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peatland and water

in the northern lake states

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PEATLAND AND WATER IN THE NORTHERN LAKE STATES

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Until recent years, hydrologic research on peatland has been limited in North America, although some intensive studies have been done in northern Europe and the Soviet Union. North American hydrologists have generally ignored peatland in favor of research in areas of water scarcity and water excess (floods). More recently the U.S. Geological Survey has completed studies on several large watersheds in northern Minnesota that include extensive peatlands.

The North Central Forest Experiment Station began studying peatland evolution in the late 50's. and in 1960 its watershed research program was expanded to include soil and hydrology studies on peatland. Much research was done at the Marcell Experimental Forest in north-central Minnesota, while organic soil data have been gathered throughout northern Minnesota, northern Wisconsin, and Michigan's Upper Peninsula. These studies were aimed at understanding the basic hydrology of peatland, the characteristics of organic soils, and the chemistry of streamflow leaving peatland.

This paper summarizes the basic principles of peatland ecology, and describes in detail just what peatlands are and how they developed. The term peatland is generic and includes many classes of peat-covered terrain. We will use terms in this paper that are accepted worldwide; however, peatland terminology varies by country. For instance, other terms for peatland include mires in Scandinavia, moors in Germany, muskeg in Canada, and, if forested, swamps in North America.

In their undisturbed state, peatlands normally accumulate organic debris, change their vegetation, and constantly grow in depth and breadth. Growing peatland is always associated with water. Indeed, water is required for peatland development. Peatland type depends on the kind and amount of water entering the peatland; the kind and amount of peatland in the immediate drainage basin can change the chemistry and behavior of water flowing from the basin. The northern Lake States contain a wide variety of water and peat types, and more than 6 million ha (15 million acres) of peatland occur in many sizes and locations. The large expanses of Glacial Lake Agassiz peatland in northern Minnesota contain watershed divides. Peat-filled kettle depressions in glacial tills or sandy outwash plains are common throughout the northern Lake States; they may occur near major watershed divides or at lower elevations. Streamside peatland is common on the Laurentian shield in northeastern Minnesota and other areas, and peatlands developed on old Lake Superior sand plains are common in Upper Michigan.

To understand why this diversity of occurrence exists, we need to consider the landscape before peat developed and the climate and processes during peat development. Knowing the way things were will help us understand the way things are.

LANDSCAPE DEVELOPMENT

Any discussion of peatland development in the northern Lake States (northern parts of Minnesota, Wisconsin, and Michigan) must begin with glaciers. The last glacial advance, called the Wisconsin age, lasted about 25,000 years. The southern part of the northern Lake States area was probably first revealed beneath the melt waters of the retreating Wisconsin ice sheet about 14,000 years ago in what is now central Wisconsin. Next, western Minnesota was exposed (about 11,000 years ago) and, finally, Michigan's Upper Peninsula was exposed (9,000 to 10,000 years ago).

While these glaciers were advancing to the south, they ground down the landscape and deposited a relatively flat ground moraine. After the ice melted, these flat areas provided the physical base for slow water movement, a general requirement for peat development. At various intervals, melt waters of retreating glaciers deposited flat, sandy, outwash plains that again provided a physical base for peat development.

Extensive end moraines of glacial till are also common in the northern Lake States. Today, as in the past, these hill areas provide enclosed basins where water accumulates and peat can grow.

Some areas were reworked by large lakes formed by the melt waters of retreating glaciers. Long sandy beaches are common in the Glacial Lake Agassiz region of northern Minnesota, and Glacial Lake Duluth deposited extensive sand plains well inland from the southern shore of today's Lake Superior. Lake-deposited clays and silts, lacustrine deposits, were laid down in glacial lakes away from the sorting action at their shorelines.

Finally, scattered throughout all of these land forms there are ice block depressions caused by large blocks of ice breaking off the edge of retreating glaciers leaving large depressions in the landscape when they melted. Many became lakes or ponds with limited outflow.

Thus, two landscape features conducive to peat development were left by the glaciers: flat topography and small ice-block basins. The stratigraphy of glacial drift is often complex with alternating layers of till and sorted sands. Ice-block depressions may occur in either tills or sandy outwash plains. So, why does peat develop in some areas and not in others? To answer this question we need to look at climate and water availability.

CLIMATE

Climate is the key to plant growth and decay, thus it largely controls the formation of organic soils. Although peatlands occur worldwide, they are most extensive where it is cool and precipitation exceeds evapotranspiration.

The climate of the northern Lake States is subhumid-continental. Summers are short and warm; winters are long and cold. Mean annual precipitation ranges from 508 mm (20 in) in northwestern Minnesota to 860 mm (34 in) in parts of Michigan's Upper Peninsula. About two-thirds of the precipitation occurs as rain during the warm season, April to September. Average January temperatures range from -17°C (2°F) in Minnesota to -10°C (16°F) in Michigan. Average July temperatures are about 20°C (67°F) in all three Lake States.

Clearly, this is a suitable climate for peat, but conducive climate and landforms are not enough for peat to develop.

WATER AVAILABILITY AND PEATLAND DEVELOPMENT

Peat development requires an abundant supply of water for most of the year. Conducive climate, landforms, and available water must have been present in the northern Lake States 11,000 years ago when, according to carbon-14 dates, the first aquatic peats began to form. These peats developed in kettles or ice-block depressions where the water source was either surface flow and interflow from surrounding tills or ground water supplied through sand aquifers. Water is available in tills because it collects in relatively impermeable till basins; it is available in sand basins because the water table is at or near the soil surface.

Aquatic peats in depressions were often covered by cattail, reed, and sedge peats that first developed on adjacent flat areas. The water supplied by surface flow and interflow was detained by the flat topography and, in time, by the peat itself, which tended to block drainage water, thus slowly raising the water table over long periods of time. Sedge peats began to accumulate about 8,000 years ago and are common today throughout the northern Lake States. Forested peats also began to develop about 8,000 years ago but they were limited at first to areas where calcium-enriched ground water was available. These sites occur around the edges of old glacial lake beds, on low "ridges" within the lake bed where ground water was forced to the surface by underlying bedrock ridges, and on sandy outwash areas with a high water table. In northwestern Minnesota, however, it appears that extensive forest peat development began 4,000 to 5,000 years ago after the warm Hipsithermal period. Again, the water table, usually a regional water table, rose as peats developed and blocked or slowed natural drainage.

About 3,000 years ago another type of peat (Sphagnum) began to accumulate as the developing peat became more isolated from the ground water influence. Sphagnum peat is acid and normally not strongly influenced by ground water. Instead Sphagnum tends to isolate itself from ground water by building extensive but low topographic domes or extensive blankets of peat. In these areas the primary source of water is rain and snow. Rainfall in excess of evapotranspiration is necessary. Only under these conditions is there enough surface water to maintain a slightly raised water table within the peat mass isolated from the regional ground water system. Today, exceptions to this occur in peat-filled ice-block depressions in sandy outwash plains where peat deposits have not built high enough to totally isolate surface water from ground water inflow. Here the high calcium bicarbonate concentrations in the incoming ground water maintain peat and water pH near neutral except for acid Sphagnum hummocks elevated as much as 50 cm above the fen surface.

Peat development over the last 11,000 years has been complex, but some generalizations will help us to understand peatland characteristics and various concepts of peatland and water management. The trend in peat development is from aquatic, sedge, and forest peat to Sphagnum peats. The sedge peat and the peat developed under the more productive forests are generally associated with a ground water source containing high calcium concentrations. Sphagnum peats, including those supporting the poorer forests, are associated with a rain and snow source of water that is low in calcium.

Now that we understand the general evolution of peatland, we need to look at the interaction of landforms (physiography), vegetation, and kinds (source and quality) of water in order to understand today's peatlands and the special names given to them.

INTERACTIONS OF WATER, VEGETATION, AND LAND

The kind of water in a peatland can determine the kind of vegetation present; conversely, over long periods, the kind of vegetation in a peatland can change the kind of water present. Once we integrate this seeming contradiction into our concepts of peatland evolution we will have a sound understanding of the way peatlands grow.

Water is generally supplied from three sources: precipitation (rain and snow), ground water (regional sand and gravel aquifers), and surface flow and interflow (literal surface flow over bedrock and exposed soils or flow through surface organic horizons of mineral soils, and interflow horizontally through the A or A&B horizons of mineral soils). Calcium content is an important characteristic of water source. The three water sources typically contain different amounts of calcium: precipitation (0.3 to 2.0 ppm Ca[1]), surface flow and interflow (2.0 to 10.0 ppm Ca), and ground water (> 10 ppm Ca; 20, 30, or greater ppm are not uncommon). These ranges have been verified in northern Minnesota, but not in northern Wisconsin and Michigan. Calcium is important because it commonly combines with carbonic acid (H_2Co_3) from rain to form calcium bicarbonate ($Ca(HCO_3)_2$) and this dissociates in water to yield bicarbonate ions (HCO_3^-). Bicarbonate ions are responsible for most buffering systems in natural waters and yield pH values around 6 to 8. Environments with near neutral pH values contain more plant available nutrients and a greater diversity of decomposing organisms.

We can also infer something about the relative amounts of water from these sources. Precipitation occurs fairly regularly, but its conversion to surface water is seasonal. In the northern Lake States, the snowpack and some rainfall are converted to streamflow or ground water recharge during 3 or 4 weeks in the spring. Most of the summer rainfall is converted to water vapor by evapotranspiration. Surface flow and interflow follow patterns similar to precipitation with most conversions to streamflow resulting from snowmelt or very heavy rains. Ground water sources, on the other hand, are huge compared to other water sources, and their annual distribution is more nearly uniform.

