The Hydrology of Several Peat Deposits in Northern Minnesota, U.S.A.

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ABSTRACT

A comprehensive peatland hydrology study has provided data on the climate, hydrogeology, water table levels, and run-off from forested peat deposits in northern Minnesota. Groundwater studies identified two types of hydrogeologic situations—perched bogs, independent of the underground flow system, and groundwater bogs, which were influenced by storage changes in the surrounding groundwater basin. Because the water tables are near the surface in undisturbed bogs, they are important in peatland hydrology. Bog water table levels indicated storage opportunity, and their reaction to precipitation was influenced in part by the type of peat material in the zone of active fluctuation. Run-off was not evenly distributed. Most of the annual water yield occurred in spring before June 1, while summer and fall water yields were generally low. Run-off was directly related to water level in the peat deposits.

RÉSUMÉ

Une étude approfondie du régime hydrologique des tourbières a fourni des données sur le climat, l'hydrogéologie, le niveau hydrostatique et le ruissellement en provenance des tourbières boisées du nord du Minnesota. Les études hydrogéologiques ont révélé l'existence de deux espèces de systèmes hydrologiques: les tourbières de pente, indépendantes du réseau d'écoulement souterrain, et les tourbières de nappe phréatique affleurante qui subissent l'influence des changements du niveau hydrostatique environnant. Les nappes d'eau souterraine, affleurant dans les tourbières vierges, déterminent le régime de leurs eaux. Le niveau hydrostatique indique les possibilités d'accumulation et l'importance de ses variations en fonction de la précipitation dépend de la nature du sol tourbeux dans la zone observée. Le ruissellement n'est pas uniforme. Le plus grand débit d'eau prend place au printemps, avant le mois de juin, mais le débit d'eau au cours de l'été et de l'automne est généralement faible. La ruissellement dépend directement du niveau hydrostatique de la tourbière.

Man has been exploiting peat deposits throughout the world for many years. Most of the effort in peatland management and research has been applied to the production of wood, agricultural crops, and raw peat and peat products, or to the difficult problems of transportation and construction on peatland terrain. One extremely important peatland resource, however, has not received attention commensurate with its importance; this resource is water.

Peatlands cover large portions of upstream catchments or entire river basins in many parts of the world. Little is known about how man influences water yield from these catchments. Does he adversely influence the hydrologic regime when peatlands are managed for timber or crop production? Or can he manage the vegetation and water levels on peat deposits to increase total water yield or distribute it more to mankind's benefit?

Parts of these questions are now being studied by a U.S. Forest Service hydrologic research team. Since 1961 this team has been studying the hydrology of forested peatland catchments in the north-central United States. The primary objective is to develop land management practices that will maintain and improve water yield, particularly augmenting low flows, from peatlands in the northern forest region. Studies are now underway in surface water hydrology, groundwater hydrology, and evapotranspiration on the peat deposits. In addition, field and laboratory techniques are being used to study the basic physical properties of peat materials. This paper discusses the water storage properties and water yield characteristics of several peat deposits.

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THE EXPERIMENTAL PEAT DEPOSITS

The experimental areas are isolated hydrologic units each of which consists of two parts—a localized peat deposit and its surrounding catchment area of mineral soil. The five bogs discussed here range in size from 8 to approximately 30 acres and make up from 12 - 33 per cent of their respective catchment areas. All of the bogs support nearly pure stands of black spruce, *Picea mariana* (Mill.) B.S.P., generally over 60 years in age. The primary ground vegetation consists of various mosses (primarily *Sphagnum*) and Ericaceous genera such as *Ledum, Chamaedaphne, Kalmia,* and *Andromeda*. Peat depths in the bogs vary from a few feet near the margins to nearly 25 ft in the deeper portions of several bogs. The uplands surrounding the peat deposits have medium-textured mineral soils and support mature stands of quaking aspen, *Populus tremuloides* Michx.

