HYDROLOGIC ANALYSIS OF TWO HEADWATER LAKE BASINS OF DIFFERING LAKE pH IN THE WEST-CENTRAL ADIRONDACK MOUNTAINS OF NEW YORK

By Peter S. Murdoch, Norman E. Peters, and Robert M. Newton

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CONVERSION FACTORS AND ABBREVIATIONS

The following factors may be used to convert International Systems (SI) units of measurement in this report to inch-pound units.

Multiply Metric Unit	by	To Obtain Inch-Pound Unit
	Length	
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	.6214	mile (mi)
	Area	
square kilometer (km^2)	.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
kilogram (kg)	2.2	pound (lb)
gram (g)	0.035	ounce (oz)
	Mass per unit area, volume	
kilogram per square kilometer (kg/km^2)	5.698	pound per square mile (lb/mi^2)
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot (lb/ft^3)
	Pressure	
pascal (Pa)	10.0	centibar (cbar)
	Temperature	
degrees Celsius (°C)	(1.8 x °C) + 32	degrees Fahrenheit (°F)

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ABSTRACT

Two small lake basins that receive similar amounts of acidic precipitation in the west-central Adirondack Mountains of New York have significantly different lake-water pH values. Basin water budgets for neutral Panther Lake (pH 5-7) and acidic Woods Lake (pH 4-5) were calculated for 1980 and 1981 to test the hypothesis that lake neutralization is dependent upon the amount of ground-water contribution. The watershed area underlain by thick glacial deposits, predominantly sandy till, is 8.5 times greater in the neutral-lake basin than in the acidic-lake basin, and thus provides a larger recharge area and greater storage capacity. Bedrock outcrop in the neutral-lake basin is restricted to the upper watershed but is extensive throughout the acidic-lake basin and restricts downslope drainage.

Water-budget calculations confirm greater ground-water storage, and thus greater ground-water contribution, in the neutral-lake basin than in the acidic-lake basin. A longer residence time of water within the neutral-lake basin is evidenced by less "flashy," more sustained basin outflow, and smaller outflow response to individual storms. Ground-water storage, recharge rates, and base flow were generally greater in the neutral-lake basin than in the acidic-lake basin except during spring, when saturated soil inhibited infiltration and increased surface runoff substantially.

Flow-duration curves of 1977-82 data for the neutral-lake outlet were much less steep than those for the acidic-lake outlet, which indicates a greater ground-water contribution to the neutral lake. Comparison of 1980 with 1981 flow-duration data shows that changes in precipitation intensity had less effect on outflows of the neutral lake than of the acidic lake. Comparison of outflow per unit area during recessions indicates that the storage capacity of the neutral-lake basin was 3.9 times greater than that of the acidic-lake basin, and the maximum outflow from ground-water reservoirs or water collected in surface depressions (base flow) was 2.2 percent greater.

Water budgets for each lake in which tributary flow was used to estimate surface runoff from the watersheds indicated 5 times greater base flow in the neutral-lake basin. Average base flow for the basins was proportional to the area of thick surface materials in each watershed. The difference in the net transport of major cations from the basins observed in previous studies was proportional to the observed difference in base-flow contribution to the two lakes. Thus, the degree of neutralization of acidified precipitation in the two watersheds is correlated with the thickness and extent of permeable surficial materials in which chemical interaction between rock and water can occur.

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INTRODUCTION

High concentrations of strong acids in atmospheric precipitation have been reported in the northeastern United States and northern Europe since 1965 or earlier (Cogbill and Likens, 1974). During the same time, decreases in the pH of surface waters at high altitudes have been documented (Likens, 1976; Babich and others, 1980). The chemical response of surface waters receiving equal amounts of acidic precipitation, even in watersheds of similar geologic terrain, is variable (Galloway and others, 1980a; Troutman and Peters, 1982).

In response to concern over the acidification of lakes in the Adirondack mountain region of New York, the U.S. Geological Survey, in cooperation with the University of Virginia, began the Integrated Lake Watershed Acidification Study (ILWAS) in 1976. The purpose of that study was to investigate why three selected lakes neutralize acidic atmospheric deposition to differing degrees.

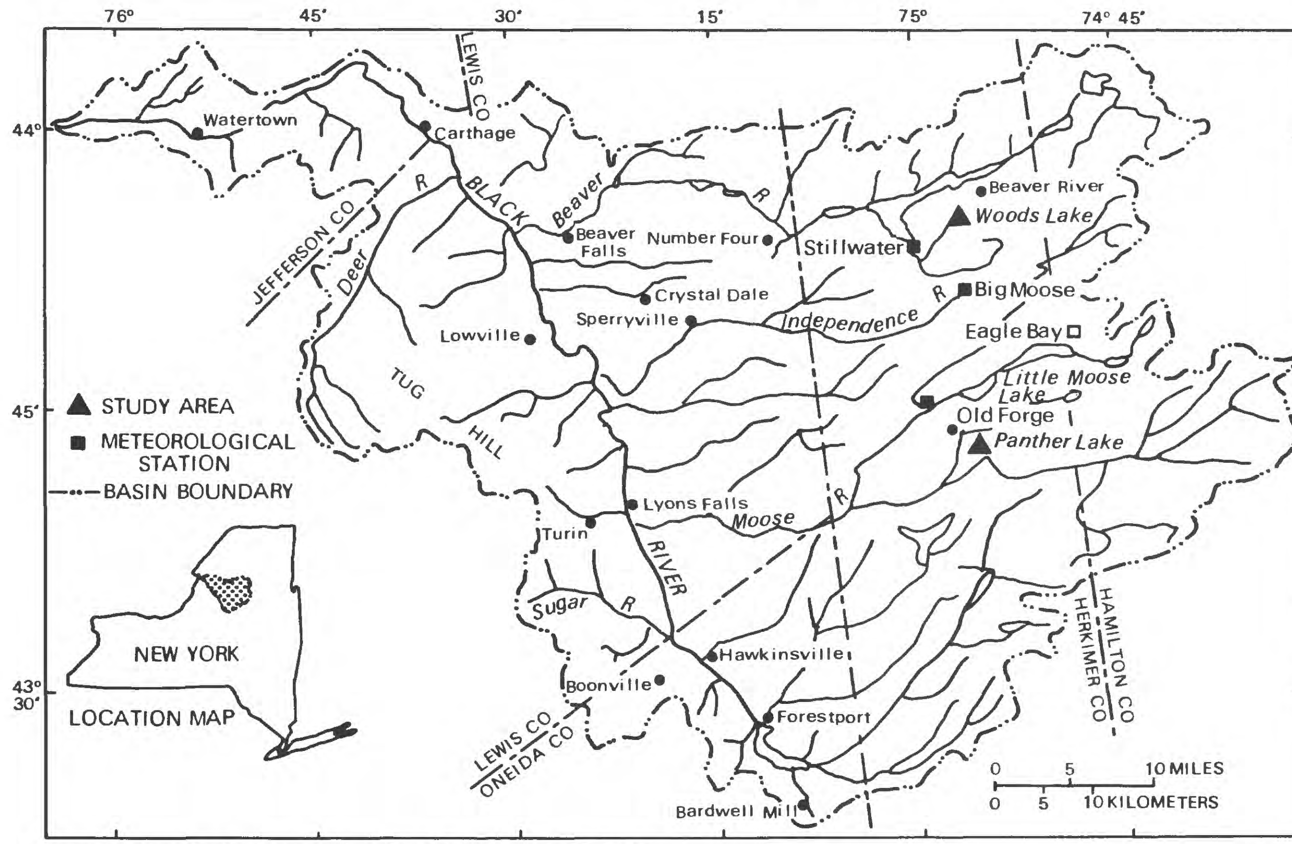
Results of the first phase of ILWAS during 1977-80 suggest that neutralization occurs as water flows through surficial glacial deposits and that the extent of neutralization is determined by the residence time of precipitation within the surficial materials of the surrounding watershed (Galloway and others, 1980a; Troutman and Peters, 1982). The net annual transport of major base cations (kg/km^2) from the neutral-lake basin was 4.4 times that from the acidic-lake basin (Galloway and others, 1983). The major base cations analyzed were calcium, magnesium, potassium, sodium, and ammonium. Because the two basins receive similar amounts of precipitation and contain similar bedrock and glacial deposits, the basin that undergoes more weathering, a process that consumes hydrogen ions, should release a larger number of cations from the soil and thus should have a higher surface-water pH and a larger net cation transport from the basin (Berner, 1971). Thus, the distribution of permeable surficial materials within each basin, and hence the residence time of "acid rain" in contact with neutralizing minerals, may be reflected in the chemical quality of water at the basin outlet. To substantiate many of the hypotheses generated from research in the first phase of the study, a second phase was begun in 1980 to compare the geohydrologic characteristics of two representative lake basins (fig. 1).

Purpose and Scope

This report summarizes results of the second phase of ILWAS from January 1980 through December 1981. The objectives of this phase of the study were to evaluate geologic and hydrologic characteristics that might affect lake-water chemistry in two of the previously studied drainage basins and to determine which of these characteristics might cause the lakes to differ in pH. Panther Lake (pH 5-7) and Woods Lake (pH 4-5) were selected because they (1) represent the extremes of lake-water pH observed in the ILWAS study, (2) are similar in size, altitude, and topographic relief, and (3) contained the most comprehensive monitoring network of the basins studied.

The components of the hydrologic budget for each of these lake basins were evaluated through field data collected from January 1980 through December

1981. Field data consisted of stage and discharge at the lake outlets and inlets, lake stage, ground-water stage, precipitation, snow accumulation, temperature and solar radiation (for evapotranspiration), and soil moisture. Mapping of bedrock outcrop and thickness and permeability of surficial materials was completed before 1980. Data were analyzed through a hydrologic budget equation, a ground-water budget equation, flow-duration curves, and a ground-water storage-capacity equation (Kneisel, 1963). Evapotranspiration was estimated by several methods that incorporate solar radiation, temperature, and daylight data. The results were related to basin characteristics that could account for differences in water flow paths and lake pH.



Base from New England-New York Inter-Agency Committee, 1954

Figure 1.--Location of Panther (neutral) Lake and Woods (acidic) Lake and meteorologic stations in Black River basin.

Acknowledgments

Both phases of the Integrated Lake Watershed Acidification Study (ILWAS) were conducted in cooperation with the University of Virginia and the Electrical Power Research Institute. Special thanks are extended to Arland H. Johannes of Rensselaer Polytechnic Institute, Troy, N.Y., for providing meteorological data, to William Kelly of the New York State Geological Survey in Albany, N.Y., for bedrock mapping, and to the many other participants for providing data and interpretation of related aspects of the research.

REGIONAL SETTING

Panther Lake and Woods Lake are approximately 15 km apart in the west-central Adirondack Mountains of northern Herkimer County, N.Y. (fig. 1). Panther Lake (pH 5-7) drains north into Little Moose Lake near the village of Old Forge, and Woods Lake (pH 4-5), nearly due north of Panther Lake, drains to the southwest near the hamlet of Big Moose. Panther Lake contains a variety of aquatic life that is typical of buffered lakes in the region. Woods Lake is acidic and has become devoid of fish. Both basins are part of the headwaters of the Black River, which flows northwest into Lake Ontario (fig. 1) along the geologic boundary between the sedimentary strata of the Appalachian Plateaus on the west and the Precambrian granite of the Adirondack Province on the east (Fenneman, 1938).

The west-central Adirondack Mountains region consists of rugged, irregular terrain and abundant surface water. The topography is largely the result of repeated glaciation, which scoured the bedrock surface and left a mantle of drift over most of the area. The last glaciers in the region receded approximately 14,000 years ago (Newton and April, 1982). Deposits of drift are relatively thin on hillsides, but the larger valleys may contain thick deposits in places. Obstruction of valleys by drift, deposition of till from stagnating ice, and glacial scouring have resulted in an abundance of lakes, swamps, and deranged drainages. Hills in the area are generally elongated along a northeast-southwest axis, are topped by ice-scoured bedrock ridges, and have topographic relief ranging from 60 to 150 meters.

Climatic conditions are similar in both basins. The west-central Adirondack Region has a humid and seasonally severe climate typical of mountain environments, with air temperatures ranging from -40° to 27°C annually (U.S. Department of Commerce, 1968). Precipitation averages 127 cm/yr, of which 40 percent is snow. Approximately 40 percent of the precipitation is returned to the atmosphere through evapotranspiration, and the rest either infiltrates the ground or drains as surface runoff. Snow accumulates to an average depth of 76 cm in the winter. Winds are variable but are predominantly from the west and southwest.

LAKE-BASIN CHARACTERISTICS

Many of the physical characteristics of the two lake basins in the study are similar (table 1 and figs. 2A, 2B). Both lakes are within headwater basins. Panther Mountain (fig. 2A) gives the neutral-lake basin a greater maximum relief (192 m) than the acidic-lake basin (122 m), but the average land slope in each basin is about the same. The effects of relief are thus assumed to be generally comparable. The drainage area of the acidic-lake basin (2.07 km^2) is 40 percent larger than that of the neutral-lake basin (1.24 km^2), and the lake-surface altitude of the acidic lake exceeds that of the neutral lake by about 49 m. The ratios of lake area to basin area are similar--0.14 for the neutral-lake basin and 0.11 for the acidic-lake basin (table 1).

Both watersheds are nearly 100 percent forested, primarily with hardwoods (C. Cronan, University of Maine, written commun., 1979). Neither watershed has been extensively logged since 1950. Both basins are remote from local population centers and are considered pristine.

Although the two basins are similar in several physical characteristics, they also differ in ways that affect the flow path of water, and these differences are reflected in the water budgets. These characteristics are summarized in table 1 and in the following discussion.

Table 1.--Hydrologic characteristics of the Panther (neutral) Lake and Woods (acidic) Lake watersheds.

[Locations are shown in fig. 1]

	Panther Lake (neutral)	Woods Lake (acidic)
Latitude	43°41'	43°52'
Longitude	75°55'	74°58'
Basin area (km^2)	1.24	2.07
Watershed area (km^2) (basin area minus lake area)	1.06	1.84
Lake area/basin area ratio	0.14	0.11
Lake-surface altitude (m)	557.2	606.5
Relief (m)	192	122
Forest cover (percent)	100	100
Basin area containing bedrock outcrop or till cover less than 10 m thick (percent)	*33	*78.8
Basin area containing till cover greater than 10 m thick (percent)	*52	*9.2
Lake area (km^2)	0.18	0.23
Lake volume (m^3)	7.08×10^5	8.13×10^5
Mean lake depth (m)	3.9	3.5
Maximum lake depth (m)	7.0	12.0
Period of lake-ice cover (days)	120	120
Lake-flushing period (days)	264	221

* Excluding lake area.

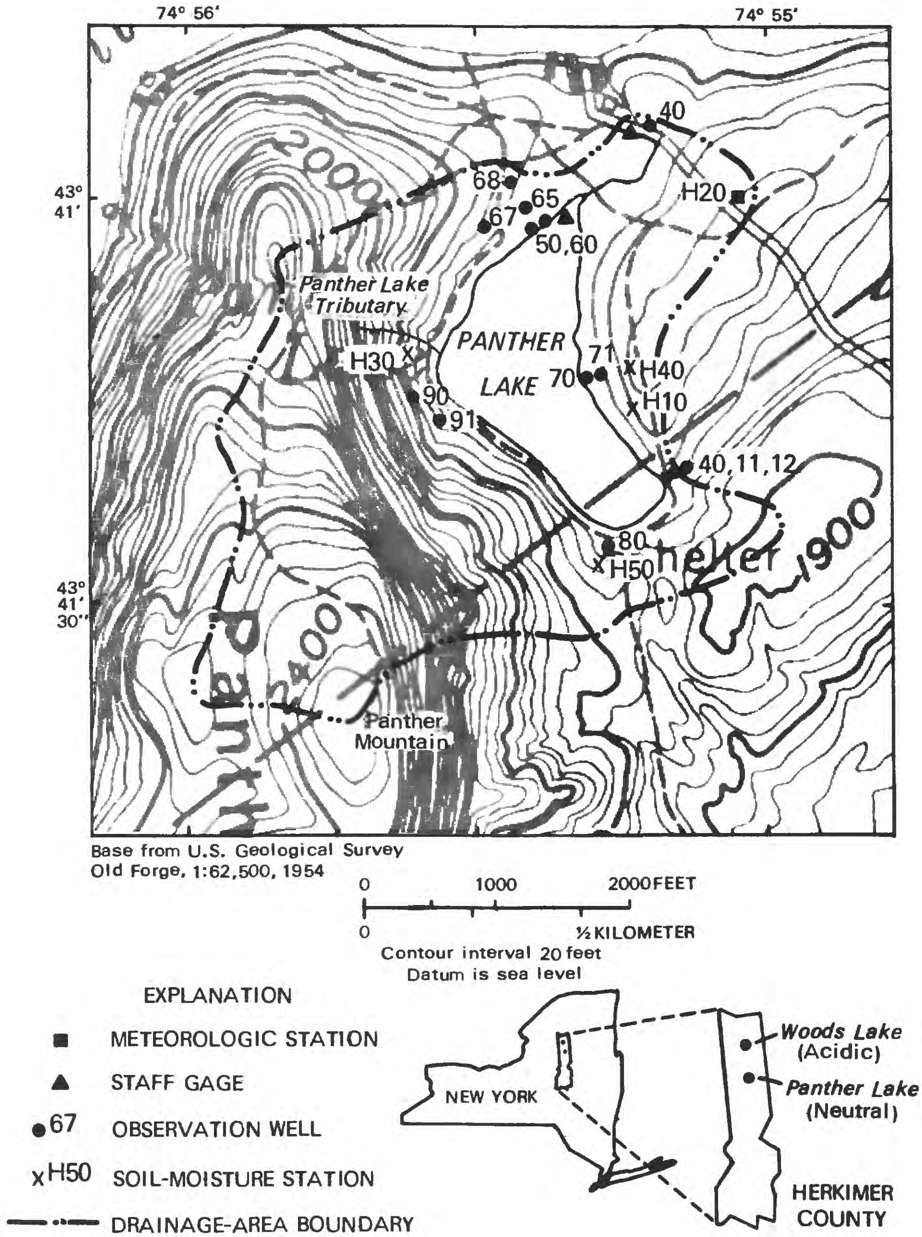


Figure 2A.--Locations of hydrologic and meteorologic monitoring stations in Panther (neutral) Lake basin.

