	2.0	9.2	16.4	1.6	7.8	14.2
XV	2.0	9.6	20.8	2.0	7.8	17.2
XVI	0	0	0	0	0	0
XVII	0	0	0	0	0	0
XVIII	2.1	5.3	16.2	2.1	5.3	16.2
XIX	13.9	15.6	17.2	10.7	12.4	13.3
XX	0	0	0	0	0	0

Table 8. Hydric soil status of pedons in this study (after Veneman and Tiner, 1990).

SITE	SOIL SERIES	CLASSIFICATION	DRAINAGE CLASS	HYDRIC STATUS
I	Limerick	Aeric Fluvaquent	somewhat poorly	nonhydric
II	*Limerick*	*Aeric Fluvaquent*	*somewhat poorly*	*hydric*
III	*Saco*	*Typic Fluvaquent*	*very poorly*	*hydric*
IV	Limerick	Aeric Fluvaquent	somewhat poorly	nonhydric
V	*Limerick*	*Aeric Fluvaquent*	*somewhat poorly*	*hydric*
VI	*Saco*	*Typic Fluvaquent*	*very poorly*	*hydric*
VII	*Saco*	*Fluvaquentic Humaquept*	*very poorly*	*hydric*
VIII	*Rippowam*	*Aeric Fluvaquent*	*poorly*	*hydric*
IX	Pootatuck	Fluvaquentic Humaquept	moderately well	nonhydric
X	*Limerick*	*Aeric Fluvaquent*	*poorly*	*hydric*
XI	*Saco*	*Fluvaquentic Humaquept*	*very poorly*	*hydric*
XII	*Winooski*	*Aquic Udifluvent*	*moderately well*	*hydric*
XIII	Winooski	Aquic Udifluvent	moderately well	nonhydric
XIV	*Saco*	*Fluvaquentic Humaquept*	*very poorly*	*hydric*
XV	*Saco*	*Fluvaquentic Humaquept*	*very poorly*	*hydric*
XVI	Hadley	Typic Udifluvent	well	nonhydric
XVII	Winooski	Aquic Udifluvent	moderately well	nonhydric
XVIII	*Limerick*	*Aeric Fluvaquent*	*somewhat poorly*	*hydric*
XIX	*Saco*	*Fluvaquentic Humaquept*	*very poorly*	*hydric*
XX	Hadley	Typic Udifluvent	well	nonhydric

given in the Federal Manual for Identifying and Delineation of Jurisdictional Wetlands (Federal Interagency Committee for Wetland Delineation, 1989) and are:

1. All organic soils (Histosols) except Folists, or
2. Mineral soils in Aquic suborders, Aquic subgroups, Albolls suborder, Salorthids great group, or Pell great groups of Vertisols that are:
   a. somewhat poorly drained and have a water table <15 cm (6 inches) from the surface for a significant period (usually a week or more) during the growing season, or
   b. poorly drained or very poorly drained and have either:
      (1) a water table at <30 cm (12 inches) from the surface for a significant period (usually a week or more) during the growing season if permeability is ≥15 cm/h (6 inches/h) in all layers within 50 cm (20 inches), or
      (2) water table <45 cm (18 inches) from the surface for a significant period (usually a week or more) during the growing season if permeability is <15 cm/h (6 inches/h) in any layer within 50 cm (20 inches), or
3. Mineral soils that are ponded for long duration (>7 days) or very long duration (more than a month) during the growing season, or
4. Mineral soils that are frequently flooded for long duration (>7 days) or very long duration (more than a month) during the growing season.

The range in characteristics of the soil series in this study were evaluated by Veneman and Tiner (1990) and the ranges of matrix color chromas were compared between series. All of the series, with the exception of Hadley, could contain hydric soils. Hydric soils should have matrix color chromas of 2 or less when mottled (1 or less without mottles). The somewhat poorly drained soils in the Limerick series can be either hydric or nonhydric. The Soil Conservation Service allows for the Winooski series to contain mottles in the upper 45 cm of the pedon. This results in some moderately well drained soils being hydric (for example, site XII).

In addition, an attempt was made to see if the frequency and duration of the saturation period could be derived based on morphology alone. Hydrologic information (water table levels) was converted into data which reflected both the frequency and duration of flooding events. The water table levels as shown in Figures 6 through 15 were used to determine the period of time that each soil horizon was saturated. The intersection of the water level with the soil horizon's lower depth was used to demark the beginning and ending of the period.

The periods of saturation of individual horizons were used in several forms. Periods in weeks (WKS) and as a percent (SAT) of the growing season (GWKS, GSAT) or for the entire year (YWKS, YSAT) were correlated to the horizon color chroma. Two different forms of color chroma data were utilized; the chroma index (Cl) (Evans and Franzmeier, 1988) and the dominant chroma (DOM). Linear correlations had very low coefficients of determination (0.01-0.10) when either Cl or DOM was compared to any of the above four variables (Table 9). A linear regression of the period of saturation as a percent of the growing season to the chroma index has a low coefficient of determination (Figure 17) due to the scatter of the saturation data. The high and low saturation data have widely varying chroma indices (from less than 1 to 8) and even the middle range of the data is spread over indices ranging from 1 to 4. A good prediction of the percent saturation from a linear model of Cl was not possible due to the bimodal distribution of the saturation data. Sorting of the data

Table 9. Coefficients of determination for linear, nonlinear and multiple regression equations.

LINEAR REGRESSIONS

Y=	GWKS	GSAT	YWKS	YSAT	OSGWKS	OSGSAT
X=						
C1	0.03	0.03	0.01	0.03		
DOM	0.09	0.10	0.03	0.03		
OSC1					0.02	0.03
OSDOM					0.08	0.11

NONLINEAR REGRESSION

Y=	DOM
X=	
GWKS	0.20

STEPWISE MULTIPLE REGRESSIONS

RAINBOW BEACH (N=32) R SQUARED = 0.9558

	COEFFICIENT	SE	P	ADJUSTED R^2
CONSTANT	15.786	1.2664	0.0000	
ORGC	6.5888	0.6596	0.0000	0.0194
C1	2.3522	0.1857	0.0000	0.3282
SILT	-0.0280	0.0197	0.1654	0.5050
DOM	-3.3685	0.4106	0.0000	0.7401
MNCD	-0.0201	0.0019	0.0000	0.9473

ALL SITES (N=122) R SQUARED = 0.2001

	COEFFICIENT	SE	P	ADJUSTED R^2
CONSTANT	19.529	2.8709	0.0000	
DOM	-7.9180	1.9713	0.0001	0.1471
C1	5.0450	2.1753	0.0221	0.1812
ORGC	-0.1743	0.1950	0.3734	0.1798

WEIGHTING VARIABLE: SITE

DEFINITIONS OF PARAMETERS

GWKS = number of weeks during the growing season that a horizon is saturated.
GSAT = percent of total growing season that a horizon is saturated.
YWKS = number of weeks during the entire year that a horizon is saturated.
YSAT = percent of total growing season that a horizon is saturated.
OSGWKS = GWKS cases sorted by color values that were less than 3 to exclude horizon that were black.
OSGSAT = GSAT cases sorted by color values that were less than 3.
C1 = chroma index (Evans and Franzmeier, 1988).
DOM = dominant color chroma of a horizon.
OSC1 = C1 cases sorted by color values less than 3.
OSDOM = DOM cases sorted by color values less than 3.
ORGC = percent organic carbon in a soil horizon.
SILT = percent by weight silt sized particles in a soil horizon.
MNCD = citrate-dithionite extractable manganese in mg/L.
SITE = site number (1-20).

