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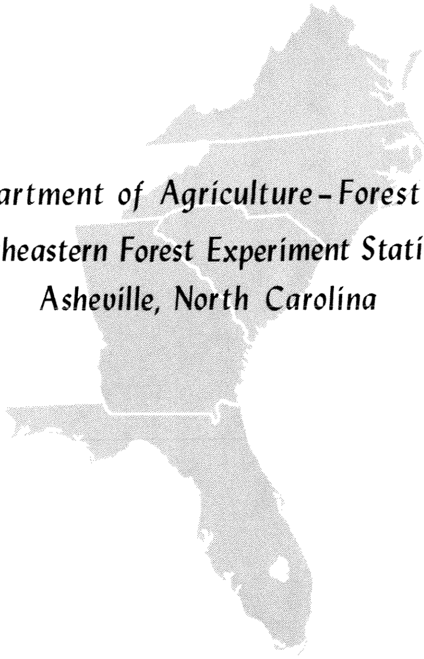
A Drought Index for Forest Fire Control



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A Drought Index for Forest Fire Control

by

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INTRODUCTION

The moisture content of the upper soil, as well as that of the covering layer of duff, has an important effect on the fire suppression effort in forest and wildland areas. In certain forested areas of the United States, fires in deep duff fuels are of particular concern to the fire control manager. When these fuels are dry, fires burn deeply, damage is excessive, and fire extinguishment unduly expensive. Even relatively small fires are costly; the larger fires may be disastrous. As an example, in 1955 and 1956, four fires in the Southeast each burned more than 100,000 acres. During these years, normally moist areas which usually served as good fire barriers, such as branch heads and bays, became so dry that the fires accelerated through the heavy fuel instead of slowing down.

Certainly, factors in addition to soil moisture influenced the occurrence and behavior of these and other less spectacular fires. However, experience over the years has established the close association of extremely difficult fire suppression with cumulative dryness, or drought.

In fire control, the critical effects of drought are not confined to deep organic soils. Dried-out organic materials are frequently imbedded in the shallow upper layers of mineral soils. These fuel pockets can become a deciding factor in whether or not firelines will hold and a further problem in mopup operations. During extreme drought conditions, the moisture content of living brush and tree crowns may be lowered, fires may crown more readily, and some of the woody vegetation may die. Furthermore, the curing of herbaceous material during the growing season is associated with periods of little or no rainfall. It is important to recognize how drought intensifies the problem of fire control.

Drought development, especially in the early stages, is frequently unrecognized and certainly is not uniformly interpreted. The need for a systematic method of estimating the progress of drought has been emphasized by State and Federal fire control officers. This recurring problem stimulated the search for a measure of drought that would be useful in planning fire control operations.

The statement that follows should be considered as a progress report. The physical theory and the general framework for a drought index have been developed, but there are gaps in our knowledge of the precise form of the moisture relationships. We believe, therefore, that the study of drought, both as to measurement and to interpretation, should be continued with increased emphasis.

GENERAL

Drought has been defined in many ways. Palmer (1965) lists seven different definitions of drought which have appeared in past studies and states that the list could be extended. For forest fire control, a useful concept of drought is one which treats it as a continuous quantity which can be described in numerical terms. The values would range from zero (soil and duff saturated with water) up to some maximum value which corresponds to an absence of available moisture in the soil and duff. This point of view does not necessarily emphasize the extreme or unusual aspects of the drought concept. However, the upper part of the scale does correspond to those conditions for which many definitions of drought require that the dryness or moisture deficiency be "abnormal" or "unusual."

As used in this paper, drought index is defined as a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or upper soil layers. Drought index is, thus, a quantity that relates to the flammability of organic material in the ground.

The material may be soil humus, in which case the upper soil may appear to burn if fires occur when the index is high. The organic material may also consist of buried wood, such as roots in varying degrees of decay, at different depths below the mineral soil surface. The relative dryness of these fuels is a direct effect of drought and, because of the problem of firelines noted previously, is of greater significance in fire suppression than in fire behavior.

There may, however, be important indirect effects of an extended drought on specific fire behavior characteristics, such as rate of spread or energy release, because these variables are affected by the size of the area on fire at one time. Fires may also crown more readily under drought conditions. A prolonged drought influences fire intensity largely because more fuel is available for combustion. The increased intensity, added to the difficulty of holding firelines, greatly adds to the effort required for fire suppression.

We emphasize that the drought index described in this report is not in any way a substitute for the moisture parameters used in the spread phase of the National Fire Danger Rating System. A drought condition is not a prerequisite for the occurrence and spread of fire in any area. The drought index does not replace the buildup index, because it represents an entirely different moisture regime in which the response to weather changes is much slower than with the buildup index. The purpose of the drought index is to provide fire control managers with a continuous scale of reference for estimating deep-drying conditions in areas where such information may be useful in planning fire control operations.

STRUCTURE OF THE DROUGHT INDEX

The physical theory and the general framework for a drought index that should operate through a wide range of climatic conditions is given in the Appendix. The theory and framework are based on the following assumptions:

1. The rate of moisture loss in a forested area will depend on the density of the vegetation cover in that area. In turn, the density of the vegetation cover, and, consequently, its transpiring capacity, is a function of the mean annual rainfall. Furthermore, the vegetation will eventually adjust itself to use most of the available moisture.

2. The vegetation-rainfall relation is approximated by an exponential curve in which the rate of moisture removal is a function of the mean annual rainfall. Therefore, the rate decreases with decreasing density of vegetation, hence, with decreasing mean annual rainfall.

3. The rate of moisture loss from soil is determined by evapotranspiration relations.

4. The depletion of soil moisture with time is approximated by an exponential curve form in which wilting point moisture[1] is used as the lowest moisture level. Thus, the expected rate of drop in soil moisture to the wilting point, under similar conditions, is directly proportional to the amount of available water in the soil layer at a given time.

5. The depth of the soil layer wherein the drought events occur is such that the soil has a field capacity of 8 inches of available water. Although the selection of 8 inches is somewhat arbitrary, a precise numerical value is not essential. Eight inches of available moisture appears reasonable for use in forest fire control because in many areas of the country it takes all summer for the vegetation cover to transpire that much water.

From these assumptions, plus supporting data, a mathematical description of the overall process was developed (see Appendix). The final equations were then expressed in a form suitable for solution by slide rule or computer.

With the exception of assumption No. 1, the basic principles upon which the drought index is based are similar to those upon which Nelson (1959) based his index. However, he used a linear relationship in assumption No. 4 instead of the exponential form. The precise nature of the soil moisture depletion curve is still in doubt, but most investigators now seem to prefer the exponential form. This question is discussed further in the Appendix.

DROUGHT INDEX COMPUTATIONS

Drought index may be computed for any desired level of mean annual rainfall, but to simplify the computations for field use, five tables of drought factors were made up. Each table covers a specified range of mean annual rainfall. Tables 1 through 5 and a sample recording form (fig. 1) with instructions are included in this section.[2]

The measurements needed for the drought index are (1) the maximum air temperature (or the dry-bulb temperature at time of basic observation) and (2) the total rainfall for the past 24 hours. This information is available at stations that regularly compute spread index.

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[1] For the purpose of this paper, the wilting point will be defined as that soil moisture content which marks the limit of the zone of available moisture and separates it from the zone of unavailable moisture. If the moisture content is greater than the wilting point moisture, the excess above the wilting point is available for transpiration; if it is below the wilting point, the moisture is not available for transpiration.

[2] The drought factors in tables 1 through 5 were taken from IBM tabulations programed by Marshall P. Waters, University of Georgia Computer Center, Athens, Georgia. Each drought factor value represents a solution of Equation 18 in the Appendix. Factors were computed to tenths, at 3-degree temperature increments, from 51° to 108° F. for mean annual rainfalls of 15 inches (table 1), 25 inches (table 2), 35 inches (table 3), 50 inches (table 4), and 70 inches (table 5). Values read from the IBM tabulations were rounded to the nearest whole number, raising fractions of 0.5 or more to the next higher number.

Table 1.--Drought factors for areas with mean annual rainfall 10 inches to 19 inches.

Temperature 2/	Drought index yesterday (or as reduced by precipitation) 1/															
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	350 to 399	400 to 449	450 to 499	500 to 549	550 to 639	640 to 699	700 to 759	760 to 799	800
	Drought factor															
107+	21	19	18	17	15	14	13	11	10	9	7	5	3	2	1	0
104-106	18	17	15	14	13	12	11	10	8	7	6	5	3	2	1	0
101-103	15	14	13	12	11	10	9	8	7	6	5	4	2	1	1	0
98-100	13	12	11	11	10	9	8	7	6	5	5	3	2	1	1	0
95-97	11	10	10	9	8	8	7	6	5	5	4	3	2	1	1	0
92-94	9	9	8	8	7	6	6	5	5	4	3	3	2	1	0	0
89-91	8	8	7	7	6	5	5	4	4	3	3	2	1	1	0	0
86-88	7	6	6	6	5	5	4	4	3	3	2	2	1	1	0	0
83-85	6	5	5	5	4	4	4	3	3	2	2	2	1	1	0	0
80-82	5	5	4	4	4	3	3	3	2	2	2	1	1	1	0	0
77-79	4	4	4	3	3	3	3	2	2	2	1	1	1	1	0	0
74-76	3	3	3	3	3	2	2	2	2	1	1	1	1	1	0	0
71-73	3	3	2	2	2	2	2	2	1	1	1	1	1	1	0	0
68-70	2	2	2	2	2	2	1	1	1	1	1	1	1	0	0	0
65-67	2	2	2	2	1	1	1	1	1	1	1	1	1	0	0	0
62-64	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
59-61	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
56-58	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
53-55	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
50-52	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0

1/ Drought index is reduced one point for each one-hundredth inch of net rainfall--refer to instructions in text.