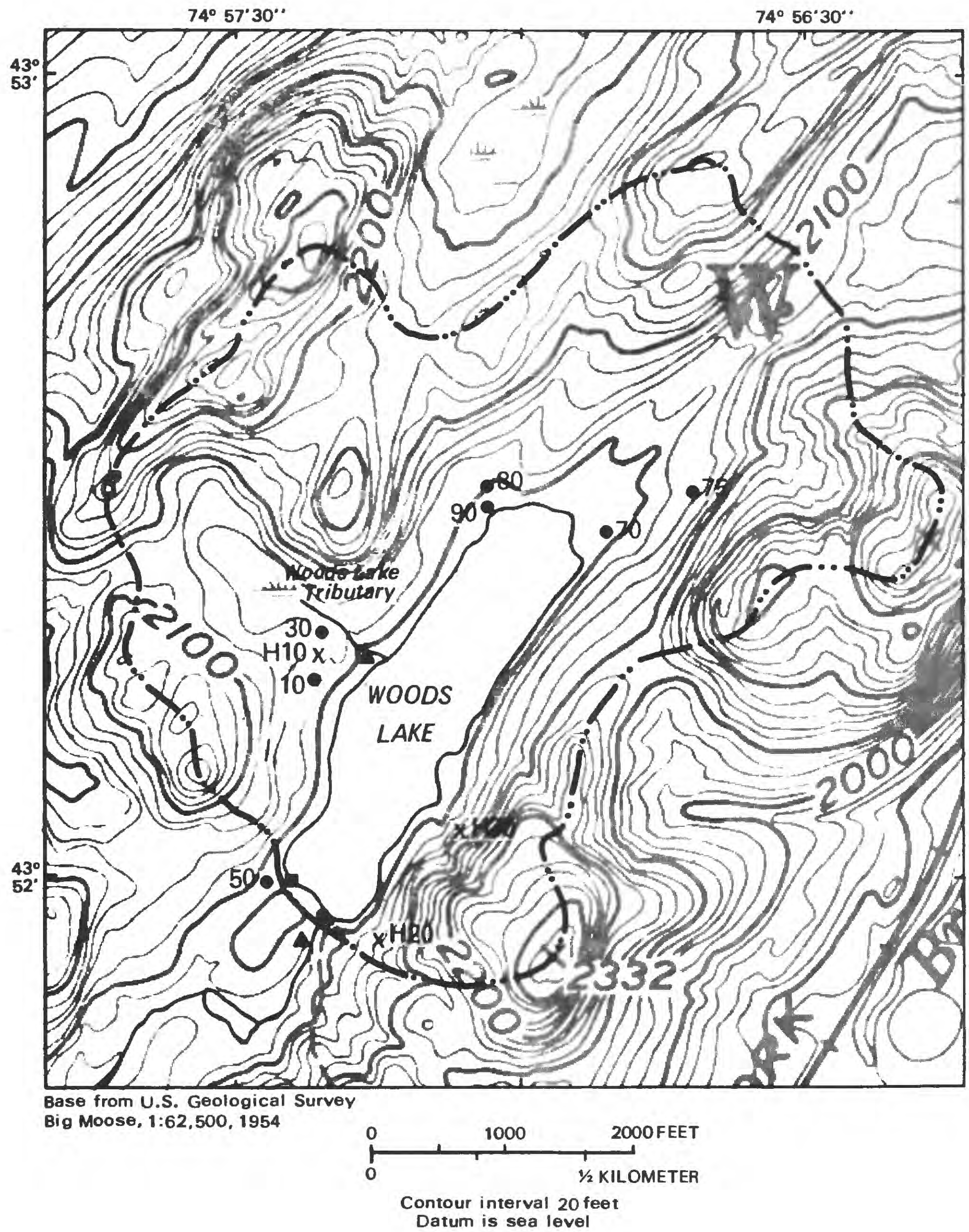


Figure 2B.--Locations of hydrologic and meteorologic monitoring stations in Woods (acidic) Lake basin.

Geology

The first mapping of bedrock and surficial deposits in this study was done from aerial photographs by the U.S. Geological Survey (Waller, 1976). Subsequent mapping by field reconnaissance and seismic methods resulted in the composite maps shown in figures 3A and 3B (p. 10-11).

Bedrock

Both basins are underlain by Precambrian granitic or charnokitic gneiss. The bedrock is not extensively fractured in either basin, which suggests that most of the ground water is stored in the unconsolidated surficial materials and that the exchange of water between the bedrock and surficial materials is minimal.

Bedrock outcrop in the neutral-lake basin (fig. 3A) is limited to the upper slopes of Panther Mountain and occupies less than 30 percent of the total basin area. Bedrock profiles derived from seismic-refraction surveys suggest a smoothed, saucer-shaped bedrock surface throughout the basin (Newton, 1983). In contrast, bedrock is exposed throughout most of the acidic-lake basin, including the southwest part of the lakebed (fig. 3B). Outcrops are elongate parallel to the long axis of the basin, creating a washboard topography, and are common near the lakeshore.

Surficial Deposits

<u>Lithology and stratigraphy</u>.--The most extensive surficial material in both basins is an anisotropic, sandy till containing interspersed ablation and lodgment till. Ablation till, which was deposited from the ice surface as the glaciers melted from the area, is generally less compacted than lodgment till, which was deposited beneath the ice and overridden as the glaciers advanced. A deeper clay till has been inferred in the neutral-lake basin, and an eolian silt mantles parts of the acidic-lake basin (Newton, 1983). The presence of the lower till was verified during drilling by Newton during the fall of 1984. Both basins contain small glaciofluvial sand deposits (fig. 3). The lithology and stratigraphy of the surficial units are described as follows:

Till units. The sandy till is the primary aquifer material in both watersheds. It contains both ablation and lodgment till. Grain-size distribution in both basins ranges from 90 percent sand, 9 percent silt, and 1 percent clay in the ablation till to 50 percent sand, 42 percent silt, and 8 percent clay in the lodgment till.

A lower till unit in the neutral-lake basin was discovered through a comparison of seismic velocities with those from a dense till exposed at Raquette Lake, 29 km to the east (Newton, 1983). The dense till at Raquette Lake lies conformably below a till similar to the sandy till at the two basins studied. The lower till unit is more consolidated than the overlying sandy till, and its grain size averages 63 percent sand, 22 percent silt, and 15 percent clay. The lower till was not detected in seismic profiles of the acidic-lake basin (Newton, 1983).

Eolian silt. The thin mantle of eolian silt covering much of the acidic-lake basin was not detected in the neutral-lake basin. Grain size of this unit averages 70 percent silt, 25 percent sand, and 5 percent clay; thickness of the layer varies and has a maximum observed value of 76 cm. The silt is mineralogically similar to the underlying till but is finer grained and less permeable. A composite section showing the relative positions of surficial materials in the two basins is shown in figure 4.

Soils. Soils developed on the glacial material of the two basins are similar and are broadly categorized as Spodozols. Spodozols are typical of forest soils with a shallow organic horizon and a definite mineralized horizon (Cronan, 1983). Soils in both basins average less than 1 m thick and range from extremely acid in the O and A horizons to slightly acid in the B horizons (April, 1983). The mineralized A2 horizon averages 4 cm thick in both basins and is a reservoir of labile aluminum and iron, which can be mobilized by acidic pore water.

Thickness and Distribution.--The two basins differ considerably in areal extent and thickness of surficial materials (figs. 3, 4, 5). Areas of thick surficial materials (>10 m) are more extensive in the neutral-lake basin than in the acidic-lake basin. The minimum thickness of overburden necessary to mask irregularities in the bedrock surfaces, and thus create a smooth topographic contour, is 3 m.

In the acidic-lake basin, surficial materials exceeding 3 m in thickness covers less than 10 percent of the basin (Troutman and Peters, 1982). The thickest deposits are in two small areas along the northwest lakeshore (9 m thick) and in pockets in the northeast part of the basin (3 m thick) (fig. 3B, 4, 5). In the neutral-lake basin, till exceeding 3 m in thickness covers more than 50 percent of the basin and extends from the eastern watershed boundary to midway up the east slope of Panther Mountain (figs. 3A, 4, 5). The maximum thickness of till in the neutral-lake basin (36.5 m) is 4 times that in the acidic-lake basin, and the area underlain by thick till (>3 m) is 8.5 times greater.

Hydrologic Properties.--Variability of soil moisture and subsurface permeability was greater within each basin than between the basins during the study. Permeability of the C horizon, which was assumed to represent the primary aquifer materials in both watersheds, was similar in both basins. Also, soils that developed on thick till (>3 m) retain less moisture in both basins, than those that developed on thin till.

Soils in the neutral-lake basin are generally saturated near the lake outlet and along the ridge of Panther Mountain, where deep drainage is restricted by bedrock. Soils in the eastern and southern part of the basin are somewhat drier than in the western part, but soil-moisture tension data suggest that all soils are near field capacity most of the time except during late summer. Soils in the acidic-lake basin are commonly saturated along most of the lower slopes adjacent to the lake; this area contains swales bordered by elongate bedrock ridges that restrict downslope drainage and cause ponding. Both basins contain other surface depressions where water can pond. The northeast end of the acidic-lake basin contains swamps and saturated soils that drain directly into the lake.

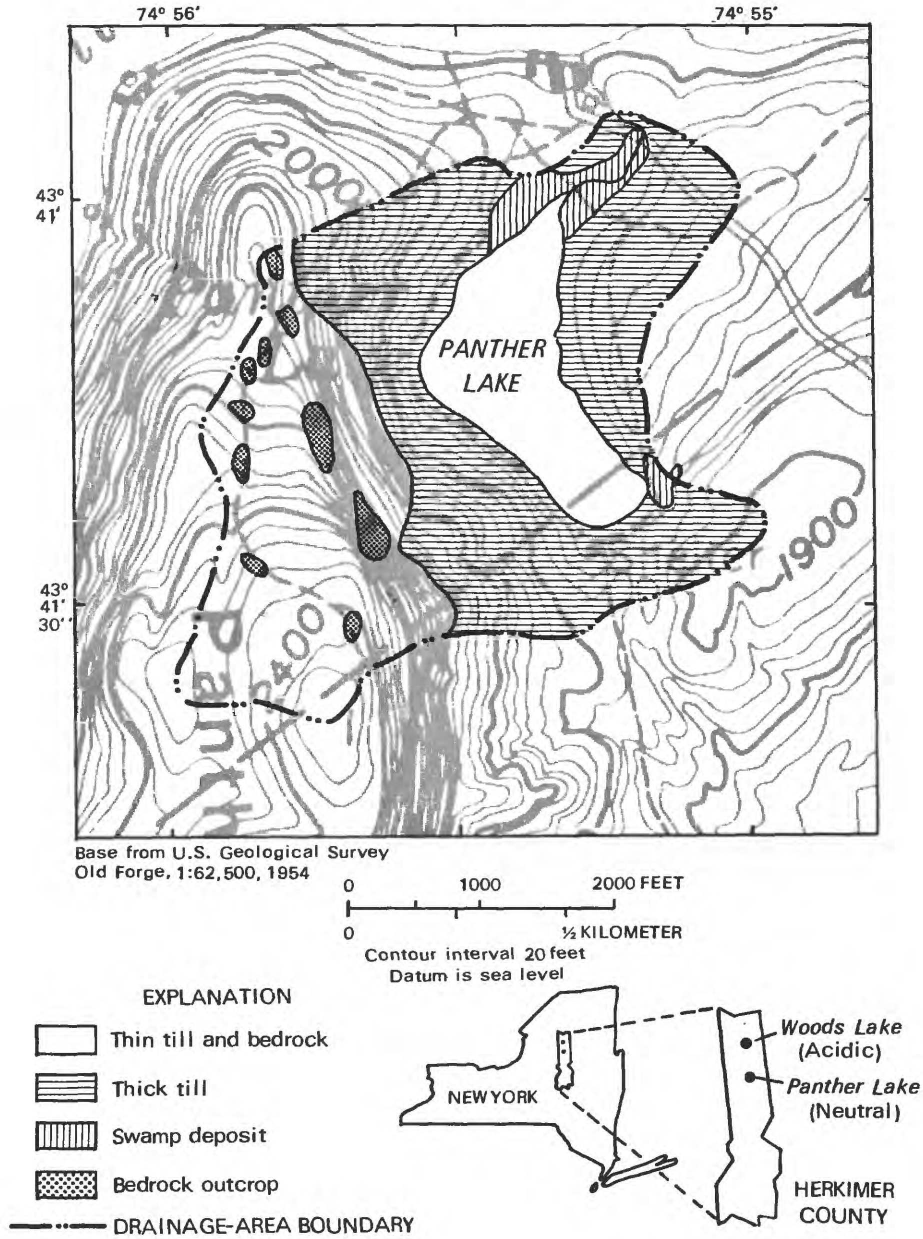


Figure 3A.--Surficial geology of Panther (neutral) Lake basin.

Figure 3B.--Surficial geology of Woods (acidic) Lake basin.

Average soil permeability is slightly greater in the neutral-lake basin than in the acidic-lake basin. Estimated average permeability of all surface materials in the neutral-lake basin was 2.16×10^{-3} cm/s and, in the acidic-lake basin, was 1.1×10^{-3} cm/s (Newton, 1983). The lower soil permeability of the acidic-lake basin may be due to the higher silt content of the upper soil horizons, which in turn probably results from the eolian layer described previously.