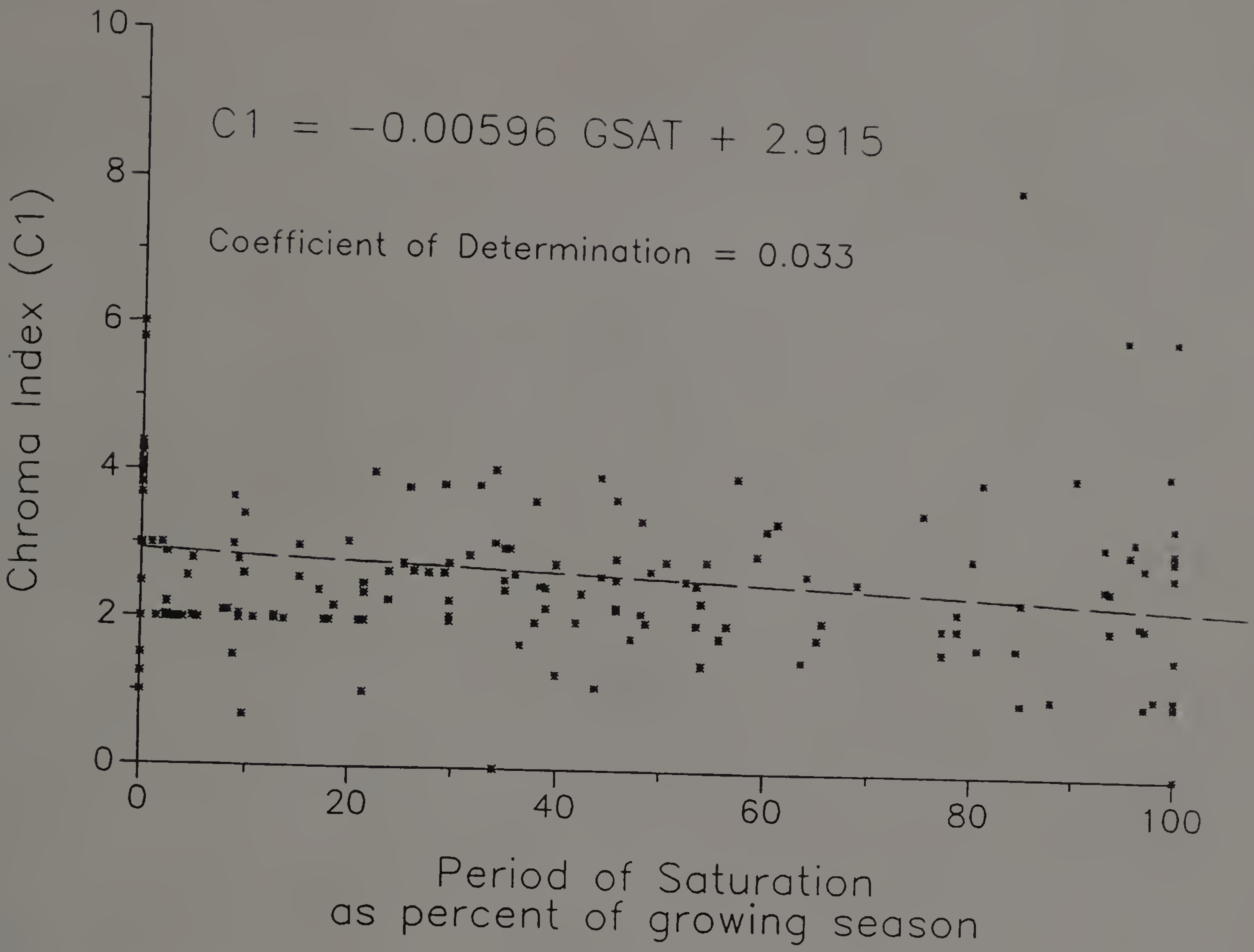


Figure 17. Relationship between the period of saturation as a percent of the growing season and the chroma index (C1) explaining 3% of the data from every horizon of sites I-XX (N = 185).

was done to throw out dark colored horizons. Horizons where Munsell color values were >3 had high organic carbon contents were not included in OSGWKS, OSGSAT, OSCl, and OSDOM, but the determination coefficients remained low (Table 9). Nonlinear regression of GWKS and DOM explained 22% of the data with an exponential curve (Figure 18).

Multiple parameter regression analysis using additional soil characteristics showed the importance of other pedological conditions (Table 9). The standard errors and p values of these regressions were included to show the low predictive qualities of such models even when correlation coefficients are high. The regression coefficient of DOM is negative in the models while the coefficient of Cl is positive. Additional parameters used were organic carbon content, particle size distribution, and extractable iron and manganese in individual soil horizons (Table 9).

Fluctuation of the organic carbon content with depth is characteristic of floodplain soil profiles (Soil Survey Staff, 1975). This feature was observed at some sites (II and VI) while at other sites the carbon values were consistantly low (Appendix A). This may have been a consequence of sampling at the midpoint of horizons, while the organic matter generally tends to accumulate on the surface of each spring flood mineral deposit. Particle size analysis of the Rainbow Beach pedons are given in Appendix B. Extractable iron and manganese concentrations are given in Appendix C.

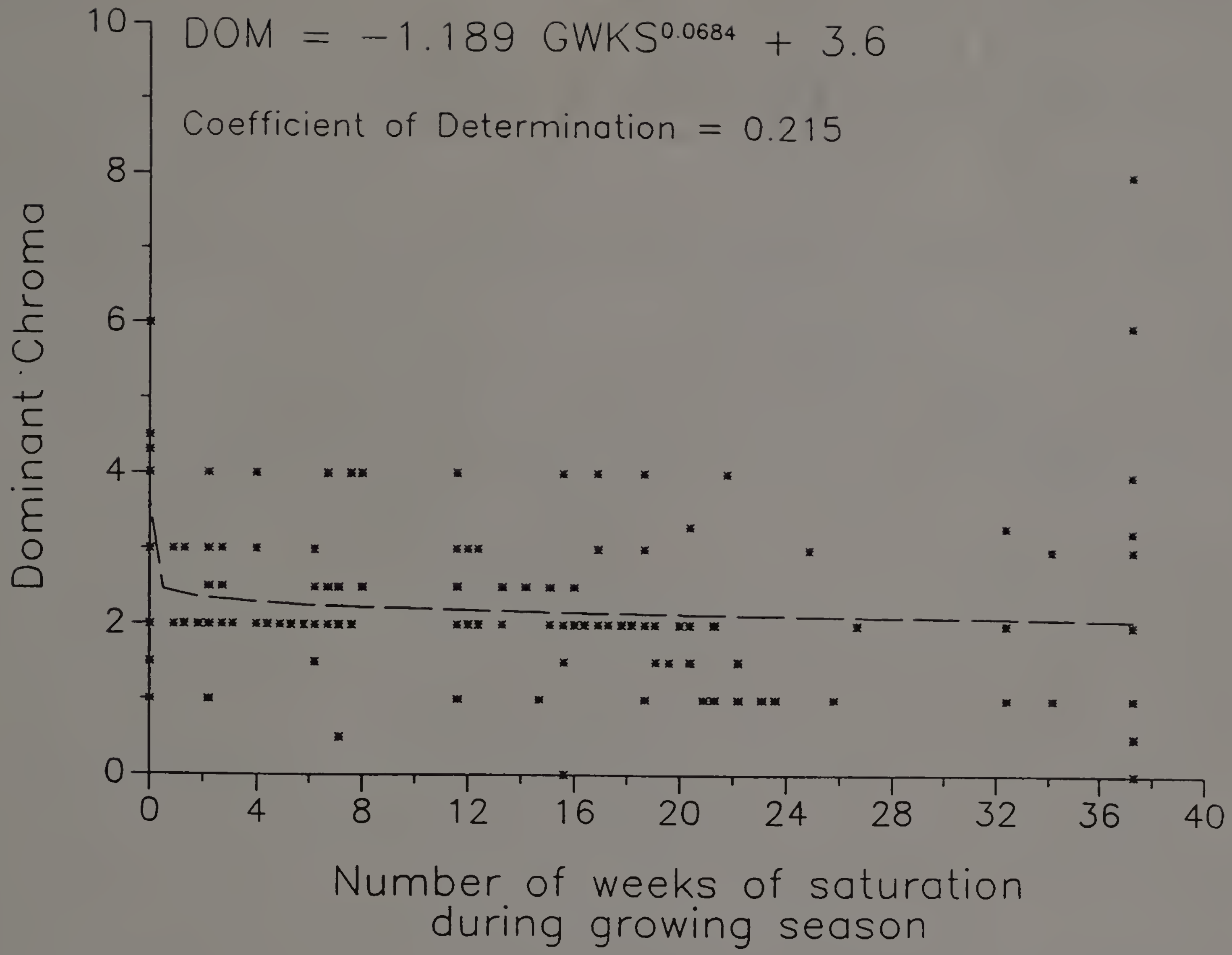


Figure 18. Relationship between the number of weeks of saturation during the growing season (GWKS) and the dominant chroma (DOM) explained 20% of the data (N = 185).

Soil Reduction Measurements

Redox Potentials

Redox potentials for the 1990 growing season were monitored at sites I-VI (Figures 19-21). The pH of all horizons at sites I-VI ranged from 5.6 to 6.4. At pH 6, the equilibrium Eh between hematite and Fe(II) would be near 0 mV and the Eh between amorphous ferric oxyhydroxide and Fe(II) would be 270 mV (Stumm and Morgan, 1981). The lower topographic positions with extended saturation periods (III and VI) exhibit much longer periods of reduction (negative Eh) and lower potentials than the other sites (Figures 19-21). The lower profiles of sites II and V have lower Eh values for longer time periods than their respective upper horizons due again to the longer periods of saturation in lower horizons. Brief periods of reduction are found even in surface horizons of the better drained sites (I and IV). Unsaturated but wet soil can have low oxygen diffusion rates to ped interiors and reduction may take place while macropores at the same depth are not saturated. This layer is also known as the capillary fringe.

Comparisons of high Eh values (oxidized conditions) were not very informative due to the unblackened platinum tipped redox electrodes used in this study. Redox measurements under oxidizing conditions are less reliable with these probes than at low oxygen or totally reducing conditions.

Comparisons of the observed morphology and the periods of reducing conditions show variable results. Site I had low chroma matrices and mottles of high and low chroma colors in horizons 2-5

Figure 19. Redox (Eh) potentials measured (mV) in 1990 for selected horizons of sites I and IV. Dashed lines are the equilibrium potentials for the transition between hematite or amorphous ferric oxyhydroxide and ferrous iron at pH 6.

