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CLIMATIC RESEARCH IN THE SOIL CONSERVATION SERVICE

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[Soil Conservation Service, Washington, D. C., December 1938]

INTRODUCTION

While accelerated soil erosion resulting from the misuse of land has been occurring in the United States since colonial days, it remained for the disastrous duststorms of the early 1930's, the acute agricultural problems in the Southeast, and the problems arising from overgrazing in the West to bring to the attention of the country as a whole the fact that soil has been and is being destroyed at an alarming rate. For some areas this realization has come almost too late. Thus, in such regions as the southeastern United States, the problem has become one not only of soil conservation but of soil regeneration as well.

The realization that soil erosion in the United States had become so serious that it could not be controlled by private or local agencies came at the time of an acute unemployment crisis and in 1933 led to the establishment of the Soil Erosion Service in the Department of the Interior to carry out those provisions of the National Industrial Recovery Act which related to the prevention of soil erosion.

For a number of years, research dealing with the problems of soil erosion had been carried on in a small way by certain State agricultural colleges, and by a few bureaus of the Department of Agriculture, notably Chemistry and Soils, Agricultural Engineering, Plant Industry, and the Forest Service. Several soil erosion experiment stations were being operated by the Bureau of Chemistry and Soils in cooperation with Agricultural Engineering. At these stations the research consisted primarily of controlled experimentation and involved the setting up of run-off plots to determine amounts of soil loss and run-off from slopes of various grade and length on different soil types and under different conditions of plant cover. These experiments were excellent demonstrations of the severity of erosion and were an important factor in arousing interest in the problem. The station research also included experimental work on the design of terraces and on erosion-resisting crop rotations and cropping practices.

It was recognized by the Secretary of the Interior that there was need for further research, and in response to his request to the Science Advisory Board in March 1934, the Land Use Committee of the Board engaged Prof. Carl O. Sauer of the University of California to prepare specific recommendations leading toward expansion of research. In a memorandum dated April 26, 1934, the Committee calls attention to the urgent need of undertaking as a unit research dealing with the relations of surface, soil, and climate to erosion.[1]

It had been recognized that soil erosion was inseparably related to land-use practices and could be controlled only through regulation of these practices. Consequently, in the spring of 1935 the Soil Erosion Service was transferred from Interior to the Department of Agriculture. Shortly thereafter the Soil Conservation Service was established by act of Congress and soil-erosion activities of the various bureaus of the Department were consolidated within it.

In July 1935, pursuant to the recommendations of the Science Advisory Board, the section of Climatic and Physiographic Research was established. In developing this portion of the research program it was recognized that erosion is a geological process which is both normal and natural and which has been in operation since the first vapors condensed and fell upon the earth's surface. Although soil erosion is a relatively new process, being a consequence of man's misuse of the land, it is nevertheless a physiographic process initiated by the impact of climatic forces upon the earth's surface and is subject to the same physiographic principles as apply to erosion in general.

Experience has shown that it is neither possible nor desirable to separate erosion problems into a number of distinct minor problems which will conform to academic disciplines as we normally think of them. While it is necessary to invoke the aid of specialists, it is also necessary for such workers to transcend the limits of their own particular field, at least to the extent of being able to view and grasp the erosion problem as a whole.

For the climatologist, this has meant conducting his investigations with constant reference to experimental and field work. Climatic factors operating to produce erosion must actually be observed and studied in the field. In order to solve climatic problems presenting themselves in the field, existing climatic records must be examined and analyzed, additional data must be obtained wherever necessary, and where special problems demand the development of new techniques such must be devised. The ways in which these lines of approach have been utilized in the climatic work of the Soil Conservation Service constitutes the theme of this paper.

THE ROLE OF CLIMATE

Climate may be regarded as operating in two ways in affecting the amount and nature of erosion. On the one hand, the mechanisms of erosion, such as sheet-wash, gullying, mass-movement, and wind scour require water or wind for their operation and are also profoundly influenced by temperature conditions. The force with which these mechanisms operate is, in any given situation, directly related to climate. For example, generally speaking, the greater the amount of precipitation for any given time interval the greater will be the amount of erosion from running water. On the other hand, it is necessary to think of surface conditions—vegetation, soil, slope—as an integral part of the erosion complex, and to appreciate that similar storms will produce dissimilar erosion results in different regions because of variations in surface and cover. Under natural conditions the vegetation, soils, and land-forms of an area

[1] Sauer, Carl O., C. K. Leith, J. C. Merriam, and Isaiah Bowman. Preliminary Recommendations of the Land-Use Committee Relating to Soil Erosion and Critical Land Margins. Science Advisory Board, Washington, D. C., 1934.

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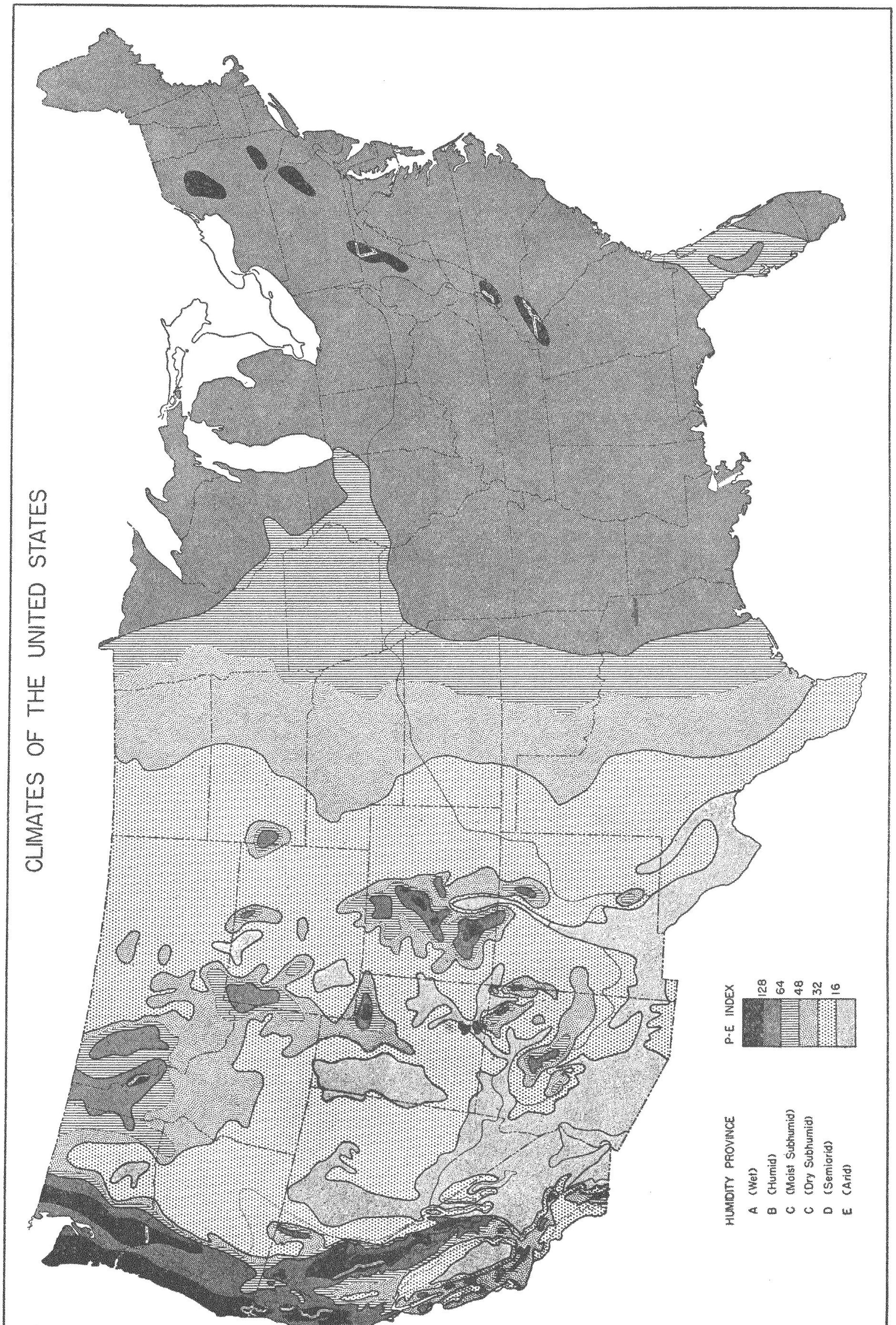

FIGURE 1.—Climates of the United States according to Thornthwaite's classification.

reflect to a large degree its climatic conditions; and even where man has engaged in farming, grazing, or lumbering, climatic influences on soil and slope and on the specific type of land utilization continue. The impact of climate, to a large extent, determines slope-soil-surface variations from region to region; and cannot be overlooked as a mode of approach to erosion problems.

CLIMATIC DELIMITATION OF EROSION REGIONS

In dealing with the climatic factors of erosion, the climatic classification has proved to be a useful tool. No classification of any body of knowledge is inherently right or wrong; rather it is more or less useful. In this instance it has been found that those climatic classifications that are oriented with specific reference to the distribution of natural vegetation and soils—such as those of Köppen [2] and Thornthwaite [3]—are of value in characterizing and differentiating natural regions (fig. 1). The areal coincidence of climatic, edaphic, and ecologic elements makes it possible to identify natural regions within which erosion problems are, in general, similar. Thus, the mesothermal humid area of the Southeastern United States is characterized by moderate to heavy precipitation, high rainfall intensities, long hot summers, short mild winters, heavy clay soils, and under natural conditions by forest vegetation. Because of high amounts and intensities of precipitation and because of the nature of the soil, the chief forms of erosion are gullying and sheet-wash. In the semiarid mesothermal southern Great Plains, wind erosion constitutes the chief hazard, and in the subhumid mesothermal summer-dry climate of California mass-movement assumes an important role. Similarly, the flood hazard is paramount in the humid microthermal region of New England, where snow melt contributes to the spring discharge of rivers.

Climatic classification has proved useful also for determining climatic risk to agriculture. In virtually all of the agricultural areas of the United States there have been occasional years when the climatic conditions were sufficiently adverse to cause total or partial crop failure. In some areas the climatic hazard is so great that crop failure is relatively frequent. If land abandonment does not result directly, it is brought about through crop failure as a consequence of soil depletion and wastage. By determining the type of climate that an area experiences during each year, or each season over a long period of years, the agricultural risk may be determined on an actuarial basis (figs. 2 and 3). Such information shows that some areas would profit by a change in crops or by reversion to grazing, and that other areas now being grazed should be allowed to return to their natural state. All such changes should be inaugurated before soil erosion becomes too severe and makes the land useless for any purpose whatsoever.

Especial care is required for land-use planning in climatic tension zones, such as the Great Plains, where the climate varies greatly from year to year. At Grant, Nebr., for example, the annual precipitation during the period of record ranged between a minimum of 9.47 inches in 1910 and a maximum of 35.84 inches in 1915. For the 17 scattered years, in which records are complete, the climatic types (following Thornthwaite's classification) were as follows: [4]

Humid 1, Moist subhumid 4, Dry subhumid 6, Semiarid 5, Arid 1. By obtaining such figures for the Great Plains and other critical regions the climatic risk can be determined. The works of Russell [5] and Thornthwaite [6] show that the determination of yearly climate serves as an effective basis for land-use planning.