2/ Dry-bulb temperature (degrees F.) today, at time of basic observation, or use maximum temperature.

Table 2.--Drought factors for areas with mean annual rainfall 20 inches to 29 inches.

Temperature 2/	Drought index yesterday (or as reduced by precipitation) 1/															
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	350 to 399	400 to 449	450 to 499	500 to 549	550 to 639	640 to 699	700 to 759	760 to 799	800
	Drought factor															
107+	30	28	26	24	22	20	18	16	14	12	11	8	5	3	1	0
104-106	25	24	22	20	19	17	16	14	12	11	9	7	4	2	1	0
101-103	22	20	19	18	16	15	13	12	11	9	8	6	3	2	1	0
98-100	19	17	16	15	14	13	11	10	9	8	7	5	3	2	1	0
95-97	16	15	14	13	12	11	10	9	8	7	6	4	3	1	1	0
92-94	14	13	12	11	10	9	8	7	7	6	5	4	2	1	1	0
89-91	12	11	10	9	9	8	7	6	6	5	4	3	2	1	1	0
86-88	10	9	9	8	7	7	6	5	5	4	4	3	2	1	1	0
83-85	8	8	7	7	6	6	5	5	4	4	3	2	1	1	0	0
80-82	7	7	6	6	5	5	4	4	3	3	3	2	1	1	0	0
77-79	6	5	5	5	4	4	4	3	3	2	2	2	1	1	0	0
74-76	5	5	4	4	4	3	3	3	2	2	2	1	1	1	0	0
71-73	4	4	4	3	3	3	2	2	2	2	1	1	1	1	0	0
68-70	3	3	3	3	2	2	2	2	2	1	1	1	1	1	0	0
65-67	3	3	2	2	2	2	2	1	1	1	1	1	1	0	0	0
62-64	2	2	2	2	2	1	1	1	1	1	1	1	1	0	0	0
59-61	2	2	1	1	1	1	1	1	1	1	1	1	0	0	0	0
56-58	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
53-55	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
50-52	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0

1/ Drought index is reduced one point for each one-hundredth inch of net rainfall--refer to instructions in text.

2/ Dry-bulb temperature (degrees F.) today, at time of basic observation, or use maximum temperature.

Table 3.--Drought factors for areas with mean annual rainfall 30 inches to 39 inches.

Temperature 2/	Drought index yesterday (or as reduced by precipitation) 1/															
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	350 to 399	400 to 449	450 to 499	500 to 549	550 to 639	640 to 699	700 to 759	760 to 799	800
	Drought factor															
107+	41	38	36	33	30	28	25	23	20	17	15	11	6	4	1	0
104-106	35	33	31	28	26	24	22	19	17	15	13	9	5	3	1	0
101-103	30	28	26	24	22	20	19	17	15	13	11	8	5	3	1	0
98-100	26	24	23	21	19	18	16	14	13	11	9	7	4	2	1	0
95-97	22	21	19	18	16	15	14	12	11	9	8	6	3	2	1	0
92-94	19	18	16	15	14	13	12	10	9	8	7	5	3	2	1	0
89-91	16	15	14	13	12	11	10	9	8	7	6	4	3	1	1	0
86-88	14	13	12	11	10	9	8	7	7	6	5	4	2	1	1	0
83-85	11	11	10	9	9	8	7	6	6	5	4	3	2	1	1	0
80-82	10	9	8	8	7	7	6	5	5	4	3	3	2	1	0	0
77-79	8	8	7	7	6	6	5	4	4	3	3	2	1	1	0	0
74-76	7	6	6	5	5	5	4	4	3	3	2	2	1	1	0	0
71-73	6	5	5	5	4	4	3	3	3	2	2	2	1	1	0	0
68-70	5	4	4	4	3	3	3	3	2	2	2	1	1	1	0	0
65-67	4	3	3	3	3	3	2	2	2	2	1	1	1	1	0	0
62-64	3	3	3	2	2	2	2	2	1	1	1	1	1	1	0	0
59-61	2	2	2	2	2	2	1	1	1	1	1	1	1	0	0	0
56-58	2	2	2	1	1	1	1	1	1	1	1	1	1	0	0	0
53-55	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
50-52	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0

1/ Drought index is reduced one point for each one-hundredth inch of net rainfall--refer to instructions in text.

2/ Dry-bulb temperature (degrees F.) today, at time of basic observation, or use maximum temperature.

Table 4.--Drought factors for areas with mean annual rainfall 40 inches to 59 inches.

Temperature 2/	Drought index yesterday (or as reduced by precipitation) 1/															
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	350 to 399	400 to 449	450 to 499	500 to 549	550 to 639	640 to 699	700 to 759	760 to 799	800
	Drought factor															
107+	62	58	54	50	46	42	38	34	30	26	22	16	10	6	2	0
104-106	53	50	46	43	39	36	33	29	26	22	19	14	8	5	1	0
101-103	46	43	40	37	34	31	28	25	22	19	16	12	7	4	1	0
98-100	39	37	34	31	29	26	24	21	19	16	14	10	6	4	1	0
95-97	33	31	29	27	25	23	20	18	16	14	12	9	5	3	1	0
92-94	28	27	25	23	21	19	17	16	14	12	10	8	4	3	1	0
89-91	24	23	21	20	18	16	15	13	12	10	9	6	4	2	1	0
86-88	21	19	18	17	15	14	13	11	10	9	7	5	3	2	1	0
83-85	17	16	15	14	13	12	11	10	8	7	6	5	3	2	1	0
80-82	15	14	13	12	11	10	9	8	7	6	5	4	2	1	1	0
77-79	12	11	11	10	9	8	8	7	6	5	4	3	2	1	1	0
74-76	10	10	9	8	8	7	6	6	5	4	4	3	2	1	1	0
71-73	8	8	7	7	6	6	5	5	4	4	3	2	1	1	0	0
68-70	7	6	6	6	5	5	4	4	3	3	2	2	1	1	0	0
65-67	6	5	5	4	4	4	3	3	3	2	2	2	1	1	0	0
62-64	4	4	4	4	3	3	3	2	2	2	2	1	1	1	0	0
59-61	3	3	3	3	3	2	2	2	2	1	1	1	1	1	0	0
56-58	3	2	2	2	2	2	2	1	1	1	1	1	1	0	0	0
53-55	2	2	2	1	1	1	1	1	1	1	1	1	1	0	0	0
50-52	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0

1/ Drought index is reduced one point for each one-hundredth inch of net rainfall--refer to instructions in text.

2/ Dry-bulb temperature (degrees F.) today, at time of basic observation, or use maximum temperature.

Table 5.--Drought factors for areas with mean annual rainfall 60 inches or more.

Temperature [2]	Drought index yesterday (or as reduced by precipitation) [1]															
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	350 to 399	400 to 449	450 to 499	500 to 549	550 to 639	640 to 699	700 to 759	760 to 799	800
	Drought factor															
107+	91	85	79	73	68	62	56	50	44	38	32	24	14	8	2	0
104-106	78	73	68	63	58	53	48	43	38	33	28	21	12	7	2	0
101-103	67	63	58	54	50	45	41	37	32	28	24	18	10	6	2	0
98-100	57	54	50	46	43	39	35	31	28	24	20	15	9	5	2	0
95-97	49	46	43	40	36	33	30	27	24	21	17	13	8	4	1	0
92-94	42	39	36	34	31	28	26	23	20	18	15	11	7	4	1	0
89-91	36	33	31	29	26	24	22	19	17	15	13	9	6	3	1	0
86-88	30	28	26	24	22	20	18	17	15	13	11	8	5	3	1	0
83-85	25	24	22	21	19	17	16	14	12	11	9	7	4	2	1	0
80-82	21	20	19	17	16	15	13	12	10	9	8	6	3	2	1	0
77-79	18	17	16	14	13	12	11	10	9	8	6	5	3	2	1	0
74-76	15	14	13	12	11	10	9	8	7	6	5	4	2	1	1	0
71-73	12	12	11	10	9	8	8	7	6	5	4	3	2	1	1	0
68-70	10	9	9	8	7	7	6	6	5	4	4	3	2	1	1	0
65-67	8	8	7	7	6	6	5	4	4	3	3	2	1	1	0	0
62-64	6	6	6	5	5	4	4	4	3	3	2	2	1	1	0	0
59-61	5	5	4	4	4	3	3	3	2	2	2	1	1	1	0	0
56-58	4	4	3	3	3	3	2	2	2	2	1	1	1	1	0	0
53-55	3	2	2	2	2	2	2	1	1	1	1	1	1	0	0	0
50-52	2	2	2	1	1	1	1	1	1	1	1	1	1	0	0	0

[1] Drought index is reduced one point for each one-hundredth inch of net rainfall--refer to instructions in text.

[2] Dry-bulb temperature (degrees F.) today, at time of basic observation, or use maximum temperature.

Only one drought factor table is needed at any selected station. Thus, to compute drought index it is first essential to decide which drought factor table to use. The appropriate table is determined by the long-term mean annual rainfall of the area. Because the range of mean annual rainfall in each table is fairly broad, a reliable estimate applicable to the rating area can usually be obtained from the nearest U. S. Weather Bureau office.

In remote areas it may be necessary to refer to state maps which show lines of mean annual rainfall drawn through points of approximately equal value (called isohyets). These maps are available in the publication, "Climates of the States," which is prepared by the U. S. Weather Bureau and issued separately for each state. Caution should be used in interpolating between the lines on these maps, particularly in mountainous areas.

