Kansas Geological Survey

Open File Report 2002-25E

Climate Variation: Implications of Long-Term Records and Recent Observations

By

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With contributions from other authors in the report series

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Kansas Geological Survey Open File Report 2002-25E

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KGS OFR 2002-25E: Climate Variation: Implications of Long-Term Records and Recent Observations

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"In a desert, you know what to expect of the climate and plan accordingly. The same is true of the humid regions. Men have been badly fooled by the semiarid regions because they are sometimes humid, sometimes desert, and sometimes a cross between the two."

(Thornthwaite, 1941)

1. Introduction

The semiarid climate of the Great Plains is characterized by variability. Wet and dry periods are natural features of the climatic system, and significantly influence water use and demand. From both an agricultural and a water supply perspective, extremely dry conditions -- droughts -- are of particular importance. A drought may be defined as a period of abnormally dry weather that persists long enough to produce a serious hydrologic imbalance (for example, crop damage, water supply shortage, etc.). The severity of a drought depends upon the degree of moisture deficiency, the duration and the size of the affected area (see http://www.nws.noaa.gov/om/drought.htm).

Every year some region of North America experiences drought. Severe droughts of the 20th century have had large impacts on society, economies and the environment, especially in the Great Plains (Woodhouse and Overpeck, 1998). In terms of duration and spatial extent, the 1930s Dust Bowl drought, which lasted up to 7 years in some areas of the Great Plains, is considered to be the major drought of the 20th century. The 1930s drought was so severe, widespread, and lengthy that it resulted in a mass migration of millions of people from the Great Plains to the western U.S. in search of jobs and better living conditions (NOAA, 2000).

For reliability of supply, water systems (including aquifers) must have sufficient reserves to sustain some minimally acceptable level of withdrawal through the targeted level of drought. Questions remain, however, about how representative the recent past has been in terms of drought occurrence or water availability. Was the Dust Bowl drought a rare event or should we expect droughts of similar, or even greater, magnitude to occur in the future?

This report looks at the climatic record at two scales: 1) the period of instrumental record and 2) the period of paleoclimatic record. The period of instrumental record is roughly the 20th century. The second half of the 20th century encompasses the experience since the onset of widespread irrigation in the Ogallala region and a period of extensive and consistent weather data collection. For the first half of the 20th century, instrumental records are available; however, the density of measurements was much lower. The paleoclimatic record covers the early historic and pre-historic period of the past several hundred years or more, which is critical to assessing the risks from less frequent major occurrences, and which can be evaluated from various types of non-instrumental evidence.

This report is written as part of the Kansas Geological Survey's report of ongoing technical support series (OFR 2002-25) to further understand the characteristics and properties of the High Plains Aquifer. This report was developed within the framework of contracts with the Kansas Water Office (KWO) and Kansas Department of Agriculture's Division of Water Resources (KDA-DWR). Contract documents are contained in Section 4 of KGS OFR 2002-25G.

2. Types and Measures of Data

2.1 Direct Observations

Scientists typically quantify drought by evaluating precipitation, temperature, and soil moisture data for the present and past months. Rainfall and precipitation records -- the basic minimal weather station data -- extend back roughly 100 years; however, the number of stations increased sharply in the late 1940s. Figure 1 shows the locations of National Climatic Data Center (NCDC) stations. Figure 2 shows the number of NCDC stations in the Ogallala (western) region of Kansas. Temperature and precipitation records for the second half of the 19th century exist from forts and stations in the Great Plains, but these records are quite fragmented and patchy (Woodhouse and Overpeck, 1998).

Other direct observations (wind, evaporation, solar radiation, soil moisture, etc.) are typically available only for the last half-century or so, and at fewer locations. These observations are arguably more precisely relevant to agricultural water demand than the important basic variables, but are not as widely available as direct measurements.

2.2 Modeled water cycle parameters

Modeled or derived water budget data -- actual evapotranspiration, adjusted potential evapotranspiration, surplus, and deficit -- may be derived from the basic weather station data, as discussed by the references listed by Willmott and Matsuura (2001). Their web page and references also describe interpolation of the point data, discussed more in section 3.1.1. Potential evapotranspiration is the calculated estimate of the amount of evapotranspiration that would occur if there were always water available.

Surplus or deficit is simply the difference between precipitation and potential evapotranspiration, and actual evapotranspiration will equal the smaller of precipitation or potential evapotranspiration. The Willmott-NCDC data set contains monthly values for those derived variables and for soil moisture over the 50-year period; the annual values in this report are derived from the monthly values.

2.3 Drought Indices

Information on drought indices reviewed or quoted in this subsection was obtained from Hayes (1999), NOAA (2000) and NOAA (2002).

A number of drought indices have been developed to quantify drought. A drought index is typically a single number, far more useful than raw data for decision making. While none of the indices are inherently better in all circumstances, some are better suited than others for certain uses. The Palmer Drought Severity Index (PDSI) has been the most commonly used drought index in the United States. The index has been used to evaluate drought impact on agriculture and to trigger drought response programs.

The PDSI was developed by Palmer (1965) to measure intensity, duration, and spatial extent of drought. It is calculated based on measurements of precipitation, temperature, and soil moisture, along with prior values of these measures. PDSI values range from roughly -6 (extreme drought) to 6 (extremely wet conditions). The values are standardized to facilitate comparisons between different locations. Some of the characteristics and limitations of the PDSI and of other drought indices are discussed by Hayes (1999) and are listed below:

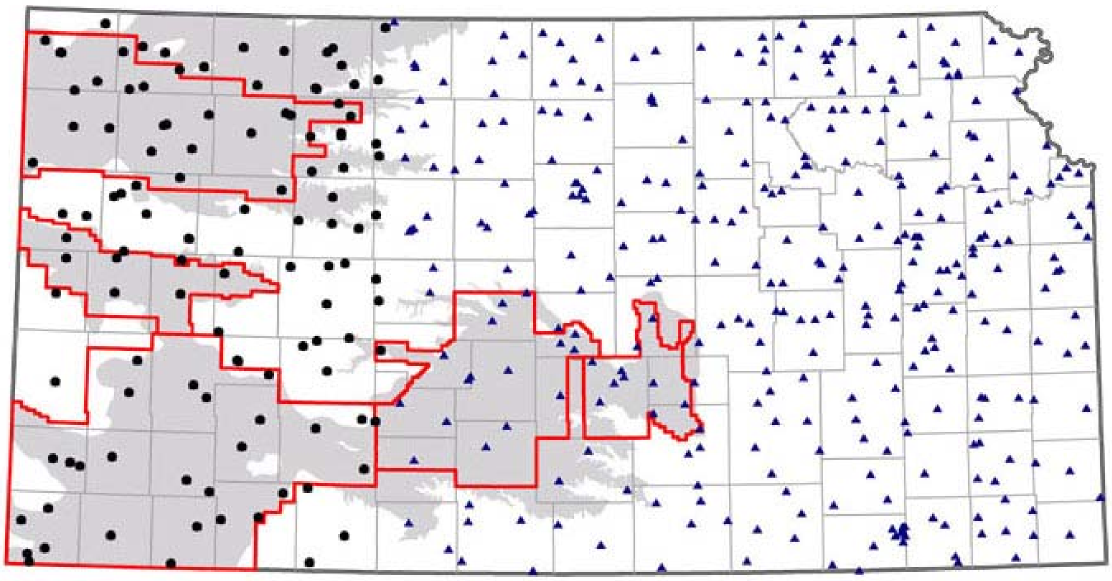


Figure 1. Location of NCDC stations in Kansas. Circles are stations used in the Ogallala climate analysis. Also shown are GMD and county boundaries and the extent of the High Plains aquifer.

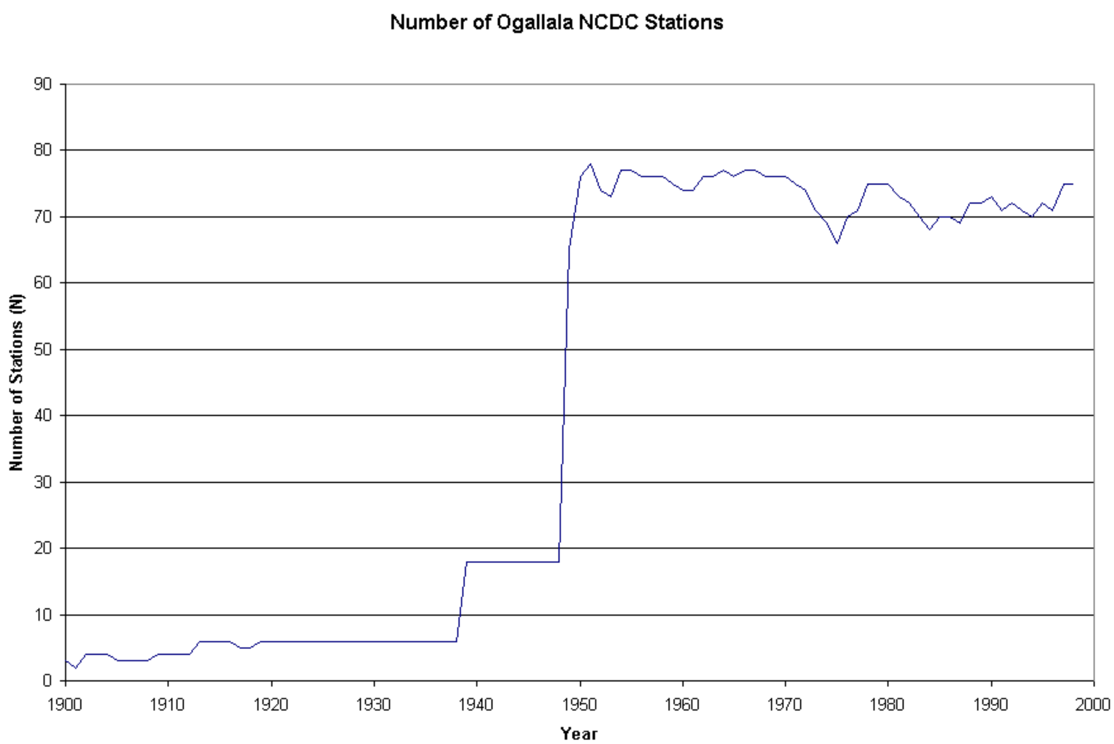


Figure 2. Number of NCDC weather stations in the Ogallala region of Kansas.

Percent of Normal (Precipitation)
· simple calculation, but can be misleading because mean precipitation is often not the same as the median precipitation.

Standardized Precipitation Index (SPI)
· a newer index developed by McKee et al. (1993 in Hayes, 1999)
· can be computed on various time scales
· can provide early warning of drought and help assess drought severity
· less complex than Palmer Drought Severity index
· values based on preliminary data may change.

Palmer Drought Severity Index (PDSI)
· developed by Palmer (1965) to measure departure of the moisture supply
· based on the supply-and-demand concept of the water balance equation
· inputs include precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil
· most effective measuring impacts sensitive to soil moisture conditions
· may lag emerging droughts by several months
· has built-in time scale that can be misleading.

Crop Monitoring Index (CMI)
· developed by Palmer (1968 in Hayes, 1999)
· reflects moisture supply in the short term, identifying potential agricultural droughts
· not intended to assess long-term droughts.

Surface Water Supply Index (SWSI)
· developed by Shafer and Dezman (1982 in Hayes, 1999) to complement the Palmer Index across Colorado
· indicator of surface water conditions in which mountain snowpack is a major component
· calculated by river basin.

Reclamation Drought Index
· developed by Bureau of Reclamation as a trigger to release drought emergency relief funds; used by Oklahoma as part of their drought plan; calculated by river basin.

2.4 Paleoclimate Data

Basic instrumental (precipitation and temperature) data are available for about the last 100 years, which is not long enough to answer questions about the frequency of droughts. However, there are a number of environmental indicators of wetness and temperature that can extend our understanding of past climate far beyond the 100-year instrument record. Analyzing these proxies allows us to put the severe droughts of the 20th century in a longer-term perspective and compare them with droughts of the past.

Scientists have developed paleoclimate records of drought from several types of proxies, including tree rings, lake and dune sediments, historical documents, and archeological remains. The National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program has created an excellent source of paleoclimate information and data. See postings at: http://www.ngdc.noaa.gov/paleo/paleo.html and http://www.ngdc.noaa.gov/paleo/drought/drght_home.html.

To reconstruct past drought conditions, the proxy data are calibrated with instrumental data. A mathematical relationship is defined and used to produce a model, which is then used to reconstruct the instrumental record (or drought index) from the proxy record (see http://www.ngdc.noaa.gov/paleo/drought/drght_paleo.html). Cook et al. (1999) reconstructed summer (June-August) PDSI over the continental United States using tree-ring data. Their paper gives a thorough discussion of the methods used, including the calibration and verification.

Regression-based tree-ring reconstructions of climate tend to underestimate extremes as a consequence of the regression technique used; however, drought duration and extent are reasonably accurate (Woodhouse and Overpeck, 1998). Figure 3 compares the 1936 PDSI for the continental United States a) determined from instrumental data and b) reconstructed from tree-ring data (Cook et al., 1999, 2000; NOAA, 2000).

The PDSI reconstructions by Cook et al. (1999, 2000) extend from at least 1700-1978, providing a longer-term context within which to evaluate the recurrence of major droughts. The data are presented and discussed in the following section.

3. Portraying the Ogallala Region

In Kansas, about 75% of the precipitation typically falls during the growing season, April through September (Sophocleous, 1998). Annual and seasonal precipitation are well correlated, however precipitation amounts very greatly from year to year. Although the average values are of interest for comparative purposes, the variations from average are of much greater practical significance. In fact, "average" precipitation seldom occurs in the Great Plains (Kromm and White, 1992).

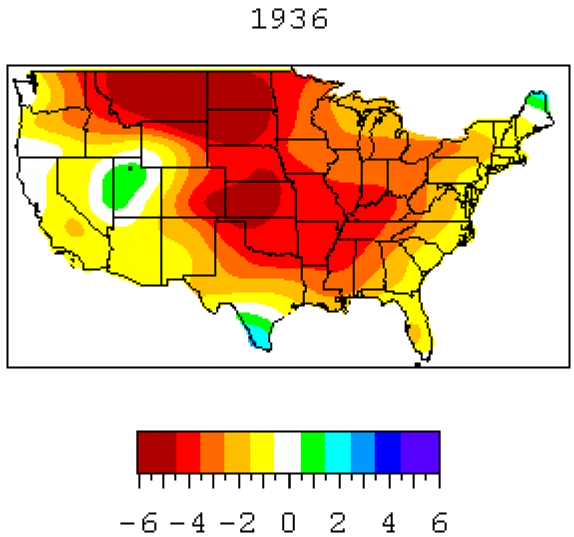
This section looks at past climate, focusing on dry spells or droughts, at two scales: 1) the period of instrumental record (the past hundred years) and 2) the paleoclimatic record (the early historic and pre-historic period of the past several hundred years or more).

3.1 The Period of Instrumental Record

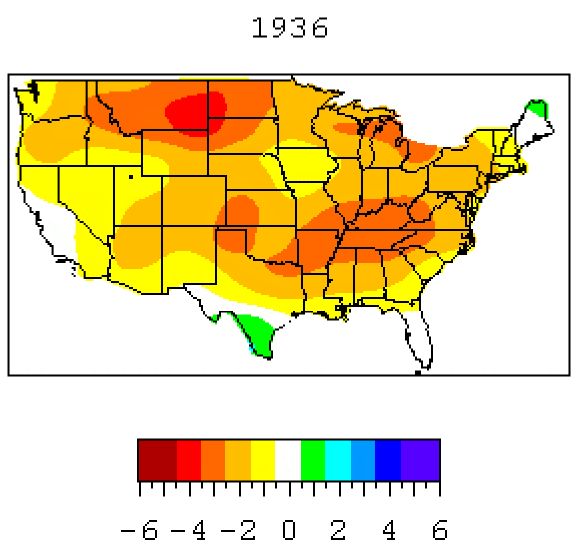
3.1.1 The Data

Two data sets are being used to analyze climatic conditions for the period of instrumental record:

1) NCDC (National Climatic Data Center) weather station data, referred to here as "**Station-NCDC**" data, are the basic data available. Figure 1 shows the NCDC stations (n = 117) in the Ogallala region. Precipitation data were obtained from EarthInfo CD. Period of record varies by station, maximum being 1900-1998. Notice in Figure 2 that the number of stations increased dramatically in the late 1940s.



a) PDSI determined from instrumental data



b) PDSI reconstructed from tree-ring data

Figure 3. 1936 PDSI for the continental United States a) determined from instrumental data and b) reconstructed from tree-ring data (Cook et al., 1999; 2000; NOAA, 2000).

2) Spatially-interpolated Station-NCDC data, referred to here as "**Willmott-NCDC**" data (Willmott and Matsuura, 2001), are available for the period 1950-1999. This data set contains monthly temperature and precipitation (and other derived water budget data -- actual evapotranspiration, adjusted potential evapotranspiration, surplus, and deficit) interpolated to a 0.5 degree by 0.5 degree latitude/longitude grid. In other words, the data are scaled to half-degree cells, an area about the size of a Kansas county (roughly 2500 square km or 1000 square mi). Figure 4 shows the half-degree cells (n = 36) covering the Ogallala region. Metadata are available at: http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_ts2.html and http://climate.geog.udel.edu/~climate/html_pages/README.wb_ts2.html.

In short, the Station-NCDC data are the NCDC weather station point data, which are available since about 1900. The Willmott-NCDC data set contains spatially-interpolated Station-NCDC data and other derived water budget data, beginning in 1950.

3.1.2 Analysis and Results

Half-degree latitude/longitude cells were identified as appropriate geographic units for the hydroclimatic analysis for the period of instrumental record. Figure 4 shows the half-degree cells covering the Ogallala region. For the hydroclimatic analysis, the Ogallala region was divided into subregions: North Ogallala, Central Ogallala, South Ogallala, West Ogallala, and East Ogallala (see Figures 5-9).

Total annual precipitation was calculated for each station (for the Station-NCDC data) or cell (for the Willmott-NCDC data). Then, for the Ogallala region, annual means were calculated from the annual totals. Time-series plots of mean (average) annual precipitation were constructed, as were plots at half-decade and decade intervals and for running averages filtered at 3, 5, 10 and 20 years. Using the Willmott-NCDC data, this procedure was repeated for each of the subregions (see Appendix 1 for precipitation plots).

Selected derived water balance data from the Willmott-NCDC data set (Ogallala-region annual values for water surplus, water deficit, evapotranspiration, and potential evapotranspiration) were also plotted as annual values and as averages over the same time periods used for the precipitation data. These plots are presented in Appendix 2 as examples of the relationships among the variables. The data set actually consists of monthly values for the entire 50-year time period, broken down to the same half-degree cells shown in Figure 4. These higher resolution data are available from the data providers or from the Kansas Geological Survey; they will be more relevant to local planning and management, but are too voluminous to plot in a printed report. The annual values plotted in Appendix 2 are sums of the monthly values, which is why the same year can show both a surplus and a deficit; one or two surplus months result in a so-called ‘annual’ surplus even if the rest of the year had an average net deficit.

Figures 10 and 11 illustrate the strong correlation between the Station-NCDC (locations shown in Figure 1) and Willmott-NCDC (station data recalculated to the grid cells shown in Figure 4). While this is not surprising, the strength of the relationship indicates that the climate data can be aggregated not only at the county scale, but in view of the irregular station distribution pattern shown in Figure 1, can also be applied at the township scale of interest from the standpoint of this report series.

The strong correlation also means that the monthly derived water balance variables contained in the Willmott-NCDC can be used with reasonable confidence in projecting both past and future conditions outside of the period of record. This is particularly important with regard to the

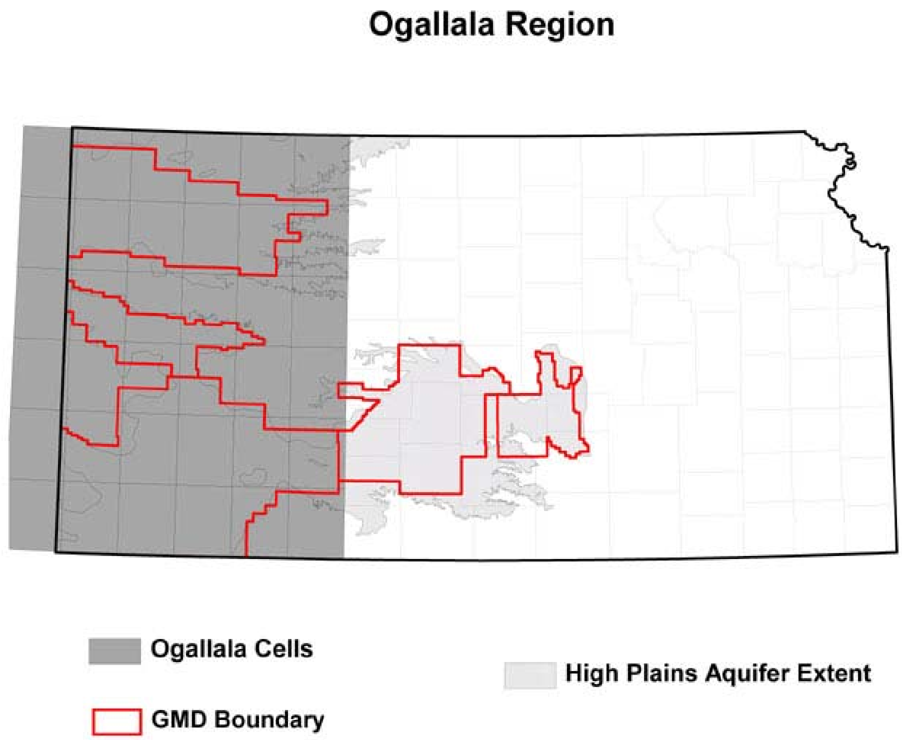


Figure 4. Half-degree cells (n = 36) covering the Ogallala region are shown by the gray - bordered rectangular boxes underlying the shaded area.

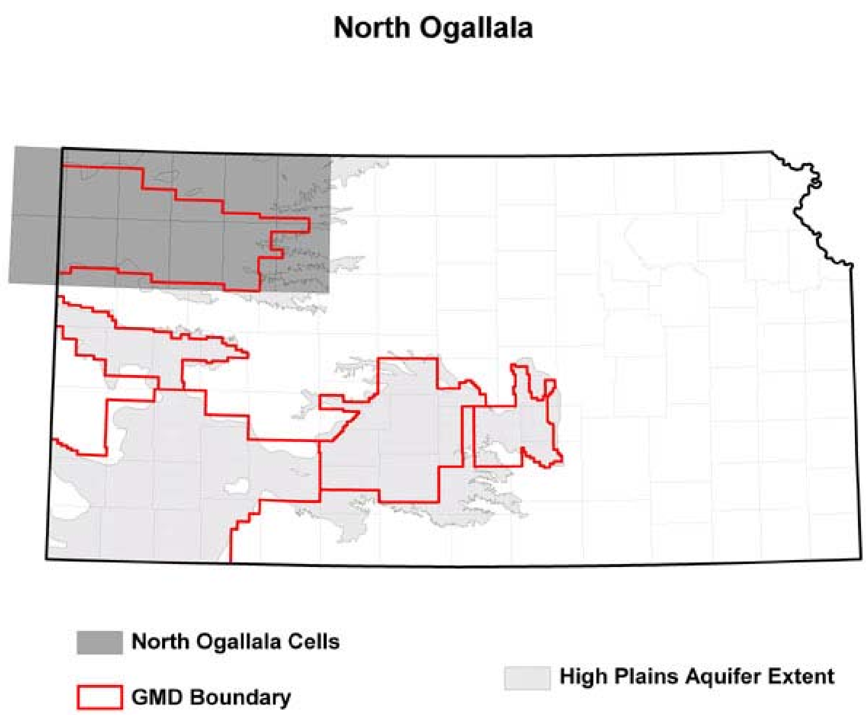


Figure 5. Half-degree cells covering the North Ogallala region.

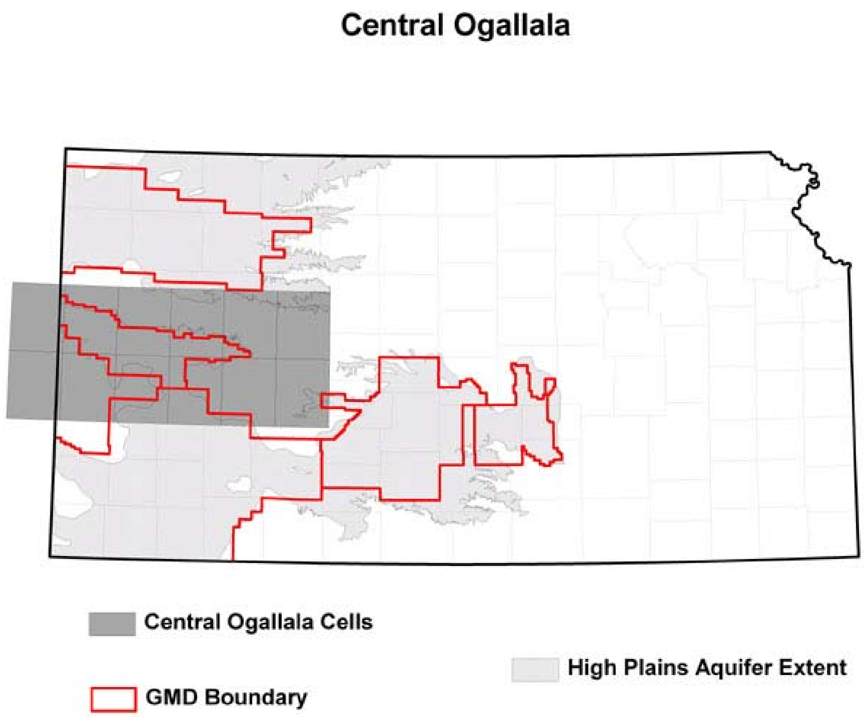


Figure 6. Half-degree cells covering the Central Ogallala region.

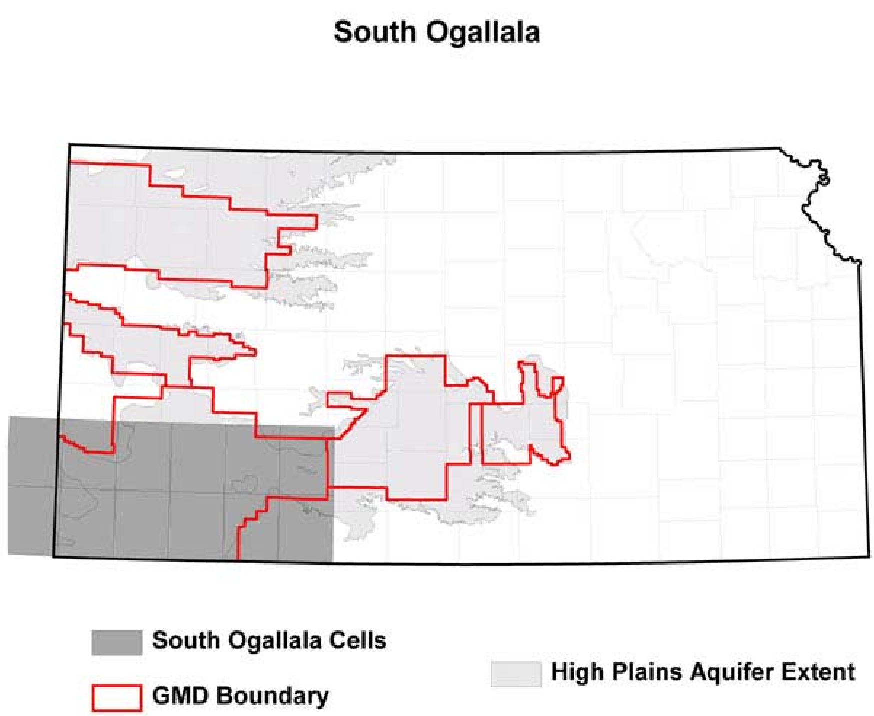


Figure 7. Half-degree cells covering the South Ogallala region.

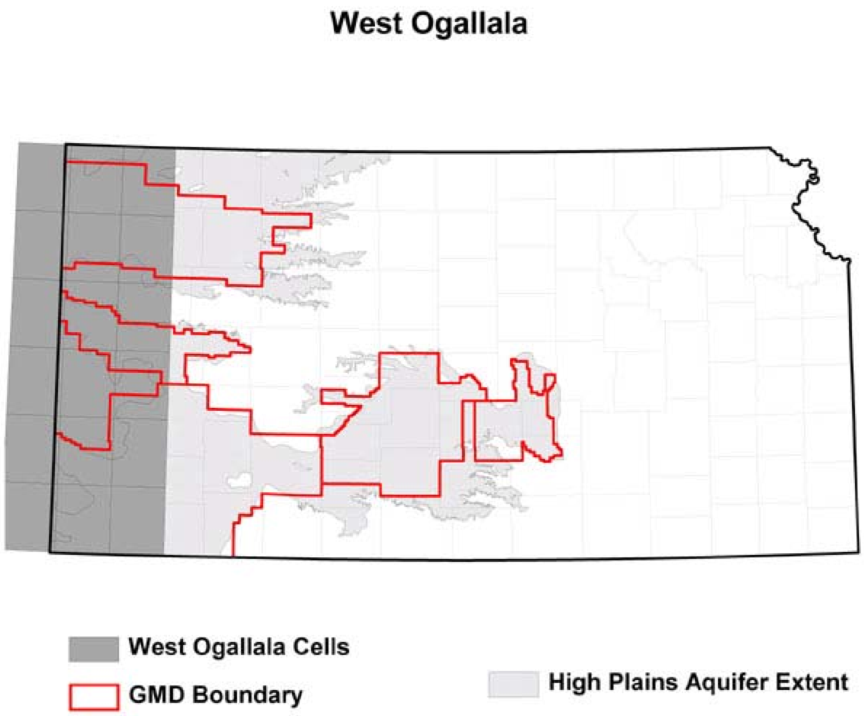


Figure 8. Half-degree cells covering the West Ogallala region.

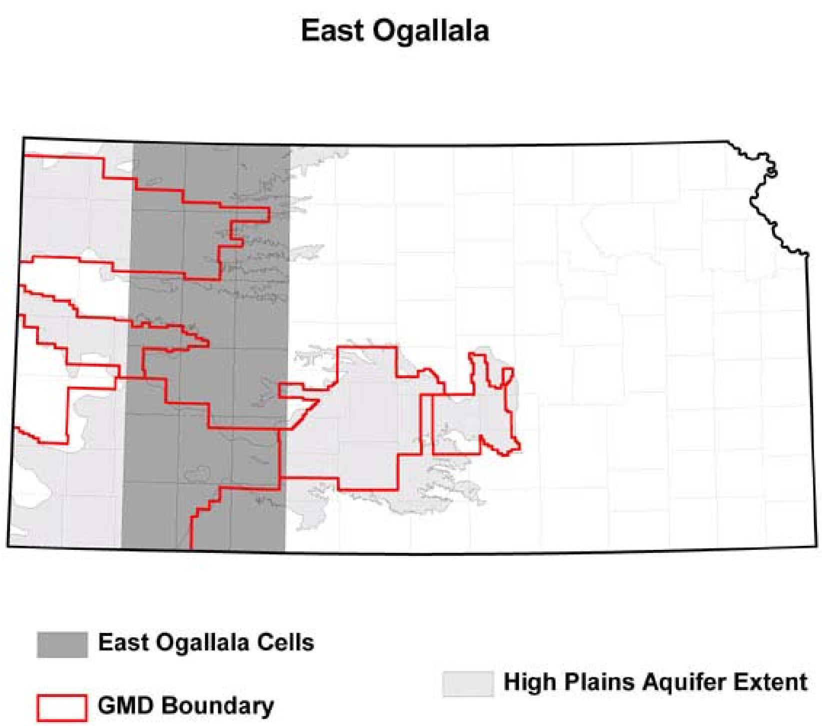


Figure 9. Half-degree cells covering the East Ogallala region.