Water source is the basis for two broad categories of peatland: Ombrotrophic and Minerotrophic. These two categories cover the range of peatland types. Ombrotrophic peatlands are defined on the lower end of a total ionic concentration scale; minerotrophic peatlands cover the rest of the scale. There are corrollary names for the same categories based on vegetation: these terms are much simpler: Bog and Fen. We'll try to sort out the differences and set a foundation for understanding peatlands today.

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[1] *Calcium concentrations in precipitation may range as high as 10 ppm in northwestern Minnesota where wind-blown dust originating in the prairies can cause slightly higher pH values in peatland.*

Ombrotrophic means the peatland derives its water from ion-poor precipitation and, as a consequence, is itself ion-poor. It is inferred that the scarce ion is calcium (bicarbonate); therefore the site is usually very acidic with water pH values near 3.6. The characteristic plant of a BOG is sphagnum moss. Sphagnum also plays a major role in keeping the environment acid because of its high cation exchange capacity and the production of organic acids. The water table in a bog is often close to the surface, but usually there is little standing water (except during snowmelt or in open ponds). A raised bog is a large ombrotrophic, sphagnum bog with a characteristic dome shape. The dome is built of sphagnum and commonly occurs on top of sedge or forest (woody) peat. The central raised area is isolated from the regional water table and thus depends on precipitation for water and minerals. These peatland types may or may not be forested.

Minerotrophic means the peatland derives the major part of its water from ion-rich ground water and, as a consequence, is itself ion-rich. It is inferred that the ion in rich or large supply is calcium (bicarbonate); therefore the site is not very acid with water pH values around 6 to 7.5. Fen is a European term originally applied to grass, sedge or reed covered peatland. True fen waters are not acid and may even be slightly alkaline, but can grade into poor fens with water pH values near 4.5. Fens are generally saturated with slowly moving water or they may have temporary or semipermanent water above the soil surface. Today the term fen is also extended to minerotrophic peatlands with a forest cover; the more productive forest sites occur where mineral and water conditions are most favorable. Typically, fens have a greater diversity of plant species than bogs. Also, organic matter in the peat is more decomposed than in bogs because of a more favorable nutrient and water environment for decomposer organisms.

Water and vegetation interact to impart distinctive characteristics to each peatland area. Physiography is also an integral part of these interactions. The physiography of underlying or surrounding materials can be broadly thought of as flat areas or depressions. Flat areas are the old glacial lake beds or glacial outwash. Depressions are ice-block depressions, scoured areas in bedrock, or simply basins formed by irregular deposition of ground and end moraines. Peatland names associated with these land forms are: lake-filled and built-up peatlands.

Lake-filled peatlands have a basin type of physiography. They may either be ombrotrophic or minerotrophic, and typically have an aquatic-sedge-woody-sphagnum peat profile (bottom to top), which reflects their former lake or pond status. Ombrotrophic, lake-filled peatlands have developed in basins that are separated from the regional ground water system by very slowly permeable peat or lacustrine deposits. They have also been called perched bogs because their water table is perched above the regional water table. There may be an unsaturated zone between the bog bottom and the regional water table, or the bog basin may be nestled in the regional aquifer, but there is essentially no mixing of their waters. Water tables in minerotrophic, lake-filled peatlands are simply an exposure of the regional water table, although it may be slightly higher in the peatland due to a damming effect of the basin peat. These peatlands have also been called ground water fens because of their water source.

Built-up peatlands develop on flat areas where peat literally develops vertically because the water table rises as the peat accumulates. These peatlands commonly develop on old glacial lake plains. In addition to building up, they also spread horizontally.

Peatland terms can be confusing if they are not thought of in the context of water source, physiography, vegetation, and stage of development. Illustrations of several terms are given in figure 1. Obviously, various intergrades or transitions between peatland type occur, and our review is not exhaustive. However, the types we've discussed and the terms used should be compatible with recent wetland classification schemes for the United States. Now we can take a close look at peatland vegetation, soil, and water.

PEATLAND VEGETATION

No peatland feature has been studied as extensively as vegetation. Species occurrence has been related to topography, water movement, water chemistry, and peatland evolution. Minerotrophic sites have a larger species diversity than ombrotrophic sites (table 1). Many species that occur on ombrotrophic sites also occur on minerotrophic sites.

Fen vegetation does not include trees if there is a deep and strong waterflow such as occurs in water tracks on large peatlands. Where water tables are not totally above the surface, there is sufficient aeration for tree establishment. Northern white-cedar on organic soils indicates a forested fen. The most productive tree growth usually

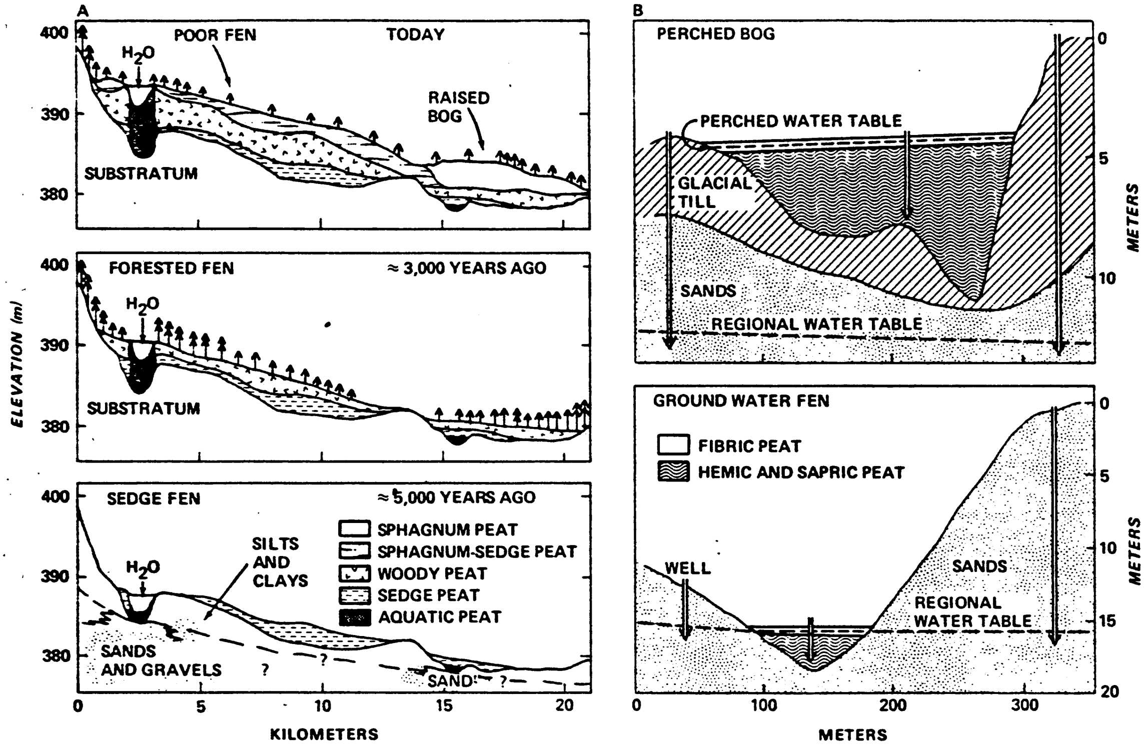

Figure 1. – *(A) Peat accumulation over 10,000 years in a built-up peatland. Peat description based on plant remains (modified from Heinselman 1963, 1970). (B) Peat accumulation in two lake-filled peatlands. Peat description based on degrees of decomposition (modified from Bay 1967).*

occurs where slopes are greatest (> 8 ft/mi) and thus ensure a balance between nutrient supply and aeration favorable for growth.

Similarly, on ombrotrophic sites, black spruce forests do best where the gradient is highest (> 8 ft/mi). The gradient results in slightly lower water tables, thus better aeration. Black spruce feather moss forests are characteristic of these sites.[2]

As seen from the air, large peatlands show various patterns: strips of vegetation radiating from the centers of sphagnum domes; patterned fen with a concave cross section that is a broad, shallow drainage channel marked by narrow ridges at right angles to the slope; teardrop shaped forested islands that appear to swim upstream in a sea of patterned fen; and water tracks, forested or nearly treeless fens, that carry the main water flow from the peatland (fig. 2). These patterns seem complex, but they are only reflecting small changes in topography, water movement, and water chemistry. A thorough treatment of peatland vegetation is cited at the end of this paper.

PEATLAND SOILS

Organic Soil Types

Peats or organic soils develop through the deposition and accumulation of organic materials in layers. The sequence and the thickness of layers vary depending on the landscape development process discussed earlier. Knowledge of peatland development is therefore essential for interpreting organic soil characteristics and in turn knowledge of organic soil characteristics is necessary for interpreting peatland hydrology.