Starting a Drought Index Record

An examination of the drought factor tables makes it clear that, for any given temperature, the drought factor to be added each day depends on the drought index yesterday. This cumulative feature means that an observer starting a drought index record cannot automatically begin at zero. The zero point may have occurred weeks or months before, or even during the previous year. It is necessary to go back in time until a day is reached on which it is reasonably certain that the upper soil layers were saturated, then bring the record forward day by day to the starting date. In areas of heavy snowfall, it is normally safe to assume saturation just after the snow melts in the spring. When starting a record in snowfree areas, it is necessary to go back to a period of abundant rainfall, such as 6 or 8 inches in a period of a week. The index must be very low, if not actually zero, at the end of the rainy period.

When the starting point has been determined and the proper drought factor table has been selected, the computation of drought index each day is a simple bookkeeping procedure. Essentially, there are two steps:

Step 1--Reduce the drought index by the amount of net rain, if any.

Step 2--Increase the drought index by the amount found in the drought factor table.

The mechanics are explained in the next subsection. (For simplicity of use in the field, the following instructions are presented in an abbreviated style.)

Instructions for Computing Drought Index (refer to sample record, fig. 1)

Column 2--24-Hour Rainfall

Record measured amount of rain to nearest 0.01 inch. Follow standard instructions for melted snow and recording the water equivalent.

sample	sample	sample	June	1966
Agency	District	Station	Month	Year

Day of the Month	24-Hour Rainfall (measured amount)	Net Rainfall (adjusted amount-- see instructions)	Air Temperature ☒ ☐ maximum temp. dry-bulb temp.	Drought Index yesterday, or as reduced by net rainfall (col. 3)	Drought Factor From Table 4	Drought Index For Today col. 5 plus col. 6	Current Stage of Drought
1	2	3	4	5	6	7	8
1		0	79	164	10	174	1
2		0	75	174	8	182	1
3	0.66	.46	70	136	6	142	1
4	T	0	76	142	9	151	1
5	0.23	.03	79	148	11	159	1
6		0	84	159	14	173	1
7	0.16	0	65	173	4	177	1
8	0.09	.05	66	172	4	176	1
9		0	83	176	14	190	1
10		0	70	190	6	196	1
11	0.08	0	67	196	4	200	2
12	0.03	0	65	200	4	204	2
13		0	76	204	8	212	2
14	0.22	.02	69	210	5	215	2
15		0	65	215	4	219	2
16	0.21	.01	75	218	8	226	2
17		0	78	226	9	235	2
18		0	85	236	13	248	2
19		0	88	248	15	263	2
20	0.01	0	79	263	8	271	2
21		0	69	271	5	276	2
22		0	75	276	7	283	2
23		0	84	283	12	295	2
24		0	89	295	16	311	3
25		0	93	311	17	328	3
26		0	92	328	17	345	3
27		0	96	345	20	365	3
28		0	91	365	13	378	3
29	0.25	.05	78	373	7	380	3
30	0.16	.16	83	364	10	374	3
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Figure 1.--Drought index sample record.

Column 3--Net Rainfall

Subtract 0.20 from amount in column 2 to obtain net rainfall. Record 0 (zero) if amount in column 2 is 0.20, or less.

Exception: If there are CONSECUTIVE rainy days, with no drying of tree canopy between showers, subtract only once, on the day that the cumulative rainfall exceeds 0.20. Thereafter, consider all of the rain in column 2 as net rainfall (and transfer the amount to column 3) until the wet spell ends. Consider wet spell ended on first 24-hour period with no measurable rain. In case of snow--consider no drying as long as snow blankets the fuels, and transfer all measured water equivalent to column 3.

Example 1--0.20 was subtracted from each of the individual rains on June 3, 5, 14, and 16. (See sample record, fig. 1.)

Example 2--Rains on June 7-8 were consecutive, so the 0.20 was subtracted when total rain exceeded 0.20, which was June 8.

Example 3--Rains on June 29-30 were consecutive, so 0.20 was subtracted on first day, and all of the rain was transferred to column 3 on second day.

Column 4--Air Temperature

Record air temperature to nearest degree, rounding fractions of 0.5 or more to next higher number. Place an "x" in appropriate box at head of column to identify the temperature used--whether maximum for the day, or dry-bulb temperature at time of basic observation.

Column 5--Drought Index yesterday, or as reduced by net rainfall in column 3

During rainless periods, or when net rainfall in column 3 is zero, enter in column 5 the drought index recorded in column 7 on the previous day. When there is net rainfall in column 3, subtract the number of hundredths inches of rain from the previous day's drought index, and record the reduced drought index in column 5.

Example 1--No net rain on June 2. Drought index was 174 (column 7) on June 1. Therefore, 174 was carried forward to column 5 for June 2.

Example 2--Net rain on June 3 was 46 hundredths. Drought index June 2 was 182 (column 7). Therefore, 182 minus 46 equals 136, the number to record in column 5 for June 3.

Column 6--Drought Factor

Use the appropriate Drought Factor Table as determined by the mean annual rainfall of the rating area. If your area has a mean annual rainfall that seems to fall right on the borderline between tables, such as 19.50 inches or 39.50 inches, use the table with the next higher number. Insert the table number used in the box provided at the top of column 6.

Procedure--refer to Temperature in column 4 and Drought Index yesterday in column 5. Record the drought factor where these numbers intersect in Drought Factor Table.

Example: For June 10, Temperature 70 and Drought Index yesterday 190 intersect at drought factor 6 in table 4.

Column 7--Drought Index For Today

Add Drought Index yesterday in column 5 to drought factor in column 6 to obtain Drought Index For Today.

Example: For June 10, 190 plus 6 equals 196.

Column 8--Current Stage of Drought

Refer to Drought Index For Today in column 7, and determine the drought stage as follows:

Index	Stage	Index	Stage
0-99	0	400-499	4
100-199	1	500-599	5
200-299	2	600-699	6
300-399	3	700-800	7

Example: The Drought Index For Today on June 10 is 196 (column 7), so the drought stage is 1.

DROUGHT INDEX INTERPRETATION

Because the drought index number expresses moisture deficiency in hundredths of an inch and the index is based on 8.00 inches of water available for transpiration, the index is on a scale ranging from 0 to 800. Zero is the point of no moisture deficiency and 800 is the maximum drought that is possible. At any point along the scale, the index number indicates the amount of net rainfall (in hundredths) that is required to reduce the index to zero, or saturation.

To facilitate the description and to clarify the discussion of drought, the available range of drought has been divided into stages. The zero or incipient stage includes the range from 0 to 99, the first stage from 100 to 199, the second stage from 200 to 299, and so on through the seventh stage from 700 to 800 (see instructions above).

Mathematically, the 800 point would require infinite time and, therefore, would never be reached. But by using the rounded off values as set up in the drought factor tables, it is possible to reach 800. Once reached, this maximum cannot be exceeded, because the drought increment at index 800 is zero.

Although the drought index number has a definite meaning in terms of moisture deficiency, the significance of a particular stage of drought for fire control must be determined locally. As a part of the exploratory study of this index, we have examined weather records from several climatic regimes extending from Alaska to Florida and including a wide range of mean annual rainfall. The results of a few of these analyses are discussed in this report to give the reader a clearer understanding of the drought stages and their implication for fire control. Certainly, they are not a substitute for local studies aimed at the same purpose.

In relating drought index to specific locations, we must select the proper drought factor table. This selection is determined by the mean annual rainfall of the area. One simple way to emphasize the importance of selecting the proper table is to compute, according to each of the five tables, the number of consecutive days having a constant maximum temperature and no effective rainfall that must elapse (after starting at zero) before a selected stage of drought is reached. The following tabulation lists the number of days required, according to each of the tables, to reach the fifth stage (500) when the observed temperature each day ranges from 80° to 82° F.:

Table number	Mean annual rainfall	Consecutive drying days needed to reach D. I. 500
	(Inches)	(Number)
1	10-19	157
2	20-29	109
3	30-39	78
4	40-59	52
5	60 or more	36

From the foregoing, we can visualize the two extremes represented by the drought factor tables. If the two areas represented by table 1 and table 5 both started with zero drought index on May 31, then the area with heavy rainfall (table 5) would reach stage 5 in 36 consecutive days, by July 6, and the area of light rainfall (table 1) would reach stage 5 in 157 consecutive days, by November 4.

In a normal or average year the drought index has a definite trend or cycle of values throughout the year with which the index at any time during a given year can be compared. Such a drought index trend (based on 10 years of record) is shown in figure 2 for the airport at Asheville, North Carolina. In the Asheville area, the normal drought index climbs rapidly during June and July, peaks in mid-September, and drops nearly to zero by late February or March. It was found that the normal cycle of drought is well understood by fire control people, both State and Federal, and is reflected in fire control action.

