16. CONCLUDING REMARKS

To a large extent this drought analysis method requires strict adherence to the procedures which have been described. Any radical departure from these procedures will produce values of Z which are incompatible with the equations for determining drought severity. However, there is no reason why one could not use a different method for computing potential evapotranspiration. Any method of monthly hydrologic accounting which is more refined and realistic than the method used here would likely produce as good or better results, but a cruder method might introduce bias or inconsistencies.

The method was specifically designed to treat the drought problem in semiarid and dry subhumid regions. Extrapolation beyond the circumstances for which it was designed may lead to unrealistic results. Some regions are so near to being a desert that there is really little point in attempting drought analysis. At the other extreme are the very humid regions where, again, "abnormal dryness" has very little meaning.

In conclusion, this method of climatic analysis must be regarded as only a step in measuring and describing meteorological drought. Real understanding can only follow measurement and description. Prediction and control await understanding.

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APPENDIX A.—AUXILIARY CLIMATIC INFORMATION

GEOGRAPHICAL DISTRIBUTION OF THE CLIMATIC CONSTANTS

The analytical technique described in this paper is rather long and tedious. The large amount of work required stems largely from the necessity for carrying out the hydrologic accounting for a long series of years in order to compute the five constants that are required for each calendar month. However, once the constants have been determined, a current drought analysis can be carried out without reference to a long historical record. If present plans can be carried out, the historical record will be analyzed for a network covering the United States. From these machine analyses 60 maps will be prepared showing each of the five constants for each calendar month.

Maps of α, the coefficient of evapotranspiration, should provide a reasonably good delineation of the agricultural capabilities of various "systems," where a system represents a particular combination of precipitation, temperature, and soil.

Likewise, from a study of maps of δ, the coefficient of soil moisture loss, one could, with some additional work, mathematically demonstrate the advantages of cultural practices which increase the available water capacity of some soils.

DISTRIBUTION OF THE MOISTURE DEPARTURES

Table 22 shows the moments of the distributions of the moisture departures for each calendar month for the three areas studied. As one would expect, the standard deviation, σ, shows that the greatest dispersion occurs during the summer months. Note the secondary minimum during July in central Iowa.

In order to test the distributions for normality, two statistics, α_3 and a, which are measures of skewness and flatness have been computed. α_3 is the standardized third moment and $a = \Sigma|d|/n\sigma$ is a measure which is highly correlated with the fourth moment [46]. On comparison of these values with Geary and Pearson's table [15] it is seen that the number of a values which fall outside the 5 percent limit is approximately the same as the number which would be expected by chance or if there were no departure from normality.

However, these distributions show a rather large amount of skewness. This is indicated by the disproportionately large number of α_3 values which exceed the 5 percent limit. This skewness is partly a result of the fact that the moisture

TABLE 22.—*Moments of the departures, d*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May to Aug.
WESTERN KANSAS													
n	71	71	71	71	71	71	71	71	71	71	71	71	71
$\bar{d}$	0	0	0	0	0	0	0	0	0	0	0	0	0
$\sigma(d)$	.35	.56	.87	1.38	1.65	2.06	1.93	1.44	1.21	1.20	.77	.60	5.54
$\alpha_3(d)$	1.321	1.234	.721	.786	.447	.435	.320	.643	.203	1.814	1.526	2.353	.624
$a(d)$	.753	.767	.821	.778	.813	.802	.789	.767	.815	.704	.746	.672	.784
NORTHWESTERN NORTH DAKOTA													
n	30	30	30	30	30	30	30	30	30	30	30	30	30
$\bar{d}$	0	0	0	0	0	0	0	0	0	0	0	0	0
$\sigma(d)$	.25	.30	.42	.87	1.34	2.05	1.21	1.04	1.30	.72	.47	.25	4.57
$\alpha_3(d)$	.173	.822	.640	−.436	−.115	1.172	.176	.259	1.573	.689	.822	.992	.204
$a(d)$	.801	.759	.796	.773	.779	.720	.779	.782	.701	.813	.809	.747	.758
CENTRAL IOWA													
n	27	27	27	27	27	27	27	27	27	27	27	27	27
$\bar{d}$	0	0	0	0	0	0	0	0	0	0	0	0	0
$\sigma(d)$	.91	.84	1.11	1.63	2.22	2.67	1.47	2.46	2.03	1.50	1.65	.94	5.99
$\alpha_3(d)$	−.049	−.617	.496	.473	−.194	.571	−.282	.807	.318	.746	.636	.302	.325
$a(d)$	.805	.784	.812	.853	.808	.711	.762	.808	.820	.745	.804	.789	.860

departure distribution has the precipitation distribution as a component. Precipitation is rather skewed because it has a lower bound of zero. The skewness in the moisture departures results in a few occurrences of large departures, especially large positive departures.

