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SOIL-WATER RELATIONS AT THE HEADWATERS OF A FOREST STREAM IN CENTRAL NEW ENGLAND

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FOREWORD

This study was conceived and carried out by Walter H. Lyford, Soil Scientist at the Harvard Forest from 1960 until 1976. I helped with its planning and instrumentation. Walter died soon after retirement, with the study unfinished. His experimental records were accompanied by hundreds of pages of notes - handwritten and typewritten observations, speculations, and musings.

It was arranged by Harvard University and the Northeastern Forest Experiment Station that I complete Walter's watershed study. The month of June 1979 was spent at the Harvard Forest, analyzing data and preparing a manuscript. Walter's ideas as well as his data were woven in to preserve as much as possible of his thinking on forest-soil-water relations. These ideas, excerpted from his notes, are identified in the text with a parenthetical (L) for Lyford. Walter had roughed out all of the figures used to illustrate this paper as well as Tables 1 to 5; Tables 6 to 9 reflect my interpretation of his data.

I thank the University and the Station for allowing me this opportunity for a last service to a good friend and gratefully acknowledge Dr. E. L. Stone's perceptive criticism of the manuscript.

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ABSTRACT

Water behavior in forest soil was observed on a 14.86-acre watershed near Petersham, Massachusetts. Soils (Gloucester catena), land use (forest), precipitation (44 inches per year), and relief (gently rolling) are typical of the region. Soils were designated by position on slope: well-drained (ridges), poorly drained (swales), and imperfectly drained (between ridges and swales). Levels of soil saturation were recorded continuously in four shallow wells. Water content of soil was measured frequently in 29 access tubes with a neutron probe. Water loss was not measurably different from soils growing red pine and mixed hardwoods. Lack of steep hydraulic gradients on this watershed strongly influenced levels of soil saturation and rates of soil drainage. Infiltration and percolation were rapid in all soils, but lateral drainage of well-drained and imperfectly drained soil was impeded when poorly drained soil was saturated. Well-drained soils never saturated to their surfaces; poorly drained soils remained near saturation throughout the dormant season and after heavy rains in the growing season. Soils always wet to maximum water content during spring snowmelt. Overland flow occurred only when soils were saturated to their surfaces. Soil-water relations, even on this gently sloping land, show that precipitation is routed through forest soil to streams as postulated by the variable source area concept.

INTRODUCTION

Precipitation is the only source of streamflow on forest land. Most rain falling to the forest floor infiltrates it immediately, then percolates rapidly into the underlying mineral soil. Percolating water tends to sink toward some less permeable stratum and then drains laterally to a stream, always propelled by gravity; i.e., positive hydraulic head under saturated conditions. Given this typical performance, overland flow occurs rarely on most forest land (Lull and Reinhart 1972). When rains are prolonged or intense, or when rain falls on melting snow, rates of percolation can exceed rates of lateral drainage and, especially on gently sloping land, soils become saturated (Lyford 1964a). Water in excess of the soil pore capacity exfiltrates only then, draining across the forest floor as overland flow to streams. Thus did Lyford conceive headwater streams to originate at their uppermost sources on forested land. Soil-water behavior as indicated by this concept is reported in several recent studies (e.g., Palkovics *et al*. 1975, Hewlett and Troendle 1975, Harr 1977, Anderson and Burt 1978). Older studies have been reviewed by Hewlett (1974).

Most such studies focus on stream behavior, devoting less attention to the passage of rain from its infiltration into the soil to its exfiltration into a stream. That passage through the soil is influenced by two energy sources, solar and gravity, with the influences of both changing with the seasons. Neither source has much effect on water during the cold northern winter when precipitation merely accumulates as snow on the forest floor. As the longer, warmer days of spring approach, solar energy melts the snow. Meltwater is drawn by gravity through the forest floor, saturating the underlying soil, and then raising the streams to high levels. With the coming of summer, maximum evaporation losses draw heavily on soil moisture, the opportunity for soil saturation decreases, and streamflow declines. Evaporation lessens with decreasing solar energy in autumn, again allowing the levels of water to rise in soil and streams.

This paper recounts Lyford's observations of water behavior on the forest floor in 1970, then summarizes his measurements of soil wetting and drying in 1971.

THE STUDY AREA

Lyford's research was conducted on the Harvard Forest near Petersham (lat. 42^{o} 32'N, long. 72^{o} 12'W), in north-central Massachusetts. The study watershed (Figs. 1,2) drains into Nelson Brook, a tributary of the Swift River. Elevation is about 1,200 feet. It is typical of much hilly land in central New England and of thousands of similar headwater catchments (L). The study area has a long history of intensive research.

Figure 1. A waterfilled micropit during spring snowmelt.

Climate

Official records of precipitation and air temperature for Petersham are collected near the forest headquarters. Precipitation averages 44.0 inches per year, evenly distributed throughout most years and within 7 inches of average all but exceptional years (L). Summer precipitation was exceptionally heavy in 1938 (8.19, 3.29, and 15.78 inches for July, August and September), and exceptionally light in 1968 (0.95, 0.65, and 2.01 inches for the same months, respectively). Annual rainfall was 6 inches below average in 1970, but spring and summer rainfall were close to average in the spring and summer of 1971:

	inches		inches
April	1.81	July	4.84
May	3.35	August	4.73
June	3.12	September	3.02

Mean annual maximum, minimum, and average temperatures for Petersham are 64.7°, 24.6°, and 44.7°F., respectively. Snowfall averages 65.0 inches per year, based on 50 years (1913-1962) of observation (unpublished data on file at the Harvard Forest, Petersham, Massachusetts). Summer 1971 was sunnier than usual for most of southern New England (NOAA 1971).