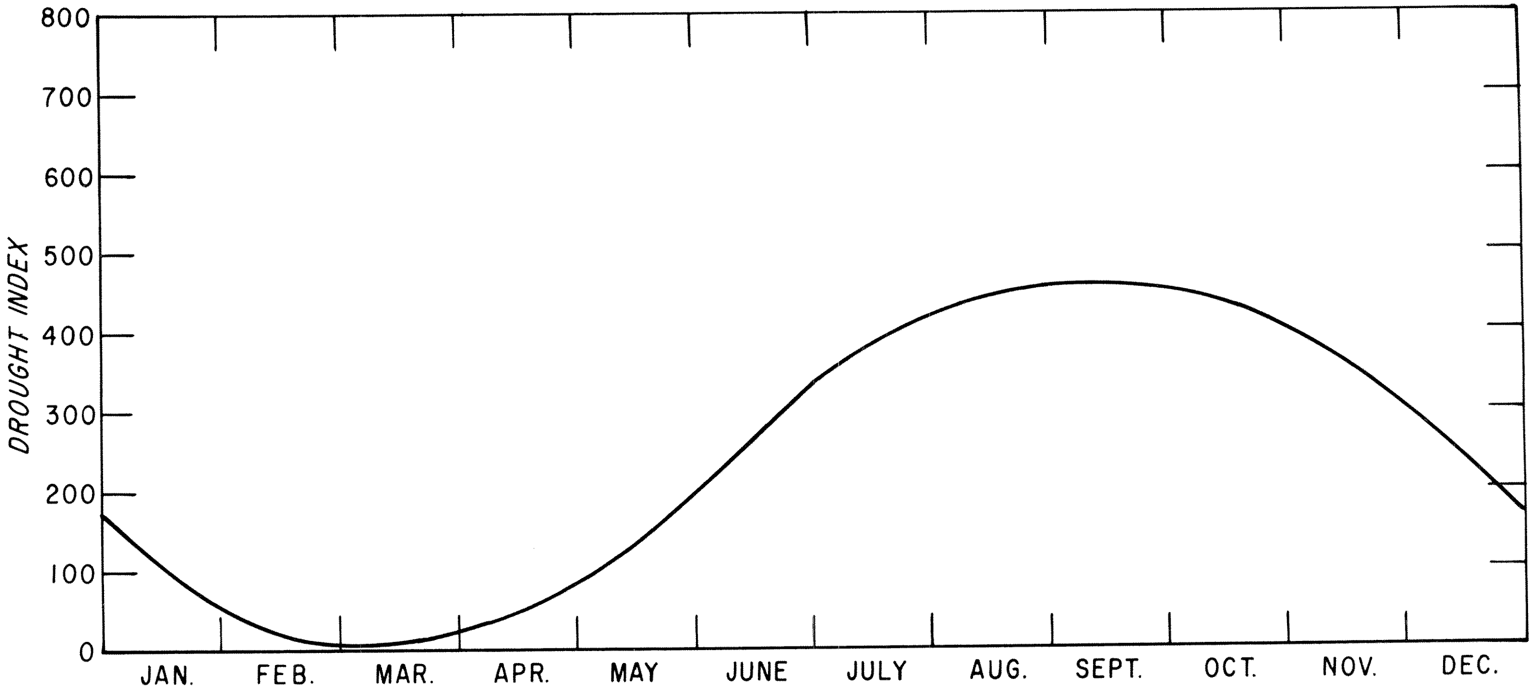


Figure 2.--Annual trend of drought index for the airport at Asheville, North Carolina. (Based on weather records for the period 1951-60.) Mean annual rainfall 48.15 inches.

Because of higher temperatures and more wind, the spring fires in the Asheville district spread faster, on the average, than those in the fall. But once the average spring fire is stopped, mopup is relatively easy. This is not the case in the fall. The typical fall fire burns in cooler weather; there is less wind, and the rate of spread is less than in the spring. Fall fires are therefore easier to stop. But they burn deeper, firelines are more difficult to build and maintain, and mopup is often an extended operation. This activity ties up supervision and manpower and will wear down the organization if fire occurrence continues. When the drought index climbs into the fifth and sixth stages, as it did in 1951, 1952, and 1953, the extinguishment problem is greatly aggravated. In contrast, during the fall of 1959 the index dropped to stage 1 and remained there through the fall season, and firelines were easy to hold.

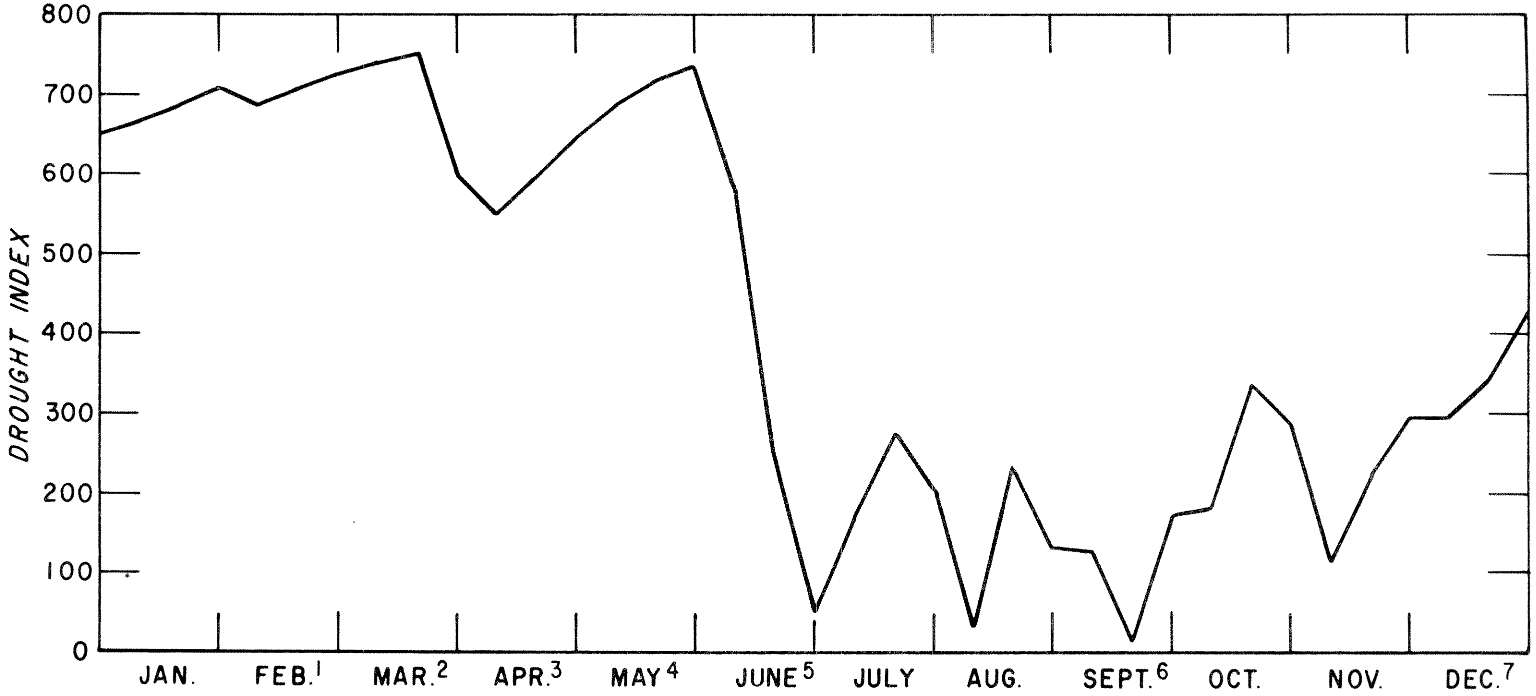
The information on drought index in figures 3 through 6, derived from reports of Monthly Local Climatological Data, gives further information on drought in several parts of the country. Figure 3 depicts the unusually severe drought that persisted near Fort Myers, Florida, during the first 5 months of 1962. From footnote 1 of figure 3, we learn that the drought started in September 1961. Going back to the records for that month, we find that the drought index was in the incipient stage (below 100) at the beginning of September, reached stage 3 on September 20, and edged into stage 4 by the end of the month. This progress seems to agree with the observations quoted in footnote 1.

Ketchikan, Alaska, where the mean annual rainfall is 151.93 inches, is one of the relatively few areas in the country to which table 5 is applicable. In this area of abundant and normally well-distributed rainfall, a drought beyond the incipient stage is unusual. The lowest mean monthly rainfall is 7.34 in June. In the period from 1956 through 1960, 92 percent of the days rated below 100. However, a drought can build up beyond stage 3 in a 30-day summer period with little rain. In 1958, the drought index exceeded 300 from June 20 through July 20 and in the last 3 days of the period was above 500, as is depicted in figure 4.

The opposite end of the climatic scale is represented by Burbank, California, in figure 5. Long rainless periods are a normal event in an area where the mean annual rainfall is only 13.88 inches. With so little rain, one might suspect that there would be relatively small change in the seasonal level of drought; and the drought index for 1961 seems to bear out this supposition. At the beginning of 1961, the area was in the fifth stage. The seriousness of the drought situation was noted by the local unit of the U. S. Weather Bureau (see the note to figure 5 for January 1961).

The moisture deficiency continued to climb throughout the dry summer, reaching a maximum in October well into the seventh stage. The lowest drought index recorded on any day in 1961 was 413, the highest was 743.

However, in going through the Burbank weather records from 1956 until they were discontinued in 1966, we found that 1961 was not a typical year. In fact, it was the most persistently dry year in the 11-year period



Footnotes are based on excerpts from reports of Monthly Local Climatological Data prepared by the U. S. Weather Bureau.

[1] Drought conditions, which began in September 1961, continued through February.

[2] The first 3 weeks of March were dry. The continuing drought of the past several months was relieved somewhat by heavy rains (1.91 in.) on the 25th and 26th.

[3] Drought conditions of the past winter, temporarily relieved during the last week of March and the first week of April, resumed during the last 3 weeks of April.

[4] Smoke and haze from forest fires to the southeast were prevalent during much of the month. This was the driest May of record, also the driest September-May of record.

[5] The 9-month drought was broken by June rains. (Total June rainfall was 12.08 in.)

[6] Temperatures were above normal from June through September. Heavy rains on September 20 and 21 washed out some early planted vegetable crops.

[7] The first half of October was abnormally warm, but November was unusually cool. Warmer weather returned in December. December rain was below normal--the end of December was unusually dry.

Figure 3.--Drought index by 10-day intervals for Fort Myers, Florida, in 1962. Mean annual rainfall 53.27 inches.

