United States
Department of
Agriculture

Forest Service

Northeastern Forest Experiment Station

General Technical Report NE-141

Thirty Years of Hydrometeorologic Data at the Hubbard Brook Experimental Forest, New Hampshire

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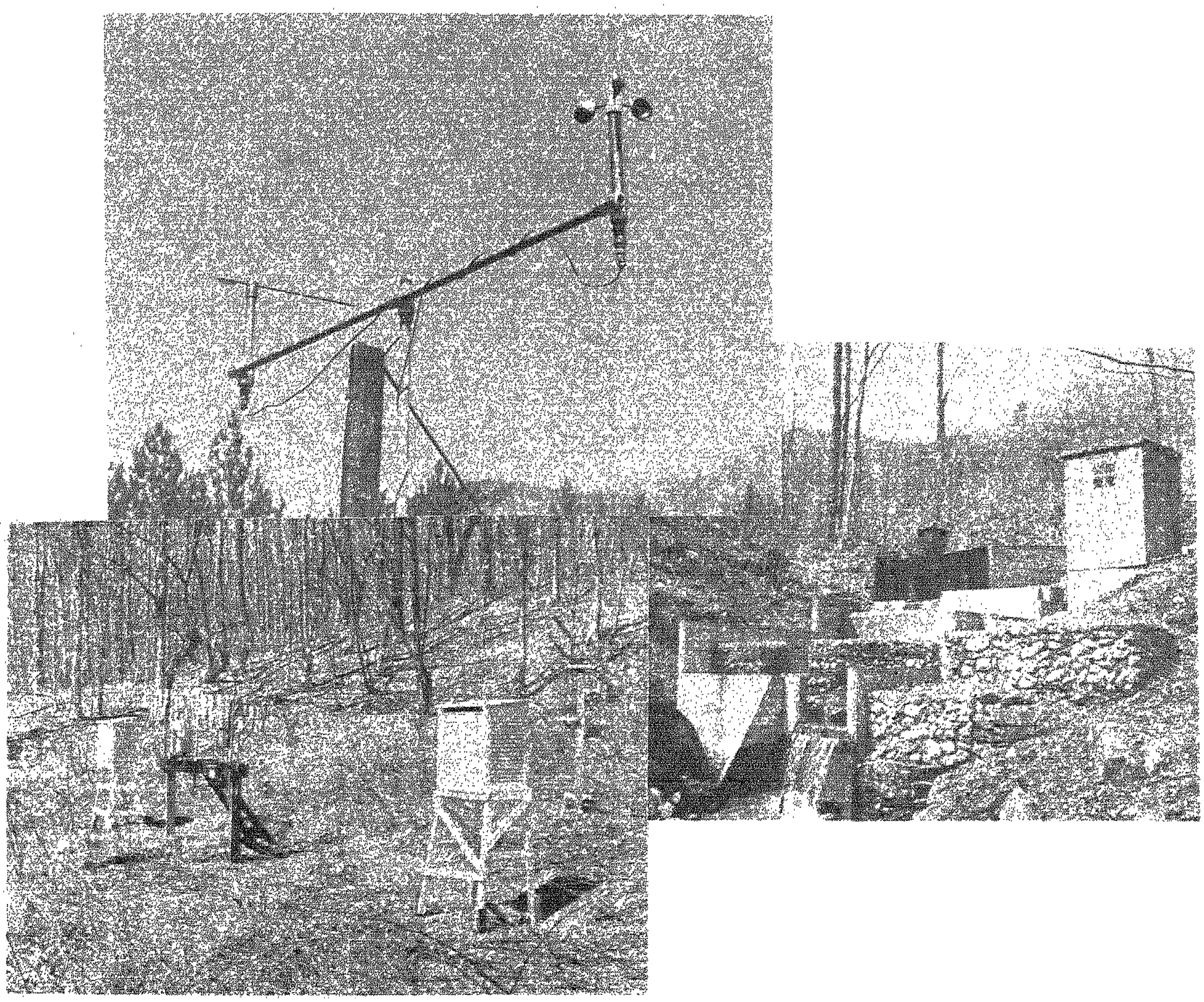
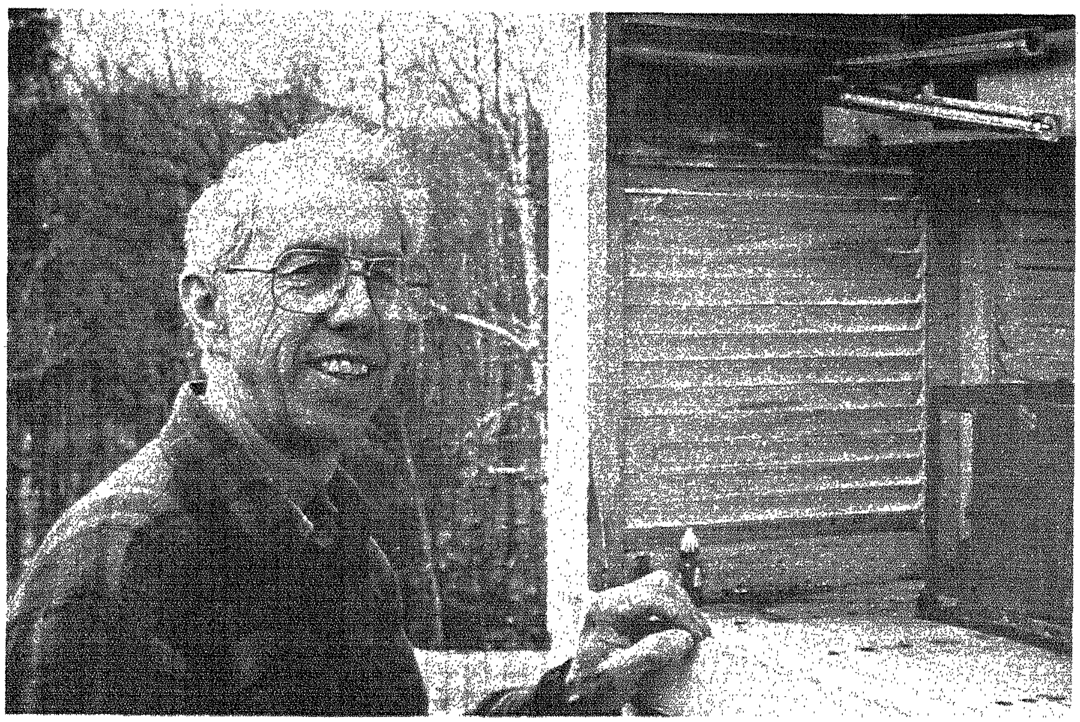


Dedication

For the past 26 years, Vincent R. Levasseur has served as a forest technician at the Hubbard Brook Experimental Forest. With year-round collection of weather and streamflow data from stations scattered over 3,200 ha of New Hampshire's White Mountains, the task is not easy. In winter, Vinnie has snowmobiled and showshoed, in bitter cold and deep snow, every Monday to a 1,000-m elevation. He has changed frozen clocks, cared for balky propane streamgage heaters, cleared overgrown raingage openings, and endured black flies and mosquitoes to obtain the data in this report. In the office, his careful and accurate reading of data from charts has been exceptional. Because Vinnie's contribution to this publication cannot be overstated, we dedicate this report to him.



Vincent R. Levasseur.

Cover Photo (clockwise): Headquarters anemometer and windvane, Streamgage 5, and Station 1.

Thirty Years of Hydrometeorologic Data at the Hubbard Brook Experimental Forest

Northeastern Forest Experiment Station
U.S. Department of Agriculture, Forest Service
Radnor, Pennsylvania 19087

May 1990

Abstract

The Hubbard Brook Experimental Forest in West Thornton, New Hampshire, was established in 1955 by the U.S. Department of Agriculture, Forest Service, as a research area for forest hydrology. Over the next 13 years 8 small (12–76 ha) watersheds were established; streamflow and precipitation on these watersheds has been measured continuously since then. Air temperature, solar radiation, wind speed and direction, soil temperature, air humidity, snow cover, and frost have also been measured at one or more locations. These data have provided the basis for hundreds of research publications by the Hubbard Brook Ecosystem Study. This report summarizes the data in various ways in order to help readers interested in climate and streamflow in the White Mountains, or specifically at Hubbard Brook.

Acknowledgment

Don Buso, Institute of Ecosystem Studies, has assisted in data collection for the past 15 years. Cindy Veen helped in the final stages of data processing for this publication. Dick Sartz, Dick Trimble, Ray Leonard, George Hart, Ray Lavigne, Herb Karsten, Mike Koterba, and Don Mower have each contributed substantially to data collection. The leadership and support of Gene Likens and Herb Bormann have played a major role in continuation of Hubbard Brook research. This publication is a contribution of the Hubbard Brook Ecosystem Study.

The Authors

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C. WAYNE MARTIN is a research forester with the Northeastern Forest Experiment Station's research unit at the Hubbard Brook Experimental Forest, West Thornton, New Hampshire. He received degrees in forest management and forest hydrology from the University of New Hampshire. He joined the U.S. Forest Service in 1966.

JAMES W. HORNBECK, principal forest hydrologist, holds B.S. and M.S. degrees in forestry from the Pennsylvania State University and a Ph.D. from State University of New York, College of Environmental Science and Forestry, at Syracuse. He has conducted research on forest hydrology at Hubbard Brook since 1967.

ROBERT S. PIERCE, principal soil scientist, holds a B.S. degree in forestry from the University of Michigan, and M.S. and Ph.D. degrees in forest soils from the University of Wisconsin, Madison. He came to Hubbard Brook in 1955, and since 1958 has been project leader of watershed management research and of the Hubbard Brook Experimental Forest. His research focuses on forest hydrology and soils.

Manuscript received for publication 21 June 1989

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Introduction

The Hubbard Brook Experimental Forest was established by the USDA Forest Service in 1955 as a field location for forest hydrology research. The Hubbard Brook Ecosystem Study has become world famous for research on cycling of water, nutrients, and energy in forests and related aquatic ecosystems. This work involves scientists from many institutions and has produced hundreds of publications (Likens 1988).

The USDA Forest Service collects hydrometeorologic data at Hubbard Brook on precipitation, streamflow, temperature, humidity, wind, and snow, which are fundamental to research by Hubbard Brook Ecosystem Study scientists. In this publication the Hubbard Brook hydrometeorologic data are summarized in various ways for use by scientists, land managers, ski-area operators, engineers, and foresters.

Hydrologic and meteorologic data have been collected at Hubbard Brook for over 30 years. The "Thirty Years" of the title is for euphony; actually the data covers 33 years: 1956–88. A publication of this kind becomes outdated immediately. Data for 1987 and 1988 have been added since preparation of the report began. Because average values change as the period over which they are calculated changes, the values differ from those published earlier.

Most of the Hubbard Brook Experimental Forest is covered by mature northern hardwood forest: some areas have been cut in various ways for research purposes. This publication is limited to a summary of routinely measured data not affected by such experimental treatments. Analysis of any treatment effects has been excluded.

Basin of the Hubbard Brook Experimental Forest; looking west.

Units and Abbreviations

The United States continues to use the outmoded system of English units. At Hubbard Brook the temperature is still measured in °F, precipitation in inches, and streamflow in cubic feet per second. These are converted to metric units in computer processing. However, there is a perennial discussion among the scientists on whether to use metric, English, or both, in a publication whose audience includes foresters, scientists, engineers, and the general public.

In order to help, rather than hinder, metric conversion, data are given here in metric (SI) units. In a few instances, particularly streamflow per unit area, English units are also presented.

Approximate unit conversion is adequate for most purposes. Because the number of digits in the result should not exceed the number in the source, none of our data have more than three significant digits. The following conversions are relevant for data herein. Brackets imply a value having the enclosed units.

[°F]	=	[°C] • 1.80 + 32
[inch]	=	[mm] / 25.4
[ft]	=	[m] • 3.28
[mile]	=	[km] • 0.621
[acre]	=	[ha] • 2.47
[m/s]	=	[km/d] / 86.4
[csm]	=	[L $s^{-1}ha^{-1}$] • 9.15
[mm/d]	=	[L $s^{-1}ha^{-1}$] • 8.64
[cal/cm^2]	=	[MJ/m^2] • 23.9
[mb]	=	[kPa] • 10.0

The word "mean" can be confusing when applied to temperature. The value of "daily mean temperature", in practice, is obtained as the average of the minimum temperature and the maximum temperature for the day; this is an approximation of the true average temperature over a 24-hour period. To avoid confusion, we use the word "average" for all other averaging processes.

Abbreviations used throughout are:
- ave — simple arithmetic average
- csm — cubic feet per second per square mile
- HQ — Headquarters
- HB — Hubbard Brook Experimental Forest
- max — maximum
- min — minimum
- sd — standard deviation

Topography and Vegetation

The Hubbard Brook Experimental Forest (HB) consists of 3,200 ha of the White Mountain National Forest set aside for research. The center of HB is at 43°56′N latitude and 71°45′W longitude, in the southwestern corner of the White Mountains of north-central New Hampshire. Elevation of HB ranges from 222 m near HB Headquarters (HQ) at the east end of HB to 1,015 m at the summit of Mt. Kineo at the west end. HB consists of most of the bowl-shaped watershed basin of Hubbard Brook, which flows easterly into the Pemigewasset River, a major tributary of the Merrimack River.

Approximately 14,000 years ago HB was covered by a kilometer of continental glacial ice. The ice sheet removed the preglacial soil and smoothed the surface of the schist and granite bedrock. The bedrock surface has weathered little since glaciation. When the ice melted, debris in the glacier became the stony till in which today's soil has formed. The till thickness over bedrock ranges from zero to several meters. Four thousand years later, forests covered the landscape and they, with the humid, cool, continental climate, caused the development of a typical spodosol soil profile: a black organic forest floor over a highly leached, thin gray horizon; then a red-orange horizon of accumulated iron and a yellowish-gray subsoil ranging from coarse and sandy to a dense hardpan.

From 1890 to 1920 the original mixed conifer-hardwood forest at HB was heavily cut for sawtimber and fuel wood. Resulting release and regeneration led to the current northern hardwood forest, which is dominated by sugar maple (*Acer saccharum* Marsh.), beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britt). Balsam fir (*Abies balsamea* (L.) Mill.) and red spruce (*Picea rubens* Sarg.) occur primarily at higher elevations, particularly on north-facing slopes. Although trees in the 60- to 80-year class dominate, the cutting left many residual trees now over 200 years old. Some salvage logging occurred after the 1938 hurricane; otherwise, the forest has been undisturbed since 1920 except for recent research treatments.

Hydrometeorologic Network

Construction of streamgages on tributaries to Hubbard Brook began at HB in 1955 and continued through 1968. Streamflow has been measured since on eight watersheds (Fig. 1). A watershed is the area upslope from the streamgage that contributes water to the stream channel at the gage location. The gaged watersheds were numbered in the order constructed. The gradual addition of gaged watersheds over a 13-year period complicates the analysis of data with respect to long-term averages (Table 1).

In or near each gaged watershed, several openings were cut in the forest; the openings are about two tree-heights in diameter. These openings or stations each include a standard precipitation gage and are numbered from 1 to 21 (Fig. 1). Station 18 was a temporary station in the middle of Watershed 2; its data are not included here. All the other stations are permanent. Stations 1, 6, 10, 14, and 19 have a weight-recording precipitation gage, and Stations 1, 6, and 14 have a temperature and humidity recorder (hygrothermograph) (Table 1).

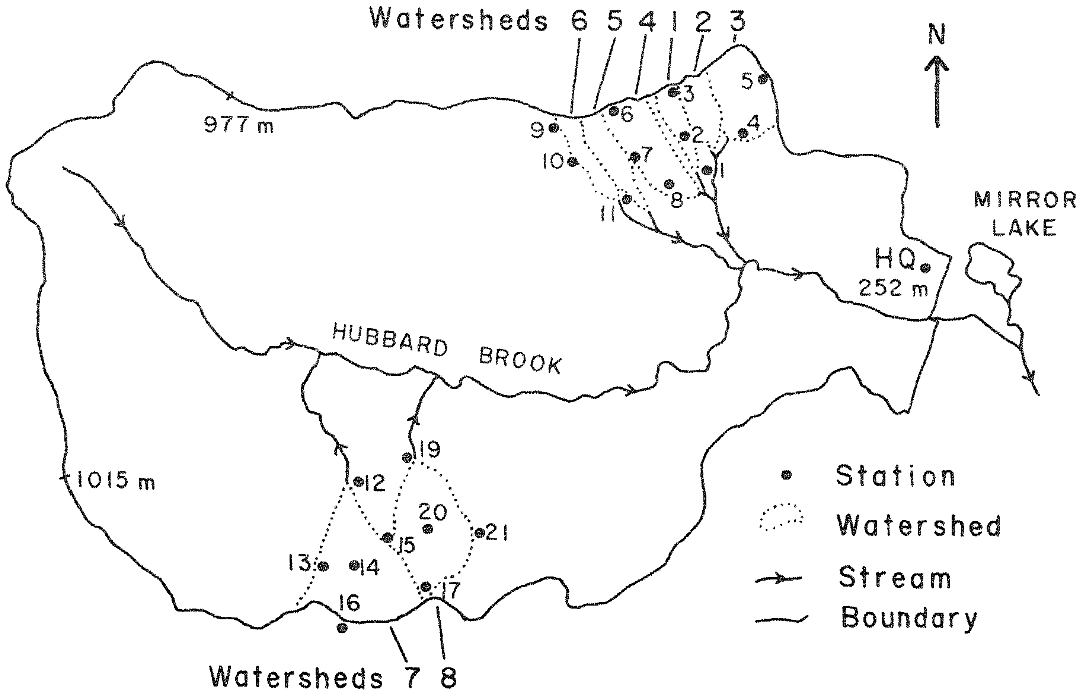


Figure 1.—Map of the Hubbard Brook Experimental Forest, showing watersheds and stations.

Table 1.—First full year of record for each streamflow, precipitation, and air temperature instrument

Streamgage		Standard raingage		Recording raingage		Air temperature	
Watershed	Year	Station	Year	Station	Year	Station	Year
1	1956	1–3	1956	1	1956	1	1957
2	1957						
3	1958	4–5	1958				
4	1961	6–8	1961	6	1961	6	1961
5	1962						
6	1963	9–11	1963	10	1963		
7	1965	12–17	1965	14	1965	14	1965
8	1969	19–21[a]	1969	19	1969		

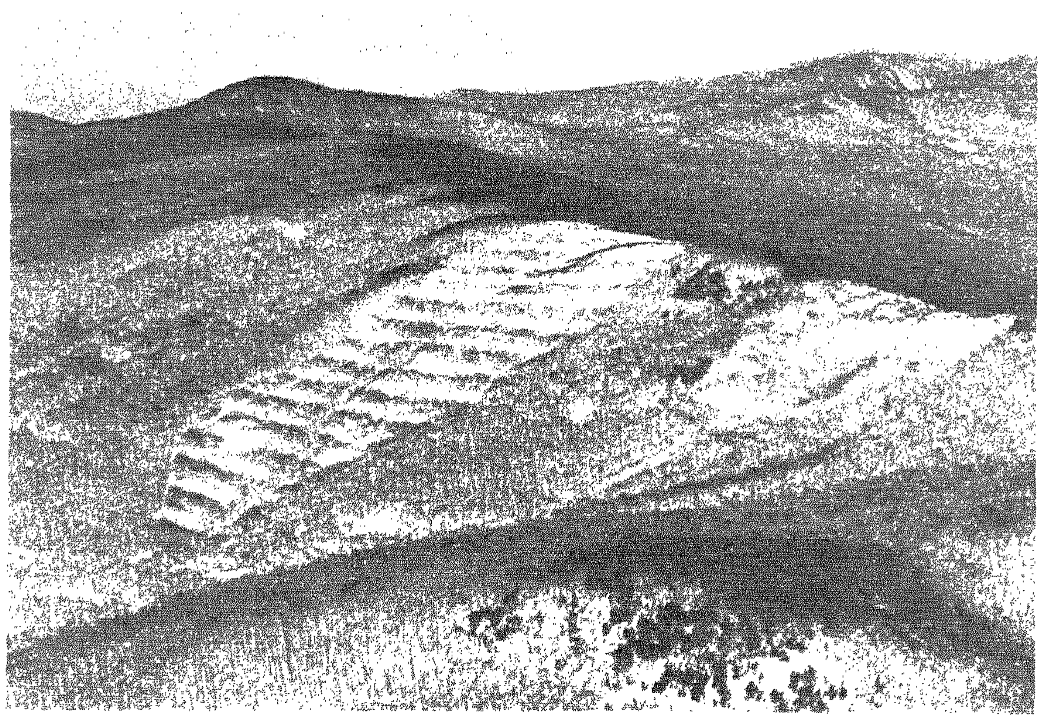
[a]Station 18 operated in Watershed 2 from 1966 to 1975.

The HQ weather station (also known as Station 22) has held a variety of sensors over the years. This HQ station has been moved twice, in 1960 and in 1962, progressing up the Mirror Lake Road to its present location next to the HQ building. Data from HQ before 1962 is not strictly comparable to more recent data. Before and since 1962, the HQ station has had heterogeneous surroundings. Since 1962 it has resided in one corner of a large field, adjacent to the HQ building. Near the building and the station the field slopes steeply downhill. The station is partly surrounded by a driveway, beyond which (10–20 m from the station) are conifer plantations and hardwood forest.

Since 1965 three experimental watersheds at HB have been subjected to various kinds of cutting. Watershed 2 was clearfelled in 1965 by cutting all stems and leaving them in place. The watershed was further devegetated by herbiciding in 1966, 1967, and 1968. Watershed 4 was commercially cut in sequential parallel strips 25 m wide in 1970, 1972, and 1974, resulting in complete cutting and log removal over the whole area except for a streamside buffer. Watershed 5 was whole-tree clearcut in late 1983. All the cut watersheds have been allowed to regrow naturally since the treatments were completed.

Electrical line power has not been available at HB except at Headquarters (HQ). Generators and solar panels have been used occasionally, but not for routine data collection. Nearly all of the data have been collected by mechanical transducers linked to pens on spring-wound strip-chart recorders. This low-tech approach has surprised many visitors. Instruments that were state-of-the-art when HB was established continue in use because they are highly reliable in the adverse winter environment. At least weekly each recorder is monitored and any malfunction immediately repaired.

Data analysis technology has changed incredibly over the past 30 years, and HB techniques have changed often. In the 1950's all data were taken from charts by eye, tabulated by pencil, and added or multiplied using electrical rotary calculators, with answers copied to data sheets by hand. In approximately 1964 the first computer analysis of streamflow data was made at HB. Over the years six mainframe and minicomputers have been used. Only in 1986 was all the data read from punch cards onto magnetic tapes. About one and a half million data points are now contained in the routine hydrometeorologic data set for HB (Table 2). Yet, requests continue to arrive saying "send me all your data!"



Watersheds 1–6 at Hubbard Brook Experimental Forest. Watershed 4 is strip cut. Note weather station openings.

Table 2.—Estimate of number of hydrometeorologic data values for HB

Variable	Number of years		Days per year		Values per day		Number of stations		Number of values
Precipitation	30	×	365	×	1	×	22	=	241,000
Temperature	30	×	365	×	2	×	5	=	110,000
Streamflow	30	×	365	×	8[a]	×	8	=	701,000
HQ Weather Station	7	×	365	×	24	×	6[b]	=	368,000
									1,420,000

[a]An estimated average; varies from 2 to >100
[b]6 values per hour at one station

Precipitation

Precipitation at HB has been measured by three types of raingages: standard gages, weight-recording gages, and tipping-bucket gages. All gages have shields to reduce wind effects and are mounted with their tops 2 1/2 m off the ground to remain above the deepest snow.