The peat deposits and their surrounding catchment areas have been intensively instrumented to measure local weather conditions, rain and snow, bog water table levels, deep underground water levels, and run-off. Automatic recorders are used for many of these measurements (Figure 1). A more complete description of the individual catchments and their instrumentation schemes has been published previously (Bay, 1967b).

GROUNDWATER HYDROLOGY

Perhaps one of the major reasons for the often conflicting hydrologic values attributed to peatlands is failure to appreciate the possible influence of local hydrogeologic systems on the hydrology of individual peatlands. Chebotarev (1962) has indicated that many early investigations of peatland hydrology ignored hydrogeological factors, thus leading to contradictory results. Underlying soils, groundwater levels, and geologic conditions need to be considered in each bog area.

Two primary types of bogs (in terms of their groundwater relations) have been recognized on the experimental catchments. Most of the deposits are perched bogs—developed in basins perched above and relatively independent of the regional groundwater system. The peat deposits are separated from the underground system by a layer of fine-textured glacial till which greatly restricts downward movement of water. Although some seepage water may recharge the peat from the surrounding uplands, the primary source of water is precipitation on the bog itself. The plant communities on these bogs tend to be oligotrophic.

A second type of bog acts as a discharge area for the regional groundwater system. Because the peat deposit is receiving mineral-influenced, or soligenous, waters in addition to normal precipitation, peat type and bog floristics are different. The peat is more decomposed and contains more wood than in the perched deposits. Water is less acid and has higher salt concentration as measured by specific conductivity (Bay, 1967a). The bog vegetation tends to be more eutrophic.

The relation of the regional groundwater system to bog water table levels and surface run-off from the bogs has been discussed to some extent in previous papers (Bay, 1966, 1967b). Changes in basin storage within the surrounding groundwater system can influence water levels in the groundwater bog (Figure 2). Annual trends of water levels in two representative deep wells located on the uplands next to the perched bog (S-2) and the groundwater bog (S-3) show that similar trends in underground basin storage existed in 1963, 1964, and early 1965 (Figure 2A). Nearly three times normal rainfall in September 1965 caused a secondary recharge period. Exceptional snow-packs (6 - 7 in. of water content) accumulated in the spring of 1966, and the combination of fall recharge and spring snowmelt recharge resulted in the high regional groundwater levels shown for 1966 (Figure 2A).

During 1964, a year of relatively normal deep groundwater fluctuations, water table levels in bogs S-2 and S-3 reacted in a similar manner (Figure 2B). Overwinter recession of the bog water table was definitely less in S-3 because of continual recharge from the regional flow system, but summer water table levels on both bogs responded rather quickly and similarly to

