ATTACHMENT A

City of Wichita Drought Response Plan

2013

Drought Response

Stages & Action Steps

City of Wichita

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How Drought Stages are Defined

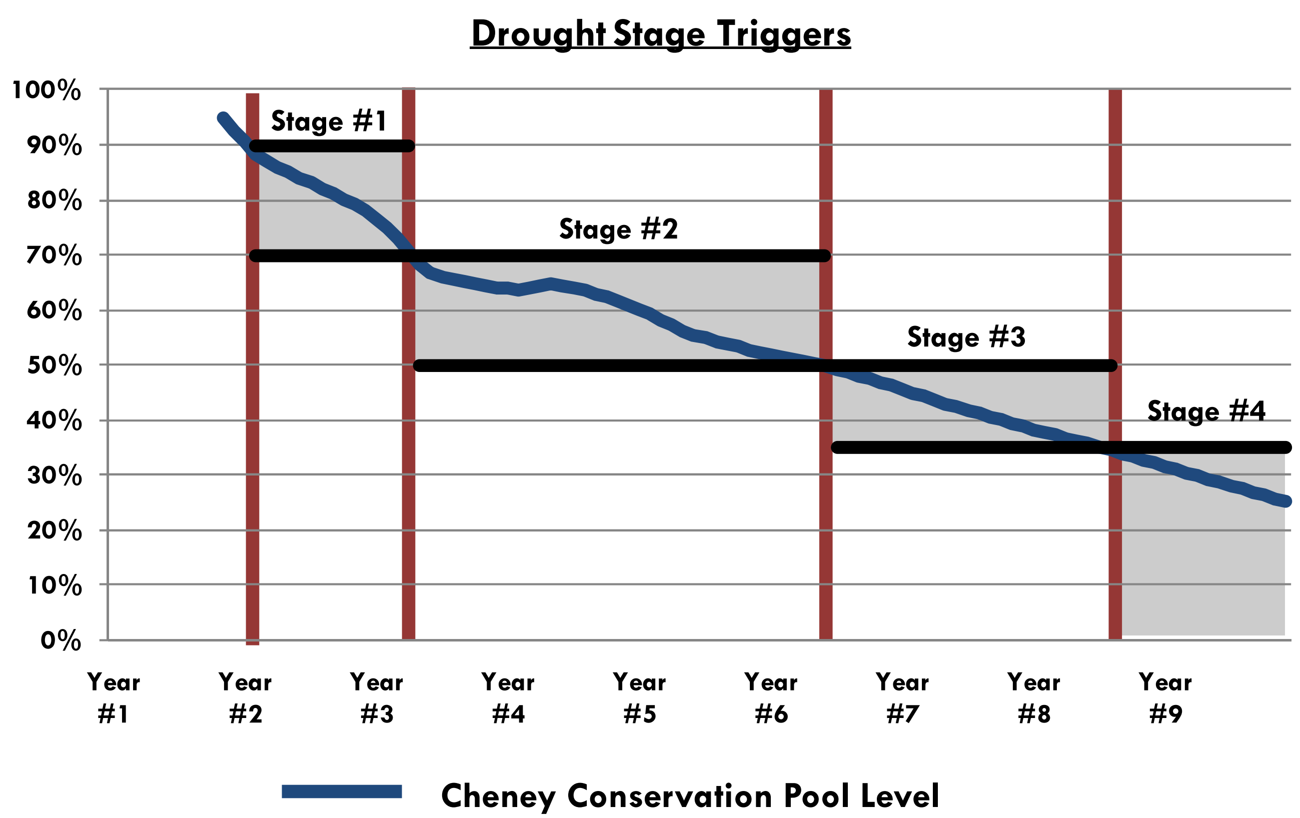
The City of Wichita will use a 12-month average of the conservation pool level in Cheney Reservoir in order to determine the establishment and severity of a drought. The US Army Corps of Engineers provides hourly data on how full the conservation pool is. Cheney Reservoir is one of the City's two water sources and is the most susceptible to drought conditions. The 12-month average will smooth out seasonal variations to ensure that low points experienced in normal years do not move the City of Wichita into a drought response.

Trigger Points for Each Stage

Four stages of progressive measures will be instituted during a long-term drought in Wichita. The lake level triggers for each stage are included in the accompanying chart and table.

CHENEY CONSERVATION POOL: 12-MONTH AVERAGE		
	Top Level	Bottom Level
Normal Conditions	100%	90%
Stage #1	89%	70%
Stage #2	69%	50%
Stage #3	49%	35%
Stage #4	34%	0%

Wichita will need to experience a multi-year drought to enter any of these stages. Should the area experience a drought similar to the 2011-2012 conditions, there would be a full year before an enhanced drought response would be initiated. The City of Wichita would then progress through different stages until the drought ends.



Monitoring Cheney Lake Levels

The Department of Public Works & Utilities is responsible for managing the City of Wichita water supply. This includes monitoring the lake levels at Cheney Reservoir. Public Works & Utilities staff will regularly review the data published by the US Army Corps of Engineers and will keep a 12-month average level of water in the conservation pool.

When the Wichita area enters a drought, the 12-month average lake level will begin to decline from its normal level. Public Works & Utilities will chart the level of the conservation pool and provide updates to the City Manager in the first year of a drought, before the first drought stage is effective.

Entering More Severe Drought Stages

This drought plan, the triggering mechanisms for each stage, and the progressive water reduction actions were approved by the Wichita City Council in 2013. Therefore, this is the official policy plan for the community when Wichita is confronted with the drought.

As these actions have already been approved by the Wichita City Council, the City Manager is responsible for carrying out this plan and providing all necessary written approvals for entering into each stage. No further action will be required by the City Council.

The Public Works & Utilities Department will provide regular updates to the level of the conservation pool at Cheney Reservoir. Should the 12-month average level reach the of the triggering point for Stage #1 or any of the further drought stages, the City Manager will provide written authorization prior to implementing the requisite actions.

Coming Out of a Drought

The same process will be used when lake levels at Cheney increase, making it necessary to declare drought stages that have ended. Staff from Public Works & Utilities will provide the City Manager with regular updates about the 12-month average level in the Cheney conservation pool.

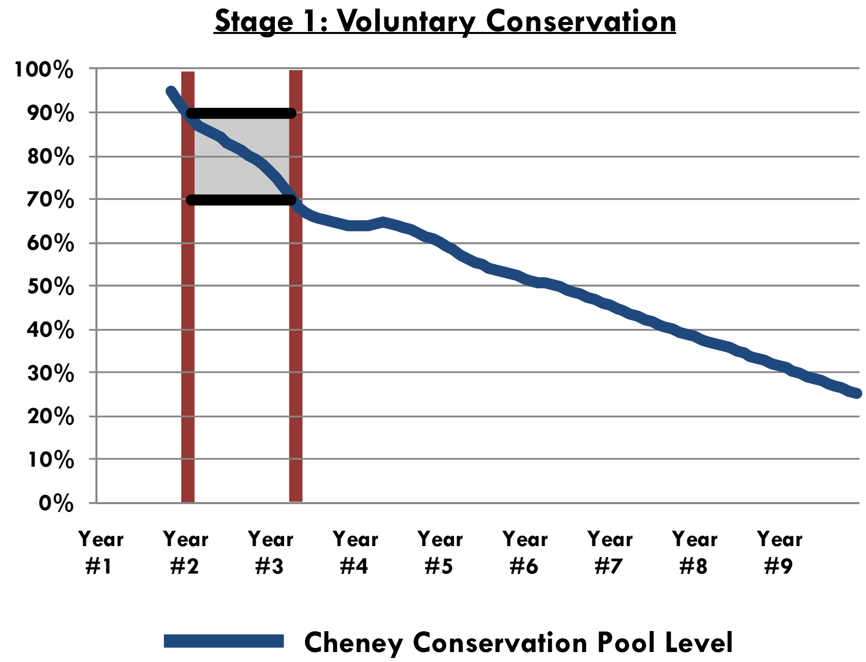
Whenever that moving average raises above a drought stage threshold, the City Manager will provide written authorization to move the utility to the less-severe drought stage. Once the level increases above the Stage #1 threshold, the City Manager's written authorization will end all drought response actions.

It may be appropriate for the City of Wichita to move out of the drought much quicker than it can enter the drought—this would be caused by a rapid re-fill of Cheney Reservoir. Should an hourly reading at Cheney Reservoir show that the capacity level has increased above the maximum threshold for Stage #1 (90%), the City Manager will authorize an immediate end to all drought actions that are presently in effect.

STAGE 1: VOLUNTARY CONSERVATION

Description

The beginning stage of drought response would likely occur after the first year of a drought and would last through a full irrigation season.



Voluntary water conservation is the focus of Stage #1. Utility customers will be encouraged to reduce water usage by participating in a rebate program that provide incentives for lower usage. The City of Wichita will culminate a high-profile marketing campaign to raise drought awareness and publicize tips for conserving water. It will also continue to implement its permanent water conservation measures for its own operations.

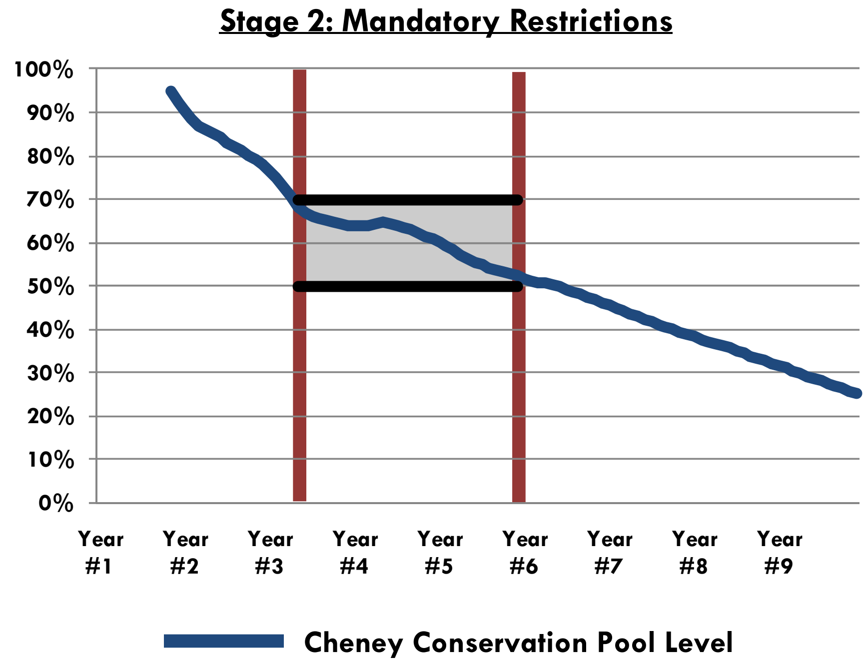
STAGE #1 ACTIONS	
Utility Customers	**City of Wichita—Internal Conservation**
♦ Respond to enhanced publicity efforts to raise drought awareness	***Continue permanent conservation measures:*** ♦ Use graywater from Herman Hill Park to water trees
♦ Conserve water voluntarily	♦ Realize water savings from motion sensors installed on splash pads and spray parks
♦ Take advantage of a rebate program to incentivize indoor and outdoor water conservation	♦ Follow landscape design guidelines for new municipal construction
	♦ Decide whether drought-tolerant grasses or artificial turf is appropriate on existing fields
	♦ Implement conservation protocol for taste and odor complaints
	♦ Mow grass to a higher length to increase shade and reduce evaporative losses

STAGE 2: MANDATORY RESTRICTIONS

Description

Stage #2 brings the first mandatory restrictions during a drought and would be triggered when the 12-month average in Cheney's conservation pool reaches 69%.

Outdoor water usage would be restricted to one day per week, using the quadrant schedule included on the following page. The City of Wichita would initiate further conservation measures for its own operations.



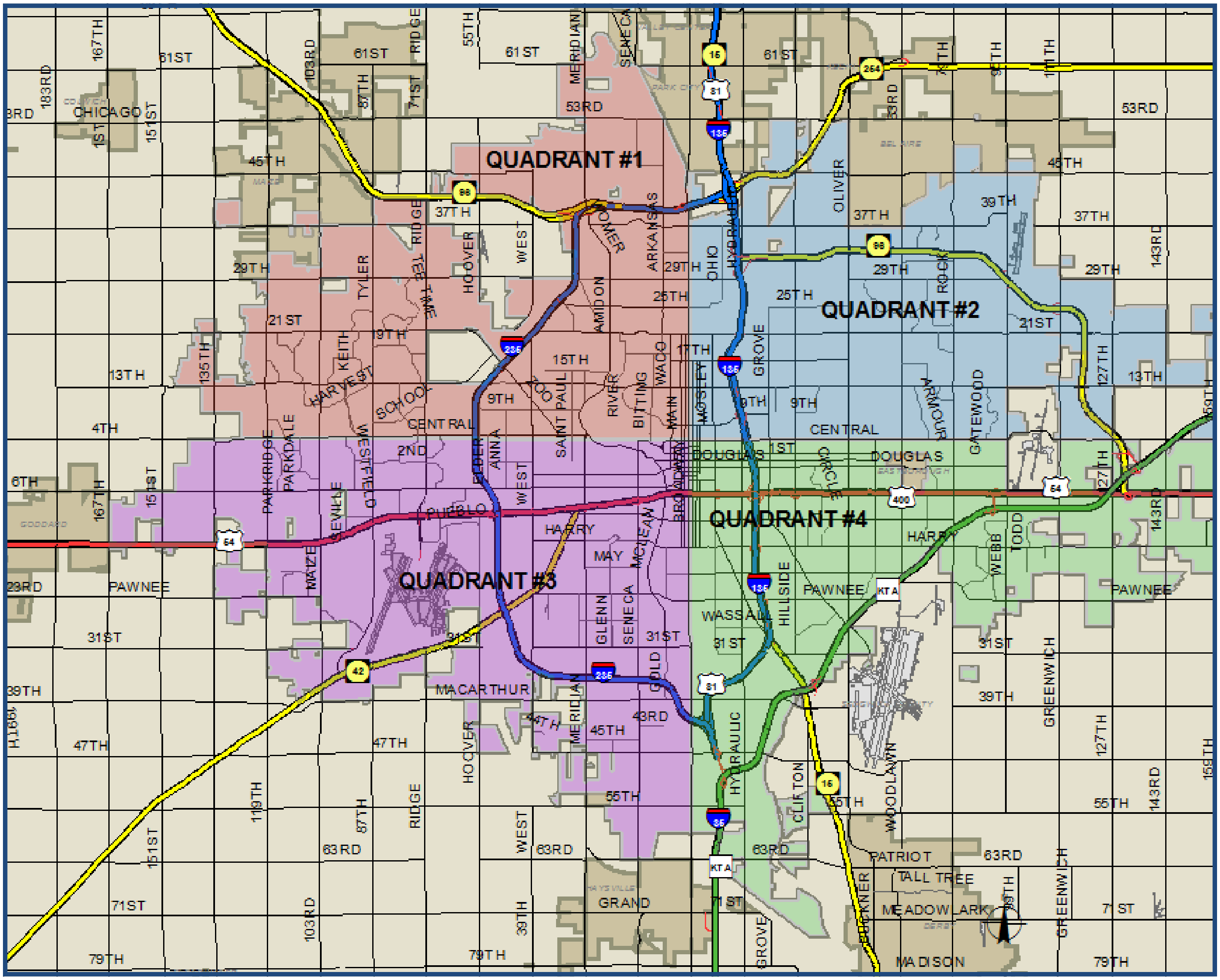
PENALTY SCHEDULE PER VIOLATION	
1st Incident	Warning
2nd Incident	$50
3rd Incident & Beyond	$100

Exemptions

Food producing gardens utilizing drip irrigation or hand watering and businesses that generate their core economic activity from outdoor usage will be exempt. Such businesses include golf courses, car-washes, nurseries, sod companies, and others identified by the City Manager.

STAGE #2 ACTIONS	
Utility Customers	**City of Wichita—Internal Conservation**
♦ Continue all measures from Stage #1	♦ Continue all measures from Stage #1
♦ Follow mandatory restrictions on outdoor water usage	♦ Follow all mandatory restrictions that are in place for water customers
♦ Outdoor water usage prohibited from 10am until 8pm on all days. It is not allowed at all on Saturdays, Sundays, or Mondays	♦ Switch water allocation to increase amount taken from the Equus Beds
♦ Quadrant #1 can water on Tuesdays; Quadrant #2 can water on Wednesdays; Quadrant #3 can water on Thursdays, and Quadrant #4 can water on Fridays	♦ Replace Wichita Fire Department spray-downs with activities from the mobile prevention truck and utilize alternative hydrant maintenance schedule
♦ Violations will be enforced through the penalty schedule included above	

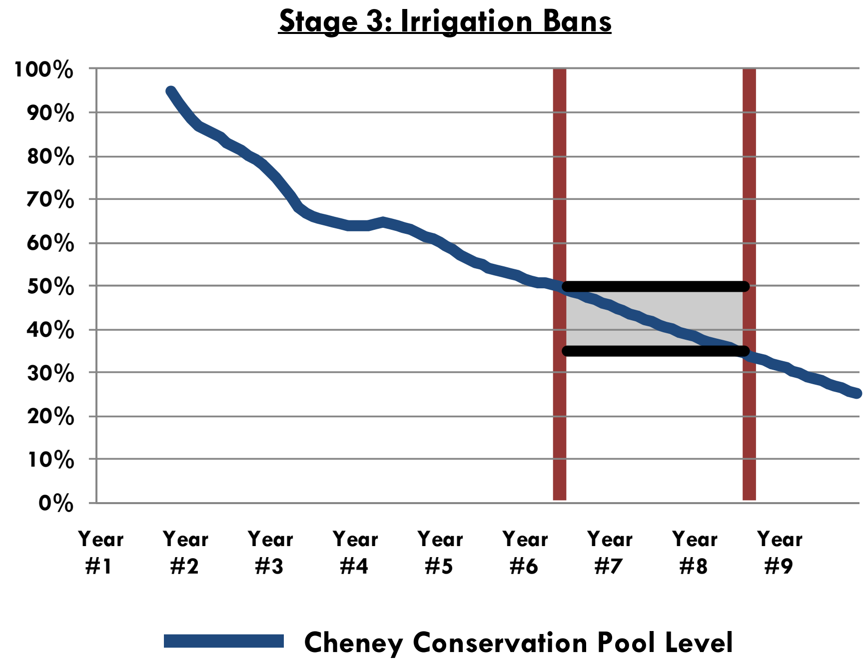
The following map illustrates the quadrants that make up the City of Wichita watering grid during Stage #2 restrictions. The intersection of Central & Broadway is the dividing point for the quadrants. Each quadrant is allowed to use water outdoors on one day per week, according to the schedule provided below. In addition, no water may be used during the hottest part of the day, from 10am until 8pm.



Watering Days & Times

Quadrant #1	Quadrant #2	Quadrant #3	Quadrant #4
Tuesdays	Wednesdays	Thursdays	Fridays

**Watering allowed from 8pm—10am*



Description

Once Cheney's conservation pool drops below 50% with a 12-month average, Stage #3 will be in effect. This is the second to last drought stage and thus includes more severe actions.

All outdoor water usage will be banned. Customers who previously could use water one day per week in Stage #2 would be prohibited from using any water outdoors. The penalty for violations will increase dramatically, topping out at $500 per incident, for repeated violations. The City of Wichita will expedite repairs on its water main breaks and irrigation leaks, to reduce water loss. Operational hours at public fountains will be reduced, while municipally owned grasses will not be irrigated, except for those that are exempt under this drought stage.

PENALTY SCHEDULE PER VIOLATION	
1st Incident	Warning
2nd Incident	$250
3rd Incident & Beyond	$500

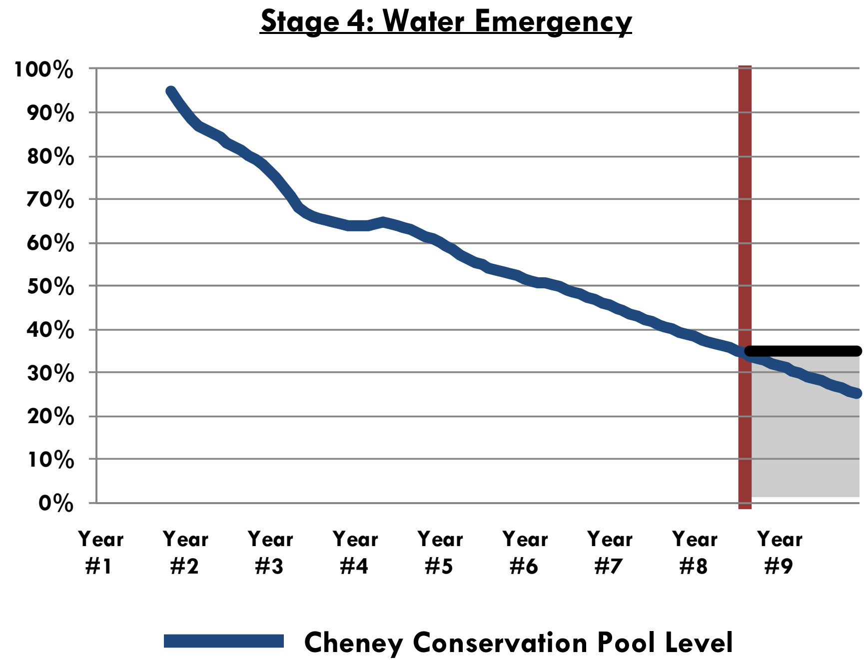
Exemptions

The same exemptions that are in effect in Stage #2 will apply to this stage. That includes food producing gardens utilizing drip irrigation or hand watering and all businesses that rely directly on outdoor water usage to generate their core economic activity.

STAGE #3 ACTIONS	
Utility Customers	**City of Wichita—Internal Conservation**
♦ Continue all measures from Stage #1	♦ Continue all measures from Stages #1-2
♦ All outdoor watering is banned	♦ Reduce hours at City-owned fountains
♦ Exemptions provided for businesses generating economic activity directly from outdoor irrigation	♦ Eliminate irrigation on City-owned grasses that are not exempted due to the economic activity they create
	♦ Expedite repair on water main breaks and irrigation leaks

Description

Triggered when the 12-month average level at Cheney is below 35%, the final drought stage would likely be reached after a prolonged and severe drought. The most restrictive water usage regulations would be applied, in order to preserve the remaining water at Cheney Reservoir.



All outdoor water usage would be banned, even from those businesses previously exempted. Customers would have to reduce base demand by 15%, meaning that their usage would need to be 15% lower than their Average Winter Consumption at the beginning of Stage #4. Repeated violations would result in a flow restrictor to ensure compliance with the regulations.

Penalty Schedule Per Violation	
1st Incident/Month	Warning
2nd Incident/Month	$250
3rd Incident/Month & Beyond	$500 + Flow Restrictor

Exemptions

Major hospitals would not need to reduce base demand. These include Wesley and Via Christi hospital campuses, the Kansas Medical Center, the VA Hospital, the Kansas Spine Hospital, the Kansas Surgery & Recovery, and Select Specialty Hospital.

Stage #4 Actions	
Utility Customers	**City of Wichita—Internal Conservation**
♦ Continue all measures from Stage #1	♦ Continue all measures from Stages #1-3
♦ All outdoor water usage is banned, without exemptions	♦ Shutdown all City-owned fountains
♦ Water usage must be 15% below the Average Winter Consumption (AWC), at the beginning of drought Stage #4	
♦ Major hospitals are exempt from the 15% water usage AWC reduction	

ATTACHMENT B
Palmer Drought Severity Index, Research Paper No. 45

U.S. DEPARTMENT OF COMMERCE
JOHN T. CONNOR, *Secretary*

WEATHER BUREAU
ROBERT M. WHITE, *Chief*

RESEARCH PAPER NO. 45

Meteorological Drought

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Office of Climatology
U.S. Weather Bureau, Washington, D.C.

WASHINGTON, D.C.
FEBRUARY 1965

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402 - Price 40 cents

FOREWORD

Drought has been cited as a scourge of mankind since biblical times. It still is a major menace to world food supplies. Insect plagues, with which it ranks as a crop threat, can be fought by modern means. Drought remains an unconquered ill.

Meteorological science has not yet come to grips with drought. It has not even described the phenomenon adequately. This is certainly the first step toward understanding. And then a long road remains ahead toward prediction and, perhaps, limited control. This paper is an important step toward these goals. It presents a numerical approach to the problem and thus permits an objective evaluation of the climatological events.

Although often so classified, drought is not just an agricultural problem. It affects the city dweller, whose water may be rationed, and the industrial consumers of water as well. In fact, water is one of the most vital natural resources. Its lack, regionally or temporally, has the most profound effect on economy. In a country as large as the United States drought is likely to affect only a part of its territory at any one time. However, no section is entirely spared of droughts and occasionally substantial areas are affected. By severity and duration these events can be calamitous not only locally but for the whole economic structure. Hence knowledge of the probability of their occurrence and their course is an essential element for planning. The thorny problem of a rational land utilization is closely tied in with these considerations.

The pioneering work of the late C. W. Thornthwaite on potential evapotranspiration has underlain all modern attempts to assess the water balance. As in his work, the aim of the effort reported on in this paper remains primarily on the climatological aspects. The new method presented here is directed at a quantitative assessment of periods of prolonged meterological anomalies. We hope it is a step forward and that it can be followed by similar analyses on a broader geographical basis.

H. E. Landsberg.

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α	coefficient of evapotranspiration	11
α_3	standardized third moment, a measure of skewness	51
β	coefficient of moisture recharge	13
γ	coefficient of runoff	13
δ	coefficient of loss	13
Δ	net change during a month	22
σ	standard deviation	51
a	a measure of kurtosis	51
AWC	available water capacity of the soil	7
c	a coefficient expressing the tendency to return to normal	22
$CAFEC$	Climatically Appropriate For Existing Conditions	12
d	moisture departure for a particular month, $P-\hat{P}$	15
$\bar{d}$	average monthly moisture departure	18
$\bar{D}$	the mean of the absolute values of d	25
ET	computed evapotranspiration for an individual month	7
$\overline{ET}$	long-term mean evapotranspiration for a calendar month	11
$\widehat{ET}$	CAFEC evapotranspiration	14
i	dummy variable denoting a particular month in a series of months	14
j	dummy variable indicating the number of months of lag	29
k	the first approximation of K	18
K'	the second approximation of K	25
K	the climatic characteristic or weighting factor	18
$\bar{K}$	a mean weighting factor	18
L	net loss of soil moisture during a month	7
$\bar{L}$	long-term mean soil moisture loss for a calendar month	13
$\hat{L}$	CAFEC soil moisture loss	14
L_s	computed moisture loss from the surface layer of the soil	7
L_u	computed moisture loss from the soil underlying the surface layer	7
P	areal average precipitation for a particular month	7
$\bar{P}$	long-term mean precipitation for a calendar month	11
$\hat{P}$	CAFEC precipitation	14
P_e	percentage probability that a weather spell has ended	29
PE	potential evapotranspiration for an individual month	7
$\overline{PE}$	long-term mean potential evapotranspiration for a calendar month	11

*Page on which symbol is introduced.

		Page*
PL	potential loss of soil moisture, PL_s+PL_u	10
$\overline{PL}$	long-term mean potential loss of soil moisture for a calendar month	13
PL_s	potential loss of soil moisture from the surface layer	10
PL_u	potential loss of soil moisture from the underlying soil	10
PR	potential recharge; amount of moisture required to bring the soil to field capacity	9
$\overline{PR}$	long-term mean potential recharge for a calendar month	13
PRO	potential runoff	11
$\overline{PRO}$	long-term mean potential runoff for a calendar month	13
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R	recharge; net gain in soil moisture during month	11
$\overline{R}$	long-term mean soil moisture recharge for a calendar month	13
$\hat{R}$	CAFEC soil moisture recharge	14
RO	computed runoff	9
$\overline{RO}$	long-term mean runoff for a calendar month	13
$\widehat{RO}$	CAFEC runoff	14
S	amount of available moisture in both layers of soil at the end of a month, S_s+S_u	9
S'	amount of available moisture in both layers of the soil at the start of a month	10
S_s	amount of available moisture in the surface soil layer at the end of a month	9
S'_s	amount of available moisture in the surface soil layer at the start of a month	7
S_u	amount of available moisture in the underlying soil at the end of a month	9
S'_u	amount of available moisture in the underlying soil at the start of a month	7
t	duration in months	21
T	areal average temperature for a particular month	10
U_d	the amount of dryness effective in ending a wet spell	30
U_w	the amount of wetness effective in ending a drought	29
V	accumulated values of U_d or U_w; the numerator of equation (30)	29
X	the index of drought (or wet spell) severity	21
X_1	(1) drought severity for an initial dry month	22
	(2) severity index for a wet spell that is becoming established. It is also the percent chance that a wet spell has begun	32
X_2	severity index for a drought that is becoming established. It is also the percent chance that a drought has begun	32
X_3	the severity index for any wet spell or any drought that has become definitely established	32
z	the preliminary estimate of Z	18
Z	moisture anomaly index	23
Z_e	the moisture anomaly required to end a "weather spell" in a single month	29

*Page on which symbol is introduced,

METEOROLOGICAL DROUGHT

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ABSTRACT

Drought can be considered as a strictly meteorological phenomenon. It can be evaluated as a meteorological anomaly characterized by a prolonged and abnormal moisture deficiency. Not only does this approach avoid many of the complicating biological factors and arbitrary definitions, it enables one to derive a climatic analysis system in which drought severity is dependent on the duration and magnitude of the abnormal moisture deficiency. Within reasonable limits, time and space comparisons of drought severity are possible. The objective of this paper is to develop a general methodology for evaluating the meteorological anomaly in terms of an index which permits time and space comparisons of drought severity.

The underlying concept of the paper is that the amount of precipitation required for the near-normal operation of the established economy of an area during some stated period is dependent on the average climate of the area and on the prevailing meteorological conditions both during and preceding the month or period in question. A method for computing this required precipitation is demonstrated. The difference between the actual precipitation and the computed precipitation represents a fairly direct measure of the departure of the moisture aspect of the weather from normal. When these departures are properly weighted, the resulting index numbers appear to be of reasonably comparable local significance both in space and time.

Successive monthly index values for past dry periods were combined by a relatively objective procedure to yield an equation for calculating drought severity in four classes—mild, moderate, severe, and extreme. The method of analysis is described and the results of applying the procedure to 76 years of western Kansas weather, 33 years of central Iowa weather, and 32 years of independent data from northwestern North Dakota are presented.

The procedure is tractable for machine data processing by weekly or monthly periods for either points or areas. When this type of climatic analysis has been carried out for a large number of contiguous areas, not only will one obtain drought severity expectancy figures but also other useful items as well. For instance, the analysis will provide wet period expectancies, maps useful in land use capability studies, and material of interest in water resources planning. In addition, some of the derived parameters will very likely prove to be useful in crop yield investigations.

1. INTRODUCTION

Drought means various things to various people, depending on their specific interest. To the farmer drought means a shortage of moisture in the root zone of his crops. To the hydrologist it suggests below average water levels in streams, lakes, reservoirs, and the like. To the economist it means a water shortage which adversely affects the established economy. Each has a concern which depends on the *effects* of a fairly prolonged weather anomaly.

A completely adequate definition of drought is difficult to find. Not only is there disagreement as to the meaning of the word, even its spelling and pronunciation provide room for discussion. It is variously spelled as "drought" and "drouth." Recommended pronunciation for the first spelling is "drout" (as in trout) and the second form becomes "drouth" (as in south) [3]. These interesting sidelights are indicative of the confusion that prevails.

DEFINITIONS

From previous drought studies one can assemble a number of definitions, such as:

1. A period with precipitation less than some small amount such as 0.10 in. in 48 hr. [6].
2. A period of more than some particular number of days with precipitation less than some specified small amount [16].
3. A period of strong wind, low precipitation, high temperature, and unusually low relative humidity (this has been referred to as "atmospheric drought") [7].
4. A day on which the available soil moisture was depleted to some small percentage of available capacity [68].
5. A period of time when one or all of the following conditions prevailed: (a) Pasturage becoming scarce, (b) Stock losing condition from fair order, (c) Hand feeding in vogue, (d) Agistment of stock [72].
6. Monthly or annual precipitation less than some particular percentage of normal [30].
7. A condition that may be said to prevail whenever precipitation is insufficient to meet the needs of established human activities [20].

The list could be extended, but nearly all have in common a certain arbitrariness difficult, in some cases, to defend. A surprising number ignore the protracted dry spell concept given in most dictionaries and emphasized by Linsley et al. [28], and only a few, such as the *Glossary of Meteorology* [22] and Blair [5] recognize that drought is a relative term.

It appears that the press and the general public use the term in a more consistent way than do meteorologists, climatologists, hydrologists, and the other scientists who have done work on the subject. It is worthy of note that the term does not ordinarily appear in the public press until an area has endured an unusual moisture deficiency for an extended period of time. Those journalists who use such expressions as "drought of investment capital" and "man-power drought" must assume their share of responsibility for using "drought" as a synonym for "shortage."

However, most farmers do not call a "dry spell" a drought until matters begin to become rather serious. In spite of the differences which exist, the people in humid climates seem to mean much the same thing when they refer to drought as do the people in a semiarid region; viz, that the moisture shortage has seriously affected the *established* economy of their region. From consideration of the many facets of the problem, it is possible to formulate a generalized definition that can be used as a starting point. Drought is therefore defined here as a prolonged and abnormal moisture deficiency. This is essentially the definition given by the American Meteorological Society [22]. At the outset this definition may appear to be too generalized for any useful purpose, but examination will show that it established the guidelines necessary for further work. Foley [14] presented an excellent discussion based on a somewhat similar generalized approach.

This may be regarded as a generalized meteorological definition rather than a specific biologic or hydrologic one. In fact, many of the specialized aspects and ramifications of drought can be accommodated by the definition. This generalized definition has been chosen deliberately in order that the phenomenon may be studied in as objective a manner as possible without first having arbitrarily defined "prolonged", or "abnormal" or "moisture deficiency."

POINTS OF VIEW

Agricultural drought is probably the most important aspect of drought, but that problem is far more specialized and complicated than some investigators seem to realize. A study of agricultural drought immediately leads one into the realms of soil physics, plant physiology, and agricultural economics. Of all the available possibilities one must choose a particular one, thereby limiting the useful results to particular crops grown under specified conditions of soil and cultural practices.

Hydrologic drought, concerned as it is with reductions in stream flow and in lake and reservoir levels, depletion of soil moisture, a lowering of the ground-water table, and the consequent decrease in ground-water runoff [21], also poses specialized problems. This is far from being a purely meteorological problem. It is, in fact, more of an engineering problem which involves not only meteorology and hydrology, but geology and other geophysical sciences as well.

As a matter of fact, both agriculture and hydrology are more concerned with the effects of the moisture shortage than with the purely meteorological aspects. The onset of the effects can be immediate or delayed; likewise, recovery from a recent moisture shortage can be almost immediate or delayed, depending on the particular circumstances of the area and activity affected. For these and other reasons crop yields, pasture conditions, stream flow, lake levels, and the like are not particularly satisfactory measures of the severity of meteorological drought. Probably the severity is most closely related to some localized economic measure of the disruption of the established economy. If such a measure exists, it has not come to the author's attention. In this connection it should be mentioned that man-made drought, a demand, created by economic development, for more water than is normally available in an area, was not considered in this study. However, the procedures developed here will shed some light on the problems of such over-developed regions.

SPECULATIONS CONCERNING THE DEFINITION

During recent years the U.S. Government has recognized and provided economic aid to areas which have endured "disaster." Among the various things that can create a disaster is drought. This is not generally considered to be a moisture deficiency that causes mere inconvenience or even one that creates mild hardship, but rather a shortage of water so unusual that it creates destruction or ruin, as of life or property [31]. It is almost impossible for this degree of drought disaster to develop over a short period of time; at least two or three months of extremely unusual weather are required and ordinarily the time is much greater, say a year or more [18].

This relatively substantial fact concerning disastrous drought provides a general framework for speculation concerning the period of time involved in a definition of "prolonged"; it is apparently of the order of months. However, it seems reasonable to postulate that a mild drought could develop in a single month.

It may at first seem that "moisture deficiency" should be easier to define than "prolonged," and in some respects it is. However, more is involved than a mere rainfall record. An area may welcome a period of dry weather if the period immediately preceding was unusually wet. The dry weather provides an opportunity for getting rid of an oversupply of water and allows the area to operate on a more normal basis—a basis which is ordinarily adjusted to the climatic averages, having been arrived at by many years of trial and error. Antecedent conditions must therefore be taken into account when evaluating the adequacy of rainfall. One indirect method for accomplishing this is through measurements or estimates of the amount of available soil moisture at the beginning of the period of little or no precipitation. Soil moisture may therefore be regarded as an *index* of antecedent weather conditions. Deficiency, of course, implies a demand which exceeds supply; however, the "abnormal" aspect must also be considered.

A thing is abnormal that deviates markedly from what has been established as some measure of the middle point between extremes. It is therefore reasonable to state that a period during which moisture need exceeds moisture supply by an *unusual* amount could be considered as a period of abnormal moisture deficiency. By this postulate of abnormality various climates can be placed on a relatively equal basis insofar as drought is concerned.

The foregoing discussion may seem to be largely a matter of semantics; however, it has served to develop a basis for a somewhat meaningful approach to the drought problem. A drought period may now be defined as an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further, the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency.

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2. THE PROBLEM AND OBJECTIVES

This paper does not deal with the fundamental causes of drought. Superficially one can say that drought periods are associated with periods of anomalous atmospheric circulation patterns, but the basic question concerning the physical reasons for the circulation anomalies remains. As Namias has pointed out [33] there are those who consider the circulation changes as self-evolving, while another school of thought holds that the anomalous states of the general circulation are due to extraterrestrial causes. Such controversies point out the necessity for fundamental research. Until such questions are answered and real understanding achieved, explanations of the cause of drought as well as attempts at drought prediction will be premature and inadequate.

Stated in the simplest terms the problem here is to develop a method for computing the amount of precipitation that should have occurred in a given area during a given period of time in order for the "weather" during the period to have been normal—normal in the sense that the moisture supply during the period satisfied the average or climatically expected percentage of the absolute moisture requirements during the period. In other words, the question is how much precipitation should have occurred during a given period to have kept the water resources of the area commensurate with their established use? After determining how much precipitation should have occurred, one can readily compare it with the amount that actually did occur and thereby have a measure of the departure of the moisture supply from the "normal" or climatically appropriate supply.

Unfortunately, the derivation of moisture excesses and deficiencies over a number of periods of time does not solve the problem because the duration factor must be considered and these moisture departures do not constitute a series drawn from a single statistical population [47]. Departures for a series of, say, Mays at a given place represent a different population from the September departures at the same place, and the departures for another month at a different place represent still another population. In order to develop a drought index which is relatively independent of space and time these various departures must be weighted in such a manner that they can be considered as comparable indices of moisture anomaly. The problem is to develop a weighting factor which transforms the various departures in accordance with their apparent significance in the weather and climate of the area being studied. For instance, if in central Iowa during March the actual moisture supply were one inch less than the expected moisture supply, the departure would not be of any great consequence because in their climate the springtime precipitation generally exceeds the water requirements. On the other hand, a similar shortage in western Kansas in August or September would be very important because in this climate any abnormal moisture shortage during the summer months serves to increase the effects of the normally inadequate supply.

The final part of the problem consists of combining these derived indices of moisture anomaly into an index of abnormality for extended *periods* of drought. At the same time systematic procedures must be derived for delineating the abnormal periods.

3. DEVELOPMENTAL DATA USED

In order to develop an index which would allow space as well as time comparisons of drought statistics, two climatically dissimilar areas were chosen for initial study.

The 31 counties comprising the western one-third of Kansas were formerly grouped by the Weather Bureau into one climatological division (now subdivided into three). Therefore the temperature and precipitation data are available [13] for the area as a unit on a monthly basis since January 1887. This region possesses a semi-arid to dry subhumid climate. The winters are rather cold and the summers rather hot with about 13 or 14 in. (70 percent) of the annual precipitation occurring during the freeze-free period of about 5½ to 6 months [58]. In addition to the availability of the data, the Kansas area was chosen because the author is well acquainted by personal experience with the climate in that region, and it was expected, or at least hoped, that his agricultural experience in the western Great Plains [36] would enable him to make a better assessment of the implications of moisture deficiencies in that area. The western one-third of Kansas is for some purposes too large an area to be treated as a unit, but for the purposes of this developmental work that is not a particularly serious objection.

The other area studied was made up of the 12 counties of the central climatological division of Iowa. For this area as a whole the monthly temperature and precipitation data were obtained for the period January 1931 through December 1957. These data probably constitute a more homogeneous series than do the Kansas data, but the sparse data coverage in Kansas during the earlier years is not likely to bias this study to any appreciable extent. The climate of central Iowa can be classed as moist subhumid. The winters are colder than those in western Kansas and the summers are not as warm. Approximately 20 in. (65 percent) of the annual precipitation occurs during the freeze-free period of about 5½ to 6 months [57]. While both areas have a continental climate, that of central Iowa is decidedly more humid as evidenced by the following facts:

(a) Average precipitation in central Iowa exceeds that of western Kansas by about 10 in. per year.

(b) Iowa has about 40 percent more days with measurable precipitation than does the Kansas area.

(c) The relative humidity in Iowa averages 12 to 15 percent higher than it does in Kansas.

(d) Western Kansas is less cloudy than central Iowa; therefore it receives more solar radiation.

(e) Average wind speeds are somewhat greater in Kansas than in Iowa.

The point in emphasizing these differences is to show that weather which would be considered normal in western Kansas would be considered exceptionally dry were it to occur in central Iowa. Inasmuch as the economy in Iowa is not geared to such dry weather, considerable loss and hardship would result; the local people would most likely consider that they were having a disastrous drought. On the other hand, a smaller absolute departure toward aridity would create a very serious disruption of the economy in western Kansas because an inch of rain is so much more important there than it is in Iowa. It is obvious that the effect of a moisture shortage is relative. Therefore these two areas were chosen because their climates are different and the problem is to fit both into a scheme which will produce locally meaningful measures of drought.

Some may wonder why areas have been chosen for study rather than points. Of course point data could have been used, but for developmental purposes it was easier to deal with areal averages, thereby avoiding the extreme variability of point weather. The objective here is to deal with drought, which is often prolonged and widespread, rather than with dry spells which are generally considered to be of shorter duration and more or less random in their occurrence at points. Actually, the method developed has been applied to point data (see Appendix C), but the results have more climatological meaning and may be easier to interpret if they apply to homogeneous climatological areas rather than to points.

This study is based on periods no shorter than one month. This is objectionable in that no account is taken of the distribution of precipitation within the month. Although this produces errors in the timing of computed moisture deficiencies, it is not likely seriously to bias the magnitude of the total moisture deficiency during abnormally dry periods, the item with which this study is primarily concerned. Shorter periods have been studied by machine methods and results seem to justify the preceding statement. Daily and weekly analyses are discussed in Appendix C. A very practical reason for using monthly data was that this is the form in which the data are most readily available, but more important is the fact that the use of daily or weekly data would have increased the amount of work almost to the point where this project would have become a career rather than an investigation.

The meteorological data used in this investigation were the monthly areal averages of temperature and precipitation for each individual month during the period January 1887 through December 1957 for the western one-third of Kansas and similar areal averages for central Iowa for the period January 1931 through December 1957.

4. TECHNIQUES USED AND THEIR LIMITATIONS

The water balance or hydrologic accounting approach to climatic analysis allows one to compute a reasonably realistic picture of the time distribution of moisture excesses and deficiencies. The advantages and disadvantages of various methods for computing the water balance have been too often discussed in the literature to require further detailed discussion here. Only a few general remarks seem necessary.

It is well known that evaporation is a very complicated function of the climatic elements; however, close network observational data are not available for some of the elements such as net radiation, vapor pressure deficit, and wind speeds at appropriate levels. This complication has led a number of investigators to attempt to estimate evaporation on the basis of the more numerous temperature and precipitation data. One of the foremost among these systems is that of Thornthwaite [48].

Thornthwaite's formula has been widely criticized for its empirical nature—but more widely used. It is obvious that Thornthwaite had long been aware of the physical factors involved in the evaporation and transpiration processes [49]. His empirical scheme merely provides a simple usable approximation to the climatic moisture demand. In spite of its simplicity and obvious limitations, no less an authority than Dr. H. L. Penman regards the Thornthwaite relationship as doing surprisingly well [39]. A rather complete account of the work of Thornthwaite with a long list of pertinent references has been published [50]. Although this drought study is based on this method of estimating potential evapotranspiration, there is no reason why a different method cannot be substituted as the basic working tool in a study such as this—if and when a more useful method is developed. The fact that a large number of such methods appears in the literature shows that the problem is not at all simple and that no solution so far has been found to be entirely satisfactory.

In this study potential evapotranspiration was computed from Thornthwaite's formula by means of the Palmer-Havens Diagram [37, 38] and used as a measure of the climatic demand for moisture. In order to carry out a realistic hydrologic accounting most investigators have found it necessary to derive "actual" evapotranspiration as a function of potential evapotranspiration and the dryness of the soil. There are some difficulties involved in this question of the availability of soil moisture. An unresolved argument of considerable proportions is, and has been for many years, underway among soil physicists, plant physiologists, and others [69]. If a climatologist may be permitted an opinion in this matter, it seems that West and Perkman [71] may have pointed to the source of the disagreements in their observations concerning the extent to which the roots of plants thoroughly permeate soils under some circumstances but only partially occupy the soil under other conditions.

As there does not appear to be a universally acceptable procedure for dealing with the question of the availability of water, rules are required to convert current ignorance into working practice. An empirical procedure which Marlatt [29] tried in 1957 at this author's suggestion and found to be fairly satisfactory was adopted here. This procedure, which was also tried by Kohler [24] at about the same time or a little earlier, consists of dividing the soil into two arbitrary layers. The undefined upper layer, called surface soil and roughly equivalent to the plow layer [52], is assumed to contain 1 in. of available moisture at field capacity. This is the layer onto which the rain falls and from which evaporation takes place. Therefore, in the moisture accounting it is assumed that evapotranspiration takes place at the potential rate from this surface layer until all the available moisture in the layer has been removed. Only then can moisture be removed from the underlying layer of soil. Likewise, it is assumed that there is no recharge to the underlying portion of the root zone until the surface layer has been brought to field capacity. The available capacity of the soil in the lower layer depends on the depth of the effective root zone and on the soil characteristics in the area under study. It is further assumed that the loss from the underlying layer depends on initial moisture content as well as on the computed potential evapotranspiration (PE) and the available capacity (AWC) of the soil system. Therefore,

$$L_s = S'_s \text{ or } (PE-P), \qquad (1)$$

whichever is smaller and

$$L_u = (PE-P-L_s)\frac{S'_u}{AWC}, \qquad L_u \leq S'_u \qquad (2)$$

where L_s=moisture loss from surface layer,

S'_s=available moisture stored in surface layer at start of month,

PE=potential evapotranspiration for the month,

P=precipitation for the month,

L_u=loss from underlying levels,

S'_u=available moisture stored in underlying levels at start of month, and

AWC=combined available capacity of both levels.