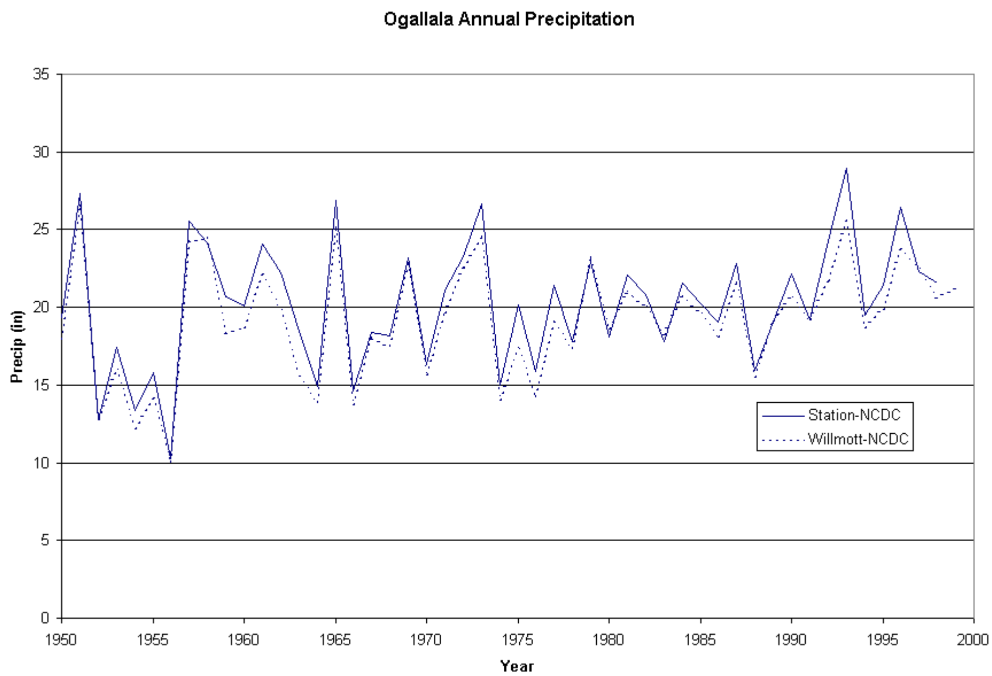


Figure 10. Ogallala precipitation: comparison between Station-NCDC and Willmott-NCDC data.

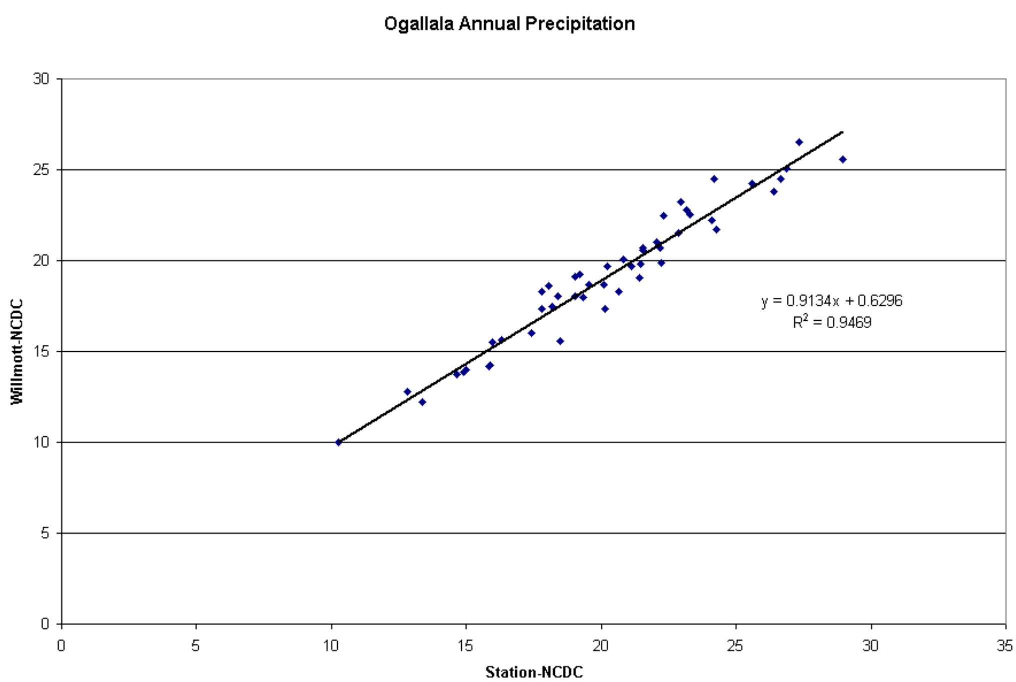


Figure 11. Correlation between Willmott-NCDC and Station-NCDC precipitation data.

potential evapotranspiration (ET) and quantities derived from that value and known or assumed precipitation – actual ET, water surplus/deficit, and soil moisture. These variables will be critical to projecting the outcomes of future management options based on crop ET and soil moisture management, and to testing their effectiveness.

The precipitation plots (Appendix 1) all show very similar trends. The drought of the 1950s is evident in all the plots. The Station-NCDC plots, which include the entire 20th century, indicate that the drought of the 1930s was of greater duration and intensity than that of the 1950s. Time averaging reduces the peaks, but gives the viewer an appreciation of the length of dry periods. Many of the figures, especially the time-averaged plots, show an increase in precipitation over at least the second half of the 20th century. The 1990s were particularly wet. Subregion plots show generally increased precipitation from west to east, and to a lesser extent from south to north.

The derived water balance plots (Appendix 2) typically confirm the conditions indicated on the precipitation plots; for example, the greatest deficit values are found in the 1950s. The trends are also consistent with the trends on the precipitation plots. For example, potential evapotranspiration (Appendix Figures 2.4: the amount of evapotranspiration that would take place if there were no water limitation) is level or shows a very slight decline over the period of record. Annual evapotranspiration (Appendix Figures 2.3: the calculated actual value) shows an increase over the same period. This reflects the increase in water available for evapotranspiration (see the precipitation and surplus curve trends), but note that actual evapotranspiration is always substantially less than potential; even in relatively wet periods, the region is severely water-limited.

Figures 12-15 compare water level and precipitation trends. Water levels are averaged over northwest, west-central, and southwest Kansas climate regions, which roughly correspond to the north, central, and south Ogallala subregions. Some water-level data prior to 1965 are available, but the quality of the data set improved substantially around 1965.

Water levels have generally declined since the 1960s, especially in the south. Depth to water and precipitation curves in these plots tend to show similar patterns or changes in slope, with the water table changes tending to lag behind the precipitation changes. This phenomenon is likely due to differences in pumping rates due to different precipitation patterns.

3.2 The Paleoclimate Record

3.2.1 The Data

The paleoclimate analysis is based primarily on summer Palmer Drought Severity Index (PDSI) reconstructions developed by Cook et al. (1999, 2000) using tree ring data (see section 2.4 above). The reconstructions are supplemented with information from the literature, including historical documents.

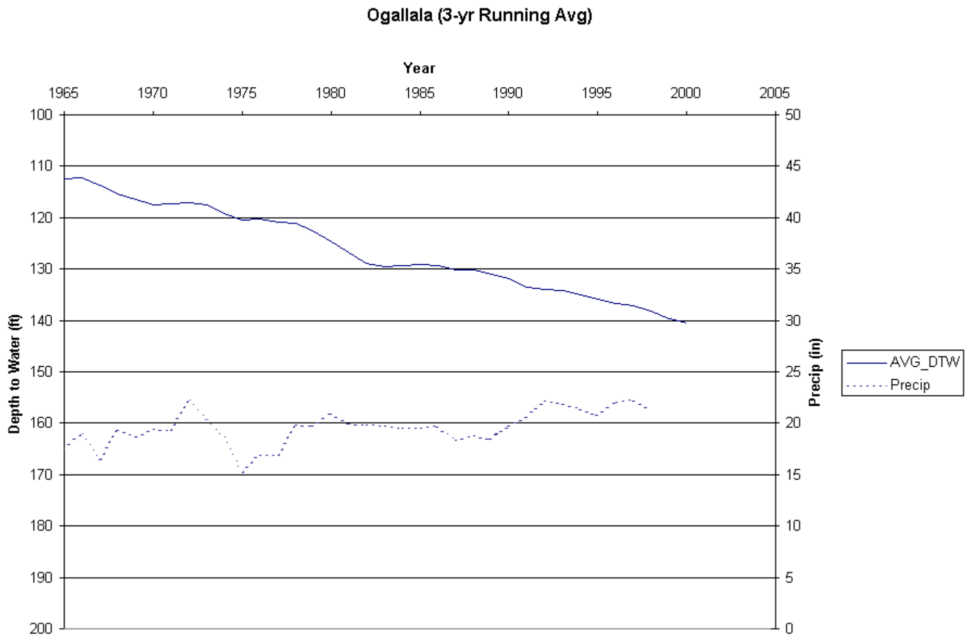


Figure 12. Comparison of water level and precipitation trends for the Ogallala region.

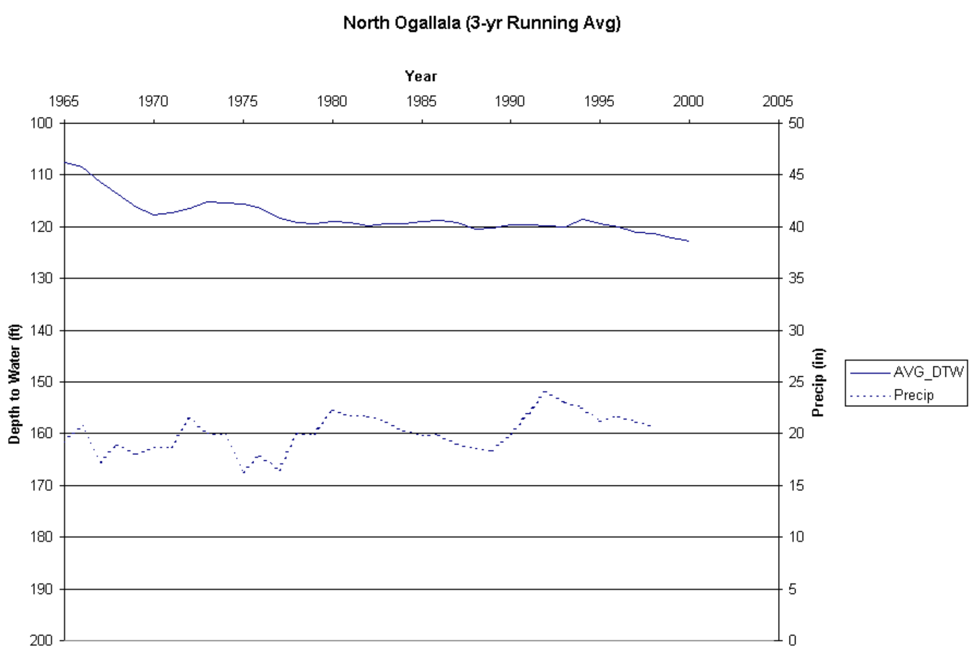


Figure 13. Comparison of water level and precipitation trends for the North Ogallala region.

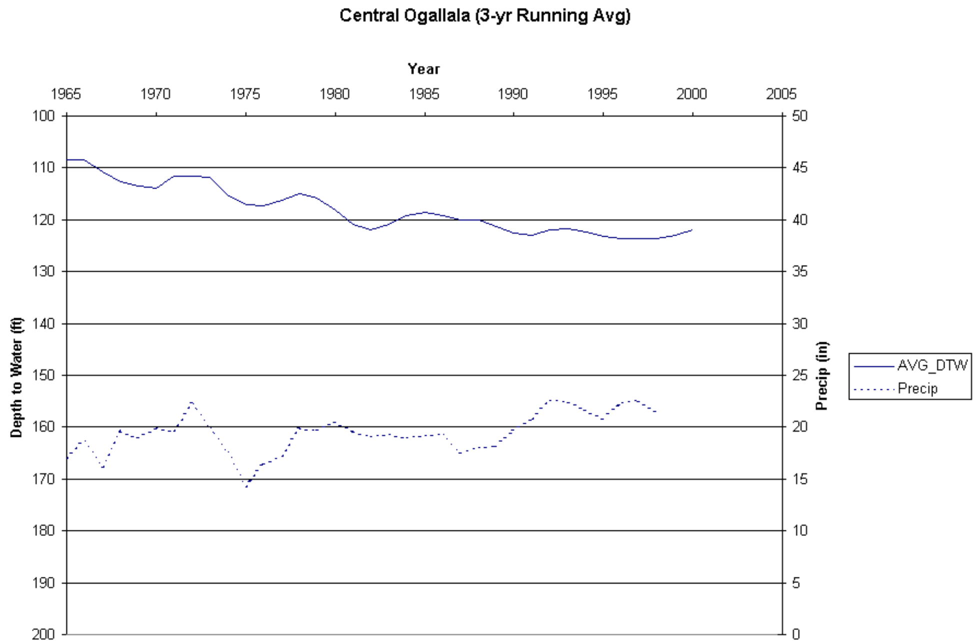


Figure 14. Comparison of water level and precipitation trends for the Central Ogallala region.

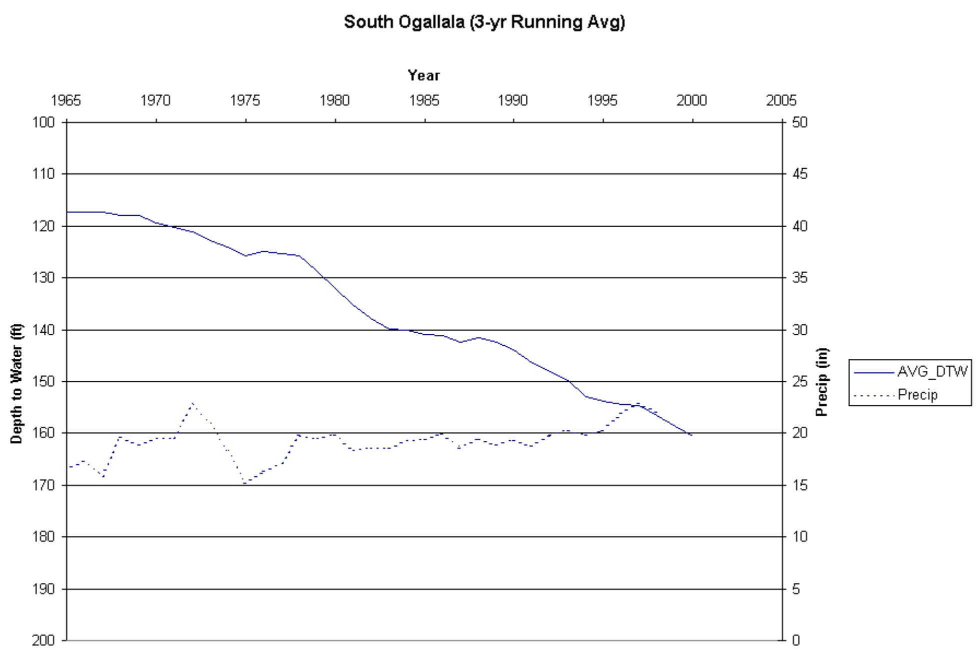


Figure 15. Comparison of water level and precipitation trends for the South Ogallala region.

3.2.2 Analysis and Results

3.2.2.1 The Past 300 Years

Plots comparing instrumental and tree-ring PDSI estimates, and PDSI with other climatic indicators, are contained in Figures 16-19. The figures show good relationships between PDSI estimated from tree-ring data and PDSI estimated from instrumental data, although the tree-ring reconstructions underestimate extreme conditions. Of course, we should not expect perfect agreement because of different spatial resolution, etc. Figures 17 and 19 also indicate good relationships between PDSI and 1) precipitation, and 2) negative deficit (deficit times minus one). Because of these good relationships, we can look at the data many ways and get approximately the same answer.

It is evident from PDSI reconstructions that multi-year droughts at least as severe as those in the 1900s occurred with some regularity over the past 300 years. Particularly noteworthy in duration and intensity are droughts the mid-1800s, the early 1800s, and the period preceding 1750 (and possibly the late 1800s). While there is not complete agreement, the literature generally confirms that droughts during the 1750s (mid 1700s), 1820s, 1890s, and especially the 1850s-1860s were at least similar in severity to major droughts of the 20th century.

European travelers in the 1800s called the Great Plains the "Great American Desert." Explorers documented blowing sand -- an indicator of drought conditions -- from northern Nebraska to southern Texas. Eolian activity was reported between 1840 to and 1865, during the late 1700s and early 1800s, and at the end of the 19th century (Muhs and Holliday, 1995 in Woodhouse and Overpeck, 1998). In 1810, explorer Zebulon Pike described the Kansas plains as a water-starved land, useless for farming (Foth, 1988).

The drought of the 1860 was arguably at least as severe as that of the 1930s. 1860 was a particularly noteworthy year in the historical data and literature. The 1860 drought was reported in Kansas newspapers (Foth, 1988), which continued to mention the severity for several decades (Woodhouse and Overpeck, 1998). Tree-ring PDSI reconstructions suggest that the two decades preceding 1860 were dry.

In areas flanking the Great Plains, Stockton and Meko (1983, in Woodhouse and Overpeck, 1998) found several periods of prolonged drought (3-10 years) that equaled or surpassed the 1930s drought in intensity and duration: the late 1750s, early 1820s, early 1860s and 1890s. Woodhouse and Overpeck (1998) cite several other dendrochronological assessments that confirm these periods of extreme drought in the west-central Great Plains.

According to Thornthwaite (1941), the period of 1920 to 1940 resembled the earlier period between 1880 and 1900 in many respects. In both a series of rainy years was followed by a disastrous drought. Both wet periods occurred when there was great pressure for more farmland, which led to extension of the cultivated area and to overgrazing. Each drought period resulted in a period of emigration that grew into a rout. In both cases the series of rainy years was mistaken for normal climate, with disastrous results.

Multiple sources of proxy data, including tree-ring reconstructions and historical accounts, work together to confirm the occurrence of several 19th century droughts (Woodhouse and Overpeck, 1998). It is clear that major multi-year droughts have occurred once or twice a century over the last 300 years.

3.2.2.2 The Past Millennium

For some grid points, including those in northwest and southwest Kansas, Cook et al. (2000) have extended the period of PDSI reconstructions. Figures 20-25 contain plots of PDSI tree-ring constructions from ~1170 for northwest and southwest Kansas at 5, 10, and 20-year running averages. (Cook et al., 2000).

These plots suggest periods of drought that exceeded the severity and length of any droughts of record. Indeed, there is evidence of two major droughts that likely significantly exceeded the severity, length, and spatial extent of any 20th century droughts that affected the high plains. Woodhouse and Overpeck (1998) cite several references to support this, including a southwestern Nebraska chronology.

There is general agreement that the "megadrought" of the second part of the 16th century far exceeded any drought of the 20th century (NOAA, 2000; Stahle et al., 2000; Woodhouse and Overpeck, 1998). Severe drought extended across most of the continental U.S. in the 1560s. Figure 26 shows coincident droughts, or the same drought, in the eastern Colorado plains, southwestern New Mexico, and Baja California, Mexico.

The other "megadrought" mentioned in the literature occurred in the last quarter of the 13th century (Woodhouse and Overpeck, 1998). The authors document that it was almost certainly of much greater intensity and duration than any drought of the 20th century. This drought coincided with the abrupt abandonment of the Anasazi settlements in the Southwest (deMenocal, 2001; Woodhouse and Overpeck, 1998).

The paleoclimatic data provide evidence that the droughts of the 20th century are common but not representative of the full range of drought occurrence. It is clear that major multi-year droughts of "Dust Bowl" magnitude have occurred once or twice a century over the last few hundred years. Over the past millennium, there is evidence of two major multidecadal droughts that likely significantly exceeded the severity, length, and spatial extent of 20th century droughts. This leads to the conclusion that droughts as severe as those of the 1930s and 1950s are likely to occur in the relatively near future, and that we should expect and plan for similar droughts. It also illustrates that far more severe droughts are possible, and their possible occurrence should not be ignored.

4. Drought Frequency and Intensity: Risk Analysis

Risk analysis and assessment (http://www.sra.org/) is a well developed discipline and can involve quite complicated analyses, but its basic principles are based on common sense, and involve considerations familiar to anyone who has ever purchased insurance or played a game of chance.

A basic consideration is something called the ‘expectation value’ of an event, which is simply the probability of occurrence times the dollar (or other) value for a given event. For example, the expectation value of a million-dollar lottery with million-to-one odds is one dollar – the product of the benefit ($1,000,000) times the likelihood of occurrence (1/1,000,000). This kind of big-picture statistical evaluation doesn’t measure anybody’s <u>actual</u> cost or benefit, but it does provide a quantitative criterion for discussing and ranking threats and costs.

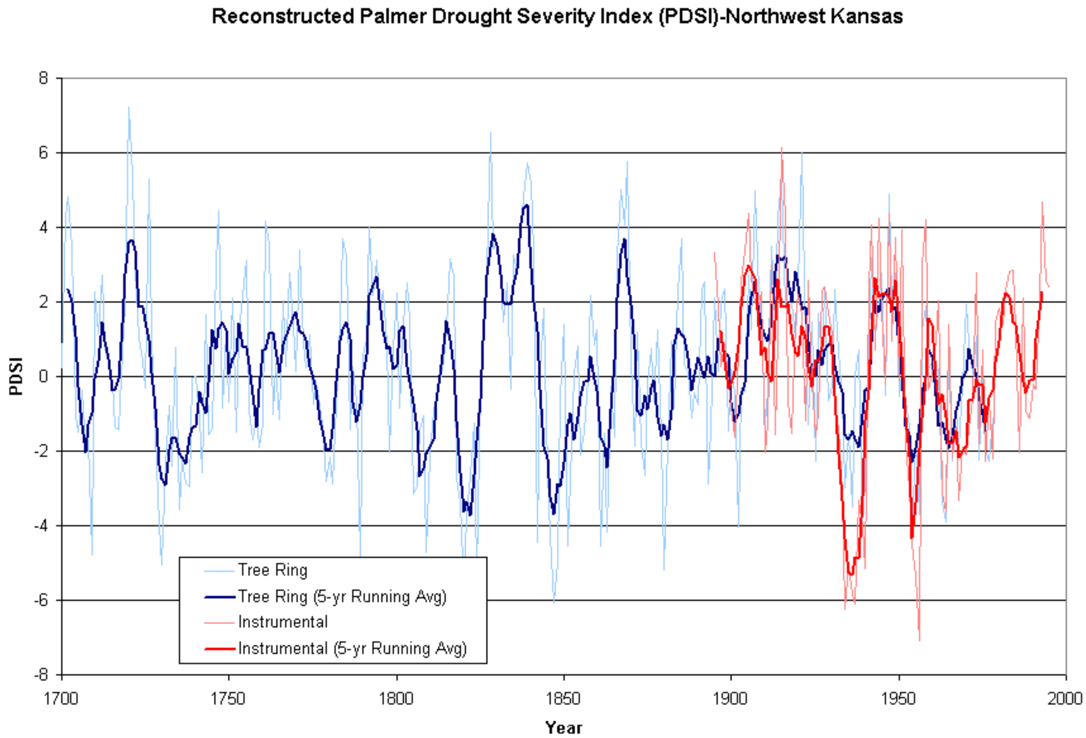


Figure 16. Reconstructed Palmer Drought Severity Index (PDSI) - Northwest Kansas.

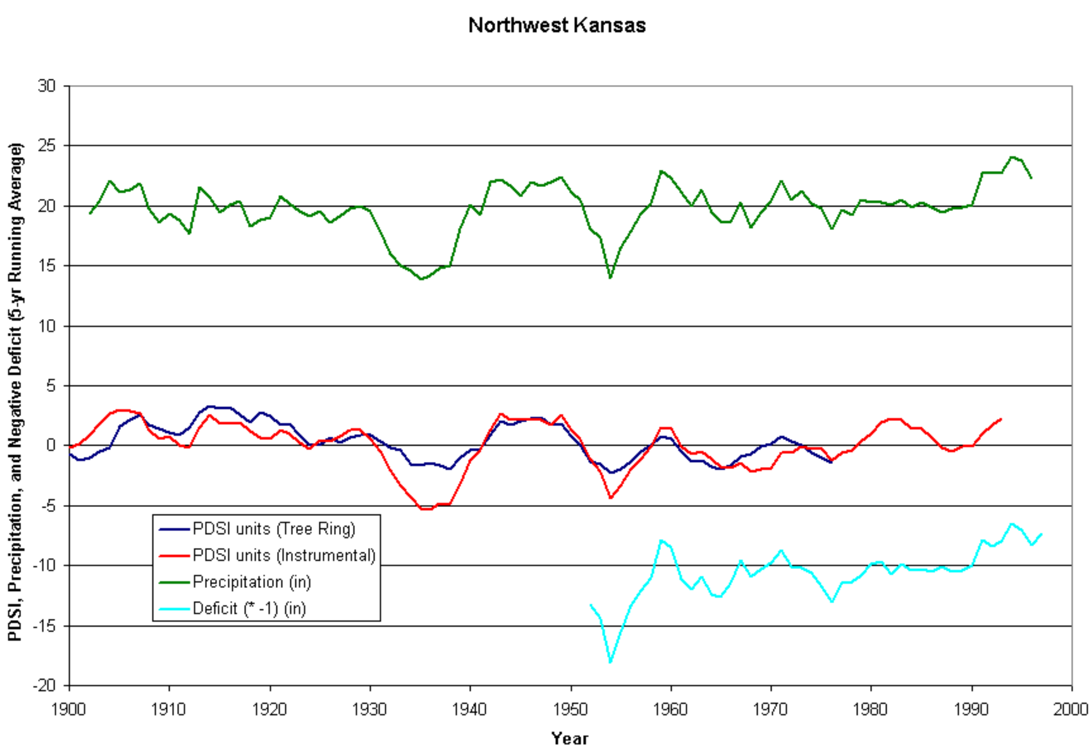


Figure 17. Comparison of some raw and derived climatic indicators - Northwest Kansas.

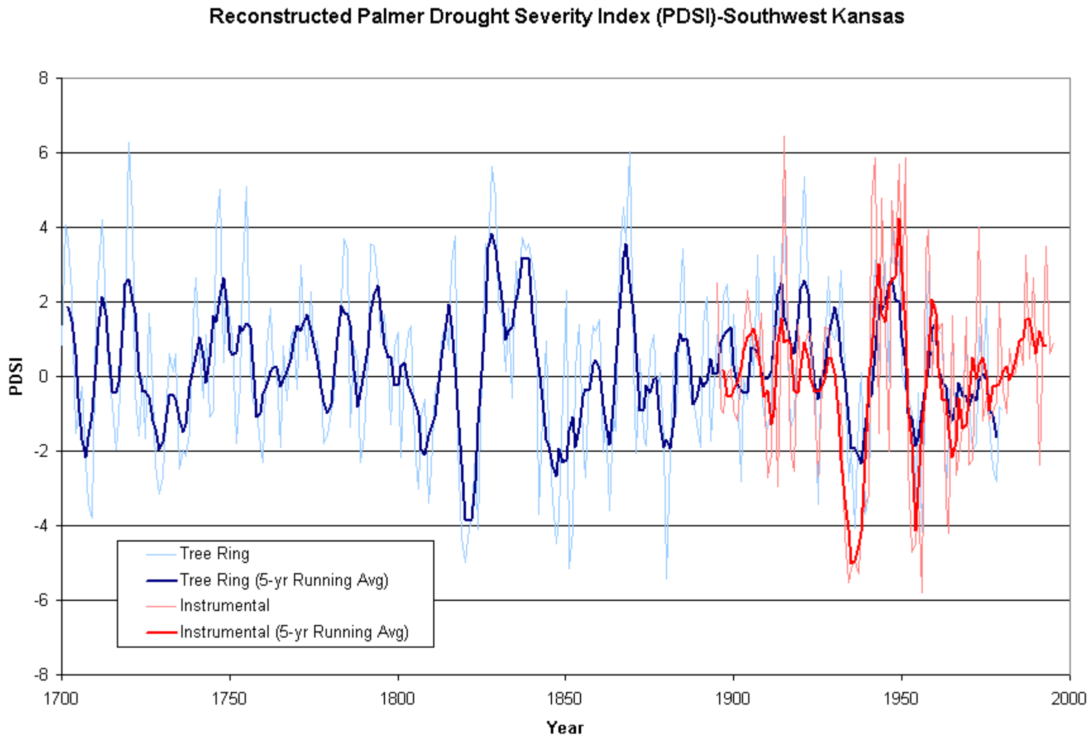


Figure 18. Reconstructed Palmer Drought Severity Index (PDSI) - Southwest Kansas.