Standard gages are maintained at 20 stations in or near the gaged watersheds (Table 1), and at HQ. A standard gage is a cylinder with an 8-inch diameter opening. The depth of water caught by the gage is measured once a week, normally on Monday. In winter, antifreeze is placed in the gage to partially melt new snow and precipitation is measured by the increased weight of the whole gage rather than by measuring depth. A small amount of light oil is kept in each gage, summer and winter, to prevent evaporation

The six weight-recording gages also have 8-inch diameter openings. Antifreeze is added in winter. The weight of the

Vinnie Levasseur at Station 10. Standard precipitation gage on right, weight-recording gage on left. Note scale on left for weighing standard gage in winter.

water caught in a bucket causes a spring balance to move a pen across a chart, which records how much rain or snow fell each day (midnight to midnight).

A tipping-bucket gage has an internal mechanism that produces an electric pulse for every 0.01 inch of precipitation. The gage is heated in winter to melt snow. Usually a tipping-bucket gage or a weight-recording gage has been operated at HQ, but those data are not used since these gages are only sporadically analyzed.

The daily precipitation for a standard gage is obtained by prorating its weekly total using daily totals from the nearest recording gage. Recording gage data are not used directly because they are less accurate.

We estimate precipitation on a whole watershed using the Thiessen weighting method (Linsley et al. 1958). In this method, daily watershed precipitation is a weighted average of daily precipitation for several standard gages. The weighting factor for each gage is the fraction of the watershed area nearest that gage (Table 3).

Orographic Effects

Much of the northeastern United States has an annual precipitation of approximately 1,000 mm. HB precipitation, generally, is greater than 1,000 mm because the White Mountains generate rain and snow. This orographic effect causes precipitation to vary by elevation and aspect. At HB the effect is demonstrated, in the average annual precipitation among standard gages, by trends that are consistently related to topography (Fig. 2).

Average annual precipitation at HB tends to increase with elevation, from 1,242 mm at HQ, at 252 m elevation, to 1,496 mm at Station 16, at 859 m elevation. In general, a linear relationship exists between elevation and annual precipitation, with precipitation increasing 41 mm per 100 m elevation (Fig. 3). North- and south-facing slopes at HB fall on the same line. Two exceptions to the pattern occur: both Stations 3 and 6 have annual precipitation about 100 mm less than expected for their elevations (Fig. 3). Station 3 is near the top of Watershed 1 and Station 6 is near the top of Watershed 4. Each is less than 20 m in elevation below the ridgeline. The other high-elevation gage on that ridge, Station 9, is 40 m in elevation below the ridge and does not have unexpectedly low precipitation. Winds at HB are often from the northwest, so the south-facing slope is a lee slope. It is possible that Stations 3 and 6 are often in the region of flow separation at the lee side of a ridgetop and are thus subject to abnormal wind conditions.

Watershed Precipitation

Annual watershed precipitation varies both by year and by watershed and ranges from just under 1,000 to 1,800 mm (Table 4).

Table 3.—Thiessen, or area, weighting factors for estimating watershed precipitation

	Watershed							
Station	1	2	3	4	5	6	7	8
1	.10	.02	.0	.03	.0	.0	.0	.0
2	.46	.41	.08	.08	.0	.0	.0	.0
3	.44	.57	.39	.01	.0	.0	.0	.0
4	.0	.0	.19	.0	.0	.0	.0	.0
5	.0	.0	.34	.0	.0	.0	.0	.0
6	.0	.0	.0	.30	.32	.0	.0	.0
7	.0	.0	.0	.30	.30	.0	.0	.0
8	.0	.0	.0	.28	.0	.0	.0	.0
9	.0	.0	.0	.0	.06	.31	.0	.0
10	.0	.0	.0	.0	.11	.49	.0	.0
11	.0	.0	.0	.0	.21	.20	.0	.0
12	.0	.0	.0	.0	.0	.0	.13	.0
13	.0	.0	.0	.0	.0	.0	.16	.0
14	.0	.0	.0	.0	.0	.0	.29	.0
15	.0	.0	.0	.0	.0	.0	.14	.14
16	.0	.0	.0	.0	.0	.0	.15	.0
17	.0	.0	.0	.0	.0	.0	.13	.14
18	.0	.0	.0	.0	.0	.0	.0	.0
19	.0	.0	.0	.0	.0	.0	.0	.16
20	.0	.0	.0	.0	.0	.0	.0	.39
21	.0	.0	.0	.0	.0	.0	.0	.17

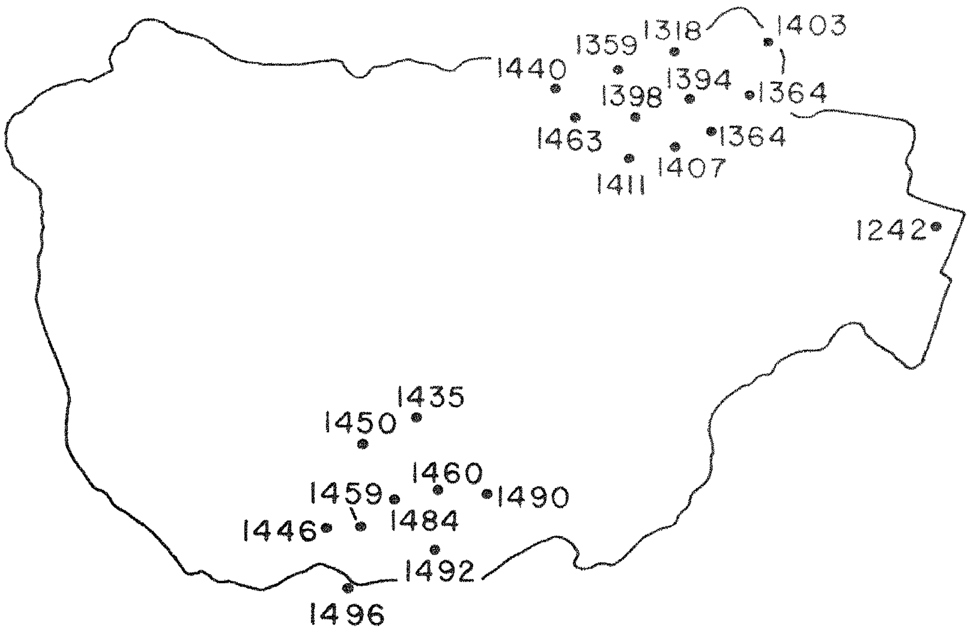


Figure 2.—Average annual precipitation for 1969–86, by location, for each standard gage. HQ value is estimated from its ratio to Station 1 for 1978–86.

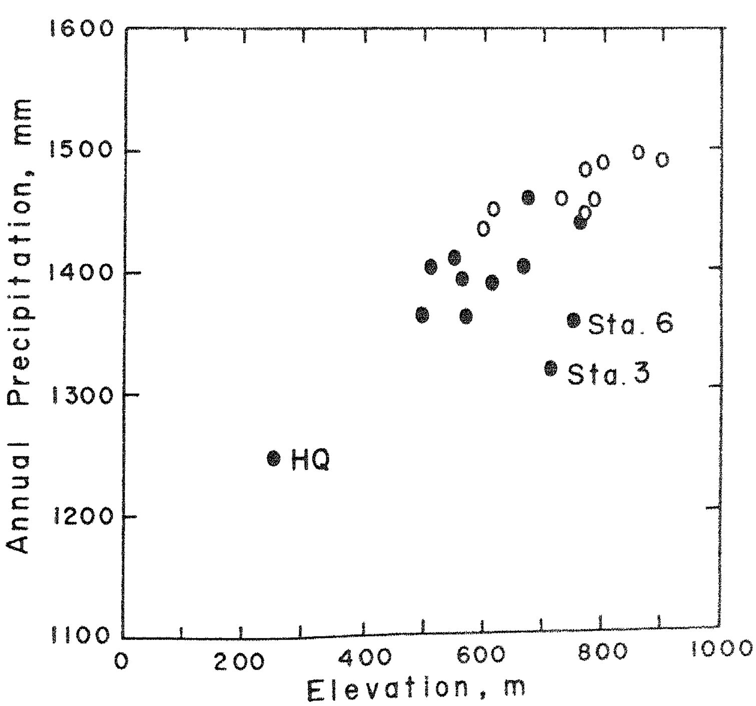


Figure 3.—Average annual precipitation for 1969–86, by elevation, for each standard gage. Solid dots are on south-facing slopes, open circles are north-facing. HQ value is estimated from its ratio to Station 1 for 1978–86.

Table 4.—Annual precipitation (mm) by watershed

Year	Watershed 1	2	3	4	5	6	7	8
1956	1439	–	–	–	–	–	–	–
1957	1216	1220	–	–	–	–	–	–
1958	1155	1168	1161	–	–	–	–	–
1959	1482	1483	1479	–	–	–	–	–
1960	1316	1321	1325	1327	–	–	–	–
1961	966	963	973	973	–	–	–	–
1962	1221	1237	1231	1234	–	–	–	–
1963	1129	1133	1145	1146	–	–	–	–
1964	1163	1160	1165	1168	1175	1194	–	–
1965	1123	1115	1121	1137	1147	1157	1142	–
1966	1229	1222	1224	1261	1284	1314	1294	–
1967	1320	1315	1297	1351	1357	1374	1347	–
1968	1270	1269	1285	1302	1334	1360	1298	–
1969	1374	1368	1403	1412	1443	1491	1568	1549
1970	1193	1185	1201	1216	1231	1263	1250	1255
1971	1172	1164	1173	1208	1228	1270	1284	1275
1972	1436	1431	1424	1412	1439	1493	1501	1495
1973	1806	1804	1793	1780	1785	1824	1815	1824
1974	1413	1407	1410	1428	1437	1475	1535	1546
1975	1433	1422	1449	1411	1432	1540	1541	1549
1976	1518	1512	1516	1528	1534	1622	1625	1626
1977	1389	1382	1388	1394	1404	1470	1488	1495
1978	1093	1088	1086	1114	1124	1176	1194	1181
1979	1425	1417	1433	1460	1462	1506	1490	1497
1980	1094	1088	1101	1118	1123	1166	1235	1218
1981	1641	1632	1665	1703	1702	1736	1763	1766
1982	1100	1089	1114	1151	1149	1174	1176	1185
1983	1447	1437	1452	1513	1522	1558	1620	1621
1984	1405	1397	1404	1467	1480	1516	1554	1558
1985	1137	1128	1137	1203	1217	1258	1275	1283
1986	1375	1364	1373	1446	1450	1479	1533	1516
1987	1228	1223	1235	1284	1298	1338	1375	1378
1988	1008	1004	1010	1060	1073	1107	1182	1157
ave[a]	1334	1327	1338	1365	1377	1423	1450	1449
sd	203	203	203	194	193	197	193	197

[a]Average (ave) and standard deviation (sd) are over years 1969–88.

The choice of which station or watershed to use as standard for HB is arbitrary. The USDA Forest Service usually uses Watershed 3 as the standard. For biogeochemistry, Watershed 6 is used as the standard because it has been intensively studied. There is a considerable difference in precipitation between the two; for the 1969–88 period, Watershed 3 averaged 1,338 mm and Watershed 6, 1,423 mm (Table 4).

For many uses, monthly precipitation is the most desirable value. Here we provide monthly precipitation for Watershed 3 (Table 5), Watershed 6 (Table 6), and the north-facing Watershed 7 (Table 7).

In many publications about precipitation chemistry at HB, annual precipitation has been reported for Watershed 6 over a "water year" beginning June 1 and ending May 31 (see Water Budget section). These annual amounts are shown in Table 19.

Generally, precipitation increases from east to west across the watersheds, both annually and in individual months (Table 8). Some, but not all, of the difference arises because the westernmost and north-facing Watersheds 7 and 8 have higher elevation. Of the south-facing watersheds, Watershed 6, the westernmost, is generally higher in precipitation than the other 5. Watersheds 1

ERRATA SHEET

Small errors have been found in watershed precipitation for the years 1956-1964. A revised portion of Table 4 is printed below.

The largest change to the original annual watershed total is 16 mm.

One or more values in Tables 5, 6, and 20 have changed. For further information, contact:

Hubbard Brook Data Manger
U.S. Forest Service
Northeastern Forest Experiment Station
P.O. Box 640
Durham, NH 03824

Table 4.—Annual precipitation (mm) by watershed

Year	Watershed 1	2	3	4	5	6	7	8
1956	1453	–	–	–	–	–	–	–
1957	1216	1220	–	–	–	–	–	–
1958	1155	1168	1161	–	–	–	–	–
1959	1472	1483	1479	–	–	–	–	–
1960	1316	1321	1325	1327	–	–	–	–
1961	966	979	979	973	–	–	–	–
1962	1221	1232	1231	1234	–	–	–	–
1963	1134	1139	1151	1152	–	–	–	–
1964	1178	1175	1175	1180	1187	1207	–	–

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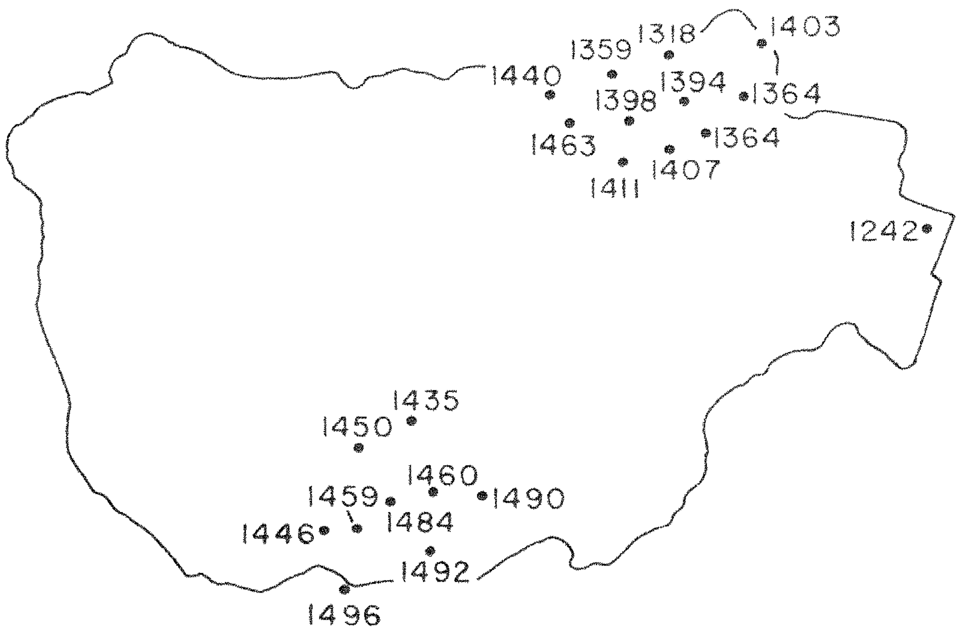

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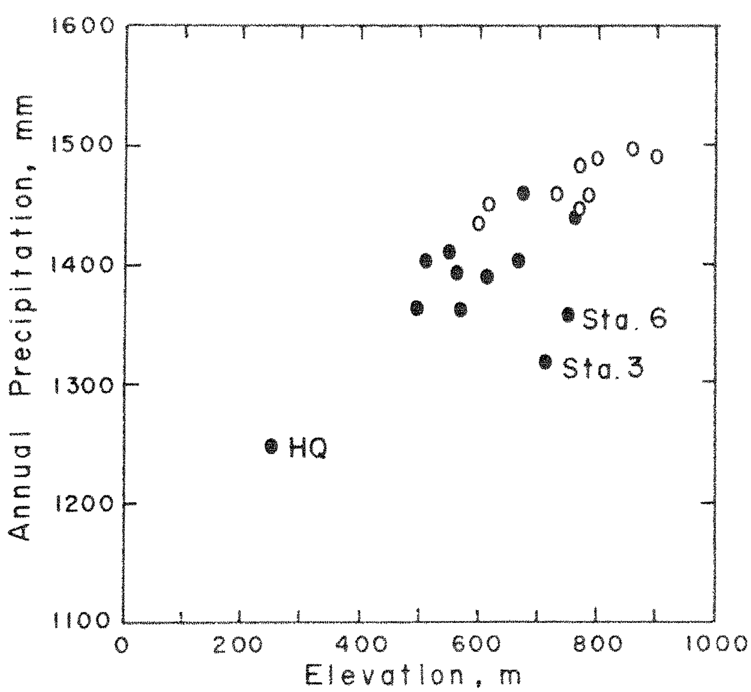

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Year	Watershed 1	2	3	4	5	6	7	8
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1957	1216	1220	–	–	–	–	–	–
1958	1155	1168	1161	–	–	–	–	–
1959	1482	1483	1479	–	–	–	–	–
1960	1316	1321	1325	1327	–	–	–	–
1961	966	963	973	973	–	–	–	–
1962	1221	1237	1231	1234	–	–	–	–
1963	1129	1133	1145	1146	–	–	–	–
1964	1163	1160	1165	1168	1175	1194	–	–
1965	1123	1115	1121	1137	1147	1157	1142	–
1966	1229	1222	1224	1261	1284	1314	1294	–
1967	1320	1315	1297	1351	1357	1374	1347	–
1968	1270	1269	1285	1302	1334	1369	1298	–
1969	1374	1368	1403	1412	1443	1491	1568	1549
1970	1193	1185	1201	1216	1231	1263	1250	1255
1971	1172	1164	1173	1208	1228	1270	1284	1275
1972	1436	1431	1424	1412	1439	1493	1501	1495
1973	1806	1804	1793	1780	1785	1824	1815	1824
1974	1413	1407	1410	1428	1437	1475	1535	1546
1975	1433	1422	1449	1411	1432	1540	1541	1549
1976	1518	1512	1516	1528	1534	1622	1625	1626
1977	1389	1382	1388	1394	1404	1470	1488	1495
1978	1093	1088	1086	1114	1124	1176	1194	1181
1979	1425	1417	1433	1460	1462	1506	1490	1497
1980	1094	1088	1101	1118	1123	1166	1235	1218
1981	1641	1632	1665	1703	1702	1736	1763	1766
1982	1100	1089	1114	1151	1149	1174	1176	1185
1983	1447	1437	1452	1513	1522	1558	1620	1621
1984	1405	1397	1404	1467	1480	1516	1554	1558
1985	1137	1128	1137	1203	1217	1258	1275	1283
1986	1375	1364	1373	1446	1450	1479	1533	1516
1987	1228	1223	1235	1284	1298	1338	1375	1378
1988	1008	1004	1010	1060	1073	1107	1182	1157
ave[a]	1334	1327	1338	1365	1377	1423	1450	1449
sd	203	203	203	194	193	197	193	197

[a]Average (ave) and standard deviation (sd) are over years 1969–88.

The choice of which station or watershed to use as standard for HB is arbitrary. The USDA Forest Service usually uses Watershed 3 as the standard. For biogeochemistry, Watershed 6 is used as the standard because it has been intensively studied. There is a considerable difference in precipitation between the two; for the 1969–88 period, Watershed 3 averaged 1,338 mm and Watershed 6, 1,423 mm (Table 4).

For many uses, monthly precipitation is the most desirable value. Here we provide monthly precipitation for Watershed 3 (Table 5), Watershed 6 (Table 6), and the north-facing Watershed 7 (Table 7).

In many publications about precipitation chemistry at HB, annual precipitation has been reported for Watershed 6 over a "water year" beginning June 1 and ending May 31 (see Water Budget section). These annual amounts are shown in Table 19.

Generally, precipitation increases from east to west across the watersheds, both annually and in individual months (Table 8). Some, but not all, of the difference arises because the westernmost and north-facing Watersheds 7 and 8 have higher elevation. Of the south-facing watersheds, Watershed 6, the westernmost, is generally higher in precipitation than the other 5. Watersheds 1 through 5 incorporate data from standard gages at Stations 3 or 6, which have low precipitation for their elevation. If the Thiessen weighting method overweights the areas represented by these two gages, annual precipitation on Watersheds 1 through 5 would be underestimated. Further analysis of this problem is in the Water Budget section.

Temporal Variation

Year-to-year variation is much larger than watershed-to-watershed variation (Table 4). The standard deviation of annual precipitation is about 200 mm regardless of watershed (Table 4). The wettest year from 1956–88 was

Table 5.—Monthly and annual precipitation (mm) for Watershed 3[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1956[b]	71	85	144	107	142	94	228	112	172	61	94	127	1439
1957[b]	71	64	48	60	87	143	137	18L	78	110	179	221	1216
1958	202	82	56	115	104	60	125	57	113	98	96	54L	1161
1959	136	91	80	80	52	113	71	142	64	304H	220H	125	1479
1960	114	125	97	121	133	93	180	28	142	130	89	73	1325
1961	32	99	63	120	85	99	86	53	49	54	113	119	973L
1962	89	109	65	112	100	53	86	98	93	253	79	95	1231
1963	99	79	117	137H	77	65	74	150	39	31L	205	71	1145
1964	121	43	144	114	101	60	118	150	36	50	114	115	1165
1965	61	100	28L	82	24L	108	91	89	195	124	147	72	1121
1966	63	60	115	66	91	106	97	194H	116	83	134	100	1224
1967	57	99	53	132	108	79	112	137	135	121	113	150	1297
1968	73	62	97	113	202	162	62	57	67	75	128	188	1285
1969	72	179	83	88	110	90	187	152	45	63	139	194	1403
1970	26	99	106	99	93	96	62	155	139	100	91	135	1201
1971	73	119	95	50L	110	68	143	114	77	103	101	120	1173
1972	69	81	169H	88	88	120	158	159	49	95	165	182	1424
1973	128	88	93	102	164	354H	85	115	149	94	133	287H	1793H
1974	115	88	123	129	162	123	102	130	167	47	118	108	1410
1975	117	81	143	69	38	167	181	95	167	143	134	114	1449
1976	146	123	110	91	187	113	107	136	133	204	61L	105	1516
1977	77	74	166	109	39	123	70	99	198H	195	99	140	1388
1978	230H	27	71	76	104	142	52L	88	35L	93	63	105	1086
1979	226	56	142	129	155	52	72	131	124	147	118	80	1433
1980	54	38	136	129	58	77	88	85	132	112	126	67	1101
1981	24L	259H	43	120	128	167	234H	139	150	197	65	139	1665
1982	119	74	112	106	29	157	70	70	110	51	146	71	1114
1983	123	84	139	118	190	33L	75	150	46	97	204	195	1452
1984	53	118	121	130	302H	176	139	31	38	79	118	98	1404
1985	60	88	92	64	104	118	54	84	146	114	131	83	1137
1986	207	75	125	61	114	85	140	168	98	63	133	105	1373
1987	90	11L	164	72	81	194	77	109	154	106	115	61	1235
1988	61	78	47	97	87	69	110	135	72	56	134	63	1010
ave[c]	101	90	103	101	110	114	107	113	106	112	124	117	1296
sd	56	45	38	25	58	61	45	42	50	62	38	51	187
ave daily	3.3	3.2	3.3	3.4	3.5	3.8	3.5	3.6	3.5	3.6	4.1	3.8	3.5

[a]H shows the highest and L the lowest value for that month.
[b]Watershed 1
[c]Average (ave) and standard deviation (sd) are over years 1958–88.

