DIVISION S-10—WETLAND SOILS

Soil Hydrology on an End Moraine and a Dissected Till Plain in West-Central Indiana

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ABSTRACT

Soil hydrologic properties are a function of precipitation (P)-evapotranspiration relations, stratigraphy, and geomorphology. An understanding of soil hydrology helps us predict many soil and ecosystem properties. We studied soil hydrology on an end moraine and on a dissected till plain in west-central Indiana. We measured hydraulic head, water table level, redox potential (E_H), and temperature, with piezometers (0.25-, 0.50-, 1.0-, 2.0-, 4.5-m depth), observation wells, platinum electrodes (0.25-, 0.50-, and 1.0-m), and thermocouples (0.25-, 0.50-, 1.0-, and 2.0-m), respectively, in soils along two soil toposequences for 9 yr. Water table levels drop rapidly when hardwood trees first leaf out in the spring, and rise rapidly after the trees go dormant in the fall. The Thornthwaite model underestimates evapotranspiration in the forest in the spring. In the dissected plain underlain with dense till, water is held up by the slowly permeable till. Water moves from the interior of the till plain to the dissected bevel where it periodically rises within 1 m of the surface but does not cause redoximorphic features. Soils on the crest of a moraine are similar in morphology to those on the till plain bevel, but have essentially no high water table because there is no upslope contributing area to serve as a water source. In the wetter soils, reduction begins when a soil horizon becomes wet but not saturated, and proceeds more rapidly when the horizon is saturated. There is a lag period of 2 to 8 wk between initial saturation of the soil at 25 cm and minimum E_H.

Hydrology is the science of the behavior of water in the atmosphere, on the earth's surface, and underground (Leopold, 1974). Soil hydrology emphasizes these relations in soils and landscapes. Soil hydrology is primarily a function of three factors: the relation between precipitation and evapotranspiration, stratigraphy, and geomorphology. Stratigraphy deals with layers of geologic materials and how they are affected by soil-forming processes. Geomorphology is the study of land surfaces in space and time.

An understanding of soil hydrology helps us predict where wet soils occur in the landscape, how water and dissolved nutrients move through soils and landscapes into aquifers and streams, and how water and sediment move on soil surfaces. Additionally, knowledge of soil hydrology is essential for identifying and preserving wetlands and draining soils for agricultural production. This understanding is important in deciding how to manage soil and water resources for agriculture and environmental uses.

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Published in Soil Sci. Soc. Am. J. 66:1367–1376 (2002).

Little is known about the relation of soil hydrology and the balance of precipitation and evapotranspiration in Indiana. Most of the knowledge is general and broad in scale. Newman (1981) estimated potential evapotranspiration (PE) to be 700 mm. Clark (1980) estimated that of the 965-mm average precipitation in Indiana, 660 mm (68%) leaves as actual evapotranspiration (AE), 215 to 230 mm (22–24%) leaves as surface runoff, and 75 to 90 mm (8–9%) recharges the groundwater. Much of this groundwater moves into streams, rivers, and lakes as seepage and underflow. Carr et al. (1987) estimated P to be 1006 mm, and AE to be 684 mm, also 68%, and Hanson (1991) estimated AE at 635 to 762 mm.

Stratigraphy and geomorphology are discussed together because they are so closely related. A few studies have dealt with the relation of soil hydrology to stratigraphy and geomorphology on Wisconsinan-age till plains [Thorp and Gamble (1972), Wayne Co., IN, 1954 to 1960; Evans and Franzmeier (1986), Tippecanoe County, IN, 1980 to 1983]. These studies are less comprehensive and of shorter duration than the one reported here.

Soils formed in silty or loamy materials over dense till of Wisconsinan age are common in Indiana and other parts of the Midwest. Their hydrology is of special interest because the till has high bulk density and low saturated hydraulic conductivity (K_{sat}) (Thorp and Gamble, 1972; Harlan and Franzmeier, 1974; King and Franzmeier, 1981; Franzmeier et al., 1987), which perches water in soil horizons in and above the till. Soils on Wisconsinan till occur in two distinct landscapes of late Wisconsinan age, moraines and till plains. On rolling moraines, better-drained soils are generally in high landscape positions and more poorly drained soils are lower in the landscape. In till plains, however, the wetter soils are on the large gently undulating plain and better drained soils are on the bevel that cut the plain, so the more poorly drained soils are higher in the landscape.

The objectives of this study are to (i) relate soil hydrology to precipitaion-evapotranspiration relations, (ii) relate soil hydrology to stratigraphy and geomorphology and (iii) to determine how soil hydrology affects soil redox properties and vegetation.

Abbreviations: AE, actual evapotranspiration; E_H, reduction-oxidation (redox) potential; K_{sat}, saturated hydraulic conductivity; P, precipitation; PE, potential evapotranspiration; PVC, polyvinyl Cl.

MATERIALS AND METHODS

Soils and Landscapes

Two toposequence transects were laid out in Parke County, IN (Fig. 1). Moore's Woods, a privately owned woodlot, is on a till plain, and Shades State Park is on a moraine. The two are separated from each other by Sugar Creek which is deeply incised into the underlying sandstone bedrock of the Mansfield Formation. There is no evidence of subsurface drainage at either site.

Moore's Woods is on a dissected till plain capped with loess. Till was deposited about 20 000 yr ago, and soon after, >1 m of loess was deposited on top of the till (Wayne, 1966). We selected four major sites at which we sampled soils and installed major sets of instruments. Delmar (fine silty, mixed, superactive, mesic Typic Endoqualf) (light surface) and Ragsdale (fine smectitic, superactive, mesic Typic Argiaquoll) (dark surface) are poorly drained soils that occur in depressions on the till plain. Fincastle (fine silty, mixed, active, mesic Aeric Hapludalf), somewhat poorly drained, is on the side of a swell, and Russell-T (T for till plain) (fine silty, mixed, active, mesic Oxyaquic Hapludalf) well drained, is on the upper backslope of the bevel, a hillslope that descends from the till plain. The well drained Russell soil is at a lower elevation than the associated more poorly drained soils. The morphology and classification of these four soils are summarized in Table 1. Additional hydrologic measurements were made between some of the sites. These data are not reported, but are considered in the discussion.

