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Interactions Between Ground Water and Wetlands, Southern Shore of Lake Michigan, USA

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Interactions between ground water and wetlands, southern shore of Lake Michigan, USA

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ABSTRACT

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Wetlands between, and within, dune–beach complexes along the south shore of Lake Michigan are strongly affected by ground water. The hydrogeology of the glacial drift aquifer system in a 26 km^2 area was investigated to determine the effects of ground water on the hydrology and hydrochemistry of Cowles Bog and its adjacent wetlands. The investigation showed that ground water from intermediate- and regional-scale flow systems discharges to Cowles Bog from confined aquifers that underlie the wetland. These flow systems are recharged in moraines south of the dune–beach complexes.

Water from the confined aquifers discharges into the surficial aquifer mainly by upward leakage through a buried till sheet that serves as the confining layer. However, the till sheet is breached below a raised peat mound in Cowles Bog, allowing direct upward discharge from the confined aquifer into the surficial sand, marl, and peat. The shallow ground and wetland water in the area influenced by this leakage is a calcium magnesium bicarbonate type, with low tritium concentrations consistent with mixing of older ground water and more recent precipitation. Ground water and wetland water from surrounding areas are less mineralized and have higher tritium concentrations characteristic of precipitation in the late 1970s.

The results of this study suggest that wetlands in complex hydrogeologic settings may be influenced by multiple ground-water flow systems that are affected by geomorphic features, stratigraphic discontinuities, and changes in sediment types. Discharge and recharge zones may both occur in the same wetland. Multidisciplinary studies incorporating hydrological, hydrochemical, geophysical, and sedimentological data are necessary to identify such complexities in wetland hydrology.

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INTRODUCTION

The Great Lakes region of Canada and the United States is underlain by a variety of glacial, lacustrine, and aeolian sediments. The landscapes developed on these deposits consist of many ridge-forming geomorphic features such as moraines and dune complexes. Commonly, the intervening lowlands contain wetlands.

Toth (1963) and Freeze and Witherspoon (1967) have shown that a hierarchy of ground-water flow systems of different scale and depth develop in such hummocky terranes. Toth used the terms local, intermediate, and regional to classify ground-water flow systems in order of increasing length of flow path. The complex spatial distribution of buried aquifers and confining beds in glacial deposits (Ashley et al., 1985) also affects ground-water flow paths. Freeze and Witherspoon have shown theoretically how hydrogeologic complexities influence ground-water flow paths, and Winter (1976) has demonstrated the same for hypothetical lake–aquifer systems. Similar work has been done in wetlands by Winter and Carr (1980) and Siegel (1981).

The work of these previous investigators has raised the interest of wetland scientists in understanding the hydrogeologic setting of wetlands. Differences in ground-water flow and ground-water chemistry associated with complex hydrogeologic settings have been shown to affect the diversity and composition of plant communities in wetland ecosystems (Siegel, 1983; Wilcox et al., 1986; LaBaugh et al., 1987). These workers and Shedlock et al. (1988) have shown that the hydrochemistry of individual wetlands is often controlled by their position in the ground-water flow system. Therefore, preservation and management of wetlands requires an understanding of the ground-water flow systems that influence the water balance and hydrochemistry of wetlands.

Because of the inaccessibility of most wetlands, detailed hydrogeologic study of wetlands is difficult, and most hydrologic studies in wetlands are local investigations with ecological objectives. Wetlands within, and between, dune complexes along the south shore of Lake Michigan in Indiana (Fig. 1) are relatively accessible, however. This area is known as Indiana Dunes and much of the shoreline property between Gary and Michigan City, Indiana, is parkland within either Indiana Dunes National Lakeshore or Indiana Dunes State Park. These parklands contain dunes, beaches, and wetlands that are relatively undeveloped and easily accessed.

One of the most ecologically significant wetland areas in the Indiana Dunes area is a National Natural Landmark known as Cowles Bog (Fig. 2), a 22 ha tract of a large interdunal wetland called the Great Marsh. Cowles Bog and surrounding areas of the Great Marsh contain a unique assemblage of swamps of red maple, tamarack, and northern white cedar, areas of sedge
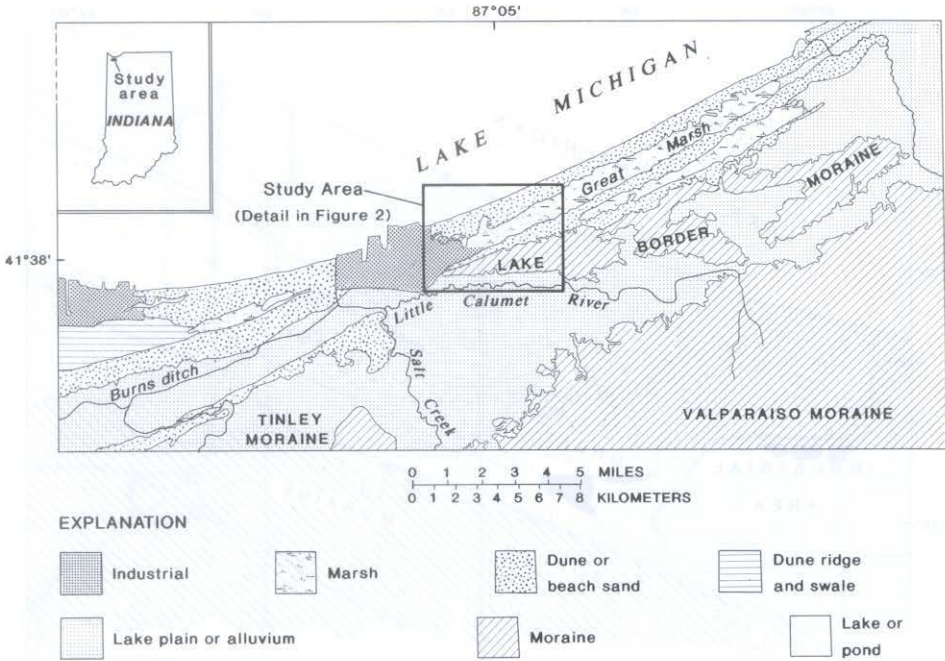
Fig. 1. Simplified surficial geology map of south shore of Lake Michigan, northwest Indiana.

meadow, and cattail/phragmites marshes interspersed with shrub zones (Wilcox et al., 1984). Cowles Bog contains a peat mound topographically raised above the surrounding wetland (Wilcox et al., 1986). Ground water from an underlying confined aquifer discharges into the sands, marls, and peats that form the mound through an underlying breach in the clay-till-confining layer. In spite of its name, Cowles Bog is not a true bog. It is ecologically classified as a fen because it receives water from the ground-water flow system (Boelter and Verry, 1977; Gore, 1983; Wilcox et al., 1986.)

Previous hydrologic studies of the region around Cowles Bog were done to assess the potential for changes in the water table caused by local industrial activities (Marie, 1976; Meyer and Tucci, 1979; Gillies and Lapham, 1980; Cohen and Shedlock, 1986). These studies investigated real and simulated changes in water levels and water quality that could affect the plant communities in the wetlands around Cowles Bog.

This paper presents results of a field study of the hydrogeology and hydrochemistry of the Cowles Bog portion of the Great Marsh and surrounding areas of Indiana Dunes National Lakeshore. The purpose of this paper is to describe the regional, intermediate, and local ground-water flow systems in the glacial drift and upper bedrock and demonstrate the effects of these flow
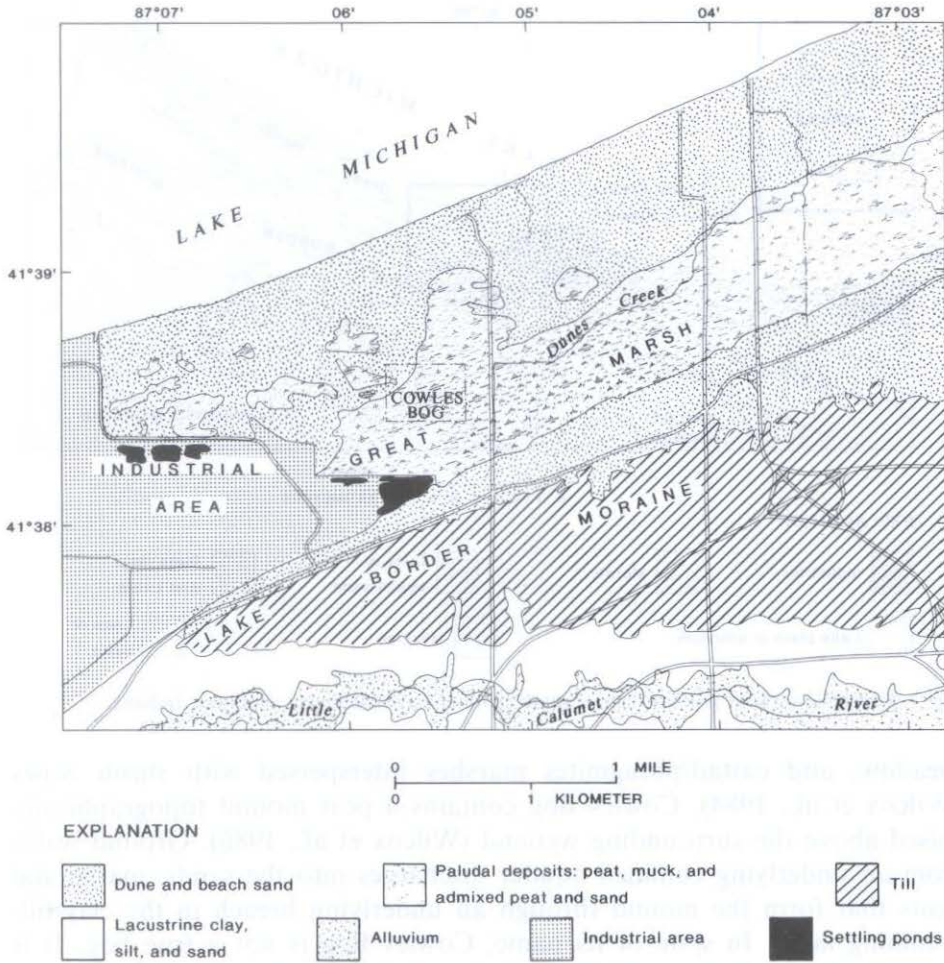
Fig. 2. Map of study area showing surficial geology, drainage, and location of Cowles Bog.

