Journal of Hydrology, 140 (1992) 279–296
Elsevier Science Publishers B.V., Amsterdam

[2]

Hydrogeologic controls on peatland development in the Malloryville Wetland, New York (USA)

J.P. McNamara[a], D.I. Siegel[a], P.H. Glaser[b] and R.M. Beck[c]

[a]*Department of Geology, Syracuse University, Syracuse, NY 13244, USA*
[b]*Limnological Research Center, University of Minnesota, Minneapolis, MN 55455, USA*
[c]*54 W. Malloryville Road, Freeville, NY 13068, USA*

(Received 6 November 1991; revision accepted 21 April 1992)

ABSTRACT

McNamara, J.P., Siegel, D.I., Glaser, P.H. and Beck, R.M., 1992. Hydrogeologic controls on peatland development in the Malloryville Wetland, New York (USA). J. Hydrol., 140: 279–296.

The Malloryville Wetland Complex, a small kettle-hole peatland, contains a diversity of peatland types. The wetland has a 'rich' side that contains wetland vegetation associated with solute-rich, near-neutral pH (minerotrophic) water, and a 'poor' side containing vegetation that grows in solute-poor and acidic (ombrotrophic) water. Vertical head gradients at piezometer clusters located in the rich side clearly show that groundwater is moving upwards towards the land surface, consistent with the vegetation types and surface water quality. In contrast, vertical head gradients also show that groundwater is moving upward in the poor side even though the vegetation and surface water chemistry are not minerotrophic. An incipient raised bog in the center of the poor side is the only site where groundwater moves consistently downward.

A peat core collected at the bog center shows that the bog site was initially covered by minerotrophic vegetation, typically found in groundwater discharge zones, which was later replaced by ombrotrophic bog vegetation. Theoretical computer simulation experiments of the bog hydrogeologic setting through time suggest that the direction of vertical groundwater flow at the bog site permanently changed from up to down when a water table mound developed under a convex-shaped fen peat mound that probably formed because of differential peat accumulation. Ombrotrophic conditions and bog vegetation probably began when the fen water table mound grew sufficiently large enough to divert the upward movement of regional groundwater. The transition from rich to poor environments probably occurred when the wetland water table was substantially below the elevation of the surrounding regional water table.

INTRODUCTION

Peatland vegetation is largely a manifestation of hydrologic influences. The hydrologic pathways of different water sources into peatlands control the peatland surface water chemistry which in turns affects which types of plants can grow. Freshwater peatlands can be classified into two general categories

Correspondence to: J.P. McNamara, Department of Geology and Geophysics, Univ. Alaska, Fairbanks, AK 99775-0760, USA.

by the major sources of water. Ombrotrophic peatlands (bogs) receive water and nutrients solely from precipitation whereas minerotrophic peatlands (fens) receive water from both precipitation and groundwater (e.g. Gorham, 1967). Fens commonly change to bogs in the typical ecological succession of peatland.

The major factors that distinguish the surface water of bogs and fens are; pH, calcium concentration and specific conductance. Bog water generally has a pH less than 4.2, and calcium concentrations less than 3.0 mg l^{-1} whereas fen water typically has pH higher than 5.8 and calcium concentration greater than 25 mg l^{-1} (Heinselman, 1970; Moore and Bellamy, 1973; Malmer, 1986).

These chemical differences between the surface water of fens and bogs reflect a 'poor' to 'rich' ecological gradient (Gorham, 1956; Heinselman, 1970; Slack and Horton, 1980; Glaser et al., 1981; Vitt and Bayley, 1984; Malmer, 1986; Comeau and Bellamy, 1986; Siegel and Glaser, 1987). Fens are typically species rich and contain 'minerotrophic indicator species' that can only grow in minerotrophic water. Bogs are typically species poor and lack minerotrophic indicator species. Bogs are characterized by a continuous mat of Sphagnum whereas Carex is the dominant taxa in fens. Ombrotrophic peatlands that are covered by trees are also called ombrotrophic swamps; fens that are covered by trees are also called minerotrophic swamps.

Despite the clear association between surface water chemistry and vegetation types, the hydrogeologic controls on peatland ecology are not clearly understood. Some common assumptions (Gore, 1983) are: (1) fen vegetation develops in peatlands formed in groundwater discharge areas; (2) bog vegetation develops in peatlands that are isolated from regional groundwater. These assumptions have been recently modified by Siegel (1983) who suggested that bogs and fens represent the end points of groundwater flow systems wherein: (1) water enters the system as precipitation through the bogs; (2) travels downward and through the underlying mineral soil; (3) then discharges at the fens near bog margins. The assumptions that fens exist in groundwater discharge areas and that bogs exist in groundwater recharge areas imply that there is a hydrologic succession coincident with the ecologic succession from fen to bog.

In the most commonly cited conceptual model for wetland succession, bogs in kettle depressions are thought to form after open water bodies are first filled by organic sediments and then later are covered by fen vegetation (Weber, 1908; Tallis, 1983). Fen peat then accumulates until the peat surface and water table are higher than the regional water table and isolates the wetland from surrounding mineral-rich groundwater. Once the wetland surface is removed from the regional groundwater, bog vegetation can colonize and grow. The bog peat then can accumulate to form the characteristic convex profile of the raised bog. Millington (1954) and Moore and Bellamy (1973) further suggest that the original minerotrophic condition succeeding the open water body in a kettle depression is caused by mineral-rich inflow streams which are dammed by the accumulating peat. The zone of standing water that often surrounds a raised bog in a kettle (called a lagg zone) may be the remnant of such a surface water stream (Moore and Bellamy, 1973).

However, kettle-hole fens and raised bogs are also found in closed basins without influent streams and in steeply sloped basins that clearly sustain water tables higher than the peatland water table. This topographic position of the wetland suggests that the transition from fen to bog may occur before peat accumulates above the regional water table. Despite these contradictions to the generally accepted model for wetland succession, little work has been done to directly evaluate the hydraulic mechanisms related to the change from minerotrophic to ombrotrophic conditions in kettle wetlands. This paper reports the results of such a study to examine the evolution of ombrotrophic conditions in a small kettle-hole wetland complex in central New York. The ombrotrophic bog is associated with other peatland types that formed over the same time during the past 6000 years. Therefore, the study has allowed us to compare and contrast the evolution of different wetland types under similar physiographic and geologic settings.