Table 6.—Monthly and annual precipitation (mm) for Watershed 6[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1964	117	50	147	110	103	58	126	154	39	54	120	117	1194
1965	66	103	29L	83	26L	115	99	84	193	127	153	78	1157
1966	72	67	129	70	94	117	100	200H	117	87	154	107	1314
1967	63	111	57	149	117	82	116	134	142	125	118	160	1374
1968	77	69	103	126	219	160	55	53	77	80	138	212	1369
1969	84	182	102	103	103	93	203	147	48	64	156	206	1491
1970	26	102	119	103	93	100	66	162	140	106	97	149	1263
1971	89	136	107	57L	120	70	151	123	75	108	114	119	1270
1972	77	83	180H	93	87	129	158	167	48	94	176	201	1493
1973	121	75	97	118	181	373H	87	115	142	99	129	287H	1824H
1974	115	94	136	145	166	121	111	138	172	48L	118	111	1475
1975	121	93	168	68	39	171	181	96	174	143	158	126	1540
1976	161	145	124	93	196	113	110	145	138	205H	77	114	1622
1977	91	86	168	117	37	133	73	96	198H	193	124	153	1470
1978	250H	32	83	85	113	148	53L	96	36L	95	70L	115	1176
1979	232	61	140	153H	162	47	82	132	128	163	128	79	1506
1980	53	41	147	135	58	81	92	92	136	124	130	77	1166
1981	26L	298H	44	122	135	150	234H	150	160	197	72	149	1736
1982	135	78	118	112	32	163	76	72	114	52	150	72	1174
1983	134	95	153	128	199	34L	77	155	47	98	217H	221	1558
1984	60	130	135	149	314H	179	143	37L	39	88	120	122	1516
1985	74	93	125	74	106	129	57	90	156	116	145	93	1258
1986	224	83	135	64	133	89	151	176	97	65	142	119	1479
1987	108	14L	178	81	91	204	75	114	166	113	123	72	1338
1988	68	94	53	108	101	68	115	147	74	58	153	67L	1107L
ave	106	97	119	106	121	125	112	123	114	108	131	133	1395
sd	59	55	41	29	66	67	47	40	52	45	32	56	189

[a]H shows the highest and L the lowest value for that month.

1973 with 1,793 mm of precipitation on Watershed 3. The driest year was 1961 with 973 mm. This dry year was caused by a series of many dry months (Table 5). However, the high precipitation in 1973 was caused completely by very abnormal precipitation in June and December (Table 5). The June 1973 precipitation of 354 mm was the highest monthly precipication on record; December 1973, at 287 mm, was the fourth highest month on record. The second and third highest months were October 1959, 304 mm, and May 1984, 302 mm.

Month-to-month variation in average precipitation on Watershed 3 is small (Fig. 4). Average daily precipitation by month on Watershed 3 has a slight minimum in February at 3.2 mm and maximum in November at 4.1 mm (Table 5). Differences in monthly precipitation among watersheds are smallest in June and July and largest in November through April (Table 8), suggesting that snowfall varies spatially more than rainfall does.

Using a >1 mm criterion for a "rain day," slightly over 1 of 3 days has precipitation, regardless of the time of the year (Table 9). In the driest months of record this drops to 1 in 5 days, while the wettest months have precipitation 1 of 2 days in summer and 2 of 3 days in winter.

The largest storms at HB caused total rainfall of 100 to 200 mm over several days (Table 10). These storms happen any time of year, usually causing local or regional flooding. Only two of the 20 largest storms (Table 10) were tropical hurricanes: the 3rd largest, Daisy, October 5–10, 1962, and the 17th largest, Donna, September 10–13, 1960. The HB record began shortly after the three severe New England hurricanes of 1954 and 1955. The storm periods given in Table 10 include consecutive days with precipitation. Most of the precipitation fell in a much shorter period than shown. The high precipitation events in winter occurred with temperatures at or above freezing, and were predominantly rain events.

Table 7.—Monthly and annual precipitation (mm) for Watershed 7[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1965	70	108	33	82	23L	122	94	79	178	136	145	72	1142
1966	89	68	127	68	105	107	89	170	122	86	159	107	1294
1967	52	96	56	136	124	104	117	136	141	121	116	147	1347
1968	69	65	107	117	172	170	33L	44	99	77	148	200	1298
1969	86	192	100	103	110	100	201	154	43	63	190	226	1568
1970	28	114	118	108	93	98	66	141	137	108	92	147	1250
1971	90	142	115	56L	119	55	155	120	81	112	113	125	1284
1972	67	97	179H	95	98	127	152	154	46	98	191	197	1501
1973	113	73	100	139	202	347H	80	111	139	102	117	290H	1815H
1974	116	98	138	145	174	124	135	145	175	48L	125	114	1535
1975	123	96	158	74	55	159	192	95	176	143	146	123	1541
1976	156	130	120	96	202	109	118	168	133	217H	73	103	1625
1977	98	85	165	115	36	140	63	96	206H	200	128	156	1488
1978	249H	29	84	93	122	154	69	85	34L	99	69L	106	1194
1979	232	58	136	153	173	39L	76	134	124	165	124	76	1490
1980	52	37	161	158	64	94	81	108	147	133	128	74	1235
1981	23L	314H	41L	127	148	169	230H	149	172	190	74	124	1763
1982	147	78	119	102	36	165	71	83	112	52	139	71L	1176L
1983	130	98	167	147	196	40	71	185	51	93	236H	207	1620
1984	64	125	129	165H	316H	185	146	34L	42	80	136	132	1554
1985	60	87	135	74	104	115	62	87	177	120	161	93	1275
1986	232	78	139	63	108	94	155	213H	94	62	160	136	1533
1987	114	13L	164	85	97	218	83	98	170	124	127	82	1375
1988	70	104	55	137	113	59	113	164	70	60	177	62	1182
ave	105	99	119	110	125	129	111	123	120	112	136	132	1420
sd	61	59	41	32	66	65	51	44	52	46	39	57	191

[a]H shows the highest and L the lowest value for that month.

Table 8.—Average monthly and annual precipitation (mm) by watershed for 1969–86[a]

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
3	107	97	115	98	121	126	112	117	111	111	119	129	1362
2	104	96	112	96	121	126	112	117	111	111	118	126	1351
1	106	97	114	96	122	126	112	117	111	111	119	128	1358
4	108	99	116	99	124	128	115	119	112	112	122	132	1387
5	109	100	118	100	125	128	116	120	112	112	124	133	1398
6	115	106	127	107	126	129	117	122	114	114	129	140	1445
8	116	107	129	111	131	128	117	125	116	116	133	140	1469
7	115	107	128	112	131	129	118	126	116	116	133	139	1469

[a]Watersheds are ordered from east to west.

Table 9.—Minimum, average, and maximum number of days per month with precipitation > 1.0 mm for Watershed 3, 1958–86

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
min	5	3	9	7	6	6	6	6	5	6	9	8	121
ave	12	11	13	12	12	12	11	11	9	11	13	14	140
max	22	17	18	17	19	18	15	15	17	16	18	22	161

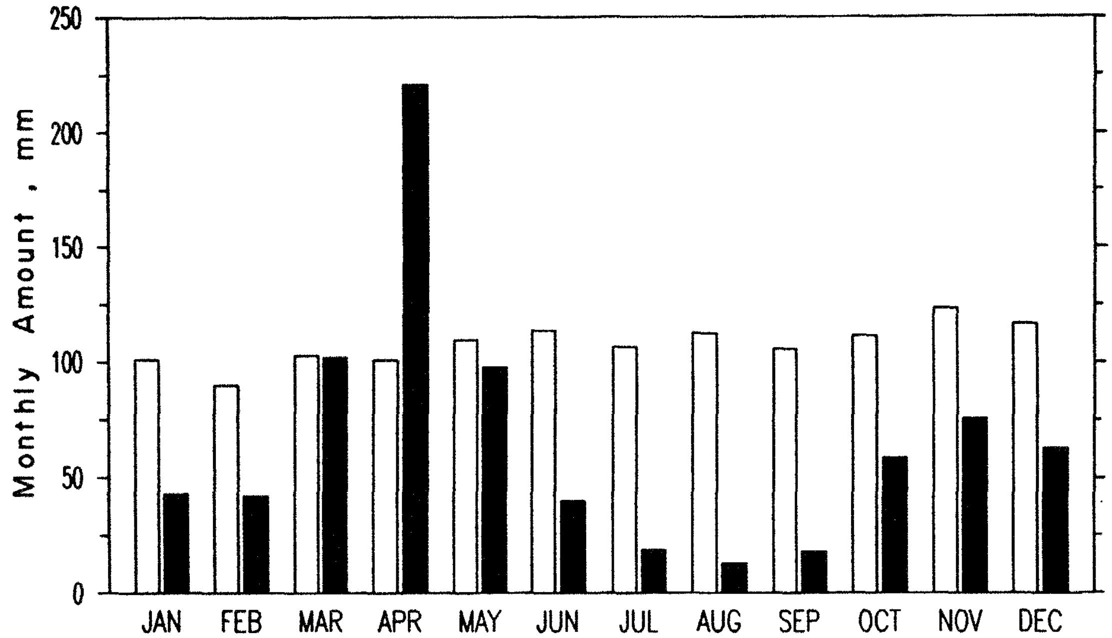


Figure 4.—Average monthly precipitation (open bars) and streamflow (solid bars) for Watershed 3, 1958–88.

Table 10.—The 20 largest precipitation events for Watershed 1, 1956-57 and Watershed 3, 1958-88

Event	mm
Jun 27 – Jul 1, 1973	211.6
Oct 23 – Oct 26, 1959	184.9
Oct 5 – Oct 10, 1962[a]	182.9
May 28 – Jun 2, 1984	162.1
Jul 26 – Aug 2, 1969	151.1
Jul 9 – Jul 15, 1975	140.4
Jan 25 – Jan 28, 1986[b]	132.2
Mar 30 – Apr 6, 1960	125.0
Sep 8 – Sep 13, 1987	116.8
Mar 30 – Apr 1, 1987	111.9
Nov 5 – Nov 17, 1985[b]	110.4
May 23 – May 30, 1979	110.2
Feb 24 – Feb 26, 1969	102.6
Jan 6 – Jan 11, 1978[b]	98.9
Nov 28 – Dec 7, 1983[b]	95.5
May 29 – May 31, 1968	95.2
Sep 1 – Sep 1, 1965	95.1
Nov 6 – Nov 11, 1963[b]	93.9
Sep 10 – Sep 13, 1960[c]	93.5
Oct 8 – Oct 9, 1977	92.8
Dec 26 – Dec 27, 1969[b]	92.2
Sep 12 – Sep 14, 1977	89.7

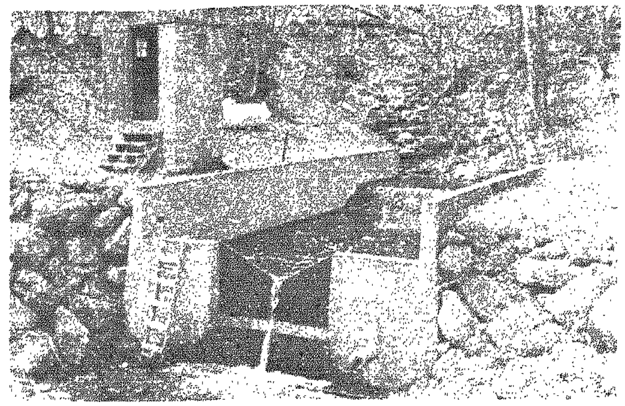
[a]Hurricane Daisy
[b]Temperature at or above freezing, predominantly rain events.
[c]Hurricane Donna

Streamflow

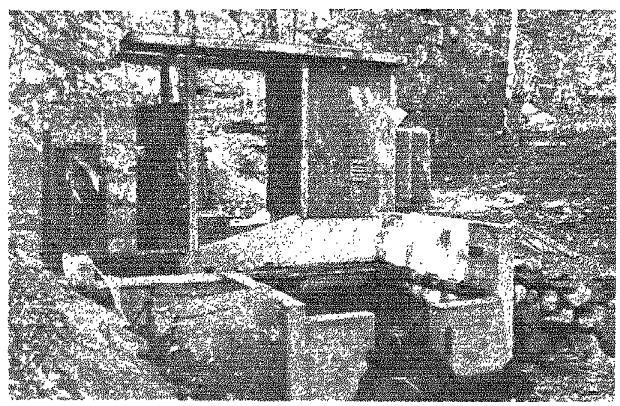
Construction of the streamgages at HB has been described by Reinhart and Pierce (1964). To prevent leakage each gage is anchored to bedrock. The streamflow is forced over a V-shaped dam, called a V-notch weir. The height of water behind the dam increases as streamflow increases. This height is measured continuously by a float attached mechanically to a pen on a springwound strip-chart recorder. For each day, between 2 and 130 points on the chart trace are digitized, depending on the rate of change of flow. These "gage heights" are converted to streamflow rate by calibration factors and then are integrated to give daily streamflow. The streamgages on Watersheds 5 to 8 have a rectangular (modified San Dimas) flume in series with the V-notch weir. When streamflow is high, the depth of the water in the flume is recorded as the measure of streamflow. To keep them ice free in winter both V-notches and flumes are heated by propane burners, so streamflow measurement is continuous throughout the year.

Streamflow rate is measured as volume per unit time (L/s) and is proportional to the watershed area. To make streamflow comparable among watersheds of different areas the streamflow rate is divided by watershed area (Table 11) to give units of depth per unit time (over the entire watershed area). After integrating over a given time, streamflow is expressed in mm, and is directly comparable to precipitation.

Streamflow varies considerably from day to day and season to season in response to precipitation, soil drying by evapotranspiration, and snow accumulation and melt. Hydrographs of daily streamflow for Watershed 1 (1956–57) and Watershed 3 (1958–88) are shown in Figure 5. These graphs give an excellent picture of hydrologic activity for any desired period.



Streamgage 4.



Streamgage 6, with flume on the left, V-notch on the right.

Table 11.—Area, slope, and aspect of gaged watersheds[a]

Watershed	Area ha	Slope deg	Aspect deg
1	11.8	18.6	S22E
2	15.6	18.5	S31E
3	42.4	12.1	S23E
4	36.1	15.6	S40E
5	21.9	15.4	S24E
6	13.2	15.8	S32E
7	76.4	12.4	N16W
8	59.4	14.0	N11W

[a]Slope and aspect are for the watershed "lid", a plane fitted to the circumference of the watershed.

Streamflow varies considerably from year to year in response to variation in annual precipitation (see Water Budget section). For Watershed 3, the highest annual streamflow occurred in 1973 at 1,396 mm, and the lowest annual streamflow occurred in 1961 at 436 mm (Table 12), corresponding to the years of highest and lowest annual precipitation. The standard deviation of annual streamflow is around 200 mm for all watersheds (Table 12), about the same as for precipitation. Annual streamflow from Watershed 6 for a water year beginning June 1 (see Water Budget section) is given in Table 19. These values frequently have been reported in publications on water chemistry at HB.

Monthly streamflow, in contrast to monthly precipitation, is highly seasonal (Fig. 4). April has the highest streamflow because the snowpack, which has accumulated through the winter, melts. Streamflow is lowest in August because of high rates of summer evapotranspiration. Monthly streamflow is given here for Watershed 3 (Table 13), Watershed 6 (Table 14), and Watershed 7 (Table 15).

Table 12.—Annual streamflow (mm) by watershed

	Watershed							
Year	1	2	3	4	5	6	7	8
1956	942	–	–	–	–	–	–	–
1957	732	–	–	–	–	–	–	–
1958	590	645	567	–	–	–	–	–
1959	947	1012	918	–	–	–	–	–
1960	761	825	752	–	–	–	–	–
1961	458	470	436	495	–	–	–	–
1962	697	777	699	710	740	–	–	–
1963	652	774	663	713	686	775	–	–
1964	653	712	630	713	683	704	–	–
1965	520	599T[a]	547	583	624	581	–	–
1966	746	1189T	757	826	826	845	851	–
1967	758	1132T	781	839	815	834	816	–
1968	771	1057T	763	823	836	835	790	–
1969	1046	1348T	999	1099	975	1070	1174	1106
1970	661	905T	698	727T	669	735	741	704
1971	641	801T	676	765T	659	718	780	737
1972	877	1006T	886	990T	903	948	995	936
1973	1403	1586T	1396	1589T	1428	1470	1408	1419
1974	887	998T	890	1021T	928	951	1004	993
1975	934	1086T	940	1085T	944	963	991	983
1976	1067	1143T	1022	1158T	1069	1074	1116	1110
1977	895	966T	844	971T	863	878	957	895
1978	650	722T	614	717T	635	683	757	701
1979	1052	1136T	1036	1085T	1035	1070	1088	1075
1980	560	585T	548	575T	554	578	693	655
1981	1098	1129T	1094	1117T	1059	1078	1208	1164
1982	756	803T	756	792T	718	743	785	774
1983	908	917T	889	916T	843T	894	980	962
1984	974	1001T	971	1003T	1129T	977	1063	1036
1985	640	635T	628	643T	704T	688	777	732
1986	958	988T	961	1005T	957T	998	1025	1067
1987	769	790T	797	804T	789T	839	919	902
1988	497	491T	502	520T	544T	574	673	644
ave[b]	864	–	857	–	–	896	957	930
sd	220	–	213	–	–	213	193	203

[a]T shows treated watersheds.
[b]Average (ave) and standard deviation (sd) over years 1969–88.

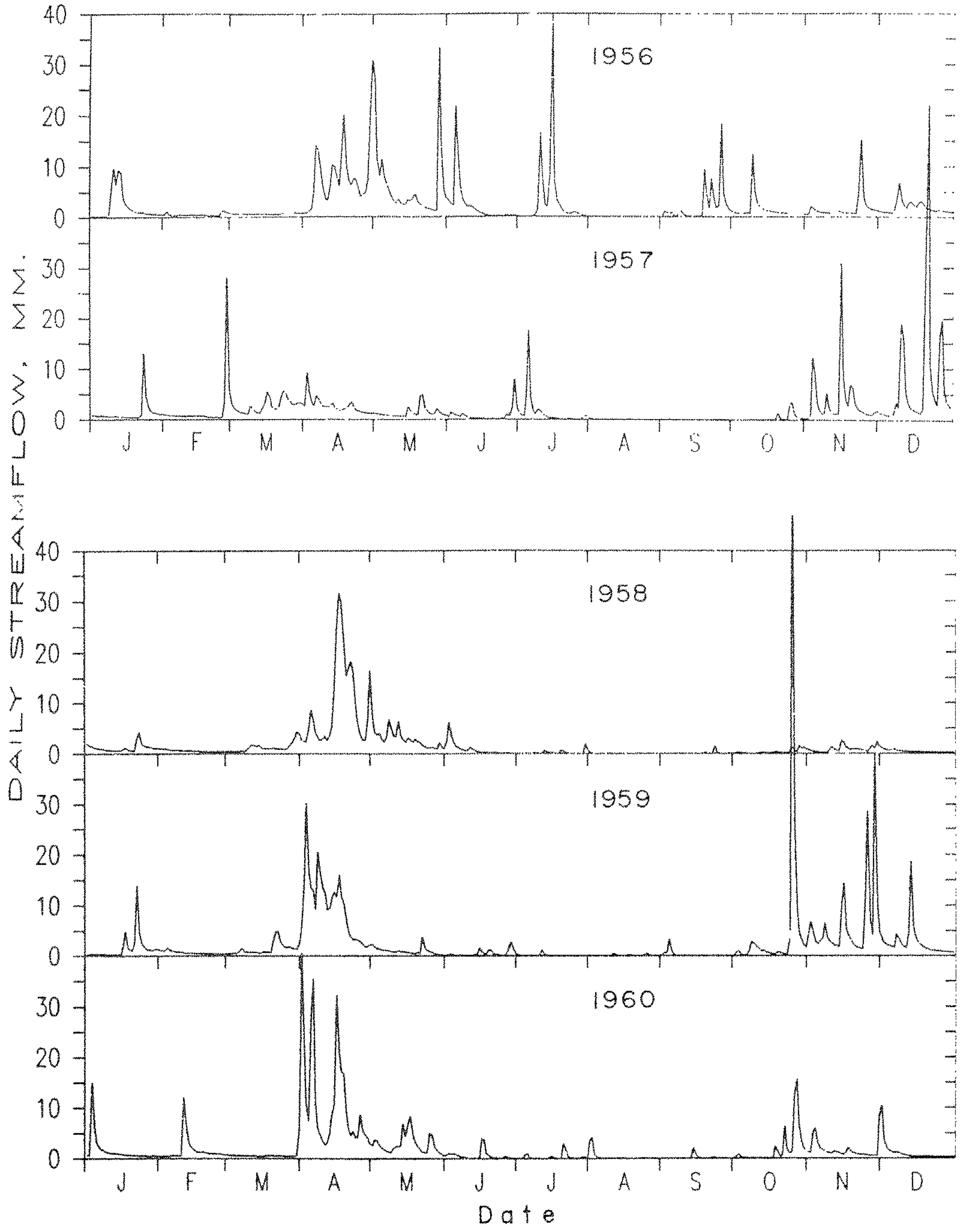


Figure 5a.—Daily streamflow for Watershed 1, 1956–57, and Watershed 3, 1958–60.

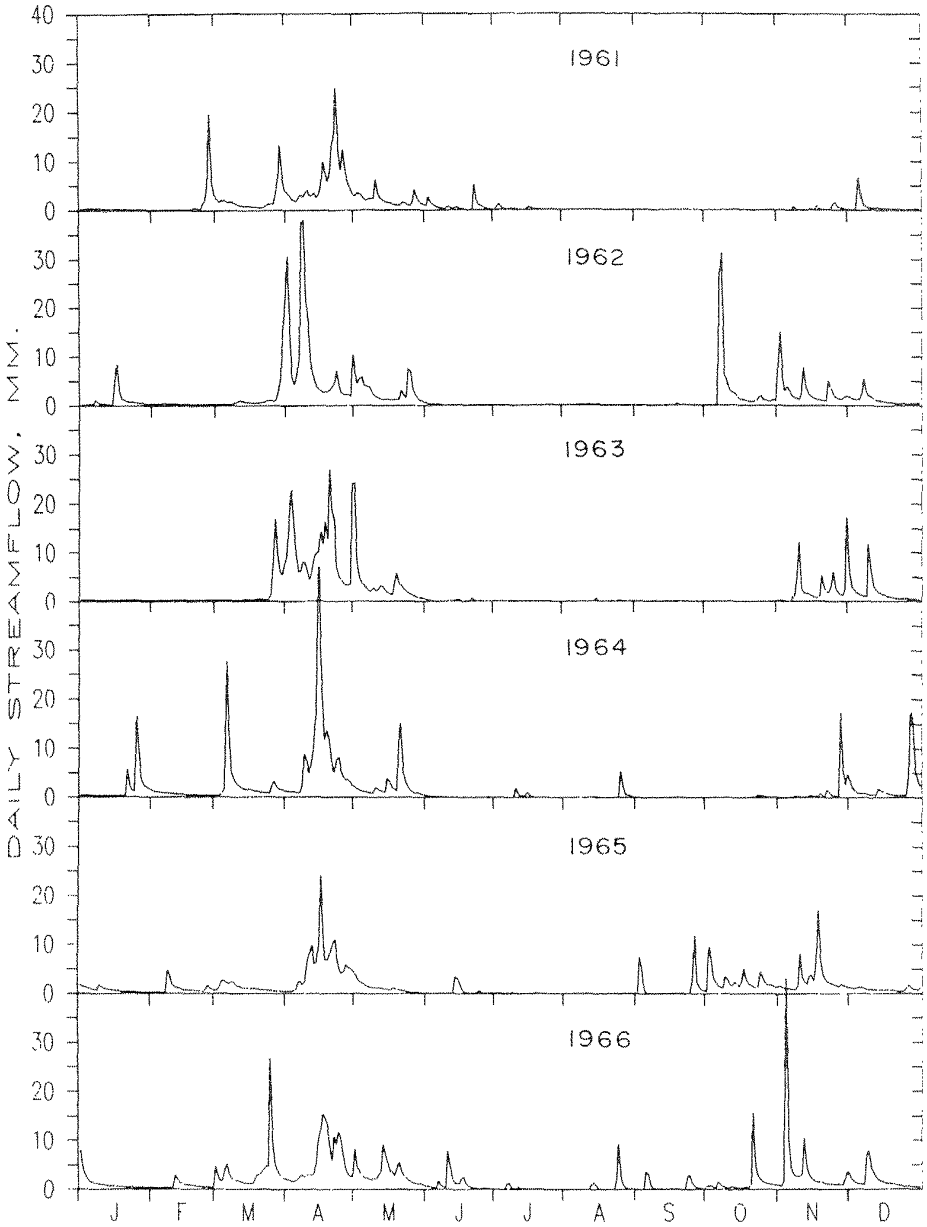


Figure 5b.—Daily streamflow for Watershed 3, 1961–66.