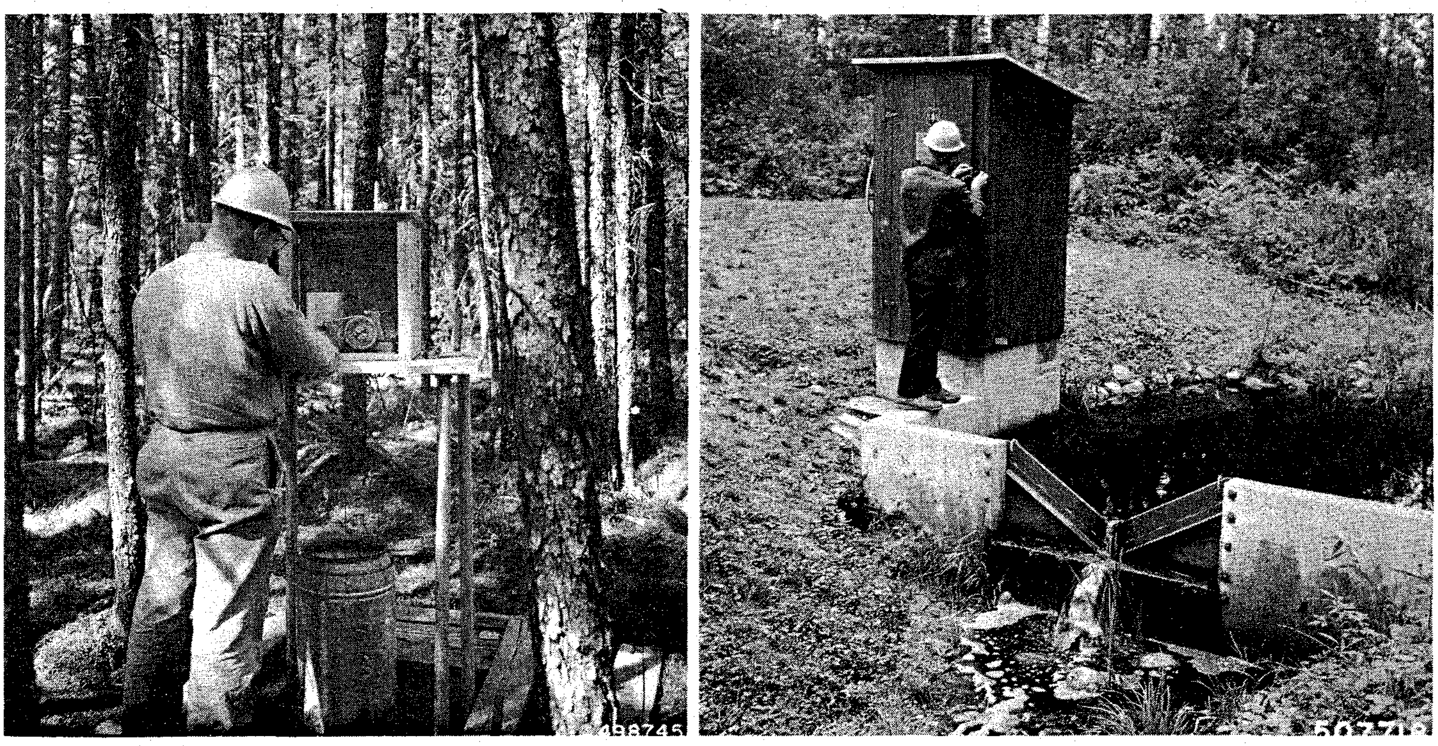

Figure 1. Recording well to measure bog water table fluctuations (left) and stream gauge for measuring run-off from an experimental peat deposit and surrounding catchment (right). (F-498745, F-507718).