STUDY AREA

The Malloryville Wetland Complex is 12 ha in area and located in a kettle–kame complex formed during Wisconsinan glaciation (1000–14 000 BP)(Von Engeln, 1959; McNamara and Siegel, 1990). The remarkable diversity of vascular plant species displayed at the site is unique for a peatland of its size (Fig. 1) and has been known to local botanists for over 100 years (Dudley, 1886) for its rare and endangered plants.

Geologic setting

The Malloryville Peatland is located on the Appalachian Upland, consisting of relatively undeformed sedimentary rocks of Ordovician, Silurian, and Devonian age that dip southward less than one degree (Muller, 1965). The uppermost bedrock underlying the peatland is upper Devonian shale and thin-bedded sandstone (Bloom, 1986). The peatland and associated glacial features lie in Fall Creek Valley, mostly underlain by glacio-fluvial stratified sand and gravel with a strongly calcareous matrix (Bloom, 1970). Overlying the sand and gravel is about 12 m of till, marking the subsequent advance of ice through the valley.

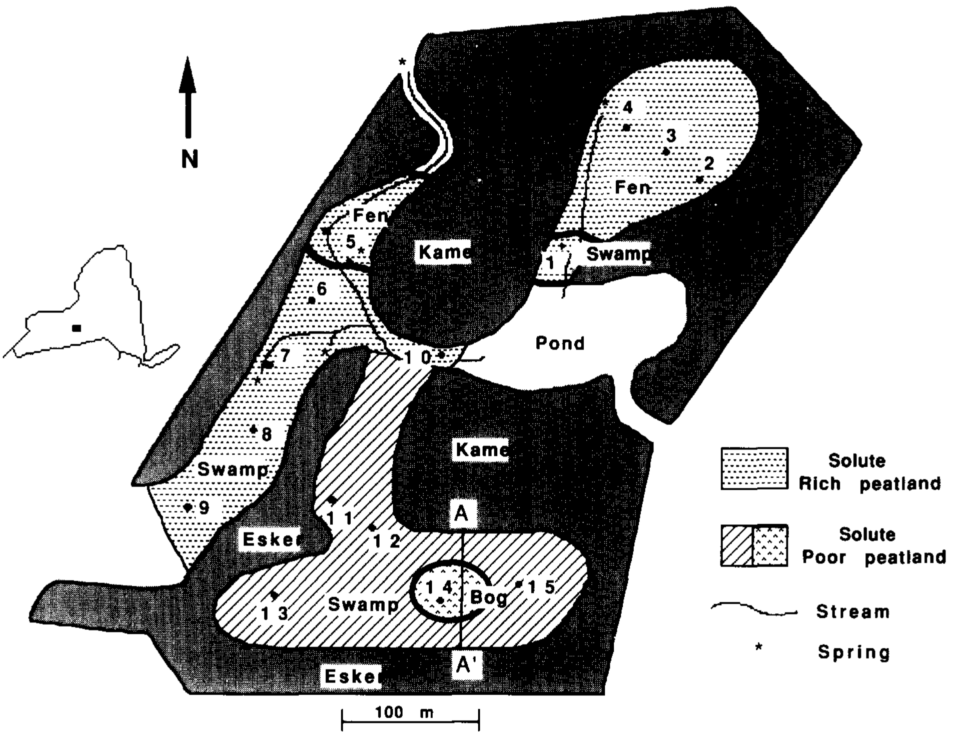

Fig. 1. The Malloryville Wetland Complex in Malloryville, NY, contains five different peatland types in an area covering approximately 12 ha (30 acres). The numbers represent piezometer clusters and sampling sites. The distribution of peatland types falls into two major groups based on surface water chemistry and vegetation. The northwest or 'rich' side is characterized by minerotrophic water and abundant fen indicator plants. The southeast or 'poor' side is characterized by acidic surface water and little or no fen indicator plants.

Drainage

Streams in the peatland originate from groundwater springs and ultimately discharge into Fall Creek which flows southeast into Cayuga Lake. Groundwater springs and diffuse discharge occurs from higher water table elevations on extensive kame deposits located to the immediate northwest. On the kames, the water table is approximately 3–4 m above the water table in the peatland (B.P. Foster, unpublished report, 1990). There are no surface water inlets to the peatland and only one outlet through a break in an esker draining a man-made pond.

Vegetation

Vegetation in the Malloryville Wetland Complex occurs in five distinct communities classified by surface water chemistry and plant communities; fen, rich fen, rich swamp, poor swamp, and bog (Fig. 1). These communities in the wetland are distributed between 'rich' and 'poor' sides, defined by an imaginary line drawn down the axis of a central esker, to the stream flowing into the pond, and out of the pond outlet. North and west of the line the rich side consists of fens and rich swamps having minerotrophic surface water. South and east of the line is the poor side consisting of poor swamps and an incipient bog containing ombrotrophic surface water.

The northern basin of the Malloryville Wetland consists of a fen having indicator species including; *Carex lacustris*, *Solidago patula*, *Thalictrum pubescens*, and several bryophytes such as *Sphagnum teres*. The tree cover is fairly open and includes *Acer rubrum*, *Pinus strobus* and *Betula alleghaniensis*. The northwest corner of the fen is classified as a 'rich' fen because of the dominance of minerotrophic indicator species over other species. This rich fen has an open canopy with a continuous cover of minerotrophic mosses and herbs. Abundant vascular species include *Aster puniceus*, *Carex flava*, *Carex sterilis*, *Cirsium muticum*, *Cypripedium reginae*, *Rhamnus alnifolia*, *Senecio aureus*, *Spiranthes romanzoffiana* and *Trollius laxus*. *Campylium stellatum* is a dominant bryophyte.