It must be recognized that climatic risk analyses can be no better than the climatic classification on which they are based. Consequently, an important objective is to refine and readjust the method of classification so as to increase the value of contingent climatic risk studies. As long as climatologists appreciate the fact that such classifications are not an end in themselves, but rather convenient modes of synthesis, the need for this constant improvement will not be overlooked. In particular, when more satisfactory evaporation data are obtained, it will be possible to modify the Thornthwaite classification and render it more specifically applicable to erosion problems. This is one of the considerations that has stimulated the studies of evaporation being carried on at present and which will be discussed later.

SPECIFIC CLIMATIC FACTORS

Within a climatic region each climatic factor has its particular significance in the processes of soil erosion. The definitive recognition of these critical factors has been achieved by working inductively from field and laboratory information and by working deductively from a consideration of general physical principles. For example, one might reasonably assume that erosion amount is directly related to rainfall intensity. Actually, field experience has demonstrated that such a simplistic view of the problem is not justified. Research in the Piedmont area of South Carolina indicates that intense local showers are chiefly responsible for gullying and sheet wash while the gentle, long continuing general rains cause gully-caving and filling.[7] Lighter rainfalls tend to induce mass-movement as contrasted with more spectacular cutting or sluicing caused by rains of high intensity. This relationship between rainfall intensity and soil erosion involves type and extent as well as amount of erosion.

The climatologist dealing with the practical solution of the erosion problem cannot be satisfied with working merely in terms of "rainfall amounts." Precipitation components such as storm duration, area, and frequency require consideration similar to that accorded rainfall intensity. Likewise, the temperature factor must be analyzed in detail. The number of times the freezing point is crossed together with prevailing soil moisture conditions are of critical significance because of their bearing on weathering and frost action. Temperature relationships as they affect snow accumulation and melting are important in any consideration of flood and run-off problems. Wind velocity is still another critical climatic element. It is necessary to compare seasonal variations in velocity with the crop calendar in order to determine whether velocities are sufficiently high to constitute a hazard at those times of the year when the fields are plowed or left fallow.

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[2] Köppen, Wladimir. Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt, Geogr. Zeitschr., Vol. 6, pp. 593–611, 657–679, 1900; idem. Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf, Petermanns Mitt., Vol. 64, pp. 193–203, 243–248, 1918; idem. Die Klimate der Erde, Berlin und Leipzig, 1923. A new classification appears in Köppen-Geiger, Klimakarte der Erde (1:20,000,000), Justus Perthes, Gotha, 1928.

[3] Thornthwaite, C. Warren. The Climates of North America According to a New Classification. Geogr. Rev., Vol. XXI, No. 4, pp. 633–655, October 1931; idem. The Climates of the Earth. Geogr. Rev., Vol. XXIII, No. 3, pp. 433–440, July 1933.

[4] Thornthwaite, C. Warren. The Significance of Climatic Studies in Agricultural Research. Soil Sci. Soc. America, Proc., vol. 1, pp. 475–480, 1937.

[5] Russell, Richard Joel. Climatic Years. Geogr. Rev., vol. XXIV, No. 1, pp. 92–103, January 1934.

[6] Thornthwaite, C. Warren. The Great Plains. Chapter V in Migration and Economic Opportunity, Univ. Pa. Press, pp. 202–250, 1936.

[7] Ireland, H. Andrew, C. F. Stewart Sharpe, and D. Hoye Eargle. Principles of Gully Erosion in the Piedmont of South Carolina. U. S. D. A. Tech. Bull. No. 633, 1939.

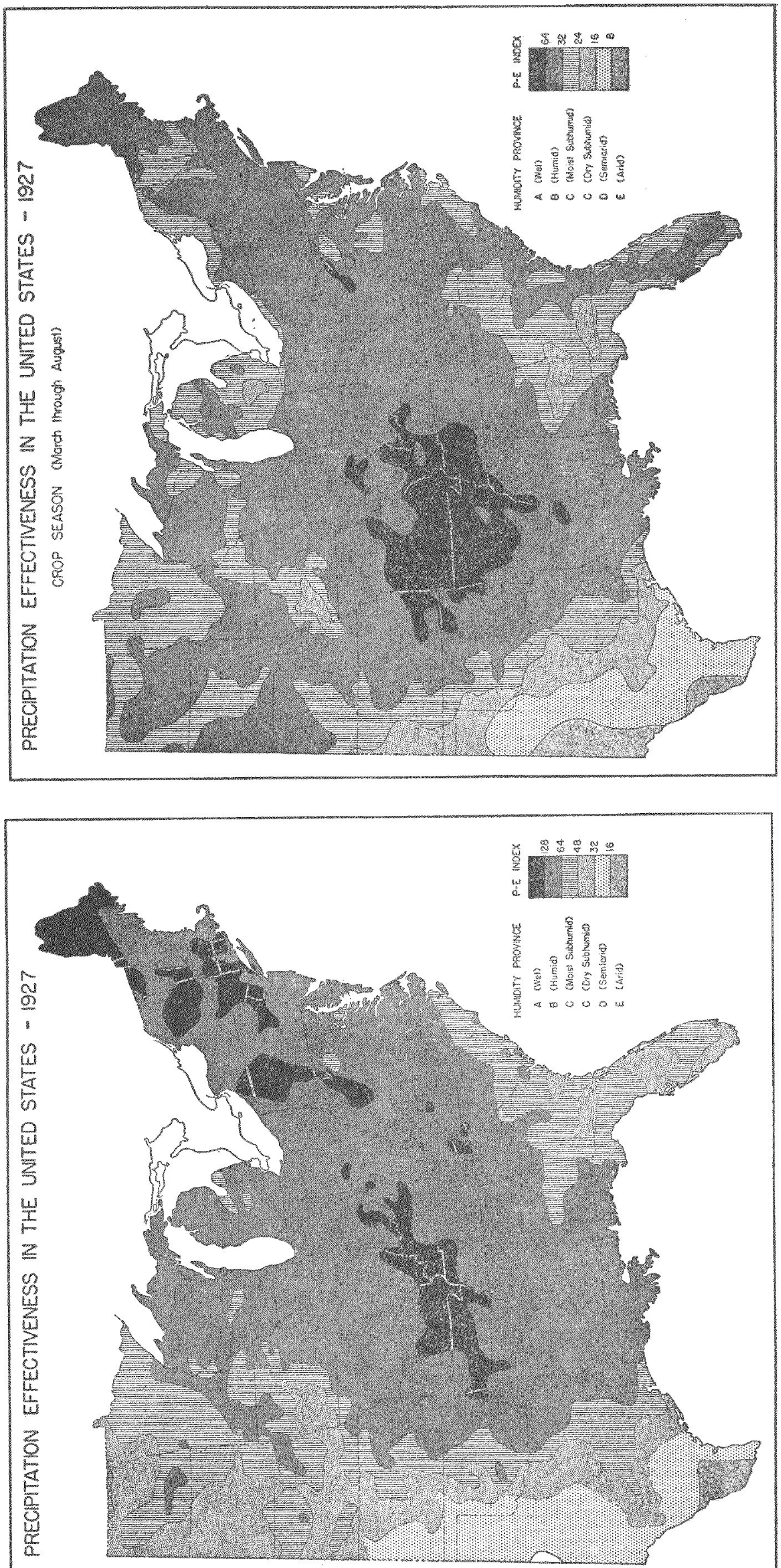

FIGURE 2.—Precipitation effectiveness for the year and the crop season of 1927 according to Thornthwaite's classification.

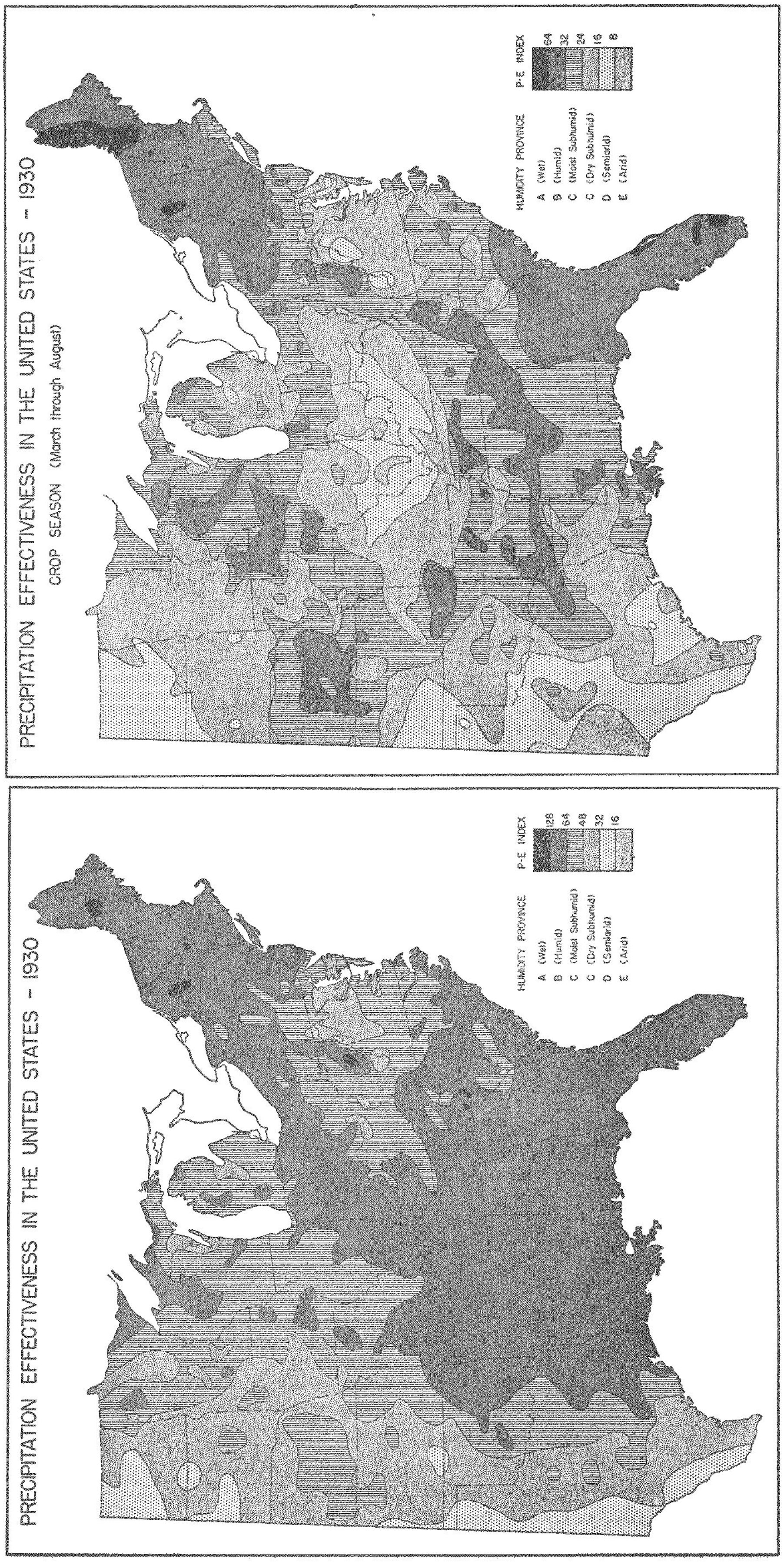

FIGURE 3.—Precipitation effectiveness for the year and the crop season of *1930* according to Thornthwaite's classification.