systems on the hydrology and hydrochemistry of the wetlands around Cowles Bog.

METHODS

The interpretations in this paper are based on sedimentological, geophysical, and hydrochemical data from a network of test holes and wells (Fig. 3) installed between 1979 and 1984. Thirteen test holes were drilled to the bedrock surface in the study area using mud-rotary methods. One to three observation wells were installed at each of these sites at different depths, depending on the vertical distribution of aquifers. Gamma-radiation logs

Fig. 3. Map of study area showing locations of test holes, wells, and cores, lines of section, and areal extent of buried aquifers.

were obtained in the deep well at each site and compared with the driller's logs to aid in interpretation of vertical lithologic changes. In addition, eight test holes, 15–30 m deep, were drilled with a power auger to collect samples to aid in differentiating till from lacustrine clay at midlevels in the glacial drift. Sedimentological and stratigraphic variations in the near-surface sediments (0–8 m deep) were determined from 15 cores obtained with a vibracorer, modified from the design of Finkelstein and Prins (1981).

Observation wells finished in buried aquifers were constructed of 10 cm

diameter plastic polyvinyl chloride (PVC) pipe with 1.5 m long slotted plastic PVC screens. Wells in the surficial aquifer at sites accessible to a drill rig were also constructed of PVC pipe, whereas wells in the surficial aquifer within the wetlands were hand-driven 10 cm diameter steel pipe with 0.75 m long slotted steel screens.

Water samples were collected for chemical analysis from wells in both the surficial and confined aquifer systems. Water on the peat surface in the Great Marsh and pore waters of peat on the raised mound in Cowles Bog were also collected at well sites. The pore waters were collected from small depressions (10–20 cm deep) dug into the peat at well sites with no standing water on the peat surface. Alkalinity, pH, temperature, and specific conductance were measured in the field using the methods recommended by Wood (1976). All samples were analyzed at U.S. Geological Survey laboratories for calcium, magnesium, sodium, potassium, sulfate, chloride, and several minor elements according to the methods of Skougstad et al. (1979). Samples of ground water and surface water at selected sites were also analyzed for tritium to distinguish ground waters recharged before atmospheric testing of thermonuclear devices in the early 1950s from those recharged after such testing (Payne, 1972).

The chemical equilibrium program WATEQF (Plummer et al., 1976) was used to compute the saturation state of several water samples with respect to calcite, dolomite, and gypsum.

HYDROGEOLOGIC SETTING

Surficial geology and drainage

Indiana Dunes is within the physiographic province known as the Calumet Lacustrine Plain (Schneider, 1966). The surficial sediments are lacustrine, beach, dune, and paludal deposits formed in the proglacial lake environment between the ice front and the Valparaiso moraine (Fig. 1), the major Wisconsinan stage end-moraine in the region. The Calumet Lacustrine Plain also contains surficial tills (including the Tinley and Lake Border moraines) formed during readvances of the glacial ice into the Lake Michigan basin that are younger than the advance that deposited the Valpariso moraine. The history of the proglacial lake that formed the Calumet Lacustrine Plain, known as Lake Chicago, is described by Leverett and Taylor (1915), Bretz (1951, 1955), and Hough (1958). Alternatives to the lake level models in these older works are discussed by Hansel et al. (1985).

Several distinct, dune–beach complexes were formed in this province when the proglacial lake levels were higher than the present mean level of Lake Michigan. These dune–beach complexes are well preserved and are now

stabilized by vegetation. They extend across the study area roughly parallel to the modern shoreline of Lake Michigan (Fig. 1). The lowlands between, and within, the dune complexes are wetlands. Cowles Bog (Fig. 2) is in the Great Marsh, an interdunal lowland and the largest wetland in the national lakeshore. The Great Marsh is bounded on the north by a dune complex that extends to the modern shoreline of Lake Michigan. The upland along the south margin of the Great Marsh consists of dune and beach sediments from both the Calumet and Glenwood levels of proglacial Lake Chicago (Leverett and Taylor, 1915; Bretz, 1951) deposited on the north slope of the Lake Border moraine.

The crest of the Lake Border moraine is a major drainage divide for the study area. North of the divide, surface flow in the eastern half of the study area is to Dunes Creek (Fig. 2), a natural stream that flows into Lake Michigan. Surface flow in the western half of the study area is to a man-made ditch system in the industrial area. South of the crest of the moraine, drainage is to the Little Calumet River, which parallels the south margin of the moraine. A network of ditches constructed in the early 1900s drains the Great Marsh near Cowles Bog (Cook and Jackson, 1978). This network is too detailed to show in any of the figures, but the entire network drains into Dunes Creek east of Cowles Bog (Fig. 2).

Hydrogeologic framework

The study area is underlain by unconsolidated glacial, lacustrine, and aeolian sediments of Pleistocene and Holocene age, ranging from 30 to 70 m thick. These sediments were deposited on a bedrock surface modified by pre-Pleistocene erosion. The bedrock consists of Mississippian and Devonian shales and Silurian carbonate rocks.

The upper part of the bedrock forms a regional aquifer that underlies the study area and all of the area show in Fig. 1. The bedrock aquifer is overlain by a sequence of undifferentiated clays with silt and sand (Figs. 4 and 5). Below the Lake Border moraine and the Great Marsh these undifferentiated clays are overlain by a unit of sand, silty sand, and sand and gravel. This unit forms a confined aquifer referred to as the subtill aquifer (Figs. 4 and 5). The subtill aquifer is overlain by the till of the Lake Border moraine.

The sandy sediments that form the surficial aquifer were deposited on the surface of the till. These deposits consist of dune and near-shore lacustrine sands with thin beds of clay, interbedded sequences of back-barrier marl and dune sand, and peat (Thompson, 1987). In the southern half of the Great Marsh, the till is overlain in ascending order by near-shore lacustrine sands and peat. In the central and northern sections of the Great Marsh, including
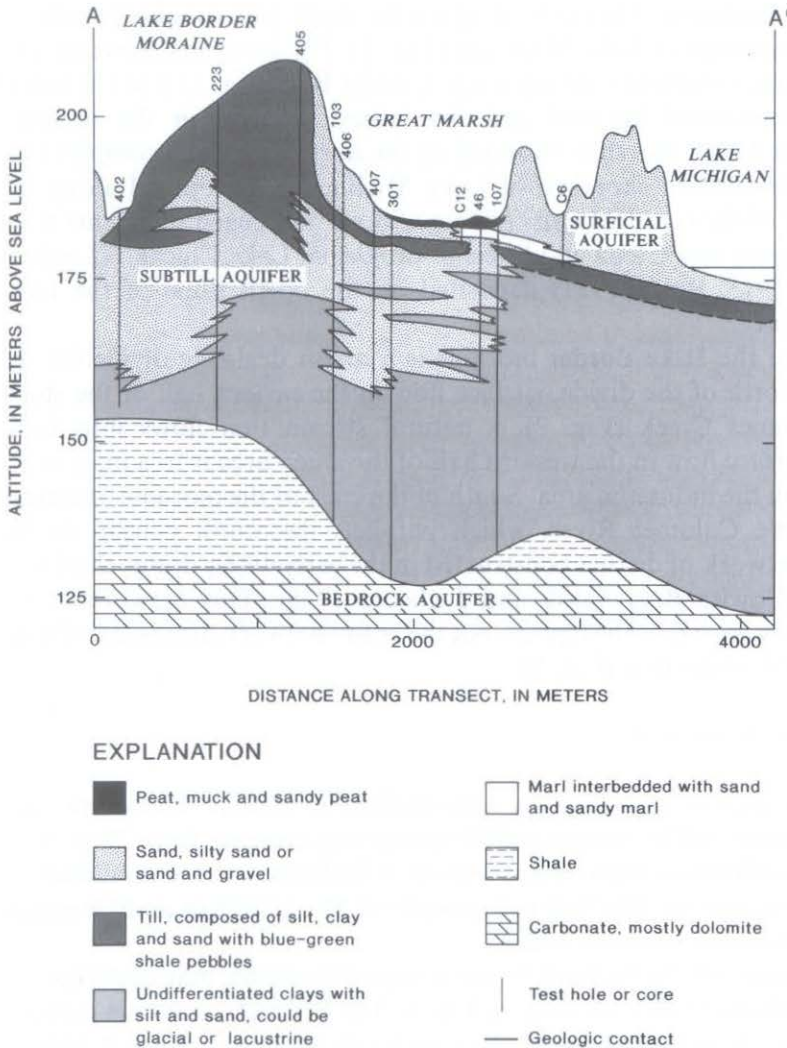
Fig. 4. Geologic section through Cowles Bog. See Fig. 3 for location.