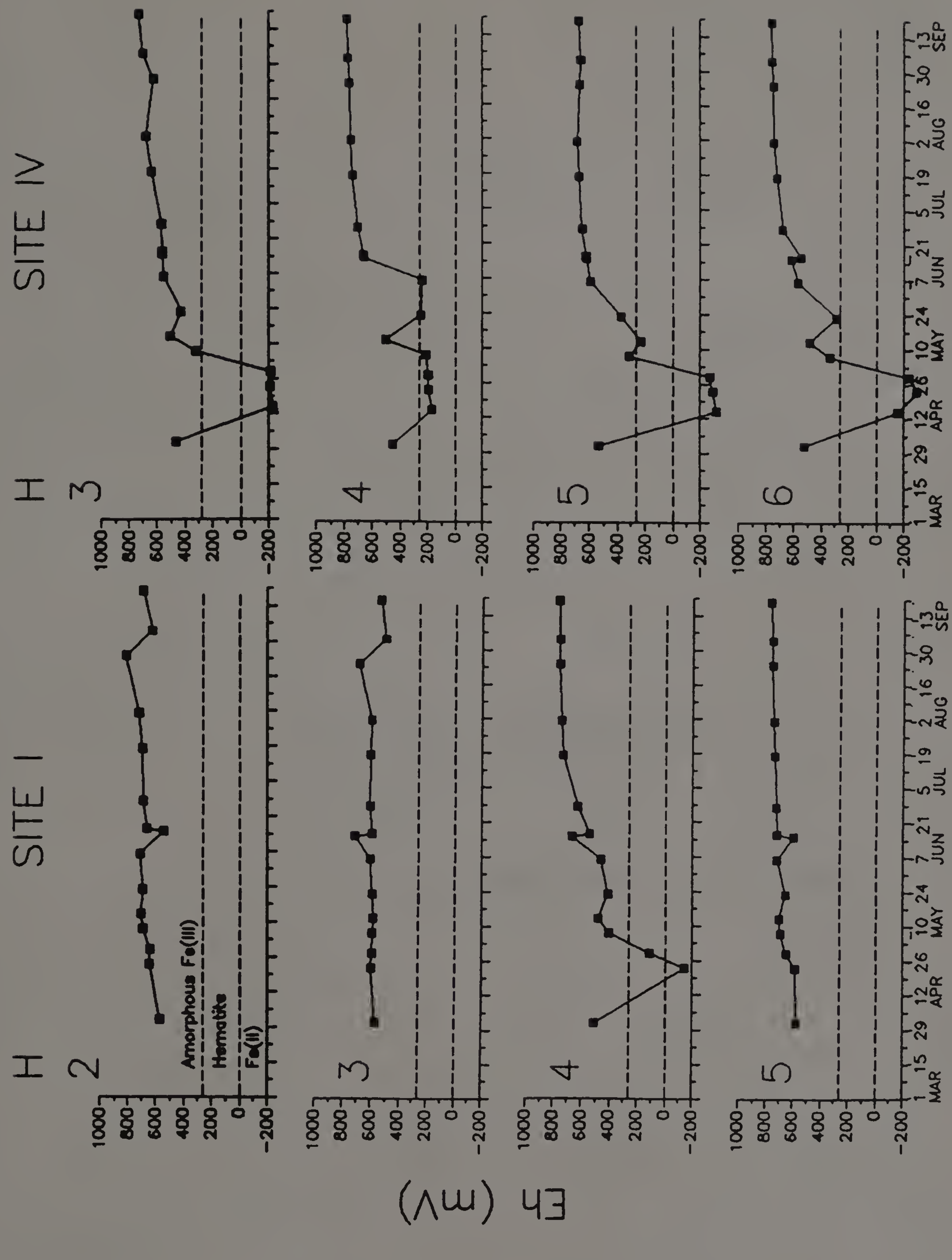

SITE I
SITE IV
Eh (mV)
H 2
H 3
3
4
5
6
Amorphous Fe(III)
Hematite
Fe(II)
1000
800
600
400
200
0
-200
1 15 29 12 26 10 24 7 21 5 19 2 16 30 13
MAR APR MAY JUN JUL AUG SEP

Figure 20. Redox (Eh) potentials measured (mV) in 1990 for selected horizons of sites II and V. Dashed lines are the equilibrium potentials for the transition between hematite or amorphous ferric oxyhydroxide and ferrous iron at pH 6.

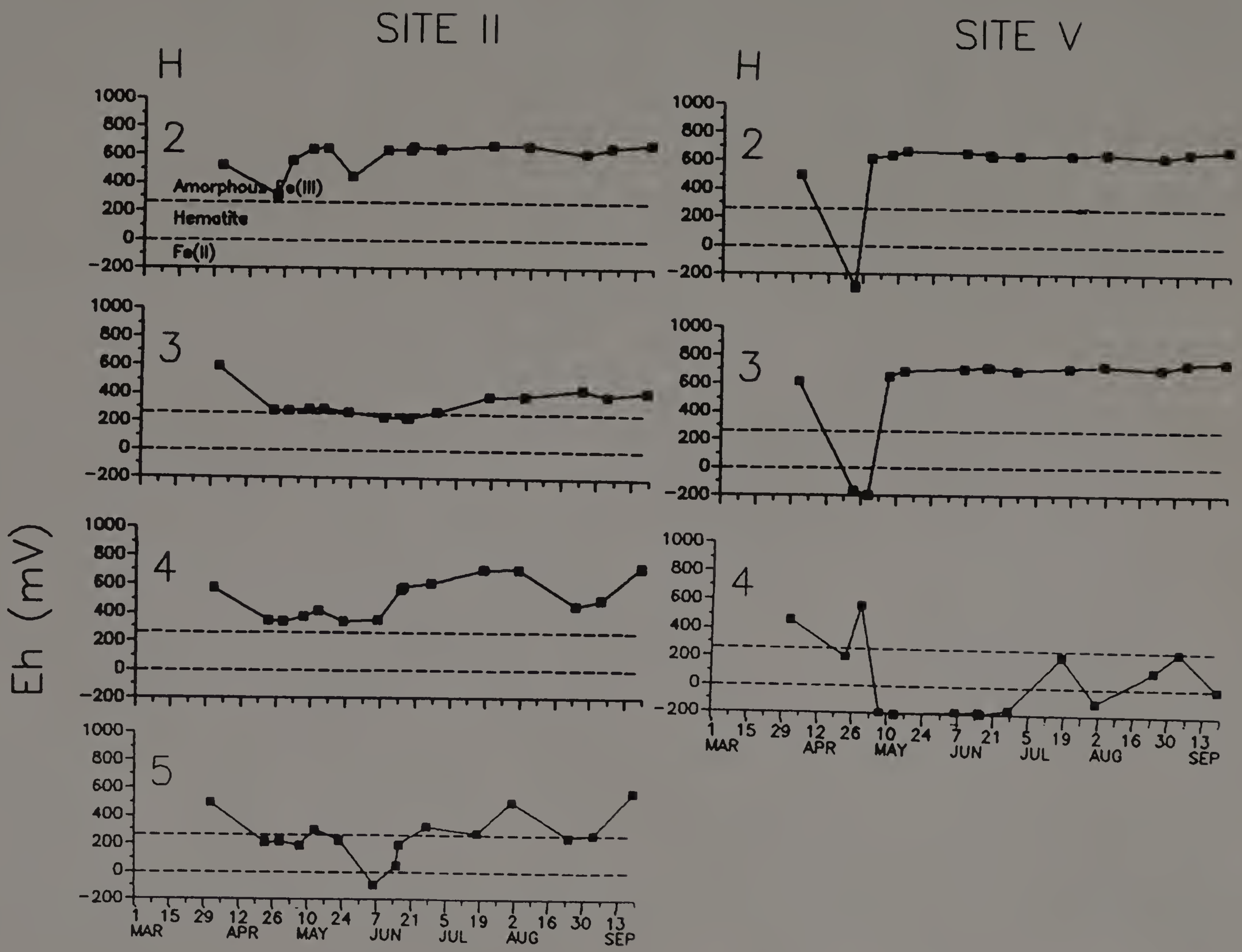
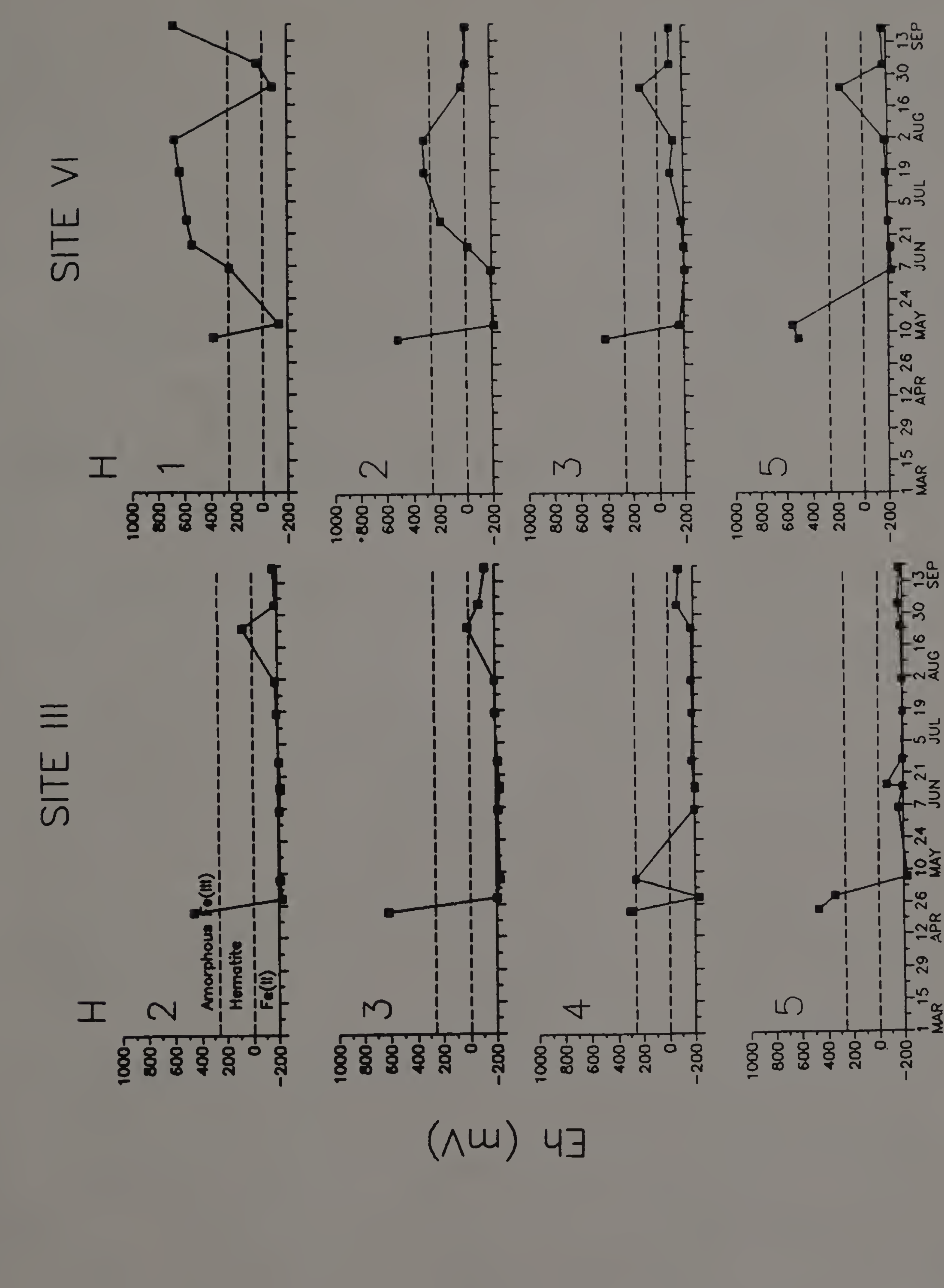

