

DIVISION S-10—WETLAND SOILS

Long-Term Evaluations of Seasonally Saturated “Wetlands” in Western Kentucky

A. D. Karathanasis,* Y. L. Thompson, and C. D. Barton

ABSTRACT

A research program was initiated in 1993 to monitor water-table depth, redox potential, and soil matric potential at four sites. The selected sites were woodlands with water tables present at or near the soil surface during late winter and spring. Soil morphology was described and permanent monitoring instruments were installed on eight soils. Hydrosequences of three soils, which represented an Endoaquept-Fragiaqualf-Fraglossudalf and a Fraguaqualf-Fraglossudalf-Fraglossudalf sequences, were studied at two sites. An Epiaqualf and a Fraguaqualf were monitored at each of the remaining sites. Six of the eight soils experienced wetland hydrology in most years, while the other two exhibited sporadic saturation events above 25 cm. Saturated conditions occurred mainly in late winter and spring, with longest duration in the lowest landscape positions. On the wettest soils, redox levels <200 mV developed during late winter and continued into the growing season. Of the six soils meeting the hydrology criterion only three experienced both, functional hydric soil conditions (<200 mV redox potential) and exhibited definitive hydric soil indicators. However, hydric soil indicators were also present in two of the three other soils that developed only moderately reduced conditions (<350 mV). In contrast, only one of the six soils with wetland hydrology did not meet the hydrophytic vegetation criterion, while one nonhydric soil met the criterion. The presence, depth, and quality of fragipans appeared to influence the expression of hydric conditions through episation, endosaturation, and amphisaturation processes, creating a range of aquic and oxyaquic conditions. These findings emphasize the complexity of seasonally saturated wetland ecosystems and the difficulties in assessing and implementing wetland identification and delineation criteria.

IN RECENT YEARS a new appreciation of the inherent values of wetlands for functions, such as flood control, water storage, and removal of contaminants from water has strengthened interest in their preservation. Since identification and delineation is a necessary step in preservation efforts, regulatory agencies have established protocols for delineation of wetlands (Environmental Laboratory, 1987; USDA-NRCS, 1991, 1996). In the past decade wetland research has evolved in response to difficulties that arose from the process of wetland delineation. The accepted criteria for wetland delineation include the presence of a hydrophytic plant community, hydric soils, and hydrology. The identification of hydrophytic vegetation frequently requires expertise in plant taxonomy. Determination of hydrologic regimes, particularly in seasonal wetlands, often mandates several years of data collection on soil saturation

or water table levels, thus, making it a time-consuming and an expensive task. In the absence of hydrology data or vegetation analysis, delineators have sometimes depended solely on hydric soil criteria to delineate wetlands. The reliance on the presence of hydric soil conditions emphasizes the need for better understanding of the relationships among soil saturation conditions, soil hydromorphic characteristics, and redox conditions. Current technical guidance for jurisdictional wetland delineations (Environmental Laboratory, 1987; Federal Interagency Committee for Wetland Delineation, 1989; USDA-NRCS, 1996; Hurt et al., 1998) relies on meeting the following criteria: (i) evidence of wetland hydrology in most years as documented by water-table monitoring studies or presence of positive wetland hydrology indicators; (ii) presence of a functional hydric soil as documented by a reduction threshold of 200 mV (adjusted for pH 7) for a continuous period constituting >5% of the growing season in the upper part of the soil (approximately 25–30 cm), with corresponding water-table data or presence of positive hydric soil indicators. In the absence of soil temperature and microbial activity documentation this period is assumed to be 14 d, and (iii) presence of dominant hydrophytic vegetation.

In an effort to establish a comprehensive hydric soils database, NRCS in collaboration with academic researchers, has initiated the Wet Soils Monitoring Project to collect data on wet soils throughout the USA (Wakeley et al., 1996). In conjunction with this project, researchers in Louisiana, Mississippi, and South Carolina investigated relationships among hydrology, redox processes, and soil redoximorphic features of forested wetlands (Faulkner and Patrick, 1992; Megonigal et al., 1993). Additional studies in Texas and Louisiana also considered the effects of soil wetness and redox levels on the expression of soil hydromorphic conditions (Griffin et al., 1992; Hudnall and Wilding, 1992; Bell et al., 1995). Megonigal et al. (1996) attempted to clarify the biological conditions necessary for reduction processes to occur within the upper part of the soil by introducing the microbial activity season in place of the growing season. Research on Mollisol hydrosequences in Minnesota also refined the relationships among hydric soil morphology, soil reduction processes, and hydrology in problem soils and seasonally saturated soils (Thompson and Bell, 1998). Other investigations evaluated effect of soil moisture regimes and soil saturation zones on the development and expression of hydromorphic soil conditions (Pickering and Veneman, 1984; Evans and Franzmeier, 1986; Khan and Fenton, 1996). While these studies have

A.D. Karathanasis and Y.L. Thompson, Dep. of Agronomy, University of Kentucky, Lexington, KY 40546-0091; C.D. Barton, Savannah River Ecology Laboratory, Aiken, SC 29802. (Univ. of Kentucky Ag. Exp. Station Publ. #02-06-21). Received 14 Feb. 2002. *Corresponding author (akaratha@uky.edu).

improved considerably our understanding of the relationships between soil saturation patterns and redoximorphic feature expression and led into the development of more consistent delineation criteria, information gaps still exist with regards to long-term assessment and interpretation of the criteria, especially in complex sites, including seasonally saturated wetlands.

The Natural Resources Conservation Service (NRCS) is one of the federal agencies that have responsibility to identify and oversee conservation of wetlands. In western Kentucky, NRCS has preliminarily designated a number of privately owned lands as potential wetlands based on the presence of hydric soil indicators. These areas are intermittent wetlands with water tables present near the surface only during late winter and spring. Because of the seasonal nature of these wetlands and the concern about land use as directed by the National Food Security Act provisions (USDA-NRCS, 1996), many landowners have appealed these wetland determinations. The NRCS is in the process of conducting more intensive surveys of the soils, vegetation, and hydrology of the areas under appeal and in need of long-term monitoring data to justify the wetland determinations. This study has evolved as a result of these efforts and was partially funded by the Wet Soils Monitoring Project (Wakeley et al., 1996). The objective of the study was to establish long-term soil hydrology and redox patterns of representative seasonally saturated "wetlands" in western Kentucky and compare them with currently used jurisdictional wetland delineation criteria in the region.

MATERIALS AND METHODS

Study Area

In 1993, four study sites were established in the Mississippi Embayment physiographic region in southern Calloway and Graves Counties of western Kentucky (Fig. 1). The parent materials are loess typically 1 to 2 m (3 to 6 ft) thick and silty alluvium derived from loess over sandy coastal plain sediments of variable thickness. The sites represent relatively young, low-relief landscapes, where drainage channels have not completely dissected the interstream divides. The selected sites have seasonally high water tables in late winter and early spring. They were cleared and farmed intermittently but not drained before the 1950's. The vegetation community at each of the study sites is bottomland or mixed hardwood forest. Average annual precipitation is about 132 cm, distributed fairly evenly throughout the year, but generally lowest in the period between August and October (Humphrey et al., 1973). The area has a thermic soil temperature regime, so that the soil temperatures at 50 cm are assumed to rarely fall below 5°C. The average high temperatures of 31 to 33°C promote high evapotranspiration rates (60–70% of precipitation) during the summer months. The average length of the growing season based on air temperature data of $>-2.2^{\circ}\text{C}$ is estimated at 225 d.