The statistical treatment of these factors through the analysis of Weather Bureau records comprises a type of climatic risk study. The problem becomes one of determining what rainfall intensities, storm durations, temperature variations, or wind velocities are to be expected in a given region during a specific period of time. Such investigations are related directly to particular erosion processes and land-use practices rather than to erosion or land utilization in general. In this respect they differ from the climatic risk studies associated with the classification of climates, but the two are complementary and integrally related.

Unfortunately, only two specific climatic factors, rainfall intensity and storm amounts of precipitation, have been treated in detail in the literature of climatology or hydrology. Hydrologists and engineers, faced with the necessity of estimating the maximum storage capacity of their reservoirs or disposal systems, have developed various methods of determining the frequency of specified amounts of precipitation. The most important of these are the Miami Conservancy District's study of storm amounts of rainfall [8] and Yarnell's [9] publication, "Rainfall Intensity-Frequency Data."

The Miami investigation utilized records from all first-order and cooperative Weather Bureau stations east of the one hundred and third meridian and, dividing the eastern United States into quadrangles 2° square, applied the station-year method in preparing expectancy figures. In brief, this method assumes that if there are x stations in a given area of assumed climatic uniformity, each having y years of record, then the product xy may be used as a total aggregate record applying to any point in the area. Thus, if there were z occurrences of any given rainfall intensity in the area its frequency would be stated as $\frac{xy}{z}$ years. Clarke-Hafstad has shown that the results obtained by this statistical technique are not as reliable as has heretofore been assumed.[10] The results are significant only when the number of random or independent observations is taken into consideration. Since rainstorms are individual entities and affect areas, not merely points, there will be correlation between rainfall records at adjacent stations. By using Bartels'[11] technique for testing persistence, the amount of correlation between the various rainfall records was determined, and the reliability of the frequencies for the higher storm amounts was shown to be exceedingly low while that for the maximum storm is completely unreliable.

Yarnell's study presents intensity-frequency data for short time intervals and thus gives particular emphasis to local intense rains. It is based on records from first-order Weather Bureau stations throughout the United States. Since there are only 211 such stations serving an area of over 3,000,000 square miles, it is clear that the storm centers of highest intensity, which are rarely more than 25 square miles in extent, would in the vast majority of cases be missed by such inadequate sampling. The chances that the center of the storm of maximum intensity would be recorded are for the United States about 1 in 600, for the Great Plains, 1 in 1,000, and for the western States even less.[12]

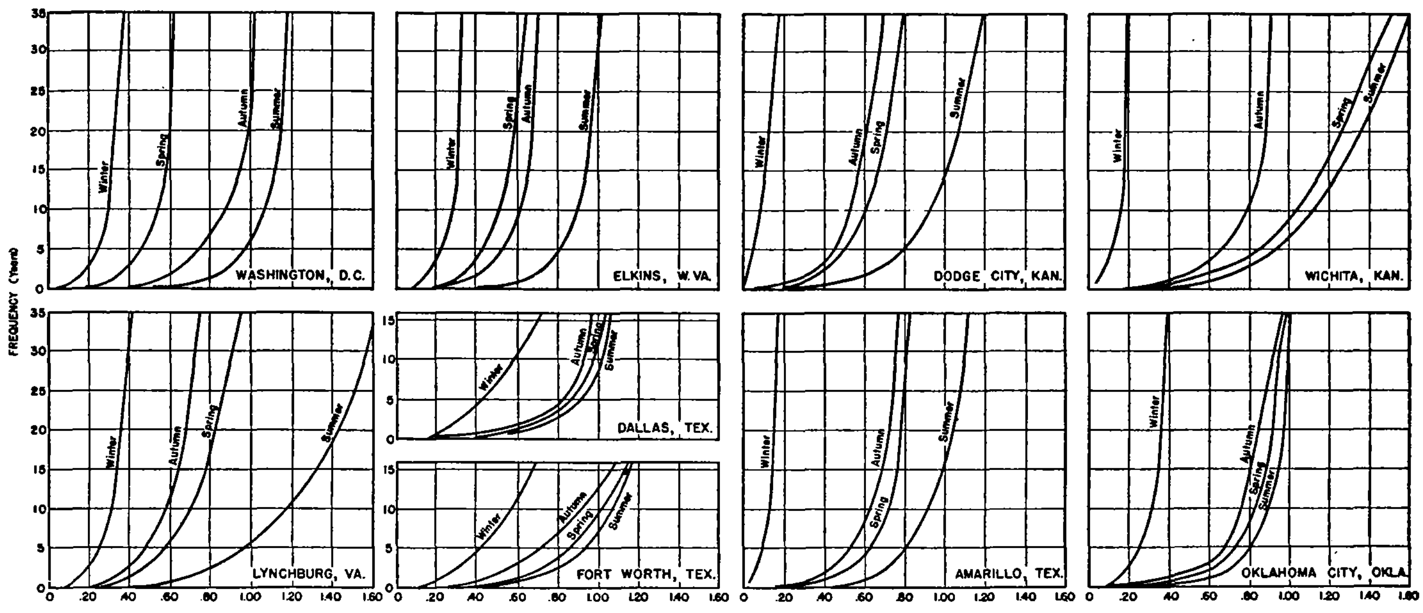

FIGURE 4.—Intensity-frequency curves of 15-minute amounts of precipitation by seasons for nine first-order Weather Bureau stations.

In order to determine the relation of Yarnell's observed values to the maximum values not observed it is necessary to have, in sample areas, a very much closer spacing of automatic raingages than is provided by the first-order Weather Bureau stations. The way in which the necessary rainfall data have become available and the manner in which they are being used will be discussed in a later paragraph.

The station-year method and Yarnell's method both give only annual intensity-frequency data. In soil conservation operations, where a seasonal rhythm of farming operations and of plant growth must be considered, it is necessary to know how precipitation intensity-frequencies vary from season to season. Under successful farm management the soil would not be left exposed to erosion in a season of serious hazard.

[8] Miami Conservancy District. Storm Rainfall of Eastern United States (Revised). Dayton, 1936.

[9] Yarnell, David L. Rainfall Intensity-Frequency Data. U. S. Dept. Agriculture Misc. Pub. No. 204, 1935.

[10] Clarke-Hafstad, Katharine. A Statistical Method for Estimating the Reliability of the Station-Year Rainfall Record. Trans. A. G. U., 1938.

[11] Bartels, J. Zur Morphologie Geophysikalischer Zeitfunktionen. Sonderausg. aus den Sitzber. der Preussischen Akad. der Wiss. Phys. Math. Klasse. Vol. 30, 1935.

[12] Thornthwaite, C. W. The Reliability of Rainfall Intensity-Frequency Determinations. Trans. A. G. U., 1937.

A recent study [13] utilizing detailed rainfall data from three eastern stations and from six stations in the southern Great Plains and southern Prairies [14] has demonstrated the practical value of detailed statistical analyses of individual climatic factors. The data were analyzed with regard to seasonal variations in rainfall intensity, storm duration, storm frequency, diurnal variations in rainfall, and length of rainless periods.

Rainfall intensities are highest during the summer and lowest during the winter due to the predominance of convective precipitation during the summer and of warm front, cyclonic precipitation during the winter. In the eastern Piedmont and mountain section, autumn and spring intensities are of equal order of magnitude; while where spring is the season having the maximum number of storms.

An analysis of diurnal variation in rainfall shows a summer afternoon maximum associated with thermal convective showers at the eastern stations, whereas there is a summer nighttime maximum in the prairies area. Although the summer nighttime maximum has been recognized for some time [16] detailed study of the diurnal variation in amount, frequency, and intensity of rainfall has suggested for the first time a number of climatic problems that are both directly and indirectly related to soil conservation problems. Not only do rains fall during periods of darkness when the evaporation rate is low, but also the intensity of precipitation usually is less than that occurring

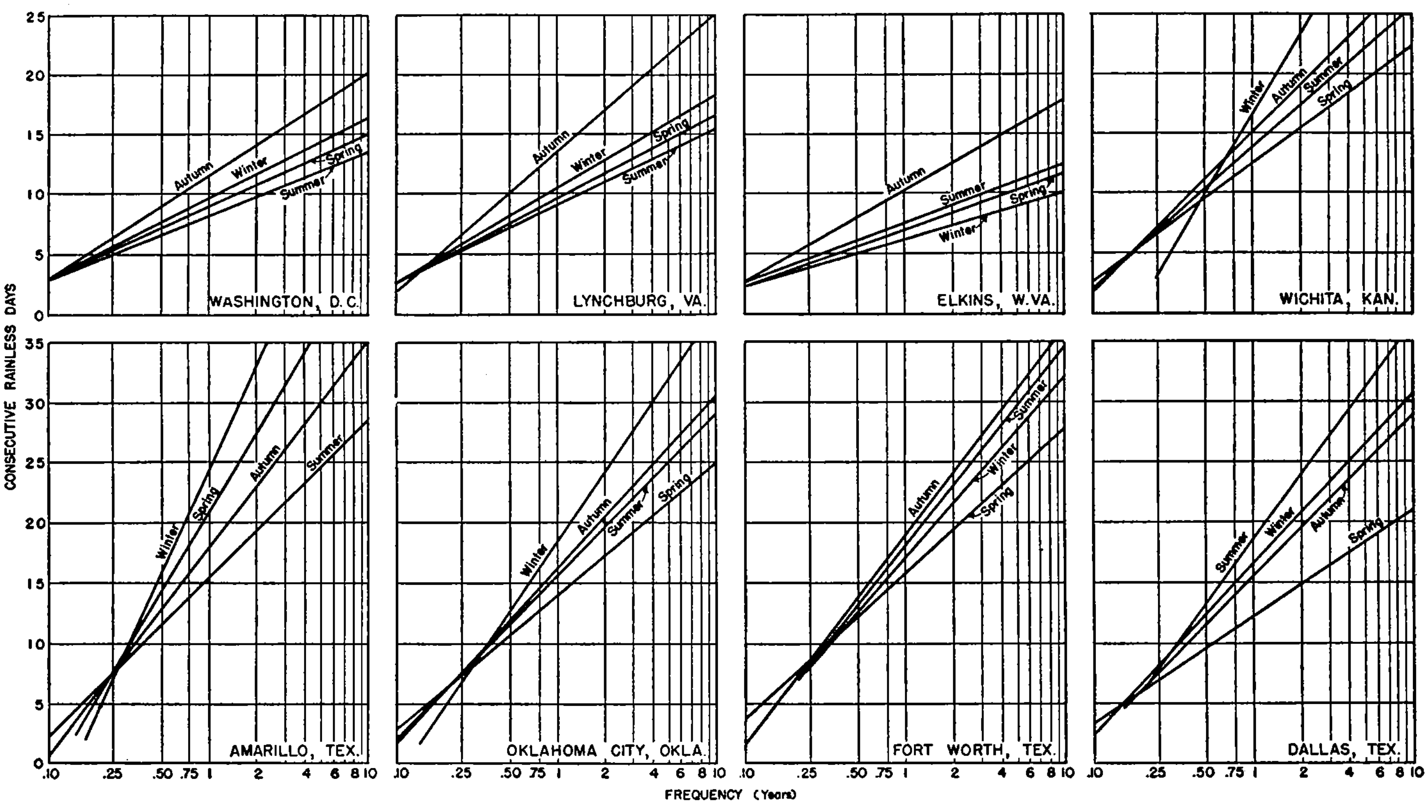

Figure 5.—Drought frequency curves by seasons for eight first-order Weather Bureau stations.

in the coastal area, as represented by Washington, autumn rains are more intense than those occurring in the spring. In the Prairie region, spring intensities for 15-minute periods are almost as high as summer intensities, while farther west at Amarillo and Dodge City intensities of spring rainfall are markedly less than those of summer but are about equal to those of autumn (fig. 4).