Soils

The last glacier melted 12 to 14 thousand years ago, leaving a landscape little changed since then. After the glacier melted, the study area was mantled with 5 to 10 feet of glacial till derived from coarse-grained gneiss and granite. Changes over time probably have been slight in the postglacial landscape -- then as now, a complex of knolls and shallow depressions, with gently sloping land between. Soil on knolls seldom saturated to its surface; indeed, the water usually lay deep, only occasionally rising to within 2 or 3 feet of the surface (Lyford 1964a). By contrast, closed depressions remain more or less continuously wet, with water tables at or near their surfaces during dormant seasons, falling beneath their surfaces only in midgrowing seasons (Lyford 1964a). There has been little or no down-cutting of channels draining these depressions since glaciation. Silt-capped pebbles, common to study area soils, indicate long-continued eluviation of fine particles (L).

Soils formed under these contrasting conditions of landform and wetness have different appearances (Table I). All of them resemble Gloucester or its catenary associates (L) and all of them embody some of that soil's physical attributes (Table II). But hereafter they will be referred to as well drained, imperfectly drained and poorly drained to avoid certain complexities of soil taxonomy. For example, Lyford's notes suggest that he never satisfied himself as to the prevalence of a fragipan that would have placed these soils firmly in the Essex (with fragipan) or Gloucester (lacking fragipan) catenas. Soils on convex surfaces (Essex or Gloucester) are called well drained. Soils in depressions and saturated within a few inches of their surfaces for several months (Brockton, Whitman, or peat) are called poorly drained. Relatively flat-lying soils between these extremes of water content (Acton, Scituate, Leicester, or Norwell) are called imperfectly drained. Half of the study area soils (7.4 acres) is well drained, 0.8 acre is poorly drained, and the balance (6.7 acres) is imperfectly drained.

Soils at Harvard Forest were mapped in 1940 by the Soil Conservation Service at a scale of 1 inch = 200 feet. In 1971, Lyford remapped the study area soils in far greater detail, at a scale of 1 inch = 20 feet. Correspondence of type lines on both maps was surprisingly close (L). However, the 1940 classification of three wetness levels (Gloucester, Acton, and Whitman) likely would have been expanded to five levels (Gloucester, Scituate, Norwell, Brockton, and peat) on a more modern soils map (L). All of these are bouldery, stony, pebbly, coarse sandy loams in the A and upper B horizons. They are friable to firm throughout their profiles and rapidly permeable except where hard, compact, brittle and slowly permeable fragipans are present.

Table I. Distinguishing internal features of soils in the study area (L)

Soil Series Name	Horizon Sequence	Color Sequence		
		A Horizon	B Horizon	C Horizon
Gloucester	O-A-B-C	brown	yellowish-brown paling with depth	gray
Acton	O-A-B-B(g)-Cg	brown	B, yellowish-brown B(g), yellowish-brown with mottles	gray with mottles
Scituate	O-A-B-Bx(g)-Cg	brown	as for Acton except with fragipan	gray with mottles
Norwell	O-A1-A2g-Bg-Bxg-Cg	A1 black A2 gray	Bg with grayish-brown matrix	gray with mottles
Brockton	O-A1-Cg-Cxg-Cg	A1 black & mucky	----------------------	gray with mottles
Peat	O-C	(3 - 20 ft. of peat over gray till)		gray with mottles

Table II. Physical properties of Gloucester soil at pit 7-62 (Lyford 1964b)[a]

Horizon	Depth	Bulk Density[b]	Pore Space[c]	Coarse fragments >2mm[d]	Ignition loss[e]
	inches	g/cm^3	- - -	percent	- - -
A 11	0-1	0.99	78	1	12.4
A 12	1-3	1.11	68	7	-
B 21	3-5	1.59	68	28	8.4
B 22	5-8	1.88	55	27	6.9
B 231	8-18	1.90	50	45	2.5
B 232	18-24	1.90	49	45	1.6
C 1	24-33	1.73	35	68	0.9
C 2	33-46	1.81	27	83	0.7
C 3	46-57	-	32	83	0.7

[a] Neutron probe access tubes 20-22 (Table IV) were installed near this soil pit

[b] Calculated for "whole soil" - including coarse fragments - as per Lyford 1964b

[c] Pore space = $100 - \frac{\text{Bulk Density}}{2.65} \times 100$

[d] Percent by volume

[e] Particles <2 mm

Land Use

The study area was cleared of old-growth forest between 1770 and 1800 and pastured for a while. It never was cultivated. Old field white pine (*Pinus strobus* L.) developed during the early 1800's and was harvested about 1890 (L). The subsequent young hardwood stand was cleared and burned in 1924. There is no evidence that any of these uses accelerated natural rates of soil erosion (L).

In 1925 the area was planted with alternate rows of red pine (*Pinus resinosa* Ait.) and white spruce (*Picea glauca* (Moench) Voss) on 5- x 5- foot spacing. Most of the spruce has died, leaving red pine at 5- x 10- foot spacing. A few spruce survive and there are some volunteer white pine and hardwoods, but red pines dominate. They range in diameter from 7 to 16 inches, are about 65 feet tall, and have a basal area of about 250 square feet per acre. The forest floor is blanketed with 2 to 3 inches of litter, mostly red pine needles. Ground vegetation is scant on well-drained and imperfectly drained soils but abundant on poorly drained soil. Most of the pine roots are in the A and B soil horizons where they create few permanent root cavities. Apparently, the sandy soils soon collapse into cavities created by the death of roots (L).

Watershed Properties

About 500 acres are needed to sustain perennial flow in streams draining the forested land of central New England (L). Most such watersheds are comprised of many smaller drainages, each contributing intermittent overland flow when its soils are sufficiently moist. Such is the study area. It has gentle slopes, averaging about 4 percent south. The few slopes exceeding 10 percent seldom exceed 50 feet in length. Drainage channels are diffuse and the watershed boundaries are indistinct. Data in Table III suggest the relative water-supplying capabilities of soils on the study area.