There are two rich swamps, forested peatlands containing min erotrophic indicator species. The west swamp tree cover is dominated by Tsuga canadensis, with *Acer rubrum* and *Betula alleghaniens* also present. Both shrubs and herbs become increasingly abundant towards the south portion of the west swamp. Minerotrophic indicator species include *Cypripedium calceolus*, *Geum rivale*, *Saxifraga pensylvanica*, *Smilacina stellata*, *Thalictrum pubescens*, and a continuous cover of minerotrophic mosses. The north swamp is similar to the west swamp, but not does not contain as many minerotrophic species. There is a sparse cover of shrubs including *Vaccinium corymbosum*, *Toxicodendron vernix* and *Amelanchier sanguinea*, and a continuous cover of herbs dominated by *Symplocarpus foetidus* and *Osmunda cinnamomea*.

The largest peatland type present at the Malloryville Peatland Complex is a poor swamp, a forested peatland that lacks minerotrophic species. Tree cover is continuous and includes *Tsuga canadensis*, *Betula alleghaniensis* and *Fraxinus nigra*. Shrubs are generally sparse and include *Vaccinium corymbosum* and *Taxus canadensis*. Herbs present include *Impatiens capensis*, *Osmunda cinnamomea* and *Osmunda regalis*. Generally, the species richness throughout the poor swamp sites is much lower than in the rich swamp. The north end of central swamp does contain some minerotrophic mosses, but the rest of the poor swamp locations have no mineral indicator species. There is nearly a continuous cover of *Sphagnum magellanicum* and of vascular species that thrive in acidic conditions including *Bartonia virginica* and *Ilex verticillata*.

A canopy opening located in the southern reaches of the Malloryville Peatland in the midst of the poor swamp is dominated by typical bog vegetation. Most ecological classification schemes would call this site a semi-ombrotrophic, or transitional bog. The tree cover is nearly open with an occasional *Pinus strobus*. A ring of *Aronia melanocarpa* nearly completely surrounds the bog, except to the south, separating it from the poor swamp. Shrubs are sparse and include *Vaccinium oxycoccus*, *Chamaedaphne calyculata* and *Andromeda glaucophylla*. The herb layer includes *Calla palustris*, *Carex trisperma*, *Sarracenia purpurea* and *Eriophorum virginicum*. There is nearly a 100% cover of mosses dominated by *Sphagnum magellanicum*, a species that thrives in acidic conditions. The margins of the canopy opening do contain some minerotrophic indicator species including *Carex palustris*.

METHODS

Hydrology

Clusters of piezometers were installed at 1 m depth intervals at 15 locations throughout the Malloryville Wetland (Fig. 1). The piezometers consisted of plastic vinyl chloride (PVC) casing with 1.27 cm (0.5 in) inside diameter and 1.9 cm (0.75 in) outside diameter (Chason and Siegel, 1986). Hydraulic head was measured monthly from October 1989 to September 1990. A detailed water table map was prepared for the bog and the north fen by detailed surveying. Precipitation data in Freeville, NY, 8 km from the Malloryville Wetland, was obtained from the Northeast Regional Climate Center at Cornell University.

Field hydraulic conductivity at seven piezometer clusters was determined using the hydrostatic time lag method (Hvorslev, 1951; Cedergren, 1967). This method involves evacuating a piezometer and relating the time of water-level recovery to hydraulic conductivity (Chason and Siegel, 1986).

Water chemistry

Groundwater from springs and samples of peat pore water from the piezometer clusters were collected in November 1989, February 1990 and April 1990, and analyzed for specific conductance, pH, alkalinity, calcium, magnesium, sodium and potassium. Surface water samples were taken from existing pools or from shallow excavations.

Specific conductance and pH were determined in the field using a Lab-line Lectro Mho meter, and a combination electrode and an Orion 250 specific-ion meter. Calcium, magnesium, potassium and sodium were measured by direct-current-plasma-emission spectrometry (Beckman Spectrospan-V DCP-Spectrometer) of water samples filtered though a 0.2 μm filter and field acidified using nitric acid. Alkalinity was determined on an unacidified sample by potentiometric titration.

Solute transport through the peat was evaluated by solving the analytical expressions for diffusion assuming an effective coefficient for molecular diffusion of 10–11 $m^2\ s^{-1}$ and an effective porosity of 0.1 (Ogata and Banks, 1961; Siegel, 1988). Saturation indices for calcite and dolomite on select samples were determined by using PCWATEQ, a computer program for calculating chemical equilibrium (Plummer et al., 1978).

Core analysis

A peat core was collected with a 7.6 cm (3 in) diameter piston sampler at the bog center to determine its vegetation history and age (Wright et al., 1984). The core sections were cut longitudinally to expose a fresh surface and described by the Troels-Smith method (1955). The ages of peat samples at three stratigraphic breaks were determined by ^{14}C by Beta Analytic.

Numerical modeling experiments

The sensitivity of vertical hydraulic head gradients in the peat to changes in the topography of the peatland water table was investigated by theoretical, steady-state, two-dimensional, numerical simulation experiments of groundwater flow along a north–south transect (Fig. 1) across the symmetrical raised bog. Specifically, the experiments were designed to evaluate the theoretical minimum height of a water table mound necessary to cause groundwater flow to reverse from upwards to downwards in a kettle fen located in the depression now containing the raised bog. The model experiments were largely conceptual, given the scant database, and used standard finite-difference approximations with a 20 $\times$ 20 grid and used the U.S. Geological Survey MODFLOW simulation program (McDonald and Harbaugh, 1988).

As a first approximation, the bedrock surface below the peat and mineral soil was assumed to be a hydrologic ‘no-flow’ boundary. Lateral hydraulic no-flow boundaries were set at surface water divides on the large eskers and kames bordering the bog. The water table was set as a constant head boundary at variable elevations. The geometric mean values for horizontal hydraulic conductivity of the hemic and sapric peat were used for the peat column (10^{-3} cm s^{-1} and 10^{-5} cm s^{-1}, respectively) and a value of 10^{-1} cm s^{-1} for the hydraulic conductivity of the underlying outwash sand was assumed (Freeze and Cherry, 1979). Vertical anisotropy was set at 0.001, typical of wetland settings in sand and gravel (Siegel and Winter, 1980).

