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FREQUENCY OF AGRICULTURAL AND FOREST DROUGHT IN NEW HAMPSHIRE: 1926 - 1975

By

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ABSTRACT

Agricultural drought is defined as a shortage of soil water for plant growth. It can be quantified in terms of soil-water deficits during the growing season. A hydrologic simulation model called BROOK was used to estimate daily soil-water deficits from daily precipitation and mean temperature for 50 years (1926-1975) at three New Hampshire locations: Berlin, Durham, and Keene. In the simulated soil, which had about 120 mm of available water, deficits greater than 60 mm may indicate occurrence of agricultural drought. This deficit is exceeded about half the time between mid-July and mid-September at all locations. Both the number of days with deficits larger than 60 mm and the mean deficit from June through August are satisfactory measures of dryness of different summers. In most years dryness at one location was not related to dryness at the other locations, indicating that agricultural drought in New Hampshire is a local rather than a regional phenomenon. Graphs provide data on the frequency of a drought of a given length, timing, and intensity. For example, on August 1 a run of deficits exceeding 75 mm for 30 days occurred in about 15% of the years at Keene and Durham and in 7% of the years at Berlin. Soil water was always recharged before late December, so agricultural drought did not carry over from one summer to the next. Estimates of soil-water deficits are much more satisfactory than precipitation for studying the relation of drought occurrence to plant growth.

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INTRODUCTION

The northeastern United States is considered a "humid" area. Often, people interpret this to mean that there is no shortage of water for either water supplies or for plant growth. However, the regional drought of the early 1960's disproved the theory of sufficient water supplies. And all gardeners in the area know that watering is often necessary for good crop growth.

The word "drought" has different meanings to different people depending on how lack of water influences them. The meanings can be classified into three types: meteorologic, agricultural, and hydrologic (Wigley and Atkinson, 1977). Meteorologic drought occurs when precipitation is lower than normal for some period of time. This may be the most commonly used definition of drought but, because it fails to consider the influence of evapotranspiration, it is an inadequate measure for human water supplies and for plant growth. Hydrologic drought occurs when water supply for human use is deficient. The water supply involved may be streamflow, reservoir storage, groundwater, or some combination. Agricultural drought occurs when plants do not have sufficient water to grow at maximum rates. It is a function of the amount of water stored in the soil within the root zone of plants.

Agricultural drought is important in New Hampshire for agriculture, for lawns and gardens, and for forestry. Agriculture in the State is limited and declining, but such agriculture as remains rarely requires irrigation and relies on natural rainfall. A better understanding of the types and occurrence of drought may help farmers react to its effects. Home gardening is increasing in New Hampshire as food prices rise. New Hampshire's water supplies are limited, particularly in the rapidly developing seacoast area, so lawn and garden watering may be restricted in the near future. Thus, a knowledge of drought occurrence can help homeowners and others plan for and manage such restrictions. The most important effect of agricultural drought in New Hampshire is on tree growth.

The State is 85% forested and the wood-producing industry is a major one. Demand for wood is expected to increase rapidly, particularly with respect to wood for fuel. Lack of soil water limits diameter growth of trees in most years (Lyon, 1943; Federer, 1980) though this is not commonly recognized. Both past occurrences and future expectations of drought need to be better understood by foresters.

Meteorologic and hydrologic drought are easy to study because data are readily available. The National Weather Service collects and publishes precipitation data, and the U.S. Geological Survey collects and publishes streamflow data, each for a number of locations in New Hampshire. However, data on soil water are not routinely collected and published for any location in New Hampshire, so agricultural drought cannot be studied easily.

This publication analyzes agricultural drought by an indirect method that uses measured precipitation and temperature to estimate soil water. The study was prompted by the availability of a hydrologic simulation model, called BROOK, that produces daily estimates of soil-water deficit. The soil-water deficit is the amount of water that must be added to the soil to bring it to a fully wet condition. The deficit increases as the soil-water content decreases; a larger deficit means a drier soil and a more severe agricultural drought.

Quantifying the beginning, ending, and intensity of any type of drought depends on individual interests. There is no standard definition of agricultural drought. In this paper I have estimated the soil-water deficits that occurred under a particular soil and plant situation and I evaluate these deficits in several ways. Although the situation is intended to be typical of New Hampshire, other conditions could have been chosen and other criteria used to evaluate the results.

This report has three purposes: (1) to analyze the historical record of soil-water deficits in New Hampshire to determine dry and wet years, (2) to estimate the probability of occurrence of agricultural droughts of different intensities and durations, and (3) to demonstrate techniques for studying agricultural drought.

SIMULATING SOIL-WATER DEFICITS

There are a variety of methods for estimating soil-water deficits from meteorological variables and characteristics of soils and plants (Zahner and Stage, 1966; Baier, 1969; Fleming, 1975). All of these are basically similar and work by adding measured precipitation to soil-water storage day by day, and subtracting estimates of evapotranspiration and of drainage. Differences among the methods occur in the details of how the estimations are made, but the results from different methods would not differ very much. In this paper I use a model called BROOK that was developed specifically for eastern forests (Federer and Lash, 1978a, 1978b). The model is described by Federer and Lash (1978a), so only a brief summary is given here (Appendix 1).

To use a model like BROOK to assess the occurrence of agricultural drought, I needed to decide on the kinds of plant and soil to work with. Obviously a wide variety of choices are available and the intensity of drought will depend somewhat on the characteristics chosen. I decided on a hardwood forest growing on a well-drained till soil (Appendix 2). Till covers 85% of New Hampshire (Bonin and others, undated), while commercial hardwood forests cover 46% of the State (Kingsley, 1976). Hardwood forest on well-drained till is certainly the dominant cover-soil combination in the State, covering perhaps 40% of the area. Not surprisingly, this is the combination that occurs at the Hubbard Brook Experimental Forest (Figure 1), and that was used to develop BROOK. Precipitation governs the occurrence of agricultural drought much more than cover-soil characteristics do, so many results do not rely much on characteristics chosen. This is considered further in the Discussion section.

The soil parameters selected provide a total available water, or a maximum soil-water deficit, of about 120 mm (Appendix 2).

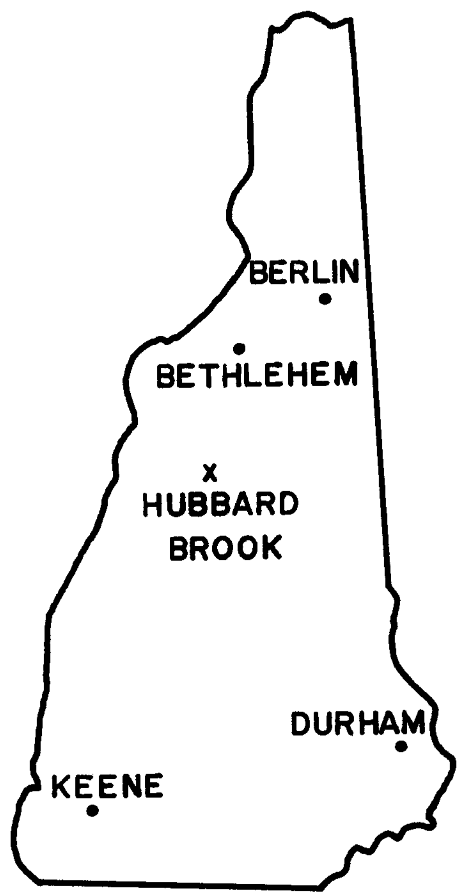

Figure 1. Locations of Berlin, Durham, and Keene, N.H., and Bethlehem, used in place of Berlin for some years, and Hubbard Brook, where the BROOK hydrologic model was developed.

In analyzing the data in this study it is useful to split the available water range into quarters, at deficits of 30, 60, and 90 mm. As an approximation, plants will not be stressed with deficits in the 0-30 mm range; slight reductions in growth might occur in the 30-60 mm range; from 60-90 mm stress is increasing; and below 90 mm plant growth will be severely limited or totally stopped (Federer, 1980).

Daily precipitation and maximum and minimum temperatures are available on computer tapes for 50 years, 1926-1975, for five New Hampshire locations: Berlin, Concord, Durham, Hanover, and Keene. The tapes were produced by the National Weather Service. For this study I used the 50-year records from the three most widely separated stations: Berlin, Durham, and Keene (Figure 1). Because of missing data for Berlin, data for Bethlehem had to be used for October, 1948, and for all of 1969-1975. Details of the climatology of Durham and Keene given by Byers and Goodrich (1977) include monthly precipitation for most of the years used here. Among the three stations, mean annual precipitation is highest at Durham and lowest at Berlin (Table 1). Mean monthly precipitation in the months of interest here (May through October) ranges from 70 to 100 mm (Table 1). In June, July, and August, precipitation is low at Durham but high at Keene and Berlin compared with other months.

The BROOK model was used to estimate daily soil-water deficits for hardwood forest on till soil at Berlin, Durham, and Keene from January 1, 1926, through December 31, 1975 (Appendix 1, 2).

The average annual cycle of soil-water deficits is nearly the same for all three stations (Figure 2). From December through April deficits are close to zero. Beginning in May the mean deficit begins to increase, reaching about 60 mm by late July and then holding steady around this value until late September. Late September to late November is, on the average, a period of declining deficits. The importance of the seasonal beginning and ending of

Table 1.

Mean monthly and mean annual precipitation and mean annual evapotranspiration, in mm, for three locations in New Hampshire, 1926-1975. Standard errors of the means are about 6 mm for monthly precipitation, 25 mm for annual precipitation, and 6 mm for annual evapotranspiration.

Item	Durham	Keene	Berlin
Measured Precipitation			
May	81.2	89.5	81.0
June	81.2	95.6	99.9
July	83.7	92.5	90.7
August	81.1	85.2	86.6
September	91.0	88.4	85.2
October	83.5	70.6	76.7
June-August	246	273	277
ANNUAL	1065	1011	959
Simulated Evapotranspiration			
ANNUAL	467	495	454

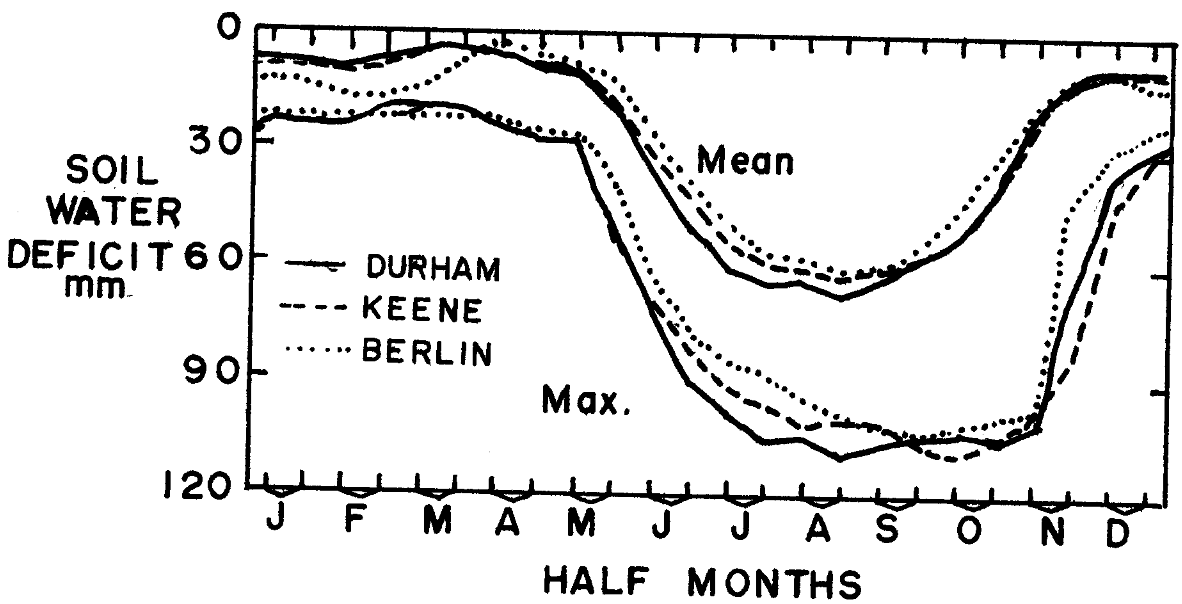

Figure 2. Mean and maximum simulated soil-water deficits by half months for 1926-1975.

transpiration is obvious and the shorter growing season at Berlin causes its mean deficit to increase later and decrease earlier than at the other stations. Failure of deficits to remain at zero through the winter is caused by drainage from the soil. Larger mean deficit in winter at Berlin is a result of fewer midwinter thaws.