The Shades State Park site is on a small end moraine segment capped with loess (Fig. 1). Two major sites were sampled and instrumented. The Russell-M (M, moraine) soil (fine silty, mixed, active, mesic Typic Hapludalf) is on the crest of the moraine, and Washtenaw (fine silty, mixed, superactive, mesic Typic Endoaqualf), poorly drained, is in a nearby depression. Well-drained Russell-M is at a higher elevation than the associated wetter soil. Soils of intermediate drainage are in narrow bands between the two sites. These soils were not sampled; however, some hydrologic measurements were made. The soil sites are named according to the published soil survey for Parke County (Ulrich, 1967).

Soil Characterization and Classification

The soils from all six sites were characterized by the National Soil Survey Laboratory. The classification given in Table 1 is for the pedon sampled (Soil Survey Staff, 1999). Bulk density was measured by the Saran-coated clod method, and pH was measured in water in the laboratory (Soil Survey Staff, 1996).

Soil Hydrology and Related Measurements

Potential evapotranspiration was calculated according to Thornthwaite (1948). Instrumentation at each site followed the protocol established for NRCS Wet Soil Monitoring sites (Hudnall et al., 1990). We took measurements approximately every 2 wk for 9 yr, 1992 through 2000.

Observation Wells

Observation Wells, to measure water table depth, were made from schedule 40 polyvinyl Cl (PVC) pipe, 76-mm i.d. and 3 m long. Transverse slots, 3 by 65 mm chord length spaced 50 mm apart were cut on opposite sides along the lower 2.5 m of the pipe. At the site, a hole 89 mm in diameter was bored in the soil with a hand auger to a depth of 2.5 m. The slotted part of the pipe was set into the hole, and soil was packed around the upper part of the pipe. One well was installed at each site.

Piezometers

Piezometers, to measure hydraulic head, were made from schedule 40 PVC pipe, i.d. of 13 mm, cut to a length 0.5 m longer than the installation depth. Transverse slots 1.6 by 20 mm chord length spaced 6 mm apart were cut on opposite sides of the lower 50 mm of the pipe. The slotted part of the pipe was covered with geofabric and attached with PVC cement. To install the pipes, a 32-mm diam. hole was bored with a hand auger 50 mm deeper than installation depth. The hole was filled with sand to the installation depth, the pipe was inserted, and sand was added to 150 mm above the installation depth. The hole was then filled with bentonite clay powder to the surface, except that for the 2 and 4.5 m pipes, 50-cm bentonite seals were placed above the sand and at the surface, and the space between them was filled with packed soil. Depth of water in the pipe was measured directly with a steel tape used as a dip stick or with a blow tube. Pipes were installed in triplicate at depths of 0.25, 0.50, 1.00, 2.00 m, and singly at 4.50 m at each site. Replicate pipes were installed 1 to 1.5 m apart.

Thermocouples

Thermocouples, to measure soil temperature, were made by welding a Cu and a constantan wire together. Two thermocouples were joined together in parallel, and these pairs and lead wires were attached to fiberglass rods at depths of 0.25, 0.50, 1.00, and 2.00 m. These two rods were installed at each site by pushing them into a hole made with a steel rod. Electrical potential was read with a potentiometer and converted to temperature.

Platinum Electrodes

Platinum Electrodes, to measure E_H, were made by sealing 18-gauge Pt wire in the bottom of a glass tube, sealing a Cu wire in the top of the tube, and creating a junction with Hg (Faulkner et al., 1989). To complete the circuit, a KCl salt bridge was made by filling a perforated PVC pipe with a saturated KCl solution in an agar gel. The electrodes were installed in triplicate at 0.25-, 0.50-, and 1.00-m depths 10 cm from the salt bridge in soils with redox features. Defective electrodes were occasionally replaced. Electrical potential was read with a potentiometer and converted to E_H according to Garrels and Christ (1965). Replicate measurements were highly variable, but an individual replicate followed the trend of the others.

RESULTS AND DISCUSSION

Relation of Soil Hydrology to Precipitation, Evapotranspiration, and Soil Temperature Precipitation and Evapotranspiration

The long-term (1961–1990) average P at Shades State Park is 1100 mm. Average annual P during the 9 yr of the study was 1048 mm (Table 2), 95% of the 30-yr normal P. If we arbitrarily consider annual P values of 80 to 120% of long-term average to be normal, 1992, 1996, 1998 were normal years, 1993 was wet, and 1994, 1995, 1997, 1999, and 2000 were dry years (Fig. 2a). Months with >200 mm P include July and November 1992, May 1996, and June 1998.

