The Stratigraphy and Composition of a Lakeside Wetland[1]

C. A. Johnston, G. B. Lee, and F. W. Madison[2]

ABSTRACT

Soils were examined at 35 locations and described in detail at 22 locations to determine the stratigraphy and distribution of materials in a lakeside wetland in Wisconsin. Histic and mineral soil samples were analyzed for organic P, inorganic P, ammonium, nitrate, and organic N. Particle size distributions were determined for the mineral soils. It was found that soils formed in the wetland are young, not well developed, and derived from a variety of parent materials: glacial till, glacio-fluvial deposits, lacustrine deposits, histic materials, colluvium, and alluvium. Major soils in the wetland include Borosaprists, Haplaquents and Fluvaquents. Phosphorus concentrations are highest in silt loam alluvium and histic deposits, and lowest in glacio-fluvial deposits, marl, and sandy alluvium. Total P in the alluvium and glacio-fluvial deposits is very highly correlated ($P < 0.01$) with percent silt plus clay. Nitrate concentrations were highest in silt loam alluvial levees and lowest in a saturated Histosol, indicating that the build-up of levees in the wetland has created aerobic soil conditions locally conducive to nitrification. The accumulation of histic materials and marl in the wetland has been an ongoing process since deglaciation, but deposition of alluvium appears to have occured primarily since logging and cultivation of the watershed began in the mid-1800's. The rate of Histosol accumulation in the wetland was estimated by ^{14}C dating as 0.17 cm/year, no more than one third of the rate of alluvial deposition. Since P concentrations are slightly higher in the silt loam alluvium than in the histic materials, alluvial deposition is more effective than Histosol formation for retaining phosphorus in the White Clay Lake wetland.

Additional Index Words: **alluvium, Histosols, Aquents, beach ridges, marl, glacio-fluvial deposits, lacustrine deposits, till, phosphorus, nitrogen.**

Johnston, C. A., G. B. Lee, and F.W. Madison. 1984. The stratigraphy and composition of a lakeside wetland. Soil Sci. Soc. Am. J. 48:347–354.

Wetlands are a pervasive feature of the glaciated Wisconsin landscape, and have often been subjected to a variety of geomorphological forces. Since wetlands usually occur in low-lying depressions, they tend to accumulate materials eroded and transported from the surrounding uplands. Wetland soil stratigraphy can provide at least a partial record of the recent geological events in a watershed, and can also serve as a basis for predicting future soil changes that would affect soil-water relationships.

This paper presents findings from a study of the White Clay Lake Marsh in northeastern Wisconsin. After monitoring upland runoff from the surrounding agricultural watershed for 2 yr, it became apparent that nutrients and sediments were being transported toward the lake in amounts that would stimulate eutrophication even though lake water quality was generally good. This enigma led to the hypothesis that much of the sediment and nutrient load leaving the upland was being trapped in the wetland fringe around the lake.

As part of the marsh study, the soils in the wetland surrounding the lake's primary inlet stream were examined in detail for evidence of past and present soil-water interactions. The specific goals were: (i) to identify the parent materials from which the wetland soils were derived; (ii) to determine the depositional history and relative age of those parent materials; (iii) to identify microtopographic features which affect soil aeration and the flow of flood waters over the wetland surface; and (iv) to determine what changes in nutrient content occur with depth and with type of depositional material.

STUDY SITE

White Clay Lake, a 95-ha lake named for its marl bottom, is in northeastern Wisconsin. The lake's 1215-ha watershed is an undulating till plain with a vertical drop of 30 m or less from upland to lake level. The lake overlies a buried river valley deeply eroded into Paleozoic sandstone and dolomite. The waters of Early Lake Oshkosh (Thwaites, 1943) filled the basin now occupied by White Clay Lake and adjacent wetlands with 3 to 60 m of lacustrine sediments (Tolman, 1975). Bedrock is within 0 to 15 m of the surface elsewhere in the watershed.

The Athelstane moraine extends to the north and south of White Clay Lake. Although Thwaites (1943) considered the moraine to be late Woodfordian in age, McCartney and Mickelson (1982) recently interpreted it to be the western limit of the Middle Inlet till, which was deposited during Greatlakean time (about 11,900 yr B.P.). A depression in the lake 14 m deep is probably a kettlehole formed in the moraine.

The 2-ha study area borders the eastern edge of the lake (SW 1/4, sec. 23, T27N, R17E). A small perennial stream delivers surface water and alluvium to the wetland during large runoff events from the south and east portions of the watershed (Fig. 1). The stream follows a well-defined, meandering channel for most of its length, but becomes diffuse near the lake edge. For much of its length, the stream flows through a lowland forest of green ash (*Fraxinus pensylvanica* Marsh.) with some balsam poplar (*Populus balsamifera* L.), white cedar (*Thuja occidentalis* L.), and peach-leaved willow (*Salix amygdaloides* Anderss.). Red osier dogwood (*Cornus stolonifera* Michx.) and willow (*Salix* sp.) comprise the overstory of the shrub carr south of the stream, with tussock sedge (*Carex stricta* Lam.) in the herbaceous layer. Sedges and cattails (*Carex* sp. and *Typha latifolia* L.) grow at the stream-lake junction. An area of white cedar occurs south of the shrub carr, and a sedge-bulrush marsh is west of it.

MATERIALS AND METHODS

Soils were examined at 35 locations and described in detail at 22 locations throughout the 2-ha wetland (Fig. 1). Wherever possible, soil pits were dug to facilitate observation, measurement, and sampling of the soil. In most cases, however, the high water table made this impractical and soil augers or probes were used. A "Dutch" auger was found to be the most useful tool for sampling pedons that included both histic and mineral soil layers.

---

[1] Research funded by U.S. EPA Grant no. R804823; Univ. of Wisconsin-Extension; and Univ. of Wisconsin-Madison, College of Agricultural & Life Sciences Hatch Project 2484. Received 6 Dec. 1982. Approved 8 Nov. 1983.