SITE II
SITE V
H
H
2
3
4
5
2
3
4
Eh (mV)
1000
800
600
400
200
0
-200
Amorphous Fe(III)
Hematite
Fe(II)
1 MAR
15
29
12 APR
26
10 MAY
24
7 JUN
21
5 JUL
19
2 AUG
16
30
13 SEP

Figure 21. Redox (Eh) potentials measured (mV) in 1990 for selected horizons of sites III and VI. Dashed lines are the equilibrium potentials for the transition between hematite or amorphous ferric oxyhydroxide and ferrous iron at pH 6.


SITE III
SITE VI
Eh (mV)
H
2
3
4
5
1
Amorphous Fe(III)
Hematite
Fe(II)
1000
800
600
400
200
0
-200
1 15 29 12 26 10 24 7 21 5 19 2 16 30 13
MAR APR MAY JUN JUL AUG SEP

even though significant periods of reducing conditions were not measured (Figure 19). Horizon 4 dropped below the iron reduction potential for a short period of time early in the season. This horizon had a matrix chroma of 2 with a few (1%) mottles with a chroma of 4, but the other horizons also had similar morphology.

Site IV was similar to that at site I in that low chroma matrices were present with high and low chroma mottles. Some horizon matrices were of high chroma colors. Differing from site I, reducing conditions were present at site IV in horizons 3-6 for a month or so at the start of the growing season.

Site II had horizons with low chroma colors but more mottles than the horizons of I or IV and contained neoferrans. The neoferrans occurred in horizon 3 where the Eh was not low (Figure 20), however, the electrode tip could have been situated in a more oxidizing microenvironment (ie., near an air-filled pore) in an otherwise reduced horizon. Horizon 5 was reduced for a longer period of time and had a low chroma matrix with many mottles of high chroma only.

The pedon at site V had low chroma matrices with high and low chroma mottles but only in horizons 1 and 3. Horizons 2 and 4 had matrix colors of chroma 3 but were occupied with low chroma strata and mottles. Horizon 2 had 15% neoalbans (chroma 2) around pores, even though, horizon 4 was the only horizon in this pedon to experience significant periods of reducing conditions (for almost the entire season).

Site III had extensive periods of reducing conditions (Figure 21). The morphology of this pedon was distinctive in that every horizon had low chroma matrices with high chroma mottles. The initial readings of oxidized values (high Eh) were taken on the day of installation when the electrodes had not equilibrated with the soil and the installation procedure itself could have pushed air in the soil with the probe.

Site VI had horizons which all experienced reducing conditions. The surface horizon (1) had a low chroma matrix with high and low chroma mottles and neoferrans even though the shortest period of reducing conditions of the pedon was measured here. The lower horizons had matrices of low chroma colors and neoferrans of high and low chroma colors. These horizons were reduced for much longer periods (Figure 21).

Ferrous Iron in Soil Water

Some lysimeters failed to produce samples probably due to dry soil conditions. At other sampling dates, anaerobically collected soil water would contain no ferrous iron. Highest seasonal totals occurred at site III, the wettest of the six sites (Figure 22). Site III had higher FeII concentrations than those found by Ransom and Smeck (1986) in their Clermont soil by a factor of 10, however the concentrations found at other sites in this study were within their reported ranges (Figures 23-25). Standard errors of the standard curves of the iron concentrations ranged from 0.1 - 0.41 mg/L throughout the 6 separate determinations (sampling dates).

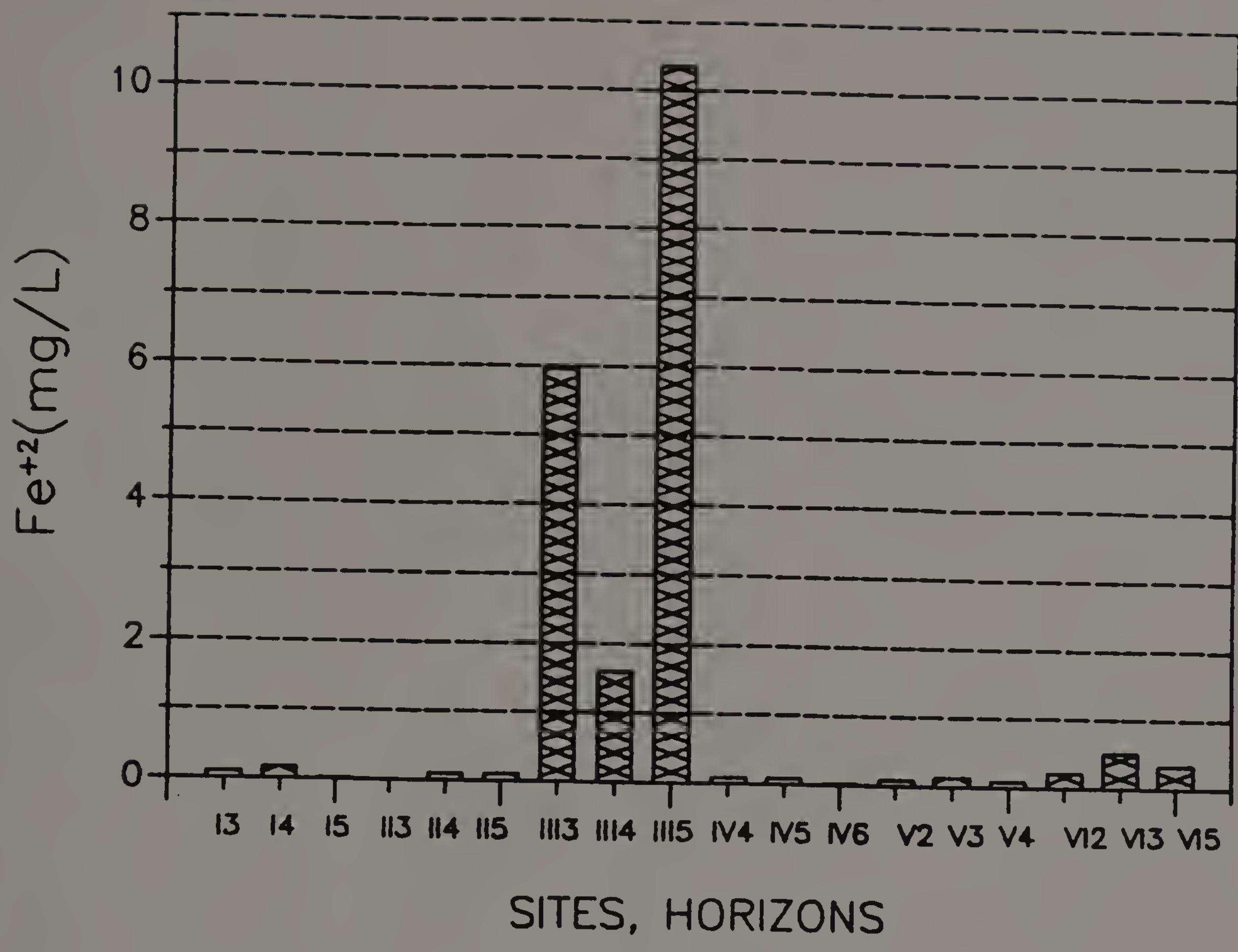


Figure 22. The average ferrous iron concentrations collected from all lysimeters at sites I-VI during the 1990 growing season.

Figure 23. Ferrous iron concentrations found in lysimeter samples in selected horizons of sites I and IV. NS = no samples were found in either of two replicated lysimeters. All concentrations were very low to zero but axes of graph are the same scale as in Figures 24 and 25 for comparison.