Rainfall duration and storm frequency both vary with the seasons. The warm-front storms characteristic of the winter season are of long duration. Summer showers of the thermal or frontal convective type [15] are short and more intense. Storm frequencies are highest during the summer and lowest during the winter, except at the three Prairie stations—Fort Worth, Dallas, Oklahoma City—during the daytime. Evidence collected on many airplane flights indicates that the moisture, which produces nighttime precipitation in the Plains, comes from the upper levels of the atmosphere and suggests that it is released primarily through convection due to radiational cooling from either the tops of cumulus clouds or moist layers of air aloft.

A study of nighttime rainfall maxima in terms of the thermodynamic structure of the upper air shows that the dearth or abundance of summer convective rainfall in the Plains is associated with abnormalities in this thermodynamic structure.

A study of the frequency of rainless periods of varying length provides a basis for determining drought and consequent erosion hazard. Frequency curves showing the seasonal expectancies of rainless periods demonstrate that in addition to quantitative differences in the expectancies from station to station and area to area there are

[14] These stations were Lynchburg, Washington, and Elkins in the East; Dallas, Fort Worth, Oklahoma City, and Wichita in the Prairie area; and Amarillo and Dodge City on the High Plains.

[13] Blumenstock, David I. Rainfall Characteristics as Related to Soil Erosion. U. S. D. A. Tech. Bull. (In press.)

[15] Thermal convection is that which arises through steepening of temperature lapse rates either by insolational heating at the surface or radiational cooling aloft. Frontal convection is caused by the release of the thermodynamic instability of the air by mechanical lifting along a frontal surface.

[16] Kincer, J. B. Daytime and Nighttime Precipitation and their Economic Significance. Monthly Wea. Rev., 44:628–633, 1916.

also contrasts in the relative rank of the four seasons (fig. 5). The number of consecutive days without rain to be expected every year varies among the stations investigated from 33 at Amarillo, Tex., to 12 at Elkins, W. Va. The maximum number of consecutive rainless days occurs variously in summer, autumn, and winter at various stations, and for the one-year frequency ranges from 25 in winter at Amarillo to 10 in autumn at Elkins. The smallest seasonal maximum period of consecutive rainless days occurs in winter, spring, and summer at various groups, but both indicate that summer drought expectancies are high, as contrasted with the lower expectancies for this season at Oklahoma City and Wichita.

By analyzing these data in connection with temperature and wind observations the drought hazard can be determined. Since only extremely high temperatures persisting several hours have in themselves a lethal effect on the type of crops raised in the Plains, it is necessary in most cases to consider temperature principally in relation to the rate of evaporation and the wilting point. Maxi-

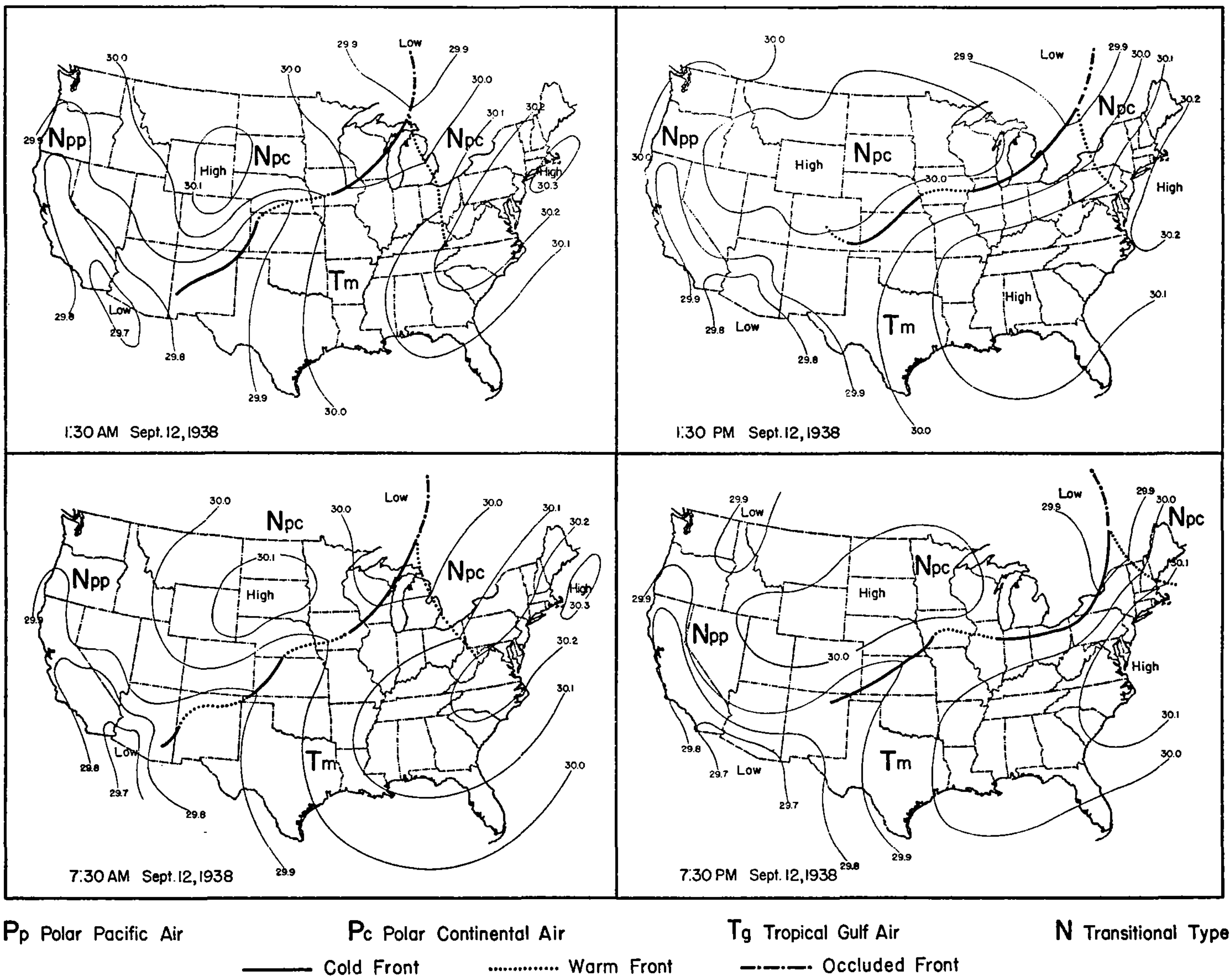

FIGURE 6.—Synoptic maps for September 12, 1938.

stations ranging from 16 in summer at Amarillo to 6 in winter at Elkins. In the East, seasonal expectancies rank in the same order at Washington and Lynchburg, summer rainless intervals being the shortest and those of autumn the longest; but Elkins, in the mountains to the west, experiences shorter rainless periods during winter and spring than during the summer. In the Prairie area, spring is characterized by the shortest rainless intervals; while on the High Plains to the west, as represented by Amarillo, the shortest rainless periods are experienced in summer, and spring has rainless intervals almost as long as those occurring during the winter. Minor differences are displayed between the Fort Worth and Dallas curve mum temperatures are experienced in the Plains area of northern Texas, western Oklahoma, and western Kansas. These data will be of greater value when they are interpreted in the light of evaporation investigations now in progress.

Since drought may destroy the vegetation cover and since the alternation of wet and dry periods tends to break down the soil aggregates, frequency and length of rainless periods determine in part the availability of soil for wind transport. Therefore, the coincidence of maximum drought expectancy with periods of maximum wind velocity would create a particularly severe wind erosion hazard. Frequently, high wind velocities are of relatively short duration and are associated with successive passages of cold or occluded fronts. The most spectacular "black" duststorms generally occur with these types of fronts but serious wind erosion can also occur during prolonged periods of moderate wind velocities. Wind erosion studies must be accompanied both by synoptic studies of the meteorological situations which yield "duststorm" conditions and by descriptive statistics on monthly and seasonal variations in wind velocity.

The various statistical studies discussed above will provide basic data for a series of climatic risk maps in terms of specific critical climatic factors. From these maps it will be possible to ascertain the climatic hazards which must be combated in any region if effective soil conservation practices and the necessary changes in farming techniques, crop calendars, and farm economy are to be adopted.

FIELD STUDIES OF CLIMATE

For climatic risk studies Weather Bureau records extending over a number of years are indispensable, since without them it would be impossible to determine frequencies of critical climatic values, such as precipitation intensity-frequency or frequency of rainless days. There is, however, in soil conservation, also a need for studies in which climatic observations are made and correlated with actual field observations of erosion processes and the resulting land forms and with observations of surface run-off. This requires the detailed study of individual rainstorms in relation to the types of run-off and erosion which they produce. Initial studies have indicated that various types of rainstorms produce characteristic patterns of run-off and forms of erosion, and have demonstrated the need for careful study of individual rainstorms and for the development of a system for rainstorm classification.

RAINSTORM MORPHOLOGY

In order to make possible the study of individual rainstorms, the Soil Conservation Service, in cooperation with the Weather Bureau, installed in October 1935, with W. P. A. funds, 200 weather stations, spaced approximately 3 miles apart, in an area of about 1,800 square miles in west-central Oklahoma. Over the entire area simultaneous observations of temperature, relative humidity, wind velocity, and wind direction were made each hour from 7 a. m. to 7 p. m., and during storms rainfall was recorded at 15-minute intervals.[17]

The results obtained were of sufficient value to justify the establishment in March 1937 of a similar microclimatic study in the Muskingum Valley in Ohio, where 500 weather stations, each including a self-recording rain gage in addition to the instruments supplied in Oklahoma, were spaced approximately 4 miles apart in the 8,000 square-mile watershed. More recently, recording anemometers and hygrothermographs were installed at half of the stations.

The records from both projects are used in the preparation of detailed climatic maps, the most significant of which are those of rainfall. The Oklahoma maps show the rainfall distribution for every 15-minute period and the accumulation of rainfall by 15-minute intervals for each storm. In Ohio, similar maps are prepared for half-hour intervals. Distribution of temperature, relative humidity, fog, dust, and wind velocity and direction are also mapped to help explain the rainstorms and permit their classification according to types. Supplementary maps show the rainfall accumulation for each day on which precipitation occurred and the daily accumulations by months as well as for the entire year.