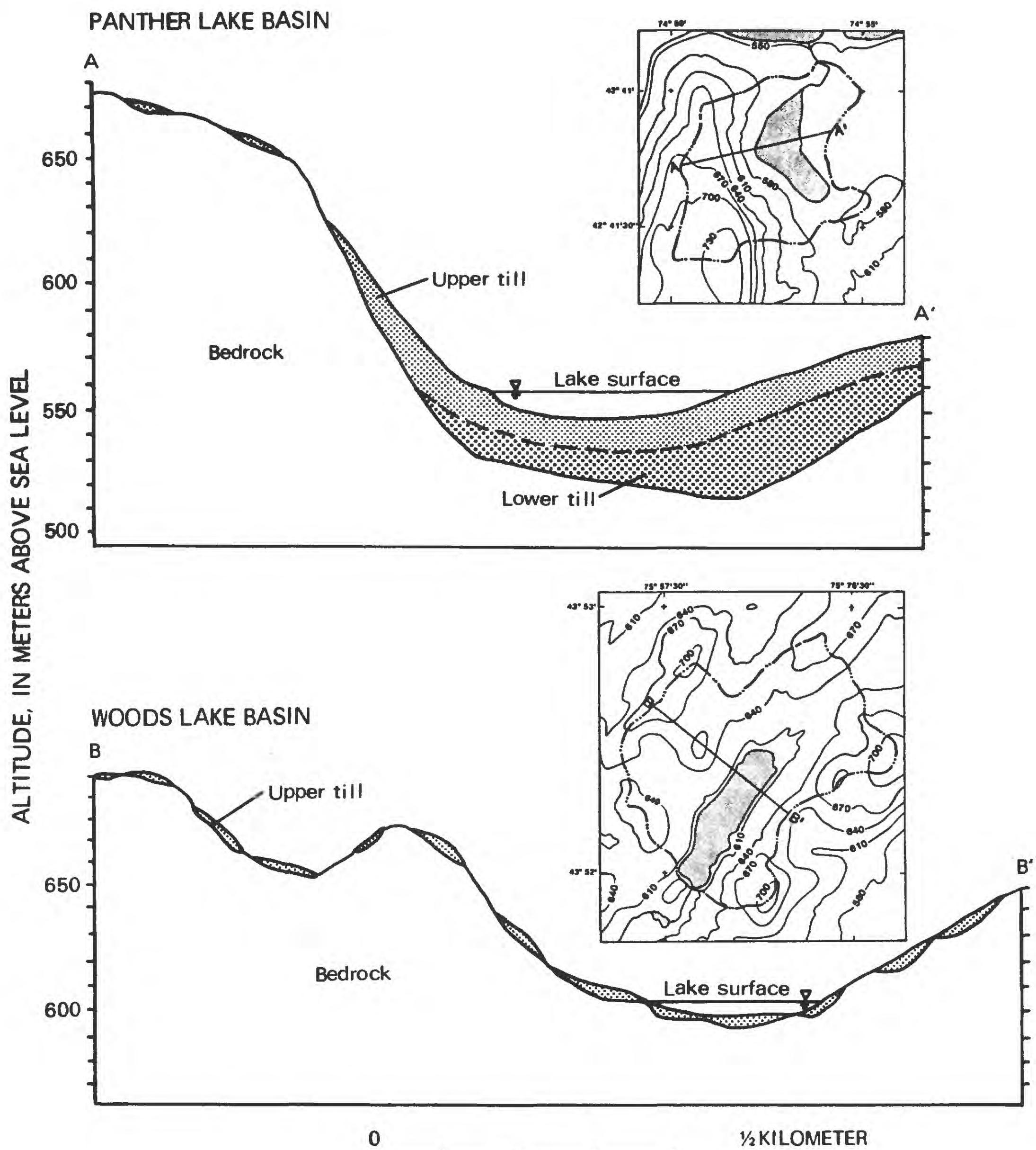


Figure 4.--Generalized geologic sections showing relative position and thickness of glacial materials.

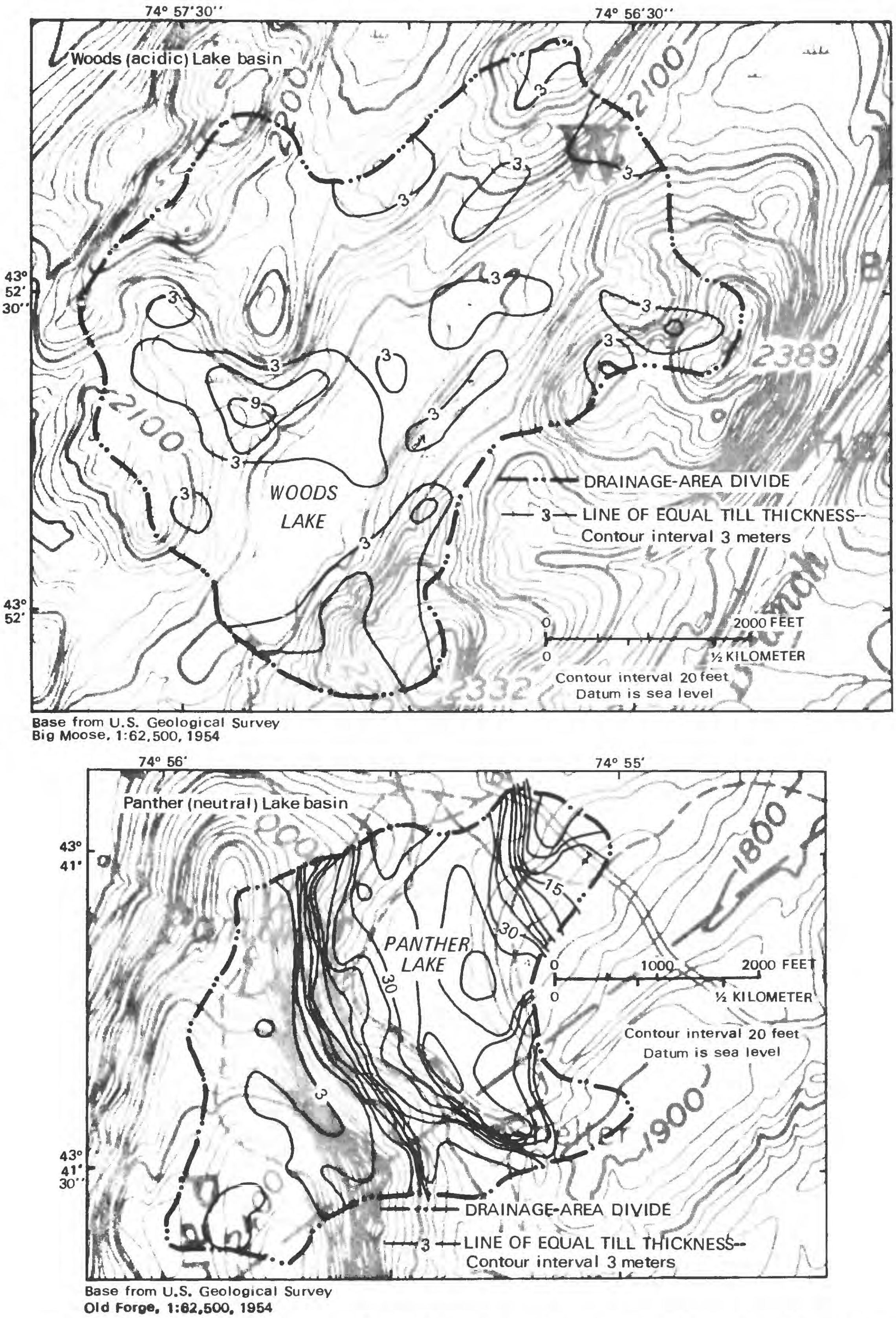


Figure 5.--Thickness and distribution of unconsolidated surficial materials. (Basin locations are shown in fig. 3.)

Ground Water

Percolation of water to the water table probably occurs in all parts of the neutral-lake basin except the steep slopes of Panther Mountain (fig. 3A). The ground-water reservoir is thick and continuous beneath most of the recharge area. In the acidic-lake basin, the primary recharge area is in the thick till along the northwest lakeshore (fig. 3B). Swales between bedrock ridges create other smaller pockets of ground-water storage throughout the acidic-lake basin.

The infiltration rate of soils was not exceeded by the precipitation rate in either basin during the 2-year study. The infiltration capacity, however, was exceeded locally during storms and snowmelt periods in the acidic-lake basin where the eolian silt and bedrock outcrops impeded percolation and, in the neutral-lake basin,along the base of Panther Mountain. Soils remained unfrozen during the winter in both basins except during December 1979 and January 1980, when snow cover was thin or absent. Soil-water flow paths, however, were assumed to be open throughout the year, and ground-water discharge occurred into the winter months.

Surface Water

Lake surface covers 14 percent of the neutral-lake basin and 11 percent of the acidic-lake basin, and lake volume and mean depth of the two lakes are also similar (table 1). The flushing period for the neutral lake is 264 days; that for the acidic lake is 221 days. This difference reflects the larger ratio of lake volume to basin area in the neutral-lake basin than in the acidic-lake basin. Both lakes have ice cover for about 120 days per year.

Outflow from the neutral lake is through a natural cobble channel that is bordered on the east by a wetland (fig. 2A). Topographic gradients adjacent to the lake are generally steep except near the outlet. Outflow from the acidic lake is through a 2-m-wide wooden dam on a bedrock channel. During the summers of 1980 and 1981, beavers periodically raised the lake level by building on top of the dam. Repeated removal of the beaver dam caused temporary increases in discharge at the outlet and a corresponding change in lake stage. Topographic gradients near the acidic lake are mostly shallow, and wetlands flank much of the shore.

The neutral lake has fewer tributary streams than the acidic lake. The largest tributary to the neutral lake originates on Panther Mountain and enters the lake along its west shore (fig. 2A). The tributary flows only during spring snowmelt and intense storms and is generally dry in summer. Other ephemeral streams draining Panther Mountain are dry for longer periods. At the south end of the lake, one tributary has steady continuous flow and water temperatures that are comparable to that of nearby ground water. The eastern part of the watershed contains no tributary streams.

The acidic-watershed basin contains several tributary streams, the largest of which is in the northwest part of the basin (fig. 2B). Other perennial and ephemeral streams arise in the northeast part of the watershed and midway along the southeast shore of the lake.

HYDROLOGIC ANALYSIS

Water-Budget Method

The water-budget method of describing basin hydrology is based on the law of mass conservation, in which water gain (from precipitation or inflow) is equated to water losses plus changes in basin storage. The general equation used in this study was:

$$P = R + ET + \Delta SN + \Delta SW + \Delta WS \qquad (1)$$

where: P = precipitation,
R = lake outflow,
ET = evapotranspiration,
ΔSN = changes in snow storage,
ΔSW = changes in lake storage, and
ΔWS = changes in watershed storage (includes ground-water, soil-moisture, and surface-depression storage in each watershed).

The water budget was used to estimate changes in watershed storage (ΔSW), from measurable or estimated hydrologic properties. All values of the equation were reported as equivalent centimeters of water per unit of basin surface area for comparison of results between basins.

Data requirements and Sample Collection

A monitoring program was designed to collect data from which the monthly and yearly value of each component of equation (1) could be calculated. In addition, data on soil moisture, ground-water stage, and tributary discharge were collected to evaluate changes in watershed storage. Station locations were identified by tape and compass measurements (figs. 2 and 3). Descriptions of monitoring equipment and sampling techniques used are given in Peters and others (1986).

The data used in the water-balance equation were compiled in equivalent centimeters of water over the total basin area and summed for monthly and yearly time intervals. Monthly change in watershed storage was calculated as a residual of the water-balance computations. Soil-moisture and ground-water level data were used to characterize the ambient conditions for periods over which the water budget was calculated and to help compare the origins of base flow from each watershed.

Base flow is generally considered to be flow derived from ground water and is quantified through recession hydrographs. The high frequency of precipitation in this study may have caused base flow to include some interflow and drainage from topographic depressions on the watersheds. An estimate of the base-flow contribution to total outflow was made by averaging the results derived through several methods. A description of field instrumentation, sample-collection procedures, and data processing for each component of the analysis is presented in the following sections.

Components of Water-Budget Equation

Precipitation.--Precipitation (P) quantity was recorded at one site within each basin (fig. 2) and at two sites outside the basins--one at the Rensselaer Polytechnic Institute field laboratory in Big Moose, 6.1 km southeast of the acidic lake, the other at Little Moose Lake, 1.9 km north of the neutral lake (fig. 1). Meteorological data from nearby National Weather Service stations were compared with data from this study to evaluate regional variation of precipitation. These stations are at Old Forge (5.6 km north of the neutral lake and 17.5 km south of the acidic lake), Eagle Bay (12.5 km northeast of the neutral lake and 15 km southeast of the acidic lake), and Stillwater Reservoir (6.9 km west of the acidic lake) (fig. 1).

Precipitation was collected at each basin in weighing-bucket rain gages that were mounted on 2-meter-high platforms erected in small clearings. A more thorough discussion of the methods of collection and station design is given in Johannes and others (1981).

Lake Outflow.--Outflow (R) represents the total basin runoff as measured at the lake outlet. Outlet stage and flow was monitored continuously at both lake outlets (fig. 2). Lake outflow was calculated from stage-discharge rating curves, then converted to equivalent centimeters of daily runoff. Complete station descriptions and records of discharge at the lake outlets are presented in Peters and others (1986).

Evapotranspiration.--Estimates of evapotranspiration (ET) were calculated from several empirical formulas that are discussed further on. The formulas require data for six climatic characteristics, described below:

Daily mean air temperature. A daily mean temperature for each day of the study was calculated by averaging the maximum and minimum air temperatures from the meteorological stations nearest each watershed. During 1980, air-temperature data from the weather station at Old Forge were used for the neutral-lake basin, and data from the Stillwater Reservoir station were used for the acidic-lake basin (National Oceanic and Atmospheric Administration, 1980-1981). During 1981, the data used were from meteorological stations close to the study basin--the Rensselaer Polytechnic Institute (RPI) station at Little Moose Lake for the neutral-lake basin and the RPI station at Woods Lake for the acidic-lake basin (A. H. Johannes, RPI, written commun., 1981). All other components of the evapotranspiration equations described below were assumed to be similar at both basins and were computed from regional data.

Solar radiation. Daily solar radiation was estimated from National Weather Service station records in Albany, N.Y. through the entire study period and from the RPI station at Little Moose from February through December 1981. Solar radiation was calculated from the Albany data and from least-square linear relationships between solar radiation at Albany and solar radiation at Little Moose from May through August 1981.

Potential sunshine. The total possible daily sunshine for 45° north latitude was calculated from data in Jensen and Haise (1963).

Percentage of actual monthly sunshine. This was averaged from the actual daily sunshine at National Weather Service stations in Syracuse, N.Y. and Burlington, Vt. (National Oceanic and Atmospheric Administration, 1980-81).

Saturation-vapor density. This was estimated from the daily mean air temperature and standard conversion tables (Weast, 1971).

Monthly pan evaporation. This was computed by averaging daily values from the National Weather Service stations in Essex Junction, Vt., and Canton, N.Y. (National Oceanic and Atmospheric Administration, 1980-82).

Changes in Snow Storage.--Changes in snow storage (ΔSN) were calculated from monthly differences in the water equivalent of the snowpack (A. Johannes, Rensselaer Polytechnic Institute, written commun., 1980 and 1981). Weekly snowcores were taken in conifer forest, hardwood forest, and open environments of both basins. Water equivalents within each environment were averaged and multiplied by the percentage of the watershed represented by that environment, and the results were summed for each basin. Additional estimates were derived from snow surveys conducted in 1980 by the U.S. Geological Survey in both basins (Peters and others, 1986) and in 1980 and 1981 by Niagara Mohawk Power Company in Big Moose and Old Forge (U.S. Geological Survey, 1980-82).

Changes in Lake Storage.--Lake stage of the neutral lake was obtained from monthly staff gage readings and, when staff-gage data were not available, from stage-discharge relationships and continuous record of outlet discharge. A continuous water-level record (1-hour recording interval) was collected at the acidic lake throughout the study (U.S. Geological Survey, 1980-81). Changes in lake volume (ΔSW) were calculated by multiplying changes in lake stage by lake area. Surface area of both lakes was assumed to remain constant throughout the range of observed lake stages.

Changes in Watershed Storage.--The watershed-storage (ΔWS) term in the water-budget analysis is a combination of water stored as surface water in topographic depressions, as soil moisture, and as ground water. Each of these terms is discussed below. Storage is calculated as a residual of the monthly water budget--the difference between precipitation and the sum of runoff, evapotranspiration, lake storage, and snowpack storage.

Surface storage. Quantitative differentiation between surface-storage components was not possible. Water was seen in surface depressions after storms and in the spring, particularly along the flank of Panther Mountain in the neutral-lake basin and throughout the acidic-lake basin, but the amount of this storage could not be measured directly.

Soil moisture. Soil-moisture tension was measured by porous-cup tensiometers at three depths at each of three sites in the acidic-lake basin and at four sites in the neutral-lake basin. Readings were taken about three times a week at one site in each basin from September 1980 through September 1981 (Peters and others, 1986) and monthly at the other sites. (Locations are shown in fig. 2). The gage readings were calibrated to the actual soil-moisture content gravimetrically, but the heterogeneity of the surficial materials prevented precise calibration. The tensiometer data, therefore, were used only for observing general trends.

Ground water. Ground-water levels were measured monthly at 24 observation wells in the two watersheds (fig. 2). Monthly and yearly changes in ground-water storage could be only qualitatively assessed because topographic irregularities, anisotropy of the surficial materials, and a lack of wells near the watershed divide made computation of an average ground-water stage or ground-water flow rates impossible. Most wells were installed close to the shore of each lake, where the water table is near land surface, and were used primarily for the collection of ground-water samples for chemical analysis.

Water levels in wells[1] PG10, PG70, and PG71 in the neutral-lake basin and WG10 and WG30 in the acidic-lake basin (fig. 2) were measured by continuous recorders to compare infiltration rates of the two watersheds and to serve as a qualitative check for changes in watershed storage. Ground-water levels were measured monthly with an electric tape in all wells.

The observation wells consisted of 3.2-cm polyvinyl chloride (PVC) or galvanized pipe with screened well points. Wells were either hand dug or augered, and the annular space was repacked with the original material. Several wells were also sealed with bentonite. A summary of well characteristics is presented in Peters and others (1986).