[2] *In the forestry profession, and in local usage in the northern Lake States, forested peatlands are often referred to as conifer swamps. Black spruce occurs on both bogs and fens, but prescribed timber management options depend on the type of peatland. Bogs are referred to as nonbrushy sites and fens are referred to as brushy sites.*

Table 1. – *Typical peatland vegetation*

Genus species	Common name	Type of site[1]
Trees		
Fraxinus nigra	black ash	M
Betula papyrifera	white birch	M
Abies balsamifera	balsam fir	M
Thuja occidentalis	northern white-cedar	M
Larix laricina	eastern larch	A (most frequent on M sites)
Picea mariana	black spruce	A (most frequent on O sites)
Tall shrubs		
Alnus rugosa	speckled alder	M
Cornus stolonifera	red-osier dogwood	M
Salix spp.	willow	M
Betula pumila	swamp birch	M
Low shrubs		
Galtheria hispidula	creeping snowberry	A
Andromeda glaucophylla	bog-rosemary	A (most frequent on M sites)
Vaccinium oxycoccos	small cranberry	A
Vaccinium vitis-idea	cowberry	A
V. Angustifolium	low-bush blueberry	A
Ledum groenlandicum	Labrador-tea	A (most frequent on O sites)
Chamaedaphne calyculata	leather leaf	A (most frequent on O sites)
Kalmia polifolia	bog laurel	A (most frequent on O sites)
Herbs		
Cornus canadensis	bunch berry	M
Rubus pubescens	dwarf raspberry	M
Iris versicolor	Blue iris	M
Potentilla palustris	marsh cinquefoil	M
Menyanthes trifoliala	bogbean	A
Smilacina trifoliata	false Solomon's Seal	A
Sarracenia purpurea	pitcher-plant	A
Grasses and sedges		
Calamagrostis canadensis	blue joint	M
Carex spp.[2]	sedge	A
Phragmites communis	reed	M
Eriophorum spp.	cotton grass	A
Mosses		
Sphagnum magellanicum	sphagnum moss	A
S. fuscum	sphagnum moss	A (more frequent on O sites)
S. spp.	sphagnum moss	A
Polytrichum spp.	hair-cap moss	A (more frequent on O sites)
Hylocomium	fern moss	O (more frequent on well drained sites)
Hypmun cristata-castrensis	feather moss	O "
Dicranum spp.	broom moss	O "
Pleurozium scherberi	Scherbers moss	A (more frequent on O sites)

[1]M = minerotrophic sites; O = ombrotrophic sites; A = almost all sites.
[2]Fine-leaved sedges are more common on ombrotrophic sites and broad-leaved sedges are more common on minerotrophic sites.

Peat materials and organic soils have been classified on the basis of plant origin, hence the names aquatic, sedge, woody, herbaceous, and sphagnum peats are common in the literature. More recently organic soils have been classified by degree of decomposition—the microbial breakdown of organic tissues into water, minerals, and gases. Carbohydrates and lignins are the major components of organic tissues. Carbohydrates (mainly cellulose and hemicellulose) decompose easily, but lignins, high in carbon content, resist decomposition. Indices of the degree of decomposition include ash content, humus content, color of peat or of water squeezed from peat, bulk density, and fiber content.

Fiber content is now used to classify organic soils (Histosols) in the United States. It does not depend on identifying plant remains, and it is well correlated with various physical characteristics such as trafficability, water content, water tension, water movement (hydraulic conductivity), and water yield coefficient (specific yield).

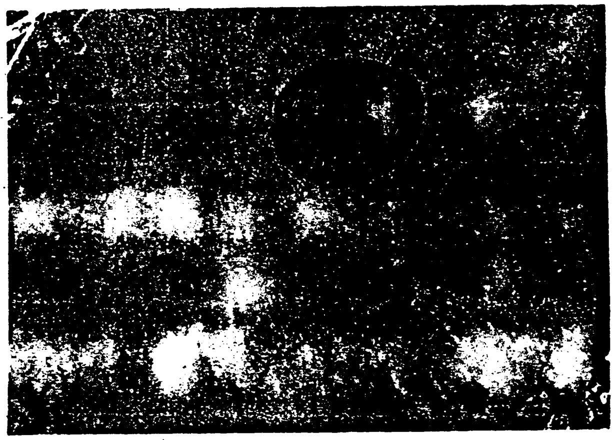

Figure 2. – *Vegetation patterns on large peatlands. (A) Radiating pattern of a sphagnum dome. (B) Patterned fen forming a water track between two large black spruce islands. (C) Teardrop shaped forest islands in a patterned fen.*

Fiber content is the portion of total peat material consisting of fibers, fragments, or pieces of plant tissue greater than 0.15 mm in size. In moderately decomposed peat materials, fibers are decomposed and easily broken down with handling. Therefore, both resistant (rubbed) and total (unrubbed) fibers are measured.[3] Three classes have been defined: fibric peats are the least decomposed with a rubbed fiber content greater than 40 percent (unrubbed fiber content greater than 67 percent); sapric peats are the most decomposed with less than 17 percent rubbed fiber content (less than 33 percent unrubbed fiber content); hemic peats are intermediate.

The organic soil profile shown (fig. 3) illustrates the filling of a lake with silt and clay followed by a marsh development characterized by reed and sedge remains. Above these layers is a distinct sapric horizon of well decomposed peat that may have resulted from a lower water table, better aeration, and thus better decomposition. Sphagnum with woody inclusions characterizes the topmost horizon. The profile becomes less acid with depth, reflecting the lack of acidifying Sphagnum and pH levels of surface flow and interflow waters present today and presumably present at the time of deposition. Bulk density increases with depth because of the accumulated weight of overlying organic deposits. Fiber content usually decreases with depth, reflecting a greater degree of decomposition. However, fiber content does not always follow this pattern because woody horizons have high fiber content due to the slow decomposition of lignins, and, at lower depths, mineral inclusions strongly bias fiber content and other determinations.

[3] *Fiber content is measured by collecting the fibers on a 100-mesh sieve using a gentle stream of water to wash away particles smaller than 0.15 mm. Rubbed fiber content is measured by first rubbing the peat material between the thumb and forefinger.*

Organic Soil Physical Properties

The physical, and consequently, hydrologic characteristics of peat materials are closely related to the degree of decomposition (table 2). Water freely drains from saturated fibric peats and a great deal more can easily be squeezed from them than from partially decomposed

Horizon label & depth	Horizon description	Fiber content	Bulk density	Soil pH in H_2O
cm		*percent*	*g/cm³*	
A 0 to 15	Fibric peat--Undecomposed sphagnum moss and leaves of heath shrubs.	90 to 98	0.015 to 0.028	4.2
B 15 to 30	Fibric peat--Relatively undecomposed sphagnum moss and roots of heath shrubs.	70 to 80	0.050 to 0.075	4.2
C 30 to 45	Hemic peat--Moderately to well decomposed sphagnum moss with wood inclusions.	40 to 45	0.08 to 0.19	4.4
D 45 to 60	Sapric peat--Well decomposed aggregated peat with no recognizeable plant remains.	15 to 30	0.21 to 0.26	4.1
E 60 to 100	Hemic peat--Moderately decomposed herbaceous peat from reeds and sedges.	40 to 55	0.12 to 0.17	4.8
100 to 200	Hemic peat--Moderately decomposed sedge peat.	--	--	5.4
200 to 225	Sapric peat--Well decomposed aquatic peat mixed with considerable sand.	--	-- (very dense)	5.3
225+	Lacustrine silt and clay	--	--	5.4

Figure 3. – *An organic soil profile from a lake-filled perched bog.*

Table 2. – *Range of important physical characteristics of fibric, hemic, and sapric peats from northern Lake States peatlands*

Degree of Decomposition	Total Porosity	Specific Yield	Hydraulic Conductivity	Bulk Density
	- *Percent*	*volume* -	10^{-5} *cm/sec*	*g/cm³*
Fibric	> 90	> 45	> 150	< .09
Hemic	84 - 90	10 - 45	1.2 - 150	.09 - .20
Sapric	< 84	< 10	< 1.2	> .20

peats (fig. 4). A hole excavated in fibric peat materials will usually fill with water to the water table elevation in the peatland in a matter of minutes.

Partially or well decomposed (hemic or sapric) peat in deeper horizons reacts differently. Little water can be drained from a sample of these peats and little can be squeezed from it even though it is saturated. If a hole is excavated in this material and water is excluded from surface fibric layers, it may be weeks before the water in the hole reaches the peatland water table elevation.

All peat types, regardless of plant source or degree of decomposition, contain more than 80 percent water by volume when saturated, indicating a high total porosity. The nature of this porosity, however, is different. The undecomposed (fibric) peats contain large, easily drained pores that permit rapid water movement. These peats release 50 to 80 percent of their water to drainage and have hydraulic conductivities as high as 4.0 x 10^{-2} cm/sec (120 feet per day). Well decomposed (sapric) peats yield only 10 to 15 percent of their water to drainage. Most of the water is retained in many small pores that are not easily drained. Hydraulic conductivities of these peats are as low as 7.0 x 10^{-6} cm/sec (0.02 foot per day).