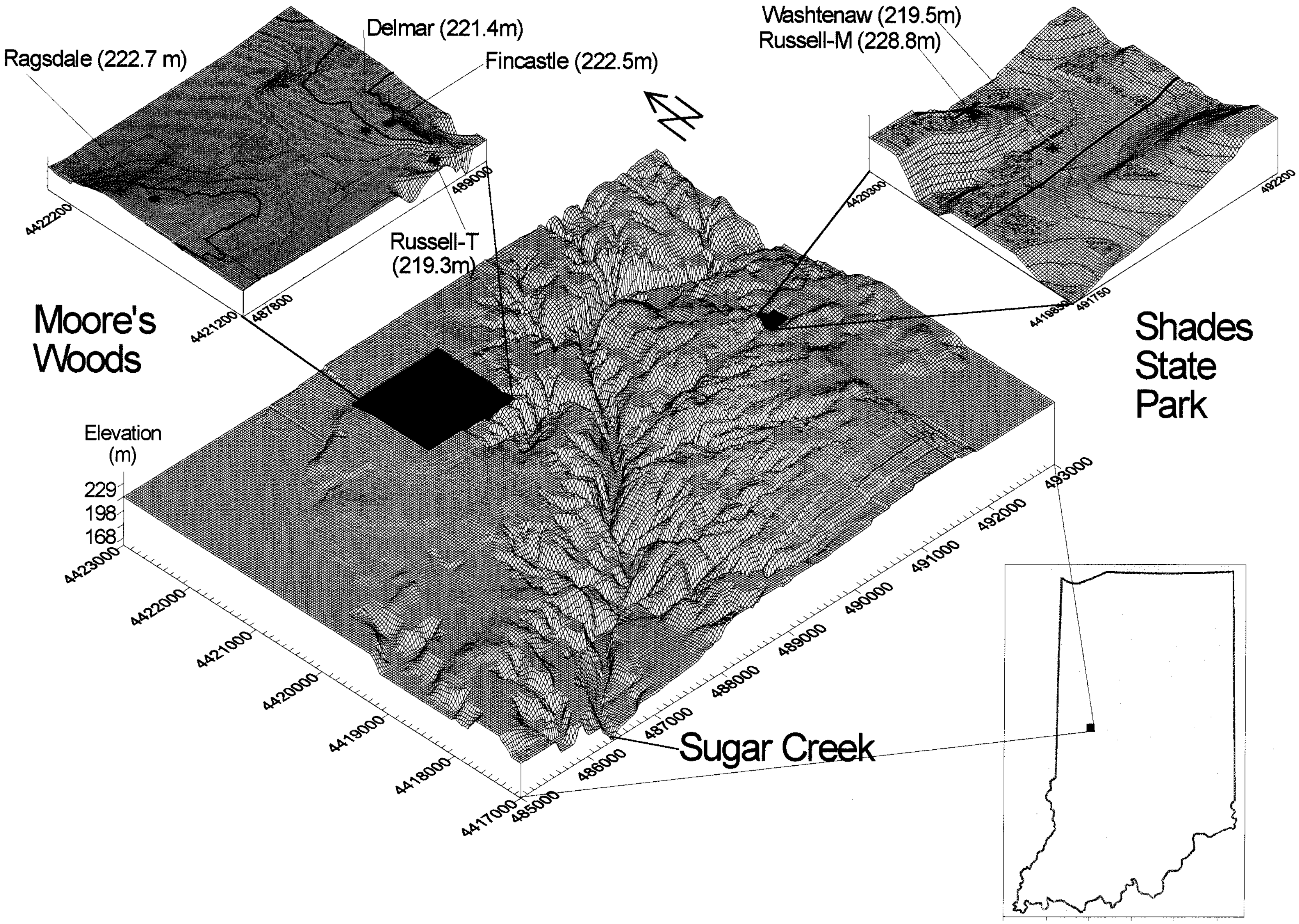

Fig. 1. Block diagram showing the sites and their elevation at Moore's Woods, a dissected till plain, and at Shades State Park, a segment of an end moraine, and the location in the state. Easting and northing numbers are for zone 16 in the Universal Transverse Mercator system are in m. Grid size is 30 m.

Table 1. Morphology and classification of soils.

Horizon depth, cm	Horizon	D_b†, Mg m^{-3}	PM‡	Texture Class§	Color (moist), abundance¶ Dominant	Depletions	Accumulations	Clay films: Abundance¶, color	Index C1
					Ragsdale (fine smectitic, superactive, mesic Typic Argiaquoll) S92IN-121-3				
0–23	A	1.06	L	SiCL	5Y 3/1				
23–40	Btg1	1.33	L	SiC	5Y 3/1			mN 2/0	0.5
40–61	Btg2	1.44	L	SiC	2.5Y 4/2		m2.5Y 5/4	m5Y 4/1	2.1
61–93	Btg3		L	SiCL	5Y 5/2		m5Y 5/4	m5Y 5/1	1.9
93–124	Bt1	1.53	L	SiCL	2.5Y 5/4	m2.5Y 5/2	m5Y 5/6	c5Y 5/1	2.7
124–150	Bt2	1.50	L	SiL	10YR 5/6	m10YR 6/1		f10YR 5/1	
150–178	BCt	1.57	L	SiL	10YR 5/6	m10YR 6/1	m10YR 5/3	f10YR 2/2	
178–196	2BCt1	1.60	T	SL/L	10YR 5/4	m10YR 6/1	m10YR 5/6	f10YR 2/2	
196–214	2BC2	1.73	T	L	10YR 5/6	m10YR 6/2		f10YR 2/2	
					Delmar (fine silty, mixed, superactive, mesic Typic Endoaqualf) S92IN-121-5				
0–7	A	0.92	L	SiL	10YR 2/2				
7–21	BE	1.49	L	SiL	10YR 7/1		c7.5YR 5/8	m10YR 4/1	1.4
21–45	Btg1	1.38	L	SiCL	10YR 6/2		m7.5YR 6/8	m10YR 6/2	3.1
45–64	Btg1	1.47	L	SiCL	10YR 6/2		m7.5YR 5/6	m10YR 6/1	2.2
64–81	Btg2	1.53	L	SiL	10YR 6/2		m7.5YR 5/6	m10YR 6/1	2.2
81–102	Bt3	1.49	L	SiL	7.5YR 5/8	m10YR 6/2		m10YR 4/1	3.5
102–122	Bt4	1.62	L	SiL	10YR 5/8	m10YR 6/2		c10YR 4/1	
122–173	Bt5	1.58	L	SiL	10YR 5.8	m10YR 6/2		c10YR 4/1	
173–188	2Bt6	1.71	T	L	10YR 5/6	m10YR 6/2		c10YR 5/1	
188–234	2BCd	1.75	T	L	10YR 5/6		m10YR 5/8	c10YR 5/1	
					Fincastle (fine silty, mixed, active, mesic Aquic Hapludalf) S92IN-121-4				
0–11	A	1.18	L	SiL	10YR 3/2				
11–22	E	1.43	L	SiL	10YR 5/3				3.0
22–38	BE	1.48	L	SiL	10YR 5/3	m10YR 5/2			3.0
38–52	Bt1	1.54	L	SiCL	10YR 5/4	m10YR 5/2		f10YR 5/2	2.4
52–72	Bt2	1.51	L	SiCL	10YR 5/4	m10YR 5/2		f10YR 4/3	3.3
72–92	Bt3	1.50	L	SiCL	5Y 5/6	m10YR 5/2		m10YR 5/2	3.3
92–134	Bt4	1.49	L	SiCL	10YR 5/4	m10YR 5/2		m10YR 5/2	2.0
134–163	Bt5	1.63	L	SiL	10YR 5/6	m10YR 6/1		c10YR 5/1	
163–178	2Bt6	1.54	T	L	10YR 5/4	m10YR 5/2		f10YR 5/2	
178–198	2BCt	1.68	T	L	10YR 4/3	m10YR 5/2		f10YR 2/1	
					Russell T (fine silty, mixed, active, mesic Oxyaquic Hapludalf) S92IN-121-6				
0–15	A	1.07	L	SiL	10YR 3/3				
15–29	E	1.24	L	SiL	10YR 4/4				4.0
29–44	Bt1	1.53	L	SiL	10YR 5/6			m7.5YR 4/6	6.0
44–64	Bt2	1.55	L	SiCL	10YR 4/4			m7.5YR 4/4	4.0
64–83	Bt3	1.67	L	SiL	10YR 4/6			m10YR 4/4	5.0
83–109	2Bt4	1.59	T	L	10YR 4/6			c7.5YR 4/3	5.0
109–133	2Bt5	1.72	T	L	10YR 5/6			c7.5YR 4/3	
133–166	2BCd	1.87	T	L	10YR 5/4	m10YR 6/2		f10YR 4/3	
166–189	2Cd	1.87	T	L	10YR 5/4			f10YR 4/3	
					Russell M (fine silty, mixed, active, mesic Typic Hapludalf) S92IN-121-2				
0–8	A	1.13	L	SiL	10YR 4/2				
8–20	AB	1.42	L	SiL	10YR 4/3				3.0
20–40	Bt1	1.55	L	SiCL	10YR 5/4				4.0
40–66	Bt2	1.58	L	SiCL	7.5YR 4/6			m7.5YR 4/4	5.0
66–99	Bt3	1.55	L	SiCL	7.5YR 4/6			m7.5YR 4/4	5.0
99–126	Bt4	1.56	L	SiL	10YR 5/6			c10YR 4/4	5.3
126–143	2Bt5	1.54	T	L	10YR 4/6			c7.5YR 5/4	
143–180	2Bt6	1.58	T	L	10YR 5/4			c10YR 3/3	
180–201	2BCt	1.63	T	L	10YR 5/3			f10YR 4/3	
201–240	2Cd	1.82	T	L					
					Washtenaw (fine silty, mixed, superactive, mesic Typic Endoaqualf) S92IN-121-1				
0–14	A	1.20	L	SiL	10YR 4/1				
14–34	BA	1.32	L	SiL	10YR 4/1		c7.5YR 4/4		1.3
34–51	Ab	1.25	L	SiL	5Y 3/1		f2.5Y 4/4		1.0
51–62	BE	1.49	L	SiL	10YR 4/1		m10YR 5/3		1.7
62–82	Btg1b	1.53	L	SiCL	N 4/0		m2.5Y 5/4	m10YR 4/1	1.2
82–125	Btg2b	1.57	L	SiCL	5Y 5/1		m10YR 5/4	m5Y 4/1	1.8
125–177	Btg3b	1.62	L	SiCL	5Y 6/1		m7.5YR 5/6	m10YR 3/1	