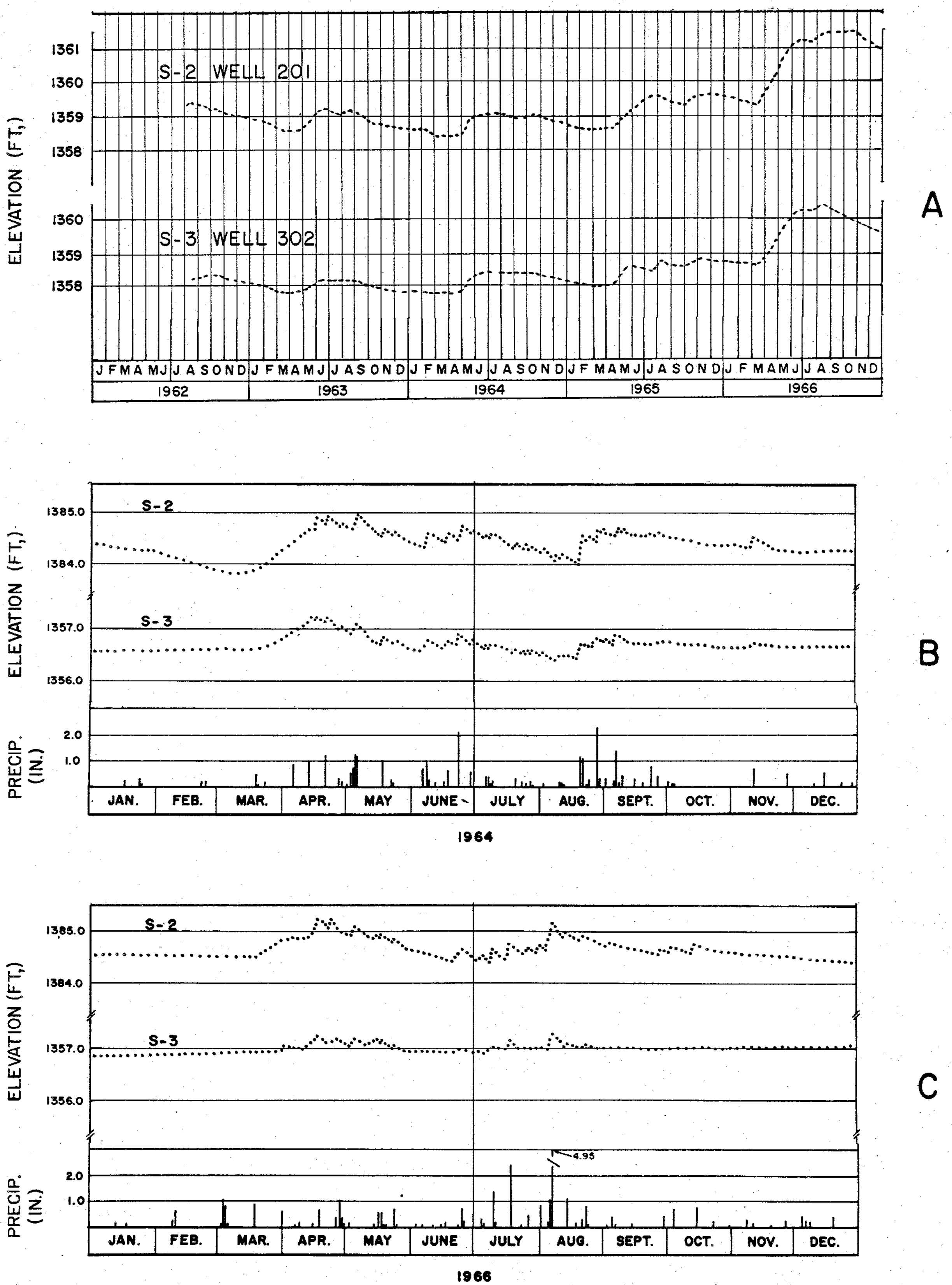

Figure 2. *A*. Water levels in deep wells on the upland catchments surrounding a perched bog (S-2) and a groundwater bog (S-3). *B*. 1964 bog water table levels in S-2 and S-3. *C*. 1966 bog water table levels in S-2 and S-3.

rainstorms and drying periods. In the summer of 1966, however, water table fluctuations in the two bogs were considerably different (Figure 2C). Exceptionally high water levels in the deep regional groundwater system surrounding bog S-3 resulted in increased discharge into the bog, maintaining the bog water table at a high, steady level; the perched bog (S-2), however, without the benefit of groundwater discharge, showed its normal summer drying trend. The smoothing effects of increased gradient from surrounding groundwater levels to S-3 is striking.

Although other investigators have recognized similar bog and groundwater relations (Graham and Satterlund, 1959; Ivitskii, 1954) few have related bog water table conditions directly to storage changes in the surrounding groundwater basin.

BOG WATER TABLE LEVELS

Water table levels are a reliable measure of the hydrologic condition of peat deposits. Water storage opportunity increases as the bog water table recedes from the surface and decreases as the water table rises.

The general trend in bog water table levels follows a similar pattern each year (Figure 2B, 2C). A low point is reached each winter just prior to spring breakup. Once snowmelt begins and the frozen organic soil begins to thaw, water tables rise rapidly to their spring high point, often the highest level reached during the year. After the spring peak there is a general downward trend during the growing season which is interrupted from time to time by precipitation. During a long dry period, such as the one in late May and June of 1966, evapotranspiration and runoff result in a continuous water table recession (Figure 2C). Water levels in fall are usually stable, depending again on the precipitation. Trends shown here are representative of the two types of bogs and are similar to water levels in neighbouring bogs.