Figure 4. – *A large amount of water drains from the undecomposed sphagnum moss peat on the left; very little water runs from the partially decomposed peat on the right. Both were saturated.*

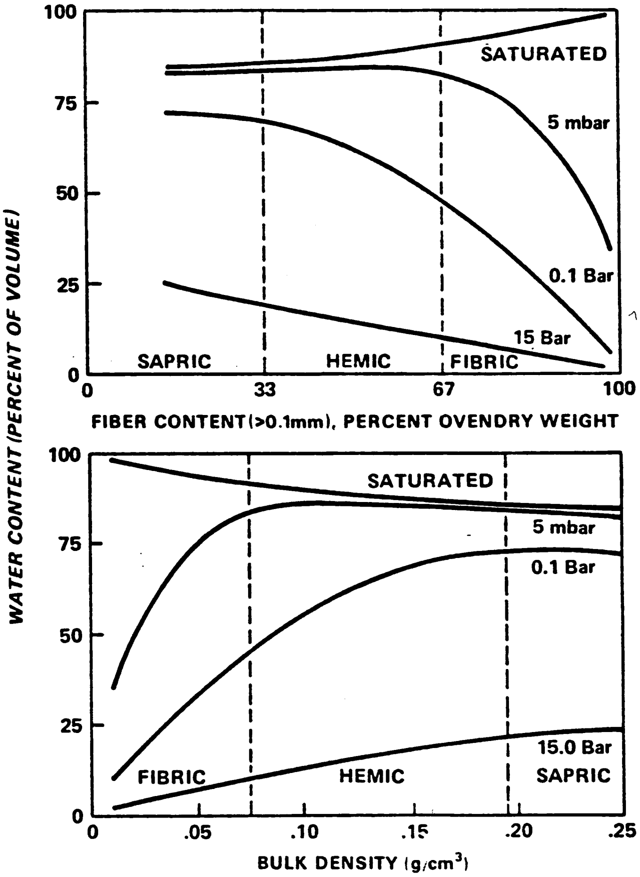

Figure 5. – *The relation of water content at saturation, 5 mbar, 0.1 bar, and 15 bar suctions to unrubbed fiber content (> 0.1 mm) and bulk density (Boelter 1969).*

The degree of decomposition, as measured by fiber content and bulk density, is well correlated with water tension (tenacity with which water is held in soil pores), and thus with water content and hydraulic conductivity. The relations between these measurements (fig. 5, table 3) can help predict the success of peatland drainage. The ease of drainage can be seen by looking at the difference between the saturated and 0.1 bar lines because this difference defines the water that easily drains from a soil under the force of gravity. The decrease in water content is large for fibric peats and much less for sapric peats.

Similarly, the rate of water movement (usually horizontal) through saturated organic soils is well correlated to degree of decomposition as measured by fiber content and bulk density. The rate of saturated water movement through fibric peats is a thousand times faster than the rate of saturated water movement through sapric peats (fig. 6).

Table 3. – *Curvilinear regression equations and coefficients of multiple determination (R^2) for the relation of water content (Y) at saturation, 5 mbar, 0.1 bar, and 15 bar suctions to fiber content (> 0.1 mm) and bulk density*[1]

Independent variable (X)	Regression equation	R^2
	Saturation	
Fiber content	$\hat{Y} = 84.23 - .0279X + .00185X^2$	.68
Bulk density	$\hat{Y} = 99.00 - 123.45X + 252.92X^2$	.68
	5.0 mbar	
Fiber content	$\hat{Y} = 52.45 + 1.5619X - .01728X^2$	.69
Bulk density	$\hat{Y} = 39.67 + 638.29X - 2,010.89X^2$	.70
	0.1 Bar	
Fiber content	$\hat{Y} = 67.91 + .4136X - .01064X^2$	.80
Bulk density	$\hat{Y} = 2.06 + 719.35X - 1,309.68X^2$	.88
	15.0 Bar	
Fiber content	$\hat{Y} = 29.34 - .3420X + .00072X^2$	.73
Bulk density	$\hat{Y} = 1.57 + 115.28X - 107.77X^2$	.82

[1]Boelter (1969).

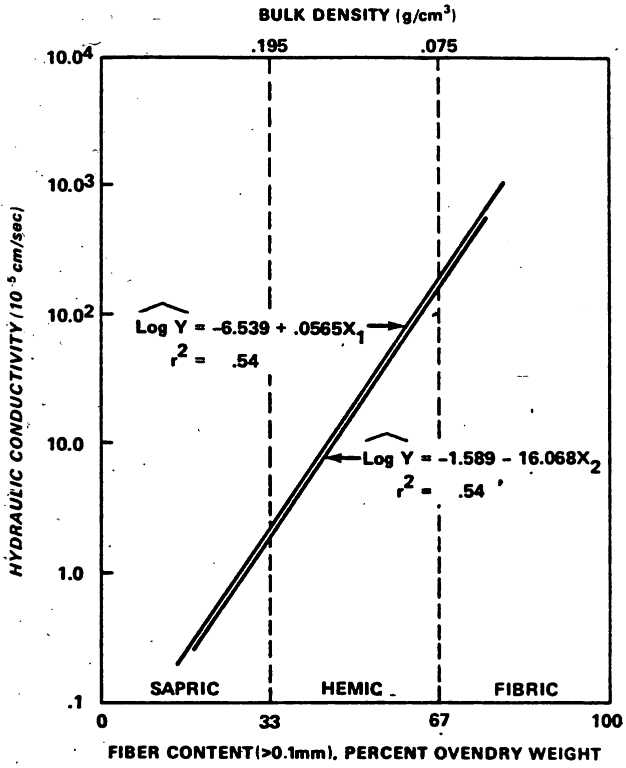

Figure 6. – *The relation of hydraulic conductivity (Y) to unrubbed fiber content (X_1) (> 0.1 mm) and bulk density (X_2) (Boelter 1969).*

PEATLAND AND WATER

Peatlands and water have held a rather mysterious place in the folklore of many peoples. The popular conception of peatlands sees them as huge natural sponges that soak up spring snowmelt and gradually release it to streamflow throughout the dry summer months. This is certainly an over-simplification at best and can lead to misunderstanding of a complex natural system.

Certainly anyone who has walked on a peatland will agree that the surface is "spongy", but the effect on streamflow does not automatically follow. A sponge must be squeezed to get much water out of it and there is no way of squeezing peatland. True, some water can be drained from peatland the same way that water will seep out of a completely saturated sponge for a short time. Also, water will flow through a saturated sponge in large amounts if there is a continuous supply, such as a faucet dripping on top. Similarily water will flow horizontally through a saturated peatland. However, a saturated sponge without a continuous supply of water will quickly dry out by evaporation and little water will flow from it; such is also the case with ombrotrophic peatlands during summer. The processes that affect sponges also affect natural peatland, but their net effect on natural streamflow does not follow the popular conception.

Hydro-Geologic Settings

Perhaps the major reason for conflicting hydrologic values attributed to peatland is failure to appreciate the influence of water source and physiography. Lake-filled peatlands may or may not be part of the regional water system (fig. 1). Those that are not are either perched above the regional water table or sealed off from any significant influence of ground water. These perched bogs receive water from precipitation, surface flow, and interflow. Thus their streamflow depends on snowmelt and rain frequency and the balance of precipitation and evapotranspiration. Lake-filled basins that are part of the regional water system receive the same water inputs as perched bogs, but they also receive much larger amounts of ground water, thus their streamflow mostly depends on the transmissibility and storage of water in regional aquifers that discharge to the fen surface. Ground water will enter the fen surface at the "uphill" edges because the basin peat acts like a dam in the regional water system; or it will enter the fen through "vertical windows" (amorphous channels) from the sand aquifer to the peat surface (fig. 7). These windows are conspicuous in mild winters when they do not freeze over like the rest of the fen. They are, in effect, artesian wells.

Built-up peatlands on large glacial lake beds or outwash plains have similar water sources, but with significant variations. The raised bogs, with their characteristic convex domes, receive only precipitation. Ground water will enter built-up peatlands from uphill edges or it can enter through artesian wells (windows) that can range up to lake size. Time works against the efficiency of artesian water supplies because the amorphous channels gradually become plugged with organic material. The plugging also modifies the water by removing calcium through cation exchange on the peat. Thus ground water becomes less minerotrophic as it moves through or across organic soils. Some artesian windows of earlier geologic times may have been completely covered by deep peat deposits acting as an aquiclude (aquifer seal). Shallow peats over sand plains

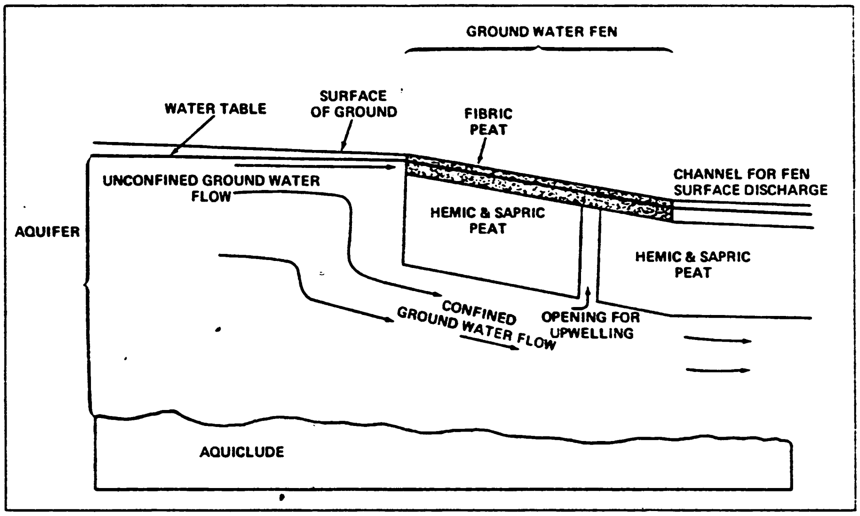

Figure 7. – *Schematic cross section of ground water flow in the region of a ground water fen on the Marcell Experimental Forest (modified from Sander 1976).*

can be fed by capillary water from a water table close to the sand surface. In this situation, peat development depends greatly on fluctuations of the regional water table that may lower the capillary fringe below the reach of vegetation and evapotranspiration demands.