[2] Research Assistant, Dep. of Soil Science; Professor, Dep. of Soil Science; Assistant Professor, Dep. of Soil Science and Univ. of Wisconsin Extension Geological and Natural History Survey, Univ. of Wisconsin-Madison, respectively.

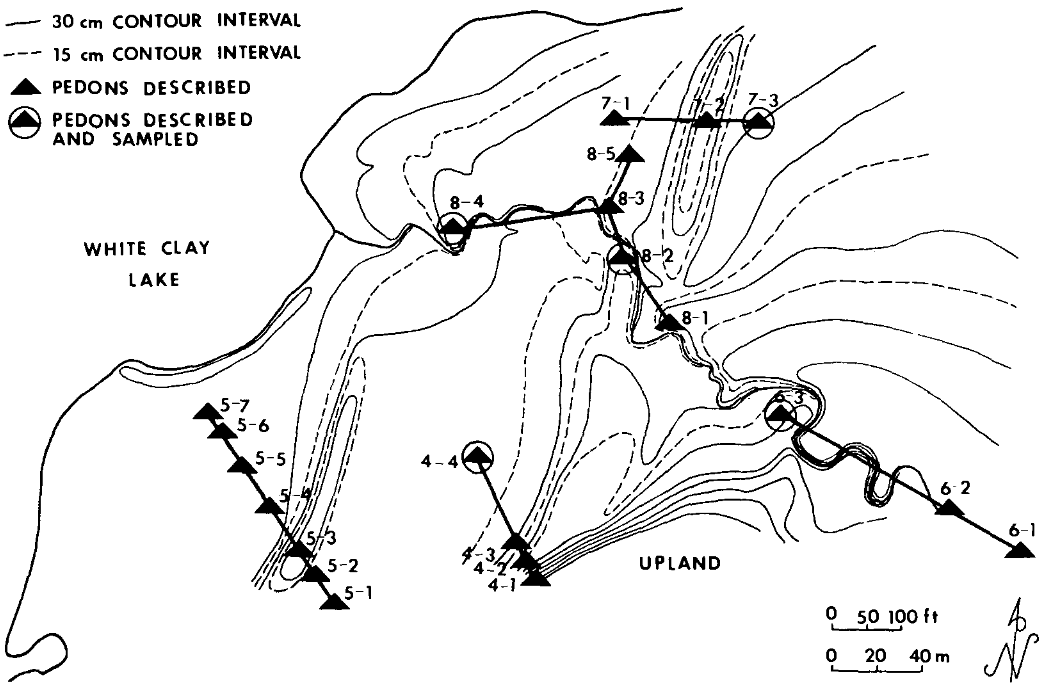

Fig. 1—Pedons described and sampled.

A soil map (Fig. 2) was constructed based on the results of the field studies. Mapping was aided by the interpretation of recent and historical air photos of the wetland. Fourteen map units were designed to graphically portray the soils of the wetland. Most of these units cover areas much smaller than would ordinarily be shown on a detailed soil survey. Two additional mapping units, Onaway sandy loam and Bach silt loam, are described by the USDA Soil Conservation Service (Gundlach et al., 1982) and are mapped on adjacent farmlands. Brief descriptions of pedons representative of all mapping units are in Table 1.

The wetland was surveyed in 1977 and 1978 to compile a detailed topographic map (Fig. 1). The relative surface elevation of each pedon described was estimated using the topographic map, and the pedons depicted in Fig. 3 to 7 were vertically arranged to scale so the thickness and elevation of similar layers could be compared. Samples representative of soil horizons and depositional layers were taken from selected pedons (Fig. 1). Subsamples taken for nutrient characterization were kept frozen until analyzed to arrest microbial activity which might have altered nutrient forms or levels.

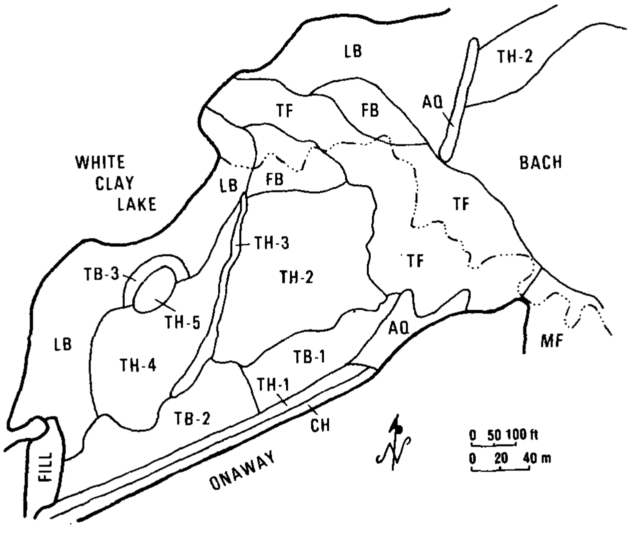

Fig. 2—Soil map of the White Clay Lake wetland. Pedons and mapping unit codes are described in Table 1.

Total P was measured using the method of Murphy and Riley (1962) following perchloric acid digestion. Organic and inorganic P was determined by the Mehta method (Mehta et al., 1954). Ammonium and nitrate were extracted from the soil samples with 2*M* KCl, and the extract was analyzed by Kjeldahl distillation (Black et al., 1965). Organic N was analyzed after digestion with H_2SO_4, K_2SO_4, and Se (Black et al., 1965). The three nitrogen forms were then summed to obtain total N. Particle size distributions were determined for the mineral soils using the hydrometer method described by Day (1956).