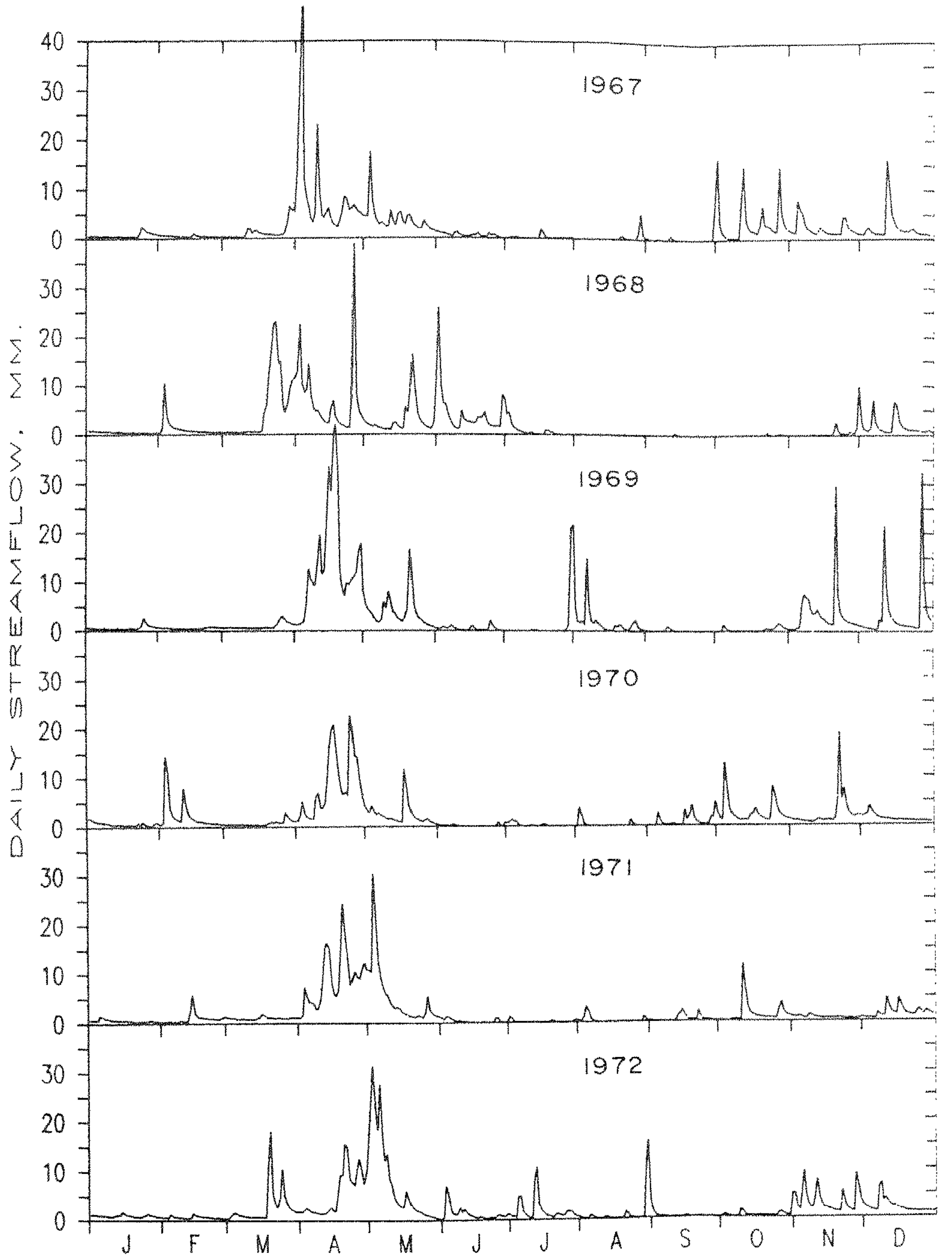


Figure 5c.—Daily streamflow for Watershed 3, 1967–72.

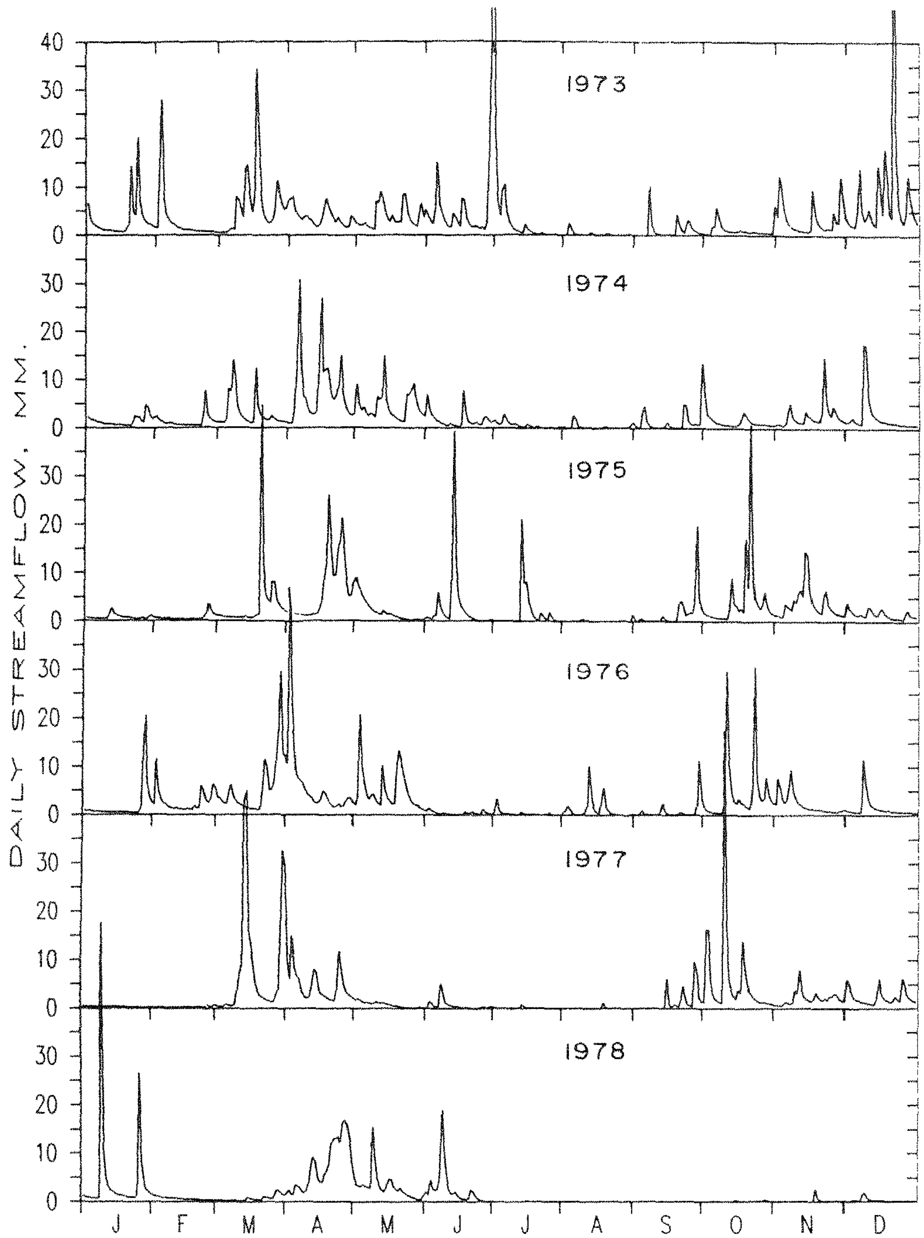


Figure 5d.—Daily streamflow for Watershed 3, 1973–78.

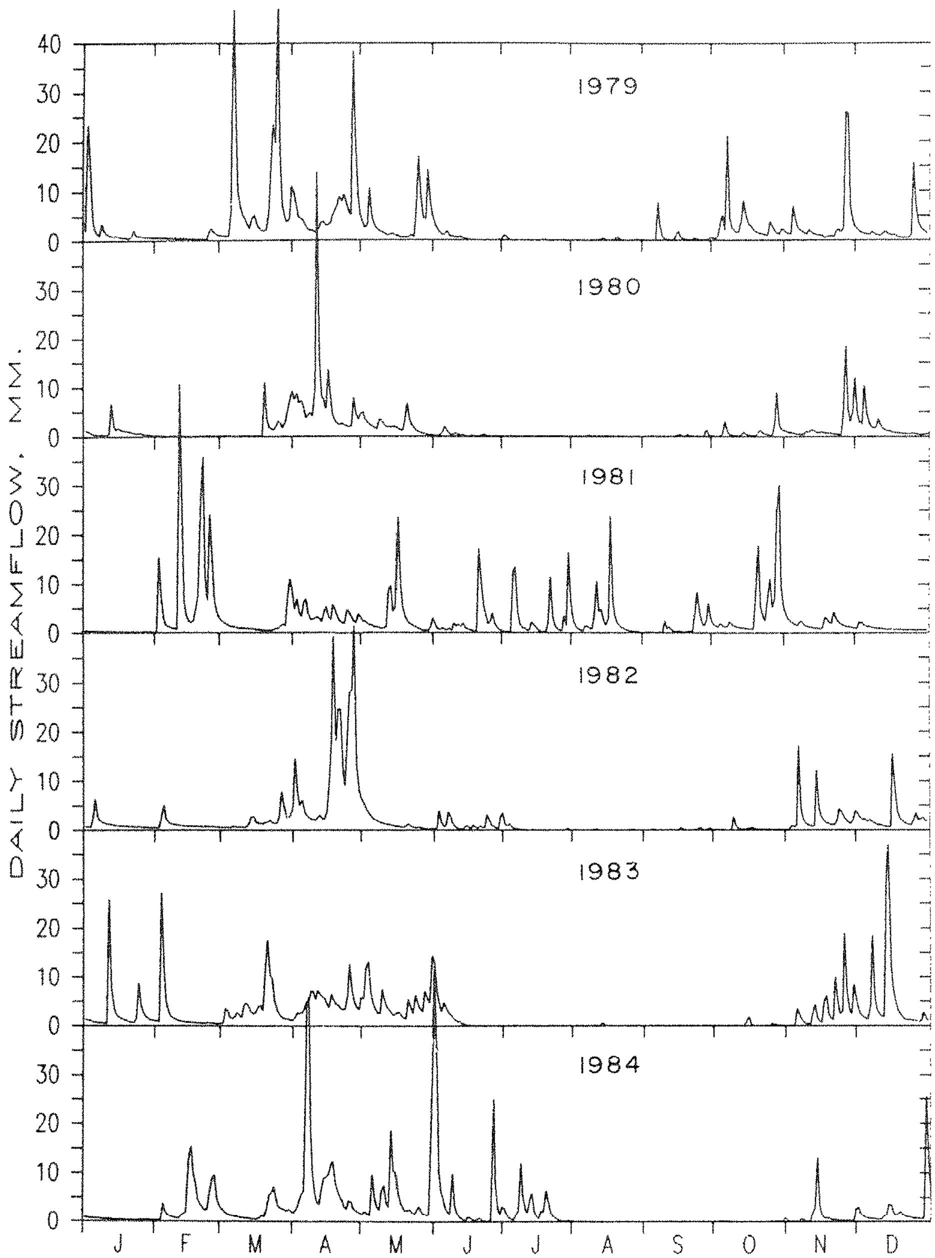


Figure 5e.—Daily streamflow for Watershed 3, 1979–84.

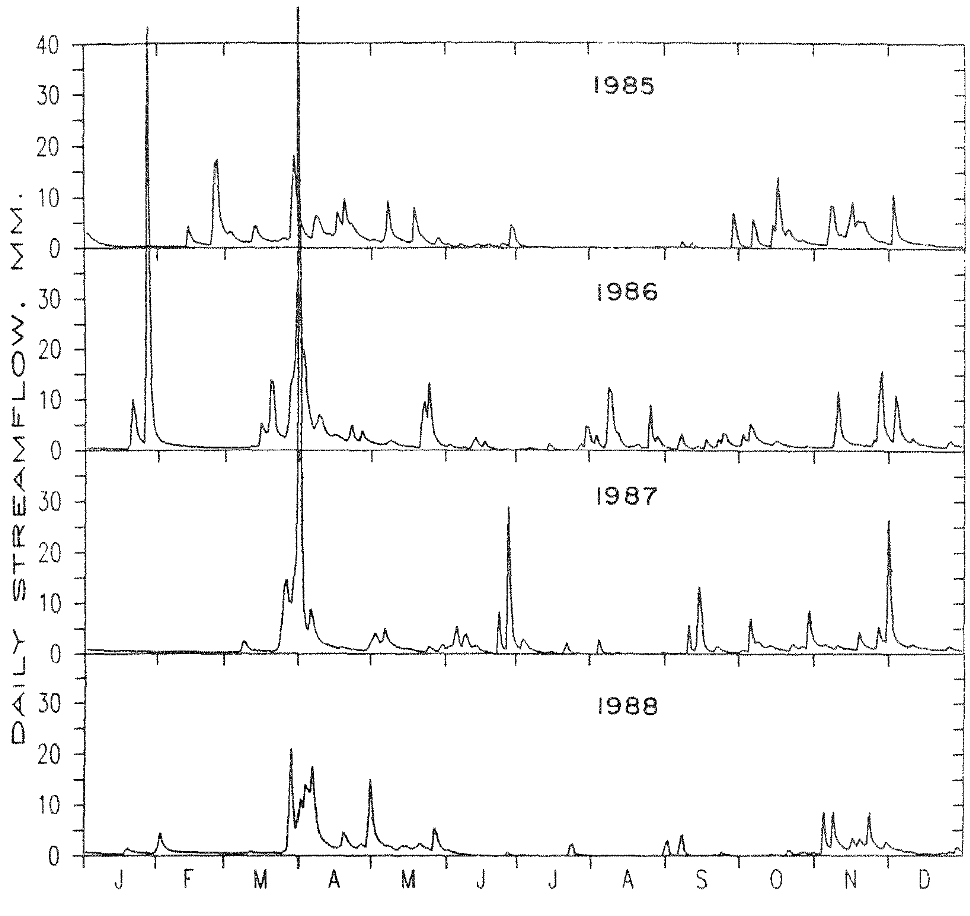


Figure 5f.—Daily streamflow for Watershed 3, 1985–88.

Table 13.—Monthly and annual streamflow (mm) for Watershed 3[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1956[b]	64	17	21	277	164	68	101	2	68	45	54	60	942
1957[b]	41	53	84	81	41	25	42	<1L	<1L	12	118	234	732
1958	38	18	40	291	89	25	7	1L	3	13	28	15	567
1959	48	19	44	295	30	15	4	3	7	176	198H	78	918
1960	48	48	64	310	88	18	19	3	5	64	61	24	752
1961	9	42	66	188	66	24	7	1L	1L	1L	10	20	436L
1962	32	10	64	268	85	4	1L	2	2	110	85	36	699
1963	12	9	65	321	103	6	1L	3	1L	1L	82	58	663
1964	56	19	92	253	71	3L	6	10	1L	4	43	71	630
1965	24	28	37	178	33	13	2	1L	35	80	88	27	547
1966	39	22	117	180	101	34	4	20	19	47	120	54	757
1967	23	15	45	272	119	19	8	11	27	96	71	75	781
1968	17	36	184	199	124	103	18	1L	2	3	24	53	763
1969	23	18	33	435H	121	17	51	50	6	15	116	114	999
1970	23	71	25	256	75	6	7	10	33	83	70	39	698
1971	20	31	33	271	159	10	6	11	14	48	20	52	676
1972	32	22	93	200	206	43	56	40	6	26	99	62	886
1973	101	84	209	112	122	245H	72	8	34	41	103	266H	1396H
1974	46	37	100	239	140	49	17	10	51	38	82	79	890
1975	25	21	118	201	62	94	53	4	56H	138	118	49	940
1976	62	83	184	186	159	13	11	35	29	151	64	45	1022
1977	12	9	258	149	24L	20	3	3	42	187H	63	73	844
1978	149	20	24L	219	100	77	1L	1L	1L	3	6L	11L	614
1979	76	20	305H	201	116	18	4	4	20	98	111	64	1036
1980	30	4L	64	217	60	11	2	2	5	33	70	51	548
1981	8L	277H	57	113	103	69	94H	80H	43	164	56	30	1094
1982	37	32	60	363	43	38	7	2	4	10	84	77	756
1983	82	67	121	151	162	35	1L	3	1L	6	102	160	889
1984	16	115	64	259	235H	95	65	1L	1L	3	38	78	971
1985	23	68	98	112	67	21	3	1L	17	75	100	44	628
1986	175H	24	180	145	75	19	19	77	37	52	90	66	961
1987	20	11	248	102L	49	95	21	7	46	64	79	54	797
1988	19	29	78	161	63	7	7	7	11	11	87	23	502
ave[c]	43	42	102	221	98	40	19	13	18	59	76	63	796
sd	39	51	75	78	50	49	25	21	18	57	39	48	205

[a]H shows the highest and L the lowest value for that month.
[b]Watershed 1
[c]Average (ave) and Standard Deviation (sd) are over years 1958–88.

Except in winter, streamflow increases from east to west across the gaged watersheds (Table 16) as a consequence of the precipitation pattern. Average annual streamflow from 1969–86 was 880 mm for Watershed 3, but 975 mm for Watershed 7. Snow melts later on the north-facing Watersheds 7 and 8 than on the south-facing Watersheds 1 to 6 because of both higher elevation and northern aspect. Consequently, March streamflow is lower and May streamflow is higher on Watersheds 7 and 8. In April peak flow is later in the month on Watersheds 7 and 8, though the average April total is about the same.

The highest monthly streamflow for Watershed 3 has been 435 mm in April 1969 (Table 13), and the highest for Watershed 7 has been 409 mm in May 1971 (Table 15). Both these months had normal precipitation (Tables 5 and 7), so the high streamflows were caused solely by melt of large snow packs (Fig. 16).

Monthly streamflows of only 1 or 2 mm are not uncommon in summer months (Tables 13–15). In winter, streamflow is maintained for long periods at about 0.3 mm/d by continuous melt from soil heating of the bottom of the

Table 14.—Monthly and annual streamflow (mm) for Watershed 6[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1963	14	11	68	383	124	9	2	5	<1L	2L	100	57	776
1964	57	19	98	266	82	4L	7	20	2	7	61	80	703
1965	27	31	38	179	40	15	5	1L	46	77	92	31	582
1966	34	22	115	199	120	41	9	32	27	52	138H	58	847
1967	26	16	43	270	136	24	13	14	36	101	77	79	835
1968	18	39	189	210	149	113	16	2	4	8	33	54	835
1969	26	19	32	449H	143	21	68	54	7	17	119	116	1071
1970	25	67	28L	267	82	9	10	15	35	77	80	41	736
1971	23	36	33	267	202	11	8	15	10	41	22	49	717
1972	33	22	99	213	219	56	60	48	8	28	101	61	948
1973	97	84	205	138	143	277H	74	11	29	42	98	272H	1470H
1974	47	40	98	265	147	52	23	15	59	38	86	81	951
1975	28	22	124	208	73	94	60	7	60H	120	112	55	963
1976	62	85	185	191	157	16	14	48	41	157	72	46	1074
1977	13	11	253	155	24L	28	5	5	50	175H	81	79	879
1978	163	24	28L	220	125	84	2	2	1	8	11L	15L	683
1979	77	20	310H	199	122	20	5	6	25	110	112	64	1070
1980	28	4L	54	219	61	13	3	3	10	57	73	53	578
1981	9L	285H	63	107L	104	58	85H	80	49	158	53	29	1080
1982	36	29	55	351	46	44	8	3	7	14	76	72	741
1983	84	67	111	168	158	35	1L	5	<1L	9	101	154	894
1984	16	110	60	285	227H	99	63	1L	<1L	5	44	68	979
1985	21	66	104	135	65	31	5	2	31	79	104	46	689
1986	174H	26	177	146	92	20	28	87H	39	54	86	69	998
1987	23	13	252	107L	56	104	22	9	54	69	78	52	839
1988	19	30	79	175	78	8	9	12	17	14	109	24	574L
ave	45	46	112	222	114	49	23	19	25	58	82	69	866
sd	43	56	79	82	54	57	26	24	20	52	30	50	200

[a]H shows the highest and L the lowest value for that month.

snowpack. So, 9 mm is about the minimum flow in January and February (Table 13). The lowest winter streamflow occurred in February 1980 when lack of snow (Fig. 16) allowed deep soil frost (Table 28), preventing melt.

Maximum Streamflow Rates

The twenty highest peak flows at Hubbard Brook (Table 17) are not well correlated with the twenty largest precipitation events. Melting snow, in addition to rain, occurred in five of the eight highest streamflow peaks. Heavy rain in summer usually does not cause high streamflow because the soil is somewhat dry from evapotranspiration. Only one of the top 16 streamflows occurred in summer; this period, June 27–July 1, 1973, had the greatest rainfall event at 212 mm, but produced only the 10th highest streamflow.

Two forms of data presentation are of particular interest to hydrologists and engineers. Calculations of flood-return periods require knowledge of the highest streamflow rate recorded each year (Table 18). The frequency of streamflow occurrence is shown by flow duration curves (Fig. 6). Daily flow greater than 10 mm occurs about 5 percent of the time, but contributes 37 percent of the annual total. Daily flow of less than 1 mm occurs on over half the days, but contributes only 10 percent of the annual total.

Flow recession after storm peaks is very rapid at HB. Daily Watershed 3 streamflows in the greatest streamflow event, October 22–30, 1959, were

10/22	10/23	10/24	10/25	10/26	10/27	10/28	10/29	10/30	
0.4	3.5	101.9	26.0	8.6	4.8	3.0	2.1	1.7	mm

Recession is even faster in June through September when the trees are fully leafed and evapotranspiration is high.