Cowles Bog, the till is overlain by marl interbedded with dune sand and peat (sites C12, 46, and 107, Fig. 4). Both the peat and marl layers are significantly thicker below the peat mound in Cowles Bog than elsewhere in the Great Marsh (site 46, Fig. 4). In addition, the till sheet seems to be breached or missing below the peat mound. Instead, a gravel-rich beach sand was encountered at two sites on the mound at the expected depth of the till sheet (Thompson, 1987).

In the industrial area west of Cowles Bog (Fig. 1), the hydrogeologic
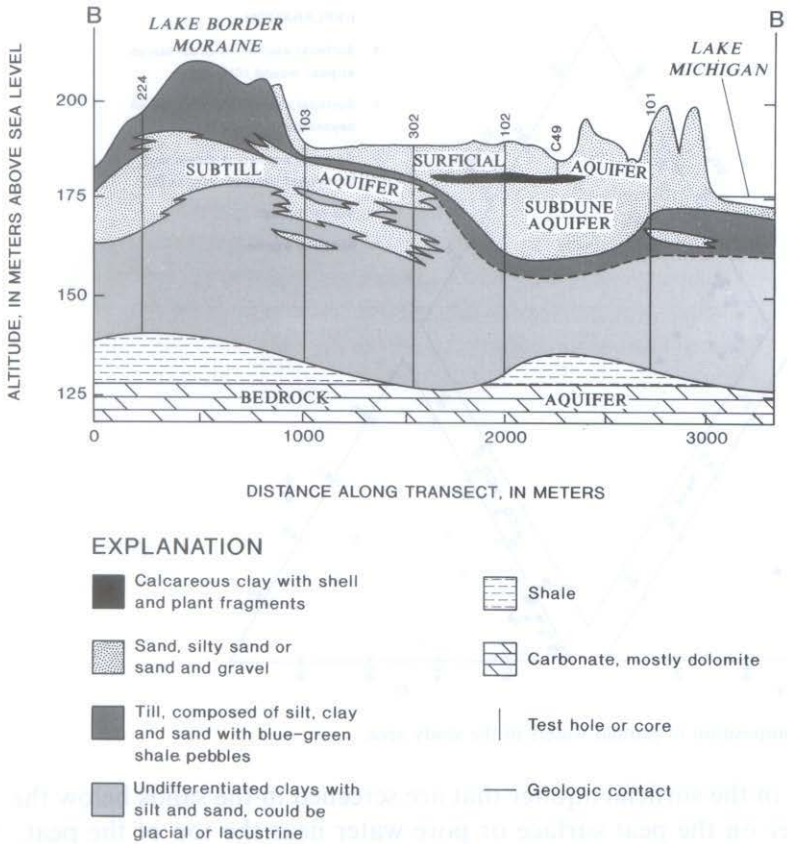
Fig. 5. Geologic section west of Cowles Bog. See Fig. 3 for location.

framework differs from that shown in Fig. 4. The sandy deposits that comprise the surficial aquifer are thicker and contain an extensive layer of calcareous clay with plant fragments (Fig. 5). The sands below this clay and above the till of the Lake Border moraine form a unit called the subdune aquifer in this paper. This aquifer is essentially a locally confined part of the surficial aquifer.

WATER CHEMISTRY

Samples of ground water, pore water near the top of the peat, and water on the peat surface were collected to investigate differences in hydrochemistry in the ground-water system and in the wetlands in the study area. Cation and anion proportions in these waters are shown on the trilinear diagrams in Figs. 6 and 7, which summarize the chemical analyses given in Table 1. The plots include analyses of samples from: wells in the subtill and subdune confined

Fig. 6. Chemical composition of ground waters in the study area.

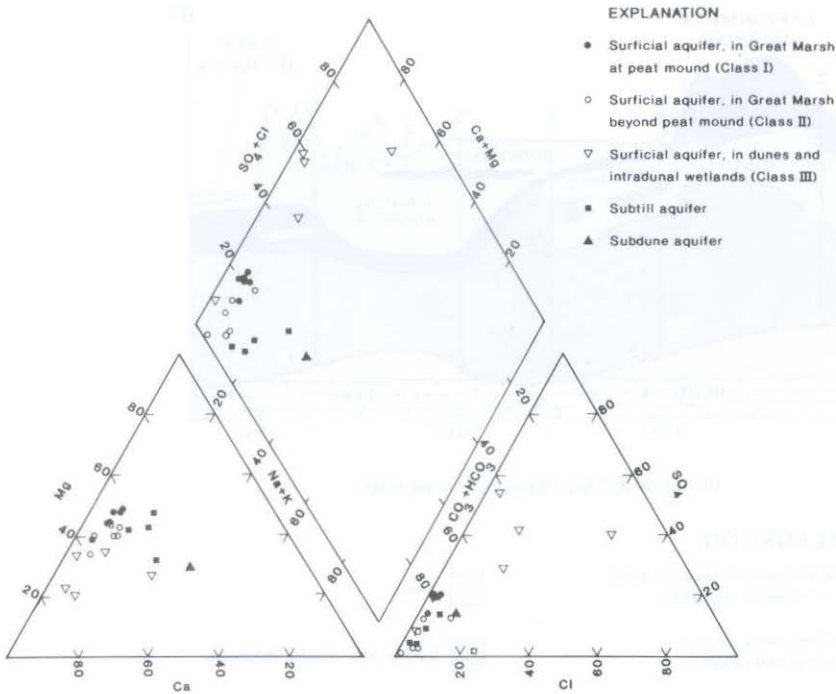aquifers, wells in the surficial aquifer that are screened in the sands below the peat, and water on the peat surface or pore water near the top of the peat.

Ground water

Waters from the subtill aquifer are bicarbonate types with roughly equal percentages of calcium and magnesium and slightly more sodium, on a proportional basis, than most of the waters in the surficial aquifer. Alkalinity ranges from 304 to 369 mg l^{-1} as $CaCO_3$, hardness from 270 to 330 mg l^{-1} as $CaCO_3$, and dissolved solids concentration from 338 to 419 mg l^{-1}.

The single analysis for the subdune aquifer indicates that the water also is a bicarbonate-type water with roughly equal percentages of sodium, calcium, and magnesium. This water has an alkalinity of 190 mg l^{-1} $CaCO_3$, hardness of 170 mg l^{-1} $CaCO_3$, and dissolved solids concentration of 271 mg l^{-1}, and is more sodic and less mineralized than the water in the subtill aquifer.

Three different classes of water in the surficial aquifer are distinguished in Table 1 and on the diagram in Fig. 6. Class I: water in the surficial aquifer below the Cowles Bog peat mound and its fringes, is a calcium magnesium bicarbonate type and plots within a small region of Fig. 6. Proportionally, this
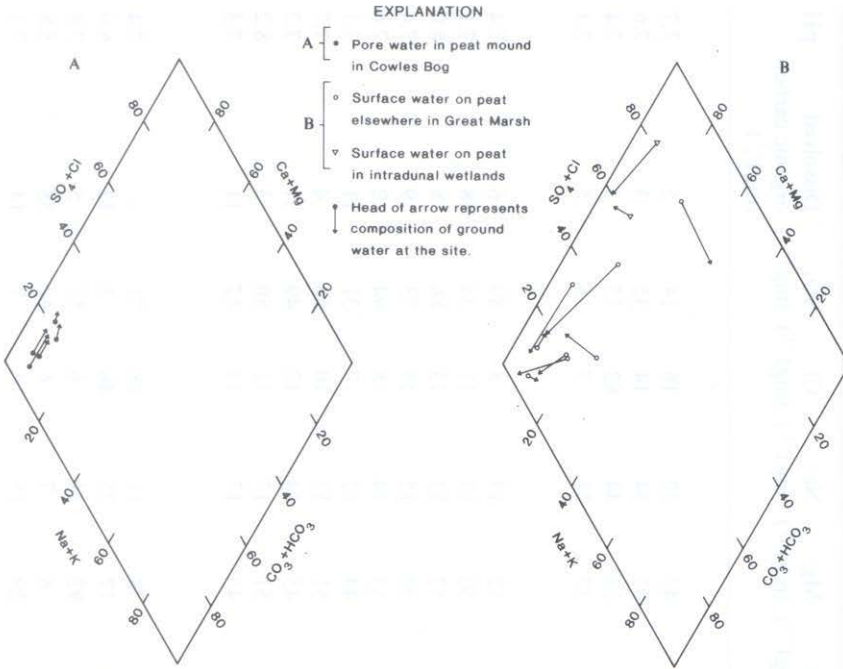
Fig. 7. Chemical composition of surface waters in the study area.