The value of deficit on any given date does not exceed 25 mm in winter, but in summer can range from 9 to nearly 110 mm (Figure 2). The annual curve of deficit for any given year has a jagged appearance as opposed to the smooth mean curve. Deficits are reduced abruptly by storms and then increase gradually. Deficits can be reduced to zero at any time in summer by large enough storms. Never in the 50 years at each station did soil-water deficit fail to be reduced to negligible amounts by the end of December.

WET AND DRY YEARS

Statements and phrases like "last year was dry", "this summer has been wet", or "the drought of the early 60's" have little quantitative meaning. Soil-water deficit quantifies dryness or wetness. Unfortunately, there are a host of ways in which the sequence of daily deficits can be used to indicate drought intensity. I can only use some of them here.

Two simple ways to quantify agricultural drought are the mean soil-water deficit for the growing season (Wigley and Atkinson, 1977) and the fraction of days wetter than a given deficit. The primary growing season in New Hampshire is from June through August, so I have made calculations for this period. By both the mean deficit (Figure 3) and the percent of days wetter than 60-mm deficit (Figure 4), 1929, 1949, and 1950 were dry throughout the State, while 1937, 1938, and 1975 were wet. But in most years some parts of the State were wet while others were dry. For instance, 1941 was wet at Berlin, moderate at Keene, and dry at Durham; 1967 was wet at Keene, moderate at Durham, and dry at Berlin (Figure 4). Agricultural drought in New Hampshire is usually local rather than statewide because summer showers vary throughout the State.

Single-valued criteria such as the two just mentioned do not contain information about the distribution of deficits. Deficit-duration curves show the amount of time that any given deficit is exceeded. However, these would take several graphs to show all years without confusion so I have plotted only 14 selected years for Keene, still using the June through August period (Figure 5). Six of the years shown are the wettest and six years are the driest, as determined subjectively by looking at all the curves. This subjective selection agreed closely with the mean deficit criterion (Figure 3), but not so well with the percent of days greater than 60 mm. The deficit-duration curves are strikingly parallel for most years (Figure 5). If the deficit that is exceeded 50% of the time is known, a line through it with a slope of about 60 mm/100%

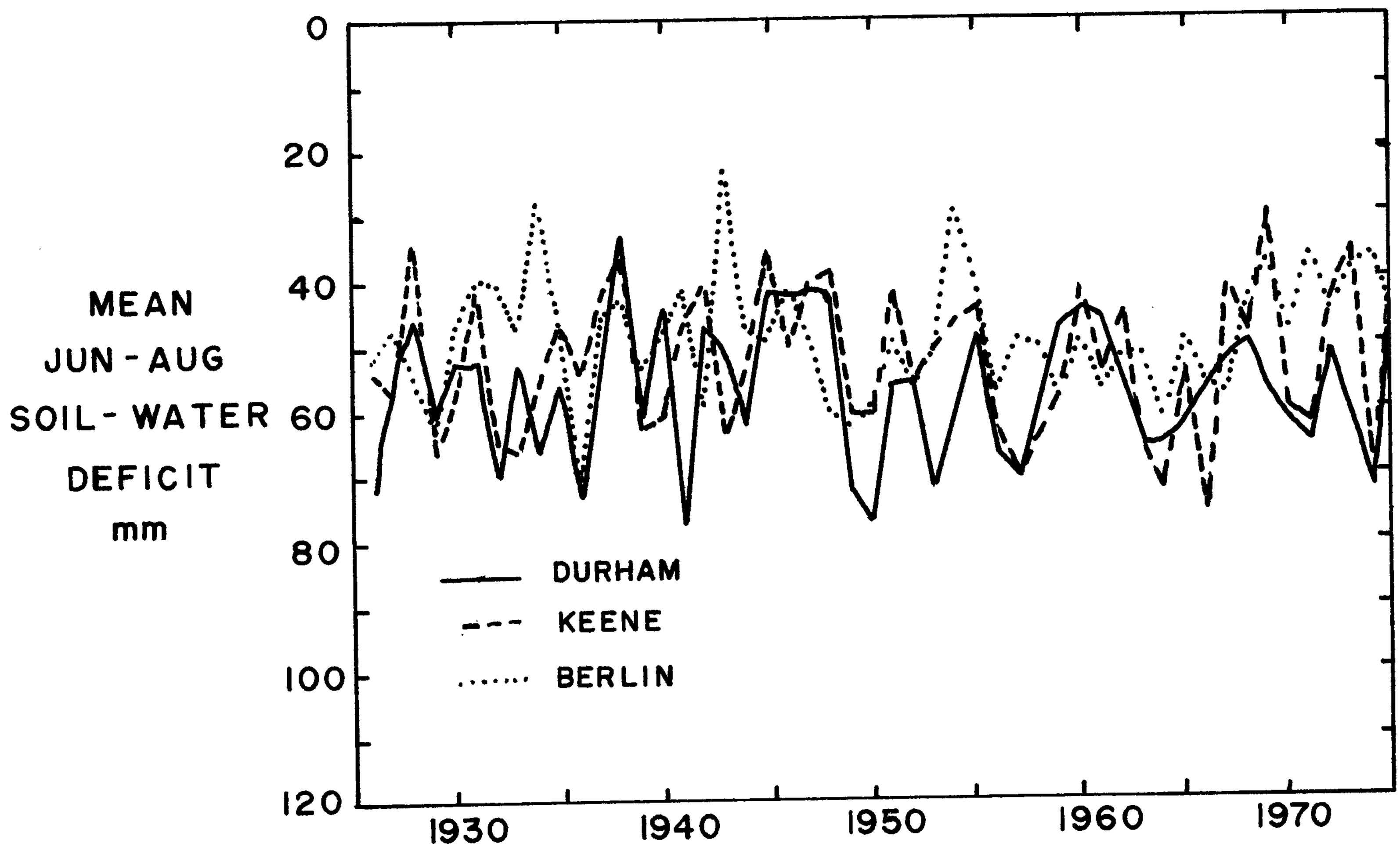

Figure 3. Mean simulated soil-water deficit from June 1 through August 31, for years 1926-1975.

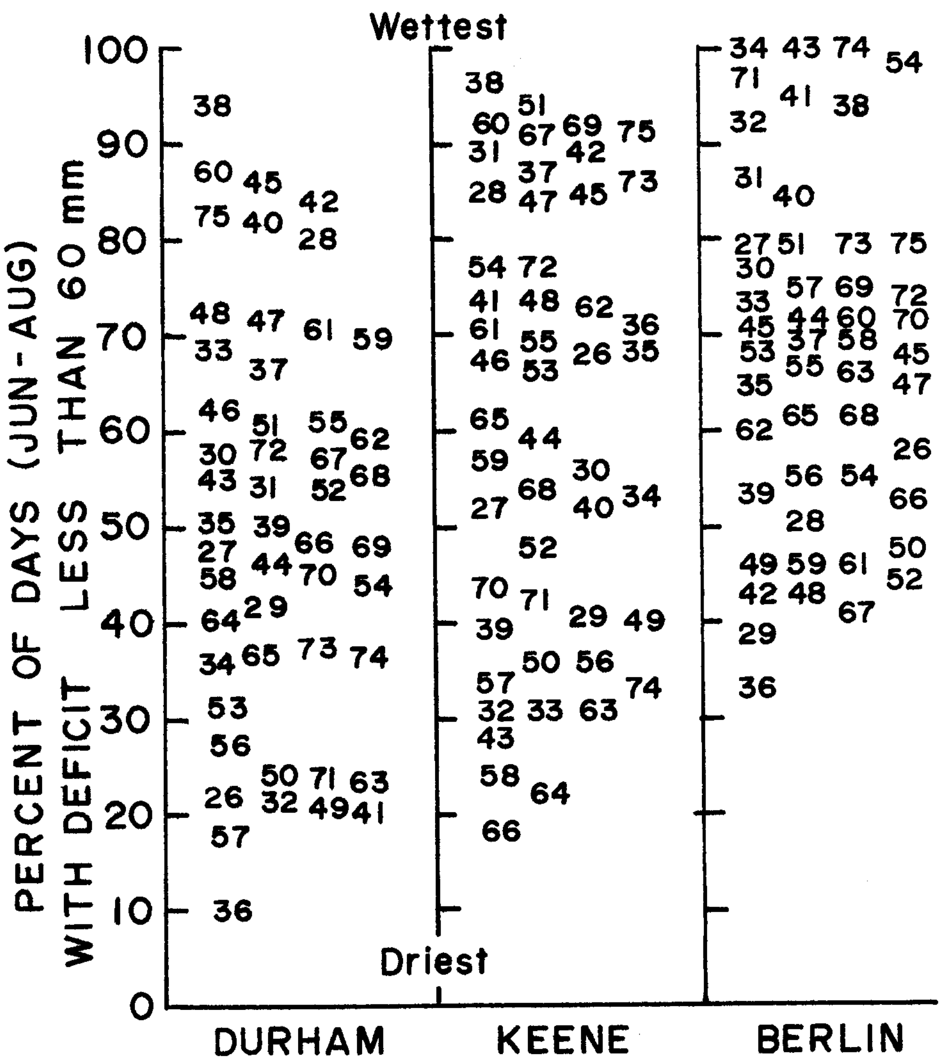

Figure 4. Ranking of years by percent of days from June 1 through August 31 with deficit less than 60 mm. Initial 19 is omitted from year designation.