Table 15.—Monthly and annual streamflow (mm) for Watershed 7[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1965	35	24	17	–	147	30	6	2	48	97	74	22	–
1966	33	15	74	130	248	50	6	14	34	64	127	57	851
1967	15	12	15L	175	247	41	16	17	39	110	60	68	816
1968	13	27	128	272	112	104	17	1L	4	8	41	62	789
1969	18	13	15L	377H	296	26	78	58	4	11	159H	120	1174
1970	20	59	16	266	138	9L	11	9	29	90	65	29	741
1971	13	23	25	129	409H	13	7	17	20	65	25	35	780
1972	26	18	71	89L	404	64	67	39	6	34	115	62	995
1973	79	66	150	259	165	228H	61	7	29	47	94	223H	1408H
1974	31	30	72	291	182	50	47	23	84H	46	85	63	1004
1975	18	14	85	111	233	117	61	4	80	121	108	40	990
1976	47	61	126	284	171	16	11	98	36	170	58	36	1116
1977	9	6	194	263	29L	36	5	11	73	202H	67	62	957
1978	142	21	15L	136	302	97	2L	2	1L	7	14L	18L	757
1979	77	16	200H	280	168	20	2L	4	29	129	115	47	1087
1980	16	1L	30	256	98	31	5	5	37	95	74	45	693L
1981	6L	271H	54	174	123	83	97H	95	71	163	49	22	1207
1982	26	27	28	301	135	63	14	3	8	24	93	62	785
1983	63	51	97	211	207	39	2	6	2	13	149	139	979
1984	13	69	38	347	283	110	69	2	1L	3L	55	74	1063
1985	21	49	52	203	88	28	8	2	61	105	123	37	777
1986	152H	20	122	226	82	19	32	133H	43	46	90	61	1025
1987	18	8	181	206	69	139	21	5	55	90	80	49	919
1988	14	25	41	240	118	10	6	19	23	16	143	18	673
ave[b]	38	39	80	227	187	61	28	25	33	72	86	62	939
sd	40	54	60	76	102	53	29	36	27	58	39	45	186

[a]H shows the highest and L the lowest value for that month.
[b]Average (ave) and standard deviation (sd) are over years 1966–88.

Table 16.—Average monthly and annual streamflow (mm) by untreated watershed, 1969–86[a]

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
3	52	56	113	213	113	49	26	19	22	65	77	76	880
1	58	61	128	204	106	49	26	18	20	63	79	77	889
6	53	56	112	221	122	54	29	23	26	66	79	76	918
8	45	43	72	220	190	57	33	30	38	74	82	63	947
7	43	45	77	234	195	58	32	29	34	76	85	65	975

[a]Watersheds are ordered from east to west.

Water Budget

At HB the "paired watershed" method is fundamental to research. In this method one watershed is treated and another remains as an untreated control. Before treatment, the water budgets of the paired watersheds ideally would be identical. Then any differences after treatment can be interpreted as treatment effects. In reality, two watersheds are never identical. Calibration, a regression comparison of the two before treatment, is used to explain the differences, but such calibrations are outside the scope of this publication. The pretreatment water budgets of HB watersheds are analyzed here: 1) to describe the degree of similarity among HB watersheds, 2) to evaluate evapotranspiration, 3) to examine the possibility of unmeasured seepage loss of water, and 4) as a test of the accuracy of precipitation and streamflow measurement.

Very little of the water moving through a forest is converted into other molecular forms. The small amount of water transformed into organic matter by photosynthesis largely is offset by water created by respiration. The annual net primary productivity at HB is around 1,000 g/m^2 (Bormann and Likens 1979), which represents the conversion of about 0.6 mm of water to organic molecules, out of about 1,200 mm of precipitation. Virtually all the water that enters a watershed, therefore, remains as water as it travels through and leaves the watershed.

The water budget of a watershed is a statement of the conservation of mass of water:

$$\text{precipitation} - \text{streamflow} - \text{evapotranspiration} - \text{increase in soil water} - \text{increase in snow water} - \text{seepage loss} = 0$$

Precipitation and streamflow have been discussed already. The evapotranspiration term represents water converted to vapor and returned directly from the watershed to the atmosphere. It includes transpiration (water taken up through plant roots and evaporated from inside the leaves), evaporation from soil or snow surfaces, and evaporation from rain and snow intercepted by the forest canopy. Direct measurement of evapotranspiration is difficult and has not been done at HB. Soil water is the amount of water stored in soil and bedrock (though change in the latter is probably small at HB). Snow water is the water content of the snowpack. If the soil or snow water contents decrease over the time period, these terms change signs in the equation.

Seepage includes any liquid water that leaves the watershed and is not measured as streamflow. At HB this

Table 17.—The 20 largest instantaneous streamflows for Watershed 1, 1956–57, and Watershed 3, 1957–88, and the associated storm precipitation

	Peak discharge		Storm precipitation	
	csm	L s^{-1}ha^{-1}		mm
Oct 24, 1959	394.3	43.1	Oct 23 – Oct 26, 1989	184.9
Mar 31, 1987	337.2	36.9	Mar 30 – Apr 1, 1987	111.9
Oct 9, 1977	256.3	28.0	Oct 8 – Oct 9, 1977	92.8
Feb 11, 1981	227.2	24.8	Feb 11 – Feb 12, 1981	65.2
Jan 27, 1986	203.4	22.2	Jan 25 – Jan 28, 1986	132.2
Dec 21, 1973	178.5	19.5	Dec 20 – Dec 21, 1973	88.9
Apr 5, 1984	159.2	17.4	Apr 5 – Apr 8, 1984	70.8
Jan 9, 1978	154.3	16.9	Jan 6 – Jan 11, 1978	98.9
Oct 20, 1975	147.6	16.1	Oct 15 – Oct 20, 1975	87.5
Mar 13, 1977	147.4	16.1	Mar 13 – Mar 14, 1977	62.3
Jun 29, 1973	145.2	16.1	Jun 27 – Jul 1, 1973	211.6
Nov 26, 1979	130.5	15.9	Nov 24 – Nov 28, 1979	69.7
Dec 21, 1957	129.1	14.1	Dec 19 – Dec 21, 1957	80.8
Apr 1, 1976	128.1	14.0	Apr 1 – Apr 3, 1958	45.8
Apr 10, 1980	115.9	12.7	Apr 9 – Apr 16, 1980	79.5
Nov 3, 1966	115.7	12.6	Nov 2 – Nov 3, 1966	72.5
Aug 27, 1972	115.2	12.6	Aug 27 – Aug 28, 1972	88.3
May 30, 1984	110.6	12.1	May 28 – Jun 2, 1984	162.1
Jul 14, 1956[a]	109.6	12.0	Jul 12 – Jul 14, 1956	87.2
Jul 29, 1969	106.4	11.6	Jul 26 – Aug 2, 1969	151.1
Jul 13, 1975	103.6	11.3	Jul 9 – Jul 15, 1975	140.4

[a]Watershed 1

might occur through fractures in the bedrock, by leaks under the streamgage, and laterally through the soil into adjacent watersheds. Water that enters the watershed laterally through bedrock or soil is a negative seepage value. Seepage at HB usually is assumed to be negligible with respect to the other terms. This assumption is important to much of the research at HB. The streamgages are anchored to bedrock and carefully maintained to eliminate leaks. Bedrock generally is close to the surface. The watershed area is surveyed using the topographic divide between watersheds; this is assumed to be the same as the bedrock divide. Failure of this assumption produces seepage gains or losses. Permeable bedrock is another cause of seepage. However, geologic surveys, behavior of bedrock wells near HQ, and annual precipitation minus streamflow (see below) suggest that the amount of water gained or lost by seepage is quite small.

Change in snow-water content is measured at Hubbard Brook on a weekly basis (see Snow and Frost section), but the measurement is much less accurate than for precipitation and streamflow. Evapotranspiration and change in soil water are not measured, so both cannot be calculated from the water budget. Snow, however, is absent most of the year, and soil water is fully recharged around May 15 every year. By assuming there is no storage change from one May 15 to the next, and neglecting seepage, the annual water balance can be written as

$$\text{evapotranspiration} = \text{precipitation} - \text{streamflow}.$$

Such use of the May 15 to May 14 period defines a "water year." Analysis of hydrologic data by water year is useful when the effect of change in water storage should be minimized.

Annual geochemical inputs and outputs that have been published for HB use a June 1 water year. This is slightly less desirable than a May 15 water year because some soil drying may have occurred by June 1, but it is more convenient because data are summarized monthly. Annual precipitation and streamflow for Watershed 6 using a June 1 water year are given in Table 19.

Variation in precipitation minus streamflow among water years is small compared to variation in either precipitation or streamflow (Table 20). This estimate of evapotranspiration normally ranges from 450 to 600 mm at Hubbard Brook. Part of this variation is not in evapotranspiration but is caused by change in soil water of up to 25 mm between successive May 15ths. Real differences in evapotranspiration among years occur both because evaporation of intercepted water in the canopy is greater with higher precipitation, and because dry summers cause lower transpiration.

Following harvest treatments, evapotranspiration is decreased for a few years because the cover of regenerating vegetation is incomplete (Table 20). However, only a few years of regrowth are sufficient to restore the preharvest rate of evapotranspiration.

Differences Among Watersheds

Precipitation minus streamflow varies somewhat among watersheds within a year (Table 20). By averaging periods several years in length, the relative effect of storage change over one water year is reduced. However, for strict comparability, watersheds can be compared only over identical periods. Treated watersheds must also be excluded.

Precipitation minus streamflow averaged over groups of years is shown in Table 21. Evapotranspiration on Watersheds 1, 2, 4, 5, and 6 should be very similar since

Table 18.—Highest instantaneous streamflow in each year for Watershed 3

Date	csm	$L\ s^{-1}ha^{-1}$
Jul 14, 1956[a]	109.6	12.0
Dec 21, 1957	129.1	14.1
Apr 17, 1958	55.3	6.0
Oct 24, 1959	394.3	43.1
Mar 31, 1960	72.6	7.9
Apr 23, 1961	46.0	5.0
Apr 7, 1962	86.1	9.4
Apr 30, 1963	54.1	5.9
Apr 14, 1964	95.3	10.4
Apr 16, 1965	38.1	4.2
Nov 3, 1966	115.7	12.6
Apr 3, 1967	85.6	9.4
Apr 25, 1968	89.7	9.8
Jul 29, 1969	106.4	11.6
Apr 24, 1970	71.5	7.8
Oct 10, 1971	42.7	4.7
Aug 27, 1972	115.2	12.6
Dec 21, 1973	178.5	19.5
Dec 8, 1974	72.0	7.9
Oct 20, 1975	147.6	16.1
Apr 1, 1976	128.1	14.0
Oct 9, 1977	256.4	28.0
Jan 9, 1978	154.3	16.9
Nov 26, 1979	130.5	14.3
Apr 10, 1980	115.9	12.7
Feb 11, 1981	227.2	24.8
Apr 27, 1982	100.8	11.0
Feb 3, 1983	77.9	8.5
Apr 5, 1984	159.2	17.4
Sep 27, 1985	50.8	5.6
Jan 27, 1986	203.4	22.2
Mar 31, 1987	337.2	36.9
Mar 27, 1988	31.6	6.5

[a]Watershed 1

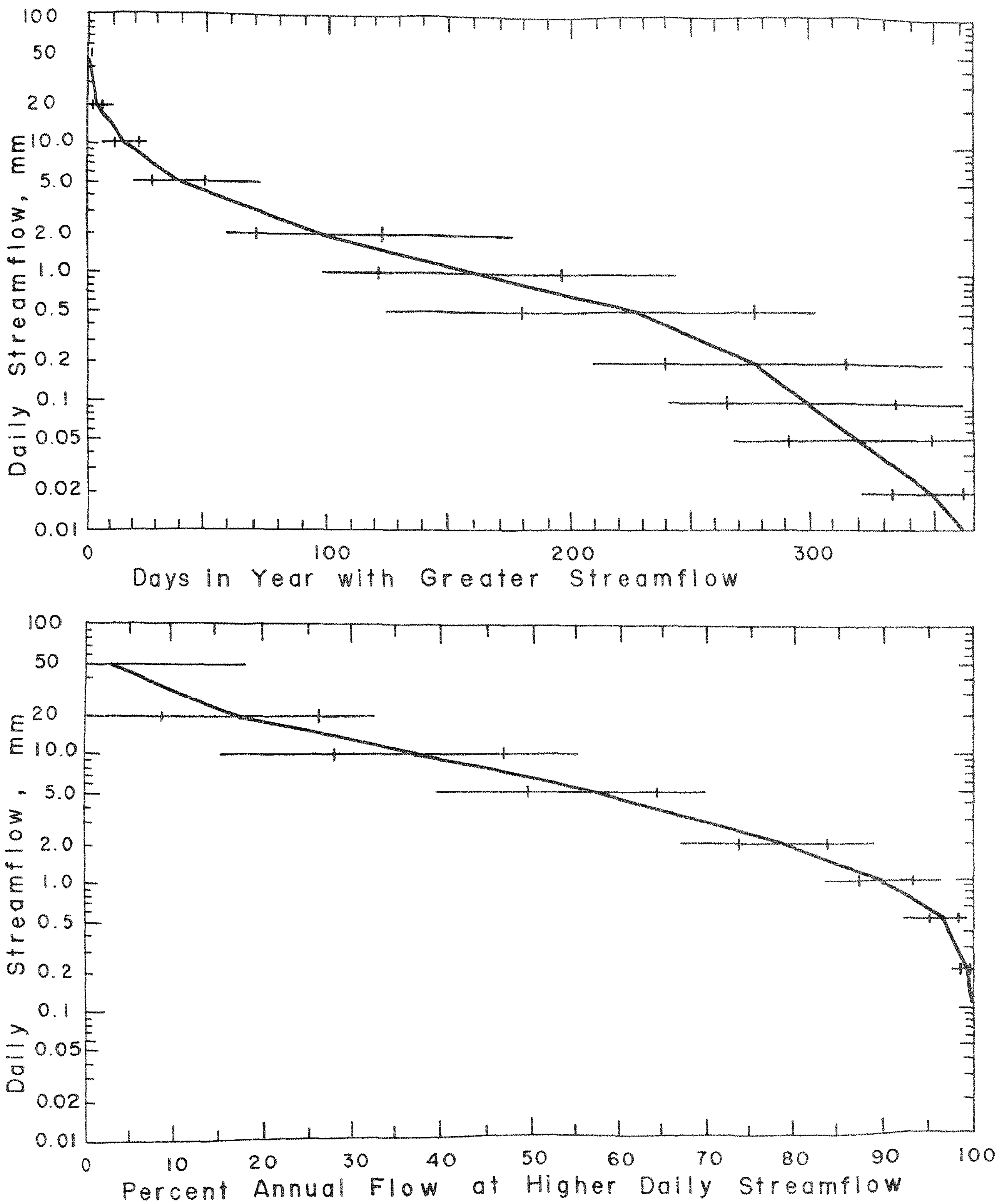


Figure 6.—Flow duration curves of daily streamflow for Watershed 3, 1958–86. Upper part is on basis of days, lower part is on total flow basis. Horizontal lines show the range, and ticks show the standard deviation.

they have similar slope, aspect, elevation, and cover; but they are not. Watershed 3 has a slightly different aspect, but its precipitation minus streamflow is quite similar to Watershed 1. Watersheds 5 and 6 have somewhat higher precipitation minus streamflow, while Watersheds 2 and 4 are low. Watersheds 7 and 8 also differ slightly from each other, though their evapotranspiration should be similar.

It has been noted that precipitation catch at Stations 3 and 6 is lower than expected for their elevations (Fig. 3). How would the precipitation minus streamflow values change if the precipitation from these gages was raised to the expected values? Multiplying the required elevation correction from Figure 3 by the Thiessen weights in Table 3 gives precipitation corrections for Watersheds 1-5 of 1.040, 1.057, 1.039, 1.028, and 1.029, respectively. Adjusted precipitation minus streamflow values can then be calculated (Table 21). Increasing watershed precipitation by about 4 percent increased precipitation minus streamflow by about 10 percent. Watersheds 1 to 5 are brought more into line with Watershed 6. The 1969-87 values for Watersheds 1, 3, and 6 become virtually identical, though differences over shorter periods remain. This is good evidence that the low precipitation at Stations 3 and 6 causes underestimates of watershed precipitation for Watersheds 1 to 5.

Table 19.—Annual precipitation (mm) and streamflow (mm) for Watershed 6 by water year beginning June 1

Water year	Precipitation	Streamflow
1963–64	–	698
1964–65	976	495
1965–66	1281	757
1966–67	1380	846
1967–68	1471	950
1968–69	1349	897
1969–70	1359	870
1970–71	1329	828
1971–72	1281	742
1972–73	1565	1030
1973–74	1888	1401
1974–75	1308	808
1975–76	1770	1188
1976–77	1402	850
1977–78	1533	982
1978–79	1361	851
1979–80	1193	708
1980–81	1356	780
1981–82	1586	1029
1982–83	1410	813
1983–84	1638	1003
1984–85	1200	671
1985–86	1425	913
1986–87	1311	834
1987–88	1290	769

Even after adjusting for Stations 3 and 6, Watersheds 2 and 4 have lower precipitation minus streamflow; such differences among watersheds indicate failure of the assumption that seepage is zero. Evapotranspiration is close to an expected regional value of 500 mm, so seepage is not a major problem. However, some seepage activity in soil or in bedrock seems likely.

Seepage in the soil is induced by failure of the topographic and bedrock divides to coincide. Because precipitation is measured in unit area but streamflow in volume divided by the watershed area, Watershed 2 values could be brought into line if the topographic area were increased by about 7 percent or about 1 ha. This would decrease the annual streamflow by about 50 mm. In other words, water from 1 ha outside the surveyed boundary actually is seeping into Watershed 2. There are, in fact, one or two areas on the Watershed 2 boundary where this could be occurring. A similar argument can be made to explain the difference between Watersheds 7 and 8.

Although this analysis seems negative, it actually shows that the agreement among watersheds is excellent in comparison with other hydrologic research areas. Paired watershed regression analysis accounts for the kind of differences discussed here, and there is no reason to alter any conclusions about treatment effects on water yield at HB. Furthermore, it is fortunate that Watershed 6 is not affected by the possible problem with Stations 3 and 6. There seems to be no reason to question the important biogeochemistry results that are based on precipitation and streamflow records for this watershed (Likens et al. 1977).

Air Temperature

Air temperature has been measured by hygrothermographs at five locations. The temperature sensor is a liquid-filled Bourdon tube that bends as temperature changes, mechanically driving a pen across a clock-driven chart. The charts are read by eye to obtain the maximum and minimum temperatures for each day (midnight to midnight). The average of these is called the mean temperature for the day. The hygrothermographs are housed in standard shelters (Stevenson screens) near the middle of certain weather station openings.

Station 1 is located near the foot of Watersheds 1 and 2 (Fig. 1). Its values are usually taken as representative for HB. Stations 6, 14, and HQ also have hygrothermographs.

Maximum daily temperature at Station 1 averages -4.2°C in January and 23.9°C in July (Table 22). Minimum daily temperature averages −13.3°C in January and 13.7°C in July (Table 23). Mean daily temperature averages -8.7°C in January and 18.8°C in July (Table 24). The average annual temperature at Station 1 is 5.6°C. The record high temperature at HB is 36°C at HQ on August 2, 1975, and July 4, 1983. Record low is -37°C at Station 14 on January 15, 1965.

Table 20.—Annual precipitation minus annual streamflow (mm) by watershed for years beginning May 15[a]

Year	Watershed 1	2	3	4	5	6	7	8
1957–1958	532	586	–	–	–	–	–	–
1958–1959	496	444	503	–	–	–	–	–
1959–1960	572	488	593	–	–	–	–	–
1960–1961	541	512	571	591	–	–	–	–
1961–1962	512	488	517	493	–	–	–	–
1962–1963	515	390	536	496	–	–	–	–
1963–1964	493	424	504	434	–	–	–	–
1964–1965	503	441	504	458	418	481	–	–
1965–1966	569	449	545	527	563	564	604	–
1966–1967	524	84T[a]	485	478	506	507	424	–
1967–1968	464	106T	461	424	453	459	423	–
1968–1969	457	138T	509	428	518	519	479	–
1969–1970	424	141T	456	404	498	470	445	481
1970–1971	502	233T	471	463T	547	514	539	586
1971–1972	545	392T	519	429T	560	553	533	574
1972–1973	532	419T	512	376T	485	496	375	384
1973–1974	545	348T	524	350T	507	512	590	587
1974–1975	452	306T	481	320T	438	491	505	539
1975–1976	465	337T	469	334T	483	577	508	504
1976–1977	458	391T	522	383T	497	555	500	546
1977–1978	472	356T	508	388T	510	527	502	585
1978–1979	445	369T	456	420T	482	498	452	449
1979–1980	468	421T	492	484T	507	532	513	529
1980–1981	484	456T	509	511T	544	553	460	488
1981–1982	431	354T	465	444T	554	563	505	552
1982–1983	486	473T	504	529T	583	573	513	549
1983–1984	523	487T	525	551T	644	623	573	596
1984–1985	442	423T	449	494T	370T	554	509	546
1985–1986	430	402T	440	466T	448T	501	459	418
1986–1987	441	396T	414	474T	487T	465	459	469
ave[b]	475		484			531	497	521
sd	40		33			41	50	62

[a]T shows treated watersheds.
[b]Average (ave) and standard deviation (sd) are over water years 1969–70 through 1986–87.

Variation of temperature for a given day of the year is considerable; the range in maximum, minimum, and mean daily temperatures is approximately 35°C in winter and 15-20°C in summer (Figs. 7, 8, and 9). Variation among years in average monthly maximum, minimum, or mean temperature is about 10°C in winter months and 5°C in summer months (Tables 22, 23, and 24).

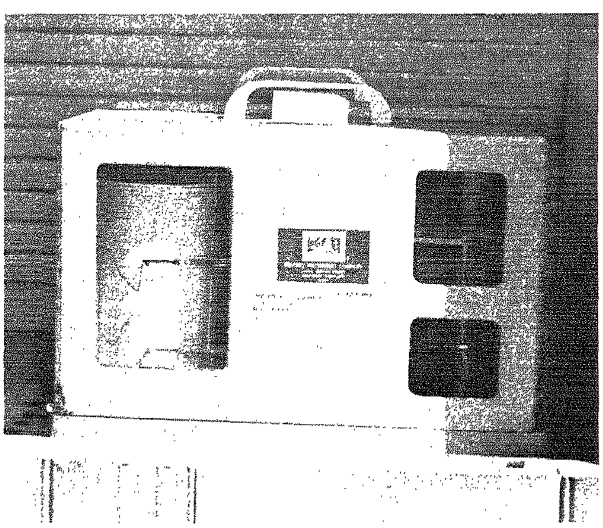
To produce a rather smooth annual curve of average temperature by date, a cubic smoothing spline with a 20-day cutoff was used (Figs. 7, 8, and 9). This curve shows that the "January thaw" is a real phenomenon, usually occurring in the latter part of the month. A brief cessation of the seasonal warming in mid-April also seems to be real, as do both a slightly warmer period around Christmas and the warm "Indian summer" days in late October.

Long-term average monthly temperatures generally decrease with elevation, from HQ at 253 m, through Station 1 at 485 m, to Station 14 at 728 m, and Station 6 at 747 m (Table 25). The decrease in temperature is 0.4–0.8°C/100 m, which is comparable to the normal temperature decrease of 0.6°C/100 m in the atmosphere. Only for minimum temperatures in summer does cooling with elevation fail to hold. Nighttime cooling causes the heavier colder air to move downslope creating a valley temperature inversion that includes HQ. From May through September, the minimum temperature at HQ averages lower than at Station 1.

The growing season is defined as the period between the last frost in spring and the first frost in autumn. If we use a minimum temperature of 0°C at Station 1, the growing season on average begins May 11, ends October 3, and is

Table 21.—Average annual precipitation minus streamflow (mm) by watershed for various periods using years beginning May 15

	Years				
Watershed	1960–66	1966–70	1970–77	1978–84	1969–87
Original data					
1	522	467	500	473	475
2	451				
3	530	477	500	494	484
4	500	433			
5		494	502	546	
6		489	528	553	531
7		442	507	502	497
8			531	535	521
After adjustment					
1	572	524	563	531	534
2	516				
3	574	529	556	546	537
4	532	471			
5		533	545	586	
6		489	528	553	531



Hygrothermograph in shelter at headquarters.

145 days long. If we use −1°C as a criterion, the growing season increases by several days. Compared to Station 1, the average growing season is 9 days shorter at HQ, 7 days shorter at Station 6, and 12 days shorter at Station 14. The shorter growing season at HQ compared to Station 1 is caused by the valley temperature inversion.