Further, it is assumed that no runoff occurs until both layers reach field capacity. This is, of course, not an entirely satisfactory assumption, as Kohler [24] has pointed out, and this point is further discussed below.

As previously stated, the maximum water requirements of a region are here estimated by Thornthwaite's potential evapotranspiration term. How realistic is this computed value? PE is an empirically derived quantity which, from the Seabrook data [10] and other sources [9], is estimated to be in error by as much as 100 percent or more on occasional individual days and to show an average daily absolute error of approximately 35 percent. However, as one increases the period of time considered, the average percent absolute error decreases to approximately 10 to 15 percent for periods of about 2 weeks or longer. This suggests that for the climatological analysis of monthly moisture requirements, the computed PE is not seriously in error in climates of the type being used in this investigation.

The PE concept is, by implication, applicable only during periods when vegetation is growing actively. This suggests that during the colder months PE may not be a particularly good measure of the moisture needs of an area. Considering the fact that in most temperate regions precipitation normally exceeds PE during these colder months, the question of moisture requirements becomes a problem concerning expected additions to rather than depletions of the moisture storage within a region. These additions may be viewed as additions to the soil moisture reserve or as the buildup of lake, reservoir, and ground water storage. In these instances PE values are relatively meaningless, and one could reasonably take the view that the moisture requirement during such periods is related to some factor which we can call "potential recharge." Just as potential evapotranspiration measures the amount of moisture that could be *used* provided the supply were not limited, potential recharge would measure the amount of moisture that could be *added* provided it rained enough. The way in which this potential recharge concept has been used in this study is discussed in the following section.

By this time it is probably fairly obvious to the reader that the supply and demand concept of the economist is being used here; and, though reasoning by analogy is often misleading, this moisture problem bears certain similarities to the supply and demand problems of a manufacturing establishment. During periods of peak demand, production may be exceeded by demand and previously created inventories are relied upon to meet this demand; whether or not the demand is completely met does not, theoretically, decrease it. During periods of minimum demand, production requirements are those necessary to create suitable inventories.

In the case of the moisture problem the supply side of the picture is represented by the moisture supplied directly by precipitation during the period *plus* the amount of previously stored moisture which is withdrawn to help meet the demand of the period. Inasmuch as the lake, reservoir, and ground water withdrawal cannot be so readily estimated, the degree to which the moisture supply is augmented by previously stored moisture is herein represented by estimates of the amount of the depletion of the available soil moisture. *This procedure was used only because it is a convenient method for converting weather into specific numbers of inches of water demand and use.*

Depletions of soil moisture must be based on evapotranspiration (ET) estimates. In addition to the problems mentioned previously, estimates of ET require that one use a realistic value for the available water capacity (AWC) of the soils in the area under consideration. The AWC varies markedly from soil to soil; however, it is probably no more variable than is microclimate and for the purposes of this study of meteorological drought AWC can be taken as a value which is more or less representative of the area in general. For studies of agricultural drought specifically, AWC must be known [19], or the problem must be solved for a wide range of capacities as was done by van Bavel and Verlinden [68]. A considerable amount of work has been done on the problem of moisture availability in soils, and a résumé of much of this work on soil water and plant growth has been published [41]. There is, however, a dearth of readily available information on even the approximate available water capacities of various soils.

The soils in question in western Kansas are predominantly of Colby series [4] and possess rather good infiltration, retention, and moisture release characteristics. An *AWC* of 6 in. was assumed for this study (1 in. in the surface layer and 5 in. in the lower layers). It is likely that 6 in. is too small a value; however, some experimenting with the use of a 4-in. *AWC* and an 8-in. *AWC* indicated that all three values would give substantially the same results in this particular study because precipitation in this area is ordinarily insufficient to provide more than 3 or 4 in. of stored moisture.

Central Iowa consists of a level to gently rolling area of dark and generally permeable soils which are quite productive. Much of the area is covered by deep soils of the Webster, Clarion, or Muscatine series. Though the Webster soils are rather poorly drained, all the soils are capable of holding fairly large amounts of available water [40]. In this study an available water capacity of 10 in. was assumed for the probable root zone in this region, with 1 in. assigned to the surface layer and 9 in. to the lower layers. Obviously, not all points in the region possess soils having an *AWC* of exactly 10 in., but this seems to be a reasonable figure to use for the area as a whole.

Another difficulty encountered in making estimates of evapotranspiration involves runoff which of course varies a great deal from place to place and depends on soil, topography, and many other factors [25]. It would be possible to incorporate into this type of study some systematic procedure for handling runoff in a more realistic manner than has been done here. Such a complication has, in fact, been adapted for machine data processing [12]. Perhaps, in time, runoff can be computed as a function of deficiency and precipitation, somewhat along the lines suggested by Kohler and Richards [26]. However, herein it has been assumed that runoff occurred whenever precipitation fell and the full amount of available water was already stored in the soil. In the western Kansas area this procedure produced an average annual computed runoff of 0.29 in. which is about 1.5 percent of the average annual precipitation. This figure agrees rather well with the Geological Survey estimate [27]. In central Iowa, on the other hand, the computed average annual runoff was 5.58 in. which is approximately 1 in. larger than the Geological Survey estimate for this region [27]. This does not appear to be a particularly serious departure from reality, the discrepancy being only a few days of moisture supply at midsummer use rates. If this were specifically an irrigation study, an error of this size would be too large to tolerate; but for the type of climatological analysis involved here the amount of precipitation which is assigned as runoff appears to be reasonably correct. The most serious objection is that the runoff is not always allowed to occur at the proper time. These timing errors probably produce some bias in the analysis. It seems likely that in the two climates studied here the moisture situation sometimes appears slightly more favorable than it really was, particularly in summer. Remember too that this study deals with areas rather than points and inasmuch as precipitation at excessive rates seldom covers large areas [45], the climatological analysis is probably not affected as seriously as one might first suppose.

5. PROCEDURE AND DISCUSSION

In brief, the procedure, which is described in some detail in subsequent sections, consists of the following steps:

1. Carry out a hydrologic accounting by months for a long series of years.
2. Summarize the results to obtain certain constants or coefficients which are dependent on the climate of the area being analyzed.
3. Reanalyze the series using the derived coefficients to determine the amount of moisture required for "normal" weather during each month.
4. Convert the departures to indices of moisture anomaly.
5. Analyze the index series to develop:
    a. Criteria for determining the beginning and ending of drought periods.
    b. A formula for determining drought severity.

HYDROLOGIC ACCOUNTING

The hydrologic accounting procedure is illustrated by the central Iowa data for the years 1933–35 in table 1. The previous year, 1932, was relatively wet in central Iowa and both layers of the soil were computed to have been at field capacity at the end of December 1932. This condition persisted until April 1933 when PE exceeded the precipitation (P) by 0.47 in. Column 5 shows that this 0.47 in. was withdrawn from the surface layer (in accordance with equation (1)), thereby reducing the surface layer storage to 0.53 in. by the end of April as shown in column 7. The loss from the underlying soil was zero (col. 6) and the storage in the underlying soil remained unchanged from the previous month (col. 8). Note also that the total loss, L, from both soil layers is carried in column 13. There was, of course, no net recharge and no runoff so columns 11 and 15 show zero for this month. The 0.47 in., withdrawn from the surface layer at the potential rate, is added to the precipitation to give a computed evapotranspiration of 1.63 in. (col. 14). Column 9 shows that the available water in both soil layers was reduced to 9.53 in. by the end of April.

May was rather wet and precipitation exceeded PE by 2.04 in. Only 0.47 in. was required to return the soil to field capacity and the remainder, 1.57 in., was assigned as runoff (col. 15). The 0.47 in. appears as a positive change in storage in the surface layer (col. 5) and since no change occurred in the underlying soils, total recharge in column 11 is also 0.47 in.

June was dry and hot and PE exceeded the rainfall by 5.34 in. After the inch of available moisture in the surface layer was used at the potential rate, the weather still "demanded" 4.34 in. from the soil. By equation (2) the loss from the lower portion of the soil was computed as 3.91 in. (col. 6), thereby reducing the available soil moisture to 5.09 in. (col. 9) all of which was in the lower layer (col. 8). The computed evapotranspiration ($P+L$) during June (5.94 in. in col. 14) was not far short of the PE for the month, but it was obtained largely at the expense of the previously stored soil moisture; column 13 shows 4.91 in. of water lost from the soil during June. The remainder of the table further illustrates this two-level moisture accounting method.

POTENTIAL VALUES

There are some items in table 1 which, although not used directly in the water balance computations, have been tabulated as part of the accounting procedure because they will be needed later. The potential recharge (PR col. 10) is such an item. Potential recharge can be considered as a measure somewhat similar to potential evapotranspiration, similar in that it measures some supposedly maximum condition that could exist. Just as the difference between evapotranspiration and potential evapotranspiration measures one aspect of the moisture deficiency during a period, the difference between recharge and potential recharge is related to another aspect of the moisture deficiency. Potential recharge is defined as the amount of moisture required to bring the soil to field capacity.

TABLE 1.—*Hydrologic accounting for central Iowa. Available water capacity=1.00 inch in surface layer and 9.00 inches in underlying levels*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Year	T (°F.)	P	PE	ΔS_s	ΔS_u	S_s (at end of month)	S_u	S	PR	R	PL	L	ET	RO
1933														
January	32.3	0.90	0.01	0	0	1.00	9.00	10.00	0	0	0.01	0	0.01	0.89
February	22.6	.21	0	0	0	1.00	9.00	10.00	0	0	0	0	0	.21
March	36.3	3.22	.31	0	0	1.00	9.00	10.00	0	0	.31	0	.31	2.91
April	48.5	1.16	1.63	−.47	0	.53	9.00	9.53	0	0	1.57	.47	1.63	0
May	60.6	5.60	3.56	.47	0	1.00	9.00	10.00	.47	.47	3.26	0	3.56	1.57
June	77.8	1.03	6.37	−1.00	−3.91	0	5.09	5.09	0	0	5.83	4.91	5.94	0
July	76.3	3.57	6.22	0	−1.35	0	3.74	3.74	4.91	0	3.17	1.35	4.92	0
August	70.3	1.84	4.84	0	−1.11	0	2.63	2.63	6.26	0	1.81	1.11	2.95	0
September	69.7	3.57	4.18	0	−.16	0	2.47	2.47	7.37	0	1.10	.16	3.73	0
October	49.8	1.95	1.52	.43	0	.43	2.47	2.90	7.53	.43	.38	0	1.52	0
November	37.9	.26	.34	−.08	0	.35	2.47	2.82	7.10	0	.34	.08	.34	0
December	26.9	.89	0	.65	.24	1.00	2.71	3.71	7.18	.89	0	0	0	0
1934														
January	26.1	1.34	0	0	1.34	1.00	4.05	5.05	6.29	1.34	0	0	0	0
February	25.1	.59	0	0	.59	1.00	4.64	5.64	4.95	.59	0	0	0	0
March	34.4	1.01	.09	0	.92	1.00	5.56	6.56	4.36	.92	.09	0	.09	0
April	50.1	.61	1.82	−1.00	−.12	0	5.44	5.44	3.44	0	1.46	1.12	1.73	0
May	70.0	.76	5.08	0	−2.33	0	3.11	3.11	4.56	0	2.76	2.33	3.09	0
June	78.4	2.10	6.53	0	−1.37	0	1.74	1.74	6.89	0	2.03	1.37	3.47	0
July	79.3	4.68	6.82	0	−.36	0	1.38	1.38	8.26	0	1.19	.36	5.04	0
August	72.9	2.83	5.25	0	−.34	0	1.04	1.04	8.62	0	.72	.34	3.17	0
September	61.1	5.59	3.02	1.00	1.57	1.00	2.61	3.61	8.96	2.57	.31	0	3.02	0
October	56.5	1.15	2.26	−1.00	−.03	0	2.58	2.58	6.39	0	1.33	1.03	2.18	0
November	41.7	5.15	.60	1.00	3.55	1.00	6.13	7.13	7.42	4.55	.15	0	.60	0
December	21.0	.34	0	0	.34	1.00	6.47	7.47	2.87	.34	0	0	0	0
1935														
January	20.6	1.53	0	0	1.53	1.00	8.00	9.00	2.53	1.53	0	0	0	0
February	28.5	1.44	0	0	1.00	1.00	9.00	10.00	1.00	1.00	0	0	0	.44
March	39.9	1.46	.62	0	0	1.00	9.00	10.00	0	0	.62	0	.62	.84
April	46.4	1.24	1.39	−.15	0	.85	9.00	9.85	0	0	1.35	.15	1.39	0
May	54.8	4.13	2.70	.15	0	1.00	9.00	10.00	.15	.15	2.51	0	2.70	1.28
June	65.4	8.65	4.27	0	0	1.00	9.00	10.00	0	0	3.94	0	4.27	4.38
July	78.6	4.43	6.66	−1.00	−1.11	0	7.89	7.89	0	0	6.09	2.11	6.54	0
August	72.9	1.64	5.25	0	−2.85	0	5.04	5.04	2.11	0	4.14	2.85	4.49	0
September	64.5	3.89	3.46	.43	0	.43	5.04	5.47	4.96	.43	1.74	0	3.46	0
October	50.7	3.55	1.60	.57	1.38	1.00	6.42	7.42	4.53	1.95	1.02	0	1.60	0
November	33.9	2.89	.07	0	2.58	1.00	9.00	10.00	2.58	2.58	.07	0	.07	.24
December	21.6	1.31	0	0	0	1.00	9.00	10.00	0	0	0	0	0	1.31

NOTE: Values in columns 3–15 are inches of water.

$$PR=AWC-S', \tag{3}$$

where S' is the amount of available moisture in both layers of the soil at the beginning of the month.

Potential loss (PL col. 12) expresses another measure of a maximum condition that could exist. It is defined as the amount of moisture that could be lost from the soil provided the precipitation during the period were zero. It is assumed that PE for the period and the initial soil moisture conditions were as "observed."

$$PL=PL_s+PL_u, \tag{4}$$

where $PL_s=PE$ or S'_s, whichever is smaller, and $PL_u=(PE-PL_s)\ S'_u/AWC$.

Potential loss allows one to evolve some measure of a condition such as existed during June 1933 in Iowa. Under the initial condition for that month (see table 1) one would expect no recharge; therefore the fact that none occurred is not surprising and cannot be used as a measure of the unusual dryness of the month. ET as computed was 93 percent of PE, so this small shortage does not adequately express the dry condition. The unusual thing was that nearly 50 percent of the available moisture was removed from the soil during a single month. When we compare this loss with the potential loss, it is seen that it represents about 84 percent of potential. This is an unusually large percentage, much larger than would normally be expected to occur in central Iowa in June. As will be shown later the actual loss in Iowa during June averages only 17 percent of the potential loss.

In hydrologic accounting one cannot neglect runoff because under some conditions it is the most important thing that is taking place. Having evolved measures of potential recharge and potential loss as well as potential evapotranspiration, there is also a need for some measure of potential runoff, *PRO*.

Consider the case of April 1935 in table 1. Note that at the beginning of April the soil was at field capacity; therefore the potential recharge is zero. The month was somewhat cooler than normal and *PE* was only 1.39 in. Inasmuch as the 27-yr. mean April rainfall is 2.58 in., it is apparent that one could reasonably expect some runoff to have occurred during that month, even if the rainfall were a good deal below average. It turns out that $ET=PE$, $R=PR$, and the loss from the soil was only 0.15 in., 11 percent of *PL;* the runoff was zero. Agriculturally speaking, there was no moisture shortage, but the fact remains that the month was a good deal drier than normal. This unusual dryness shows up in the stream-flow data. The Des Moines river, which drains the western part of the central division of Iowa, averaged 2.4 ft. below its long-term mean stage [59]. If this scheme is to measure the moisture abnormalities of the weather, it must take account of the fact that in situations such as this one the runoff was not as large as one might have expected. Having a measure of potential runoff makes it possible to handle this part of the moisture situation in a manner similar to that used for the other aspects.

Developing this turned out to be more difficult than expected. Actually, of course, the maximum runoff that could occur in a given situation (assuming $PE=0$ and following the accounting rules which are being used) would be equal to the precipitation minus the amount that could be added to the soil. It turns out that this measure cannot be used in this particular study because the approach being used requires that the actual precipitation should not be introduced at this stage of the development. After experimenting with at least a dozen measures and estimates of potential runoff, the following simple reasoning was used.

At the outset one can reasonably assume that runoff is most likely to be small when potential recharge is large and to be large when the soil is already at field capacity and recharge can, therefore, be only zero. Returning to equation (3), it is obvious that potential recharge is largest when S' is smallest and vice versa. For want of a more satisfying relationship one can assume that potential runoff is some function of the amount of soil moisture available and simply write,

$$PRO=AWC-PR=S' \tag{5}$$

This assigns "potential precipitation" as being equal to *AWC*. While this is not a particularly elegant way of handling this problem, it seemed to be the best that could be done at the time. It has worked out better than expected.[1]

The water balance computations were carried out for 27 years of central Iowa data and for 71 years of western Kansas data. The monthly means of the various important items for both areas are shown in table 2. Note that when one processes the data in this manner, one derives a value of average soil moisture recharge as well as a value for average soil moisture loss for most months. For example, in western Kansas many Aprils show a gain in soil moisture and the 71-yr. average gain is 0.55 in. On the other hand many Aprils show a loss for the month and the 71-yr. average loss is 0.26 in. The values of potential evapotranspiration tabulated in table 2 are the averages of all the individual values. This is the reason they do not exactly correspond to the average temperature values.

COEFFICIENT OF EVAPOTRANSPIRATION, α

In humid climates,[2] evapotranspiration is usually nearly equal to potential evapotranspiration; but in rather dry climates the usual condition is for the evapotranspiration to fall a good deal short of the potential. This fact can be used to estimate the amount of *ET* that one can normally expect in any particular climate; i.e., in terms of the *PE* for that climate. For example, consider June in Kansas in table 2. The average *PE* is 5.20 in. and the average *ET* is 3.69 in.; therefore, the average *ET* is about 71 percent of average *PE* in western Kansas in June. This 0.71 is here called the coefficient of evapotranspiration, α

$$\alpha=\overline{ET}/\overline{PE}. \tag{6}$$

Similarly, α for June in central Iowa is about

[1] At the time of this writing so much machine work has been based on "potential precipitation" $=AWC$, that it would be difficult to justify a change in equation (5). However, if the job were to be done over, it now appears that the computed potential runoff would generally be closer to reality if one assigned some rather large constant value to "potential precipitation." For example, one might assume that "potential precipitation" for a month is equal to 3 times the normal precipitation for the month. If this were done, equation (5) would become $PRO=3P-PR$.

[2] "Climate" as used here refers to time as well as place. Each month has a climatic average; so central Iowa has 12 climates.

TABLE 2.—*Long-term means*

	T (° F.)	ET	PE	R	S'	PR	RO	L	S'_s	S'_u	PL	P
Western Kansas: 1887-1957, 71 years AWC_s=1.00 in., AWC_u=5.00 in.												
January	29.8	0.04	0.05	0.34	1.33	4.67	T	0.02	0.61	0.73	0.04	0.37
February	33.3	.13	.14	.51	1.65	4.35	T	.03	.76	.89	.13	.62
March	41.6	.62	.64	.44	2.12	3.88	0.07	.21	.87	1.25	.55	.92
April	52.9	1.62	1.76	.55	2.35	3.65	.08	.26	.70	1.65	.97	1.99
May	62.3	2.90	3.38	.38	2.64	3.36	.07	.53	.59	2.05	1.46	2.83
June	72.6	3.69	5.20	.09	2.52	3.48	.06	.86	.40	2.12	1.97	2.99
July	78.4	3.61	6.37	.03	1.75	4.25	0	.85	.13	1.62	1.65	2.79
August	76.9	2.89	5.69	.02	.93	5.07	0	.44	.03	.90	.84	2.47
September	68.4	1.80	3.67	.01	.50	5.50	0	.15	.03	.47	.29	1.65
October	55.8	1.04	1.88	.25	.35	5.65	0	.04	.01	.35	.11	1.25
November	41.6	.34	.52	.35	.56	5.44	.01	.03	.13	.43	.10	.68
December	32.2	.08	.09	.46	.89	5.11	0	.02	.34	.55	.05	.52
Σ		18.76	29.39	3.43			.29	3.44				19.08
Central Iowa: 1931-57, 27 years AWC_s=1.00 in., AWC_u=9.00 in.												
January	20.5	0	0	0.58	7.49	2.51	0.58	0	0.98	6.51	0	1.16
February	24.5	.02	.02	.49	8.07	1.93	.54	0	1.00	7.07	.02	1.04
March	34.6	.26	.26	.45	8.56	1.44	1.33	0	1.00	7.56	.26	2.04
April	49.1	1.71	1.72	.28	9.01	.99	.83	.23	1.00	8.01	1.57	2.58
May	60.5	3.49	3.59	.26	9.05	.95	.90	.57	.79	8.26	3.10	4.09
June	70.4	4.89	5.19	.09	8.75	1.25	.78	.71	.65	8.10	4.24	5.06
July	75.4	5.56	6.13	0	8.13	1.87	0	2.12	.56	7.57	4.67	3.44
August	72.8	4.40	5.26	.41	6.04	3.96	.02	1.07	.05	5.99	3.13	3.75
September	64.8	3.08	3.52	.74	5.37	4.63	0	.59	.18	5.19	1.81	3.23
October	53.7	1.78	1.97	.45	5.53	4.47	.13	.27	.34	5.19	1.13	2.09
November	36.9	.30	.30	1.36	5.71	4.29	.23	.02	.44	5.27	.21	1.87
December	24.8	0	0	.73	7.04	2.96	.42	0	.84	6.20	0	1.15
Σ		25.49	27.96	5.84			5.76	5.58				31.50

0.94. These coefficients have been computed[3] for each month in both regions and are shown in column 2 of table 3.[4]

These coefficients in themselves do a fairly good job of measuring the agricultural climate. For example, the fact that *ET* averages only a little over one-half of *PE* in July in western Kansas ties in with the fact that this is a very unsatisfactory region for corn production. However, in this study these coefficients are used to estimate the amount of *ET* that would be normal for a particular place after having taken account of the moisture demand (*PE*) during that month. In other words, if in western Kansas a particular June was much warmer than normal, say $PE=6.00$ in., then *ET* would have to be 0.71×6 or 4.26 in. in order that *ET* should bear its normal relation to the climatic demand for moisture. This derived evapotranspiration, 4.26 in. in this case, will be called the "*CAFEC*" (Climatically Appropriate For Existing Conditions) evapotranspiration. This derived evapotranspiration can be compared with the *ET* as computed in the original hydrologic accounting and thereby one gains some measure of the abnormality of this particular aspect of the moisture situation. For

TABLE 3.—*Climatic coefficients and constants*

1	2	3	4	5	6	7
	α	β	γ	δ	k	K
WESTERN KANSAS						
January	0.9466	0.0722	0.0023	0.4694	0.99	2.58
February	.9754	.1166	.0020	.2290	1.00	2.20
March	.9679	.1136	.0317	.3730	.96	1.84
April	.9218	.1499	.0359	.2688	1.02	1.54
May	.8581	.1155	.0266	.3613	1.12	1.38
June	.7099	.0268	.0251	.4332	1.38	1.28
July	.5660	.0071	0	.5151	1.76	1.38
August	.5074	.0040	0	.5274	1.96	1.66
September	.4899	.0009	0	.5272	2.04	1.87
October	.5533	.0436	0	.3519	1.65	1.82
November	.6596	.0652	.0195	.3245	1.23	2.04
December	.9223	.0900	0	.4055	1.01	2.26
CENTRAL IOWA						
January	1.00	0.2315	0.0776	0	0.50	1.55
February	1.00	.2530	.0670	.1538	.48	1.61
March	1.00	.3129	.1554	0	.35	1.41
April	.9968	.2804	.0919	.1495	.71	1.14
May	.9727	.2790	.0996	.1835	.83	.97
June	.9425	.0709	.0897	.1677	.92	.94
July	.9081	0	0	.4535	1.10	1.28
August	.8357	.1027	.0028	.3418	1.18	.93
September	.8738	.1603	0	.3246	1.12	1.04
October	.9035	.1012	.0244	.2420	1.02	1.28
November	1.00	.3171	.0408	.1150	.88	1.16
December	1.00	.2453	.0603	0	.63	1.52

[3] The coefficients were computed from long-term sums rather than from long-term means which accounts for the slight discrepancies noted when one tries to compute table 3 from table 2. The coefficients in table 3 are shown to four decimals to avoid cumulative rounding errors in subsequent calculations.

[4] When $\overline{ET}$ and $\overline{PE}$ both equal zero, consider $\alpha=1.0$; $\alpha=0$ only when $\overline{ET}=0$ and $\overline{PE}>0$.

example, PE in Iowa in June 1934 (see table 1) was 6.53 in. Using $\alpha=0.9425$, from table 3, the *CAFEC* evapotranspiration is 6.15 in. Note, however, that because of the initial dryness of the soil and the shortage of rainfall during June, the computed ET was only 3.47 in. The difference, 2.68 in., measures the amount by which the moisture supply failed to provide the amount of ET that, from climatic considerations, one might reasonably expect in central Iowa during such a warm June.

COEFFICIENT OF RECHARGE, β

In many places soil moisture recharge is a seasonal affair. Table 2 shows that the main recharge period in central Iowa is November through March. During this period PE is very small, and the moisture need is a need for rebuilding the moisture supply that was depleted by the weather of the past summer. Just as ET cannot exceed PE, the recharge R cannot exceed the potential recharge PR and is ordinarily a good deal less than the potential except in climates that are humid to superhumid and in areas with small water storage capability.

The ratio of the average recharge to the average potential recharge is called the coefficient of recharge, β

$$\beta=\overline{R}/\overline{PR}. \tag{7}$$

The monthly values of β are shown in table 3. They range from at or near zero during the moisture-depletion seasons of the year to as high as 32 percent during some months of the moisture-recharge season in Iowa. These coefficients, when used in conjunction with the potential recharge for a particular month, enable one to estimate the *CAFEC* recharge, i.e., the recharge that would have been climatically appropriate for the conditions of the time and place being examined. For example, PR in Iowa at the beginning of June 1934 (see table 1) was 6.89 in. The coefficient of recharge during June in Iowa is 0.0709. *CAFEC* recharge is therefore $6.89\times0.0709=0.49$ in. This is to say that the addition of 0.49 in. of moisture to the soil during June 1934 would have been climatically appropriate in view of the initial dryness of the soil. Actually, the computed recharge was zero, so the 0.49 in. represents an abnormal deficit of soil moisture recharge.

In the preceding section on the coefficient of evapotranspiration it was shown that the expected evapotranspiration for June 1934 in central Iowa was 6.15 in. To this we can add the 0.49 in. of expected recharge and show, so far, a need for 6.64 in. of moisture. This is not a "maximum moisture need" measurement; it might better be called a "customary or established moisture use" estimate.[5]

COEFFICIENT OF RUNOFF, γ

As pointed out earlier, potential runoff is related to the initial amount of available water in the soil and for simplicity has been set equal to it as shown in equation (5). The coefficient of runoff γ can be obtained in the same manner as were previously discussed coefficients.

$$\gamma=\overline{RO}/\overline{PRO}=\overline{RO}/\overline{S'}. \tag{8}$$

The monthly values of γ for both central Iowa and western Kansas are shown in column 4 of table 3.

Returning to the trusty example of June 1934 in central Iowa, the *CAFEC* runoff can be calculated by multiplying 0.0897, the June value of γ from table 3, by 3.11, the amount of moisture in the soil at the end of May 1934 (see table 1). This gives 0.28 in. for the *CAFEC* runoff for this particular month.

Adding this to the *CAFEC* evapotranspiration and the *CAFEC* recharge for this month, we have $6.15+0.28+0.49=6.92$ in. This represents the amount of moisture that was needed in order to maintain the water resources of the area at a "normal" level. However, this does not represent the amount of precipitation that was "needed", because there was at the beginning of June some moisture in the soil which could be expected to supply a part of the evapotranspiration, if necessary. The computation of the "expected" loss from the soil is discussed in the following section.

COEFFICIENT OF LOSS, δ

Following the same reasoning used previously, the Coefficient of Loss δ can be determined:

$$\delta=\overline{L}/\overline{PL}. \tag{9}$$

The monthly values of δ are shown in table 3.

[5] It is unfortunate that these rather odd expressions need be introduced, but we are not well-equipped verbally for the task of dealing with some of these concepts.

Note that during summer in Kansas the average computed moisture loss from the soil is approximately 50 percent of the average potential loss. Although the coefficients are larger in western Kansas than they are in central Iowa, the potential loss averages a good deal larger in Iowa (see table 2); therefore, the expected withdrawal of soil moisture is smaller in Kansas—as one would expect.

The example of June 1934 in Iowa can now be completed. The *CAFEC* loss from the soil$=\delta \times PL=0.1677\times 2.03=0.34$ in. This can be subtracted from the previously computed 6.92 in. of moisture needed thereby giving 6.58 in. of *CAFEC* precipitation. This is the amount of precipitation that would have maintained the water resources of the area at a level appropriate for the established economic activity of the area.

CAFEC PRECIPITATION, $\hat{P}$

Summarizing, we have, for any individual month the *CAFEC* quantities (denoted by a circumflex) for evapotranspiration, recharge, runoff, loss, and precipitation:

$$\widehat{ET}=\alpha PE \tag{10}$$

$$\hat{R}=\beta PR \tag{11}$$

$$\widehat{RO}=\gamma PRO \tag{12}$$

$$\hat{L}=\delta PL \tag{13}$$

$$\hat{P}=\widehat{ET}+\hat{R}+\widehat{RO}-\hat{L}. \tag{14}$$

Because of the manner in which each of these components of the *CAFEC* precipitation is computed, each has a mean value equal to the mean value of its counterpart as given in table 2. This is true because,

$$\widehat{ET}_i=\alpha PE_i=\frac{\sum_{i=1}^{n}(ET)}{\sum_{i=1}^{n}(PE)}PE_i,$$

and

$$\sum_{i=1}^{n}(\widehat{ET})=\frac{\sum_{i=1}^{n}(ET)}{\sum_{i=1}^{n}(PE)}\sum_{i=1}^{n}(PE).$$

Therefore

$$\sum_{i=1}^{n}(\widehat{ET})=\sum_{i=1}^{n}(ET)$$

This is to say, for example, that the 71-yr. mean value of the *CAFEC* evapotranspiration for July in western Kansas is 3.61 in., the same as the 71-yr. mean value of the evapotranspiration as determined from the original hydrologic accounting. The same reasoning holds for the other components of the *CAFEC* precipitation. (Of course, the *CAFEC* value and the "actual" value seldom agree in a particular month.)

From this it follows that the long-term mean of the *CAFEC* precipitation is equal to the long-term mean of the actual precipitation. This simply means that the average departure of the actual precipitation from the *CAFEC* precipitation is zero and no bias has been introduced. The departures in individual months therefore represent departures from the average moisture climate of the area being considered. These departures are correlated with, but are by no means identical to, the monthly departures of the precipitation from its long-term mean; in fact, on occasion the two departures may be of opposite sign. In the case of June 1934 in Iowa, the actual precipitation, 2.10 in., departed from the *CAFEC* precipitation, 6.58 in., by -4.48 in., while the departure of the actual from its long-term mean was only -2.96 in. As one would expect from considerations of the antecedent weather, and as was actually the case, the moisture situation during June 1934 in central Iowa was a good deal more serious than is represented by the -2.96 in. departure from long-term mean precipitation. As a matter of fact, the *Iowa Weekly Weather and Crop Bulletin* of July 3, 1934, carried such remarks as: ". . . more wells failing and water being bought and hauled from long distances . . .", ". . . pastures burned up . . ." and ". . . livestock fast going down in flesh . . ." [61].

It should be pointed out that on rare occasions $\hat{P}$ turns out to be negative. This occurs only when the weather has been very wet during a season which is normally quite dry. Negative values are interpreted as indicating that the past weather has been so unusually wet that the area will remain abnormally wet for another month even though no precipitation at all occurs during the month. Although the idea of "negative precipitation" is a bit disconcerting, the few instances in which $\hat{P}$ has been negative have produced reasonable appearing results without introducing any difficulties.

PRECIPITATION EXCESSES AND DEFICIENCIES

When the entire series of data had been reworked and the *CAFEC* precipitation had been computed for each individual month, the difference between the actual precipitation and the *CAFEC* precipitation for each month,

$$d=P-\hat{P}, \tag{15}$$

provided what appear to be meaningful measures of the departure of the moisture aspect of the weather from normal. Table 4 shows an example of the computations for a selected period from the western Kansas record. This period contains the "infamous" year of 1934 when drought forced many of the inhabitants to leave or face starvation. This extremely long period of drought (July 1932 through October 1940) was characterized by unusually warm weather as well as exceptionally dry weather. July 1934 was the most extreme month. The *CAFEC* precipitation for this month (col. 10) was computed by equations (10) through (14) as follows:

$$\hat{P}=(.5660\times 7.90)+(.0071\times 5.86)+(0\times 0.14)-(.5151\times 0.14)=4.44 \text{ in.}$$

This unusually large value is a consequence of the extremely hot weather coupled with the initial dryness created by the hot dry weather which preceded July. Ordinarily almost 25 percent of the evapotranspiration during July comes from previously stored soil moisture, but in this case there was hardly any soil moisture; therefore,

TABLE 4.—*Climatic analysis of moisture departures in western Kansas*

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	PE	PR	PRO	PL	αPE $\hat{ET}+$	βPR $\hat{R}+$	$\gamma S'$ $\hat{RO}-$	δPL $\hat{L}=$	$\hat{P}$ (*)	P	d $(P-\hat{P})$	z $(d\ k)$	Z (dK)
1932													
June	4.80	4.67	1.33	1.06	3.41	0.12	0.03	0.46	3.10	5.56	2.46	3.39	3.15
July	7.04	3.91	2.09	2.09	3.98	.03	0	1.08	2.93	1.78	−1.15	−2.02	−1.59
August	5.97	5.66	.34	.34	3.03	.02	0	.18	2.87	1.53	−1.34	−2.63	−2.22
September	3.41	5.93	.07	.04	1.67	.01	0	.02	1.66	1.28	−.38	−.78	−.71
October	1.63	5.95	.05	.01	.90	.26	0	0	1.16	.62	−.54	−.89	−.98
November	.53	5.97	.03	0	.35	.39	0	0	.74	.10	−.64	−.79	−1.31
December	0	5.97	.03	0	0	.54	0	0	.54	.24	−.30	−.30	−.68
1933													
January	.21	5.73	.27	.21	.20	.41	0	.10	.51	.02	−.49	−.49	−1.26
February	0	5.92	.08	0	0	.69	0	0	.69	.18	−.51	−.51	−1.12
March	.94	5.74	.26	.23	.91	.65	.01	.09	1.48	.58	−.90	−.86	−1.66
April	1.72	5.97	.03	.01	1.58	.90	0	0	2.48	2.17	−.31	−.32	−.48
May	3.36	5.52	.48	.46	2.88	.64	.01	.17	3.36	3.48	.12	.13	.17
June	6.50	5.40	.60	.60	4.61	.14	.01	.26	4.50	.88	−3.62	−5.00	−4.63
July	6.91	5.99	.01	.01	3.91	.04	0	0	3.95	1.84	−2.11	−3.71	−2.91
August	5.41	5.99	.01	.01	2.74	.02	0	.01	2.75	4.91	2.16	4.23	3.59
September	4.30	5.99	.01	.01	2.11	.01	0	.01	2.11	1.33	−.78	−1.59	−1.46
October	2.03	5.99	.01	0	1.12	.26	0	0	1.38	.50	−.88	−1.45	−1.60
November	.78	5.99	.01	0	.51	.39	0	0	.90	.97	.07	.09	.14
December	.40	5.80	.20	.19	.37	.52	0	.08	.81	1.04	.23	.23	.52
1934													
January	.21	5.16	.84	.21	.20	.37	0	.10	.47	.11	−.36	−.36	−.93
February	.18	5.26	.74	.18	.18	.61	0	.04	.75	1.36	.61	.61	1.34
March	.82	4.08	1.92	.82	.79	.46	.06	.31	1.00	.55	−.45	−.43	−.83
April	2.15	4.35	1.65	.95	1.98	.65	.26	.06	2.43	.39	−2.04	−2.10	−3.14
May	4.60	5.23	.77	.59	3.95	.60	.02	.21	4.36	1.24	−3.12	−3.49	−4.31
June	6.16	5.67	.33	.33	4.37	.15	.01	.14	4.39	2.39	−2.00	−2.76	−2.56
July	7.90	5.86	.14	.14	4.47	.04	0	.07	4.44	.74	−3.70	−6.51	−5.11
August	6.54	5.99	.01	.01	3.32	.02	0	.01	3.33	1.44	−1.89	−3.70	−3.14
September	2.80	5.99	.01	.01	1.37	.01	0	0	1.38	1.45	.07	.14	.13
October	2.42	5.99	.01	0	1.34	.26	0	0	1.60	.66	−.94	−1.55	−1.71
November	.80	5.99	.01	0	.53	.39	0	0	.92	.66	−.26	−.32	−.53
December	.08	5.99	.01	0	.07	.54	0	0	.61	.15	−.46	−.46	−1.04
1935													
January	.21	5.92	.08	.07	.20	.43	0	.03	.60	.31	−.29	−.29	−.75
February	.32	5.82	.18	.17	.31	.68	0	.04	.95	.25	−.70	−.70	−1.54
March	1.26	5.89	.11	.10	1.22	.67	0	.04	1.85	.61	−1.24	−1.19	−2.28
April	1.57	5.99	.01	0	1.44	.90	0	0	2.34	.25	−2.09	−2.15	−3.22
May	2.52	5.99	.01	0	2.16	.69	0	0	2.85	4.65	1.80	2.02	2.48

* Col. 10=col. 6+col. 7+col. 8−col. 9.

TABLE 5.—*Monthly moisture departures, d, western Kansas*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1887	−0.21	−0.05	−1.03	1.63	−0.74	−1.24	−0.98	1.48	−0.08	−0.13	−0.29	−0.13
1888	−.23	−.74	.44	2.03	.87	−.57	.30	1.33	−1.13	.38	−.28	−.47
1889	.72	−.12	.38	.35	.56	.82	.27	−.03	−1.09	1.13	.17	−.79
1890	.10	−.26	−.96	1.57	−2.07	−2.28	−2.65	−.98	−.73	−.51	−.17	−.64
1891	.72	−.34	1.74	−.28	1.39	3.07	3.06	0	2.17	.30	−.43	.75
1892	−.04	.64	1.33	−.64	3.52	−.22	.72	1.12	−1.12	−.57	−.37	.11
1893	−.31	−.35	−.71	−1.80	−1.74	−2.14	−.39	−.21	−.05	−.90	−.38	−.61
1894	−.22	.47	−.67	−1.33	−2.17	−1.17	−1.93	−2.08	−.05	−1.07	−.73	.18
1895	.07	.60	−.52	−.99	−.49	1.83	3.56	.09	−1.12	−.26	.11	−.07
1896	.45	−.67	−.36	1.33	−1.32	.14	−.17	−.45	.18	.64	−.16	−.41
1897	.03	.33	.25	2.03	−.92	−.27	.45	1.31	−.41	2.02	−.37	.03
1898	.30	−.44	−.52	−.68	2.86	1.11	.92	−.78	1.97	−.05	.02	.67
1899	0	−.08	−.02	−.93	−1.74	.28	2.72	−1.66	−.47	−.65	.92	.10
1900	−.30	.41	−.25	2.93	−.79	.52	−.12	−1.46	1.50	−.96	−.62	−.43
1901	−.18	.04	.41	1.14	−1.16	−1.91	−2.33	.22	1.25	−.41	−.75	−.22
1902	.06	−.18	.30	−1.44	.67	.43	.24	−.02	.77	.78	−.58	0
1903	−.23	2.16	−.11	1.03	1.88	.96	1.09	.90	−1.00	−.27	−.07	−.43
1904	−.35	−.69	−1.16	−.34	.11	1.05	.51	.41	.60	.20	−.78	.22
1905	.37	.06	−.14	2.20	1.50	.26	2.99	−.67	.08	−.17	1.27	−.40
1906	−.06	−.31	.69	1.20	−.80	.54	2.38	.53	1.07	1.67	.35	−.15
1907	.05	−.39	−.92	−.95	−.91	.37	.60	.24	−.29	−.12	−.44	.73
1908	−.33	.36	−1.03	−1.80	−1.31	1.49	.27	0	−1.06	.42	1.35	−.37
1909	−.10	−.30	.66	−1.20	−.61	2.46	.72	−1.58	.36	−.21	2.83	.60
1910	.23	.01	−1.43	−1.31	−.28	−1.78	−1.61	.68	−.73	−1.24	−.77	−.49
1911	−.40	1.30	−1.06	−1.23	−1.24	−3.61	−.21	.09	−1.15	.07	−.06	.97
1912	−.20	1.46	1.29	.37	−1.08	2.02	.98	2.75	.66	−.57	−.17	−.43
1913	−.13	.31	−.47	−.35	−2.20	−.84	−2.55	−2.81	1.79	−.76	.32	2.64
1914	−.23	.03	−.65	−.05	1.16	.19	.12	.56	−1.11	.09	−.91	−.06
1915	.10	.75	.62	1.58	3.52	2.97	4.25	4.56	1.80	.71	−.31	.03
1916	.46	−.23	−.69	.53	−1.29	.90	−1.90	−.29	−.94	−.32	−.59	−.16
1917	−.19	−.59	−.55	−.10	−.16	−2.11	−1.85	.30	.42	−.76	−.53	−.36
1918	.05	.01	.37	.09	−.13	−2.88	−.15	−1.13	.77	.80	−.17	2.58
1919	−.18	1.18	.56	1.57	.06	.87	.94	−1.31	1.61	.31	.80	−.25
1920	−.21	−.44	−.72	.49	.09	−.24	−.39	.77	.98	1.37	.06	.09
1921	.39	−.23	−.85	.17	−1.29	.39	.39	−.80	.03	−1.10	−.75	.01
1922	−.21	.01	1.02	1.52	.51	−.44	.23	−.81	−1.29	−1.26	.15	−.53
1923	−.52	−.58	−.41	−.25	3.85	2.57	2.08	1.37	1.84	3.42	.02	.41
1924	.03	.51	2.49	−.11	−.35	−1.26	−.10	−.16	.29	−.25	−.66	.72
1925	−.25	−.45	−.88	−.89	−1.53	−2.59	−.93	1.03	.99	0	.35	−.37
1926	−.21	−.58	.27	−.61	−1.47	−1.56	−1.00	−1.01	−.24	−1.28	.17	.07
1927	−.26	−.02	.65	.33	−2.35	1.38	.60	1.65	.01	−1.10	−.70	−.36
1928	−.45	.61	.39	−.53	2.46	3.88	2.87	1.55	−.25	1.67	1.12	.08
1929	.03	.21	−.41	−.27	.69	−.13	.34	−.62	.96	.53	1.23	−.34
1930	−.03	−.72	−.67	−.67	.44	−.68	−.76	−.39	.01	4.32	1.20	.12
1931	−.12	.54	1.84	.38	−.04	−.85	−1.03	.05	−1.62	−.55	.44	−.29
1932	.69	−.32	.18	.14	−1.81	2.46	−1.15	−1.34	−.38	−.54	−.64	−.30
1933	−.49	−.51	−.90	−.31	.12	−3.62	−2.11	2.16	−.78	−.88	.07	.23
1934	−.36	.61	−.45	−2.04	−3.12	−2.00	−3.70	−1.89	.07	−.94	−.26	−.46
1935	−.29	−.70	−1.24	−2.09	1.80	.03	−2.99	−1.69	.51	−.68	.39	−.38
1936	−.04	−.50	−1.08	−1.63	1.25	−2.66	−3.22	−2.07	.31	−.23	−.76	−.11
1937	−.01	−.29	.01	−1.70	−2.49	−.68	−2.25	−1.94	−.69	−.14	−.57	−.25
1938	−.37	−.32	−.35	.02	1.53	−.70	−.98	−2.28	.45	−1.38	−.50	−.52
1939	−.02	.38	.60	−.94	−2.11	−1.18	−2.49	−1.64	−1.99	−1.37	−.67	.10
1940	.23	−.19	.24	−.81	.54	−1.50	−2.33	.62	−.13	−1.19	.93	.05
1941	.68	.31	.08	1.07	1.45	3.78	3.47	1.61	1.83	1.60	−.05	.29
1942	−.02	.29	.38	3.08	−1.11	2.23	.22	.81	.31	1.58	−.35	.52
1943	−.16	−.57	−.36	−.49	−.94	−.73	−1.52	−.68	−1.13	−.63	−.60	.27
1944	1.33	.33	.95	4.91	2.44	−.38	3.56	.29	−.76	−.04	.39	.41
1945	.79	−.03	−.90	1.34	−.59	.98	.13	.09	.18	−.70	−.78	−.07
1946	−.17	−.21	.35	−2.35	.40	−1.01	−1.72	−.96	1.10	4.63	2.73	−.13
1947	.49	.23	1.01	1.01	2.49	1.56	.90	−.79	−1.49	−1.06	.47	.71
1948	.06	.80	1.56	−1.82	−.22	2.17	1.03	1.70	−.86	−.87	.88	−.20
1949	.61	.30	1.19	.23	2.50	4.32	2.65	2.66	−.14	.74	−.81	−.34
1950	−.25	−.17	−.44	−1.05	−1.00	−2.15	3.88	3.98	.12	−.46	−.52	−.55
1951	.31	.10	−.08	.05	2.78	6.15	3.34	1.90	1.79	−.05	.02	−.27
1952	−.18	−.28	.69	1.09	−.47	−3.24	−1.74	−.78	−1.34	−1.15	.20	.01
1953	−.44	−.57	−.21	−.08	−.88	−3.09	−.67	−.06	−1.54	.03	1.29	.71
1954	−.08	−.69	−.34	−1.92	.80	−2.30	−2.19	−.69	−1.40	.18	−.90	−.31
1955	.02	−.16	−.70	−.75	.57	−.17	−2.97	−1.93	.58	−1.27	−.52	−.31
1956	.13	−.21	−.80	−1.39	−2.65	−3.47	−.96	−1.61	−1.82	−.95	−.40	−.69
1957	−.18	−.68	2.13	.68	2.82	3.48	1.30	−.01	1.02	.38	.15	−.58
1958	.16	.20	2.58	.34	1.14	.72	4.44	1.76	.09	−.93	.31	−.05
1959	.36	−.08	.69	−.86	−.42	−1.58	.10	−.22	1.08	2.36	−.32	−.02
1960	1.11	1.84	.74	.03	.08	1.66	−.23	−1.12	−.01	.49	.11	.29
1961	−.36	−.51	.37	−.47	1.21	1.22	.82	1.21	−.69	−.10	1.21	.13
1962	.20	−.27	.90	−.79	−.82	3.09	2.82	.05	.71	−.57	−.15	−.22
*Σ (+)	9.50	15.35	25.07	38.09	46.63	57.66	54.08	38.81	30.38	29.97	20.40	14.41
*Σ (−)	9.21	15.16	25.04	38.12	47.57	57.65	54.04	39.61	30.38	30.00	20.37	14.25
$\bar{d}$	0	0	0	0	0	0	0	.01	0	0	0	0
**$\overline{D}$	.26	.43	.71	1.07	1.34	1.62	1.52	1.10	.86	.84	.57	.40

*Sums are for 1887–1957.