RESULTS AND DISCUSSION

Stratigraphic Units (Mineral Deposits)

Glacial Till

Reddish-brown (5YR 5/3), loamy till identified as Valders in age by Thwaites (1943) and Middle Inlet by McCartney and Mickelson (1982) covers the surface of the White Clay Lake watershed to a depth of 3 to 9 m. In the eastern portion of the watershed, the Middle Inlet till overlies mid- or late-Woodfordian till, which is brown (10YR 4/3–5/3) and has a sandy loam texture.

Middle Inlet till is absent in the wetland pedons except along the southern edge of the wetland (Fig. 3) at the scarp of the buried interglacial valley. A small knob of Middle Inlet till is also located beneath the level surface of a sedge meadow adjacent to White Clay Lake (Fig. 2). At one time, this knob must have been a small island in the lake that was later buried by sand, marl, and histic materials (Fig. 4, pedons 5-6 and 5-7). Mid- or late-Woodfordian till was not found in the wetland pedons, but occurs near the surface on the eastern slope of the stream valley (Fig. 5).

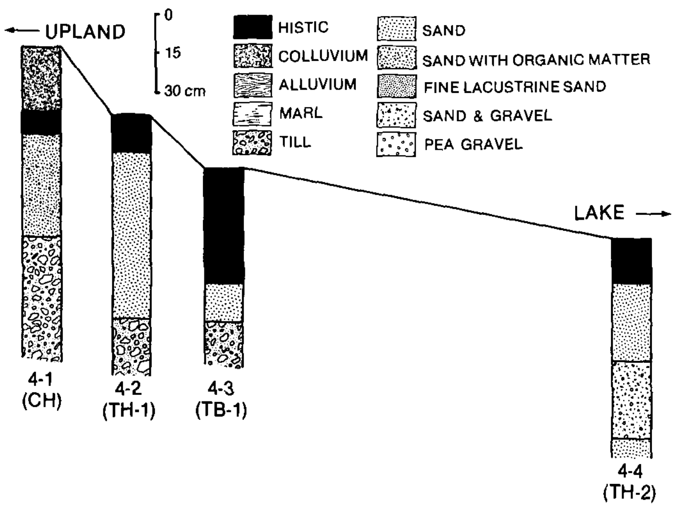

Fig. 3—Transect showing pedons at the southern edge of the wetland.

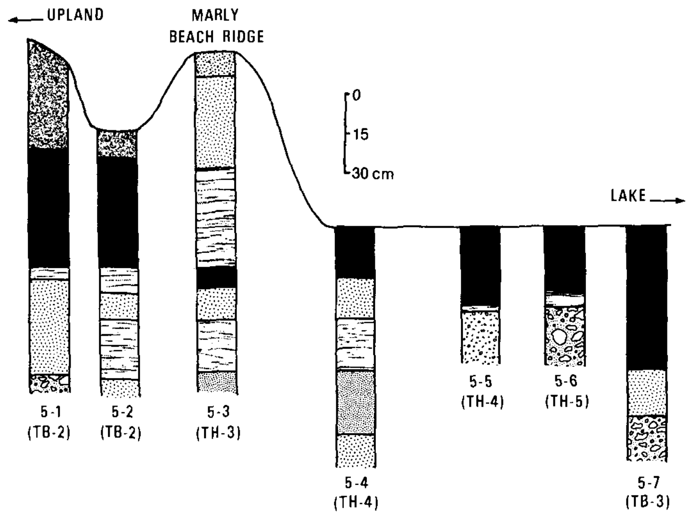

Fig. 4—Transect across marl beach ridge.

Glacio-fluvial Deposits

Most of the wetland is underlain by glacio-fluvial deposits consisting of interbedded sand and gravel. These deposits appear to be confined to the wetland and stream valley, because drill logs for wells in the watershed describe only till and lacustrine deposits (Tolman, 1975). The existing stream apparently flows down a glacial outwash channel that once entered the lake. At the valley-lake plain juncture (Fig. 5, pedons 6–2 and 6–3), the outwash is well sorted and contains shell fragments, which suggests that it was reworked by wave action. The deposits become finer and deeper closer to the lake, where they grade into lacustrine sands and marls. In the middle of the wetland, outwash occurs at 18 cm and is overlain by a histic epipedon (Fig. 3, pedon 4-4). At the northern edge, near the lake, outwash lies at depths of 1.2 m or more (Fig. 7, pedon 8–5) and is overlain by limnic sediments.

Lacustrine Deposits

Aerial photos show six distinct beach ridges across the lacustrine plain at the western edge of White Clay Lake, suggesting progessively lower water levels as glacial waters receded. The beach ridges must be younger than the Early Lake Oshkosh sediments they overlie, and were presumably deposited during the latter part of the Greatlakean substage as the meltwaters filling White Clay Lake receded.

Only two beach ridges are readily apparent in the wetland area studied (Fig. 4, pedon 5–3; Fig. 6, pedon 7–2). There is some topographic (Fig. 1), stratigraphic, and vegetative evidence of a third beach ridge (see Fig. 5, pedon 6–3), but sediments deposited by the existing stream have obliterated most of it.

The two well-defined beach ridges are oriented in a north-south direction. The eastern ridge (Fig. 2) is higher in elevation and is presumably older. It is composed of well-sorted sand (Fig. 6, pedon 7–2), and extends from the upland to the lake edge, except for the section eroded away by the existing stream. The second ridge is parallel to and about 137 m to the west of the first. It separates the shrub carr from a sedge-bulrush marsh adjacent to the lake. This ridge is composed mainly of marl and shelly sand (Fig. 4, pedon 5–3). It is easily seen on the 1938 aerial photographs,

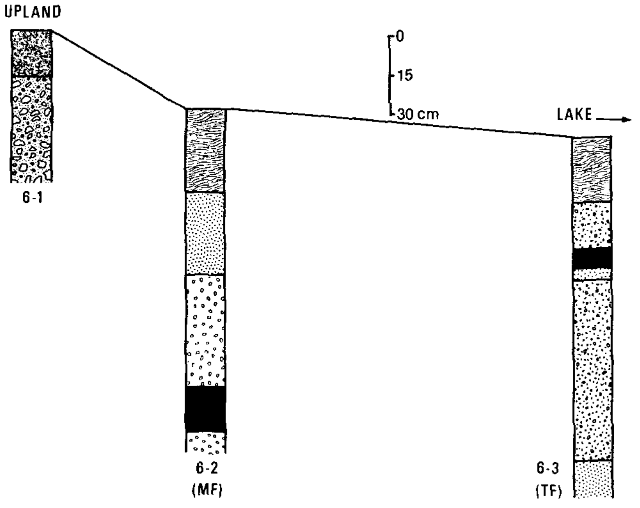

Fig. 5—Transect showing pedons upstream of the wetland.