The primary factors which influence bog water table fluctuations are vegetation, local hydrogeology, precipitation, and type of peat material. Vegetation influences water table levels through interception of some precipitation before it reaches the ground and through evapotranspiration. These two processes have been studied to some extent on peatlands in Finland (Päivänen, 1966; Heikurainen, 1966) and Russia (Molchanov, 1960). The effect of vegetation manipulation on bog water levels and run-off will be studied on the Department's experimental peat deposits in the near future through the calibration-treatment watershed approach.

The influence of hydrogeologic factors on water table levels in the study bogs has been illustrated earlier. The exceptionally high water level in the groundwater bog (S-3) during the 1966 growing season indicates that little storage space was available for summer rainstorms (Figure 2C). In the perched bogs, groundwater recharge was not a factor in bog water table fluctuations and consequently did not affect storage opportunity in the peat deposits. Thus, perched bogs are primarily affected by current climatic conditions while groundwater bogs have carryover from wet and dry years.

The shallow water levels found in natural bogs are most directly influenced by precipitation. Vorob'ev (1963) points out, however, that not all precipitation reaches the bog water table; part is intercepted by vegetation, part is absorbed by dry mosses in the upper peat profile, part is suspended in the capillaries, and part increases osmotic and pellicular moisture in the peat above the water table. Precipitation amount, intensity, and areal distribution all affect water table fluctuations.

The type of peat material in the zone of active water table fluctuation also influences the water table reaction to precipitation. Boelter (1964) has shown that various peat types have different physical properties which in turn influence water storage characteristics. Water level response to precipitation thus depends in part upon the position of the water table in the peat profile.

The effect of peat type on water storage capability was shown by comparing water table response to precipitation on the same bogs when water tables were at high and low extremes. The peat types differed in the upper and lower horizons of the deposits; thus when water tables were low, response to precipitation was governed by a different peat type than when water tables were high. Because peat types were limited in the bogs, extreme differences in physical properties could not be sampled. Even these small differences, however, appear to be important.

A regression analysis showed a greater water table rise per unit of precipitation at low water table levels (high regression coefficients), indicating less storage in the lower peat horizons (Table I). Conversely, less water table response per unit of precipitation was shown at high water table levels (low regression coefficients), indicating more storage capacity in the upper peat horizons.

Because of the limited range of precipitation and water level response, and stratification into high and low water table positions, the linear relations shown in Table I represent only short sections of the overall curve of water level response to precipitation. The regression coefficients indicate the slope of the regression line and the ratio of water level rise to rainfall input. The constants in the regression equations should be less than one because some precipitation should be intercepted by vegetation before it reaches the water table. The positive values shown for two equations are probably due to variability in the data caused by differences in rainfall intensity and the fact that exceptionally small storms were not included in the analysis.

The coefficients of determination in Table I indicate less variability in the data for high water tables. This is no doubt due to similar peat types in the upper horizons of the deposits. More heterogenous peat materials in the lower horizons and variable drying conditions before storms probably account for the variations shown at low water tables. There is still, however, a distinct difference in response to precipitation between the upper and lower peat materials in the bog profile. Thus, although bog water level is an indicator of storage opportunity, the type of peat material in the zone of active water table fluctuations must also be considered.

TABLE I

Comparison of Water Level Response to Precipitation on Three Bogs When Water Tables Were at High and Low Extremes

Bog	Bulk density*	Regression equation†	Coefficient of determination r^2
High Water Table—Peat Type Surface Mosses, Hummock, and Hollow Microrelief			
S-1	.02–.06	Y = 1.51X − .21	.88
S-2	.02	Y = 1.49X − .04	.86
S-3	—	Y = 1.34X − .02	.87
Low Water Table—Peat Type Near Surface Moss to Moss Peat With Wood Inclusions			
S-1	.08–.12	Y = 2.51X + .43	.69
S-2	.06–.08	Y = 3.47X + .25	.63
S-3	—	Y = 2.59X − .22	.57

*Data not available for the specific horizons in S-3. All bulk density data were collected by Dr. D. H. Boelter for other studies.