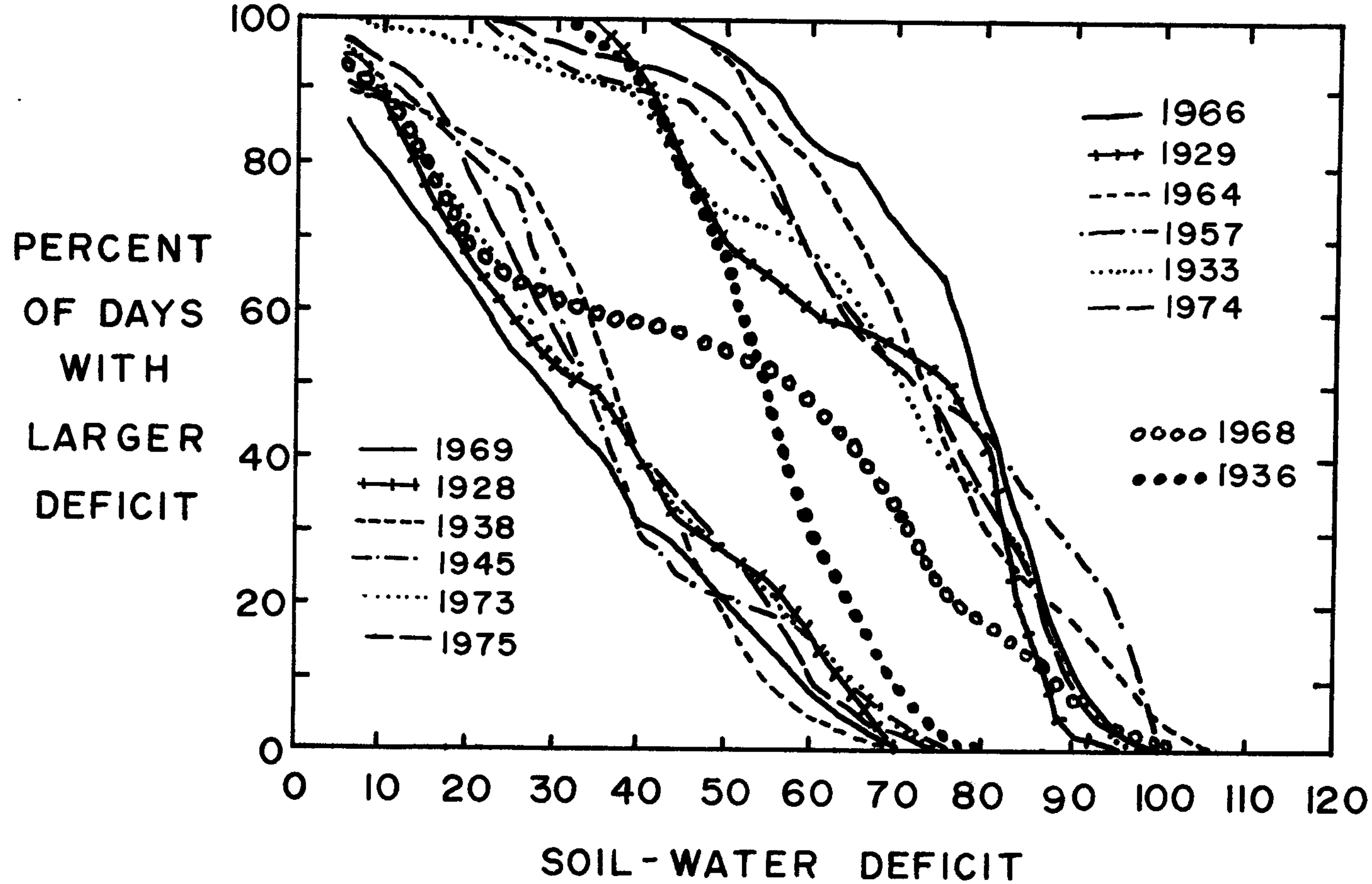

Figure 5. Deficit-duration curves for Keene, N.H., from June 1 through August 31. Six of the wettest and 6 of the driest years are shown along with 2 years (1936 and 1968) with extreme slopes.

would be a good approximation to the curve for that year. Figure 5 also shows the extreme variations of slope: 1968, which had a very wide range of deficits; and 1936, with a very narrow range of deficits.

None of the drought criteria discussed so far consider the timing of dry or wet periods. Yet for many plants a dry period in June may have very different effects from an equally dry period in August. For the user of this publication who may want to analyze the historical record in a particular way, I have given the mean deficit by half months (in millimeters) for all years and stations (Appendix 3). The half month is used as a convenient compromise between daily and monthly intervals. The month is too long an averaging period from the standpoint of effects of water deficits on plants.

PROBABILITIES OF DROUGHT

The 50-year record for each station provides a way of analyzing the probability of drought. The analysis given here shows the frequency of occurrence over the past 50-year period, but this also represents an empirical probability of occurrence. Note, however, that this probability is contingent upon the questionable assumption of an unchanging climate.

One simple presentation of both timing and intensity of drought shows the percent of days that exceed any given deficit in each half month (Figure 6). The 90-mm deficit indicating severe drought was exceeded on about 15% of days in late August at Durham, but only 7% at Berlin. At Keene, a 60-mm deficit was reached 25% of the time by late June and 50% of the time by mid-July. Many similar results can be obtained from Figure 6.

The duration of drought requires more complicated presentation. The question here is "how long is it likely to stay dry?". To answer this, I have defined a "run" as beginning when the deficit begins to exceed a given amount for five consecutive days, and ending when the deficit begins to be less than that amount for five consecutive days. The 5-day criterion is arbitrary, but ensures that the dry period persists long enough to be meaningful, and is not ended by just a few days of slightly smaller deficit. I have done two analyses, both based on the existence of a run at the beginning of each half month. One gives the percent of years in which a run of given length and deficit occurred at the beginning of each half month (Figure 7). The other shows the probability of how long such a run will continue (Figure 8). For Berlin, a run of deficits exceeding 60 mm for at least 30 days occurred on July 16 in 25% of the years, but on August 16 in nearly 50% (Figure 7). Half of such runs occurring on July 16 continued for at least 45 more days, while half of the runs on August 16 continued for at least 36 more days (Figure 8). Many other such statements can be derived from Figures 7 and 8.

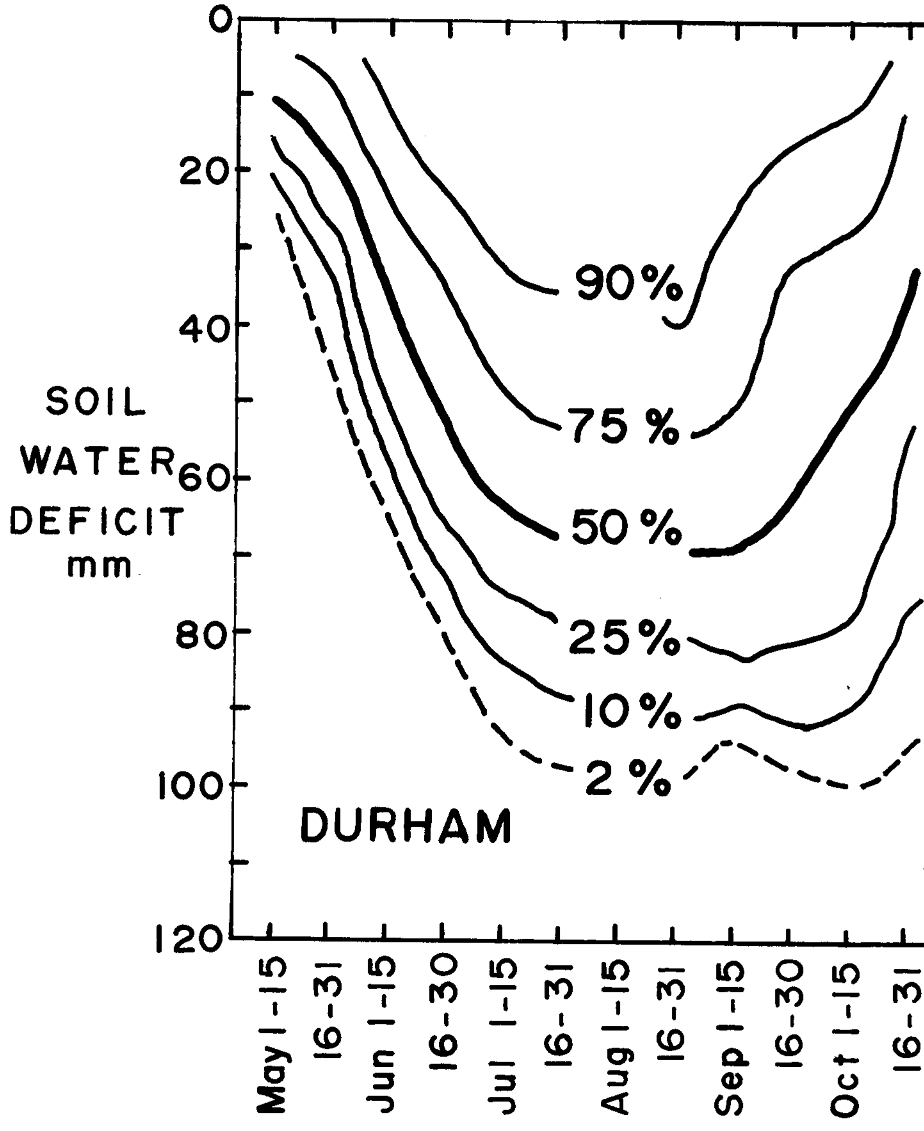

Figure 6a. Percent of days in each half month over period 1926-1975 with deficits greater than a specified amount.

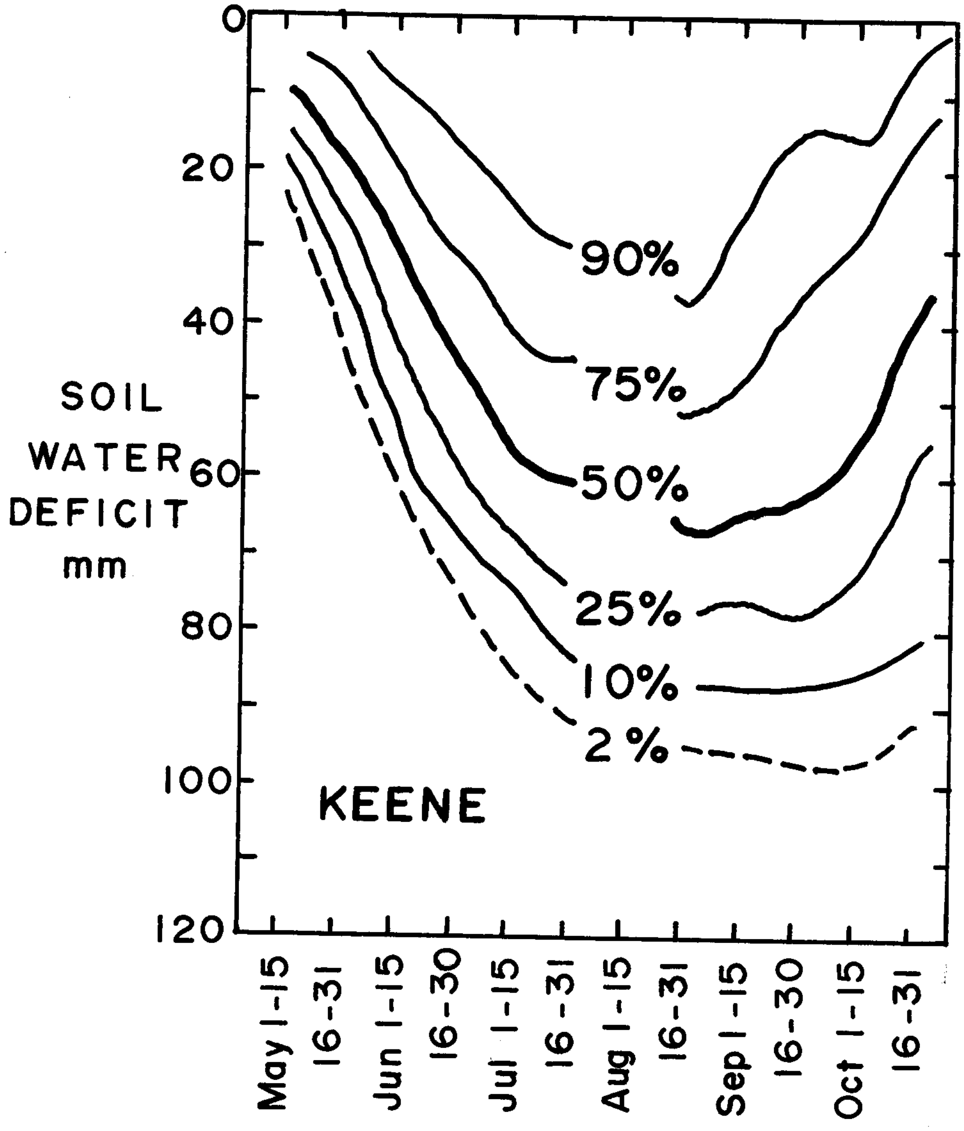

Figure 6b. Percent of days in each half month over period 1926-1975 with deficits greater than a specified amount.