ground water is slightly higher in sulfate and lower in sodium than waters in the subtill aquifer south and east of Cowles Bog. This water also has the greatest hardness and dissolved solids concentration (Table 1) of all the ground waters sampled and alkalinity that is similar to the water from the subtill aquifer. Class II: water from the surficial aquifer in the Great Marsh but not on the peat mound, is similar in composition to the waters below the mound, differing only in having proportionately lower magnesium and sulfate concentrations and slightly lower hardness. Class III: waters from the surficial aquifer in the dunes and intradunal wetlands north and south of the Great Marsh, are more variable in composition (Fig. 6) than the other two classes. The different water types in this class include dilute calcium sulfate and calcium bicarbonate waters and several mixed-water types. As a class, they are the least mineralized ground waters sampled in this study and have the lowest alkalinity, hardness, and dissolved solids concentrations.

The waters analyzed in this study also showed differences in saturation state with respect to calcite, dolomite, and gypsum. The waters from the subtill aquifer and surficial aquifer (sites 222, 4B, 4C, 38, and 46 in Table 2) in the Great Marsh (both at, and beyond, the peat mound) were computed to be near saturation ($0.2 >$ saturation index > -0.2) with respect to calcite and

TABLE 1

Chemical characteristics and partial chemical analysis of ground water (GW), pore water near top of peat (PW), and water on the peat surface (SP)

Site and water type	Date of sample	Specific conductance (μS at 25°C)	Dissolved solids (mg l⁻¹)	Alkalinity (as CaCO₃) (mg l⁻¹)	Hardness (as CaCO₃) (mg l⁻¹)	Ca (mg l⁻¹)	Mg (mg l⁻¹)	Na (mg l⁻¹)	Cl (mg l⁻¹)	SO₄ (mg l⁻¹)	Dissolved organic carbon (mg l⁻¹)	pH
Subtill aquifer												
220	4/30/80	707	361	369	330	54	47	32	16	14	5	7.7
222	4/30/80	717	419	333	330	62	43	34	14	35	3	7.6
223	4/29/80	635	394	304	270	60	28	44	62	15	5	7.4
243	4/30/80	649	338	328	310	64	37	21	7	15	5	7.3
Surficial aquifer at peat mound in Cowles Bog (Class I)												
4C-GW	4/22/80	768	493	379	440	91	52	13	8	89	6	7.4
4C-PW	4/22/80	772	509	421	420	85	50	13	11	34	18	7.1
38-GW	4/23/80	741	477	332	410	79	52	13	13	86	8	8.0
38-PW	4/23/80	747	485	335	400	79	50	15	15	73	9	7.4
46-GW	4/29/81	852	488	396	470	96	55	14	8	94	2	7.6
46-PW	4/29/81	715	453	378	380	79	44	12	7	31	11	7.1
39-GW	4/23/80	736	465	380	390	73	51	17	10	58	4	7.7
39-PW	4/23/80	840	546	445	430	96	45	14	12	49	31	7.2
4B-GW	4/23/80	732	447	339	400	75	51	17	11	80	3	8.2
4B-PW	4/23/80	720	446	324	350	70	43	17	14	52	11	7.3
Surficial aquifer in Great Marsh, beyond peat mound (Class II)												
1-GW	4/23/81	683	420	304	360	81	38	11	18	71	–	7.4
1-SP	4/23/81	455	274	173	180	44	17	25	46	3	12	6.9
2-GW	4/29/80	640	421	378	360	75	93	14	6	57	5	7.8
2-SP	4/29/80	204	68	59	90	23	8	7	8	42	58	5.8
3-GW	4/23/81	538	358	327	270	60	29	15	14	7	14	7.1

3-SP	4/23/81	408	280	181	200	46	20	17	26	11	15		7.3
7-GW	4/29/80	196	173	65	90	22	8	4	6	29	17		8.1
7-SP	4/29/80	265	190	115	140	36	12	4	4	13	4		6.5
44-GW	4/23/80	653	354	357	320	67	38	17	11	11	4		7.8
44-SP	4/23/80	797	506	390	380	85	41	16	15	5	28		7.2
45-GW	4/22/80	822	491	465	410	94	42	8	4	52	14		7.2
45-SP	4/23/80	315	235	131	130	32	13	10	13	13	18		7.1
Surficial aquifer in dune-beach complexes (Class III)													
4A-GW	4/24/80	165	329	68	98	32	5	2	11	53	82		5.7
4A-SP	4/24/80	113	353	34	65	19	4	3	10	31	90		5.9
5-GW	4/22/81	278	277	114	150	40	12	3	8	70	49		6.1
5-SP	4/22/81	102	96	9	99	13	4	2	3	33	25		5.5
6-GW	4/24/81	611	379	68	170	37	18	58	10	67	7		6.3
6-SP	4/24/81	154	152	16	64	15	6	8	13	36	21		5.4
221	9/15/81	465	268	235	240	69	16	1	1	23	1		7.5
222	4/21/81	358	280	31	130	32	12	21	59	71	2		6.1
Subdune aquifer													
102	4/14/77	501	271	190	170	35	19	41	20	35	–		7.1

TABLE 2

Tritium concentrations and mineral saturation states in ground water (GW), pore water near top of peat (PW), and water on the peat surface (SP)

Site	Date of sample	Type of water	Concentration of tritium $(pCi l^{-1})$	Mineral saturation indices		
				Calcite	Dolomite	Gypsum
Subtill aquifer south of Great Marsh						
220	4/30/80	GW	< 1			
222	4/30/80	GW	2	0.126	0.093	
223	4/29/80	GW	< 1			
109	8/21/83	GW	5			
Shallow ground water and peat water at raised mound in Cowles Bog						
4B	10/22/80	GW	2	−0.03	−0.15	−1.66
4B	10/22/80	PW	40			
4C	4/22/80	GW	2	0.05	−0.05	−1.55
4C	10/21/80	PW	27			
38	4/23/80	GW	2	0.06	0.03	−1.66
38	10/22/80	PW	29			
39	10/23/80	GW	13			
46	4/22/80	GW	2	0.17	0.26	−1.62
46	10/22/80	PW	19			
Shallow ground water in Great March beyond raised peat mound						
1	10/29/80	GW	93			
2	4/29/80	GW	< 1			
2	10/28/80	SP	160			
3	12/08/80	GW	59			
7	10/24/80	GW	153			
7	10/24/80	SP	120			
44	10/22/80	GW	6			
44	10/22/80	SP	63			
220	4/30/80	GW	147			
Shallow ground water in dunes and wetlands within dunes						
4A	10/23/80	GW	150	−2.86	−6.30	−2.30
222	4/30/80	GW	116			

dolomite and undersaturated with respect to gypsum. The water from the surficial aquifer in the dunes (site 4A, Table 2) was significantly undersaturated (saturation index < -1.0) with respect to each of these three minerals.

Pore water in peat and water on peat surface

The chemistry of surface and near-surface waters was compared with the chemistry of ground water below the peat at most of the well sites in the wetlands. Major cation proportions in waters on the peat surface in the Great Marsh and pore waters at the top of the peat on the raised mound in Cowles Bog are plotted in Fig. 7. The lines on the parallelogram connect points representing the composition of waters on, or in, the peat to points representing the composition of the ground water in the underlying sand at each site (plotted in Fig. 6).

The lines representing the sites at the peat mound and its fringes show that the waters in the peat at the mound have nearly the same composition as the ground water in the underlying sands. The small difference in composition is almost entirely accounted for by differences in sulfate. The waters in the sands below the peat mound are both proportionally, and absolutely, higher in sulfate than the overlying pore waters in the peat. In addition, both the pore waters of the peat mound and the underlying ground waters have slightly higher values of alkalinity, hardness, and specific conductance than waters in the subtill aquifer south of Cowles Bog (Table 1).

The chemistry of waters at the peat surface and the underlying ground water is less similar beyond the raised peat mound in Cowles Bog. The length of the lines in Fig. 7 indicates differences in the relative proportions of major ions between the ground and surface waters, while the different orientations of the arrows indicate that several factors probably account for the differences in ion proportions between these waters. In both groups, sulfate and calcium are proportionally higher in the surface water than in ground waters in the underlying sands. The source of the sulfate and some of the calcium in these dilute waters may be from snowmelt. Hardy (1981) reported average respective values of 52 and 25 mg l^{-1} for calcium and 100 and 69 m l^{-1} for sulfate in precipitation from late November 1977 to early April 1978 at two sites in an area near a coal-fired electric power plant west of Cowles Bog.