Since the addition of non-normal distributions produces a distribution which approaches normality, the "summer months," May through August, have been combined to produce a single climatological series for each of the three areas. The moments for these three distributions of total moisture departure for the 4-month period are shown in the last column of table 22. On referring to Geary and Pearson's table one finds the values of both a and α_3 are reasonably close to their expected value in a normal distribution. From these tests it was concluded that the normal distribution could be used to represent the 4-month moisture departures.

The mean and the standard deviation contain all the information needed to estimate the normal distribution in the population from a normal sample. In the samples with which we are dealing here the mean is zero. This is very convenient inasmuch as one must determine only the standard deviation in order to estimate the probability that any particular moisture departure will be exceeded during this 4-month period. It therefore seems likely that a map of the standard deviation could be prepared as soon as a sufficient number of areas have been analyzed and that the map would be all that is required in order to prepare probability statements concerning the "summer" moisture departures. Such information might be very useful for the planning of hydrologic structures.

It may well be that for crop yield investigations the moisture departure, d,—for the appropriate phenological periods—is the most useful variable in this study. For instance, the moisture departure in June 1961 in northwestern North Dakota was -3.69 in. This very abnormal moisture deficiency during a critical month was the most important variable responsible for the much below normal wheat yields in that area. Of course the moisture variable is only one of the factors affecting crop yields, but in the drier regions it is one of the most significant. In the wetter areas, such as central Iowa, yield reductions may often be related to the positive moisture departures at planting and harvesting times.

APPENDIX B.—EFFECT OF THE AVAILABLE WATER CAPACITY TERM

PURPOSE OF THE *AWC* VALUE

As mentioned earlier in this paper, the computed soil moisture is used primarily as a device for taking account of antecedent weather. It allows one to derive a number which is regarded as an index of the amount of previously stored water available for future use. If the assigned available water capacity is too small, we tend to underestimate the amount of water in storage. On the other hand, too large an available capacity will, in humid climates where runoff is large, lead to an overestimation of the supply of water available. That is, the computations will show water in storage for some time after the actual supply has diminished to the point where the local economy is beginning to suffer. In semiarid regions the *AWC* value is not so critical, and little difficulty is introduced by assuming too large a value for *AWC* in such areas of little runoff.

EXPERIMENTS AT DOVER, DELAWARE

While it has been known all along that reasonable final results required the use of a fairly realistic value for *AWC*, it was not entirely clear as to the effect on the drought index of using an unrealistic *AWC* value. Therefore, we analyzed a 44-yr. period of Dover data, with assumed values of *AWC* of 2.0 in., 4.0 in., and 8.0 in. That is, the complete analysis from water balance bookkeeping through the final drought index values was carried out three times, the only difference being the assigned value of *AWC*. Apparently, somewhere around 4.0 to 6.0 in., could be considered as realistic for that area.

Results were somewhat unexpected. The analysis using $AWC = 2.0$ in. produced a maximum drought severity index of -3.45, thereby indicating that extreme drought never occurred during this 44-yr. period. The analysis using $AWC = 4.0$

in. gave a maximum drought severity index of −4.51, and *AWC* =8.0 in. gave a maximum index of −6.17. When one recalls that the driest year in 30 years was to be used to define extreme drought, it is apparent that either this 44-yr. period was a very biased sample or the assigned *AWC* value of 2.0 in. was somehow limiting the method.

EFFECT OF UNREPRESENTATIVE *AWC* VALUES

Why should an *AWC* value that is too small tend to limit the method's capability for showing large departures from normal? If, for the moment, we assume a ridiculously small value for *AWC*, say 0.10 in., it is apparent that the main effect is a loss of the capability for taking account of antecedent weather. One dry day or one completely dry year will produce the same result, viz, no water in storage. Likewise, a wet day or a wet year will produce full storage. In either instance the system is no longer capable of taking adequate account of past weather. As the assigned storage becomes smaller and smaller, we begin to lose a part of the basis for estimating the amount of rain needed. Finally, all estimates will tend to lie very close to the normal precipitation itself, irrespective of the dryness or wetness of the past. Large values of the moisture departure (the *d* values) are therefore ruled out, which also rules out large drought index values.

If, in humid climates, the assigned storage capability is too large, rather than too small, it will allow insufficient runoff during wet periods, introduce fictitious water supplies and over-optimistic expectations during dry periods, and thereby tend to make the area appear more humid than it actually is. As a consequence, drought severity will tend to be somewhat inflated. It does not appear, now, that the consequences from the use of too large a storage capacity are as misleading as those stemming from the use of too small a storage capacity. Actually, the system is not as sensitive to this factor as this dissertation might suggest. In general, the Dover results for *AWC*=4.0 in. and *AWC*=8.0 in. were very similar. It was only the results from using *AWC* =2.0 in. that seemed to be markedly different.