Table III. Water retention by surface (0 to 10-inch) soils at selected tensions[a]

Soil Type	Drainage	Water retention at 1/10 atmosphere	Water retention at 1/3 atmosphere	Water retention at 15 atmosphere
		- - percent moisture by volume - -		
Gloucester fine sandy loam	Well	23.1	12.8	5.2
Scituate loam	Imperfect	40.7	22.0	8.4
Norwell stony loam	Imperfect	41.2	27.4	11.6
Brockton very stony loam	Poor	48.4	31.4	14.0

[a] Assembled from published descriptions of stone-free (<2 mm) Gloucester soils

Mound and pit microtopography is pronounced on the study area, evidence of much windthrow in ages past (Stephens 1956). A few large pits, 10 to 20 feet in diameter, are relic depressions from melted glacial ice. A lack of brisk overland flow and soil erosion has prevented the filling of pits as well as the formation of drainageways among them (L). Pits in imperfectly drained and poorly drained soils become waterfilled in late winter and early spring (Fig. 1). Then water flows sluggishly overland from pit to pit, in a string-of-beads fashion. However, the velocity of overland flow is far too slow to erode the nearly flat intermittent channels. Often it sinks below ground, and is heard running among the stones in subsurface channels.

The following phenological observations for 1971 suggest the influence of forest vegetation on soil-water relations of the study area (L):

April 24	Buds swelling on red maple, elm, and aspen. Snow becoming patchy.
April 28	Snow almost gone.
May 4	All leaves growing except red oak.
May 14	Leaf canopy almost fully developed.
May 18	Red oak leaves three-fourths grown.
Sept. 24	Black gum and red maple leaves coloring.
Sept. 29	All leaves coloring.
Oct. 3	Most leaves colored, some falling.
Oct. 11	All leaves colored, some falling.
Oct. 19	Leaves 90 percent fallen.
Nov. 26	Three to four inches of old snow on ground, ten to twelve inches of new snow today.

THE STUDY OBJECTIVE

The preceding "watershed properties" cast some light on soil-water relations of the study area, but they provide an inadequate base to comprehend how headwater catchments nourish perennial streams. The objective of this study was to learn more about the levels and movement of water in well-drained, imperfectly drained, and poorly drained soils located at the uppermost source of an intermittent stream.

METHODS

Surficial Drainage

The following measures were taken to allow close observation of surface drainage on the forest floor when soil moisture was athigh levels during the spring of 1970.

1. A grid was established over the entire watershed, its north-south baseline roughly parallel to the eastern boundary of the study area. Perpendiculars to the baseline were established at 100-foot intervals but with no slope corrections because of the nearly flat topography. One hundred-foot spacing between grid stakes was presumed accurate to ± 6 inches. A watershed map (Fig. 2) was prepared following the grid system.

2. On April 14, warm rain fell on the 6- to 12-inch snow cover. A wire-stemmed flag was placed in each mound and pit micropool, filled at the time to near capacity with water. Flags of another color were placed along the courses of water flowing overland across the forest floor. Crossed flags were placed wherever subsurface flow could be heard underground.

3. Location of micropools and overland flow was plotted on the map of the study area. About 3 inches of rain fell in mid-May, recharging soil moisture and reestablishing pools and drainage which permitted a check of their locations on the map. The coincidence of well-drained soil with waterless windthrow pits, of imperfectly drained soil with micropools, and of poorly drained soil with overland flow was almost exact (Fig. 2).

Soil Saturation

During 1970, fluctuating levels of saturation (i.e., perched water tables) were observed in the micropools. Because it seemed possible that water levels in these pools showed some more or less permanent level of soil saturation, post-hole size "wells" were dug in about 50 of them. Soil slumping into 23 wells of continuing interest was prevented by placing lengths of Orangeburg tile upright in them. A backhoe was used to dig three wells as deep as possible, striking bedrock at 4 to 6 feet. Saturation depth below the soil surface was measured to the nearest inch with a rule mounted on a float. Measurements were taken daily in wet weather and at 2- to 3-day intervals in dry weather. Many wells were abandoned late in 1970 after close similarity of water-level fluctuation had been established among them.

Observation during 1970 established that water level in four of the wells (Fig. 2) consistently reflected the level in most other wells on similarly drained soils. Wells 1 and 2 were in imperfectly drained soils (Acton and Scituate); wells 3 and 4 in poorly drained soils (Norwell and Brockton). These wells were fitted with gas-operated recorders (Helmers 1968) during the winter of 1970-1971, which permitted continuous observation of water levels in them. Wells were not placed on well-drained soils because water levels in them seldom rose to measurable levels (Lyford 1964a).