Five soil series were represented at the sites: Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs), Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs), Henry silt loam (coarse-silty, mixed, active, thermic Typic Fragaqualls), and Waverly silt loam (coarse-silty, mixed, active, acid, thermic Fluvaquentic Endoaquepts) in Calloway County and Routon silt loam (fine-silty,

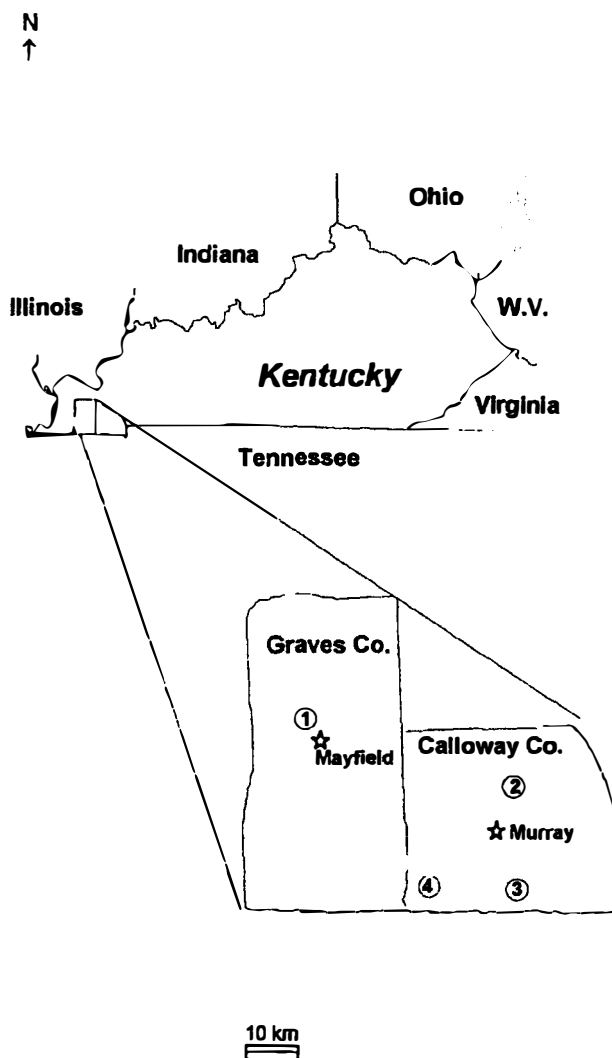


Fig. 1. Location of the sites studied in Graves and Calloway Counties, Kentucky.

mixed, active, thermic Typic Epiaqualls) in Graves County (Soil Survey Staff, 1999). Soil stratigraphic relationships, parent materials, and generalized soil profiles of monitoring station locations at Sites 2 and 4 are shown in Fig. 2 and 3. Although the Grenada soils are not considered hydric, they were included in the study to allow comparisons with other hydric soils in the hydrosequence (USDA-NRCS, 1991). The Routon and Waverly soils have formed in silty alluvium deposits and occupy a low stream terrace and a near level flood plain, respectively (Humphrey et al., 1973).

At Site 1, in Graves County (Fig. 1), a single monitoring station was established on a Routon silt loam soil. The site is located on a level terrace with a 0 to 1% slope gradient, approximately 800 m east of Mayfield Creek with mixed hardwoods as the dominant vegetation. Site 2 encompasses a Grenada-Henry-Waverly hydrosequence in Calloway County, north of Murray, KY (Fig. 1) and approximately 300 m west of the East Fork of Clarks River. The Grenada and Henry soils are situated on a terrace with a 1 to 2% slope gradient, while the Waverly is on an adjacent floodplain with a 0 to 1% slope gradient (Fig. 2). Vegetation consists of mixed hardwoods interspersed among farm fields. Site 3 is located south of Murray, KY in a level area (0–1% slope gradient) of mixed hardwoods

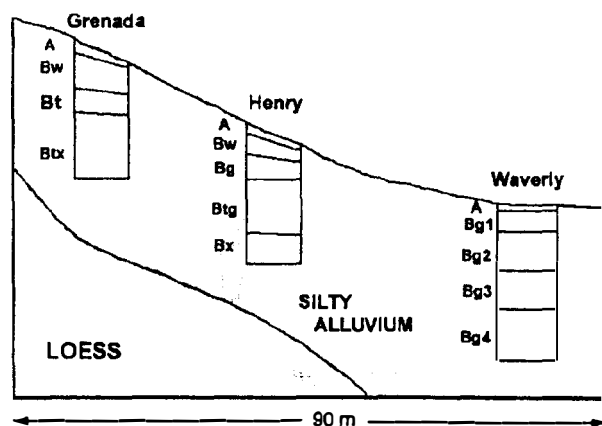


Fig. 2. Hillslope cross-section showing topography, parent materials, and generalized soil profiles of monitoring station locations at Site 2.

between Brushy Creek and East Fork of Clarks River. A single monitoring station was established on a Henry silt loam soil. Site 4 is located southwest of Murray, KY in a nearly level area (0–2% slope gradient) of small headwater tributaries to the Middle Fork of Clarks River (Fig. 3). Much of the site is an upland hardwood forest, but the Henry soil supported bottomland hardwoods.

Field Procedures

At each monitoring station soil pits were excavated, and pedons were described and sampled by horizon (Soil Survey Staff, 1993). Soil samples were sealed in polyethylene bags and saved for physicochemical analyses. Duplicate sets of piezometers, tensiometers, and Pt electrodes were installed at each location to monitor water-table depth, soil matric potential, and redox potential, respectively. Collection of piezometer data for the soils Routon (site 1), Waverly (Site 2), and Henry (Sites 3 and 4) began in September 1993. For the other soils, Grenada and Henry (Site 2) and Grenada and Calloway (Site 4), data collection was initiated in October 1994. Missing data during some summer and fall months indicate that there was no water in the piezometers or the water table was too deep to measure. Collection of redox and matric potential data for all soils commenced in October 1994. The sites were monitored weekly in the spring, biweekly in the summer, and monthly in the fall and winter.

Instrument installation procedures were adapted from Hudnall and Wilding (1992). Water-table depths were determined with piezometers installed at depths of 25, 50, 100, and 150 cm. Piezometers were constructed of 1.9-cm (0.75 in) polyvinyl chloride (PVC) pipe with holes drilled into the bottom and covered with geofabric. The piezometer was placed in an auger hole that was filled with sand followed by soil. The opening was sealed near the surface with packed soil to prevent surface water infiltration. Soil matric potential was determined with jet filled tensiometers at depths of 25, 50, and 100 cm. Tensiometers were filled with water, and then placed into probe holes at the appropriate depths. The holes were sealed with packed soil near the soil surface. Matric potential was measured with a model SW-O10 tensiometer (Soil Measurement Systems, Tucson, AZ). Redox potential was measured with Pt electrodes permanently installed at depths of 25, 50, and 100 cm. The electrode was placed into a hole formed by a thin steel rod. The Pt end was pushed into solid contact with the soil at the desired depth. Packed soil was used to seal the opening at the soil surface. Redox potentials were measured with a

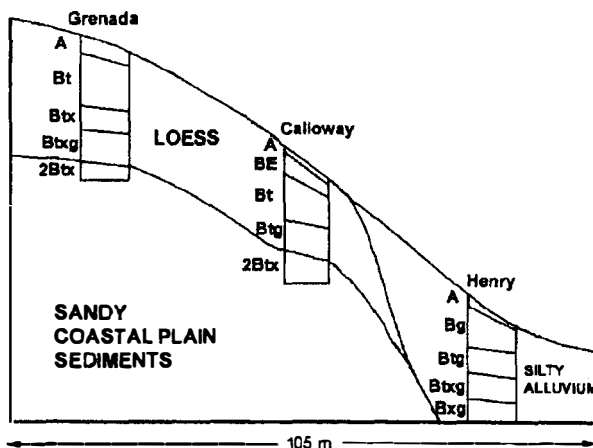


Fig. 3. Hillslope cross-section showing topography, parent materials, and generalized soil profiles of monitoring station locations at Site 4.

Jensen model P5E voltmeter and a Jensen model RC5 saturated calomel electrode (Jensen Instruments, Tacoma, WA). To allow comparisons of redox data among soils with different pH values, E_H measurements were adjusted to represent the E_H value at pH 7 by subtracting 59 mV from the field reading for each unit of decrease in pH below 7. Redox potential readings were considered to represent moderately reduced conditions if below 350 mV, reduced conditions if below 200 mV, and highly reduced conditions if below –100 mV (Szogi and Hudnall, 1992).

Two vegetation transects were run at each site in 1994 and 1995, using procedures adapted from the Corps of Engineers (Environmental Laboratory, 1987; Federal Interagency Committee for Wetland Delineation, 1989). Plant species were identified and quantified along a 67-m (200-ft) transect. The vegetation prevalence index was determined by a computer program. A vegetation index of ≤ 3 indicated that the plant community was dominated by hydrophytic species.

Laboratory Analyses

Physical and chemical properties of samples from each soil horizon were determined by the University of Kentucky Agronomy Department and Soils Testing Laboratory following methods described by the Soil Survey Laboratory Staff (1996). Air-dried sieved samples were analyzed for particle size by the pipette method, pH by 1:1 soil/water suspension, and extractable acidity by BaCl_2 -triethanolamine extraction. Exchangeable bases (Ca, Mg, K, and Na) were extracted by NH_4OAc , pH 7, and analyzed on a Model S-11 AA/AE Instrumentation Laboratory Spectrometer (Thermo Jarrell Ash, Franklin, MA). Organic C was determined by a modified Walkley-Black procedure.