AREAS WITH SMALL STORAGE CAPABILITY

What sort of results can we expect in an area—particularly a humid area—which actually has a rather small capability for storing water? In the first place, the analysis indicates that, as far as water is concerned, cumulative weather has little significance. This lack of an adequate moisture carryover capability makes it impossible to fully utilize the humid climate. Such an area has a water use expectation characteristic of a more arid climate which does have an adequate capability for the carryover of water. During periods of high moisture demand the small amount in storage is soon exhausted, and, even though the area is very dry, there is no expectation that a large moisture recharge will take place—in spite of the fact that the humid climate is capable of producing such a recharge. The outcome is that the full extent of the abnormal wetness or dryness of the climate cannot be completely utilized or taken into account; therefore, there is no opportunity for cumulative weather to build up to a point where the index indicates either extreme wetness or extreme drought.

In view of the "droughty soil" concept, this is a rather surprising development. However, if one recognizes that expectations are actually diminished by the lack of an adequate water storage facility, the reasonableness of the result is quite apparent. On a relative basis, an area which lacks an adequate capability for storing water is not as affected by prolonged dry weather as is an adjoining area which has this capability. This, too, may at first seem illogical; however, on a relative basis, it is true because the favored area is accustomed to and expects an adequate supply of water at all times. If the supply cannot meet the demand, a serious disruption of the economy takes place. On the other hand, the less-favored area is accustomed to frequent water shortages; the demands and operations are geared to the fact that water shortages are to be expected. Therefore, while drought may become apparent sooner in the area of little moisture carryover capability, it will never reach the peak severity that will, in time, occur in the more favored area. This interpretation seems to conform to reality, and this is the sort of result the drought index will show.

APPENDIX C.—ANALYSIS OVER OTHER TIME OR SPACE UNITS

WEEKLY ANALYSES

The foregoing discussion applies entirely to the use of monthly temperature and precipitation data as input. Inasmuch as monthly hydrologic accounting is a rather crude way of estimating the water balance [51] some experiments were conducted using weekly, and even daily, data as input.

It turned out that the daily accounting followed by weekly summarization and weekly drought severity computations introduced some difficulties, much unnecessary detail, and considerable expense without producing results which were appreciably different from those obtained from the use of weekly input data. This "daily-weekly" approach was soon abandoned.

As far as procedure is concerned, the weekly analysis was carried out by the same steps that were used in the monthly analysis. The main difference was that the long-term means of P, PE, etc. were computed for each of the 52 standard climatological weeks, whereas the monthly program requires such means only for the 12 months.

Originally, it had been estimated that the weekly constants and weekly equations could be derived from the monthly constants and equations. However, the problem is not that simple and the weekly work required the repetition of all the steps used to develop the monthly equations and constants.

Results.—Weekly analyses were compared with monthly analyses at two stations, Gothenburg, Nebr. and Ames, Iowa. The weekly system gave more detail; it came closer to pinpointing the time when events such as the beginning of a drought happen; and it allows one to keep up with a currently developing situation. But, overall results were, from a climatological standpoint, very similar to those obtained from monthly data with only a fraction of the work and expense.

Briefly, the weekly results and the monthly results were in agreement over 90 percent of the time; i.e., when one system indicated drought underway, the other system generally agreed. Also, the systems seldom disagreed by as much as 2 percent as to the percentage of time each class of drought (mild, moderate, etc.) existed. The two indications of maximum drought severity (62 cases) never differed by more than 0.7 of a drought class and the mean absolute difference was about 0.2 of a drought class. The average difference between the two indications of the time of occurrence of the most severe point in each of the 62 drought periods was about 11 days. In general, when the two sets of drought index values were plotted against time, the agreement looked very good, both at Ames and at Gothenburg.

Conclusions.—On the basis of the records analyzed from both weekly and monthly input data, it appears that results are not very much different. The weekly data provide more detail and apparently get just a little closer to a realistic measure, but for climatological purposes the differences are slight. The monthly analysis can be done manually without spending too much time. On the other hand, weekly analysis requires much more than four times as much work. Either could be done by machine, but of course it costs more to do the job by weeks. Also, weekly data are not readily available either in published form or on punch cards. One main advantage of weekly analysis is that it enables one to keep up with a current drought.

However, it has been found possible to accomplish much the same "weekly" result by using the monthly system in such a way that the middle of the monthly interval successively moves ahead by about one-fourth of a month. That is, drop the first 8 days of the month, add the first 8 days of the next month and compute on the basis of the new "month", etc. The coefficients for the midpoints of these new "months" can be graphically determined from a plot of the previously computed monthly coefficients. This procedure requires that one carry on 3 *independent* sets of "monthly" analyses in addition to the regular monthly analysis. This scheme is not as difficult as it seems and it does enable one to keep up with a currently developing drought situation and to capture some of the detail that is lost in a regular monthly analysis.