To estimate the height of the present-day regional water table immediately adjacent to the peatland, the simulated regional water table elevation was first varied under the adjacent kames and eskers until the simulated hydrologic gradient in the raised bog center was calibrated to the average observed vertical gradient measured at the piezometer nest in the center of the raised bog. The predicted elevation of the regional water table was then held constant and the water table profiles at appropriate elevations in the kettle depression were varied to simulate the following hydrogeologic settings: (1) before peat developed; (2) when a raised fen peat mound could have generated sufficient vertical downward head gradients to isolate the mound from regional groundwater discharge. It was assumed that little change occurred in the elevation of the regional water table during the periods modeled. Post-glacial climate in the study area was sufficiently similar to that of today to assume that the configuration of the regional water table was not significantly lower or higher than now.

RESULTS

Water chemistry

Surface water

Surface water chemistry follows the same rich/poor boundary as vegetation. Surface water in the fen and rich swamp sites has the highest pH, specific conductivity, alkalinity and dissolved solute concentrations and is clearly minerotrophic to highly minerotrophic. The pH is typically greater than 7, the carbonate alkalinity ranges from 0.7 to 5.9 mEq l^{-1}, the specific conductivity ranges from 155 to 625 μS cm^{-1}, and the calcium concentration ranges from 0.5 to 2.1 mmol l^{-1}. In contrast, the surface water in the bog and poor swamp is dilute and acidic. Average pH ranges from 4.1 to 4.8, carbonate alkalinity is typically 0 or slightly above, specific conductivity ranges from only 27 to 79 μS cm^{-1} and calcium content ranges from only 0.05 to 0.16 mmol l^{-1}.

Peat pore water

Water samples collected from springs and the deepest piezometers in fen and rich swamp sites contain groundwater having chemical characteristics typical of that found in calcareous mineral soils. Groundwater has a pH of

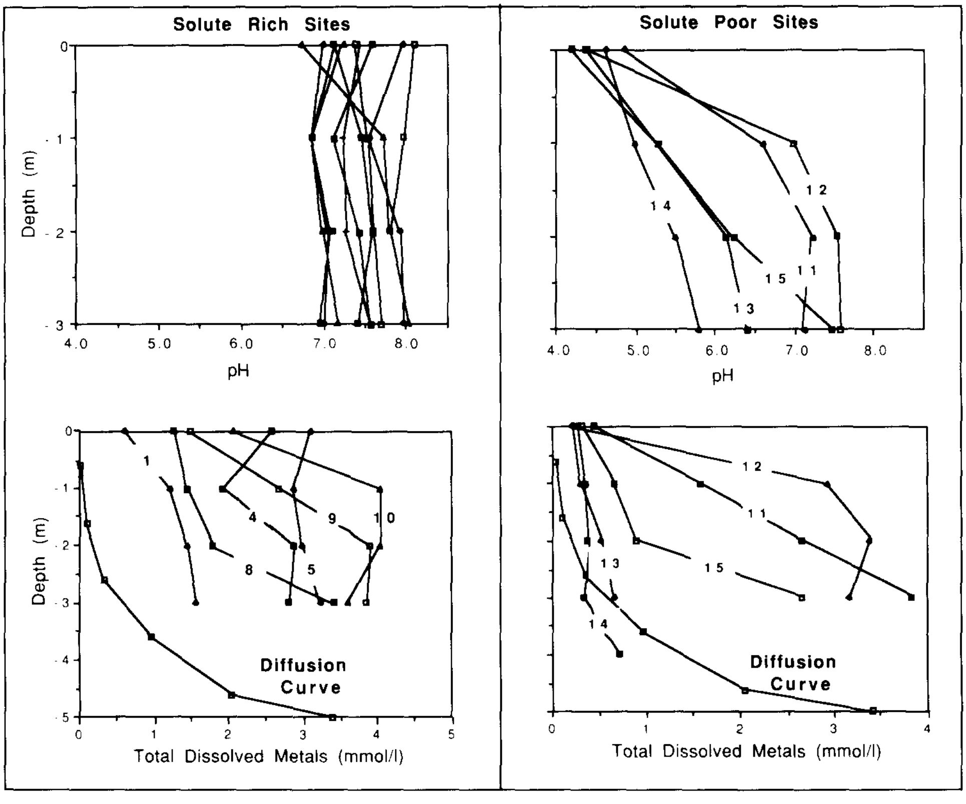

Fig. 2. Vertical profiles of pH and total dissolved metals (TDM) for selected sites from the rich side of the peatland and all sites from the poor side of the peatland. The numbers refer to site locations (see Fig. 1). Note the significant differences between the two sides at 0 depth, but that the differences diminish with depth. Theoretical concentration profiles are lower than the TDM plots indicating upward movement of groundwater.

about 7.8, a specific conductivity of about 600 $\mu S\ cm^{-1}$, alkalinity of about 3.4 $mEq\ l^{-1}$ and calcium concentration of about 2.3 $mmol\ l^{-1}$. The groundwater samples collected from the springs discharging at the fen and swamp margins are oversaturated with respect to both calcite and dolomite because of carbon dioxide degasing.

The chemical differences between rich and poor locations diminish with depth. At all piezometer clusters, concentrations of dissolved solutes and pH typically increase with depth and approach those found in groundwater from the underlying mineral soils (Fig. 2). The fen and rich swamp locations commonly show nearly vertical concentration profiles of most solutes. In contrast, the bog and poor swamp sites have more variable concentration profiles of major solutes and specific conductance with depth. For example,