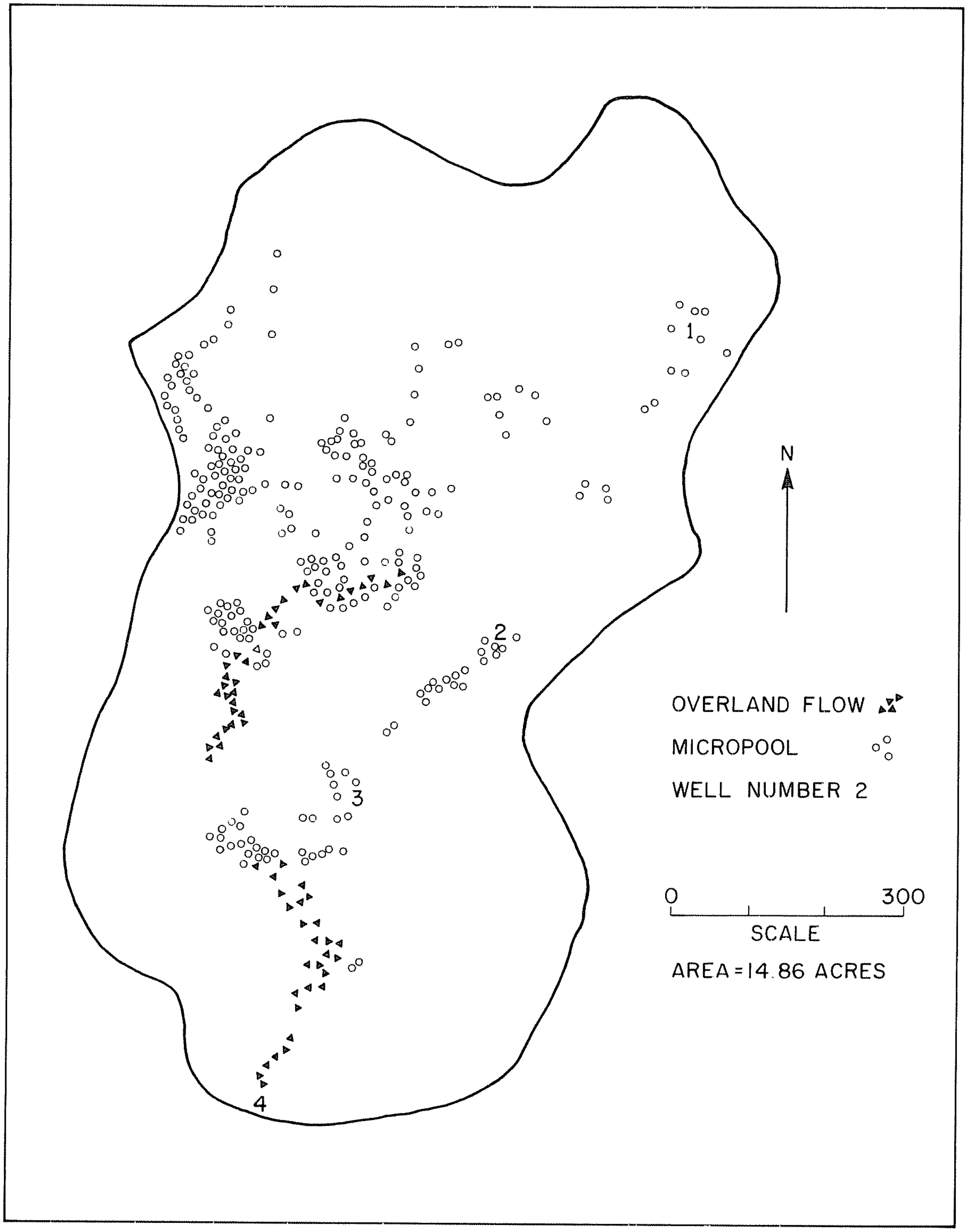

Figure 2. Location of micropools and overland flow on the study area.

Soil Water Content

Neutron probe (Nuclear Chicago, Model P-19) access tubes were installed during spring 1971, a difficult job in the stony soil. A favored method for placing tubes was probing between stones with a thin metal rod, then installing a tube wherever the rod could be driven at least 30 inches into the soil. As many as 30 to 40 probings usually were needed to locate a tube installation site.

Lyford was concerned that large stones in the soil might function as voids during soil moisture sampling, providing false evidence of minimal and relatively unchanging water content. This concern was partially allayed by installing the tubes in clusters (Table IV); presumably, average water content for the tube cluster would provide the most realistic data for each sampling.

Soil moisture was sampled at 6-inch intervals to a depth of 30 inches in all of the access tubes, and to 36 inches in the deepest tubes. Thirty-second counts were recorded at each sampling interval, prior trials having demonstrated adequate consistency of data obtained at this counting rate (L). Counts were converted to soil water content by volume by using locally prepared conversion tables.

Soil moisture records for earliest installed tubes began late in April 1971, records from last-installed tubes began in mid-June. All tubes were read on a given sampling day, immediately before and after rains when possible. With respect to frequent (2- to 5-day intervals) and full-cluster readings, the best soil moisture data were obtained May 1 through July 12, 1971. The probe was inoperative from mid-July until early August. After probe repair, only the tube Lyford judged most representative of those in a cluster usually was read, and that at irregular intervals. A few soil moisture readings were obtained in May and June 1972.

Overland Flow Duration

Beginning in 1970, the dates were recorded when water visibly flowed from the study area.

Table IV. Dispersion of neutron probe access tubes on and close to the study area. Access tube locations are keyed to well locations on Fig. 2.

Access Tubes	Soil Drainage	Location
1-5, 10-12	Imperfect	Vicinity of well 1
20-22	Well	Hardwood-covered knoll about 700' south of well 4 (near soil pit 7-62)
30-32	Well	Hardwood-covered knoll about 300' south of well 2
40-42	Well	Red pine-covered knoll about 200' north of well 1
50-52	Well	Hardwood-covered knoll about 750' east of well 1
60-62	Well	Red pine-covered knoll about 450' northwest of well 1
70, 71	Imperfect	Red pine, about 250 feet west of well 1
80, 81	Poor	Red pine, in shallow drainage depressions at well 3
90, 91	Poor	Red pine, in intermittent stream at well 4

RESULTS AND DISCUSSION

Surficial Drainage

More than 600 flags were needed to mark water-filled micropools on the study area (L), most of them on imperfectly drained soil (Fig. 2). Upslope, (e.g., around well 1) micropool bottoms had gleyed soils with thicker organic and A_1 horizons than did adjacent unpitted soils.

At midslope (e.g., around well 3) micropools saturated more often and had bottoms covered with mucky soil. Downslope (e.g., around well 4) windthrow pits had filled with peat, the frequency of soil saturation in poorly drained soil precluding normal leaf decay (L).

Most micropools contained 6 to 10 inches of water, not as cisterns, but because water in them accurately reflected levels of saturation in the surrounding soil (L). Few of the pools drained by overland flow; rather, drainage in them was concurrent with falling saturation levels in the adjacent soil. Pools ordinarily drained at rates around 1½ to 2 inches per day.

More than 300 flags were needed to mark the courses of overland flow on the study area (L). Most water courses flowed in shallow longitudinal depressions, far downslope on poorly drained soils (Fig. 2); others flowed in mere "sags" among the micropools. Once identified, these overland flow courses became visible, but nevertheless were indistinct and within banks never more than 1 foot high. Overland flow was too sluggish to carry away even the leaves that lined its courses. All overland flow was caused, not by failure of rain to infiltrate, but by exfiltration from the surrounding saturated soil. Overland flow never persisted for more than a day or two after snowmelt or heavy rain. There is no evidence that these ephemeral water courses (all of them on slopes <4 percent) have deepened since glaciation (L).