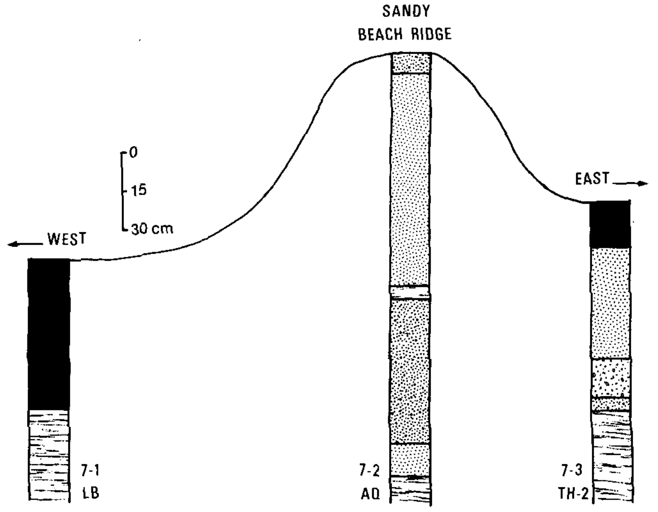

Fig. 6—Transect across sand beach ridge.

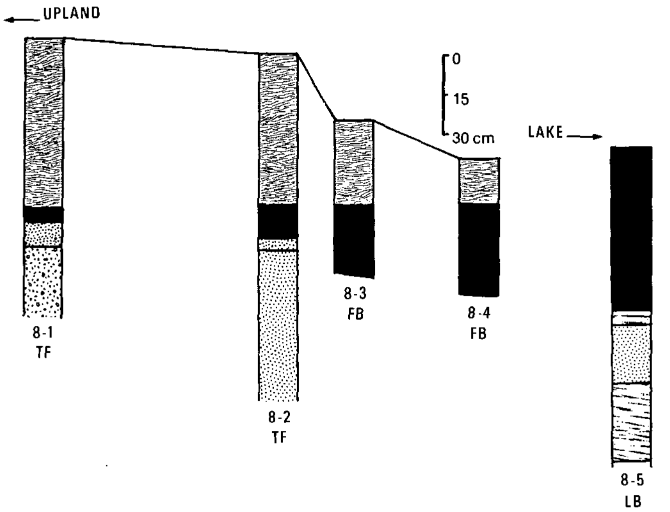

Fig. 7—Transects showing alluvial deposition in the wetland.

but is less visible on subsequent photography. Part of the ridge was apparently excavated and removed, as indicated by its irregular surface topography and a horse-drawn scoop found buried in the muck nearby. The northern end of the ridge terminates near the outlet of the stream, while the southern end terminates near the upland (Fig. 2).

The marl layers that occur in many of the pedons varied in color, particle size distribution, and organic matter content. Some were composed of shell fragments and quartz sand, while others consisted of finely-divided calcite. *Chara*, a marl-forming algae, is the dominant aquatic macrophyte in White Clay Lake (Sullivan, 1978), and was probably instrumental in the deposition of the fine-textured marl.

The uppermost marl layer occurs at a depth of about 0.6 m on the lakeward side of the sandy (eastern) beach ridge, below a very dark brown (10YR 2/2) layer of sapric material. This marl layer was found in pedons 5–1, 5–2, 7–1, and 8–5. It is pale brown in color (10YR 6/3) and contains sedimentary peat (approximately 10% organic matter). It is 5 to 10 cm thick and is underlain by shelly sand or other marl. Its location suggests that it was deposited after the sandy ridge formed. Other marl units in the wetland are thicker and more extensive (Fig. 4, 6, and 7), contain less organic matter, and are lighter colored (5Y 7/2–8/0).

Although most of the sandy layers in the wetland contain pebbles and appear to be of glacio-fluvial origin, other sandy sediments contain large quantities of shell fragments and appear to have been reworked in a lake environment. In most instances it was difficult to determine the origin of sandy layers on the basis of their composition alone. A yellowish brown (10YR 5/8) silt loam stratum containing gleyed (10YR 7/1) laminae appears to be of glacio-lacustrine origin. This deposit lies between the marl beach ridge and the till knob near the lake (Fig. 4, pedon 5–4).

Thick lacustrine silts and clays, assumed to have been deposited in Early Lake Oshkosh, were reported in well logs from the northwestern portion of the watershed (Tolman, 1975), but were not encountered within the wetland.

Colluvium

Colluvium occurs only on sloping land at the southern edge of the wetland (Fig. 3, pedon 4–1; Fig. 4, pedons 5–1, and 5–2). The colluvium is black (10YR 2/1) due to its high organic matter content, and overlies a sapric layer. Its sandy loam texture corresponds to the texture of soils (Onaway sandy loam) on the surrounding upland (Fig. 2).

Alluvium

Alluvium has been deposited over much of the wetland surface by the small stream that transports sediment from the watershed. These sediments are thickest in the low natural levees adjacent to the stream where it enters the wetland (Fig. 7, pedon 8–1). Here, up to 66 cm of silt loam alluvium have buried the Histosol which was probably the preagricultural wetland surface.