Rainfall records from 120 self-recording gages distributed over the entire upper Ohio and Susquehanna watersheds have been available since January 1, 1938, and maps of the rainfall of each hour are being made (figs. 6 to 11). Figures 6 to 11, inclusive, are presented to illustrate the type of material available for the investigations discussed in the following pages.

In each case the battery of raingages is regarded as a single instrument for obtaining simultaneous samples in different parts of rainstorms in sufficient number to determine their characteristics. Rainstorms are subject to the same kind of observation and classification as other phenomena, and through the analysis of a large number already observed, a beginning on a taxonomy of rainstorms has been made. It has been found that rainstorms have characteristics of size, shape, internal structure, distribution of intensity, and migration patterns.[18]

It is known from general meteorological considerations that rainstorms of other sections of the United States are of the same types as those in Oklahoma, Ohio, and Pennsylvania, and that the differences in rainfall characteristics which may exist in two regions are due to variations in storm type frequencies. Recognizing that each storm type is responsible for particular combinations of erosion forms, the great variation in erosion pattern in the different climatic regions becomes apparent.

When the characteristics of various rainstorm types are known it becomes possible to relate soil erosion to the particular storm which produced it; to note the effect of different rainfall intensities and durations in producing specific erosion results which can be determined in the field; and to contrast immediately adjacent areas where the rainfall sequences for the particular storm were not alike. In short, climatic data in a detailed quantitative form can be matched with corresponding quantitative field data based on observations made while erosion was actually in progress. The field thus becomes a laboratory in which the climatic factors of soil erosion become known.

SPACING OF RAINGAGES

The determination of the distribution, intensity, and duration of rainfall requires a sampling procedure since it is manifestly impossible to measure every drop. The accuracy of these determinations depends upon the relation of raingage spacing to size and structure of rainstorms. All storms possess basically similar structural characteristics, each having one or more nuclei of high rainfall intensity and large total precipitation amounts which diminish as one approaches the periphery. General storms covering several hundred thousand square miles require no more gages to obtain an adequate sample than do local showers of only a few hundred square miles in extent, since with an increase in storm size the precipitation variability per unit area decreases. For sampling general storms the existing network of first-order and cooperative Weather Bureau stations is adequate as to spacing, but recording gages are needed at more of these stations. For small summer thunderstorms the network is totally inadequate both with respect to spacing and type or record obtained.

The question of raingage spacing depends first of all on the specific purpose for which the observations are to be

[17] Thornthwaite, C. Warren. The Life History of Rainstorms. Progress Report from the Oklahoma Climatic Research Center. Geogr. Rev., Vol. XXVII, No. 1, pp. 92-111, January 1937.

[18] Thornthwaite, C. Warren. Microclimatic Studies in Oklahoma and Ohio. Science, Vol. 86, No. 2222, pp. 100-101, July 30, 1937.

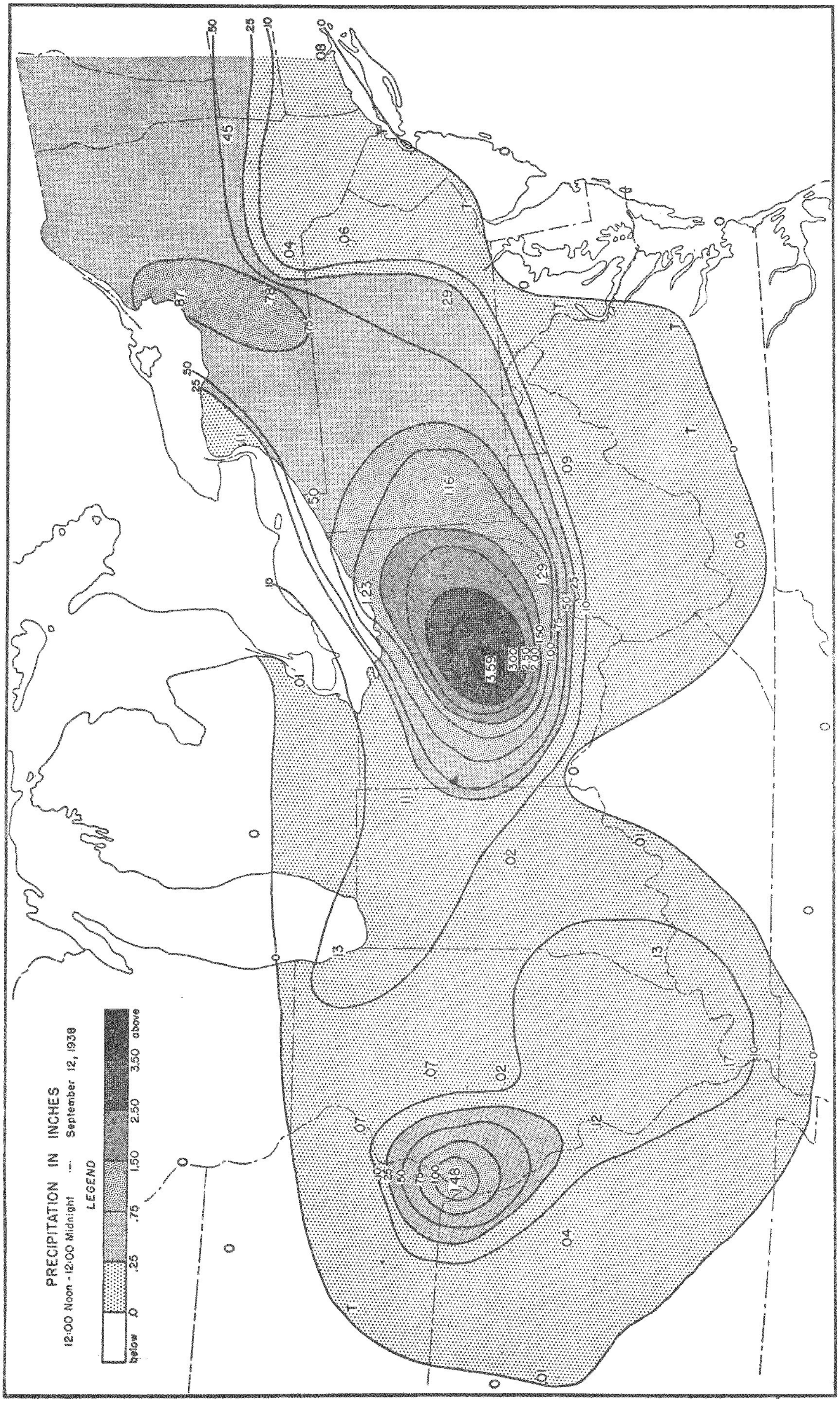

FIGURE 7.—Precipitation in inches over northeastern United States for the 12-hour period, noon to midnight, September 12, 1938. Records are from the first-order stations of the Weather Bureau.

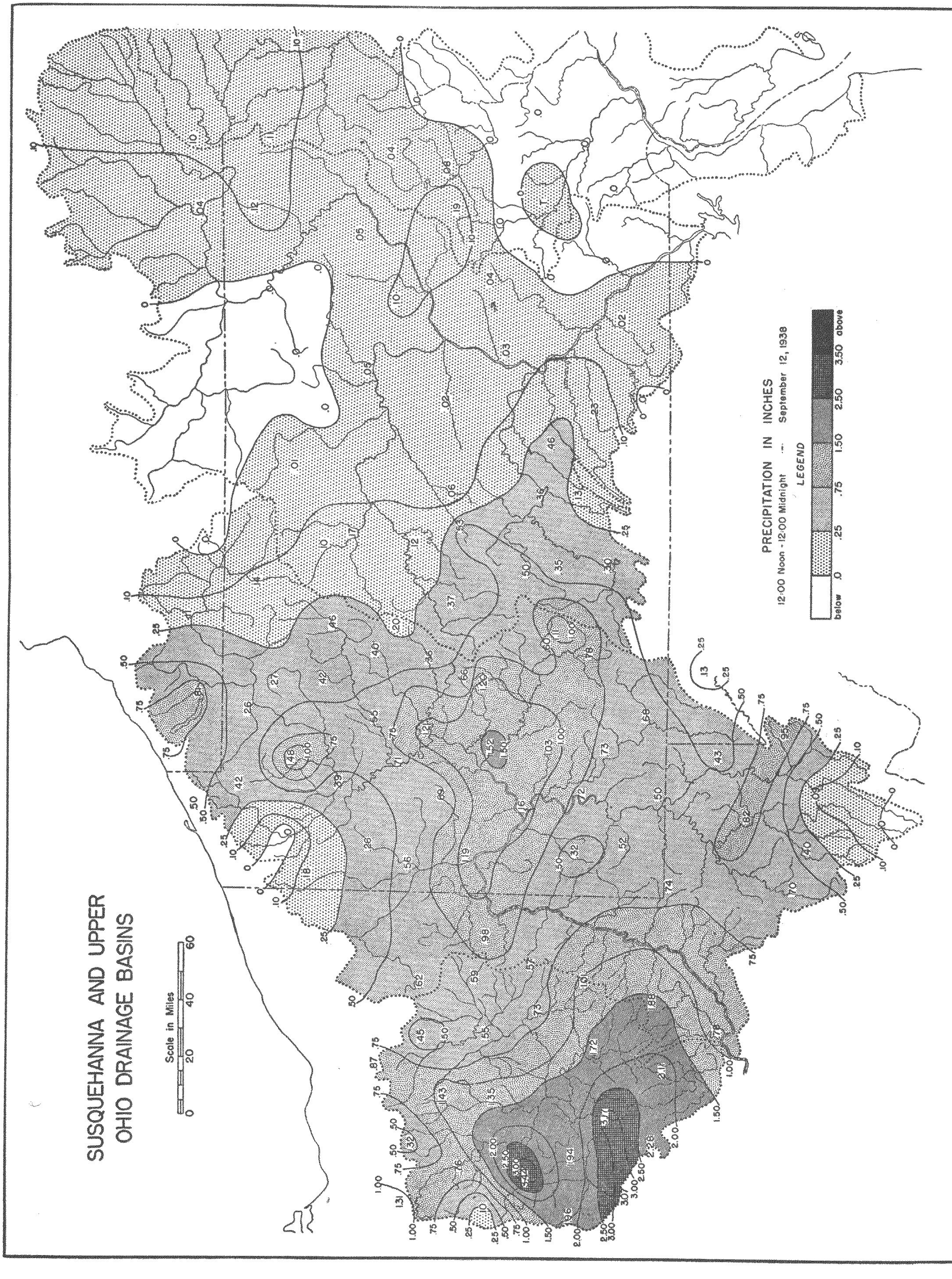

FIGURE 8.—Precipitation in inches over the upper Ohio and Susquehanna drainage basins for the 12-hour period, noon to midnight, September 12, 1938. Records supplied by the Soil Conservation Service, the Weather Bureau, the Forest Service, the Geological Survey, the Army Engineers, the Commonwealth of Pennsylvania, and private interests.