Comparison of Basin Water Budgets

Comparison of the annual water budgets indicates similar precipitation, lake outflow, and evapotranspiration in both lake basins (table 2). Approximately 60 percent of annual precipitation was transported from each system as basin outflow, and the remaining 40 percent was returned to the atmosphere through evapotranspiration. The temporal distribution and intensity of precipitation in 1980 differed from that in 1981. The maxima and standard deviations of daily precipitation were larger at both basins in 1981 than in 1980. Therefore, the 2 years of data provided two different sets of hydrologic conditions through which the basins can be compared. Annual watershed storage showed some change at both basins, but total change in watershed storage in each basin over the 2-year period was negligible.

The monthly values of all hydrologic components fluctuated in each basin, and the fluctuation patterns within the two basins differed from one another. Monthly changes in watershed storage reflected the amount and intensity of precipitation. Differences in the monthly hydrologic values between basins are attributed to the differences in soil-infiltration rates and storage capacities of each system. A comparison of annual and monthly values of each component of the water budgets for the two basins is given in table 2 (p. 20) and discussed below.

Precipitation

Annual Trend.--Annual precipitation (P) at both basins ranged from 116.0 to 124.5 cm during 1980-81, and the amount received by each basin differed by less than 5 percent of total annual precipitation, which is within the

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[1] Well-number prefix P designates Panther Lake (neutral); W designates Woods Lake (acidic).

accuracy suggested for weighing-bucket rain gages such as those used at the meteorological stations (Winter, 1980). Annual precipitation at nearby National Weather Service stations was within 8 percent of precipitation recorded in both lake basins in 1980 and within 2 percent in 1981, which indicates similar precipitation throughout the region during the study period. Annual precipitation at the neutral-lake basin was approximately 6 cm less than at the acidic-lake basin. Greater volume and intensity of rainfall occurred in both basins during 1981 than during 1980.

Monthly Trend.--Precipitation was not a significant factor in the observed hydrologic differences between the two basins. Precipitation for a given month differed only slightly between basins (table 2). The standard error of estimate for monthly precipitation at the neutral-lake basin, derived from that at the acidic-lake basin, was 9 percent in a least-squares regression of 1980-81 data. The variance in monthly precipitation at the neutral lake explained by this relationship was 89 percent, and the slope of the regression line was 0.95. During the fall of both years, monthly precipitation was less at the neutral-lake basin than at the acidic-lake basin, but during the remainder of both years, precipitation differences seem to be random (table 2). At both basins, greatest seasonal precipitation occurred in the spring and fall (fig. 6).

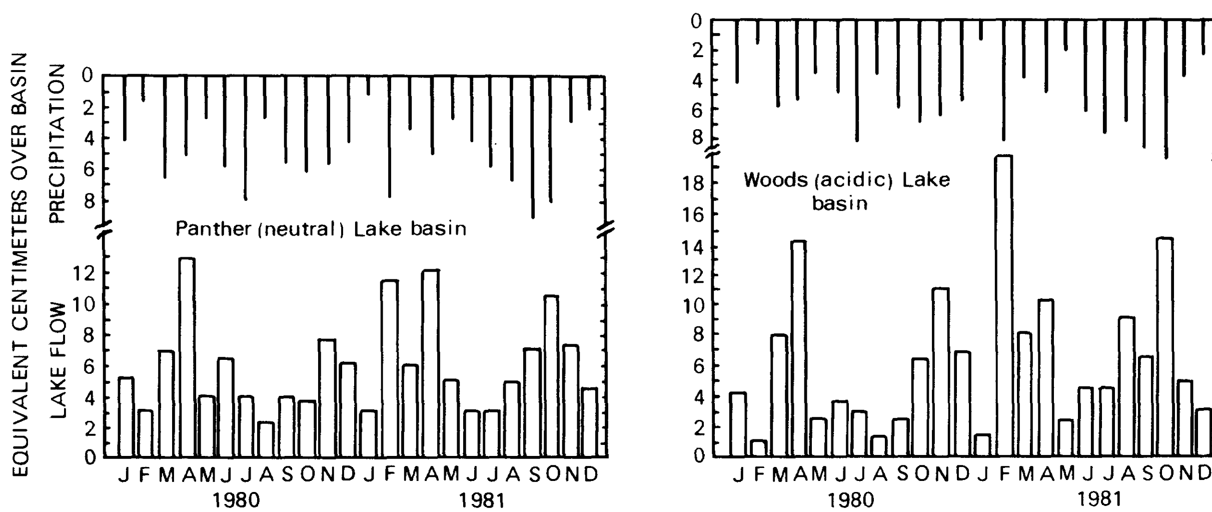

Figure 6.--Monthly lake outflow and precipitation, 1980-81.

Changes in Snow Storage

Total snow accumulation in both years was slightly less in the neutral-lake basin than in the acidic-lake basin. Because the study period was from January 1980 to December 1981, water that accumulated in the snowpack affected the annual water budgets at both basins. When the study began in January 1980, no snow was on the ground, and similarly, snow that accumulated during the following December did not contribute to runoff or ground-water recharge in 1980, but rather in 1981, when it melted. As a result, the effective water input for 1980 was 7.6 cm less than the precipitation recorded at both basins,

Table 2.--Results of the monthly and yearly water balance for neutral- and acid-lake basins.

[Values are in centimeters of water. P is precipitation; SN is snowpack; R is runoff; ET is evapotranspiration; SW is lake storage; and WS is watershed storage.]

A. Neutral-lake basin.

	P	ΔSN	R	ET	ΔSW	ΔWS
1980						
January	8.25	+3.56	5.21	0.00	0.00	-0.51
February	3.07	+3.05	3.07	0.00	-0.23	-2.82
March	12.85	-2.29	6.86	0.00	+0.96	+7.31
April	10.18	-4.32	12.83	3.28	-0.89	-0.71
May	5.66	--	4.01	6.37	-0.66	-4.06
June	11.68	--	6.43	7.67	+0.23	-2.64
July	15.57	--	3.96	10.24	+0.23	+1.14
August	5.43	--	2.34	8.89	-0.79	-5.00
September	11.18	--	3.96	4.95	+0.13	2.14
October	12.45	--	3.73	2.34	+1.24	+5.13
November	11.33	--	7.64	0.00	-0.15	+3.83
December	8.38	+7.62	6.25	0.00	-0.66	-4.83
1980 yearly total	116.05	+7.62	66.29	43.74	-0.58	-1.02
1981						
January	2.41	+1.98	3.03	0.00	-0.71	-1.89
February	15.39	-6.10	11.35	0.00	+2.08	+8.05
March	7.16	-2.54	5.99	0.00	+0.61	+3.10
April	9.91	-0.96	12.04	3.33	-1.60	-2.90
May	5.23	--	5.03	6.30	-0.71	-5.39
June	8.53	--	3.05	8.69	-0.00	-3.21
July	11.86	--	2.97	10.39	+0.08	-1.58
August	13.44	--	4.88	7.95	+0.08	+0.53
September	18.11	--	7.03	4.52	+0.84	+5.72
October	16.00	--	10.34	2.31	+0.79	+2.56
November	5.71	--	7.19	0.00	-1.02	-0.46
December	4.16	+4.16	4.44	0.00	-0.05	-4.39
1981 yearly total	117.93	-3.45	77.34	43.48	+0.38	+0.14
Total for study	233.98	+4.16	143.64	87.23	-0.08	-0.88
Percentage of precipitation		1.8	61.5	38.0	negligible	-1.5

Table 2.--Results of the monthly and yearly water balance for neutral- and acid-lake basins (continued).

[Values are in centimeters of water. P is precipitation; SN is snowpack; R is runoff; ET is evapotranspiration; SW is lake storage; and WS is watershed storage.]

B. Acidic-lake basin.

	P	ΔSN	R	ET	ΔSW	ΔWS
1980						
January	8.13	+3.81	4.16	0.00	-0.23	+0.38
February	3.30	+2.72	0.99	0.00	-0.41	+0.00
March	11.45	-3.12	7.87	0.00	+1.12	+5.59
April	10.72	-3.40	13.87	3.58	-0.48	-2.84
May	7.06	--	2.44	6.78	+0.23	-2.39
June	9.55	--	3.55	8.48	-0.58	-1.90
July	16.03	--	2.97	10.77	+0.41	+1.88
August	6.96	--	1.29	9.55	+0.20	-4.09
September	11.30	--	2.34	5.54	+0.20	+3.22
October	13.11	--	6.43	2.11	+0.10	+4.47
November	12.85	--	10.84	0.00	+0.08	+1.93
December	10.49	+7.97	6.88	0.00	-0.20	-4.16
1980 yearly total	120.95	+7.97	63.65	46.81	+0.43	+2.08
1981						
January	2.59	+2.59	1.42	0.00	-0.02	-1.40
February	15.72	-7.24	19.15	0.00	+0.13	+3.68
March	7.52	-2.54	8.03	0.00	+1.29	+0.74
April	8.58	-0.79	10.08	3.43	-1.29	-2.85
May	3.96	--	2.34	6.15	+0.02	-4.55
June	11.76	--	4.52	10.16	-0.33	-2.59
July	14.43	--	4.52	9.60	-0.02	+0.33
August	13.00	--	9.07	7.39	-1.32	-2.13
September	16.69	--	6.63	4.98	+1.22	+3.86
October	18.16	--	13.99	2.51	+0.08	+1.57
November	7.44	--	4.98	0.00	-0.20	+2.67
December	4.62	+4.62	3.02	0.00	-0.18	-2.84
1981 yearly total	124.48	-3.35	87.76	44.22	-0.63	-3.51
Total for study	245.44	+4.62	151.41	91.03	-0.20	-1.42
Percentage of precipitation		1.9	61.7	37.0	negligible	-0.6

and the effective water input for 1981 was increased by the same amount. Snow that accumulated at the end of 1981 was subtracted from the total recorded precipitation over the 2-year study. Therefore, the amount of snow accumulated at the end of 1981, which was 4.2 cm at the neutral-lake basin and 4.6 cm at the acidic-lake basin, did not contribute to runoff and recharge during the study. In both basins, the snowpack from December 1980 increased the movement of water through the hydrologic system in 1981.

In both basins, snow melted during March and early April of 1980 and during February and late March 1981. The maximum accumulation of snowpack for 1980 was 11.4 cm of water in the neutral-lake basin and 12.1 cm in the acidic-lake basin. Both maxima occured just before the snowmelt in late March. The maximum accumulation of snowpack for 1981 was 14.8 cm of water at the neutral-lake basin and 15.8 cm at the acidic-lake basin. In both years, lake ice began to break up in early April. Soils became saturated during the early thaw of February 1981 and were probably still saturated at the time of the second snowmelt in late March 1981. This, coupled with greater snow accumulations and heavier spring rains in 1981 than 1980, caused significantly greater spring runoff in 1981 than in 1980 at both basins.

Changes in Lake Storage

Annual Trends.--The annual change in lake storage (ΔSW) at both basins equaled less than 0.5 percent of the total precipitation (P) and is therefore considered to be a negligible component of the annual water budgets. Stage of the neutral lake was lower at the end of 1980 than at the beginning but had returned to the original level by the end of 1981. Stage of the acidic lake was higher at the end of 1980 than at the beginning but had dropped to its original level by the end of 1981.

Monthly Trends.--Monthly increase in lake storage of the neutral lake never exceeded 10 percent of the monthly precipitation, and that of the acidic lake never exceeded 12 percent. Monthly changes in lake storage were therefore small, and differences in storage between the lakes resulted mostly from the beaver dam at the outlet of the acidic lake. Beaver dams raised the stage of the acidic lake during both summers of the study, and periodic removal of the dams caused anomalous changes in lake stage and discharge. Stage at the neutral lake was not recorded during some months[1]. The stage values for those months were calculated from a linear regression of lake stage against basin runoff (table 2). The R^2 value for the relationship equation was 0.79.

In the computation of changes in lake storage, lake area was assumed to be constant. This assumption is suitable for the neutral-lake basin because topographic gradients next to the lake are steep, but for the acidic basin it probably introduces some error, possibly as large as 15 percent, because the terrain next to the lake contains low gradients and several swamps. Yet, even if the change in the lake storage (ΔSW) error is as great as 15 percent, its effect on the magnitude of other components in the water budget remains small (table 2).

[1] December 1980 and January, February, March, and September 1981.

Lake Outflow

Annual Trends.--In both years of the study, annual outflow from the neutral-lake basin was similar to that from the acidic-lake basin; average values were 61.5 and 61.3 percent of total precipitation, respectively. In 1980, total outflow from the neutral-lake basin was 2.5 cm greater than that from the acidic-lake basin, but in 1981, outflow from the acidic-lake basin was 10.4 cm greater than that from the neutral-lake basin (table 2). Because the two basins are of different sizes, the outflow hydrographs were calculated in $(m^3/s)/km^2$ to facilitate basin comparisons.

Monthly Trends.--In both basins the maximum, mean, and standard deviations of daily outflow, averaged by month, were larger in 1981 than in 1980. Monthly outflows from each basin are summarized in table 3; hydrographs of daily outflow are given in figure 7. Months with high outflow from both basins coincide with periods of high precipitation during the fall and with snowmelt during the spring (fig. 6), and months with low outflow coincide with high evapotranspiration during summer and with precipitation storage in the snowpack during winter.

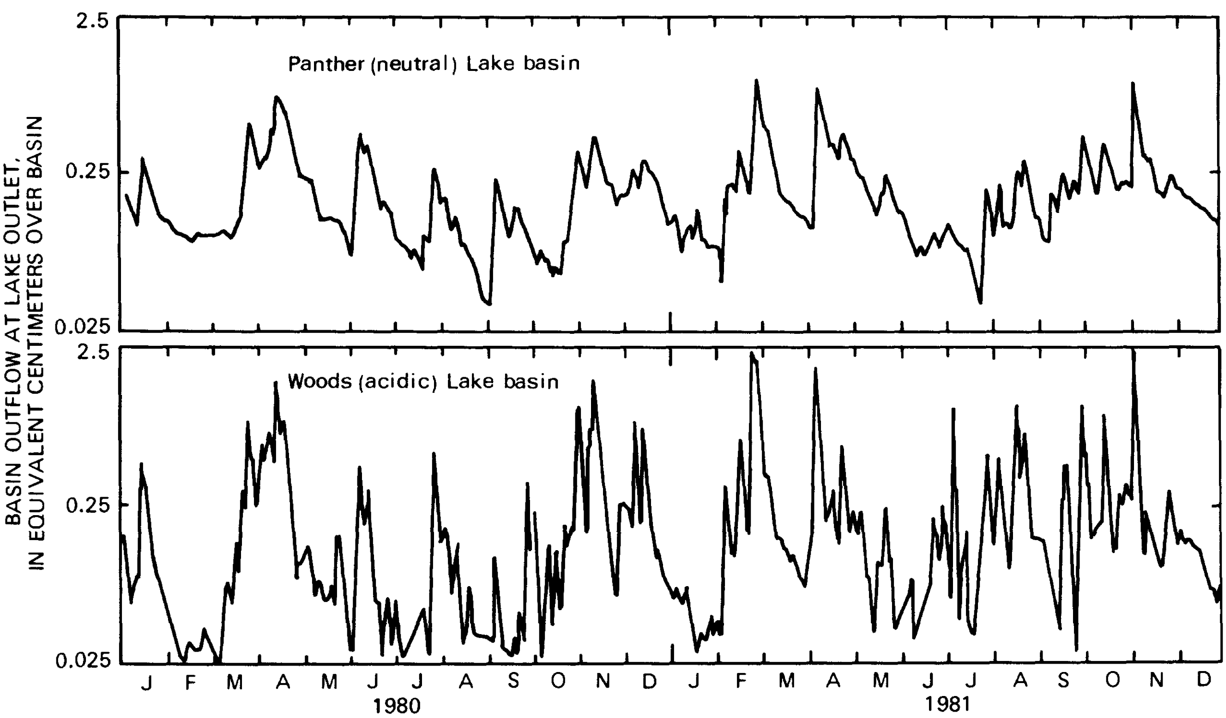

Figure 7.--Hydrographs of daily basin outflow, 1980-81.

Hydrograph Characteristics.--The hydrograph characteristics examined in this study were daily outflow, base flow, response to precipitation, and flow duration, as discussed in the following paragraphs.

Daily outflow. Daily outflows at the two basin outlets were most similar during periods of high flow, when the soils were saturated, but differed substantially during flow recessions (fig. 7). Recession curves for the two basins are similar after the highest flows, but during normal or low-flow conditions, the curves for the neutral-lake basin are generally less steep than those for the acidic-lake basin. Most individual peaks of daily outflow from the acidic lake were much greater than those from the neutral lake, but outflows during low-flow periods were several times greater at the neutral lake. Daily records from the neutral-lake outlet therefore show a more sustained, less "flashy" flow here than at the acidic lake.

Differences in outflow "flashiness" can be caused by the combined effects of three factors--the ratio of lake-surface area to basin area, outlet configuration, and the contribution of ground water.