POINT VERSUS AREA ANALYSIS

Although this method of drought analysis is based on areal data, it is of interest to determine its applicability to single station data within the area. Studies have been made for a few points, but at this writing there is only one area-single point comparison which is available.

Since only one case (in Iowa) has been analyzed, it must be realized that the results are tentative. The conclusions are that the analysis at a point tells one a good deal about the weather and climate of a sizable surrounding area. This is, of course, not so true in more rugged terrain. Likewise, areal analysis gives a fairly good picture of the dry and wet periods at points within the area. For climatological purposes areal analyses are probably adequate, and it is likely that future work will be concentrated on areal analyses.

APPENDIX D.—RELATIVE INSTABILITY OF THE CLIMATE OF WESTERN KANSAS SINCE THE EARLY 1930'S

If one accumulates the monthly values of d or Z for western Kansas and plots them against time, the curve shows rather a large amplitude since the early 1930's as compared to the preponderance of relatively small oscillations in the previous years. Of course, the index values in table 13 show the same sort of thing. Prior to 1932 a fairly sizable number of months show an index value indicating near normal or only an incipient wet or dry condition. However, since 1932 small index values are rather rare.

This can be demonstrated in a crude fashion by counting the number of months with $|X| < 1.0$ each year and plotting the cumulative total against time. Such a plot appears in figure 7.

This figure shows that the period 1887 through 1932 was *not* marked by numerous large anomalies. At the end of this 46-yr. period, 223 months, about 5 per year, had had small index values. In other words the weather was definitely abnormal only 60 percent of the time.

However, since 1932 the climate has been noteworthy for the absence of near-normal weather. In fact, more than 11 months per year have produced either drought or unusually wet conditions. It is easy to see how the area gained its "feast or famine" reputation in recent years.

Unfortunately, there is no handy explanation for this apparent shift in the frequency of abnormal weather. It may continue and it may not. The warming trend in mean annual temperatures in the latitude zone 40° to 70° N. seems to have come to an end at about this time [32]. Also, an apparent increase in the frequency of tropical storms in the north Atlantic began in the early 1930's [8]. Are these various events coincidental? Probably not, but we simply do not yet know enough about the fundamentals of atmospheric actions and interactions really to explain what, if anything, has taken place. Only when such things can be adequately explained will there be hope for prediction on a time scale measured in years or decades.

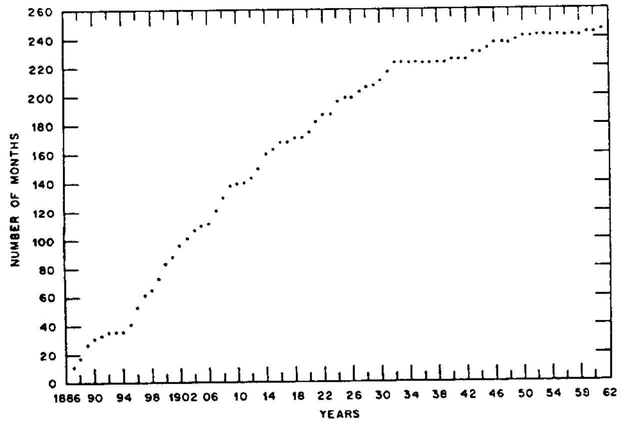

FIGURE 7.—Cumulative annual number of months with $|X| < 1.0$, western Kansas.

APPENDIX E.—RECURRENCE OF SERIOUS DROUGHT IN WESTERN KANSAS

Although no effort was made to discover "cycles of drought," the relative regularity of the occurrence of severe and extreme drought in western Kansas is rather striking. From table 13 one can see that the index indicated extreme drought in 1894, 1913, 1934 (and following years), and in 1954 (and following years). These four fairly regularly spaced occurrences of extreme drought may be accidental. However, when one recalls that the discussion of the drought of 1913 [17] mentioned damaging drought in 1874 and in the early 1850's, there appears to be sufficient evidence to lead one to speculate concerning the possibility that an extreme drought will again occur in western Kansas sometime between 1972 and 1975. We have no basis or method for estimating the probability of such an occurrence, but one could reasonably think it may be greater than the 6 percent probability of extreme drought shown in table 17.

It is interesting to note that Tannehill reached a similar conclusion in 1954 [44]. In a study of the long-range prospects for rainfall in the United States he concluded that ". . . another dry cycle in this country should begin near the middle of the 1970's, probably in 1975." Tannehill, too, was concerned with the occurrence of widespread, disastrous drought, the sort of thing that produces dustbowls and dry reservoirs.

The only thing that seems to be certain is that future years will sooner or later bring a recurrence of extreme drought in the area. The question is, when? On the basis of past history the early 1970's may be years one might well anticipate.

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