Peatland Water Tables

Peatland water levels depend on water source. This relation can be illustrated by comparing the regional water table and the water tables of both a perched bog and a ground water fen (both lake-filled basins) within 0.8 km (1/2 mi) of each other on the Marcell Experimental Forest (fig. 8).

Water levels of the regional aquifer measured in wells adjacent to each lake-filled peatland basin show similar trends over several years (fig. 8a). A low point is reached each winter before snowmelt. When snow begins to melt and frost disappears, the water table steadily recharges (usually during April and May). By mid-June the water table recharge is interrupted by high evapotranspiration demands. This, coupled with discharge to surface areas, accounts for the steady decline of the water table until the next snowmelt-spring rain recharge cycle. The high peak in 1966 resulted from heavy fall rains in 1965 and the melting of an exceptionally deep snowpack in March and April of 1966. During years of both normal and above-normal precipitation annual water table fluctuations in the ground water fen are less than in the perched bog because ground water input tends to smooth out the water table fluctuations caused by precipitation and evapotranspiration (fig. 8b and c).

The response of peatland water tables to precipitation depends on the type of peat material in the zone of active water table fluctuation. This is best illustrated by comparing water table response to rain in a perched bog where the water table fluctuation is great enough to encompass both fibric and hemic peat materials in the same profile. There is a distinct difference in response to rain between the upper (fibric) and lower (hemic) peat materials (fig. 9). Both water table hydrographs were produced by rainstorms of nearly equal amount and intensity. The difference is due to the initial position of the water table in different peat types. Storm A occurred after a midsummer drying period when the water table was 25 cm (0.8 feet) below the surface and in moderately decomposed (hemic) peat. Storm B occurred in the spring when the water table was at the average bog surface in live, undecomposed sphagnum mosses.

Peatland water tables may also be affected by vegetation. Closed-in canopies of black spruce will intercept 15 to 20 cm (6 to 8 in) of rain and snow per year, thus forested peatland receives less precipitation on the peat surface than does nonforested peatland. Harvesting a peatland forest may or may not raise the water table, depending on water source. In ground water-fed peatlands the differences in precipitation reaching the surface will probably not be reflected in water table fluctuations because the supply of water from the regional aquifer greatly exceeds precipitation. The effect of ground water supply simply overrides the effect of forest harvesting. In perched peatlands, however, the effect of forest harvesting on water tables depends on

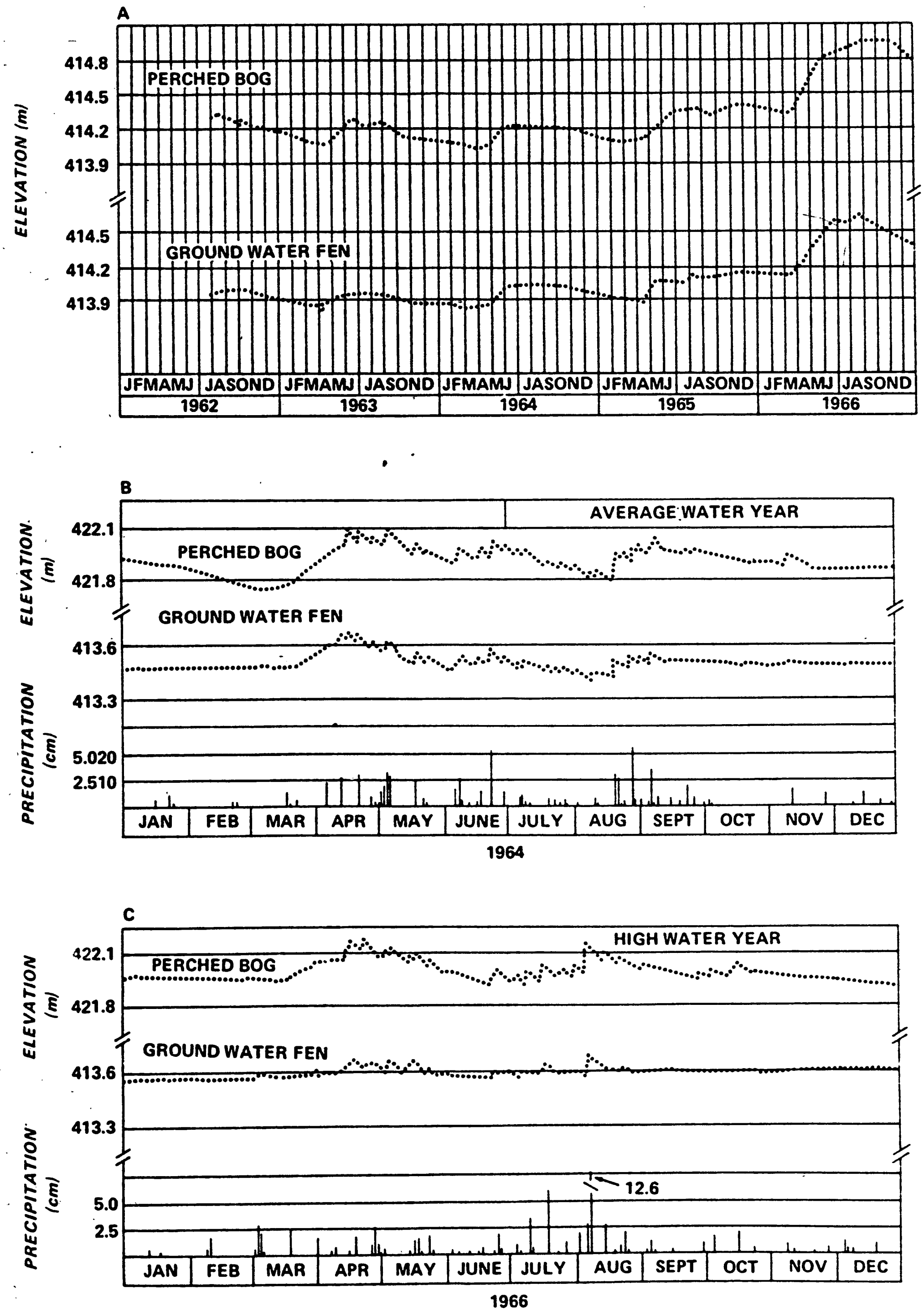

Figure 8. – *(A) Water levels in deep wells on the upland watersheds surrounding a perched bog and a ground water fen. (B) 1964 water tables in a perched bog and ground water fen. (C) 1966 water table levels in a perched bog and ground-water fen (Bay 1970).*

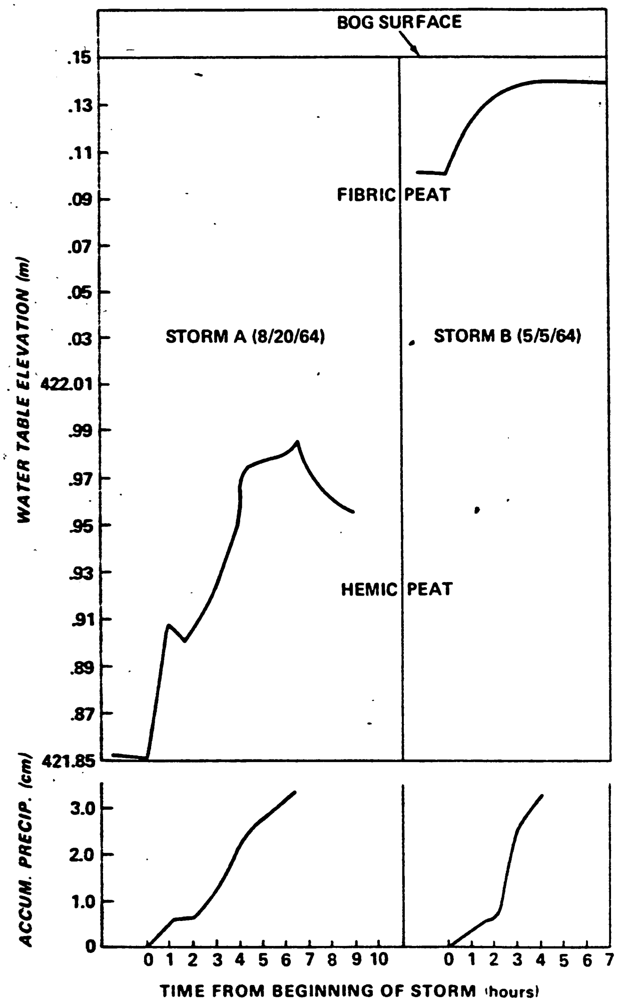

Figure 9. – *Water table response to storms of equal size depends on initial water table elevation and the degree of decomposition at that point. The water table response to Storm A is four times that of Storm B.*

the frequency of rainfall. During prolonged dry periods water tables will be lower after harvesting because of an increase in surface wind and a large increase in the biomass of transpiring sedges which can pull water from lower depths than Sphagnum. With increasing rainfall frequency, water tables in harvested areas will be higher because there is less interception loss.

Evapotranspiration

Annual evapotranspiration from forested peatland is, in general, similar to potential evapotranspiration calculated by the Thornthwaite method. Long-term annual potential evapotranspiration in the northern Lake States is 533 mm (21 in) with a range of 432 to 584 mm (17 to 23 in). Monthly values range from 2.5 mm (0.1 in) in March and November to more than 100 mm (4 in) in June, July, and August. One study in north-central Minnesota measured actual evapotranspiration from a forested bog by the water balance method. Over a 6-year period, the evapotranspiration from May 1 to November 1 ranged from 465.1 to 526.3 mm (18.31 to 20.72 in).