†Where { Y = Water level response; X = Precipitation

(Number of storms ranged from 12 to 29 for any one equation)

RUN-OFF

Run-off reflects the net effect of all processes that influence the hydrologic cycle on a catchment. Total quantity, seasonal distribution, peak flows, and minimum flows need to be measured and evaluated to fully understand the influence of peat deposits on water yield and regulation. Although some limited studies of run-off from peatland catchments have been conducted in northern Europe, the British Isles, and the USSR, no detailed, controlled run-off experiments have been reported on peat deposits in the northern United States. Even though the experimental catchments in this study are a composite of bog and associated uplands, the run-off records collected by weirs and flumes provide important data on the overall effectiveness of peat deposits as water storage areas and regulators of streamflow.

SEASONAL WATER YIELD

Because of extremely low temperatures during winter, run-off from the perched bogs occurred only between the spring thaw period in late March or early April and fall freezeup in late November or early December—a period of about 8 months. Run-off from the groundwater bog was not measured because of a wide outlet that precluded construction of a stream gauge. Seepage from the bog, however, was observed to continue through the winter.

The distribution of flow during the run-off period was studied by dividing the flow-year into three parts: spring (beginning of flow to June 1), summer (June 1 to September 1), and fall (September 1 to the end of flow). Each period is distinct in terms of climate, vegetation development and hydrology.

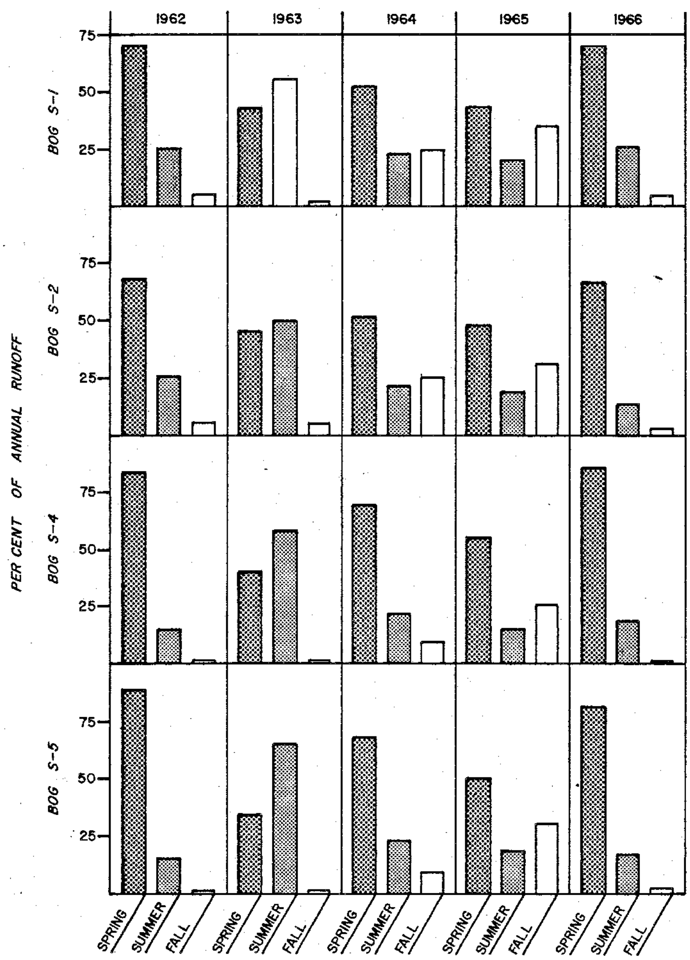

Figure 3. Percentage of annual run-off by seasons from four peat catchments.