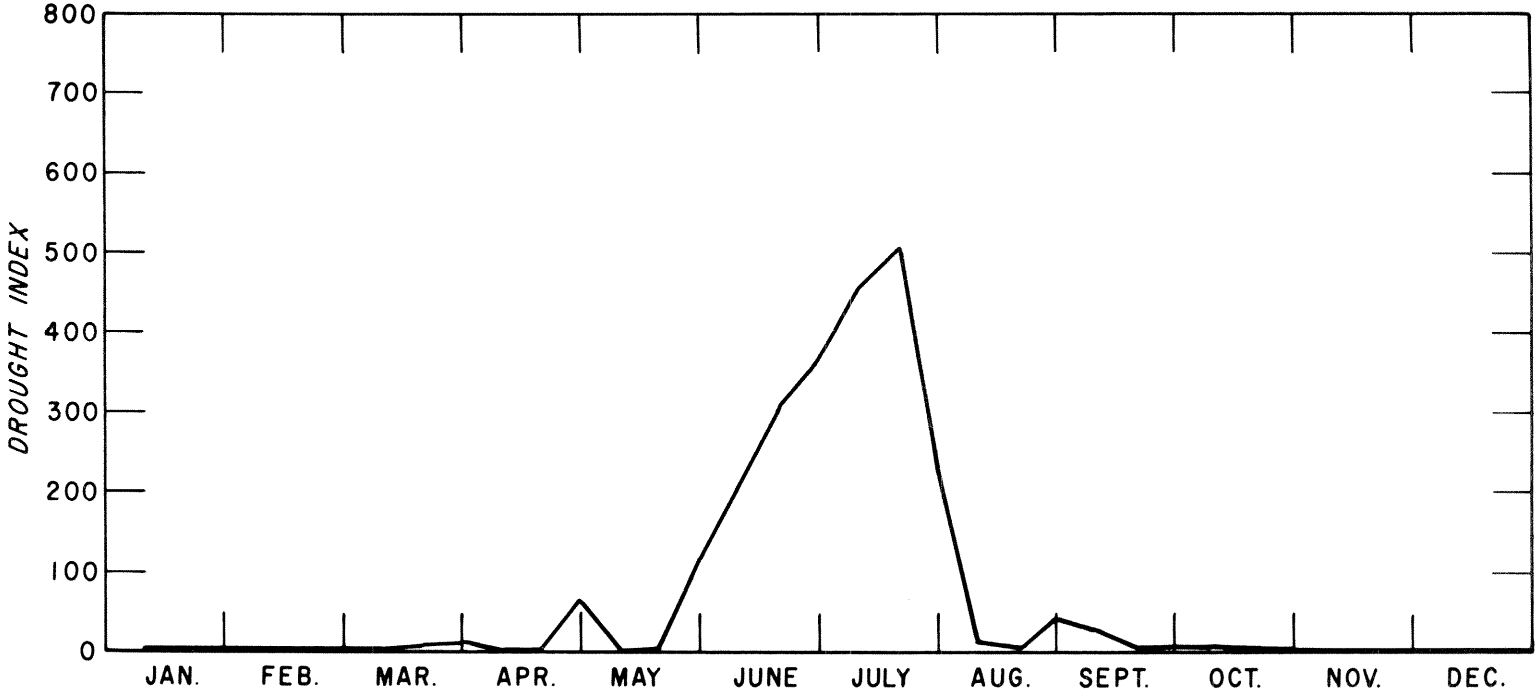
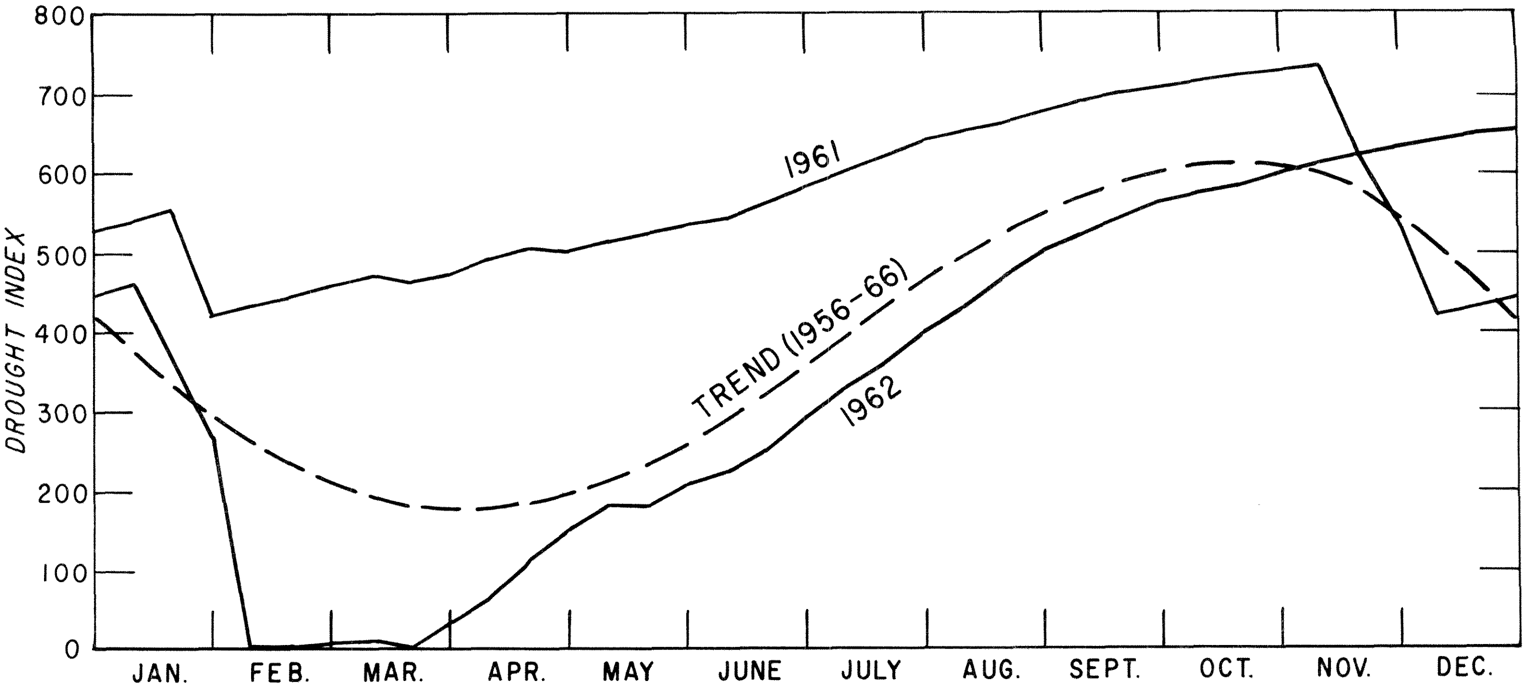


Figure 4.--Drought index by 10-day intervals for Ketchikan, Alaska, in 1958. Mean annual rainfall 151.93 inches.



Notes based on excerpts from reports of Monthly Local Climatological Data prepared by the U. S. Weather Bureau.

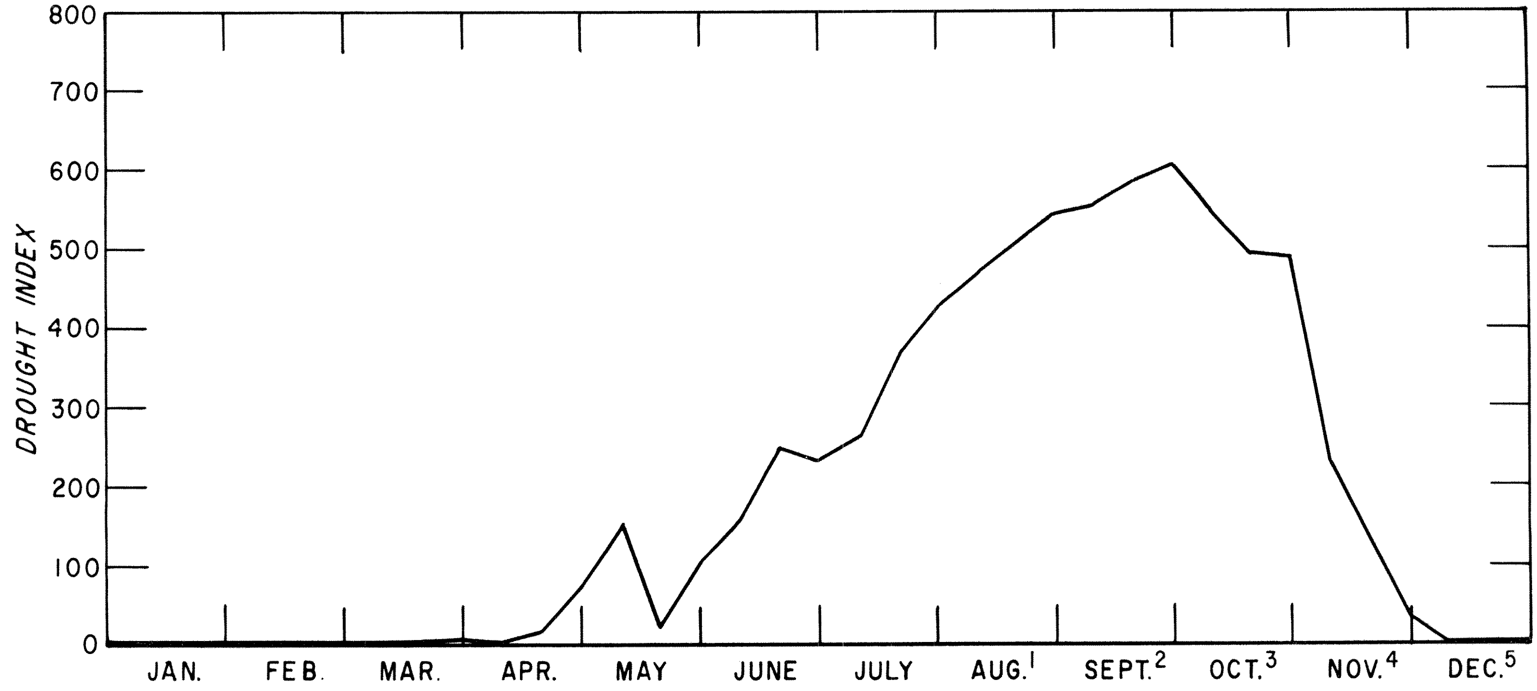
1961

January--The warmest of record. The serious drought situation was eased by substantial rains (1.64 in.) on the 25th and 26th.
April--The fifth consecutive month having below-normal rainfall (now 45 percent of normal) and above-normal temperatures.
June--The precipitation season was the driest of record; only 23.43 in. of precipitation has fallen in the past three precipitation seasons.
October--Only 0.30 in. of rain has fallen since June. Drought is at a maximum.
November--Substantial rains after the 19th (2.70 in.) greatly moderated the severe fire hazard.