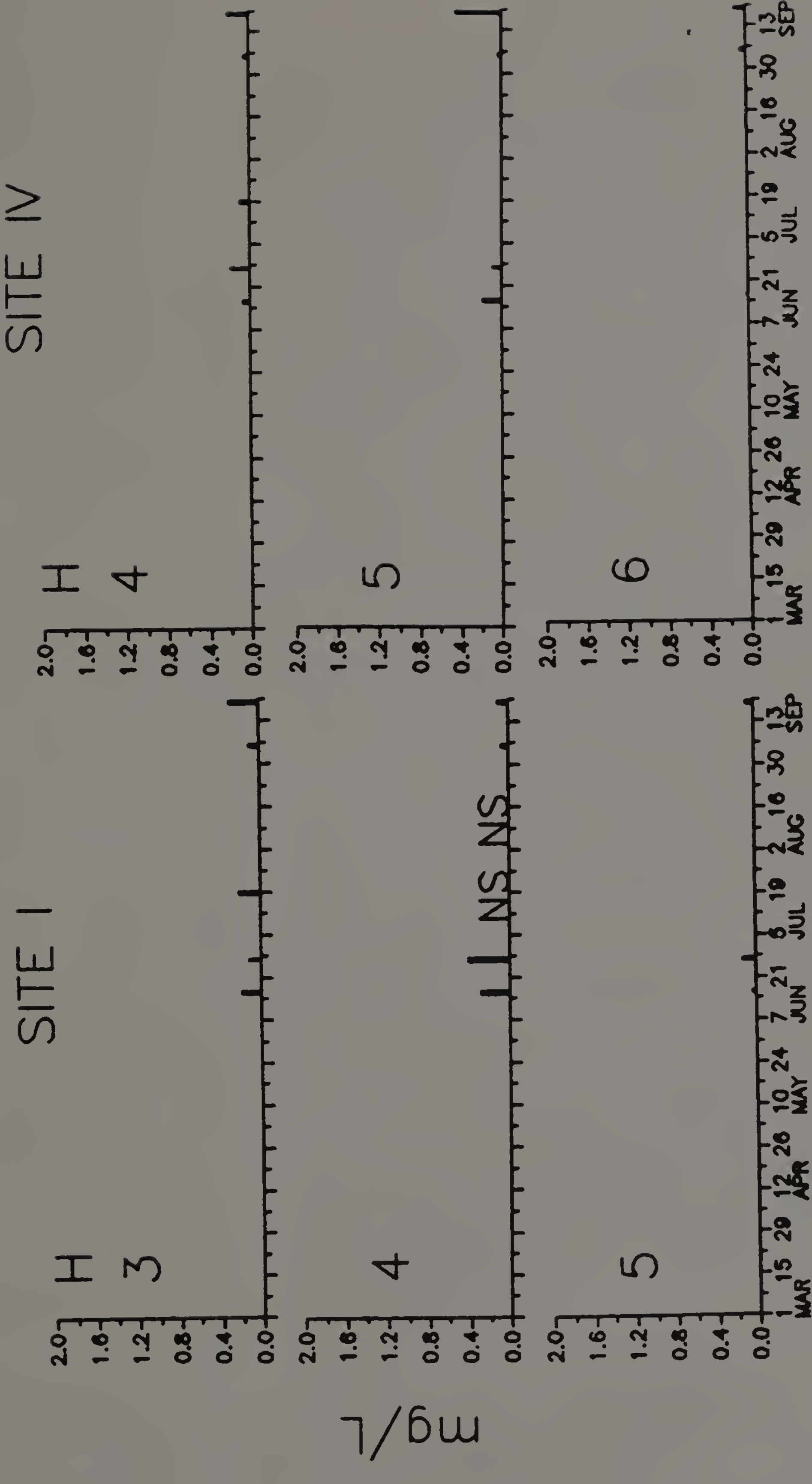

SITE I
SITE IV
H
3
4
5
H
4
5
6
mg/L
2.0
1.6
1.2
0.8
0.4
0.0
NS NS
1 MAR
15
29
12 APR
26
10 MAY
24
7 JUN
21
5 JUL
19
2 AUG
16
30
13 SEP

Figure 24. Ferrous iron concentrations found in lysimeter samples in selected horizons of sites II and V. NS = no samples were found in either of two replicated lysimeters. All concentrations were very low to zero but axes of graph are the same scale as in Figures 23 and 25 for comparison.

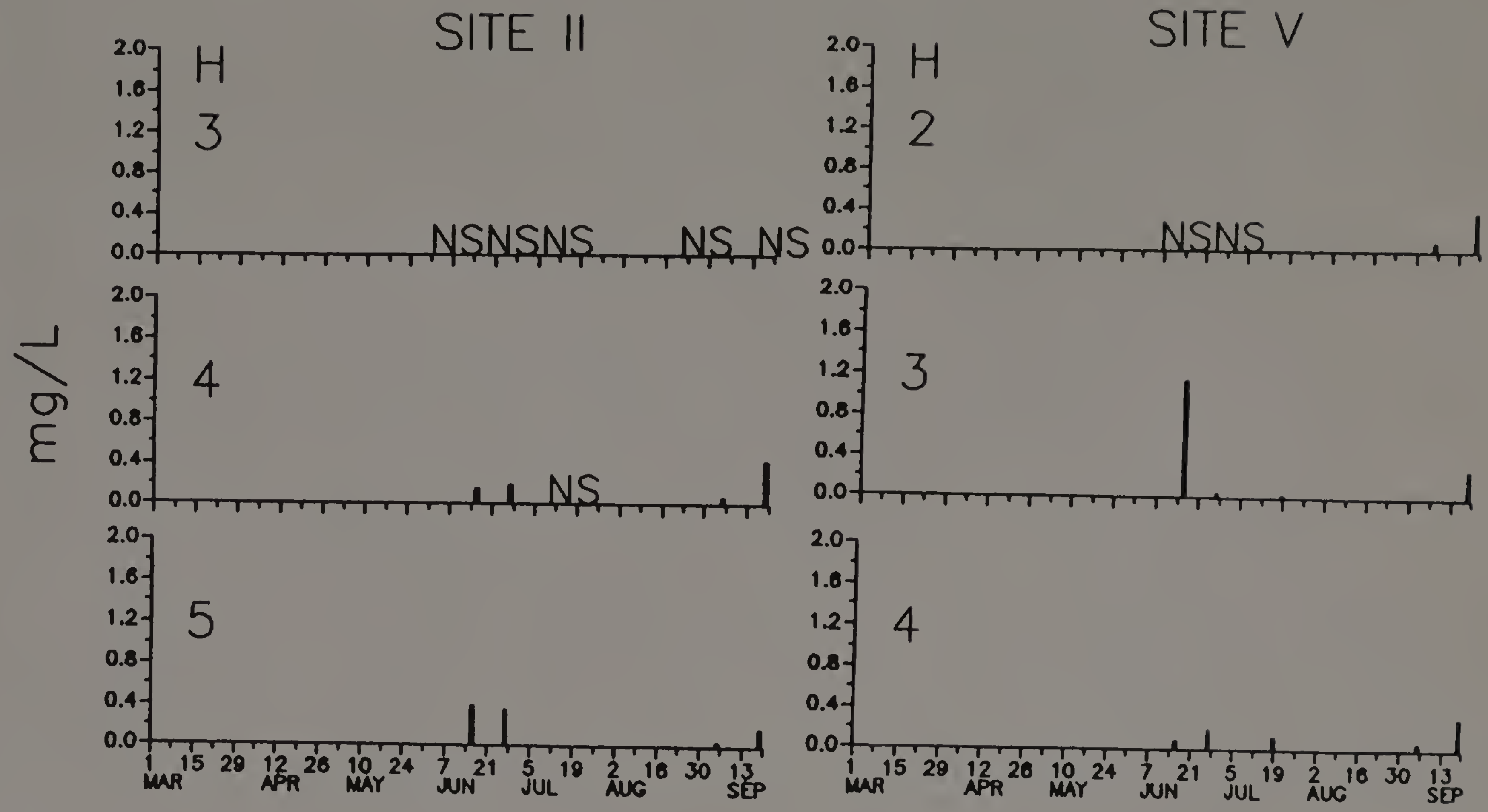
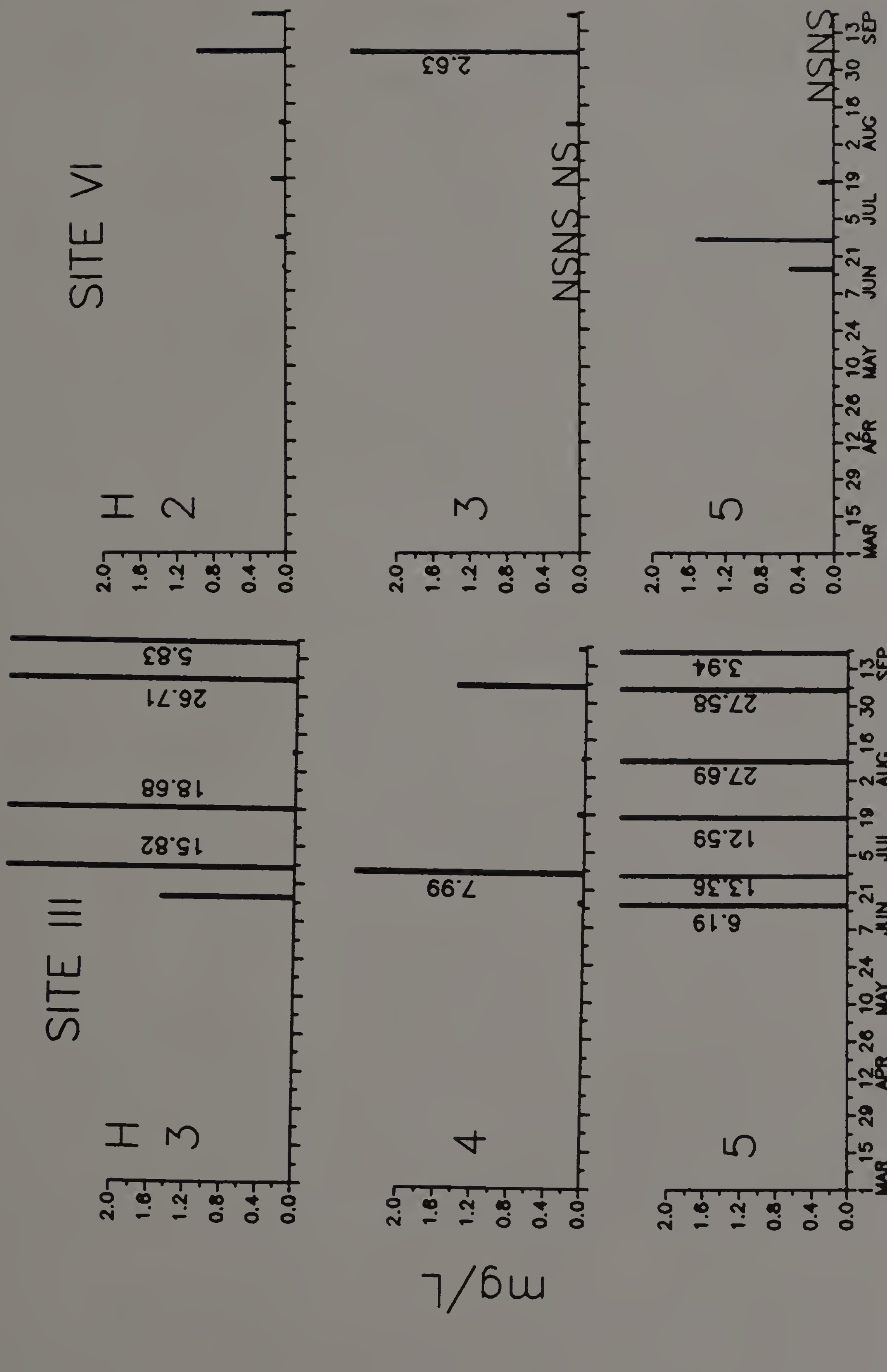