Some of the differences in composition may be caused by urban and industrial influences. Several of the data points on Fig. 7 represent sites within a few hundred meters of U.S. Highway 12, which are probably influenced by road salting. Besides road salt, atmospheric deposition from coal-fired power plants and the steel mills west of Cowles Bog also may affect the compositions of the waters in the wetland.

Concentrations of tritium

The concentration of tritium was measured in different types of water in the study area (Table 2) that were collected in 1980 (with the exception of one sample collected in 1983). Tritium was analyzed in samples of ground water from the surficial aquifer and the subtill aquifer, pore waters in the peat on the raised peat mound, and surface water in the Great Marsh beyond the peat mound. For the samples collected and analyzed in this study, those with tritium concentrations below 15 pCi l^{-1} represent waters derived mainly from ground water recharged before atmospheric testing of thermonuclear devices (old water) in the early 1950s (Payne, 1979; Freeze and Cherry, 1979). Concentrations of tritium in precipitation were generally below 15 pCi l^{-1} before this testing, but increased by several orders of magnitude during the period of testing in the 1950s and 1960s. At the time the samples in this study were collected, the average concentration of tritium in precipitation at a station in nearby Chicago, Illinois, was between 140 and 160 pCi l^{-1} (International Atomic Energy Agency (IAEA), 1981).

Based on the data in Table 2, waters from both the subtill aquifer (tritium concentrations from 1 to 5 pCi l^{-1}) and the sands below the peat at the raised mound in Cowles Bog (tritium concentrations from 2 to 13 pCi l^{-1}) seem to be derived primarily from ground water recharged before the early 1950s. In addition, all of these waters with low tritium concentrations are near saturation with respect to calcite and dolomite (Table 2), which is consistent with a residence time in the subtill aquifer of several decades or more.

The data also show that the pore waters of the peat at the mound (19–40 pCi l^{-1}) are mixtures of old and recently recharged water, dominated by old water. Assuming an average tritium concentration of 2 pCi l^{-1} for the old water and 150 pCi l^{-1} for 1980 precipitation in the study area, the percentage of old water in the peat pore water at the four sites on the mound ranges from 73 to 87%.

Tritium concentrations in ground waters in the surficial aquifer beyond the peat mound ranged from less than 1 to 153 pCi l^{-1}. At sites 2 and 44 in the Great Marsh, the tritium concentrations were less than 10 pCi l^{-1} for shallow ground water, suggesting upward leakage as the dominant source. Shallow ground water at sites at the margins of the Great Marsh east of Cowles Bog (sites 7 and 220) have tritium concentrations above 147 pCi l^{-1}. Tritium concentrations of shallow ground waters in the dune complexes at sites 4A and 222 were 150 pCi l^{-1} and 116 pCi l^{-1}, respectively. However, shallow ground water at sites 1 and 3 in the Great Marsh had respective tritium concentrations of 93 pCi l^{-1} and 59 pCi l^{-1}, values indicative of mixing of pre-1950s water with much younger water. Generally, a tritium concentration

of less than 100 pCi 1^{-1} was assumed to indicate that an appreciable percentage of the water at a site in the study area was derived from upward leakage from the subtill aquifer. This broad range of tritium concentrations in ground water suggests that rates and direction of leakage between the surficial aquifer and the subtill aquifer vary considerably in the study area.

Tritium concentrations in waters on the peat surface in the Great Marsh beyond the peat mound were measured at three sites (sites 2, 7, and 44). Site 2 is about 400 m from Cowles Bog and the surface water on the peat there had a tritium concentration of 160 pCi 1^{-1}. Site 7 is about 800 m from the peat mound and the peat surface water there had a tritium concentration of 120 pCi 1^{-1}. Both of these tritium concentrations are within the range of concentration of atmospheric precipitation at the time of sampling. However, the third site (site 44) is only about 100 m south of the peat mound, and the tritium concentration of the peat surface water there (63 pCi 1^{-1}) is characteristic of a mixture having 50–60% of old water. This information suggests that upward leakage from the subtill aquifer is probably a significant source of surface water in ponded areas of the Great Marsh within a few hundred meters of the raised peat mound.
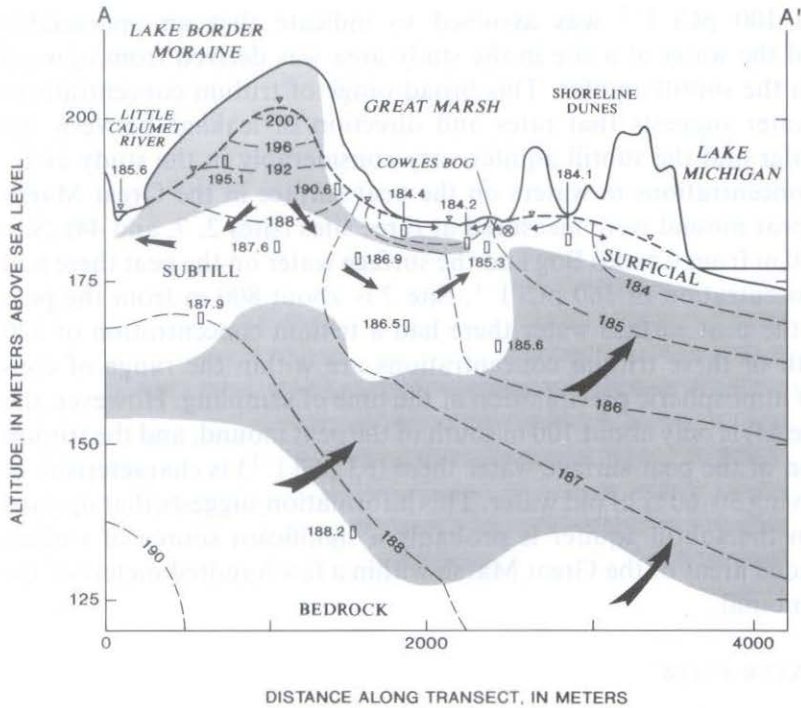
GROUND-WATER FLOW

Vertical flow patterns

A ground-water flow system, consisting of regional, intermediate, and local flow patterns (Toth, 1963) has been conceptualized for the glacial drift and upper bedrock aquifer system in the study area. This conceptual flow system (Fig. 8) is based on previous work by Rosenshein and Hunn (1968a,b) and Shedlock et al. (1988), and water-level measurements in observation wells in the study area.

The flow system in Fig. 8 shows a general pattern of upward flow from the bedrock through the overlying glacial drift. This upward pattern is interpreted as the distal part of a regional flow system that begins at water-table highs in the Valparaiso moraine south of the study area. The regional system extends into the bedrock below the Valparaiso moraine and discharges into the glacial drift near Lake Michigan. Evidence for the regional system is found in the water levels of wells finished in the base of the glacial drift below the dune–wetland complexes within, and east of, the study area. Most of these wells have water levels above the water table and some even have water levels above land surface (Shedlock et al., 1988).

The study area also contains an intermediate flow system that begins at water-table highs in the Lake Border moraine. The intermediate system

Fig. 8. Vertical ground-water flow patterns for section through Cowles Bog in Fig. 4.

extends into the subtill aquifer and discharges by upward leakage into the Great Marsh on the north side of the Lake Border moraine and to the Little Calumet River on the south side of the moraine. Water levels in most wells finished in the subtill aquifer in the Great Marsh are higher than the water table and some are higher than land surface.

Nearly all the discharge in the intermediate flow system is by upward leakage to the surficial aquifer in the Great Marsh. At the breach in the till below the Cowles Bog peat mound, water flows directly from the subtill
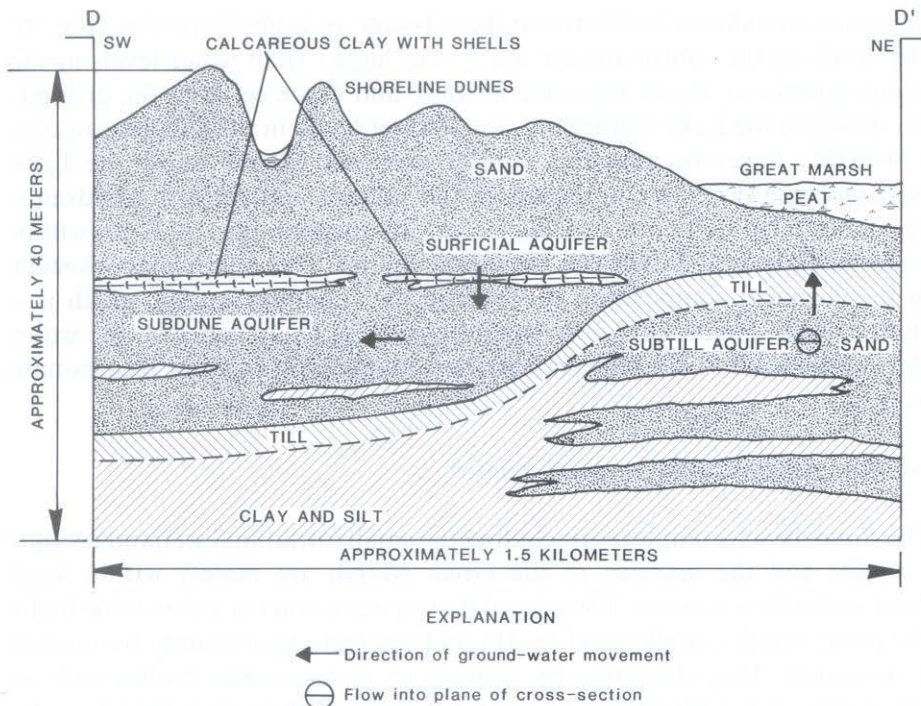
Fig. 9. Schematic section showing geometric relations between subtill and subdune aquifers. See Fig. 3 for approximate line of section.

aquifer into the overlying marl, sand, and peat. The upward vertical gradient within the subtill aquifer below the peat mound also indicates that some water from the regional flow system discharges into the subtill aquifer and ultimately into the Great Marsh.