Water table level affects the rate of evapotranspiration so that day-to-day rates do not correspond to calculated potential evapotranspiration. Evapotranspiration from an open sphagnum bog with a grass, sedge, and *Ericaceae* cover is greatest when water level is 10 cm (about 4 in) below the bottom of hollows because the evaporative surface of sphagnum moss is greatest at this point and grass and sedge roots are well aerated. Raising the water table above this point will decrease evapotranspiration because grass and sedge roots are flooded as is some of the evaporative moss surface. Dropping water levels to 33 cm (about 13 in) below the bottom of the hollows will drastically reduce evapotranspiration because the capillary fringe does not reach to the surface mosses and herbaceous roots. At this point, surface mosses will dry out, and herbaceous sedges and grasses will be dominated by *Ericaceae* shrubs with xeromophic features such as thick leaves with waxy layers and fuzzy undersides.

Streamflow from Peatlands

Streamflow is the net effect of all processes that influence the hydrologic cycle of a watershed. Streamflow is most easily measured on small watersheds containing lake-filled peatland (fig. 10). Although these small watersheds contain both peatland and their associated uplands, they provide data on the overall effectiveness of peat deposits as water storage areas and regulators of streamflow. Perched bog basins are easiest to measure because nearly all the streamflow from the peatland is measured at the weir (fig. 11). Ground water fens are difficult to measure because stream gages do not measure all the discharge and the contributing area of ground water is uncertain.

Most of the annual flow from perched bogs occurs before June 15, while the distribution of flow from ground water fens is much more uniform. This striking difference in seasonal streamflow distribution from perched and ground water basins is shown by the monthly percentages for two basins on the Marcell Experimental Forest (fig. 12).

Figure 10. – *Aerial view of a small watershed with a perched bog in the center. The approximate watershed boundary is shown as a dashed line.*

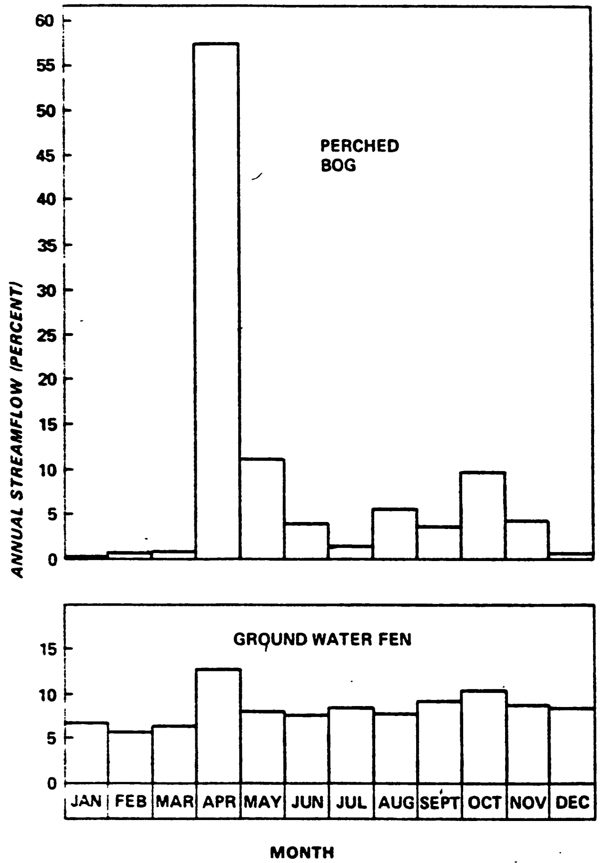

Figure 12. – *Monthly distribution of annual streamflow from a perched bog and a ground water fen, 1969.*

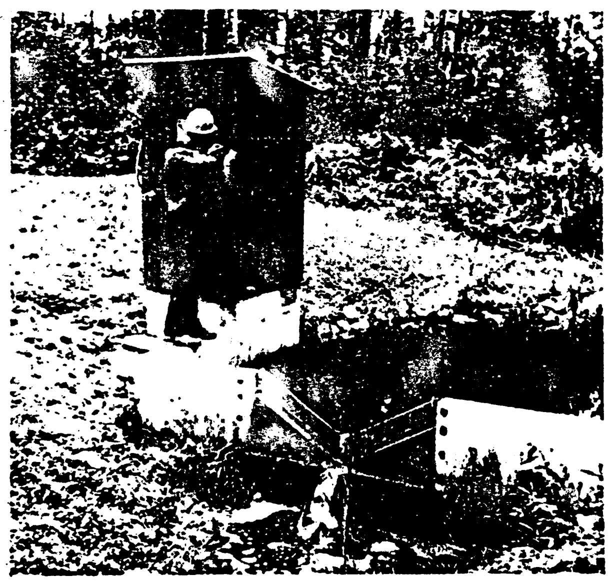

Figure 11. – *Stream gauge for measuring run-off from a perched bog and surrounding watershed.*

The large portion of annual runoff from perched bogs in April results from melting snow, early spring rains, high antecedent soil moisture conditions, and low evapotranspiration. By the end of snowmelt, the water level is generally near the surface in perched peat deposits, and these peat deposits behave much like lakes or reservoirs filled with water: additional water quickly contributes to streamflow. Streamflow is low during late spring, summer, and early fall, even though much of the annual precipitation occurs then (fig. 13). This rainfall is quickly returned to the atmosphere by evapotranspiration at the expense of streamflow and deep seepage. Evapotranspiration increases with increased solar radiation and the return of annual leaves. On the Marcell Experimental Forest in north-central Minnesota, average rainfall for the period May 1 to November 1 is 546 mm (21.5 in) and evapotranspiration estimates average 505 mm (19.9 in). Assuming no changes in storage, average runoff for the period is 41 mm (1.6 in), less than 8 percent of the rainfall. Only large summer rains will significantly increase streamflow.

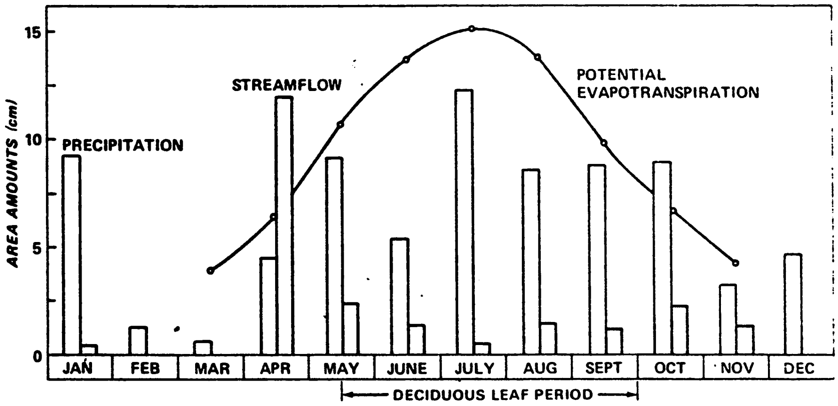

Figure 13. – *Monthly precipitation, streamflow, and potential evapotranspiration for a perched bog watershed, 1969 (modified from Verry and Boelter 1975).*

The uniform distribution of annual streamflow from the ground water fen can be explained by the behavior of the regional water table (fig. 14). Over winter there is a gradual decline in the water table. With the beginning of snowmelt and disappearance of frost, there is a quick, sustained high rate of recharge. The high recharge occurred April 8-24 and extended about 5 days beyond the disappearance of snow. From late April until mid-June there is another stable, though lesser rate of recharge. This reflects drainage from unsaturated soil and parent material and may include short periods of saturated flow following spring rains. By mid-June, however, the continuity of water flow to deep seepage is broken as summer rains usually replenish soil moisture depleted by high evapotranspiration. This coupled with discharge to surface areas, such as fens, accounts for the steady decline of the water table until the next snowmelt-spring rain recharge cycle.

Some have speculated that peatlands, because of their high water storage capacity and flat slope, regulate the distribution of streamflow. This does not appear to be so in small lake-filled bogs in bog-upland watersheds. Streamflow from perched bogs is not well regulated; flow duration curves have steep slopes because streamflow and evapotranspiration depletes basins that have little perennial storage (fig. 15).