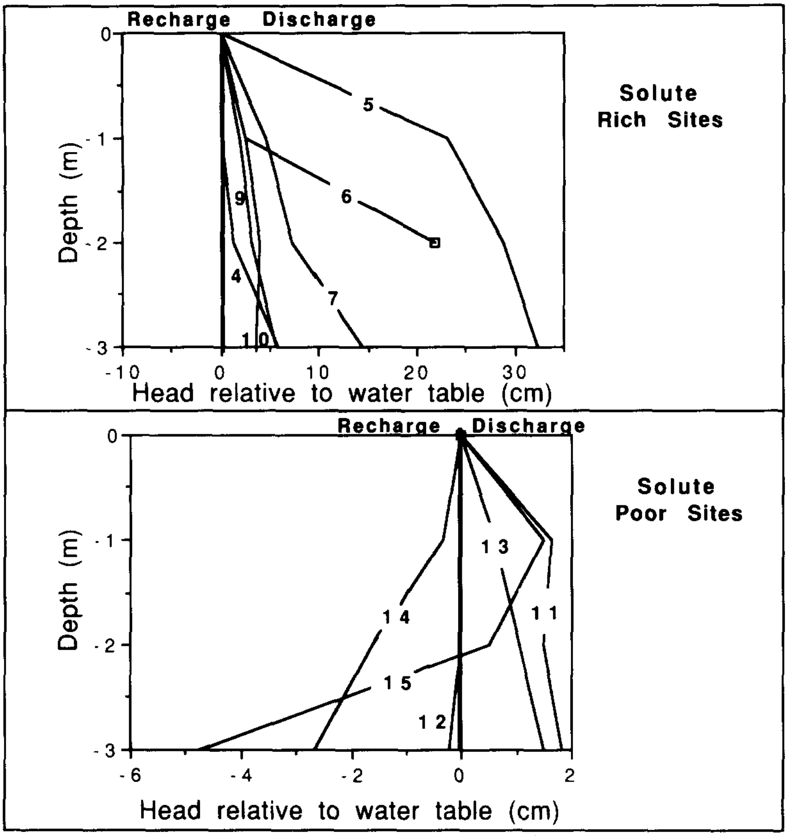

Fig. 3. Hydraulic head (24 May 1990) vs. depth for select rich locations and poor locations. When a profile is negative it indicates downward movement of groundwater. When a profile is positive it indicates upward movement of groundwater.

pore water in the central poor swamp contains minerotrophic groundwater at a depth of only 1 m, whereas bog pore water only 25 m away is very dilute at a depth of 4 m. The south and east poor swamp locations have concentration–depth profiles similar to that at the bog. A piezometer 2 m deep at the bog margin, however, shows minerotrophic conditions; a pH of 6.8, and a specific conductivity of 164 μS cm^{-1}.

Hydrology

Water levels in the piezometers located in the rich sites were above the water table at all depths for most of the year. This indicates groundwater is moving upward (Fig. 3). The consistently highest piezometer water levels occurred at sites 5 and 6 in the piezometers located in glacial sediments below the peat in the rich fen. Here, hydraulic head at 3 m depth was over 20 cm higher than the water table (May 1990). Other locations in the west swamp had maximum water levels ranging from 5 to 15 cm higher than the water table. The northern basin, including sites 1–4, had the lowest water levels of the rich sites. Water levels at sites 2 and 3 occasionally dropped below the water table in a reversal of hydraulic gradients.

Remarkably, given the dilute surface water chemistry, piezometers in the poor swamp also had water levels above the water table for most of the year, although not as high as those found in the rich locations (Fig. 3). Maximum water levels were only about 2 cm above the water table during the wettest months and typically decreased below the water table during dry months. The bog, site 14, was the only site that showed water levels consistently below the water table. Even here, however, the deepest piezometers in the bog had water levels above the water table in February.

The water table in the peatland slopes towards the pond from all directions. The raised bog has a symmetrical water table mound about 7 cm high. An asymmetrical water table mound, about 20 cm high, slopes towards a spring in the north fen (Fig. 4).

Hydraulic conductivity

The hydraulic conductivity for the fen and swamp sites averaged 10^{-3} cm s^{-1} ($n = 9$). Hydraulic conductivity of the bog peat averaged 10^{-5} cm s^{-1} ($n = 6$). There were no noticeable trends with depth, and no differences between rich and poor swamps.

Stratigraphy

The core taken in the bog contained two major biostratigraphic units in the peat above layers of gytjja (lake organic sediment) and marl (Fig. 5). The upper part of the core (0–450 cm) consists primarily of Sphagnum peat increasingly humified with depth. At 450 cm the Sphagnum peat was dated as 4567 years old by ^{14}C dating methods. Below the Sphagnum peat occurs 300 cm of deeply humified sedge peat. The base of this section is 6200 years old. Below the sedge peat is 4 m of algal gytjja, which began depositing 11 000 years BP, over 1 m of marl. The marl grades into sandy gravel.

Numerical modeling

The numerical modeling experiments suggest how a hydrologic reversal probably occurred at the bog site as a result of peat mounding. The 7 cm high

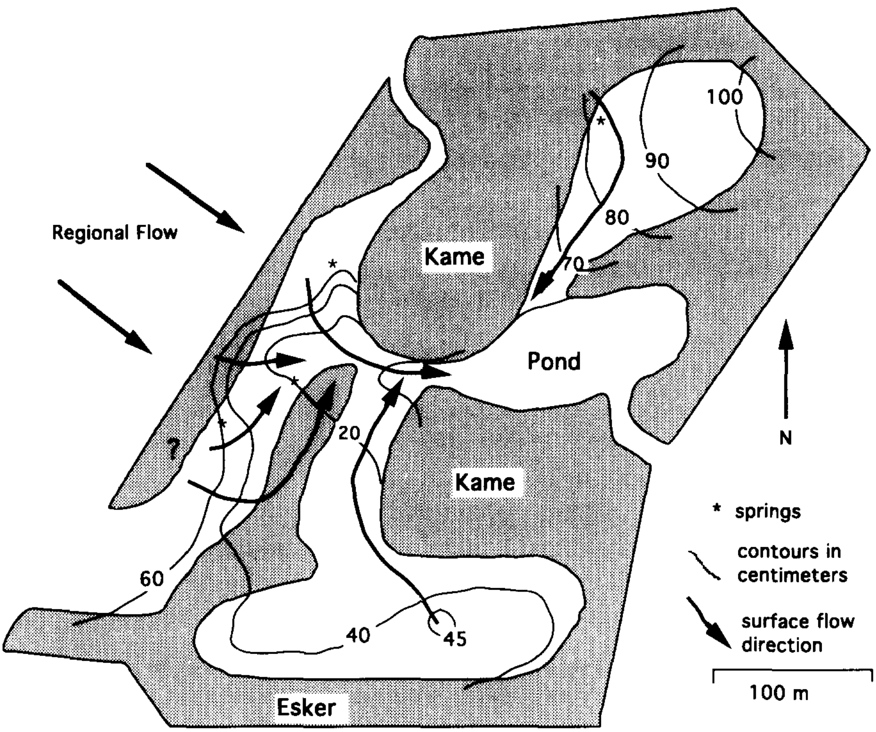

Fig. 4. Water table map (15 June 1990) of the Malloryville Wetland Complex. The water levels in the surrounding glacial features are unknown. Note the water table mound in the bog, and the sloping water table in the north fen.

water table mound and a vertical downward hydraulic gradient of 4 cm over 3 m were used as the present hydrogeologic setting in the bog. The calibrated model of the present-day hydrogeologic setting showed that the water table under the glacial features bounding the bog is now probably 3 cm below the water table at the bog margin. However, fen vegetation in the lower part of the peat core indicates that the water table must have been at one time higher than the peatland water table to enable groundwater to discharge to the basin now occupied by the bog.