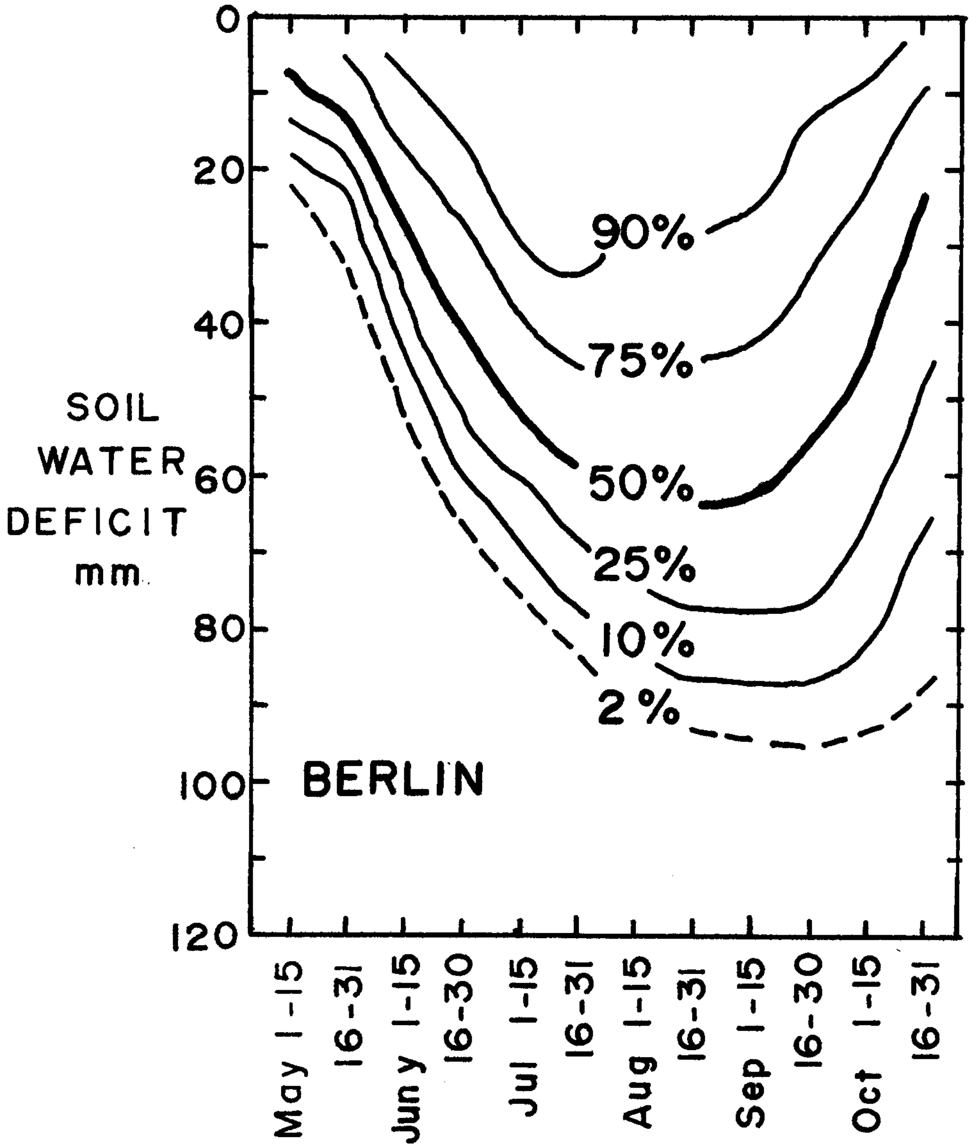

Figure 6c. Percent of days in each half month over period 1926-1975 with deficits greater than a specified amount.

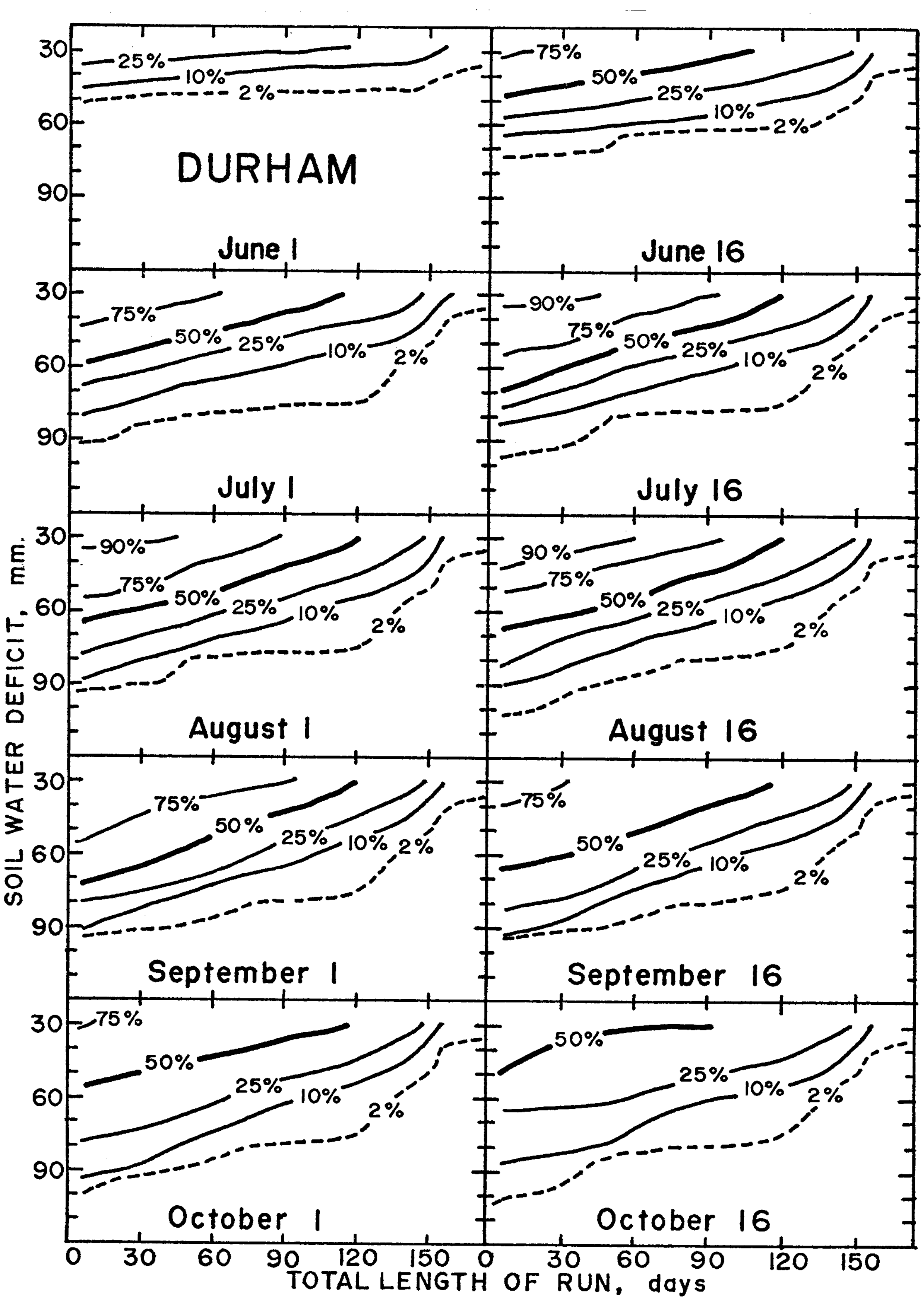

Figure 7a. Percent of years in which a run exceeding a specified deficit for a specified length of time exists at the beginning of each half month, for Durham.

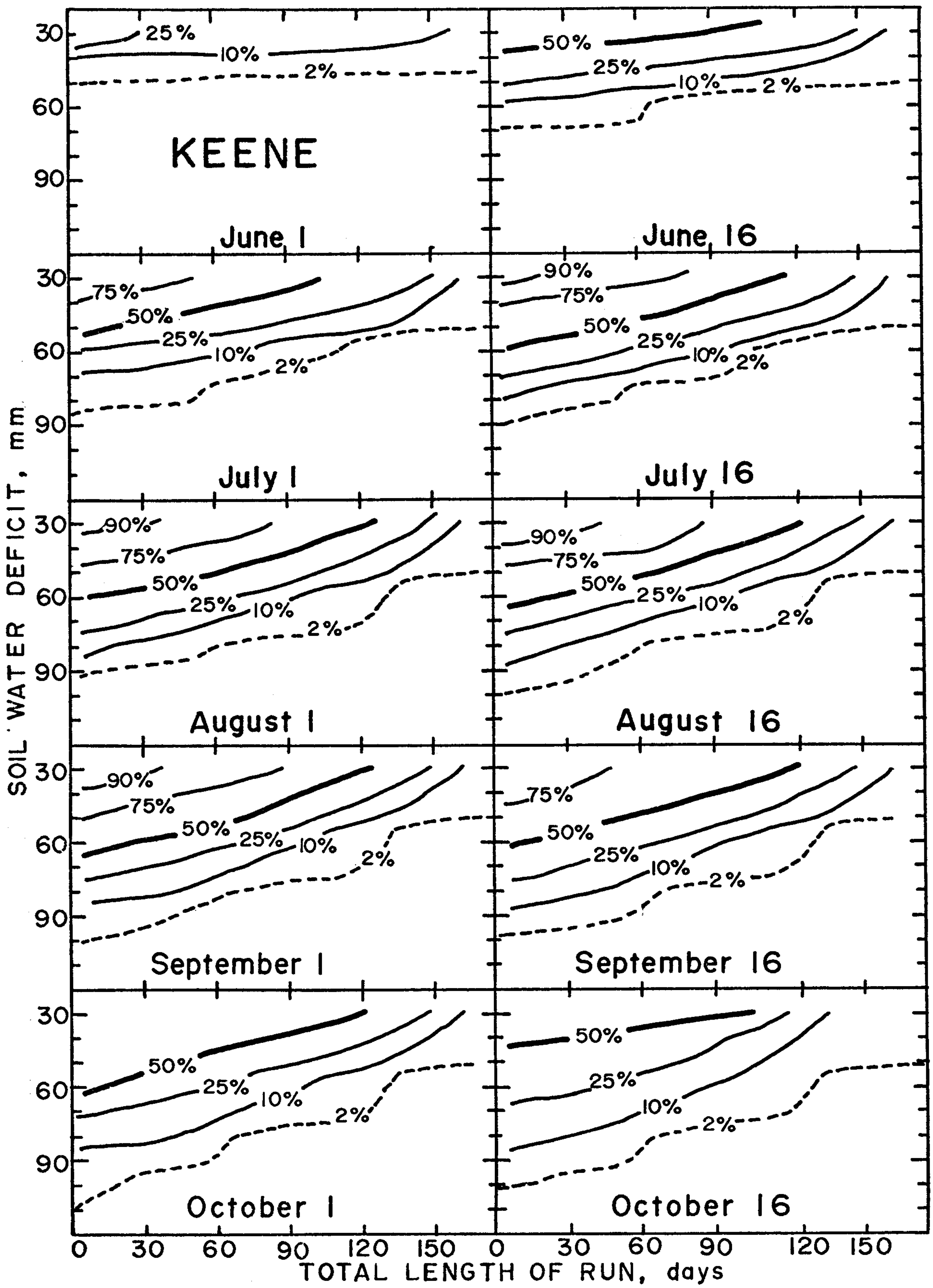

Figure 7b. Percent of years in which a run exceeding a specified deficit for a specified length of time exists at the beginning of each half month, for Keene.