For many years one hygrothermograph was routinely operated under the forest canopy west of Streamgage 4, rather than in an opening like the routine stations. Comparison of its data with temperatures in the Station 1 opening nearby shows the differences in air temperature between the opening and the under-canopy position (Table 26). In summer, maximum temperature is 2–3°C higher in the opening, and minimum temperature is 0.7°C lower. In winter, the trends are the same, but the magnitude is smaller. Under the forest canopy the air is cooler in the daytime and warmer at night than in the open. The effect is less in winter partly because there are no leaves on the trees. The often-referenced air temperature data in Federer (1973) are under-canopy temperatures, though that is not made clear in the publication.

Table 22.—Average daily maximum temperature (°C) by month for Station 1[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	-6.1	1.0	3.3	12.0	17.6	24.0	23.0	21.7	18.9	13.5	6.7	2.1H
1958	-2.2	-4.4	4.3	10.4	15.1	18.0	22.4	23.3	17.4	11.0	5.1	-5.4
1959	-5.2	-3.8	1.7	9.1	19.8	19.4	25.2	23.7	19.6	10.9	3.4	-0.2
1960	-2.6	0.2	-0.6L	9.0	18.4	21.1	23.2	23.3	18.6	10.6	6.5	-2.8
1961	-6.1	0.1	2.6	7.0	15.5	23.0	24.5	22.8	23.5H	13.5	4.1	-2.3
1962	-4.9	-4.7	3.7	9.9	17.2	23.2	21.9	22.5	16.1	10.2	3.9	-1.8
1963	-3.7	-4.3	3.5	10.3	18.3	24.0	25.2	20.3	17.1	17.9H	6.1	-6.6L
1964	-1.8	-2.4	3.0	8.9	19.6	22.3	24.9	20.3	16.7	11.7	4.9	-1.8
1965	-6.2	-3.4	1.3	8.1	19.6	22.0	23.0	22.5	17.7	9.9	1.3L	-1.4
1966	-3.8	-1.6	2.8	7.7	16.9	23.4	24.6	22.9	16.9	12.3	7.4	-0.5
1967	-0.8H	-3.9	0.8	7.5	11.9L	24.7H	25.1	23.4	19.9	11.5	1.8	-0.6
1968	-4.9	-5.5	3.5	11.9	16.1	19.7	26.4H	22.4	20.8	14.0	3.1	-3.1
1969	-1.6	-0.3	1.8	9.7	16.0	22.6	23.1	25.1H	19.5	11.7	4.0	-3.4
1970	-9.2L	-2.8	0.1	8.5	18.4	22.9	26.1	25.0	18.9	13.5	6.7	-3.6
1971	-5.8	-0.8	2.5	8.0	16.2	22.4	23.4	22.3	19.4	15.6	3.8	-1.0
1972	-2.6	-2.9	0.4	5.0	17.2	17.4L	21.6	20.0L	17.4	9.5	1.7	-2.0
1973	-2.0	-3.1	5.1	9.7	14.0	19.5	22.4	23.2	15.5	13.3	3.3	0.3
1974	-2.7	-2.7	0.6	8.8	12.6	21.2	23.1	22.7	16.7	8.8L	5.6	0.4
1975	-1.8	-1.8	0.6	4.6L	20.3	21.0	24.5	21.5	15.4L	12.7	8.3H	-2.6
1976	-5.8	0.7	3.1	12.1	16.1	23.5	22.5	21.5	17.5	9.9	1.4	-5.2
1977	-7.6	-3.2	6.0H	11.1	20.4H	19.4	23.7	22.6	15.9	11.8	6.2	-2.7
1978	-4.0	-4.0	1.6	6.5	18.7	20.6	23.9	22.6	17.5	11.3	5.8	-1.5
1979	-3.7	-6.6L	4.2	8.0	16.8	22.5	25.6	21.5	18.9	10.7	7.5	-0.3
1980	-2.5	-4.2	2.3	8.8	18.0	19.6	23.4	22.8	17.7	9.4	2.1	-4.4
1981	-6.2	2.1	3.8	10.3	17.9	21.3	23.1	21.5	16.3	10.2	4.4	-1.9
1982	-8.0	-3.0	1.5	6.8	18.8	18.2	24.0	20.5	18.6	13.4	6.4	1.4
1983	-2.4	0.5	3.5	9.4	14.6	24.0	25.4	23.9	21.0	12.8	5.3	-3.1
1984	-4.2	3.1H	-0.2	10.9	15.1	22.5	23.9	24.4	18.1	15.1	5.5	1.4
1985	-6.7	-0.9	4.4	10.1	17.4	18.6	24.8	22.3	19.2	12.8	4.2	-3.7
1986	-2.6	-3.0	3.8	13.1H	18.0	19.2	21.0L	20.9	17.1	12.0	3.4	-0.6
1987	-3.1	-3.5	4.6	11.4	17.5	20.8	24.1	21.5	17.4	12.3	4.8	-0.5
1988	-3.4	-1.2	2.8	8.4	17.8	20.8	25.0	24.0	18.2	9.6	5.6	-1.9
ave	-4.2	-2.2	2.6	9.2	17.1	21.3	23.9	22.5	18.1	12.0	4.7	-1.9
sd	2.1	2.3	1.6	2.0	2.1	2.0	1.3	1.3	1.7	2.0	1.9	2.0

[a]H shows the highest and L the lowest value for that month.

Solar Radiation

Solar radiation has been measured at HQ since 1958. Before 1981 several bimetal recording pyranographs (actinometers) were used. The pyranograph has both black and white bimetal strips exposed to the sun under a glass dome. The temperature difference between the strips causes differential curvature, which moves a pen across a spring-wound chart. Daily incoming solar radiation is calculated by integrating two-hour periods by eye. Since 1981 a Li-Cor[1] solar-cell sensor has been operated as part of the automatic weather station at HQ. This provides hourly solar radiation and its daily integral. A pyranograph continues to operate as a backup.

Maximum daily solar radiation on a horizontal surface is limited seasonally to about 90 percent of the potential solar radiation because of absorption and scattering by the atmosphere (Fig. 10). Potential radiation represents the radiation that would be received in the absence of the atmosphere; it varies seasonally (Fig. 10).

Clear-day radiation in June at HB is over 30 MJ/m^2 (Fig. 10), equivalent to the heat and light produced by 10 100W light bulbs burning in each square meter of land for about 8 hours. In winter, clear-day radiation is about 10 MJ/m^2. Lower radiation is caused by cloudiness. Heavily overcast days have only 1 or 2 MJ/m^2 of radiation.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Solar radiation varies among years for a given month (Table 27), but most months are within 15 percent of the long-term average for that month. Missing data occur throughout the radiation record. During 1960-73 missing days were estimated from National Weather Service stations in New England; this network no longer exists. For other years, months with missing days have no values in Table 27; daily values have been interpolated to give estimated annual totals.

From May through September the maximum daily radiation at HQ is much less than 90 percent of the potential radiation (Fig. 10). In summer, trees near the HQ weather station shade the sensor in early morning and late evening and the effective horizon is elevated about 15°. Thus, summer radiation on an unobstructed horizontal surface is underestimated by perhaps 10 percent, particularly on clear days. Growth of these trees may be gradually reducing measured solar radiation (Federer 1990).

Calibration differences among radiation sensors can be as much as ± 5 percent and five different sensors have been used over the years. Trends in solar radiation over time may be due to differences among sensors.

Table 23.—Average daily minimum temperature (°C) by month for Station 1[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	−16.2	−10.1	−5.5	0.2	5.1	12.1	12.0	10.0	8.8	3.6	−1.1	−5.8
1958	− 9.8	−14.2	−3.2	0.7	3.1	7.5L	13.4	11.7	7.6	1.3	−2.8	−15.3
1959	−13.8	−16.9L	−8.3	−0.6	6.7	10.2	14.6	13.6	10.0	3.7	−3.7	− 6.5
1960	−10.2	− 8.0	−9.5	0.0	8.2	10.2	12.8	12.5	8.8	1.5	−1.1	−12.7
1961	−15.8	−10.2	−6.8	−0.2	3.8	11.3	14.2	13.4	12.8H	3.5	−2.2	− 9.1
1962	−15.6	−14.6	−6.6	−1.4	5.2	11.6	10.9L	12.2	7.0	1.2	−3.3	−11.8
1963	−12.1	−16.0	−6.7	0.8	4.8	11.7	14.0	11.0	5.3L	4.2	−0.5	−14.6
1964	−10.4	−12.7	−5.7	−1.5	5.8	9.3	14.3	9.6L	6.4	1.0	−3.1	− 9.4
1965	−15.3	−14.3	−7.3	−1.5	5.0	9.1	10.9L	12.0	7.6	0.8	−5.9L	− 8.3
1966	−13.4	−11.6	−6.2	−1.6	4.8	11.5	13.1	13.1	6.8	1.1	−0.4	− 9.1
1967	− 9.2H	−15.7	−9.6	−2.9	1.6L	13.3H	15.3	13.4	8.5	1.9	−5.8	− 8.8
1968	−15.4	−16.3	−6.0	0.5	4.3	11.4	15.2	11.9	11.1	5.3	−3.3	−10.9
1969	−10.4	− 9.0	−6.7	−0.3	4.7	12.1	14.1	14.6	10.1	2.4	−2.6	−10.6
1970	−19.6L	−14.6	−9.1	−1.6	6.4	11.0	15.6H	13.8	9.7	4.4	0.1	−12.4
1971	−16.9	−10.2	−7.5	−1.0	6.9	12.3	14.0	13.8	11.9	7.5H	−3.3	− 8.9
1972	−11.6	−11.6	−7.1	−1.9	7.6	10.9	13.9	13.0	8.8	1.6	−3.2	− 8.5
1973	−10.1	−11.8	−1.3H	2.1H	6.7	12.2	14.5	15.4H	8.7	4.7	−2.8	− 7.1
1974	−10.8	−12.5	−7.8	0.3	4.6	12.3	14.5	14.2	9.8	0.5L	−1.8	− 5.1H
1975	− 9.5	−10.0	−7.7	−2.6	9.8H	12.1	14.7	12.2	7.3	2.8	0.2	−11.7
1976	−16.0	−10.2	−7.0	1.6	4.7	12.7	11.9	12.5	7.8	1.2	−5.1	−15.5
1977	−16.3	−11.2	−2.3	−0.2	6.2	10.2	12.4	12.7	6.6	1.5	−1.2	−10.3
1978	−13.2	−14.0	−7.8	−0.8	7.5	10.9	13.0	12.8	5.8	2.4	−3.0	− 9.8
1979	−10.6	−14.5	−3.4	−0.2	7.6	10.6	15.3	12.6	7.0	2.7	0.4H	− 8.3
1980	−11.5	−13.5	−7.0	0.1	5.7	9.0	13.6	13.3	6.9	1.0	−4.8	−16.3L
1981	−17.5	− 7.1	−5.2	0.1	5.8	9.9	12.9	11.6	7.9	1.0	−2.9	− 7.7
1982	−17.5	−12.9	−7.7	−3.3L	5.9	9.6	12.8	10.2	9.1	2.1	−1.2	− 7.2
1983	−11.2	− 8.7	−3.9	1.3	5.4	11.7	14.3	13.2	9.1	2.1	−1.1	−12.2
1984	−13.5	− 5.8H	−9.9L	1.0	4.2	11.0	13.8	14.7	5.8	2.8	−3.2	− 7.5
1985	−15.6	−10.5	−6.3	−0.6	5.4	9.6	13.3	12.9	9.9	3.3	−1.5	−11.7
1986	−12.2	−11.8	−5.9	2.0	6.9	8.7	12.7	12.1	7.5	1.9	−4.8	− 8.0
1987	−11.1	−13.3	−4.7	1.5	5.6	11.8	14.0	10.6	9.1	1.8	−3.5	− 6.9
1988	−12.8	−11.3	−6.9	0.6	7.8	9.3	15.5	14.5	7.9	2.1	−1.4	−10.6
ave	−13.3	−12.0	−6.5	−0.3	5.7	10.8	13.7	12.7	8.4	2.5	−2.5	−10.0
sd	2.8	2.7	2.0	1.4	1.6	1.4	1.2	1.4	1.8	1.5	1.7	2.9

[a]H shows the highest and L the lowest value for that month.

Table 24.—Average daily mean temperature (°C) by month for Station 1[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	-11.1	-4.5	-1.1	6.1	11.3	18.1	17.5	15.8	13.8	8.5	2.8	-1.8H
1958	-6.1	-9.3	0.5	5.5	9.1	12.8L	17.9	17.5	12.5	5.9	1.1	-10.3
1959	-9.5	-10.3	-3.3	4.2	13.2	14.8	19.9	18.7	14.8	7.2	0.2	-3.4
1960	-6.4	-3.9	-5.0L	4.5	13.3	15.7	18.0	17.9	13.7	6.0	2.7	-7.8
1961	-11.0	-5.0	-2.1	3.4	9.7	17.1	19.4	18.1	18.2H	8.5	0.9	-5.7
1962	-10.2	-9.6	-1.5	4.2	11.2	17.4	16.4	17.4	11.6	5.7	0.3	-6.8
1963	-7.9	-10.1	-1.6	5.6	11.5	17.9	19.6	15.6	11.2L	11.0	2.8	-10.6L
1964	-6.1	-7.6	-1.3	3.7	12.7	15.8	19.6	14.9L	11.6	6.3	0.9	-5.6
1965	-10.7	-8.8	-3.0	3.3	12.3	15.5	16.9	17.2	12.7	5.3	-2.3L	-4.9
1966	-8.6	-6.6	-1.7	3.0	10.9	17.5	18.8	18.0	11.9	6.7	3.5	-4.8
1967	-5.0H	-9.8	-4.4	2.3	6.7L	19.0H	20.1	18.4	14.2	6.7	-2.0	-4.7
1968	-10.2	-10.9L	-1.3	6.2	10.2	15.5	20.8	17.1	15.9	9.6	-0.1	-7.0
1969	-6.0	-4.7	-2.5	4.7	10.3	17.3	18.6	19.9H	14.8	7.1	0.7	-7.0
1970	-14.4L	-8.7	-4.5	3.5	12.4	17.0	20.9H	19.4	14.3	8.9	3.4	-8.0
1971	-11.4	-5.5	-2.5	3.5	11.6	17.3	18.7	18.1	15.7	11.5H	0.3	-5.0
1972	-7.1	-7.3	-3.3	1.5	12.4	14.2	17.8	16.5	13.1	5.5	-0.7	-5.3
1973	-6.0	-7.5	1.9H	5.9	10.3	15.8	18.4	19.3	12.1	9.0	0.2	-3.4
1974	-6.7	-7.6	-3.6	4.5	8.6	16.7	18.8	18.4	13.2	4.6	1.9	-2.4
1975	-5.6	-5.9	-3.5	1.0L	15.1H	16.5	19.6	16.9	11.3	7.8	4.3H	-7.2
1976	-10.9	-4.8	-1.9	6.8	10.4	18.1	17.2	17.0	12.6	5.6	-1.9	-10.4
1977	-12.0	-7.2	1.9H	5.4	13.3	14.8	18.0	17.6	11.3	6.7	2.5	-6.5
1978	-8.6	-9.0	-3.1	2.8	13.0	15.7	18.5	17.7	11.7	6.8	1.4	-5.7
1979	-7.2	-10.6	0.4	3.9	12.2	16.5	20.5	17.1	12.9	6.7	4.0	-4.3
1980	-7.0	-8.9	-2.3	4.4	11.9	14.3	18.5	18.0	12.3	5.2L	-1.4	-10.3
1981	-11.8	-2.5	-0.7	5.2	11.9	15.6	18.0	16.5	12.1	5.6	0.7	-4.8
1982	-12.8	-7.9	-3.1	1.7	12.4	13.9	18.4	15.3	13.8	7.7	2.6	-2.9
1983	-6.8	-4.1	-0.2	5.3	10.0	17.9	19.9	18.6	15.0	7.4	2.1	-7.6
1984	-8.9	-1.3H	-5.0L	6.0	9.6	16.7	18.8	19.5	12.0	9.0	1.1	-3.0
1985	-11.2	-5.7	-1.0	4.7	11.4	14.1	19.1	17.6	14.6	8.1	1.3	-7.7
1986	-7.4	-7.4	-1.1	7.5H	12.5	13.9	16.8L	16.5	12.3	7.0	-0.7	-4.3
1987	-7.1	-8.4	0.0	6.4	11.5	16.3	19.1	16.1	13.2	7.0	0.7	-3.7
1988	-8.1	-6.3	-2.0	4.5	12.8	15.0	20.3	19.3	13.1	5.9	2.1	-6.3
ave	-8.7	-7.1	-1.9	4.4	11.4	16.1	18.8	17.6	13.2	7.2	1.1	-5.9
sd	2.4	2.4	1.8	1.6	1.7	1.5	1.2	1.3	1.6	1.7	1.7	2.4

[a]H shows the highest and L the lowest value for that month.

Humidity

The humidity of the air is an important meteorological variable; unfortunately, it is difficult to measure accurately. It also can be expressed in several meaningful but different ways.

Amount of water vapor is usually measured as a vapor pressure (kPa), though other measures, such as mass per unit mass of air, also are used. Relative humidity is a measure of the actual amount of water vapor in the air as a percent of the maximum amount that could be present at the air temperature. The maximum, or saturated, vapor pressure increases exponentially with temperature, so a given relative humidity in winter represents a very different amount of water vapor from that in summer. Humidity is given in this report as vapor pressure. Vapor pressure does not vary with temperature, so changes little through one day and only as the amount of water vapor in the air varies.

At HB, the hygrothermographs at the weather stations measure humidity as well as temperature. The humidity sensor consists of a set of human hairs which expand and contract as relative humidity changes. The length change is transferred mechanically to a pen on the spring-wound recorder chart. Before 1970, the sensors were not maintained or calibrated. Since then, the sensors have been calibrated and adjusted annually in the spring. Since 1981

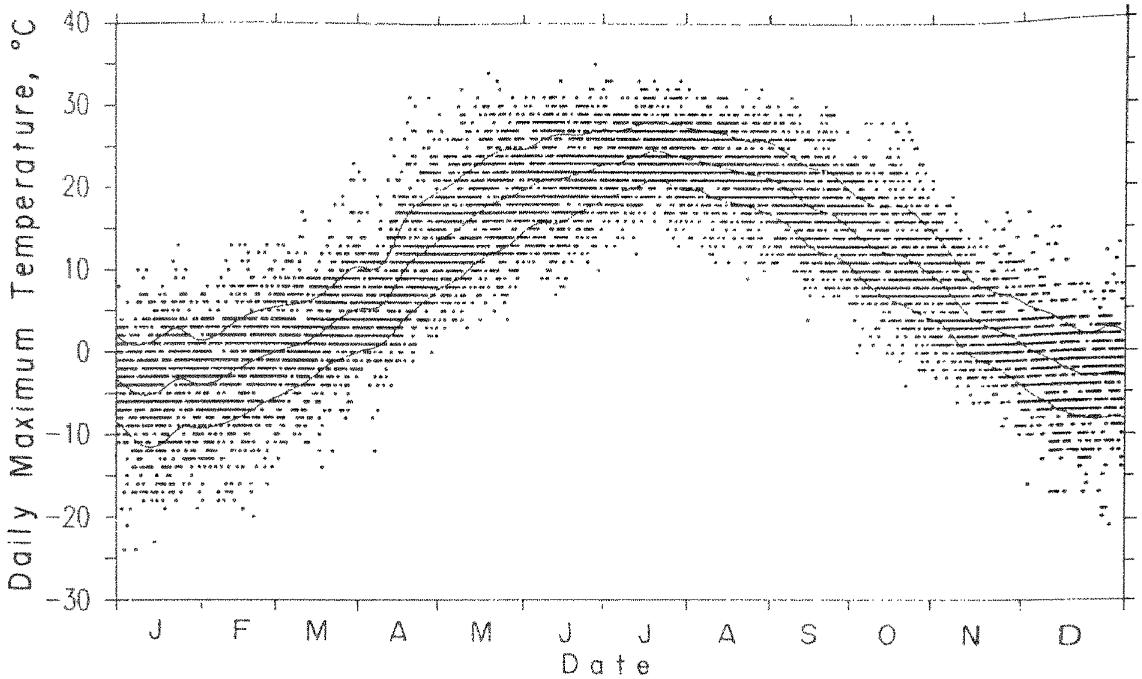


Figure 7.—Daily maximum temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

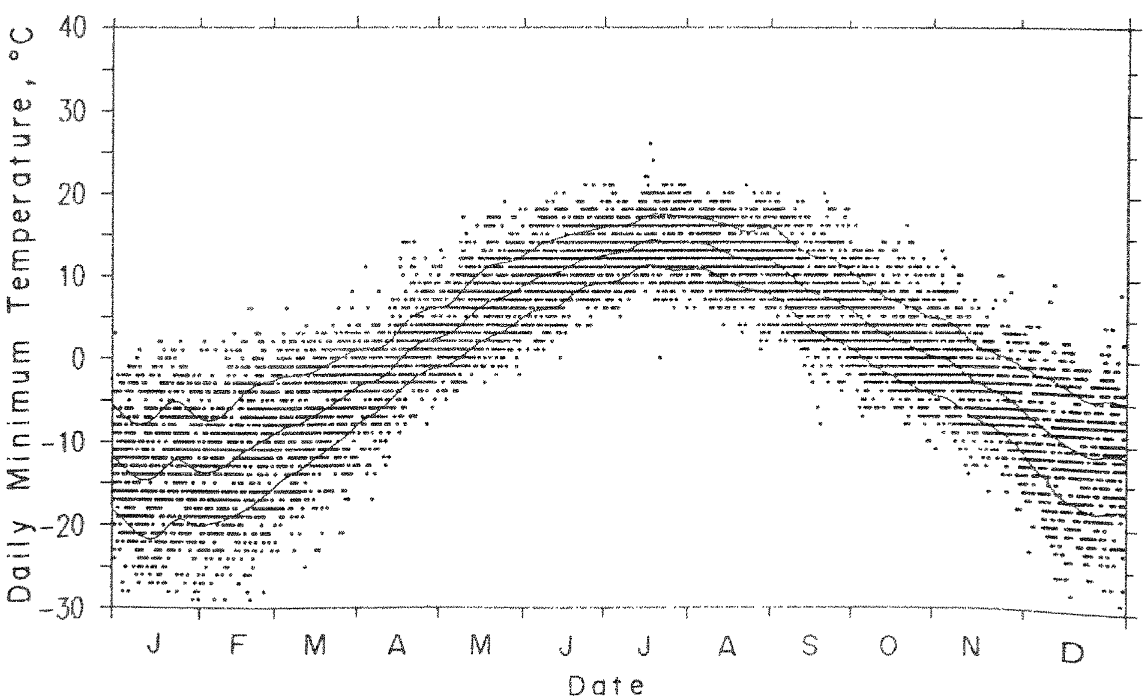


Figure 8.—Daily minimum temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

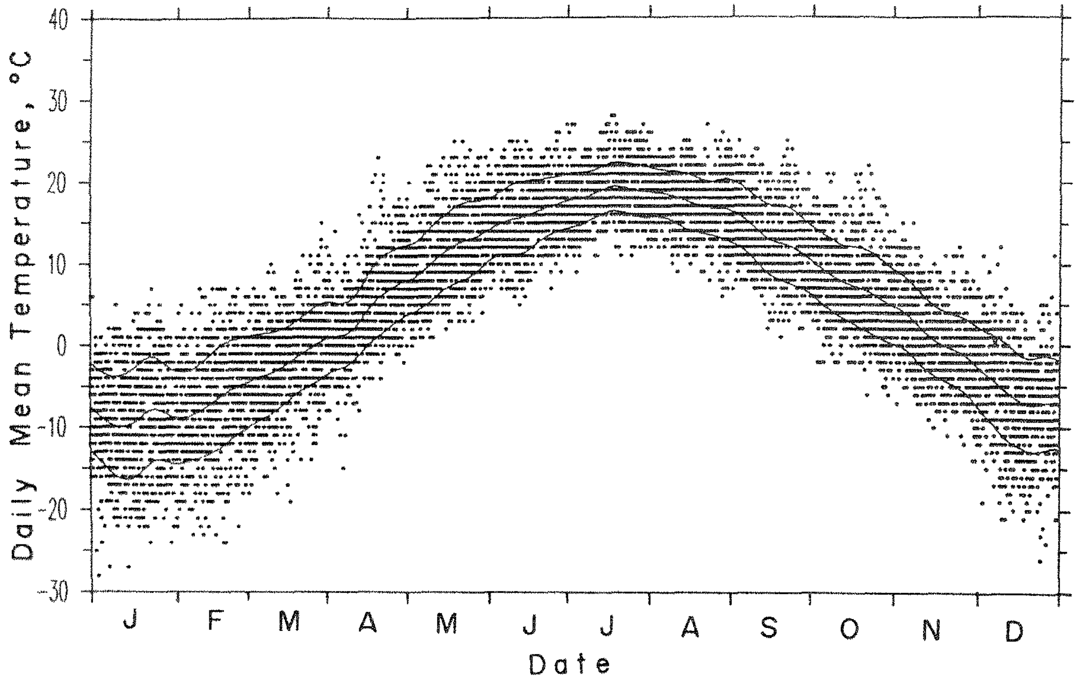


Figure 9.—Daily mean temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

Table 25.—Average daily maximum, minimum, and mean temperature (°C) by station and month