SITE II
SITE V
mg/L
H
3
4
5
H
2
3
4
2.0
1.6
1.2
0.8
0.4
0.0
NSNSNS
NS NS
NS
NSNS
1 MAR
15
29
12 APR
26
10 MAY
24
7 JUN
21
5 JUL
19
2 AUG
16
30
13 SEP

Figure 25. Ferrous iron concentrations found in lysimeter samples in selected horizons of sites III and VI. NS = no samples were found in either of two replicated lysimeters. All concentrations were very low to zero in site VI, horizon 2 while at site III, horizons 3 and 5 some samples were off the scale of the graphs. Axes of graph are the same scale as in Figures 23 and 24 for comparison.

mg/L
SITE III
H
3
2.0
1.6
1.2
0.8
0.4
0.0
15.82
18.68
26.71
5.83
4
7.99
5
6.19
13.36
12.59
27.69
27.58
3.94
1
MAR
15
29
12
APR
26
10
MAY
24
7
JUN
21
5
JUL
19
2
AUG
16
30
13
SEP
SITE VI
H
2
3
2.63
NSNS NS
5
NSNS
NSNS

The dates when ferrous iron was found at sites III and VI (Figure 25) lagged behind the onset of reducing conditions (Figure 21). The length of time that reducing conditions existed within a horizon correlated to the season averages of ferrous iron (Figure 22); $R^2 = 0.39$.

There were no significant differences in the amounts of iron and manganese extracted between sites (Appendix C). Most profiles exhibited an initial increase in the concentrations with a subsequent decrease with depth. A comparison of the extractable iron to the ferrous iron found in the lysimeters showed, at sites III and VI (the only sites to produce significant ferrous iron), the average ferrous iron content fluctuated with depth and was not related to the fluctuations in extractable iron with depth.

CHAPTER 6

DISCUSSION

Morphology as a Predictor of Hydrology

Soil morphology does reflect the moisture regimes monitored at these sites with a few exceptions. The measurements of soil reduction by electrode and the presence of ferrous iron confirmed that significant periods of saturation (>1 week) must be present for reducing conditions to exist.

The linear and nonlinear models of Cl and DOM give negative coefficients which is consistant with theory (Evans and Franzmeier, 1988), however when the multiple regression models were attempted the Cl coefficient was positive while the DOM remained negative. The Cl coefficients for the linear models were small and negative and the data were bimodal with most values occurring at high and low values of GWKS or GSAT. It is important to note that the predicted variable (Y) for the multiple regressions was the X variable in Figures 16 and 17. The switching of these axes would force a linear model prediction to average the ranges of values for the two ends of the bimodally distributed data and this could result in large standard errors for the models.

In sharp contrast to the correlation coefficients found with this data set (0.03), Evans and Franzmeier (1988) found high correlation coefficients (0.6-0.8) for their Cl index for a defined depth zone (moisture control section) with the fraction of time the soil was saturated at a preset depth. The parameters compared here are not in .

exactly same form but the theoretical background should be transferrable.

Even using strictly physical or hydrologic parameters to determine the water table level is a difficult task. Nelson _et_ _al_. (1973) using hydrologic parameters (such as antecendent precipitation and relative humidity) could predict only the water tables at individual sites given previous on-site data of water tables for two years at least. Soil factors were not included in their models which might have explained the variation in water tables from site to site. Burt and Butcher (1985) had difficulty correlating depth to soil saturation topographic indicies (i.e. upslope area and local gradient) with any consistency for prediction.

Characterization of Hydrology

The duration of flooding events cannot be directly extrapolated from the river stage data without the precise elevation changes over time. In addition, flood water may infiltrate faster or slower than runoff back into the channel. Historical geomorphic information of how the point bar has changed shape and position over time (sites I-VI) and how restricted the flow of water has been through the oxbow (sites X, XI and XII) are crucial. Temporary dams of debris restrict drainage of flood waters and can drastically alter the saturation period depending on their presence. Channel migration of the Connecticut River has been significant in the last century (Grossman, 1981).

Tensiometric measurements would have aided in the interpretation of data which showed reduction occuring even when water tables were lower than the horizon. Water potential measurements, however, were not collected.

Acknowledging the extreme variation in hydrologic data, the short period of record in this study doesn't allow an accurate yearly prediction of the duration based solely on the hydrologic measurements. These observations should be considered descriptive and not necessarily representative of the moisture regime. It can be noted that the climatologic data during the period of observation showed longer growing seasons and more precipitation than normal suggesting that the durations observed could be longer than those occurring under "normal" conditions.

Study duration has an effect on the accuracy and predictive capability of models derived from data sets. The length of this study was 2.5 years and was probably not representative of the normal climatic conditions of the area due to higher precipitations. Zobeck and Ritchie (1984a) determined that the springtime water table depths measured in soils in Ohio for a duration of 2 years were found to vary significantly from the 10-year average depths by as much as 50 cm earlier in the season (January and February) while being closer in April and March. The accuracy of the growing season water tables is important to the determination of the water table from visible signs of biologic soil reduction.

Variations in Soil Morphology and Chemistry

The presence of neoferrans by itself was a general indicator of wet conditions. Neoferrans only occurred in the wetter pedons (II, III, V, and VI) which exhibited significant periods of reduction. The presence of low chroma colors in the drier pedons (I and IV) did not coincide with measured redox potentials and may have been partly inherited.

The suction lysimeters also provided variable results. The distinction between a value of zero and "no sample" in the data set is significant (Figures 22-24 and Appendix D). A possible explanation for an empty lysimeter was that no water was present in the soil at the tension (1/3 bar or 0.03 MPa) placed upon the lysimeter. The soil sampled by the lysimeter in that specific location was not necessarily drier when another lysimeter in the same horizon would produce sample. The second lysimeter could also contain high amounts of iron (Appendix D). Lysimeters could have been disturbed, lost tension and subsequently the sample drained back out of the instrument. Evidence of an intact seal on the lysimeters was noted when a hissing sound was emitted from the tubing upon sampling. Tension could also have been released when sufficient soil water had entered the instrument through the porous cup. Therefore, when no hiss was emitted and no sample was found in the lysimeter it was concluded that the instrument had lost tension but still no conclusion on whether the horizon had been wet could be made.

On other sampling dates, high and low concentrations were found in replicated lysimeters located in the same horizon at site III

(Appendix D). This could be explained by the presence of conducting macropores (such as worm holes) near a lysimeter where no iron was found. Horizons 3, 4 and 5 had continuous vertical earthworm channels. These macropores could conduct aerated water as well as allow gaseous oxygen to enter the pore after water had drained. In the soil near a lysimeter with no conducting macropores, reduced conditions would be more prevalent due to the slower diffusion rates of both air and water through the finer pore system in the matrix.

CHAPTER 7

CONCLUSIONS

The morphologies of the soils in this study were distinctive due to the floodplain conditions underwhich they were formed. The parent material of these soils was variable and masked some effects of weathering occuring in place. Interpretation of the morphology to determine the hydric status of the soils at these sites must be accomplished by additional hydrologic observations to determine the actual frequency and duration of saturated conditions and flooding events. The amount of time and effort necessary for monitoring such sites is significant but crucial to the accurate determination of hydric soils and wetland boundaries.

The results of the regression analyses show that prediction of the duration and frequency of saturation in soils by morphology alone is difficult because the error in these models is larger than the needed accuracy (i.e., 1 week). Longer periods of observation of hydrologic conditions are needed to assure that normal patterns of water level fluctuations are used to formulate the models.

Floodplains in Massachusetts are regulated at the present time and so wetland delineation for the purposes of protection of these sites is not necessary. Floodplain jurisdiction covers the 100 year floodplain and most of these sites, with the possible exception of XVI, XVII and XX, should fall within this area.

The overall objective of this study was met to the extent that the predictive capacity of models to determine water levels from soil morphology was tested. The conclusion drawn from the analysis of the research thusfar is that predictions cannot be made with the models given here. Reasons for the poor predictive ability of these models are:

1) Bimodal (or random) distribution of predictor variable, GWKS, which is not discrete for every parameter value. In other words, there are large ranges in the values of GWKS for a given parameter value.