1962

February--The wettest February of record (13.30 in.)--seasonal precipitation is 9.62 in. above normal. Rains caused damage from flooding and silting.
June--The driest April of record; the coolest March, May, and June in 10 years.
December--Total precipitation since June was 0.04 in., the lowest ever recorded and 4.53 in. below normal.

Figure 5.--Drought index by 10-day intervals for Burbank, California, in 1961 and 1962. Mean annual rainfall 13.88 inches.



Footnotes based on excerpts from reports of Monthly Local Climatological Data prepared by the U. S. Weather Bureau.

[1] August--The coolest August since 1927, but also the driest since the record-setting August drought of 1947. This month is the eighth in a row with subnormal precipitation.

[2] September--The accumulated drought has dried out many wells and brought about a shortage of water for power generation. There is a potentially dangerous threat of forest fires this fall unless rains in October alleviate the situation.

[3] October--Fortunately, rainy periods were well distributed (although below normal in amount); and the fire hazard that had threatened at the beginning of the month was reduced.

[4] November--Copious precipitation was well spaced throughout the month. The total (5.85 in.) amounted to 35 percent above normal.

[5] December--Rivers rose sharply to normal in December, but no flooding occurred.

Figure 6.--Drought index by 10-day intervals for Portland, Maine, in 1957. Mean annual rainfall 41.78 inches.

and averaged the highest drought index. We found further that zero drought index occurred in one or more of the spring months in 6 of the 11 years. The trend of drought in the Burbank area according to the 1956-66 average is represented by the dashed line in figure 5. In an average year the low point in the drought curve descends into stage 1 in March and April. Thereafter, the index climbs steadily for the next 6 months, peaking just into stage 6 in October.

The 1962 drought, a more typical situation than that in 1961, is represented by the lower line in figure 5. Substantial rains in February brought the index all the way back to zero. Thereafter, the index climbed slowly back to stage 5 at the end of August and into stage 6 by October 31.

A difference in the drought index curves of the magnitude depicted in figure 5 for 1961 and 1962 indicates that soil moisture during the first 10 months of 1961 was markedly lower than for the corresponding months in 1962, at the Burbank station. Additional measurements from several surrounding stations would be needed to determine whether the observed difference in the 1961-62 drought index was localized or was representative of an extensive area.

An interesting comparison can be made, however, with moisture measurements of plant foliage that were taken on the nearby Angeles National Forest. The moisture content of chamise foliage on study plots in the Angeles National Forest has been reported by the Pacific Southwest Forest and Range Experiment Station. These data are contained in a series of 10-day reports on California Fire Weather. A report covering the period from April 10 to October 20 shows the percent moisture content of chamise foliage in 1961 and 1962. The moisture content of the foliage during the period from April to October varied greatly from 1961 to 1962; the distinction was similar to the difference in drought index from 1961 to 1962 shown in figure 5. In 1962 the lowest moisture content reached by October was about 75 percent (at which time the drought index was in the fifth stage). In 1961 the moisture content reached the 75-percent level in May (when the drought index was in the fifth stage) and then dropped to less than 30 percent in October (when the drought index was in stage 7).

A drought in the opposite corner of the country is depicted in figure 6 for Portland, Maine, in 1957. Starting from stage 1 in June, the drought had reached the sixth stage by late September. As the footnote for September indicates, a water shortage was evident at that time. Copious precipitation in the latter part of October and through mid-December (9.49 inches) brought the drought index back to zero. It is probable that the September drought was indeed over by December, because, as the footnote for December indicates, the rivers rose sharply to normal during that month.

SUMMARY AND DISCUSSION

A drought index based on 8 inches of available moisture and the accompanying computational procedures have been discussed. The drought increment on a given day, called the drought factor, is determined by

(1) the mean annual rainfall for the area, (2) the drought index yesterday, and (3) the maximum temperature for today. Reduction in drought occurs only when the 24-hour rainfall exceeds 0.20 inch (called net rainfall). A sample recording form with instructions is included.

Drought development in five areas of the country is illustrated graphically in figures 2 through 6. Selected comments from reports of Local Climatological Data by the U. S. Weather Bureau supplement the graphical record. From this information and other pertinent material assembled for this preliminary study of drought, the following general conclusions seem reasonable:

1. Drought development occurs only during extended periods of little or no rainfall, when the daily maximum temperature is 50° F. or higher.

2. Consistently high daily temperatures, averaging more than 70° F., are required for the development of an appreciable drought, starting from saturation. Because of this requirement, the opportunities for drought development are mainly limited to the period June-September in states along the Canadian border. The period lengthens to March-November in the southern tier of states from Florida westward.

3. Some degree of summer drought is normal in most areas of the country. This development has variable significance, depending upon the stage that is reached and whether or not deep duff fuels are present in the rating area.

In deep duff fuels, characteristic, for example, of the spruce-fir region of the Northeast, trouble with deep-burning summer fires (in the local vernacular, "those that go down") may be expected at stage 3; this problem becomes serious at stage 4 and extremely troublesome at stage 5. In the higher stages of drought, small fires of an acre or less may require the attendance of a pumper crew for a week or longer before they are completely extinguished.

A further word of explanation is needed to make clear the significance of the drought index in the spruce-fir region. The direct association of deep burning fires and costly suppression with high drought conditions is well understood. But these fires will not necessarily be major fires. Often the summer season is characterized by subnormal, but well-distributed, rainfall. In such seasons the drought index climbs persistently upward because there is little net rain. However, the buildup and spread indexes of the National System may remain low. Under these conditions, the upper litter layer, represented by the buildup index, will be relatively moist, and with little wind, the fires that start move slowly, but burn deeply, creating a potentially dangerous situation. Given a week or two of warm, dry weather, the buildup index will rise. Then may come a windy day, when all indexes are high, and the stage is set for such devastating high-intensity fires as occurred in Maine in the fall of 1947 and the summer of 1952.

4. Drought conditions in the fall or winter result from prior development during the preceding summer. In the Southern Appalachians, drought stages of 3 or 4 are to be expected in the fall of most years. Fall fires are persistent in that region, but the usual careful preparation of firelines is sufficient to contain the burning perimeter, once the forward spread is stopped. In years when the fall drought reaches the fifth and sixth stages, however, normal fireline preparation is not enough. Instances of fires escaping under firelines through dead roots or buried tree limbs a foot or more beneath the mineral soil surface were reported in the Southern Appalachians during the fall seasons of 1952 and 1953.

5. The significance of the drought index changes from the deep duff country to areas of lighter fuels. In deep fuel areas it is important to know when drought starts to build up; thus, fire control managers in these areas are interested in all stages of drought. In light fuel areas, such as those where the litter and duff average considerably under 10 tons per acre, the lower stages of drought are less important. In such areas the drought index described here may not be an important factor in fire suppression until it reaches the upper half of the scale. There are several possible exceptions to this generalization about the nonimportance of the lower half of the scale in light fuel areas. For instance, in areas where a certain stage of drought is associated with the incidence of crown fires or with the development of grassland curing. Although these possible associations are worth considering, they were not studied in the preparation of this report.

APPENDIX

THE THEORY OF SOIL MOISTURE DEPLETION IN WILDLAND AREAS

The following analysis presents the physical theory and general framework for a drought index which should function throughout a wide range of climatic and rainfall conditions in forested or wildland areas. At the present time there are gaps in our knowledge of the precise form of the relationships between certain variables. These gaps may take several years to fill. Meanwhile, if the essential physical concepts and theory can be developed, the gaps can be replaced by effective assumed relationships. Such assumptions will permit the use of an index, or method for estimating drought, during the time in which more data are being obtained and with little subsequent change required in the general system.

In developing the equations which describe the degree of drought or moisture deficiency which exists in a forested or wildland area, it will be assumed that:

1. From the standpoint of fire control, the significant moisture relationships are those which exist in an upper layer of soil and a covering layer of duff. The field capacity of the soil-duff layer will be taken as 8.0 inches of water in excess of the moisture which the layer holds at the wilting point. For a heavy soil at field capacity, 8.0 inches of free water would require a soil layer about 30 to 35 inches deep. In a lighter sandy soil the depth would be somewhat greater.

2. The soil-duff layer gains moisture from rainfall and loses moisture by evapotranspiration. Its lowest level of moisture content occurs at the wilting point.