Along the stream banks, the thickness of alluvium decreases with distance from the upland (Fig. 7). Surficial alluvium thickness also decreases with distance perpendicular to the stream, becoming negligible 25 m away from it (compare pedons 8–3 and 8–5, Fig. 7). Loamy alluvium is on the steeper slopes of the stream valley above the wetland (Fig. 5). Sandy alluvium far from the upland is assumed to be the bottom of an abandoned stream channel (Fig. 7, pedon 8–4).

Stratigraphic Units (Histic Deposits)

Wetlands are very productive ecosystems (Moore and Bellamy, 1974; Richardson, 1979). However, anaerobic conditions in wetland soils provide a poor environment for most organisms that decompose organic matter. This combination of high productivity and slow decomposition promotes the accumulation of histic materials.

The rate of peat accumulation is controlled by wetland hydrology, wetland chemistry, the quality and amount of plant litter, the kind and number of decomposers, and climatic conditions. Once deposited, histic materials can be removed by streams, glacial scouring, or fire (Heinselman, 1963). Published estimates of peat accumulation rates in the U.S. vary substantially. Heinselman reported a value of 0.05 cm/yr in Minnesota, while Heilman (1968) reported values of up to 0.38 cm/yr in Alaska. For the White Clay Lake wetland, Madison (unpublished data, 1983) reports a radiocarbon date of 620 ± 70 B.P. (Wis–1397) on wood fragments collected between 40 and 60 cm in the marl below the histic materials, which are characteristically 50 cm thick. Therefore, approximately 50 cm of histic materials and 50 cm of marl have accumulated in about 600 years. If marl and peat have formed at equal rates, this is equivalent to the rate of 0.17 cm/yr of peat accumulation reported by Curtis (1959) for a bog in the Valders Moraine of Vilas County, WI.

Histic layers occur all over the White Clay Lake wetland, usually at the soil surface. The histic deposits between the marly beach ridge and the lake are about 30 cm thick, and are probably the youngest histic materials in the wetland. Those in the northern part, over the "organic marl" layer previously described, are

Table 1—Characteristics of pedons typical of soil mapping units in the White Clay Lake wetland.

Depth of layer	Kind of material	Munsell color	Texture or decomposition
cm			
	Pedon 4-1 Cumulic Haplaquolls (CH)†		
0–25	Colluvium	10YR 2/1	sl
25–36	Histic	10YR 2/1	sapric
36–76	Beach	10YR 3/1	sl
76–107	Water-worked Middle Inlet till	5YR 5/3	scl
107+	Middle Inlet till	5YR 5/3	cl
	Pedon 4-2 Typic Haplaquents (TH-1)		
0–15	Histic	10YR 2/1	sapric
6–81	Beach	10YR 8/2	sand w/pebbles and shells
81+	Middle Inlet till	5YR 5/3	cl
	Pedon 4-3 Terric Borosaprists (TB-1)		
0–46	Histic	10YR 2/1	sapric
46–61	Beach	10YR 8/2	calcareous sand
61+	Middle Inlet till	5YR 5/3	cl
	Pedons 4-4, 7-3 Typic Haplaquents (TH-2)		
0–18	Histic	10YR 2/1	sapric
18+	Glacio-fluvial	--	sand w/pebbles and marl
	Pedons 5-1, 5-2 Terric Borosaprists (TB-2)		
0–38	Colluvium	10YR 2/1	sl
38–84	Histic	10YR 2/1	sapric
84–89	Lacustrine	10YR 6/3	marl w/organic matter
89–148	Beach	5Y 6/1	calcareous sand
148+	Middle Inlet till	5YR 5/3	cl
	Pedon 5-3 Typic Haplaquents (TH-3)		
0–10	Beach	10YR 4/2	sl
10–25	Beach	10YR 7/2	sand w/shells
25–33	Beach	10YR 7/2, mottled	sand
33–48	Beach	5Y 7/2	sand w/shells
48–64	Beach	10YR 6/3	sandy marl
64–86	Beach	2.5Y 5/2	sandy organic marl
86–94	Histic	2.5Y 3/2	coprogenous earth
94–107	Glacio-fluvial?	5Y 6/1	sand w/shells
107–127	Lacustrine	5Y 7/1	marl
127+	Lacustrine	5YR 5/8	sand
	Pedons 5-4, 5-5 Typic Haplaquents (TH-4)		
0–30	Histic	10YR 2/2	sapric
30+	Lacustrine, glacio-fluvial	--	marl and sand
	Pedon 5-6 Typic Haplaquents (TH-5)		
0–25	Histic	10YR 2/2	sapric
25–30	Lacustrine	5Y 6/1	marl
30+	Middle Inlet till	5YR 5/3	cl
	Pedon 5-7 Terric Borosaprists (TB-3)		
0–30	Histic	10YR 2/2	sapric
30–56	Histic	10YR 2/2	sapric w/marl
56–71	Glacio-fluvial?	--	sand
71+	Middle Inlet till	5YR 5/3	cl
	Pedon 6-2 Mollic Fluvaquents (MF)		
0–10	Alluvium	10YR 3/1	sl
10–33	Alluvium	10YR 3/1, mottled	sl
33–53	Beach?	10YR 6/3	sand
53–66	Beach?	10YR 3/2	ls w/wood fragments
66–109	Glacio-fluvial?	--	coarse pea gravel
109–127	Histic	10YR 2/1	sapric
127+	Glacio-fluvial	--	gravel
	Pedons 6-3, 8-1, 8-2 Thapto-histic Fluvaquents (TF)		
0–58	Alluvium	10YR 2/2	fsl to sil
58–71	Sapric	10YR 2/1	sapric
71–76	Glacio-fluvial	10YR 3/1	ls
76+	Glacio-fluvial	--	sand w/ or w/o marly layers
	Pedons 8-3, 8-4 Fluvaquentic Borosaprists (FB)		
0–33	Alluvium	10YR 2/2	sil
33–51	Histic	10YR 2/1	sapric
51–74	Histic	10YR 2/2	hemic
74–79	Lacustrine	2.5YR 6/2	marl w/organic matter
79+	Lacustrine, glacio-fluvial	--	marl and shelly sand
	Pedons 7-1, 8-5 Limnic Borosaprists (LB)		
0–10	Histic	10YR 2/1	silty sapric
10–28	Histic	10YR 2/1	sapric
28–51	Histic	10YR 2/2	hemic
51–58	Histic	10YR 2/2	hemic
58–66	Lacustrine	2.5Y 6/2	marl w/organic matter
66–112	Lacustrine	5Y 6/1	marl
112+	Glacio-fluvial	--	sand w/pebbles
	Pedon 7-2 Aquic Quartzipsamments (AQ)		
0–8	Beach	10YR 3/1	ls
8–15	Beach	10YR 5/3	ls
15–91	Beach	10YR 7/2	sand
91–97	Lacustrine	10YR 6/1	marl w/sand
97–122	Beach	--	coarse sand
122–135	Beach	10YR 4/1	sand
135–152	Beach	10YR 5/2	sand w/shells
152+	Glacio-fluvial, lacustrine	--	sand w/pebbles near upland marl near lake
	Bach silt loam Mollic Haplaquepts		
0–20	Lacustrine	10YR 2/1	sil
20–30	Lacustrine	10YR 5/1, mottled	sil
30–41	Lacustrine	10YR 6/2, mottled	vfs
41–61	Lacustrine	10YR 6/2, mottled	vfsl and sil
61–74	Lacustrine	10YR 6/2, mottled	vfs and vfsl
74–122	Lacustrine	10YR 6/2, mottled	sil and vfs
122–152	Lacustrine	10YR 5/1	sil
	Onaway fine sandy loam Alfic Haplorthods		
0–23	Middle Inlet till	7.5YR 3/2	fsl
23–38	Middle Inlet till	7.5YR 5/2	fsl
38–58	Middle Inlet till	5YR 3/4	loam
58–71	Middle Inlet till	5YR 3/4	loam
71–152	Middle Inlet till	7.5YR 4/4	sl