Dr. Earl L. Stone (Professor of Forest Soils, Cornell University) accompanied Lyford in 1970, when surficial drainage features on the ground were checked against their mapped locations. I examined flag and pool locations in 1971. Both of us confirmed that surficial drainage coincided closely with the soil drainage classes.

Levels of Soil Saturation

Well records of fluctuating levels of soil saturation could not be found for 1970.

Levels of saturation for the 1971 period of record are summarized in Fig. 3. Water standing to the soil surface in all wells indicated soil moisture at or near saturation levels during snowmelt in April and during the rainy weather of early May. From May 14 until June 24, well levels fell at rates relative to their positions on slope; at rates of 1-1/4 inches, 3/4 and 3/8 inch per day for wells 1, 2, and 3, respectively. Well 4, farthest downslope, remained saturated essentially to the soil surface throughout this period. Water levels in well 2 fell more rapidly throughout the summer than did levels in well 3, but all wells drained at rates more rapid during midsummer than during the May-June period following snowmelt.

The August-October 1971 data suggest a reverse order of soil resaturation, with soils farthest downslope (near well 4) saturating soonest. In fact, only at well 4 were soils saturated to the surface at least once per month throughout the summer. Despite the fact that all well levels rose immediately at the onset of rain, often within 15 minutes (L), soils downslope always saturated first. During the rainy weather of late July, for example, soils at well 4 were fully saturated on July 30, at well 3 on July 31, and at well 2 on August 3. Well 1 remained dry throughout the late summer. The trend was similar after the large storm of July 2. The duration of soil saturation was even more closely related to position on slope, with soils at well 4 remaining saturated longest, soils at well 2 draining soonest. This performance suggests that water blocks water, that drainage of upslope soils was inhibited whenever soils downslope were fully charged with water.

Soil saturation levels from June through September, entirely controlled by water supply (rainfall) and demand (evapotranspiration), are subject to all of the large and unpredictable fluctuations caused by weather. Dormant season levels of soil saturation are far more predictable, rising gradually throughout the autumn and winter, then attaining recurrent annual peaks during snowmelt.

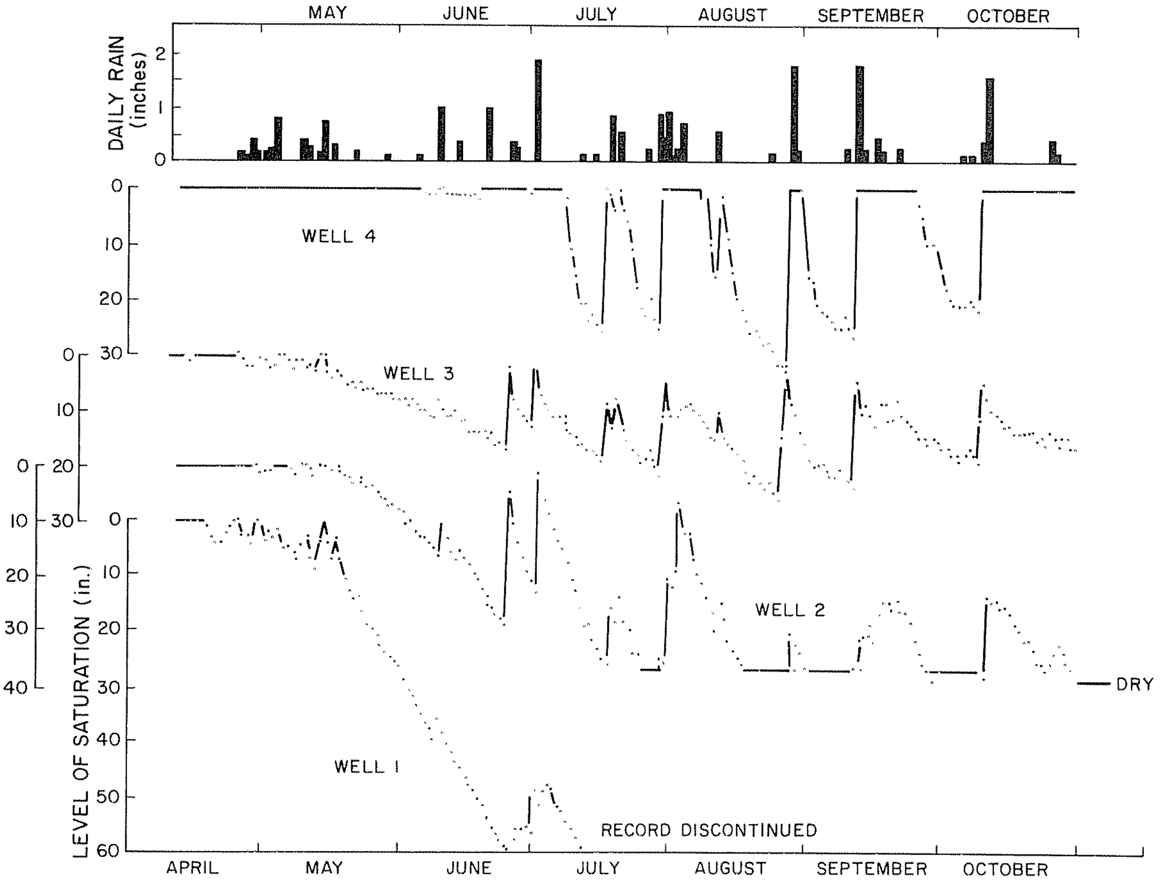

Figure 3. Levels of soil saturation at recording well sites.

Dormant season levels usually varied only with position on slope.