The numerical modeling experiments show that a water table mound of only 20 cm imposed at the stratigraphic break from fen to bog would be sufficient to cause groundwater to flow downwards in the wetland (recharge) and exclude upward groundwater flow from the basin. This experimental result was obtained while maintaining the elevation of the regional water table at its present elevation 3.5 m above the stratigraphic break.

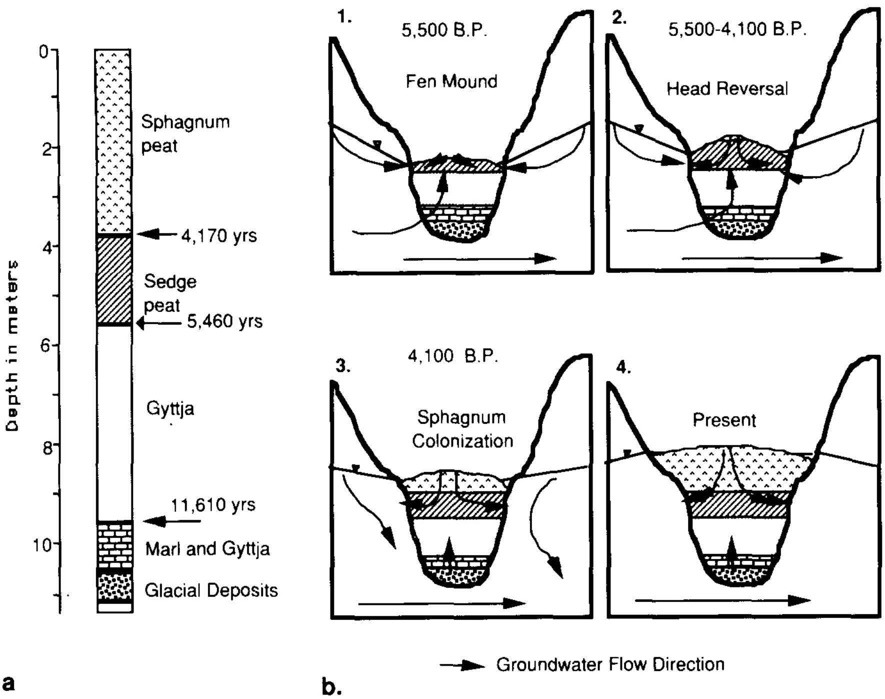

Fig. 5. (a) Core taken from the bog crest (site 14) in the Malloryville Wetland Complex. The stratigraphy (bog overlying fen) suggests that a hydrologic reversal occurred whereas at one time the basin was a groundwater discharge site and today it is a recharge site. (b) The developmental history of the bog in the Malloryville Wetland Complex. (1) Groundwater discharge formed a peat mound due to differential accumulation of peat. The water table rose with the accumulating peat. (2) The mound continued to grow until the upward moving groundwater could no longer sustain the water table mound and downward movement was then induced. Sphagnum moss colonized in the newly ombrotrophic conditions. (3) Continued accumulation of Sphagnum peat buried the marginal springs. (4) The peat water table rose to where it is today, higher than the surrounding water table.

DISCUSSION

It is well understood that calcium and pH primarily determine the major vegetation differences between rich and poor peatlands, and that high values for both of these parameters typically indicate the influence of groundwater (e.g. Glaser et al., 1981). The distribution of peatland types in the Malloryville Wetland raises an interesting question: how can the bog and surrounding poor peatlands, which appear at the surface to be separated from mineral-rich groundwater, exist in such close proximity to peatlands that are so clearly maintained by groundwater discharge? Pore water concentration profiles (Fig. 2) and upward vertical head gradients indicate that the poor peatland is actually not separated from groundwater. Statistical analyses of variance of concentration means and standard deviations clearly documents the similarity between peat pore water and underlying groundwater where head gradients are upward (McNamara and Siegel, 1990), although peat decomposition may contribute some solutes to pore water.

Solutes originating from groundwater are transported upward by advective and diffusive transport. Advection occurs when solutes are transported by the bulk motion of the flowing groundwater. Diffusion occurs when constituents move under the influence of their own kinetic activity in the direction of their concentration gradient. One-dimensional solute transport calculations at the Malloryville sites show that the concentration profiles for metals at all rich and poor locations, except at the bog crest, are greater than those predicted by chemical diffusion alone (Fig. 2). The only way for the profile to have occurred is by upward movement of groundwater — even under the poor side of the peatland despite the lack of evidence in the surface water chemistry.

The seepage velocity of diffuse groundwater discharge upward through the peat can be calculated using:

$$v = -KI/n$$

where v is the seepage velocity, K is the hydraulic conductivity, I is the hydraulic gradient and n is the porosity, 0.1 (Siegel and Glaser, 1987).

The rich fen probably has groundwater moving upward in the underlying glacial deposits on the order of 1 m day^{-1}. Movement in the peat is significantly slower, ranging from less than a millimeter to about 10 cm day^{-1} upward throughout the rich side of the peatland. Velocities at poor locations probably range from 10^{-3} to 10^{-5} cm s^{-1}. The upward movement of groundwater throughout the poor side is well documented, but in contrast to the rich side, groundwater does not significantly influence surface water chemistry and vegetation because advection flux of solutes is slower.