† Bulk density at 1/3 bar by method 4A1d, Soil Survey Staff (1996).
‡ PM = parent material, L = Loess, T = Glacial Till.
§ Si, silt(y); C, clay; L, loam.
¶ abundance: f = few, c = common, m = many.

Potential evapotranspiration, calculated according to Thornthwaite (1948), from Crawfordsville climatological data (20 km northeast), averaged 780 mm for the 9 yr of the study, or 74% of P (Fig. 2b, Table 2). This compares with estimates of 635 to 762 mm of AE for the state as a whole quoted in the introductory paragraphs.

We agree with climatologists (Newman, 1981) that the Thornthwaite method provides accurate estimates

Table 2. Total annual precipitation at Shades State Park and total annual potential evapotranspiration calculated from Crawfordsville temperature data.

Year	Precipitation	Potential evapotranspiration
	mm	
1992	1150	737
1993	1421	786
1994	826	811
1995	844	796
1996	1282	715
1997	813	727
1998	1251	845
1999	783	809
2000	1065	793
Avg.	1048	780

of PE over the long term (months, years). The question is, how much of the ~780 mm of PE actually evaporates from this forest. Reynolds and Thompson (1988) quote data from the former European USSR showing that deciduous forests with trees between 20- to 130-yr-old evaporate (including transpiration) more water than row crops. For mid-age (60-yr old) forests, the E_{forest}/E_{field} ratio is 1.34. Forests also evaporate more water than most nonrow crops. In Indiana, the 635- to 762-mm average AE represents all land uses. There is much more cropland (61% of the state) than forest land (17%), so AE from cropland is likely to be slightly below average AE, and AE from forest land, substantially above average AE. Also, there is less runoff from forested land than from cropland, leaving more soil water available for AE. Further evidence that AE is greater in forest than in crops is from observations and measurements of soil water content under forest and under crops. At our sites, we observed that the soil in the woods was drier than the soil in nearby crop fields in the summer. This relationship was measured elsewhere (Franzmeier et al., 1973; Hodnett et al., 1995). Therefore, we estimate that at our sites, AE is 762 mm, near the upper limit of the state average AE.

According to Newman (1981), AE is greater than Thornthwaite PE during April, May, and June, but less than PE in October and November in Indiana. The main reason that AE $<$ PE in the fall is that in most years there is less available soil water in the fall than in the spring, and AE is greater when soil water is more available (Hanson, 1991). There are several reasons why AE $>$ PE in the spring. First, AE is a function of net radiation, but PE is calculated mainly from air temperature, and the seasonal net radiation maximum precedes the seasonal air temperature maximum by 4 to 6 wk (J.E. Newman, personal communication, 2001). Secondly, the Thornthwaite model does not consider vegetation growth patterns. In central Indiana, the main period of tree leaf out is between mid April and mid May. Potential evapotranspiration, calculated mainly from air temperature, is somewhat greater in mid May than mid April, but AE is much greater in mid May because deciduous trees do not use water when they have no leaves, but once leaves start to grow, they incorporate water into their structure and transpire much water.