3. The evapotranspiration rate will be a function of the weather variables and the vegetation density.

4. The vegetation density, and hence the rate at which the vegetation can remove moisture from the soil-duff layer when the weather variables are constant, is a function of the amount of mean annual rainfall. This rate will be characterized by a single parameter defined as the evapotranspiration timelag.[3]

5. As a first approximation, simple exponential functions can be used to express the relationships between essential variables in the basic equations.

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[3] The tendency of vegetation to adjust to the rainfall of a given area is discussed by Tannehill (1947, pp. 39, 67).

If the weather variables which affect transpiration such as temperature, relative humidity, and sunshine are constant, and if the rate at which the soil-duff layer loses water is directly proportional to the amount of water in the layer, then an equation can be written in the form

$$w = w_c \exp(-\tau/t) \tag{1}$$

in which

w = the inches of water available for plant use in the soil-duff layer,

w_c = the corresponding field capacity in inches of available water in the layer,

τ = the time in days during which the soil-duff has been losing moisture, and

t = the evapotranspiration timelag in days (the time required for the moisture content of the soil-duff layer to drop to $1/e$ of its initial value, where e is the base of natural logarithms).

Equation (1) is the basic equation in the analysis and is identical to that given by Liacos (1962) for soil moisture depletion in a layer 90 cm. deep in grassland plots. He discusses briefly the work of several other investigators who also found exponential depletion curves for different types of vegetation cover. Their results are also in agreement with the statements of Thornthwaite (1948) on soil moisture depletion. However, agreement on this point is not unanimous; Veihmeyer and Hendrickson (1955) suggest a linear type of depletion curve.

The next step in the development of the equations is to establish a relationship between the evapotranspiration timelag t, the temperature T (maximum daily temperature will be used), and the mean annual rainfall R. This part of the analysis will depart considerably from the procedures of other investigators. It will be assumed that a functional equation can be written in the form

$$1/t = f(R, T) \tag{2}$$

where t is the evapotranspiration timelag for maximum daily temperature T in a vegetated area for which the mean annual rainfall is R inches per year. Vegetation density does not appear in this equation because, in accordance with assumption 4 above, this variable is a function of R. It is simpler to write the left member of Equation (2) as $1/t$ instead of t because at a given moisture content the evapotranspiration rate varies directly as $1/t$. Other factors such as latitude, slope and aspect, and probably soil type, affect vegetation density; but it will be assumed that their effects are small compared to that of rainfall. Perhaps more questionable is the apparent omission of sunshine intensity, wind, and relative humidity from Equation (2). However, as a first approximation, it will be assumed that over a period of time Equation (2) will reflect the mean contribution of these variables.

The next step is to write Equation (2) in a more restricted form,

$$1/t = f_1(T)f_2(R) \tag{3}$$

in which f_1 and f_2 are functions which for the time being can remain undetermined. Equation (3) is illustrated by the curves in figure 7 in which t is shown as a function of R for two different values of T. Since there would be no vegetation for $R = 0$, it might appear that $t \rightarrow \infty$ as $R \rightarrow 0$. However, there would still be evaporation which would require finite values of t as $R \rightarrow 0$. Also, that region of the t curve in which $R \rightarrow 0$ can be regarded as a mathematical extrapolation from the region in which a definite relation exists between t and R. An analogous situation exists in the region where $R \rightarrow \infty$. This region is best interpreted as that for which the root systems of the vegetation have access to free water. Probably 150 inches of well-distributed annual rainfall could be considered "infinite" for the middle latitude regions. Thus, for any given value of T, the timelag t should approach a limiting value as R becomes very large.

The equation for estimating the daily decrease in the available moisture (that is, the daily increment in moisture deficiency) can be found from Equations (1) and (3). Taking the logarithm of both sides of Equation (1), differentiating with respect to τ, and combining with Equation (3), gives

$$\frac{1}{w}\frac{dw}{d\tau} = \frac{-1}{t} = -f_1(T)f_2(R) \tag{4}$$

Taking the logarithm of both sides of this equation gives a form suitable for solution by slide-rule methods. This form is

$$\log(-dw) = \log w + \log f_1(T) + \log f_2(R) + \log d\tau \tag{5}$$

The moisture deficiency Q will be defined by the equation

$$Q = w_c - w$$

from which

$$dw = -dQ$$

Equation (5) can thus be written in the form

$$\log dQ = \log(w_c - Q) + \log f_1(T) + \log f_2(R) + \log d\tau \tag{6}$$

Equations (4), (5), and (6) are alternate general forms of the desired drought equation. None of these equations, however, can be used for numerical computations of dQ (or -dw) until $f_1(T)$ and $f_2(R)$ have been determined and the associated constants evaluated. Considerable information is available for estimating the form of $f_1(T)$, but little is known about the precise form of $f_2(R)$. However, for the purpose of first approximation, a preliminary equation will be derived for $f_2(R)$. When more information is available, new calculations based on a more precise form of this function can be readily obtained with no change in the procedure or form of the results.

In determining the functions $f_1(T)$ and $f_2(R)$, it is desirable to write the evapotranspiration timelag t with the more specific notation t_{T_1R}. For example, $t_{80,50}$ represents the timelag t for a daily maximum temperature of 80° F. in a region where the mean annual rainfall is 50 inches. Differentiating Equation (1) with respect to τ, gives for the evapotranspiration rate $dw/d\tau$:

$$\frac{dw}{d\tau} = \left(-w_c/t\right) \exp(-\tau/t)$$

Letting $\tau = 0$ and changing to the specific notation results in

$$\left(\frac{dw_{T,R}}{d\tau}\right)_{\tau = 0} = -w_c/t_{T,R} \tag{7}$$

The left member of this equation is the evapotranspiration rate at $\tau = 0$ and is equivalent to a quantity usually defined as the potential evapotranspiration rate. This quantity represents the rate for a saturated soil and is shown as a function of T in figure 8. The curve in this figure was plotted from tabulated values given by Nelson (1959)[4] which in turn were based on the work of Thornthwaite (1948) and the data of Moyle and Zahner (1954). The vegetation density (and hence the value of R) corresponding to the curve in figure 8 is not precisely known, but it will be assumed that R is 50 inches per year.

If two equations are formed from Equation (7), one with $T = T$ and the other with $T = T_o$ and with R having the same value in both equations, then their ratio can be expressed as

$$\frac{t_{T,R}}{t_{T_o,R}} = \left[\frac{dw_{T,R}}{d\tau} \Big/ \frac{dw_{T_o,R}}{d\tau}\right]^{-1}_{\tau = 0} \tag{8}$$

where T_o is some reference temperature. Forming similar ratios from Equation (3) and holding R constant in any given ratio, yields

$$\frac{t_{T,\infty}}{t_{T_o,\infty}} = \frac{t_{T,0}}{t_{T_o,0}} = \frac{t_{T,R}}{t_{T_o,R}} = \left[\frac{f_1(T)}{f_1(T_o)}\right]^{-1} \tag{9}$$

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[4] An extensive list of 28 references on drought, soil moisture, and vegetation-soil moisture relationships is cited in Nelson's paper.

because $f_2(R)$ cancels out. Thus, a comparison of Equation (8) with the last of Equations (9) shows that the function of $f_1(T)$ is directly proportional to the potential evapotranspiration rate for a given value of R (that is, for a given vegetation density).

The form of the relationship represented by Equation (3) and illustrated by the curves in figure 7 may not be precisely known for several years. Meanwhile, it is necessary to approximate the relationship with an empirical equation which seems reasonable and is consistent with the basic physical concepts involved. For this purpose, it will be assumed that Equation (3) can be approximated by the exponential equation

$$t_{T,R} - t_{T,\infty} = K \exp(-aR)$$

in which a is a constant and K is a function of T only. However, when $R = 0$, then $t_{T,R} = t_{T,0}$, and therefore $K = t_{T,0} - t_{T,\infty}$. Thus, it follows that

$$y = y_0 \exp(-aR) \tag{10}$$

where

$$y+1 = \left(t_{T,R}\right) / \left(t_{T,\infty}\right)$$

and

$$y_0+1 = \left(t_{T,0}\right) / \left(t_{T,\infty}\right)$$

The curve in figure 9 shows y+1, or the ratio $\left(t_{T,R}\right) / \left(t_{T,\infty}\right)$, plotted as a function of R. Substituting the value of $t_{T,\infty}$ from Equation (9) into Equation (10) gives

$$t_{T,R} = \left[t_{T_0,\infty}\, f_1(T_0) / f_1(T)\right] \left[1+y_0 \exp(-aR)\right]$$

where t is written with the appropriate subscripts for the specific notation form. A comparison of this equation with Equation (3) shows that $f_2(R)$ can be regarded as the quantity

$$f_2(R) = \left(t_{T_0,\infty}\, f_1(T_0) \left[1+y_0 \exp(-aR)\right]\right)^{-1} \tag{11}$$

Equation (4) can now be written in the form

$$\frac{1}{w_c - Q} \frac{dQ}{d\tau} = \frac{f_1(T)}{t_{T_0,\infty}\, f_1(T_0) \left[1+y_0 \exp(-aR)\right]} \tag{12}$$

in which $w_c - Q$ has replaced w.