Annual run-off was not evenly distributed during the 5 years of study (Figure 3). Most of the annual water yield occurred in spring due to snowmelt, early spring rains, and low evaporation. Two to six inches of water accumulated in the snowpack on the catchments. Upon melting, some of this was stored in the upland soil, a minor amount evaporated, some recharged bog storage, and the remainder ran off. By the end of snowmelt, water tables were generally near the surface of the peat deposits, and any additional melt-water or rain ran off because the available storage space was filled. At this time the peat deposits behaved much like lakes or reservoirs filled with water—when more water was added, some had to run off. During spring any regulating effect of the peat deposits on run-off was due more to their relatively flat topography than to the hydrologic characteristics of the peat materials.

During the 5-year study period annual precipitation averaged approximately 31 in.; 42 per cent of this (about 13 in.) came during June, July, and August. Yet, summer water yields were low. The mean summer water yield from bog S-2 (which has the most accurate area control) was only 2 in., or about one-fourth of the mean annual water yield for the flow-year. High evapotranspiration reduced the amount of water that might have been available for run-off.

Evapotranspiration was less during the fall but also precipitation was usually less. Much of the rainfall recharged water storage in the peat deposits, and thus fall run-off was generally low.

Run-off stopped on most of the watersheds sometime during each flow-year, usually in August or July when evapotranspiration was high. Groundwater was not a component of flow from these perched deposits, and the low flow records indicate that water yield from the peat itself was negligible during dry weather.

RELATION OF RUN-OFF TO BOG WATER TABLE

Water discharge from the peat deposits was closely related to the water table elevation in each bog (Figure 4). Mean daily flow in cubic feet per second (CFS) on the first day of each month was plotted against bog water table elevation at a recording well located near the centre of bog S-2 (Figure 4). The expected exponential increase in run-off occurred as bog water table level rose. Comparisons on the other catchments showed similar close relationships between bog water table levels and run-off. Regression coefficients and coefficients of determination were of the same general magnitude.

Run-off ceased at the same approximate water table position in each bog. Above this point, water stored in the bog was available for run-off. Below this level, water was retained within the peat deposit. Thus, each bog had a specific point at which it stopped contributing to streamflow. Any further lowering of bog water tables was accomplished only by evapotranspiration.

The relations outlined above show that bog water table levels within the study catchments play an integral part in catchment hydrology. The various factors that influence water levels in peat deposits are extremely important to water yield.

These data also suggest that water table reactions can be used to evaluate the influence of such things as forestry practices and drainage on peatland hydrology. Hydrologists should then have some confidence that any change in water levels due to treatment would have a corresponding influence on actual water yield. Water levels would be much easier to measure than discharge from peatlands with numerous or ungaugeable outlets. Thus, for some research purposes, measurement of water levels may be sufficient for evaluating certain aspects of bog hydrology.