In summertime, water tables fluctuated diurnally as well as seasonally, a commonly observed response to transpiring vegetation. Diurnal fluctuations also reflect the position of wells on slope. On July 7, soil at well 4 was saturated to its surface but water levels were at depths of 11, 15, and 53 inches at wells 3, 2, and 1, respectively (Fig. 4). During the next 4 days, the saturation level at well 3 fell more than 2 inches per day but recovered 1 inch at night, an overall fall rate close to 1 inch per day. The saturation level at well 2, upslope from well 3, fell nearly 3 inches per day but recovered only 1/2 inch at night, an overall fall rate of 2-1/2 inches per day. Transpiration rates probably were equal at all of the well sites, but water draining from upslope moved more rapidly into well 3 than into well 2. Little or no water was available to drain from the well-drained soils surrounding well 1 to replace losses from it. Some losses from well 2, further downslope in imperfectly drained soil, were replaced but not rapidly enough to nullify losses.

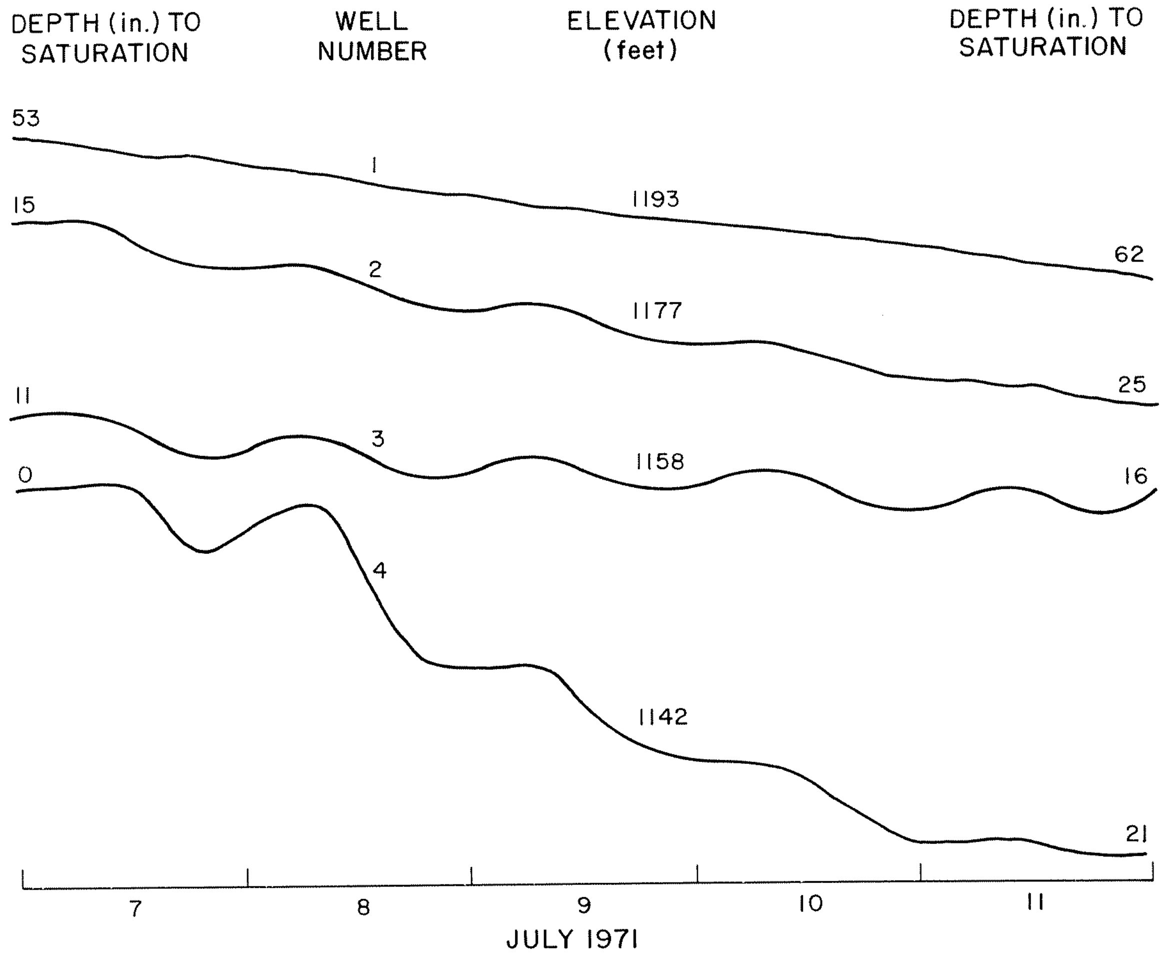

Figure 4. Diurnal fluctuation of water levels during midsummer.

Saturation levels in well 4 fell more than 20 inches between July 7 and 11, with greatest diurnal fluctuation earliest in that period. Reasons for this performance are not known but it suggests a rapid emptying of macropores as soon as drier soils upslope ceased draining toward well 4. A concentration of understory plant roots near the soil surface also may have contributed to the rapid fall of water level.

Soil Water Content

Position on slope (Table V) also controlled soil water content as measured with the neutron probe. Poorly drained soils (farthest downslope) contained nearly twice as much water as well-drained soils (farthest upslope). Imperfectly drained soils (at midslope) held consistently between these extremes. On any sampling date, all tubes in well-drained soil were surrounded by soil less moist than any tube in imperfectly or poorly drained soils. All tubes in poorly drained soil were surrounded by soil more moist than any tube in well-drained or imperfectly drained soils. In short, the water content of well-drained, imperfectly and poorly drained soil was entirely consistent with position on slope. In most studies of forest soil moisture, the data are not so neatly stratified, probably because small catenary changes in drainage are not mapped in sufficient detail to show the effects of slope position on soil water content (Lyford 1974). Regardless of slope position, soil of all drainage classes contained least water in summer months.

Data in Table V, because of their nonrandom nature and differing sample sizes, are unsuited for further statistical treatment (personal communication from Joseph Mawson, Biometrician, University of Massachusetts, Amherst). These data do roughly reflect amounts and distribution of rainfall as shown in Fig. 3.