RESULTS AND DISCUSSION

Site Characteristics

Site 1 (Routon)

The original hydrologic regime of Site 1 was altered somewhat in 1994, when a drainage ditch was installed near the site to aid farming of adjacent fields. Although the water table dropped slightly that year, soil saturation conditions within the upper 25 cm were sufficient to meet wetland hydrology criteria in 5 out of 6 yr, in spite of the fact that the mean annual precipitation was below

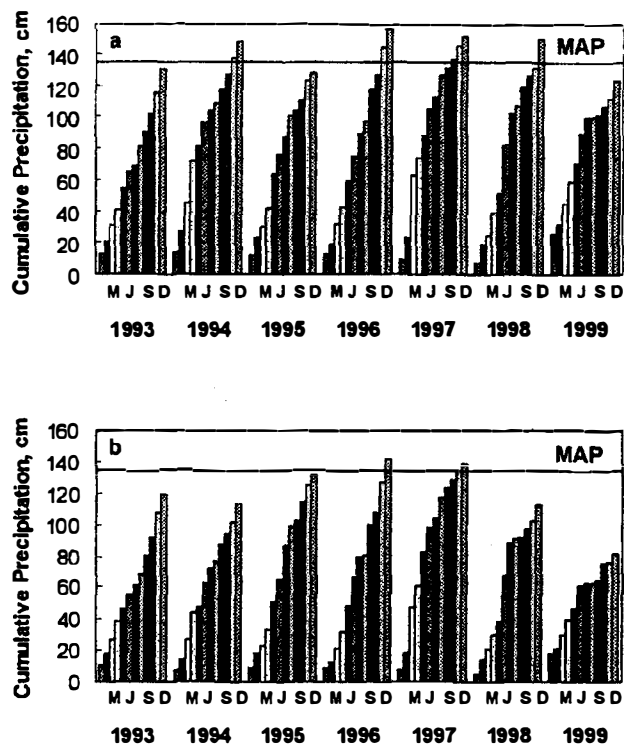


Fig. 4. Cumulative monthly precipitation (1993–1999) and 30-yr mean annual precipitation (MAP) for Calloway (a) and Graves (b) Counties in Kentucky.

normal in 3 out of 6 yr (Fig. 4). The water table reached the surface of this site 4 out of 6 yr (Fig. 5). The consistently lower water-table levels indicated by the 150-cm piezometer throughout the monitoring cycle can be explained by the prevailing episaturation conditions at this site and the presence of a weak fragipan (aquiclude). According to Wakeley et al. (1996) capillary fringes for soils with silt loam textures may cover the range of 20 to 50 cm. In this study soil matric-potential data (Fig. 5) indicated that soil saturation conditions were met within 25 cm from the surface by capillary fringe above the shallow water table for >14 d during the growing season in all years. In spite of the evident wetland hydrology, the Routon soil generally remained oxidized in the upper 25 cm, exhibiting reducing conditions (<200 mV) long enough only in the spring of 1997, one of the wettest years in the monitoring cycle (Fig. 4a), and briefly in the spring of 1999 (Fig. 5). This soil developed moderately reduced conditions (<350 mV) in the upper 25 cm for >14 consecutive days in 3 out of 6 yr (1997, 1998, and 1999). Apparently, the episaturation pattern of the soil allows enough oxygen in the flooding waters to sustain an oxaquic environment and prevent consistent development of anoxic conditions. However, the presence of a reduced matrix with prominent redox concentrations (F3 hydric soil indicator) starting at 10 cm, suggests that this soil historically has consistently experienced Fe-reducing conditions during the growing season (Table 1). It is likely, that the generally dry spell that this site experienced during the course of the study has not allowed the development of reducing conditions consistent with

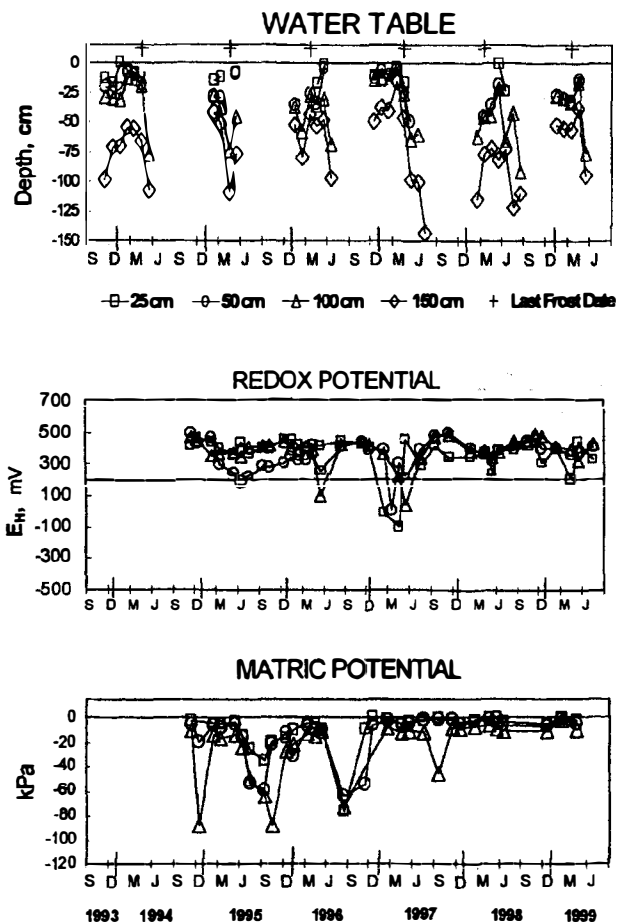


Fig. 5. Water-table fluctuation, redox conditions, and soil matric potential data for the Routon soil at Site 1.

the expression of its hydromorphology (Fig. 4a). Vegetation prevalence indices for this site ranged from 2.80 to 2.98, with red maple (*Acer rubrum*, *trident*), black gum (*Nyssa sylvatica* Marshall), sweet gum (*Liquidambar styraciflua* L.), shagbark hickory [*Carya ovata* (Mill.) K. Koch], winged elm (*Ulmus alata* Michx.), and poison ivy (*Toxicodendron radicans* (L.) Kuntze) being the dominant species. Overall, this site met wetland hydrology and hydrophytic vegetation criteria, and exhibited well-expressed hydric soil indicators, but reduced conditions did not develop consistently in most years of this monitoring cycle to qualify as a functional hydric soil. It is possible, that the opening of the drainage ditch on the adjacent field may have altered the hydrology of the site just enough to prevent sustaining a functional hydric soil.

Site 2 (Grenada–Henry–Waverly Hydrosequence)

Three soils were monitored at this site. The Grenada soil showed a consistent development of a perched water table above the fragipan (approximately 40 cm) during the wettest part of the year in all years, which only sporadically reached the upper 25 cm of the soil (Fig. 6). In spite of the presence of the fragipan, this soil showed saturation throughout its depth in most years during the wettest part of the year, suggesting epi- and endosatura-

Table 1. Soil characteristics and field classification of the sites studied.