**$\overline{D}$ is the mean of the absolute values.

additional rainfall was required if moisture use was to be "normal."

For the 35-month period beginning with July 1932 the total computed need for precipitation (col. 10) was 69.09 in. This is 14.84 in. greater than the average precipitation (54.25 in. from table 2) for such a period. Actually, the precipitation totaled only 40.66 in. (col. 11), which is 28.43 in. less than the amount that would have been climatologically appropriate for the existing conditions. The point is that although the below-average precipitation, in itself, accounts for 13.59 in. of the computed abnormal moisture deficiency, the procedure outlined here brings to light an additional abnormality of −14.84 in. which is by no means insignificant. This is the result of having taken account of temperature and the other aspects of the water balance.

THE CLIMATIC CHARACTERISTIC, *K*

Column 12 of table 4 shows a sample of the derived monthly moisture departures. Such values were computed for the 852 months of western Kansas data and the 324 months of central Iowa data. These values are shown in tables 5 and 6. From practical as well as statistical considerations it is apparent that a given departure means different things at different places and at different times. We can compare a series of such departures for, say, September in western Kansas; but we cannot compare September departures with, say, February departures, or with departures computed for a different area unless we determine beforehand that the sets of data are truly comparable. This suggests that the importance or significance of each departure somehow depends on the normal moisture climate for the month and place being considered.

In order to evaluate this importance, it was assumed that the economic consequences of the driest year in central Iowa were approximately as serious for the inhabitants of central Iowa as were the consequences of the driest year in western Kansas for the inhabitants of western Kansas. It turned out that the driest period of approximately 1-yr. duration in central Iowa began with June 1933 and continued through August 1934, a period of 15 months. The computed total moisture departure for the entire 15-month period was −30.67 in. or an average of −2.045 in. per

TABLE 6.—*Monthly moisture departures, d, central Iowa*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1930	0.26	−0.40	−1.06	0.18	−0.22	0.09	−2.04	−2.65	−2.14	−0.20	−1.42	−1.32
1931	−1.44	−2.10	−1.51	−1.65	−2.26	−2.62	−.89	−1.65	2.90	.07	.85	2.31
1932	1.25	−.02	−.33	−1.07	.19	.18	.04	3.97	.50	.01	1.39	.76
1933	.11	−.46	1.36	−1.15	1.66	−4.89	−.64	−2.23	−.90	−.15	−2.42	−1.04
1934	−.41	−1.00	−1.32	−2.54	−5.48	−4.48	−.97	−2.20	1.61	−1.31	2.11	−.79
1935	.36	.59	−.71	−.87	.94	4.39	1.14	−1.57	.63	1.76	1.71	.71
1936	.86	.47	−.72	−.79	−1.78	−1.04	−3.97	−2.44	3.83	−.08	−.88	.53
1937	1.03	.39	.14	1.28	.71	−1.05	−.95	.23	−2.17	−.11	−1.36	−.85
1938	−.38	−.75	−.47	1.84	2.59	−.22	1.23	−.81	1.87	−1.48	1.11	−.03
1939	.02	1.42	−.39	−.67	−2.85	.76	−.50	.87	−2.41	−.70	−2.01	−1.05
1940	−.83	−.08	−.61	.83	−1.15	−2.37	1.60	3.65	−1.79	−.26	1.17	.56
1941	1.04	−.21	−.78	−1.34	−2.53	1.78	−.85	−1.36	4.35	4.03	1.05	1.70
1942	.29	.41	.03	−1.89	.96	1.57	2.28	1.29	1.65	.51	.67	.69
1943	0	.19	.09	1.07	1.10	.84	3.00	1.95	1.09	−.03	.27	.18
1944	.59	.31	.96	2.56	4.76	.80	1.81	3.21	−.07	−.95	−.33	.58
1945	−.23	.98	.89	2.35	3.46	−.10	−.40	.70	1.05	−1.56	−.69	.99
1946	1.35	−.50	1.58	−1.90	1.02	2.57	.40	−.24	1.99	2.03	.44	−.18
1947	.76	−.30	−.07	3.15	1.65	7.87	−1.89	−3.39	−3.02	1.77	−.20	.10
1948	−1.06	1.10	1.04	−.29	−1.79	−1.92	.74	−1.47	−2.42	−.46	.56	.49
1949	1.68	.29	.52	−1.23	−2.41	−.50	−.99	−2.44	.09	−.14	−2.17	−.99
1950	−.22	.50	−1.05	.31	2.28	1.35	−.26	−.98	−1.54	−1.28	−1.74	−1.12
1951	−1.07	.91	2.40	3.05	.56	1.40	1.66	2.90	.42	1.54	.90	.35
1952	.51	−.11	2.25	−.90	.22	.36	.85	1.13	−2.07	−1.64	.64	−.01
1953	−.19	.77	.93	1.46	−1.16	−.12	−.16	−2.49	−2.98	−2.59	−1.77	−.94
1954	−1.55	−.45	−.48	.78	.99	1.66	−1.99	6.56	.49	2.56	−.84	−.05
1955	−.03	.56	−.69	.10	−.90	−2.59	.19	−2.57	−.55	−1.29	−2.25	−1.49
1956	−1.33	−1.45	−1.87	−1.41	−1.94	−3.72	−.69	−1.00	−1.73	−1.07	−1.25	−1.46
1957	−1.18	−1.47	−1.15	−1.06	1.10	.08	.14	−.39	−.80	.81	1.02	.07
1958	−.21	−.41	−1.07	−.60	−2.02	.83	6.25	.28	1.11	−1.25	−.10	−.77
1959	−.33	.36	2.06	.80	2.64	−1.46	−.54	−.75	.44	.44	1.02	.42
1960	1.90	.43	.04	.90	2.91	−1.38	−.11	2.38	.86	.09	−1.05	−.40
1961	−.88	1.29	2.37	.50	−1.86	−1.36	3.38	−.33	5.24	1.40	1.64	.92
1962	−.49	1.12	−.02	−.33	.74	−1.93	2.63	−.47	−.76	.56	−1.53	−1.05
*Σ(+)	9.85	8.89	12.19	18.78	24.19	25.61	15.08	26.85	22.47	15.09	17.89	10.02
*Σ(−)	9.92	8.90	12.15	18.76	24.25	25.62	15.15	26.84	22.45	15.10	17.91	10.00
$\bar{d}$	0	0	0	0	0	0	0	0	0	0	0	0
**$\bar{D}$	.73	.66	.90	1.39	1.79	1.90	1.12	1.99	1.66	1.12	1.33	.74

*Sums are for 1931–1957.

**$\bar{D}$ is the mean of the absolute values.

month. Considering the same 27 years as were considered in Iowa, the driest period of similar length in western Kansas was a 14-month period from March 1934 through April 1935. The total moisture departure for this period (see column 12, table 4) was -19.11 in. or an average of -1.365 in. per month.

On the assumption that these dry periods were of approximately equal significance locally, we can multiply each by some factor, K, and write

$$\overline{K}_{Iowa}\times\overline{d}_{Iowa}=\overline{K}_{Kan}\times\overline{d}_{Kan} \tag{16}$$

and

$$\overline{K}_{Iowa}/\overline{K}_{Kan}=\overline{d}_{Kan}/\overline{d}_{Iowa}=-1.365/-2.045=0.67. \tag{17}$$

The $\overline{K}$'s represent averages for some, as yet, undefined characteristics of the climates of these two areas during the 14- and 15-month periods; i.e., they apply to the periods as a whole rather than to each month individually. However, for the moment they can be treated as constants to be evaluated from some measured aspects of the local climate.

From equation (17) it is apparent that $\overline{K}$ for western Kansas must be about 1½ times as large as $\overline{K}$ for central Iowa. Now, the average moisture demand in the two areas is roughly the same but the average moisture supply in Iowa is roughly 1½ times larger than in Kansas. This suggests that the values of the constants may depend on the average moisture shortage in the two places. This seems reasonable inasmuch as the less the supply, in relation to the demand, the greater the significance of a given shortage.

How can one best measure average moisture demand? In some months it can be reasonably estimated by $\overline{PE}$, and in some months it can be estimated by the average amount of recharge that occurs. However, in some spring and fall months $\overline{PE}$ and $\overline{R}$ are roughly equal and both are important. Therefore average moisture demand for any period can be estimated by $\overline{PE}+\overline{R}$.

The average moisture supply is not always dependent entirely on the precipitation. In some cases the precipitation alone does not truly represent all of the moisture supply because previously stored moisture is used also. Therefore, average moisture supply for a month or period can be measured by $\overline{P}+\overline{L}$.

The normal moisture demand for the 14-month dry period in Kansas can be found from table 2 as:

$$\sum_{n=1}^{14}\overline{PE}+\sum_{n=1}^{14}\overline{R}=36.21 \text{ in.}$$

The normal moisture supply for the same period can also be found from table 2 as:

$$\sum_{n=1}^{14}\overline{P}+\sum_{n=1}^{14}\overline{L}=25.90 \text{ in.}$$

If we take the ratio of demand to supply, we get $36.21/25.90=1.398$, which we can call $\overline{K}$ for this 14-month period in Kansas.

Turning to the 15-month period in Iowa and following the same procedure,

$$\left(\sum_{n=1}^{15}\overline{PE}+\sum_{n=1}^{15}\overline{R}\right)/\left(\sum_{n=1}^{15}\overline{P}+\sum_{n=1}^{15}\overline{L}\right)=50.88/53.23=0.956,$$

which can be considered as $\overline{K}$ for this 15-month period in Iowa.

If this ratio of moisture demand and supply can be used as a measure of the importance of moisture departures, then according to equation (17), $\overline{K}_{Iowa}/\overline{K}_{Kan}$ should be about 0.67. It turns out that $0.956/1.398=0.68$, which is in surprisingly good agreement.

From the above it appears that K, the climatic characteristic, can be reasonably estimated for each of the 12 calendar months as:

$$k=(\overline{PE}+\overline{R})/(\overline{P}+\overline{L}) \tag{18}$$

where k is a first approximation of K.

The k-values in column 6 of table 3 were computed by this equation. These numbers are intended as measures of the local significance of the moisture departures which have been derived. However, it later turned out that equation (18) did not work very well in some other climates and a different equation for K had to be derived. Since the work on the final K was dependent on this first approximation, k, the following few pages describe the development based on k and are followed by the "back tracking" which evolved the final equation for K.

THE MOISTURE ANOMALY INDEX, z

These monthly constants, the k-values, were used as weighting factors for each of the monthly moisture departures during the two dry periods being considered. Beginning with March 1934 the departures listed in column 12 of table 4 were multiplied by the corresponding factors in column 6 of table 3 to obtain the index values shown in column 13 of table 4. When the index values, z, were algebraically added for the 14-month Kansas dry period which ended with April 1935, the sum was -25.51. This represents an average index of -1.82 per month.

When the same procedure was followed for the 15-month dry period in Iowa, the 15-month index sum was -27.06 or -1.80 per month. This agrees very well with the average index for the driest Kansas period and suggests that the derived index values do, in fact, provide comparable measures of relative climatic abnormalities. The monthly "moisture anomaly index, z," is therefore defined as:

$$z=dk. \tag{19}$$

What are these z values and what do they mean? They cannot be regarded as inches of departure of the moisture supply from normal as are the values in column 12 of table 4. Those departures have now been weighted and must be regarded only as index numbers. Each number expresses on a monthly basis and from a moisture standpoint the departure of the weather of the month from the average moisture climate of the month. Each has, presumably, been adjusted or weighted in such a way that the same scale—the ordinate, if you wish to think of it graphically—is applicable to all values in both areas.

Small abnormalities of moisture can occur at any time in any place. Of course, this is hardly surprising. Equally to be expected is the fact that in these climates large abnormalities very rarely occur during the cold season from November through February. The largest cold-season anomalies are positive and occur mostly in November as would be expected from the fact that large monthly amounts of precipitation can and sometimes do occur in November. On the other hand, even a complete failure of the moisture supply during any cold month will not result in any very great departure of the moisture supply from normal because in these particular climates the cold season moisture demand or *CAFEC* precipitation is always rather small.

In Kansas and Iowa the really important negative moisture anomalies occur during the warm season. This, again, is as one would expect because the moisture requirement during summer can be rather large and, on occasion, the moisture supply can fail almost completely. Note the very large negative anomalies during July in the 1930's in western Kansas. The -6.51 in 1934 is the largest negative anomaly that has thus far been computed. This large value is a direct consequence of the extremely warm and dry weather which preceded July, coupled with the hot dry weather of July itself. The mean temperature over the area during July 1934 was an all-time record 85.6° F. and the area rainfall averaged only 0.74 in.

While central Iowa has not produced such an extremely dry single month, a number of negative anomalies of the order of -4 have occurred. Also the Iowa data show a greater tendency for long uninterrupted runs of abnormally dry months. The 15-month period which began in June 1933 and the 21-month period beginning with August 1955 were both uninterrupted by even a single wet month.

Some of the unusually wet months in both Kansas and Iowa produce some really outstanding positive anomalies. For example, it rained 12.26 in. over central Iowa in June 1947 and the anomaly index, z, was $+7.24$. Likewise, western Kansas had an index of $+8.49$ for June 1951 owing to 7.89 in. of rainfall which was 267 percent of normal and produced much flooding.

6. THE DURATION FACTOR

THE EFFECT OF TIME

As Hildreth and Thomas have pointed out [18] in most cases it is not the first year of low rainfall that is disastrous to farming and ranching, but the prolonged periods which extend for 2, 3, or 4 years in a row. The same reasoning applies if one is concerned about the hydrologic aspects of drought. A relatively short period of abnormally dry weather will lower lake and reservoir levels, but matters do not become really serious until a prolonged drought period has brought the water supply to a critically low level. Therefore, if one wishes to make a distinction between, say, mild drought and extreme or disastrous drought, the duration of the abnormally dry period must be taken into account.

DROUGHT CATEGORIES

It is reasonable, and it certainly would be convenient, to have names assigned to the various categories of drought severity just as arbitrary names and definitions have been assigned to such things as dense fog, moderate rain, and other phenomena. It appears that drought severity could be adequately expressed by four classes, mild, moderate, severe, and extreme—terms which are frequently used by the U.S. Department of Agriculture as well as by the Weather Bureau. Unfortunately, no satisfactory definitions exit for these expressions. There doesn't seem to be much hope for making even a semi-objective approach to specific definitions of "mild," "moderate," or "severe" drought; but if we assume that "extreme" drought occurred in the two areas being studied during some of the driest periods of record, we can describe extreme drought in terms of the accumulation of the monthly index values.

THE DRIEST INTERVALS

Table 7 shows some accumulated moisture anomaly index values in both central Iowa and western Kansas. These periods were selected as

TABLE 7.—*The driest intervals*

	From—	To—	Number of months	Σz
Kansas	June 1936	August 1936	3	−13.40
Do	May 1913	August 1913	4	−13.62
Do	April 1934	July 1934	4	−14.86
Do	May 1934	August 1934	4	−16.46
Iowa	April 1934	do	5	−14.14
Kansas	do	do	5	−18.56
Iowa	June 1933	June 1934	13	−23.39
Do	do	August 1934	15	−27.06
Kansas	June 1955	September 1956	16	−29.71
Do	do	October 1956	17	−31.28
Do	April 1934	August 1935	17	−31.59
Do	do	August 1936	29	−46.82
Do	do	September 1937	42	−62.55

representing the maximum rate at which the negative values of the monthly index have accumulated during various time intervals. These data are shown in figure 1. The straight solid line thereon was drawn by eye. This line itself does not show rate of accumulation of the index values; it merely indicates the approximate maximum rates which have been observed during extremely

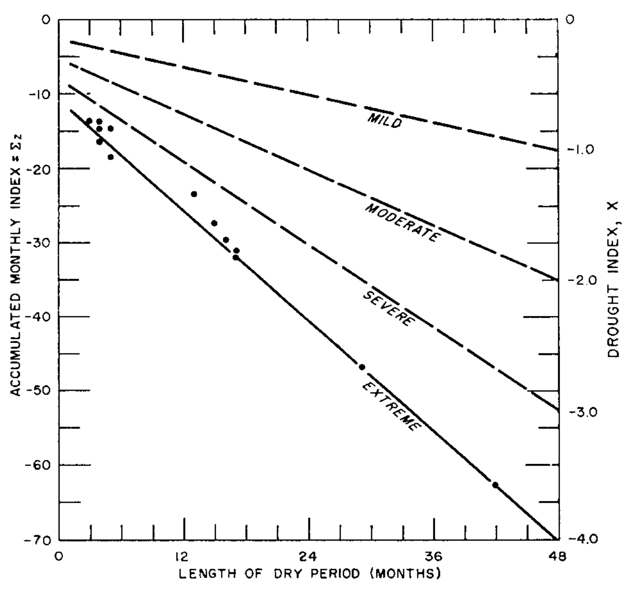

FIGURE 1.—Accumulated index during the driest periods of various lengths.

dry periods of various lengths. For instance, z-values have been known to accumulate at the rate of about -3.0 per month for 6 months, but at the average rate of only -1.5 per month over a 42-month period. Therefore, this line can represent extreme drought; i.e., an extremely dry and very unusual condition exists if $z=-12.00$ for one month as well as if $\Sigma z=-70.1$ in 4 years. This is one of a family of lines that can be drawn. Since the horizontal line at the top of this chart represents "normal," the ordinate from normal to extreme was divided into four equal lengths and the body of the graph was correspondingly divided by the dashed lines arbitrarily labeled "mild," "moderate," and "severe" drought. It is convenient to assign a numerical drought severity value of -4.0 to the line for extreme drought, -3.0 to severe drought, -2.0 to moderate drought, and -1.0 to mild drought. The solid line drawn is therefore the -4.0 line and the equation can be determined by noting that from t (duration)$=1$ month and $z=-12.0$ to $t=48$ months and $\Sigma z=-70.1$, the drought severity$=-4.0$. Drought severity is therefore approximated by

$$X_i=\sum_{t=1}^{i} z_t/(0.309t+2.691). \qquad (20)$$

DETERMINING MONTHLY INCREMENTS OF DROUGHT SEVERITY

Equation (20) is only a first approximation to the relationship sought because it is based on algebraic sums of the index, z, over various periods of time. This is not the best way to handle the problem because this cumulative procedure causes the effect of a single month—say, a very wet month in a long series of dry months—to be directly reflected in Σz even years later. Obviously, this is unrealistic because a single wet month during a given dry summer should not, by the following summer, have any great influence on the severity of a drought which had continued during the intervening period. For instance, August 1933 was a very wet month in Kansas (see table 4) and it greatly reduced the severity of the drought that was underway. However, the drought continued and by the end of May 1934 the situation was very, very serious. But, this seriousness is not completely apparent when the z-values are accumulated and plotted on a diagram such as figure 1. In fact this procedure will create a misleading picture.

Figure 2 demonstrates how misleading the cumulative procedure can be. Figure 2A was constructed by assuming that $z=-1.0$ each

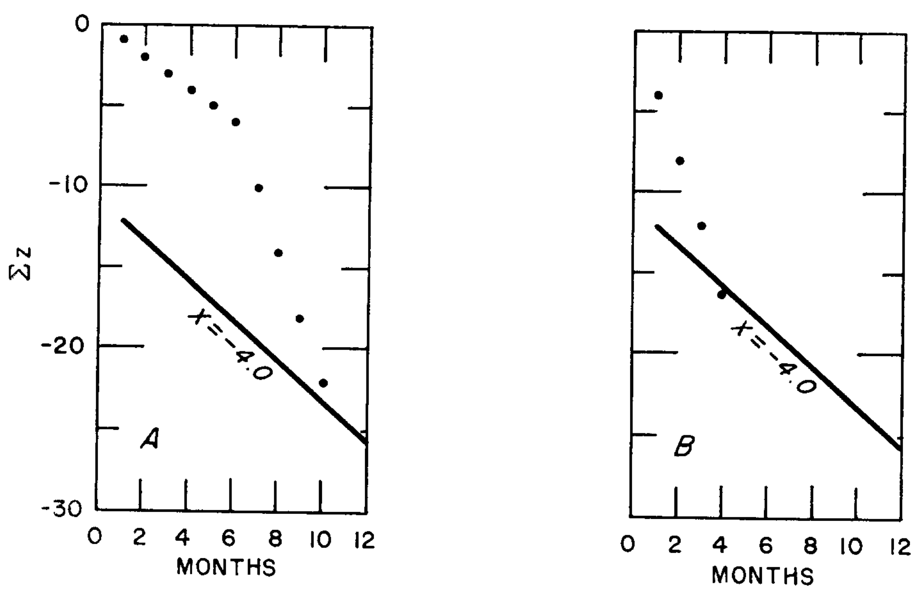

FIGURE 2.—An illustration of the cumulative procedure. (A) Six relatively dry months followed by four very dry months; (B) The four very dry months by themselves.

month for 6 months and then $z=-4.0$ during each of the following 4 months. The total accumulated value is therefore -22.0 in 10 months. Note that the 10th month does not quite reach the extreme drought line.

Now assume that the first 6 months were each very wet and that the remaining 4 months each had $z=-4.0$ as before. In this case the dry period begins with the first month in which $z=-4.0$ and these 4 dry months give the curve in figure 2B. Note that the value for the last month now falls below the extreme drought line.

We are now confronted with a result which indicates that four very dry months following six wet months produce a more serious drought than is produced by the same four very dry months following six months of relatively dry weather. Obviously, this is a fallacy. The cumulative procedure is misleading and cannot be used as a method of taking account of the duration of the dry period.

The problem must, therefore, be handled on an increment basis such that each successive month is evaluated in terms of its contribution to the severity of drought. In effect, this will eliminate direct consideration of the duration factor and bring duration in indirectly as a consequence of the accumulation of successive monthly contributions to drought severity.

In order to evaluate the contribution of each month, we can set $i=1$ and $t=1$ in equation (20) and we have,

$$X_1=z_1/3. \tag{21}$$

Since this is an initial month,

$$X_1-X_0=\Delta X_1=z_1/3. \tag{22}$$

However, this is not the whole story because in successive months a certain amount of abnormal dryness ($z<0$) will be required merely to maintain the severity of the existing dry spell. For instance, one knows intuitively that an extreme drought will not continue in the extreme category if subsequent months are normal or only very slightly drier than normal. The question is, how much dryness is required to maintain a drought of given severity; i.e., for $\Delta X=0$?

From equation (20) or from figure 1, it is apparent that Σz must increase as t increases in order to maintain a given value of X. The rate of increase of t is constant; i.e., t increases by 1 each month, thereby increasing the denominator by steps of 0.309. Therefore, the rate at which the index, z, must increase in order to maintain a constant value of X ($\Delta X=0$) depends on the value of X that is to be maintained. This reasoning suggests that for all months following an initial dry month an additional term must be added to equation (22), and that the equation is of the form,

TABLE 8.—*The amount of abnormal dryness required to maintain a given drought severity*

t	X_{i-1}	$\sum_{t=1}^{i-1} z_i$	ΔX_i	X_i	$\sum_{t=1}^{i} z_i$	z_i
2	−1.0	−3.0	0	−1.0	−3.309	−0.309
10	−1.0	−5.472	0	−1.0	−5.781	−.309
2	−3.0	−9.0	0	−3.0	−9.927	−.927
10	−3.0	−16.416	0	−3.0	−17.343	−.927

$$\Delta X_i=(z_i/3)+cX_{i-1}, \tag{23}$$

where

$$\Delta X_i=X_i-X_{i-1}.$$

The problem is to determine c. Returning to equation (20), we can compute the value of z_i which will maintain a given value of X from month to month. Table 8 shows the computed values of z in the ith month for two arbitrary values of $X_{i-1}=X_i$ and two arbitrary values of t.

If we place these values of z_i, X_{i-1} and ΔX into equation (23), we have,

$$\Delta X=0=(-0.309/3)-1.0c,$$

and

$$\Delta X=0=(-0.927/3)-3.0c.$$

c is therefore -0.103 and the final equation is:

$$\Delta X_i=(z_i/3)-0.103X_{i-1}. \tag{24}$$

This equation can be used to compute the monthly contributions to drought severity. Of course, the sum of the increments gives the severity itself, i.e.,

$$X_i=X_{i-1}+\frac{z_i}{3}-0.103X_{i-1}. \tag{25}$$

7. RE-EVALUATION OF THE WEIGHTING FACTOR

EVIDENCE OF UNSATISFACTORY K VALUES

Originally, this study was carried through to completion on the basis of the equations shown above. Results for western Kansas and central Iowa appeared reasonable and realistic. However, when the entire method was subsequently applied to other areas with rather different types of climate, some of the results were definitely peculiar and unrealistic. For example, in Kansas and Iowa the most extreme drought periods produced maximum drought index values around -5.0 to -6.0. These seemed reasonable inasmuch as the system is designed to indicate extreme drought whenever the index exceeds -4.0. However, an analysis for the southern climatological division of Texas produced index values ranging as large as -10.23. Such values were obviously rather far from the expected maximum around -6.0. On inspection it was found that some of the monthly weighting factors were inflating the departures, the d values, in an unrealistic fashion.

The other analysis that showed peculiar results was done for western Tennessee by Mr. M. H. Bailey, then State Climatologist for Tennessee. The worst flood in the history of the area (January 1937) produced an index, X, only slightly larger than zero. Again, the k values were at fault. They were so small that even huge moisture departures were rendered quite insignificant when multiplied by the weighting factor, k. In this particular January in western Tennessee, rainfall averaged 19.35 in. over the area and $P-\hat{P}$ was a huge $+12.26$ in. As will be shown later on, this system should measure unusually wet periods as well as unusually dry periods. Obviously, the index, X, should receive a large positive increment during this extremely wet month. From equation (22)[6] one can see that this will occur only if K for January (see eq. (19)) is of the order of 0.5 to 0.7, say, 0.6. Actually, k had been computed (by eq. (18)) as 0.051 for January.

[6] From here on z becomes Z and k becomes K in equations 19 through 25, as these are the final estimates of these indices.

PROCEDURE FOR ESTIMATING MEAN VALUES OF K

It seemed the simplest procedure for re-evaluating the weighting factor was to use equation (20) to determine what ΣZ should be for extreme drought over a 12-month period. It turned out that for $X=-4.0$ and $t=12$ months, the sum of the weighted departures should be -25.60. If we again assume that the driest 12-month period represents extreme drought in any area, we can obtain a new 12-month mean weighting factor, $\overline{K}$, by dividing -25.60 by the 12-month sum of d for the driest periods of record.

Referring to table 5, it will be noted that the driest 12-month period in western Kansas began with May 1934 and continued through April 1935. The sum of the d values for this period is -16.62. A period almost as dry began with March 1956 and extended through February 1957. This 12-month sum of d was -15.60. Averaging these two, to eliminate a little of the sampling variability, gives a mean 12-month sum of d of -16.11. Dividing -25.60 (12-month ΣZ for extreme drought) by -16.11 gives 1.59. This is $\overline{K}$ for western Kansas. It is a mean weighting factor—the mean of the 12 monthly weighting factors.

In central Iowa the driest 12-month periods were June 1933 through May 1934 and August 1955 through July 1956 (see table 6) when the 12-month sums of d were -23.02 and -20.56. The mean is -21.79. When we divide -25.60 by -21.79 we get 1.17 for $\overline{K}$ is central Iowa.

By this time analyses and a monthly table of d values were available for nine different areas, viz, the climatological divisions of northwestern North Dakota, western Kansas, central Iowa, Texas High Plains, Edwards Plateau of Texas, southern Texas, western Tennessee, west central Ohio, and a point analysis for Scranton, Pa. The values computed for $\overline{K}$ ranged from 1.06 in western Tennessee to 1.73 in northwestern North Dakota. In addition, there is the previously mentioned estimate that K for January in western Tennessee should be around 0.6 if the 1937 case is to look at all reasonable.

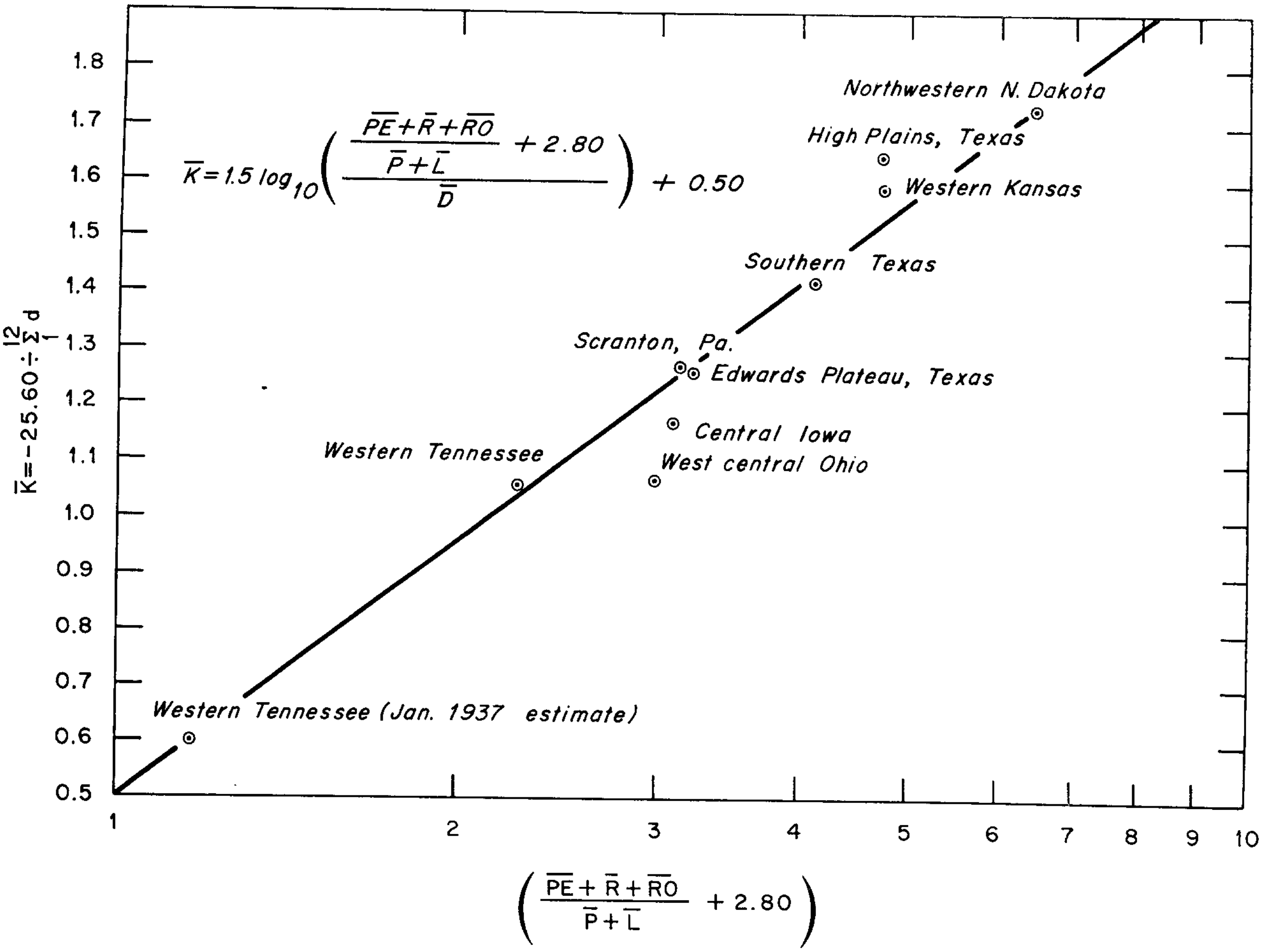

FIGURE 3.—Mean annual weighting factor as related to average moisture demand, average moisture supply, and average absolute moisture departure.

K AS A FUNCTION OF OTHER ASPECTS OF CLIMATE

From an inspection of the failures of the original k values it was apparent that K should depend on average water supply, $\overline{P}+\overline{L}$, as originally used. It was also apparent that the average runoff, $\overline{RO}$, should be considered as a part of the moisture "demand" in addition to the average potential evapotranspiration, $\overline{PE}$, and the average recharge, $\overline{R}$. Also, it was apparent that K varies inversely with $\overline{D}$, the mean of the absolute values of d.

After some experimenting with various empirical relationships, the semi-logarithmic plot shown in figure 3 was evolved. No doubt, greater scatter would result if more stations or areas were added. This relationship may be fortuitous, but it seems reasonable. The problem is also complicated by sampling variability.

The K values in figure 3 were based on the driest 12-month periods in these various places and the abscissa is made up of mean values for the entire period of record analyzed, the 30 years 1931–1960 in most cases. For example, $\overline{PE}$ is average annual PE divided by 12, and the other mean values were computed in the same fashion.

MONTHLY WEIGHTING FACTORS

The next step was to apply this empirical relationship to each of the 12 calendar months in each of the various places and thereby derive the 12 K values for each place. These results are shown in table 9. In this table $\bar{D}$ is the monthly mean of the absolute values of d, and K' is the weighting factor computed for each month by the equation developed from figure 3; viz,

$$K'=1.5\log_{10}\left[\left(\frac{\overline{PE}+\bar{R}+\overline{RO}}{\bar{P}+\bar{L}}+2.80\right)\Big/\bar{D}\right]+0.50. \tag{26}$$

TABLE 9.—*Monthly weighting factor, K, for selected places*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Sum
WESTERN TENNESSEE													
$\bar{D}$	3.24	1.89	1.45	1.40	1.50	1.70	1.60	1.25	1.68	1.31	1.92	1.88	----------
K'	.60	.95	1.13	1.15	1.11	1.05	1.12	1.34	1.10	1.21	.95	.96	----------
$\bar{D}K'$	1.94	1.80	1.64	1.61	1.67	1.78	1.79	1.68	1.85	1.59	1.82	1.80	20.97
K	.51	.80	.95	.97	.94	.86	.94	1.13	.93	1.02	.80	.81	----------
WEST CENTRAL OHIO													
$\bar{D}$	1.93	1.00	1.04	1.20	1.40	1.74	1.36	1.18	1.31	1.11	1.16	1.09	----------
K'	.94	1.37	1.34	1.25	1.15	1.01	1.19	1.29	1.22	1.31	1.27	1.31	----------
$\bar{D}K'$	1.81	1.37	1.39	1.50	1.61	1.76	1.62	1.52	1.60	1.45	1.47	1.43	18.53
K	.90	1.31	1.28	1.19	1.10	.96	1.14	1.23	1.16	1.25	1.21	1.25	----------
CENTRAL IOWA													
$\bar{D}$	0.73	0.66	0.90	1.39	1.79	1.90	1.12	1.99	1.66	1.12	1.33	0.74	----------
K'	1.58	1.64	1.44	1.16	.99	.96	1.31	.95	1.06	1.31	1.18	1.55	----------
$\bar{D}K'$	1.15	1.08	1.30	1.61	1.77	1.82	1.47	1.89	1.76	1.47	1.57	1.15	18.04
K	1.55	1.61	1.41	1.14	.97	.94	1.28	.93	1.04	1.28	1.16	1.52	----------
SCRANTON, PA.													
$\bar{D}$	0.86	0.70	0.81	0.96	1.30	1.35	2.27	1.60	1.43	1.29	1.27	0.95	----------
K'	1.47	1.60	1.51	1.40	1.20	1.19	.86	1.09	1.18	1.21	1.21	1.40	----------
$\bar{D}K'$	1.26	1.12	1.22	1.34	1.56	1.61	1.95	1.74	1.69	1.56	1.54	1.33	17.92
K	1.45	1.58	1.49	1.38	1.18	1.17	.85	1.07	1.16	1.19	1.19	1.38	----------
EDWARDS PLATEAU, TEXAS													
$\bar{D}$	1.16	0.85	0.95	1.40	1.61	1.90	1.59	1.14	2.08	1.61	0.77	1.10	----------
K'	1.28	1.48	1.42	1.18	1.09	1.06	1.27	1.58	1.01	1.13	1.56	1.32	----------
$\bar{D}K'$	1.48	1.26	1.35	1.65	1.75	2.01	2.02	1.80	2.10	1.82	1.20	1.45	19.89
K	1.14	1.31	1.26	1.05	.96	.94	1.13	1.40	.90	1.00	1.39	1.17	----------
SOUTHERN TEXAS													
$\bar{D}$	0.97	0.80	0.63	1.39	1.33	1.55	1.23	1.49	1.73	1.36	0.66	0.90	----------
K'	1.41	1.53	1.76	1.29	1.29	1.29	1.57	1.41	1.15	1.30	1.73	1.47	----------
$\bar{D}K'$	1.37	1.22	1.11	1.79	1.72	2.00	1.93	2.10	1.99	1.77	1.14	1.32	19.46
K	1.28	1.39	1.60	1.17	1.17	1.17	1.43	1.28	1.04	1.18	1.57	1.33	----------
WESTERN KANSAS													
$\bar{D}$	0.26	0.43	0.71	1.07	1.34	1.62	1.56	1.10	0.86	0.84	0.57	0.40	----------
K'	2.25	1.92	1.60	1.34	1.20	1.12	1.20	1.45	1.63	1.59	1.78	1.97	----------
$\bar{D}K'$	.58	[illegible]	1.14	1.43	1.61	1.81	1.87	1.60	1.40	1.34	1.01	.79	15.41
K	2.58	2.20	1.84	1.38	1.54	1.28	1.38	1.66	1.87	1.82	2.04	2.26	----------
TEXAS HIGH PLAINS													
$\bar{D}$	0.51	0.42	0.63	0.86	1.50	1.48	1.40	0.89	1.28	1.22	0.52	0.65	----------
K'	1.81	1.94	1.70	1.54	1.15	1.23	1.33	1.66	1.37	1.32	1.85	1.66	----------
$\bar{D}K'$	.92	.81	1.07	1.32	1.72	1.82	1.86	1.48	1.75	1.61	.96	1.08	16.40
K	1.95	2.09	1.83	1.66	1.24	1.32	1.43	1.79	1.48	1.42	1.99	1.79	----------
NORTHWESTERN NORTH DAKOTA													
$\bar{D}$	0.20	0.23	0.33	0.67	1.04	1.48	0.98	0.81	0.91	0.59	0.38	0.19	----------
K'	2.42	2.33	2.08	1.64	1.37	1.14	1.48	1.66	1.59	1.81	2.00	2.45	----------
$\bar{D}K'$	.48	.54	.69	1.10	1.42	1.69	1.45	1.34	1.45	1.07	.76	.47	12.46
K	3.43	3.30	2.95	2.33	1.94	1.62	2.10	2.35	2.25	2.57	2.84	3.47	----------
													Mean=17.67

As mentioned previously, the mean values used in the development of this equation were average annual values divided by 12. In applying equation (26) to compute monthly weighting factors the mean values used are means for one of the 12 calendar months.

FINAL ADJUSTMENT OF THE MONTHLY *K* VALUES

If equation (26) is producing reasonably "correct" values for use in equation (19), then the average annual sum of the weighted average departures should be about the same for all places analyzed. Table 9 shows these weighted average departures, $\overline{D}K'$ for each month and their sum for the 12 months. These sums agree fairly well, but not well enough. The disagreement indicates that the departures are being given more weight in some places than in others. For example, the Tennessee weighting factors must be too large while the North Dakota weighting factors must be too small. This discrepancy was demonstrated by using the K' values to compute drought severity (using equation (19) and (25)) for some of the driest periods of record in each of these places. As an example, drought index values computed on the basis of K' indicated that drought in western Tennessee becomes more extreme than does drought in northwestern North Dakota or western Kansas. This did not seem reasonable and suggested that the weighting factors needed further adjustment.

The annual sums of $\overline{D}K'$ in table 9 range from 12.46 to 20.97. The mean sum for the nine areas is 17.67. If all weighting factors are adjusted so that all the annual sums of $\overline{D}K=17.67$, drought analysis results should be more comparable. The K values shown in table 9 were computed on this basis. For example, for January in west Tennessee, $0.51=(17.67/20.97)0.60$. This can be expressed as,

$$K=\frac{17.67}{\sum_{1}^{12}\overline{D}K}K'. \tag{27}$$

This completes the derivation of the weighting factors. They apparently establish reasonable comparability between areas, but there seems no way of assuring that they establish more than fair to good comparability between months. No doubt it would have been better to base the constant, 17.67, on analyses from many more places, but quite a range of climates is represented by these nine areas and the value 17.67 seems to work fairly well.

STANDARD DEVIATION OF *d* AS A WEIGHTING FACTOR

Some surely wonder why the standard deviation of d was not used as a weighting factor, thereby permitting one to deal with a standardized variable. This, of course, was tried, but results were definitely unrealistic partly because some of the distributions of d are rather skewed. Another likely factor is that the local significance of a given moisture departure is not solely dependent on its place in the distribution of departures. For example, the standard deviation of d is 1.64 in. in October in western Tennessee and it is also 1.64 in. in July in southern Texas. In the Tennessee case average moisture demand, $\overline{PE}+\overline{R}+\overline{RO}$, is 3.27 in. and average moisture supply, $\overline{P}+\overline{L}$, is 2.99 in. On the other hand, southern Texas has an average July moisture demand of 7.57 in., but an average moisture supply of only 2.13 in. Here demand is about 3½ times supply, while in Tennessee they are roughly equal. It seems obvious that a given moisture shortage would not be equally significant in both places. We would be assuming equality if we used the standard deviation as a weighting factor.

AN EXAMPLE OF THE DROUGHT SEVERITY COMPUTATIONS

At this point it is probably time to stop and take stock of the relationships which have been developed. It seems likely that a short example will best illustrate some of the more important steps. The year 1947 was a rather unusual one for central Iowa. April, May, and June were very wet and July, August, and September were very dry. The data for the 3 dry months are shown in table 10.

Inasmuch as June had been very wet, the *CAFEC* precipitation computed by equation (14) was only 2.81 in. for July. However, the actual precipitation was so small that the departure (by equation (15)) was -1.89 in. The final climatic characteristic, K, for July in central Iowa is (table 3) 1.28, therefore, the July anomaly was (by equation (19)) -2.42. The next three columns in table 10 show the parts of equation (24). Since this was the first dry month, the drought

TABLE 10.—*A selected 3-month dry period in 1947 in central Iowa*

Month	Actual precip. P	Comp. precip. $\hat{P}$	Clim. char. K	Moisture anomaly Z	Severity for month $Z/3$	Index to maintain severity $-.103X_{i-1}$	Change in severity ΔX	Drought index X
July	0.92	2.81	1.28	−2.42	−0.81	0.0	−0.81	−0.81
August	1.36	4.75	.93	−3.15	−1.05	.08	−.97	−1.78
September	1.28	4.30	1.04	−3.14	−1.05	.18	−.87	−2.65

index for the previous month was, of course, zero. The change in drought severity due to the dryness in July was therefore −0.81. We have previously defined mild drought as beginning when the severity index reaches −1.0; therefore the index value of −0.81 indicates that the drought was still not serious at the end of July. For convenience we can call this "incipient" drought, a condition which we will now arbitrarily define by a severity index value between −0.50 and −1.0. Inasmuch as the drought index is only 81 percent as large as is required to establish mild drought, we can state that there is an 81 percent probability that this July marks the beginning of a drought period. Not until the severity index reaches −1.0 can we say with certainty that (by definition) a drought began in July. This provides a very convenient method for methodically determining the beginning of drought periods. In addition, it provides a basis for preparing statements expressing the probability that a drought *has* begun. The tendency for persistence during drought makes such probability statements worthwhile from a practical standpoint.

Table 10 shows that the dry August intensified the drought (equation (25)) and matters were beginning to get a little serious by the end of the month. The drought reached a severity of −1.78, which is classed as mild, but it was approaching moderate severity. By the end of September a moderate drought existed. The comments published in the *Iowa Weekly Weather and Crop Bulletins* [62] agree reasonably well with this analysis. Early in August there seems to have been a good deal of concern about the fact that the area was rapidly running out of moisture and that crop damage might become serious unless rains came in the next week or 10 days. By the end of August it was apparent that the dry weather had produced serious damage to some crops and that pastures were no longer supplying adequate forage for livestock. By the end of September there were general complaints of dry soil, delayed seeding, and poor pastures, but the growing season had essentially ended and the agricultural remarks cease to be particularly useful in estimating drought severity. However, as far as one can tell, moderate drought appears to be a reasonable classification for the September weather. It is difficult to estimate the severity of meteorological drought from remarks concerning agricultural conditions because fortuitous rains sometimes produce very satisfactory yields of some crops during seasons which were, as a whole, much drier than normal. Also there seems to be a tendency for exaggeration in crop condition reports. A week of hot, dry weather seems to foster reports that the crops are practically ruined, while rain of less than 1 in. the following week may lead to forecasts of a bumper crop. This is one of the reasons it was necessary to start this drought analysis development with selected cases in which it was so dry that there could be no disagreement as to the fact that the drought was very serious from all standpoints—agricultural as well as hydrologic.