The neutral lake is slightly larger than the acidic lake in relation to its basin area, but the difference is small and is thus probably not a major cause of differences in the outlet hydrographs. Some of the differences in the slope of the two recession curves can be attributed to differences in outlet-channel configuration. The water-stage monitoring station in the neutral-lake basin is approximately 300 m downstream from the lake control,

Table 3.--Outflow from the neutral-lake and the acidic-lake outlets, by month and year.

[Values are in centimeters per day.]

Period	Neutral-lake basin Maximum	Minimum	Standard deviation	Mean	Acidic-lake basin Maximum	Minimum	Standard deviation	Mean
1980	0.800	0.035	0.074	0.180	1.65	0.002	0.162	0.175
1981	.996	.038	.086	.211	2.36	.002	.244	.239
1980								
Jan	0.330	0.117	0.053	0.168	0.48	0.048	0.109	0.135
Feb	.117	.091	.005	.102	.046	.025	.005	.033
Mar	.526	.096	.135	.221	.81	.025	.229	.254
Apr	.800	.234	.173	.427	1.65	.081	.389	.462
May	.213	.076	.033	.129	.165	.010	.035	.079
June	.429	.091	.107	.213	.424	.023	.109	.119
July	.272	.058	.063	.127	.508	.002	.124	.096
Aug	.137	.035	.028	.076	.152	.002	.043	.043
Sept	.234	.063	.041	.127	.320	.005	.079	.076
Oct	.350	.053	.091	.124	1.09	.010	.277	.213
Nov	.429	.160	.079	.246	1.54	.068	.340	.350
Dec	.312	.122	.058	.208	.851	.063	.216	.231
1981								
Jan	0.155	0.081	0.018	0.102	0.079	0.030	0.015	0.048
Feb	.996	.051	.256	.366	2.36	.035	.584	.617
Mar	.625	.114	.114	.201	1.89	.074	.439	.267
Apr	.858	.234	.147	.389	1.54	.142	.279	.325
May	.254	.114	.035	.168	.249	.005	.061	.079
June	.124	.076	.013	.099	1.03	.002	.213	.147
July	.213	.038	.046	.099	.508	.002	.145	.150
Aug	.312	.099	.058	.157	1.03	.096	.236	.292
Sept	.449	.099	.079	.234	1.09	.005	.254	.221
Oct	.935	.188	.206	.333	2.24	.129	.480	.439
Nov	.409	.183	.061	.239	.307	.104	.053	.165
Dec	.183	.122	.015	.147	.152	.058	.030	.102

whereas that in the acidic-lake basin is only about 15 m below the control. The flow capacity of the neutral lake's outlet channel, or possibly of a culvert beneath the access road (fig. 2), is probably diminishing peak flow slightly at the monitoring flume, but at a discharge of 0.03 m^3/s, the water in the outlet channel between the lake control and the monitoring station can be drained in less than 4 hours. In an experiment at the neutral lake in which outlet flow was temporarily dammed above the access-road culvert, drainage upon removal of the dam was too rapid to suggest any influence of the culvert on the outlet hydrograph. Thus, the effects of channel configuration alone are probably insufficient to cause error in the daily mean-flow values.

Perhaps more important may be differences in the configuration of the control, which directly affects lake storage in each basin. The control at the acidic lake is an 8-ft-wide weir with a sharp drop downstream; the control at the neutral lake is a wide cobble channel. The effects of lake-outlet control could be assessed by computing a "lake inflow" hydrograph--the daily sum of outflow plus change in lake storage, but a lack of continuous lake-stage data at the neutral lake makes this impossible. During October 6-8, 1984, lake stage was recorded during a rising discharge at the neutral-lake basin, and the ratio of change in lake volume to lake inflow was calculated for both the neutral- and acidic-lake basins for that period. Lake stage increased 0.061 m at the neutral lake and 0.085 m at the acidic lake, which accounted for 48 percent of lake inflow at the former and 40 percent of lake inflow at the latter. These values suggest a slightly greater lake-outlet control of discharge in the neutral lake for that storm, but this cannot account for the large differences in "flashiness" between the two systems. Thus, the hydrographs may be interpreted to suggest a larger ground-water storage and greater base-flow contribution to outflow in the neutral-lake basin than in the acidic-lake basin.

Base flow.--Established methods for graphical separation of base flow from total basin outflow could not be applied to either basin because rain was too frequent to allow an interpretable base-flow recession to develop. However, base-flow recessions did develop during the two winters when precipitation was stored within the snowpack and did not enter the ground-water system. Qualitative comparisons between the two basins can therefore be made for the winter periods.

Base-flow recessions during winter were longer than in summer. The curves in figure 8 represent the typical recession patterns of the two basins during winter snowcover. The flatter slope of the neutral-lake curve again suggests a larger ground-water-storage capacity and a more sustained release of the ground water than in the acidic-lake basin.

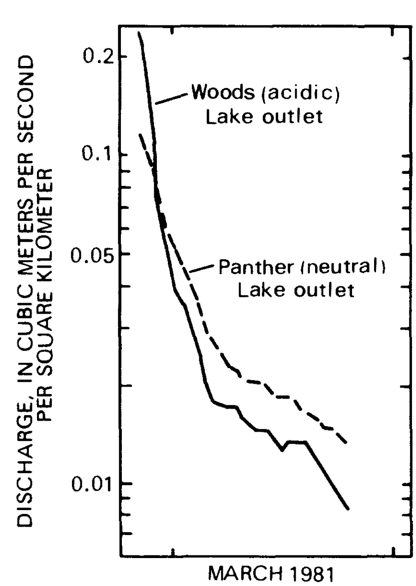

Figure 8.--Lake-outflow recession, winter 1980-81.

Response to precipitation. The two basins respond differently to precipitation volume and intensity. To compare this response, the monthly maximum, minimum, and mean of daily outflow were plotted (fig. 9), and standard deviations calculated (table 3). Increases in precipitation intensity were found to cause smaller monthly increases in outflow from the neutral lake than from the acidic lake. Both lakes had similar mean daily outflows when averaged for 1980, but for 1981 the mean annual daily outflow from the acidic lake was 14 percent greater than that from the neutral lake. Also, mean daily outflow from the neutral lake during months of high flow was generally lower than that from the acidic lake (table 3). Mean daily outflow from the neutral lake exceeded that from the acidic lake during a given month only if the outflow was receding from a high in the previous month. Minimum daily outflow from the neutral lake was higher than from the acidic lake for all months (fig. 9). Together these observations indicate a more sustained flow and hence larger base-flow component within the neutral-lake basin. The maximum daily outflow and the standard deviation of flow (table 3) from the neutral lake are smaller than those from the acidic lake, which further suggests a more sustained outflow from the neutral-lake basin.

The increase in annual precipitation volume and intensity from 1980 to 1981 produced a greater increase in annual outflow from the acidic lake than from the neutral lake. Similarly, maximum daily outflow from the acidic lake increased from twice the neutral-lake outflow in 1980 to 2.5 times the neutral-lake outflow in 1981 (table 3). The standard deviations of the outflow from both lakes show a similar increase from 1980 to 1981. In

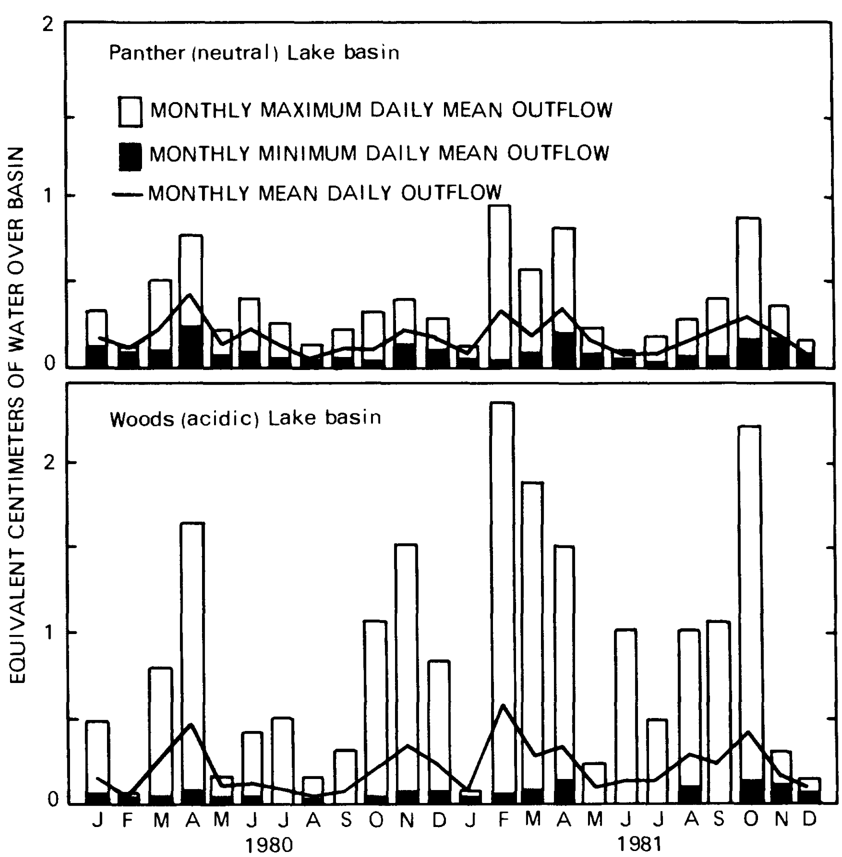

Figure 9.

Monthly maximum, minimum, and mean daily lake outflows, 1980-81.

summary, the hydrographs for the two basin outlets show a more sustained, less "flashy" outflow from the neutral lake than from the acidic lake, which again indicates a greater base-flow contribution within the neutral-lake basin.

Flow Duration.--Flow-duration curves depict the temporal variation in streamflow by indicating the percentage of time a specific daily flow was equaled or exceeded over a given period. A curve with a steep slope represents a system in which flow is highly variable and consists mainly of surface runoff; a curve with a flattened slope indicates a sustained flow, which is indicative of appreciable discharge from ground-water storage (Searcy, 1963).

Flow-duration curves can be used to compare two lake-outlet streams if lake storage and lake outlet controls are similar. As discussed previously, the differences in lake storage and lake-outlet configurations here are minor and do not appear to significantly affect discharge. Two sets of flow-duration curves were developed from outflow records--one for a 5-year period (1977-81), and one for the 2 years of the study (1980-81). The 5-year curves were used to compare variations in average flow and groundwater contribution; the 2-year curves were used to calculate the effect of precipitation on ground-water contribution.

The 5-year flow-duration curve for the neutral lake (fig. 10) has a shallow slope throughout the duration intervals, and the flat lower end of the curve indicates substantial ground-water contribution. In contrast, the steep curve for the acidic lake suggests that most of the flow was derived from surface runoff. Outflow from the neutral lake exceeded that from the acidic lake at all but the highest flows (those of less than 15-percent duration), especially those exceeding 90-percent duration. Also, outflow from the neutral lake decreased much more slowly during periods of low flow (flows exceeding 50-percent duration) than outflow from the acidic lake. Thus, the differences in shape and slope of these curves suggest that ground-water contribution and storage in the neutral-lake basin were greater than those in the acidic-lake basin.

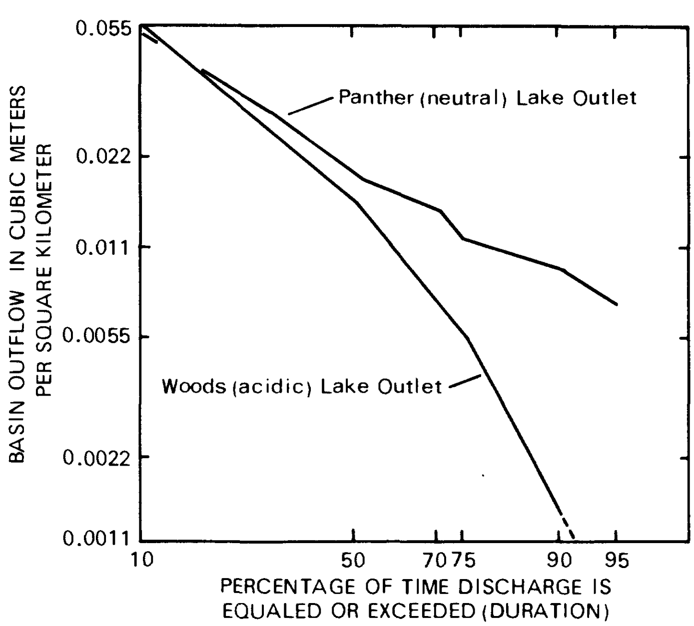

Figure 10.

Five-year duration curves of daily outflow, 1977-81.

The annual differences in outflow from the two basins are reflected in the 2-year flow-duration curves (fig. 11). Precipitation was of greater volume and intensity in 1981 than in 1980; thus, outflow from both basins was higher in 1981 than in 1980. Yet, the two duration curves for the neutral-lake outlet have practically the same slope for both years. The slight decrease in outflow in 1981 at the 70- to 90-percent duration interval is balanced by a slight increase in the 25- to 50-percent interval, but for the duration intervals greater than 90 percent and less than 25 percent, the two curves are identical. In the acidic-lake basin, daily outflow from the acidic lake at very low flows (90- to 95-percent duration) remained the same from 1980 to 1981, but runoff at all higher flows (below 90-percent duration) was greater in 1981. Thus, the 1-year curves for both basins indicate that daily outflow from the neutral lake was less affected by annual fluctuations in amount and intensity of precipitation than daily outflow from the acidic lake.

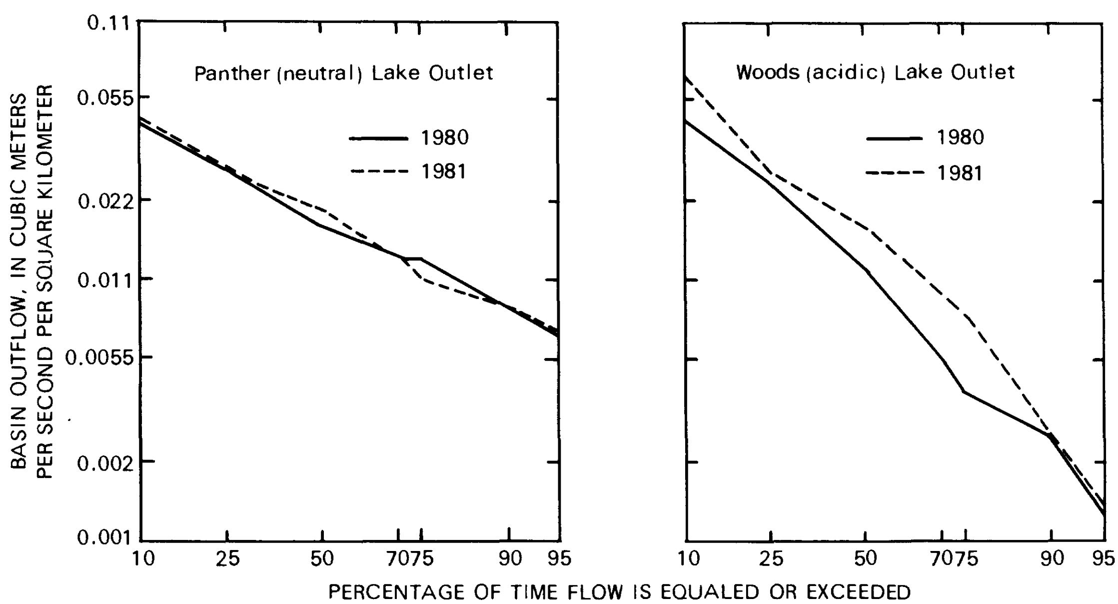

Figure 11.--Flow-duration curves of daily outflow, 1980 and 1981.

Ground-Water Flow Systems

Both basins contain two ground-water flow systems--a shallow system within or over the thin till that forms a discontinuous veneer over an irregular bedrock surface; and a deeper flow system within the thick till (fig. 3). Water movement in the shallow flow system during storms was observed to be a combination of shallow seepage, macropore flow through burrows and root holes, overland flow when the soil column became saturated, and sheet flow over the interspersed bedrock outcrops. Flow in the deeper system includes percolation to a water table and lateral flow toward the lake and its tributaries. Flow in the deeper system is less variable than flow in the shallow system and continues well into periods of dry weather. Flow in bedrock could not be assessed but was considered to be negligible.

The field observations of water movement suggest a difference between flow patterns of the two basins, and this difference appears to be related to the percentage of the basin containing thick till and the distribution of bedrock barriers that restrict downslope drainage. Hydrographs of wells tapping the thick till indicate a rapid water-table response to precipitation.