Our data and observations also provide evidence about springtime AE. We observed very little runoff from these sites and downward seepage is very slow through the dense till C horizons. Thus, water must leave the soil mainly as AE and subsurface flow. Water tables usually peak in the spring (Fig. 2b). At that time subsurface flow should be at its seasonal maximum because the hydraulic head is greatest. As the water table recedes, hydraulic head and subsurface flow decrease. The time when PE $>$ P (deficit period) is shown by a shading pattern in Fig. 2b–g. We expected that water tables would begin to drop in the first month of the deficit period (PE $>$ P) in the spring. In many cases, however, the water table began to fall well before the deficit period (Fig. 2b–g). When the water table is falling rapidly, subsurface flow is decreasing and becoming a smaller component of total water loss. We believe that this is further evidence that AE is greater than PE in the spring.

Soil temperature was measured at four depths at all sites for 9 yr, but is reported here for one soil, 1 yr (Fig. 3c). Like PE, it shows regular seasonal variation. The temperature at the 25-cm depth is warmer than at greater depths in the summer and colder in the winter. The temperature lines cross in the few weeks around the spring equinox and a few weeks after the fall equinox. The minimum temperature at 2-m lags behind the minimum at 0.25 m by ~6 wk.

Plant roots grow very little at temperatures below 5°C (Soil Survey Staff, 1999), and it has been implied that there is little microbiological activity at cold temperatures. Figures 3c and 3d show that the temperature at 25 cm was $<$5°C during January, February, and most of March, and that E_H decreased during that same period. This is evidence that microbial activity occurs when the Fincastle and other soils are cold and wet.

Relation of Soil Hydrology to Stratigraphy and Geomorphology

The previous section explained that of the 1048 mm of P, ~762 mm is lost to the atmosphere. In this section we discuss the fate of the other 286 mm of water.

The strata most significant to soil hydrology in these soils is dense till (Cd horizons) that underlies till plains and many moraines. The till was compacted by the weight of a few thousand feet of glacial ice when it was deposited (Wayne, 1966) so it has little pore space to conduct water. In two transects across east-central Indiana, the bulk density of till-derived C horizons was $>$1.80 Mg m^{-3} in 44 of 45 sites (Franzmeier et al., 1987). Also, the till may have been weakly cemented during soil formation to further reduce its K_{sat} (McBurnett and Franzmeier, 1997). Dense till has very slow K_{sat} (~10^{-7} m s^{-1})(Harlan and Franzmeier, 1974; King and Franzmeier, 1981; Evans and Franzmeier, 1986; Allred, 2000).

In this research, we used the Cd soil horizon designation for horizons with bulk density $>$1.80 Mg m^{-3}. In Moore's Woods, Russell-T soil, two horizons below 133 cm have moist bulk densities of 1.87 Mg m^{-3} (Table 1) and are considered to be dense till. No other C horizons in the transect are considered to be dense till, but the