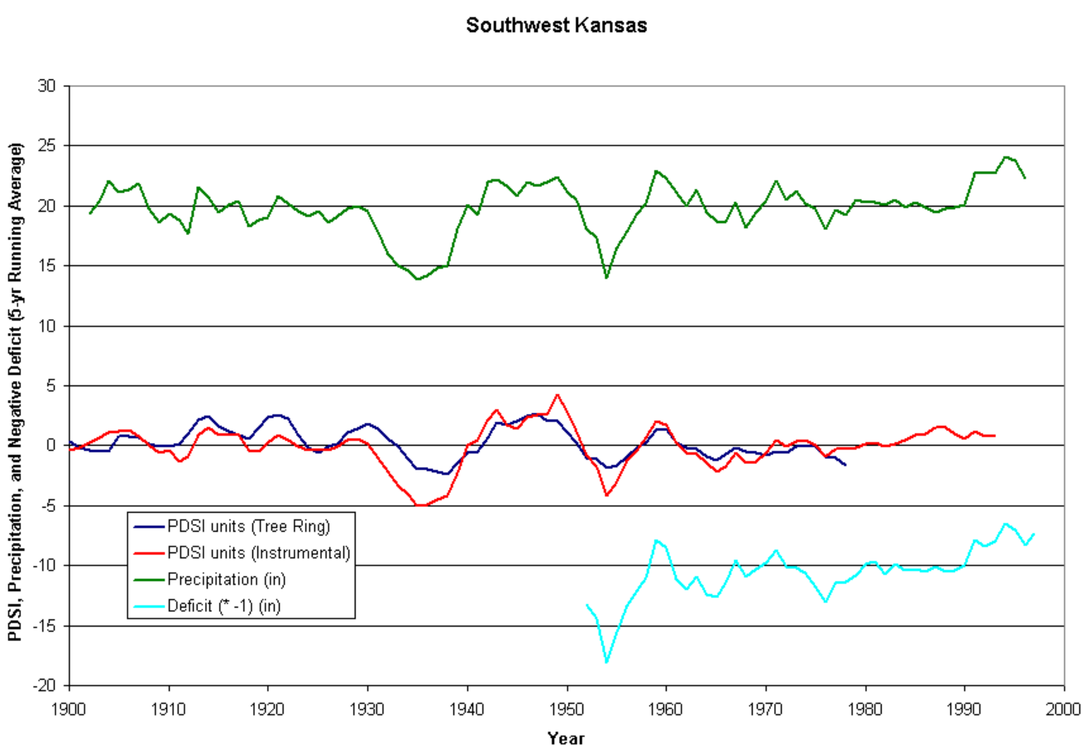


Figure 19. Comparison of some raw and derived climatic indicators - Southwest Kansas

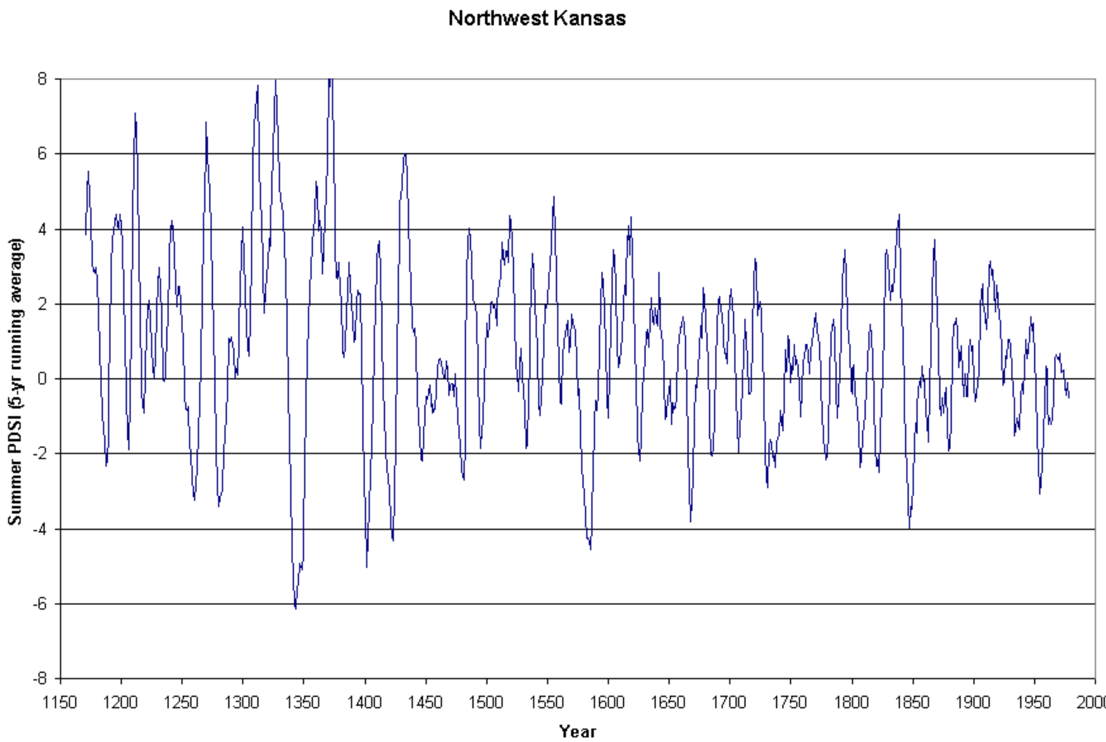


Figure 20. Northwest Kansas PDSI reconstructions (5-yr running average).

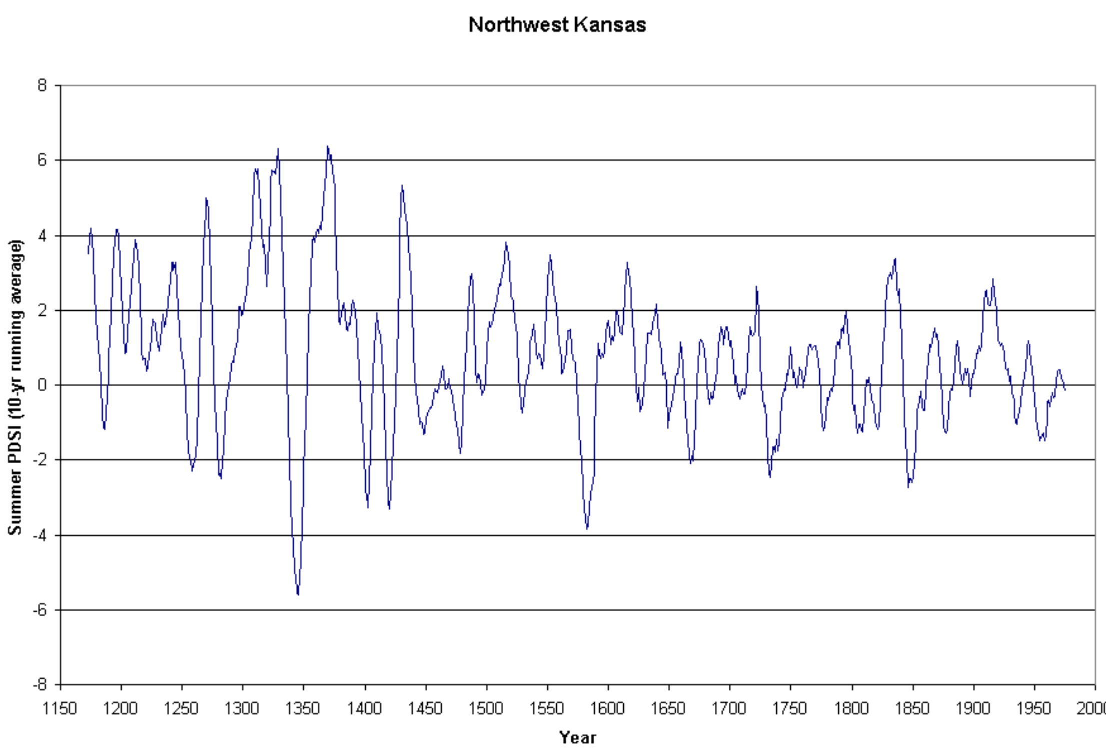


Figure 21. Northwest Kansas PDSI reconstructions (10-yr running average)

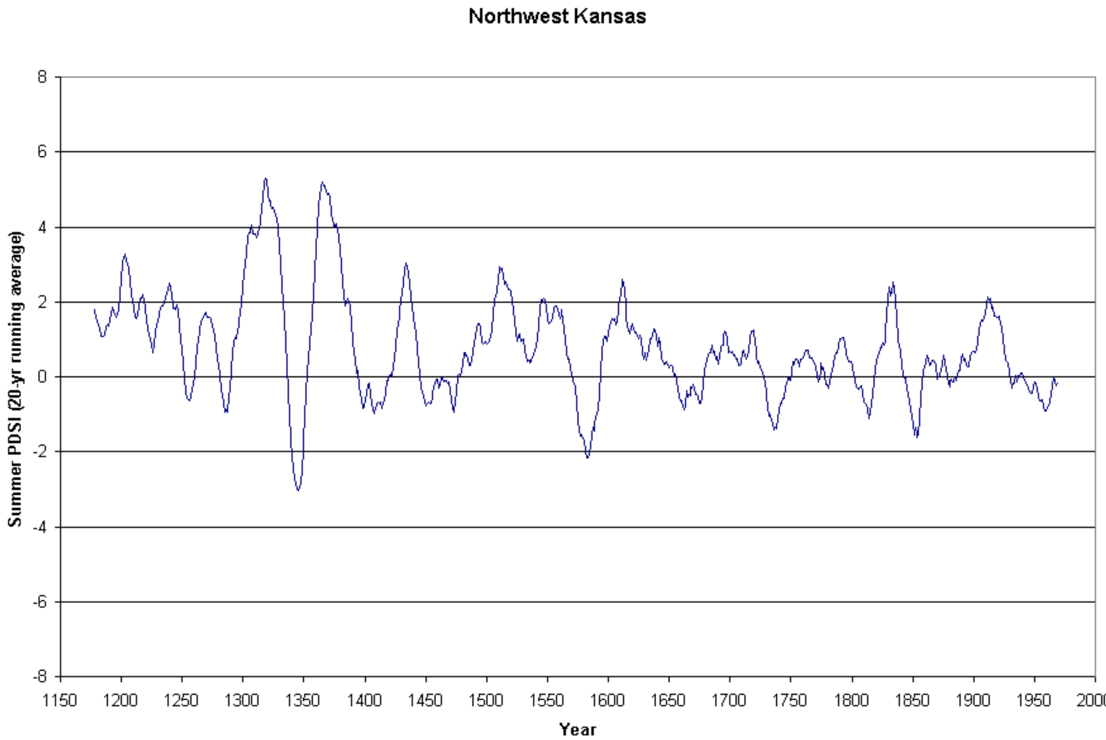


Figure 22. Northwest Kansas PDSI reconstructions (20-yr running average).

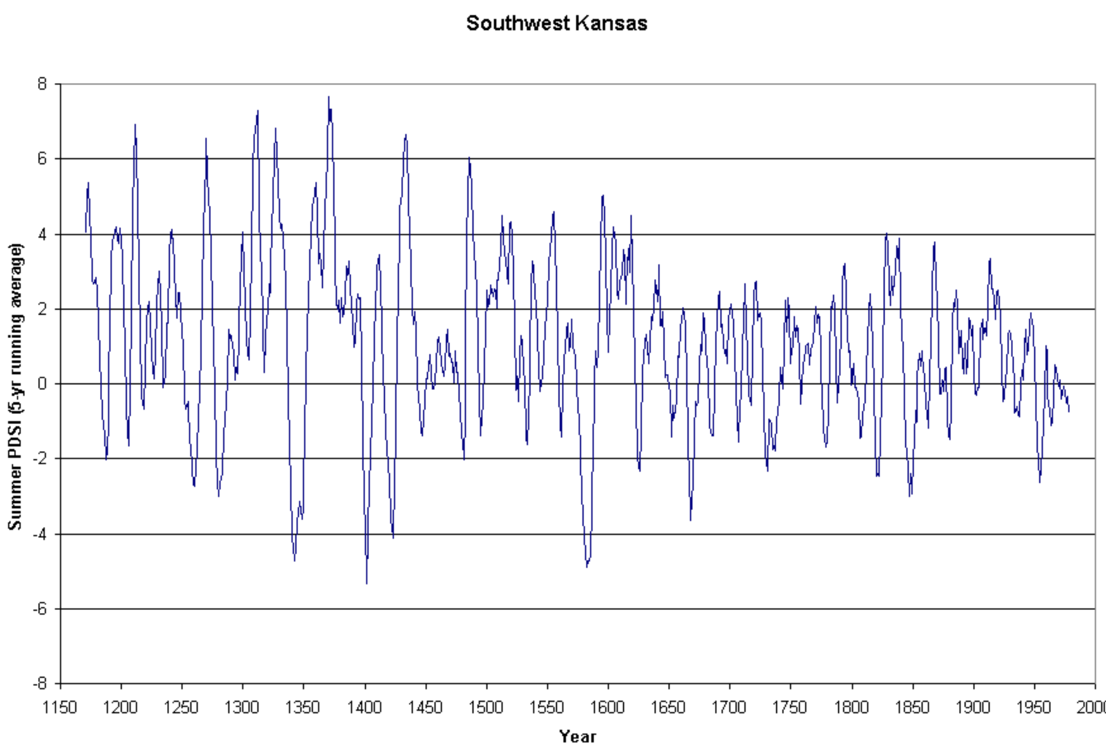


Figure 23. Southwest Kansas PDSI reconstructions (5-yr running average).

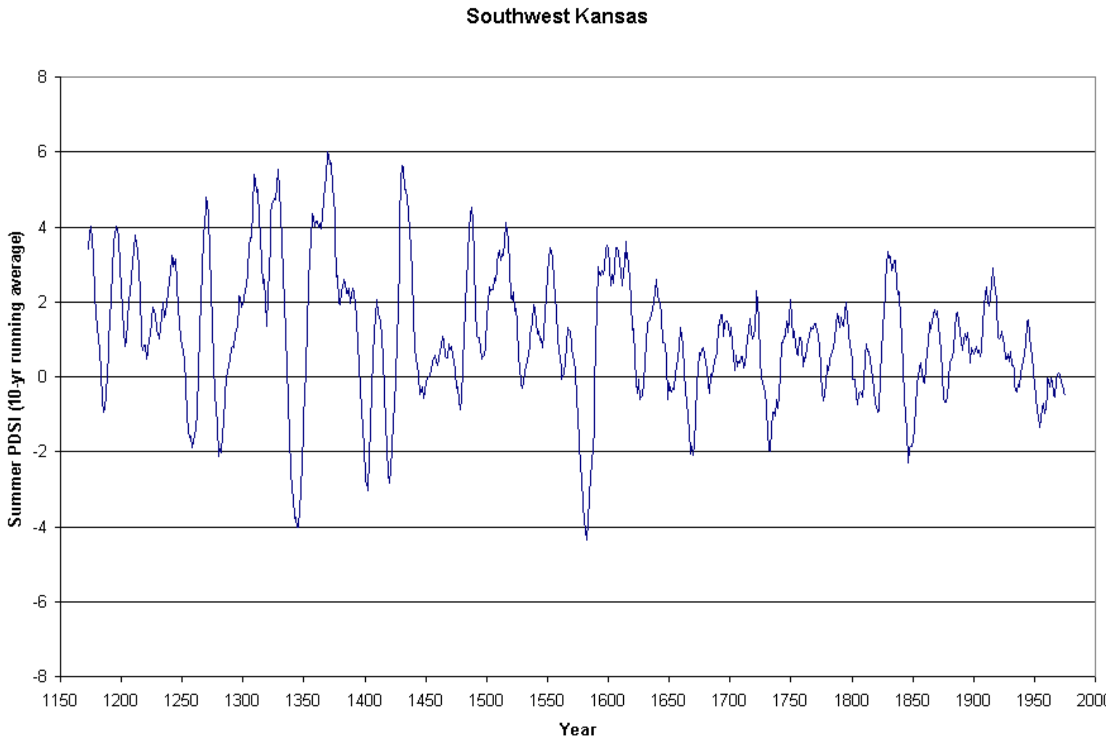


Figure 24. Southwest Kansas PDSI reconstructions (10-yr running average).

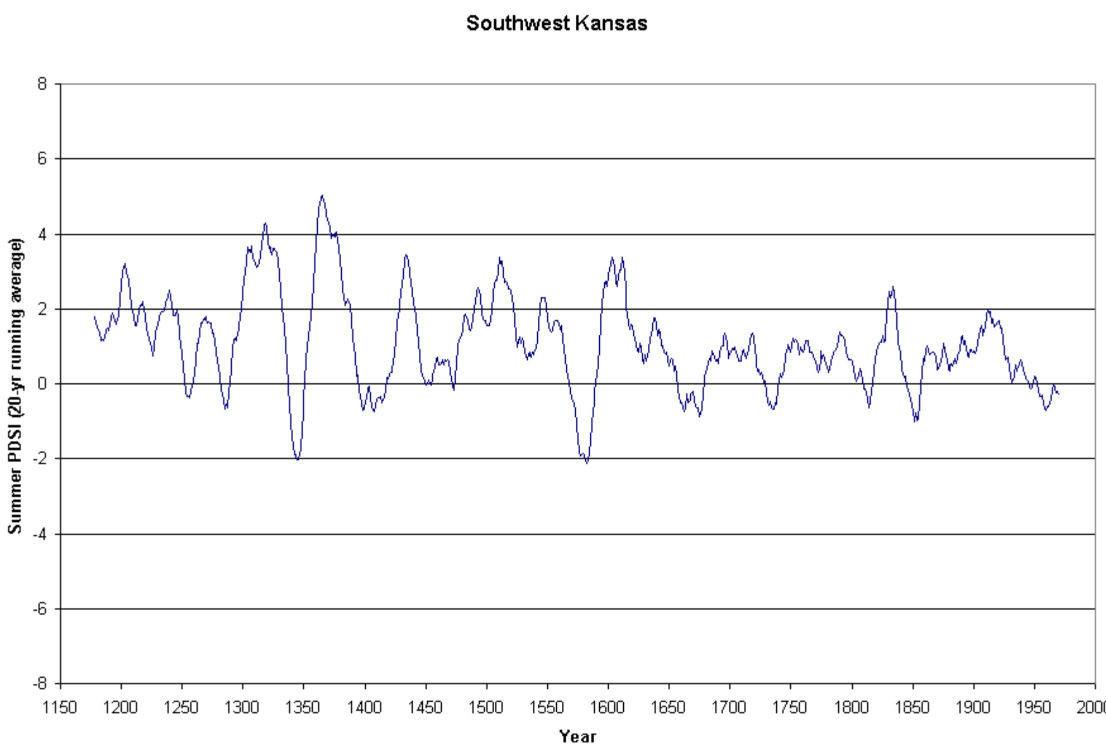


Figure 25. Southwest Kansas PDSI reconstructions (20-yr running average).

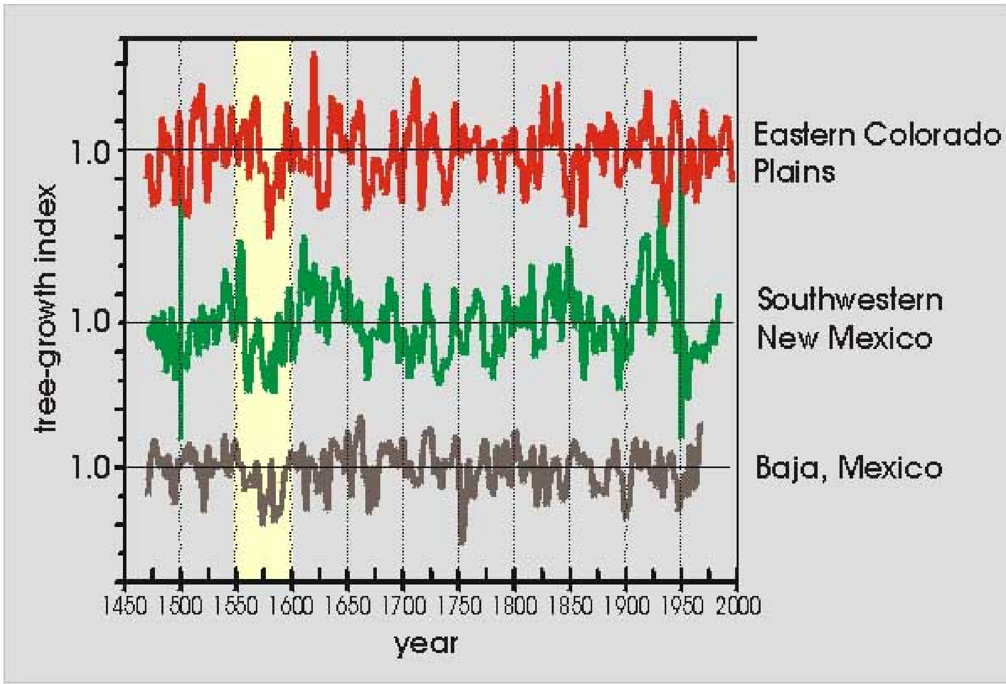


Figure 26. Coincident droughts, or the same drought, in the eastern Colorado plains, southwestern New Mexico, and Baja, Mexico (from http://www.ngdc.noaa.gov/paleo/drought/drght_500years.html).

As a water resources example, consider the observation that droughts of the "Dust Bowl" magnitude (or greater) have occurred once or twice a century for as long as we can reconstruct the climate records. If we take that as a prediction, we can do some simple arithmetic. If we take 'once or twice per century" to mean an average of 1.5 dust-bowl-or-bigger droughts per hundred years, then there is a 1.5% chance that any of the hundred years in the century will be the one in which the drought starts. Arithmetic takes us to the further conclusion that we can estimate a similar probability for any period -- a 15% chance of a big drought starting in any decade, 30% over a 20 year planning horizon, 60% for the estimated 40-year working lifetime of an individual farmer. Note that these calculations may be misleadingly optimistic – a drought can only start in one year, but it will consist of 4-5 (or more) consecutive years. This means that there is a 5-10% chance that any randomly selected year in a century will be part of a major drought.

The previous paragraph gives an estimate of probability, but what is the potential cost? Economic statistics or estimates are available from which to construct an expectation value. However, at the local level of planning and management, considerations that go beyond simple dollar values may be important. Farmers without water and businesses without customers or suppliers will not only suffer economic hardship, but if the hardship is sufficiently protracted they will fail, leading to fundamental disruption of the agricultural, business, and social infrastructure of the region (as occurred with the great westward migration during the Dust Bowl era).

Having water available in reserve is an obvious line of defense against drought, whether it is the 4-5 year, once or twice a century drought, or the 10-20 year drought that appears to happen every few centuries. Such considerations are included in reservoir design – flood control systems are designed and managed to hold the runoff from a 'design flood,' (often the 50-year or 100-year flood), and water supply reservoirs typically have a conservation pool that can meet essential demand for an extended period of sub-normal input. In the case of groundwater aquifers, design and construction are out of our hands, but management can be designed to consider issues of insuring against protracted high demand and low recharge, whether the goal is sustainable use or simply an extended useable lifetime.

5. Data Limitations and Applications

Future general climate conditions are increasingly difficult to predict because of climate changes, and specific short-range predictions remain difficult although capabilities are improving; using the historical record as a statistical predictor is probably optimistic (i.e., things might very well be worse).

Some research suggests that drought in the future may be amplified due to climate change, particularly in semiarid (and mid-continental) areas, (NOAA, 2000; Buddemeier, 1998; Gleick, 2000). Buddemeier (1998) notes the special vulnerability of water resources, agriculture, and freshwater ecosystems in arid to semiarid environment to climate change. Thus, we must recognize that the past may not represent the future, and that assumptions made about the future based on the climate of the past may be inappropriate (Gleick, 2000; Frederick and Gleick, 1999).

6. Policy and Management Implications

Policy-makers and managers can anticipate that any reasonable (decade-scale) planning horizon will carry a significant chance of 'major' drought experience; drought conditions will heighten demand, reduce recharge and accelerate groundwater depletion. Responses to regional stresses are by their nature communal -- one farmer cannot opt to save 'his' groundwater if his neighbors are committed to pumping theirs down. What level of protection is prudent and desirable, given that some sacrifice of present value will be necessary to provide 'insurance' against foreseeable future shortages?

In a semiarid region like that of the Great Plains, wide climatic fluctuations, including droughts, are to be expected, and we must plan for these events. The paleoclimate analysis indicates that droughts of the 20th century have been characterized by moderate severity and comparatively short duration, relative to the full range of drought variability. This indicates the possibility that future droughts may be of much greater severity and duration than what we have yet experienced.

Typical management strategies may include assessing risks and probabilities. For example, an option may be to adopt a probabilistic approach to drought forecasting and planning that incorporates the range of variability suggested by the proxy data: a Dust Bowl drought once or twice a century over the past 300-400 years, and a decadal-length drought once every 500 years.

However, two factors may compound the susceptibility of the Great Plains to drought in the future: 1) increased vulnerability due to human land use practices such as increased cultivation of marginal lands and the escalated use of groundwater from the Ogallala aquifer, where water withdrawal has exceeded recharge for many years (Woodhouse and Overpeck, 1998); and 2) enhanced likelihood of extreme conditions due to climate change. Watersheds where water resources are already stressed are most likely to be vulnerable to changes in mean climate and extreme events (Hurd et al., 1999).

Therefore it is appropriate to develop **flexible** strategies and policies that allow **adaptation** to changing environmental conditions and other unknowns. Irrigation itself was an adaptation to a dry and variable environment--agricultural productivity would be at risk if the available water supply were to diminish, or its variability increase. The flexibility and adaptiveness of future strategies and policies must address the recognition that, at the rate of depletion of the Ogallala that has been occurring, we won't always have the option of compensating for environmental shortfalls with large-scale irrigation or groundwater withdrawals in western Kansas.

This may involve rethinking objectives, which may need to be more closely related to environmental conditions in the region and land uses compatible with those conditions. Assuming that a long-term objective would be some sort of sustainability or new achievable equilibrium (if just to sustain humanity), the preliminary appraisal would be to measure the imbalance between the current level of appropriations and the level required in the long term (Quinodoz, 1998).

A transition is necessary, but the transition will require a dynamic policy. Because of uncertainties, the process of adjustment should be viewed as a learning experience in itself (see how the aquifer responds to less pumping), and decisions will have to be revised and updated periodically. This type of adaptive management (http://www.iatp.org/AEAM/) necessarily requires greater scientific input and continuing monitoring than is currently practiced.

7. Potential for Improved Data or Applications

Refinement of climate data for local-scale applications (i.e., smaller than the township-to-county scale supported by NCDC stations) is straightforward, and involves deploying additional measuring stations (usually automated) in a finer spatial grid. Such actions have already been undertaken by some Kansas water managers. The greater challenge lies in improving projections and planning for future conditions.

Two possible closely related areas for improving climate-scale data and applications can be identified: improved estimates of risk, vulnerability and potential responses; and improved understanding of the relationships between climate and water demand on various scales and under different scenarios.

The projection of climate change or statistical probability scenarios of drought occurrence can permit managers and policy makers to assess not only the likelihood of drought, but the vulnerability of the water resource and the regional socioeconomic structure to the stresses and increased demand resulting from drought. This in turn provides the information needed to make intelligent decisions about the kind of 'insurance policies' to build into management practices and regulations.

It is clear that in many areas of the High Plains/Ogallala system groundwater use is closely related to climate (Wilson et al. 2000) and groundwater declines are closely related to water use (Wilson et al. 2002). Refinement of these relationships will make it possible to project in detail the effects on remaining resources for any specified drought condition in any region. This will in turn provide critical management information for drought response planning and on the necessary – or feasible – level of water reserves to plan for.

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Appendix 1. Precipitation Plots

Station-NCDC data are the NCDC weather station point data, which are available since about 1900. The Willmott-NCDC data set contains spatially-interpolated Station-NCDC data, beginning in 1950.

Data plotted are the regional annual averages, which are the sums of monthly values for the year of interest averaged over all the Willmott-NCDC half-degree cells in the designated region (Figures 4-9).

Values are plotted as individual year totals and as running averages (also called "boxcar" averages) of the annual totals over 3, 5, 10, and 20 year time periods. In this presentation, the 3-year average for 1990, for example, is the average of values for 1989, 1990, and 1991. This averaging has the effect of making long-term trends or large-scale features in the data more visible.