Ground water in the acidic-lake basin flows primarily through a shallow system because the till is thin, although some deep flow may occur in the one area of thick till along the northwest shore. Along the southeast shore, longitudinal bedrock ridges restrict downslope drainage and cause ponding in the swales behind the ridges; subsequent lateral drainage occurs around each ridge and to the lake. During dry periods, this drainage is downward through the organic material that has accumulated in the swales. During wet periods, when the soil column becomes saturated in the swales, drainage channels expand headward and then laterally into the swale. In the south end of the basin, similar bedrock ridges channel the flow of ground water toward the lake. During wet periods, surface flow is common in the swales of that area. In the area of thick till along the northeast shore, ground-water flow is toward the lake's main tributary (fig. 2B). Springs are common along the lower slope of the thick-till area, in a line parallel to the lakeshore. Some ground water also seeps directly into the lake through the littoral zone.

Ground water in the neutral-lake basin seems to move from the shallow system to the deep system and from there to the littoral zone of the lake. Precipitation on the upper slopes of Panther Mountain results in sheet flow that either infiltrates the thick till at the base of the mountain or flows overland to the lake or to tributary channels. During major storms, water also flows through root holes and burrows at the base of the mountain. Except on the mountain, surface runoff was observed only during spring snowmelt and short periods immediately after storms, which indicates that most of the precipitation infiltrates the soil. A small spring at the south end of the watershed flows continuously throughout the year and has only minor fluctuations in discharge, even during wet periods; all other tributaries are dry during most of the summer. The infiltration capacity of the soils in most of the neutral-lake basin is seldom exceeded.

Estimates of Base Flow from Outflow Recession.--A comparison of ground-water storage capacity and yield of the two basins can be made through a method of base-flow-recession analysis introduced by Knisel (1963). The method is based on the empirical expression of Barnes (1939):

$$q_t = q_o K^t \tag{2}$$

where: q_o = initial discharge rate,
q_t = discharge rate at time, t, and
Kt = a recession constant.

The recession constant (K) is determined from a plot of q_t against q_o. This method, first used by Langbein (1938) to delineate the transition from surface runoff to base flow in individual stream-hydrograph recessions, consists of a plot of mean daily discharge on one day against that on the following day. As the recession progresses, the data points approach the common recession line that intercepts the origin. The slope of a line drawn through the data points is the base-flow rate for that recession. The Langbein (1938) approach requires that recessions continue over several days--a condition seldom observed in the two study basins because of frequent precipitation. Knisel (1963) expanded this method for use in humid regions by plotting a series of recessions over a given period on the same graph. The slope of the line drawn through the origin and the end points of each recession line is an average base-flow rate for that period. The maximum daily rate of base flow, in (m3/s)/km2, is the largest q_o that falls on the constant line. The computed recession constant is independent of basin area.

An estimate of ground-water storage capacity was also derived by Knisel (1963) by integrating equation 2 with respect to time and yield:

$$S = - Q_o / 2.3026 \log K \qquad (3)$$

where: S = storage, in day-second-meters,
Q_o = discharge, in m^3/s, and
K = recession rate constant.

Units of storage were converted to equivalent centimeters of water over the basin so that the results could be compared between basins. Maximum storage for each basin was calculated from a maximum K and the maximum daily base flow (Q_o) in equation 3.

Application of the Knisel (1963) method to the two lake-outlet hydrographs indicates that base flow at the neutral-lake outlet receded more gradually and that maximum base flow was greater than at the acidic-lake outlet (fig. 12 and table 4). The recession constant (K) for outflow from the neutral-lake basin was closer to unity than that for the acidic lake, which indicates a more uniform day-to-day outflow from the neutral lake (fig. 12). Among the recessions analyzed, maximum base flow per unit area was 2.2 times greater in the neutral-lake basin than in the acidic-lake basin (table 4).

The neutral-lake recession plots (fig. 12) adhere closely to the recession-constant (K) line except at highest flows, which indicates a predominance of ground-water contribution over surface runoff from the basin (Knisel, 1963). In contrast, the acidic-lake recession plots show a deviation

Table 4.--Recession rate constants, maximum base flow, and maximum ground-water storage capacity of the basins studied, derived from 1980-81 runoff-recession curves.

	Average K value	Maximum base runoff, Q_t [(m3/s)/km2]	Maximum ground-water storage (cm)
Panther Lake (neutral)	0.952	3.9×10^{-2}	6.86
Woods Lake (acidic)	0.915	1.8×10^{-2}	1.75

from the "K" line over a large part of most of the curves, and the deviation increases significantly at high flows. Peak discharge from the acidic lake at the beginning of each recession was often significantly higher (fig. 12), which further indicates greater surface runoff here than at the neutral lake.

Solutions of equation 3 indicate that ground-water-storage capacity at the neutral-lake basin is 3.9 times greater per unit area than that at the acidic-lake basin. The calculated storage capacity is that necessary to produce the maximum base flow measured for each basin outflow by the Kneisel method. Thus, the analysis of outflow-recession curves indicate a large difference in ground-water flow and storage capacity between basins.

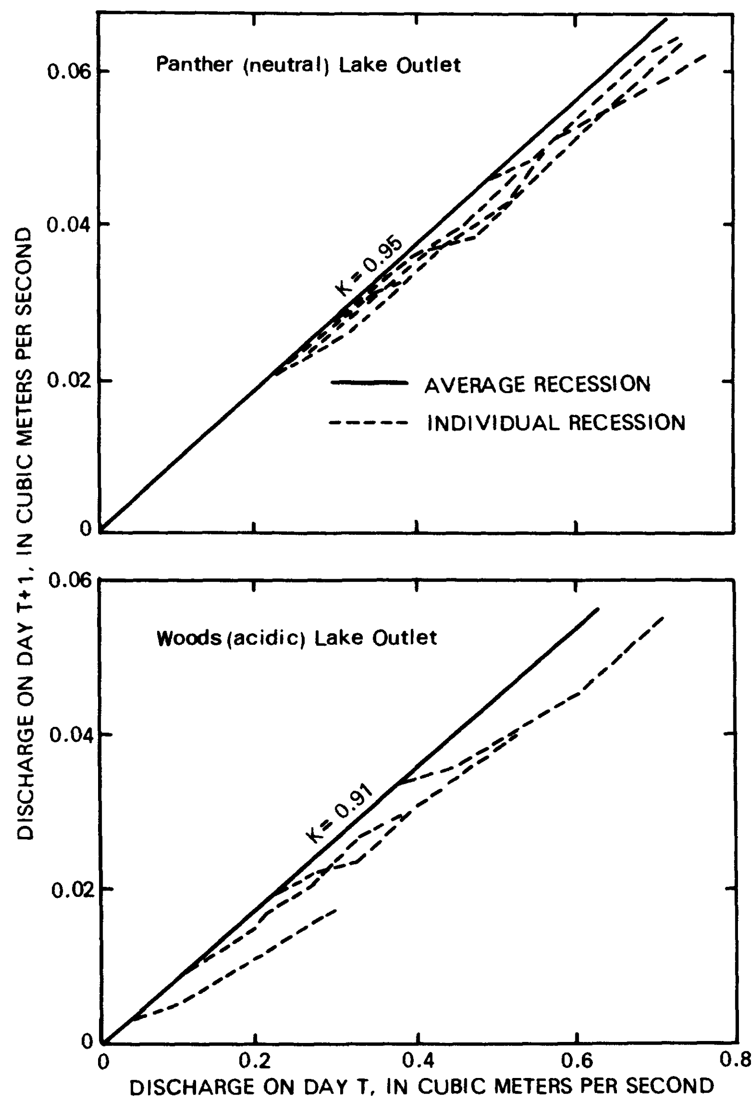

Figure 12.--Recession-rate curves for basin outflow. (Dashed lines represent high-flow part of the recession.)

Evapotranspiration

Estimation of evapotranspiration (ET) is difficult because all methods of estimation contain inherent sources of errors. A simplified equation and three empirical equations were used and the results compared.

Simplified Equation.--The simplest approach assumes a negligible annual change in basin storage, and the annual water balance equation becomes:

$$\text{Evapotranspiration} = \text{Precipitation} - \text{Basin outflow} \qquad (4)$$

The assumption of a negligible change in annual storage is supported by ground-water level and discharge records for each basin; well hydrographs for both watersheds (fig. 13) show only minor annual differences between 1980 and 1981. Outflows from the two basins were also similar, which suggests either that both basins store the same percentage of annual precipitation or that seepage losses, if present, are at least comparable.

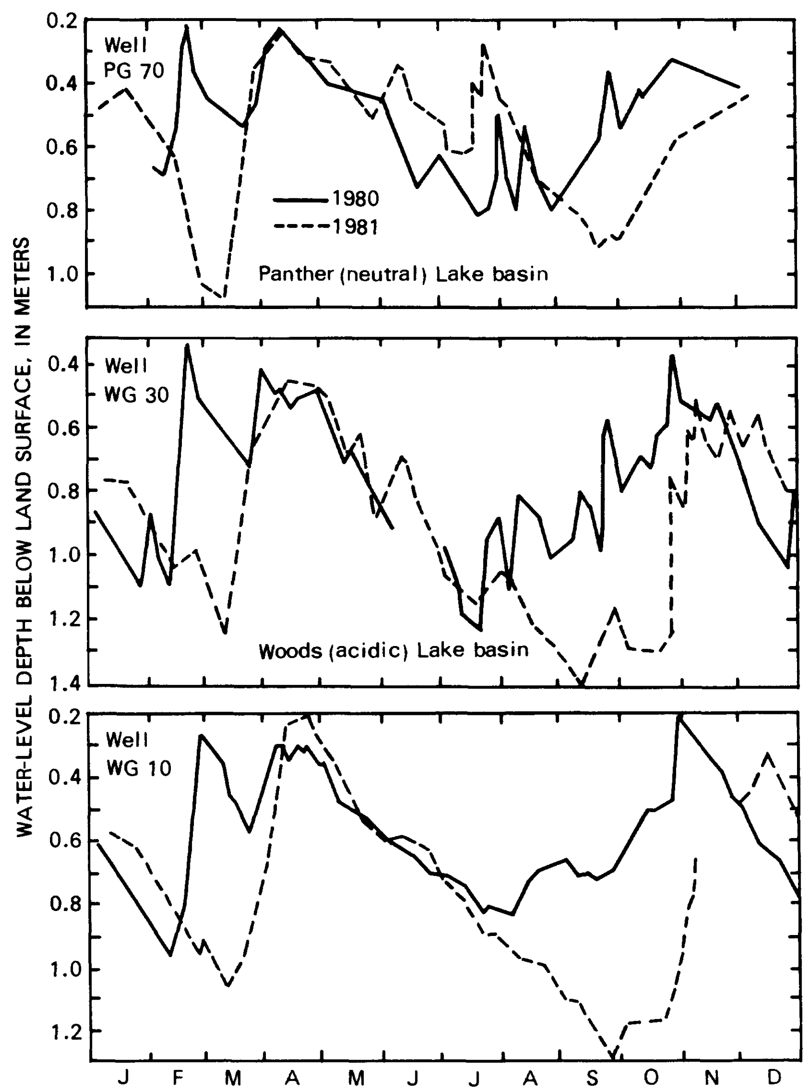

Figure 13.--Hydrographs of daily ground-water levels, 1980-81. (Well locations are shown in figure 2.)

One reason that ET rates at the two basins are similar is that the controlling conditions, that is, the weather patterns, latitude, and local physiographic characteristics--are similar. Furthermore, both watersheds are 100 percent forested and contain mostly hardwood vegetation, and basin relief and lake-surface altitudes are similar. From April through October, average daily air temperature at the neutral-lake basin was less than 3°C higher than at the acidic-lake basin, which is less than the potential error in temperature measurements between the basins.

The annual ET value obtained by subtracting annual outflow from precipitation (eq. 4) can be evaluated further through comparison with the sum of monthly ET values calculated by methods described below. Because these controlling conditions are similar at both basins, ET is probably not a cause of the aformentioned differences in outflows. Therefore, errors resulting from the following ET estimation methods will not be critical in the general basin comparisons, especially if the same method is used for each basin.

Empirical Equations.--Monthly evapotranspiration (ET) was estimated from three empirical equations, as follows:

$$ET = 0.014\ D2\ P_{tN} \text{ (Hamon, 1961)} \qquad (5)$$

where: D = hours of daylight,
P_t = saturation vapor density, in g/cm3, and
N = number of days in the month.

$$ET = (0.025T + 0.08)R_s \text{ (Jensen and Haise, 1963)} \qquad (6)$$

where: T = mean air temperature, in °C, and
R_s = incoming solar radiation, in cm/mo, either measured or calculated (6a) from:

$$R_s = (0.61S + 0.35)R_{so} \qquad (6a)$$

where: S = percentage of possible sunshine received, and
R_{so} = potential solar radiation at 45°N lat. in cm/mo.

$$ET = 0.7P \text{ (Schulz, 1976).} \qquad (7)$$

where: P = pan evaporation, in cm/mo.

These formulas were selected because the required data were available and because they have yielded favorable results in previous studies (Schulz, 1976). Also, comparison of results would test the use of regional data in developing ET estimates for the Adirondack region. Direct measurement of related variables such as wind speed and solar radiation at the sites was attempted, but equipment failure prevented continuous record. Local data on air temperature for equation 6a and the calculations of vapor density for equation 5 were available, however. (A. H. Johannes, Rensselaer Polytechnic Institute, written commun., 1982.)

Comparison of Estimates

Yearly ET estimates derived for 1980 and 1981 from the simplified equation (eq. 4) were lower than those computed from regional long-term pan-evaporation data by equation 7 (U.S. Department of Commerce, 1968). Estimates from the simplified equation suggest that ET represents approximately 40 percent of the annual precipitation, whereas the regional, long-term estimate from 13 years of pan-evaporation data indicates an average of 47 percent. The average estimate of yearly ET for 1980-81 calculated from the Hamon method (eq. 5), was 37 percent; the Jensen-Haise methods (eqs. 6a, 6b) gave values of 48.3 and 48 percent, respectively; and the pan-evaporation method (eq. 7) gave a value of 43 percent (fig. 14).

Evapotranspiration measurements in areas of the Northeast similar to the Adirondacks support the 40-percent estimate calculated from the simple equation (eq. 4). For example, estimates of annual evapotranspiration from the Hubbard Brook Experimental Forest in New Hampshire and the Sleeper's Rivers Watershed in Vermont, both similar in latitude and altitude to the Panther Lake-Woods Lake area, ranged between 34 and 40 percent of annual precipitation (Borman and Likens, 1979; Dingman, 1981). Estimates derived from runoff and precipitation maps of New York also yielded a value of 40 percent (Knox and Nordenson, 1955). A computation based on a graphic method developed by Langbein (1949), which relates evapotranspiration to mean annual temperature, runoff, and precipitation, also yielded 40 percent.

The closest weather stations producing the data needed for the empirical methods, except equation 5, are outside the physiographic environment of the Adirondacks and thus do not accurately estimate evapotranspiration in the mountainous terrain. Evapotranspiration estimates calculated from the Jensen-Haise methods (6a, 6b), the pan-evaporation method (eq. 7), and from the generalized estimates of the Department of Commerce (1968) were based on data averaged from National Weather Service stations at Canton, Syracuse, Ithaca, and Albany, N.Y., and at Burlington, Vt. All of these sites are in

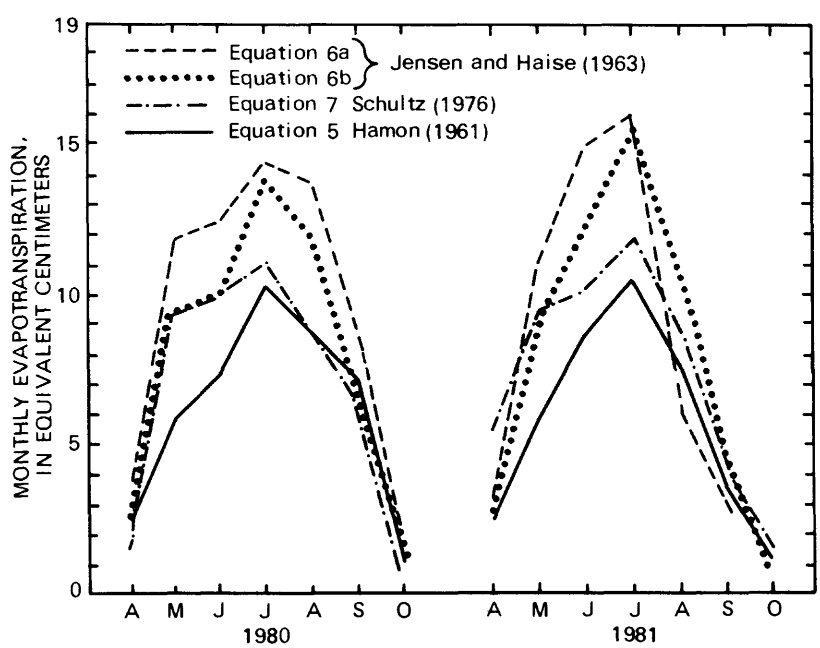

Figure 14.