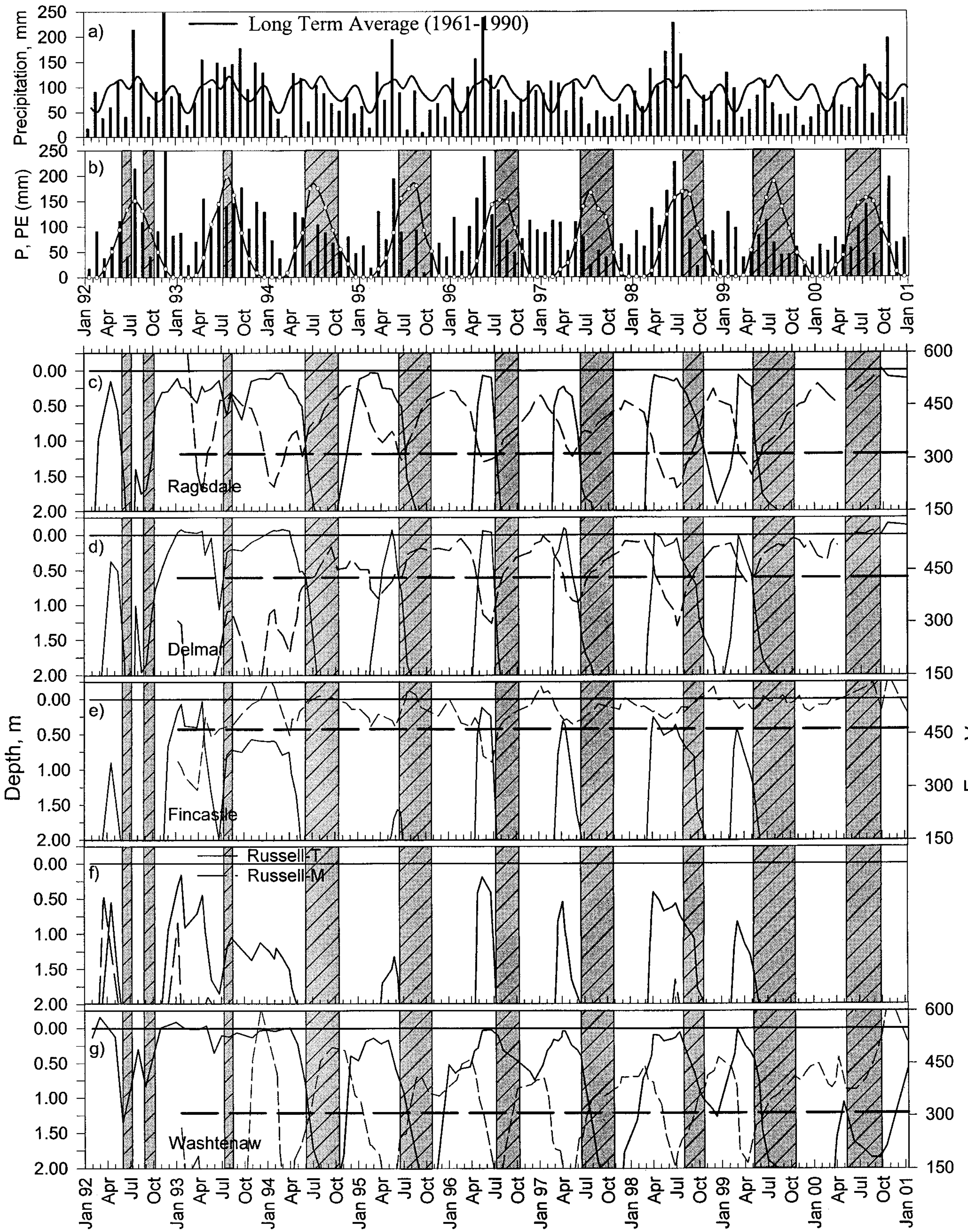

Fig. 2. Measurements during a 9-yr period of climatic and soil properties. (a) monthly precipitation (P) (bars) and long term average P (line); (b) monthly P (bars) and potential evapotranspiration (PE) (line); (c–g) water table depth from observation wells (solid line) and E_H (broken line) in all soils except Russell. In 2c through g, the horizontal dashed line represents oxidation/reduction equilibrium (McBride, 1994, Fig. 7.6). The shaded area represents the time when PE > P.

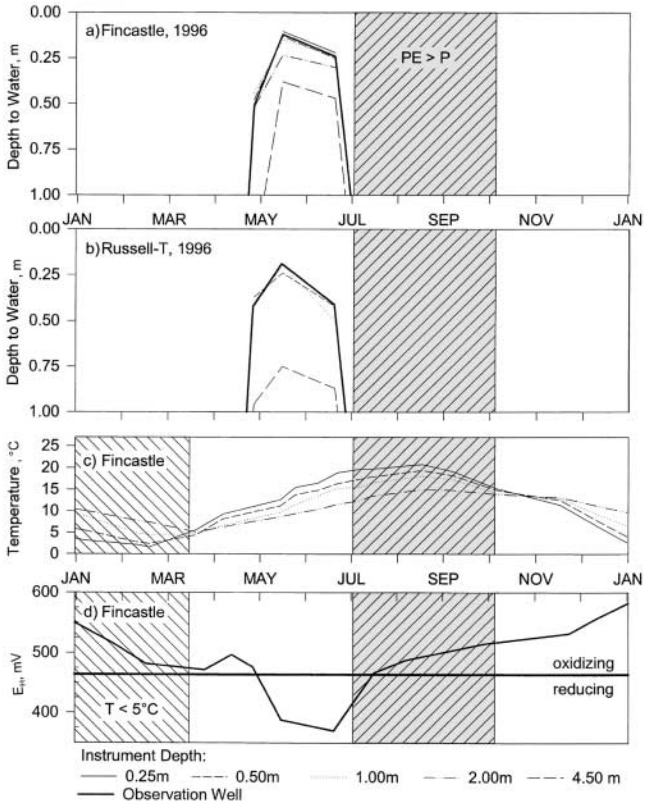

Fig. 3. Measurements during 1996 of water levels in piezometers and observation wells in (a) Fincastle and (b) Russell-T soils; (c) soil temperature, and (d) E_H in Fincastle. The ▨ shaded area represents the time when the temperature at 25 cm was <5°C, and the ▧ shaded area represents the time when PE > P. The oxidizing/reducing line is from McBride (1994), Fig. 7.6

deepest horizons in Delmar and Ragsdale soils have bulk densities of 1.75 and 1.73 Mg m^{-3}, respectively, which could result in relatively low K_{sat}. It is likely, however, that all soils in the transect are underlain by dense till at some depth because they have seasonally high water tables. In this transect, well-drained Russell-T soil is at a lower elevation than the associated wetter soils. The till at the Shades site is also dense. The 2Cd horizon has a bulk density of 1.82 Mg m^{-3} below 201 cm. This dense till perches water in horizons above it, as discussed in more detail later.

Moore's Woods consists of a gently undulating till plain with randomly arranged swells and swales that have slopes of <2%. This plain is cut by the till plain bevel, a hillslope that cuts and descends from the till plain. Delmar and Ragsdale soils are in swales, and Fincastle is on a swell. Russell-T is on the shoulder of a till plain bevel. Figures 3a and 3b show the water levels in piezometers installed at five depths and in the observation wells for the Fincastle and Russell-T soils for 1996. Water levels were similar to each other in the 0.25-, 0.5-, 1.0-, and 2.0-m piezometers (except in the 2.0-m piezometer in Fincastle), but this level was higher than in the 4.5-m piezometer. Thus, there are two hydraulic heads. This trend applies whenever the water table is high in these soils (other data not shown). The upper hydraulic head (in the 0.25- to 2.0-m piezometers) is apparently held up by dense till. Similar water levels in the four shallow piezometers suggests that there is no significant upward or downward water movement above 1 m. We believe that the hydraulic head in the 4.5-m piezometer is lower because it is in an aquitard (material with very slow K_{sat}), and is not in equilibrium with the other piezometers.

The till itself (4.5-m piezometer) is saturated essentially all the time that horizons above it are saturated, and sometimes when those above are not saturated. The only time water is in a shallower piezometer, but not in a deeper one in dense till, is temporarily after a large rain.

The two piezometric levels are shown in cross section when the water tables were high, on 15 Apr. 1993 (Fig. 4). The depth to dense till, also plotted, was deduced from measured bulk density, observations when installing the deep piezometers, and additional auger borings. From other measurements (Franzmeier et al., 1987) and observations, we believe that dense till underlies the entire till plain. The poorly and somewhat poorly drained soils themselves are further evidence of extensive dense till. Where underlying materials are more permeable, the soils are better drained.

We believe that water percolates into the sola of Fincastle and Delmar, where it perches on the dense till of the till plain, then moves laterally as throughflow through those soils and into the Russell-T solum, and then moves further downslope. Seasonal hillside seep areas downslope from Russell-T are further evidence of this water movement. Daniels et al. (1967, 1971) refer to similar shoulder positions as the dry edge. We observed very little surface runoff except when the soils are saturated to the surface or ponded.