Developmental history of the raised bog

The assumed end point of peatland succession is a raised bog with a convex surface caused by differential peat accumulation (Granlund, 1932) enhanced by minerotrophic stream or spring water, entering at the peatland margins, that retards peat accumulation at the margins (Ivanov, 1975). Clymo (1984) suggested that peat growth begins in the center of a basin and accumulates both vertically and laterally resulting in the convex shape and Ingram (1982) showed that a peat mound can remain saturated because of impeded drainage at the peatland margins so that a water table mound survives in a peat mound.

Most work describing peat doming has concentrated on bogs. There is, however, no reason that the same processes can not occur in fens. Indeed, many domed fens are reported (Freisner and Potzger, 1946; Havas, 1961; Kukla, 1965; Holte, 1966; Moore and Bellamy, 1973; Lahermo et al., 1977; Kratz et al., 1981; Wilcox et al., 1986). Our study suggests that peat doming and a subsequent water table mound on a fen caused the initial hydrologic reversal which initiated bog succession at the Malloryville wetland.

The peat core from the bog has the typical successional sequence for a peatland (Weber, 1908). Marl at the base of the core taken at the bog crest indicates that at one time groundwater entered the basin and ^{14}C dating of the fen peat indicates that from about 5460 BP until 4170 BP the bog site was minerotrophic and receiving groundwater discharge. Our numerical modeling experiments show that a water table mound, only 20 cm high, under accumulating fen peat would cause a vertical hydrologic reversal and divert regional groundwater discharge — even when the peatland water table surface was still meters below the surrounding regional water table. The diversion of groundwater flow would have changed the chemical environment to favor bog formation. Twenty centimeters is a feasible height for a mound to develop on a peatland the size of the Malloryville bog, based on annual rainfall and hydraulic controls over mounding (Granlund, 1932; Marino, 1974; Ingram, 1982).

The hypothesis of fen peat mounding as the initial step to ombrotrophic peatland succession in kettle lake depressions clarifies and expands upon Granlund's (1932) model whereby differential peat accumulation causes the convex shape of raised bogs. Most raised bogs have a surrounding lag zone of mineral-rich water previously thought to be diverted surface water streams. At Malloryville, these lags are probably remnant springs. Indeed, the pore water sample at 2 m depth at the bog margin is clearly minerotrophic.

The developmental history of the Malloryville bog probably occurred as follows. First, the initial peatland was a fen that was maintained by springs at the margins (Fig. 5). Peat accumulated and formed a dome mimicked by the underlying water table mound. About 4100 years ago, the mound grew large enough such that its recharge function (sensu Siegel, 1983) prevented the upward movement of groundwater from supporting the fen peat vegetation. Recharge in the basin center was then induced and ombrotrophic species of Sphagnum became established. The margins, however, still received groundwater discharge through shallow springs. As peat continued to accumulate, the influence of the springs decreased, and the ombrotrophic center grew. Eventually, peat accumulation became great enough to bury the margin springs and the peat surface accumulated to the point where it is today, above the surrounding water table. It must be emphasized, however, that the fen/bog succession occurred well before that happened.

The vegetation and water chemistry of the bog site indicate that it is not fully ombrotrophic yet. Perhaps the peat mound has been limited to a height that cannot completely preclude deep groundwater discharge. Seasonal reversals in the vertical flow direction may contribute small amounts of dissolved solutes to the surface, and a diminished water table mound during dry times will allow for additional groundwater discharge at the margins. Such discharge has been observed in the glacial Lake Agassiz Peatlands where after 5 years of severe drought, strong upward movements of groundwater are occurring at the crests of large raised bogs (Romanowicz et al., 1990).

The processes described for the bog succession are likely responsible for the dramatic ecological differences between the rich and poor sides of the Malloryville Peatland. At one time, the entire basin was probably a small pond. The distribution of springs and subsequent fen peat accumulation probably imposed a north-sloping water table in the southern half of the peatland (Fig. 5). Shallow groundwater that once moved through the central esker to the west swamp was diverted north, cutting off the majority of groundwater discharge to the east side. Deeper groundwater discharge still enters the east side, but hydraulic head is attenuated before it can transport significant amounts of groundwater to the surface. Those deep groundwater sources are the likely sources of the springs that once maintained the fen, now covered by the bog, and which have long been cut off.

The shape of the north fen suggests that it too may become ombrotrophic. Here, the fen is maintained by a single spring on the west side and the peat surface and water table slope towards that spring. Eventually, the east side of the north fen will rise high enough to create downward movement of groundwater to allow ombrotrophic conditions to prevail. The ecological status of the Malloryville wetland is clearly delicately poised with respect to regional and local groundwater hydrology. This degree of interaction between subsurface hydrology and ecological community growth where hydrologic succession precedes ecologic succession may well be the norm with respect to other kettle wetlands in similar hydrogeologic settings.

REFERENCES

Bloom, A.L., 1970. Glacial history of the Fall Creek Valley at Ithaca, New York. In: New York State Geological Society, Field Trip Guidebook, 42nd Annual Meeting, Cortland, NY, pp. K1–K5.

Bloom, A.L., 1986. Geomorphology of the Cayuga Lake Basin. In: New York State Geological Society, Field Trip Guidebook, 58th Annual Meeting, Ithaca, NY, pp. 261–279.

Cedergren, H.R., 1967. Seepage, Drainage, and Flow Nets. John Wiley and Sons, New York, 489 pp.

Chason, D.B. and Siegel, D.I., 1986. Hydraulic conductivity and related physical properties of peat, Lost River Peatland, northern Minnesota. Soil Sci., 142: 91–99.

Clymo, R.S., 1984. The limits to peat bog growth. Philos. Trans. R. Soc. London, 303: 605–654.

Comeau, P.L. and Bellamy, D.J., 1986. An ecological interpretation of mire waters from sites in eastern Canada. Can. J. Bot., 64: 2576–2581.

Dudley, W.R., 1886. The Cayuga Flora. Andrus and Church, Ithaca, NY, 132 pp.

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

Freisner, R.C. and Potzger, J.E., 1946. The Cabin Creek Raised Bog, Randolph County, Indiana. Butler Univ. Bot. Stud., 8: 24–43.