† Letters in parentheses stand for map unit.

thickest. Histic layers at or near the wetland surface along its southern boundary slope gently upward (Fig. 3). Tolman (1975) has shown that the groundwater in this vicinity has an upward gradient which would permit organic matter accumulation on a sloping surface.

No hemists or fibrists are mapped in the SCS Soil Survey for Shawano County (Gundlach et al., 1982), and none were found in the White Clay Lake wetland. The organic epipedons in the wetland are all sapric. Hemic layers lie above the marl in the Fluvaquentic Borosaprist and Limnic Borosaprist pedons (Table 1), but are overlain by 28 cm or more of sapric material.

Several factors probably promote decomposition of organic matter in the White Clay Lake wetland. Seasonal fluctuation of the water table allows the surface layers to dry out periodically, creating an environment suitable for aerobic decomposition. The parent materials from which the Histosols are now being derived (predominantly sedges and grasses) are easily decomposed, and the high pH is also conducive to microbial activity. The hemic layers contain more wood fragments than the overlying saprics, and were probably derived from plant species more resistant to decay. The water table was probably also more stable at the time the hemic layers were being deposited, keeping them saturated most of the time.

Some Histosols in the wetland appear to have been partially eroded by stream flow (Fig. 7, pedons 8–3 and 8–4). The present sandy stream bottom overlies histic material west of the sandy beach ridge. Alluvial silts are mixed with the surface layers of the Histosols in those areas where flooding has occurred.

Although most of the histic material in the wetland accumulated after formation of the older beach ridge, some histic layers pre-date the ridge, and lie deeper in the soil profile. In pedon 6–2 an 18 cm thick sapric layer at 109 cm underlies coarse pea gravel, which is assumed to be of glacial-fluvial origin. Other glacio-fluvial deposits occur below the sapric layer. Using the estimate of 0.17 cm/yr it would take at least 100 yr for an organic layer 18 cm thick to form. If erosion and compression of the organic layer occurred during deposition of the upper gravelly deposit, the time interval between deposition of the two outwash deposits probably exceeds 200 yr.

Wetland Topography

After glacial ice receded from the Athelstane moraine, the topography of the area now occupied by the wetland was probably much more hilly. The kettlehole in the lake and the knob of Middle Inlet till under the wetland (Fig. 4, pedon 5–6) indicate the variation in surface elevation which could have occurred at that time, about 11,900 yr B.P. As glacial meltwaters flowed into the area from the valley southeast of the wetland, the Middle Inlet till was subsequently buried by nearly horizontal glacial-fluvial beds. Marl and other glacio-lacustrine sediments further subdued the surface topography of the wetland area, creating a shallow water bay in the post-Greatlakean White Clay Lake. As wetland plants grew and decomposed in the bay, histic materials accumulated. Low beach ridges were deposited and Histosol formation began with the recession of the lake level.

Although the resulting wetland appears to be flat and level, there are small but significant variations in its topography. The stream flowing through the wetland has eroded through the beach ridges and Histosols in places, and deposited alluvium in others. Field observations during runoff events which flooded the wetland revealed that the low natural levees and beach ridges have an important effect on patterns of water flow through the wetland. Once floodwaters overtop the levees, they tend to stagnate in slackwater areas having histic epipedons farther from the stream (soil LB north of the stream and soil TH–2 south of the stream in Fig. 2). The decrease in flow velocity would promote settling of suspended solids, and prolong soil-surface water interaction. The levees act as leaky dams, keeping some of the floodwaters in the wetland long after peak flow. The two beach ridges have a similar effect, maximizing the retention time of floodwaters in the wetland.