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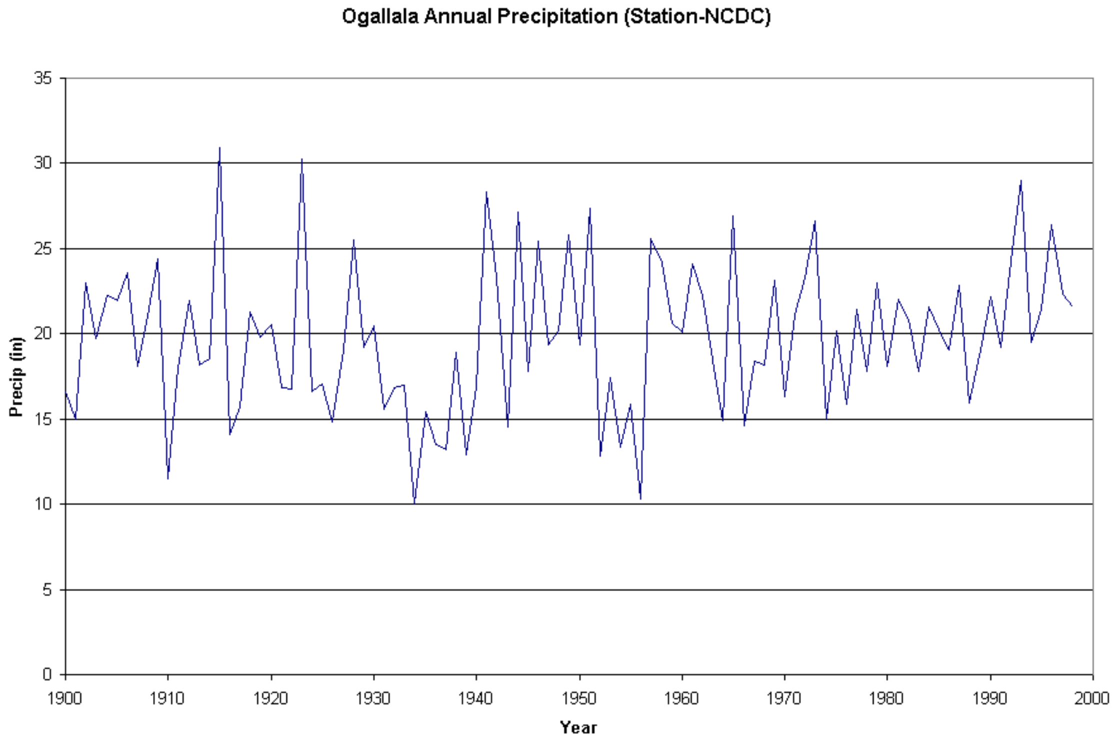
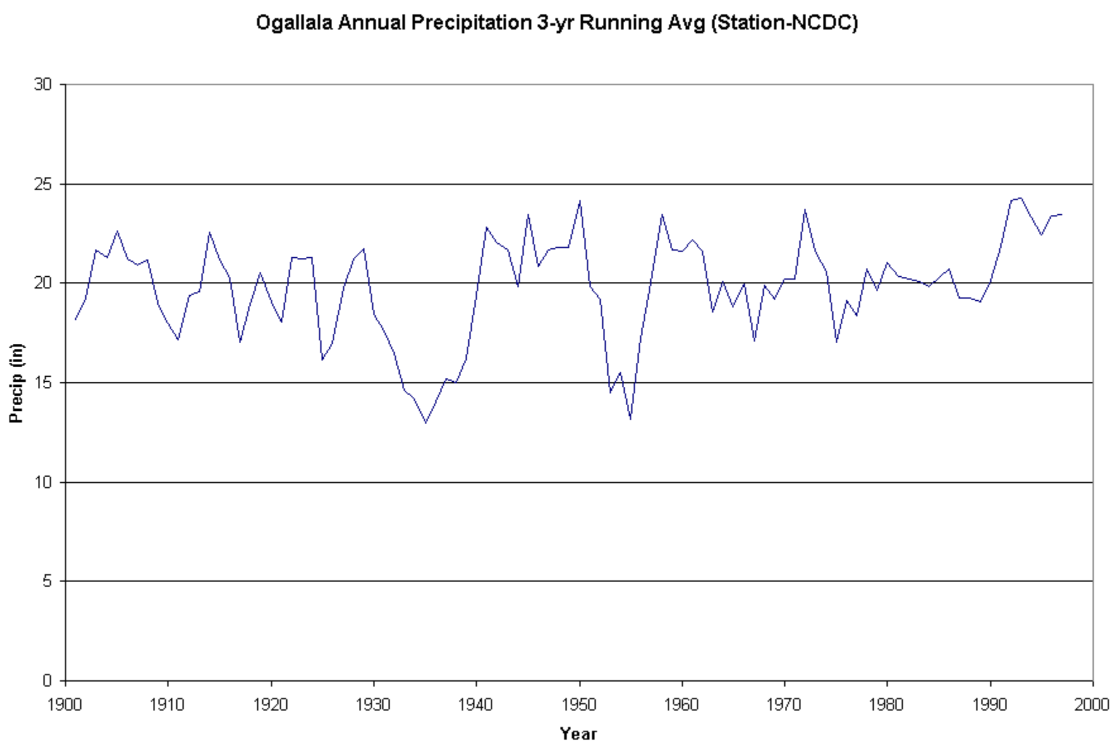
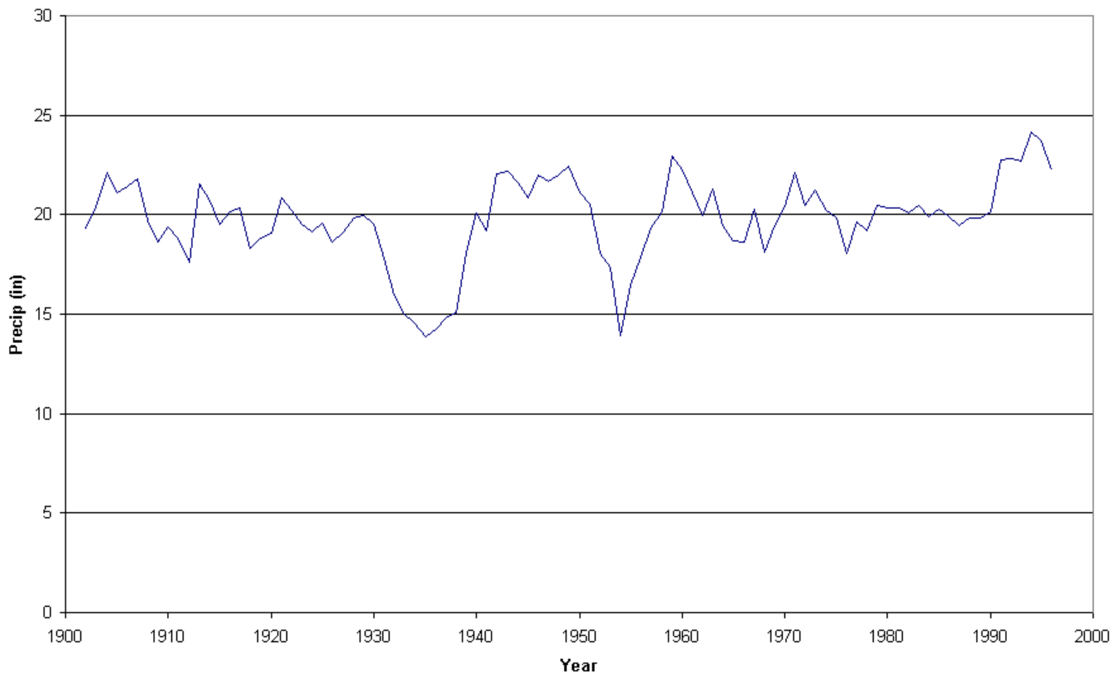
Appendix Figures 1.1. Ogallala as a whole (Station-NCDC)

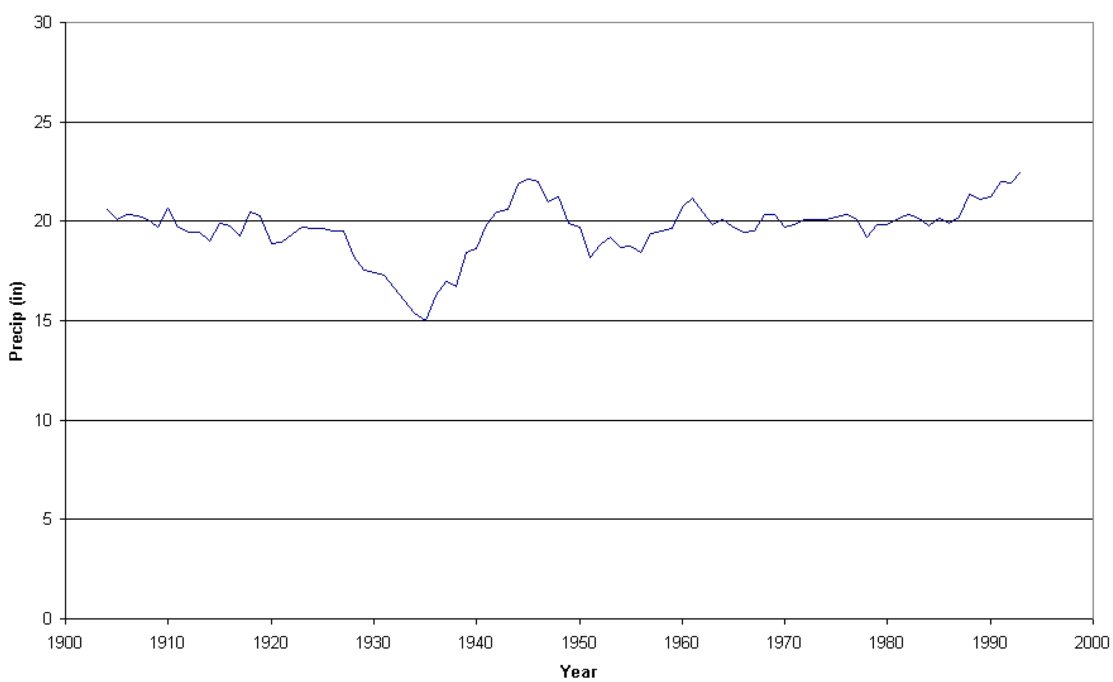




Ogallala Annual Precipitation 5-yr Running Avg (Station-NCDC)



Ogallala Annual Precipitation 10-yr Running Avg (Station-NCDC)



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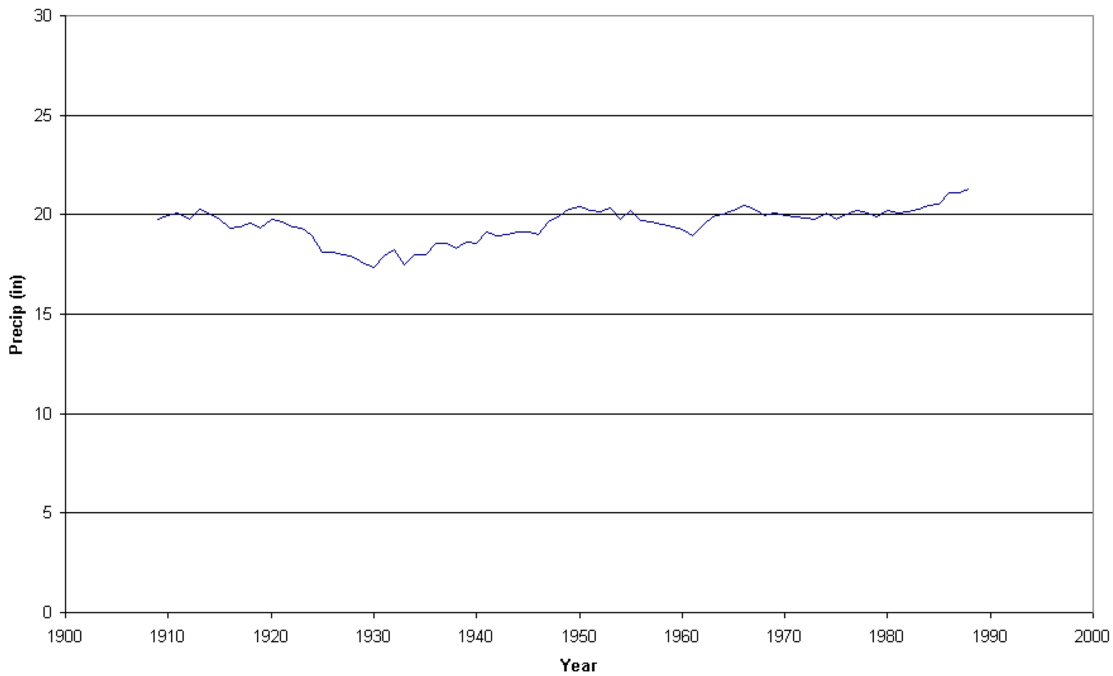
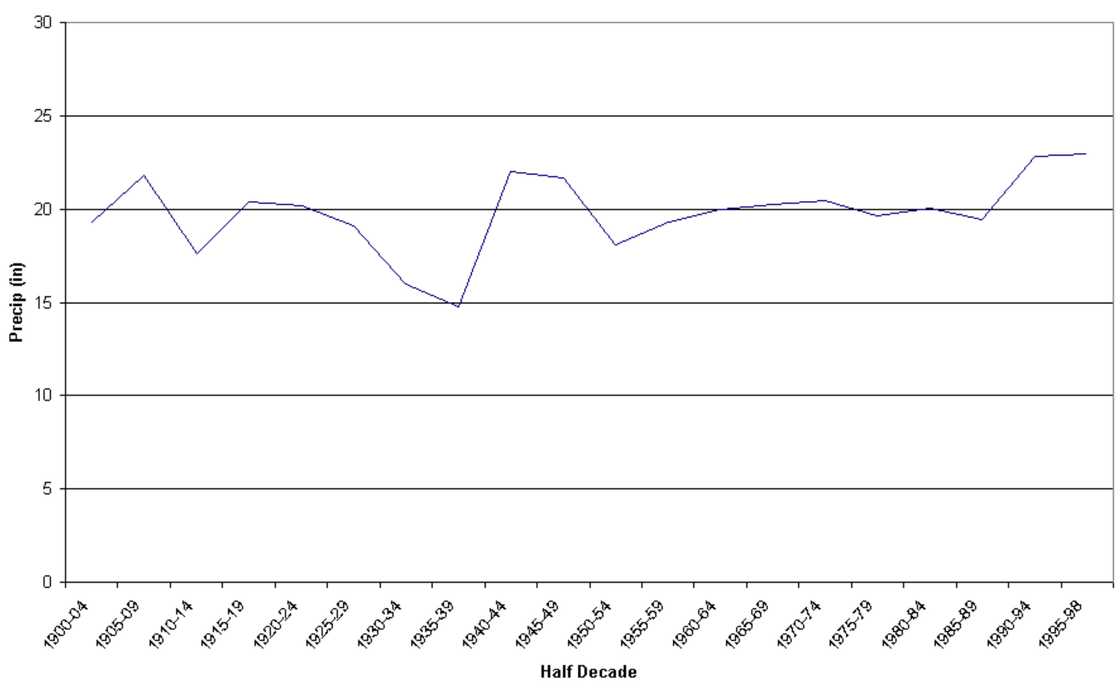
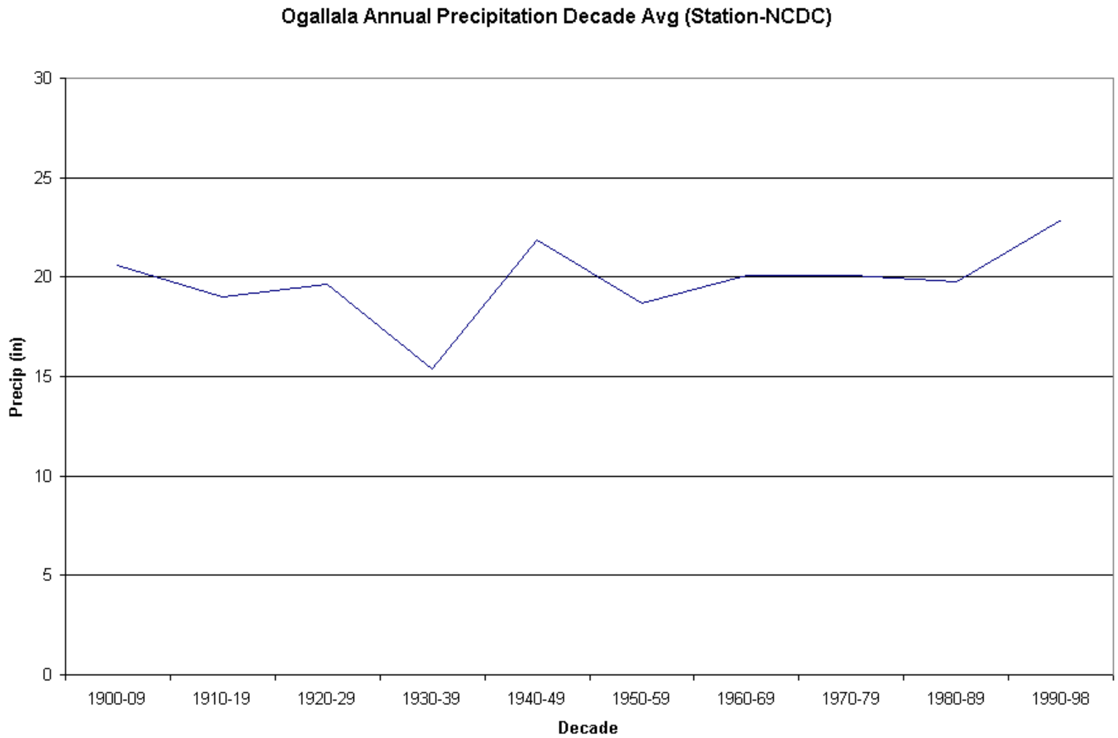
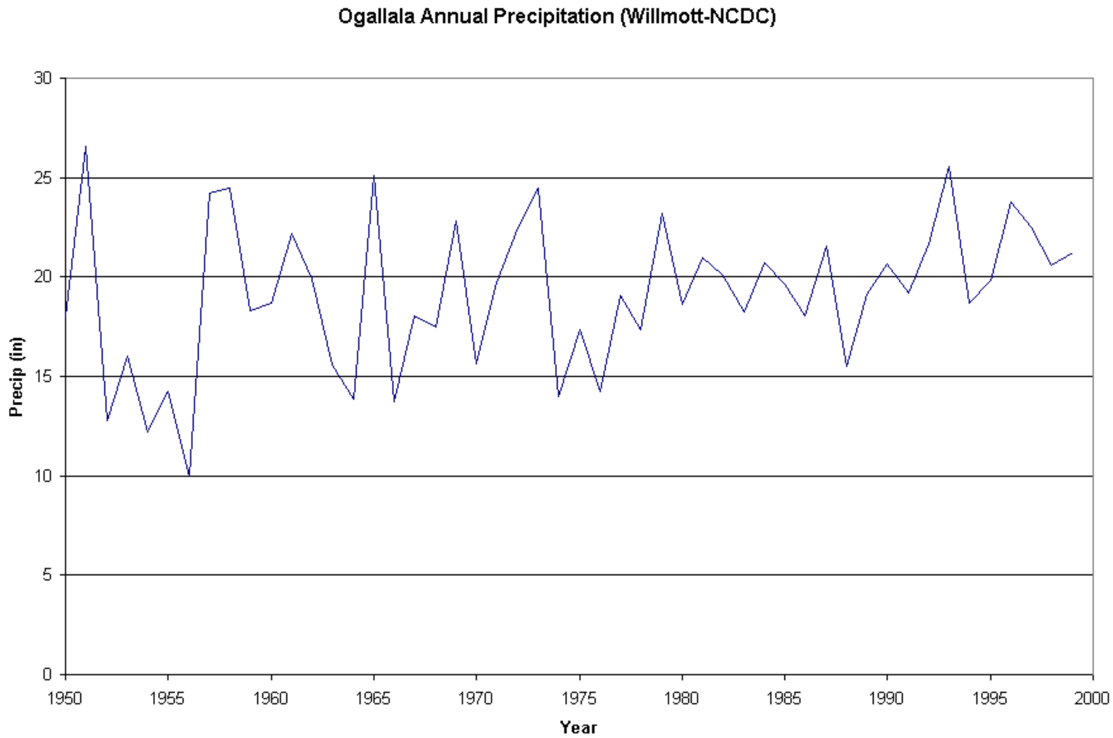


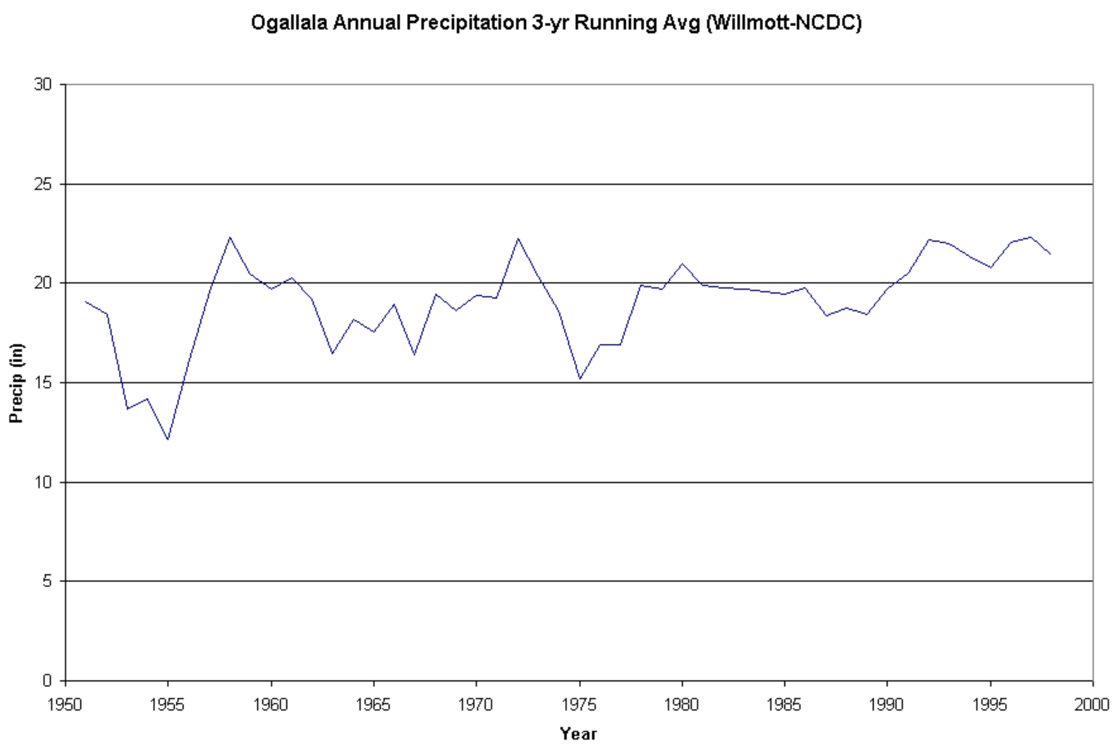
Ogallala Annual Precipitation Half-Decade Average (Station-NCDC)




Ogallala Annual Precipitation Decade Avg (Station-NCDC)
30
25
20
15
10
5
0
Precip (in)
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-98
Decade

Appendix Figures 1.2. Ogallala as a whole (Willmott-NCDC)





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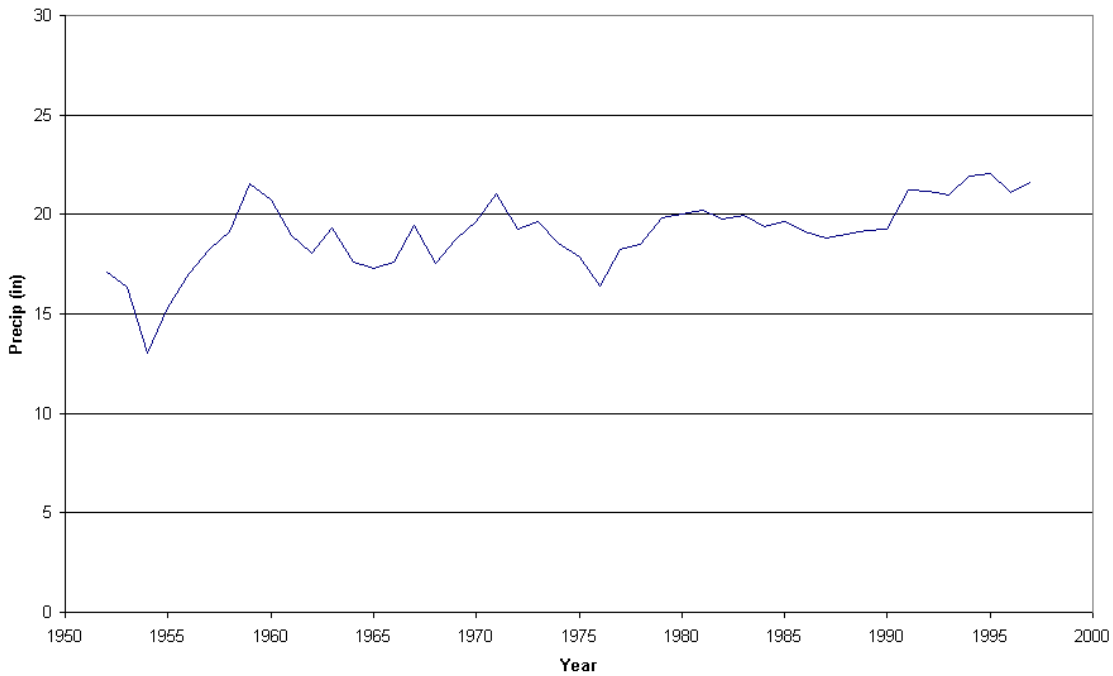

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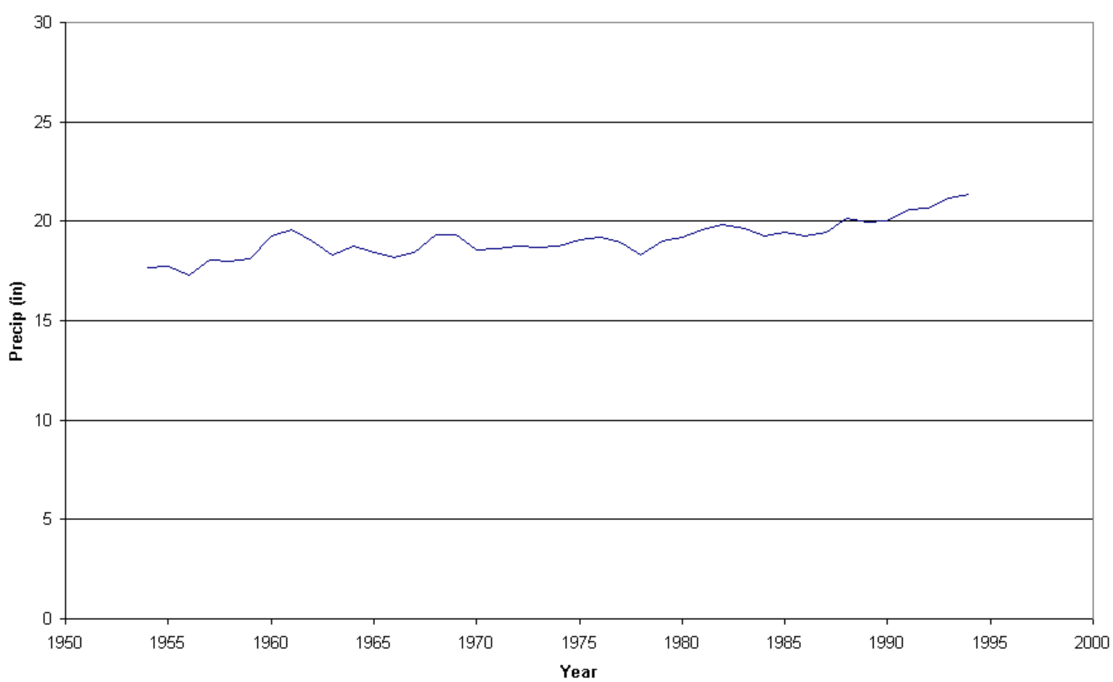
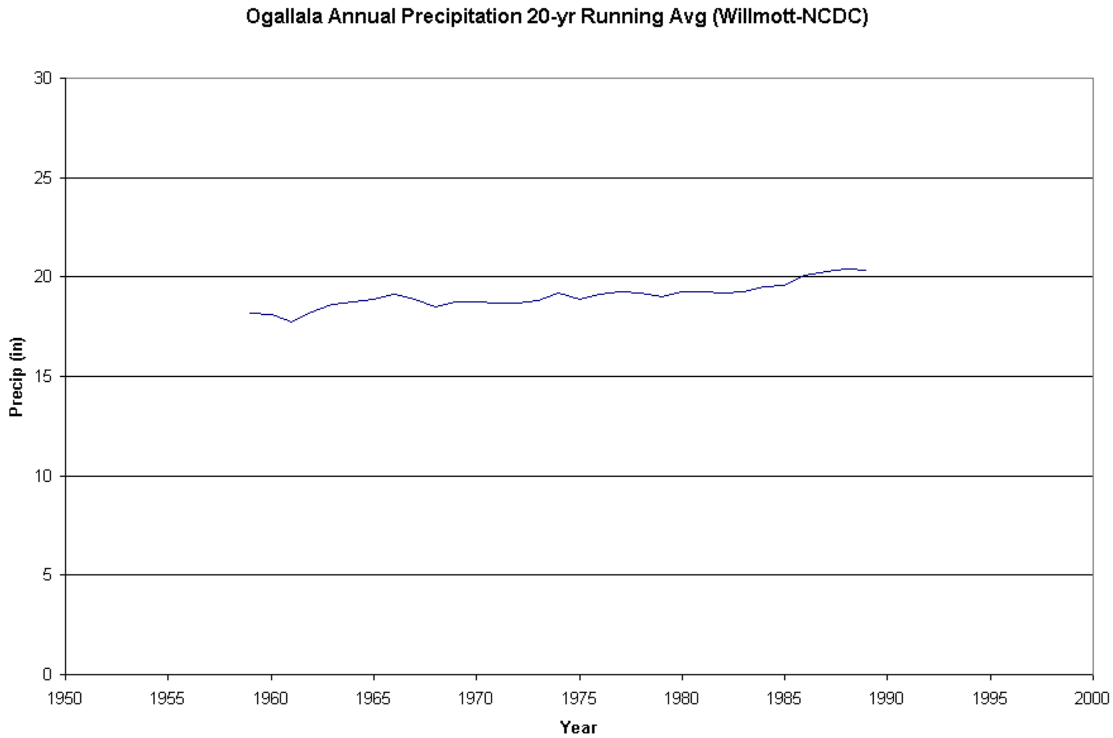
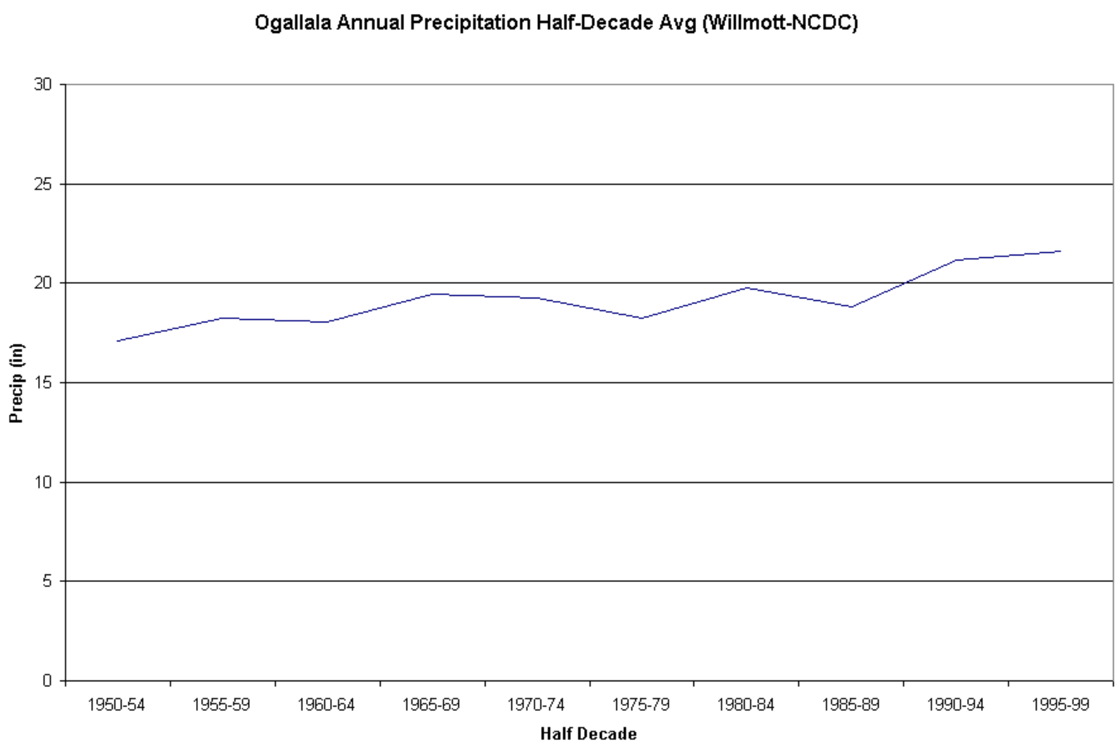