By way of comparison it is interesting to see what happens to the examples of figure 2 when one analyzes these data by equation (25). At the end of the sixth month in figure 2A the drought severity is −1.54; at the end of the 10th month it is −5.55. The four very dry months increase the severity by 4.01 and produce an extreme drought condition. On the other hand, the four very dry months in figure 2B give a drought severity of −4.53 at the end of the fourth month.

8. APPLICATION OF THE DROUGHT FORMULAS TO WET PERIODS

It seems reasonable to assume that the abnormal moisture deficiencies which could create, say, a moderate drought would have created a moderately wet period had they been positive rather than negative moisture departures. In other words, could not the drought equations be applied to wet periods merely by changing the signs where necessary? For example, equation (15) yields positive departures as well as negative. Also by equation (19) the monthly moisture anomaly Z, may be positive as well as negative. Likewise, equation (25) will give positive values when the monthly index is positive. Inasmuch as the equations will provide a measure of wetness the following categories were more or less arbitrarily set up, and are given in table 11.

TABLE 11.—*Classes for wet and dry periods*

X	Class
$\geq$ 4.00	Extremely wet.
3.00 to 3.99	Very wet.
2.00 to 2.99	Moderately wet.
1.00 to 1.99	Slightly wet.
.50 to .99	Incipient wet spell.
.49 to −.49	Near normal.
−.50 to −.99	Incipient drought.
−1.00 to −1.99	Mild drought.
−2.00 to −2.99	Moderate drought.
−3.00 to −3.99	Severe drought.
$\leq$ −4.00	Extreme drought.

Originally the objective of this study was to deal only with abnormally dry periods, but this proved to be not entirely feasible. It is difficult to determine the beginnings and endings of dry periods unless one also recognizes and takes account of the wet periods. For example, a relatively dry month such as August 1935 in central Iowa (see table 6) will appear as a separate drought period unless one recognizes that this month constituted only a slight and probably beneficial interruption in a fairly long period of unusually wet weather.

9. END OF DROUGHT (OR WET SPELL)

Generally speaking, the beginning of drought closely follows the onset of an extended period of unusually dry weather. It follows, therefore, that the end of meteorological drought should coincide with the time when some rather major and fairly abrupt readjustment in the large-scale circulation pattern begins to produce weather which is normal or wetter and continues so for a significant length of time. This return to normal weather terminates the meteorological drought, but it does not ordinarily end the effects of the drought. The effects may linger for weeks or months or even years depending on which effects are considered [70]. These persistent effects constitute a separate problem which is outside the scope of this study.

CHANGES IN THE SEVERITY INDEX

If a drought has been going on and the weather turns consistently normal or wetter, the severity index will, by equation (25) eventually reach zero. However, it does not seem reasonable to require that the index drop all the way to zero before concluding that a drought has definitely ended. From examination of a number of cases this seems to be too stringent a requirement. For example, a drought that was just barely established, say $X=-1.10$, would, by equation (25), require $Z=+2.97$ in order to reduce the index to zero in a single month. This seems like an excessive requirement, but it is plainly so if one computes the number of months of exactly normal weather ($Z=0$) required to bring X to zero. This can also be done from equation (25). We find that X reduces from -1.10 to -0.99 in 1 month, to -0.52 in 7 months, and approaches zero in about 3 years. Obviously, one would consider the drought over long before the end of 1 year of normal weather, let alone 3 years. On the other hand, if one ends drought as soon as the index is numerically less than -1.0, normal weather would end the -1.10 drought in a single month. This is a little extreme in the other direction, because it would certainly not be a definite fact that a drought had ended merely because one month had been normal.

From the speculations above it would appear reasonable to assume that drought ends when the severity index reaches some value between 0 and -1.0. In order to have some consistency and at the same time not risk breaking long drought periods into a number of short but barely separate drought periods, the lower limit of incipient drought, -0.50, was chosen as the value of X

which will be considered to definitely end a drought. In other words, as soon as the severity index reaches the "near normal" category, which lies between -0.50 and $+0.50$, no drought exists.

DETERMINING THE END OF A DROUGHT

In the previous section it was assumed that drought can be considered as definitely terminated as soon as the drought index reaches the "near-normal" category. The question, then, is, how much moisture would be required to reduce the severity of a given drought to -0.50? This can be solved by substituting the appropriate values into equation (25). Let $X_i=-0.50$, then

$$-0.50=X_{i-1}+Z/3-0.103X_{i-1}$$

and

$$Z=-2.691X_{i-1}-1.50.$$

Therefore, the Z-value that will end a drought in a single month is:

$$Z_e=-2.691X_{i-1}-1.50. \tag{28}$$

By saying that drought has definitely ended when $X=-0.50$, we are also saying that there is some algebraically smallest value of Z which could occur month after month and eventually produce $X=-0.50$ for month after month. When this occurs $\Delta X=0$ and $X_{i-1}=-0.50$, so by equation (24) one finds that $Z=-0.15$. This indicates, and quite reasonably so, that a drought period can end even though the weather is consistently just slightly drier than normal. Therefore, any value of $Z\geq-0.15$ will tend to end a drought, and the "effective wetness" is:

$$U_w=Z+0.15 \tag{29}$$

(After a drought has definitely begun ($X\leq-1.00$), equation (29) applies to the first "wet" month; i.e., the first month having $Z\geq-0.15$. U_w should then be computed for each successive month until the computations show either a 0 percent or a 100 percent likelihood that the drought has ended.)

If the amount of wetness required to end a drought in the first wet month (Z_e from equation (28)) is greater than the effective wetness (U_w from equation (29)) for that month, the drought severity will decrease, but the drought has not definitely ended. However, since the drought severity will have been diminished by the first wet month, it will not require as much wetness to end it the second month; i.e., Z_e will be smaller the next month and the total amount of wetness required to end the drought will be the new Z_e computed for the ith month plus the previously accumulated wetness, viz,

$$Z_e+\sum_{j=0}^{j=j^*}U_{i-j}-U_i$$

where

$U=U_w$, i refers to the ith month; i.e., the month being considered, j indicates the number of months of lag; e.g., U_{i-j} at $j=1$ refers to the value of U_w in the preceding month, and $j=j^*$, the upper limit of the summation, indicates that U_w is to be summed back in time to and including the value at the j^* month, where the j^* month is the first month of the current wet spell. If $\Sigma U_w<0$, $\Sigma U=0$. Otherwise, one comes out with negative probabilities. (See table 12, column 5.)

The percentage probability [7] that a drought has ended is therefore:

$$P_e=\frac{\sum_{j=0}^{j=j^*}U_{i-j}}{Z_e+\sum_{j=0}^{j=j^*}U_{i-j}-U_i}\times100=\frac{100V}{Q}. \tag{30}$$

Now it frequently happens that a drought period is temporarily interrupted by a month or so of abnormally wet weather. Such occurrences nearly always give rise to speculations that the drought has ended. From the strictly soil moisture standpoint of agricultural drought, the drought has ended, at least temporarily; but from the meteorological standpoint or even from an economic standpoint the short wet spell may turn out to be of little consequence. The wet August of 1933 in western Kansas is a good example of a temporary interruption of a serious drought. The drought had begun in July 1932 and by the end of July 1933 the drought index stood at -4.07, which is extreme drought for the area as a whole. August 1933 was cool and wet over the area. The average precipitation was 4.91 in. and the index for the month was $Z=+3.59$. This was, however, far from enough moisture really to end the drought. From equation (28) one can compute that Z_e, the amount needed to end the drought in August, was $+9.45$. From equation (29), the effective wetness, $U_w=+3.74$, and from

[7] P_e actually expresses moisture received as a percentage of the amount of moisture required definitely to terminate a drought. Of course, the probability that a particular drought has ended is either zero or 1.0, but it is convenient to think of P_e as the probability that a drought *has* ended.

equation (30) the probability that the drought had ended turns out to be 40 percent. The drought index stood at -2.45 at the end of August. However, the dry weather was resumed in September and October (see table 5), and the probability that the drought had ended had dropped to 12 percent by the end of October. Subsequent dry weather reduced the probability to zero in the spring of 1934. If, however, the wet August had been followed by continued wet weather, the probability that the drought had ended would have reached 100 percent and *the last month of drought would have been the last month in which the probability was not greater than zero;* i.e., July 1933.

DETERMINING THE END OF A WET SPELL

In order to treat wet periods methodically in the same fashion as dry periods, some sign changes are required in the equations for computing the probability that a dry spell has ended. To determine the index, Z_e, which will end a wet spell in a single month, an equation similar to equation (28) must be developed. In this case one can substitute $X=+0.50$ in equation (25) and get:

$$Z=-2.691X_{i-1}+1.50. \tag{31}$$

This gives a measure of the amount of abnormal dryness ($-Z$) required to reduce the severity of a wet spell to $+0.50$ in a single month.

Just as a drought period can end even though the weather is consistently just slightly drier than normal, a wet period can also end with the weather continuing very slighty wetter than normal. By substituting $\Delta X=0$ and $X_{i-1}=+0.50$ in equation (24) one gets the value of Z which will tend to end a wet spell. The "effective dryness" becomes:

$$U_d=Z-0.15. \tag{32}$$

Equation (30) for determining the probability that a drought has ended can be used to compute the probability that a wet spell has ended.[8]

The following section describes the procedure for using these equations to make a complete climatological analysis of the moisture aspects of the weather. The term, severity, which is ordinarily applied to drought rather than to wet periods, is here applied to both. This may not be a very accurate use of the term, but it is convenient, and there does not seem to be a satisfactory word to use in place of it.

[8] In equation (30), $U=U_d$ for the case in which the termination of a wet spell is being considered.

10. PROCEDURE FOR COMPUTING SEVERITY OF DROUGHT AND WET SPELLS

In order to carry out the computations for determining monthly drought severity, X, from a long series of monthly values of the index, Z, one must keep track of the wet spells as well as the dry spells. Therefore, a number of things must be computed for each month. For example, when there is no drought or wet spell going on, one must each month compute the "probability" that a wet spell or a dry spell has begun. After this probability has reached 100 percent and a drought or a wet spell is actually underway, one must examine each month in turn to determine the probability that the spell has ended and at the same time determine the probability that a spell of the opposite sign has begun.

The computations are really quite simple. Were they being made by hand, simultaneous computations of various items would not be necessary because one could easily go back and pick up anything that later turned out to be important, but for machine data processing the simultaneous computations save time in the long run. The computational routine will be explained by describing an example.

Table 12 shows a 40-month period from the western Kansas record. It was necessary to turn so far back into history for the example, because it was difficult to locate a short period that would illustrate most of the points that can come up.

There are four sub-routines illustrated. Columns 3 to 8 show the routine for computing the probability that a drought or a wet spell has ended. Columns 10 to 12 show the routine for computing the probability that a wet spell has begun. Columns 13 to 15 show the routine for computing the probability that a drought has

Table 12.—*An example of the computational procedure for determining the beginning and ending of wet periods and dry periods and the monthly severity index of each (western Kansas data)*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Month	Z	U_w $Z+.15$	U_d $Z-.15$	V*	Z_e	Q**	P_e	$\frac{Z}{3.0}$	$-.103\ X_{1,i-1}$	ΔX_1	X_1	$-.103\ X_{2,i-1}$	ΔX_2	X_2	$-.103\ X_{3,i-1}$	ΔX_3	X_3	X
1888																		
April	3.13			0			0	1.04	−0.03	1.01	1.28			0			1.28	1.28
May	1.20			0			0	.40			0			0	−0.13	0.27	1.55	1.55
June	−.73		−0.88	−.88	−2.67	−2.67	33	−.24			0			−.24	−.16	−.40	1.15	1.15
July	.41		.25	−.63	−1.59	−2.47	26	.14			0	0.02	0.16	−.08	−.12	.02	1.17	1.17
August	2.21		2.06	0			0	.74			0	.01	.75	0	−.12	.62	1.79	1.79
September	−2.11		−2.26	−2.26	−3.32	−3.32	68	−.70			0			−.70	−.18	−.88	.91	−.70
October	.69		.54	−1.72	−.95	−3.21	54	.23			.23	.07	.30	−.40	−.09	.14	1.05	−.40
November	−.57		−.72	−2.44	−1.33	−3.05	80	−.19	−.02	−.21	.02	.04	−.15	−.55	−.11	−.30	.75	−.55
December	−1.06		−1.21	−3.65	−.52	−2.96	100	−.35	0	−.35	0	.06	−.29	−.84			0	−.84
1889																		
January	1.86			0			0	.62			.62	.09	.71	−.13			0	.62
February	−.26			0			0	−.09	−.06	−.15	.47	.01	−.08	−.21			0	.47
March	.70			0			0	.23	−.05	.18	.65	.02	.25	0			0	.65
April	.58			0			0	.19	−.07	.12	.77			0			0	.77
May	.77			0			0	.26	−.08	.18	.95			0			0	.95
June	1.05			0			0	.35	−.10	.25	1.10			0			1.10	1.10
July	.37			0			0	.12			0			0	−.11	.01	1.11	1.11
August	−.05		−.20	−.20	−1.49	−1.49	13	−.02			0			−.02	−.11	−.13	.98	−.02
September	−2.04		−2.19	−2.39	−1.14	−1.34	100	−.68			0	0	−.68	−.70			0	−.70
October	2.06			0			0	.69			.69	.07	.76	0			0	.69
November	.35			0			0	.12	−.07	.05	.74			0			0	.74
December	−1.79			0			0	−.60	−.08	−.68	.06			−.60			0	−.60
1890																		
January	.26			0			0	.09	−.01	.08	.14	.06	.15	−.45			0	−.45
February	−.57			0			0	−.19	−.01	−.20	0	.05	−.14	−.59			0	−.59
March	−1.77			0			0	−.59			0	.06	−.53	−1.12			−1.12	−1.12
April	2.42	2.57		2.57	1.51	1.51	100	.81			.81			0			0	.81
May	−2.86			0			0	−.95	−.08	−1.03	0			−.95			0	−.95
June	−2.92			0			0	−.94			0	.10	−.84	−1.79			−1.79	−1.79
July	−3.66			0			0	−1.22			0			0	.18	−1.04	−2.83	−2.83
August	−1.63			0			0	−.54			0			0	.29	−.25	−3.08	−3.08
September	−1.37			0			0	−.46			0			0	.32	−.14	−3.22	−3.22
October	−.93			0			0	−.31			0			0	.33	.02	−3.20	−3.20
November	−.35			0			0	−.12			0			0	.33	.21	−2.99	−2.99
December	−1.45			0			0	−.48			0			0	.31	−.17	−3.16	−3.16
1891																		
January	1.86	2.01		2.01	7.00	7.00	29	.62			.62			0	.33	.95	−2.21	.62
February	−.75	−.60		1.41	4.45	6.46	22	−.25	−.06	−.31	.31			−.25	.23	−.02	−2.23	.31
March	3.20	3.35		4.76	4.50	5.91	81	1.07	−.03	1.04	1.35	.03	1.10	0	.23	1.30	−.93	1.35
April	−.43	−.28		4.48	1.00	5.76	78	−.14	−.14	−.28	1.07			−.14	.10	−.04	−.97	1.07
May	1.92	2.07		6.55	1.11	5.59	100	.64	−.11	.53	1.60	.01	.65	0			1.60	1.60
June	3.93			0			0	1.31			0			0	−.16	1.15	2.75	2.75
July	4.22			0	1.00		0	1.74			0			0	−.28	1.46	4.21	4.21

*V=numerator of eq. (30)=$\Sigma\ U_w$ or $\Sigma\ U_d$.
**Q=denominator of eq. (30)=Z_e+V_{i-1}.

begun. Columns 16 to 18 show the computations for determining the severity of any wet spell *or* any drought that *has been established.*

Prior to the period shown in table 12, the weather had been slightly dry and "near normal." The index value, Z, for March 1888 was $+0.81$ and had produced a severity index value of $+0.27$. This value of X_1 (which would have appeared in col. 12) indicated a 27 percent chance that a wet spell had begun with March. April was rather wet with $Z=3.13$ (see col. 2 of table 12) so no "probability of end" computations are necessary. April was the second wet month in this spell and the next step is to determine the probability that a wet spell has begun. This is done by equation (25) and turns out to be 1.28 as shown in column 12. Without, at this point, going into the details, column 15 shows that there is a 0 percent probability that a drought has begun. However, a wet spell has been definitely established; therefore $X_3=X_1$, and subsequent computations for this spell are transferred to columns 16–18. (Remember that X_3 is reserved for indicating the severity of any wet spell or any drought which has become definitely established; i.e., $X_1 \geq 1.00$ or $X_2 \leq -1.00$). Column 19 will be discussed later. So, at the end of April we have a wet spell underway.

By the end of May the wet spell has continued and intensified as shown by the fact that $X_3=1.55$.

June was drier than normal; $Z=-0.73$. The first operation is to determine the probability that this dry month has ended the wet spell. From equation (31) $Z_e=-2.67$. By equation (32) one finds that $U_d=-0.88$, as shown in column 4. This is the first dry month, so $V=U_d$, and by equation (30) we get a 33 percent chance that the wet spell has ended. The computations for this particular wet spell have been shifted from column 12 to column 18, so $X_1=0$. Inasmuch as this was a dry month, it may turn out to be the beginning of a drought period, provided that this wet spell ends. The drought severity index, X_2 in column 15, turns out to be -0.24 (from equation (25)). This shows a 24 percent chance that a drought has begun. We must continue to compute X_3 until this particular wet spell ends. Column 18 shows that the dry month has reduced the wet spell index to 1.15.

July, being a little wetter than normal, reduces the probability that the wet spell has ended to 26 percent. It also reduces the probability that a drought has begun to 8 percent (col. 15). Even though there is only a 26 percent chance that this wet spell has ended, we must compute the probability that July marks the beginning of another wet spell, because under certain rare circumstances a value of X_1 for this month will be needed later on. For example, this or any wet spell will have ended if the weather is near normal month after month. When this happens, it turns out that the best measure of the weather (X in col. 19) must be obtained from the computed values of X_1 and X_2. Therefore, both must be computed at every opportunity.

August ends all questions about a drought beginning or a near-normal period being underway, because it was so wet that P_e dropped to 0 percent. Since the probability of ending dropped to zero, we must wait for a subsequent dry period to end the existing wet spell. Note also that when $P_e=0$, X_1 and X_2 also equal zero.

We do not have to wait long for another dry period. September 1888 was rather dry and starts a new "ending period." Looking ahead we note that by the end of December P_e has reached 100 percent. Actually $P_e>100$ percent, so it is entered as 100. Therefore a wet spell has been delineated as beginning with March and extending through August 1888. April, May, June, July, and August qualify as "slightly wet" (refer to table 11). Having defined the beginning and ending of the wet spell, we can now determine the proper values for X (col. 19). During the early portion of the wet spell, before X_1 reached 1.00 (not shown), $X=X_1$; thereafter $X=X_3$ until August, the last wet month.

Inasmuch as the period September through December 1888 was essentially dry and finally produced $P_e=100$ percent, the X_3 values entered for September, October, and November are of interest only in that they enable one to compute the values in column 6. By December there is no more interest in X_3 ($P_e=100$ percent) for this past wet spell; so $X_3=0$.

September began a 9-month period in which neither a drought nor a wet spell became established. X_1 and X_2 were computed at every opportunity, of course, and during most months we have two severity index values, one indicating slightly wetter than normal, the other indicating slightly drier than normal. Which one best represents the weather for each month?

If one accumulates the Z values from September

1888 through June 1889 and prepares a time graph of the accumulated sum at the end of each month, the following points will be readily apparent. Note in column 2 that the period September through December 1888 was predominantly dry and that the wetness index, X_1 in column 12, became zero during December. During December and on back through this predominantly dry period assign $X=X_2$.

Following the slightly dry period was a period which was, in general, a bit wet. This wet period began in January 1889 and continued through July 1889. During this period the drought index, X_2, was gradually approaching zero and finally reached zero in March of 1889. During March and on back through this predominantly wet period assign $X=X_1$.

The next month, April, was wetter than normal, so X_2 is again zero and $X=X_1$. For the same reason $X=X_1$ in May. June produces an X_1 value >1.00, so $X_3=X_1$ and $X=X_3$. July was wet also, and X_1 is set to zero, $X_2=0$, and $X=X_3$. August was slightly drier than normal and produces a small chance (13 percent) that the wet spell has ended. X_1 remains zero, but X_2 is -0.02. Uncertainty exists as to whether the wet spell has ended or not. There is no way of knowing (at the end of August) whether X should equal 0.98 or -0.02. The assignment of the X value for August must await further developments.

September was rather dry; P_e reaches 100 and answers the question left over from August. The wet spell ended; therefore, $X=-0.02$ in August and -0.70 in September.

October was wet. This again reduces X_2 to zero, so $X=X_1$. November was also slightly wet and again $X=X_1$.

December was dry and began what later turned out to be a brief mild drought. However, during December and on through January 1890, the computations give values for both X_1 and X_2. (X_3 has remained at zero because no drought or wet spell has become established during this period.) Again there is a period of uncertainty as to whether X should equal X_1 or X_2. By the end of February X_1 dropped to zero, so we assign $X=X_2$ in February and also for the preceding January and December.

This systematic procedure of assigning the value of X in accordance with the times when X_1 and X_2 equal zero enables one to obtain an index value for each month when no drought or wet spell is underway. This somewhat arbitrary rule almost always assigns what appear to be reasonable values for the final index, X. Once in a while one can argue that the wrong value has been assigned, but in such cases X_1 and X_2 are both so small that there isn't really much room for argument either way.

March 1890 established mild drought and $X_3=X_2$ and $X=X_3$. April put an abrupt end to the drought as shown by $P_e=100$ percent. For April X_3 again becomes zero and $X=X_1$.

May 1890 marks the beginning of another drought period of 8 months duration. This drought reached its greatest severity, -3.22, by the end of September. The next 3 months were drier than normal, but not sufficiently dry to maintain the severity that was reached in September, and the severity generally decreased until the abnormally wet weather beginning with January 1891 brought an end to this drought period. By May it was definitely established (col. 8) that the drought had ended and that another wet spell had begun.

If the above discussion seems confusing at first, please recall that table 12 covers a period which was selected to illustrate all aspects of the many problems that can arise. During many rather long periods of the record, such as that shown in table 4, the only computations consistently required are those for X_3 because a serious drought is underway and only occasionally does one encounter a month that is sufficiently wet to require computation of the probability that the drought has ended. The slightly wet May 1933 in Kansas produced a 6 percent probability that the drought had ended, but this dropped to zero the following month. The wet August 1933 produced a 40 percent probability that the drought had ended, but the probability never got above 47 percent (in February 1934) and by the following spring it again became zero, thereby bringing an end to the computations of P_e, X_1, and X_2.

August 1933 in Kansas raised one problem that is not included in the example in table 12. This month produced a 40 percent probability that the drought had ended, and it also produced an X value of 1.20 which indicates that a wet spell has begun. However, in this case—and a very few others like it—the drought did not end, and we cannot use this as the beginning of a wet spell unless the drought ends. In such instances X_3

does not equal X_1 and the X_1 computations must be continued in column 12 until P_e reaches zero or 100 percent or until X_1 returns to zero.

It might be well to point out that tables 1, 4, and 12 make up the work sheet that one uses to make these computations.

11. RESULTS FOR WESTERN KANSAS DROUGHTS

The monthly index computations were carried out for western Kansas for the 71-yr. base period, 1887–1957, and later for the years 1958–1962. The values of X are listed in table 13. Let us examine the index values for some of the individual months to see what one might conclude as to their reasonableness or representativeness.

As has been pointed out previously, there is hardly any satisfactory means for checking the validity of index values which indicate "mild" or "moderate" drought. However, "extreme" drought produces conditions which can be recognized and more or less agreed upon.

THE DROUGHT OF 1894

It is difficult to locate any very concrete information concerning the drought of 1894 in western Kansas, but the following statements are indicative of the situation. Tannehill [43] wrote, ". . . the great drought of 1894 brought complete crop failure and disaster [to the Great Plains]. As many as 90 percent of the settlers abandoned their farms in some areas." In the Department of Agriculture *Yearbook* for 1894 [11] we find, "During the prevalence of this hot period [in late July 1894] the prospects for crops [over portions of Kansas and Nebraska], already unfavorable on account of prolonged drought, were greatly reduced. Much corn was completely dried up and cut for fodder."

From other sources [13] it is apparent that western Kansas was included in these rather general statements. At any rate 1894 has gone down in history as a year of disastrous drought and it seems reasonable to assume that the drought was "extreme" during at least the latter part of the summer. In table 13 the index indicates extreme drought (>-4.00) from July through December 1894.

THE DROUGHT OF 1913

The next serious dry period in western Kansas reached its peak of severity in August 1913. Fortunately, the drought months during 1913 did not follow directly on the heels of the very dry period of 1910 and 1911; the intervening year of 1912 was abnormally wet. Even so, 1913 produced some memorable comments in the *Monthly Weather Review* of August 1913 [17]. For example, "The month [of August] will long be remembered as one of the most disastrous from an agricultural standpoint ever experienced." Also, "The drought of the summer of 1913 was one of the most damaging droughts that Kansas has experienced since authentic weather records were begun in the State." And, ". . . with the possible exception of the summer of 1874, the summer of 1913 stands alone as the driest the State [as a whole] has experienced since the early fifties. . . ." The index shows moderate drought in July and extreme drought in August.

THE DROUGHT OF THE 1930's

Agricultural Aspects.—The drought during the 1930's was the longest and most serious of record in western Kansas. Between August 1932 and October 1940 the index indicates 38 months of extreme drought. There is a great deal of information about this drought period and its effects. Many books and innumerable articles have been written. One useful source of information of a agricultural nature is the *Weekly Weather and Crop Bulletin* [65]. From the Kansas reports representative remarks pertinent to the western third of the State are listed below.

July 25, 1933	Corn needing rain badly and some greatly damaged.
Aug. 1, 1933	Pastures poor or dried up, cattle being shipped out in some localities. Stock water scarce in many places.
June 26, 1934	Needing rain badly in all parts.
July 3, 1934	Hot and dry. All crops need rain badly. Corn condition critical, crop badly stunted. Pastures insufficient to support livestock in much of west.
July 17, 1934	Corn stunted and burned until

TABLE 13.—*Drought (and wet spell) index, X, western Kansas*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1887	−0. 18	−0. 20	−0. 81	−0. 84	−0. 34	−0. 83	−1. 19	0. 82	−0. 05	−0. 12	−0. 31	−0. 38
1888	−. 54	−1. 02	. 27	1. 28	1. 55	1. 15	1. 17	1. 79	−. 70	−. 40	−. 55	−. 84
1889	. 62	. 47	. 65	. 77	. 95	1. 10	1. 11	−. 02	−. 70	. 69	. 74	−. 60
1890	−. 45	−. 59	−1. 12	. 81	−. 95	−1. 79	−2. 83	−3. 08	−3. 22	−3. 20	−2. 99	−3. 16
1891	. 62	. 31	1. 35	1. 07	1. 60	2. 75	4. 21	3. 78	4. 74	4. 43	3. 68	3. 87
1892	3. 44	3. 56	4. 01	3. 27	4. 55	3. 99	3. 91	4. 13	−. 70	−. 98	−1. 13	−. 93
1893	−1. 10	−1. 25	−1. 56	−2. 32	−2. 88	−3. 49	−3. 31	−3. 09	−2. 80	−3. 06	−2. 96	−3. 12
1894	−2. 99	−2. 34	−2. 51	−2. 93	−3. 63	−3. 76	−4. 26	−4. 97	−4. 49	−4. 68	−4. 70	−4. 08
1895	−3. 60	−2. 71	−2. 75	−2. 98	−2. 90	. 78	2. 34	2. 15	−. 70	−. 79	−. 64	−. 62
1896	−. 17	−. 64	−. 79	−. 03	−. 64	−. 51	−. 54	−. 73	−. 54	−. 09	−. 19	−. 48
1897	. 03	. 27	. 39	1. 39	. 83	. 62	. 77	1. 41	1. 00	2. 13	−. 25	. 02
1898	. 28	−. 32	−. 61	−. 91	1. 32	1. 65	1. 90	1. 27	2. 37	2. 10	1. 89	2. 20
1899	0	−. 06	−. 06	−. 53	−1. 28	. 12	1. 32	−. 92	−1. 12	−1. 39	. 63	. 65
1900	. 32	. 59	. 38	1. 84	−. 36	−. 10	−. 15	−. 94	. 93	−. 58	−. 94	−1. 16
1901	−1. 19	. 03	. 28	. 84	−. 53	−1. 29	−2. 23	−1. 88	−. 91	−1. 07	−1. 47	−1. 49
1902	−1. 29	−1. 29	−. 98	−1. 62	. 31	. 46	. 52	. 46	. 89	1. 27	−. 39	−. 35
1903	−. 51	1. 58	1. 35	1. 74	2. 43	2. 58	2. 81	3. 02	−. 62	−. 72	−. 70	−. 95
1904	−1. 17	−1. 56	−2. 11	−2. 06	. 05	. 49	. 67	. 83	1. 11	1. 12	−. 53	. 17
1905	. 47	. 46	. 32	1. 42	1. 96	1. 87	3. 06	2. 37	2. 18	1. 86	2. 52	1. 96
1906	1. 71	1. 30	1. 59	2. 05	1. 47	1. 55	2. 48	2. 51	2. 92	3. 63	3. 50	−. 11
1907	−. 07	−. 35	−. 87	−1. 27	−1. 56	. 16	. 42	. 51	−. 18	−. 23	−. 51	. 55
1908	. 21	. 45	−. 63	−1. 49	−1. 94	. 64	. 69	. 62	−. 66	. 25	1. 14	−. 28
1909	−. 34	−. 52	−. 07	−. 68	−. 89	1. 05	1. 27	−. 87	. 22	. 33	1. 98	2. 23
1910	2. 20	1. 98	−. 88	−1. 46	−1. 44	−2. 05	−2. 58	−1. 93	−2. 19	−2. 71	−2. 95	−3. 02
1911	−3. 05	−1. 79	−2. 26	−2. 46	−2. 78	−4. 03	−3. 71	−3. 28	−3. 66	−3. 24	−2. 95	. 73
1912	. 45	1. 47	2. 11	2. 08	1. 37	2. 09	2. 32	3. 60	3. 64	−. 35	−. 43	−. 71
1913	−. 75	−. 44	−. 68	−. 79	−1. 72	−1. 90	−2. 87	−4. 12	1. 12	. 54	. 70	2. 62
1914	−. 20	−. 16	−. 54	−. 51	. 53	. 56	. 56	. 81	−. 69	−. 57	−1. 13	−1. 06
1915	. 09	. 63	. 95	1. 66	3. 11	4. 06	5. 59	7. 53	7. 87	7. 49	6. 51	5. 86
1916	5. 66	−. 17	−. 57	−. 24	−. 81	−. 35	−1. 18	−1. 22	−1. 68	−1. 70	−1. 92	−1. 84
1917	−1. 81	−2. 05	−2. 18	−2. 01	−1. 87	−2. 58	−3. 16	−2. 66	−2. 13	−2. 37	−2. 49	−2. 50
1918	−2. 20	−1. 96	−1. 53	−1. 32	−1. 24	−2. 34	−2. 17	−2. 58	. 48	. 92	. 71	2. 58
1919	2. 16	2. 81	2. 86	3. 38	3. 06	3. 11	3. 22	2. 17	2. 95	2. 84	3. 09	2. 58
1920	2. 13	1. 59	. 99	1. 14	1. 06	. 85	. 58	. 95	1. 46	2. 14	1. 96	1. 83
1921	1. 98	−. 17	−. 67	−. 51	−1. 05	. 17	. 33	−. 44	−. 37	−1. 00	−1. 41	−1. 25
1922	−1. 30	. 01	. 64	1. 35	1. 44	−. 19	−. 06	−. 50	−1. 25	−1. 88	−1. 59	−1. 83
1923	−2. 09	−2. 30	−2. 31	−2. 20	1. 77	2. 69	3. 37	3. 78	4. 54	6. 14	5. 52	5. 26
1924	4. 75	4. 63	5. 68	−. 06	−. 21	−. 73	−. 70	−. 72	−. 47	−. 57	−. 96	−. 32
1925	−. 50	−. 78	−1. 24	−1. 57	−2. 11	−3. 00	−3. 12	−2. 23	−1. 38	−1. 24	−. 87	−1. 06
1926	−1. 13	−1. 44	−1. 12	−1. 31	−1. 86	−2. 34	−2. 56	−2. 86	−2. 72	−3. 22	−2. 77	−2. 43
1927	−2. 40	−2. 16	−1. 54	−1. 21	−2. 17	. 59	. 81	1. 64	. 01	−. 67	−1. 08	−1. 24
1928	−1. 50	. 45	. 64	. 30	1. 40	2. 92	3. 94	4. 39	3. 78	4. 40	4. 71	4. 25
1929	3. 84	3. 59	2. 97	2. 52	2. 58	2. 25	2. 18	1. 62	2. 05	2. 16	2. 78	−. 26
1930	−. 26	−. 76	−1. 09	−1. 32	−. 98	−1. 24	−1. 46	−1. 53	. 01	2. 63	3. 18	2. 94
1931	2. 54	2. 68	3. 53	3. 37	−. 02	−. 38	−. 81	−. 70	−1. 64	−1. 80	. 30	. 05
1932	. 63	. 34	. 41	. 44	−. 85	1. 05	−. 53	−1. 22	−1. 33	−1. 52	−1. 80	−1. 84
1933	−2. 07	−2. 23	−2. 55	−2. 45	−2. 14	−3. 46	−4. 07	−2. 45	−2. 69	−2. 94	−2. 59	−2. 15
1934	−2. 24	−1. 56	−1. 68	−2. 56	−3. 74	−4. 20	−5. 47	−5. 96	−5. 31	−5. 33	−4. 96	−4. 80
1935	−4. 56	−4. 60	−4. 89	−5. 46	−4. 07	−3. 64	−4. 65	−5. 11	−4. 26	−4. 23	−3. 52	−3. 45
1936	−3. 12	−3. 17	−3. 50	−3. 98	−2. 99	−3. 81	−4. 90	−5. 55	−4. 79	−4. 44	−4. 50	−4. 12
1937	−3. 71	−3. 54	−3. 17	−3. 71	−4. 48	−4. 31	−4. 90	−5. 47	−5. 34	−4. 87	−4. 76	−4. 46
1938	−4. 32	−4. 11	−3. 90	−3. 49	−2. 43	−2. 48	−2. 67	−3. 65	−2. 99	−3. 52	−3. 50	−3. 53
1939	−3. 19	−2. 58	−1. 94	−2. 22	−2. 96	−3. 16	−3. 98	−4. 48	−5. 26	−5. 55	−5. 44	−4. 80
1940	−4. 11	−3. 83	−3. 29	−3. 37	−2. 77	−3. 12	−3. 87	−3. 13	−2. 89	−3. 31	. 63	. 61
1941	1. 13	1. 24	1. 16	1. 59	2. 10	3. 49	4. 73	5. 13	5. 74	6. 12	5. 46	5. 10
1942	4. 55	4. 29	4. 08	5. 24	4. 19	4. 71	4. 32	4. 33	4. 07	4. 61	3. 90	3. 89
1943	−. 14	−. 55	−. 71	−. 89	−1. 23	−1. 41	−1. 96	−2. 14	−2. 62	−2. 73	−2. 86	. 20
1944	1. 32	1. 42	1. 85	4. 18	4. 87	4. 21	5. 42	5. 02	4. 03	3. 59	3. 49	3. 44
1945	3. 77	3. 36	2. 46	2. 90	2. 33	2. 51	2. 31	2. 12	2. 01	−. 42	−. 91	−. 87
1946	−. 93	−. 98	−. 67	−1. 81	−1. 44	−1. 72	−2. 33	−2. 62	. 69	3. 43	4. 94	4. 33
1947	4. 30	4. 03	4. 23	4. 31	5. 02	5. 17	5. 05	4. 09	2. 74	1. 82	1. 95	2. 28
1948	2. 10	2. 47	3. 18	1. 92	1. 62	2. 38	2. 60	3. 27	2. 39	1. 61	1. 18	. 91
1949	1. 34	1. 42	2. 00	1. 91	2. 86	4. 40	5. 17	6. 11	5. 39	5. 28	−. 55	−. 75
1950	−. 88	−. 91	−1. 09	−1. 52	−1. 82	−2. 55	1. 78	3. 80	3. 48	2. 84	2. 20	1. 56
1951	1. 67	1. 57	1. 36	1. 25	2. 40	4. 77	5. 82	6. 27	6. 74	6. 02	5. 41	4. 65
1952	4. 02	3. 40	3. 47	3. 67	−. 22	−1. 58	−2. 22	−2. 02	−2. 65	−3. 08	−2. 62	−2. 34
1953	−2. 48	−2. 64	−2. 50	−2. 28	−2. 45	−3. 52	−3. 47	−3. 14	−3. 78	−3. 37	−2. 14	−1. 39
1954	−1. 32	−1. 69	−1. 73	−2. 54	−1. 91	−2. 69	−3. 42	−3. 45	−3. 96	−3. 44	−3. 70	−3. 55
1955	−3. 16	−2. 95	−3. 08	−3. 15	−2. 57	−2. 38	−3. 50	−4. 21	−3. 42	−3. 84	−3. 79	−3. 63
1956	−3. 15	−2. 98	−3. 16	−3. 55	−4. 40	−5. 43	−5. 31	−5. 65	−6. 20	−6. 14	−5. 78	−5. 70
1957	−5. 26	−5. 22	1. 31	1. 53	2. 67	3. 87	4. 07	3. 64	3. 91	3. 74	3. 45	2. 65
1958	2. 52	2. 41	3. 74	3. 52	3. 68	3. 61	5. 28	5. 71	5. 18	4. 09	3. 88	3. 44
1959	3. 40	2. 99	3. 10	2. 34	1. 91	1. 04	. 98	. 76	1. 35	2. 64	2. 15	1. 91
1960	2. 66	3. 74	3. 80	3. 43	3. 12	3. 51	3. 04	2. 11	1. 88	1. 99	1. 86	1. 89
1961	1. 39	. 88	1. 02	. 67	1. 16	1. 56	1. 78	2. 27	1. 61	1. 38	2. 06	1. 95
1962	1. 92	1. 52	1. 91	1. 30	. 79	2. 03	3. 12	2. 83	2. 98	−. 35	−. 41	−. 54

almost ruined. Pastures too poor to support livestock.

Aug. 7, 1934 ------ Conditions worst ever known in many places. Corn not sufficient growth even for fodder in many western counties.

Aug. 14, 1934 ----- Pastures generally bare. Distressed animals being shipped out in increasing numbers.

Sept. 4, 1934 ------ Russian thistles being put up as fodder.

Oct. 9, 1934 ------ Winter wheat sowing delayed by dryness and crop making little growth.

Nov. 27, 1934 ----- Wheat fields bare in nearly all of western third.

Feb. 27, 1935 ------ Severe duststorms.

Apr. 16, 1935 ----- Severe duststorms; practically no pastures in western half.

May 7, 1935...... Duststorms [continue] frequent in western half; wheat crop very poor to poor in western half and deteriorating.

May 28, 1935..... Rain. Pastures greening.

July 2, 1935...... Moderate rains in northwest, southwestern counties are needing moisture.

July 30, 1935..... Dry. Much [of corn crop] damaged beyond recovery. Pastures deteriorating rapidly in west.

Aug. 27, 1935..... Corn in southwest counties not worth cutting. Grain sorghums badly stunted. Pastures deteriorating.

Oct. 29, 1935..... Wheat very poor to poor in extreme west.

Nov. 19, 1935..... Forage scarce in most of western half where wheat pastures poor.

Mar. 17, 1936..... Duststorms again reported.

Apr. 21, 1936...... Many [wheat] fields bare.

May 26, 1936..... Pastures much improved.

June 23, 1936..... Wheat badly damaged.

July 28, 1936...... Little [corn] in the western half will be fit for forage.

Sept. 1, 1936...... Pastures brown and scanty.

Nov. 24, 1936..... Wheat needs moisture rather badly; some soil blowing. Pastures scanty.

Dec. 1, 1936...... Wheat deteriorating. Moderate duststorms.

Mar. 2, 1937...... Considerable damage from previous duststorms. Substantial moisture badly needed.

Apr. 27, 1937..... Duststorms frequent.

May 25, 1937..... Wheat deteriorated in most of west and greatly damaged in southwest.

June 22, 1937..... Pastures weedy in west [from previous rains].

July 20, 1937..... Corn stunted and not tasseling.

Aug. 31, 1937..... Soil moisture very deficient. Pastures dried badly.

Sept. 28, 1937..... Duststorms in southwest.

Nov. 16, 1937..... Duststorms. Wheat deteriorating.

Dec. 7, 1937...... Wheat deteriorating in southwest.

Apr. 26, 1938..... Duststorms.

June 28, 1938..... Corn making satisfactory growth. Pastures improving.

Aug. 30, 1938..... Soil very dry; corn badly burned.

Sept. 20, 1938..... Soil moisture sufficient for early growth [of wheat].

Nov. 15, 1938..... Many wheat fields bare, some showing drill rows and, in favored localities, covers ground; root system there poor.

Dec. 6, 1938...... Wheat deteriorated.

Jan. 10, 1939..... Heavy duststorms.

Feb. 21, 1939..... [More] duststorms.

Mar. 14, 1939..... Sufficient topsoil moisture for present needs and outlook is improved.

Apr. 11, 1939..... Soil moisture now ample except in some western counties. Winter wheat improved; rank growth in southwest.

May 2, 1939...... Winter wheat deteriorated.

May 23, 1939..... Lack of rain being felt in west, especially in southwest where condition serious. Wheat deteriorated.

Aug. 1, 1939...... Corn deteriorated; bulk in west damaged beyond recovery.

Sept. 5, 1939...... Record-breaking heat, soil moisture badly depleted. Condition of all crops declined. Wheat seeding halted account dry soil.

Oct. 17, 1939..... Severe duststorms. Pastures very poor.

Oct. 31, 1939..... [Still] waiting for rain [before seeding winter wheat]. Sowing so far has been done in dust.

Nov. 28, 1939..... Much [wheat] not germinated, seeding still underway.

Dec. 19, 1939..... Winter wheat condition generally lowest on record. Duststorms.

Mar. 5, 1940...... Moisture ample for current needs.

Apr. 30, 1940..... Moisture deficient in western third, especially in southwest where duststorms [occurred]. Wheat fair in west.

May 28, 1940..... Wheat crop poor and weedy. Pastures growing well.

July 2, 1940...... Hot winds shriveled [wheat].

July 30,1940...... Severe damage to corn; half to three-fourths tassels burned white. Grain sorghums deteriorating. Pastures not sufficient to support livestock.

Aug. 13, 1940..... Rain adequate for current needs. More than half of corn [Statewide] past help. Pastures poor, but will revive.

Aug. 27, 1940..... Soil mostly too dry [for wheat seeding]. Pastures poor.

Oct. 1, 1940...... Topsoil moisture sufficient to abundant. Bulk of wheat up to excellent stands.

Oct. 29, 1940..... Moisture badly needed. Wheat growth slowed. Pastures dry.

Dec. 3, 1940...... Soil moisture penetrated to 1 to 2 feet or more. Wheat good to excellent condition with sufficient moisture to carry it through the winter.

Dec. 24, 1940..... [Wheat] prospects better than for a considerable number of years.

When one compares these remarks with the index values for the corresponding months in table 13, it becomes apparent that the index numbers are fairly representative of the severity of the agricultural drought. Consider, for instance, the fall of 1939. Many accounts of this great drought of the 1930's fail to point out that this was the worst fall season that occurred. The index indicates extreme drought, and the published remarks during October, November, and December substantiate it: pastures were very poor; it was too dry to plant wheat; and dust storms raged nearly every week.

Vegetative Cover Measurements.—Weaver and Albertson [70] have presented so many observations and interesting details of the effects of drought on the plant communities of the Great Plains that it is difficult to select an illustrative example. However, the basal cover measurements which they made annually (apparently in the fall) for over two decades in an ungrazed area near Hays, Kans. are indicative of the seriousness of the drought that prevailed in the 1930's and again in the 1950's. (Hays lies just to the east of the western Kansas area studied here.)

The most interesting feature of the figures in table 14 is the fact that they show that the drought in the 1930's was essentially continuous until revival of the vegetation began in 1941. The data (not shown) from the moderately grazed and overgrazed plots at Hays show a much more rapid deterioration of basal cover during the initial drought years. The overgrazed plot was reduced from 80 percent cover in 1932 to 30 percent cover in 1934. The minimum of 3 percent was reached in 1936. Some slight increase in cover took place in 1937, 1938, and 1939, but by 1940 the cover was only 14 percent. Incidentally, recovery in 1941 was slightly more rapid than on the ungrazed area.

The Duststorms.—Other aspects of the drought picture in western Kansas during the early 1930's have been pieced together by Johnson [23]. He paints a fairly vivid picture of the trials and tribulations of those people who were struggling to eke out a living from the land during those dry years. From Johnson as well as from the numerous publications of Albertson and coworkers at Kansas State College, Fort Hays, it is very clear that much of the notoriety associated with the years of 1934–1936 is a direct result of the unusually strong winds which created the terrible duststorms during those years. The wind combined with the drought to produce the disastrous conditions *and* the publicity. Other years have been about as dry and nearly as warm, but they lacked the strong winds, and the droughts were therefore less spectacular as well as less damaging.

TABLE 14.—*Total basal cover of short grasses in an ungrazed prairie near Hays, Kansas (after Weaver and Albertson [70])*

Year	Percent cover	Year	Percent cover	Year	Percent cover	Year	Percent cover
1932	89	1938	30	1944	95	1950	91
1933	86	1939	22	1945	93	1951	90
1934	85	1940	20	1946	89	1952	93
1935	65	1941	56	1947	88	1953	38
1936	58	1942	94	1948	93	1954	20
1937	26	1943	90	1949	92		

Disaster Declaration.—On June 19, 1934 Congress passed an emergency appropriation bill providing funds for the purchase of drought-stricken livestock. This program got underway at approximately the same time that the index indicates the existence of an extreme drought condition. Apparently at that time there was recognition that an extreme and disastrous condition had developed. On this basis one could postulate that extreme drought may well have coincided with the conditions which led to an official designation of "drought disaster area."