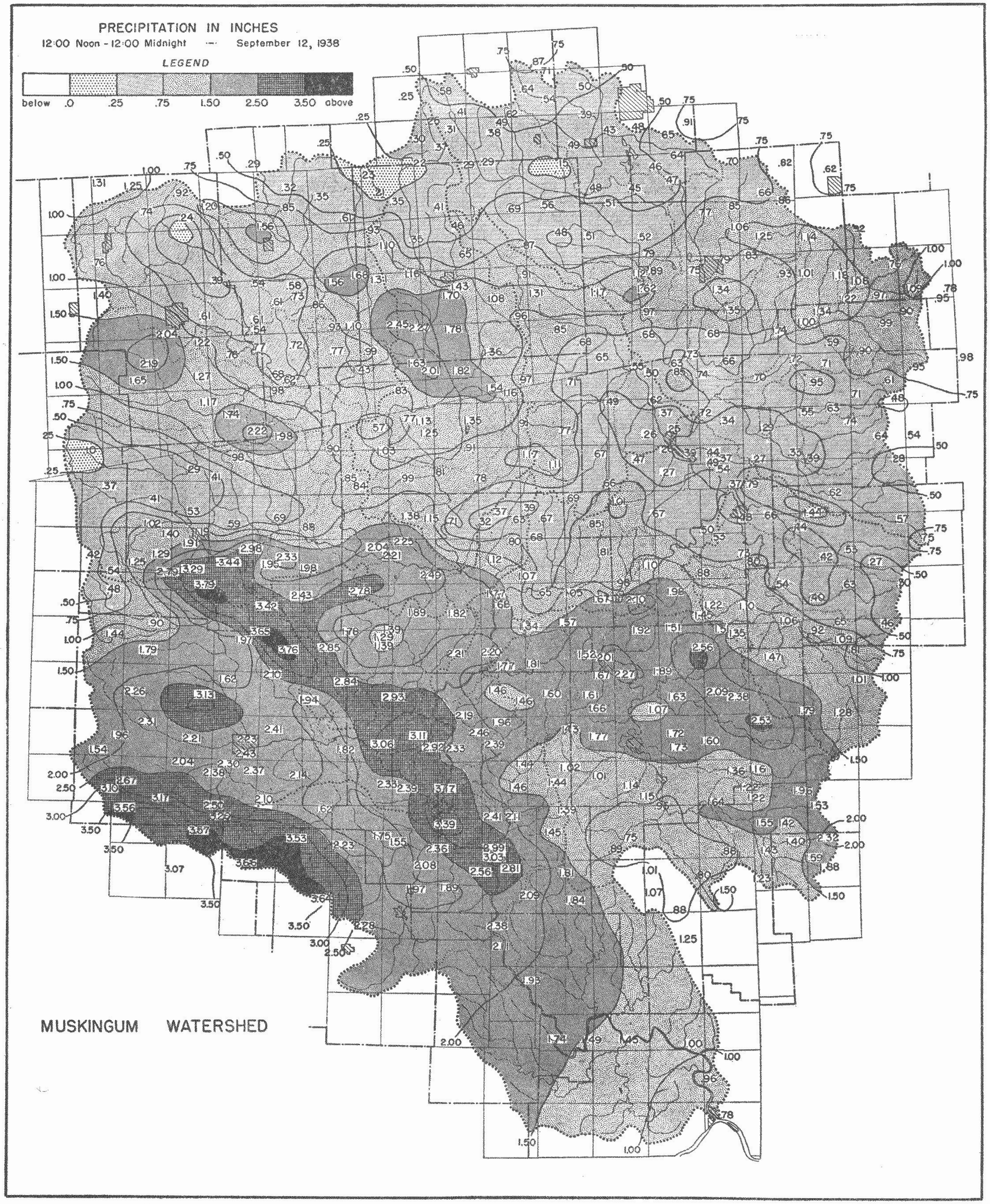

FIGURE 9.—Precipitation in inches over the Muskingum drainage basin for the 12-hour period, noon to midnight, September 12, 1938. Records from the Soil Conservation Service.

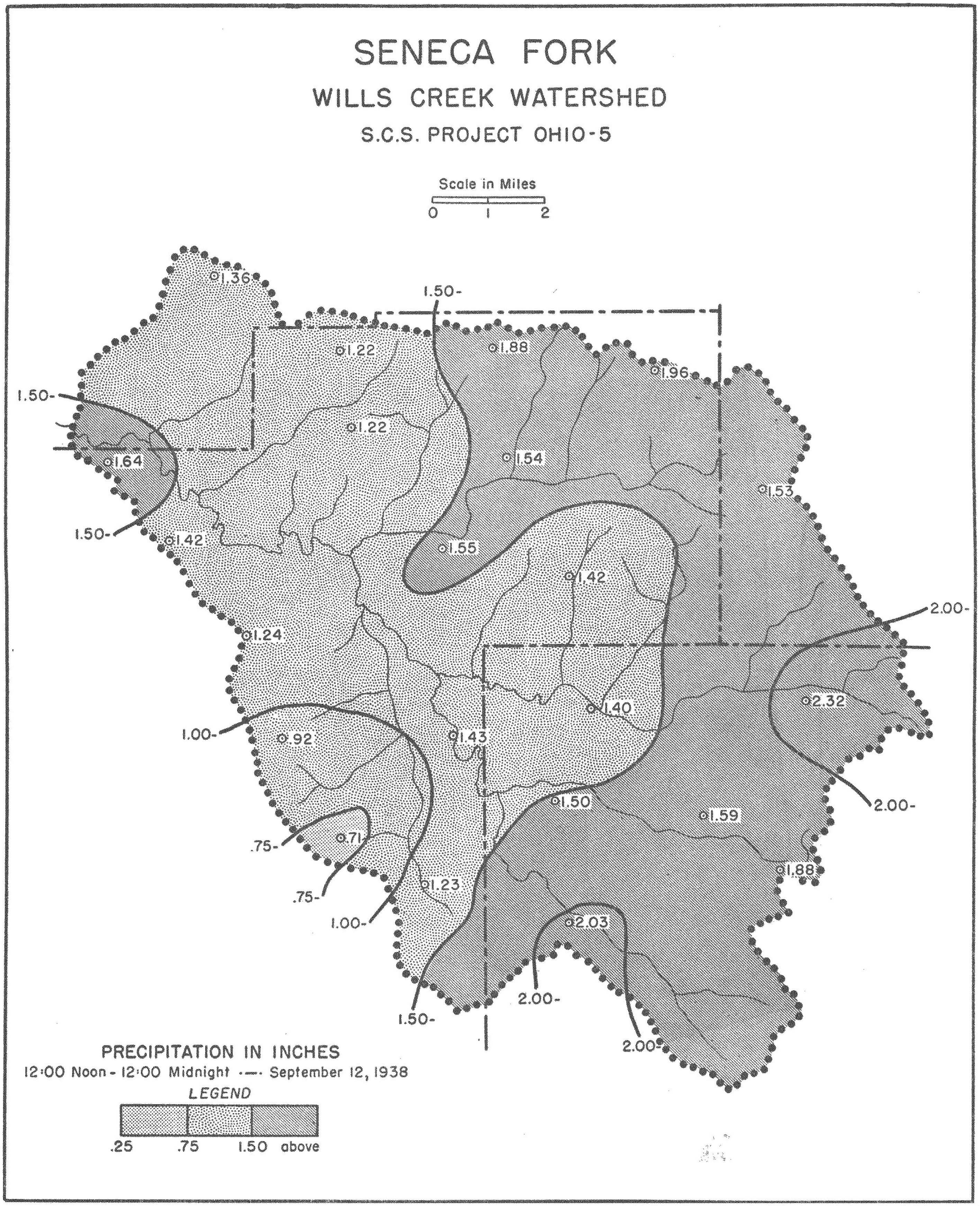

Figure 10.—Precipitation in inches over the Senecaville, Ohio, project area for the 12-hour period, noon to midnight, September 12, 1938. Records from the Soil Conservation Service.

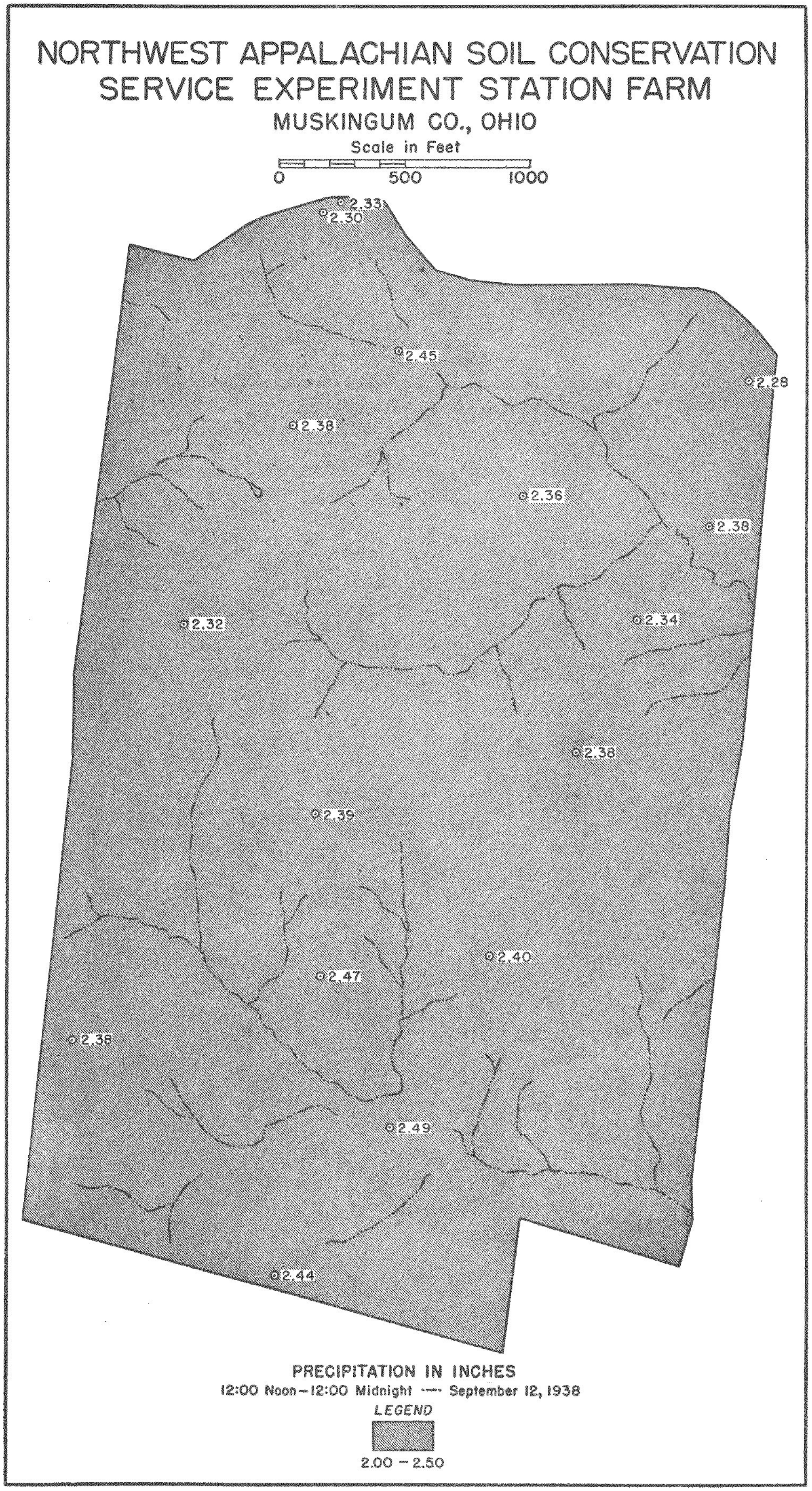

FIGURE 11.—Precipitation in inches over the Soil and Water Conservation Experiment Station at Zanesville, Ohio, for the 12-hour period, noon to midnight, September 12, 1938. Records from the Soil Conservation Service.

made. For flood forecasting, water stages in excess of definite critical height in given reaches of a stream must be anticipated. A given water level in a stream is produced by a definite discharge in cubic feet per second which, under conditions of 100 percent run-off, is due to a definite rate of rainfall. Knowing the area-depth relations of various rainstorm types it is possible to determine the area of the smallest storm that would yield a discharge which would produce the critical flood stage. The determination of the spacing of raingages necessary to permit adequate sampling of such a storm is a straightforward procedure.