Entries in Table VI are the highest and lowest water content observed for each soil drainage class. Maximum water content considerably exceeded the 1/10 atmosphere values listed in Table III; probably the maxima are real because they were obtained when study area soils were at or near saturation. In all cases, minima for the study area approach the 1/3 atmosphere values listed in Table III. If study area soils actually did dry to only 1/3 atmosphere, then even the well-drained soils never even approached a drought condition.

Table V. Average water content, in 30-inch profiles of forest soil (1971)

Month	Soil Drainage Class		
	Well	Imperfect	Poor
	- -	percent moisture by volume	- -
April	24(6)[a]	36(4)	46(4)
May	24(48)	32(47)	45(12)
June	20(48)	26(47)	37(20)
July	21(20)	25(22)	37(14)
August	20(21)	27(20)	37(28)
September	22(17)	24(14)	36(20)
October	21(15)	26(12)	37(13)
November	22(4)	25(6)	37(5)
December	24(2)	28(3)	52(2)

[a] Figures in parentheses are number of neutron probe measurements, for 30-inch profiles, from which the averages were calculated.

This apparent but likely unreal lack of soil drying is evidence of a problem previously foreseen by Lyford (1964b):

> Because of the difficulty of sampling stony soils there has been a tendency to concentrate field studies on non-stony soils. When stony soils are used ... there is a tendency to disregard completely the content of fragments larger than...[4 cm]. In some very stony soils this introduces considerable error in calculations designed to find the amount of moisture ... in given volumes [of soil].

The neutron data embody the error foreseen by Lyford because they derive from "whole soils" in which a considerable content of large stones functioned as voids within the soil. Thus, the data are not comparable to water retention data in Table III, likely derived from stone free (>2 mm) soil. I assume that the nonstone material in well-drained soil did dry below the 1/3 atmosphere level during periods of prolonged rainless weather. Reinhart (1961) discussed the complexity of applying neutron probe data to stony soils on an areal basis.

The lower limits of water content (Table VI) seem suspect in accuracy because large stones must have functioned as voids in the study area soils. But based on the remarkable precision provided by clustering the access tubes, I maintain that the neutron probe data show valid changes in soil water content over time. Thus, these changes were further examined.

Table VI. Maximum and minimum water content observed[a] at neutron probe measurement depth in forest soils

Measurement depths	Drainage class of soil: Well	Imperfect	Poor
	- - Percent by Volume - -		
6 inches			
Maximum	32	54	59
Minimum	16	21	23
12 inches			
Maximum	31	46	50
Minimum	16	20	34
18 inches			
Maximum	29	39	41
Minimum	17	20	31
24 inches			
Maximum	27	35	36
Minimum	18	21	21

[a] Absolute highs and lows from 5,314 observations.

If well-drained soil actually dried only to 1/3 atmosphere, then evaporation throughout the growing season took place at climatically determined (i.e., potential) demand rates on all soils. Evaporative demand was estimated (Malmstrom 1969) on the basis of average monthly air temperature. Daily soil water loss was computed for periods between major rains, during which only small showers occurred:

$$\text{Water loss} = \frac{(\text{SM}_1 + \text{rain} < 1.0 \text{ inch}) - \text{SM}_2}{\text{days between rain} > 1 \text{ inch}} \text{ in which}$$

SM_1 = Water in 36 inches of well-drained soil after a storm >1 inch

SM_2 = Water in 36 inches of well-drained soil before the next storm >1 inch

Water loss (drainage + transpiration) was not significantly different ($P = 0.05$) under red pine and hardwood forest (Table VII). Similarity of these water losses suggests little or no species-related difference between transpiration rates, consistent with Douglass' (1967) conclusion that annual evapotranspiration does not appear to differ between forest species grown at the same location under similar soil and atmospheric conditions. Lyford's notes show that he too had arrived at this conclusion but his computations are lost. Sunnier weather than usual (NOAA 1971) may account for soil water losses exceeding the computed average evaporative demand for May, July, and August. Hardwood leaves were sufficiently grown in May to transpire at the same rates as red pine needles but lower rates for September may reflect approaching leaf senescence. Leaf color change in autumn marks a sharp decline in transpiration from hardwood forests (Gee and Federer 1972). Water loss double the evaporative demand for October, probably is attributable to increasing drainage from rapidly recharging soils.

Data in Table VII suggest transpiration by trees at near-potential rates throughout the 1971 growing season despite reservations concerning related data in Table VI. Regardless, trees on imperfectly and poorly drained soils probably transpired at potential rates throughout the year. Occasional wilting of understory foliage on poorly drained soil (L) suggests recurrent drought of sorts caused by the shallow rooting habit of most such vegetation.

Water was lost more rapidly from 30 inches of imperfectly drained soil than from a like depth of well-drained soil (Table VIII). This computation, based on neutron probe data obtained during nearly rainless weather, omits the small rainfalls and deeper sampling used in Table VII. Hardwood leaves were fully emerged at this time. Imperfectly drained soil, containing more water throughout the year than did well-drained soil (Table V), simply had more water to lose. If all loss of water from well-drained, imperfectly and poorly drained soil had been attributed solely to transpiration, then all three estimates of transpiration would have been inflated by the amount of soil water actually lost as subsurface drainage.

Table VII. Average daily evaporative demand compared to average daily water loss from 36 inches of well-drained soil

Month	Evaporative Demand	Soil Moisture Loss Under Pine	Soil Moisture Loss Under Hardwood
	- - - - - inch	- - -	- -
May	0.08	0.10	0.10
June	0.11	0.11	0.11
July	0.13	0.18	0.15
August	0.12	0.13	0.16
September	0.10	0.17	0.07
October	0.08	0.17	0.16

Table VIII. Measured water loss from 30 inches of soil after 0.92 inches of rain on May 14, 1971

Days since Wetting	Well-Drained[a] Soil	Imperfectly Drained[b] Soil
	- - - - inch -	- - - - -
5	0.06 ± 0.009[c]	0.07 ± 0.014
11	0.05 ± 0.008	0.08 ± 0.014
19	0.03 ± 0.004	0.05 ± 0.011
26	0.01 ± 0.002	0.04 ± 0.008

[a] Based on data from 15 access tubes

[b] Based on data from 6 access tubes

[c] Standard error of the mean

Percolation was rapid in all of the study area soils. Within 24 hours after five summer rains, each exceeding 1-1/2 inches, only about half of the added water remained in 30-inch soil profiles (Table IX). This performance showed that substantial amounts of the infiltrated water had percolated deeper than 30 inches during the time between rainfall and soil moisture measurements. Beasley (1976) reported similarly rapid subsurface flow in permeable soils of the southern coastal plain.