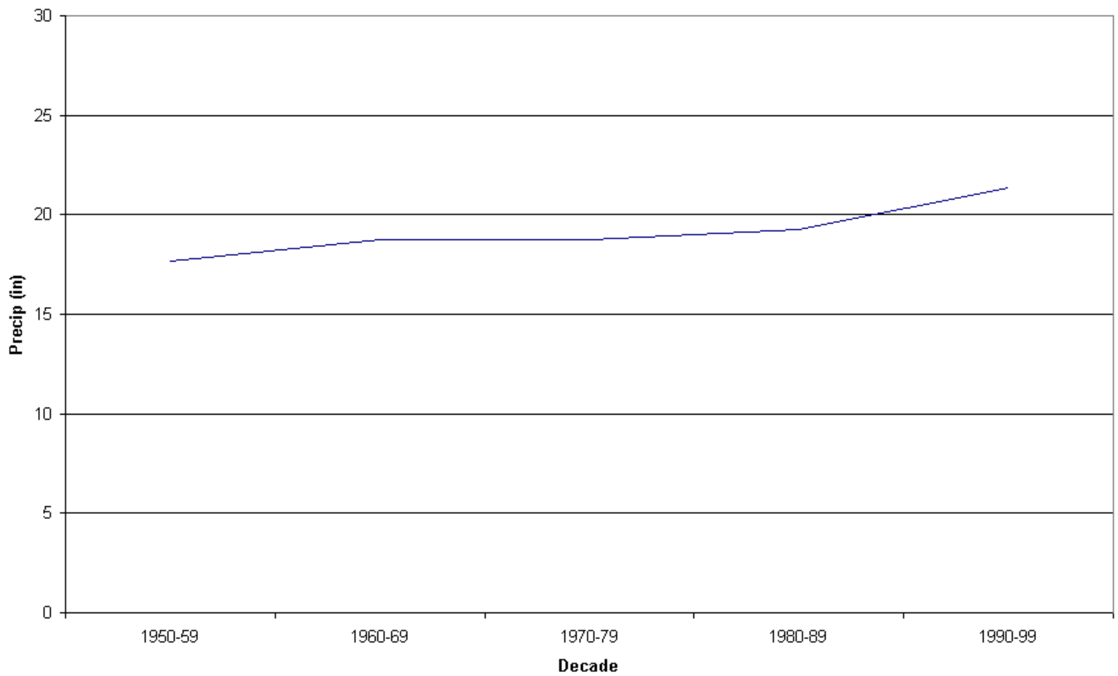


Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year

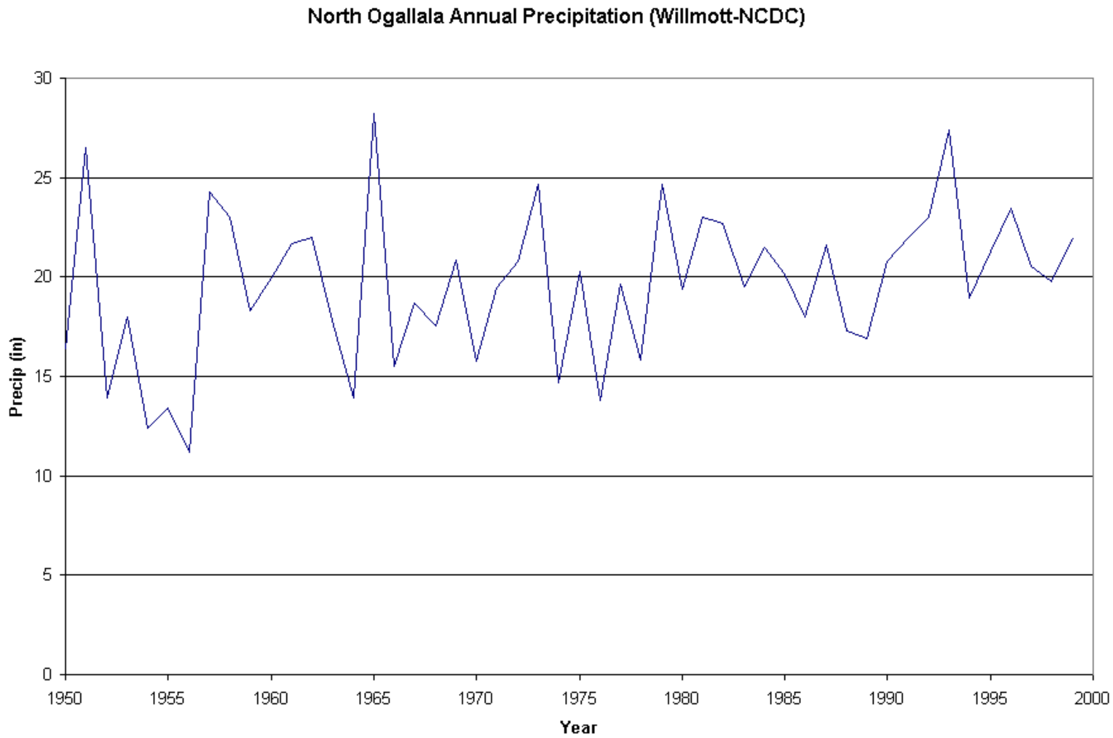


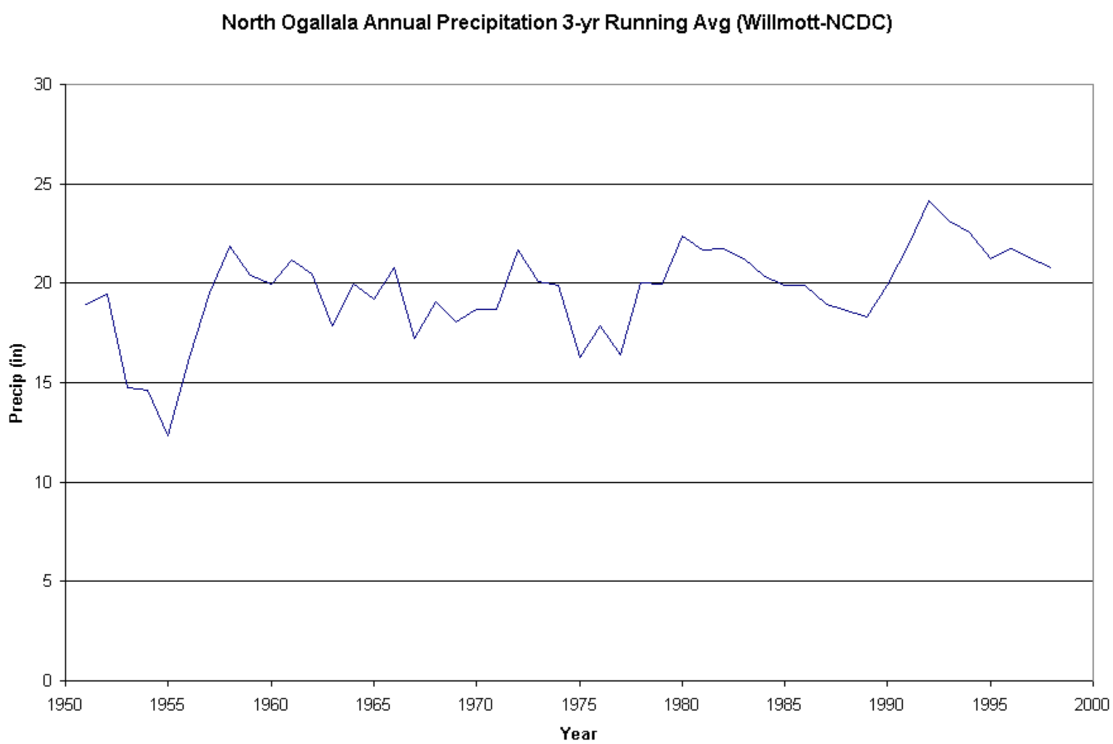
Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-54
1955-59
1960-64
1965-69
1970-74
1975-79
1980-84
1985-89
1990-94
1995-99
Half Decade

Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)

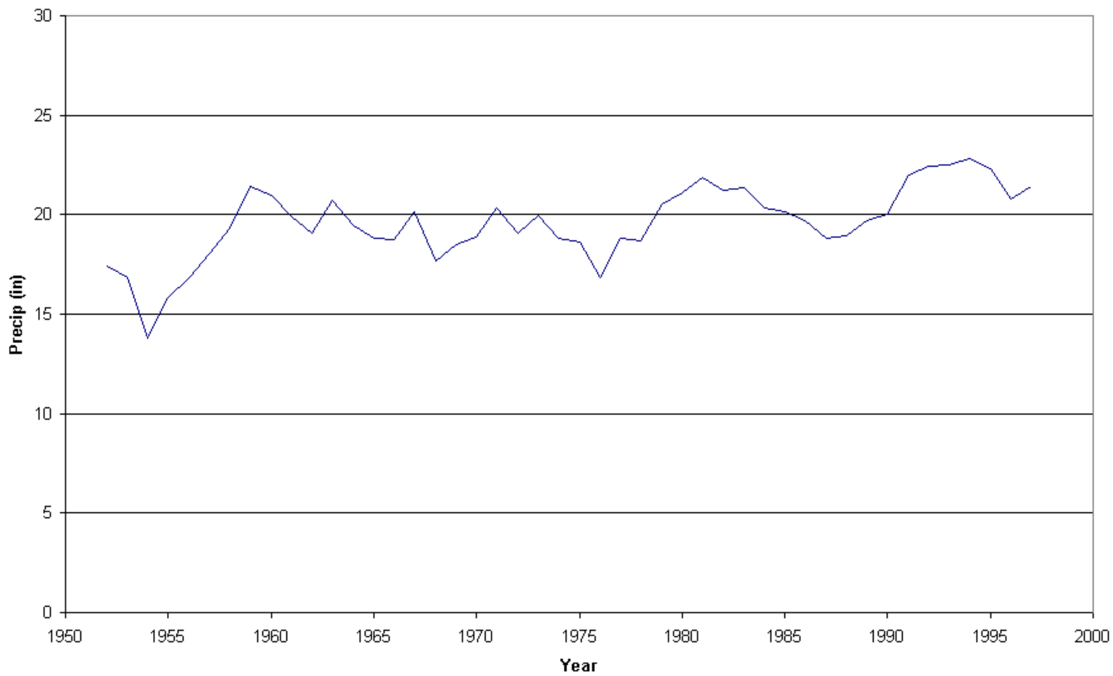


Appendix Figures 1.3. North Ogallala (Willmott-NCDC)





North Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



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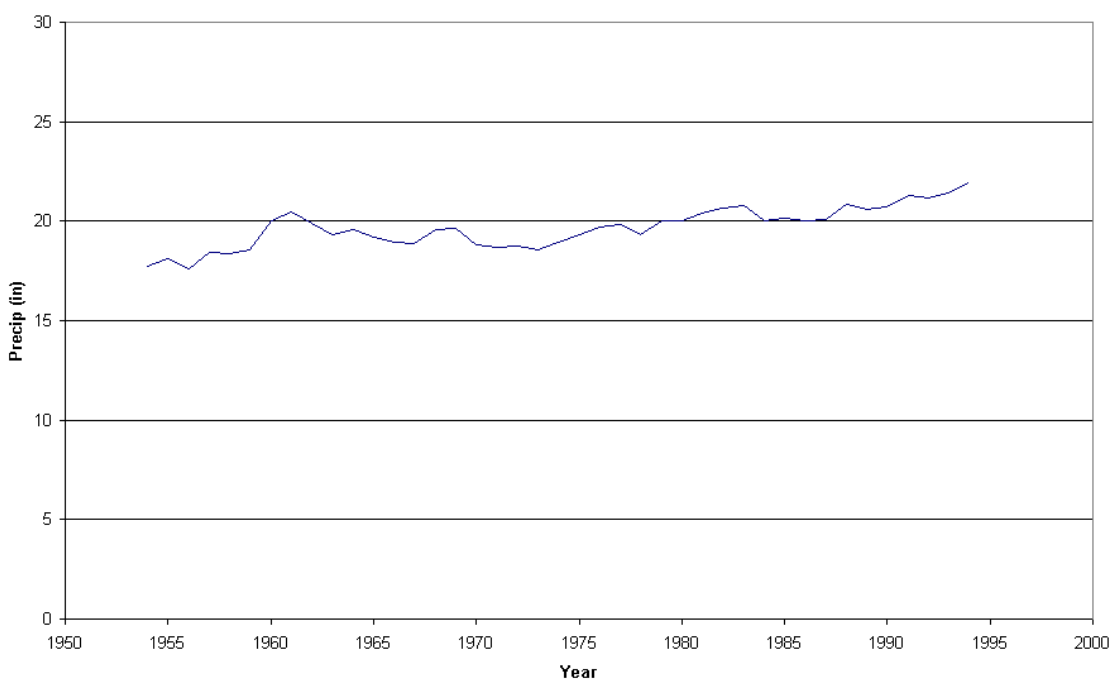

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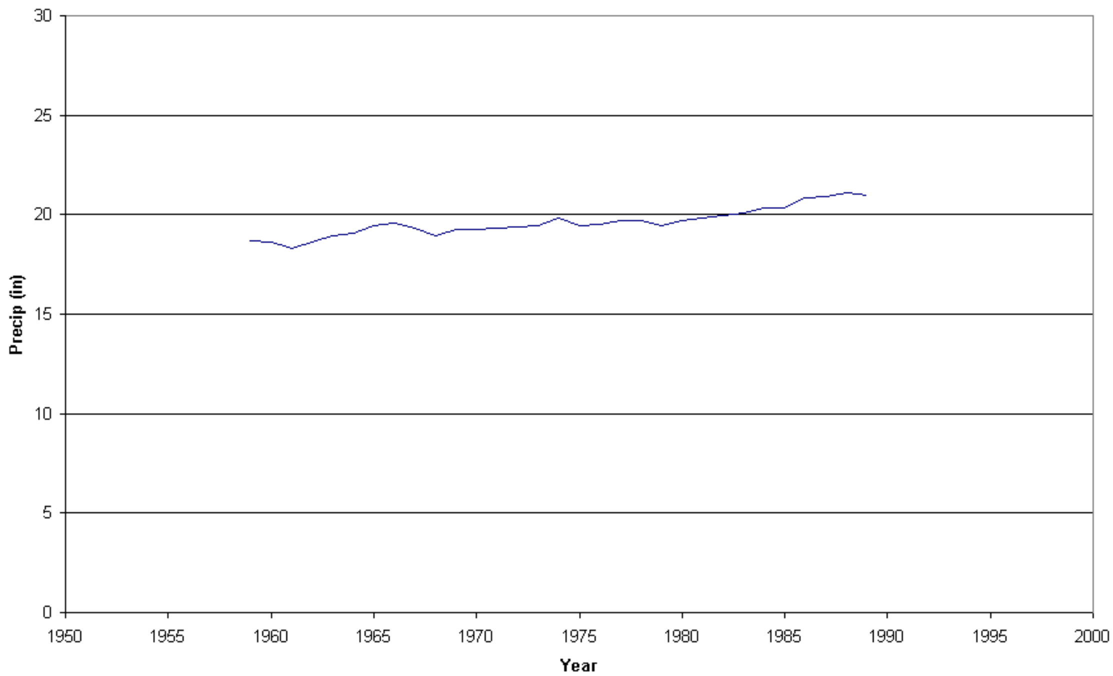
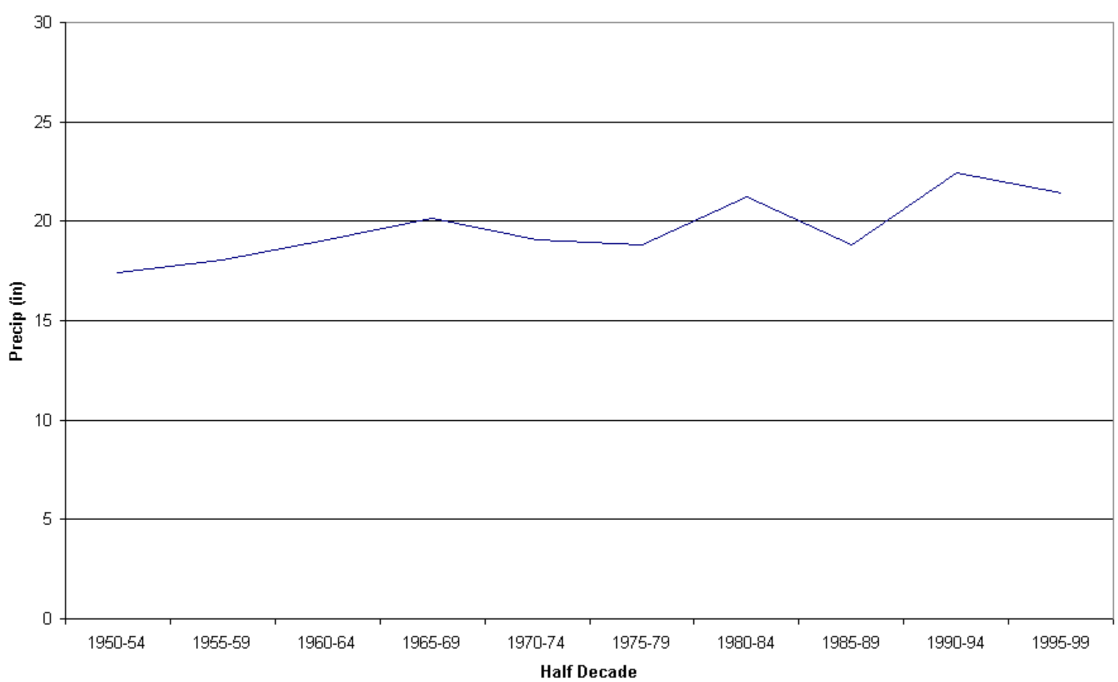
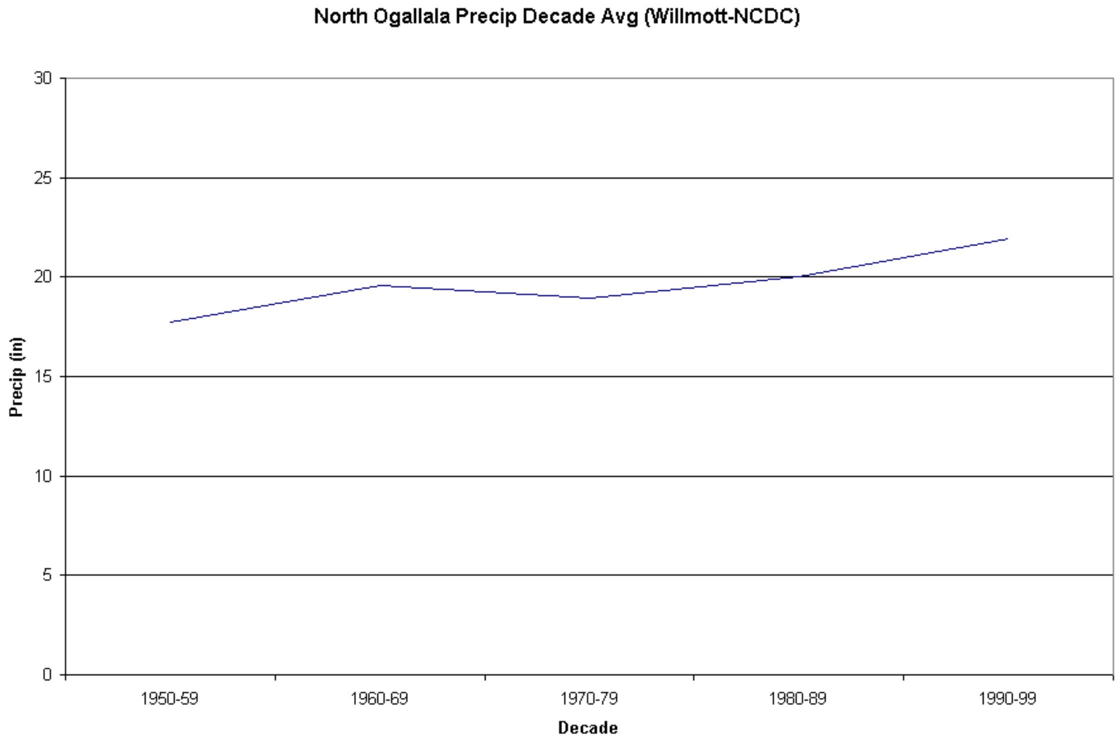
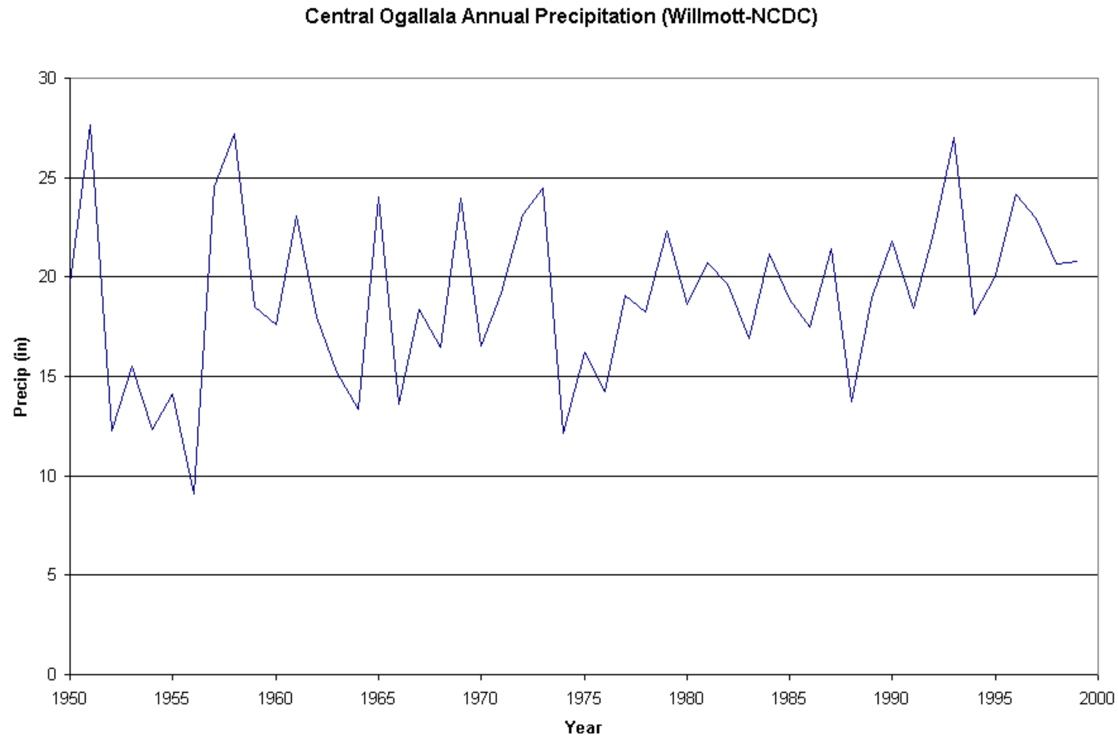


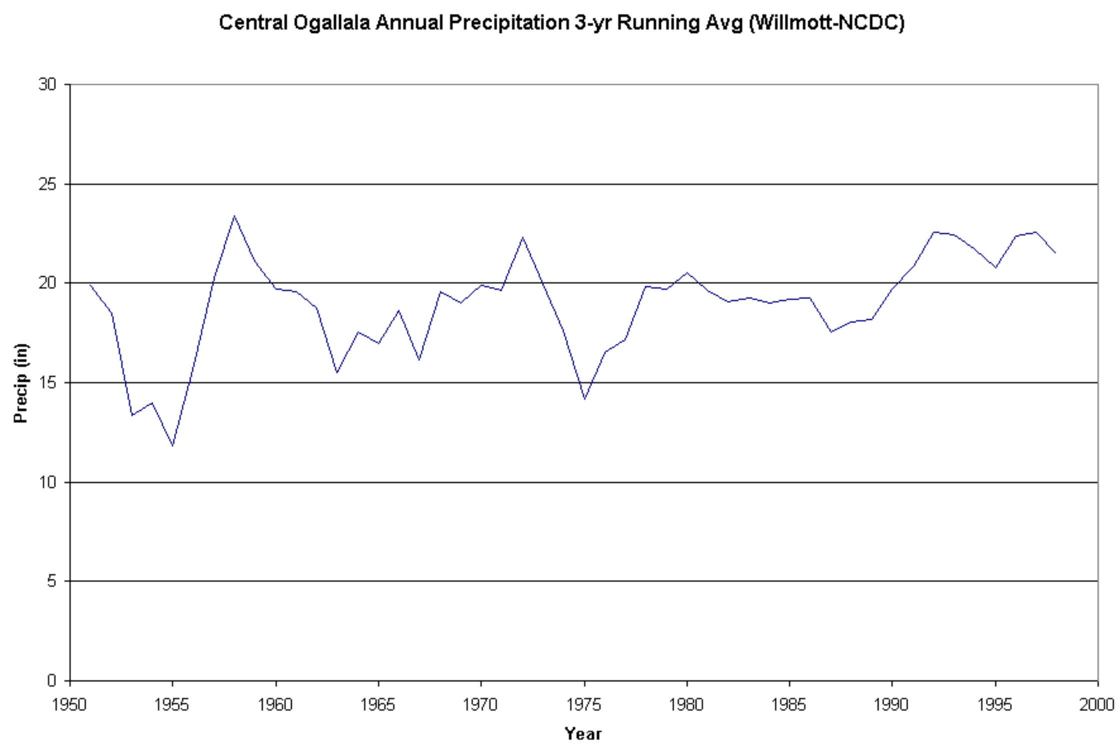
North Ogallala Annual Precipitation Half-Decade Average (Willmott-NCDC)




North Ogallala Precip Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.4. Central Ogallala (Willmott-NCDC)





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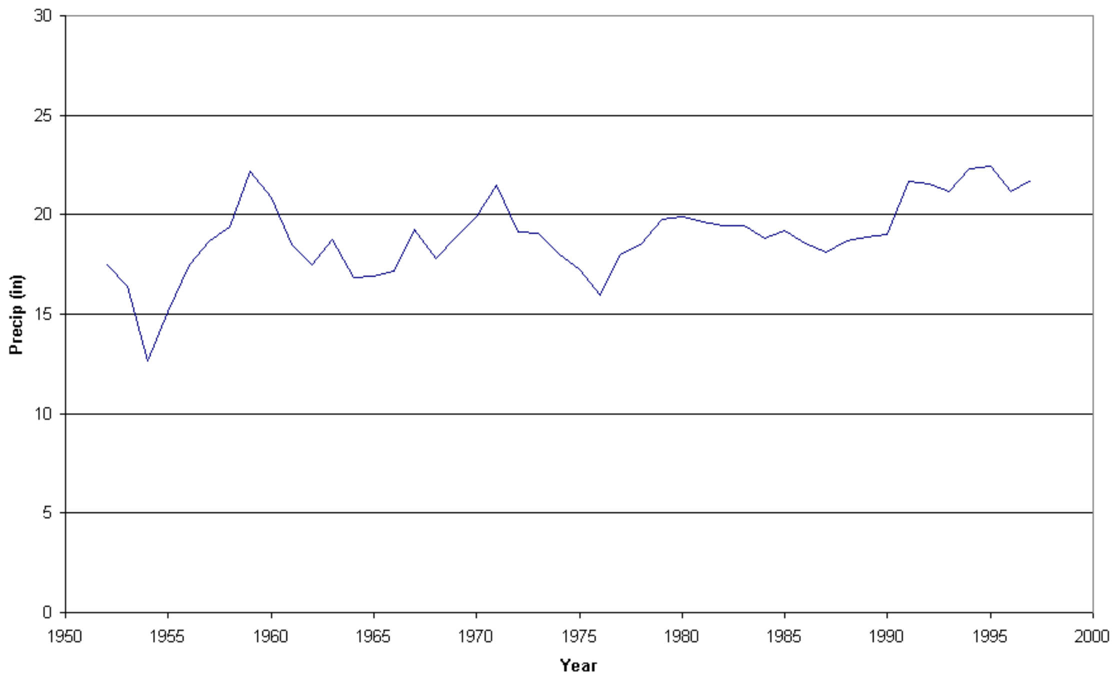
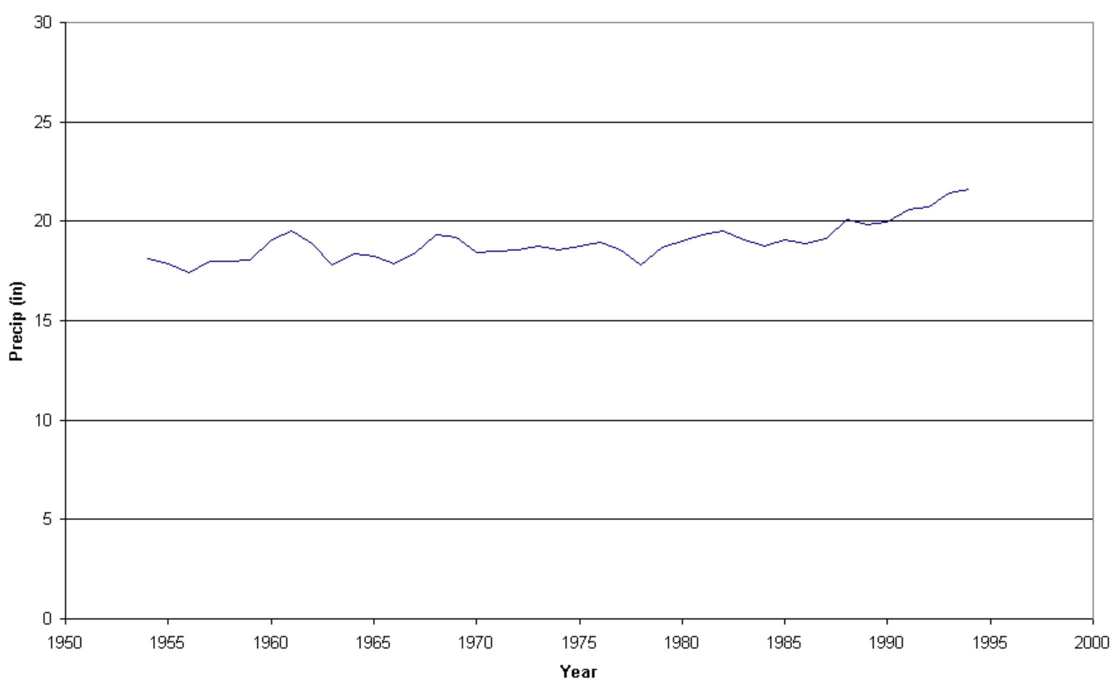
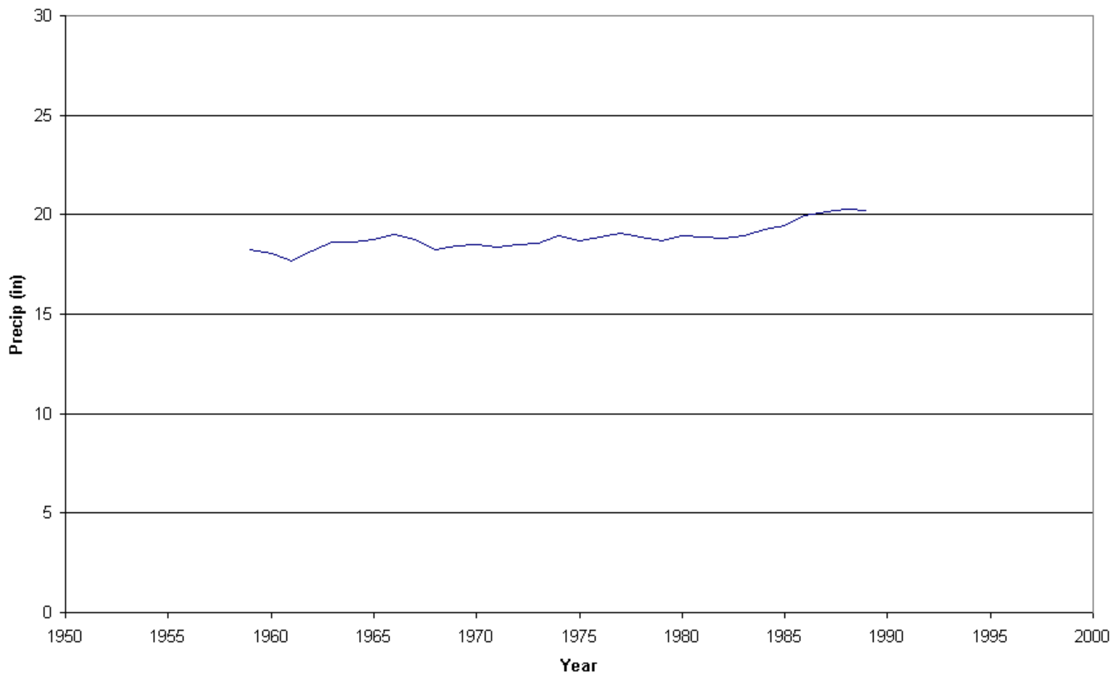