Horizon	Depth cm	Matrix color	Redox features		Texture‡	Structure§	pH	OC¶ %
			Concentrations†	Depletions				
(Site 1) Ronton fine-silty, mixed, active thermic Typic Epiaqualfs								
A	0–10	10YR 4/2	—	—	sil	2fgr	4.84	5.12
Bg	10–43	10YR 6/2	m2p, 7.5YR 5/6	—	sil	2f+msbk	4.60	1.04
Btg1	43–84	10YR 6/2	m2p, 7.5YR 5/6	—	sil	2msbk	4.69	0.65
Btg2	84–107	10YR 6/1	m1p, 7.5YR 4/3 c1p, 7.5YR 5/6	— —	sil	2f+msbk	4.76	0.95
Btg3	107–132	10YR 6/1	c2p, 7.5YR 5/6	—	sicd	2msbk	4.63	0.80
Btx	132–173	7.5YR 5/6	—	m3p, 10YR 6/1	sil	1mpr-2mabk	4.89	0.24
(Site 2) Waverly coarse-silty, mixed, active acid, thermic Fluvaquentic Endoaquepts								
A	0–5	10YR 5/3	f1f, 10YR 5/6	f1f, 10YR 7/2	sil	1fgr	4.51	8.17
Bg1	5–25	10YR 5/2	c2d, 10YR 5/6 c2d, 7.5YR 4/4	— —	sil	1fsbk	4.98	1.70
Bg2	25–63	10YR 5/2	c2d, 10YR 5/6 c2d, 7.5YR 4/4	— —	sil	1,2msbk	5.27	1.46
Bg3	63–102	10YR 6/1	c1d, 7.5YR 5/6 c2f, 10YR 5/6	— —	sil	1,2msbk	4.98	0.99
Bg4	102–168	10YR 6/2	c2d, 7.5YR 5/6 c2p, 2.5YR 4/4	— —	sil	1msbk	5.04	0.66
(Site 2) Henry coarse-silty, mixed, active thermic Typic Fraguaqualfs								
A	0–8	10YR 4/3	—	—	sil	1fgr	5.13	3.73
Bw	8–28	10YR 4/3	f1d, 7.5YR 5/6	f1f, 10YR 6/2	sil	1f+msbk	5.38	1.37
Bg	28–53	10YR 6/2	c1d, 7.5YR 5/6 c2d, 7.5YR 4/4	— —	sil	1msbk	5.23	1.22
Btg1	53–97	10YR 6/2	c1, 2d, 7.5YR 5/6 c1, 2d, 7.5YR 4/4	— —	sil	1msbk	5.15	0.86
Btg2	97–114	10YR 5/2	c2p, 7.5YR 4/4 c2d, 10YR 5/6	c2p, 7.5YR 5/2	sicd	1msbk	5.19	0.41
Bx	114–152	7.5YR 4/3	c2, 3p, 7.5YR 5/6	c2, 3p 10YR 5/2	sil	1cpr-2msbk	5.07	0.50
(Site 2) Grenada fine-silty, mixed, active thermic Oxyaquic Fraglossudalfs								
A	0–15	10YR 4/3	—	—	sil	1fgr	5.53	3.33
Bw	15–48	7.5YR 4/4	—	—	sil	2msbk	5.25	1.88
Bi	48–69	10YR 4/4	f1f, 7.5YR 5/6 f1f, 10YR 6/3	f1f, 10YR 6/2	sil	2msbk	5.11	0.20
Btx1	69–122	10YR 4/4	c1d, 7.5YR 5/6	c1d, 10YR 5/2	sil	1cpr-2msbk	4.92	0.18
Btx2	122–152	7.5YR 4/3	c2d, 7.5YR 5/6 c2d, 10YR 5/6	c2d, 10YR 5/2	sil	2cpr	5.06	0.41
(Site 3) Henry coarse-silty, mixed, active thermic Typic Fraguaqualfs								
A	0–7	10YR 4/1	mf, 7.5YR 4/4	—	sil	1gr-msbk	4.79	5.64
Bg1	7–27	10YR 6/1	md, 7.5YR 4/6	—	sil	msbk	4.79	1.12
Bg2	27–43	10YR 6/1	mf, 10YR 6/8	—	sil	sbk	4.7	0.61
Bg3	43–75	10YR 6/1	c, 10YR 7/6	—	sil	sbk	5.12	0.58
Eg/Bxg	75–88	10YR 6/1	mp, 7.5YR 5/6	—	sicd	abk	5.07	0.49
Bxg1	88–120	10YR 6/1	mp, 7.5YR 5/6	—	sicd	abk	5.02	0.51
Bxg2	120–140	10YR 6/1	mp, 7.5YR 5/6	—	sil	abk	4.85	0.58
(Site 4) Henry coarse-silty, mixed, active thermic Typic Fraguaqualfs								
A	0–5	10YR 4/2	—	—	sil	1fgr	4.14	5.19
Bg1	5–36	10YR 6/2	f1p, 5YR 5/8 c2p, 10YR 5/6	— —	sil	2f+msbk	4.28	1.12
Bg2	36–51	10YR 6/1	f1d, 10YR 5/6	—	sil	2f+msbk	4.84	0.51
Btg	51–86	10YR 6/1	f1d, 10YR 5/6	—	sicd/sic	2csbk	4.37	0.27
Btxg	86–124	2.5YR 5/2	c2p, 7.5YR 5/6	—	sil	1cpr-3mabk	4.71	0.23
		2.5YR 6/2	c2p, 10YR 5/6	—	—	—	—	—
Bxg	124–152	10YR 6/2	c1p, 7.5YR 4/3 c1d, 10YR 5/8	— —	sil	1cpr-3mabk	4.73	0.39
(Site 4) Calloway fine-silty, mixed, active thermic Aquic Fraglossudalfs								
A	0–8	10YR 4/2	—	—	sil	1fgr	4.74	2.66
BE	8–30	10YR 5/3	—	—	sil	1f+mgr	4.43	6.25
Bt1	30–56	10YR 5/4	c2f, 10YR 5/6	c2f, 10YR 5/2	sil	2msbk	4.4	0.72
Bt2	56–86	10YR 5/3	c2p, 7.5YR 5/6	m2f, 10YR 6/2	sil	2msbk	4.71	0.48
			—	—	—	—	—	—
Btg	86–127	2.5YR 5/2	f2p, 7.5YR 5/6	cp2, 10YR 6/1	sicd	1csbk	4.72	0.38
		2.5YR 6/2	—	—	—	—	—	—
2Btx	127–165 +	7.5YR 4/4	c2d, 10YR 5/8	—	l	3csbk	4.59	0.36
(Site 4) Grenada fine-silty, mixed, active thermic Oxyaquic Fraglossudalfs								
A	0–18	10YR 4/2	—	—	sil	1fgr	5.04	6.86
Bt1	18–48	7.5YR 4/4	f1f, 10YR 4/3	—	sil	1msbk	5.18	1.07
Bt2	48–81	7.5YR 4/4	f1p, 10YR 6/4	—	sil	2msbk	5.07	0.68
Btx	81–109	7.5YR 4/4	c2d, 10YR 6/4	c2d, 10YR 6/2	sil	1cpr-2msbk	4.98	0.43
		7.5YR 5/6	—	—	—	—	—	—
Btxg	109–152	10YR 5/2	m1p, 7.5YR 5/6	f1f, 10YR 7/1	sil	1cpr-2msbk	4.87	0.41
2Btx	152–165 +	5YR 4/6	c2d, 10YR 5/8	—	l	1cpr	4.89	0.29
		10YR 5/3	—	—	—	—	—	—
		7.5YR 5/6	—	—	—	—	—	—

† Abundance: f, few; c, common; m, many; 1, fine; 2, medium; f, faint; d, distinct; p, prominent.

‡ Texture: silt, silt loam; l, loam; sicl, silty clay loam; sic, silty clay.

§ Structure: 1, weak; 2, moderate; 3, strong; f, fine; m, medium; c, coarse; gr, granular; sbk, subangular blocky; abk, angular blocky; pr, prismatic.

¶ OC, organic content.

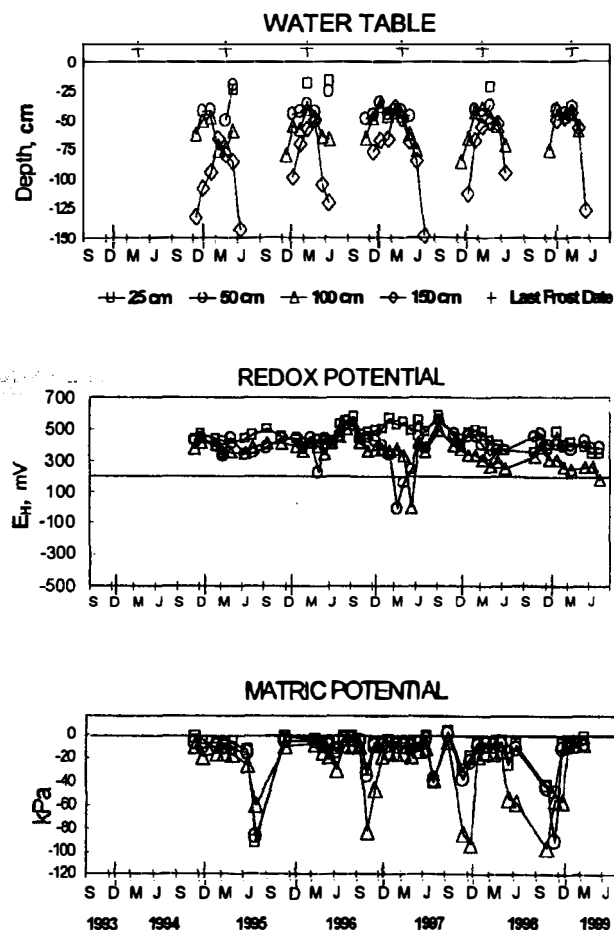


Fig. 6. Water-table fluctuation, redox conditions, and soil matrix potential data for the Grenada soil at Site 2.

tion trends. Matric-potential data suggested only sporadic saturation to the surface, not coinciding with water-table elevation maxima, which were associated with major precipitation events. The summer of 1995 and the fall of 1998 appeared to be the driest periods for the upper 50 cm of the soil, while in the fall of 1996 and 1997 the soil was drier at depth but still maintained some moisture above the aquitard. The upper 25 cm of the soil were maintained well oxidized (>350 mV) throughout the monitoring cycle. Reduced conditions developed only two times at the 50- and 100-cm depths, being more prominent in 1997, one of the wettest years of the study (Fig. 4b). Soil matrix chromas were above three in all horizons, with redox concentrations and depletions being present only below the 48-cm depth (Table 1). Vegetation indices for this site ranged from 2.91 to 2.92, with red maple, American elm (*Ulmus Americana* L.), black oak (*Quercus velutina* Lam.), green ash (*Fraxinus pennsylvanica* Marshall), river birch (*Betula nigra* L.), and trumpet creeper vine [*Campsis radicans* (L.) Seem.ex Burea] as dominant species. Overall, this station met only the hydrophytic vegetation criterion.