THE 1950's DROUGHT

The drought which began in Kansas in 1952 was a very serious matter by the summer of 1953. At the end of June the drought index indicates a severe drought. On the last day of June the Disaster Designation Committee of the U.S. Department of Agriculture, on the basis of first-hand reports from the drought area, declared all 31 counties of western Kansas a disaster area. Although the index does not show extreme drought it is interesting to note that the index value is very close to the value it had when drought disaster was recognized in 1934.

By the end of September 1953 the drought situation was even more critical. The index is −3.78 and the agricultural reports [66] indicate a serious shortage of feed with farmers faced with the choice of selling part of their breeding herds or buying high-priced feed. Table 14 shows the astonishing decrease in measured basal cover that had occurred during 1953. Also the streamflow records (table 15) indicate that only 1956 and 1939 produced less runoff during September than did 1953.

In September of 1954 the moisture shortage was apparently more pronounced; but, the published Crop Bulletins for that period are unfortunately rather vague. The comments are so general that it is difficult to tell very much about the specific situation in the western part of

Kansas. From reading all the reports one is aware that the area was very dry with delayed wheat seeding, feed shortages, and poor prospects in general.

The streamflow data for September 1954 show very slightly more runoff than during September 1953, but apparently this was the result of fairly heavy rains between the eastern border of the area and the gaging station at Beloit. The basal cover data in table 14 give a specific bit of information which reinforces the idea that very serious drought conditions existed in September 1954.

In 1955 the spring rains again produced some temporary alleviation of the drought, but during July the situation became critical and the *Kansas Weekly Weather and Crop Reports* [63] of August 2 indicate that the crop, pasture, and hay prospects were fading rapidly, with supplemental livestock feeding on the increase. By the end of August (report of Aug. 30) it was apparent that many grain sorghum fields would not head, corn would not produce grain, and the pastures were supplying practically no feed at all. Further evidence of the extreme drought during August is the fact that the runoff for the month established a record low for August (see table 15).

The moisture situation was dismal all during 1956. The spring was dry and the summer and fall were drier. The total runoff for the year, computed by the method described in the next section, was the lowest of record. The following remarks [67] illustrate the extreme seriousness of the drought in western Kansas.

May 28, 1956	Pastures furnishing little or no grazing.
July 2, 1956	Dry soil delayed planting [of grain sorghums] and stands poor. Rain urgently needed. Supplemental feeding of livestock still necessary. Drought intensified.
July 30, 1956	Grain sorghums at a standstill; plants firing. Corn tassels turned white and stalks firing.
Aug. 27, 1956	Droughty conditions steadily increasing. Crops continue to deteriorate. Many sorghum fields beyond help. No available soil moisture to 4 ft. at Garden City.
Sept. 10, 1956	Supplemental feeding general and liquidation of herds increasing.
Sept. 17, 1956	Drought situation aggravated by 100° weather. A few plantings [of wheat] emerged to uneven stands, but plants beginning to die. Herds being liquidated.
Sept. 24, 1956	Seeding being delayed. Much damage to seedbeds [by severe duststorms]. Wheat plants dying. Kansas River last three days lowest stage of record.
Oct. 8, 1956	All major streams at near-record low flows.
Oct. 22, 1956	Fields [for wheat] powder dry and seeding awaiting rains.
Oct. 29, 1956	Strong winds and dust severely damaged newly emerged [wheat] seedlings. Winter roughage supplies critically low.
Nov. 12, 1956	[Wheat] seeding continues in southwest and west central where soil powder dry.

When one compares the above remarks with the appropriate index values in table 13, it becomes apparent that the index values are relatively representative of the general agricultural situation. An index value of -4.00 seems to correspond reasonably well with "extreme" drought.

DROUGHT AND STREAMFLOW

Records of rates of streamflow can also be examined to determine whether or not such data show a useful relationship to drought severity. However, the available data pertinent to the western third of Kansas are far from satisfactory inasmuch as the stream-gaging stations are so located that the measured flow is not by any means dependent on only this area.

Four drainage basins are represented in the western third of Kansas [42]. An area in the northwestern corner, the equivalent of four or five counties, lies in the Upper Republican River basin and the drainage is toward the northeast. There are no long-record gaging stations which could be used to represent the runoff from this relatively small area. A similar situation exists in the southwestern part of the State where the Cimarron River carries the runoff from seven or eight counties. Here too no records are available for the period of concern in this study.

At Garden City, Kans., there is a long record of runoff on the Arkansas River [54]. This record is not particularly well suited for the purposes of this study because it represents too large an area, but it appears to be about the only one that can be used for this portion of the State.

With the exception of the previously mentioned counties in the northwest, the northern half of the western third of Kansas is drained by the Smoky Hill, the Saline, and the Solomon Rivers. Good runoff records exist for all three rivers [55]. The long-record stations are all a little too far east of our area, but the data may be at least partially indicative of the runoff from the area of concern.

The stations used were at Ellsworth, on the Smoky Hill River, Tescott on the Saline River, and Beloit on the Solomon River. The records of monthly runoff in thousands of acre feet were tabulated for these three stations and for Garden City for the period May 1929–August 1950 and the period October 1952–September 1957. No effort was expended in weighting or adjusting these records because even at best one could hardly expect to get more than a rough indication of the runoff from the study area. Therefore the runoff from the four stations was merely added to obtain a single value for each month. From these records table 15 was prepared. The three lowest index values for each month from table 13 have also been entered on table 15 for convenience.

From this table a number of things are apparent. First, the record low runoff for the 1–5-month period ending with April occurred in 1935. One can see also that the most serious April drought, as indicated by the index, also occurred in 1935.

The lowest 1-month and 2-month runoff values for the other months appear to coincide reasonably well with the lowest index values. For instance, the least April and May runoff (11,600 acre feet) occurred in 1937. The index, −4.48, also indicates the most serious May drought occurred that same year. Also, the least May and June runoff occurred in 1933 with 1956 not far behind (see footnote, table 15). The driest June according to the index was 1956 which was also the year with the least 3-month total runoff.

The remaining months in the table show much the same sort of thing. Considering the crude method of handling the only partially representative runoff information, the correspondence between years of very low index numbers and years of very small runoff is rather encouraging, but not unexpected. Both are a consequence of about the same climatic elements.

The reader will no doubt have noticed that the largest negative index value occurred in 1956 rather than in 1934 or 1936 as might have been expected. The runoff data for the periods ending with September seem to confirm that this dryness in 1956 was at least as extreme as that during the drought in 1934. As previously mentioned, some *effects* were worse in 1934 than in 1956 because of the wind and dust in 1934.

PASTURE FEED CONDITIONS

At the beginning of each month during the period April 1 to November 1 the United States Department of Agriculture receives numerous reports on pasture feed conditions in each State.

TABLE 15.—*Drought index values and the least amount of runoff (thousands of acre-feet) during periods of various lengths ending with the month and year shown, western Kansas*

	Length of period (months)										Year and amount of the 3 lowest index values for the month		
	1		2		3		4		5				
	Yr.	Amt.	Yr.	Amt.	Yr.	Amt.	Yr.	Amt.	Yr.	Amt.			
April	1935	2.9	1935	5.2	1935	8.0	1935	10.2	1935	12.5	−5.46 1935	−3.98 1936	−3.71 1937
May	1937	6.9	1937	11.6	1937	22.8	1934	[a] 38.9	1956	45.8	−4.48 1937	−4.40 1956	−4.07 1935
June	1933	5.3	1933	[b] 43.1	1956	56.4	1940	65.3	1940	68.2	−5.43 1956	−4.31 1937	−4.20 1934
July	1934	9.8	1933	25.6	1933	63.4	1933	88.4	1933	95.6	−5.47 1934	−5.31 1956	−4.90 [c] 1936
August	1955	5.0	1934	15.5	1940	88.9	1956	122.6	1956	128.7	−5.96 1934	−5.65 1956	−5.55 1936
September	1956	1.0	1956	18.4	1934	45.3	1956	110.5	1956	123.6	−6.20 1956	−5.34 1939	−5.31 1934
October	1939	1.5	1956	2.7	1956	20.1	1934	47.9	1956	112.2	−6.14 1956	−5.55 1939	−5.33 1934
November	1939	2.1	1939	3.6	1956	5.9	1956	23.3	1934	50.4	−5.78 1956	−5.44 1939	−5.96 1934

[a] 39.1 in 1956.
[b] 50.3 in 1956.
[c] also 1937.

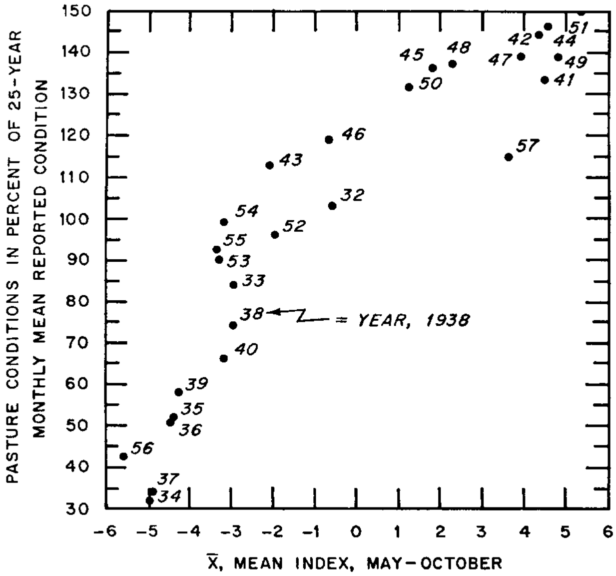

FIGURE 4.—Mean pasture condition, western Kansas June 1 to November 1, versus the average index $\overline{X}$ for the same growing season. (Data for period 1932–57.)

These subjective reports are expressed in terms of percent of normal condition, where "normal" indicates not the average but the expected condition under very favorable weather.

These monthly data for the western third of Kansas for 1932 through 1957 were obtained from the United States Department of Agriculture Crop Reporting Board by personal communication. Each monthly value represents approximately 200 individual reports. These data apparently contain some month-to-month and season-to-season fluctuations and trends which are in part dependent on the outlook and state of mind of the observers. It is suspected that the reports tend to show an exaggerated response to month-to-month weather changes. For example, from other accounts, such as table 14, there is evidence that pastures became gradually poorer and poorer during the drought in the 1930's. However, these condition reports show a very abrupt drop to a minimum of 11 percent of normal during 1934 followed by an improvement to 30 to 50 percent of normal during 1939.

In addition there are month-to-month trends in the data which indicate that a given percentage does not mean the same thing from month to month. For example, the average reported conditions for 25 years were as follows:

	Percent		*Percent*
Apr. 1	64	Aug. 1	62
May 1	64	Sept. 1	60
June 1	68	Oct. 1	59
July 1	69	Nov. 1	62

In order to remove this variability all the monthly values were recomputed in terms of mean reported condition. For example, a report of 34 percent of normal on June 1 becomes 50 percent of mean reported condition.

From these monthly values of mean reported condition it was possible to obtain a mean value for the period June 1 to November 1 for each year. Figure 4 shows the relation between this measure of pasture condition and the average April to October index (from table 13). The poorer condition in the 1930's as compared to the 1950's may be related to the amount of wind. The relatively poor condition in 1957 is the result of the poor condition (55 percent) that existed in the spring of this wet year. All in all, the index appears to be relatively representative of pasture conditions in western Kansas. No effort was made to investigate similar relationships in other areas.

12. DROUGHT CONDITIONS IN CENTRAL IOWA

The monthly index values for central Iowa for the period 1930–1962 [9] are shown in table 16. Only in 1931, 1934, 1936, 1956, and early 1957 does the index indicate really serious drought. Crops were rather poor in 1931, especially in the northern part of the area and average corn yield for the entire area was only 38.9 bushels per acre.

[9] 1930 and the years since 1957 were analyzed using the coefficients from the base period, 1931–57.

THE DROUGHT OF 1934

The severity of the drought in 1934 is evidenced by the following remarks [61] concerning the agricultural situation in central Iowa.

May 15, 1934 ..... Intense duststorms; meadows poor; hay and oats practically ruined; farm crop outlook poorest in memory; water scarce on great many farms.

TABLE 16.—*Drought (and wet spell) index, X, central Iowa*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1930	0.13	−0.21	−0.69	−0.55	−0.56	−0.47	−1.29	−1.98	−2.48	−2.31	−2.62	−3.02
1931	−3.26	−3.81	−3.94	−3.97	−4.12	−4.45	−4.14	−4.09	1.13	1.14	2.99	3.85
1932	4.10	3.67	3.13	2.40	2.21	2.04	1.85	2.89	2.76	2.48	2.76	2.87
1933	2.63	2.11	2.53	−.44	.54	−1.53	−1.64	−2.16	−2.25	−2.08	−2.81	−3.05
1934	−2.95	−3.19	−3.48	−4.09	−5.11	−5.98	−5.77	−5.86	.56	−.56	.82	.34
1935	.49	.76	.35	−.63	.30	1.65	1.97	1.28	1.37	1.98	2.44	2.55
1936	2.73	2.71	−.34	−.60	−1.12	−1.33	−2.88	−3.34	1.33	1.16	.70	.90
1937	1.34	1.41	1.33	1.68	1.74	−.33	−.71	−.71	−1.39	−1.30	−1.70	−1.95
1938	−1.95	−2.15	−2.15	.70	1.47	1.25	1.64	1.21	1.74	.93	1.26	1.11
1939	1.01	1.67	−.18	−.41	−1.29	−.92	−1.04	−.66	−1.43	−1.58	−2.20	−2.52
1940	−2.69	−2.45	−2.49	−1.91	−2.09	−2.61	.68	1.74	.94	.73	1.10	1.27
1941	1.68	−.11	−.47	−.93	−1.65	−.92	−1.19	−1.49	1.51	3.07	3.16	3.69
1942	3.43	3.31	2.98	1.95	2.06	2.24	2.98	3.07	3.32	3.20	3.13	3.16
1943	2.83	2.64	2.41	2.57	2.67	2.65	3.56	3.77	3.76	3.36	3.11	2.88
1944	2.88	2.75	2.92	3.59	4.76	4.52	4.82	5.32	4.75	3.85	3.32	3.27
1945	2.81	3.05	3.15	3.72	4.46	3.97	3.39	3.26	3.28	2.27	1.76	2.07
1946	2.58	2.04	2.57	1.55	1.72	2.35	2.28	1.98	2.49	3.10	2.95	2.56
1947	2.69	2.25	1.99	2.99	3.21	5.35	−.81	−1.78	−2.65	.76	−.08	−.02
1948	−.57	.59	1.02	−.11	−.68	−1.21	−.77	−1.15	−1.87	−1.88	.22	.45
1949	1.27	1.30	1.41	−.47	−1.20	−1.24	−1.53	−2.13	−1.88	−1.75	−2.41	−2.66
1950	−2.50	−1.97	−2.26	.12	.85	1.18	−.11	−.40	−.89	−1.35	−1.88	−2.26
1951	−2.58	.49	1.57	2.57	2.49	2.67	3.10	3.68	3.45	3.75	3.71	3.51
1952	3.41	3.00	3.75	3.02	2.78	2.60	2.69	2.76	−.72	−1.35	.25	.21
1953	.09	.49	.88	1.34	−.38	−.38	−.41	−1.14	−2.05	−2.95	−3.33	−3.47
1954	−3.91	−3.75	−3.59	.30	.59	1.05	.09	2.12	2.07	2.95	−.32	−.32
1955	−.31	.30	−.32	−.26	−.52	−1.28	−1.07	−1.76	−1.77	−2.14	−2.79	−3.25
1956	−3.61	−4.02	−4.49	−4.57	−4.73	−5.41	−5.14	−4.92	−5.01	−4.95	−4.92	−5.15
1957	−5.23	−5.48	−5.46	−5.30	−4.39	−3.91	−3.45	−2.97	−2.94	−2.28	−1.66	−1.45
1958	−1.41	−1.48	−1.83	−1.87	−2.33	.26	2.90	2.51	2.63	1.83	1.60	1.05
1959	.77	.88	1.76	1.88	2.54	1.82	1.40	1.03	1.07	1.15	1.42	1.48
1960	2.31	2.30	2.08	2.21	2.92	2.19	1.91	2.45	2.50	2.28	1.64	1.17
1961	.60	1.23	2.21	2.17	1.35	.78	2.14	1.82	3.45	3.69	3.94	4.00
1962	3.34	3.60	3.22	2.76	2.72	1.84	2.77	−.15	−.39	−.11	−.69	−1.15

June 5, 1934------ Pastures parched to tinder, feed situation acute; some corn dying; livestock being being sold for lack of pasture; one-half or more of the farmers [in Polk Co.] having to haul water.

June 19, 1934----- Pastures brown; corn fair; oats short and light.

July 3, 1934------ Corn rolled; small grain withered; more wells failing [in Hamilton Co.] and water being bought and hauled from long distances; pastures burned up; barley hardly tall enough to cut and very thin; wheat yield 5 to 20 bushels.

July 17, 1934----- Rain; pastures greening; corn now growing; oats and barley very poor.

July 31, 1934----- Oats yield 3 to 15 bushels per acre with quality very poor to fair; corn suffering; hauling water still in vogue [in Hamilton Co.]; cattle picking up since pastures improved; water situation [in Polk Co.] becoming more critical every day.

Aug. 14, 1934----- Corn badly hurt, some being cut for fodder; tomatoes and cucumbers not setting; potatoes not doing anything; forage not growing well; pastures very short and furnish practically no feed; practically every farmer [in Polk Co.] hauling water.

Aug. 28, 1934----- Corn will yield 10 to 40 bushels, only fair quality; ground too hard and dry for fall plowing; much of the corn crop going into silage or fodder.

When one compares the remarks above with those which applied to western Kansas, it may appear that 1934 did not produce extreme drought in central Iowa. However, the weather was *extreme for Iowa;* at no other period during the years studied was the moisture shortage in that area so disastrous. The drought index seems to be measuring this drought situation rather accurately.

Hydrologic Data.—It was not possible to locate any stream-gaging station or combination of stations that would reasonably represent the runoff from this relatively small area. The Des Moines River and the Iowa River both pass through the area but the gaging-station records probably reflect conditions outside the area at least as much as inside it. The Skunk River originates in and drains the central portion of the area, but the only long-record station is at Augusta about 75 or 80 miles to the southeast of the area of concern.

THE DROUGHT OF 1936

Fortunately, only July and August were extremely hot and dry, but they produced a very serious agricultural situation. By the third week in July there were reports [65] of moderate drought damage to corn. By late July it was estimated that the corn crop had been reduced by one-fourth and there were no good pastures. Rains in early September came too late for much of the corn, but produced a good supply of fodder and helped pastures. Corn yields turned out to be better than expected. The index reached its largest value, −3.34, in August.

THE DROUGHT OF 1947

In September of 1947 there were complaints [62] of pastures dry and short, corn and soybean crops being injured by drought, and soil too dry for fall plowing and seeding. But the situation did not approach the seriousness of the extreme drought of 1934. The index, −2.65, at the close of September also indicates a much less serious drought than in 1934.

THE DROUGHT DURING THE 1950's

During most of the first half of the summer of 1953 growing conditions were ideal [62]. (Note that the index indicates this as a period of mostly near-normal weather.) The moisture shortage began to develop about the middle of the growing season, and ". . . by the end of the season it was quite dry over the entire State, with some areas in critical condition." In October "Reports of dry wells are common over the State." "The fire hazard has increased, . . . communities have banned all outdoor fires."

The really serious dryness occurred so late in the year that the agricultural reports are very meager, but from the quoted reports above one can estimate that the drought was quite serious. Apparently it lasted all winter because the first *Iowa Weekly Weather and Crop Bulletin* of the spring of 1954 (April 5) reported, "water is still being hauled for livestock."

Noteworthy dryness returned in late 1955, and 1956 brought the most serious drought since the 1930's. The following selected excerpts from the Crop Bulletins [67] are more or less indicative of the agricultural situation in central Iowa during the 1956 growing season. Most of the reports were worded in such general terms that one cannot tell what area of the State they apply to; only a few contain remarks specifically pertinent to the problem being considered here.

May 28, 1956	Some late corn and soybeans not germinating because of a lack of moisture. Pastures and meadows need rain.
June 4, 1956	Poor yields on first cutting of alfalfa; oats heading only 6 to 8 in. tall. Only 1.4 in. of available moisture in 5-ft. root zone of alta fescue at Ames.
June 11, 1956	Corn and soybeans look good; pastures very dry and furnishing little forage.
June 18, 1956	Oat crop light; pastures very dry; yields of first cutting of alfalfa generally poor; some stands of red clover did not survive the dry fall and winter; corn generally not showing drought damage yet.
June 25, 1956	Oats being harvested as hay or pasture.
July 16, 1956	Corn in excellent condition; second cutting of alfalfa short with poor yields.
July 23, 1956	Corn and soybeans developing unevenly; excellent prospects where rains received, but prospects declining in drier spots.
July 30, 1956	Hay fields damaged by lack of moisture, some too far gone to recover if rains came now. Soybeans hurting for rain. Many meadows too dry to furnish forage. Rains badly needed in most of State.
Aug. 6, 1956	Corn prospects deteriorated in drier spots. Many clover seedlings destroyed by drought. Only 0.9 in. of available soil moisture in top 5 ft. at Ames.
Aug. 20, 1956	Corn crop uneven with best prospect in years in some areas, while other areas need rain to avoid further deterioration. Fall plowing retarded by dry soil.
Aug. 27, 1956	Crop prospects very uneven; some areas damaged beyond help by drought. Only 1.5 in. of available soil moisture (to 5 ft.) at Ames on August 31.
Sept. 24, 1956	Fall plowing and wheat seeding at a standstill because of dry soil.
Oct. 8, 1956	No available moisture to 5 ft. under alta fescue at Ames. Wheat only 50 percent planted, latest in 10 yr.

As they stand these remarks are not very informative; however, 1956 produced the least rainfall recorded for central Iowa during any year from 1930–60. It therefore seems likely that such remarks as "in the drier areas" included central Iowa. Insofar as the soil moisture measurements at Ames are representative, they certainly indicate an unusually dry condition at every sampling date.

As further evidence of the drought in central Iowa all rivers draining the area reached or almost reached record low stages during the latter half of 1956 [60]. As measured at Augusta the Skunk River equaled its 41-yr. record low in October, November, and December. The Iowa River at

Wapello was near its 42-yr. record low stage in both October and November. At Des Moines the Des Moines River equaled its 60-yr. record low in October and very nearly equaled it in July, September, and November.

The combined evidence indicates very unusual dryness in central Iowa during 1956. The index values show extreme drought from February 1956 through May 1957. This classification seems reasonable.

13. SUMMARY OF DROUGHT PERIODS AND FREQUENCY OF DROUGHT CLASSES

Tables 17 and 18 were prepared from tables 13 and 16. These tables show the month in which each of the various drought periods became established in western Kansas and central Iowa and the last dry month in each drought period. Also, the maximum value of the drought index has been tabulated for each period, as well as the number of months of mild, moderate, severe, and extreme drought as defined in table 11. The total duration of each drought period does not in every instance agree with the sum of the number of months in each class because on occasion a month or so in the incipient class occurred in the middle of a long drought period. July 1948 in central Iowa (see table 16) is an example of this.

WESTERN KANSAS

In western Kansas the median duration of drought is about 4 months, but the distribution is very skewed and the mean is about 12 months. A total of 339 months of drought occurred in the 76 years. This is 37 percent of the time. From table 13 one can also determine that a wet spell was underway in 37 percent of the months and that near-normal conditions existed in 12 percent of the months. It may at first seem unrealistic to have

TABLE 17.—*Drought periods, western Kansas, 1887–1962*

Start		End		Maximum severity	Number of months				
Year	Month	Year	Month		Mild	Moderate	Severe	Extreme	Total
1887	July	1887	July	−1.19	1				1
1888	February	1888	February	−1.02	1				1
1890	March	1890	March	−1.12	1				1
1890	June	1890	December	−3.22	1	2	3		6
1892	November	1895	May	−4.97	4	12	8	6	31
1899	May	1899	May	−1.28	1				1
1899	September	1899	October	−1.39	2				2
1900	December	1901	January	−1.19	2				2
1901	June	1902	April	−2.23	8	1			11
1904	January	1904	April	−2.11	2	2			4
1907	April	1907	May	−1.56	2				2
1908	April	1908	May	−1.94	2				2
1910	April	1911	November	−4.03	4	9	6	1	20
1913	May	1913	August	−4.12	2	1		1	4
1914	November	1914	December	−1.13	2				2
1916	July	1918	August	−3.16	12	13	1		26
1921	May	1921	May	−1.05	1				1
1921	October	1922	January	−1.41	4				4
1922	September	1923	April	−2.31	4	4			8
1925	March	1927	May	−3.22	12	11	3		27
1927	November	1928	January	−1.50	3				3
1930	March	1930	August	−1.53	5				6
1931	September	1931	October	−1.80	2				2
1932	August	1940	October	−5.96	8	22	30	39	99
1943	May	1943	November	−2.86	3	4			7
1946	April	1946	August	−2.62	3	2			5
1950	March	1950	June	−2.55	3	1			4
1952	June	1957	February	−6.20	6	17	23	11	57
Number of months					101	101	74	58	339
Percent of 912 months					11	11	8	6	37

Months of Beginning and Ending of Drought

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
First month	1	1	4	4	4	3	2	1	3	1	3	1
Last month	3	2	1	3	6	1	1	4	0	3	2	2

TABLE 18.—*Drought periods, central Iowa, 1930–1962*

Start		End		Maximum severity	Number of months				
Year	Month	Year	Month		Mild	Moderate	Severe	Extreme	Total
1930	July	1931	August	−4.45	2	3	5	4	14
1933	June	1934	August	−5.98	2	5	3	5	15
1936	May	1936	August	−3.34	2	1	1	----	4
1937	September	1938	March	−2.15	5	2	----	----	7
1939	May	1940	June	−2.69	5	7	----	----	14
1941	May	1941	August	−1.65	3	----	----	----	4
1947	August	1947	September	−2.65	1	1	----	----	2
1948	June	1948	October	−1.88	4	----	----	----	5
1949	May	1950	March	−2.66	6	5	----	----	11
1950	October	1951	January	−2.58	2	2	----	----	4
1952	October	1952	October	−1.35	1	----	----	----	1
1953	August	1954	March	−3.91	1	2	5	----	8
1955	June	1958	May	−5.48	10	6	4	16	36
1962	December	----	----	----	1	----	----	----	1
Number of months					45	34	18	25	126
Percent of 396 months					11	9	5	6	32

Months of Beginning and Ending of Drought

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
First month	0	0	0	0	4	3	1	2	1	2	0	1
Last month	1	0	3	0	1	1	0	4	1	2	0	0

three-fourths of the time devoted to either a drought or abnormally wet weather; but it is a well-known fact that normal or average weather does not occur very frequently, even on a monthly basis. This, coupled with the tendency for persistence, helps to explain the high percentage of abnormal conditions.

Table 17 also shows that western Kansas has mild drought during 11 percent of the months, moderate drought in 11 percent, severe drought in 8 percent, and extreme drought in 6 percent of the months.

At the bottom of table 17 is an auxiliary tabulation showing the number of times (out of the 28 drought periods) that each of the calendar months established a drought period. Spring and early summer account for about half of the drought beginnings, but apparently there is no really preferred time of beginning, so the information is neither startling nor particularly useful.

On the other hand it was a little surprising to find that almost one-third of the drought periods ended with April or May. This may be useful information in that it suggests that if a drought continues through May there is a good chance that June and July will also be drought months. There seems to be a slight tendency for the change to normal or wetter weather to occur during September, but the evidence is rather meager.

CENTRAL IOWA

The shorter record from central Iowa produced only the 14 drought periods shown in table 18. From this table and table 16 the following facts are evident.

Mild drought occurred 11 percent of the time, moderate drought 9 percent, severe drought 5 percent, and extreme drought 6 percent of the time. Drought was underway in 32 percent of the months, and a wet spell was underway in 50 percent of the months. In 11 percent of the months the weather was near-normal. (The remainder were "incipient.")

The average duration of drought was about 9.6 months, but the median was about 7 months. Half the droughts became established in May or June and all but three started between May and September. With the possible exceptions of March and August no month seems to have been a particularly preferred final drought month.

From these facts it is apparent that drought is almost as frequent in central Iowa as in western Kansas, but it is a little dangerous to make comparisons between the two areas because the analyses cover unequal periods of record.

MEANING OF THE DROUGHT CLASSES

On the basis of available evidence it appears that the drought index values are reasonably comparable in their local significance both in space and time. It seems reasonable to postulate that a drought index of −4.0 spells economic disaster in any region in which the established economy is significantly dependent on the vagaries of weather for its moisture supply.

As a point of departure the following descriptions of the consequence of each of the four classes of drought are proposed. These descriptions are more or less ecological and are probably not as close to being universally applicable as is the drought index itself. However, they may be useful for certain purposes.

Mild drought: Some of the native vegetation almost ceases to grow.

Moderate drought: The least drought-resistant members of the native plant community begin to die and the more xerophytic varieties start to take their place.

Severe drought: Only the most xerophytic varieties of native vegetation continue to grow. And vegetal cover decreases.

Extreme drought: Drought-resistant varieties gradually give way to open cover. More and more bare soil is exposed.

14. PROGNOSTIC VALUE OF THE INDEX

This index apparently measures something that might be of value in forecasting. Inasmuch as it provides a single number which is a function of many aspects of the current and recent weather, it seems likely that the index could, under certain circumstances, be useful in predicting the precipitation for the following month.

Figure 5 shows that not only does precipitation average much less during drought periods than during wet periods, but also that the two regimes show some remarkable departures from the average precipitation climate of central Iowa. For example, the fact that February produces near normal precipitation, on the average, during wet periods warrants some investigation. Can one use the previous index value as an indicator that February precipitation is not likely to exceed the normal by any substantial amount?

Monthly precipitation forecasts are ordinarily issued in terms of "light," "near-normal" or "heavy." These classes are defined in such a way that each contains 1/3 of the total number of occurrences. For central Iowa the February limit for "light" for this 33-yr. period is about 0.58 in. and "heavy" includes all amounts in excess of about 1.25 in.

There were 13 years during this period when the index was $>+1.50$ at the end of January. These 13 cases were followed by 5 Februaries which had "light" precipitation, 6 with "near-normal" precipitation, and 2 with "heavy" precipitation. This suggests only a 15 percent probability of heavy February precipitation when the index is greater than +1.50 at the end of January.

Table 19 shows the relationship between May precipitation and the index value at the end of April. The class limits for May are shown in the table. Of particular interest is the fact that the index at the end of April was positive in 16 of the 33 years, and in only 2 of those 16 years did "light" precipitation occur during the following May. Even more surprising is the fact that in 13 of the 16 cases (81 percent) the May precipitation was greater than the long-term mean with 8 of the 16 falling into the "heavy" category. Equally surprising is the fact that in 12 of the 17 Mays which followed Aprils having a negative index value the precipitation was less than the long-term mean. "Light" precipitation was observed in about half of these cases and only 3 years produced "heavy."

This relationship seems too good to be true and very likely it is to some extent fortuitous, but the chance of its breaking down completely on subsequent data seems a bit remote.

This relationship suggests a number of things.

TABLE 19.—*Contingency table showing May precipitation in central Iowa as a function of the index value at the end of April, 1930–62*

Index value at end of April	May precipitation: Light <3.00 in.	Near normal: <Mean	Near normal: >Mean	Heavy >4.80 in.	Total
X >0	2	1	5	8	16
X<0	9	3	2	3	17
Total	11	11		11	33

As far as drought is concerned there does not appear to be much chance of April being the last of a drought period. As a matter of fact one can determine from table 16 that 12 of the 15 Aprils having a negative index were followed by Mays which added to the droughtiness.

Of course, the factor that is being reflected in these relationship is persistence. It may be that this index is a more useful parameter for studying certain types of persistence relationships than is precipitation by itself.

Another subject for speculation arises here. Perhaps the persistence in the moisture aspect of this continental climate is related to the sources of the precipitation. It may well be that a good deal of the precipitation in continental climates represents moisture re-evaporated from land areas. This portion may be more substantial than some authorities have surmised. If it is, it would afford a partial explanation of the persistence of wet and dry periods. Begemann and Libby [2], from studies of the tritium content of rainfall, estimated that about one-third of the rain in the upper Mississippi Valley is ocean water and about two-thirds represents re-evaporated surface water.

As can be seen from figure 5, the July precipitation during drought periods in central Iowa does not average as much as it does during wet periods. Also, the difference between June and July is much less during drought periods than in the mean or during wet periods. This is an interesting difference which bears looking into.

The most striking thing that one finds on examination of the data is that there were 7 years when the *June* precipitation was less than the *July* normal with a drought underway at the end of June; and in all of these cases the July precipitation exceeded the June precipitation with the average difference being 1.98 in. Further, the July rainfall was normal or above in all but one of these 7 years.

Figure 5 also shows a large percentage difference in November precipitation between wet periods and drought periods. Apparently drought is rather persistent during the fall months because there were 12 years when drought was underway at the end of October and 9 of these were followed by Novembers in which the precipitation was below normal, the average departure being about 1 in.

Figure 6 shows a decrease in the average rainfall

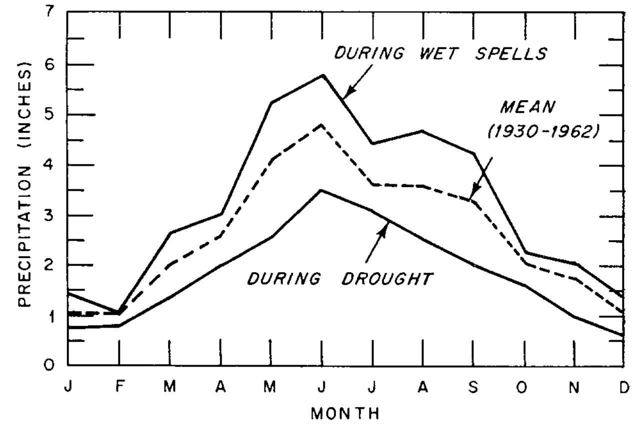

FIGURE 5.—Mean monthly precipitation in central Iowa.

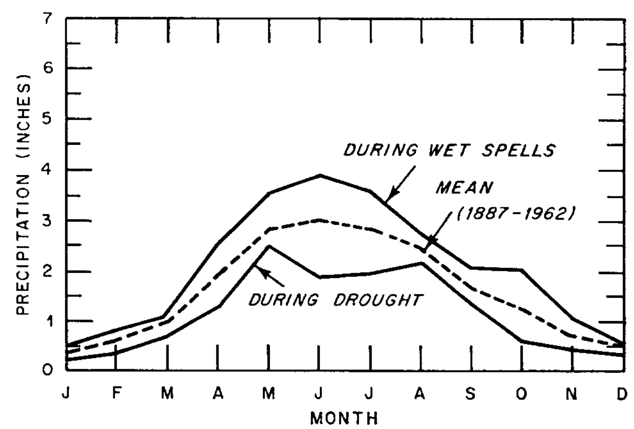

FIGURE 6.—Mean monthly precipitation in western Kansas.

from May to June in western Kansas during drought. This is in contrast to both the average change and the change during wet periods. On examination of the data it turns out that the drought index at the end of May was negative in 42 of the 76 years. In 30 of the 42 years the subsequent rainfall during June was less than the 76-yr. mean. There were 30 years when the May index was < -1.00 and 77 percent were followed by drier than average Junes.

The unusual dryness of October during drought periods in Kansas led to further examination of those years. There were 28 years when drought was underway at the end of September and 26 (93 percent) were followed by below average rainfall during October. In 24 of the years the October rainfall totaled less than 1 in. over the area. So, in Kansas too, we find some evidence that the index may be useful in forecasting.

These few examples demonstrate the need for further study of these and similar aspects of the usefulness of the index values.

15. THE METHOD APPLIED TO NORTHWESTERN NORTH DAKOTA

RESULTS AND VERIFICATION

In order to determine whether or not this method of analysis would provide reasonable final results in an area other than those on which it was primarily based, the data from the northwestern climatic division (six counties) of North Dakota were analyzed for the 30 years beginning with 1931. The derived means, coefficients, and constants are shown in table 20.

This Dakota area was chosen for analysis in 1961 because a drought was underway at the time, and it seemed timely to study an area in which drought was a problem of current concern. As it turned out this was not a particularly satisfactory region for a test because of the difficulty of locating auxiliary information for judging the reasonableness of the final index values.

Streamflow in this region (the Souris River) is almost completely regulated by controlled lakes and reservoirs. In addition, a number of new dams were built during the 1930's and there seems reason to believe that some of the low flows recorded at that time were a consequence of the flow being impounded behind newly constructed dams upstream.

The agricultural reports are at times a little misleading because the crops are so dependent on June precipitation. Ordinarily, almost one-fourth of the annual precipitation comes in June, and a hot dry June has a tremendous effect. As long as crops are deteriorating day by day, the agricultural reports stress the urgent need for moisture; but after the crops are harvested or dried up, published complaints of a moisture shortage diminish unless the shortage is so severe that even drinking water must be hauled in.

Table 21 summarizes the drought periods in northwestern North Dakota. The index reached its maximum negative value, −6.66, in August 1934 during the 20-month drought which began in August 1933. Note that this drought was in the extreme class 60 percent of the time. This drought was mostly in the mild class until April 1934 when the index, −2.41, showed it as moderate. By the end of the very dry May (rainfall 0.76 in.) the drought was in the extreme class with an index of −4.11. The next 11 months (except one) were all abnormally dry and the drought severity increased. The following index values were computed: June, −4.76; July, −6.24; August, −6.66; September, −6.04; October, −6.26; November, −6.13; December, −5.69. Drought severity continued to decrease in the following months, but moisture remained abnormally short until May 1935 when the drought ended. There is evidence that the drought in 1934 definitely reached an extreme severity.

TABLE 20.—*Means, coefficients and constants for northwestern North Dakota, 1931–1960*

AWC_s=1.00 in., AWC_u=5.00 in.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
T	6.3	10.5	21.4	40.5	53.2	61.3	69.2	66.9	56.1	44.4	26.0	13.6
ET	0	0	T	.86	2.40	3.52	3.46	2.32	1.25	.64	.02	0
PE	0	0	T	.91	2.95	4.26	5.52	4.69	2.68	1.13	.02	0
R	.41	.39	.59	.40	.13	.32	0	0	.21	.21	.54	.37
S'	1.76	2.16	2.56	3.15	3.30	2.69	2.44	1.11	.64	.67	.81	1.35
PR	4.24	3.84	3.44	2.85	2.70	3.31	3.56	4.89	5.36	5.33	5.19	4.65
RO	.01	T	.01	.02	0	.15	0	0	0	0	0	0
L	0	0	0	.25	.91	.57	1.33	.48	.17	.07	T	0
PL	0	0	T	.80	1.64	1.83	2.08	.86	.28	.17	.01	0
P	.42	.40	.61	1.02	1.80	3.43	2.13	1.85	1.26	.77	.55	.37
α	1.00	1.00	1.00	.9410	.8142	.8272	.6272	.4953	.4647	.5672	.9492	1.00
β	.0970	.1029	.1727	.1400	.0467	.0976	0	0	.0392	.0385	.1040	.0800
γ	.0042	.0017	.0050	.0064	0	.0565	0	0	0	0	0	0
δ	0	0	0	.3180	.4450	.3141	.6396	.5546	.5967	.4368	.5172	0
K	3.43	3.30	2.95	2.33	1.94	1.62	2.10	2.35	2.25	2.57	2.84	3.47

TABLE 21.—*Drought periods, northwestern North Dakota, 1931–1962*

Start		End		Maximum severity	Number of months				
Year	Month	Year	Month		Mild	Moderate	Severe	Extreme	Total
1931	March	1932	September	−5.05	2	6	4	7	19
1933	August	1935	April	−6.66	6	2	-	12	21
1935	September	1935	October	−1.45	2	-	-	-	2
1936	June	1937	August	−4.14	1	1	12	1	15
1938	September	1938	September	−1.01	1	-	-	-	1
1939	September	1941	March	−2.18	13	2	-	-	19
1946	April	1946	September	−2.40	2	4	-	-	6
1949	April	1949	September	−2.00	4	1	-	-	6
1952	April	1953	February	−3.44	1	5	5	-	11
1955	October	1959	August	−5.30	17	5	8	4	47
1960	September	1962	April	−5.67	7	1	4	3	16
Number of months					56	27	33	27	163
Percent of 368 months					15	7	9	7	42

Months of Beginning and Ending of Drought

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
First month	0	0	1	3	0	1	0	1	4	1	0	0
Last month	0	1	1	2	0	0	0	2	4	1	0	0

Bavendick [1] leaves no doubt of this. He wrote:

> It was not until June [1934] that any semblance of normal precipitation occurred and even that month showed a deficiency [59 percent of 30-yr. mean]. To further aggravate the situation, duststorms of unprecedented severity occurred during April and May. Much of the livestock was shipped out of the State due to lack of feed. Drought was so severe that plans for the evacuation of farmers from western North Dakota were seriously discussed. . . . Many cattle died from lack of feed and water and from dust which accumulated in their lungs and stomach. Some persons died from "dust pneumonia" caused by an accumulation of dust in their lungs.

As was the case in Kansas the effects of the abnormal moisture deficiency were greatly increased by the windstorms and dust, but the driest spring and summer on record certainly seems a likely candidate for the classification of extreme drought.

Turning to the drought in 1961, we find serious complaints of drought as the hottest and driest June on record reduced the wheat crop to about one-fourth of average. There were a few local showers in July and those areas enjoyed some temporary relief, but this was followed by the driest and hottest August on record. The following selected comments from the *North Dakota Weekly Weather and Crop Report* of August 29, 1961 [64] illustrate the seriousness of the drought at this time.

"Stock water situation is serious with many hauling water to livestock [in Burke Co.]. [The same was true in Mountrail Co.] Wheat yields averaged 4 to 7 bushels with a variation of 1.5 to 17 bushels. [Much of this was summer-fallowed wheat.] Very little barley and oats was harvested. Wells and dugouts are being constructed. Majority of [Renville] County remains extremely dry. Fall tillage delayed because of dry weather. Everything is at a standstill."

By way of comparison, the computed drought index values during 1961 were as follows: May, −1.16; June, −3.11; July, −4.14; August, −5.67. The peak severity during this drought was the −5.67 at the end of August. Severity decreased during subsequent months until the drought ended with April 1962.

This drought does not appear to have been as devastating as the drought of 1934, and from a crop yield standpoint the drought of 1936 ($X = -3.28$ at the end of July) was apparently more serious [1] than this one in 1961. There are many reasons why the effects were not as serious in 1961. In the first place there is a good deal more know-how these days for coping with the problems of dryland agriculture. There is evidence here that the Great Plains Conservation Program [53] has already met with some success in its objective—"to assist farmers and ranchers to develop for themselves a land use program which will help them avert many of the hazards that come with the recurring droughts common to the region." In addition, the availability of livestock feed on soil-bank acreages greatly alleviated the stockmen's problems in 1961. This feed was made available for haying and grazing by an official

U.S. Department of Agriculture action in late June declaring this a drought disaster area.

This action—possibly necessitated by the wording of the soil-bank law—led to much confusion concerning the seriousness of the drought during June and July. Some noted this disaster designation and visualized conditions similar to those in the dustbowl days of the 1930's in the southern Plains.

Conditions in July 1961 were by no means as serious as those which prevailed at the peak of the droughts in the southern Plains in the 1930's and in the 1950's. Descriptions such as [56] bear this out. The index also reflects this fact. At the end of July 1961 the index showed −4.14 in northwestern North Dakota. This value compares with the western Kansas values of −5.96 in August 1934 and −6.20 in September 1956.

It is also interesting to note that in the Kansas cases the index was around −3.5 to −4.0 when disaster was declared, but in the case of northwestern North Dakota the index was only about −3.00. There seems to be some evidence that the index provides a better estimate of the severity of this drought than does the disaster declaration. However, one must always bear in mind that this index is a function of the anomalous weather rather than of the *effects* of the weather. Agriculturally, one might be justified in considering the June weather as a calamity, but from a meteorological standpoint the drought at the end of June could not reasonably be placed in the same category with the drought of 1934.

AN EXAMPLE OF CURRENT DROUGHT ANALYSIS

During the summer of 1961 there was a considerable amount of public interest in the drought in the northern Great Plains and the Prairie Provinces of Canada. A period of showery weather began early in July and immediately there were reports that the drought had ended. On the basis of this analysis an article was prepared [35] pointing out that the weather of June had already used nearly all the antecedent moisture so that above normal July rainfall was required if the evapotranspiration was to be normal. It was further demonstrated that July had increased rather than ended the water shortage in this area. Early in August another article was released [34] pointing out the strong climatological likelihood for the drought gradually becoming worse during August. This article was based, in large part, on equation (14) which estimates the amount of precipitation needed for "normal" weather. It turned out that August had provided this much rain only eight times during the last 30 years, with most of the eight occurring during years in which most months were wetter than normal. From this it was concluded that the drought was more likely to become worse than to end during August. Actually, this turned out to be the driest and hottest August in 30 years and the drought became more extreme by September 1.

During September it rained 2.79 in. over the area. This was, by equations (29) and (30), far from being enough moisture definitely to establish an end to the long period of drought, but it did produce a 27 percent probability that the drought had ended. At that time there was no way of being certain that September was not just an interruption in the long drought. In fact, October and November were among the driest of record and both reduced the probability that the drought had ended. By the first of December the probability had been reduced to 9 percent with no prospect of its reaching 100 percent before the following spring. The unhappy truth is that under the existing circumstances there was no way of making a reasonable estimate as to whether this very serious drought period had ended or if the area was destined to suffer through another hot dry summer. This is in marked contrast to the situation in July and early August when there existed relatively high probabilities that the drought would get worse before it got better.

Actually, the change from prevailingly dry weather to unusually wet weather did not take place until May of 1962. It turned out, therefore, that the wet weather of September 1961 was only a brief interruption in the dry weather. That this would be the case was suspected in early winter, but there was no certainty until the following spring. This demonstrates that the need for reliable seasonal weather forecasts remains. However, under certain circumstances this method does provide a useful substitute.

In general this method of analysis seems to have provided fairly good results in North Dakota. There seems no way of measuring exactly how well the index is describing the moisture variable. The best one can say is that the results seem reasonable both in time and in comparison with the results obtained in Kansas and Iowa.

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.