If rainfall observations are made for the purpose of storm sewer design in a city the raingage network must be such as to obtain an accurate measure of the structure of small storms. In order to obtain representative data it would be necessary to have the network cover an area much larger than that involved in the particular design problem; otherwise too few storms would be sampled. The method of determining the appropriate spacing would be the same as that already described.

Rainfall figures used by agronomists in studying climate-crop relationships must be sufficiently detailed so that the sampling error is not large enough to affect the significance of their conclusions and will depend on the type of investigation being conducted. In no case would a single raingage in a county be sufficient because of the small size and random distribution of summer convectional storms, which are of paramount importance to growing crops.

The problem of crop forecasting is complementary to that of flood forecasting, the former being concerned with the portion of the precipitation which is retained on the land and the latter with that which runs off. Nevertheless, the raingage spacing appropriate for agronomic studies cannot be determined in the same manner as that for hydrologic studies since climate-crop studies involve a consideration of local variations in distribution of rainfall due to the random occurrence of storms as well as a consideration of storm sequence while flood studies are concerned only with the volume of water delivered into a stream. The problem of raingage spacing for agronomic studies, however, requires for its solution a knowledge of rainstorm pattern and frequency.

There can be no single ideal raingage spacing equally desirable for all purposes. A network perfectly adapted for one purpose may be grossly inadequate for another and at the same time extravagantly excessive for a third. It is, thus, unfair to criticize the Weather Bureau for the distribution of its network of raingages, since it is adequate for certain purposes. On the other hand it would be unfortunate if the Weather Bureau were to fail to recognize that other problems require more detailed rainfall data than can be supplied by the existing network.

Since station-spacing as a sampling problem is of critical practical significance in soil erosion studies, work leading to the solution of this problem is now in progress. Data from the Oklahoma and Ohio climatic research centers and principles of rainstorm morphology already developed are being employed.

The analysis of rainstorms and the detailed precipitation data on which it is based are of practical significance in hydrologic studies. Total precipitation on a watershed can be calculated for any storm with greater accuracy than ever before, permitting refinements in rainfall-run-off studies not previously possible. The determination of precipitation intensity-frequencies by the station-year method and by Yarnell has already been discussed. It was pointed out that the chief limitation of Yarnell's material was due to the wide spacing of raingages. For such areas as the Muskingum Watershed, where micro-climatic studies are in progress, Yarnell's intensity-frequency figures may be corrected to include the observations of small intense storms which were not recorded by first-order Weather Bureau stations. The magnitude of correction necessary will indicate the reliability of Yarnell's figures and it will then be possible to adjust the intensity frequencies accordingly, not only in areas where closely-spaced raingages are in operation but also, by extrapolation, in other regions. Results thus obtained, while not absolutely accurate, will be more reliable than those derived by Yarnell, who was unable to include the large number of intense storms that were not recorded at first-order Weather Bureau stations.

DETERMINATION OF THE MAXIMUM STORM

In addition to the statistical methods of determining frequencies of intense rains a technique for transposing maximum storms from the area where they occurred to other areas where they might reasonably have occurred and where a maximum of run-off would be produced, has been in use for several years.[19] The technique of storm transposition is a useful means of supplementing the statistical methods and increases the applicability of precipitation intensity-frequency data, but it, like the other techniques, is subject to limitations imposed by the length of records for the stations used. These techniques involve the analysis of past rainfall experience and have no way of determining the probability that the maximum storm already experienced can be surpassed in the future, nor can they indicate by what amount and with what frequency it might be surpassed.

Studies of individual storms have suggested a new approach to the problem of calculating possible storm maxima. By studying the detailed synoptic maps for a variety of storms which yielded excessive amounts of rainfall it would be possible to determine the values of meteorological elements involved in producing precipitation. Such factors as the slope of frontal surfaces, rate of ascension of moist tropical air over polar air, and the thermodynamic structure of air masses with respect to potential energy available for convection and maximum total precipitable moisture could all be ascertained. From the values derived, the factors most favorable to prolonged and intense precipitation could be selected and, by adjusting their values upward within reasonable meteorologic limits, possible synoptic situations which would provide higher rainfall than had previously been recorded could be anticipated. In some meteorological situations the possibility of altering the value of certain factors that participate in the production of high precipitation amounts is precluded, but in every synoptic situation there would be some elements that could logically be altered to increase the computed maximum rainfall. The method employed would be based on real data representing specific conditions already experienced but would yield rainfall figures which although in excess of the maxima recorded to date, would still be below the maximum possible. A genetic classification of rainstorms, now being developed, will bring out the salient points regarding storm evolution in any climatic region. Such a classification will be of value in the analysis of individual storms. That some such technique is needed is shown by the numerous instances of dam failure, which indicate that maximum storm amounts have been seriously underestimated.

[19] The method of storm transposition was described and illustrated by Adolph F. Meyer in a text, "Elements of Hydrology" first published in 1917. Merrill Bernard has introduced certain refinements through the use of the unit hydrograph (U. S. Geological Survey, Water-Supply Paper 772, pp. 218-244) and Gail Hathaway has followed the practice of studying the meteorological background of storms transposed.

FIELD MOISTURE DEFICIENCY AS A CLIMATIC FACTOR

Studies of climatic risk and of climate-crop relationships where precipitation is the climatic factor involved, have yielded results less precise than are needed. One important reason for the failure of these studies is that it was attempted to relate the total precipitation to the crop growth or yield data. Since losses through run-off and evaporation are considerable but variable it is obvious that correlations should be made with that portion of the precipitation remaining in the soil and available for plant use, rather than with the total. This residual precipitation is field moisture and should be obtainable as a difference between precipitation and run-off. Attempts to derive an equivalent index or coefficient, evaluating precipitation in terms of evaporation, temperature, or other factors have been made by many investigators.[20]

Hydrogologists have made use of similar run-off coefficients in which the ratio of run-off to precipitation is determined. Such coefficients are unsatisfactory because they ignore the fact that precipitation is a definite physical quantity and that those portions which run off and which do not are likewise definite physical quantities. In order to be satisfactory a precipitation-effectiveness index would be expressed in the same units as the precipitation and would include only that portion of the precipitation which is available for plant growth.

Researches leading to the development of a climatic index of soil-moisture conditions have required a detailed study of rainfall-run-off relationships. For this purpose, data collected in the Muskingum Valley in Ohio have been drawn upon. There, run-off has been determined for several years at many stream gaging stations on the main stream and its tributaries, and with the establishment of a dense network of raingages and other meteorological instruments it became possible to examine the rainfall-run-off problem in great detail. For practical reasons the study was limited to the Upper Licking watershed, approximately 800 square miles in area.

Familiar are the hydrologic generalizations that run-off equals rainfall minus losses through evaporation and transpiration and that run-off consists of surface run-off plus base flow or ground water run-off. It has been possible with a fair degree of accuracy to determine surface run-off and base flow as well as precipitation on the Upper Licking. The portion of the precipitation which does not run off remains in the soil to replace the soil moisture which has previously been lost by evaporation and transpiration. The amount of this replacement, being the difference between the two known values, is easily determined. The rate at which the loss is built up and its areal distribution cannot be determined in this straightforward manner. Progress in the instrumental determination of evapo-transpiration will be discussed in a later section. Recognizing the practical impossibility of obtaining observational measures of evapo-transpiration losses on any widespread scale for some time, a plan to determine them empirically was inaugurated.

A number of basic postulates were necessary: (1) Water in the soil consists of soil moisture and ground water; (2) soil moisture is the capillary moisture or field moisture which the soil can hold against gravity plus hygroscopic water; hygroscopic water is an inseparable part of the soil complex, while the remaining water can be lost only through evaporation and transpiration; (3) ground water is a surplus which the soil cannot hold against gravity and which produces base flow or ground water run-off in streams; (4) soils have inherent field moisture capacities and have inherent rates at which field moisture and ground water can be increased; (5) surface run-off occurs only after the inherent moisture capacities have been reached or when the rate of infiltration is exceeded by the rate of precipitation; (6) field moisture deficiencies at the time of a rainstorm largely determine the characteristics of run-off resulting from the storm.

At the present stage of inquiry the rate of moisture loss from the soil through evaporation and transpiration is assumed to be a direct function of the saturation deficit and the wind velocity. While this assumption is not strictly warranted because of the other parameters involved in the evaporation relationship, it is being used pending the completion of evaporation studies, now in progress, which will provide new information regarding the evaporation process. Furthermore, there is a decrease in the rate of evaporation from the soil during rainless periods, as the moisture surface moves downward in the profile. New moisture cannot be supplied from below because the rate of evaporation far exceeds that of capillary movement. There is a similar decrease in transpiration since the number of rootlets supplied with ample water constantly decreases during rainless periods. For these reasons the general assumption involving wind and saturation deficit has been modified to allow for a deceleration in rate of moisture loss.

Using this method, reasonably accurate continuous values of surface run-off and base flow have been calculated from meteorological observations alone. These values provide the only possible present check to the accuracy of the empirically determined field-moisture deficiencies. Further refinements are, however, necessary and will involve the use of infiltration rates for specific soil types and a consideration of the influence of farming operations.

The recency of plowing, the depth of the furrows, and the nature and maturity of the crop will affect the amount of surface storage of water, the rate of overland flow, and the rates of evaporation and transpiration. Since early spring of 1938 the farming operations and the condition of land and crops over the entire Upper Licking watershed have been under constant observation by field men who cover established routes once each week. From their reports on the condition of the land at the time of each rain it is hoped that a definitive answer may be given to the question of the influence of land-use practices on run-off and floods on large watersheds.

Because of the small size of many rainstorms in summer especially and their random distribution in an area, resulting in great areal variations in rainfall even in a region of limited size, there is frequently developed considerable local variation in field-moisture deficiency even where potential evaporation and transpiration losses are uniform. Where climate-crop studies are based on effective precipitation rather than total precipitation it is especially necessary that a fine network of rain gages be available.

It has been pointed out that because of the infinite variety of possible combinations and sequences of individual climatic elements the climate of each crop year is unique and could never be repeated exactly (see footnote 4). It is equally true not only that the field moisture deficiency regime of a place will not be duplicated in

[20] Discussions of a number of such attempts will be found in Thornthwaite's Climates of North America According to a New Classification (footnote 3, p. 634). The following recent summary articles should be consulted in this connection:

Philippis, A. de. Classificatione ed indizi del clima in rapporto alle vegetatione forestale Italiana. Nuovo Glor. Bot. Ital. N. Ser., vol. 44, No. 1, pp. 1-169, 1937.