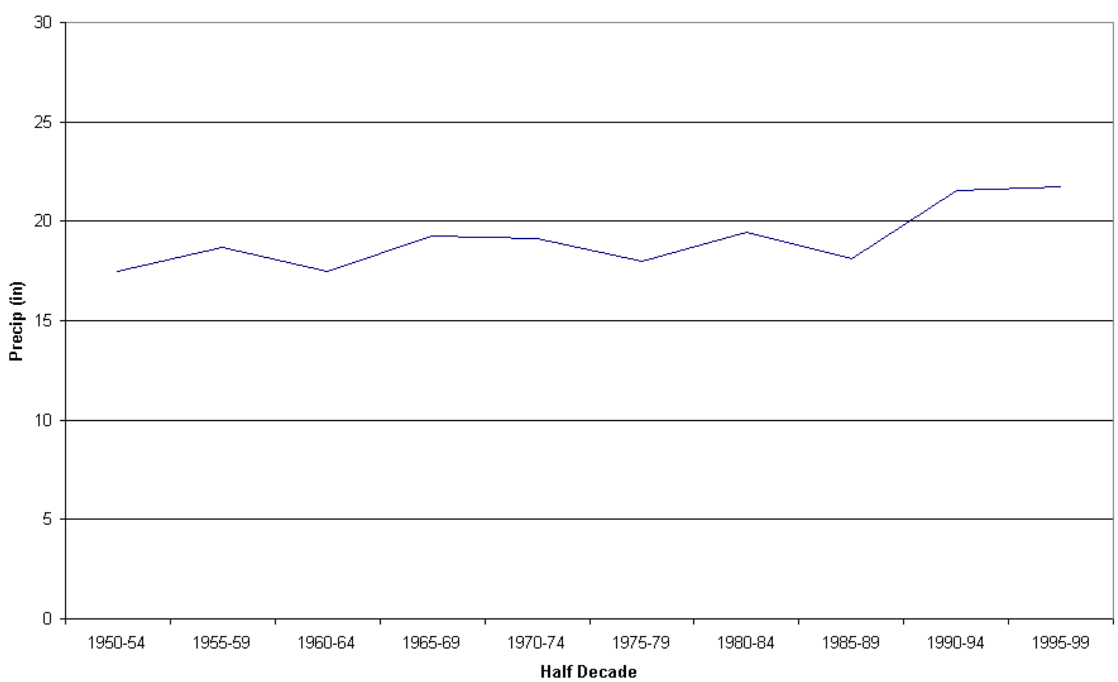
Central Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

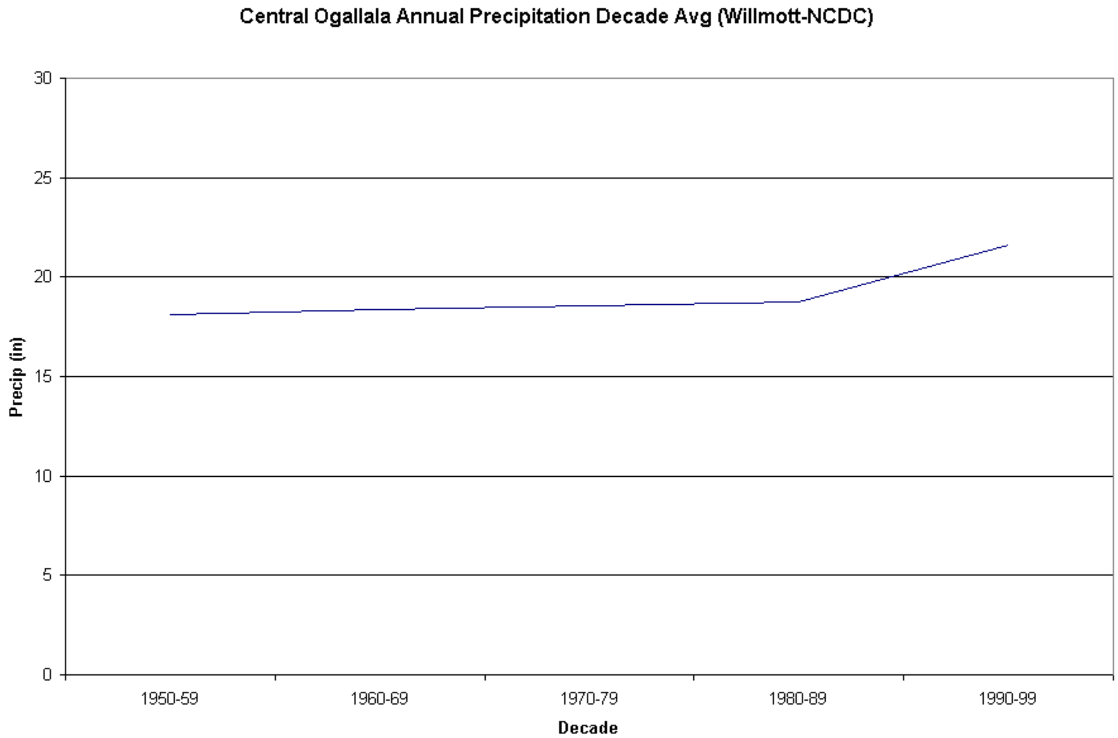


Central Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

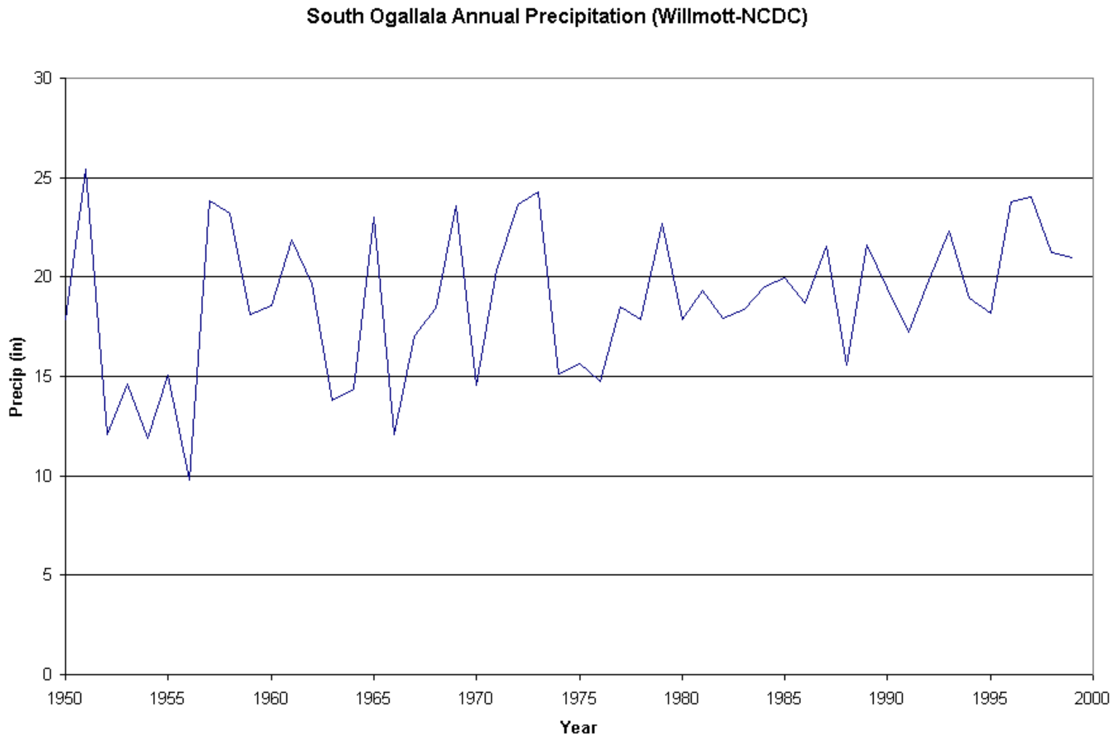


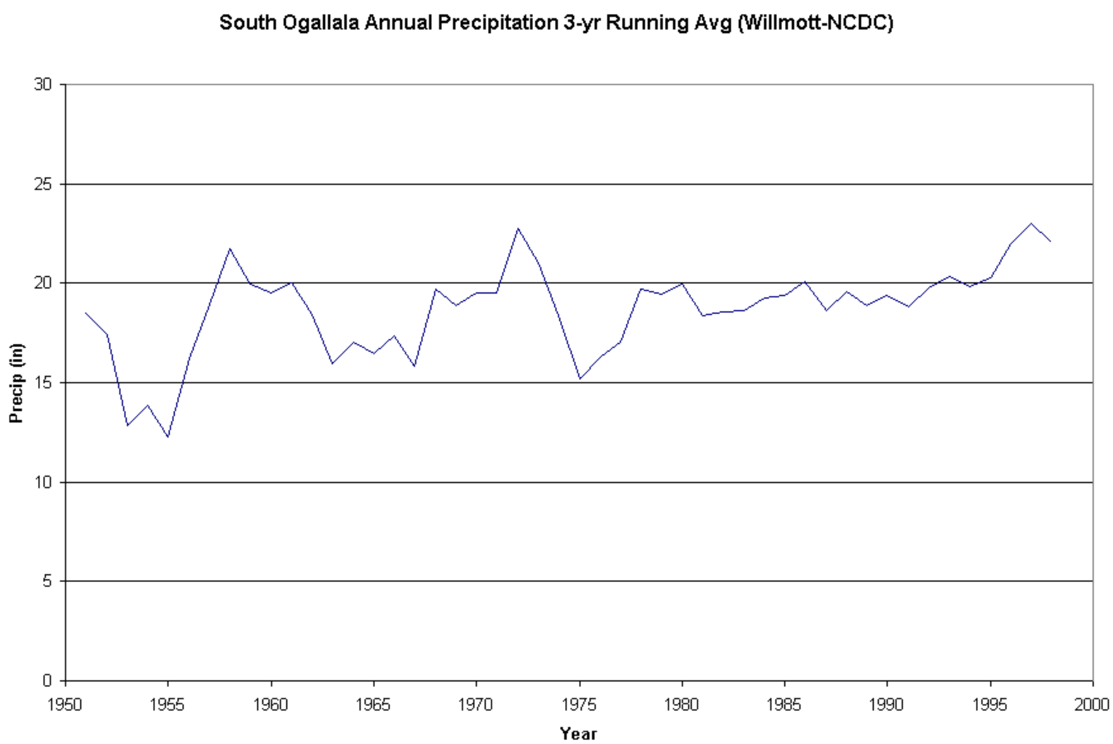
Central Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)



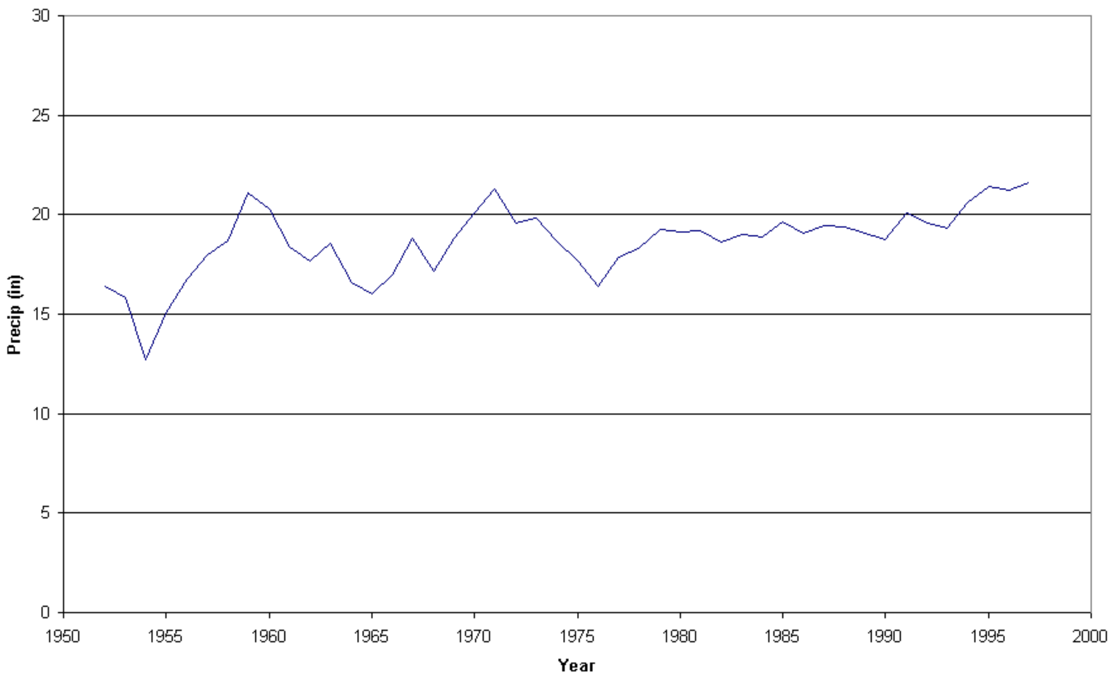

Central Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.5. South Ogallala (Willmott-NCDC)

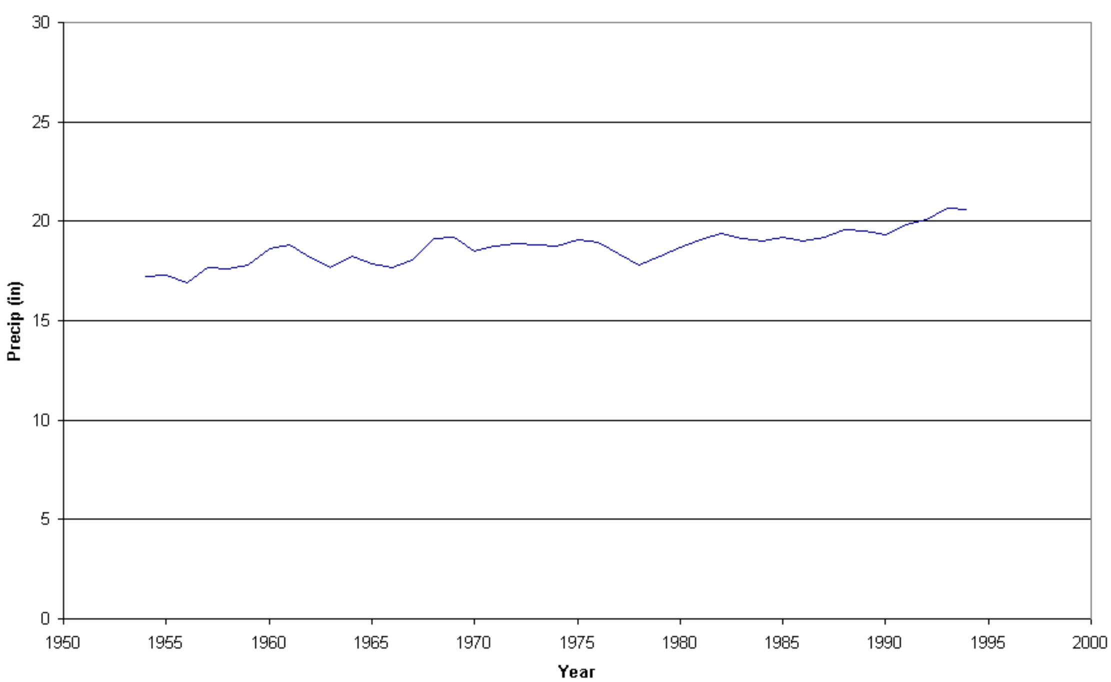




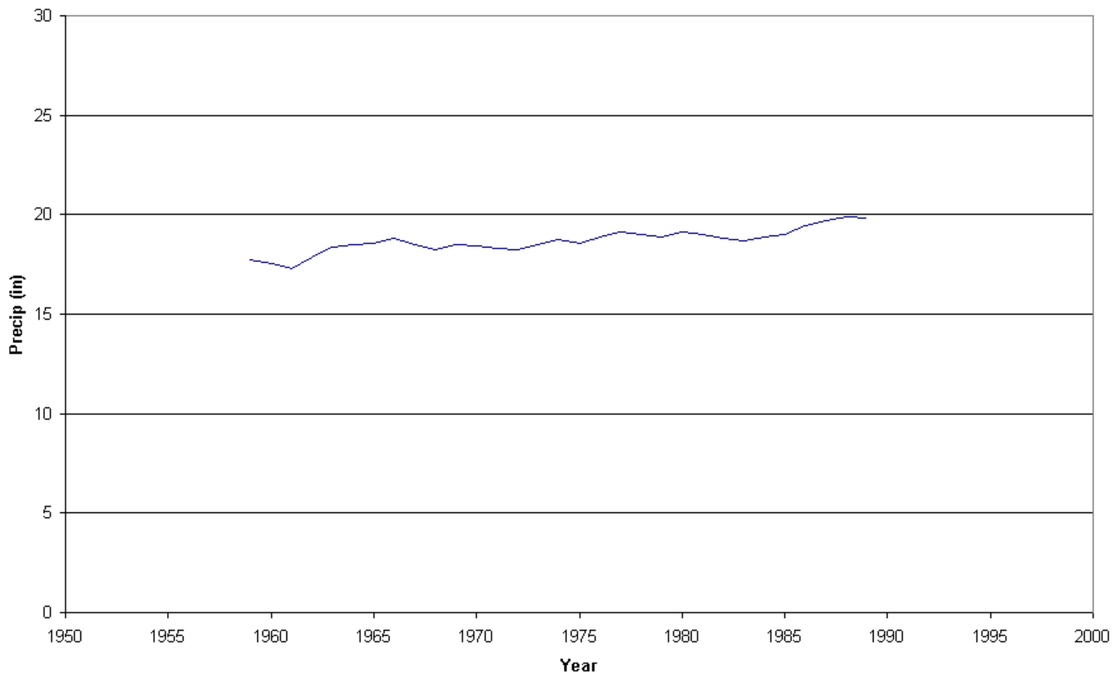
South Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



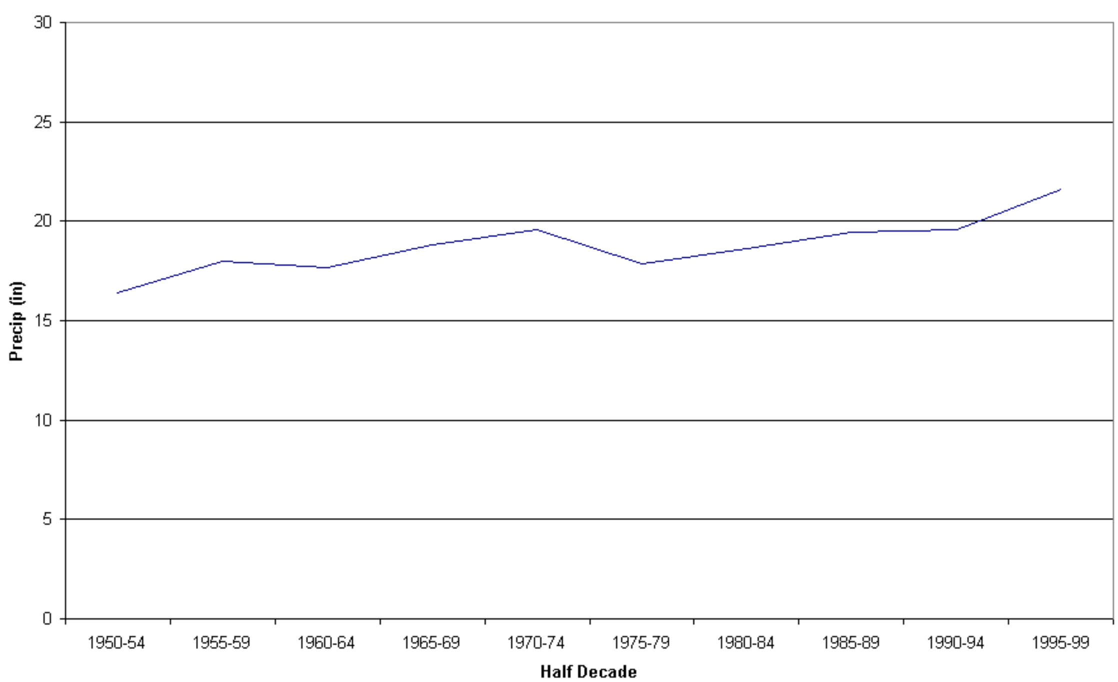
South Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

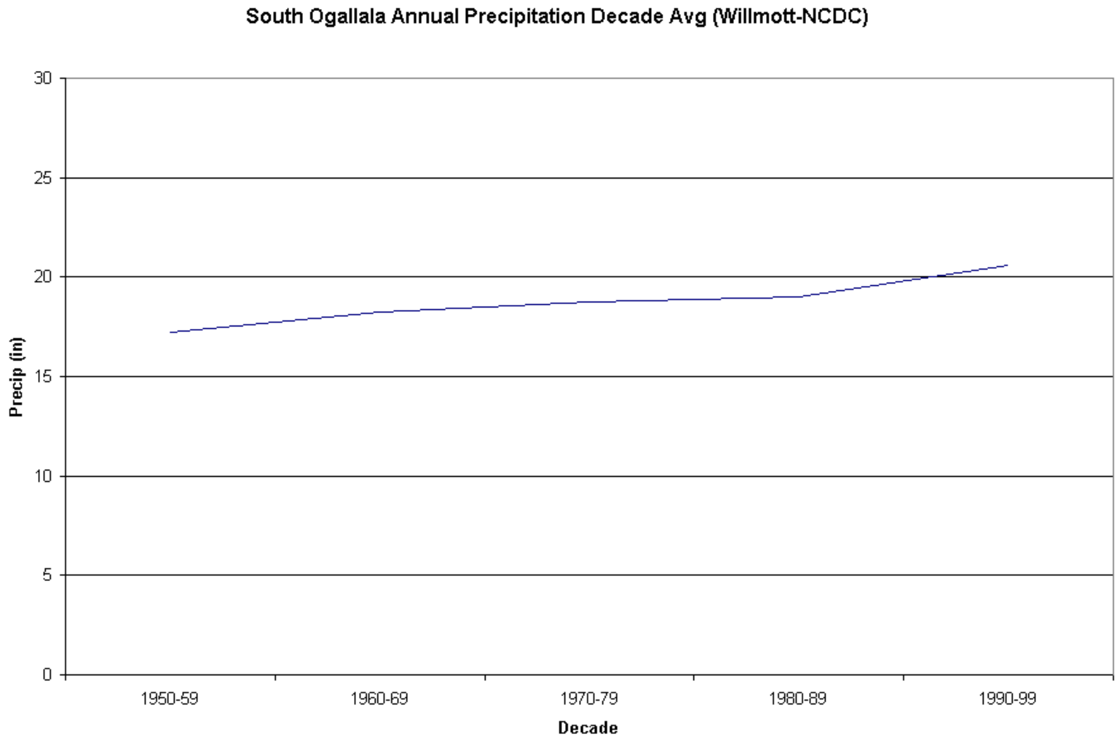


South Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

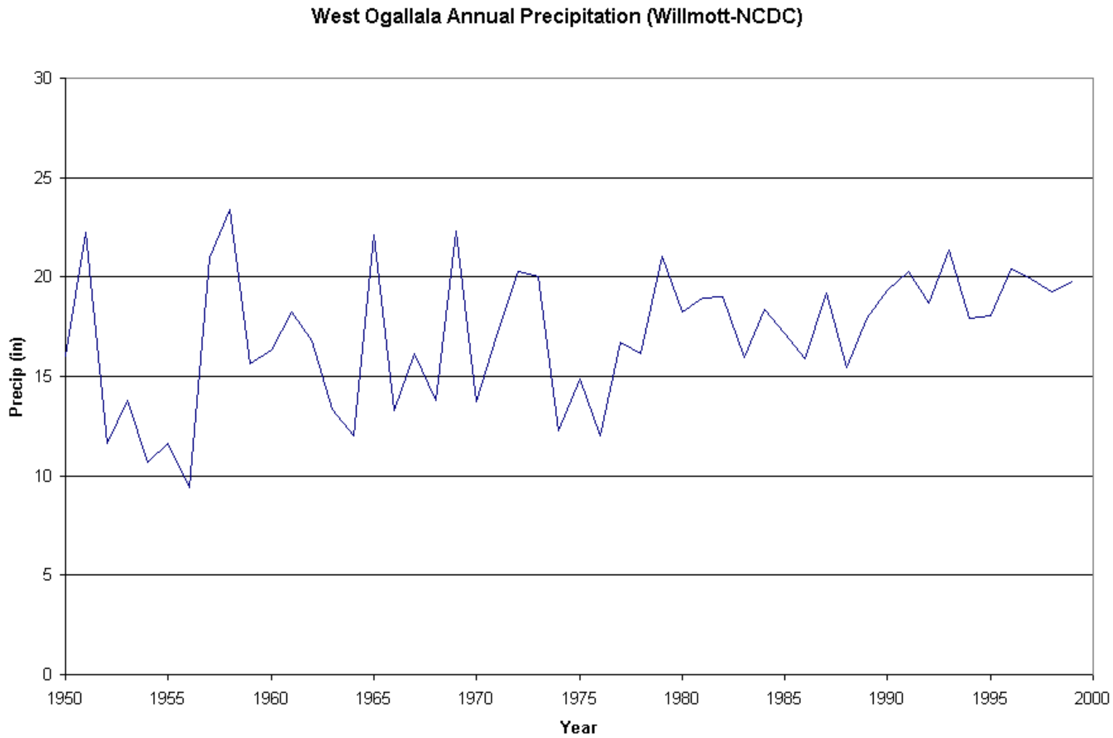


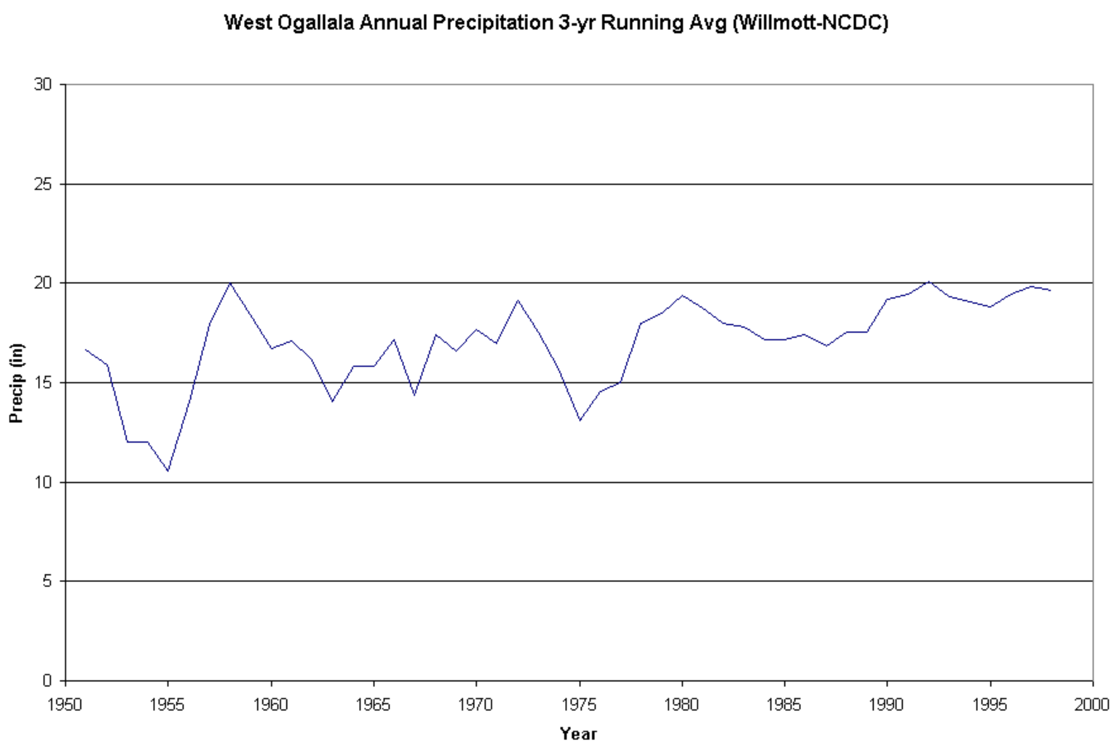
South Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)



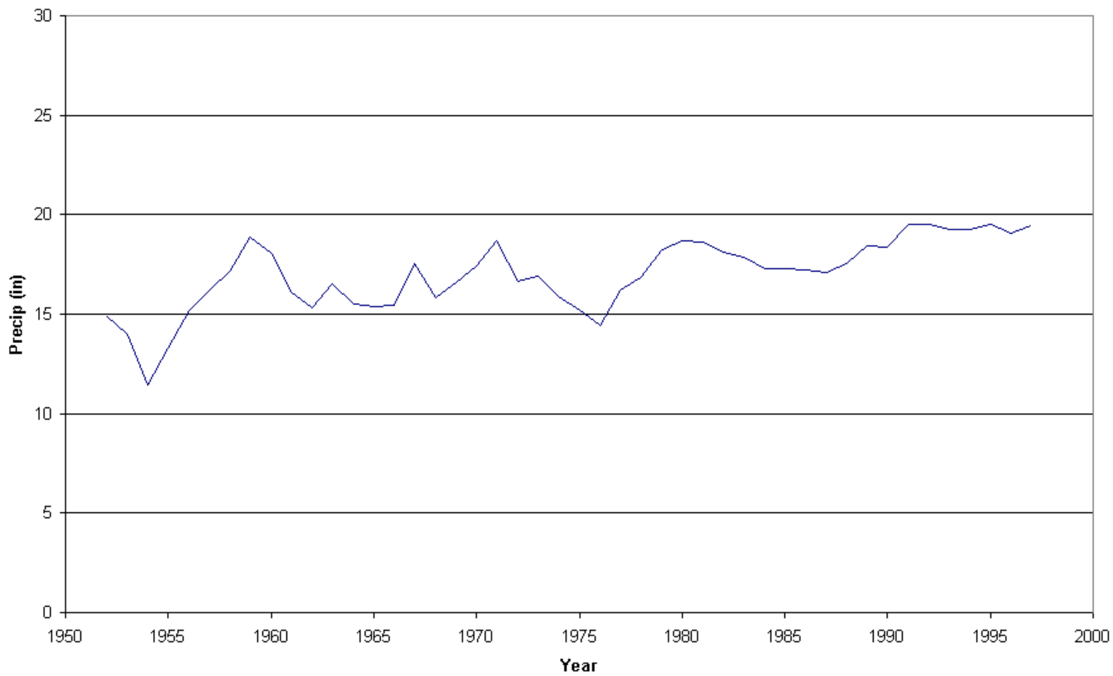

South Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
30
25
20
15
10
5
0
Precip (in)
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.6. West Ogallala (Willmott-NCDC)