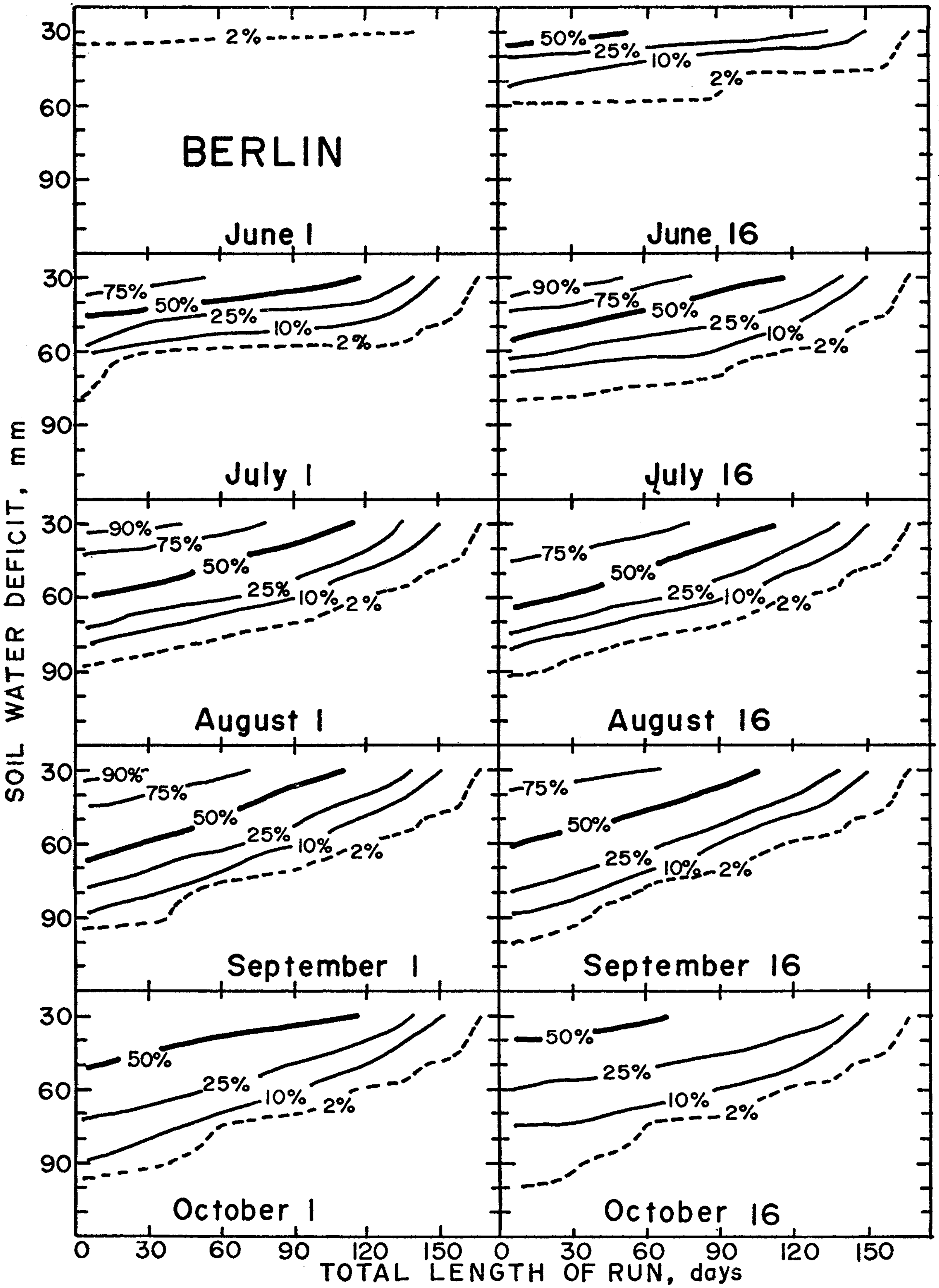

Figure 7c. Percent of years in which a run exceeding a specified deficit for a specified length of time exists at the beginning of each half month, for Berlin.

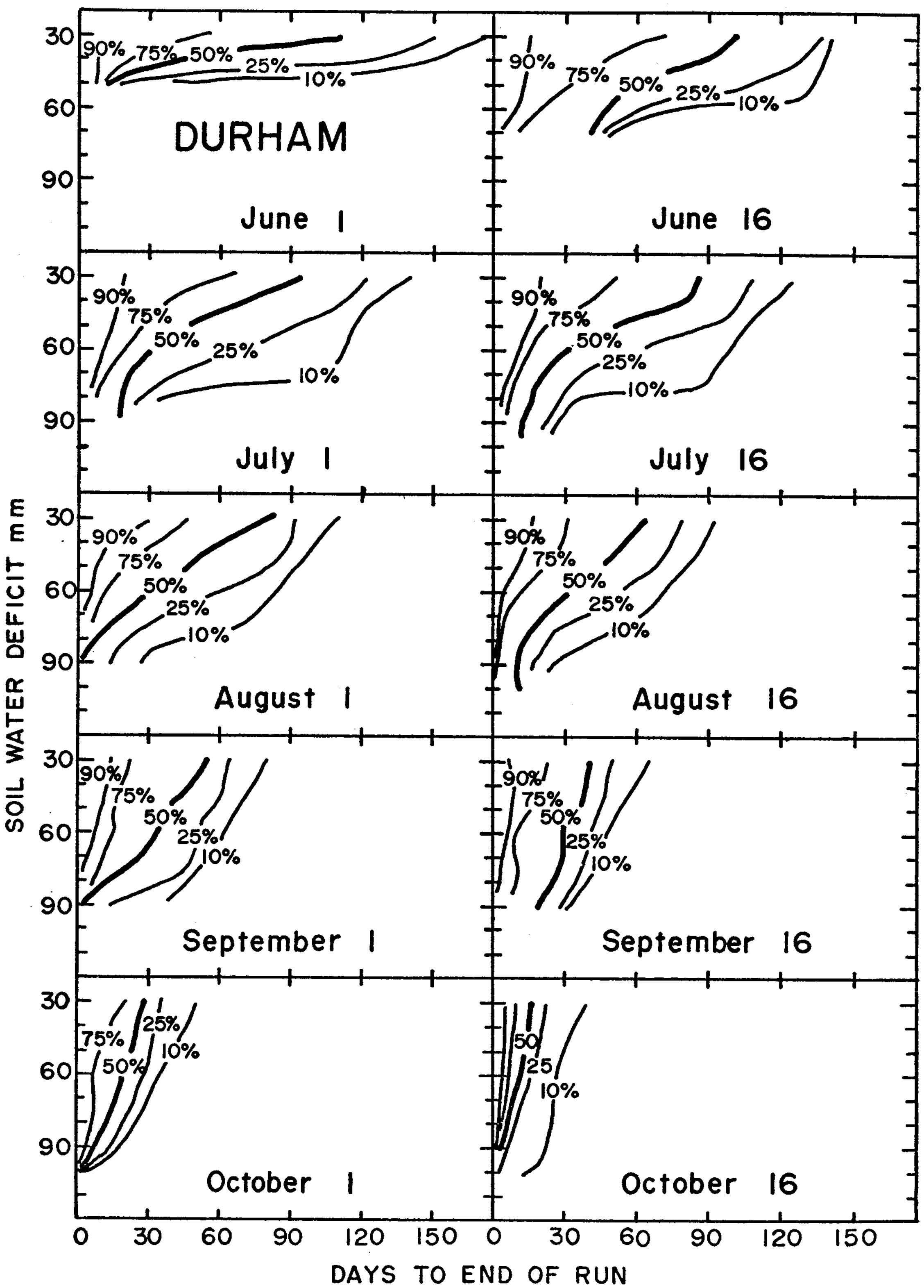

Figure 8a. Percent of runs existing at the beginning of each half month that continue for a specified number of days, for Durham.

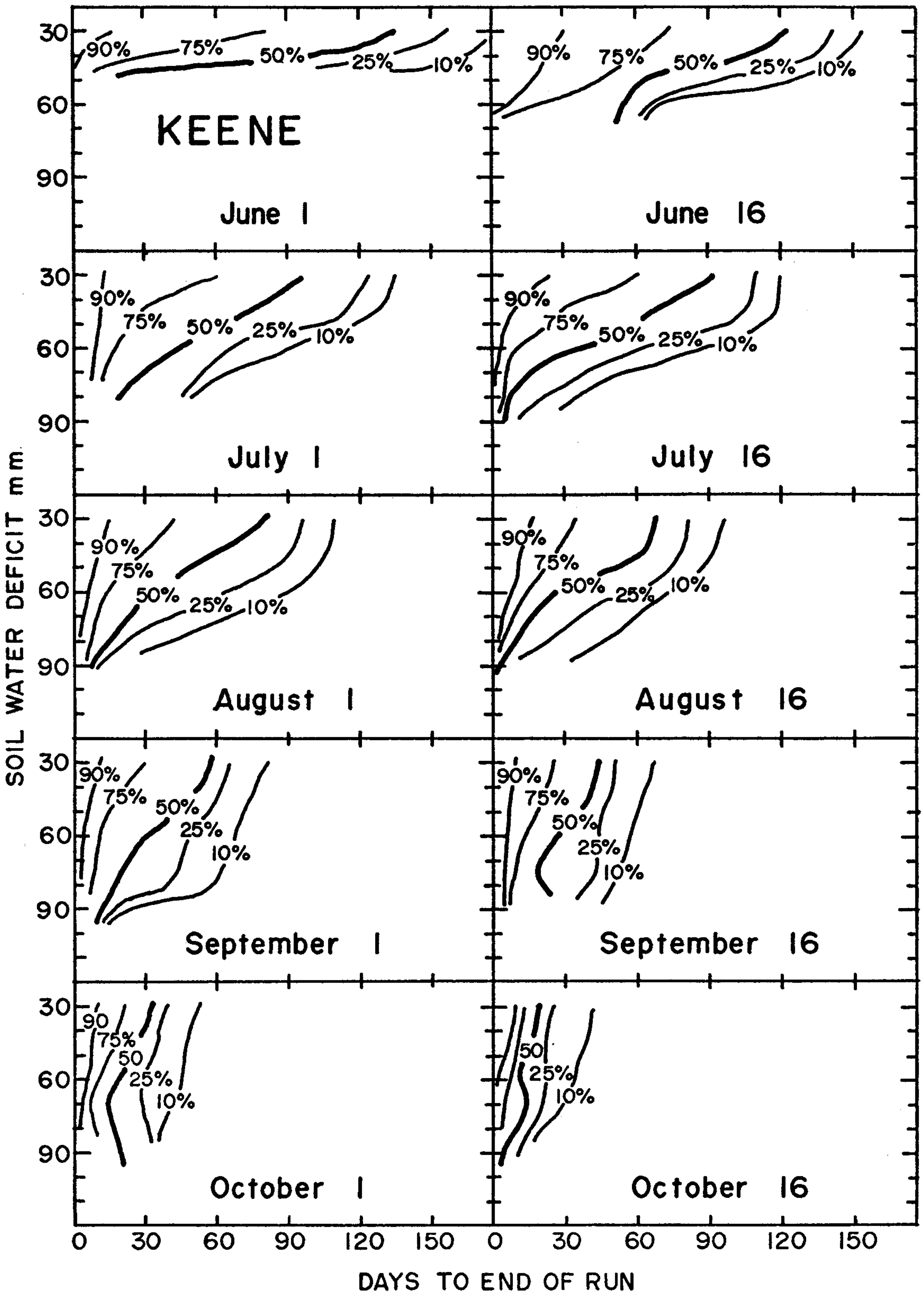

Figure 8b. Percent of runs existing at the beginning of each half month that continue for a specified number of days, for Keene.