Station	Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						Daily Maximum							
HQ	1957–1986	-2.8	-0.8	3.9	10.8	18.3	22.8	25.3	24.2	19.8	13.8	6.3	-0.6
1	1957–1986	-4.3	-2.2	2.5	9.1	17.1	21.4	23.8	22.4	18.1	12.1	4.7	-1.9
6	1961–1986	-5.7	-4.1	0.5	6.7	14.9	19.6	22.0	20.7	16.7	11.1	3.3	-3.2
14	1965–1986	-7.0	-4.9	0.4	7.0	15.1	20.2	22.6	21.1	16.2	9.5	2.2	-3.8
						Daily Minimum							
HQ	1957–1986	-13.2	-11.7	-5.8	-0.3	5.3	10.1	12.9	12.1	7.8	2.5	-1.9	-9.5
1	1957–1986	-13.4	-12.0	-6.5	-0.4	5.7	10.9	13.6	12.7	8.3	2.5	-2.5	-10.0
6	1961–1986	-14.3	-12.9	-7.9	-1.9	4.7	10.0	12.5	11.7	7.6	2.4	-3.4	-10.8
14	1965–1986	-14.9	-13.4	-8.4	-2.3	4.1	9.7	12.5	11.6	7.2	1.5	-4.1	-11.1
						Daily Mean							
HQ	1957–1986	-8.0	-6.2	-1.0	5.2	11.8	16.4	19.1	18.2	13.8	8.2	2.2	-5.0
1	1957–1986	-8.8	-7.1	-2.0	4.3	11.4	16.1	18.7	17.6	13.2	7.3	1.1	-6.0
6	1961–1986	-10.0	-8.5	-3.7	2.4	9.8	14.8	17.3	16.2	12.1	6.7	-0.1	-7.0
14	1965–1986	-11.0	-9.1	-4.0	2.4	9.6	15.0	17.5	16.3	11.7	5.5	-0.9	-7.4

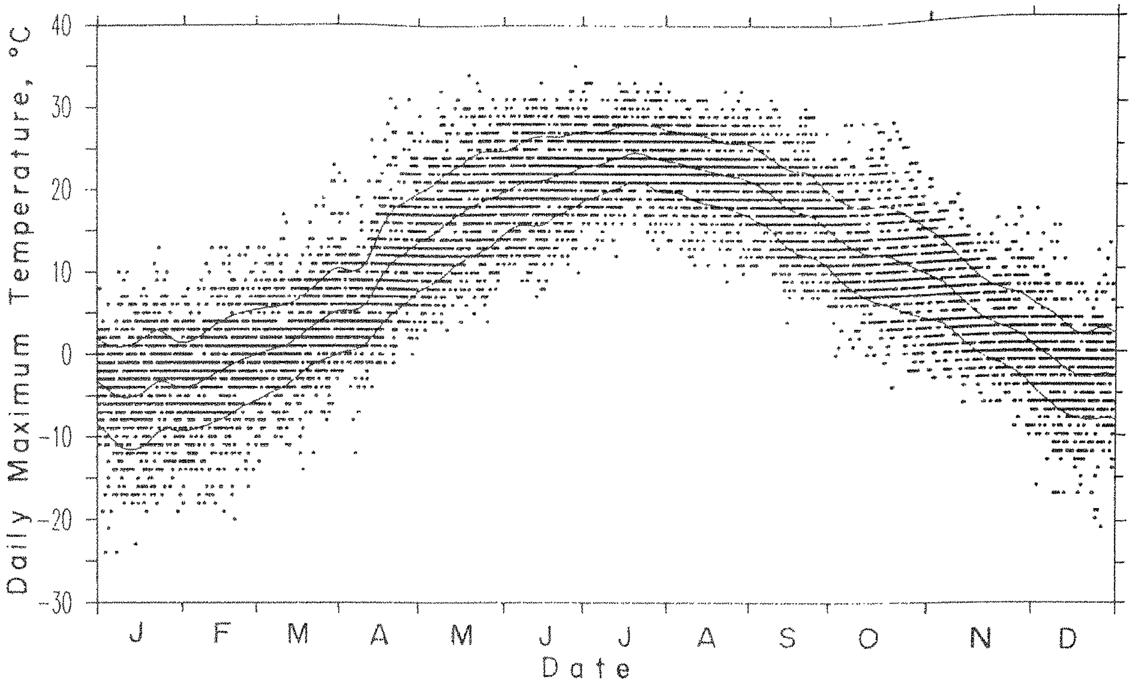


Figure 7.—Daily maximum temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

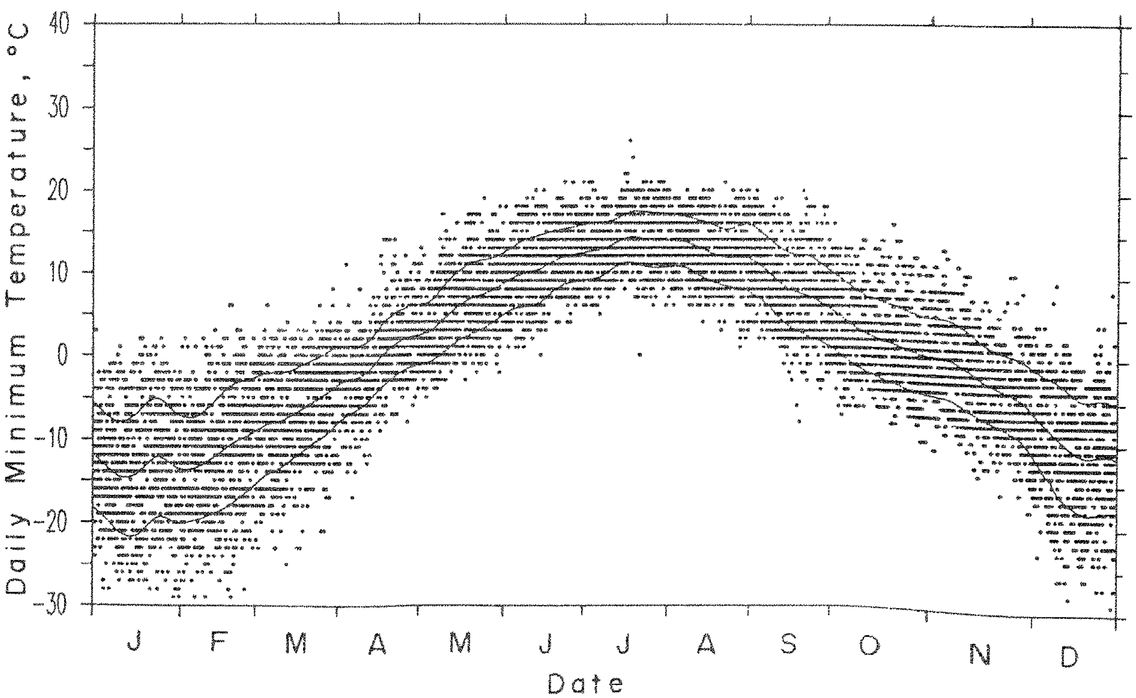


Figure 8.—Daily minimum temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

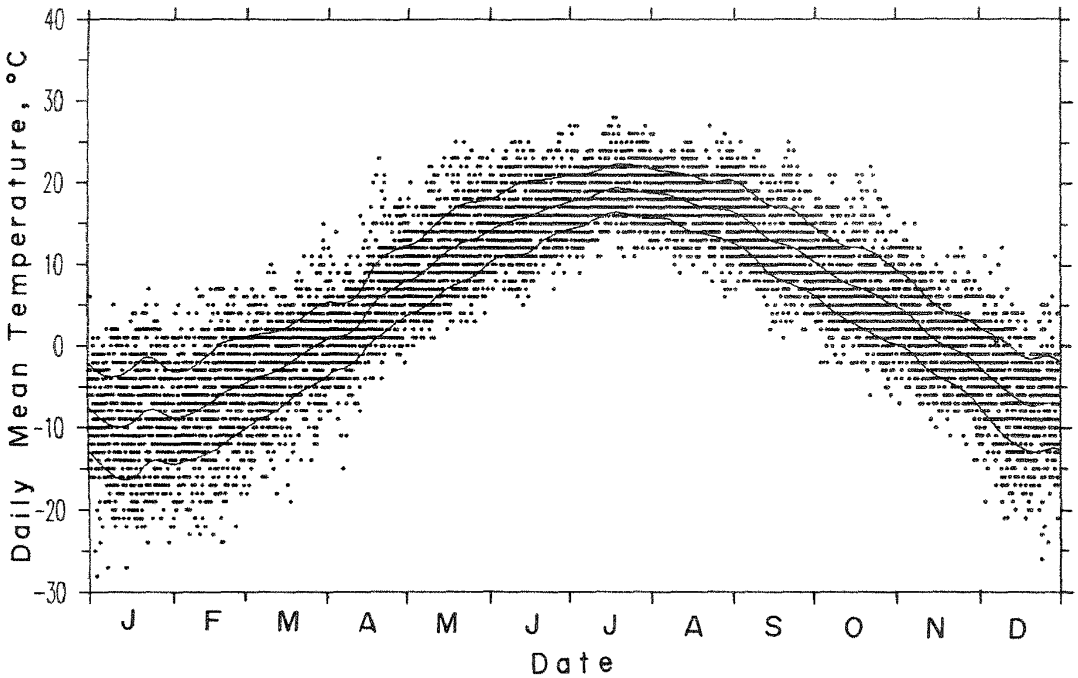


Figure 9.—Daily mean temperatures for Station 1 by day of the year, 1957–86. Middle curve is a smoothing spline through the daily averages. Upper and lower curves show one standard deviation.

Table 25.—Average daily maximum, minimum, and mean temperature (ºC) by station and month

Station	Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						Daily Maximum							
HQ	1957–1986	-2.8	-0.8	3.9	10.8	18.3	22.8	25.3	24.2	19.8	13.8	6.3	-0.6
1	1957–1986	-4.3	-2.2	2.5	9.1	17.1	21.4	23.8	22.4	18.1	12.1	4.7	-1.9
6	1961–1986	-5.7	-4.1	0.5	6.7	14.9	19.6	22.0	20.7	16.7	11.1	3.3	-3.2
14	1965–1986	-7.0	-4.9	0.4	7.0	15.1	20.2	22.6	21.1	16.2	9.5	2.2	-3.8
						Daily Minimum							
HQ	1957–1986	-13.2	-11.7	-5.8	-0.3	5.3	10.1	12.9	12.1	7.8	2.5	-1.9	-9.5
1	1957–1986	-13.4	-12.0	-6.5	-0.4	5.7	10.9	13.6	12.7	8.3	2.5	-2.5	-10.0
6	1961–1986	-14.3	-12.9	-7.9	-1.9	4.7	10.0	12.5	11.7	7.6	2.4	-3.4	-10.8
14	1965–1986	-14.9	-13.4	-8.4	-2.3	4.1	9.7	12.5	11.6	7.2	1.5	-4.1	-11.1
						Daily Mean							
HQ	1957–1986	-8.0	-6.2	-1.0	5.2	11.8	16.4	19.1	18.2	13.8	8.2	2.2	-5.0
1	1957–1986	-8.8	-7.1	-2.0	4.3	11.4	16.1	18.7	17.6	13.2	7.3	1.1	-6.0
6	1961–1986	-10.0	-8.5	-3.7	2.4	9.8	14.8	17.3	16.2	12.1	6.7	-0.1	-7.0
14	1965–1986	-11.0	-9.1	-4.0	2.4	9.6	15.0	17.5	16.3	11.7	5.5	-0.9	-7.4

solid-state humidity sensors of two types have operated as part of the automatic HQ weather station. Hourly humidity is available when the weather station is working properly.

Humidity data from the hygrothermographs have been read from the charts for only three periods: January to April 1966, June to September 1967, and May 1971 to April 1973. Combining these data with data from the HQ sensor since 1981 gives a picture of the average monthly vapor pressure at HB (Fig. 11). For any month of the year, the ratio of average vapor pressure to the saturated vapor pressure at the average maximum temperature is about 60 percent (Fig. 11). This is an estimate of the average minimum daily relative humidity.

Wind

Wind speed and direction have been measured at HQ since 1965 by an anemometer mounted at 3 m above the ground. The HQ anemometer is in a somewhat sheltered location with surrounding trees, a nearby building, and some topography. Until 1981, every mile of wind movement caused a tick mark on a strip-chart recorder, and wind direction, as N, S, E, W, or a combination, was recorded continuously. At 23 cm/day this is 1300 m of charts. Only the data from October 1965 to August 1967 and April 1971 to June 1973 have been analyzed. Since 1981 wind speed and direction have been measured as part of the automatic weather station at HQ. This record has both short and long

Table 26.—Average difference between temperature (°C) at Station 1 and below the canopy by month[a]

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	0.5	0.8	0.7	0.1	0.6	2.2	2.6	2.3	2.1	0.8	0.5	0.6
Minimum	–0.4	–0.3	–0.3	–0.4	–0.4	–0.5	–0.7	–0.7	–0.6	–0.8	–0.2	–0.2
Mean	0.2	0.2	0.2	–0.3	0.1	0.8	1.0	0.9	0.7	–0.1	0.1	0.1

[a]Positive values mean Station 1 is warmer

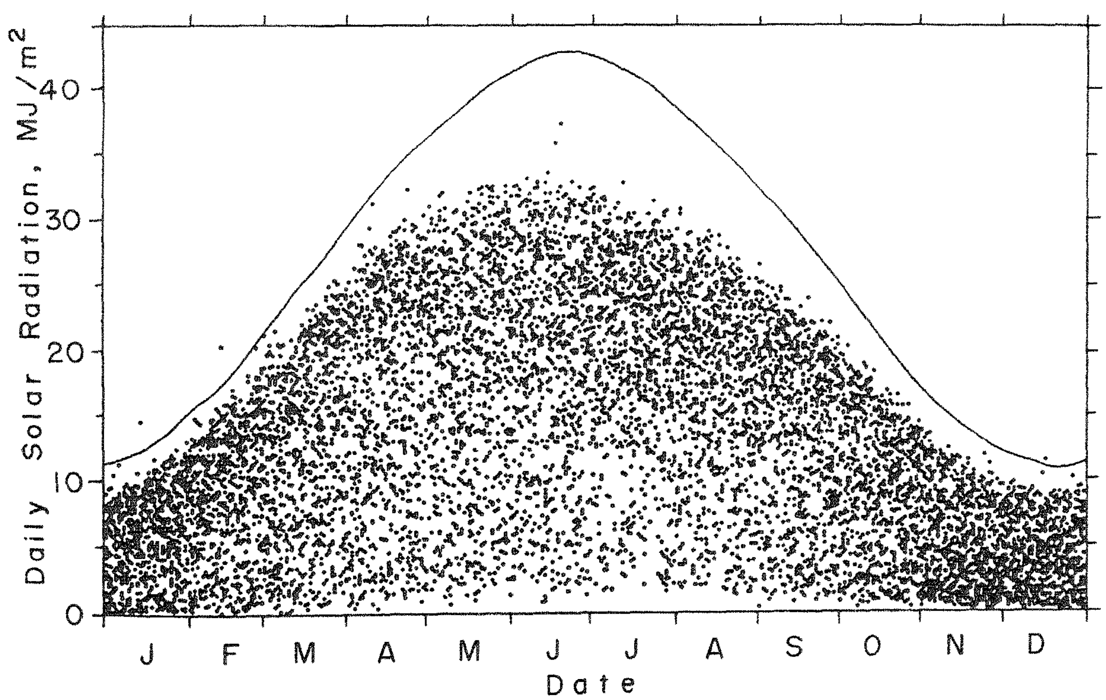


Figure 10.—Daily solar radiation at Headquarters by day of the year, 1960–87.
Curve is potential solar radiation.

Table 27.—Average daily solar radiation (MJ/m²) by month at HQ[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annu Tota
1958	–	–	–	–	18.7	13.9L	12.2L	15.1	10.1L	7.4	4.3	–	
1959	3.8L	–	–	14.8	17.6	–	19.3	–	–	–	4.3	–	
1960	7.2	8.3	13.2	16.1	17.6	20.3	19.8	18.6	14.1	10.7	6.1	5.4	480[illegible]
1961	6.7	8.7	13.4	13.7	17.5	19.7	18.8	16.4	15.1	9.9	5.2	4.1	4545
1962	6.2	7.6	14.6	16.2	18.9	21.3	20.0	17.2	14.0	8.2	6.5	5.5	4758
1963	5.0	9.8	12.5	16.6	18.1	21.1	19.8	15.2	15.5	12.8H	4.1	5.7H	4758
1964	5.0	9.6	11.9	15.6	20.8	22.7	19.3	17.0	14.4	10.6	6.3	3.6	4779
1965	5.5	8.5	13.2	17.2	21.1	21.4	20.3	16.3	13.3	8.9	4.7	3.9	4709
1966	4.9	9.6	11.8	15.5	17.8	21.0	21.7	17.9	14.8	10.5	5.2	4.6	4731
1967	5.0	8.6	13.2	14.9	16.3	16.3	16.3	14.9L	14.2	8.0	4.3	4.1	4144
1968	–	9.2	11.1	17.2	17.5	11.7	19.9	16.5	11.5	5.5L	3.1L	1.6L	4000
1969	4.5	7.3L	10.7	15.1	16.9	18.2	14.8	16.4	11.4	10.0	4.5	4.9	4108
1970	7.5H	8.7	13.2	17.3	19.9	20.4	20.6	19.1	11.4	8.5	5.2	4.3	4759
1971	6.3	7.9	14.4	17.3	18.0	24.7H	22.7	18.9	13.2	10.1	5.9	5.1	5012
1972	6.4	9.6	10.9	18.2	19.7	16.5	20.5	17.7	13.9	10.6	4.4	3.4	4632
1973	6.7	10.7	11.7	16.1	15.0	18.4	20.4	16.9	12.8	11.0	6.8	4.3	4586
1974	–	–	–	–	17.2	21.0	–	19.3H	12.5	10.5	6.0	3.9	4727
1975	5.5	8.2	11.9	17.7	20.7	19.9	21.0	17.6	13.0	10.6	6.4	–	4778
1976	6.1	9.1	14.0	19.2H	18.8	22.3	21.2	18.2	14.7	9.3	6.4	5.5	5028
1977	7.1	8.2	12.8	18.1	23.1H	16.6	–	15.9	11.3	9.2	5.4	5.1	4706
1978	5.5	12.2H	13.5	17.0	20.5	–	21.9	17.8	16.3	9.3	7.1H	4.8	5028
1979	4.2	11.1	10.5L	15.8	16.1	23.1	21.3	15.4	16.3	7.4	5.7	5.4	4630
1980	6.9	10.4	13.5	–	21.4	20.5	20.7	17.1	15.8	–	5.6	–	4937
1981	7.5H	7.9	13.5	16.2	20.3	–	21.0	17.0	12.0	9.2	6.6	4.2	4759
1982	6.6	10.1	13.9	19.1	21.8	18.5	23.9H	–	13.9	11.1	4.7	4.1	5052
1983	5.9	9.6	10.9	13.7	14.4L	24.4	22.3	18.9	16.7H	10.8	5.0	4.3	4777
1984	6.0	–	–	16.2	–	22.5	–	18.3	15.4	10.2	6.5	4.3	4832
1985	6.3	9.6	16.1H	17.7	19.8	18.7	–	19.3H	15.5	–	4.8	4.1	5049
1986	5.2	8.6	11.6	16.8	–	–	16.6	15.7	11.9	9.0	5.3	4.0	4386
1987	5.0	10.3	11.4	13.5	18.2	–	19.4	18.4	11.5	9.6	5.1	3.9	4290
1988	5.4	7.8	12.3	12.9L	17.0	21.2	18.6	17.2	13.7	7.2	4.9	4.8	4365
ave[b]	5.9	9.2	12.7	16.3	18.7	20.1	20.1	17.3	13.8	9.6	5.4	4.4	4678
sd	0.9	1.2	1.4	1.6	2.1	2.8	2.0	1.3	1.7	1.5	0.9	0.8	283

[a]H shows the highest and L the lowest value for that month; – indicates that missing data were not estimated that month.
[b]Ave and sd are over years 1960–1988.

gaps because of various problems.

From approximately 7 years of processed data, the average daily wind movement has been calculated by months (Fig. 12). Dividing these values by 24 gives an average speed in km/hr, which is somewhat misleading because wind speeds are usually considerably higher during the day than at night. Dividing by 12 gives a better picture of average daytime speed.

February is the windiest month, averaging 119 km/d, or about 3 m/s during the daytime. July is the calmest month, averaging 58 km/d. The wind speed 3 m above the ground at HQ is probably lower than wind speed at 3 m above the forest canopy at HB.

Wind direction at HQ has been analyzed only from November 1965 to August 1967. For each 6-hour period starting at midnight, the number of kilometers of wind movement was assigned to one of eight possible directions. Average daily kilometers by direction were calculated for semiannual periods (Fig. 13). From November through April, north and northwest winds strongly dominate movement. In May through October, west wind becomes somewhat more important than north wind; northwest is still the dominant direction. South winds occur fairly frequently but are usually light, so contribute little to total distance. East winds are almost nonexistent.

›il Temperature

ı temperature has been measured at several locations at . Weekly values from a location 300 m southwest of the ›amgage for Watershed 4 are available for most of the ›iod from August 1959 to the present. The sensors are ›rmistors, part of Colman fiberglass soil-moisture sensors, ›lepths of 3, 8, 15, 30, 61, and 91 cm below the litter layer horizon). An analysis of these data has been published viously (Federer 1973).