The Henry soil had a mean water-table depth of 12 cm. Piezometer data indicated a significantly longer than 14 consecutive days saturation of the upper 25 cm

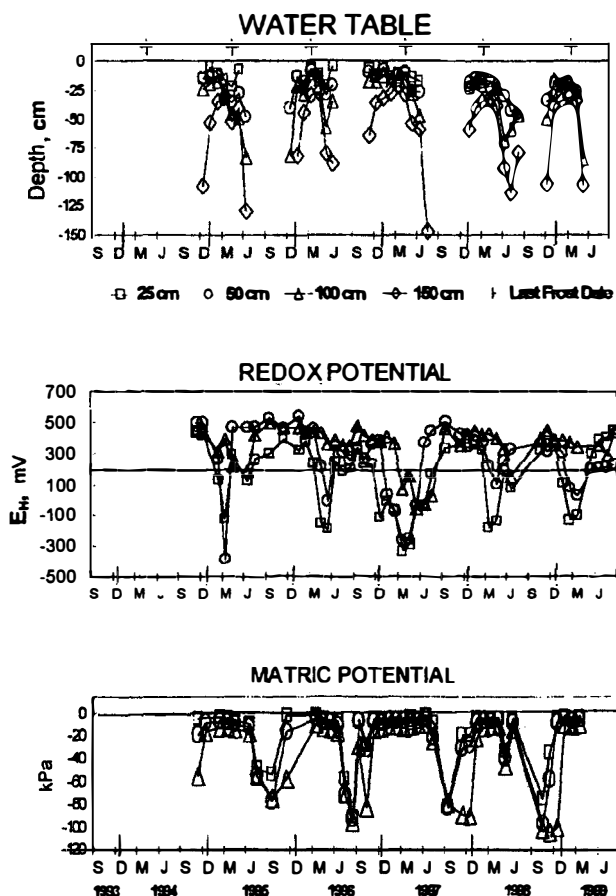
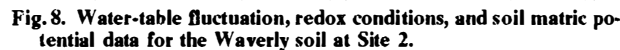


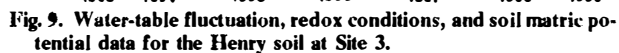
Fig. 7. Water-table fluctuation, redox conditions, and soil matrix potential data for the Henry soil at Site 2.

of the soil in all years (Fig. 7). In spite of the presence of a fragipan at 114 cm, this soil experienced saturation throughout its depth during the wettest periods, suggesting both epi- and endosaturation modes. The soil matrix potential increased with depth at each monitoring date, indicating downwards water movement, but once the soil became wet, the differences in water tension were minimal. Since the matric potential was similar at the 25-, 50-, and 100-cm depths, water flow through the soil must be generally slow. Reducing conditions developed each year, most pronounced at 25 and 50 cm, and lasted long enough (>14 d) during the growing season to sustain a functional hydric soil. Surprisingly, reduced conditions were not as prevalent at the 100-cm depth, suggesting that the water flowing laterally over the fragipan may contain enough dissolved oxygen to prevent sustaining anoxic conditions. The expression of redoximorphic features was consistent with the soil hydrology and redox conditions, with redox depletions starting at 8 cm, reduced matrix at 28 cm, and abundant redox concentrations in most horizons (Table 1). Even though a reduced soil matrix with redox concentrations was encountered at 28 cm in this soil, this depth is within the clear boundary range (25–31 cm) to allow acceptance of the F3 hydric soil indicator. Vegetation indices ranged from 2.85 to 2.92, with the same dominant species as in the Grenada



The Waverly soil was the wettest of this hydrosequence, with a mean water-table depth of 4 cm. This soil had water present at the soil surface from January through a good part of April in all years (Fig. 8). Matric potential data corroborated the piezometer readings, indicating long periods of soil saturation during the growing season. Strong reducing conditions developed throughout the soil profile by mid-winter and persisted until June. Hydric soil indicators were consistent with the soil hydrology and redox conditions, with redox depletions all the way to the surface, and reduced matrix below 5 cm, with abundant redox concentrations (F3) throughout the soil (Table 1). Vegetation indices ranged from 2.80 to 2.89, with the same dominant species as in the other two stations. Overall, this station met all wetland criteria.

Site 3 consisted of a single monitoring station on a Henry soil. Except for 1998 and 1999, this soil had water present at or very near the surface for extensive time periods (Fig. 9). During wet periods, water-table levels at the 25- and 50-cm piezometers were at about the same level, while at the 100-cm piezometers the water level stayed considerably deeper, indicating the presence of



an aquitard. This aquitard was morphologically identified as a weak fragipan or fragic horizon with some brittle properties between 75 and 88 cm, which causes the development of a perched water table during the winter and spring months each year (Table 1). The clearly epiaquic hydrology of this site is deduced from the much longer period during which the 25- and 50-cm piezometers contained water, even into the dry months, compared with the 100-cm piezometers. Matric-potential data were consistent with the piezometer measurements, suggesting soil saturation all the way to the surface in all years through the end of April and sometimes into early May. The data also confirmed the presence of an aquitard below 50 cm. Strong reducing conditions (< -100 mV) developed in the upper 50 cm and persisted for >14 consecutive days in the growing season, sometimes until June, except during the 1999 drought. In 1996 and 1997, strong reducing conditions were attained as early as November (Fig. 9), following higher than usual precipitation levels (Fig. 4b). Soil redoximorphic features included matrix chroma values of 1 and abundant redox concentrations in all horizons starting at the surface (F3) (Table 1). Vegetation prevalence indices at this site ranged from 2.57 to 2.58, with red maple, sweet gum, black oak, pin oak (*Quercus palustris* Munchh.), and honeysuckle

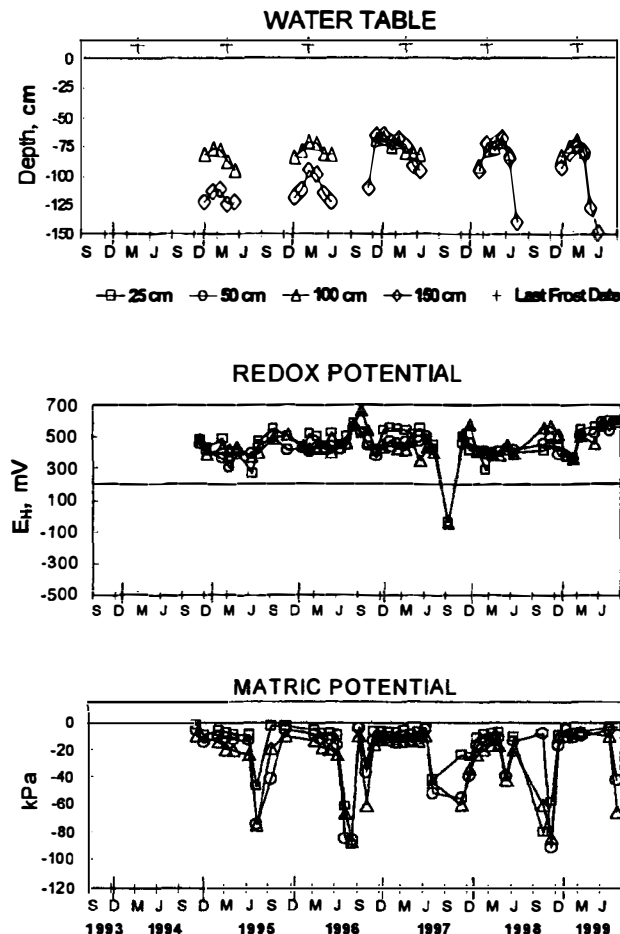


Fig. 10. Water-table fluctuation, redox conditions, and soil matrix potential data for the Grenada soil at Site 4.