Nutrient Content of Stratigraphic Units

Other work by the authors (Johnston, 1982) has shown that P concentrations in the upper 15 cm of the soil are highly correlated with distance from the stream that flows through the White Clay Lake wetland. In this study, nutrient concentrations were measured in depositional units from throughout five pedons (see Fig. 1 and Table 2) to evaluate recent alterations of wetland soil chemical properties by accelerated erosion from surrounding agricultural lands.

The concentrations of organic N, NH_4^+-N, and NO_3^--N in the wetland soils are related not only to the amount of organic matter in the material deposited but to the topography of those deposits. Organic N and ammonium are very highly correlated ($P < 0.01$) with percent organic matter in the soil, but nitrate concentrations are not related to percent organic matter. The highest NO_3^--N concentration (41.1 mg/kg) is in the upper 20 cm of profile 8–2 (Fig. 7), indicating that nitrification may be taking place locally in the aerobic zone of the alluvial silt loam levees. The surface horizons of pedons 4–4 and 6–3 are also relatively high in nitrate (8.1 and 9.7 mg/kg, respectively), but pedon 8–4 has almost no nitrate in its upper 30 cm. The same horizons of pedon 8–4 have the highest ammonium concentrations of any layers sampled. Since this Histosol is usually saturated to the surface, there is probably insufficient oxygen present for the ammonium to be nitrified to nitrate, and denitrification may be depleting whatever nitrate is produced within the soil or added to it by floodwaters. There is very little nitrate or ammonium in the lower horizons of any soil.

In contrast, phosphorus concentrations are more related to type and age of deposit rather than to the topography of the deposits (Table 2). Total P concentrations are lowest in glacio-fluvial deposits and marl. Organic P concentrations are highest in silt loam alluvium and histic deposits, while inorganic P is highest in silt loam alluvium. Total P in the alluvium and glacio-fluvial deposits is very highly correlated ($P < 0.01$) with percent silt plus clay.

Because P concentrations vary so much with the type of material deposited, it is difficult to differentiate the effects of time alone. With the exception of sandy alluvium, the oldest deposits (i.e., glacio-fluvial and marl deposits) have much lower P concentrations than do more recent deposits (Table 2). This is partially due to increased erosion of P from the watershed with time. However, age of the deposit is not the only factor

Table 2—Average nutrient concentrations (mg/kg) in depositional units from five wetland soils.

Type of material	Inorganic P	Organic P	Total P	NH_4^+-N	NO_3^--N	Organic N	Total N
Sapric	394	391	786	17.2	4.7	14 690	14 712
Alluvium (sil)	525	401	926	9.8	27.1	7 090	7 127
Alluvium (sl-ls)	325	107	432	6.8	6.5	894	907
Sand alluvium	178	42	220	8.4	0.8	1 135	1 144
Marl	109	42	151	1.6	0.8	2 854	2 856
Glacio-fluvial	114	29	143	1.1	1.2	431	433

affecting P concentrations because recently deposited sandy alluvium has only slightly higher P concentrations than the older glacio-fluvial and marl deposits (Table 2). This is presumably because sand has a lower P sorbing capacity than the finer materials found elsewhere at the wetland soil surface (i.e., the silt loam alluvium and histic deposits).

CONCLUSIONS

Soils of the White Clay Lake wetland contain a variety of stratigraphic units. The thickness of the various depositional layers is quite variable, but their sequence is predictable in most places. They are of both glacial and recent origin. Till or glacio-fluvial deposits underlie most of the pedons described. All of the till found in the wetland pedons is of Middle Inlet age.

Although Glacial Lake Oshkosh deposited very deep lacustrine sediments in the basin now occupied by White Clay Lake, the lacustrine deposits found in the White Clay Lake wetland appear to be of more recent origin. Marl, a constituent of many of the wetland pedons, is no longer being deposited in the wetland, although it continues to accumulate in the adjacent lake bottom. Thwaites (1943) included White Clay Lake as part of later Glacial Lake Oshkosh, which formed at the face of what he called the Valders ice sheet, but the location of beach ridges around White Clay Lake and the stratigraphy of its wetland soils support Horn's (1959) contention that White Clay Lake was isolated from Later Lake Oshkosh. The uppermost elevation of those beach ridges, 247 m, indicates that White Clay Lake's post-Greatlakean elevation was at least 1.5 m higher than at present.

With the exception of the two beach ridges in the study site, the glacial and lacustrine deposits in the wetland are all overlain by sapric material. Alluvium and colluvium cover the sapric material near the stream and upland, respectively. Soils formed in the wetland are very young and not well developed. Alluvium, colluvium, and histic materials continue to be deposited in the White Clay Lake wetland.

Because the band of alluvial soils adjacent to the stream in the wetland is relatively narrow (Fig. 2), and the alluvium overlies histic layers having surface elevations similar to adjacent histic epipedons (Fig. 7), the alluvium was probably deposited very recently. Most of the wetland probably had a histic epipedon until the late 1800s, when agricultural cultivation accelerated soil erosion from the watershed. Upland erosion has been most severe since fast-maturing corn was introduced to the watershed in the 1950s. The recent build-up of silt loam levees next to the stream has created aerobic soil conditions locally conducive to nitrification. Nitrification does not appear to be occurring at other locations in the wetland.

Histosol formation is regarded as the most important soil nutrient-trapping mechanism in wetlands by at least one wetland evaluation scheme (Tilton et al., 1978). Although histic materials have been shown to be effective for removing P from sewage effluent in both natural (Kamppi, 1971; Surakka and Kamppi, 1971; Kadlec, 1979) and artificial waste treatment systems (Farnham, 1974; Stanlick, 1976), it is probably because P-containing particles are settling out of the water or P is being sorbed onto the soil particles. Histosol formation is too slow a process to account for substantial P removal.