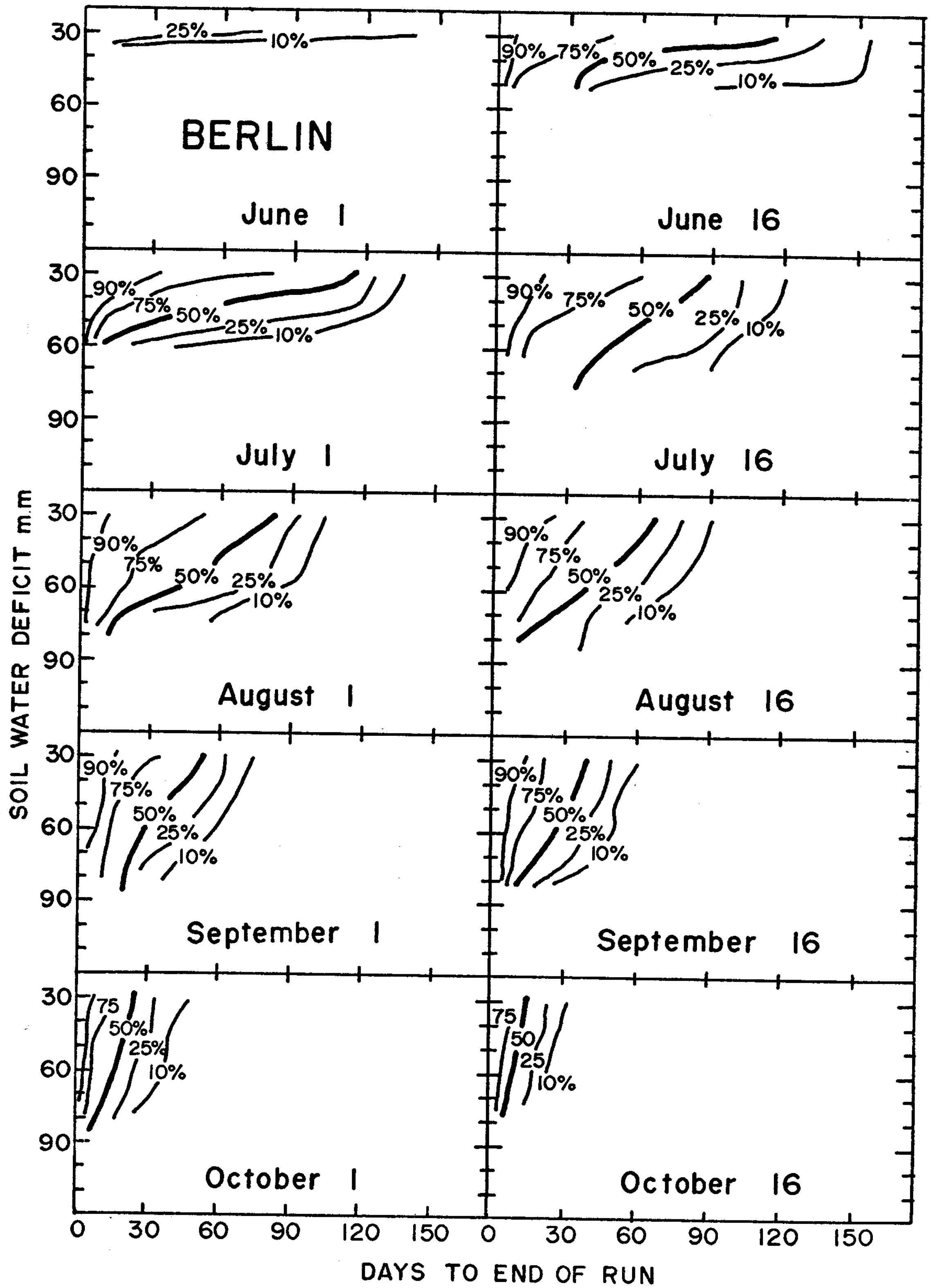

Figure 8c. Percent of runs existing at the beginning of each half month that continue for a specified number of days, for Berlin.

DISCUSSION

The most commonly used values for the intensity of drought is the Palmer Drought Index (Palmer, 1965). To obtain the Palmer Index, precipitation and estimated soil-water deficit are combined in a complex way and related to normal precipitation and deficit for the location to give a value ranging from +4 for very wet to -4 for very dry. Its value is relative only to normal conditions at that location, and it evaluates a hybrid of meteorological and agricultural drought. Fieldhouse and Palmer (1965) calculated the Palmer Index for northern and southern New Hampshire from 1929 through 1963. My results cannot be easily compared with theirs as they do not show Palmer Index values by months. Further, drought defined by the Palmer Drought Index can last through the winter and even over several years in New Hampshire. However, as I have shown, agricultural drought in New Hampshire always ends by the end of December.

The relation between tree-ring widths and drought has been studied in the Northeast as well as in drier climates. Cook and Jacoby (1977) recently used ring widths to estimate the Palmer Drought Index in the Hudson Valley of New York back to 1728. Lyon (1936, 1943) showed that ring widths are highly correlated with summer rainfall in New England. His work and a recent study by Federer (1980) imply that the later in the summer that moderate deficits (perhaps around 60 mm in this study) develop, the wider the ring will be. Widest rings occur only in years that are wet throughout the summer, perhaps only in the 10% of years in which runs drier than 40 mm do not occur (Figure 7). Lyon (1943) found that ring-width chronologies only correlated over distances up to 50 miles because of local variability in rainfall. This agrees with my conclusion that agricultural drought in New Hampshire is usually a local rather than a statewide phenomenon.

The value of using soil-water deficit rather than precipitation to study drought effects on plants seems self-evident, but too often scientists persist in using monthly rainfall as a drought index. Zahner and Stage (1966) pioneered the use of soil-water deficits for tree growth, while soil-water budgeting (Baier, 1969) has often been used to schedule irrigation of crops. Certainly the effect of 75 mm of rain on dry soil will be different if it occurs on July 1 than if it occurs on July 31, but the monthly precipitation will be the same. A complex model like BROOK may not be necessary as Federer (1980) showed that daily soil-water deficit estimated from daily precipitation and a constant monthly evapotranspiration was related to tree-ring width.

The soil-water deficits estimated in this study were for a specific plant cover on a specific soil and topography: mature hardwood forest on a well-drained upland till with little slope. How would these deficits vary if site characteristics were changed? First, it is important to remember that the situation studied is characteristic of nearly half the land area of New Hampshire. Age or size of the hardwood trees would make little difference once the stand was more than five years old. Similarly, the species of hardwood trees would make little difference. Precipitation in New Hampshire increases about 7.5 mm/100 m elevation increase (Dingman, 1979). So soil-water deficits should decrease slightly as elevation increases. Aspect is not important when slopes are less than 5° or 10%. But for greater slopes, south aspects will have somewhat higher evapotranspiration in autumn than will north-facing slopes, so deficit runs will last slightly longer on the south slopes.

A pure conifer stand begins transpiration earlier in the spring and ends it later in the autumn than hardwoods. Conifers also intercept more rain than hardwoods in spring and fall, when hardwoods are leafless. Consequently, soil-water deficits under conifers would develop sooner in spring and persist longer in autumn than under hardwoods. Thus, runs of a given deficit will be longer and more frequent under conifers. Also, if summer deficits are relatively small, they will be greater under conifers. But if drought becomes severe, the conifers will reduce their transpiration sooner because of their larger deficits, allowing hardwoods to "catch up", and the large deficits to become nearly equal.

Crop and pasture land would cause tendencies in the opposite direction from conifers. Crop and pasture evapotranspiration in summer is perhaps 10-20% less than that from hardwoods. Pasture transpiration in spring and fall tends to compensate for this. Pasture deficit runs may be somewhat longer than in hardwoods in spring and fall, but will be slightly less frequent in summer. Crops which have bare or only partly vegetated ground until late June or July, and after harvest in September, would have shorter runs at a given deficit and would reach that deficit less frequently.

Soil texture and drainage can cause significant deviation from the behavior simulated here, but only in extreme cases. Well-drained and moderately well-drained sandy loams and loamy sands with about 120 mm of available water predominate in New Hampshire. The soil parameters used here are typical for those soils. In excessively well-drained, coarse sands derived from glacial outwash, available water may be less than 100 mm. Surprisingly, however, this does not increase the amount of soil-water deficit at any particular time, but, if anything, decreases it. At deficits greater than 50 mm there would be no difference in deficit behavior. As soil dries further, transpiration is limited first in the coarse soil, so its deficit does not become as large. What does change is the meaning of a given deficit.

A deficit of 60 mm means moderate stress in a soil with 120 mm of available water, but means severe stress in a soil with 90 mm of available water. Moving to the other extreme, drought in poorly drained soils and in fine-textured soils can be quite different from the situation simulated here. In New Hampshire, silt loam soils tend to be poorly drained, but some coarser soils are also poorly drained. "Poorly drained" may imply that a water table is close to the surface year round. Such a water table could supply sufficient water to plants to keep them stress-free even if deficits in the upper soil layers became large. However, plants accustomed to growing with plenty of water from water tables may become heavily stressed, even killed, if drought lowers the water table out of the root zone.

The foregoing discussion of the effects of vegetation, topography, and soil on soil-water deficits has been qualitative. Obviously a variety of situations can be postulated. Simulation with BROOK could produce drought results for most of them as it has here for the most common situation. Limitations of time and money have prevented me from doing this, but the method has now been described and others are welcome to try it.

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APPENDIX 1: HOW BROOK WORKS

In BROOK, interception by the plant canopy and overland flow from saturated source areas are subtracted from daily precipitation before it is added to soil-water. Interception is a part of the total evapotranspiration and is determined by the amount of rain, the amount of potential evapotranspiration, and characteristics of the plant canopy. Overland flow is precipitation falling on saturated portions of the watershed. These saturated areas increase in size as the soil gets wetter. Remaining precipitation is added to the root zone of the soil; and transpiration, soil evaporation, and drainage are subtracted from the root zone each day.

Drainage increases exponentially with the water content in the root zone. Zero soil-water deficit is defined as the water content at which drainage is 2 mm/day. This is a definition of the "field capacity" of the soil. The soil can be wetter than this, but only for short periods of time unless precipitation or snowmelt inputs are sustained.

Transpiration depends on potential evapotranspiration, soil-water, and canopy cover. Potential evapotranspiration is calculated by the Hamon method, which requires only the mean daily temperature and the day length. The Hamon method does not estimate the real day-to-day changes in potential evapotranspiration; that would require solar radiation data, which is unavailable. But because soil-water deficits develop slowly, simulation of the real day-to-day variability is not necessary for drought studies. When the plant canopy is fully developed, transpiration is equal to the lesser of either soil-water times a constant or potential evapotranspiration. This expresses the belief that transpiration is limited either by soil-water supply or by atmospheric demand.

Soil evaporation depends on the amount of water in the surface 50 mm of soil, on potential evapotranspiration, and on plant cover. It is quite small when canopy cover is complete but is important, for instance, in autumn after hardwood trees have lost their leaves.

Some parts of BROOK are not important to this study although they were used in the simulation. The behavior of accumulation and melt of snow is relevant neither to this study nor to agricultural drought in New Hampshire. Behavior of water below the root zone is also not relevant because agricultural drought depends only on water in the root zone and BROOK does not allow upward movement of water from below into the root zone. BROOK also allows for varying slopes and aspects, but in this study only a horizontal surface is considered.