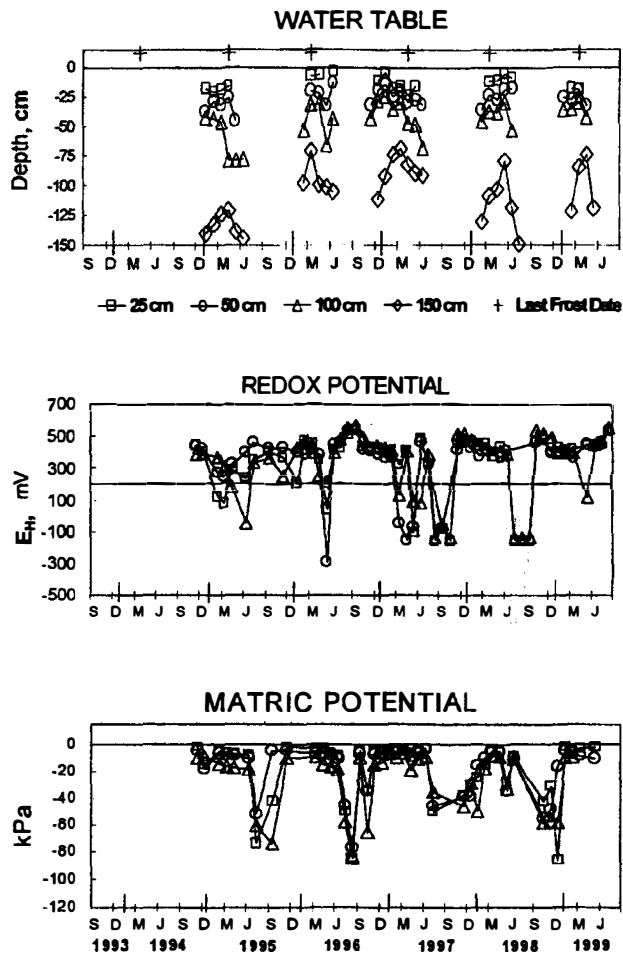


Fig. 11. Water-table fluctuation, redox conditions, and soil matrix potential data for the Calloway soil at Site 4.

(*Lonicera japonica* Thunb.) as the dominant species. Overall, this site met all wetland criteria.

Site 4 (Grenada–Calloway–Henry Hydrosequence)

Three soils were monitored in this hydrosequence. Grenada was one of the driest soils encountered in the study. Water appeared in the piezometers only at depths >60 cm during the wet months of each year (Fig. 10). In 1994 and 1995 the piezometric head was higher in the 100-cm than in the 150-cm piezometer, apparently as a result of the aquitard (fragipan) presence at 81 cm. In subsequent years, the piezometric heads at 100 and 150 cm were the same, suggesting both, epi- and endo-saturation hydrology trends. However, the presence of free water in the 100-cm piezometer while the respective tensiometer registered appreciable tension may also indicate possible by-pass flow. On most of the monitoring dates, the matric potential increased with the depth indicating a wetting front from the surface downward. Maximum drying occurred within a 2-wk period at each tensiometer depth. Lower tensiometer readings near the surface than at lower depths during summer periods are attributed to rain showers that did not penetrate very deep. Redox-potential data indicated that this soil was well oxidized throughout the monitoring cycle, except for

a brief period in the summer of 1997, following intense rainfall activity (Fig. 4b). No hydric soil indicators were present. Redox concentrations were found in most horizons, but redox depletions were first observed at 81 cm and a reduced matrix at 109 cm (Table 1). Vegetation prevalence indices ranged from 3.71 to 3.73, with white oak (*Quercus alba*), shagbark hickory, slippery elm (*Ulmus rubra*), post oak (*Quercus stellata*), white ash (*Fraxinus americana*), and poison ivy as the dominant species. This soil did not meet any wetland criteria.

The Calloway soil at this site displayed transitional features between wet and dry conditions. The water table was present in the upper 25 cm early in the growing season and lasted >14 consecutive days in most years (Fig. 11). The consistent separation in the water-table data between the piezometers at 150 cm and those at shallower depths confirmed the presence of an aquitard between a 100 and 150 cm. During wet periods the piezometric head decreased with depth indicating a downward wetting front in the upper 100 cm of the soil. However, the presence of water in the 100-cm piezometer while the 100-cm tensiometer showed tension, suggests some by-pass flow. Soil matrix-potential data corroborated the piezometer observations, suggesting that dry-

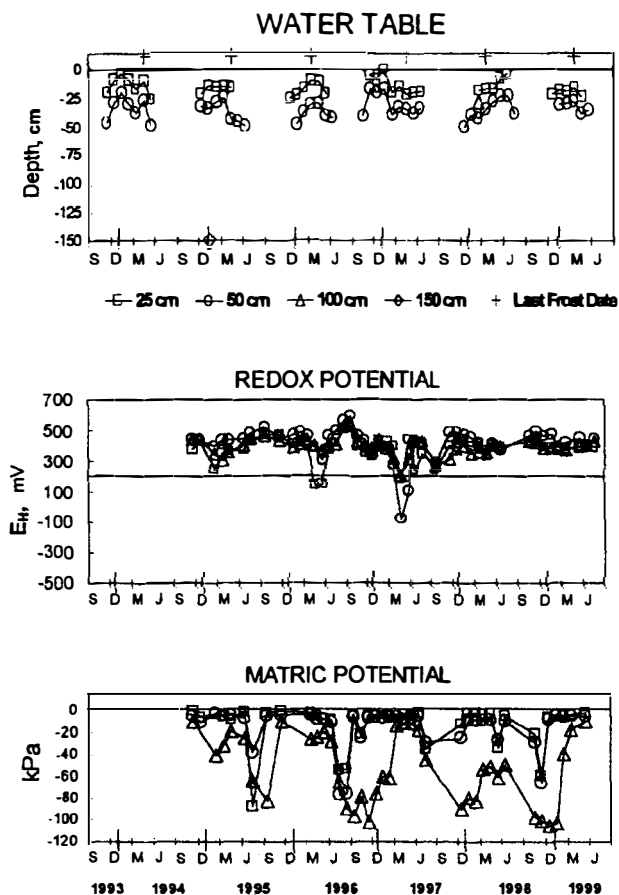


Fig. 12. Water-table fluctuation, redox conditions, and soil matrix potential data for the Henry soil at Site 4.

ing in early spring occurred within 2 to 4 wk. Redox levels at this site indicated considerable fluctuation, but development of reduced conditions for brief periods of early spring in 1995, 1996, and 1997 was consistent. The low redox values observed in late spring or summer months of 1997 and 1998 are probably because of the excessive rainfall received during those periods in the above years (Fig. 4b). Soil redoximorphic features, including redox depletions starting at 30 cm, reduced matrix at 86 cm, and redox concentrations at 30 cm did not meet hydric soil indicators (Table 1). Vegetation prevalence indices ranged from 2.95 to 3.31, with white oak, slippery elm, shagbark hickory, poison ivy, and trumpet creeper vine as the dominant species. Overall, this station met only wetland hydrology criteria.

The Henry soil was the wettest of the three soils at this site, with a mean water-table depth of 14 cm (Fig. 12). The water table reached the surface for brief periods in the winter of 1993 and 1997, and the spring of 1998. Criteria for soil saturation at the surface were easily met by capillary fringe (Wakeley et al., 1996) and corroborated by matrix potential data. The consistent lack of water at the 100- and 150-cm piezometers suggests a dominantly episaturation hydrology for this soil, with an aquitard present at the fragipan depth (86 cm). In spite of the wet hydrology of the site, redox levels were

generally above 200 mV in most years. Reduced conditions developed long enough during the spring of 1996 and 1997, two of the wettest years in the monitoring cycle (Fig. 4b), to meet the growing season requirement of a functional hydric soil. Apparently, under normal rainfall conditions the water flowing above the aquitard has enough dissolved oxygen or is replenished at a rate that is able to sustain only moderately reduced conditions. Hydric soil indicators were present in the form of a reduced matrix with redox concentrations starting at 5 cm (F3) (Table 1). The development of well-expressed redoximorphic features under moderately reduced conditions poses some questions as to the validity of the 200 mV Fe-reduction threshold at this site. Vegetation prevalence indices ranged from 2.83 to 2.97, with white oak, slippery elm, black oak, green ash, shagbark hickory, poison ivy, and trumpet creeper vine as the dominant species. Overall, this station met wetland hydrology and hydrophytic vegetation criteria, but not the redox requirements for a functional hydric soil.