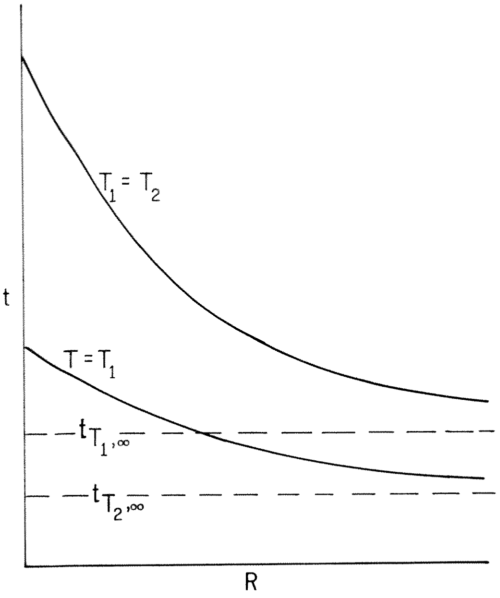

Figure 7.--The possible relationship between the evapotranspiration timelag t, the daily maximum temperature T, and the mean annual rainfall R. The line $t = t_{T_1,\infty}$ represents the timelag for $T = T_1$ and $R = \infty$ and is an asymptote for the curve for which $T = T_1$. Likewise, the line $t = t_{T_2,\infty}$ is an asymptote for the curve for which $T = T_2$.

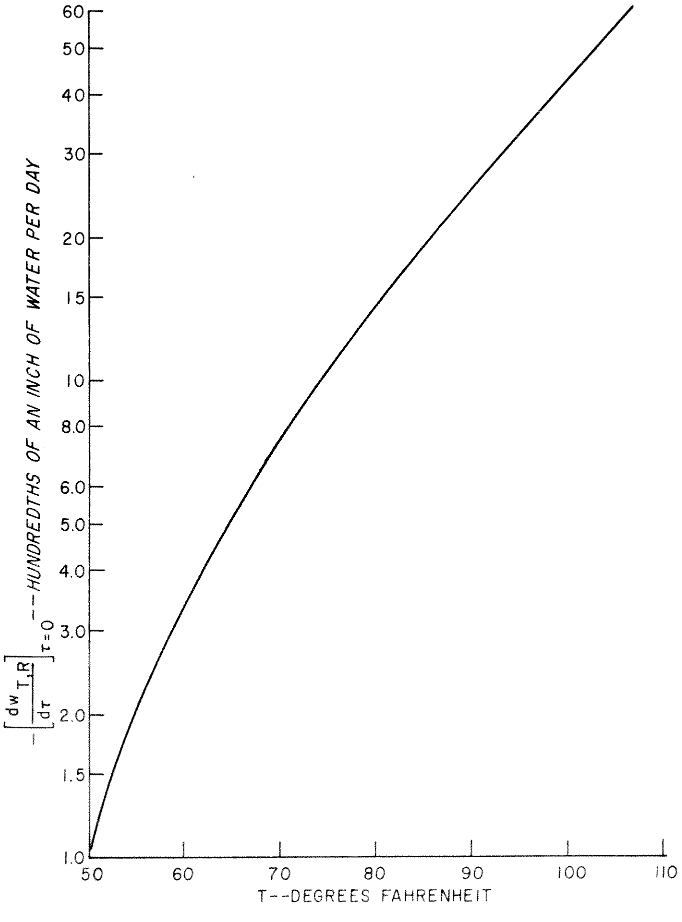

Figure 8.--Daily potential evapotranspiration as a function of maximum daily temperature.

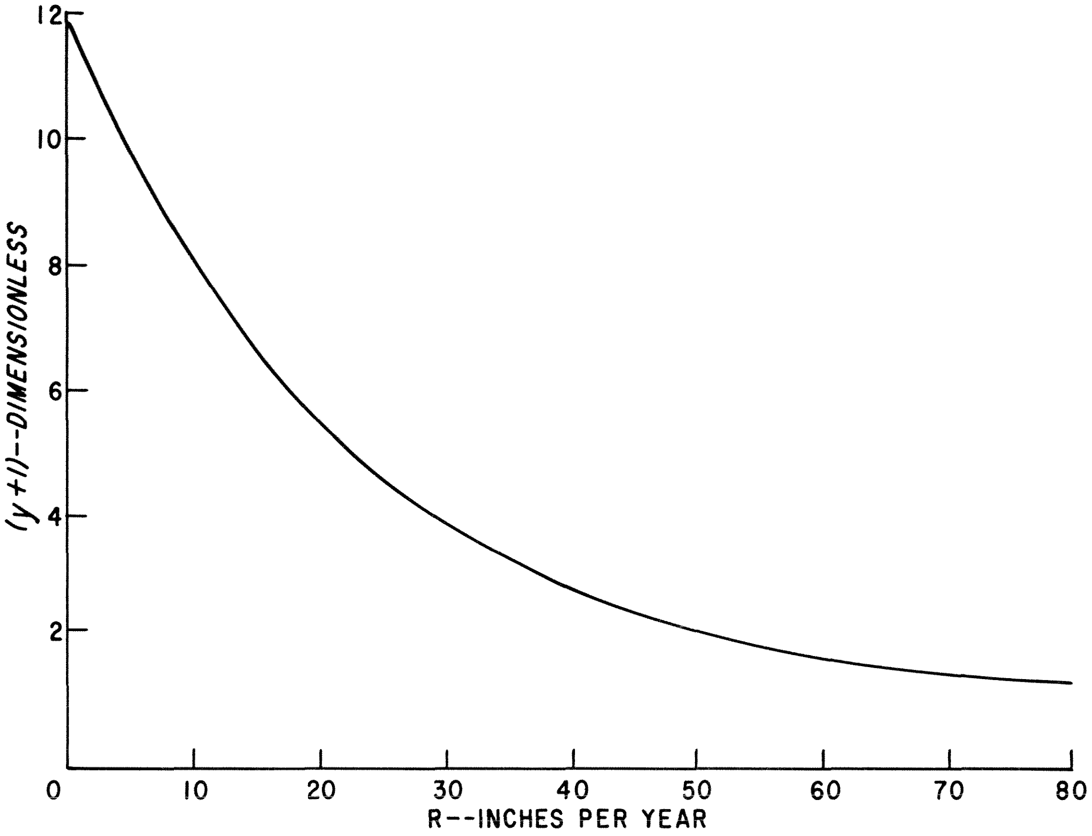

Figure 9.--The relationship between the dimensionless quantity (y+1) and the mean annual rainfall R.

In the range from T = 50° F. to T = 110° F., the potential evapotranspiration rate curve in figure 8 can be closely approximated by the empirical equation

$$-\left[\frac{dw_{T,\,50}}{d\tau}\right]_{\tau\,=\,0} = .352\ \exp(.0486T) - 3.015 \tag{13}$$

the units of which are in hundredths of an inch of water per day. From Equations (8) and (9) it follows that

$$\frac{f_1(T)}{f_1(T_o)} = \left[\frac{dw_{T,\,R}}{d\tau}\bigg/\frac{dw_{T_o,\,R}}{d\tau}\right]_{\tau\,=\,0} \tag{14}$$

The potential evapotranspiration ratio in the right member of this equation will be the same for all values of R; hence it can be expressed in terms of the curve in figure 8 or Equation (13). If the reference temperature T_o is set at 80° F., then Equation (13) gives a numerical value of -14.18 hundredths of an inch per day for the potential evapotranspiration rate. This is also the value of the denominator of the ratio in the right member of Equation (14) when R = 50 inches per year. Hence, combining Equations (13) and (14) gives

$$f_1(T) \big/ f_1(T_o) = .02481 \exp(.0486T) - 2.113 \tag{15}$$

The values of the constants $\underline{a}$ and y_o in Equation (10) will eventually have to be determined by experiment, but tentative values can be found by assuming values of y for two different values of R in Equation (10). For example, if y = 7 when R = 10 inches per year and if y = 1.2 when R = 50 inches per year, then $\underline{a}$ = .04409 years per inch and the dimensionless constant y_o is 10.88.

The last constant which must be evaluated in Equation (12) is $t_{T_o, \infty}$. The first step in this procedure is to form two equations from Equation (3), one with R = R and the second with R = R_o. If T is the same in both equations, then it follows from Equation (11) that the ratio of the two equations is

$$\frac{t_{T,R}}{t_{T,R_o}} = \frac{f_2(R_o)}{f_2(R)} = \frac{1 + 10.88 \exp(-.04409R)}{1 + 10.88 \exp(-.04409R_o)} \tag{16}$$

If R = ∞ and R_o = 50 inches per year, then Equation (16) gives

$$t_{T,\infty} = .4545\, t_{T,50} \tag{17}$$

On combining Equations (13) and (7) and solving for $t_{T,50}$ one obtains when R = 50 inches per year

$$t_{T,50} = \frac{w_c}{.352 \exp(.0486T) - 3.015}$$

When T = T_o = 80° F. (arbitrarily chosen as the reference temperature) and w_c = 800 hundredths of an inch of water, then, from the above equation, $t_{80,50}$ = 56.41 days. Hence, from Equation (17), it follows that $t_{80,\infty}$ = 25.64 days. Expressing Equation (12) in terms of the evaluated numerical constants with only dQ in the left member gives

$$dQ = \frac{[800-Q]\,[.968 \exp(.0486T) - .830]\, d\tau}{1 + 10.88 \exp(-.0441R)} \times 10^{-3} \tag{18}$$

the form of the equation needed for computing the drought factor dQ. This computing is most conveniently done on a daily basis in which case the time increment $d\tau$ is placed equal to 1 day. Special slide rules based on the logarithmic form of Equation (18) can be used to obtain rapid solutions of this equation, although the tables given in the main body of the report are probably best for routine use.

In the derivation of the basic equations, the fuel layer has been included with the soil. In the setting of w_c at 8.0 inches of water, it is assumed that w_c refers both to the soil and to the fuel layer. Some slight improvement might be obtained by treating the layers separately, but the procedure would be more complex. It is doubtful that any substantial improvement in drought evaluation can be obtained unless the soil and fuel zones are divided into a number of discrete layers and computer methods are used. Although such methods would permit the use of a larger value of w_c (possibly 15 or more inches of water), it is not likely that the improvement would justify the complexity of such a system at the present time.

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