2) Other forms of data, not tried in the models here (i.e. the longest continuous period of saturation), could result in better predictive models. Additional parameters not considered here could also help. It is possible that other models can be found to explain the data in this study.

3) The period of record for the water table levels was only 2.5 years which is shorter than a representative hydrologic data set should be (Zobeck and Ritchie, 1984b). In addition, the climatic conditions during the study were notably different than previous years possibly skewing the data to higher values of duration and frequencies.

4) Distinct morphologies present in these soils mask, modify and interupt the classical redoximorphic features and gleying. Low chroma parent materials are deposited that do not reflect the moisture regime at the time

of observation. High chroma mottles do not reduce easily when removed from the more oxidized conditions they were formed in. Organic matter masks chroma determinations. The chroma index (C1) overemphasizes low percentages of high chroma colors, while the dominant chroma (DOM) does not account for nondominant but substantial amounts of low chroma colors.

5) Microbial activities are probably ubiquitous but little is understood about the dynamics and cycling of biologic iron reduction. Iron reducing microorganisms should be present in aerated soils but only start to become active to affect the morphology when conditions permit. The process of soil reduction from an aerated state is caused by an entire community of organisms consuming additional electron acceptors in the soil and the concentrations of these would determine when iron reduction would eventually occur. Since FeIII is ubiquitous, the microbial reduction should continue as long as carbon sources are present and Eh remains low. The type of soils occurring at wetland boundaries are ones undergoing short periodic cycles of reduction therefore iron reducing microorganisms might never get a chance to play a role in this reducing order if reaeration occurs too soon.

Taking these into account, more modeling and data analysis could result in better predictions. More field data might also prove useful by increasing the number of sites or lengthening the period of record.

The level and period of saturation are the factors which determine whether a wetland exists. These should be determined by direct hydrologic measurement or by field observation of hydrophilic plants and hydric soils. The formation of hydric soil is also dependent upon the water level. Many morphologies are possible depending upon the parent material and the effect of other factors of soil formation. The quantification of morphologic data is inadequate so far to predict the ground water level with any accuracy.

APPENDIX A

ORGANIC CARBON CONTENT

Organic carbon content by percent of soil horizons at sites I-XIII.

SITE	HORIZON	%C
I	2	0.39
	3	1.22
	4	0.94
	5	0.46
II	2	0.39
	3	2.00
	4	1.07
	5	0.46
	6	0.27
III	1	0.49
	2	1.70
	4	1.63
	6	1.22
IV	2	1.06
	3	1.54
	4	0.76
	5	0.38
	6	0.60
	7	0.69
V	1	1.82
	2	1.33
	3	1.21
	4	0.87
	5	0.67
	6	0.59
VI	1	1.61
	2	1.64
	3	1.60
	4	1.07
	5	0.88
	6	0.57
	7	1.01
VII	A	3.47
	AC	5.66
	C1	1.42
	C2g	0.74
	2Cg	0.76
	3C	0.33
VIII	A	2.63
	ACg	0.45
	Cg1	0.24
	Cg2	0.63
	2Ab	1.13
	2Cb1	1.13
	2Cb2	0.89
	3C	0.32
IX	A	10.31
	Bw1	4.82
	Bw2	1.09
	BC	0.33
	Cg1	0.22
	Cg2	0.13
X	A	6.05
	C1	1.29
	C2	0.62
	C3	0.33
	C4	0.36
XI	A	9.94
	C1	1.03
	C2	0.48
	C3	0.28
	C4	0.33
	C4s	0.19
	C5	0.48
XII	Ap	3.12
	C1	0.46
	C2	0.31
	C3	0.21
XIII	Bs	2.69
	Bw1	3.06
	Bw2	1.01
	BC1	0.41
	BC21	0.30
	BC22	0.45
	C	0.17
	Cs	0.20

Organic carbon content by percent of soil horizons at sites XIV-XX.

SITE	HORIZON	%C
XIV	Oi	13.43
	Oe	13.30
	Oa	2.65
	A	24.16
	15-18	0.74
	Bw	5.25
	A′	0.54
	Cg2	0.23
XV	Oi	39.02
	A	5.14
	C	4.20
	Ab	23.51
	ACg	1.17
	Cg	0.61
XVI	Ap	1.26
	Bw1	0.86
	Bw2	0.49
	BC	0.34
	C1	0.19
	C2	0.14
XVII	AC	1.07
	Bw1	1.12
	Bw2	0.06
	Bw3	0.40
	BC	0.34
XVII	C1	0.35
	C2	0.17
	C3	0.08
	C3m	0.12
XVIII	A	2.90
	A	0.82
	A	1.14
	ACg1	0.57
	ACg2	0.98
	ACg2	1.13
XIX	Cg1	2.85
	Cg2	0.75
	Cg3	0.51
	Cg4	0.43
	Cg5	0.33
XX	A1	2.08
	2Ap	1.49
	2Bw	0.44
	2BC	0.34
	2C1	0.25
	2C2	0.19
	2C3	0.16
	2C4	0.11

APPENDIX B

PARTICLE SIZE ANALYSIS

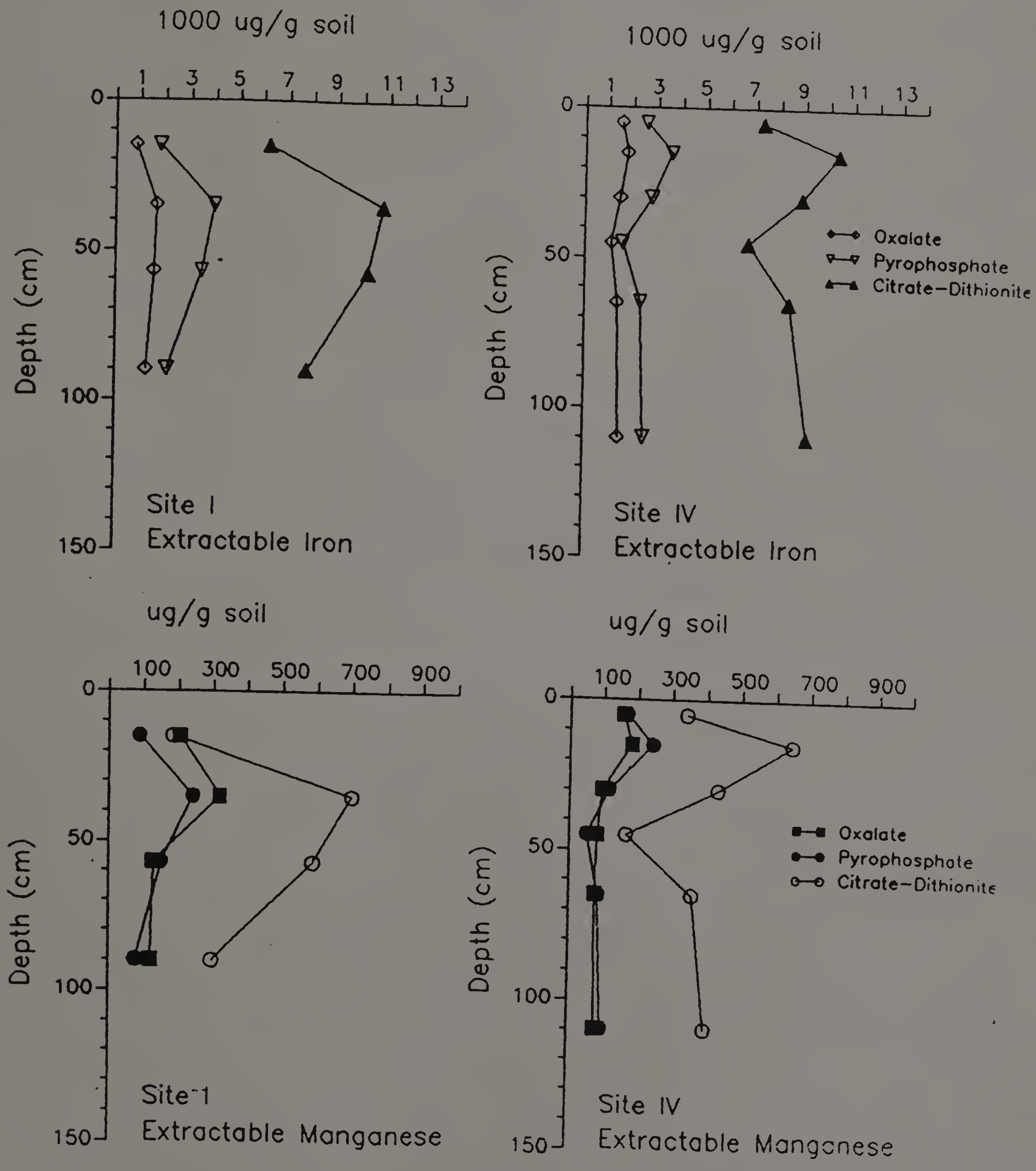
Particle size analysis by horizon of the Rainbow Beach sites.