Wetland Criteria

Hydrology

In all six soils exhibiting wetland hydrology, the highest water-table levels were reached during the winter and were maintained within 25 cm from the surface until the early spring months. The wetter the site, the earlier the water table reached the upper 25 cm of the soil in the winter and the later subsided in the spring. The average number of consecutive days in which the piezometric surface was within the upper 25 cm of the soil decreased in the following sequence: Waverly (Site 2) (114) > Henry (Site 3) (98) > Henry (Site 4) (76) > Henry (Site 2) (57) > Routon (Site 1) (41) > Calloway (Site 4) (29). The hydrosequence on Site 2 generally exhibited higher water tables and of longer duration than the hydrosequence on Site 4, most likely because of the lower landscape position. The largest water-table fluctuations between years were observed in the Calloway and Routon soils, which were the driest of this sequence. Similar trends have been reported by Reuter and Bell (2001) for a sandy hydrosequence in east-central Minnesota. Both of these soils also had the deepest aquitards, in the form of weak fragipans, starting at 127 and 132 cm, respectively, thus forming perched water tables at greater depths than the rest of the soils. The effect of the aquitard depth on soil saturation length and frequency is evident when comparing the three Henry stations, which show increasing prominence of wetland hydrology with proximity of the fragipan to the surface. The episaturation hydrology imposed in these three soils by the presence of the fragipans is more evident at the two Henry stations with fragipans above 100 cm (Site 3 and 4), which show clear separation in the hydrology patterns. The percentage of time during the monitoring period that these two soils were saturated in the upper 50 cm compared with >100-cm depths were 52 vs. 19%, and 36 vs. 1%, for Sites 3 and 4, respectively.

Generally, the tensiometer data were in agreement

Table 2. Summary of wetland criteria information for the sites studied.

Site	Soil	Piezometric surface within 25 cm	Soil saturation based on matric potential	Redox potential within 25 cm		Hydrophytic vegetation index	Hydric soil indicators
				< 200	< 350		
1	Routon	4/6†	5/5	1/5	3/5	<3.0	F3
2	Grenada	1/5	0/5	0/5	1/5	<3.0	-
	Henry	5/5	5/5	5/5	5/5	<3.0	F3
	Waverly	6/6	5/5	5/5	5/5	<3.0	F3
3	Henry	6/5	5/5	5/5	5/5	<3.0	F3
4	Grenada	0/5	1/5	0/5	0/5	>3.0	-
	Calloway	4/5	5/5	3/5	5/5	>3.0	-
	Henry	6/6	5/5	2/5	5/5	<3.0	F3

† 4/6 = met criteria 4 out of 6 yr.

with the piezometer readings with respect to soil saturation occurrences within the upper 25-cm soil zone. However, these saturation periods appeared to be of longer duration when assessed by tensiometers and in some of the wettest soils lasted 2 to 3 wk longer than the piezometric surface indicated (Table 2). Similar observations were made by Thompson and Bell (1998) in lower landscape positions of a Mollisol catena in Minnesota, and attributed to the presence of saturated conditions above the water table that cannot be measured by the piezometers, but may be detected by the tensiometers as near 0 positive or negative matric potential. Similar readings occurring sporadically during dry periods probably reflect direct rainfall events and should be distinguished from true water table elevations. Therefore, the findings of this study suggest that matric potential data are more sensitive in assessing the duration of wetland hydrology cycles than piezometers.

Hydric Soil and Reduced Conditions

Hydric soil characteristics develop as a result of saturation with water for periods long enough and at a time conducive to establishment of anaerobic conditions. This time should coincide with biological activity within the soil, because reducing conditions develop as result of O₂ depletion by microbial respiration. Typically, microbial activity occurs during the growing season, when soil temperatures are maintained >5°C. Therefore, the development of reducing conditions within the soil may not coincide with the development of water saturated conditions. As it is evident in the wettest soils in this study (Fig. 7 and 8), reducing conditions did not develop until 3 to 4 wk after the soil in the upper 25 cm reached saturation and they lasted through June and at times early July. However, redox thresholds of 200 mV were reached before the estimated start of the growing season based on air-temperature data and peaked after March. This indicates that reduced microbial activity could exist in these soils even during the colder winter months, which is consistent with the thermic temperature regime of the area. The Waverly soil (Site 2) exhibited redox readings <200 mV in the upper 25 cm in November of 1996, in January of 1998, and in December of 1999 (Fig. 8). Reduced conditions in the Henry soil of Site 2 developed in December of 1996, and in January of 1999 (Fig. 7). At Site 3, the Henry soil developed reduced conditions in November of 1996 and 1998 (Fig. 9). These

findings are consistent with observations of a year-round microbial activity in soils of the southern region of the US (Meronigal et al., 1996), and with reports of moderate biological activity and development of reducing conditions even during the winter months in some soils of Massachusetts (Pickering and Veneman, 1984).

Since the reduced conditions in the upper 25 cm of the wettest soils were sustained for longer periods than those supported by piezometric observations, there was a better correlation with matric potential than piezometer data. The average number of consecutive days with reducing conditions (<200 mV) at 25 cm below the surface in the wettest soils followed the sequence: Waverly (Site 2) (75) > Henry (Site 3) (48) > Henry (Site 2) (39). Although only these three among six soils with wetland hydrology met the functional hydric soil definition in most years, the other three did show development of moderately reduced conditions in early spring (<350mV) in most years (Table 2). Since the pH of these soils is much lower than 7 (4.1 to 5.4, Table 1), anaerobic and Fe-reducing conditions may develop at <400mV redox levels (McBride, 1994). This is corroborated by the presence of well-expressed redoximorphic features, in the form of reduced matrix and redox concentrations, in the upper 10 cm of the Henry (Site 4) and Routon (Site 1) soils and in the form of redox depletions and concentrations in the upper 30 cm of the Calloway (Site 4) soil. The Calloway soil was the only one of the six with wetland hydrology that failed the F3 hydric soil indicator, even though it did have brief periods in most years during which redox levels dropped <200 mV. Overall, the expression of the hydric soil indicators in the sites studied was more consistent with hydrology patterns and soil saturation data than the <200 mV redox threshold of a functional hydric soil (Table 2). However, the location of redoximorphic features, especially that of reduced matrix, in reference to the mean water-table level was variable (Veneman et al., 1998; West et al., 1998). In most soils, reduced matrix started either slightly above (10–15 cm) or at about the same depth with the mean water table during the wet period of the year. However, in the Henry (Site 2) and the Calloway (Site 4) soils, the location of reduced matrix was 10 to 45 cm below the mean water table. This indicates that the expression of redox features in these two pedons reflects a normally lower water table. The deeper aquitard depth in these soils may contribute to this different

pattern, but discrepancies, even among soils within the same hydrosquence, may also suggest active changes in the regional water table, as a result of land use and management changes in the surrounding areas. Therefore, the relationship between the time of the season at which reduced conditions develop and the threshold at which Fe-reduction occurs in different soils needs further clarification.

Hydrophytic Vegetation

Six of the eight soils studied had dominant hydrophytic vegetation, as documented by <3.00 vegetation prevalence index (Table 2). Five of the six soils with wetland hydrology and one nonhydric soil (Grenada, Site 2) met the hydrophytic vegetation criterion. In spite of an apparent high water table until the early part of the growing season, and the development of moderately reduced conditions, the Calloway soil (Site 4) had an average vegetation prevalence index of 3.13. The relatively wide range (2.95–3.31) in the prevalence index for the two transects run at this station suggests considerable variability in the hydrology of the site. Indeed, a survey of hydric soil indicators within the transect boundaries indicated a substantial range in the starting depth and expression of redoximorphic features. Generally there was a good correlation between vegetation prevalence index and soil hydrology. However, the lowest vegetation prevalence index (Henry, Site 3) was not associated with the wettest soil (Waverly, Site 2). Most sites had vegetation prevalence indices just below three, emphasizing their borderline wetland status and their strong dependency on seasonal hydrological conditions.