At the White Clay Lake wetland, P concentrations are highest in the silt loam alluvium, and up to 66 cm of alluvium have been deposited over the pre-settlement wetland soil since cultivation of the watershed began in the late 1800s. Although a considerable amount of P is also contained in histic deposits, an equivalent depth of organic soil would take approximately 390 years to form, no more than one third of the rate of alluvial deposition. Therefore, the accumulation of alluvium has been the most effective mechanism for the retention of P in the White Clay Lake wetland.

ACKNOWLEDGMENTS

This study was supported through U.S. Environmental Protection Agency Grant no. R804823, Univ. of Wisconsin-Extension and Univ. of Wisconsin-Madison, Dep. of Soil Science. Support is also acknowledged for Hatch Project 2494, "Characteristics, Classification and Evaluation of Wisconsin Histosols." K. Lund performed the laboratory analyses.

The cooperation of residents of the watershed, particularly Thomas and David Brunner and their families, was an essential part of this entire study, and is greatly appreciated.

REFERENCES

1. Black, C.A., D.D. Evans, J.L. White, L.E. Ensminger, F.E. Clark, and R.C. Dinauer (ed.) 1965. Methods of soil analysis, Part 2. Agronomy 9. Am. Soc. of Agron., Madison, Wis.
2. Curtis, J.T. 1959. The vegetation of Wisconsin: An ordination of plant communities. Univ. of Wisconsin Press, Madison.
3. Day, P.R. 1956. Report of the Committee on Physical Analyses, 1954–55, Soil Science Society of America. Soil Sci. Soc. Am. Proc. 20:167–169.
4. Farnham, R.S. 1974. Use of organic soils for wastewater filtration. p. 111–118. *In* A.R. Aandahl et al. (ed.) Histosols: Their characteristics, classification, and use. Soil Sci. Soc. Am. Spec. Publ. no. 6. Madison, Wis.
5. Gundlach, H.F., J.E. Campbell, T.J. Huffman, W.L. Kowalski, R.L. Newbury, and D.C. Roberts. 1982. Soil Survey of Shawano County, Wisconsin. U.S. Government Printing Office, Washington, D.C.
6. Heilman, P.E. 1968. Relationship of availability of phosphorus and cations to forest succession and bog formation in interior Alaska. Ecology 49:331–336.
7. Heinselman, M.L. 1963. Forest sites, bog processes, and peatland types in the Glacial Lake Agassiz region, Minnesota. Ecol. Monogr. 33:327–374.
8. Horn, M.E. 1959. A pedological study on red clay soils and their parent materials in eastern Wisconsin. Ph.D. Thesis. Univ. of Wisconsin-Madison. Univ. Microfilms, Ann Arbor, Mich. (Diss. Abstr. 20:3909).
9. Johnston, C.A. 1982. Effects of a seasonally flooded freshwater wetland on water quality from an agricultural watershed. Ph.D. Thesis. Univ. of Wisconsin-Madison. Univ. Microfilms, Ann Arbor, Mich. (Diss. Abstr. 43:34B).
10. Kadlec, R.H. 1979. Wetlands for tertiary treatment. p. 436–456. *In* P.E. Greeson et al. (ed.) Wetland functions and values: The state of our understanding. Proc. Nat. Symp. on Wetlands. Lake Buena Vista, FL. 7–10 Nov. 1978. Am. Water Res. Assoc., Minneapolis.
11. Kamppi, A. 1971. Studies of wastewater disposal on peatland forest basin infiltration systems which were in effect in Finland in 1970. Report A4, Nat. Board of Waters, Finland. (Finnish-English summary).
12. McCartney, M.C., and D.M. Mickelson. 1982. Late Woodfordian and Greatlakean history of the Green Bay Lobe, Wisconsin. Geol. Soc. Am. Bull. 93:297–302.
13. Mehta, N.C., J.O. Legg, C.A.I. Goring, and C.A. Black. 1954. Determination of organic phosphorus in soils. I. Extract method. Soil Sci. Soc. Am. Proc. 18:443–449.
14. Moore, P.D., and D.J. Bellamy. 1974. Peatlands. Springer-Verlag, New York.
15. Murphy, J., and J.P. Riley. 1962. A modified single solution

method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

16. Richardson, C.J. 1979. Primary productivity values in freshwater wetlands. p. 131–145. *In* P.E. Greeson et al. (ed.) Wetland functions and values: The state of our understanding. Proc. Nat. Symp. on Wetlands. Lake Buena Vista, FL. 7–10 Nov. 1978. Am. Water Res. Assoc., Minneapolis.
17. Stanlick, H.T. 1976. Treatment of secondary effluent using a peat bed. p. 257–268. *In* D.L. Tilton et al. (ed.) Proc. Nat. Symp. on Freshwater Wetlands and Sewage Effluent Disposal. Univ. of Michigan, Ann Arbor. 10–11 May 1976. Univ. of Michigan, Ann Arbor.
18. Sullivan, J.F. 1978. Distribution of aquatic macrophytes in White Clay Lake, Wisconsin. Report to the Office of Inland Lake Renewal, Dep. of Natural Resources, Madison, Wis.
19. Surakka, S., and A. Kamppi. 1971. Infiltration of waste water into peat soil. Suo 22:51–58. (Finnish-English summary).
20. Thwaites, F.T. 1943. Pleistocene of part of northeastern Wisconsin. Bull. Geol. Soc. Am. 54:87–144.
21. Tilton, D.L., R.H. Kadlec, and B.R. Schwegler. 1978. The ecology and values of Michigan's coastal wetlands, Phase II. Great Lakes Shoreland Section, Div. of Land Resources Program, Michigan Dep. of Natural Resources.
22. Tolman, A.L. 1975. The hydrogeology of the White Clay Lake area, Shawano County, Wisconsin. M.S. Thesis, Univ. of Wisconsin-Madison.