APPENDIX 2: PARAMETERS SELECTED

The soil parameters used in the simulation were those used by Federer and Lash (1978a) for Berkshire and Becket soils at Hubbard Brook. The depth of the root zone was 635 mm. Hydraulic conductivity of the soil, K, was

$$K \text{ (mm/day)} = 2.04 \times 10^7 \, \theta^{12.56}$$

where θ is the fractional soil water content by volume. At field capacity, defined as K = 2 mm/day, θ was 0.277 and the total water in the root zone was 635 x θ or 175.7 mm. This water content was defined as zero soil-water deficit. The water potential, Ψ, for a given water content is determined for this soil by

$$\Psi \text{ (kPa)} = -0.0129 \, \theta^{-4.782}$$

so the potential at field capacity was -6 kPa (-0.06 bar). Plants cannot remove all the water from the soil. The lower limit of water useful to plants is usually assumed to be at a potential of -1500 kPa, which in this soil was a fractional water content of 0.087 and a root-zone water content of 55.2 mm. The difference of 120.5 mm between field capacity and the lower limit is called the maximum available water. The soil-water deficit is zero when all this water is present, and increases as the amount of available water decreases.

Taking the root zone as a whole, the relation of soil-water deficit to soil-water potential is:

soil-water deficit	0	30	60	90	120	mm
soil-water potential	-6	-15	-44	-186	-1500	kPa

At a given soil-water deficit, the soil will actually have a much lower potential (more negative) than this in its upper layers where the roots are concentrated, and a higher potential in deeper layers.

In BROOK, density of the plant canopy is controlled by a leaf area index that varies from 0 to 4. For the hardwood forest studied, this value was 0 in winter and 4 in summer, with a linear transition over a month in spring and autumn. For Berlin, I used the same transition period as Hubbard Brook, May 15 to June 15, and September 15 to October 15. For Keene and Durham, largely on the basis of mean dates of last and first frost, I chose transitions a week earlier and later, May to June 8, and September 22 to October 22. These dates control the beginning and the end of transpiration.

As soil dries, plants become less successful at removing all the water they need from the soil. This is the reason water stress occurs in plants, and is reflected in actual transpiration becoming less than potential evapotranspiration. This is quantified in BROOK by having transpiration equal the lesser of either potential evapotranspiration or a constant times amount of available water. A constant of 0.036/day, obtained for Hubbard Brook, was used in this study. Therefore, the critical soil-water deficit below which transpiration was less than potential evapotranspiration varied as follows:

Hamon potential evapotranspiration	1.5	2.5	3.5	4.5	mm/day
critical soil-water deficit	78	50	22	0	mm

The Hamon value of potential evapotranspiration varies from about 2.5 to 5.0 mm/day in July, averaging 3.5.

APPENDIX 3:

MEAN DEFICITS BY HALF MONTHS

(JANUARY 1926 - DECEMBER 1975)

D U R H A M

MEAN DEFICIT

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
HALFMONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1926	9	5	13	13	5	4	1	10	18	32	59	70	86	85	58	73	82	87	81	40	6	1	8	14
1927	12	6	8	5	2	7	21	22	19	10	34	63	70	63	57	46	9	18	22	6	6	2	0	5
1928	15	7	6	1	11	11	20	7	11	11	23	44	59	60	42	43	30	29	43	40	28	23	3	7
1929	0	6	5	11	2	4	7	0	3	13	51	61	57	76	66	53	60	72	53	33	25	5	11	8
1930	2	9	14	2	5	1	6	14	20	14	30	36	51	58	66	69	84	93	96	53	25	3	11	14
1931	9	11	17	3	0	8	3	12	8	16	23	23	54	72	72	63	68	71	84	51	41	30	13	2
1932	4	2	6	14	2	11	6	11	17	38	58	73	61	84	75	69	88	12	31	7	4	11	20	17
1933	14	5	6	3	1	3	0	3	15	27	45	62	64	50	49	44	54	28	15	5	14	16	7	5
1934	3	4	13	13	3	12	3	3	4	23	45	41	68	74	78	89	78	22	6	8	2	14	7	5
1935	4	5	15	2	0	2	5	8	8	28	35	14	46	67	77	91	60	51	59	60	27	7	4	9
1936	2	3	14	18	6	0	0	8	13	24	56	70	78	76	80	79	81	81	85	58	41	38	5	1
1937	2	0	6	2	9	2	4	4	8	6	24	31	60	83	63	48	55	32	47	16	8	2	1	3
1938	5	6	0	3	5	3	6	5	16	8	33	40	32	11	23	56	69	13	28	18	10	6	2	6
1939	3	14	18	12	1	2	0	3	19	24	44	48	69	89	69	47	62	78	81	79	10	23	22	10
1940	14	4	9	3	5	4	1	2	9	25	21	52	37	37	46	69	69	49	43	52	7	5	14	4
1941	4	12	8	7	10	9	20	24	13	19	41	68	87	87	85	91	91	99	89	77	20	20	22	18
1942	5	4	4	4	1	0	5	8	14	28	49	42	37	49	39	62	77	82	87	65	24	7	3	11
1943	4	14	8	4	1	7	14	3	1	11	37	66	80	70	14	42	72	89	64	28	3	2	11	16
1944	7	8	13	7	1	0	3	2	15	34	61	46	52	49	74	88	75	14	21	8	7	2	0	5
1945	4	14	18	4	0	2	8	10	2	8	33	23	36	38	52	66	64	66	59	42	21	2	1	6
1946	0	9	16	17	3	4	7	12	3	7	21	56	72	71	20	15	37	61	19	21	21	22	25	10
1947	12	4	3	4	0	8	6	4	4	20	16	27	61	23	47	71	72	84	95	103	70	8	14	11
1948	5	9	11	0	9	13	9	11	10	6	12	24	38	51	59	72	87	95	89	70	29	3	10	13
1949	2	10	12	0	9	13	8	4	15	15	41	62	76	85	97	71	46	32	44	40	4	5	3	12
1950	5	2	10	5	14	5	6	8	15	34	44	71	88	100	95	64	20	47	45	16	11	6	2	14
1951	5	1	4	0	2	0	4	17	20	19	47	60	66	60	56	45	34	63	59	31	0	2	7	3
1952	3	1	0	1	1	4	2	7	6	5	21	57	64	76	68	44	63	67	61	67	65	36	7	2
1953	3	0	2	2	5	0	1	2	3	19	54	81	94	86	54	61	83	83	87	66	6	6	1	6
1954	10	11	9	1	3	1	12	3	0	5	41	58	67	73	54	63	15	12	37	26	6	4	4	0
1955	5	16	10	0	1	2	14	10	10	24	19	26	61	79	69	32	56	63	29	6	0	5	10	18
1956	11	4	3	5	0	1	1	3	8	21	25	61	68	67	86	94	93	59	39	20	15	6	2	1
1957	11	15	15	9	3	13	6	18	22	15	44	67	72	83	78	80	89	94	85	56	9	3	2	1
1958	1	0	4	11	9	4	2	8	2	23	32	65	61	52	71	75	84	42	28	22	2	6	2	12
1959	6	7	3	6	3	1	4	10	12	31	49	24	32	37	65	73	44	56	28	6	3	2	1	5
1960	4	8	4	0	7	8	1	7	3	7	30	61	51	40	40	42	43	9	16	8	3	16	11	6
1961	15	19	20	3	0	3	2	1	11	21	21	33	55	32	66	71	63	31	17	17	12	2	9	5
1962	6	8	13	17	12	0	1	9	9	18	30	51	59	52	65	79	82	78	20	12	0	3	4	11
1963	11	4	13	6	3	0	14	17	8	10	45	64	74	76	65	70	85	72	52	54	0	4	1	8
1964	14	20	12	14	5	5	3	5	17	29	55	76	48	56	82	72	81	92	97	61	50	20	2	7
1965	7	15	7	4	3	14	14	3	17	27	31	30	65	79	85	78	72	77	57	44	42	16	9	9
1966	7	7	1	1	1	10	15	20	8	16	24	43	72	65	66	63	35	18	12	7	2	10	5	13
1967	13	7	3	13	6	2	4	2	2	6	34	33	34	59	78	72	81	87	72	71	58	29	4	4
1968	6	10	4	13	11	4	19	5	10	6	18	24	36	71	63	79	76	80	70	55	26	0	1	0
1969	6	7	2	3	8	2	11	6	13	30	57	64	65	61	39	60	44	36	43	38	5	4	7	0
1970	7	15	2	6	12	1	4	9	15	12	39	53	53	71	78	74	67	53	58	23	6	2	10	16
1971	19	21	17	0	0	0	2	11	2	16	48	67	78	66	58	75	77	63	58	29	9	6	0	3
1972	2	5	2	5	1	1	6	4	4	12	8	28	42	59	76	90	48	58	44	27	1	0	0	0
1973	3	2	1	4	3	2	0	8	1	3	34	59	61	78	62	73	87	78	81	77	15	13	2	0
1974	7	6	5	6	14	2	2	4	1	12	35	42	67	85	99	105	68	54	26	13	12	5	1	1
1975	3	1	9	7	4	3	4	13	17	35	26	39	53	38	47	52	21	19	12	1	3	0	4	6
ALL YEARS	7.2	8.2	8.8	6.3	4.8	4.8	6.8	8.5	10.5	18.6	36.6	50.1	60.8	64.7	63.9	66.6	64.2	57.5	52.2	37.1	16.8	9.7	7.0	7.8