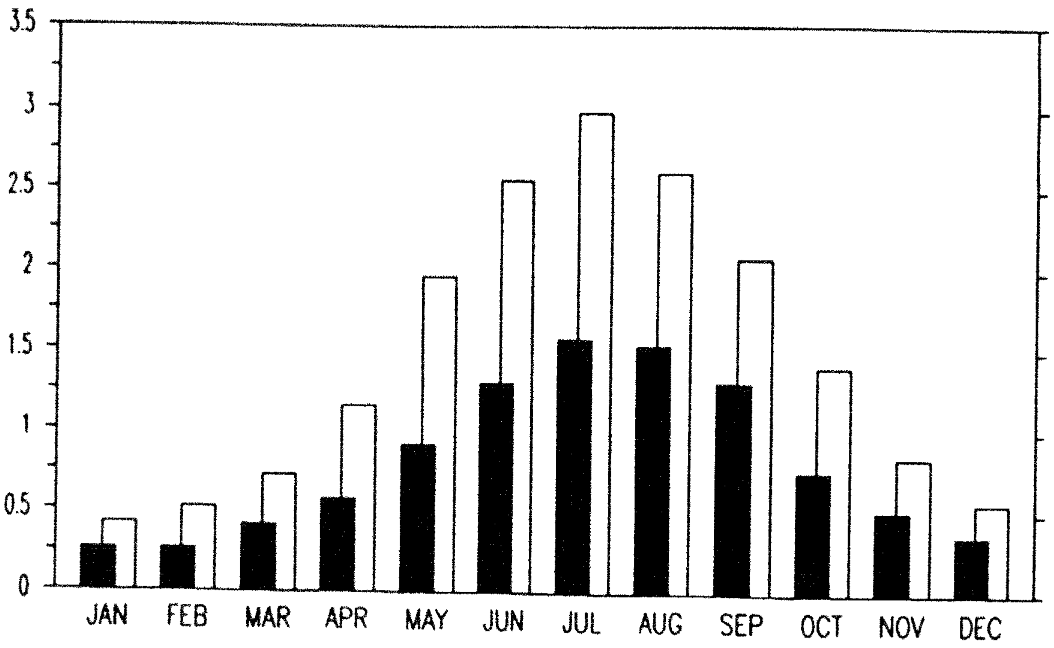
iation in soil temperature by day of the year is shown for m (Fig. 14) and 61 cm (Fig. 15) depth. Near the surface vinter, temperatures go below freezing only when soil ›zes. Soil frost occurs only in winters when snow cover is ı or late in developing (see Snow and Frost section). rming at 8 cm is rapid in April after snowmelt, because sun is high and leaves are not yet developed. Maximum ıperatures occur in July and August. The average ximum temperatures, approximately 17ºC at 8 cm depth ı. 14), are slightly lower than the average daily mean air ıperature. Soil temperature varies much less at 61 cm ›th than at 8 cm. The soil warms more slowly at greater ›th and reaches a summer maximum at 61 cm of 13ºC. pproximately mid-April and early October the soil is hermal; it has the same temperature at all depths. In ımn, cooling is slower at greater depth.

Snow and Frost

At HB, snow has been measured in a forest plot near each station. Each "snow course" consists of an area of approximately 1/4 ha and is designated by the nearby station number. On each weekly measurement date, ten points are sampled for depth and water content at intervals of 2 m along a line. On the next date, a parallel line, 2 m from the previous line, is used. Values from the 10 points are averaged. The number of snow courses measured in any year has varied, first as new locations were added, then as the network was reduced to save time. On the south-facing side, only Station 2 has a continuous record, and on the north-facing side, only Station 17. Snow-water contents measured at these two locations are given in Figure 16. Station 2 is at 560 m elevation on the south-facing side and is typical of low to mid-elevations in south-facing hardwood forest. Station 17 is at 893 m elevation, in mixed hardwood-conifer forest at high elevation on a north-facing slope.

Snow generally accumulates more and lasts weeks longer at Station 17 than at Station 2 (Fig. 16). This causes the delay in snowmelt streamflow on the north-facing watersheds.

The lowest snow years on the south-facing side have been 1974, 1980, 1981, 1983, and 1985, with maximum water



ıre 11.—Average vapor pressure, by month, at Headquarters (solid bars) and ırated vapor pressure at the average monthly maximum temperature (open bars).

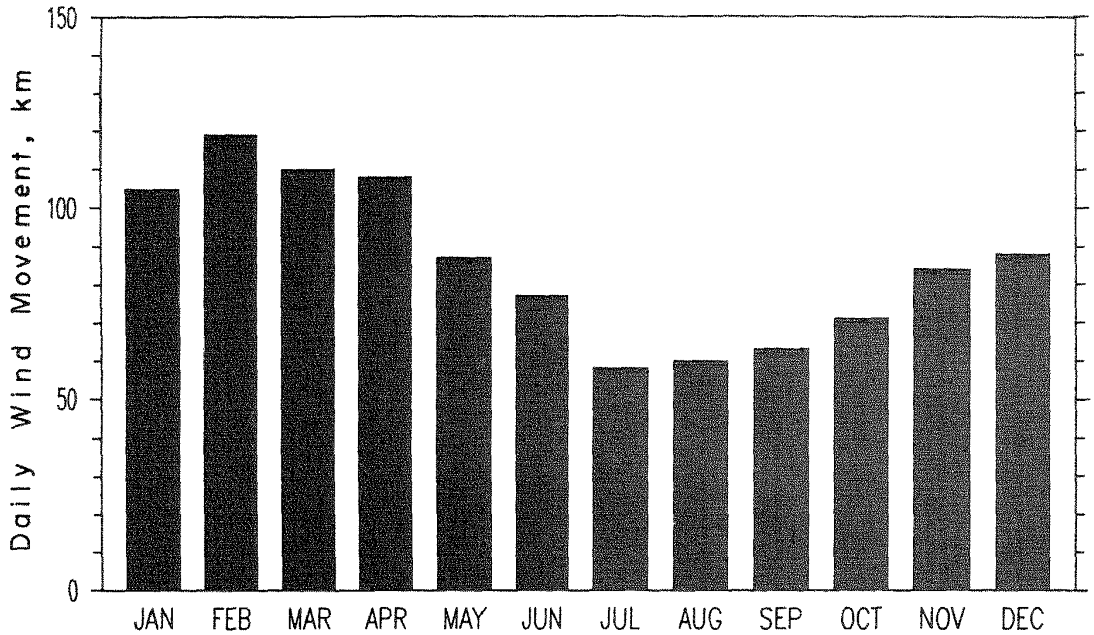


Figure 12.—Average daily wind movement at Headquarters by month.

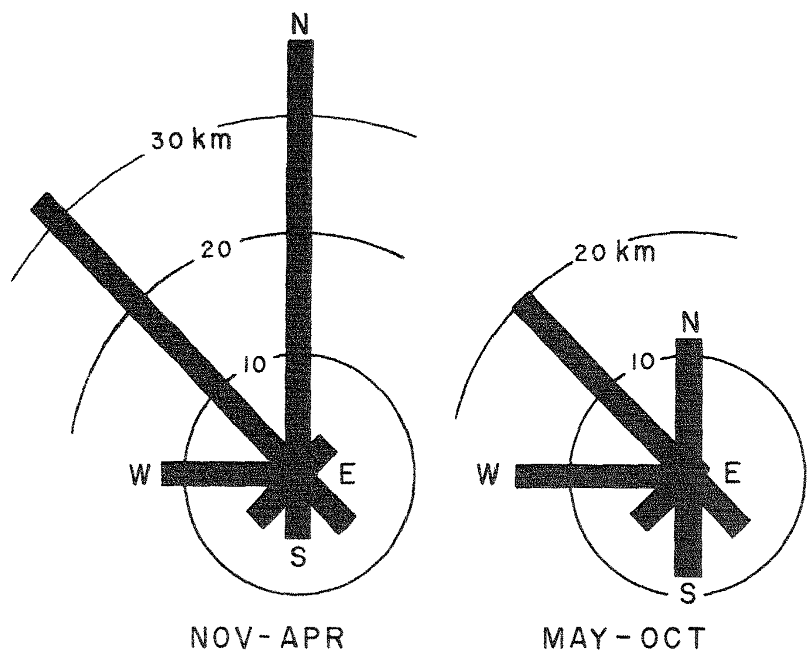


Figure 13.—Average daily wind movement at Headquarters by direction and season.

contents of about 150 mm. Deep snow years on the south-facing side include 1963, 1969, 1971, and 1982, with about 350 mm peak water content. At Station 17, water contents normally peak 100 to 200 mm higher than at Station 2.

Snow depth is not shown directly here, but the density of "ripe", or melting, snow at Hubbard Brook is about 0.35, so maximum depths are at least three times the maximum water content. Depths, therefore, reach 1/3 to 1 m on the south-facing side and approach 1.5 m at high elevation on the north-facing side.

Soil frost is measured at each measured snow course. At two points adjacent to each of the 10 snow sample points, the ground is probed with a ski pole to detect presence or absence of frost. At the first two points for which frost is detected, the soil is dug into and frost thickness is measured.

For many years in the late 1950's and early 1960's frost was seldom detected (Table 28). It was not measured in the late-1960's. Since 1970 frost has been present in February at south-facing Station 2 approximately one year out of three (Table 28). At Station 17, which is at high elevation and has some conifers, frost is detected at some points virtually every February. In heavy frost years all points can have frost, with frost thickness over 10 cm. These winters correlate well with winters of thin and late snow cover.

Frost develops in December in the absence of snow cover and can thicken if snow is thin in January. Once an insulating snow blanket is present, frost begins to melt from below because the soil is warmer at deeper levels (Figs. 14 and 15). Light early frost may even disappear in January or February. Heavy frost persists until spring when melting occurs from above.

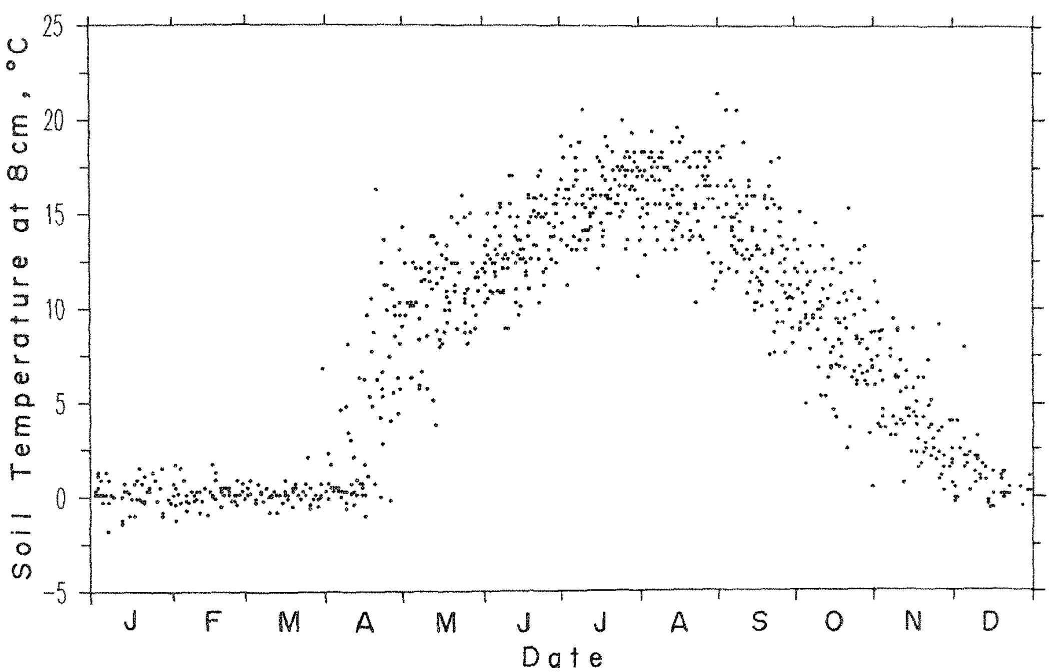


Figure 14.—Soil temperature at 8 cm depth by day of the year, 1959–86.

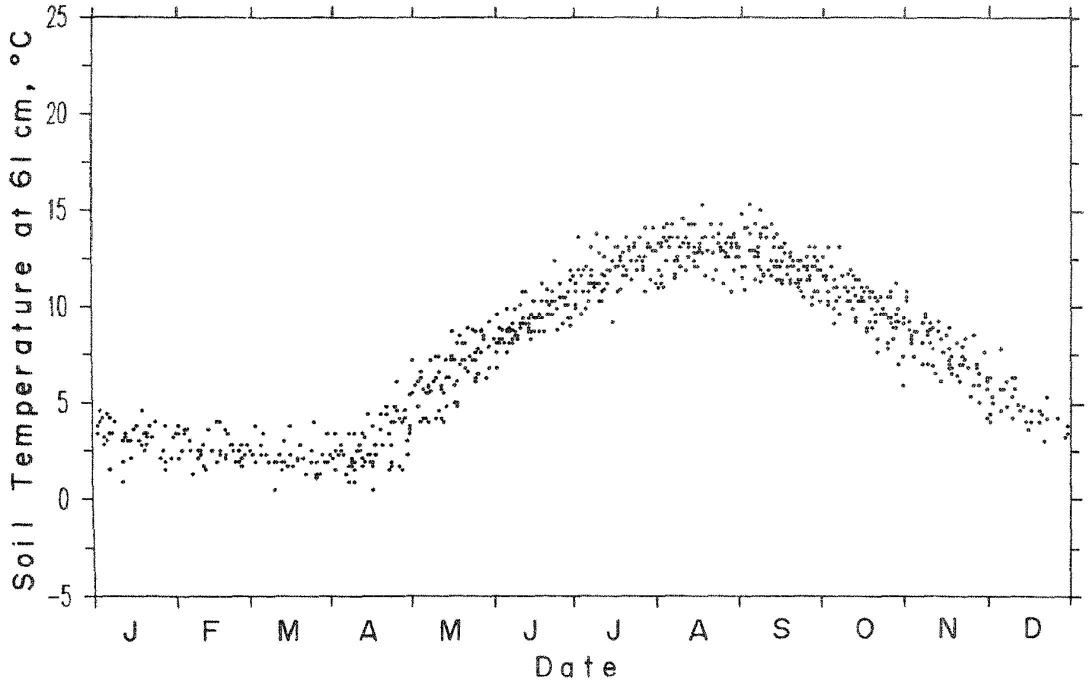


Figure 15.—Soil temperature at 61 cm depth by day of the year, 1959–86.

Dick Sartz, weighing snow tube for snow-water content, 1956.

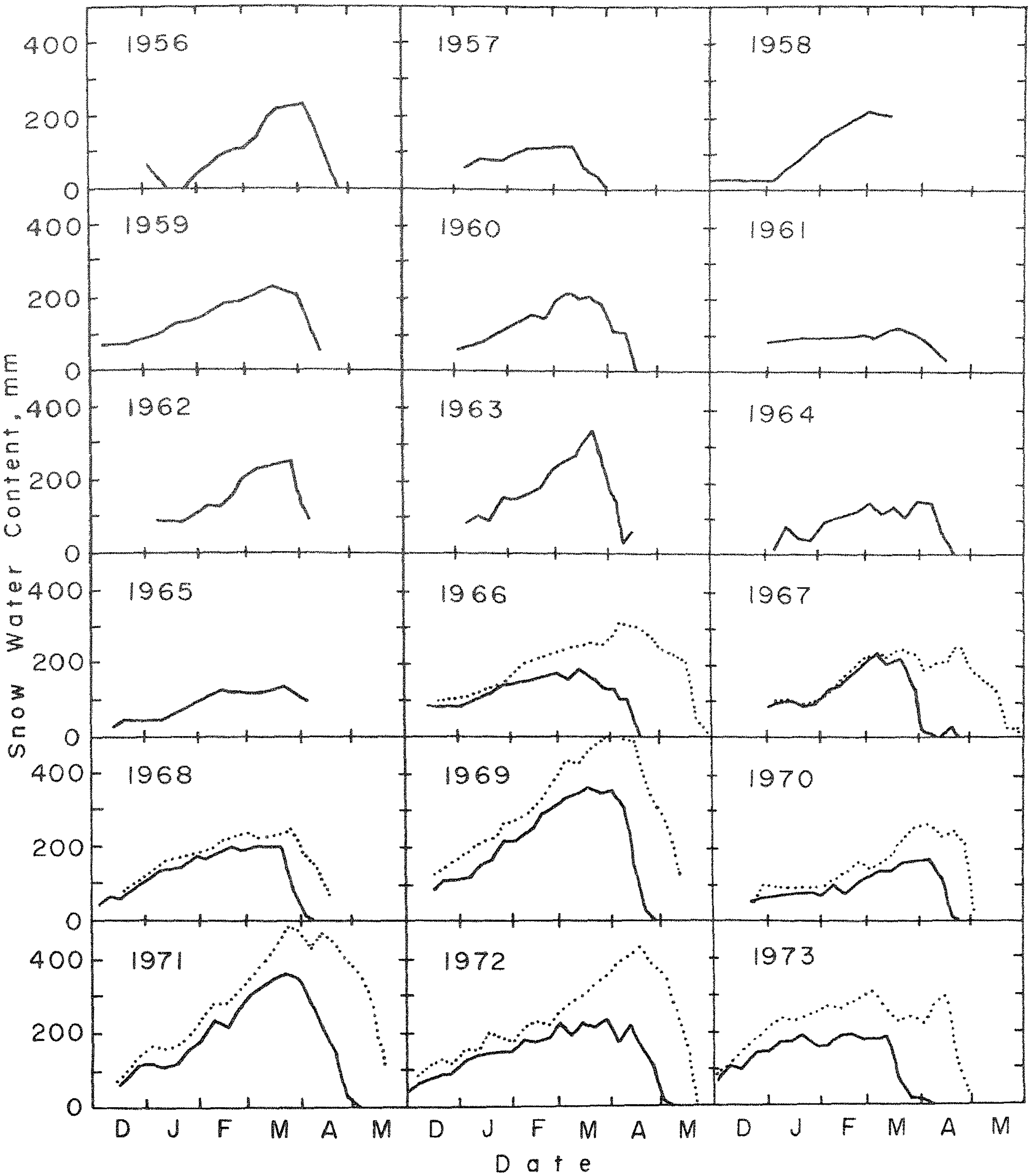


Figure 16a.—Snow water content for Station 2 (solid line) and Station 17 (dotted line), 1956–73.

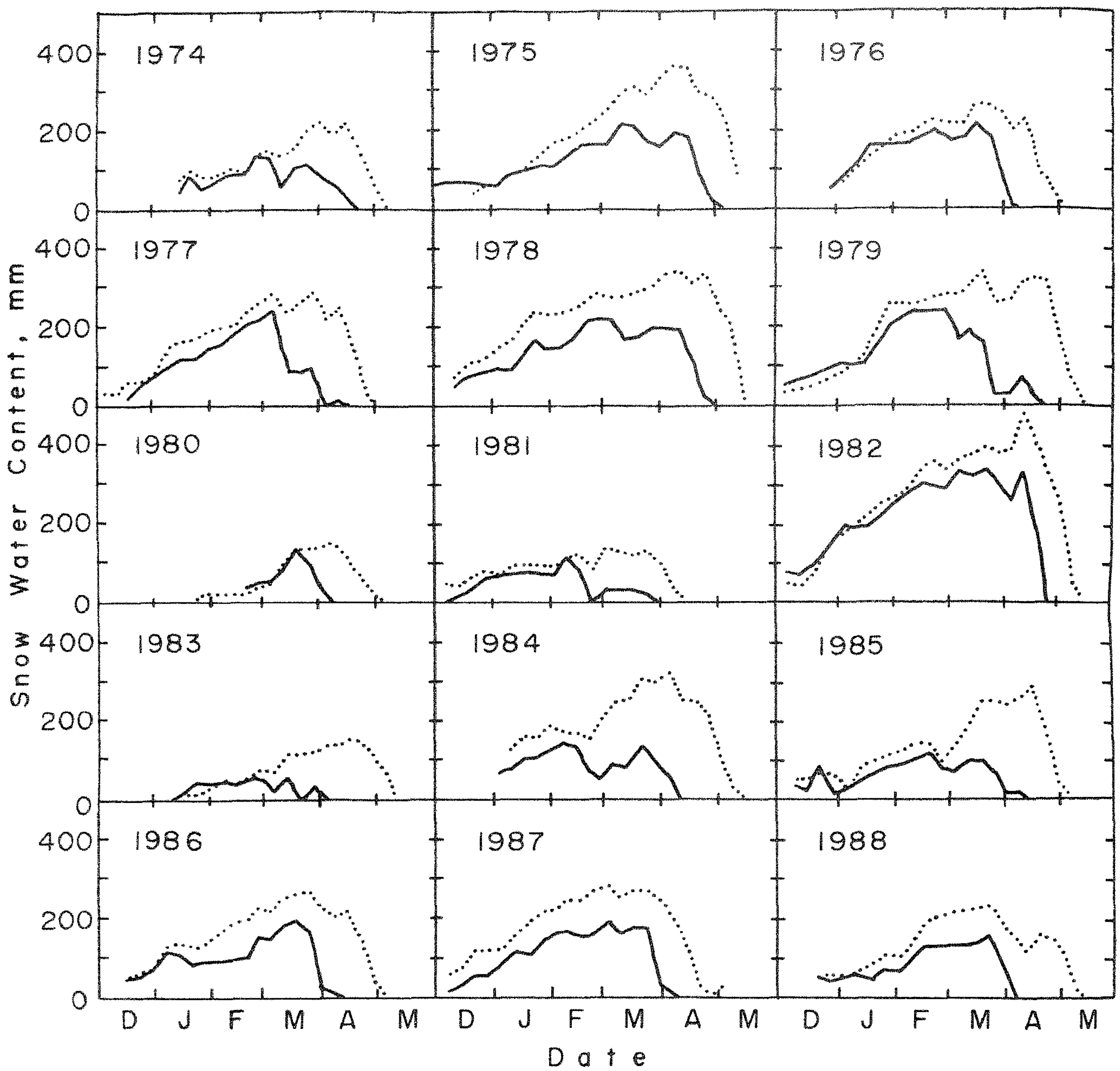


Figure 16b.—Snow water content for Station 2 (solid line) and Station 17 (dotted line), 1974–88.

Table 28.—Average soil frost incidence and thickness in February, by year, for Stations 2 and 17

Year	Station 2		Station 17	
	Incidence	Thickness	Incidence	Thickness
	%	cm	%	cm
1956	20	5	–	–
1957	0	0	–	–
1958	0	0	–	–
1959	0	0	–	–
1960	0	0	–	–
1961	0	0	–	–
1962	0	0	–	–
1963	0	0	–	–
1964	0	0	–	–
1965	–	–	–	–
1966	–	–	–	–
1967	–	–	–	–
1968	–	–	–	–
1969	–	–	–	–
1970	56	6	95	12
1971	0	0	43	1
1972	0	0	17	1
1973	0	0	0	0
1974	76	9	100	13
1975	0	0	50	1
1976	26	2	100	2
1977	0	0	91	1
1978	0	0	32	3
1979	0	0	30	1
1980	100	17	100	22
1981	0	0	92	6
1982	0	0	29	2
1983	100	8	100	12
1984	0	0	25	1
1985	0	0	60	1
1986	16	0	66	2
1987	0	0	13	1
1988	0	0	83	3
1989	84	2	100	10

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Summarizes and interprets hydrologic and meteorologic data collected at the USDA Forest Service's Hubbard Brook Experimental Forest. Data are included on precipitation, streamflow, air temperature, solar radiation, humidity, wind speed and direction, soil temperature, snow, and soil frost. These variables have been measured on or near eight small gaged watersheds since 1956, and form the basis of extensive research studies on cycling of water, energy, and nutrients in a northern hardwood forest.

Keywords: precipitation; streamflow; temperature; solar radiation; snow; Hubbard Brook