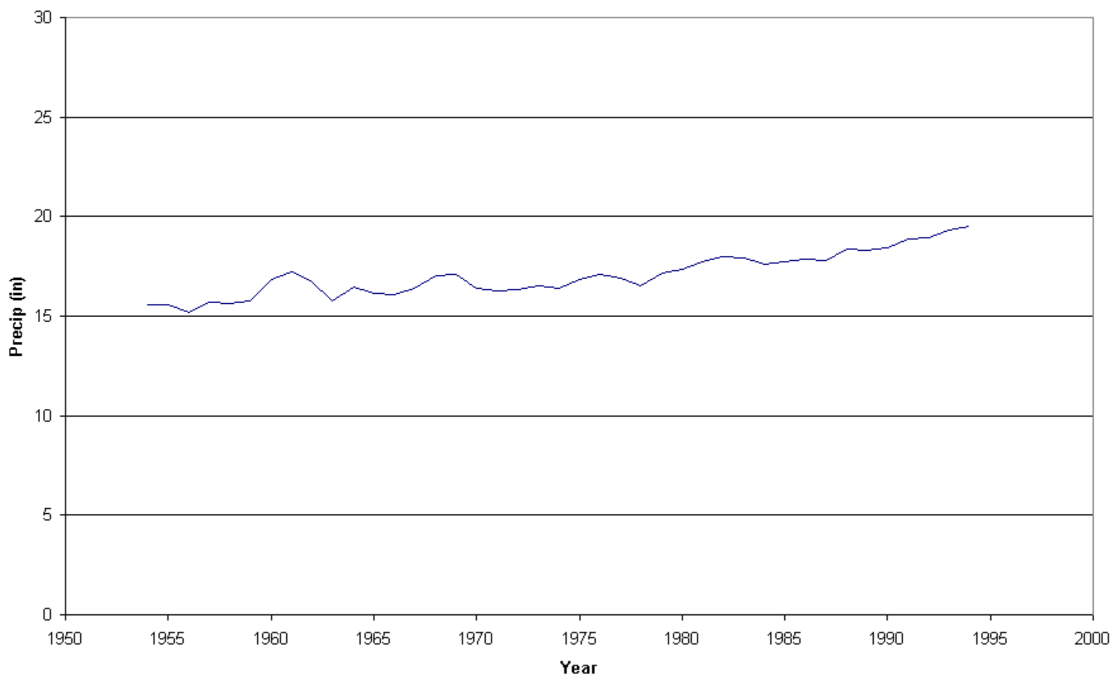




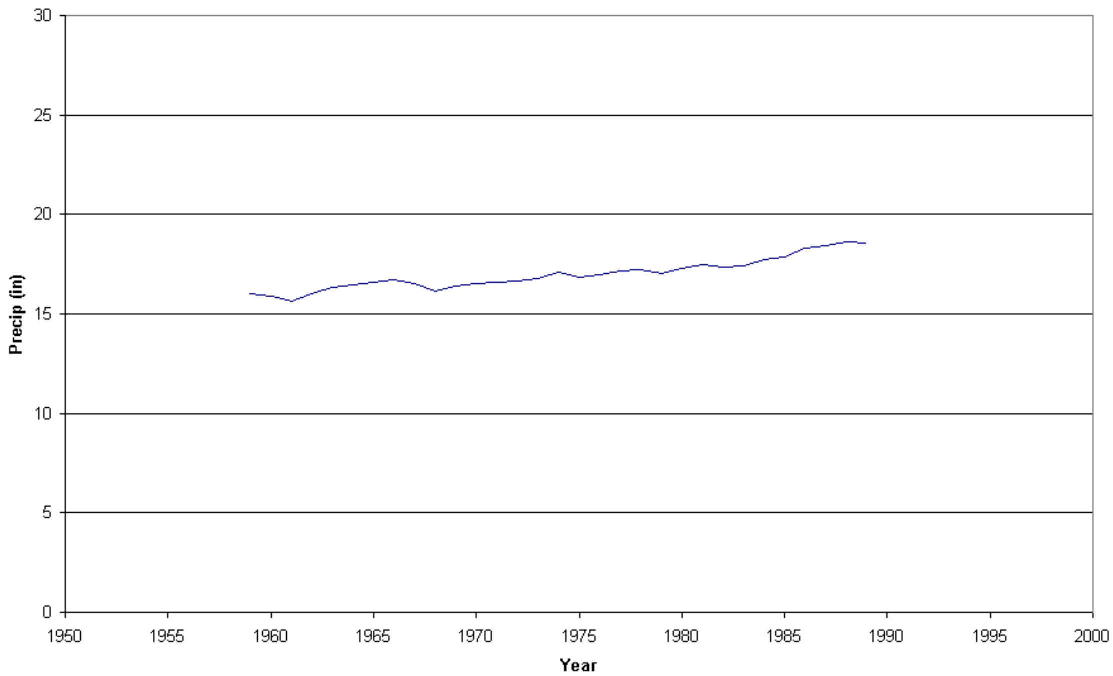
West Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



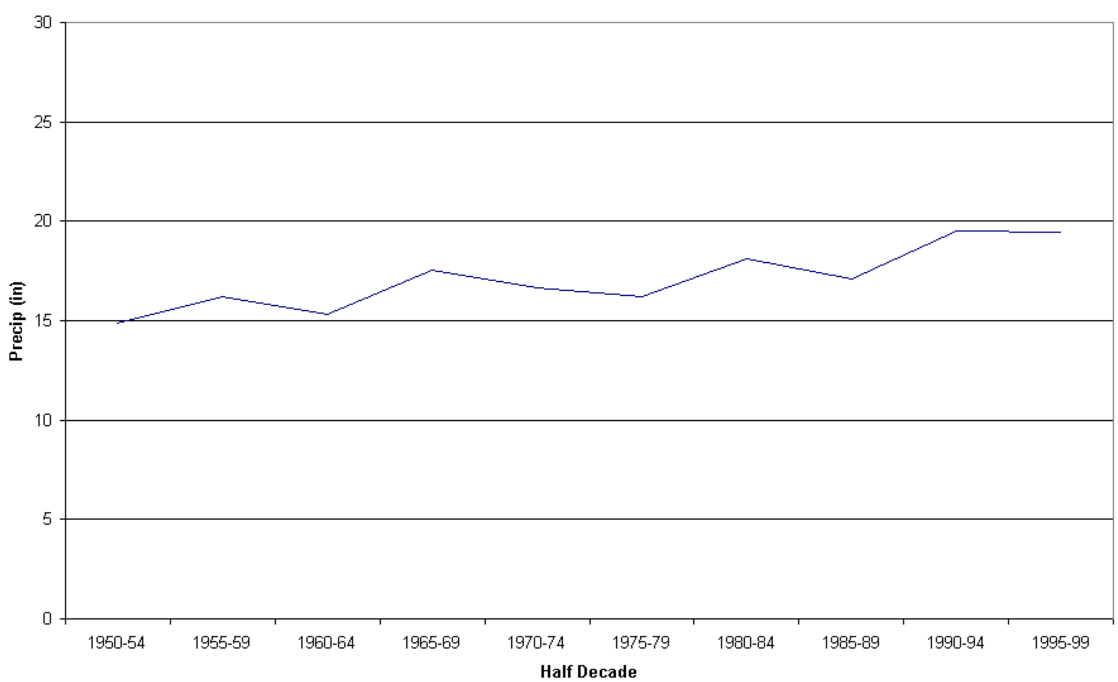
West Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

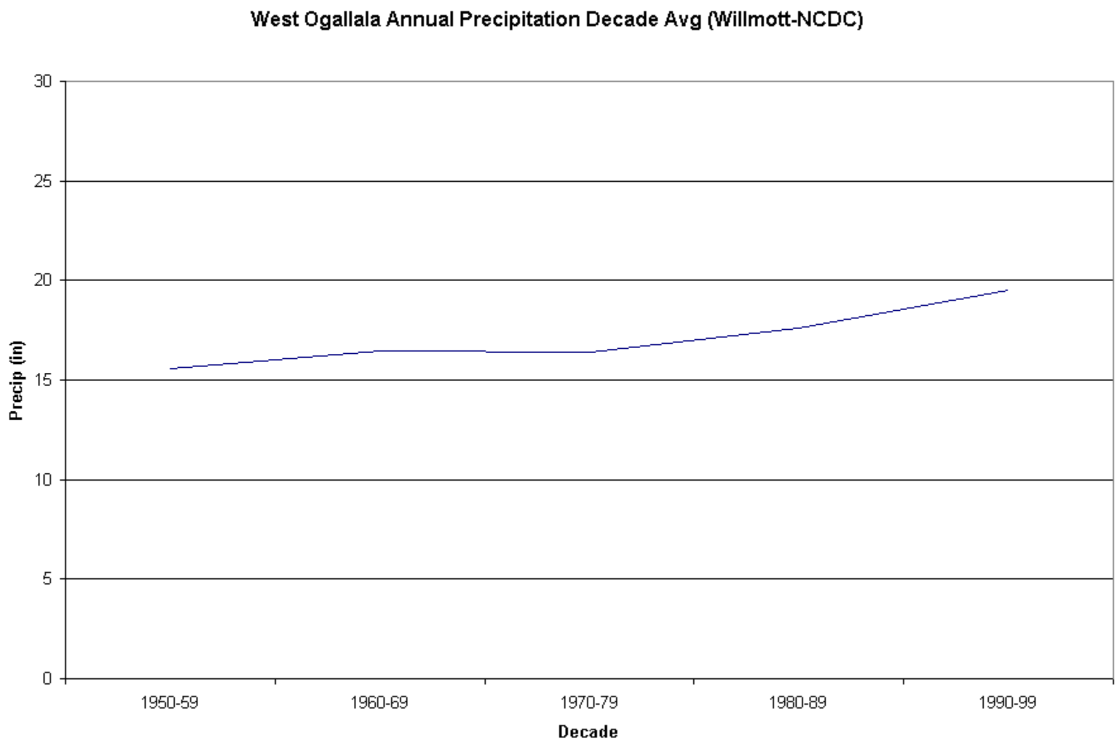


West Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

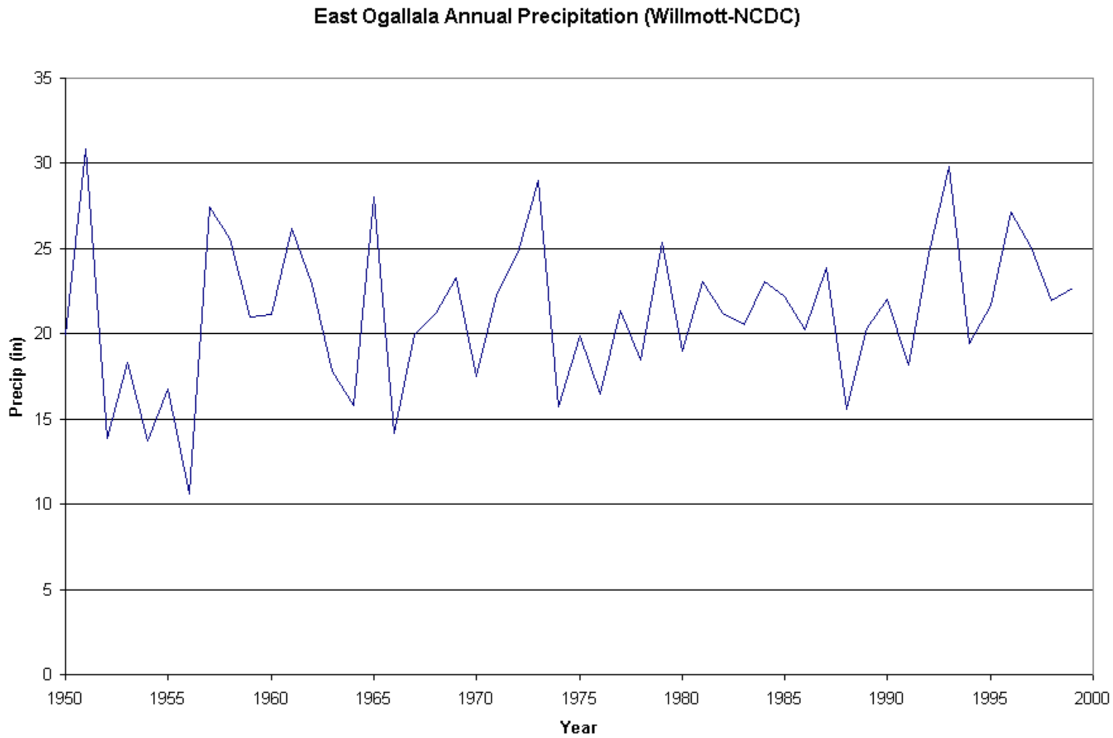


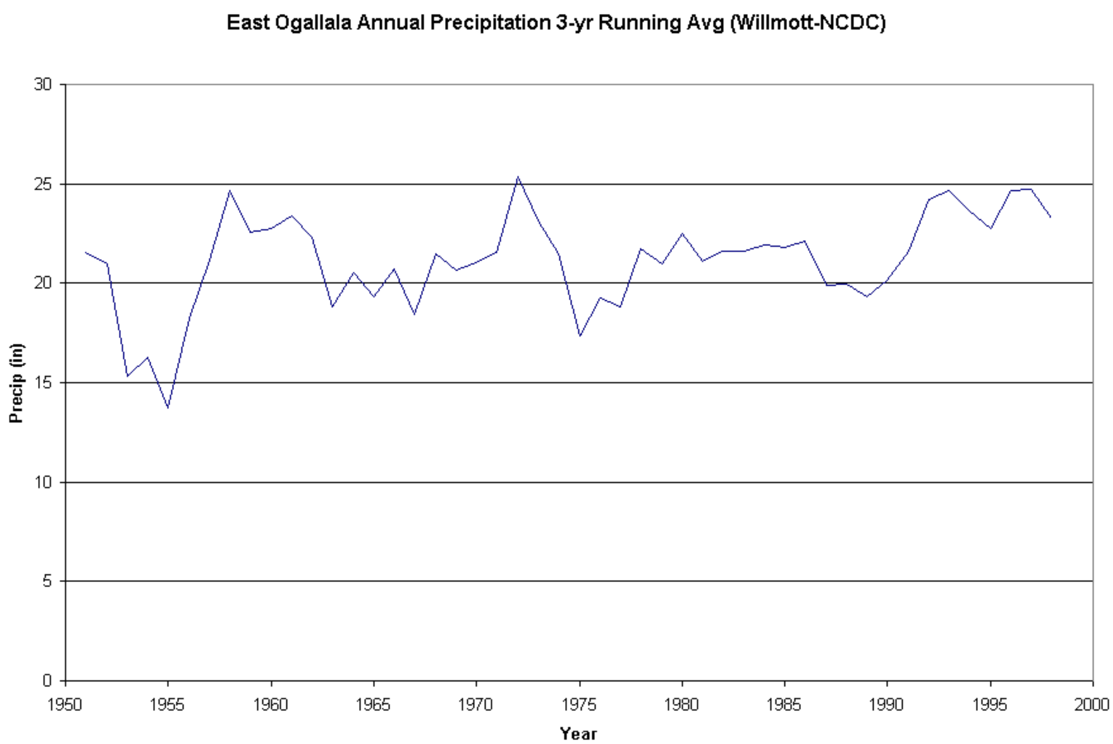
West Ogallala Annual Precipitation Half Decade Avg (Willmott-NCDC)



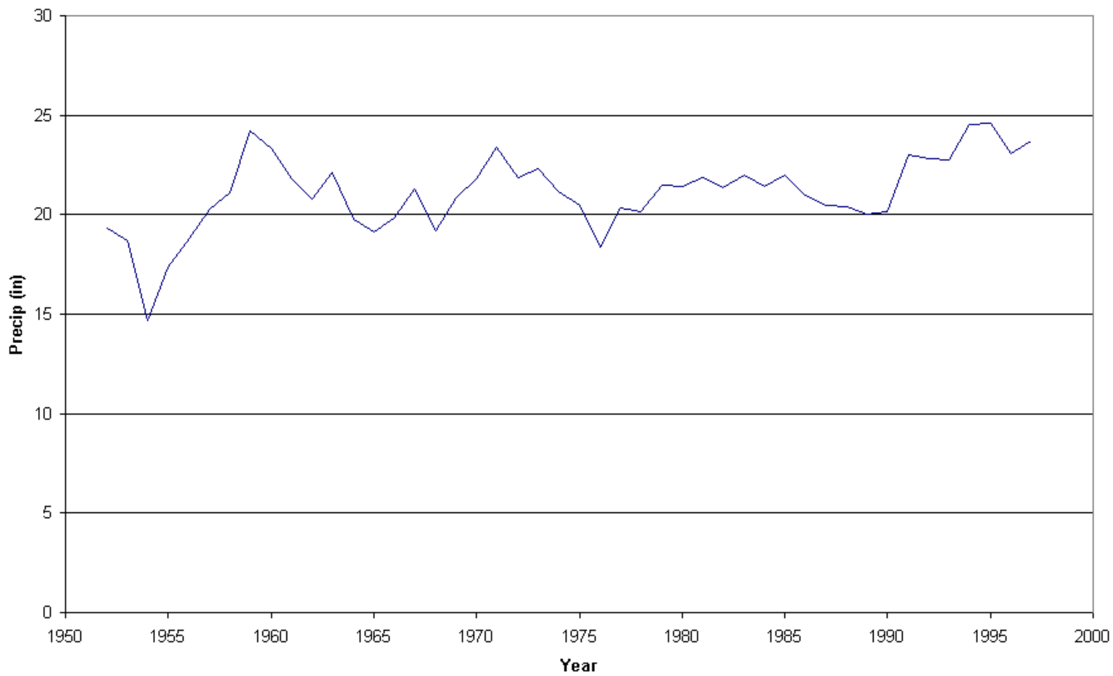

West Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
Precip (in)
0
5
10
15
20
25
30
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.7. East Ogallala (Willmott-NCDC)

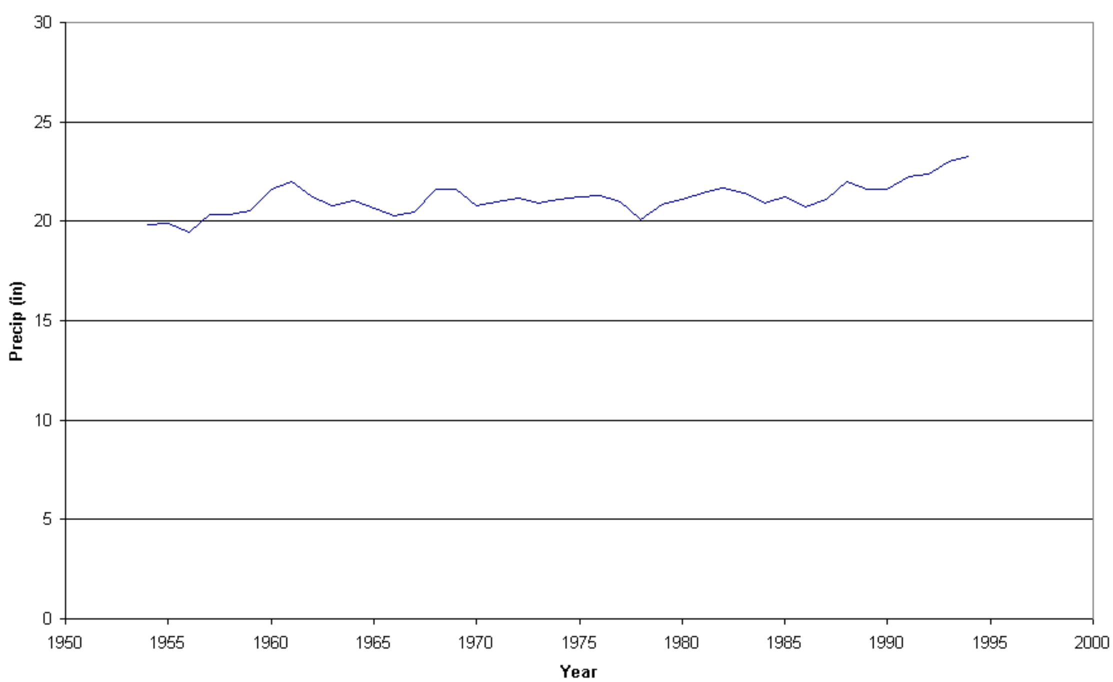


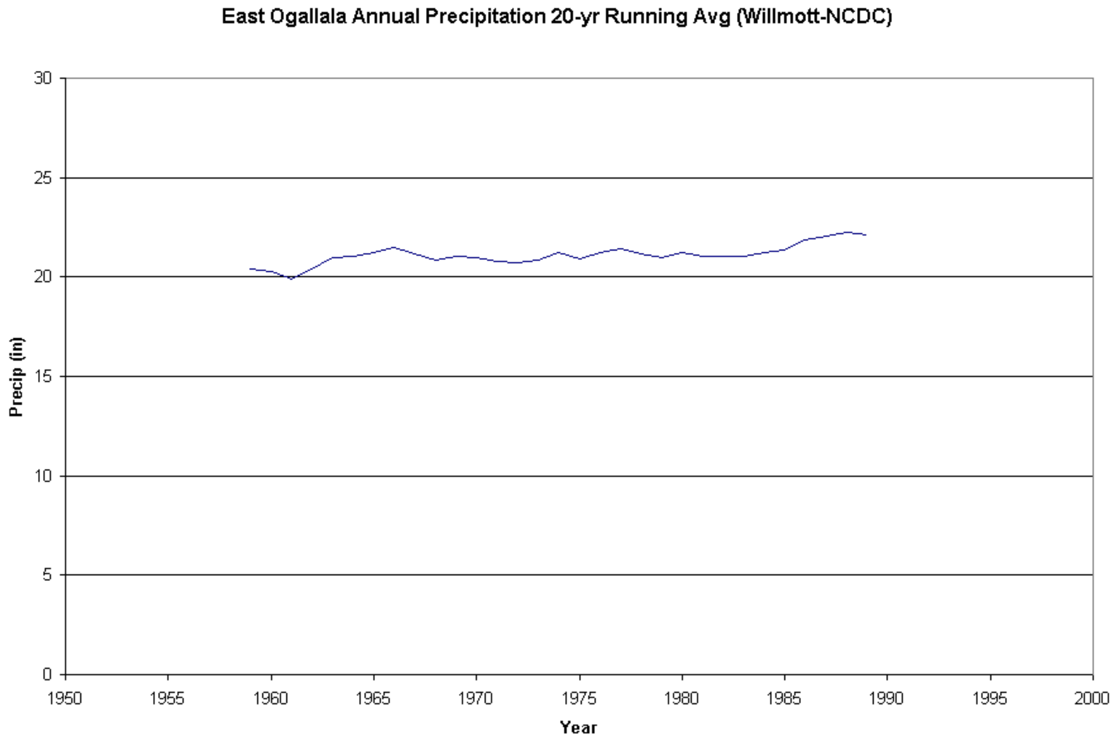


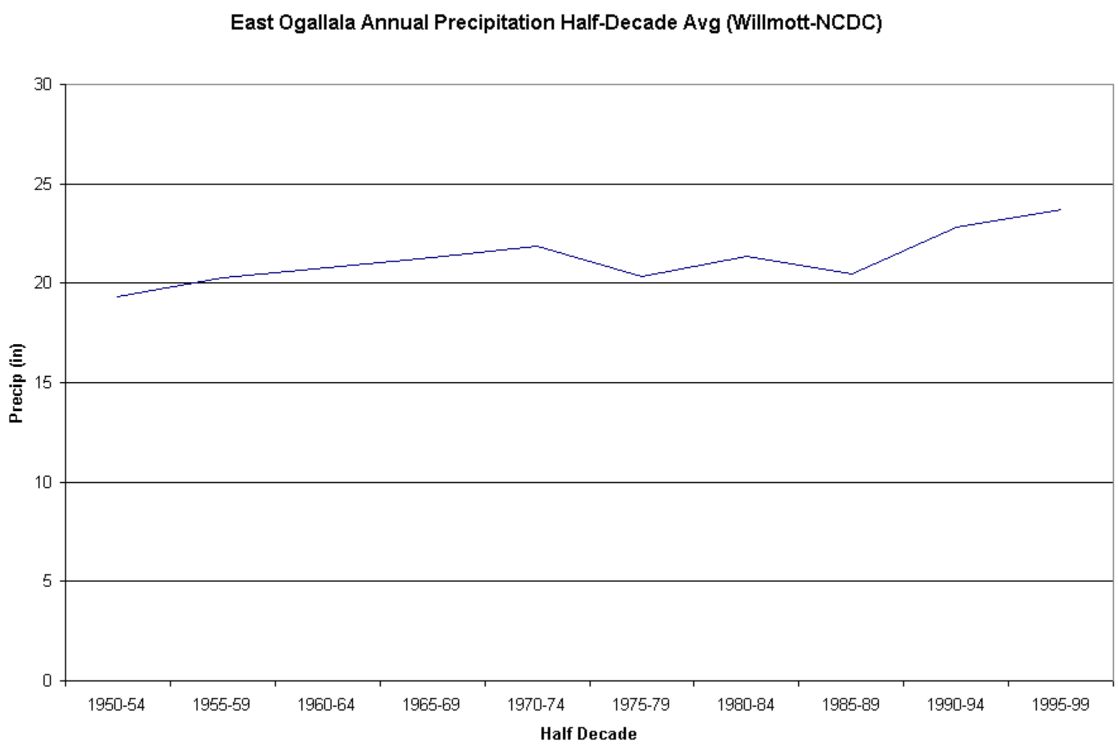
East Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)

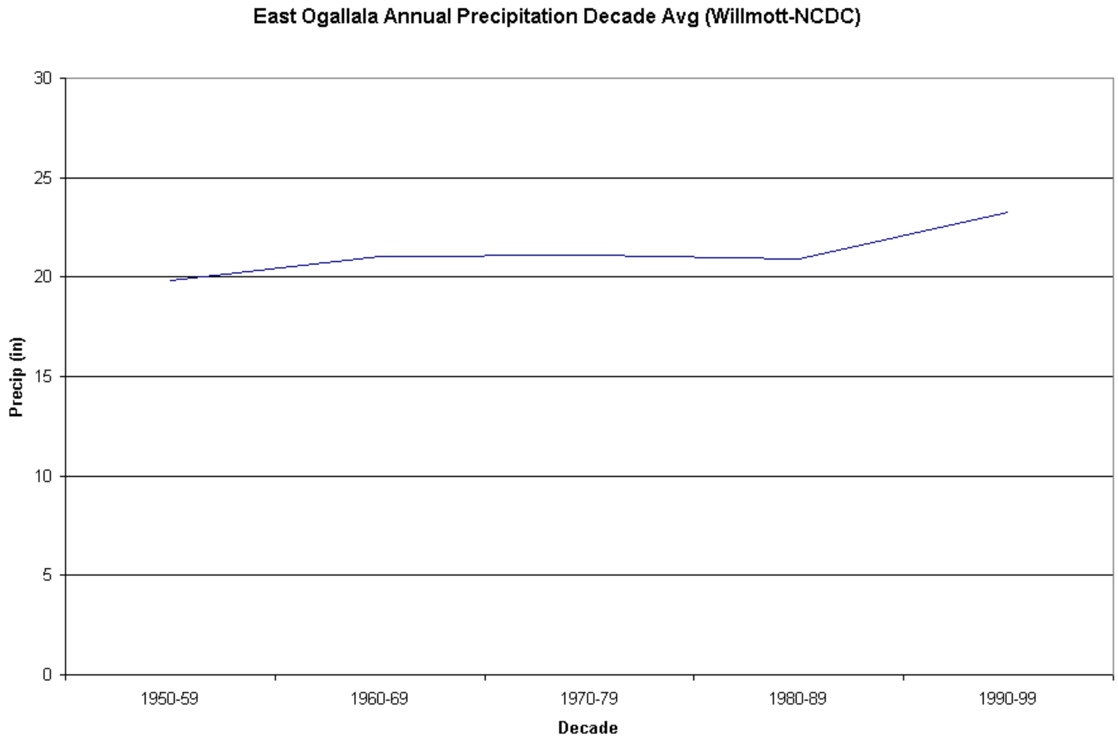


East Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)




East Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)
Precip (in)
0
5
10
15
20
25
30
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year


East Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)
Precip (in)
0
5
10
15
20
25
30
1950-54
1955-59
1960-64
1965-69
1970-74
1975-79
1980-84
1985-89
1990-94
1995-99
Half Decade


East Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
30
25
20
15
10
5
0
Precip (in)
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix 2. Derived Water Balance Plots

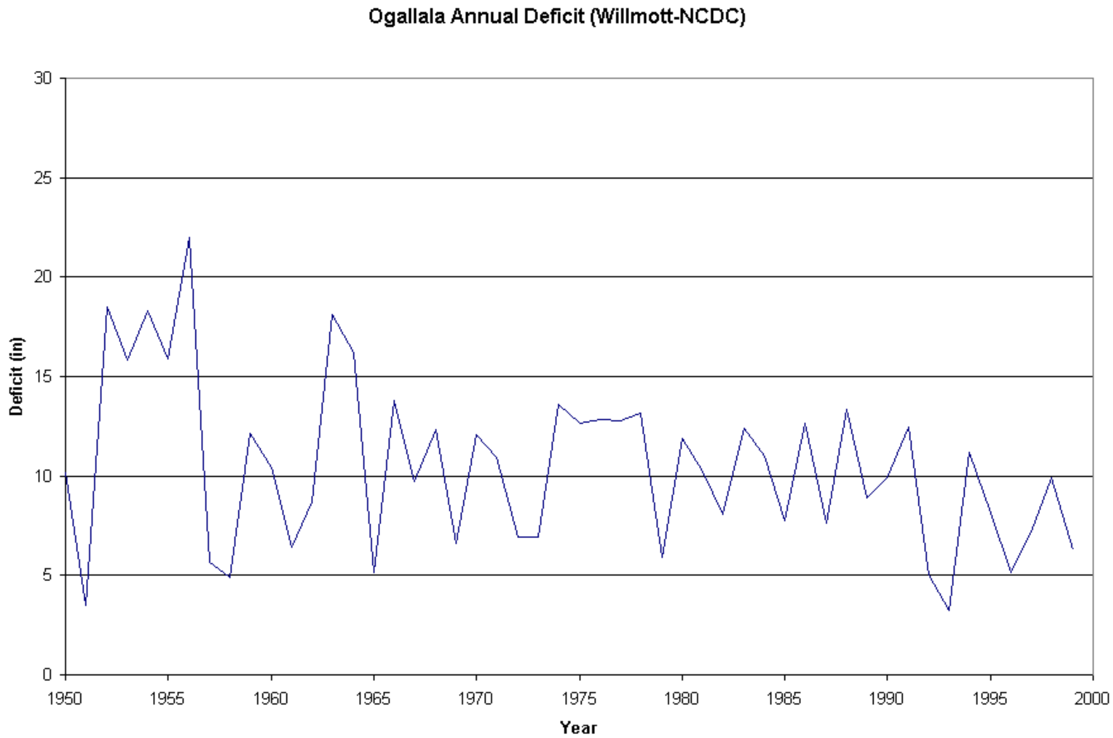
Data plotted are the regional annual averages, which are the sums of monthly values for the year of interest averaged over all the Willmott-NCDC half-degree cells in the designated region (Figure 4).