Even though the water table is relatively high in the Russell-T soil, it has no redoximorphic features (Table 1). A possible explanation is that on the edge of the till plain, near the bevel, the soils are not as uniformly saturated as they are in the interior of the till plain. There might be unsaturated zones intermingled among saturated zones. If after a rain, water moves through a zone that was previously unsaturated, it could pick up O_2, as it moves through the soil. In contrast, water in till plain depressions is more stagnant.

In contrast, Russell-M, on the crest of a moraine, hardly ever has a high water table because it is high in the landscape and receives no water through overland flow or throughflow. According to *Soil Taxonomy* (Soil Survey Staff, 1999), Hapludalfs that are saturated at one meter for 1 mo or more per year are Oxyaquic, and those saturated for less time are Typic. Thus, Russell-T, on the bevel, is an Oxyaquic Hapludalf, and Russell-M, on a crest, is a Typic Hapludalf.

Water Table Levels Versus Natural Drainage Class

Soil scientists have identified natural drainage classes in Indiana for ~75 yr. In the poorly drained Ragsdale, Delmar, and Washtenaw soils (Fig. 2c,d,g), water table levels rose to depths of 25 to −10 cm (ponded) almost

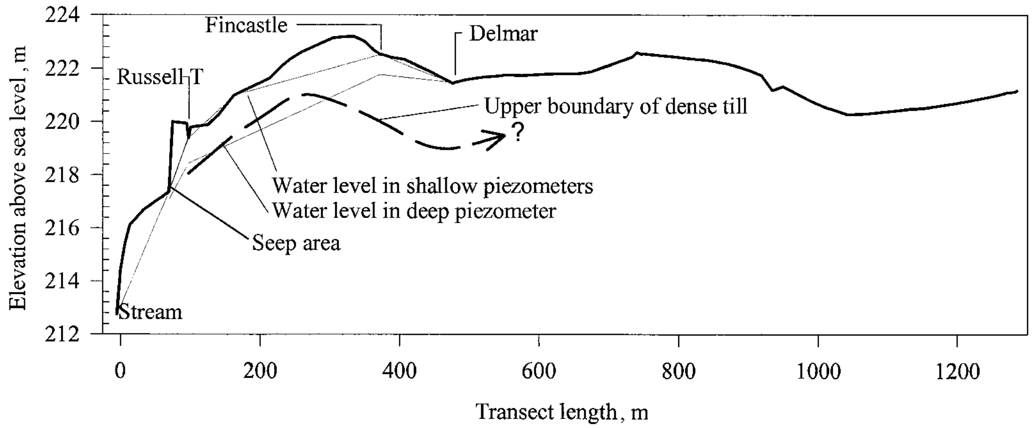

Fig. 4. Cross section diagram through the Moore's Woods sites showing two hydraulic head surfaces when water tables were high on April 15, 1993. The elevation scale is exaggerated 38 times relative to the length scale.

every year (except Delmar in 1992 and all sites in 2000). High P in November 1992, and most months of 1993 resulted in high water tables for most of 1993, continuing into 1994. All the poorly drained soils are in depressions that receive water from nearby higher areas, but of the three soils, Washtenaw appeared to receive more water as overland flow than Delmar and Ragsdale according to our observations. Compared with Delmar, Ragsdale is in a more closed depression and has a darker surface horizon (Table 1), and thus appears to be the wetter soil, but Delmar has somewhat higher measured water table levels with occasional ponding. Landowners might have enhanced the surface drainage of Ragsdale. We observed minor channelization that could easily change the maximum water table levels a few centimeters.

Yearly water table maxima varied from 0 to >2 m in somewhat poorly drained Fincastle. Except for 1995, the water table curves paralleled, but were a bit lower, than those in the nearby Delmar and Ragsdale soils.

Well-drained Russell soils were studied on two landforms. Russell-T is on the upper backslope of a till plain bevel and is at a lower elevation than associated more poorly drained soils (Fig. 1). Russell-M is on the crest of an end moraine and is at a higher elevation than associated more poorly drained soils (Fig. 1). Russell-T had a higher water table than Russell-M, almost as high as in Fincastle.

Redox and Vegetation as a Function of Soil Hydrology

Redox Potential

The reduction-oxidation (redox) potential is represented by E_H, measured in millivolts. Large E_H numbers represent relatively more oxidizing conditions, and small numbers, more reducing conditions in the soil. At a depth of 25 cm in poorly and somewhat poorly drained soils, the slope of the E_H curve vs. time was approximately opposite that of the water table curve (Fig. 2 and 3). Generally, E_H began to drop a few months after P first exceeded PE, and dropped more sharply when the soil became saturated at 25 cm. The steepest rise of the water table, after heavy rains in April and May 1996 coincides with the steepest drop in E_H at 25 cm (Fig. 2 and 3). Usually there is a lag period of 2 to 8 wk between the time when the soil at 25 cm first becomes saturated and when it reaches its seasonal minimum redox potential. Very low E_H values were recorded in 1993, a year with high rainfall. Unexpectedly high E_H was measured in Washtenaw around December 1993, however, when the water table had been high for several months. This site receives much water by overland flow, and perhaps this water percolated to 25 cm to cause the high E_H.

The line representing Fe^{+3}-Fe^{+2} E_H equilibrium in pure solutions slopes sharply downward as pH increases (Garrels and Christ, 1965; McBride, 1994). Soils are much more complex systems, however, and in soils the line separating oxidizing and reducing conditions also slopes downward, but less steeply (McBride, 1994, Fig. 7.6). In Fig. 2 and 3, the horizontal oxidizing-reducing line is plotted according to the pH of the soil at the 25-cm depth using McBride's Fig. 7.6. The soil pH values are Ragsdale, 7.0; Delmar, 4.8; Fincastle, 4.4; and Washtenaw, 6.6. For all soils with Pt-electrode installations, E_H dropped below the oxidizing-reducing line, but for some, only for short periods. Several times during the study, we observed a positive reaction with α-α-dipyridyl, showing the presence of Fe^{2+} when E_H readings were below this line.