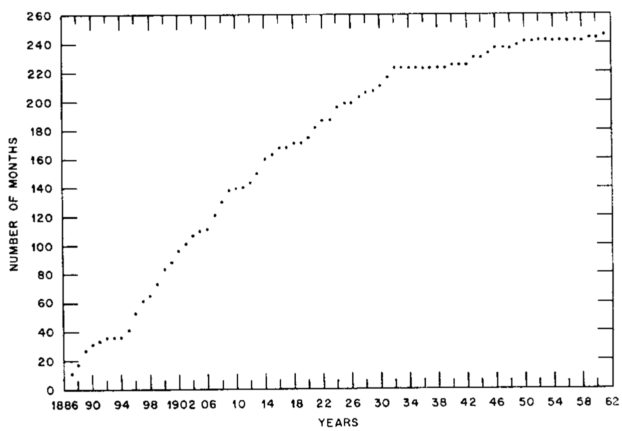

FIGURE 7.—Cumulative annual number of months with $|X| < 1.0$, western Kansas.

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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ATTACHMENT C

HCH 1% Drought Reconstruction Technical Memorandum

Technical Memorandum

Date: March 14, 2013
To: Paul Johnson, SAIC
Cc: Nathan Winkley, Mike Jacobs, John Christopher, Lynn Moore
From: John Winchester, High Country Hydrology, Inc.

Re: Extended drought reconstruction from PDSI

This memo summarizes the development of long-term reconstructed streamflows.

Background

Stream gauge records in south-central Kansas generally start in the 1920s. These cover the droughts of the 1930s, 1950s and 1990s, but do not necessarily reflect the long-term hydrologic variability.

Our research found that the only long-term surrogate data for south-central Kansas is approximately 1000 years of summer Palmer Drought Severity Index (PDSI) data developed by Dr. Edward Cook at the Lamont-Doherty Earth Observatory of Columbia University.[1] The Palmer soil moisture algorithm is calibrated for relatively homogeneous regions. The Palmer Index varies roughly between -6.0 and +6.0, which Palmer arbitrarily selected based on his original study areas in central Iowa and western Kansas.[2] The PDSI is a meteorological drought index, and it responds to abnormally wet or dry weather conditions. For example, when precipitation increases from below average to above average, the PDSI shows an end to the drought without considering streamflow, lake and reservoir levels, and other longer-term hydrologic impacts.

The Available PDSI Data

Cook originally produced a gridded network for the continental United States in 1999, based on 388 tree ring chronologies. In 2004 he expanded the spatial and temporal coverage to include 286 points in a 2.5 degree grid covering most of North America, as shown in Figure 1. The 2004 PDSI reconstructions are based on 835 tree-ring chronologies. Figure 2 shows the tree ring sites used for the 1999 network (there was no comparable map for the 2004 chronologies on the NOAA web site). As shown in the figure, in 1999 there are no tree ring sites located in Kansas, so PDSI values for the six locations in Kansas are interpolated from sites in other states.

[1] http://www.ncdc.noaa.gov/paleo/pdsi.html
[2] Palmer, Wayne C., Meteorological Drought – Research Paper No. 45. Office of Climatology, Washington DC. 1965.

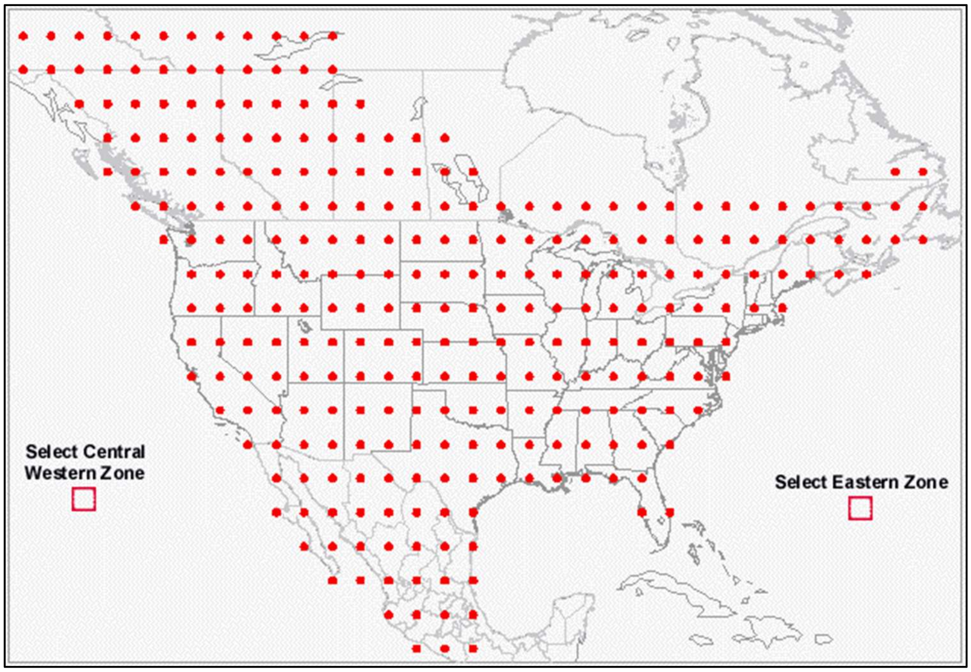

Figure 1. Grid locations where PDSI has been generated (Cook, 2004).

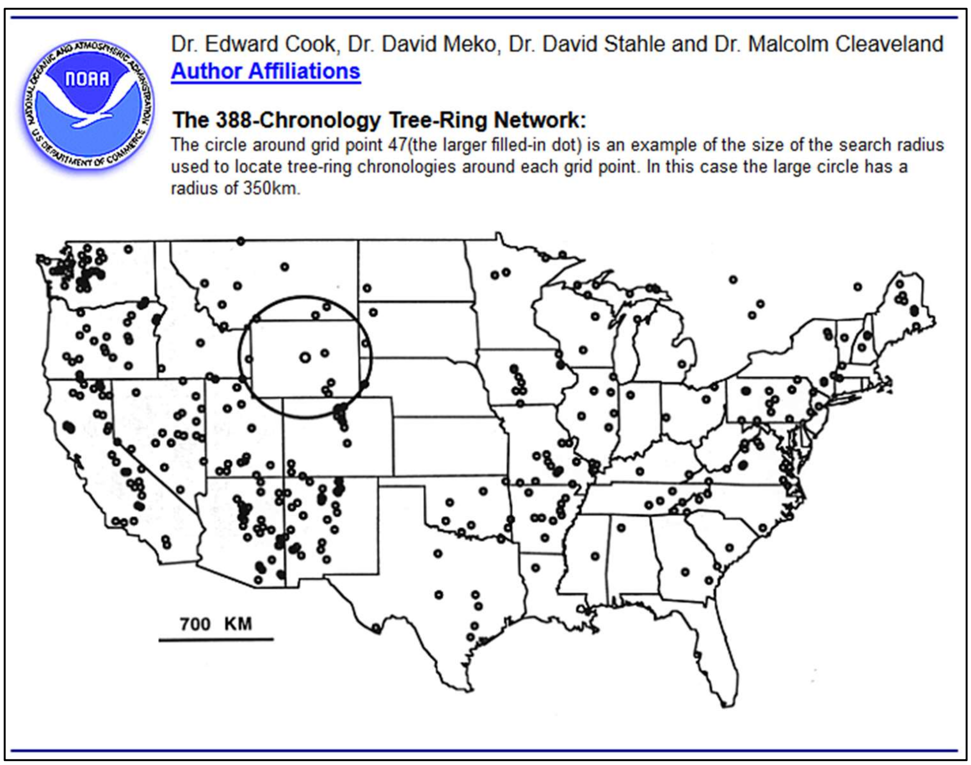

Figure 2. Locations of tree ring chronologies used by Cook in 1999.

The PDSI values generated in 2004 represent the average summer (June-August) PDSI.[3] Six of the grid locations published in 2004 fall within Kansas. Comparing the summer PDSI with annual flows for the Little Arkansas River at Valley Center, we found that the best correlation between streamflow and PDSI was obtained when we used the PDSI for southwestern Kansas.

The PDSI data for southwestern Kansas has a period of record from 887 AD – 2003 AD. Figure 3 shows a time series of the PDSI and the number of tree ring sites used to reconstruct the PDSI for the period of record.

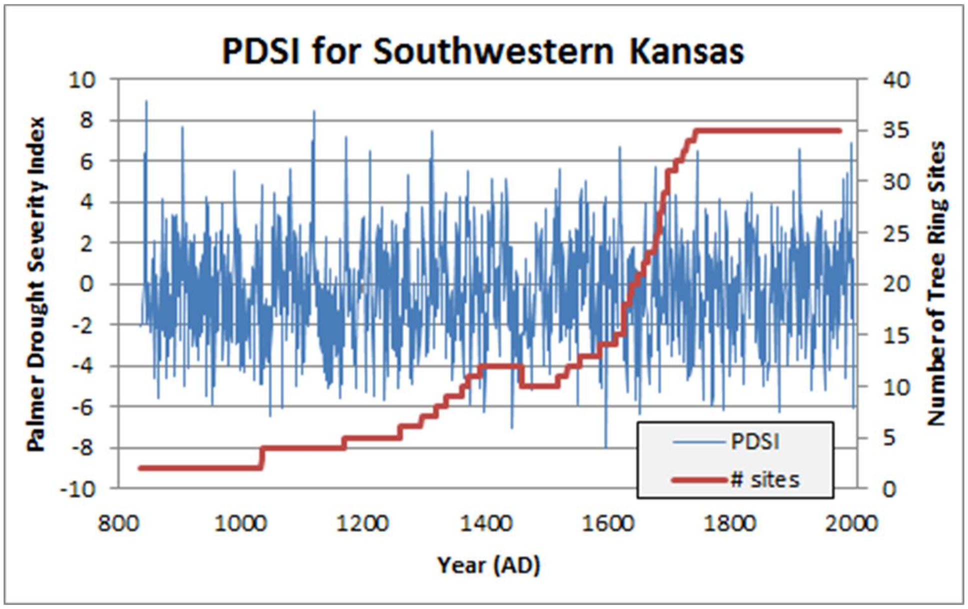

Figure 3. PDSI and number of tree sites.

The Cook data set included both the PDSI calculated from historical records for 1900-2003, and the reconstructed PDSI for 887-2003. The correlation between these two data sets had an r^2 of 0.82. For the following analyses, we used a composite PDSI that was made up of the reconstructed values for the years 887-1899, and actual values for 1900-2003.

Drought Return Period

Using the PDSI data, we calculated the return period for various droughts. While the method for calculating the return period for a single year is well documented, there is no standard method for calculating the return period for multi-year droughts.

We calculated and compared the return period for droughts in three ways: using single years, using the number of consecutive years in a drought, and using the cumulative PDSI.

[3] http://www.ncdc.noaa.gov/paleo/pdsi.html

Single Year Severity

To calculate the return period of single years, we sorted the annual PDSI values into ascending order, so the most negative values were first. We ranked the data, with 1 being the most negative value.

We applied the equation for recurrence intervals to this data,

$$T = (n+1)/m$$

where
T = recurrence interval in years
n = number of years in the time series
m = rank of the individual year (1, 2, 3…)[4]

While there were drier years before 1900, during the gauged period of record covered by the PDSI (1923-2003), defining droughts based on single years showed that 2002 was the driest single year in the 1900-2003 period of record, followed by 1956 and 1934.

While individual years are interesting, they do not adequately describe the droughts experienced in Kansas.

Number of Drought Years

Counting the number of years with below average precipitation and runoff can be used to determine the duration of a drought.

Rather than simply count the number of sequential years with a PDSI below zero, we modified our calculation of duration to account for variation of average years, and to allow for single years with average conditions that occur in a string of drought years.

Based on Palmer's original paper, the range of -0.49 to 0.49 is considered "near normal." Because there are years with a negative PDSI that are still considered within the normal range, we did not consider a year a drought year until the PDSI was less than -0.5. This assumption eliminated 82 of the 1167 years from the drought classification.[5]

In recognition that droughts can last through a single near-average year, series of drought years were considered unbroken if it contained a single year with a positive PDSI less than 0.5. While there were individual positive years in strings of drought years, this assumption did not change any of the calculated drought durations because all the individual years had a PDSI of greater than 0.5.

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[4] Dunne, Thomas, and Leopold, Luna. Water in Environmental Planning, 1978.
[5] PDSI drought durations.xlsx

Drought Duration and Severity

City staff at Wichita asked us to analyze surrogate hydrologic data to determine long-term drought durations and severities. This memo discusses long-term droughts and potential data sets that could be used for planning purposes.

Drought Duration and Severity

There are no long-term streamflow reconstructions for south-central Kansas, however Ed Cook and John Krusic have reconstructed annual values of the Palmer Drought Severity Index (PDSI) across North America, including six points in Kansas. We compared the annual values of PDSI with gauged streamflows for 1923-2003, and found that the PDSI for southwest Kansas was the best match for streamflows near Wichita. The PDSI reconstruction for southwest Kansas covers 1166 years, from 837 to 2003.

The PDSI reconstruction for southeast Kansas is based on tree ring chronologies. The number of sites used to develop the PDSI for southwest Kansas ranges from 2 to 35. Statistically comparing different periods of the reconstructed PDSI, we determined that years with more than 15 tree ring sites produced statistics more comparable with the historical record, whereas earlier values based on fewer sites tended to be biased toward drought. Consequently we have limited our use of reconstructed PDSI to the years 1640-2003, which are based on 15 or more tree ring sites.

To determine drought duration, we counted the number of below-average years that occurred in a row, and then calculated the exceedance probability for the different durations using the standard equation,

Exceedance = Rank / (Sample Size + 1)

Using the same PDSI data, we calculated the total cumulative PDSI for each drought. Because annual PDSI data does not correlate well with historical daily stream gauge data, we suggest that the simplest strategy to generate model input for drought sequences is to use historical streamflow data from years with similar PDSI values. Based on historical PDSI data, we have assembled combinations of gauge data to represent the historical droughts portrayed in the PDSI data. Drought duration, severity and representative years from the historical gauge record are shown in Table 1 for various droughts.

Table 1. Drought Durations and Severity from PDSI Data

Suggested Drought Intervals based on reconstructed PDSI (1640-2003)				Representative Historical Years	
Exceedence Probabilty	Duration (yrs)	Cumulative PDSI	Mean pdsi	Years	Actual Cum. PDSI
10%	2	-4.4	-2.20	1925-1926	-4.9
4.0%	4	-8.8	-2.21	1925-1926, 1981 x 2	-8.8
2.0%	6	-15.6	-2.60	1952-1956, 1959	-16.1
1.3%	7	-19.6	-2.80	1946, 1952-1956, 1981	-19.6
1.0%	8	-22.4	-2.80	1933-1940	-24.4
0.40%	10	-31.4	-3.14	1952-1956 x 2	-31.1
0.20%	12	-38.2	-3.18	1952-1956 x 2, 1963-1964	-38.4
0.10%	14	-45.0	-3.21	1925, 1933-1940, 1936-1937, 1937, 1940, 1976	-45.0

Design Drought

City staff requested that we fit the drought-duration data to a distribution so they can see how much of the data is included in various multiples of the standard deviation.

The annual PDSI data were classified into wet and dry years, with wet years having a PDSI greater than 1, dry years less than a PDSI of -1, and normal years between 1 and -1. If two dry years were separated by a single wet year with a PDSI of 0.5 or less, the dry streak was considered to be continuous.

Assuming the year counts were divided into 9 bins, the Johnson's Special Unbounded (SU) distribution best matched the number of consecutive drought years. The analysis of fit was made using sequential years for both wet and dry years (both positive and negative values of PDSI). The red data points show the number of droughts that occurred for each drought duration on the x-axis. Note that the secondary axis only approximately matches the function because it is not possible to mix x-y and bar graph types in Excel.

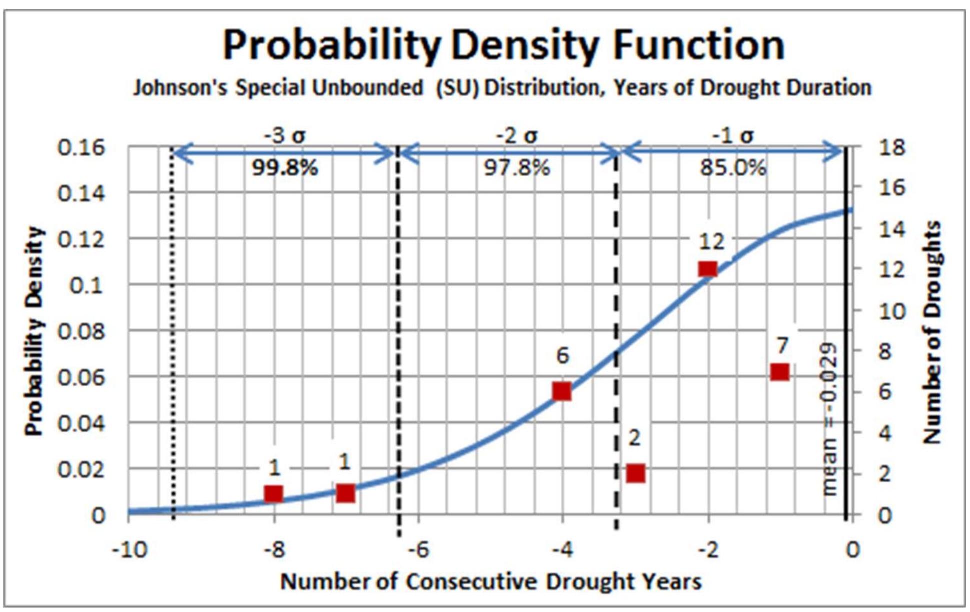

Figure 4. Fitted distribution and actual number of droughts

The graph shows the actual number of droughts for durations of 1, 2, 3… years. The analysis was done using an odd number of bins (9 bins for 16 years), which eliminated the outliers for droughts of 1- and 3-years.

Assuming the distribution represents the data, this graph shows that droughts with durations within 2 standard deviations would represent 97.8 percent of the droughts, including the drought with a 2-percent chance of occurring.

ATTACHMENT D
City of Wichita Water Demand Assessment

Technical Memorandum

Water Demand Assessment

City of Wichita

August 2013

SAIC

PEC

PROFESSIONAL ENGINEERING CONSULTANTS, P.A.

Technical Memorandum

Water Demand Assessment

City of Wichita

August 2013

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INTRODUCTION

A major part of the Water Demand and Supply Assessment Study is the Water Demand Assessment, which identifies forecasted water demands for the area served by the Wichita Water Utilities. In this report, water demand refers to the total amount of water used from the Wichita Water Utilities within the Wichita Water Utilities service area. The Water Demand Assessment was developed to show how water demand will change for the Wichita Water Service Area (WWSA) through 2060. Assessing future water demand will aid in monitoring balances between water supply and water demand.

Population projections through 2060 were completed for the WWSA. To determine future water demand, a per capita annual water demand rate was multiplied by the future population. Due to uncertainties in future population change, three scenarios were developed: low growth, medium growth, and high growth. The scenarios provide a likely range for future population growth and water demand within the WWSA.

Typical of many water demand and supply studies, peak day water demand was also assessed as part of the Water Demand Assessment. The peak day is the demand during a single day of the year when water use is the greatest. The peak day water demand typically occurs during the summer months. Peak day demand assessments are useful in making sure supply can meet demands. They can also be very useful in identifying whether the conveyance system has the capacity to meet future peak day demands.

Section 1
METHODOLOGY

The Water Demand Assessment focuses on demand for treated water. Raw water must be supplied, delivered to a treatment facility, treated, and then pumped into the distribution system where it will be delivered to the end user. The user may be a residence, business, city department, home owners association, or other entity. Based on limited available consumption data for different types of end users, it was decided to base demand projections on the total per capita annual water demand. This method takes into account all types of water users, but bases total usage on the total amount of water pumped to serve the WWSA population.

The assessment includes water demand projections out to 2060. The base year for the Water Demand Assessment is 2010. This year was chosen because reliable water usage data and location-specific population data was readily available.

The first step in determining the per capita annual demand was to define the area of the WWSA. The WWSA is comprised of two service areas: retail and wholesale. Because these areas have distinct characteristics (and available data), they are treated separately in much of the Water Demand Assessment. The current boundaries for the two service areas were defined for the base year. Over time, the WWSA is expected to expand beyond the base year boundary. The Water Demand Assessment includes projected expansion of the WWSA, which defines the geography for 2060.

The second step was to collect historical population data and forecast future population for the WWSA. The Cohort Survival Method was used to forecast future population through 2060. This methodology relies on a base year population, death rates, birth rates, and net migration rates. Three population growth scenarios were developed for the Water Demand Assessment: high growth, medium growth, and low growth. The medium growth scenario provides the best estimate for population growth. The high growth scenario assumes higher birth rates and lower death rates. The low growth scenario assumes lower birth rates and higher death rates. Multiple scenarios provide an increased level of confidence by showing a band of population growth and therefore a band of water demand.

After forecasting population, the next step was to determine total annual water demand. The 2010 total water usage was divided by the total population of the WWSA to provide a base year per capita annual water demand. Although there has been a trend of decreasing water demand per capita, the forecasted water demand used the 2010 per capita demand. The Water Demand Assessment assumes the base year per capita water demand will stay constant through 2060. The different population growth scenarios provide a band of likely water demand. Based on an evaluation of historic consumption, per capita demand tends to be largely correlated to factors such as climate, precipitation, and private irrigation well drilling.

Using the overall per capita annual demand for the WWSA, the next step was to distribute the overall demand among customer types. This provides granularity to the demand per capita, showing how much water will be used by each customer type. Water sales data was available on the following customer types: residential, non-residential, wholesale, department no-charge, and unaccounted-for water.

The final step was to forecast water demand for the day of highest use. Every year there is a day when demand is the highest, which typically occurs during the summer months. The demand for this particular day is greater than the annual average day demand by a factor; the peak day factor. Over the past 22 years, this factor has ranged from 1.5 to 2.07. Due to this variability, two peak day demand scenarios were developed. Each of the scenarios uses a different peak day factor and provides a range for future peak day demand.

Wichita Water Service Area

The Wichita Water Service Area (WWSA) is defined as the area to which Wichita Water Utilities provides water. This area includes residences, businesses, industries, and other users. The water customers served by Wichita yesterday and today set the stage for who will be served in the future.

Current Wichita Water Service Area

Wichita Water Utilities identified the current WWSA geography[1], considered the 2010 WWSA, since 2010 is the base year used in the Water Demand Assessment. To aid in assessing population growth for the WWSA, the boundary was slightly adjusted to follow US Census Block boundaries. As a conservative measure, this adjustment included very small areas outside of the area defined by Wichita Water Utilities.

The 2010 WWSA includes two separate and distinct service areas: retail and wholesale. The WWSA encompasses 375 square miles and includes over 460,000 residents. Exhibit 1 shows the current WWSA.

The Retail WWSA (WWSA-R) is the area where Wichita sells and meters treated water to specific addresses or locations. The WSSA-R includes customers in Wichita, Andover, Eastborough, and portions of unincorporated Sedgwick County. The WWSA-R covers 192 square miles and includes a population of 402,640.

The Wholesale WWSA (WWSA-W) is the area outside the WWSA-R to which Wichita provides treated water through wholesale contracts. The WWSA-W includes Bel Aire, Benton, Derby, Kechi, Park City, Rose Hill, Rural Water District (RWD) 1, RWD 2, RWD 3, and Valley Center. Wichita Water Utilities sells and meters water at a single connection point to each of these areas. The individual jurisdictions then sell the water to customers. The WWSA-W covers 183 square miles and includes a population of 58,032.

Forecasted Wichita Water Service Area

The area served by Wichita Water Utilities is expected to expand. Wichita does not have a policy or criteria to guide future expansion of water service, which makes it difficult to predict where service area expansion may occur. Wichita has historically provided water to customers that request water service. It is assumed that retail water will continue to be provided to new developments outside of the Wichita city limits. The expansion is anticipated to be incremental through 2060. It is important to note that the WWSA-R and the WWSA-W are anticipated to expand at different rates. Exhibit 1 shows the forecasted WWSA boundaries.

The future WWSA has gaps in the service area, such as that between the expanded WWSA and Benton. These gaps are due to the expectation of limited growth in these outlying areas.

Retail Service Area Expansion

The first step in determining the future WWSA-R eliminated the option of using the historical expansion rate of the WWSA-R. The expansion rate from 2000 to 2010 was 4.52 square miles per year. At this rate, by the year 2060 the WWSA-R would include an additional 225 square miles for a total of 418 square miles, more than doubling the current area of 192 square miles. The historic expansion rate was deemed unrealistic due to limitations on expansion, particularly because the current WWSA-R area abuts with other existing water service areas (municipal or water districts).

The next option was to use older geographic data[1] from the Water Utilities Department from the area defined as planned or potential growth area as the basis for the future WWSA-R. This expansion area includes an additional 92 square miles, which would equate to an additional 1.85 square miles per year through 2060. The planned or potential growth area was consistent with the Wichita-Sedgwick County Metropolitan Area Planning Department's defined Urban Growth Area[2] for the City of Wichita. The growth area was also consistent with the US Census defined Urban Area Boundary. For these reasons, and because there is no policy for future expansion of the WWSA-R, the Water Utilities Department defined planned and potential growth area was used as the expansion area through 2060.

Wholesale Service Area Expansion

The WWSA-W is expected to expand at a much slower rate than the WWSA-R. Three rural water districts are wholesale customers of Wichita and they will not expand. Many of the municipal wholesale service areas abut other municipal service areas and cannot expand in certain directions. Also, if municipal wholesale service areas expand, much of the expansion will be into rural water district service areas that are already served by Wichita.

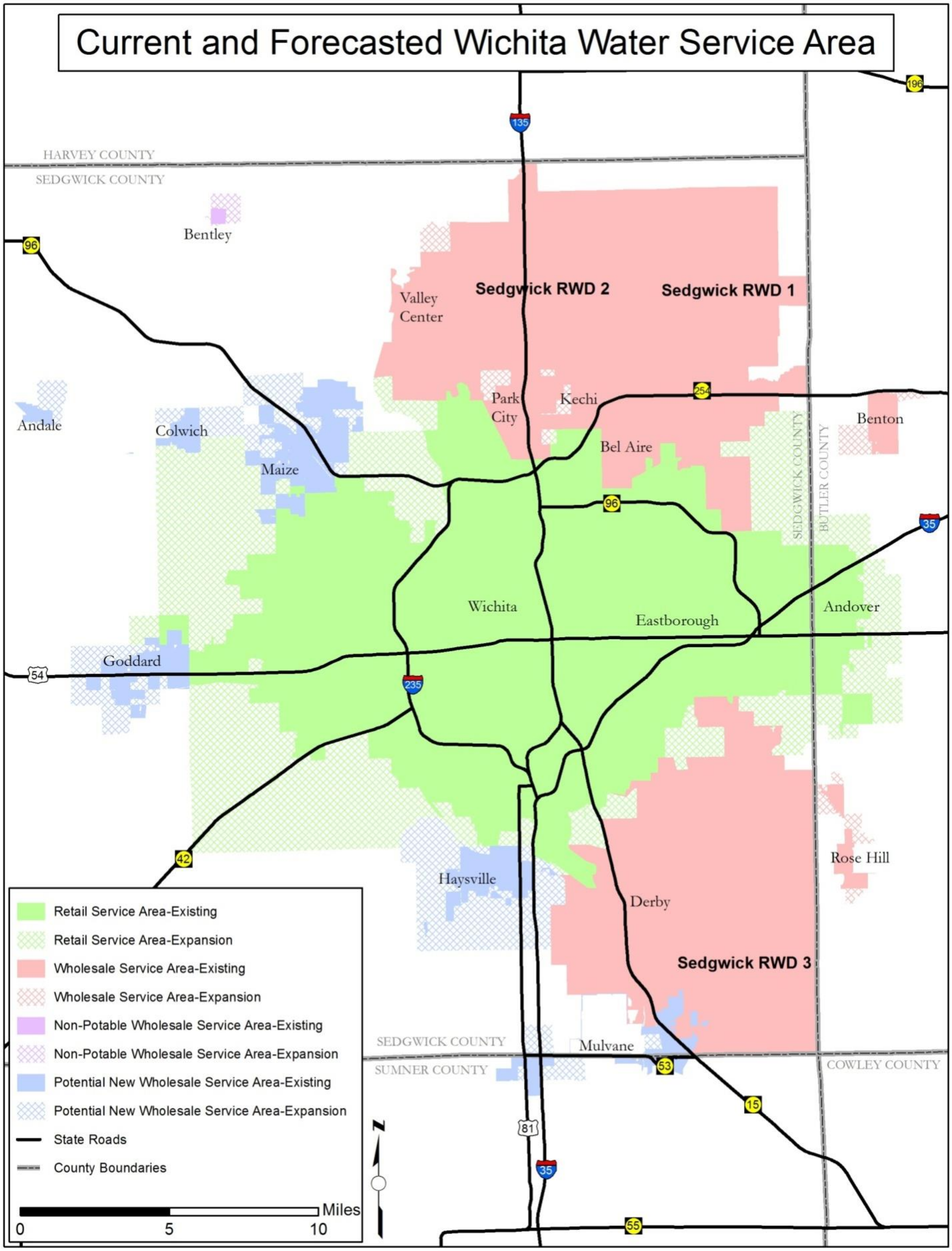
The area of expansion of the WWSA-W was based on the Urban Growth Boundaries for those municipalities currently served by Wichita. Only areas not currently served by any of Wichita's wholesale contracts and within each of the municipality's Urban Growth Boundaries were identified as wholesale expansion areas. The wholesale service area is projected to expand approximately 0.10 square miles per year from 183.3 square miles in 2010 to 188.3 square miles in 2060.

Other Wichita Water Service Areas

It is important to note that two other service areas are discussed in this report. The non-potable wholesale water service area includes the area served by Wichita Water Utilities that receives untreated (raw) water. The other service area includes municipalities that are not currently served by Wichita Water Utilities. These municipalities have been identified as being potential additions to the WWSA via new wholesale contracts.

The current and forecasted geographic bounds for the non-potable wholesale service area and the potential new wholesale service area are shown in Exhibit 1. Information on projected population growth, service area expansion, annual water demand, and peak water demand for the non-potable wholesale service area and the potential new service areas are available in Appendix B. This report, however, focuses on the retail and wholesale service areas.

Exhibit 1: Current and Forecasted Wichita Water Service Area



Population

The Cohort Survival Method was used to develop population forecasts for the WWSA. This method relies on death rates, birth rates, and net migration for 36 age/sex cohort groups. The method was modified slightly to account for expansion of the WWSA.

Data for the base year (2010) population was collected[3] for US Census Blocks for each of the 36 age/sex cohort groups within the WWSA. Data was collected in the same manner for the Census Blocks that are expected to be included in the WWSA by 2060 as it expands. The data for each jurisdiction (city and county) was kept separate as different areas have different migration rates. The projections for each jurisdiction were carried out through 2060 then combined to show the population projections for the WWSA-R and the WWSA-W.

Population projections were completed through 2060 in 5 year timeframes and were based on the 2010 population. The projected population per age/sex cohort depends on deaths, migration, and new population due to expansion of the WWSA. The population for males and females aged 0-4 depends on the same variables but also includes births.

The population projections include three scenarios: medium growth, high growth, and low growth. Each uses different assumptions for future birth rates and death rates. The medium growth scenario is what is expected, and the high and low growth scenarios give a range for likelihood for population growth.

Births

In the Cohort Survival Method of projecting future population, births are added to the population over time. The births are based on the birth rate of the total population and are added to the population from 0-4 years of age.

Current Birth Rates

Data on per person birth rates for Sedgwick County for 2005-2010 were collected[4]. Sedgwick County birth rate data was deemed appropriate to use for the WWSA since the majority of the water service area is within Sedgwick County, and Butler County birth rates are very similar to Sedgwick County. Sedgwick County birth rates were compared to birth rates for 2005-2010 for the entire United States[5]. Sedgwick County birth rates were 20.3% higher than the US birth rates from 2005-2010.

Based on Kansas data[4] from 2000-2010, 51% of births were male and 49% of births were female. These percentages were used to distribute total births into the proper age/sex cohort.

Future Birth Rates

Data was collected on projected birth rates for the US in five year increments through 2060[5]. Projected birth rates were not available for Sedgwick County but were available for the US. The US birth rates in each five year increment were increased by 20.3% to give the projected birth rates for Sedgwick County. The total population for the beginning of each five year timeframe was multiplied by the birth rate then multiplied by five to provide the number of births over each five year timeframe. The population added through births was included in the males and females aged 0-4. Male births were 51% of the total births and female births were 49% of the births.

The medium growth scenario used the projected birth rates using the medium-fertility variant data for the US. The high growth scenario used the projected birth rates using high-fertility variant data for the US. The low growth scenario used the projected birth rates using the low-fertility variant data for the US. All three were increased by 20.3% to be representative of Sedgwick County.

Deaths

In the Cohort Survival Method of projecting future population, deaths are subtracted from the population over time. The deaths are based on the death rate of the total population and distributed based on death rates per age/sex cohort.

Current Death Rates

Data on the death rate per person per year from 2005-2010 was collected for Sedgwick County[4]. Sedgwick County death rate data was deemed appropriate to use for the WWSA since the majority of the water service area is within Sedgwick County and Butler County death rates are very similar to Sedgwick County. Sedgwick County death rates were compared to death rates for 2005-2010 the entire United States[6].

Based on US and Sedgwick County death rates from 2005-2010, Sedgwick County death rates were 3.08% less than the US. It was assumed that the Sedgwick County death rate would stay 3.08% less than the US death rate.

The death rate per person for each age/sex cohort for Kansas for 2005-2010 was collected[4]. Deaths per age/sex cohort were not available at a smaller scale so it was assumed that the WWSA would have the same age/sex distribution of deaths as the entire state of Kansas. It was also assumed that the distribution of deaths per age/sex cohort would stay the same through 2060. The average death rate per age/sex cohort was the baseline in calculating future death rates per age/sex cohort for the WWSA through 2060.

Future Death Rates

Data was then collected on projected death rates[6] for the US in five year increments through 2060, as projected death rates were not available for any smaller geography. The projected US death rates were decreased by 3.08% to provide projected death rates for Sedgwick County.

The change in projected death rates for Sedgwick County from one five year timeframe to the next was calculated through 2060. Each rate of change was divided by 36 age/sex cohort groups to give the change per timeframe for each age/sex cohort. The change was added to previous death rate per age/sex cohort to get the next timeframe's death rate. These rates were then multiplied by five (to get the five year totals) then multiplied by the beginning population for the age/sex cohort. This gave the total deaths per age/sex cohort for each five year timeframe. The deaths per age/sex cohort were subtracted from each beginning year timeframe when calculating the population for the following timeframe.

The medium growth scenario used the projected death rates using the medium-fertility variant data for the US. The high growth scenario used the projected death rates using high-fertility variant data for the US. The low growth scenario used the projected death rates using the low-fertility variant data for the US. All three were decreased by 3.08% to be representative of Sedgwick County.

Migration

In the Cohort Survival Method of projecting future population, net migration is added to or subtracted from the population over time. The net migration is based on the migration rate of the total population and distributed based on migration rates per age/sex cohort.

Current Migration Rates

The total net migration for Sedgwick County[7] and Butler County[8] from 2000-2011 was collected. The migration was then divided by the number of years to get the yearly net migration for both counties. The next step was to determine the percent of the total 2010 county population that lived within each jurisdiction. The net migration for each county was divided by the percent of the 2010 county population that lives within each jurisdiction. This provided the annual net migration for each jurisdiction within the WWSA. This method assumes that net migration will be distributed based on current population distribution with a county.

Next, data on the age and sex distribution of migration was collected for the US[9], as smaller geography was not available. This provided the basis for distributing the annual migration into the 36 age/sex cohorts.

Future Migration Rates

The annual net migration was assumed to stay constant at the historic average through 2060. The annual net migration was then multiplied by five to get the five year net migration. Areas in Sedgwick County used the Sedgwick County migration rate and areas in Butler County used the Butler County migration rate.

The five year net migrations were then multiplied by the percent of the total net migration for each age/sex cohort to get the five year net migration for each age/sex cohort. It was assumed that age/sex distribution of net migration would stay constant at the historic average through 2060.

Service Area Expansion

It was assumed that the expansion of the WWSA-R and WWSA-W areas would have a linear growth and expand incrementally. In each five year increment, the WWSA-R would add 9.24 square miles and the WWSA-W would add 0.50 square miles.

The 2010 age/sex distribution of population was collected[3] for the US Census Blocks for the entire expansion area. The same Cohort Survival Method for forecasting population was used for these expansion areas as was used for the current WWSA. However, as the service area expanded to include areas not currently served by Wichita, the population of these areas was added to the WWSA population. It is important to note that the 2010 age/sex population data was not added. The Cohort Survival Method was carried out for each census block until the time came where the block became part of the WWSA. That calculated population was added to the WWSA population.

Section 2
RESULTS OF POPULATION FORECAST

The population of the WWSA is projected to increase in all three of the growth scenarios. The medium growth scenario, which is what is expected, adds 168,073 people to the WWSA. This shows an annual growth rate of 0.62 percent. Table 1 shows projected population growth of the WWSA-R, WWSA-W, and the entire WWSA for all three growth scenarios.

Table 1: Projected Population for WWSA-R, WWSA-W, and Entire WWSA

	WWSA-R Population			WWSA-W Population			Total WWSA Population		
Year	High Growth	Medium Growth	Low Growth	High Growth	Medium Growth	Low Growth	High Growth	Medium Growth	Low Growth
2010	402,640	402,640	402,640	58,032	58,032	58,032	460,672	460,672	460,672
2015	426,098	422,221	418,309	61,504	60,948	60,387	487,601	483,168	478,696
2020	451,505	441,306	431,009	65,251	63,784	62,303	516,755	505,090	493,312
2025	478,020	459,718	441,244	68,966	66,334	63,677	546,985	526,052	504,921
2030	502,963	476,357	449,537	72,377	68,556	64,704	575,340	544,913	514,241
2035	526,753	491,251	455,630	75,570	70,480	65,371	602,323	561,731	521,001
2040	550,622	504,615	459,064	78,700	72,119	65,602	629,322	576,734	524,666
2045	575,209	515,991	458,795	81,970	73,507	65,333	657,178	589,499	524,127
2050	602,631	527,032	456,191	85,693	74,903	64,790	688,324	601,935	520,981
2055	632,751	538,373	452,435	89,805	76,353	64,102	722,556	614,726	516,538
2060	665,357	550,623	448,669	94,459	78,122	63,605	759,816	628,745	512,274

Comparison to Other Population Projections

The population forecast was compared to previous population projections completed for areas surrounding and including the WWSA. Population projections for previous Wichita water studies and those completed for other purposes provide a means of comparison.

The Wichita-Sedgwick County Metropolitan Area Planning Department (MAPD) regularly completes population projections for all of Sedgwick County. The 2010 Development Trends Report[10] produced by MAPD includes population projections through 2035. The annual average growth rate in this report for Sedgwick County is 0.72 percent, 0.1 percent higher than the Water Demand Assessment population projections.

The Center for Economic Development and Business Research (CEDBR) at Wichita State University also completed population projections recently. The CEDBR population projections[11] show an annual growth rate of 0.6 percent for Sedgwick County and 0.7 percent for the Metropolitan Statistical Area through 2030. An important finding of this study, which was assumed for the Water Demand Assessment, is that population is the limiting factor to growth, meaning that the employment potential is greater than the projected supply of employees. This finding validates the use of population projections for determining future population growth of the WWSA.

Previous Wichita water studies have projected population growth for the WWSA. The Water Demand Assessment population projections were compared to the previous population projections. This comparison is available in Appendix A.

Section 3
ANNUAL WATER DEMAND

Water usage data is collected for many different purposes and shows different aspects of water usage. The collected data provides a view into the historic and current demand for water in the WWSA and is used to project future water demand. The projected annual water demand, which is the total amount of water used per year, is based on per capita water use of the projected population. This methodology was chosen based on the availability and reliability of the population data and the total amount of treated water pumped from Hess Pump Station. To add granularity to the projections, the annual demand was distributed based on customer type to provide demand per customer type.

Annual Water Demand per Capita

Data on the amount of water pumped from Hess Pump Station was obtained from 1990 to 2012[12]. The water pumped from the Hess Pump Station provides the total amount of water initially treated and pumped to serve the WWSA-R and WWSA-W. The total volume sets the total demand for WWSA.

Population data for 1990[13], 2000[14], and 2010[3] was collected for the areas within the WWSA for the corresponding years. Per capita water consumption was calculated for 1990, 2000, and 2010. The data shows a fairly constant amount of water being pumped and an increasing population within the WWSA. This leads to a decreasing per capita water usage rate from 1990 to 2010. Table 2 shows historic population of the WWSA, total annual demand, annual average day demand, and per capita annual demand.

Table 2: Historic Water Demand

Year	Annual Demand (MG)	Annual Demand (Ac-Ft/Yr)	Average Day Demand (MGD)	WWSA Population	Per Capita Annual Demand (G)	Per Capita Average Day Demand (G/Day)
1990	21,324.52	65,442.55	58.42	335,456	63,569	174.16
1991	22,244.84	68,266.91	60.94			
1992	19,363.76	59,425.20	52.91			
1993	19,304.89	59,244.53	52.89			
1994	19,721.36	60,522.63	54.03			
1995	18,304.81	56,175.40	50.29			
1996	19,740.21	60,580.48	54.38			
1997	18,812.87	57,734.58	52.85			
1998	21,231.79	65,157.97	58.17			
1999	19,208.39	58,948.38	52.63			
2000	21,451.95	65,833.62	59.59	383,674	55,912	153.18
2001	21,668.79	66,499.07	59.37			
2002	20,640.59	63,343.64	56.55			
2003	20,090.95	61,656.86	55.04			
2004	20,110.20	61,715.94	54.95			
2005	20,973.23	64,364.48	57.46			
2006	22,367.07	68,642.01	61.28			
2007	21,536.19	66,092.15	59.00			
2008	19,872.93	60,987.78	54.30			
2009	19,710.05	60,487.92	54.00			
2010	20,913.51	64,181.21	57.28	460,672	45,398	124.38
2011	22,452.67	68,904.72	61.51			
2012	22,321.52	68,502.23	60.99			

From 1990 to 2010, the per capita volume of water pumped has decreased at a rate of about 910 gallons per person per year. If we carry out this decreasing usage rate, the water usage by 2060 would be negative 115 gallons per capita. Due to this being highly unlikely, 2010 per capita water usage rates were used through 2060. The most recent US Census data on population was in 2010, which provided reliable data for the WWSA. Relating annual water demand to population for 1990, 2000, and 2010 indicates a declining trend in per capita water use. 2010 provides the most recent per capita water use indicator on a trend that will eventually change, but data does not indicate when this will happen or to what degree.

Using 2010 per capita water usage provides projected water usage based on today's usage rate. This allows further modeling of how exterior forces will affect future demand, rather than building these variables into the demand projections. Changing per capita consumption is caused by many variables including private well drilling and conservation measures. Quantifying the future effects on per capita consumption of these variables was not possible based on available data. Data on potential impacts of private well usage on future water demand are available in Appendix C.

Data on per capita usage for 2010 was used to calculate total annual water demand through 2060. The per capita usage was multiplied by the projected population for each service area to get the total annual water demand. Average day water demand was calculated by dividing the total annual demand by the number of days per year. Chart 1 shows the projected annual water demand for the entire WWSA (combined retail and wholesale) for the three growth scenarios. Table 3 shows the projected per capita demand, population, annual water demand, and average day demand for the three growth scenarios for the entire WWSA.

It is important to state that the assumption of the Water Demand Assessment is that the limitations on water supplied to wholesale customers via contract will not limit water use in the future.

Chart 1: Projected Water Demand

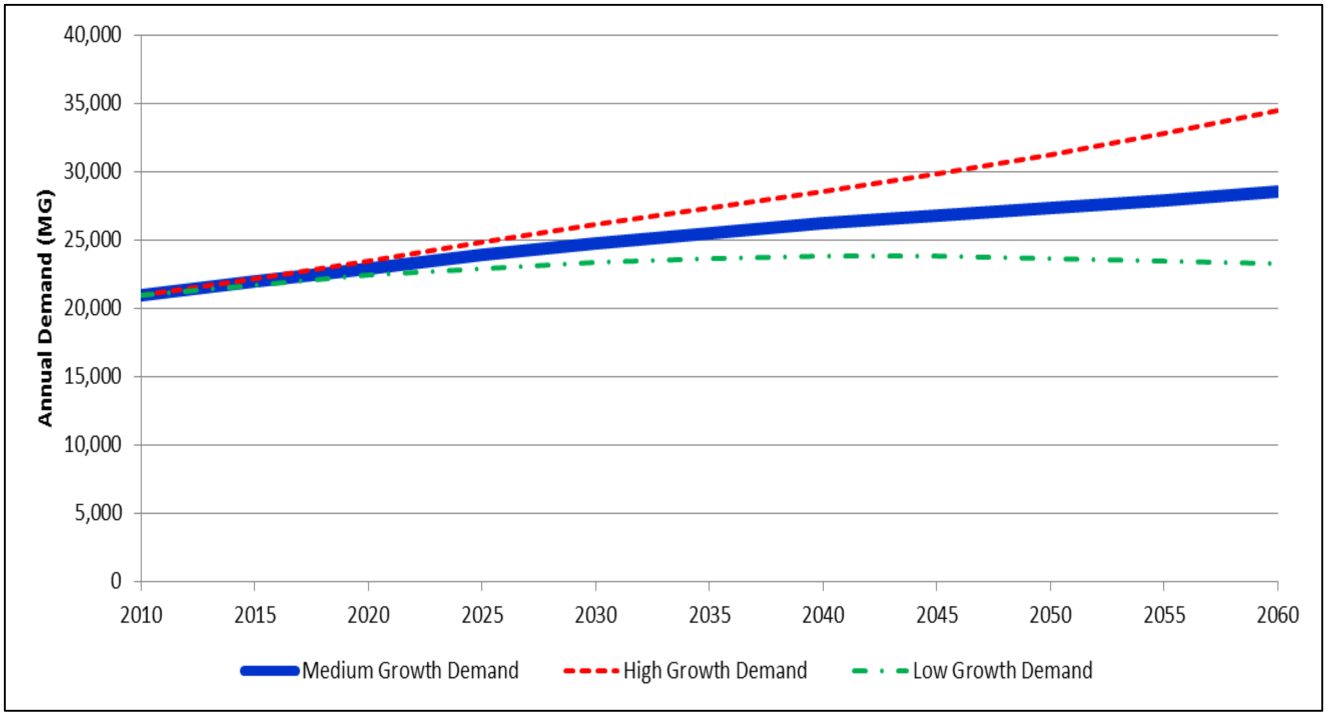


Table 3: Projected Water Demand

Year	Per Capita Annual Demand (G)	WWSA Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)
Medium Growth					
2010	45,398	460,672	20,914	64,181	57.297
2015	45,398	483,168	21,935	67,315	60.095
2020	45,398	505,090	22,930	70,370	62.822
2025	45,398	526,052	23,882	73,290	65.429
2030	45,398	544,913	24,738	75,918	67.775
2035	45,398	561,731	25,501	78,261	69.867
2040	45,398	576,734	26,182	80,351	71.733
2045	45,398	589,499	26,762	82,129	73.320
2050	45,398	601,935	27,327	83,862	74.867
2055	45,398	614,726	27,907	85,644	76.458
2060	45,398	628,745	28,544	87,597	78.202
High Growth					
2010	45,398	460,672	20,914	64,181	57.297
2015	45,398	487,601	22,136	67,933	60.647
2020	45,398	516,755	23,460	71,995	64.273
2025	45,398	546,985	24,832	76,206	68.033
2030	45,398	575,340	26,119	80,157	71.559
2035	45,398	602,323	27,344	83,916	74.915
2040	45,398	629,322	28,570	87,678	78.274
2045	45,398	657,178	29,834	91,559	81.738
2050	45,398	688,324	31,248	95,898	85.612
2055	45,398	722,556	32,802	100,667	89.870
2060	45,398	759,816	34,494	105,858	94.504
Low Growth					
2010	45,398	460,672	20,914	64,181	57.297
2015	45,398	478,696	21,732	66,692	59.539
2020	45,398	493,312	22,395	68,729	61.357
2025	45,398	504,921	22,922	70,346	62.801
2030	45,398	514,241	23,345	71,644	63.960
2035	45,398	521,001	23,652	72,586	64.801
2040	45,398	524,666	23,819	73,097	65.257
2045	45,398	524,127	23,794	73,022	65.190
2050	45,398	520,981	23,651	72,584	64.798
2055	45,398	516,538	23,450	71,964	64.246
2060	45,398	512,274	23,256	71,370	63.715

For the medium growth scenario, annual demand increases by 36% from 2010 to 2060. Annual demand increases by 65% for the high growth scenario and 11% for the low growth scenario.