Because the vegetation in the studied sites is dominated by woody species of 20 to 80 yr old, this criterion may not be the most sensitive in reflecting 5- to 10-yr term changes in the hydrology of a site, but mostly the hydrological history of a site. This is more evident in the relatively uniform Site 2, occupying a low-level stream terrace–floodplain hydrosquence, in which the dominant species remained the same throughout the landscape, with minor changes in the vegetation prevalence index (2.80–2.92). The fact that this site involved one of the driest soils (Grenada) in the study supports the earlier claim for active changes in the regional hydrology of the area associated with shifts in land use and management practices. This is also a good site to demonstrate the greater sensitivity of the vegetation prevalence index over the 50/20 method for documenting the presence of the hydrophytic vegetation criterion. For the same dominant species in all three sites the vegetation prevalence index averaged 2.92 for the driest (Grenada), 2.89 for the intermediate (Henry), and 2.85 for the wettest (Waverly). Even though the final interpretation would be the same by the two methods on this site, it could have been different on another site.

CONCLUSIONS

All of the six soils monitored in this study that are included in the hydric soils list showed consistent hydrology patterns lasting at least 14 consecutive days into the

growing season in most years. The frequency and duration of soil saturation within 25 cm of the surface was affected by the amount of rainfall, but generally it was greater in soils of lower landscape positions or soils with shallow aquitards. Tensiometer readings were generally consistent with piezometer data, but suggested even longer duration of soil saturation in the upper 25 cm, thus making them more sensitive sensors for hydrology assessments. Redox potential measurements were also consistent with the hydrology trends, indicating development of moderately reduced conditions (<350 mV) for at least 14 d into the growing season in most years in all six hydric soils. However, only three of these soils developed reduced conditions (<200 mV) long enough to meet the functional hydric soil criteria. Based on the low pH of the soils (<5.2), it is anticipated that the 350 mV threshold is adequate for Fe-reduction. This is corroborated by the clear expression of F3 hydric soil indicators in five of the six soils. The investigation also provided additional evidence for development of reducing conditions during the winter season, suggesting microbial activity within the upper 25 cm, in some cases as early as 1 to 2 mo before the theoretical start of the growing season. The development and location of redoximorphic features was generally consistent with mean water-table fluctuations, as affected by epi-, endo-, and amphi-saturation patterns. However, in some soils the expression of redox features may reflect historical rather than current hydrology, because of regional water-table changes caused by shifts in land use and management of the area. Five of the six hydric soils met the hydrophytic vegetation criterion, making the vegetation criterion consistent with the wetland hydrology and the hydric soil conditions of the sites. However, the mature woody nature of the dominant plant communities may reflect the past hydrological history of the sites rather than being a sensitive indicator of current hydrology patterns. The findings of this study clearly demonstrate the importance of long-term hydrology and redox assessments for better understanding the dynamic processes driving seasonal wetlands and for more concise implementation of wetland identification and delineation criteria.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of the NRCS soil scientists S. Sykes, J. McIntosh, R. Toor, and R. Forsythe in site selection, and data collection in the field during the course of this study; the private land-owners for allowing access to their property; and the National Soil Survey Laboratory for providing funding for the purchase of the monitoring instruments.

REFERENCES

- Bell, J.C., J.A. Thompson, and C.A. Butler. 1995. Morphological indicators of seasonally-saturated soils for a hydrosquence in south-eastern Minnesota. *J. Minnesota Acad. Sci.* 59(4):25–35.
- Environmental Laboratory. 1987. Corps of Engineers Wetlands Delineation Manual. Tech. Rep. Y-87-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Evans, C.V., and D.P. Franzmeier. 1986. Saturation, aeration, and

- soil color patterns in a toposequence of soils in north-central Indiana. *Soil Sci. Soc. Am. J.* 50:975-980.
- Faulkner, S.P., and W.H. Patrick, Jr. 1992. Redox processes and diagnostic wetland soil indicators in bottomland hardwood forests. *Soil Sci. Soc. Am. J.* 56:856-865.
- Federal Interagency Committee for Wetland Delineation. 1989. Federal Manual for Identifying and Delineating Jurisdictional Wetlands. U.S. Army Corps of Engineers, USEPA, U.S. Fish and Wildlife Service, and USDA-SCS, Washington, DC.
- Griffin, R.W., L.P. Wilding, and L.R. Drees. 1992. Relating morphological properties to wetness conditions in the Gulf Coast prairie of Texas. p. 126-134. *In* J.M. Kimble (ed.) Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, classification, and utilization of wet soils. October 1990. Lincoln, NE. USDA-SCS, National Soil Survey Center, Lincoln, NE.
- Hudnall, W.H., and L.P. Wilding. 1992. Monitoring soil wetness conditions in Louisiana and Texas. p. 135-147. *In* J.M. Kimble (ed.) Proceedings of the eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, classification, and utilization of wet soils. October 1990. USDA-SCS, National Soil Survey Center, Lincoln, NE.
- Humphrey, M.E., F.L. Anderson, R.A. Hayes, and J.D. Sims. 1973. Soil Survey of Calloway and Marshall Counties, Kentucky. USDA-SCS. U.S. Gov. Print. Office, Washington, DC.
- Hurt, G.W., P.M. Whited, and R.F. Pringle (ed.) 1998. Field indicators of hydric soils in the United States. A guide for identifying and delineating hydric soils (version 4.0), prepared in cooperation with the National Technical Committee for Hydric Soils. USDA-NRCS, Fort Worth, TX.
- Khan, F.A., and T.E. Fenton. 1996. Secondary iron and manganese distributions and Aquic conditions in a Mollisol catena of central Iowa. *Soil Sci. Soc. Am. J.* 60:546-551.
- McBride, M.B. 1994. Environmental chemistry of soils. Oxford Univ. Press, New York.
- Megonigal, J.P., S.P. Faulkner, and W.H. Patrick, Jr. 1996. The microbial activity season in southeastern hydric soils. *Soil Sci. Soc. Am. J.* 60:1263-1266.
- Megonigal, J.P., W.H. Patrick, Jr., and S.P. Faulkner. 1993. Wetland identification in seasonally flooded forest soils: Soil morphology and redox dynamics. *Soil Sci. Soc. Am. J.* 57:140-149.
- Pickering, E.W., and P.L.M. Veneman. 1984. Moisture regimes and morphological characteristics in a hydrosequence in central Massachusetts. *Soil Sci. Soc. Am. J.* 48:113-118.
- Reuter, R.J., and J.C. Bell. 2001. Soils and hydrology of a wet-sandy catena in East-Central Minnesota. *Soil Sci. Soc. Am. J.* 65:1559-1569.
- Soil Survey Staff. 1993. Soil survey manual. USDA-SCS Agric. Handb. 18. U.S. Gov. Print. Office, Washington, DC.
- Soil Survey Laboratory Staff. 1996. Soil survey laboratory methods manual. Soil Surv. Inv. Rep. 42. Version 3.0. Natl. Soil Surv. Center. Lincoln, NE.
- Soil Survey Staff. 1999. Soil Taxonomy. USDA-NRCS. U.S. Gov. Print. Office, Washington, DC.
- Szogi, A.A., and W.H. Hudnall. 1992. Classification of soils in Louisiana according to endoaquic and "epiaquic" concepts. p. 271-278. *In* J.M. Kimble (ed.) Proceedings of the eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, classification, and utilization of wet soils. October 1990. Lincoln, NE. USDA-SCS, National Soil Survey Center, Lincoln, NE.
- Thompson, J.A., and J.C. Bell. 1998. Hydric conditions and hydromorphic properties within a Mollisol catena in southeastern Minnesota. *Soil Sci. Soc. Am. J.* 62:1116-1125.
- USDA-NRCS. 1996. National Food Security Act Manual, 3rd ed. USDA, Washington, DC.
- USDA-NRCS. 1991. National list of hydric soils. USDA in cooperation with the National Technical Committee for hydric soils, Washington, DC.
- Veneman, P.L.M., L.A. Spokas, and D.L. Lindbo. 1998. Soil moisture and redoximorphic features: A historical perspective. p. 1-23. *In* M.C. Rabenhorst et al. (ed.) Quantifying soil hydromorphology. SSSA Spec. Publ. 54. SSSA, Madison, WI.
- Wakeley, J.S., S.W. Sprecher, and W.C. Lynn (ed.) 1996. Preliminary investigations of hydric soil hydrology and morphology in the United States. Tech. Rep. WRP-DE-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- West, L.T., J.N. Shaw, E.R. Blood, and L.K. Kirkman. 1998. Correlation of water tables to redoximorphic features in the Dougherty Plain, southwest Georgia. p. 247-258. *In* M.C. Rabenhorst et al. (ed.) Quantifying soil hydromorphology. SSSA Spec. Publ. 54, SSSA, Madison, WI.