The relationship of water table depth, saturation, and E_H is plotted by many soil-year combinations, but is illustrated by the relationship for the Delmar soil in 1996 (Fig. 2d). The water table was below 2 m, and apparently the soil was relatively dry during the fall of 1995. During the winter of 1996, it began to wet up and the E_H at 25 cm decreased gradually, even before the soil was saturated at that depth. When free water moved into the 25-cm piezometer in May, E_H decreased more rapidly as the whole soil mass became saturated.

A similar relationship is shown in more detail for the Fincastle soil in 1996 (Fig. 3). Redox potential at 25 cm decreased from January through April even though the soil at 25 cm was not saturated. The E_H curve descends more sharply when the water table rises above 25 cm in May, however (Fig. 3d).

Table 3. Dominant tree species at each site and the classification of the site according to wetness and vegetative prevalence based on four or five strata of vegetation.

Tree species	
Common name	**Scientific name**
Moore's Woods, Ragsdale (88% wet, 45% dry, wet rating)	
American Basswood	*Tilia americana* L.
American Elm	*Ulmus americana* L.
Black Ash	*Fraxinus nigra* Marsh.
Black Walnut	*Juglans nigra* L.
Coffeetree	*Gymnocladus dioicus* (L.) K. Koch
Green Ash	*Fraxinus pennsylvanica* Marsh.
Ohio Buckeye	*Aesculus glabra* Willd.
Pignut Hickory	*Carya glabra* (P. Mill.) Sweet
Red Oak	*Quercus rubra* L.
Shellbark Hickory	*Carya laciniosa* (Michx. f.) G.
Sugar Maple	*Acer saccharum* Marsh.
Sycamore	*Platanus occidentalis* L.
Moore's Woods, Delmar (141% wet, 9% dry, wet rating)	
Black Ash	*Fraxinus nigra* Marsh.
Bur Oak	*Quercus macrocarpa* Michx.
Cottonwood	*Populus* L.
Red Maple	*Acer rubrum* L.
Shellbark Hickory	*Carya laciniosa* (Michx. f.) G.
White Oak	*Quercus alba* L.
Moore's Woods, Fincastle (19% wet, 122% dry, dry rating)	
American Beech	*Fagus grandifolia* Ehrh.
Americal Elm	*Ulmus americana* L.
Sugar Maple	*Acer saccharum* Marsh.
Moore's Woods, Russell-T (25% wet, 164% dry, dry rating)	
American Beech	*Fagus grandifolia* Ehrh.
American Elm	*Ulmus americana* L.
American Basswood	*Tilia americana* L.
Sugar Maple	*Acer saccharum* Marsh.
Tuliptree	*Liriodendron tulipifera* L.
Shades State Park, Russell-M (82% wet, 115% dry, dry rating)	
American Elm	*Ulmus americana* L.
Black Cherry	*Prunus serotina* Ehrh.
Flowering Dogwood	*Cornus florida* L.
Honeylocust	*Gleditsia triacanthos* L.
Sassafras	*Sassafras albidum* (Nutt.) Nees
Shades State Park, Washtenaw (98% wet, 14% dry, wet rating)	
American Elm	*Ulmus americana* L.
Black Cherry	*Prunus serotina* Ehrh.
Honeylocust	*Gleditsia triacanthos* L.

Hydric Soil Indicators

Using soil morphology information (Table 1) the Ragsdale soil qualifies as a hydric soil according to hydric indicator F-5, thick dark surface, and Delmar and Washtenaw soils qualify according to hydric indicator F-3, depleted matrix (USDA-NRCS, 1996).

Color Index

The C1 index (Evans and Franzmeier, 1988) is a measure of the reduction status of soil horizons based on soil color. Matrix and clay film colors are both considered in calculating the index. Grayer colors have lower C1 index numbers. This index ranges from 0.5 to 1.4 in the uppermost B horizon in the three hydric soils, and from 3.0 to 4.0 in the uppermost B horizon in the three nonhydric soils (Table 1). These horizons appear to be the most sensitive in the profile to natural drainage and redox differences. The weighted index for the 25 to 50 cm zone was 1.13 to 2.28 in the hydric soils, and 3 to 5 in the nonhydric soils.

Vegetation

The kinds of vegetation on a site is also used to identify wetlands. At Shades State Park, no trees have been cut since the 1920s. Moore's Woods has never been cleared, but trees have been cut occasionally and it has been grazed, especially the Ragsdale site which is fenced separately from the others.

The vegetation type on a site in the tree stratum, sapling stratum, shrub stratum, and herbaceous stratum was characterized (D. Berna, USDA-NRCS, Indianapolis, IN, personal communication, 1992). The dominant tree species are listed in Table 3. Plant species were identified at each site and their relative abundance was estimated for each stratum. According to the vegetation (Federal Interagency Committee for Wetland Delineation, 1989), Ragsdale, Delmar, and Washtenaw are wet sites, and the others are dry.

CONCLUSIONS

Relation of soil hydrology to precipitation and evapotranspiration. At the research sites, annual P during the study was 1048 mm and Thornthwaite PE was 780 mm. We estimate that AE was about 762 mm. Water table levels begin to drop rapidly in the spring when hardwood trees leaf out, but before PE exceeds P. Water levels rise after the trees become dormant and P exceeds PE. Based on seasonal patterns of net radiation and air temperature, tree phenology, and water table levels compared with P deficit periods, we believe that AE is greater than Thornthwaite PE in the spring.

Relation of soil hydrology to stratigraphy and geomorphology. On a dissected till plain underlain with dense till, water is held up by the low K_{sat} till. Water moves from the interior of the till plain to the dissected bevel of the plain where it causes relatively high water tables in soils that have no redoximorphic features. Soils on the crest of a moraine are similar in morphology to those on the till plain bevel (both lack redox features), but have essentially no high water table because there is no higher area to serve as a water source. The Russell soil on the till plain bevel has oxyaquic characteristics. Water table levels can be predicted from natural drainage class.

Relation of soil hydrology to soil redox and vegetation. Reduction begins when a relatively dry soil horizon becomes moist, before it is saturated. There is a lag period of 2 to 8 wk between the time a horizon is first saturated and when it reaches it lowest redox potential. Hydric indicator classes and color index values are related to soil hydrology.

ACKNOWLEDGMENTS

This research was supported by a grant from the USDA-NRCS.

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