However, the vertical flow regime is different beyond the areal extent of the subtill aquifer, where the intermediate flow system generated in the Lake Border moraine is absent. For example, in the dunes north of the Great Marsh, the local flow system is underlain by upward flow from the regional system (Fig. 8). In the dunes west of Cowles Bog (Fig. 9), vertical flow is downward from the surficial aquifer into the subdune aquifer through the calcareous clay. For example, in March 1980 at site 102 (Fig. 3), the water level in the well finished above the calcareous clay in the surficial aquifer was 1.3 m higher than the water level in the well finished below the calcareous clay in the subdune aquifer. In the dunes west of Cowles Bog the local flow system seems to extend into the subdune aquifer.

Thus, there is an abrupt change in vertical flow regime between Cowles Bog and the area of dunes to the west. In this area, the westward-sloping till sheet

functions as a confining bed between the subdune and subtill aquifers (Fig. 9). Water levels in the subtill aquifer are 2–3 m higher than water levels in the subdune aquifer at about the same altitude and distance from the ground-water divide in the Lake Border moraine. Water levels in the subdune aquifer are probably lower because this aquifer does not extend below the Lake Border moraine (Fig. 5). Consequently, the subdune aquifer is not hydrauli-cally connected to potentiometric highs beneath the moraine and is not within the intermediate flow system as is the subtill aquifer. This relation is consistent with the chemical composition of water in the subdune aquifer, which is a sodium calcium magnesium bicarbonate type (Fig. 6). In contrast, the water in the subtill aquifer is a more mineralized magnesium calcium bicarbonate type.

Local flow systems in the surficial aquifer

The dune–beach complexes (including the small intradunal wetlands within the dunes) and the margins of the Great Marsh are mainly within local ground-water flow systems. These local flow systems start at water-table highs in the dune–beach complexes (Fig. 10) and are recharged mainly by rainfall and snowmelt. They discharge by seepage to surface water bodies such as Dunes Creek, Lake Michigan, and ponded areas of the Great Marsh, or by evapotranspiration in both the dunes and the wetlands.

The study area can be divided into three subregions based on the discharge zones of the local flow systems. The first subregion is the area north of the water-table high in the shoreline dune complex. In this part of the surficial aquifer all the flow is toward Lake Michigan and ground water in the local flow system discharges by evapotranspiration in the dune complexes or by direct seepage into Lake Michigan.

The second subregion is south of the water-table high in the shoreline dune complex and east of the water-table high between Cowles Bog and the industrial area west of Cowles Bog (Fig. 10). In this subregion, flow is from the water-table highs in the dune–beach complexes to the Great Marsh. These flow systems discharge by evapotranspiration in the dune complexes and the Great Marsh or by direct seepage to Dunes Creek and ponded areas of the Great Marsh.

The third subregion is in the industrial area west of the Cowles Bog, south of the water-table high in the shoreline dune complex. In this region the local flow systems discharge to a ditch system that drains into the Little Calumet River west of the study area.
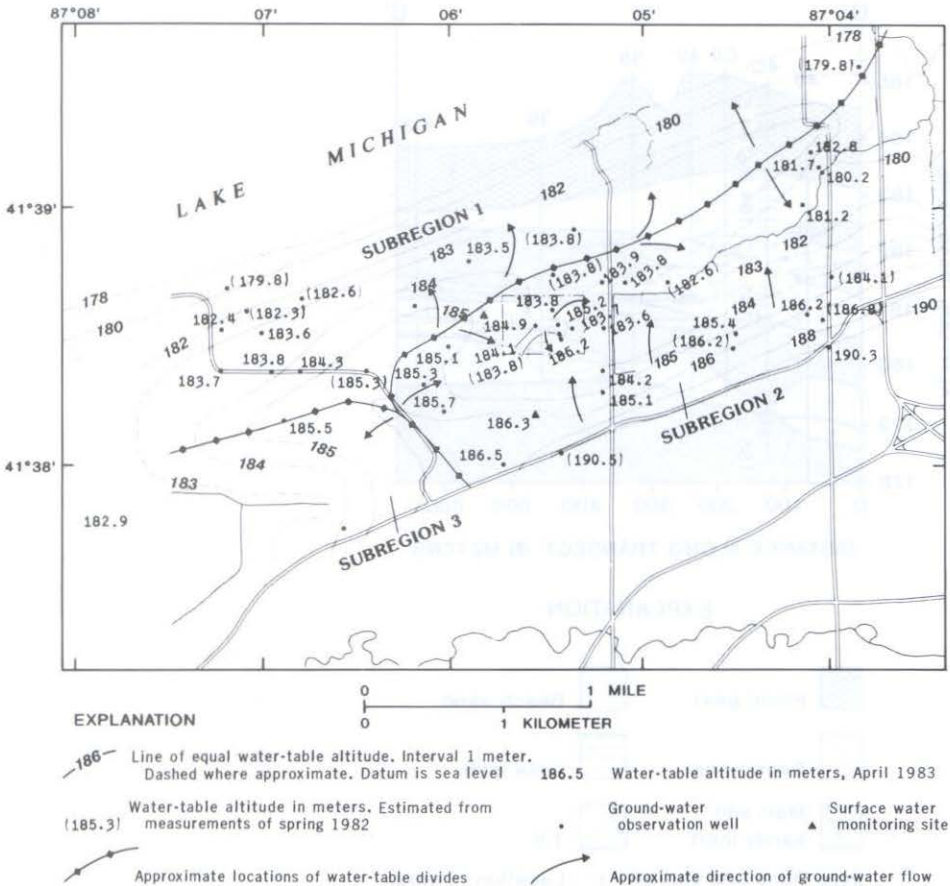
Fig. 10. Map showing altitude of water table and directions of ground-water flow in the surficial aquifer.

Ground-water flow at the peat mound in Cowles Bog

The water table is at the surface nearly everywhere on the raised peat mound in Cowles Bog. Therefore, the peat mound is underlain by a water-table mound that is higher than the water table in surrounding areas of the Great Marsh (Fig. 10). This water-table mound causes a local pattern of flow away from the peat mound in at least three directions (north, east, and south). Flow may also occur off of the west side of the peat mound but no observation wells were installed west of the mound to test this possibility.

Wilcox et al. (1986) have shown that upward leakage from the subtill aquifer through an underlying breach in the till has caused the growth of the peat mound and the water-table mound in Cowles Bog. In fact, wells on the
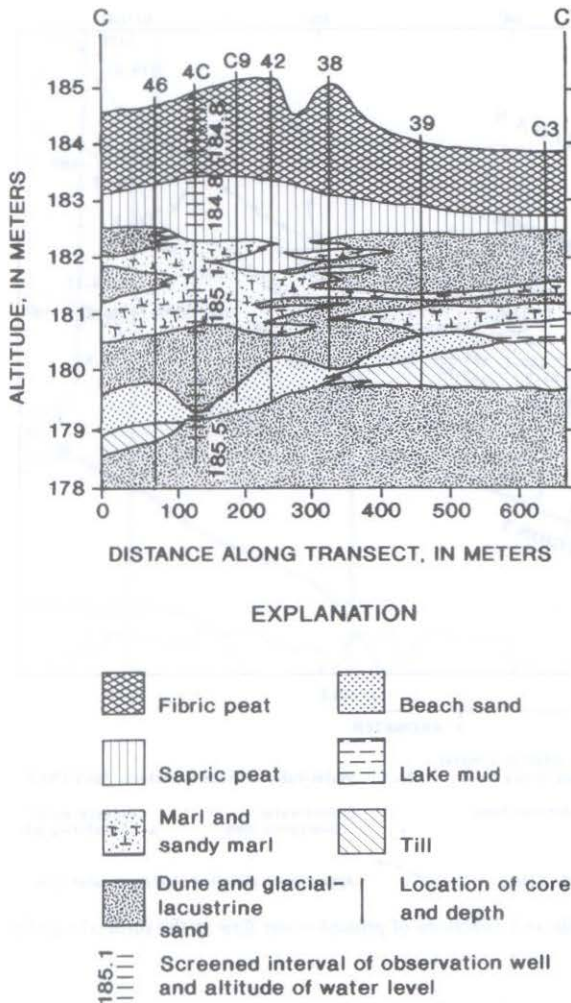
Fig. 11. Hydrogeologic section through the raised peat mound at Cowles Bog. See Fig. 3 for location.

peat mound finished in sand below the surficial peats and marls have water levels as much as 60 cm above the surface of the peat mound (Fig. 11).