Glaser, P.H., Wheeler, G.A., Gorham, E. and Wright, H.E., 1981. The patterned peatlands of the Red Lake Peatland, northern Minnesota: vegetation, water chemistry and landforms. J. Ecol., 69: 575–599.

Gore, A.J.P., 1983. Introduction. In: A.J.P. Gore (Editor), Ecosystems of the World 4A. Elsevier, New York, pp. 1–34.

Gorham, E., 1956. The ionic composition of some bog and fen waters in the English Lake District. J. Ecol., 44: 142–151.

Gorham, E., 1967. Some chemical aspects of wetland ecology. Tech. Mem. 90. Assoc. Comm. on Geotechnical Res, National Research Council of Canàda, pp. 20–38.

Granlund, E., 1932. De svenska hogmossarnas geologi. Sver. Geol. Unders., Ser. C, 373: 1–193.

Havas, P., 1961. Vegetation and okologie der ostfinnischen hangmoore. Ann. Bot. Soc. Zool. Bot. Fenn. 'Vanamo', 31: 1–188.

Heinselman, M.L., 1970. Landscape evolution, peatland types, and the environment in the Lake Agassiz Peatlands Natural Area, Minnesota. Ecol. Monogr., 40: 235–261.

Holte, K.E., 1966. A floristic and ecological analysis of the Exelsior Fen Complex in northwest Iowa. Ph.D. Dissertation, University of Iowa, 306 pp.

Hvorslev, M.T., 1951. Time lag and soil permeability in groundwater observations. U.S. Army, Corps Eng. Waterways Exp. Stn, Bull. 36, U.S. Army, Corps of Engineers, Vicksburg, MS, 50 pp.

Ingram, H.A.P., 1982. Size and shape in raised mire ecosystems: a geophysical model. Nature, 329: 300–303.

Ivanov, K.E., 1975. Water Movement in Mirelands. Academic Press, New York, 276 pp.

Kratz, T.K., Winkler, M.J. and DeWitt, C.B., 1981. Hydrology and chronology of a peat mound in Dane County, southern Wisconsin. Trans. Wis. Acad. Sci., Arts, Lett., 69: 37–45.

Kukla, S., 1965. Rozwoj torfowisk zrodliskowych no terenack Polnocno-wachodniej Polski. Zesz. Probl. Postepow Nauk Roln., 57: 395–483.

Lahermo, P., Valovirta, V.E. and Sarkioja, A., 1977. The geobotanical development of spring-fed mires in Finish Lapland. Geol. Surv. Finl., Bull., 287, 44 pp.

Malmer, N., 1986. Vegetational gradients in relation to environmental conditions in northwestern European mires. Can. J. Bot., 64: 375–383.

Marino, M.A., 1974. Growth and decay of groundwater mounds induced by percolation. J. Hydrol., 22: 295–301.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. U.S., Geol. Surv., Open-File Rep. 83-875, 488 pp.

McNamara, J.P. and Siegel, D.I., 1990. The hydrogeology and ecology of the Malloryville Wetland Complex, Malloryville, New York. Eos, 71: 1299.

Millington, R.J., 1954. Sphagnum bogs of the New England Plateau, New South Wales. J. Ecol., 42: 328–344.

Moore, P.D. and Bellamy, D.J., 1973. Peatlands. Elek, London, 221 pp.

Muller, E.H., 1965. Quaternary geology of New York. In: H.E. Wright and D.G. Frey

(Editors), The Quaternary of the United States. Princeton University, Princeton, NJ, pp. 99–112.
Ogata, A. and Banks, R.B., 1961. A solution of the differential equation of longitudinal dispersion in porous media. U.S., Geol. Surv., Prof. Pap. 411-A, 7 pp.
Plummer, N.L., Jones, B.F. and Truesdell, A.H., 1978. WATEQF — a Fortran IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters. U.S., Geol. Surv., Water-Resour. Invest. No. 76-113, 61 pp.
Romanowicz, E.A., McNamara, J, P., Siegel, D.I., Glaser, P.H., Nelson, D., Neuzil, S.G., Frederick, B.C. and Struck, C.N., 1990. Groundwater discharge beneath raised bogs, Lake Agassiz Peatlands, Minnesota: Part I: hydrogeologic evidence. Eos, 71: 1299.
Siegel, D.I., 1983. Groundwater and the evolution of patterned mires, Glacial Lake Agassiz Peatlands, northern Minnesota. J. Ecol., 71: 913–921.
Siegel, D.I., 1988. The recharge–discharge function of wetland near Juneau, Alaska: Part 1. Hydrogeological Investigations. Ground Water, 26: 580–585.
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.
Siegel, D.I. and Winter, T.C., 1980. Hydrogeologic setting of Williams Lake, Hubbard County, Minnesota. U.S. Geol. Surv., Open-File Rep. 80-403.
Slack, N.G.D. and Horton, D.G., 1980. Vegetation gradients of minerotrophically rich fens in western Alberta. Can. J. Bot., 58: 330–349.
Tallis, J.H., 1983. Changes in wetland communities. In: A.J.P. Gore (Editor), Ecosystems of the World 4A. Elsevier, New York, pp. 311–348.
Troels-Smith, J., 1955. Karakterisering af lose jordarter (Characterization of unconsolidated sediments). Geol. Surv. Den., Ser. IV, 3: 7–73.
Vitt, D.H. and Bayley, S., 1984. The vegetation and water chemistry of four oligotrophic basin mires in northwestern Ontario. Can. J. Bot., 62: 1485–1500.
Von Engeln, O.D., 1959. The Finger Lakes Region: its Origin and Nature. Cornell University, Ithaca, New York, 156 pp.
Weber, C.A., 1908. Aufbau und vegetation der moore norddeutschlands. Englers Bot. Jahrb. 40: 19–34.
Wilcox, D.A., Shedlock, R.J. and Hendrickson, W.H., 1986. Hydrology, water chemistry and ecological relations in the raised mound of Cowles Bog. J. Ecol., 74: 1103–1117.
Wright, H.E., Jr., Mann, D.H. and Glaser, P.H., 1984. Piston corers for peat and lake sediment. Ecology, 65: 657–659.