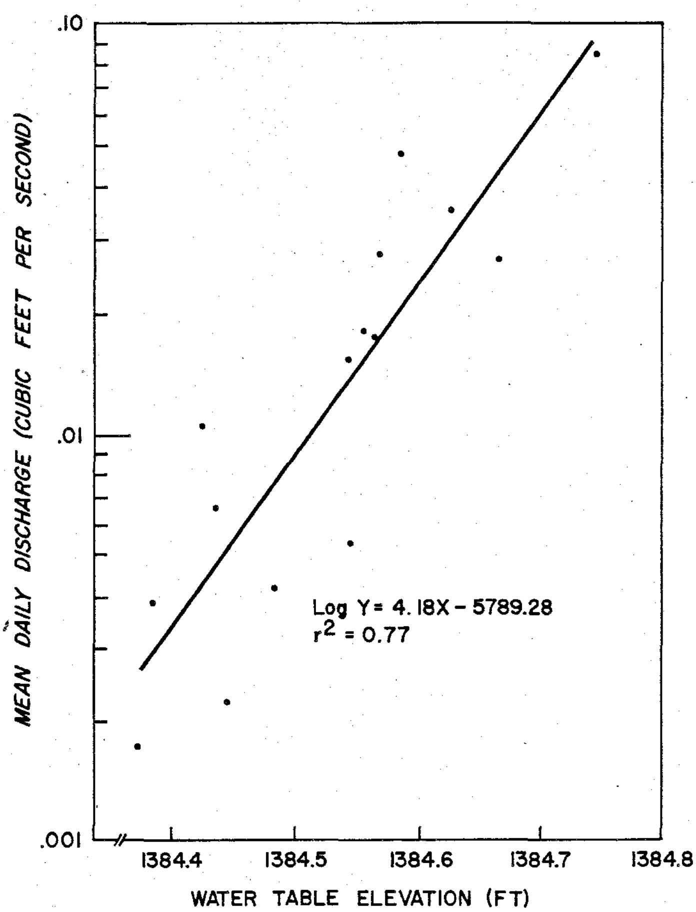

Figure 4. Relationship between mean daily discharge and bog water table elevation, bog S-2.

SUMMARY AND CONCLUSIONS

This comprehensive study of peatland hydrology has provided valuable information on the water storage properties and water yield characteristics of small peat deposits. Although each of the study catchments is a case history, several basic hydrologic characteristics have been identified which should also apply to other peat deposits.

Local hydrogeologic characteristics were found to exercise an important influence on the hydrology of a particular bog. In the one groundwater bog studied, changes in regional groundwater basin storage were reflected in the bog water table. On the other hand, perched bogs were independent of the underground system and not influenced by variations in basin storage.

The frequency of each type of bog throughout the north-central United States is not known. Many of the small, pothole type bogs found in glacial moraines and till plains are probably perched. Peat deposits in sandy outwash areas that have a shallow water table aquifer, however, are likely to be groundwater bogs. Because of the different sources of water supply, vegetation on the two types of bogs may be considerably different and could be the key to identifying these two hydrogeologic situations (Bay, 1967a).

Extremely large peatlands, such as those developed in glacial lake basins, are more complex and may contain both bog types. Certain portions of the peatland interior may be raised and receive water only from precipitation while some edges of the peatland may receive groundwater from nearby uplands. Much more needs to be known about the complex hydrology of large peatland areas.

The position of the bog water table was particularly important to the hydrologic reaction of each experimental peat deposit. Height of the bog water table and to some extent the type of peat, indicated storage capacity still available for snowmelt or rainfall recharge. Water table levels were also good indicators of run-off. When water tables were low, little water was available for run-off because it was retained within the peat profile and lost to evapotranspiration. High run-off was associated with high water tables in spring and after excessive rains. During these periods run-off rates were affected more by climatic conditions and the relatively flat topography of the peat deposits than by the hydrologic characteristics of peat materials. The importance of water table position and the characteristics of peat materials in the zone of water level fluctuation have also been recognized by Novikov (1964) and Vorob'ev (1963).

Run-off from the bogs was not evenly distributed throughout the year. Most of the annual water yield occurred during spring before June 1 and was not sustained during dry periods in late summer and fall. Thus the contribution of certain peatlands to low streamflow and the regulatory effect of perched bogs on run-off is questionable. Groundwater bogs may contribute to base-flow, but only because of discharge from the surrounding groundwater basin.

Groundwater bogs, however, could also decrease flow because discharge from the surrounding underground flow system is then available to plants for maximum transpiration loss rather than contributing directly to streamflow. Evapotranspiration was believed to cause a significant reduction in base-flow from the Great Swamp in New Jersey (Vecchioli *et al.*, 1962). During the dormant season, precipitation was thought to exceed storage capacity of the Great Swamp and run-off was considered to be greater than from the surrounding uplands.

Studies in Germany have shown sharp run-off peaks and long periods without flow from small, undeveloped raised bogs (Baden and Eggelsmann, 1964; Vidal, 1960). Investigation in Russia showed that run-off from swamp watersheds stopped in summer and winter (Chebotarev, 1962). A recent analysis of hydrologic data from a river basin in northern Minnesota containing considerable areas of peat showed run-off trends similar to those of the experimental bogs reported here (Winter *et al.*, 1967).

Thus, the study bogs appear to react hydrologically much like other peatlands, including some catchments containing large peat deposits. Future water production research on these bogs should contribute information helpful in the management of more extensive peat deposits.

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