Annual Water Demand per Customer Type

Water usage data on certain customer types was also available, providing a more in-depth look at how much demand particular customers place on overall water demand. The projected total annual water demand was distributed based on historical customer type sales data to get the projected demand per customer type.

The difference between the measured amount of pumped water and the total amount of water sold and used is unaccounted water, or water loss. In estimating unaccounted water, there are inherent measurement errors at every point in the system. Inaccuracies, even though small, in the production well flow meters, treatment plant flow meters, Hess pump station flow meters, and the many customer meters introduce accumulated errors in the metering of water use through the distribution system. In some cases, such as firefighting, pipe breaks or pipe flushing, water losses are estimated, not measured. Reported water use and estimated losses are therefore approximate values.

Data on water sales per customer type allows a more detailed look at water demands. The City of Wichita collects much more detailed information on the WWSA-R than the WWSA-W because usage in the WWSA-R is metered at specific addresses or locations of meters. Wichita collects usage for the following customer types in the WWSA-R: residential, non-residential, and department no-charge. The total amount of water sold to these three customer types is less than what is pumped from Hess Pump Station, leaving unaccounted-for water. Unaccounted-for water is caused by leaks, flushing new pipes, inaccurate meters, and various other reasons. Sales data prior to 2001 was deemed unreliable due to changes in data tracking methodology. Sales data[15] and no-charge data[16] from 2001-2012 were available and used to determine the percent of water used by each customer type.

Wichita also collects data on the total amount of water sold to the WWSA-W. For this area, water usage is monitored at a master meter where the water enters each wholesale service area. Therefore, no customer type information is available for the WWSA-W. Only overall water sold to wholesale customers is available. Table 4 shows the historic distribution of water to different customer types based on sales data.

Table 4: Historic Sales Data per Customer Type

Year	Total Pumped (MG)	Residential (MG)	Residential (%)	Non-Residential (MG)	Non-Residential (%)	No-Charge (MG)	No-Charge (%)	Unaccounted For (MG)	Unaccounted For (%)	Wholesale (MG)	Wholesale (%)
2001	21,669	10,809	49.9%	9,256	42.7%	242	1.1%	522	2.4%	839	3.9%
2002	20,641	10,553	51.1%	8,622	41.8%	229	1.1%	416	2.0%	820	4.0%
2003	20,091	10,139	50.5%	8,249	41.1%	111	0.6%	857	4.3%	735	3.7%
2004	20,110	9,600	47.7%	7,841	39.0%	160	0.8%	1,355	6.7%	1,154	5.7%
2005	20,973	10,232	48.8%	8,126	38.7%	105	0.5%	1,098	5.2%	1,412	6.7%
2006	22,367	10,962	49.0%	8,350	37.3%	124	0.6%	1,490	6.7%	1,442	6.4%
2007	21,536	9,803	45.5%	7,841	36.4%	118	0.5%	2,403	11.2%	1,371	6.4%
2008	19,873	9,153	46.1%	7,611	38.3%	145	0.7%	1,618	8.1%	1,347	6.8%
2009	19,710	9,251	46.9%	7,076	35.9%	256	1.3%	1,753	8.9%	1,375	7.0%
2010	20,914	9,842	47.1%	7,348	35.1%	472	2.3%	1,762	8.4%	1,489	7.1%
2011	22,453	10,429	46.4%	7,664	34.1%	315	1.4%	2,252	10.0%	1,793	8.0%
2012	22,322	10,111	45.3%	7,660	34.3%	317	1.4%	2,453	11.0%	1,781	8.0%

Residential, non-residential, department no-charge, and unaccounted-for water are directly attributable to the WWSA-R. Totaling these categories provides an overall demand for the WWSA-R. The percent of the total for these categories provides the distribution of the retail water. Table 5 shows the percent distribution of water sold to different customer types in the WWSA-R.

Table 5: Percent Distribution of Sales per Customer Type and Average Distribution

Year	Residential (MG)	Non-Residential (MG)	No-Charge (MG)	Unaccounted For (MG)
2001	51.9%	44.4%	1.2%	2.5%
2002	53.2%	43.5%	1.2%	2.1%
2003	52.4%	42.6%	0.6%	4.4%
2004	50.6%	41.4%	0.8%	7.1%
2005	52.3%	41.5%	0.5%	5.6%
2006	52.4%	39.9%	0.6%	7.1%
2007	48.6%	38.9%	0.6%	11.9%
2008	49.4%	41.1%	0.8%	8.7%
2009	50.5%	38.6%	1.4%	9.6%
2010	50.7%	37.8%	2.4%	9.1%
2011	50.5%	37.1%	1.5%	10.9%
2012	49.2%	37.3%	1.5%	11.9%
Average	51.0%	40.3%	1.1%	7.6%

*Data does not include wholesale water

Wholesale water sales have been removed from Table 5 because they are not attributable to the retail service area and no customer type sales information was available. Calculating the projected distribution of water per customer type starts with the total water demand of the WWSA. This total demand is then distributed to the four customer types based on the average percent distribution from 2001 through 2012. It was assumed that this percent distribution would be constant through 2060. It was also assumed that the distribution of water within the WWSA-W would be the same as the WWSA-R. Table 6 shows the projected water demand per customer type for the WWSA.

Table 6: Projected Water Demand per Customer Type

Year	Total (MG)	Residential (MG)	Non-Residential (MG)	No-Charge (MG)	Unaccounted For (MG)
Medium Growth					
2010	20,914	10,661	8,438	229	1,587
2015	21,935	11,181	8,850	240	1,664
2020	22,930	11,688	9,251	251	1,740
2025	23,882	12,174	9,635	261	1,812
2030	24,738	12,610	9,981	271	1,877
2035	25,501	12,999	10,289	279	1,935
2040	26,182	13,346	10,563	286	1,986
2045	26,762	13,642	10,797	293	2,030
2050	27,327	13,930	11,025	299	2,073
2055	27,907	14,226	11,259	305	2,117
2060	28,544	14,550	11,516	312	2,165
High Growth					
2010	20,914	10,661	8,438	229	1,587
2015	22,136	11,284	8,931	242	1,679
2020	23,460	11,958	9,465	257	1,780
2025	24,832	12,658	10,019	272	1,884
2030	26,119	13,314	10,538	286	1,981
2035	27,344	13,939	11,032	299	2,074
2040	28,570	14,563	11,527	312	2,167
2045	29,834	15,208	12,037	326	2,263
2050	31,248	15,929	12,607	342	2,371
2055	32,802	16,721	13,234	359	2,488
2060	34,494	17,583	13,917	377	2,617
Low Growth					
2010	20,914	10,661	8,438	229	1,587
2015	21,732	11,078	8,768	238	1,649
2020	22,395	11,416	9,035	245	1,699
2025	22,922	11,685	9,248	251	1,739
2030	23,345	11,900	9,419	255	1,771
2035	23,652	12,057	9,543	259	1,794
2040	23,819	12,142	9,610	261	1,807
2045	23,794	12,129	9,600	260	1,805
2050	23,651	12,056	9,542	259	1,794
2055	23,450	11,953	9,461	256	1,779
2060	23,256	11,855	9,383	254	1,764

Section 4
PEAK DAY WATER DEMAND

Peak day water demand refers to the amount of water consumed during the day of highest use. The day is identified annually as the peak day and usually occurs during the summer months. The peak day demand is calculated by dividing the total usage during the peak day by the annual average usage per day. This calculation provides the "peak factor", showing the increased demand during the peak day compared to the annual average day demand. From 1990 through 2012, the peak factor has ranged from 1.50 to 2.07 and has averaged 1.83. Since 1990, the peak day occurs on average 200 days into the calendar year, which is July 19th.

Similar to the growth scenarios developed for the population projection, two scenarios were developed for the peak day water demand. The high peak scenario uses 2.07 as the peak day factor and the medium peak scenario uses the average peak day factor over the past 22 years, which is 1.83. Chart 2 and Table 7 show the historic annual average day demand, peak day demand, peak day factor, and the day for the peak occurred.

Chart 2: Historic Peak Day Factor and Peak Day Demand

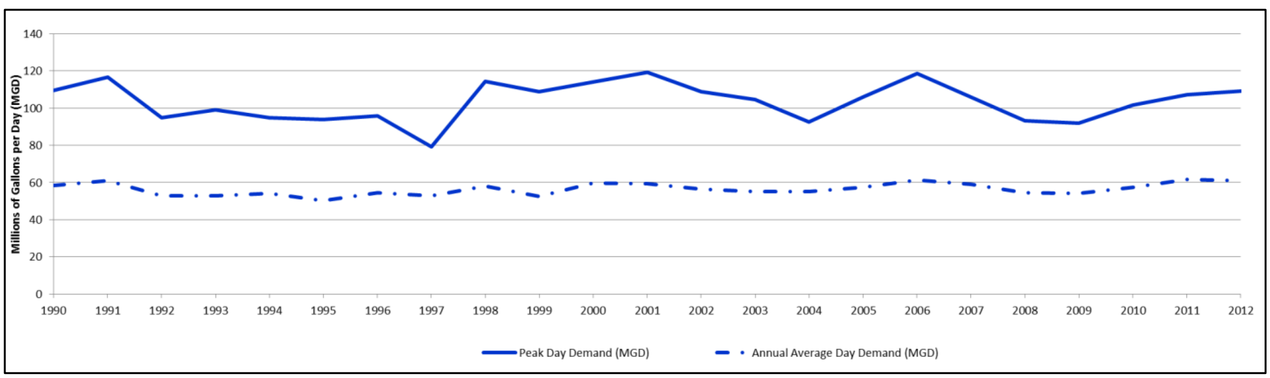


Table 7: Historic Peak Day Factor and Peak Day Demand

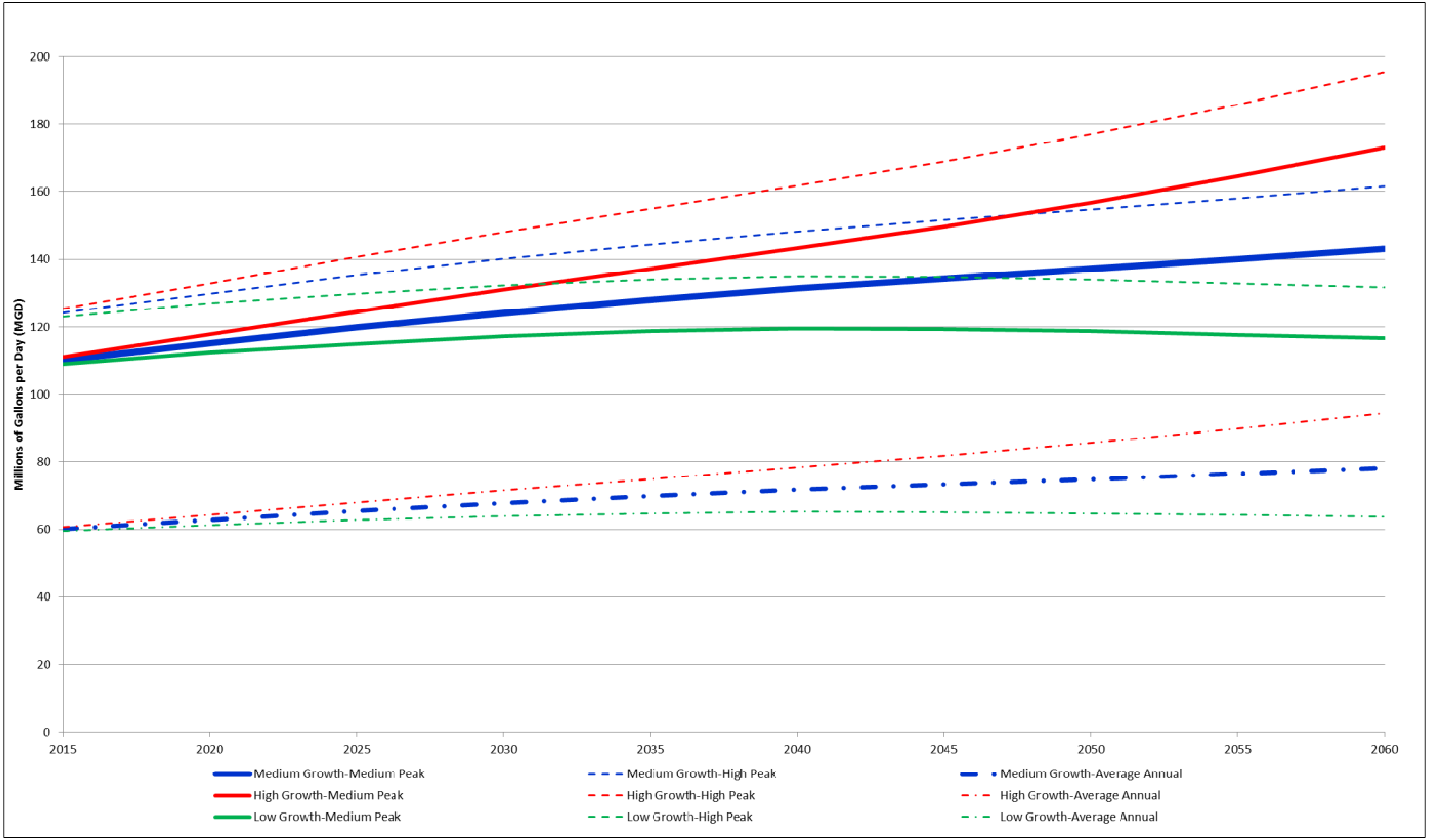
Year	Annual Average Day Demand (MGD)	Peak Day Demand (MGD)	Peak Day Factor	Date of Peak Day
1990	58.42	109.50	1.87	7/9
1991	60.94	116.52	1.91	7/17
1992	52.91	94.90	1.79	7/9
1993	52.89	99.13	1.87	8/18
1994	54.03	94.89	1.76	6/28
1995	50.29	93.74	1.86	7/13
1996	54.38	95.84	1.76	6/22
1997	52.85	79.08	1.50	8/1
1998	58.17	114.37	1.97	6/29
1999	52.63	108.77	2.07	7/29
2000	59.59	114.12	1.92	8/29
2001	59.37	119.40	2.01	7/21
2002	56.55	108.93	1.93	7/28
2003	55.04	104.74	1.90	7/29
2004	54.95	92.59	1.69	7/22
2005	57.46	105.99	1.84	8/3
2006	61.28	118.59	1.94	7/19
2007	59.00	105.87	1.79	8/8
2008	54.30	93.27	1.72	8/4
2009	54.00	92.00	1.70	6/26
2010	57.28	101.82	1.78	8/9
2011	61.51	107.07	1.74	7/11
2012	60.99	109.16	1.79	7/30

The projected peak day demand was calculated using the projected annual average day demand and the peak factor. For the three growth scenarios, the high peak factor and medium peak factor were multiplied by the annual average day demand to provide peak day projected demand. Table 8 and Chart 3 show the projected annual average day demand as well as the projected peak day demand for the three growth scenarios and the two peak scenarios.

Table 8: Projected Peak Day Demand

	Medium Growth			High Growth			Low Growth		
Year	Annual Avg Demand (MGD)	Medium Peak Demand (MGD)	High Peak Demand (MGD)	Annual Avg Demand (MGD)	Medium Peak Demand (MGD)	High Peak Demand (MGD)	Annual Avg Demand (MGD)	Medium Peak Demand (MGD)	High Peak Demand (MGD)
2015	60.10	110.03	124.21	60.65	111.04	125.35	59.54	109.01	123.06
2020	62.82	115.02	129.84	64.27	117.68	132.84	61.36	112.34	126.82
2025	65.43	119.79	135.23	68.03	124.56	140.61	62.80	114.98	129.80
2030	67.77	124.09	140.08	71.56	131.02	147.90	63.96	117.10	132.20
2035	69.87	127.92	144.40	74.92	137.16	154.84	64.80	118.64	133.93
2040	71.73	131.33	148.26	78.27	143.31	161.78	65.26	119.48	134.88
2045	73.32	134.24	151.54	81.74	149.65	168.94	65.19	119.35	134.74
2050	74.87	137.07	154.74	85.61	156.75	176.95	64.80	118.64	133.93
2055	76.46	139.99	158.03	89.87	164.54	185.75	64.25	117.63	132.79
2060	78.20	143.18	161.63	94.50	173.03	195.33	63.72	116.66	131.69

Chart 3: Projected Peak Day Demand



Section 5
CONSERVATION MEASURES

The annual and peak day water demand projections do not account for new conservation measures, which can reduce annual and peak day per capita demands. The 2010 per capita water demand was the basis for projections, but it is possible that per capita demand will fluctuate based on the implementation of different conservation measures.

Increasing levels of conservation require increasing levels of effort for implementation, enforcement, and consequently, increasing costs to both the utility and the customers. A 2% reduction in annual water demand was chosen to assess impacts on water demand. This number represents an achievable reduction with a initial efforts by users and/or Wichita Water Utilities. Any reduction greater than 2% would require more effort; in terms of education, information, Incentives, and administrative expense; on the part of Wichita Water Utilities.

It is not assumed that the City of Wichita will develop and implement long-term conservation measures. However, if Wichita decides to implement conservation measures, the effect on annual and peak day water demand is available in Appendix D.

Section 6
CONCLUSIONS

The population of the WWSA is expected to increase through 2060 and the area served by Wichita Water Utilities is expected to expand, leading to an increase in annual and peak day water demand.

Based on three growth scenarios, the annual water demand by 2060 varies from 63.7 MGD (71,370 Ac-Ft/Yr) for the low growth scenario to 94.5 MGD (105,858 Ac-Ft/Yr) for the high growth scenario. The medium growth scenario, which is anticipated to be the most likely representation, forecasts 78.2 MGD (87,597 Ac-Ft/Yr) by 2060.

The peak day water demand is also expected to increase over time. The highest peak day demand (high growth/high peak) is forecasted to be 195.3 MGD. The lowest peak day demand (low growth/medium peak) is predicted to be 116.7 MGD.

There are other variables that may affect future water demand. The variables addressed in this assessment include new wholesale service areas, private well drilling, and conservation measures. These variables are addressed in the appendices, but it is uncertain if they will play a role in future water demand. As such, they are not assumed to occur and have been removed from the water demand projections.

Appendix A
COMPARISON TO OTHER WICHITA STUDIES

Projections from 1993 in Comparison to 2013

The 1993 Water Supply Study[17] was similar to the 2013 Water Demand and Supply Assessment Study. Since the 1993 Study was similar, it provides a good comparison for the 2013 Study. Other studies since the 1993 used the methodology and assumptions of the 1993 Study, but included updated data based on known values.

The 1993 Study and the 2013 Study forecasted water demand, however, different methodologies were used and different assumptions were made. Here is a summary of the key assumptions and methodologies used and how they differ. Table A1.1 and Chart A1.1 show the comparison of projections for population, annual average day water demand, and peak day demand using the medium growth projections and the medium peak day factors.

- Population projection methodology
  - 1993 Study used linear regression methodology and compared to population projections by the US Department of Commerce-Bureau of Economic Analysis, 1985 Regional Projections and the Metropolitan Area Planning Department.
  - 2013 Study used Cohort Survival Methodology and compared annual population growth rate to that of the Center of Economic Development and Business Research at Wichita State University and the Metropolitan Area Planning Department.
  - 1993 Study assumed a 0.89% annual growth rate.
  - 2013 Study assumed a 0.62% annual growth rate.
- Service area
  - 1993 Study assumed 85% of Sedgwick County would be served by Wichita Water Utilities by 2030.
  - 2013 Study assumed the future service area would include only those municipalities and rural water districts currently served by Wichita Water Utilities.
- Water usage rates
  - 1993 Study was largely based on customer type usage rates.
  - 2013 Study is based on a per capita overall usage rate.
- Peak demand
  - 1993 Study developed 3 scenarios for different peak day factors.
    - High factor (2.14) was the highest peak day factor from 1960-1991.

  - Medium factor (2.0) was the design value of the September 1992 draft of the Water System Master Plan.
  - Low factor (1.8) was the average peak day factor from 1960-1991.
- 2013 Study developed 2 scenarios for different peak day factors.
  - High factor (2.07) was the highest peak day factor from 1990-2012.
  - Medium factor (1.83) was the average peak day factor from 1990-2012.
  - Low factor not used as it was not assumed to aid in planning for demand.

Table A1.1: 1993 Study Comparisons to 2013 Study

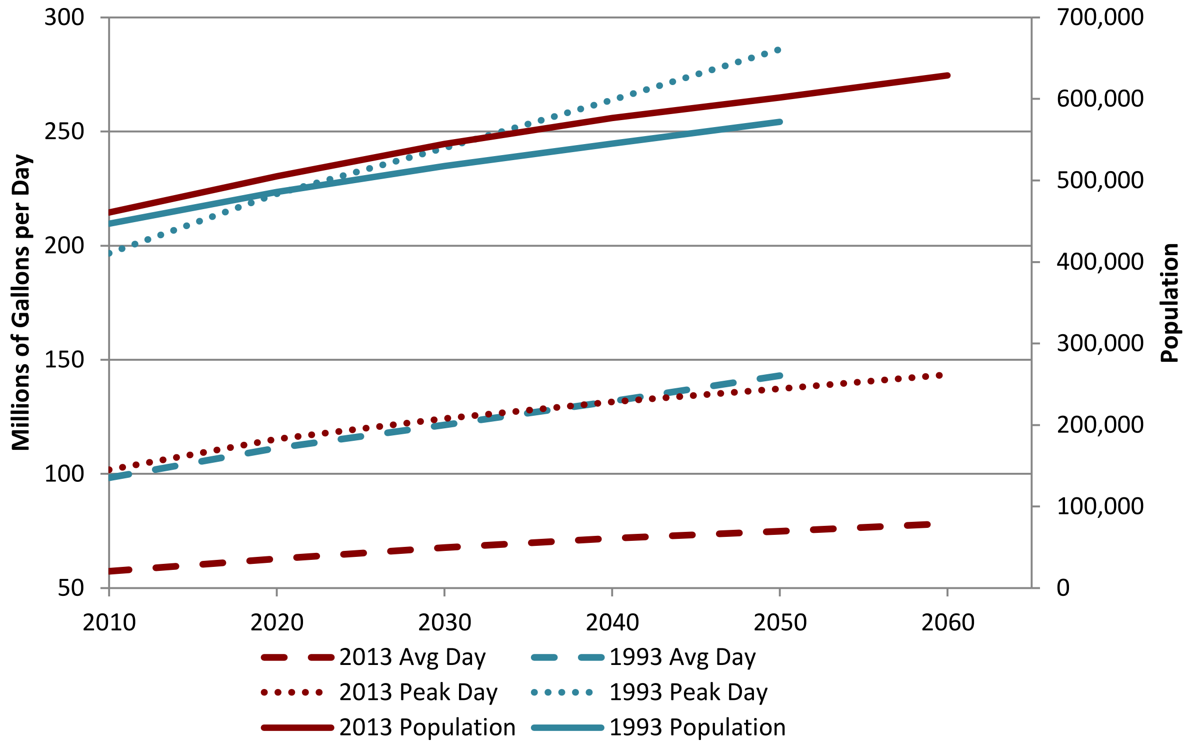
(medium growth and medium peak factor)

	Water Demand and Supply Assessment Study 2013			Water Supply Study 1993		
Year	Population	Avg Day Demand (MG)	Peak Day Demand (MG)	Population	Avg Day Demand (MG)	Peak Day Demand (MG)
1990		*58.4*	*109.5*	335,487		
2000		*59.6*	*114.1*	387,218	83.0	166.0
2010	*460,672*	*57.3*	*101.8*	447,058	98.3	196.6
2020	505,090	62.8	115.2	485,759	111.4	222.8
2030	544,913	67.8	124.3	517,604	121.4	242.8
2040	576,734	71.7	131.6	545,284	131.9	263.8
2050	601,935	74.9	137.3	571,784	143.0	286.0
2060	628,745	78.2	143.4			

Grey Shade is Actual

Chart A1.1: 1993 Study Comparisons to 2013 Study

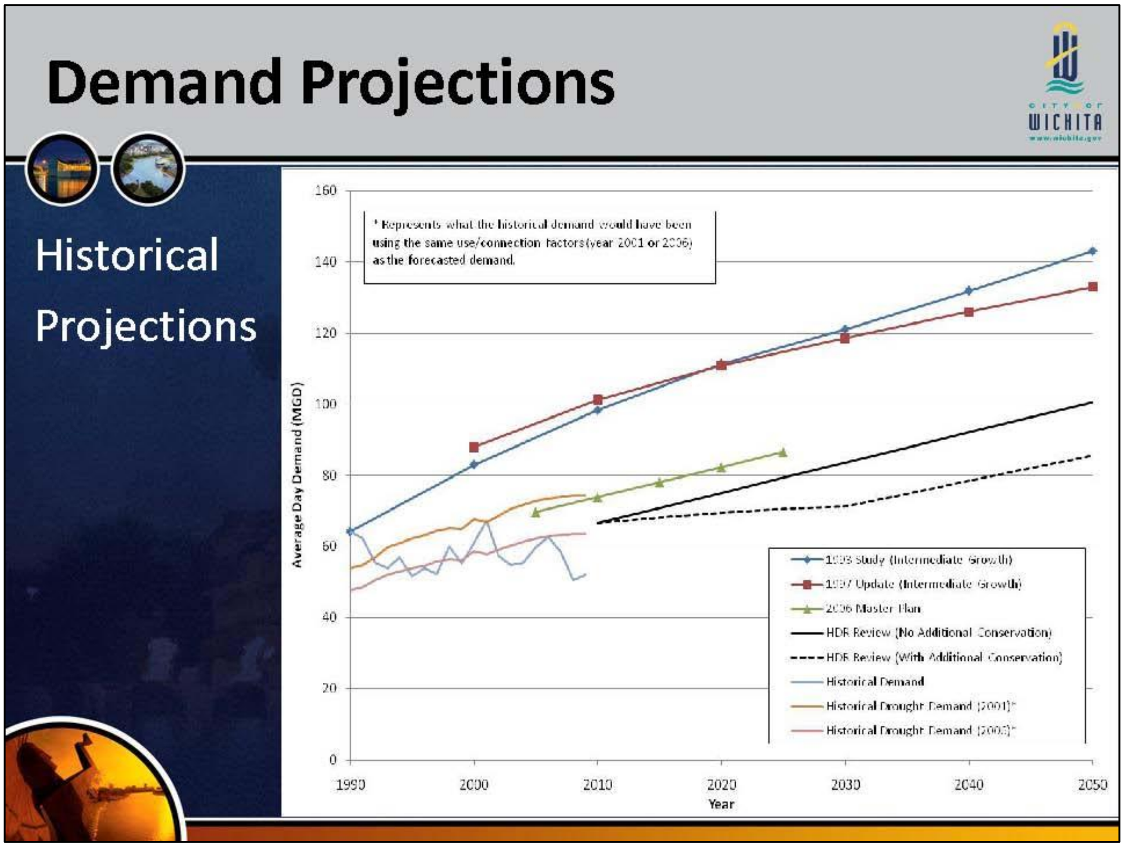
(medium growth and medium peak factor)

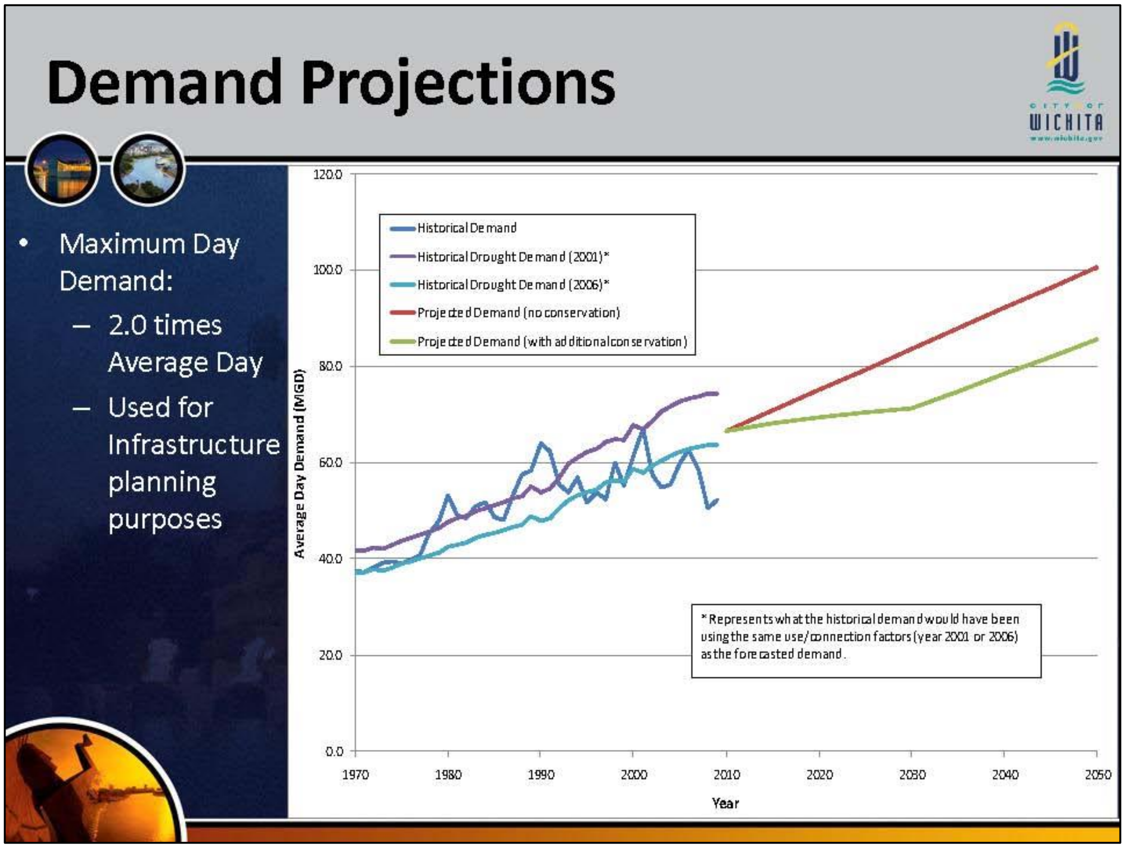


Additional Projections for Comparison

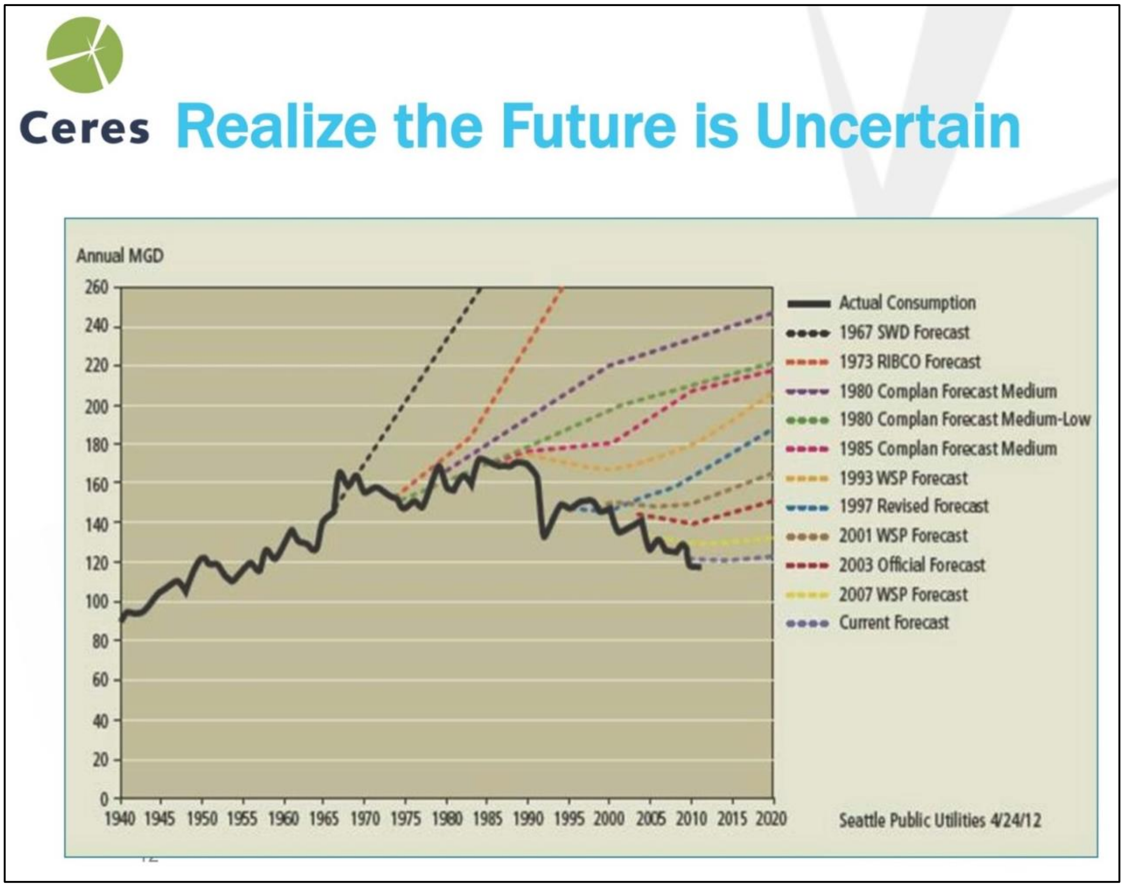
Charts from intermediate studies between 1993 and 2013 are presented on the next three pages for review. By review, one can note that the historical conditions, trending method, and the selection of the point from which to project future conditions have an effect on the projection results.

From Wichita ASR Program Review
HDR presentation to Wichita City Council June 2, 2010




Demand Projections
CITY OF WICHITA
www.wichita.gov
Maximum Day Demand:
2.0 times Average Day
Used for Infrastructure planning purposes
Historical Demand
Historical Drought Demand (2001)*
Historical Drought Demand (2006)*
Projected Demand (no conservation)
Projected Demand (with additional conservation)
*Represents what the historical demand would have been using the same use/connection factors (year 2001 or 2006) as the forecasted demand.
Average Day Demand (MGD)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Year

Financing Sustainable Water Infrustructure



Appendix B
NON-POTABLE WHOLESALE SERVICE AREA AND POTENTIAL ADDITIONAL SERVICE AREAS

As referenced in the Water Demand Assessment, there are two service area types that were kept separate from the rest of the WWSA water demand projections. They are separate because the characteristics of the areas differed greatly from the WWSA. The non-potable wholesale service area is separate because this service area receives untreated (raw) water from Wichita, whereas the WWSA receives treated water pumped from Hess Pump Station. Wichita also desired projected water demand for six cities not currently served by Wichita Water Utilities. Since it is unknown whether these cities will be served by Wichita Water Utilities, the water demand projections for these cities were kept separate.

The methodology for projecting water demand was very similar to that used for the WWSA. The Cohort Survival Methodology was used to project population change, with the addition of population due to expansion of the service area. The three growth scenarios were used; high growth, medium growth, and low growth. Per capita consumption rates for the WWSA were used to calculate future annual demand. Finally, the peak demand was calculated by using the peak factor and the annual demand.

Potential Additional Water Service Area

In addition to existing retail and wholesale customers, it was desired to assess water demand for certain municipalities that are not currently served by Wichita Water Utilities. Separate water demand forecasts were completed for each potential additional wholesale service area. The data can be used to assess future demand if the cities desire to become part of the WWSA. The additional cities include Andale, Colwich, Goddard, Haysville, Maize, and Mulvane. These cities would likely be served by wholesale contracts.

To determine the current service area for these municipalities, assuming they became customers immediately, current city boundaries served as the service area. For future service areas for these municipalities, urban growth boundaries were used. A map of the current and future service area boundaries for these municipalities are available in Exhibit 1. For all six municipalities, the service area is projected to expand from 24.3 square miles in 2010 to 52.2 square miles in 2060.

The projected population growth, per capita annual demand, annual demand, annual average day demand, and peak day demand for the potential additional water service areas are shown in Table A2.1 through A2.6. These tables include data on the three growth scenarios and three peak demand scenarios. The projected demand for these areas was based on the per capita annual water demand and peak day factors used for the WWSA. It is important to note that actual water usage rates from these municipalities would provide a better projection.

Table A2.1: Andale Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	928	42	129	0.115	0.239	0.211
2015	45,398	978	44	136	0.122	0.252	0.223
2020	45,398	1,027	47	143	0.128	0.264	0.234
2025	45,398	1,077	49	150	0.134	0.277	0.245
2030	45,398	1,124	51	157	0.140	0.289	0.256
2035	45,398	1,170	53	163	0.146	0.301	0.266
2040	45,398	1,216	55	169	0.151	0.313	0.277
2045	45,398	1,252	57	174	0.156	0.322	0.285
2050	45,398	1,289	59	180	0.160	0.332	0.293
2055	45,398	1,322	60	184	0.164	0.340	0.301
2060	45,398	1,382	63	192	0.172	0.356	0.314
High Growth							
2010	45,398	928	42	129	0.115	0.239	0.211
2015	45,398	987	45	138	0.123	0.254	0.225
2020	45,398	1,051	48	146	0.131	0.270	0.239
2025	45,398	1,119	51	156	0.139	0.288	0.255
2030	45,398	1,185	54	165	0.147	0.305	0.270
2035	45,398	1,252	57	174	0.156	0.322	0.285
2040	45,398	1,322	60	184	0.164	0.340	0.301
2045	45,398	1,390	63	194	0.173	0.358	0.316
2050	45,398	1,466	67	204	0.182	0.378	0.334
2055	45,398	1,544	70	215	0.192	0.398	0.351
2060	45,398	1,658	75	231	0.206	0.427	0.377
Low Growth							
2010	45,398	928	42	129	0.115	0.239	0.211
2015	45,398	970	44	135	0.121	0.250	0.221
2020	45,398	1,004	46	140	0.125	0.258	0.228
2025	45,398	1,034	47	144	0.129	0.266	0.235
2030	45,398	1,062	48	148	0.132	0.273	0.242
2035	45,398	1,088	49	152	0.135	0.280	0.248
2040	45,398	1,110	50	155	0.138	0.286	0.253
2045	45,398	1,119	51	156	0.139	0.288	0.255
2050	45,398	1,123	51	157	0.140	0.289	0.256
2055	45,398	1,120	51	156	0.139	0.288	0.255
2060	45,398	1,135	52	158	0.141	0.292	0.258

Table A2.2: Colwich Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	1,327	60	185	0.165	0.342	0.302
2015	45,398	1,386	63	193	0.172	0.357	0.315
2020	45,398	1,446	66	201	0.180	0.372	0.329
2025	45,398	1,505	68	210	0.187	0.387	0.342
2030	45,398	1,571	71	219	0.195	0.404	0.357
2035	45,398	1,626	74	227	0.202	0.419	0.370
2040	45,398	1,678	76	234	0.209	0.432	0.382
2045	45,398	1,724	78	240	0.214	0.444	0.392
2050	45,398	1,765	80	246	0.219	0.454	0.402
2055	45,398	1,813	82	253	0.226	0.467	0.413
2060	45,398	1,853	84	258	0.230	0.477	0.422
High Growth							
2010	45,398	1,327	60	185	0.165	0.342	0.302
2015	45,398	1,399	64	195	0.174	0.360	0.318
2020	45,398	1,479	67	206	0.184	0.381	0.337
2025	45,398	1,564	71	218	0.195	0.403	0.356
2030	45,398	1,658	75	231	0.206	0.427	0.377
2035	45,398	1,742	79	243	0.217	0.449	0.397
2040	45,398	1,828	83	255	0.227	0.471	0.416
2045	45,398	1,918	87	267	0.239	0.494	0.437
2050	45,398	2,012	91	280	0.250	0.518	0.458
2055	45,398	2,125	96	296	0.264	0.547	0.484
2060	45,398	2,233	101	311	0.278	0.575	0.508
Low Growth							
2010	45,398	1,327	60	185	0.165	0.342	0.302
2015	45,398	1,373	62	191	0.171	0.354	0.313
2020	45,398	1,412	64	197	0.176	0.364	0.321
2025	45,398	1,445	66	201	0.180	0.372	0.329
2030	45,398	1,483	67	207	0.184	0.382	0.338
2035	45,398	1,510	69	210	0.188	0.389	0.344
2040	45,398	1,529	69	213	0.190	0.394	0.348
2045	45,398	1,537	70	214	0.191	0.396	0.350
2050	45,398	1,532	70	213	0.191	0.395	0.349
2055	45,398	1,529	69	213	0.190	0.394	0.348
2060	45,398	1,515	69	211	0.188	0.390	0.345

Table A2.3: Goddard Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	4,344	197	605	0.540	1.118	0.989
2015	45,398	4,618	210	643	0.574	1.189	1.051
2020	45,398	4,909	223	684	0.611	1.264	1.117
2025	45,398	5,172	235	720	0.643	1.331	1.177
2030	45,398	5,458	248	760	0.679	1.405	1.242
2035	45,398	5,695	259	793	0.708	1.466	1.296
2040	45,398	5,912	268	824	0.735	1.522	1.346
2045	45,398	6,094	277	849	0.758	1.569	1.387
2050	45,398	6,252	284	871	0.778	1.610	1.423
2055	45,398	6,422	292	895	0.799	1.653	1.462
2060	45,398	6,661	302	928	0.828	1.715	1.516
High Growth							
2010	45,398	4,344	197	605	0.540	1.118	0.989
2015	45,398	4,660	212	649	0.580	1.200	1.061
2020	45,398	5,021	228	700	0.624	1.293	1.143
2025	45,398	5,373	244	749	0.668	1.383	1.223
2030	45,398	5,756	261	802	0.716	1.482	1.310
2035	45,398	6,094	277	849	0.758	1.569	1.387
2040	45,398	6,431	292	896	0.800	1.656	1.464
2045	45,398	6,766	307	943	0.841	1.742	1.540
2050	45,398	7,113	323	991	0.885	1.831	1.619
2055	45,398	7,507	341	1,046	0.934	1.933	1.709
2060	45,398	8,008	364	1,116	0.996	2.062	1.823
Low Growth							
2010	45,398	4,344	197	605	0.540	1.118	0.989
2015	45,398	4,575	208	637	0.569	1.178	1.041
2020	45,398	4,796	218	668	0.596	1.235	1.092
2025	45,398	4,968	226	692	0.618	1.279	1.131
2030	45,398	5,158	234	719	0.642	1.328	1.174
2035	45,398	5,295	240	738	0.659	1.363	1.205
2040	45,398	5,397	245	752	0.671	1.390	1.228
2045	45,398	5,444	247	759	0.677	1.402	1.239
2050	45,398	5,443	247	758	0.677	1.401	1.239
2055	45,398	5,433	247	757	0.676	1.399	1.237
2060	45,398	5,462	248	761	0.679	1.406	1.243

Table A2.4: Haysville Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	10,718	487	1,493	1.333	2.759	2.440
2015	45,398	11,401	518	1,588	1.418	2.935	2.595
2020	45,398	12,302	558	1,714	1.530	3.167	2.800
2025	45,398	13,360	607	1,861	1.662	3.440	3.041
2030	45,398	14,515	659	2,022	1.805	3.737	3.304
2035	45,398	15,854	720	2,209	1.972	4.082	3.609
2040	45,398	16,333	741	2,276	2.031	4.205	3.718
2045	45,398	16,805	763	2,341	2.090	4.327	3.825
2050	45,398	17,408	790	2,425	2.165	4.482	3.962
2055	45,398	17,937	814	2,499	2.231	4.618	4.083
2060	45,398	18,343	833	2,556	2.281	4.723	4.175
High Growth							
2010	45,398	10,718	487	1,493	1.333	2.759	2.440
2015	45,398	11,507	522	1,603	1.431	2.963	2.619
2020	45,398	12,593	572	1,754	1.566	3.242	2.866
2025	45,398	13,908	631	1,938	1.730	3.581	3.166
2030	45,398	15,356	697	2,139	1.910	3.954	3.495
2035	45,398	17,048	774	2,375	2.120	4.389	3.880
2040	45,398	17,881	812	2,491	2.224	4.604	4.070
2045	45,398	18,801	854	2,619	2.338	4.841	4.279
2050	45,398	19,984	907	2,784	2.486	5.145	4.549
2055	45,398	21,169	961	2,949	2.633	5.450	4.818
2060	45,398	22,259	1,011	3,101	2.769	5.731	5.066
Low Growth							
2010	45,398	10,718	487	1,493	1.333	2.759	2.440
2015	45,398	11,294	513	1,573	1.405	2.908	2.571
2020	45,398	12,008	545	1,673	1.494	3.092	2.733
2025	45,398	12,807	581	1,784	1.593	3.297	2.915
2030	45,398	13,669	621	1,904	1.700	3.519	3.111
2035	45,398	14,657	665	2,042	1.823	3.774	3.336
2040	45,398	14,804	672	2,062	1.841	3.811	3.369
2045	45,398	14,881	676	2,073	1.851	3.831	3.387
2050	45,398	14,999	681	2,090	1.866	3.862	3.414
2055	45,398	15,001	681	2,090	1.866	3.862	3.414
2060	45,398	14,872	675	2,072	1.850	3.829	3.385

Table A2.5: Maize Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	3,425	155	477	0.426	0.882	0.780
2015	45,398	3,629	165	506	0.451	0.934	0.826
2020	45,398	3,835	174	534	0.477	0.987	0.873
2025	45,398	4,052	184	565	0.504	1.043	0.922
2030	45,398	4,206	191	586	0.523	1.083	0.957
2035	45,398	4,353	198	606	0.541	1.121	0.991
2040	45,398	4,485	204	625	0.558	1.155	1.021
2045	45,398	4,608	209	642	0.573	1.186	1.049
2050	45,398	4,744	215	661	0.590	1.221	1.080
2055	45,398	4,849	220	676	0.603	1.249	1.104
2060	45,398	4,964	225	692	0.617	1.278	1.130
High Growth							
2010	45,398	3,425	155	477	0.426	0.882	0.780
2015	45,398	3,662	166	510	0.455	0.943	0.834
2020	45,398	3,923	178	547	0.488	1.010	0.893
2025	45,398	4,212	191	587	0.524	1.085	0.959
2030	45,398	4,439	202	618	0.552	1.143	1.010
2035	45,398	4,663	212	650	0.580	1.201	1.061
2040	45,398	4,887	222	681	0.608	1.258	1.112
2045	45,398	5,126	233	714	0.638	1.320	1.167
2050	45,398	5,411	246	754	0.673	1.393	1.232
2055	45,398	5,684	258	792	0.707	1.463	1.294
2060	45,398	5,981	272	833	0.744	1.540	1.361
Low Growth							
2010	45,398	3,425	155	477	0.426	0.882	0.780
2015	45,398	3,596	163	501	0.447	0.926	0.818
2020	45,398	3,746	170	522	0.466	0.964	0.853
2025	45,398	3,890	177	542	0.484	1.002	0.885
2030	45,398	3,971	180	553	0.494	1.022	0.904
2035	45,398	4,041	183	563	0.503	1.040	0.920
2040	45,398	4,086	185	569	0.508	1.052	0.930
2045	45,398	4,106	186	572	0.511	1.057	0.935
2050	45,398	4,118	187	574	0.512	1.060	0.937
2055	45,398	4,089	186	570	0.509	1.053	0.931
2060	45,398	4,060	184	566	0.505	1.045	0.924

Table A2.6: Mulvane Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	45,398	5,920	269	825	0.736	1.524	1.347
2015	45,398	6,225	283	867	0.774	1.603	1.417
2020	45,398	6,631	301	924	0.825	1.707	1.509
2025	45,398	6,980	317	972	0.868	1.797	1.589
2030	45,398	7,244	329	1,009	0.901	1.865	1.649
2035	45,398	7,498	340	1,045	0.933	1.931	1.707
2040	45,398	7,694	349	1,072	0.957	1.981	1.751
2045	45,398	7,924	360	1,104	0.986	2.040	1.804
2050	45,398	8,090	367	1,127	1.006	2.083	1.841
2055	45,398	8,232	374	1,147	1.024	2.119	1.874
2060	45,398	8,408	382	1,171	1.046	2.165	1.914
High Growth							
2010	45,398	5,920	269	825	0.736	1.524	1.347
2015	45,398	6,283	285	875	0.781	1.618	1.430
2020	45,398	6,788	308	946	0.844	1.748	1.545
2025	45,398	7,263	330	1,012	0.903	1.870	1.653
2030	45,398	7,657	348	1,067	0.952	1.971	1.743
2035	45,398	8,052	366	1,122	1.001	2.073	1.833
2040	45,398	8,409	382	1,172	1.046	2.165	1.914
2045	45,398	8,852	402	1,233	1.101	2.279	2.015
2050	45,398	9,272	421	1,292	1.153	2.387	2.110
2055	45,398	9,703	440	1,352	1.207	2.498	2.208
2060	45,398	10,191	463	1,420	1.268	2.624	2.320
Low Growth							
2010	45,398	5,920	269	825	0.736	1.524	1.347
2015	45,398	6,167	280	859	0.767	1.588	1.404
2020	45,398	6,473	294	902	0.805	1.667	1.473
2025	45,398	6,693	304	933	0.832	1.723	1.523
2030	45,398	6,828	310	951	0.849	1.758	1.554
2035	45,398	6,943	315	967	0.864	1.788	1.580
2040	45,398	6,986	317	973	0.869	1.799	1.590
2045	45,398	7,030	319	979	0.874	1.810	1.600
2050	45,398	6,984	317	973	0.869	1.798	1.590
2055	45,398	6,894	313	960	0.857	1.775	1.569
2060	45,398	6,826	310	951	0.849	1.757	1.554

Non-Potable Wholesale Water Service Area

The non-potable wholesale service area is the area to which Wichita provides untreated (raw) water through wholesale contracts and includes the City of Bentley. The raw water is sold and metered similar to other wholesale contracts.