Nevertheless, ground water does not discharge up through the peat surface at a rate sufficient to cause perceptible surface flow off the peat mound in Cowles Bog. The absence of perceptible surface discharge at the peat mound is caused by the complex stratigraphy of the deposits below the peat mound and the vertical distribution of hydraulic head through the different deposits. As Fig. 11 shows, the fibric peat at the surface of the peat mound is underlain in descending order by a sapric (less fibric peat) peat, a unit of interbedded

marl and dune sand, and sands of dune, beach, and lacustrine origin at the breach in the till.

At site 4C in the peat mound, most of the difference in head between the sand at the breach in the till and the water table in the peat mound is dissipated through the interbedded marl and dune sand. Wells at different depths in the peat at this site showed no measurable vertical head gradient in the peat. However, hydrochemical evidence presented earlier shows that pore water in the peat on the mound is derived from upward leakage from the subtill aquifer. This apparent anomaly may be caused by very slow upward flow through the peat in response to imperceptibly small gradients, or by other mechanisms such as ionic diffusion or capillary action in the peat.

EFFECTS OF GROUND-WATER FLOW ON WATER CHEMISTRY

The hydrochemical data (Table 1) suggest that shallow ground water and peat pore water in the study area are derived from two sources: (1) upward leakage of water from an underlying confined aquifer, the subtill aquifer; (2) water in local ground-water flow systems recharged by precipitation (areal recharge), which may also be locally influenced by road salting and atmospheric deposition. The water from the subtill aquifer is a calcium magnesium bicarbonate type. The water in the local ground-water flow systems is a much less mineralized calcium sulfate bicarbonate type (Fig. 6) similar in composition to the local precipitation (Hardy, 1981). The relative proportions of these two end-member waters at a particular site depends on the position of that site in the ground-water flow system.

For example, shallow ground water in dunes and water in intradunal wetlands north and south of the Great Marsh seem to be derived predominantly from local ground-water flow systems recharged by precipitation, as indicated by their high tritium concentrations (Table 2). These waters also have lower hardness, alkalinity, and dissolved solids concentrations than waters derived by upward leakage from the subtill aquifer. The reason the waters in the dunes north of the Great Marsh are not influenced by upward leakage is because the subtill aquifer does not extend north of the Great Marsh and upward leakage from the regional system is not significant (Fig. 4). On the other hand, the dunes south of the Great Marsh are underlain by the subtill aquifer, but because the water table there is higher than the head in the subtill aquifer vertical flow there is downward. However, in the Great Marsh the water table is lower than the head in the subtill aquifer, so the direction of flow between the subtill and surficial aquifers is upward.

Shallow ground waters in the Great Marsh are, therefore, derived from varying proportions of upward leakage of water from the subtill aquifer and

water from local ground-water flow systems recharged by precipitation in the adjacent dune–beach complexes. The high alkalinity, high dissolved solids, and low tritium concentrations of waters at the raised peat mound in Cowles Bog indicate that both shallow ground waters and peat pore waters there are derived predominantly from upward leakage from the subtill aquifer. A short distance away from the mound, the higher tritium concentrations (Table 2) and changes in proportions of major ions suggest that waters in the peat and the underlying sand are mixtures of upward leakage from the subtill aquifer and local ground-water flow from the adjacent dune complexes. At distances greater than 300 m from the peat mound, the waters in, or on, the peats are much less mineralized than the shallow ground water in the underlying sand (sites 1–7, Fig. 2 and Table 1). The low dissolved solids concentration of the waters in the peat at these sites indicates that these waters are derived primarily from local ground-water flow and precipitation. However, the waters in the underlying sand at these sites have higher dissolved solids concentrations indicative of mixtures of varying proportions of upward leakage and local ground-water flow. In one extreme case (site 2, Fig. 2 and Table 1), the water at the peat surface seems to be derived mainly from local ground-water flow and precipitation (low alkalinity, high tritium concentration). The shallow ground water in the underlying sand of the surficial aquifer at site 2 seems to be entirely derived by upward leakage from the subtill aquifer (high alkalinity, low tritium concentration). These observations suggest that upward leakage is a very important component of the water budget not only at the peat mound in Cowles Bog but also in surrounding areas of the Great Marsh.

DISCUSSION AND CONCLUSIONS

The hydrochemical patterns and vertical hydraulic gradients observed in this study area are evidence that the wetlands here are influenced by ground-water flow paths of variable length. The nature of these ground-water–wetland interactions underscores the importance of understanding the hydrogeologic setting of an area much larger than that of the wetland(s) of concern. Such an understanding is especially important in the complex ground-water flow regimes of glacial–lacustrine sediments, such as in this study. This complexity is caused by the topography of the glacial and lacustrine landforms, abrupt changes in sediment types common in deposits derived from the glacial ice, and also by the many different lithofacies developed in proglacial lacustrine and paludal sediments.

In this study, a key element of the conceptual model of the aquifer system is the presence of two distinct confined aquifers (subtill and subdune aquifers)

at about the same altitude in the glacial drift. The tops of the different confining beds that overlie these two aquifers are at about the same altitude also. For this reason, the two confining beds and the two aquifers were previously thought to be the same hydrogeologic unit (Meyer and Tucci, 1979; Gillies and Lapham, 1980). However, (Thompson, 1987) has shown that these confining beds are distinctly different strata of a different origin. One is a buried till sheet, the subsurface extension of a moraine that outcrops immediately south of the dunes and wetlands. The other confining bed is a calcareous clay with plant and shell fragments deposited in a quiet-water environment, most likely a flooded lowland behind a beach barrier.

The aquifer below the till sheet (subtill aquifer) is hydraulically connected to potentiometric highs below the outcrop of the Lake Border moraine. In wetland areas underlain by this aquifer (Cowles Bog and interior parts of the Great Marsh), water leaks upward through the till sheet to the surficial aquifer. This leakage imparts a more mineralized and alkaline character to the water in wetland areas affected by it, and is a significant component of the water budget of the shallow ground-water system in these wetlands.

Conversely, the confined aquifer below the calcareous clay (subdune aquifer) is not connected to potentiometric highs beneath the moraine. Leakage between the surficial aquifer and the subdune aquifer is downward. As a result, water in the subdune aquifer does not affect shallow ground waters in wetlands in the dunal areas. These waters are almost entirely derived from local ground-water flow systems recharged by precipitation. These waters generally have appreciably lower dissolved solids concentrations than ground waters in the Great Marsh which are influenced by the upward leakage of more mineralized waters from the subtill aquifer.

The results of this study have implications for the hydrology and hydrochemistry of dunes and wetlands all along the southeast shore of Lake Michigan. Northeast of the study area, the area between Lake Michigan and the Valparaiso moraine contains several smaller morainal ridges. The Valparaiso moraine is the largest, and most landward, moraine deposited during the maximum advance of the Wisconsinan ice into the Lake Michigan basin. If areally significant aquifers underlie the smaller morainal ridges, ground-water flow in these areas would probably be characterized by a number of different intermediate and local flow systems superimposed on the regional system that begins in the Valparaiso moraine and discharges to Lake Michigan.

In contrast, in the more urbanized and industrialized areas of the Lake Michigan shoreline, southwest of the study area, there are only a few isolated outliers of ground moraine and, thus, essentially no intermediate flow systems (Shedlock et al., 1988). Local flow systems that begin in the dune complexes and discharge to streams and wetlands in the lowlands are underlain by an

upward flow regime representing discharge only from the regional system associated with the Valparaiso moraine. Therefore, the hydraulic connection of confined aquifers to potentiometric highs beneath morainal uplands is an important control on ground-water flow and on wetland hydrology in this physiographic setting. A good understanding of the stratigraphy and sedimentology of such deposits is very important to understanding the hydrology of wetlands in glacial–lacustrine settings.

Two more general observations about wetland hydrology have emerged from this study and the recent work of Siegel (1983), Siegel and Glaser (1987), and Winter (1988). First, the often-asked question of whether wetlands are recharge or discharge areas is probably too simply stated. For example, the interior sections of the Great Marsh, including Cowles Bog, are clearly discharge zones, whereas the margins of the Great Marsh can function as recharge areas during wet periods. Thus, it cannot necessarily be assumed that interactions with ground water are uniform over a wetland area. In addition, ground-water flow systems of different scale can influence different sections of a wetland, as happens in this study area.