Monthly evapotranspiration estimates calculated by four empirical methods, April through September 1980 and 1981.

rolling or flat terrain, in contrast to the mountainous Adirondack region. The study area is at higher altitude, has lower temperatures, and has a lower number of freeze-free days than these National Weather Service stations. Also, local storms are common in the Adirondacks, and clouds that develop locally reduce the amount of sunshine received, decreasing evapotranspiration. Mean annual precipitation at these stations is 60 to 80 percent less than in the study area. Air temperatures can drop considerably at night, and condensation (fog and dew) is common even in midsummer. The first incoming solar radiation each morning must heat each system above dew-point temperatures before evapotranspiration can begin. It is not surprising, therefore, that the evapotranspiration estimates obtained by these methods were greater than those calculated from the simplified equation (eq. 4).

Average annual evapotranspiration obtained from the Hamon equation (eq. 5) was comparable to the values derived from the simplified equation (eq. 4) and was the lowest obtained from any of the empirical equations (fig. 14). In a similar study at Coshocton, Ohio, McGuiness and Bordne (1972) found evapotranspiration estimated from the Hamon method (eq. 5) to be 30 to 40 percent lower than that estimated from either of the Jensen-Haise methods (eqs. 6a, 6b) or the pan-evaporation method (eq. 7). Estimates derived from the Hamon method (eq. 5) were based on air-temperature data from meteorologic stations in the study areas, which may partly explain the greater similarity to the value calculated from the simplified annual equation (eq. 4). Slight differences in values for the two basins obtained from the Hamon equation (eq. 5) are attributed to differences in average monthly air temperature. The monthly evapotranspiration values used in analysis of monthly water budgets were those obtained by the Hamon method (eq. 5).

Changes in Watershed Storage

Watershed storage was calculated as a residual of the water-balance equation (eq. 1) and represents ground water, soil moisture, and water in surface depressions within each watershed. The uncertainty of this value is equal to the sum of errors in estimates or measurements of every other component of the water-balance equation; thus, the resulting value has a large potential error.

Sources of Error.--The combined annual error typically applied to the instruments for precipitation and discharge measurements ranges from 10 to 15 percent. The errors in snow-storage estimates could be as much as 25 percent for a given month but were probably much less because snow-survey results in the two basins were comparable to those from other snow surveys in the area. Precipitation at multiple sites within each basin was not significantly different from those at the precipitation stations used in this study, which indicates that the precipitation values used were reasonably accurate. The similarity in percentage of annual precipitation that becomes outflow from each basin suggests that the outflow data are also reliable. Annual evapotranspiration estimates for both basins were based on the difference between annual precipitation and outflow; therefore the errors in each component of the water budget are probably less than standard error usually assigned. Use of the same methods for both basins does not negate the errors in the calculated watershed storage but facilitates comparison of the trends in watershed storage within the basins. These trends are discussed below.

General Trends.--Even though well records suggested only a negligible change in watershed storage over the 2-year study, a net change was indicated in both basins. The values were less than 3 percent of the annual precipitation, however, and were within the error margin of each factor in the budget.

Watershed storage in cold regions generally has two periods of recharge and two periods of depletion annually (see table 2 and fig. 15). Recharge results from precipitation exceeding evapotranspiration in the fall and from snowmelt commonly accompanied by rain in the spring; depletion results from evapotranspiration during summer and continued drainage while recharge is prevented by the snowpack during winter. Minor recharge periods coincided with major rainstorms during July 1980 in both watersheds. Recharge in spring 1981 was more sustained than that in spring 1980 as a result of two snowmelt periods and unusually heavy rains.

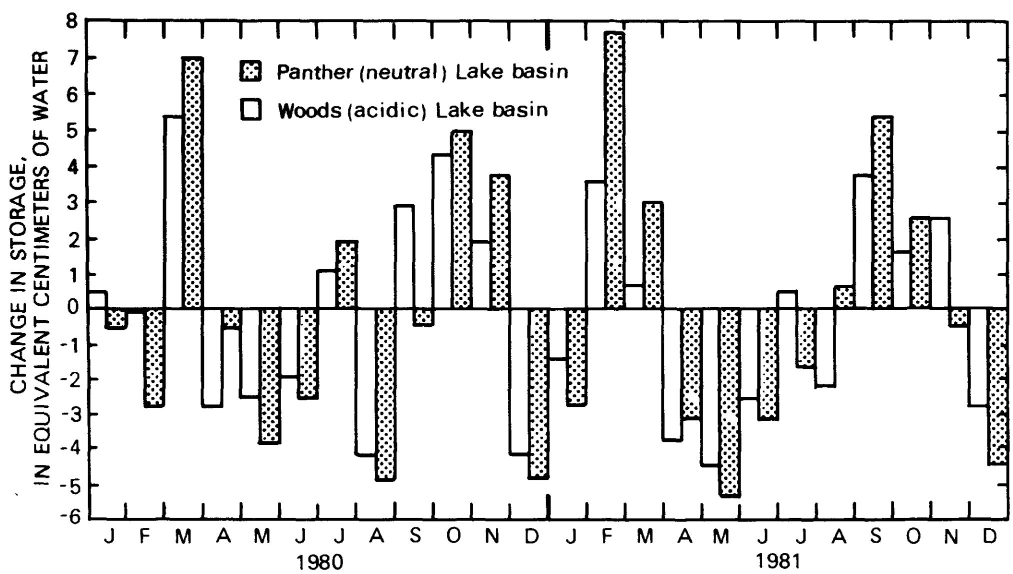

Figure 15.--Changes in monthly watershed storage, 1980-81, as estimated from the water-budget equation (eq. 1).

Comparison Between Basins.--Results of the watershed-storage calculation indicate greater ground-water storage and base flow at the neutral-lake basin than at the acidic-lake basin. During months of net recharge, the increase in watershed storage is also larger at the neutral-lake basin, and likewise, the release of water from storage during dry periods is greater and is sustained over a longer period than in the acidic-lake basin.

Differences in the response of monthly watershed storage to precipitation reflect the relative importance of shallow and deep watershed storage reservoirs in each basin. Field observations indicated that ponded water in surface depressions is rare in the neutral-lake basin, except during spring, but is common in the acidic-lake basin throughout the year. Water that is held in surface depressions is released either by flow around drainage barriers or by evapotranspiration and minor seepage. Water from surface depressions can sustain some flow briefly after storms or snowmelt, but this flow diminishes more quickly than that from ground-water storage. The remaining water either evaporates or remains trapped and will not contribute to the annual cycle. As discussed previously, the shallow ground-water-flow system at the acidic-lake basin is depleted more rapidly in relation to the deeper flow system at the neutral-lake basin.

Analysis of the spring melt period reveals a larger watershed storage capacity and a smaller percentage of shallow or surface-depression storage in the neutral-lake basin. During spring snowmelt, the soils of both basins were saturated, which reduces infiltration capacity. Snow and ice cover also decreased the area of the watershed where infiltration could occur. Therefore, despite the large spring recharge of ground water, most meltwater or rainwater in both basins either flowed over the watershed surface to the lake or was held in surface depressions. During April of both years, this depression storage was depleted in both watersheds. Snowmelt occurred rapidly at the end of March 1980, and watershed storage was depleted more during March and April in the acidic-lake basin than in the neutral-lake basin, which suggests that storage in surface depressions is greater in the acidic-lake basin. In April 1981, the actual change in watershed storage appears similar between basins, but, again, a greater percentage of the spring recharge left the acidic-lake basin.

By May, surface-depression storage was largely depleted, and the decrease in watershed storage resulted primarily from discharge of ground water. During May and June, monthly storage depletion tapered off more rapidly in the acidic-lake basin, which caused a smaller total discharge from watershed storage after the spring melt than in the neutral-lake basin.

Whether precipitation occurred at the beginning, middle, or end of a month also seemed to affect the monthly watershed-storage term and thus reveals something of watershed-storage characteristics in the basins. In general, if rain occurred at the beginning or middle of the month, it resulted in a net storage gain at the end of the month in the neutral-lake basin, but not in the acidic-lake basin. Only rain occurring at the end of the month appeared as a net gain in watershed storage in the acidic-lake basin. When the acidic-lake basin received more rain at the end of the month than the neutral-lake basin (September, 1980; November, 1981), or when drainage from the ground-water reservoir at the neutral-lake basin over the month was significantly greater than precipitation at the end of the month (July, 1981; November, 1981), the greater apparent watershed-storage increase was in the acidic-lake basin. A month-by-month analysis of storage in relation to the date and volume of precipitation showed that watershed storage is discharged faster in the acidic-lake basin, which is consistent with the greater storage in surface depressions in the acidic-lake basin and the greater storage in the ground in the neutral-lake basin.

Water held in surface depressions is less buffered than ground water, as reflected by soil water collected in tension lysimeters at the boundary between the organic and mineral horizons, because it has had less contact time with surficial deposits and consequently less time to be neutralized by reaction with surficial materials (Cronan, 1984). In addition, most surface depressions contain decaying organic matter, which has an acidifying effect on the water. Therefore, water derived from watershed storage in the acidic basin is less likely to become buffered than that in the neutral-lake basin.

Estimation of Ground-Water Contribution to Outflow

Methods of Computation.--The monthly ground-water contribution to lake outflow was computed from a water balance that equates ground-water discharge with the deficit between the inflow and outflow of each lake. This relationship is expressed as:

$$G = R - S - P_L + E_L + \Delta SW \tag{8}$$

where: G = ground-water contribution to the lake,
R = outflow at the lake outlet,
S = surface runoff (tributary flow) into the lakes,
P_L = precipitation directly on the lake,
E_L = evaporation from the lake, and
ΔSW = change in lake storage

(All values in this equation are in cm of water per unit area.)

The ground-water contribution was calculated for months in which complete tributary discharge data were available. Surface runoff was calculated for the main tributary to each lake, and this value was apportioned to the surface area in each basin that produces surface runoff. For purposes of this analysis, surface runoff was defined as all flow in the tributary stream, and ground water was defined as water that entered the lake directly from the watershed without first entering a tributary stream. The calculation assumed (1) that ground water did not enter the tributaries, (2) that all tributary flow consisted of surface runoff, and (3) that the surface runoff from the major tributary watershed represented surface runoff from the whole basin. Because some of the tributary flow was derived from ground water, the equation yielded a low estimate of ground-water contribution to total basin runoff. The lake-evaporation value was calculated as a percentage, based on area, of the ET estimate for the whole basin.

During parts of each year, no overland flow was seen in areas of either basin. For those periods, the above calculation would overestimate surface runoff and hence underestimate ground-water flow. Equation 8 was therefore refined by decreasing the surface-runoff component (S) to account for areas in which the infiltration rate usually exceeded precipitation rates, which were the areas underlain by thick till (fig. 3). Except during snowmelt, surface runoff generally was not observed in areas underlain by thick sandy till. Surface runoff occurred at the base of Panther Mountain on areas of thick till, where the infiltration capacity of the soil was often exceeded by sheet flow off the mountain. To account for this area, a second adjustment was made to the surface-runoff component for the neutral-lake basin.

Results.--Estimates of monthly ground-water contribution from equation 8, in which the tributary flow was assumed to represent surface runoff from the entire watershed, ranged from -1.2 cm to 3.6 cm at the neutral-lake basin and from -0.66 cm to 0.74 cm at the acidic-lake basin (table 5). The average ground-water contribution to basin outflow was 30 percent for the neutral-lake basin and less than 1 percent for the acidic-lake basin. The second set of ground-water estimates, in which surface runoff was associated only with areas underlain by thin till and bedrock, gave slightly greater values; 54 percent for the neutral-lake basin and 5 percent for the acidic-lake basin. The third estimate for the neutral-lake basin, in which surface runoff was associated only with areas underlain by either thin till or bedrock on Panther Mountain and by the thick till at its base, yielded a 39-percent ground-water contribution to total outflow. The second and third estimates, which are most representative of field observations, indicate that ground-water contribution to total outflow from the neutral-lake basin is substantial and is 8 to 10 times greater than that in the acidic-lake basin.

Table 5.--Monthly ground-water contribution to lake outflow, 1980-81.

[Values are in centimeters; dashes indicate that tributary-flow data were not available]

Date	Neutral-lake basin			Acidic-lake basin	
	First calculation[1]	Second calculation[2]	Third calculation[3]	First calculation[1]	Second calculation[2]
July 80	--	--	--	0.00	+0.18
Aug	+1.83	+2.03	+1.93	-.15	-.02
Sept	+2.54	+3.10	+2.69	-.33	-.15
Oct	-1.19	+1.60	-0.05	+.48	+.84
Nov	--	--	--	--	--
Dec	--	--	--	--	--
Apr 81	+3.02	+6.83	+4.52	+0.13	+0.74
May	+2.77	+3.96	+3.10	-.66	-.41
June	+3.10	+3.15	+3.07	-.08	+.20
July	+1.14	+2.31	+1.68	+.71	+.96
Aug	-0.99	+1.83	+0.10	+.74	+.99
Sept	--	--	--	--	--
Oct	--	--	--	--	--
Nov	+2.21	+4.06	+2.89	--	--
Dec	+3.56	+3.56	+3.56	-.56	-.35
Average annual centimeters of ground-water flow	21.6	38.9	28.2	.33	3.6
Average percent of outflow*	30	54	39	<1	5

* Raw data used in calculation.
1 1st calculation: surface runoff assumed over entire watershed.
2 2d calculation: surface runoff assumed only over areas of thin till and bedrock.
3 3d calculation (neutral lake only): surface runoff assumed only in areas of thin till and bedrock, on Panther Mountain, and over thick till at base of mountain.

Effects of errors and adjustments. Errors in ground-water-discharge estimates from the first method of calculation (surface runoff assumed over entire watershed) are probably the result of overestimates of the area having overland flow in each basin. Studies of forested New England watersheds containing thick till have shown that overland flow in the litter layer occurs only during spring snowmelt (Patric and Lyford, 1980; Nutter, 1973). Overland flow was observed over most of both watersheds during spring snowmelt in 1980 and 1981; therefore, the ground-water estimates from the first calculation should be accurate at least for April of both years. During dry periods such as August 1980, when tributary flow was negligible or zero in both watersheds, ground-water discharge should equal the total outflow from each lake minus the change in lake storage (fig. 15). Between these periods, the area that contributes surface runoff varies according to the permeability and thickness of the overburden, the intensity of rainfall, and the antecedent soil-moisture content, and the suitability of each equation would vary accordingly.

Field evidence suggests that the most accurate estimates of ground-water contribution are those derived from the second calculation, which assumes surface runoff only from areas of bedrock and thin till in both basins. During most of the year, overland flow was not observed in areas underlain by thick till in either basin, except at the base of Panther Mountain, but was common in areas underlain by thin till and bedrock. The areas of thick till have rapid infiltration and thus a low potential for runoff, as evidenced by the rapid water-table response to precipitation (fig. 13). In contrast, soils overlying thin till were consistently wetter than those overlying thick till, even at the base of Panther Mountain, where sheet runoff from above was common. Because water can infiltrate dry soils more rapidly than wet soils and because thick tills have greater storage capacity, surface runoff is more likely to occur in the areas of thin till, which are between bedrock highs and are commonly saturated, than in the areas of thick till, which are unsaturated.

The negative base-flow values for some months could indicate water leaving the basin through deep seepage, which is improbable as mentioned earlier, or they may be artifacts of the simplifying assumptions inherent in the equations, measurement errors, or an underestimation of lake evaporation. The two assumptions that could have affected the ground-water estimates most severely are that runoff in the two tributary channels is derived solely from surface runoff and that surface runoff occurs in all parts of each watershed.

The percentage of tributary flow that consists of ground water is greatest during dry months, but tributary flow in both basins was "flashy" and the recessions steep, which suggests that ground-water contribution was insignificant. In fact, the tributary in the neutral-lake basin was often dry during low-flow periods (fig. 16). However, tributary flow in the acidic-lake basin was sustained during low-flow periods and was probably derived partly from ground water. The tributary to the acidic lake drains a thick-till area, whereas the neutral-lake tributary drains a thin-till area. Therefore, the assumption that ground water does not enter the tributaries is a reasonable interpretation of field conditions in the neutral-lake basin but may cause a slight underestimate of ground-water contribution in the acidic-lake basin.