In periodically saturated soils, water levels can be easily observed in small wells, cheaply and often. Furthermore, the water content of the study area soils can be estimated from well observations (Fig. 5). These equations are valid only for the climate, soil, and vegetation of the study area in 1971. Equations defining the relation of saturation level to soil water content at other times and places are certain to differ.

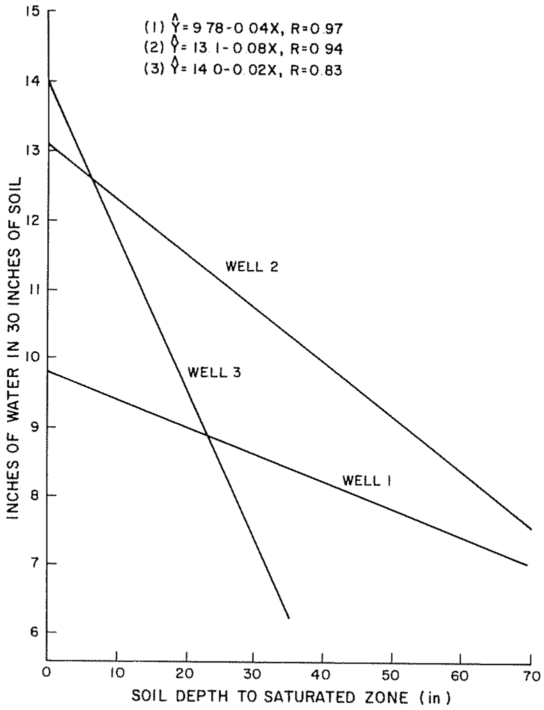

Figure 5. Equations for estimating soil water content from depth of saturation.

Table IX. Water retained[a] in 30 inches of forest soil 24 hours after rewetting by large storms in 1971.

Drainage of soil	Amount of rain[b]	Water in Soil		Retention by Soil	
		Before	After	Inch	Percent
	- - - inches	- - -			
Well	1.86	5.53	6.41	0.88	47
Imperfect	1.86	7.32	8.27	0.95	51
Poor	1.86	10.30	10.91	0.80	43

[a] Mean of all observations

[b] Average for 5 large storms

Duration of Flow

Annual precipitation exerted only minor influence on streamflow duration at the study area.

Year	Flow Duration (days)	Precipitation (inches)
1970	189	34.88
1971	110	39.28
1972	97	49.07
1973	132	48.57

The distribution of rainfall and evaporative demand within the growing season probably overrode the influence of annual precipitation on flow duration.

COMMENT

Of the 44 inches of precipitation falling yearly at Petersham, about half evaporates, about half becomes streamflow. Lyford once commented that unevaporated water on the study area became streamflow by processes other than those he had read about. He saw, for example, no failure of rain to infiltrate, no overland flow except on saturated soil, no evidence of erosion, no wetting front seeping evenly downward in the soil, and no network of interconnected passages for carrying subsurface flow to streams. He undertook this study to learn how rain actually does move from the soil surface to streams, first by closely observing water behavior on the forest floor, then by measuring water content within the forest soil.

Many of Lyford's notes express gratification that the study area so clearly demonstrated position on slope as a determinant of soil saturation levels. I was pleased with the close relationship of soil drainage classes to water content. Actually, our satisfaction derived from different aspects of the same elementary physical phenomenon - water always flows downhill - even within the soil. As long as infiltration in the humid climate forest is not limiting, forest soils must rid themselves of infiltrated water internally.

Nowhere does the literature express this elementary phenomenon so clearly. I attribute Lyford's success to (1) meticulous delineation of Gloucester soil and its catenary associates, (2) careful distribution of sampling sites within the catenary members, and (3) adequate replication of sampling sites among the catenary members, thus nullifying effects of their natural variation on forest-soil-water relations. Other studies fail to demonstrate the effects of slope position on soil water content (Patric 1973) or demonstrate them weakly (Helvey et al. 1972). Most such studies, however, have been more concerned with the temporal than with the spatial aspects of water behavior in forest soils.

Lyford endeavored to compare water use by red pine with use by hardwoods, based on soil moisture losses. He fared no better than others to devise a valid separation of soil moisture loss to gravity from loss to transpiration. The accurate measurement of transpiration from significant areas of tree covered land remains a major unsolved problem in forest hydrology.

This study advances the concept of variable source area first proposed by Hewlett (1961), and since accepted by most forest hydrologists. The concept is that forest streams are nourished between storms largely by unsaturated flow that passes through areas of moist soil which shrink slowly downslope in rainless weather, and that streams are nourished during storms largely by saturated flow as areas of very moist soil expand rapidly upslope. According to this theory, infiltration is seldom limiting, and the formation of saturated layers within the soil accompanies intense or prolonged rainfall. Water exfiltrates when thickening layers of saturation rise to the soil surface. Rain or snowmelt on exfiltrating soil becomes overland flow, the only source of such flow on most forest land. This concept seems clearly applicable to the three-fold, slope-related drainage classes of soil on the study area. The results of this study forge one more link in a lengthening chain of evidence supporting the variable source area concept; affording our clearest understanding of how streams originate on forested land in New England.

CONCLUSIONS

Given the topography, climate, soil and vegetation of the study area:

1. Water content of Gloucester catena soils is regulated by their position on slopes.

2. Water loss from stony soil provides an inadequate basis for estimates of transpiration.

3. Headwater streams are nourished from soil moisture as postulated in the concept of variable source area.

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