Rubner, K. Die forstlich-klimatische Einteilung Europas. Zeitschr. für Weltforstwirtschaft, Band 5, heft 6, pp. 422–434, March 1938.

Moreau, R. E. Climatic Classification from the Standpoint of East African Biology. Jour. Ecol., vol. 26, No. 2, pp. 467–496, August 1938.

another year but also that it will not be duplicated in another place.

Since the rainfall sequences at stations within a few miles of each other are frequently quite different, what amounts to several years of rainfall experience can be obtained in a single year. Hence, where the climate-crop studies involve field experimentation, as is frequently the case, simultaneous identical experiments in a number of places would yield in a single year the equivalent of several years results from ordinary climatic records. Recognizing this fact, the Ohio Agricultural Experiment Station and the Division of Crop and Livestock Estimates are planning active cooperation with the Soil Conservation Service in Ohio, where the wealth of detailed climatic data are being obtained.

A further implication of local variations in field-moisture deficiency should be mentioned briefly. In run-off and flood forecasting studies where run-off coefficients are used, great difficulty is encountered in determining in advance just what percentage of the precipitation will run off, a necessary factor where run-off is predicted from rainfall values alone. The great variation in the run-off coefficient is due largely to variations in field moisture deficiency since generally little run-off will occur, except in intense rains, from an area until the deficiency is removed.

In order to determine a run-off coefficient to be used in forecasting run-off using rainfall data the so-called index area method has been suggested. The method requires a small watershed within the large one for which forecasts are to be made and which is supposed to be representative of the large one. On the small index watershed, detailed rainfall and run-off data make prompt determination of a run-off coefficient possible. Assuming, then, that the run-off coefficient of the index watershed bears some consistent relation to the coefficient of the large watershed, it becomes possible to obtain the required run-off coefficient.

As has been pointed out previously, the effect of small local storms is to develop considerable local variation in field-moisture deficiency. Since the local storms occur in random fashion, the index area will frequently be missed by a series of small storms which occur elsewhere over the large watershed or the index area may be visited by storms not received elsewhere. In the first instance the field-moisture deficiency of the index area will be greater than that elsewhere in the watershed, whereas in the second case the deficiency will be less. In either case a run-off coefficient derived from the index area and applied to the watershed will yield erroneous run-off determination.

Almost invariably floods on large watersheds are due to general rains, which remove the field-moisture deficiency from a considerable area. Insofar as the field-moisture deficiency of the watershed varies from that of the index area at the time of a flood-producing rain the flood forecasts using the index area method will be in error.

If it becomes possible to determine field-moisture deficiency from meteorological data alone each station on a watershed from which rainfall records are obtained for flood forecasting should serve as an index station. When a general rain occurs the portion required to restore soil moisture in the neighborhood of each station could be deducted and the remainder used in the run-off computations. In this manner flood forecasts should be improved.

STUDIES ON EVAPORATION

In the consideration of the relationships between rainfall, run-off, and soil-moisture deficiency it has been seen that evaporation is a critical quantity. In climatic classification the need is felt for refinement based on further knowledge of actual evaporation, and in investigation of climatic risks, such as drought, evaporation is a highly significant element. However, among all the climatic factors of agricultural significance, the measurement of evaporation has probably offered the most difficulty and for that reason is least well-known. Work has, therefore, been initiated with a view towards obtaining more specific information concerning evaporation.

Of the total precipitation that falls on continental areas, part is returned to the oceans as run-off and underground water flow and the remainder is eventually returned to the atmosphere by evaporation from the surface of the ground and from water surfaces such as rivers and lakes, and by transpiration from plants. A recent publication [21] based on aerological data and using modern meteorological analysis, has shown that the amount of reprecipitation over land areas of land-evaporated moisture is so small in comparison with the precipitation derived from oceanic source regions that it is of minor significance in any general consideration of the hydrologic cycle. Precipitation is derived principally from air masses whose source regions are the oceans and evaporation takes place mainly into dry continental air masses.

The role of evaporation in the hydrologic cycle is significant, therefore, not because of the amount of reprecipitation which may occur but because evaporation is the mechanism whereby soil moisture and stored water are depleted. Hydrologists and agronomists are both vitally concerned with the rate at which this loss occurs. It is therefore the task of the climatologist to determine actual evaporation rates under different atmospheric conditions and under different conditions of surface cover and land use. Such information would make possible the determination of the moisture regime of climatic regions and subregions or of areas of even smaller size.

THE DETERMINATION OF ACTUAL EVAPORATION

Most of the current methods of measuring evaporation employing some type of pan or atmometer have proved unsatisfactory. These methods have led to the development of empirical evaporation formulae whose parameters include such surface observations as temperature, salinity, relative humidity, barometric pressure, and wind velocity.

While pan and atmometer measurement permit a general qualitative estimate of the evaporation-opportunity, they are useless in determining actual transpiration and water losses from extensive land areas. As plant physiologists have shown, the amount of transpiration for any plant type is partly a function of the leaf area of the plant. This introduces a factor which varies seasonally and is associated with the growth curve of the plant. Transpiration also varies from one plant species to another, depending upon the water requirements of the plant, the osmotic pressure in the leaves, and the number, nature, and size of the stomata. None of these factors is reflected by pan or atmometer measurements of evaporation.

Furthermore, such evaporation data do not measure evaporation from the soil. When the surface soil is moist the evaporation, in the case of finer soils, exceeds pan measurements because the soil presents a greater

[21] Holzman, Benjamin. Sources of Moisture for Precipitation in the United States. U. S. D. A. Tech. Bull. No. 589, October 1937.

evaporating surface associated with minute irregularities in the soil surface and because surface soil temperatures are usually higher than evaporimeter surface temperatures during that part of the day when most of the evaporation occurs. When, however, the surface soil is dry or partially dry, less evaporation occurs from the soil than from a pan. Even though the subsoil is moist, capillary action cannot supply the surface with water at a rate at all comparable to the evaporation from a free body of water. Hence water molecules can escape to the outer air only through a very slow diffusion process which takes place from the lower soil levels and through the soil air.

A method is needed which will measure the rate at which moisture enters the lower air, regardless of the type of surface involved. This involves a consideration not only of surface parameters but also of specific humidity gradients and conditions of turbulence in the atmosphere. In general, it may be said that when atmospheric turbulence is at a minimum, evaporation will also be at a minimum. When there is no turbulent motion, the upward transport of water vapor can take place only by diffusion. This process is analogous to the transfer of heat by conduction. In the atmosphere both of these processes are negligible when compared to the magnitude of heat or moisture transfer by turbulent or convective phenomena.

Although the theoretical treatment of problems of turbulence is highly complex mathematically, significant progress has nevertheless been made in this field especially through the efforts of the Göttingen School of Aerodynamicists—Prandtl,[22] von Karman,[23] Tollmien,[24] and others. Many of their ideas have been extended and applied to the atmosphere and ocean by Rossby[25] and Sverdrup.[26] As an outgrowth of Rossby's research an atmospheric turbulence, a method for determining evaporation is being tested at the Muskingum Climatic Research Center and at the Arlington Experimental Farm. Preliminary data already obtained indicate the complete feasibility of the technique.

The method depends upon a measurement of the specific humidity gradient and a measure of the intensity of the turbulent mixing conditions in the lower levels of the atmosphere. Turbulence tends to establish an adiabatic distribution of properties of the air and thus a constancy in the moisture concentration. In other words, the specific humidity throughout the turbulent layer would be constant provided no moisture were added or subtracted from the layer. Thus, in the turbulent layer immediately adjacent to the ground, a moisture gradient directed upward, that is, a lower specific humidity aloft than at the surface, indicates an addition of moisture from below by evaporation and its upward transport. On the other hand, if the gradient is directed downward, moisture is being abstracted at the ground surface by dew or frost, and downward transport of moisture results.

Experiments being conducted at present are limited to plots in which the ground surface is relatively smooth and homogeneous. The turbulent mixing condition is determined from simultaneous measurements of wind velocity at various elevations above the ground. Hygrothermographs are stationed adjacent to the ground surface and at different elevations so that the specific humidity gradient can be determined. A relatively simple formula gives evaporation in inches per hour where specific humidity and wind velocity at two different levels and the height of the two observation points above the ground are known.

If this method of determining the amount of moisture returned to the atmosphere proves to be practical it will have the obvious advantage of measuring the actual rate of transfer of water vapor into the atmosphere. The isolated local factors that influence evaporation would be combined and a true value for the moisture losses to the air obtained. These true values are the ones so urgently needed in the refinement of many agricultural and hydrologic problems.

SUMMARY

Climatic work carried on as an integral part of the research program of the Soil Conservation Service has clearly demonstrated the need for a variety of specialized limatic investigations into soil erosion problems. Many of these climatic problems have already been undertaken, several have been completed, but there are still numerous questions which, while clearly recognized, have yet to be subjected to study. General climatic considerations are useful in defining "erosion regions" and in treating the element of climatic risk. Analyses of precipitation records in terms of storm duration, intensity, and storm area have been undertaken and are being directly related to field phenomena. Drought is being considered as a type of climatic risk particularly significant in the Great Plains and the semiarid West. Temperature in its bearing on climatic risk and weathering processes is also being scrutinized. Likewise, a consideration of the flood problem in its bearing on erosion hazards requires studies of excessive precipitation, actual evaporation from various types of land surfaces, and soil-moisture deficiency. Thus, in a wide variety of ways, a number of climatic studies are being carried out. That climate is an inseparable major theme in the soil erosion complex is clear. The objective is to orient the climatic work in such a way that results of maximum practical value will be obtained.

[22] Prandtl, L. The Mechanics of Viscous Fluids. Aerodynamic Theory. Wm. Frederick Durand (Editor-in-chief), vol. III, Div. G, pp. 34–207, Berlin, Julius Springer, 1935.

[23] von Karman, Th. Mechanische Ahnlichkeit und Turbulenz. Nachrichten von Geseltschaft der Wissenschaften zu Göttingen. Math. Phys. Klasse, Heft 1, pp. 58–76, 1930. idem: Turbulence. Jour. Royal Aeronautical Soc., vol. XLI, No. 324, pp. 1109–1143, illus. December 1937.

[24] Tollmien, Walter. Berechung turbulenter Ausbreitungsvorgänge. Zeitschr. für angewandte Mathematik und Mechanik, band 6, heft 1, pp. 468–478, 1926.

[25] Rossby, C. G., and R. B. Montgomery. The layer of Frictional Influence in Wind and Ocean Currents. Mass. Inst. of Tech. Papers in Phys. Oceanography and Meteorology, vol. III, No. 3, Cambridge, Mass., 1935.

Rossby, C. G. A Generalization of the Theory of the Mixing Length with Applications to Atmospheric and Oceanic Turbulence. Mass. Inst. of Tech. Meteorol. papers, vol. I, No. 4, pp. 1–36, 1932.

[26] Sverdrup, H. U. Das maritime Verdunstungproblem. Annalen der Hydrographie und Maritimen Meteorologie, band 64, heft 2, pp. 41–47, 1936.