Site	Horizon	Sand	Silt (%)	Clay	Texture
I	2	80.0	16.6	2.5	loamy sand
	3	9.3	78.1	7.0	silt loam
	4	12.3	77.2	6.0	silt loam
	5	46.1	47.2	2.6	sandy loam
II	2	73.6	22.8	0.6	loamy sand
	3	6.0	83.3	4.0	silt
	4	8.5	83.1	5.8	silt
	5	49.0	46.5	3.4	sandy loam
	6	71.0	25.6	1.5	loamy sand
III	1	61.9	32.9	1.3	sandy loam
	2	23.9	66.9	4.7	silt loam
	4	11.7	76.1	6.1	silt loam
	6	63.1	28.9	3.5	sandy loam
IV	2	49.2	45.4	2.3	sandy loam
	3	17.8	70.7	4.2	silt loam
	4	21.5	72.2	3.6	silt loam
	5	61.9	33.7	0.6	sandy loam
	6	34.8	59.1	2.7	silt loam
	7	25.6	69.2	1.6	silt loam
V	1	10.3	75.9	6.0	silt loam
	2	10.6	78.2	5.5	silt loam
	3	8.8	80.4	5.1	silt
	4	31.5	62.8	3.6	silt loam
	5	44.5	37.2	2.7	sandy loam
	6	62.8	31.5	2.1	sandy loam
VI	1	24.5	64.0	4.7	silt loam
	2	7.4	79.5	8.0	silt loam
	3	5.7	83.8	3.4	silt
	4	20.8	64.3	7.0	silt loam
	5	42.4	50.1	1.5	silt loam
	6	51.6	44.0	2.0	sandy loam
	7	42.7	53.5	6.5	silt loam

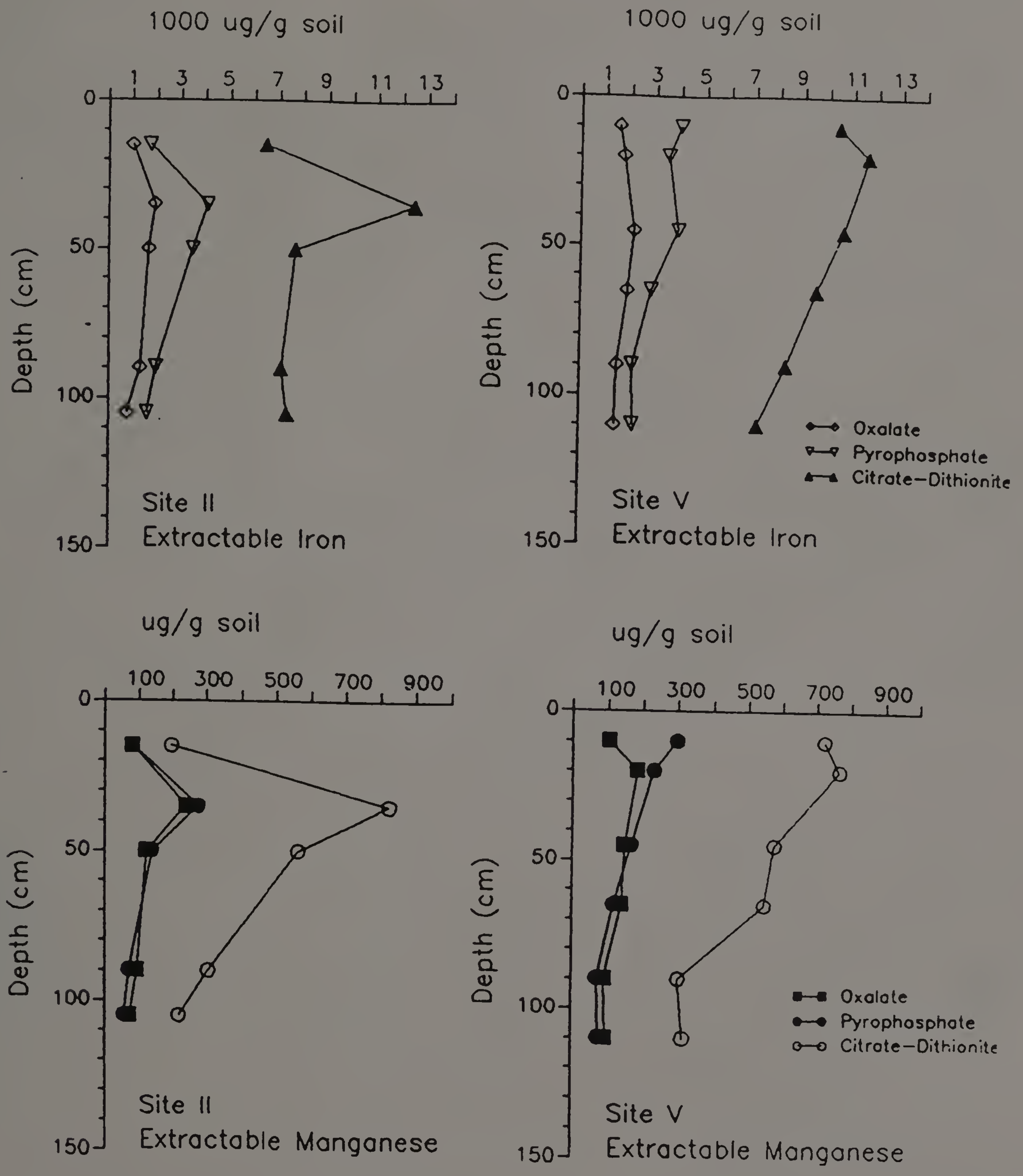
APPENDIX C

IRON AND MANGANESE EXTRACTIONS

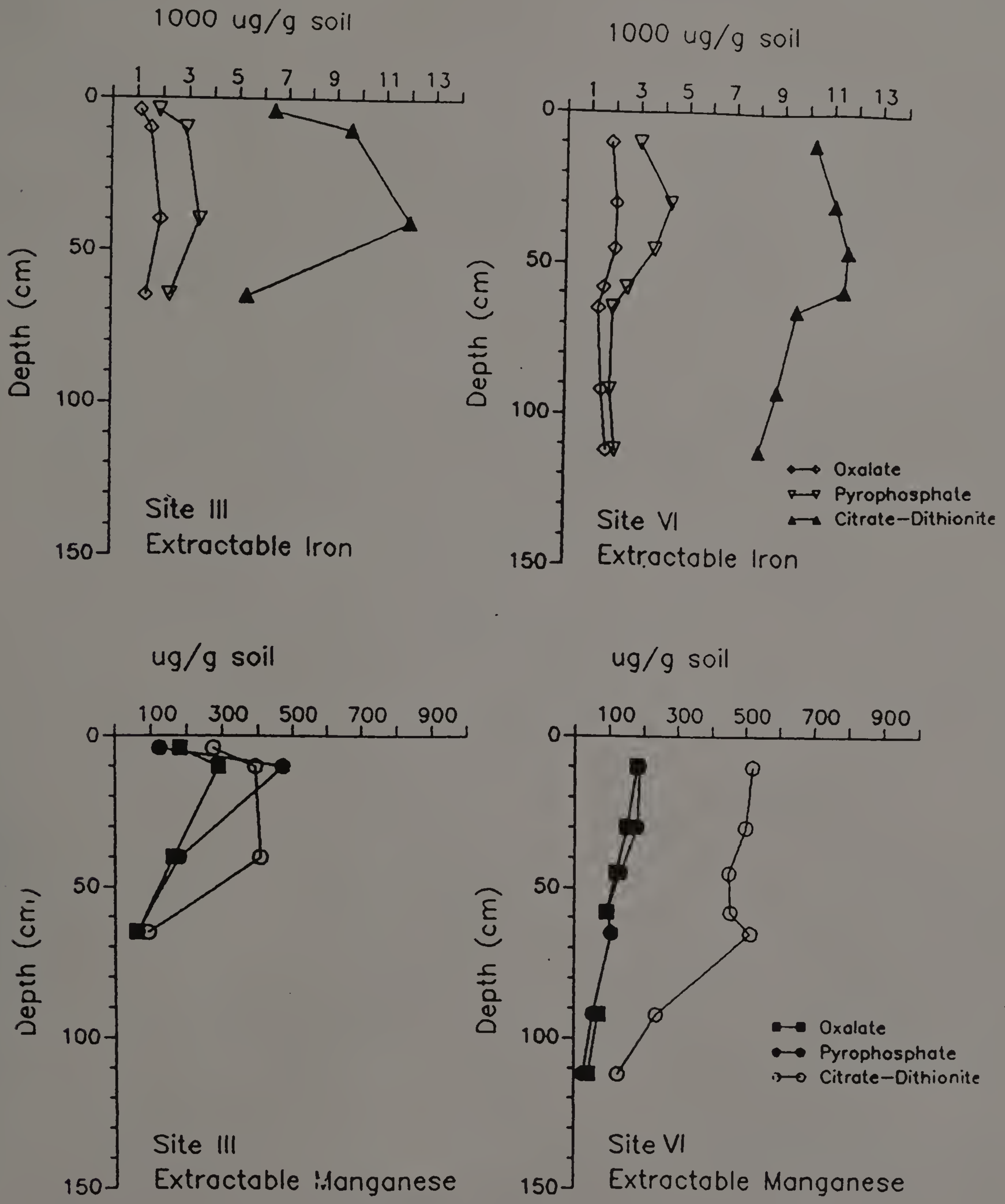
Iron and manganese extractions for selected horizons of sites I and IV.



Iron and manganese extractions for selected horizons of sites II and V.



Iron and manganese extractions for selected horizons of sites III and VI.



APPENDIX D

FERROUS IRON IN LYSIMETERS

Ferrous iron concentrations (mg/L) at Site III, Rainbow Beach.

DATE	6/15/90	6/26/90	7/18/90	8/8/90	9/4/90	9/18/90
HORIZON						
3	0.62	NS	0.07	0.00	NS	4.98
3 REP	0.85	15.82	18.61	0.03	26.71	0.85
4	NS	7.99	NS	NS	1.40	0.08
4 REP	0.05	NS	0.07	0.03	0.00	NS
5	1.21	13.24	12.59	0.11	27.58	3.94
5 REP	4.98	0.12	NS	27.58	NS	NS

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