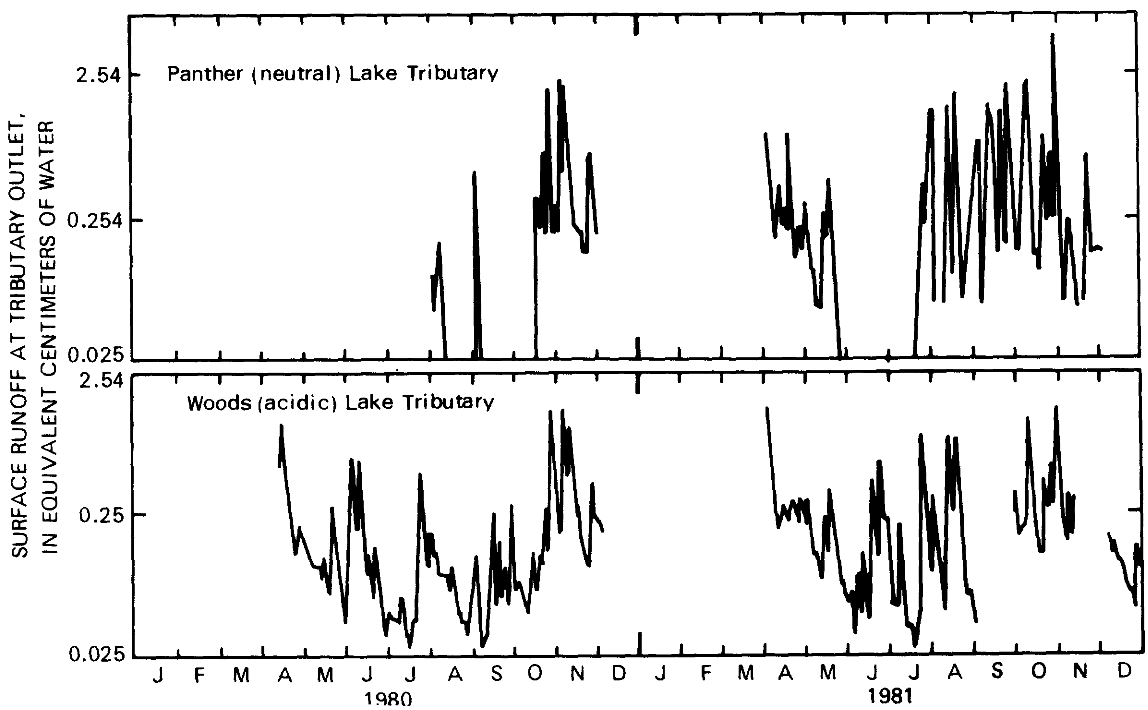

Figure 16.--Surface runoff at the main tributary outlets, 1980-81. (Locations are shown in figure 2.)

Monthly ground-water contribution to the neutral lake. The most accurate estimates of ground-water contribution in the neutral-lake basin, during at least a part of each year, are probably those obtained by the third calculation, which allows for surface runoff only on the thin till and bedrock on Panther Mountain and the thick till at its base. Tensiometers at the base of the mountain (fig. 2A, station H30) in soil underlain by thick till, were often saturated and gave moisture readings similar to those of soils underlain by thin till in the acidic-lake basin.

If 50 percent of the outflow from the neutral lake is assumed to be derived from ground water, then the average monthly contribution would be 3.0 cm. This value recurs in all three ground-water calculations in a pattern consistent with the seasonal variation mentioned earlier. For example:

(1) During April 1981, surface runoff was observed over most of the neutral-lake basin, and the estimate of monthly ground-water contribution from the first calculation, which assumes runoff from the whole watershed, is 3.0 cm.

(2) Both May and November 1981 were preceded by periods of high surface runoff, and the estimate of monthly ground-water contribution from the third calculation, which assumes runoff only from the thin till and bedrock on Panther Mountain and the thick till at its base, is 3.0 cm.

(3) During September 1980 and June 1981, surface runoff was at minimum, and the estimate of base flow from the second calculation, which assumes runoff only from the area underlain by thin till and bedrock on Panther Mountain, is 3.0 cm. Furthermore, months for which the second calculation yielded values less than 3.0 cm were those in which water-table gradients were the lowest of the year; thus, the average ground-water contribution during those months would be expected to be less than this average.

Monthly outflow from the neutral lake was 3.0 cm in several months of both years--February 1980 and January, June, and July 1981, all of which were low-flow periods. The low flows of February 1980 and January 1981 are attributed to snow cover and temperatures well below freezing. Those of June and July reflect a lack of tributary flow in June and intermittent tributary flow during most of July. In August 1980, lake outflow was less than 3.0 cm, which can be explained by low ground-water flow, low precipitation, and high evapotranspiration during that month. These observations support the estimate of 50 percent as the ground-water contribution to total outflow from the neutral lake.

Monthly ground-water contribution to the acidic lake. The seasonal patterns of ground-water flow in the acidic-lake basin did not parallel those of the neutral-lake basin, which is consistent with the observation that shallow surface-depression storage is recharged and depleted more rapidly than ground-water storage. Negative values for ground-water discharge were more common in the acidic-lake basin than the neutral-lake basin, which suggests either that ground water contributes flow to the tributary or that the watershed area contributing surface runoff is larger than estimated. During April, however, when surface runoff occurs over most of both basins, ground-water contribution to the acidic lake was only 0.13 cm, compared to 3.02 cm to the neutral lake. All values of monthly ground-water contribution to the acidic lake are substantially smaller than those to the neutral lake, and many are near zero, which indicates that the ground-water contribution to the acidic lake is relatively small.

Relationship Between Ground-Water Contribution and Basin Characteristics

Results of the storage analysis suggest that the percent contribution of ground water to the neutral lake is 8 to 10 times greater than that to the acidic lake. Similarly, the recharge area in the neutral-lake basin is 8.5 times greater than that in the acidic-lake basin. Even though the difference in size of recharge and storage areas may not be the sole cause of differences in ground-water contribution, it is probably the most significant. Two other likely factors--the eolian silt layer in the acidic-lake basin and soil permeability--are discussed below.

Effects of Eolian Silt Layer

The eolian silt layer (up to 17 cm thick) that mantles part of the acidic-lake basin is highly impermeable, as inferred from grain-size distribution, (Newton and April, 1982), and thus could cause local semiconfined conditions that could force horizontal drainage within the soil zone above it. The rate of infiltration to materials underlain by the silt is low--less than or equal to 10-4 cm/s. However, specific yields of eolian silt samples were similar to those of B-horizon samples from the neutral-lake basin. Furthermore, the silt was not found in all parts of the acidic-lake basin. Numerous exposures of the rock-and-till interface, together with the mound-and-pit microtopography resulting from tree blowdowns, would disrupt any continuous impermeable layer. These facts suggest that the silt layer is not an effective barrier to recharge. In addition, water-table fluctuations were similar at both basins and seem to be affected more by topography and altitude above lake surface than by the character of materials (fig. 13), and hydrographs of wells in the thick till indicate that infiltration is rapid and similar in both basins (fig. 17). Thus the eolian silt layer probably does not significantly deter recharge or storage in the acidic-lake basin.

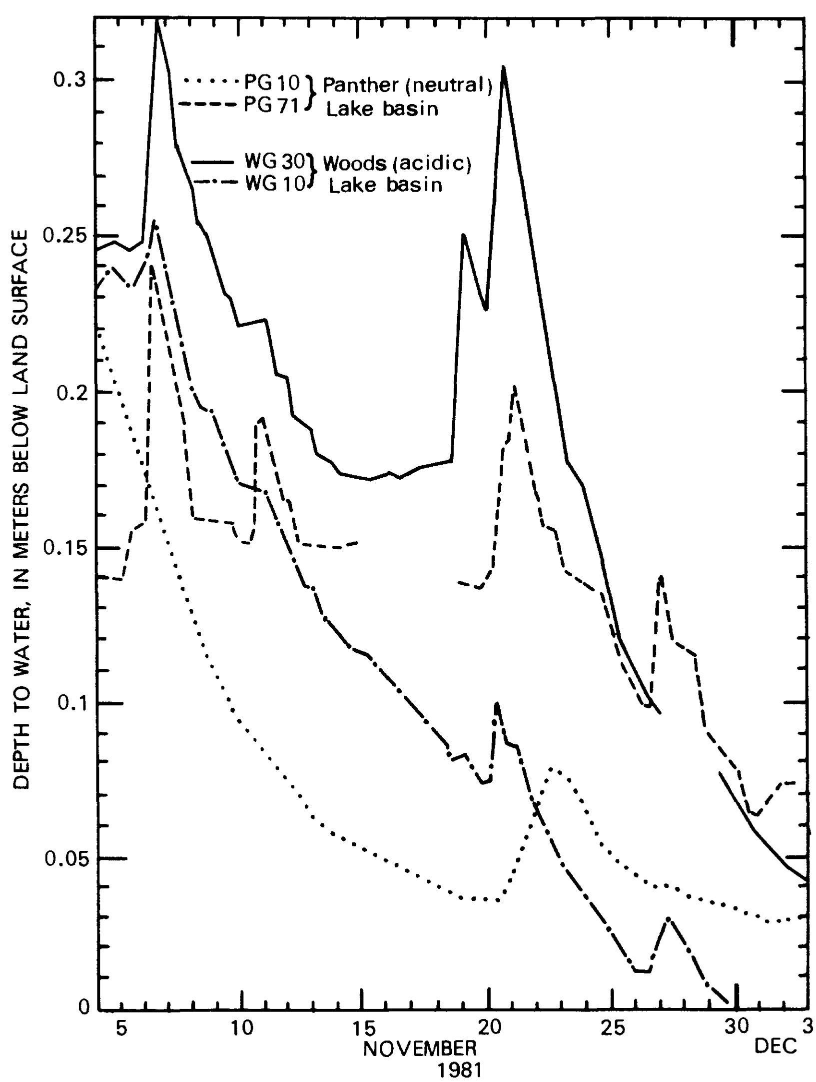

Figure 17.--Water-table altitude, November 1981. (Well locations are shown in fig. 2.)

Permeability of Surface Materials

Laboratory tests showed the average permeability of samples from the lower B-soil horizon of the neutral-lake basin to be 3.5 times greater than those of the acidic-lake basin, and the average permeability of the soil and upper till in the neutral-lake basin to be an order of magnitude greater than in the acidic-lake basin (Newton and April, 1982). Average infiltration rates in the neutral-lake basin likewise were greater in field testing. In neither basin was the average infiltration rate exceeded by even the most intense storms during the study, except during snowmelt. Local infiltration rates were exceeded by sheet runoff near bedrock outcrops, however. Although this was more prevalent in the acidic-lake basin than in the neutral-lake basin, it likely occurred also at the base of Panther Mountain during major storms. Differences in permeability are apparently minor between basins, but may contribute a small percentage of the differences in ground-water storage between basins.

Relationship Between Ground-Water Contribution and Lake-Water Chemistry

Results from the hydrologic analyses explain the differences in alkalinity, pH, and the net transport of major base cations at both lake outlets, as described by Galloway and others (1983). Both basins received similar acidic atmospheric deposition (pH 4.2) (Johannes and others, 1981), yet the lake outflows differed in average pH and alkalinity. At the acidic-lake outlet, pH was 4.7 and alkalinity was -10.0 μeq/L, and at the neutral-lake outlet, pH was 6.2 and alkalinity was 147 μeq/L. Alkalinity values were determined by gran titration (Talling, 1973). Similarly, the net annual transport of the sum of major base cations (calcium, magnesium, sodium, potassium, and ammonium) from the neutral-lake basin was 4.4 times greater than that from the acidic-lake basin.

These differences are attributed to the greater ground-water contribution to the neutral lake than to the acid lake. A longer storage time of water can generally be assumed for a system with a greater ground-water component. The longer the acidic water is in contact with the neutralizing minerals in the mineral soils and surficial materials, the more alkaline (higher pH) the water derived from them will be. Weathering through hydrogen-ion transfer will not only increase the alkalinity of this water but will also increase the sum of base cations. Therefore, outflow from the neutral lake, which contains a higher percentage of ground water than outflow from the acidic lake, will also have a higher alkalinity and greater cation transport.

The relative contribution of ground water to outflow can also explain the short-term changes in alkalinity and pH at the two lake outlets. During the spring snowmelt, surface runoff was prevalent within both basins, and a 1978-79 study showed a pronounced decrease in pH and alkalinity at both lakes during the snowmelt. (Galloway and others, 1980b). The pH of the neutral lake was still higher than that of the acidic lake. Therefore, ground-water neutralization appears to have some effect on lake chemistry even during the extreme of the snowmelt period.

SUMMARY AND CONCLUSIONS

Water budgets for two headwater lake basins that receive similar amounts of acid precipitation were calculated for 1980 and 1981 to determine which factors could account for observed differences in lakewater pH. The basins are of similar size, elevation, and vegetation cover, and both are underlain by glacial drift and relatively impermeable weather-resistant crystalline bedrock. The basins differ considerably in the amount and distribution of bedrock outcrop and in the size of their respective ground-water recharge and storage areas. Bedrock outcrops in the acidic-lake basin are distributed evenly, and the surficial material in most places is thin (<3 m). Bedrock outcrop in the neutral-lake basin occurs only on the upper slopes of Panther Mountain, and the percentage of basin area covered by thick surficial material is 8.5 times greater than that in the acidic-lake basin. Thus, the neutral-lake basin has a far greater storage capacity and recharge area.

Annual precipitation, lake outflow, and evapotranspiration were similar between basins throughout the study. Annual precipitation ranged from 116 cm to 125 cm. Basin outflow (measured at the lake outlets) accounted for approximately 60 percent of the annual precipitation in both basins; evapotranspiration accounted for the remaining 40 percent. Evapotranspiration calculated as a residual in the annual water budget was lower than estimates made from empirical formulas that required data from sites adjacent to the Adirondack region. Annual changes in storage were negligible at both basins, and no major loss of water from the basins through deep seepage was indicated. At both basins, annual precipitation was greater in 1981 than in 1980, resulting in more runoff in 1981 than 1980.

Results of the monthly water budget indicate that watershed storage and the ground-water contribution are greater in the neutral-lake basin than in the acidic-lake basin, which accounts for the differences in monthly lake outflows and the higher pH, alkalinity, and net ion transport from the neutral lake. Daily mean discharge from the neutral lake was also steadier, with lower peaks and higher low flows than that from the acidic lake. The greater intensity of precipitation in 1981 than in 1980 caused outflow from the acidic lake to be "flashier" in 1981 than in 1980. More sustained flow from the neutral lake is attributed to the basin's larger ground-water-storage capacity and the sustained release of water to the lake. Watershed storage in the acidic-lake basin appears to be primarily in surface depressions, which drain more quickly than ground-water systems and provide little or no acid neutralization.

A larger ground-water storage in the neutral-lake basin than the acidic-lake basin is further supported by base flow patterns in the lake outlet streams. Similarities between basins in lake storage and effects of outlet control on discharge allowed that flow-duration curves to be used to assess ground-water contribution to outflow. Flow-duration curves based on 5 years (1978-82) of discharge records from the neutral-lake basin had a flatter slope, with well-sustained flows even above 90-percent duration, which is indicative of substantial ground-water contribution. The duration curve for the acidic-lake basin was steep and dipped sharply at the 90-percent duration, which indicates a predominance of surface runoff and negligible ground-water contribution. The increase in precipitation intensity in 1981 caused a significant increase in basin outflow at all but the lowest flows at the acidic-lake basin but only minor variations in mid-range flow durations at the neutral-lake basin. Analyses of runoff-recession rates indicate that the maximum storage per unit area of the neutral-lake basin is 3.9 times that of the acidic-lake basin. The maximum daily base flow per unit area from the neutral lake was 2.2 times greater than that from the acidic-lake basin.

Computations of ground-water contribution, in which flow in the largest tributary of each basin was used to estimate surface runoff from the entire basin, suggest that the ground-water contribution to the neutral lake is about 10 times greater than that to the acidic lake. Depending on the size of the area in each watershed said to produce surface runoff, the ground-water contribution to the neutral lake is from 3 to 11 times greater than that to the acidic lake. Surface runoff was not observed in areas underlain by thick till in either basin except during the snowmelt period and was assumed to occur only in areas underlain by thin till or bedrock the rest of the time. Under these assumptions, the ground-water contribution at the neutral-lake basin was 8 to 10 times greater than at the acidic-lake basin.

The areal percentage of each basin underlain by thick surficial materials (>3 m) is the primary factor controlling ground-water flow and acid neutralization within each basin. Ground-water levels rise quickly after precipitation, which indicates rapid recharge in the thick sandy till of both basins. The eolian silt layer that mantles some of the acidic-lake basin may inhibit infiltration locally, but not enough to significantly decrease recharge in the thick till. Permeability tests indicate a greater average soil permeability in the neutral-lake basin, but in neither basin was the infiltration capacity exceeded by even the most intense precipitation. Thus, the similarity of infiltration rates of the thick till deposits in both basins suggest that the greater extent of such deposits in the neutral basin, rather than a difference in their composition between the two basins, is the reason for the greater ground-water storage and discharge in the neutral-lake basin.

The higher average pH, average alkalinity, and annual net transport of base cations in the neutral lake than in the acidic lake can be attributed to the greater ground-water storage and discharge within the neutral-lake basin. Ground water, unlike surface runoff, becomes buffered by neutralizing minerals within the unconsolidated materials, whereas surface runoff remains unbuffered or may even become acidified by contact with decaying organic matter in surface depressions.

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