The second observation is that a multidisciplinary approach is very valuable, if not essential, in conducting wetland hydrology studies (Wilcox, 1988). The interpretations in this study probably could not have been made without the collection of a considerable amount of hydrochemical, geophysical, and sedimentological data. These data allowed more precise definition of the complex glacial–lacustrine sediments here as hydrostratigraphic units (Maxey, 1964) and more accurate determination of the length of ground-water flow paths and the spatial distribution of hydrochemical types. Such information can indicate important differences in the flow and chemistry that could go unrecognized even with a dense array of potentiometric data points. Recognition of such differences is important because wetland plant communities are commonly influenced by water chemistry as well as saturation levels. Therefore, the multidisciplinary approach yields a more comprehensive understanding of the hydrology of wetlands. This approach also recognizes wetlands as integrated natural systems with geologic, hydrologic, hydrochemical, and biologic components.

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REFERENCES

Ashley, G. M., Shaw, J. and Smith, N. D., 1985. Glacial Sedimentary Environments, Notes from Short Course No. 16. Society of Economic Paleontologists and Mineralogists, Tulsa, OK, 246 pp.

Boelter, D. H. and Verry, E. S., 1977. Peatland and water in the northern lake states. USDA Forest Service General Technical Report NC-31. North Central Forest Experiment Station, St. Paul, Minnesota, 22 pp.

Bretz, J. H., 1951. The stages of the Lake Chicago, their causes and correlations. Am. J. Sci., 249: 401–429.

Bretz, J. H. , 1955. Geology of the Chicago region, part II — the Pleistocene. Illinois State Geol. Surv., Bull., 65, Champaign, IL, 132 pp.

Cohen, D.A. and Shedlock, R.J., 1986. Shallow ground water flow, water levels, and quality of water, 1980–84, Cowles Unit, Indiana Dunes National Lakeshore. U.S. Geol. Surv., Water Resour. Invest. Rep. 85-4340, Washington, DC, 25pp.

Cook, S. G. and Jackson, R. S., 1978. The Bailly area of Porter County, Indiana. Robert Jackson and Associates, Evanston, IL, 110 pp.

Finkelstein, K. and Prins, D. D., 1981. An inexpensive portable vibra-coring system for shallow water and land applications. Coastal Engineering Research Center, Technical Aid No. 81-8, 15 pp.

Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ, 604 pp.

Freeze, R. A. and Witherspoon, P. A., 1967. Theoretical analysis of regional ground-water flow. 2. Effect of water-table configuration and subsurface permeability variation. Water Resour. Res., 3 (2): 623–634.

Gillies, D. G. and Lapham, W. W., 1980. Reassessment of the effects of construction dewatering on ground-water levels in the Cowles Unit, Indiana Dunes National Lakeshore, Indiana, supplement to WRI 78-138. U.S. Geol. Surv., Open-File Rep. 80-1105, Washington, DC, 50 pp.

Gore, A. J., 1983. Mires. Swamp Bog, Fen, and Moor. General Studies. Elsevier, Amsterdam, 440 pp.

Hansel, A. K., Mickelson, D. M., Schneider, A. F. and Larsen, C. E., 1985. Late Wisconsinan and Holocene history of the Lake Michigan basin. In: P.F. Karrow and P.E. Calkin (Editors), Quaternary Evolution of the Great Lakes. Geological Association of Canada Special Paper 30, St. Johns, Nfld., pp. 39–53.

Hardy, M. A., 1981. Effects of coal fly-ash disposal on water in and around the Indiana Dunes National Lakeshore, Indiana. U.S. Geol. Surv., Water Resour. Invest. Rep. 81-16, Washington, DC, 64 pp.

Hough, J. L., 1958. Geology of the Great Lakes. University of Illinois, Urbana, 313 pp.

International Atomic Energy Agency (IAEA), 1981. Technical Report Series No. 206. IAEA, Vienna, 255 pp.

LaBaugh, J.W., Winter, T.C., Adomaitis, V.A. and Swanson, G.A., 1987. Hydrology and

chemistry of selected prairie wetlands in the Cottonwood Lake Area, Stutsman County, North Dakota, 1979–82. U.S. Geol. Surv., Prof. Pap. 1431, Washington, DC, 26 pp.

Leverett, F. and Taylor F. B., 1915. The Pleistocene of Indiana and Michigan and the history of the Great Lakes. U.S. Geol. Surv., Monogr. 53, 529 pp.

Marie, J. R., 1976. Model analysis of effects on water levels at Indiana Dunes National Lakeshore caused by construction dewatering. U.S. Geol. Surv., Water Resour. Invest. Rep. 76–82, Washington, DC, 95 pp.

Maxey, G.B., 1964. Hydrostratigraphic units. J. Hydrol., 2: 124–129.

Meyer, W. and Tucci, P., 1979. Effects of seepage from fly-ash settling ponds and construction dewatering on ground-water levels in the Cowles Unit, Indiana Dunes National Lakeshore, Indiana. U.S. Geol. Surv., Water Resour. Invest. Rep. 78-138, Washington, DC, 95 pp.

Payne, B. R., 1972. Isotope hydrology. Adv. Hydrosci., 8: 95–138.

Plummer, L. N., Jones, B. F. and Truesdell, A. H., 1976. WATEQF — A FORTRAN IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters. U.S. Geol. Surv., Water Resour. Invest. Rep. 76-13, Washington, DC, 61 pp.

Rosenshein, J. S. and Hunn, J. D., 1968a. Geohydrology and ground-water potential of Lake County, Indiana. Bulletin 31, Indiana Department of Conservation, Division of Water Resources, Indianapolis, IN, 35 pp.

Rosenshein, J.S. and Hunn, J.D., 1968b. Geohydrology and ground-water potential of Porter and LaPorte Counties, Indiana. Bulletin 32, Indiana Department of Conservation, Division of Water Resources, Indianapolis, IN, 22 pp.

Schneider, A. F., 1966. Physiography. In: A.A. Lindsey (Editor), Natural Features of Indiana. Indiana Academy of Science and Indiana State Library, Indianapolis, IN, pp. 40–56.

Shedlock, R.J., Loiacono, N.J. and Imbrigiotta, T.E., 1988. Effects of ground water on the hydrochemistry of wetlands at Indiana Dunes, northwest Indiana. In: D.A. Wilcox (Editor), Interdisciplinar Approaches to Freshwater Wetlands Research. Michigan State University, East Lansing, MI, pp. 37–55.

Siegel, D. I., 1981. Hydrogeologic setting of the glacial Lake Agassiz peatlands, northern Minnesota. U.S. Geol. Surv., Water Resour. Invest. Rep. 81-24, Washington, DC, 30 pp.

Siegel, D. I., 1983. Ground water and the evolution of patterned mires, glacial Lake Agassiz peatlands, northern Minnesota. J. Ecol., 71: 913–921.

Siegel, D.I. and Glaser, P.H., 1987. Groundwater flow in a bog–fen complex, Lost River peatland, northern Minnesota. J. Ecol., 75: 743–754.

Skougstad, M.W., Fishman, M.J., Friedman, L.C., Erdman, D.E. and Duncan, S.S. (Editors), 1979. Methods for determination of inorganic substances in water and fluvial sediments. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chapter A1, Washington, DC, 626 pp.

Thompson, T.A., 1987. Sedimentology, internal architecture and depositional history of the Indiana Dunes Natinal Lakeshore and State Park. Ph.D. Thesis, Indiana University, Bloomington, 129 pp. (Unpubl.)

Toth, J., 1963. A theoretical analysis of ground-water flow in small drainage basins. J. Geophys. Res., 68: 4795–4812.

Wilcox, D.A., 1988. The necessity of interdisciplinary research in wetland ecology: the Cowles Bog example. In: D.A. Wilcox (Editor), Interdisciplinary Approaches to Freshwater Wetlands Research. Michigan State University, East Lansing, MI, pp. 1–9.

Wilcox, D. A., Apfelbaum, S.I. and Hiebert, R. D., 1984. Cattail invasion of sedge meadows following hydrologic disturbances in the Cowles Bog Wetland Complex, Indiana Dunes National Lakeshore. Wetlands, 4: 115–128.

Wilcox, D. A., Shedlock, R. J. and Henderickson, W. H., 1986. Hydrology, water chemistry, and ecological relations in the raised mound of Cowles Bog. J. Ecol., 24: 1103–1117.

Winter, T. C., 1976. Numerical simulation of the interaction of lakes and ground water. U.S. Geol. Surv., Prof. Pap. 1001, Washington, DC, 45 pp.

Winter, T. C., 1988. A conceptual framework for assessing the cumulative impacts on the hydrology of nontidal wetlands. Environ. Manage., 12: 605–620.

Winter, T. C. and Carr, M. R., 1980. Hydrologic setting of wetlands in the cottonwood Lake area, Stutsman County, North Dakota. U.S. Geol. Surv., Water Resour. Invest. Rep. 80-99, Washington, DC, 42 pp.

Wood, W. W., 1976. Guidelines for collection and field analysis of ground-water samples for selected unstable constituents. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 1, Chapter D2, Washington, DC, 24 pp.