Streamflow from ground water-influenced peatland is much more uniformly distributed because the fen is a surface discharge point for the regional ground water system, which provides a more constant supply of water. The flow duration curve is nearly flat, and shows a nearly constant rate of flow 70 percent of the time because of the large amount of perennial storage. The characteristics of streamflow are again due to the hydro-geologic characteristics. Only a minor effect is due

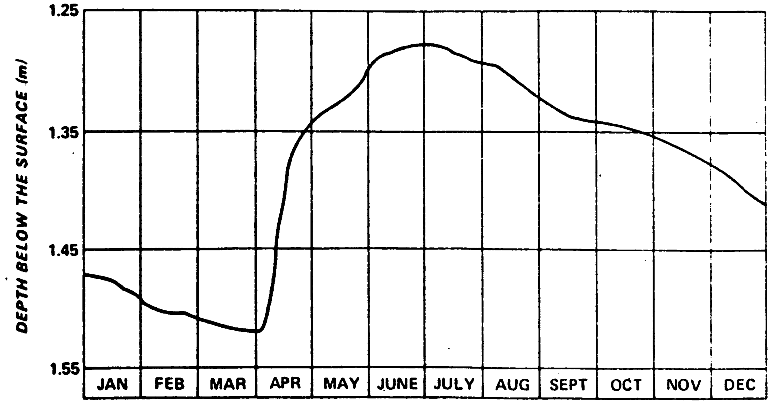

Figure 14. – *Hydrograph of the regional ground water table on the Marcell Experimental Forest, 1969.*

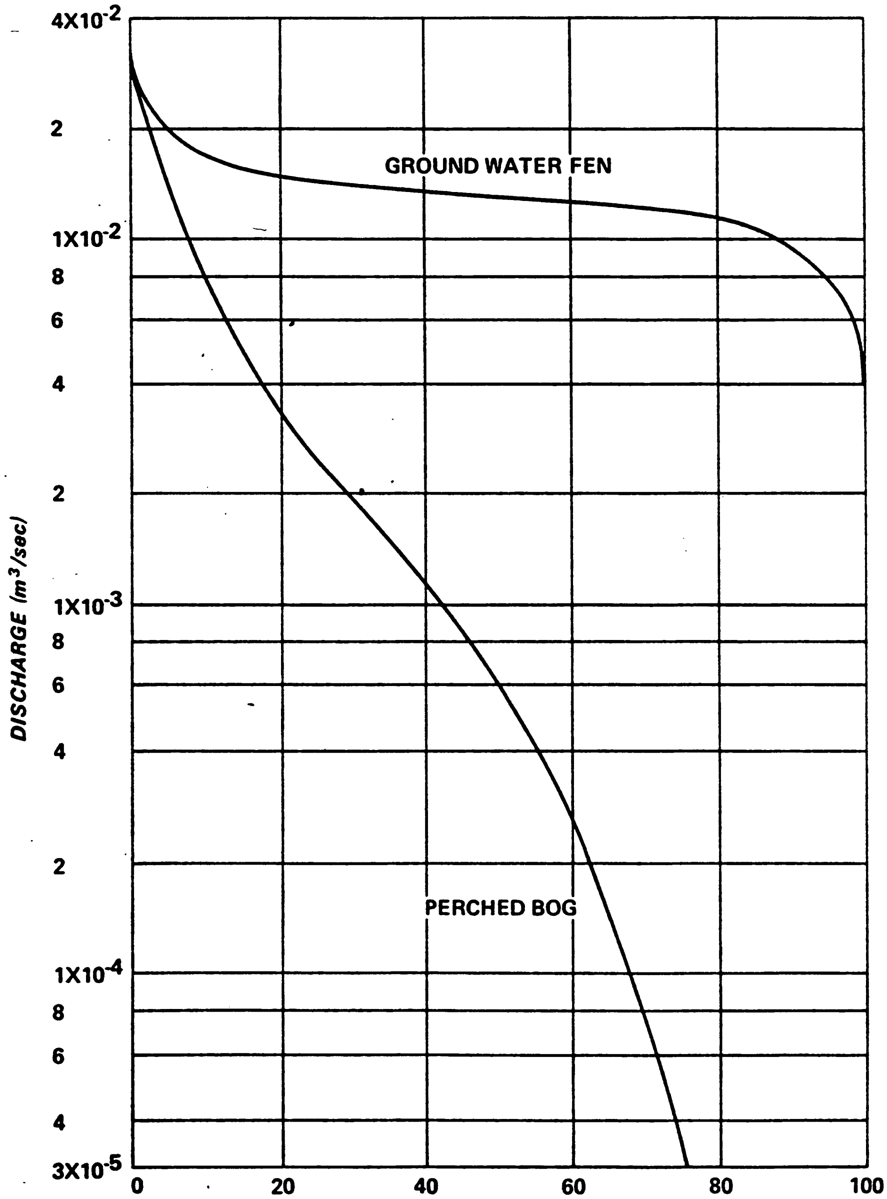

Figure 15. – *Streamflow-duration curves for a ground water fen and perched bog watershed. Both watersheds are about 53 ha in size.*

to the fen. Instead of regulating streamflow, the ground water fen may do the opposite by releasing excess water more quickly than mineral aquifers during periods of high precipitation and losing more water by evapotranspiration during dry periods.

Stormflows are generated by heavy rains, but the most common contributor to maximum annual streamflow rate is snowmelt. Maximum streamflows (floods, if you will) are not a function of the kind of basin, perched or ground water. Rather, they are affected by watershed size, the amount of water in the snowpack, the rate of snowmelt, infiltration characteristics of the basin soil, and the percentage of peatland or lake in a watershed. The two watersheds represented in figure 15 are about the same size, have the same snow and rainfall and about the same percentage of peatland, and thus have the same maximum streamflow rate even though one watershed contains a perched bog and one contains a ground water fen.

Stormflows resulting from spring, summer, and fall rains are modified by peatland. Typical storm hydrographs from perched bogs have long, drawn out recession curves (fig. 16). The recession leg of the dormant season hydrograph approaches a straight line on semi-logarithmic paper rather quickly and remains well above the prestorm discharge level. This characteristic indicates a temporary storage and slow release of storm flows due primarily to the nearly level bog topography and the large detention storage of surface peats. The recession leg of the growing season hydrograph is broken by daily evapotranspiration losses that reduce streamflow. However, the storage and slow release of stormflow are still evident from the small decay rate (flattening of the hydrograph) during periods of low evapotranspiration.

Peak stormflows are related to climatic and physiographic variables including the short-term storage capacity of the watershed. In organic soils, storage capacity depends greatly on the level of the water table in the peat profile. Therefore, storm peaks are directly related to water table level (fig. 17). Greatest runoff occurs when the water table is high because there is little available storage capacity and water moves directly to the bog outlets. Surface peats also have high hydraulic conductivity and drain quickly while deeper peats are more decomposed, retain more water, and drain slowly.

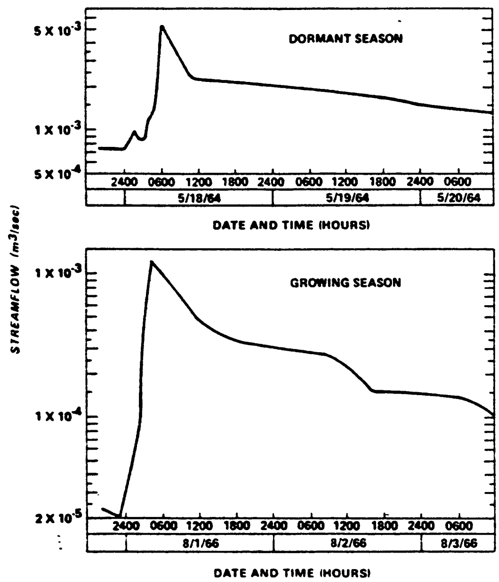

Figure 16. – *Hydrographs for a dormant season storm (2.5 cm) and a growing season storm (2.2 cm) on a perched bog watershed (modified from Bay 1969). Note the nearly straight recession leg for the dormant season storm while the growing season recession leg is broken by daily evapotranspiration losses.*

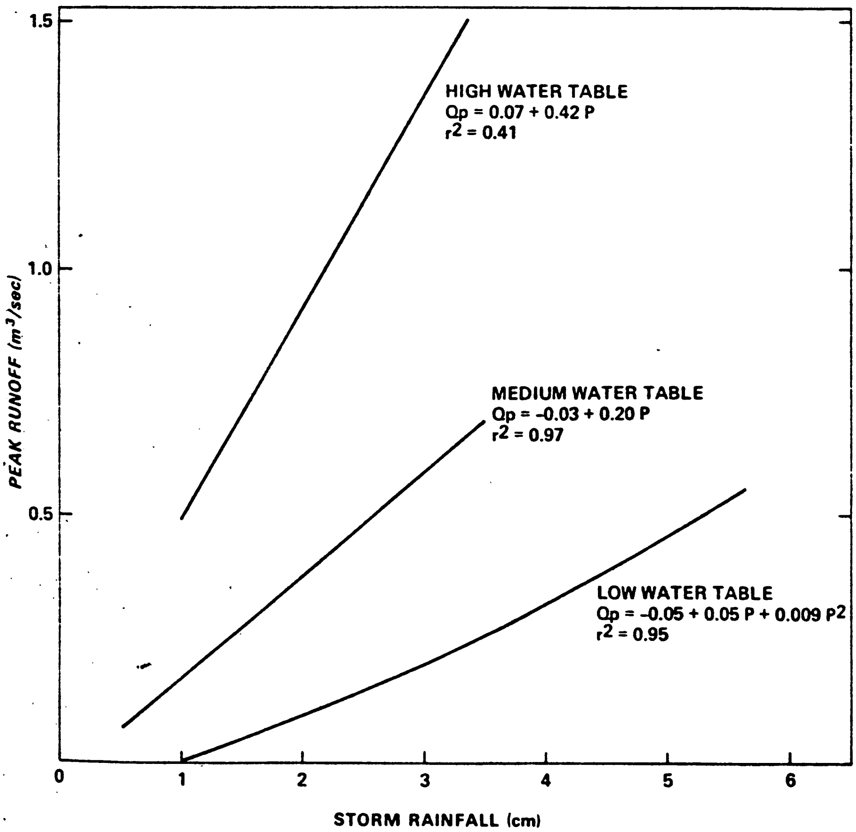

Figure 17. – *Relation of peak flow (Q_p) to storm rainfall (P) and water table position in a perched bog. High water table conditions existed when water tables were fluctuating above the average moss surface and within the hummock and hollow micro-topography. Low water table values were computed when water tables were greater than 15 cm below the average hollow elevation (modified from Bay 1969). Watershed size is 9.7 ha.*

We have considered peatland hydrology largely from data gathered on small watersheds around 40 ha in size, but similar conclusions have been reached for large watersheds in northern Minnesota where peatland constitutes 40 percent or more of the area. In general, water is released from peatland very slowly and is not a significant source of low streamflow. In peatland areas, water is discharged mostly by evapotranspiration. Streamflow is maintained by discharge from ground water reservoirs and lakes. But both lakes and flat peatland areas reduce flood peaks.