The non-potable area covers just over ¼ square mile in Bentley and includes a population of 481. The area is projected to expand approximately 0.016 square miles per year from 0.26 square miles in 2010 to 1.05 square miles in 2060. The expansion of this area quadruples the size of current area. The reason for such an expansion is that the US Census Blocks surrounding Bentley are mostly large. When including extra Census Blocks in this area, the area quickly increases in size.

The non-potable service area per capita consumption of raw water from Wichita was 22,518 gallons in 2010 based on the population of Bentley and the amount of water raw water sold to Bentley. This rate was projected to continue through 2060. Table A2.7 shows the projected population growth, per capita annual demand, annual demand, annual average day demand, and peak day demand for the non-potable water service area.

Table A2.7: Non-Potable Water Service Area Water Demand

Year	Per Capita Annual Demand (G)	Population	Annual Demand (MG)	Annual Demand (Ac-Ft)	Average Day Demand (MGD)	High Peak Demand (MGD)	Medium Peak Demand (MGD)
Medium Growth							
2010	22,519	481	11	33	0.030	0.061	0.054
2015	22,519	508	11	35	0.031	0.065	0.057
2020	22,519	565	13	39	0.035	0.072	0.064
2025	22,519	588	13	41	0.036	0.075	0.066
2030	22,519	614	14	42	0.038	0.078	0.069
2035	22,519	629	14	43	0.039	0.080	0.071
2040	22,519	657	15	45	0.041	0.084	0.074
2045	22,519	668	15	46	0.041	0.085	0.075
2050	22,519	681	15	47	0.042	0.087	0.077
2055	22,519	693	16	48	0.043	0.088	0.078
2060	22,519	748	17	52	0.046	0.096	0.084
High Growth							
2010	22,519	481	11	33	0.030	0.061	0.054
2015	22,519	513	12	35	0.032	0.066	0.058
2020	22,519	579	13	40	0.036	0.074	0.065
2025	22,519	612	14	42	0.038	0.078	0.069
2030	22,519	649	15	45	0.040	0.083	0.073
2035	22,519	675	15	47	0.042	0.086	0.076
2040	22,519	718	16	50	0.044	0.092	0.081
2045	22,519	746	17	52	0.046	0.095	0.084
2050	22,519	780	18	54	0.048	0.100	0.088
2055	22,519	817	18	56	0.050	0.104	0.092
2060	22,519	909	20	63	0.056	0.116	0.103
Low Growth							
2010	22,519	481	11	33	0.030	0.061	0.054
2015	22,519	504	11	35	0.031	0.064	0.057
2020	22,519	552	12	38	0.034	0.071	0.062
2025	22,519	565	13	39	0.035	0.072	0.064
2030	22,519	579	13	40	0.036	0.074	0.065
2035	22,519	583	13	40	0.036	0.074	0.066
2040	22,519	596	13	41	0.037	0.076	0.067
2045	22,519	592	13	41	0.037	0.076	0.067
2050	22,519	587	13	41	0.036	0.075	0.066
2055	22,519	580	13	40	0.036	0.074	0.065
2060	22,519	605	14	42	0.037	0.077	0.068

Appendix C
DOMESTIC LAWN AND GARDEN WELLS

Appendix C is a very general assessment of the potential impact of changes in private well drilling patterns on the future water demand for the WWSA. During the Water Demand Assessment, it was found that per capita water demand has been decreasing since at least 1990. A significant portion of this decrease may be the result of increased drilling of private irrigation (domestic lawn and garden) wells and various conservation measures. The focus of this assessment is to identify the impact of domestic lawn and garden well use on future demand.

Data from permits on domestic lawn and garden wells was available from the Kansas Geological Survey from 1975 through 2012[18]. The data for the WWSA, non-potable water service area, potential water service areas, and all expansion areas was pulled and used for this assessment. The number of wells drilled for domestic lawn and garden use has increased since 1975. The depth of wells and the static water depth below ground level have also increased during that time. The impacts of more wells, deeper wells, and deeper water have potential impacts on future water demand in the WWSA.

This assessment is separate from the main water demand assessment because it is not assumed that there will be changes in private well drilling patterns. However, since wells are increasing in number, getting deeper, and the water level appears to be dropping, it was deemed appropriate to assess potential impacts of changes in the private well drilling pattern.

Domestic lawn and garden wells are the focus of this assessment. The reason is that the owners and operators of these wells likely use water from Wichita Water Utilities for domestic use except for irrigation. If wells are unusable due to poor water quality or water becomes too deep to reasonably access, these users will likely use Wichita water to irrigate. The increased use of Wichita water for irrigation will increase the future water demand.

Residential Lawn Use

Data on water usage for residential lawn meters[15] as well as the number of residential lawn meters[19] was collected for 2012 since previous year data was not available on the number of residential lawn meters. In 2012, there were 6,452,000 gallons sold via residential lawn meters and there were 1,486 active residential lawn meters. This shows water usage per residential lawn meter was 4,342 gallons per year. This may be applied as the rate of increased water usage if customers with lawn and garden wells would switch to irrigating with Wichita water. It is noted that 4,342 gallons per year is likely much lower than actual annual usage rate for many residential irrigation users. This number should not be used to determine the amount of water needed to irrigate residential lawns. Since it is a quantity of record, it is used in this assessment to measure potential impacts on demand.

Number of Wells, Well Depth, and Static Water Depth

The number of new domestic lawn and garden wells has increased at an average annual rate of 32.74 wells per year since 1975. The drilling depth of new or reconstructed wells has increased since 1975 at a rate of 0.7 feet per year. Not only has the depth of wells increased, the static water depth has also increased since 1975 at a rate of 0.23 feet per year. The rates were used to develop a linear forecast for number of new wells, depth of wells, and static water depth. The historic data on the number of new wells, new and reconstructed average well depth, and new and reconstructed average static depth is shown in Table A3.1. The historic and projected number of new wells, average depth of new and reconstructed wells, and average static water depth of new or reconstructed wells are shown in Chart A3.1. The historic and projected number of total wells, the average depth of new and reconstructed wells, and average static water depth of new or reconstructed wells are shown in Table A3.2. The projections assume no change in drilling patterns. It is also important to note that data was available on plugged wells. However, the number of reported plugged wells has very little bearing on the overall number due to the low number reported. This either points to an incomplete data set or the number of plugged wells is so low that it has very little impact on overall domestic lawn and garden well drilling.

Table A3.1: Historic Number of New Wells, Average Well Depth, and Average Static Depth

YEAR	New Wells (#)	AVG WELL DEPTH (ft.)	AVG STATIC DEPTH (ft.)
1975	22	49.14	17.95
1976	111	51.72	19.10
1977	125	61.34	21.25
1978	106	55.81	20.41
1979	104	55.46	19.31
1980	180	62.20	24.00
1981	157	53.47	21.97
1982	98	58.45	20.62
1983	116	52.68	19.84
1984	190	57.14	21.79
1985	185	54.94	21.00
1986	116	54.54	20.12
1987	72	55.33	20.77
1988	120	52.71	20.29
1989	210	55.00	22.29
1990	162	59.58	23.79
1991	325	57.13	24.67
1992	370	59.52	24.35
1993	255	59.33	20.75
1994	647	62.68	22.12
1995	397	66.22	23.35
1996	510	68.33	24.45
1997	412	72.54	25.13
1998	169	73.48	23.11
1999	509	71.94	22.40
2000	502	70.07	23.04
2001	720	70.21	24.08
2002	828	70.54	26.56
2003	1,220	73.35	25.11
2004	1,283	74.54	25.10
2005	1,272	74.99	24.58
2006	1,316	73.43	25.73
2007	1,269	74.87	25.66
2008	913	75.77	26.05
2009	787	73.59	24.87
2010	796	71.45	25.40
2011	1,019	72.15	25.62
2012	987	71.39	25.63

Exhibit A3.1: Domestic Lawn and Garden Wells – Year Completed

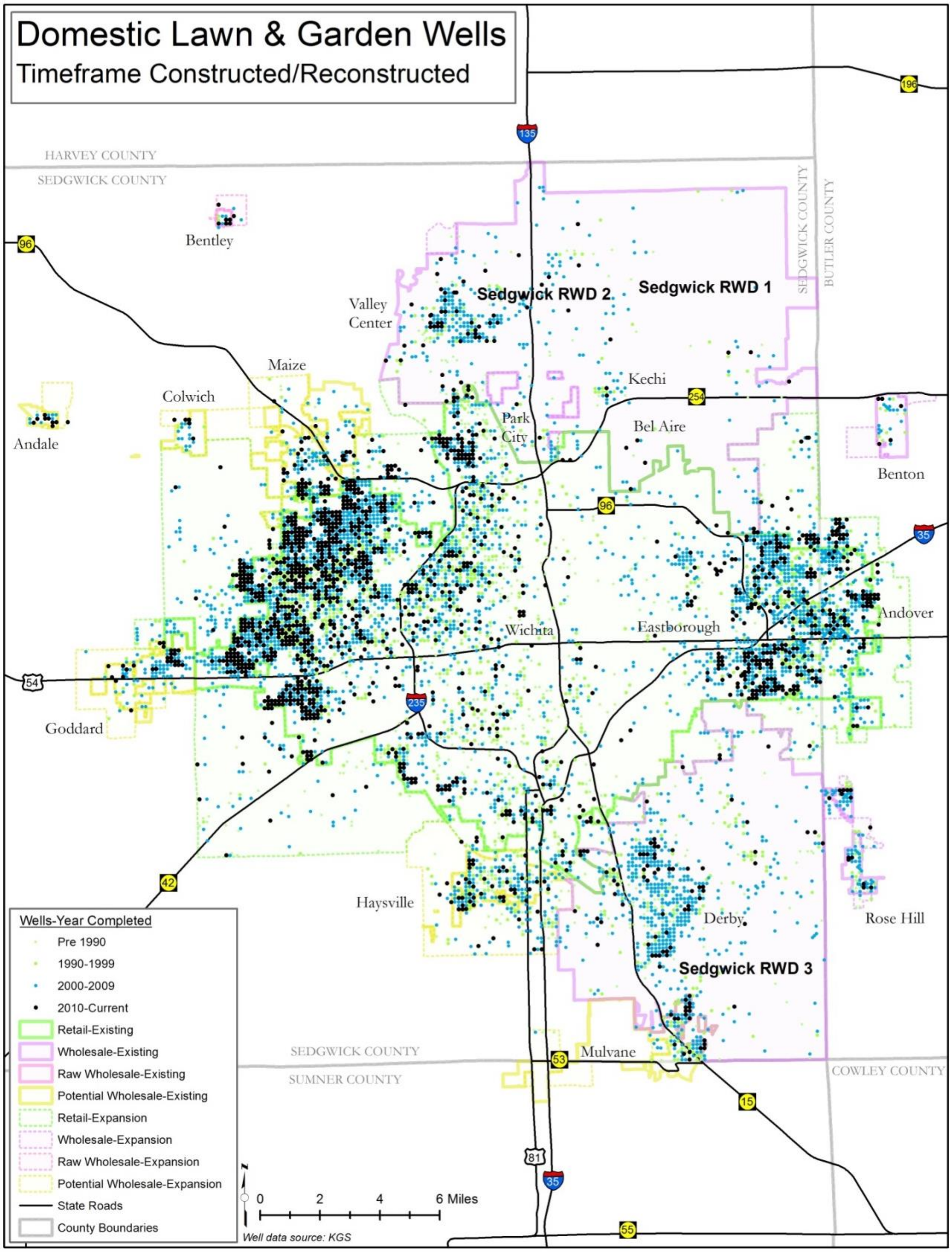


Exhibit A3.2: Domestic Lawn and Garden Wells – Static Depth

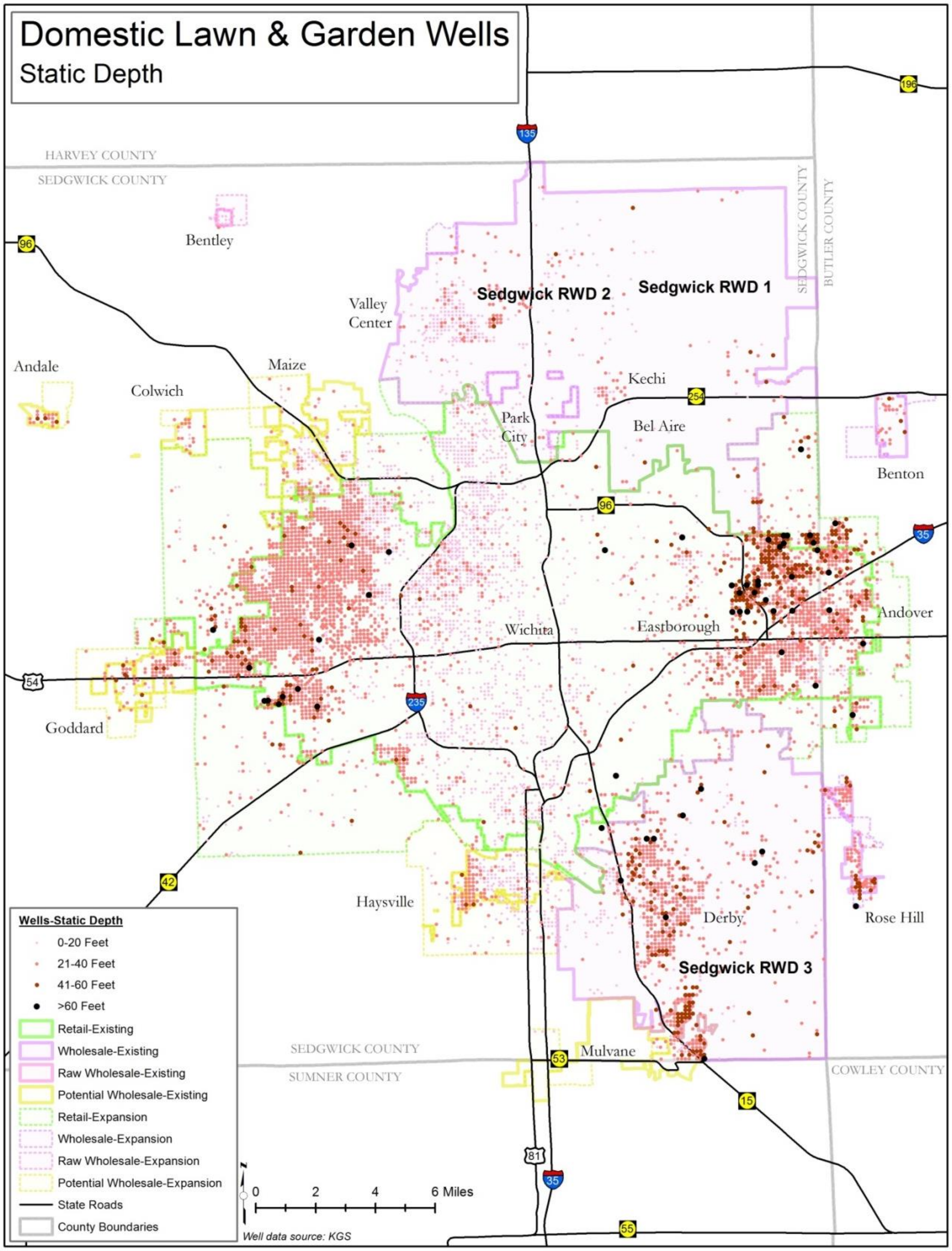


Chart A3.1: Historic and Projected Number of New Wells, Average Well Depth, and Static Depth

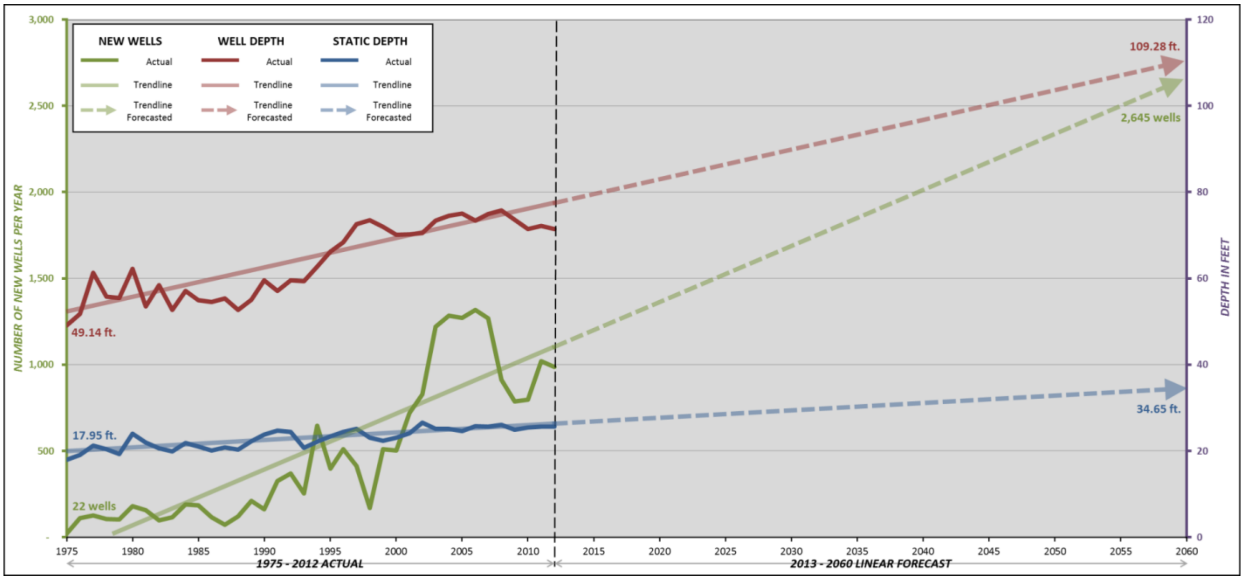


Table A3.2: Historic and Projected Number of Wells, Average Well Depth, and Average Static Depth

By end of year	Total Wells	Avg Well Depth	Avg Static Depth
1975	22	49.14	17.95
1980	648	62.20	24.00
1985	1,394	54.94	21.00
1990	2,074	59.58	23.79
1995	4,068	66.22	23.35
2000	6,170	70.07	23.04
2005	11,493	74.99	24.58
2010	16,574	71.45	25.40
2015	22,041	78.55	26.73
2020	28,457	81.97	27.61
2025	35,684	85.38	28.49
2030	43,721	88.80	29.37
2035	52,569	92.21	30.25
2040	62,228	95.62	31.13
2045	72,697	99.04	32.01
2050	83,976	102.45	32.89
2055	96,066	105.87	33.77
2060	108,967	109.28	34.65

Impacts on Future Annual Water Demand

Domestic lawn and garden well users could potentially use Wichita water for irrigation in the future. This could be caused by declining quality of well water, increasing depth to water, or other circumstances where it would not be feasible, financially or otherwise, to drill and operate private wells. This would impact future water demand for Wichita Water Utilities. The time at which this change would occur has implications on when that demand would happen.

As shown in Chart A3.1, the number of wells is expected to increase along with the depth to static water. The linear projection shows a static water depth of 34.65 feet by 2060. It is assumed, based on local knowledge, that the water will be available at this depth. However, water quality could decline making it unusable without treatment. This could push more well users to Wichita water. At this time, it is uncertain if and when private wells will fail in this way. The typical pattern is for a well performance to decline to the extent that the well owner will drill a new well nearby.

Based on the permit data, there are 18,580 documented domestic lawn and garden wells. If all of these well users stopped using wells for irrigation and used Wichita water instead, the immediate increase in water demand is estimated to be 80.67 million gallons per year (18,580 x 4,342). This assumes that well users will use water at the same rate as those that used residential lawn meters in 2012. Table A3.3 shows the impact of this increased demand.

Table A3.3: Projected Additional Annual Demand from Well Users

By end of year	Total Wells	Annual Demand from Wells (MG)	Annual Demand From Wells (Ac-Ft/Yr)
1975	22	0.10	0.29
1980	648	2.81	8.63
1985	1,394	6.05	18.58
1990	2,074	9.01	27.64
1995	4,068	17.66	54.21
2000	6,170	26.79	82.22
2005	11,493	49.90	153.15
2010	16,574	71.96	220.85
2015	22,041	95.70	293.70
2020	28,457	123.56	379.19
2025	35,684	154.94	475.49
2030	43,721	189.84	582.59
2035	52,569	228.26	700.49
2040	62,228	270.19	829.19
2045	72,697	315.65	968.69
2050	83,976	364.62	1,118.99
2055	96,066	417.12	1,280.09
2060	108,967	473.13	1,451.99

In many ways, the projected additional annual demand from well users is an unlikely scenario. All well users will likely not switch to irrigating with Wichita water and the economics of irrigating at this rate will likely deter usage at this rate. However, the data does provide a likely upper limit to additional demand from well users.

As noted, the annual water usage for residential irrigation purposes is likely higher than that identified by historic data. The water demand on Wichita Water Utilities from well users moving to Wichita water would likely be greater than that shown above.

Impacts on Future Peak Day Water Demand

The impact of domestic lawn and garden well drilling has a relatively small potential impact on the annual water demand. It has a much larger potential impact on peak day water demand, since the peak day typically occurs during the summer months when outdoor water use is high. Removing domestic lawn and garden wells would lead to higher peak day water demand.

It is not possible to identify the direct impact of increased demand on the peak day because data on peak day demand caused by residential lawn meters was not available. However, water sales data was available by month. Data was collected[20] on water sold to residential lawn meters per month from 2009 to 2011. The data showed that the highest month averaged 21.7% of the total annual distribution. The peak day is assumed to occur in the month of highest use. 21.7% of the total annual water demand was calculated to get the highest month annual demand. That number was then divided by 31 to get the daily demand, which was assumed to be the peak day demand. The peak day demand is likely to be higher, but it was not possible to identify the variability in peak day demand with only peak month usage available. Table A3.4 shows the projected increase in peak day demand.

Table A3.4: Projected Additional Peak Demand from Well Users

Year	Additional Peak Day Demand (MGD)
2015	0.670
2020	0.865
2025	1.085
2030	1.329
2035	1.598
2040	1.891
2045	2.210
2050	2.552
2055	2.920
2060	3.312

It is important to note that well users are likely high water consumers, especially during the summer months. If these well users were to require water from Wichita Water Utilities, the annual demand and peak demand would likely be higher than those outlined in Appendix C. However, the degree of increased demand is not possible to quantify completely because the needed data is not available.

Trend analyses of the indicated rate of increase in private wells and the rate of decline in the groundwater level indicate that in general the groundwater level will decline. By 2060, the depth from the ground surface to groundwater may increase to an average of 35 feet. In some very local areas, this could cause wells to become useless. For the most part, the aquifer below the Wichita service area will remain useful.

Some wells may fail due to mineralization or contamination. Records are not available to indicate the local rate of failure. Subsurface conditions and known large contamination zones could indicate that approximately 30% of wells may fail in east Wichita and north central Wichita by 2060.

Appendix D
CONSERVATION MEASURES

Appendix D shows the potential impacts on water demands if a 2% conservation level is achieved.

The conservation scenario is only applied to the WWSA-R. This was done because of the difficulty in developing and implementing conservation measures, especially when coordinating with other municipalities or water districts. It was assumed that conservation measures would only be developed and implemented in the WWSA-R, which only impacts the demand for this area. The water demand for the WWSA-W was then added to the WWSA-R to get the annual and peak day water demand for the WWSA. Table A4.1 shows the water demand for the conservation scenario, three growth scenarios, and two peak day scenarios.

Conservation measures by definition will restrict the amount of water available for customers to use. Some customers will seek to continue their customary water use by substituting groundwater from private wells for the water that they can no longer purchase or that they feel they cannot afford.

Possible negative consequences from effective conservation measures are:

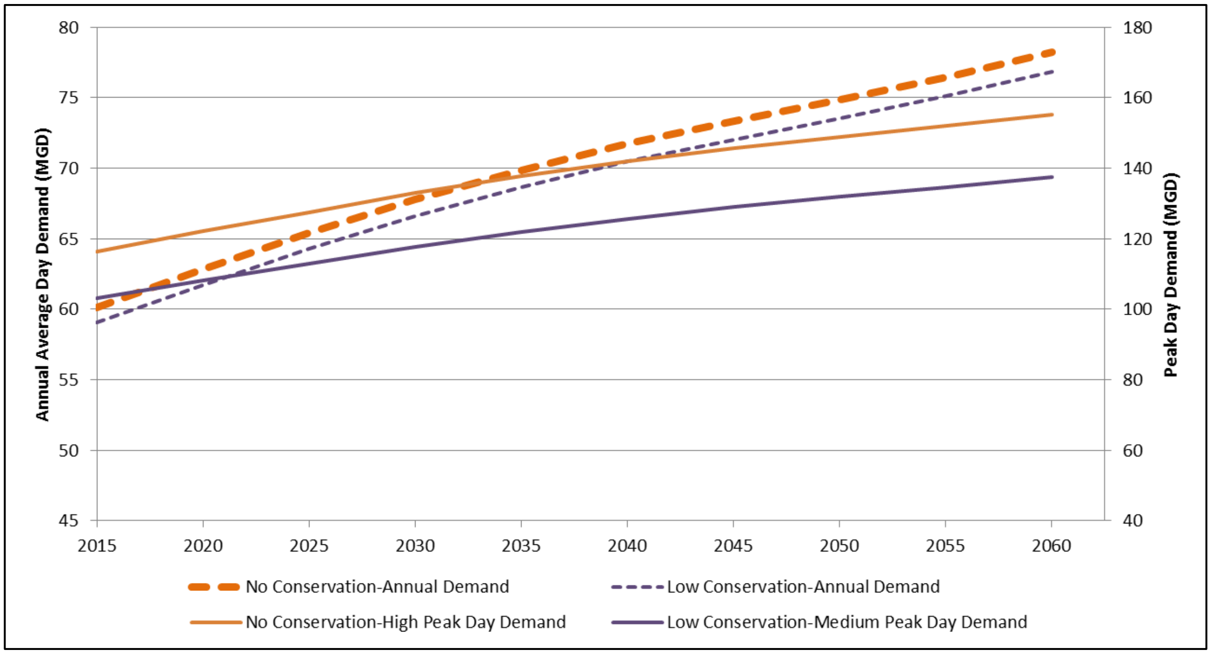
- Groundwater will be depleted in local areas. The effect of this will be generally greater in the area east of the Arkansas River. Groundwater is more difficult to find and the subsurface formations hold and yield less water than those west of the river. West of the river, groundwater in the sand formations there will deplete less noticeably and will continue to be available beyond 2060.
- Groundwater quality may decline in certain areas as increased pumping influences the flow of contaminated water into areas that are not currently contaminated. This can particularly be observed where water is now pumped from known contaminated zones such that pumping in nearby areas will create hydraulic gradients to mobilize the contaminated water.
- Water theft will increase. More customers will feel justified and motivated to find ways to use water without paying, either for supplemental purposes or for all uses.
- Changes in landscaping, gardening, and other outdoor uses. While these are intended consequences of conservation measures, market influences will emerge to favor and promote xeriscape landscaping and gardening.
- Reduced utility revenue, unless the water rate structure adequately compensates for the reduced unit sales.
- Reduced energy costs for treatment and pumping in proportion to the reduced use.
- Increased risk of DBE formation in the distribution system due to water age.

Table A4.1: Conservation Measure Impacts on Annual and Peak Day Water Demand

	No Conservation			Low Conservation (-2%)		
Year	Avg Day (MGD)	High Peak (MGD)	Medium Peak (MGD)	Avg Day (MGD)	High Peak (MGD)	Medium Peak (MGD)
Medium Growth						
2010	57.30	118.43	104.90	56.30	116.36	103.07
2015	60.10	124.21	110.03	59.05	122.04	108.10
2020	62.82	129.84	115.02	61.72	127.58	113.01
2025	65.43	135.23	119.79	64.29	132.87	117.70
2030	67.77	140.08	124.09	66.59	137.63	121.92
2035	69.87	144.40	127.92	68.64	141.88	125.68
2040	71.73	148.26	131.33	70.48	145.67	129.04
2045	73.32	151.54	134.24	72.04	148.89	131.89
2050	74.87	154.74	137.07	73.56	152.03	134.67
2055	76.46	158.03	139.99	75.12	155.26	137.53
2060	78.20	161.63	143.18	76.83	158.80	140.67
High Growth						
2010	57.30	118.43	104.90	56.30	116.36	103.07
2015	60.65	125.35	111.04	59.59	123.16	109.10
2020	64.27	132.84	117.68	63.15	130.52	115.62
2025	68.03	140.61	124.56	66.84	138.16	122.38
2030	71.56	147.90	131.02	70.31	145.32	128.73
2035	74.92	154.84	137.16	73.61	152.13	134.76
2040	78.27	161.78	143.31	76.90	158.95	140.80
2045	81.74	168.94	149.65	80.31	165.98	147.03
2050	85.61	176.95	156.75	84.11	173.85	154.00
2055	89.87	185.75	164.54	88.30	182.49	161.66
2060	94.50	195.33	173.03	92.85	191.91	170.00
Low Growth						
2010	57.30	118.43	104.90	56.30	116.36	103.07
2015	59.54	123.06	109.01	58.50	120.91	107.10
2020	61.36	126.82	112.34	60.28	124.60	110.37
2025	62.80	129.80	114.98	61.70	127.53	112.97
2030	63.96	132.20	117.10	62.84	129.89	115.06
2035	64.80	133.93	118.64	63.67	131.59	116.57
2040	65.26	134.88	119.48	64.11	132.52	117.39
2045	65.19	134.74	119.35	64.05	132.38	117.27
2050	64.80	133.93	118.64	63.66	131.58	116.56
2055	64.25	132.79	117.63	63.12	130.46	115.57
2060	63.72	131.69	116.66	62.60	129.38	114.61

Chart A4.1 shows the annual average day water demand for the conservation scenario under the medium growth scenario, as well as the two peak day water demand scenarios for the medium growth scenario under the conservation scenario.

Chart A4.1: Conservation Measure Impacts on Annual Demand (Medium Growth Scenario)



Appendix E
POTENTIAL WATER DEMANDS

Appendix E shows the potential water demands if various assumptions change from the projected water demand as outlined in Appendix B and Appendix C. Appendix B identifies potential additional wholesale water service areas and Appendix C identifies additional demand if patterns change in domestic lawn and garden wall drilling. Changing the assumption of who will be served would impact overall water demand. Also, if patterns in well drilling change, demand will also likely change. Appendix E combines all of the potential demands to provide demands based on different assumptions.

In the original water demand projections on p. 10-19, it was assumed Andale, Colwich, Goddard, Haysville, Maize, and Mulvane would not be served by Wichita Water Utilities. The projected water demands for each of these municipalities under each growth scenario are provided in Appendix B. The original projections also assume domestic lawn and garden well drilling and use will continue on the historic trend. The following figures show the demand based potential changes in WWSA coverage and the well use outlined in Appendix B and Appendix C. The figures also include the three population growth scenarios and two peak day scenarios.

Chart A5.1 and Table A5.1 show the annual water demand for the existing and expanded retail service area; existing and expanded wholesale service area; and potential additional wholesale service areas and their expansion areas. It includes the annual demand for all three growth scenarios. This basically adds the annual demand for all six cities to the annual demand projections for the WWSA. It does not include the annual demand for the non-potable wholesale service area.

Chart A5.1: Annual Demand for All Area

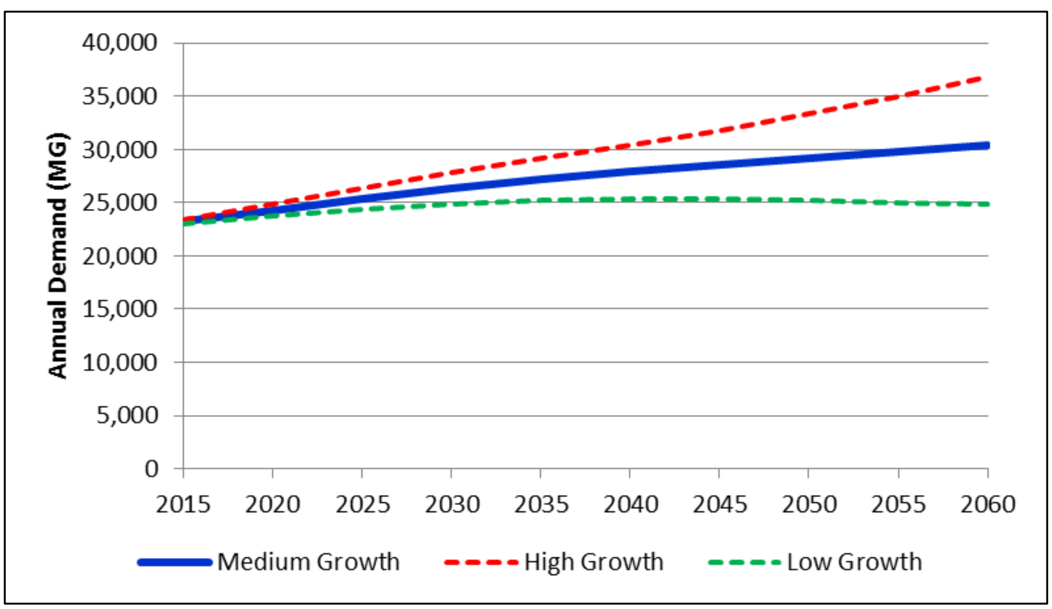


Table A5.1: Annual Demand for All Areas

Year	Medium Growth Annual Demand (MG)	Medium Growth Annual Demand (Ac-Ft)	High Growth Annual Demand (MG)	High Growth Annual Demand (Ac-Ft)	Low Growth Annual Demand (MG)	Low Growth Annual Demand (Ac-Ft)
2015	23,217	71,249	23,430	71,903	23,002	70,590
2020	24,299	74,570	24,860	76,293	23,732	72,830
2025	25,341	77,768	26,350	80,865	24,322	74,642
2030	26,287	80,671	27,756	85,179	24,806	76,127
2035	27,145	83,304	29,108	89,329	25,175	77,258
2040	27,877	85,550	30,420	93,356	25,358	77,822
2045	28,506	87,480	31,780	97,529	25,343	77,775
2050	29,122	89,372	33,303	102,203	25,204	77,348
2055	29,749	91,297	34,969	107,317	24,996	76,711
2060	30,433	93,395	36,779	112,870	24,794	76,089

Chart A5.2 and Table A5.2 show the peak day water demand for existing and expanded retail service area; existing and expanded wholesale service area; and potential additional wholesale service areas and their expansion areas. It includes the peak day demand for all three growth scenarios and two peak day scenarios. This adds the peak day demand for all six cities to the peak day demand projections for the WWSA. It does not include the peak day demand for the non-potable wholesale service area.

Chart A5.2: Peak Demand for Existing Retail, Existing Wholesale, Potential Additional Wholesale Service Areas, and all Expansion Areas

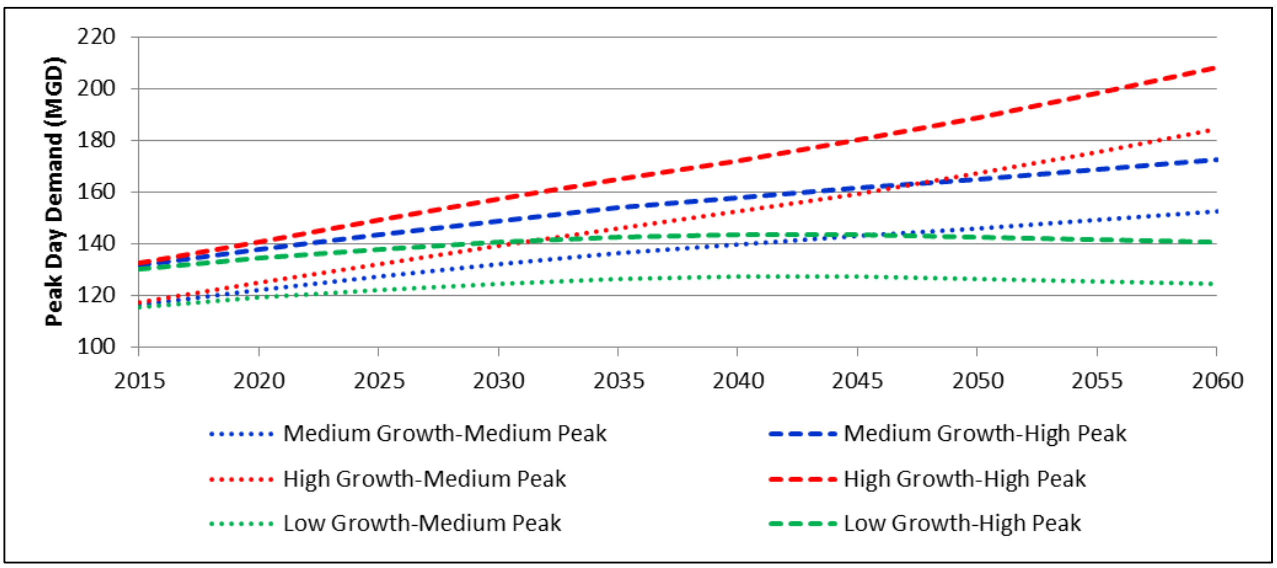


Table A5.2: Peak Demand for Existing Retail, Existing Wholesale, Potential Additional Wholesale Service Areas, and all Expansion Areas

Year	Med Growth Med Peak (MGD)	Med Growth High Peak (MGD)	High Growth Med Peak (MGD)	High Growth High Peak (MGD)	Low Growth Med Peak (MGD)	Low Growth High Peak (MGD)
2015	116.46	131.47	117.53	132.67	115.38	130.25
2020	121.89	137.59	124.70	140.77	119.04	134.38
2025	127.11	143.50	132.18	149.21	122.00	137.73
2030	131.86	148.85	139.23	157.17	124.43	140.47
2035	136.16	153.71	146.01	164.83	126.28	142.55
2040	139.83	157.85	152.59	172.26	127.20	143.59
2045	142.99	161.42	159.41	179.96	127.12	143.51
2050	146.08	164.91	167.05	188.58	126.43	142.72
2055	149.23	168.46	175.41	198.02	125.38	141.54
2060	152.65	172.33	184.49	208.26	124.37	140.40

Table A5.3 shows the annual water demand for the existing and expanded retail service area; existing and expanded wholesale service area; and potential additional wholesale service areas and their expansion areas under the assumption that domestic lawn and garden wells will no longer be used. It includes the annual demand for all three growth scenarios, along with the annual demand for all six cities and the well users. It does not include the annual demand for the non-potable wholesale service area.

Table A5.3: Annual Demand with No Lawn and Garden Well Use

Year	Med Growth Annual Demand (MG)	Medium Growth Annual Demand (Ac-Ft)	High Growth Annual Demand (MG)	High Growth Annual Demand (Ac-Ft)	Low Growth Annual Demand (MG)	Low Growth Annual Demand (Ac-Ft)
2015	23,312	71,543	23,525	72,197	23,097	70,883
2020	24,422	74,949	24,984	76,673	23,855	73,209
2025	25,496	78,244	26,505	81,341	24,477	75,118
2030	26,477	81,254	27,946	85,762	24,996	76,709
2035	27,373	84,004	29,336	90,030	25,403	77,959
2040	28,147	86,379	30,690	94,185	25,628	78,651
2045	28,821	88,449	32,096	98,498	25,659	78,744
2050	29,487	90,491	33,668	103,322	25,569	78,467
2055	30,166	92,577	35,387	108,597	25,413	77,991
2060	30,906	94,847	37,252	114,322	25,267	77,541

Table A5.4 shows the peak day water demand for existing and expanded retail service area; existing and expanded wholesale service area; and potential additional wholesale service areas and their expansion areas under the assumption that domestic lawn and garden wells will no longer be used. It includes the peak day demand for all three growth scenarios and two peak day scenarios. This essentially adds the peak day demand for all six cities and the well users to the peak day demand projections for the WWSA. It does not include the peak day demand for the non-potable wholesale service area.

Table A5.4: Peak Day Demand with No Lawn and Garden Well Use

Year	Med Growth Med Peak (MGD)	Med Growth High Peak (MGD)	High Growth Med Peak (MGD)	High Growth High Peak (MGD)	Low Growth Med Peak (MGD)	Low Growth High Peak (MGD)
2015	117.13	132.14	118.20	133.34	116.05	130.92
2020	122.75	138.46	125.57	141.64	119.91	135.25
2025	128.20	144.58	133.26	150.30	123.09	138.81
2030	133.19	150.18	140.56	158.50	125.76	141.80
2035	137.76	155.31	147.61	166.43	127.88	144.15
2040	141.72	159.75	154.48	174.15	129.09	145.49
2045	145.20	163.63	161.62	182.17	129.33	145.72
2050	148.63	167.46	169.60	191.14	128.98	145.27
2055	152.15	171.38	178.33	200.94	128.30	144.46
2060	155.97	175.64	187.80	211.58	127.68	143.71

Appendix F
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