KEENE

MEAN DEFICIT

HALFMONTH	Jan 1	Jan 2	Feb 3	Feb 4	Mar 5	Mar 6	Apr 7	Apr 8	May 9	May 10	Jun 11	Jun 12	Jul 13	Jul 14	Aug 15	Aug 16	Sep 17	Sep 18	Oct 19	Oct 20	Nov 21	Nov 22	Dec 23	Dec 24
1925	8	5	13	12	13	6	0	7	16	30	48	54	54	47	50	71	74	78	60	17	2	0	9	16
1927	19	12	14	11	2	3	17	15	11	10	30	51	62	71	57	68	64	77	55	14	4	1	0	5
1928	9	5	8	3	12	7	14	4	11	10	10	34	57	48	21	29	10	18	34	42	34	22	12	10
1929	3	10	8	9	3	1	6	0	3	13	45	42	60	80	83	85	83	82	87	86	72	45	36	8
1930	1	8	15	5	3	2	8	18	11	13	34	48	54	64	74	70	79	88	91	73	48	15	11	14
1931	14	18	20	15	7	1	1	9	8	8	11	27	52	44	49	59	54	51	64	44	24	20	11	2
1932	4	3	5	13	6	5	2	11	15	32	37	65	59	81	71	73	87	48	39	14	2	3	16	15
1933	11	5	6	3	1	1	0	2	12	28	54	71	84	88	67	32	23	11	21	4	7	12	7	12
1934	7	3	12	17	6	4	2	2	5	25	40	29	50	65	71	72	61	27	18	16	3	12	4	8
1935	5	8	15	7	4	1	7	6	7	27	38	26	27	49	65	69	40	38	38	43	21	6	4	8
1936	2	4	14	18	9	0	0	8	18	21	48	57	66	47	54	53	54	76	66	19	5	15	4	1
1937	3	0	7	1	12	1	6	5	3	5	21	26	42	54	57	51	54	56	69	26	13	2	2	4
1938	5	5	1	5	12	12	10	7	18	12	38	41	40	18	20	51	61	12	26	18	15	8	3	8
1939	5	13	17	3	1	1	0	2	16	29	52	46	65	78	68	64	70	76	54	51	8	20	10	7
1940	12	7	9	9	6	4	0	3	6	13	23	52	55	59	83	85	73	77	79	83	26	6	9	9
1941	3	13	10	11	14	8	9	20	9	21	31	27	44	39	59	74	47	68	70	63	19	18	18	4
1942	7	6	8	7	2	2	10	15	17	11	29	32	27	44	46	59	65	70	68	47	3	3	5	11
1943	5	10	7	5	6	5	17	3	1	10	29	56	77	78	66	72	86	93	88	43	10	2	12	20
1944	12	14	18	5	4	0	6	2	14	22	45	18	44	61	66	76	72	16	29	19	17	14	5	13
1945	4	14	18	5	0	1	3	3	0	8	31	9	31	27	42	64	70	75	66	56	44	13	4	9
1946	4	6	11	11	4	15	14	17	5	2	13	43	65	67	55	54	69	70	27	20	24	22	19	6
1947	10	10	1	11	2	1	5	4	4	23	32	30	41	20	52	62	61	71	8[illegible]	82	36	4	12	11
1948	17	20	21	12	12	0	2	7	9	2	10	21	20	43	60	69	90	102	99	94	69	13	13	15
1949	1	6	11	0	3	12	12	5	8	13	40	47	58	69	75	70	54	17	24	26	11	11	4	3
1950	1	0	7	4	13	5	3	4	12	19	25	47	68	73	83	65	12	34	51	43	25	6	1	13
1951	7	1	7	1	0	1	2	6	13	20	44	29	37	38	54	45	30	23	16	9	1	4	7	14
1952	7	0	0	2	2	3	6	7	7	12	14	44	52	69	77	74	63	74	66	72	72	49	22	8
1953	4	0	2	2	5	0	1	1	2	8	39	61	69	54	33	39	68	68	67	47	8	9	1	7
1954	13	12	7	0	3	2	11	1	1	5	16	33	51	55	43	70	33	12	35	30	8	4	5	2
1955	4	17	9	0	1	1	13	11	13	31	11	32	51	76	71	19	53	65	37	3	0	5	10	18
1956	11	8	4	1	1	1	1	2	7	28	25	56	64	60	81	89	74	34	17	27	16	4	6	0
1957	9	13	13	9	1	8	5	16	16	7	35	61	57	79	91	97	95	74	72	56	14	3	2	0
1958	6	3	6	14	0	5	8	11	1	20	29	59	71	69	70	79	80	64	48	47	15	11	2	12
1959	12	1	6	12	3	0	2	11	10	28	50	57	63	67	64	38	46	58	44	14	1	3	1	5
1960	3	7	6	1	4	8	1	5	6	10	24	26	45	48	44	56	58	9	26	12	4	16	10	16
1961	20	21	22	6	0	5	5	2	5	20	32	50	46	49	65	78	74	68	65	48	28	7	12	5
1962	5	2	9	8	5	3	2	13	6	18	32	55	66	53	25	36	60	66	22	14	3	8	7	12
1963	15	12	17	11	5	0	9	15	9	16	49	56	78	72	67	74	84	90	58	65	16	6	1	11
1964	11	4	4	12	3	3	5	4	18	24	54	70	70	84	93	64	75	94	100	86	80	63	28	15
1965	7	15	10	6	7	14	11	5	18	31	38	55	67	60	63	37	36	28	13	19	23	11	10	10
1966	9	11	11	3	2	8	12	19	9	23	52	70	84	82	85	79	58	53	29	11	3	14	14	14
1967	17	8	7	12	6	2	5	1	3	4	29	35	39	37	52	52	55	70	65	38	22	10	1	7
1968	16	18	5	13	8	1	15	15	11	7	13	13	35	65	71	89	88	83	70	55	30	1	1	2
1969	13	11	11	10	4	1	4	3	8	16	19	8	40	33	17	57	54	57	64	59	19	3	7	4
1970	9	16	6	8	9	1	4	10	11	10	24	41	58	74	85	76	60	41	40	26	22	9	6	14
1971	16	18	16	2	1	1	1	14	5	15	48	62	70	72	54	66	51	62	66	43	28	12	2	5
1972	4	3	5	8	3	0	5	1	2	13	7	39	36	40	62	67	57	58	62	55	22	0	0	5
1973	2	2	3	11	3	4	1	11	5	4	17	26	20	52	31	59	76	81	84	79	34	25	2	2
1974	5	5	5	6	6	1	4	8	1	10	42	55	66	78	88	83	24	15	18	11	9	4	4	4
1975	4	2	4	5	5	4	2	11	16	36	27	35	50	24	29	48	33	24	13	2	9	1	6	11
ALL YEARS	8.6	8.9	9.9	7.8	5.4	3.9	6.3	8.2	9.4	16.9	32.2	43.0	54.2	58.5	60.6	63.8	60.4	56.5	52.4	39.9	21.1	11.9	8.4	9.1

B E R L I N

MEAN DEFICIT

HALFMONTH	Jan 1	2	Feb 3	4	Mar 5	6	Apr 7	8	May 9	10	Jun 11	12	Jul 13	14	Aug 15	16	Sep 17	18	Oct 19	20	Nov 21	22	Dec 23	24
1926	11	14	18	20	21	16	1	0	9	17	35	29	50	56	66	73	81	76	68	41	16	4	11	17
1927	20	18	19	20	15	3	16	16	12	4	22	49	47	54	63	43	36	53	41	3	3	3	3	8
1928	6	8	16	19	21	9	0	1	11	7	15	49	65	75	58	62	65	42	47	28	22	14	18	14
1929	18	8	14	17	18	0	0	1	3	9	40	51	62	73	75	74	85	93	81	73	57	24	22	20
1930	6	8	16	8	2	2	1	14	16	7	19	43	57	59	54	50	74	79	91	52	13	8	10	15
1931	10	14	18	15	11	5	3	12	10	6	13	32	43	43	41	61	65	30	20	8	9	13	13	4
1932	3	6	14	18	15	13	0	8	17	15	20	46	40	43	37	57	70	12	5	14	4	4	15	14
1933	11	10	14	17	11	16	0	1	5	20	40	56	63	59	27	38	50	59	35	7	12	11	5	14
1934	18	20	21	22	8	7	0	1	6	15	37	21	31	30	23	22	20	16	20	13	5	5	10	19
1935	11	8	16	19	17	2	2	3	8	19	15	12	43	56	65	79	75	37	35	31	22	2	3	11
1936	10	15	18	20	15	0	0	6	12	10	39	57	64	80	89	94	68	48	35	3	2	12	12	2
1937	2	3	13	3	8	2	2	2	3	4	23	21	37	59	70	57	54	18	30	8	4	1	2	6
1938	14	13	9	15	18	3	2	7	11	7	38	51	47	47	33	36	44	10	21	16	16	8	4	7
1939	14	17	20	20	19	20	2	0	10	14	27	32	43	64	70	81	80	81	43	26	2	16	15	11
1940	14	7	15	18	6	10	0	1	7	14	26	50	48	55	48	57	34	24	19	19	4	4	14	16
1941	8	16	9	10	16	19	4	7	14	13	27	47	45	30	49	48	52	54	39	18	3	14	19	16
1942	14	18	20	21	4	0	0	5	15	22	32	17	56	76	89	82	92	79	61	44	16	12	12	17
1943	20	21	22	21	19	9	8	0	0	10	19	10	28	31	18	29	9	20	32	1	2	1	9	16
1944	19	21	21	22	23	12	0	0	10	18	34	26	40	49	63	70	68	42	23	9	5	7	1	10
1945	6	14	18	20	16	0	3	6	0	5	20	32	48	45	65	83	73	54	6	9	10	4	7	13
1946	9	14	18	20	9	1	10	12	5	10	13	46	70	67	20	27	40	48	7	8	6	11	7	10
1947	16	19	12	15	16	2	1	3	1	11	7	22	50	54	71	85	71	85	92	97	65	11	13	18
1948	20	21	22	22	23	5	10	8	3	3	29	42	59	72	74	80	96	99	34	48	21	2	12	17
1949	1	12	17	9	10	4	6	5	7	17	37	38	52	73	81	91	83	74	59	51	15	10	11	5
1950	2	5	10	16	19	14	0	5	13	21	27	47	51	74	76	73	54	64	71	53	40	16	0	11
1951	15	17	19	16	10	0	0	3	14	21	37	61	45	43	57	50	54	56	45	34	4	4	9	15
1952	9	16	17	19	17	3	0	8	13	9	14	39	59	73	82	68	64	80	56	53	41	29	12	2
1953	6	7	11	16	16	0	3	0	6	10	35	61	62	44	40	58	75	71	62	46	18	13	1	8
1954	13	13	15	2	1	2	2	2	1	7	11	22	19	39	30	48	5	5	14	4	3	6	7	9
1955	12	17	19	14	4	6	0	2	5	10	11	19	50	71	62	25	54	75	80	58	12	12	14	19
1956	11	5	15	18	20	21	4	2	4	10	29	57	46	55	75	78	45	38	32	29	23	12	10	7
1957	15	19	21	18	6	3	6	16	17	6	28	41	43	45	54	77	87	70	57	46	10	6	3	1
1958	1	1	5	14	2	0	2	8	1	11	23	52	52	49	54	68	82	66	55	24	6	9	15	18
1959	20	13	15	18	12	9	1	16	23	28	49	24	46	74	83	71	57	73	53	20	2	5	3	11
1960	17	19	19	5	12	16	0	11	13	7	35	28	33	54	59	80	77	27	30	13	6	13	11	16
1961	20	21	22	15	1	5	1	1	10	17	16	44	56	64	75	81	93	77	71	48	33	10	4	10
1962	16	19	21	22	19	2	2	8	5	9	30	48	67	64	55	40	37	38	13	10	1	3	4	12
1963	17	19	21	22	20	9	3	6	8	17	45	66	62	63	48	27	57	78	67	68	15	3	1	10
1964	16	6	10	16	5	5	1	6	15	12	33	51	52	68	88	74	71	86	88	59	42	18	8	10
1965	7	15	19	19	4	10	7	9	22	26	30	21	44	56	70	67	55	45	3	7	13	2	9	16
1966	12	17	18	10	4	2	0	14	14	15	33	39	51	72	75	65	76	76	63	35	8	14	7	15
1967	19	19	18	20	21	18	0	2	3	1	27	39	62	64	73	79	72	79	60	29	20	15	10	10
1968	16	19	21	22	22	2	6	3	13	12	14	16	27	59	75	66	70	77	78	71	47	4	1	4
1969	14	18	19	21	21	7	0	0	7	8	27	39	62	61	14	16	37	38	37	28	6	2	9	7
1970	7	15	15	13	16	3	0	0	2	5	23	49	48	68	55	42	16	30	11	6	19	10	8	15
1971	19	21	21	19	20	4	0	1	7	10	17	35	51	34	35	41	42	42	39	19	12	16	10	8
1972	15	16	19	21	22	3	1	0	3	23	7	36	51	55	50	69	81	90	81	66	38	18	7	14
1973	10	5	8	15	7	0	1	9	3	2	21	11	21	46	53	74	63	48	30	25	6	0	2	2
1974	10	12	7	8	1	5	1	3	1	4	25	48	40	31	32	39	18	17	12	11	12	18	8	4
1975	12	13	15	12	7	3	1	5	18	27	10	42	61	45	49	59	38	20	15	3	16	25	18	12
ALL YEARS	12.7	14.4	16.9	16.9	13.5	6.7	2.7	5.7	9.2	12.6	26.2	38.8	49.5	56.9	57.8	60.7	59.8	54.5	44.7	30.3	16.3	10.2	9.2	11.7