Half of the popular concept concerning peatland and water is true. Peatland does reduce the peak rates of streamflow from snowmelt and heavy summer rains because it is flat and there is some short-term detention storage in the surface horizons. However, peatland does not sustain streamflow during dry summer months by slowly releasing stored water. To the contrary, it uses water at maximum rates of evapotranspiration and at the expense of streamflow.

Peatland Water Chemistry

Peatland water chemistry depends on the kind and amount of water source and the distance water has traveled through the peatland. Ombrotrophic raised bogs and perched bogs reflect precipitation chemistry and have a narrow pH range because Sphagnum moss controls acidity through cation exchange reactions. In general, ombrotrophic bog waters have a pH of 3 to 4, a specific conductance less than 80 μ mhos, and a calcium concentration less than 4 or 5 mg/1. The predominant anion is sulfate and the predominant cation is hydrogen (table 4).

Fens, fed by a ground water source, generally have water pH values of 4 to 8, a specific conductance more than 100 μ mhos, and calcium concentrations more than 15 mg/1. The predominant anion is bicarbonate and the predominant cation is calcium. Poor fens have values grading downward into the ombrotrophic values. Minerotrophic fens in general have a much wider range

Table 4. – *Average concentration of water quality indicators in the streamflow of perched bog and ground water fen watersheds*[1]

Water characteristics	Perched bog watersheds				Ground water fen watersheds			
	$\bar{X}$	±	SD	N[2]	$\bar{X}$	±	SD	N[2]
Color units	336	±	145	170	100	±	64	22
pH units	3.6	±	0.3	93	6.5	±	0.28	15
Specific conductance (μmho at 25°C)	51	±	13	104	125	±	48	16
MG/LITER								
Total acidity 1± (as $CaCO_3$)	48.2	±	24	132	--	±	--	--
Total alkalinity (as $CaCO_3$)	--	±	--	--	54.2	±	28.0	18
Total-N	1.34	±	0.64	167	0.58	±	0.29	21
Organic-N	0.69	±	0.40	165	0.33	±	0.22	21
Ammonia-N	0.45	±	0.39	165	0.15	±	0.14	21
Nitrate-N	0.20	±	0.25	168	0.10	±	0.07	21
Nitrite-N	0.003	±	0.003	166	0.003	±	0.003	21
Total-P	0.06	±	0.06	136	0.03	±	0.01	17
Cl	0.7	±	0.8	172	0.4	±	0.4	22
SO_4	4.6	±	2.2	73	6.0	±	4.2	7
Fe	1.35	±	0.8	166	0.98	±	0.48	21
Ca	2.4	±	1.0	170	16.6	±	9.0	22
Na	0.6	±	0.3	164	2.0	±	1.0	22
Mg	0.97	±	0.36	136	2.88	±	0.93	15
Mn	0.06	±	0.05	136	0.08	±	0.06	14
K	1.3	±	0.6	128	1.1	±	0.4	22
Al	0.79	±	0.43	135	0.16	±	0.06	14
Pb[3]	<0.05	±	--	116	<0.05	±	--	12
Zn	0.08	±	0.11	123	0.11	±	0.17	12
Si	2.7	±	2.1	49	4.9	±	4.0	3

[1]Verry (1976).
[2]Number of samples.
[3]Usually below detection limit of 0.05 mg/liter.

of chemical values because there is great variation in the kinds and amounts of ground water. Some perched bogs in lake-filled basins might have a thin boundary of poor fen resulting from mineral soil surface flow and interflow, but the volume of flow is not large enough to overcome the exchange capacity of Sphagnum peats more than a few meters from the bog edge.

In large, built-up peatlands the minerals in ground water may be depleted by cation exchange as they flow farther and farther away from their source. A progression of rich to poor fen results. Poor fens can also result from ground water low in dissolved minerals (especially calcium). The amount and type of dissolved minerals in ground water depends on the mineralogy of the aquifer and confining units and the time that water has traveled in contact with various materials.

Annual yields of nutrients have been calculated for upland-peatland watersheds containing perched bogs in north-central Minnesota (table 5). Because the sphagnum bogs control the chemistry of these small watershed streams, the values should also apply to other ombrotrophic bogs such as raised bogs in built-up peatlands.

Table 5. — *Annual yield (kg/ha · yr) of nutrients and other chemicals for perched bog watersheds, WS-2 and WS-4*[1]

Chemical constituent	WS-2[2]	WS-4[2]
Total-N	1.91	1.97
Organic-N	0.99	1.02
Ammonia-N	0.64	0.66
Nitrate-N	0.28	0.29
Nitrite-N	0.01	0.01
Total-P	0.08	0.08
Cl	0.87	0.87
SO_4	7.75	9.17
Fe	1.81	1.66
Ca	3.46	3.55
Na	1.06	1.25
Mg	1.46	1.52
Mn	0.08	0.08
K	1.26	1.41
Al	1.12	1.04
Zn	0.08	0.09
Si	1.71	1.21
Total acidity (as $CaCO_3$)	72.01	74.19

[1]Verry (1976).
[2]WS-2 and WS-4 refer to numbered watersheds on the Marcell Experimental Forest in north-central Minnesota.

The annual yields of nutrients are similar to those from other undisturbed forested watersheds in humid areas of the northern United States and southern Canada.

It has not been possible to calculate annual nutrient yields from a ground water fen because the contributing area of ground water is difficult to determine. However, we can compare the concentrations for the ombrotrophic, perched bog and minerotrophic, ground water fen (table 4) by weighting them by amount of annual streamflow. Weighted concentrations for the two watershed types are similar for organically derived ions (total-P, total-N, and total-Fe) and for chloride, which is mainly atmospheric in origin and moves freely in the environment (table 6). Weighted concentrations of minerals derived from solution of aquifer and overburden materials are greatest in the ground water fen watershed.

In general, nearly equal amounts of organically derived nutrients are leached from both watershed types in an equal volume of water leaving the watershed as streamflow. The total yield (kilograms/year) of all chemical constituents is primarily a function of the annual volume of streamflow.

Table 6. — *Average annual flow weighted*[1] *concentrations for perched bog and ground water fen watersheds (g/m^3) (annual streamflow averages for WS-2, WS-4, and WS-3 are 16,278, 67,429, and 574,954 m^3, respectively*[2]

Chemical constituent	Perched bog watersheds: WS-2[3]	Perched bog watersheds: WS-4[3]	Ground water fen WS-3[3]
Total-P	0.05	0.04	0.03
Total-N	1.1	1.0	0.6
Total-Fe	1.1	0.8	1.0
Cl	0.5	0.4	0.4
K	0.8	0.7	1.1
Al	0.67	0.53	0.16
SO_4	3.6	3.5	6.0
Na	0.6	0.6	2.0
Mg	0.9	0.8	2.9
Ca	2.1	1.8	16.6
Mn	0.05	0.04	0.09
Zn	0.05	0.04	0.11
Si	1.0	0.6	4.9

[1]Perched bog watershed concentrations have been weighted by flow rate for some nutrients which show an inverse relation between flow rate and concentration.
[2]Verry (1976).
[3]WS-2, WS-3, and WS-4 refer to numbered watersheds on the Marcell Experimental Forest in north-central Minnesota.

SUMMARY

Peatland is different from other land forms in many ways. Formed as a result of excessively wet conditions, peatland remains saturated or nearly saturated in its natural undrained condition. Although these conditions have led to speculation that these wetlands play a unique hydrologic role, this role may not be as different as first thought.

Although saturated and containing 80 percent or more water by volume, organic soils do not always permit rapid water movement or easily give up their water to drainage because the more decomposed materials hold their water tenaciously.

Peatland can be broadly classed into two groups: ombrotrophic (ion-poor) peatland (bog) receives precipitation as its primary water source; minerotrophic (ion-rich) peatland (fen) receives large ground water supplies as well as precipitation.

Contrary to popular belief, neither bogs nor fens maintain an even distribution of annual streamflow. Seasonal distribution within the year is governed primarily by the hydrogeologic setting, water source, and evapotranspiration relations. The organic soils have only a minor effect. The flat topography and physical detention of flow in the surface layer do regulate individual stormflows by reducing peaks and delaying the release of stormflow volumes.

The water chemistry of streams draining peatland depends primarily on water source. Nutrients in rain, snow, and dust, modified by organic soils and Sphagnum moss, play a major role in the composition of on-site water in ombrotrophic peatland, but they do not greatly affect the ionic composition of streams draining large areas of land. The water composition of streams draining minerotrophic peatland is primarily determined by the solution of ground water aquifer and overburden parent materials. The downstream influence of peatland in large watersheds is only seen in color values and perhaps some organically derived anions. Concentrations of these materials decrease with distance from the peatland.

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The North Central Forest Experiment Station expanded its watershed research program in 1960 to include basic peatland studies. This paper reviews and summarizes basic principles developed from these studies of peatland hydrology, organic soil characteristics, and streamflow chemistry.

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