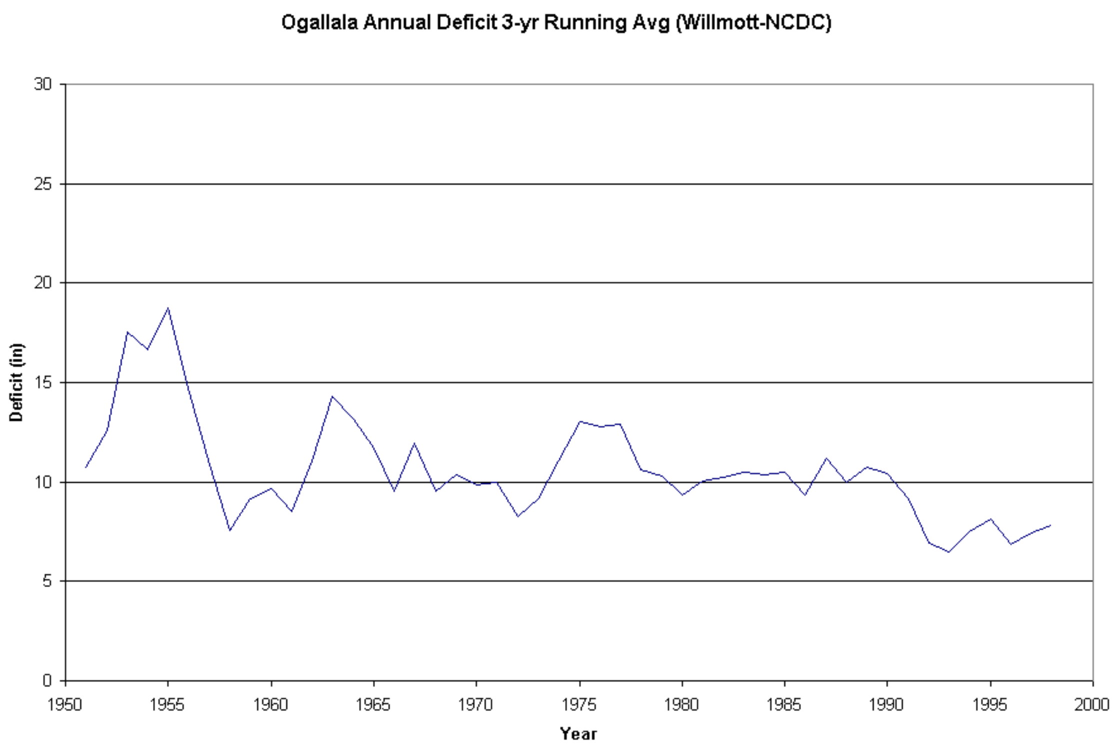
Values are plotted as individual year average totals and as running averages (also called "boxcar" averages) over 3, 5, 10, and 20 year time periods. In this presentation, the 3-year average for 1990, for example, is the average of values for 1989, 1990, and 1991. This averaging has the effect of making long-term trends or large-scale features in the data more visible.

Surplus and deficit values are the difference between the monthly precipitation and potential evapotranspiration values, which are summed to obtain an annual value. Evapotranspiration is the smaller of precipitation or potential evapotranspiration, taken on a monthly basis and summed for the annual value.

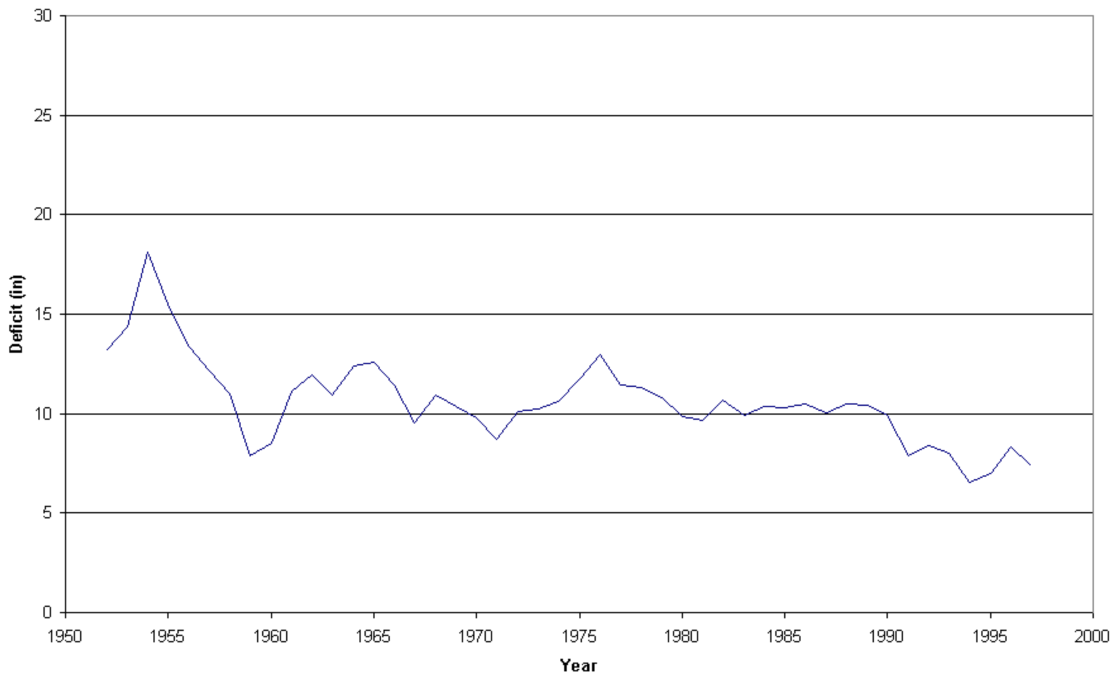
Contents

Appendix Figures 2.1. Deficit (Willmott and Matsuura, 2001)

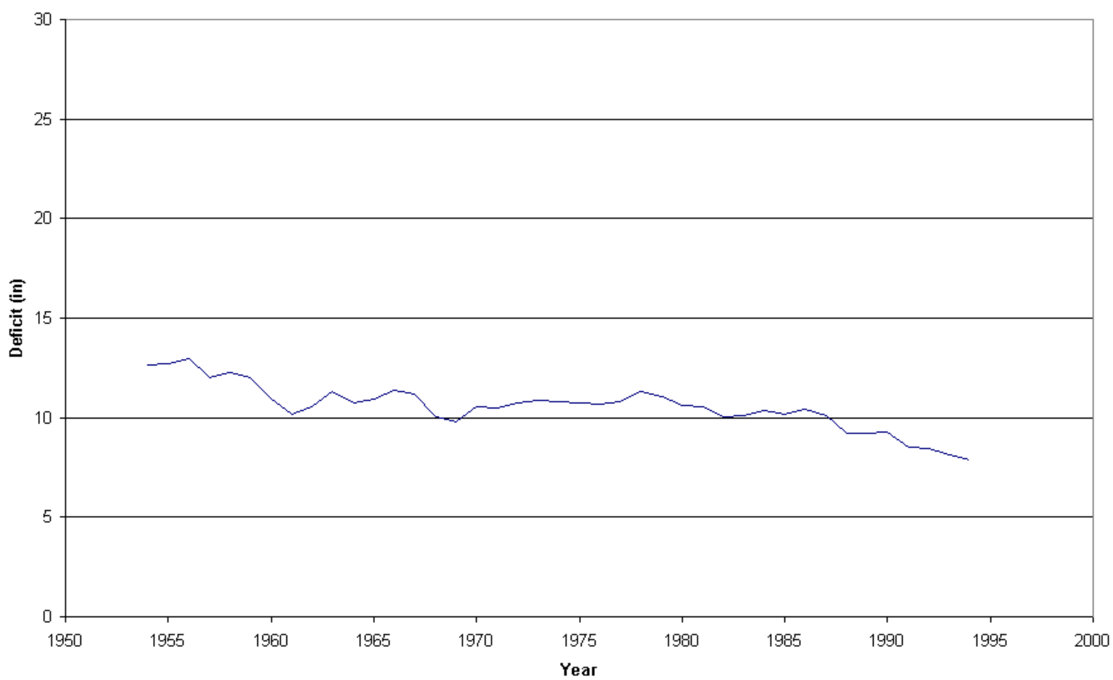




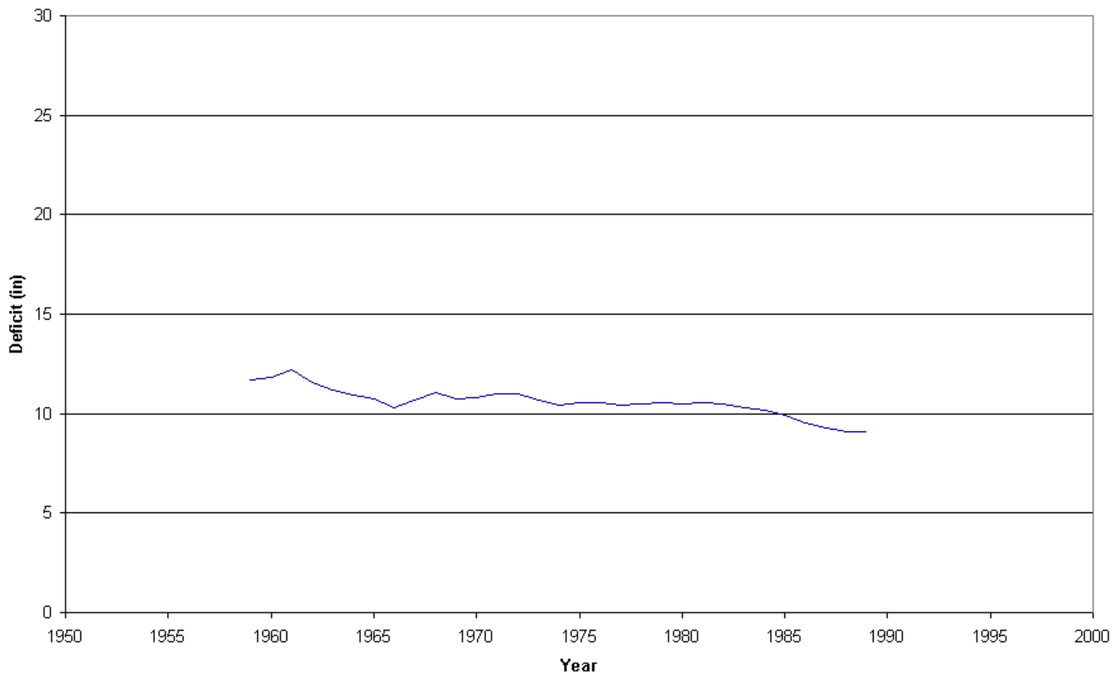
Ogallala Annual Deficit 5-yr Running Avg (Willmott-NCDC)



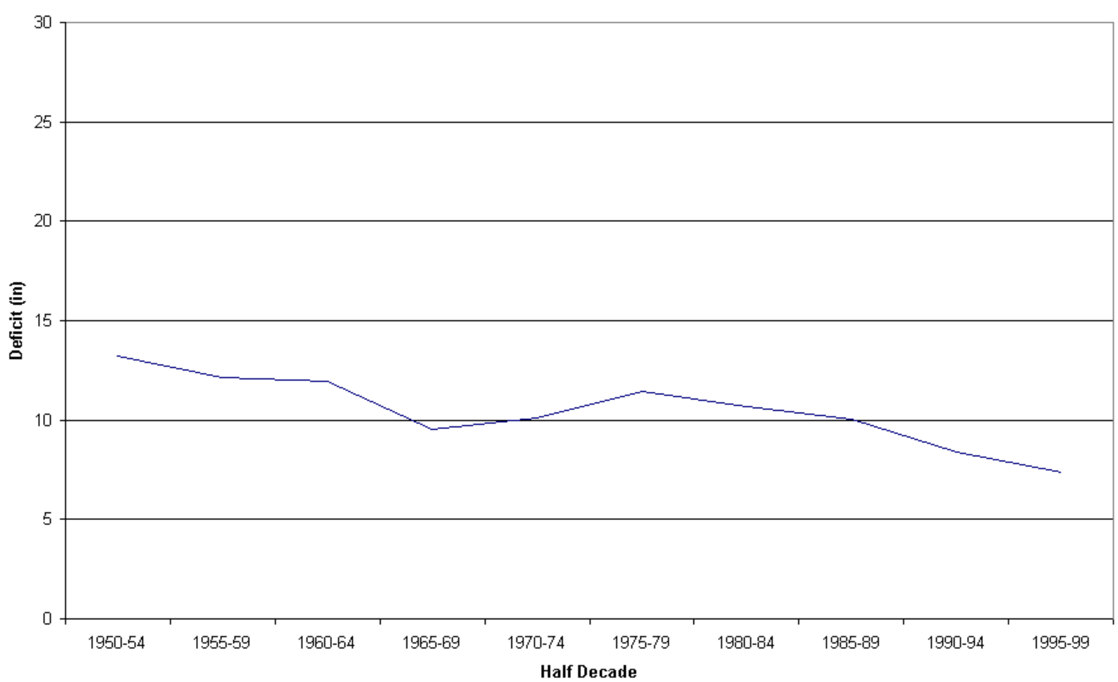
Ogallala Annual Deficit 10-yr Running Avg (Willmott-NCDC)

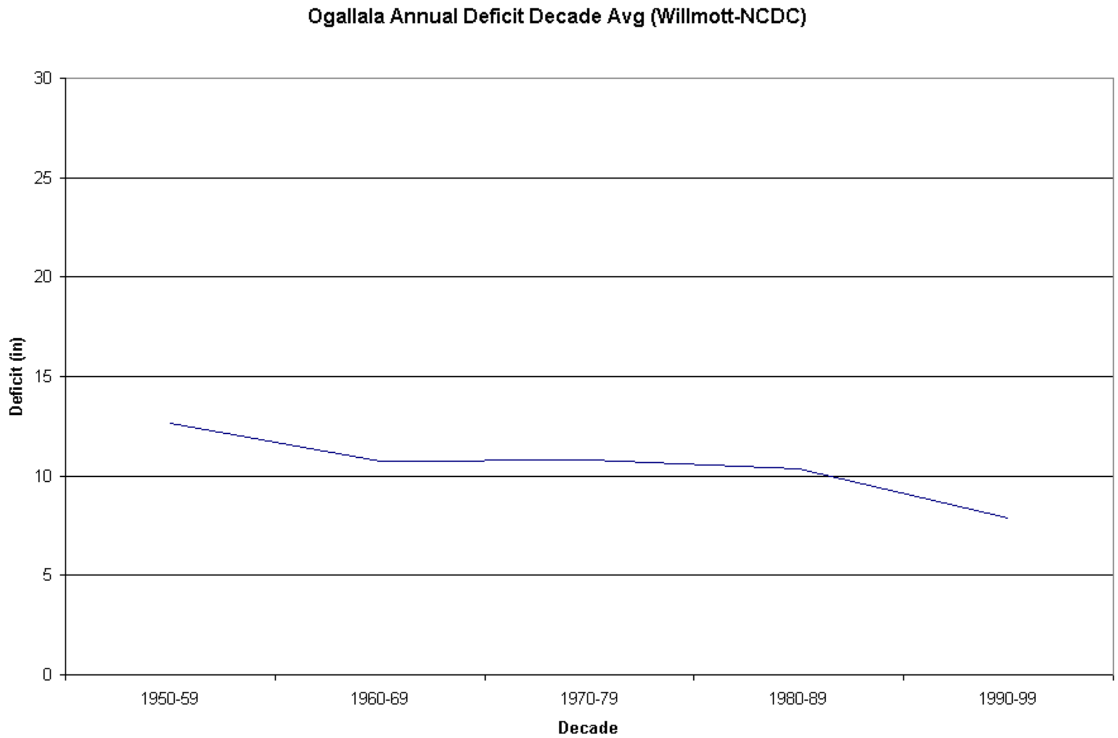


Ogallala Annual Deficit 20-yr Running Avg (Willmott-NCDC)

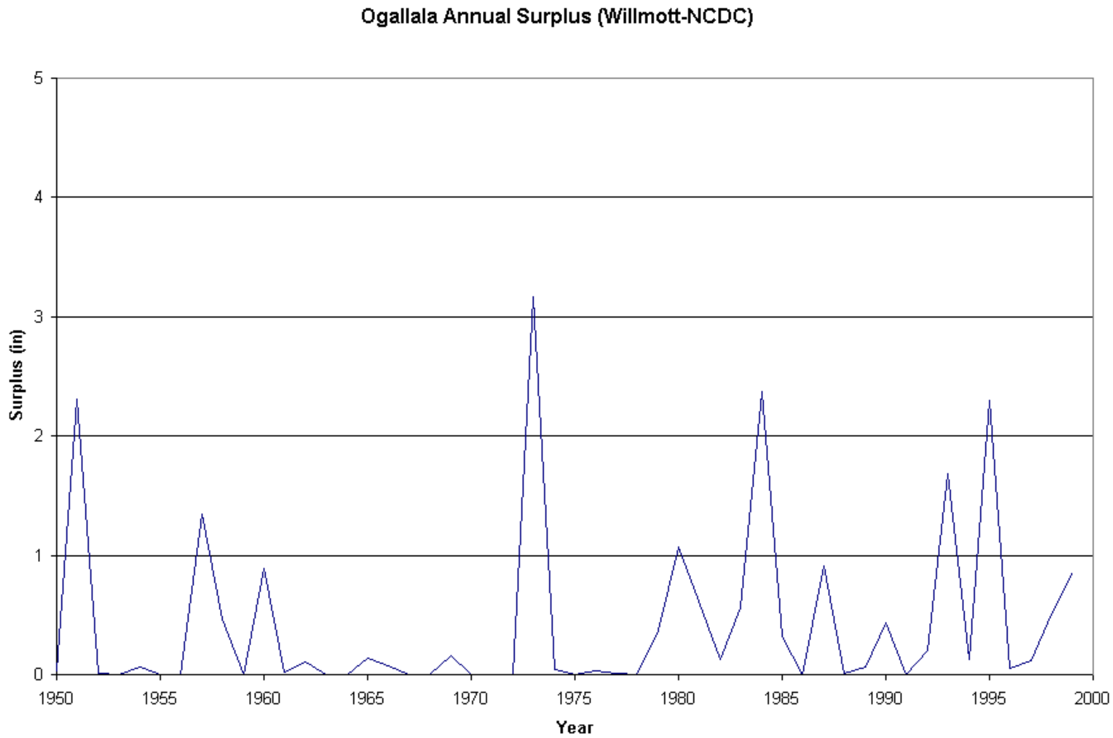


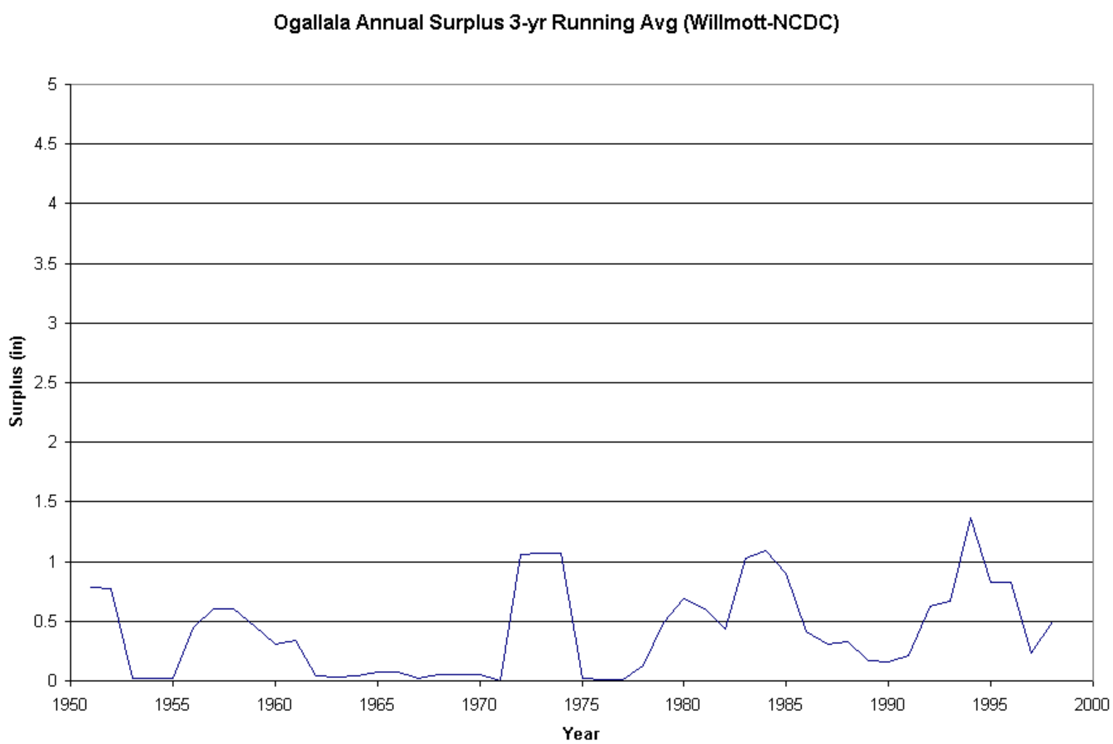
Ogallala Annual Deficit Half-Decade Avg (Willmott-NCDC)



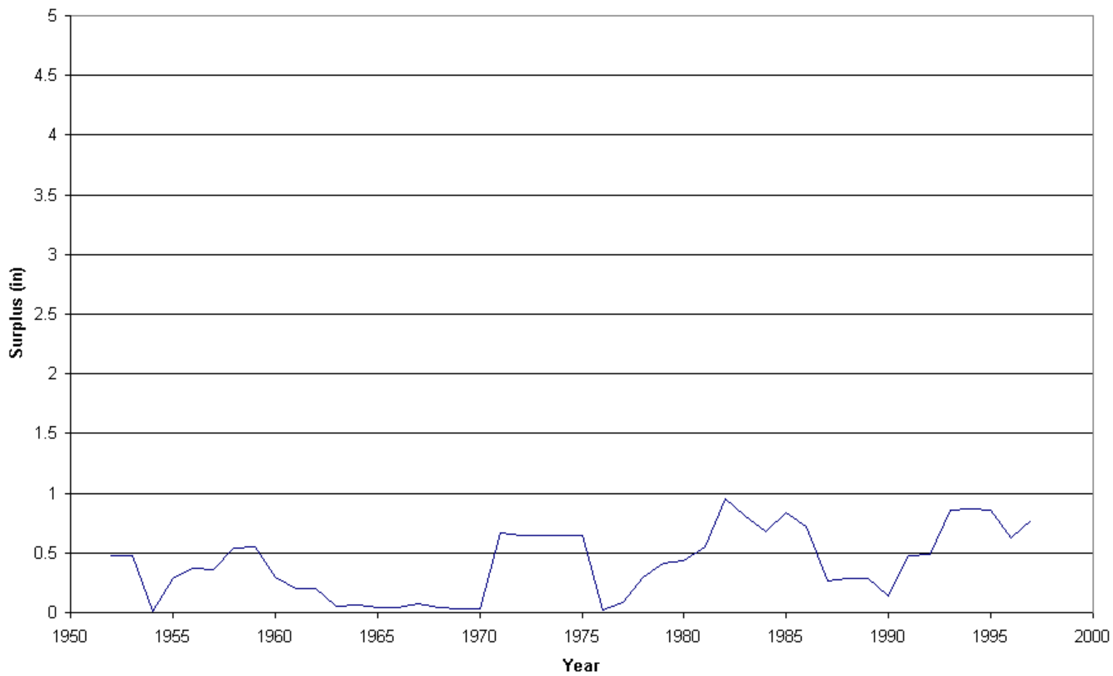

Ogallala Annual Deficit Decade Avg (Willmott-NCDC)
Deficit (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 2.2. Surplus (Willmott and Matsuura, 2001)

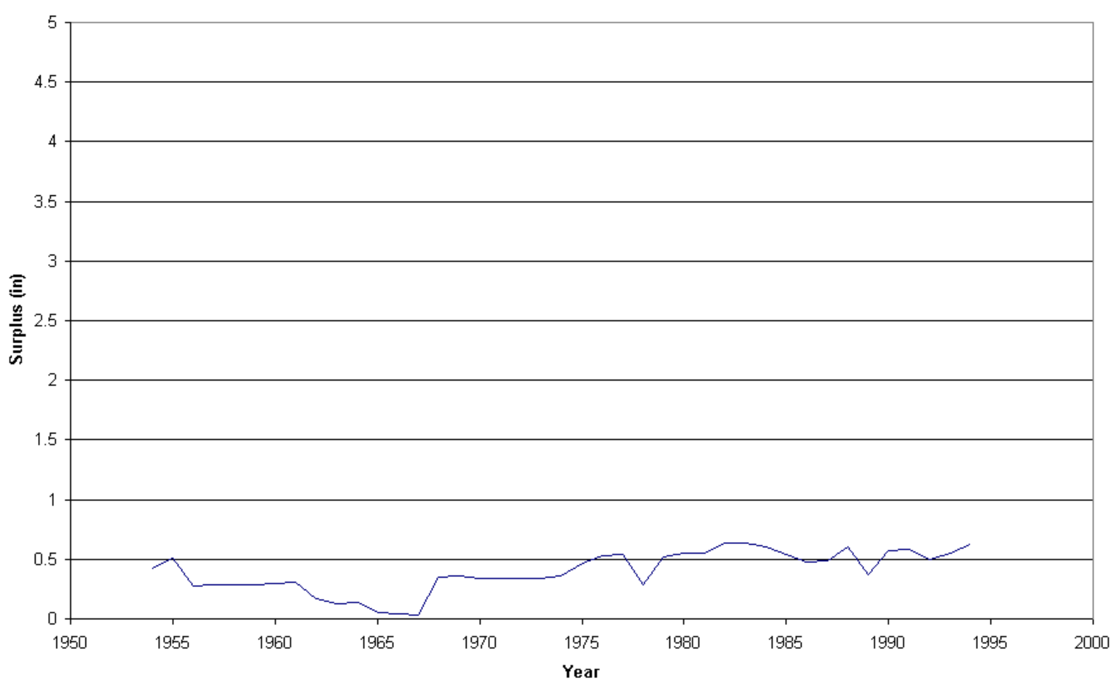


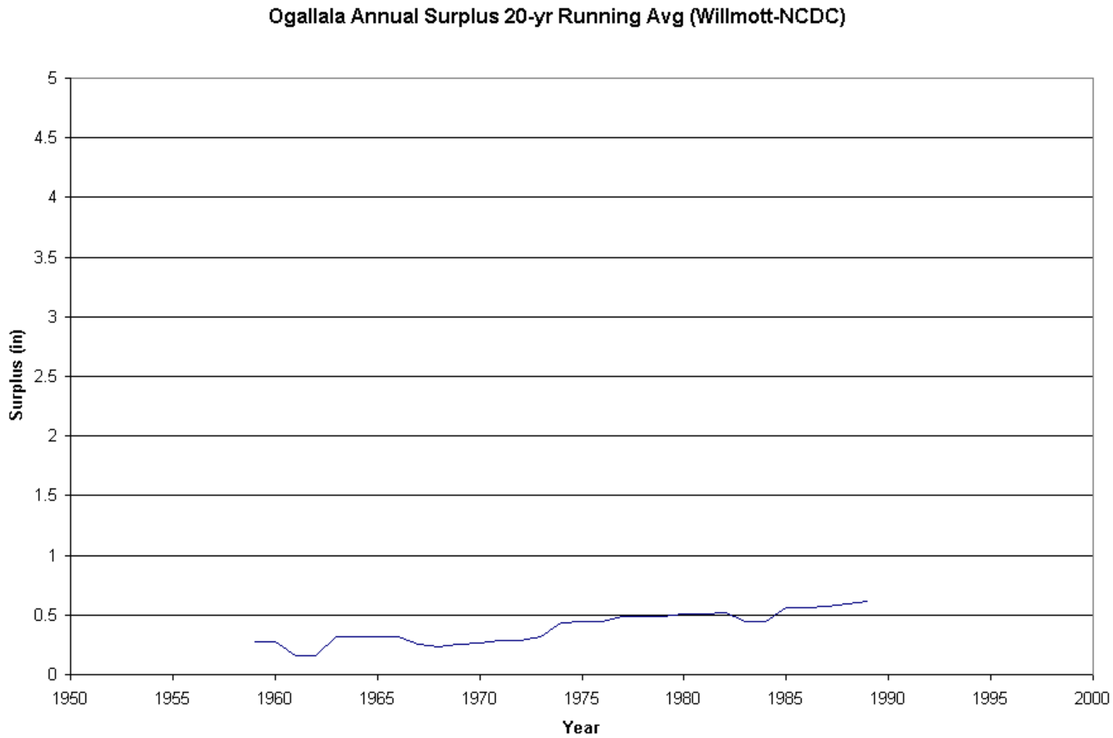


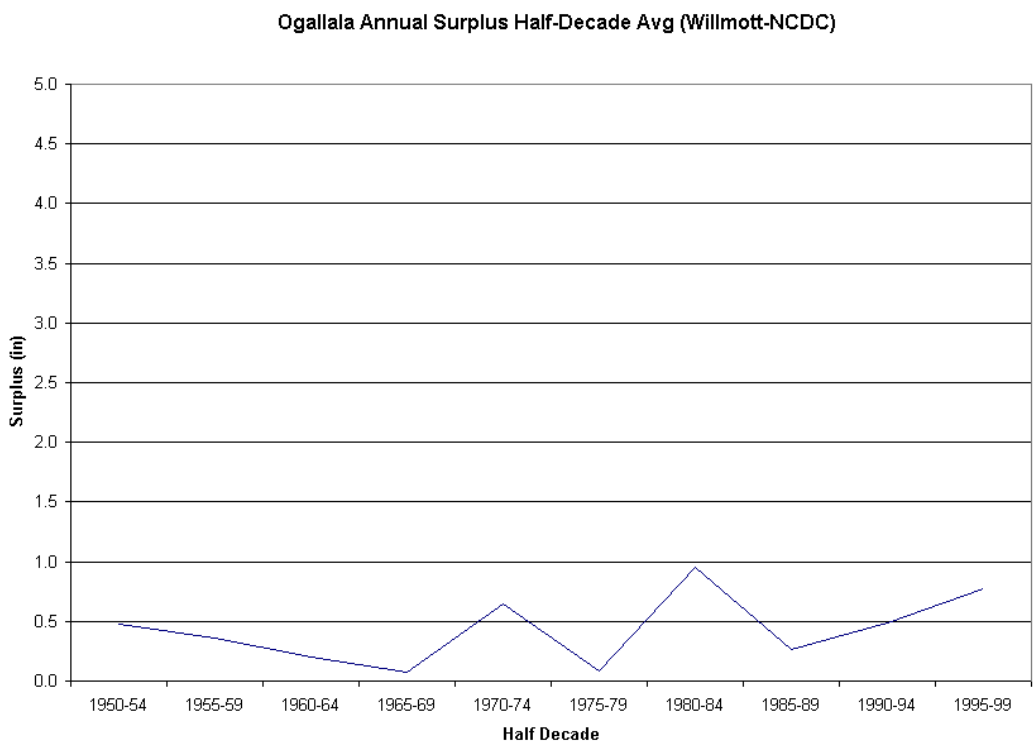
Ogallala Annual Surplus 5-yr Running Avg (Willmott-NCDC)

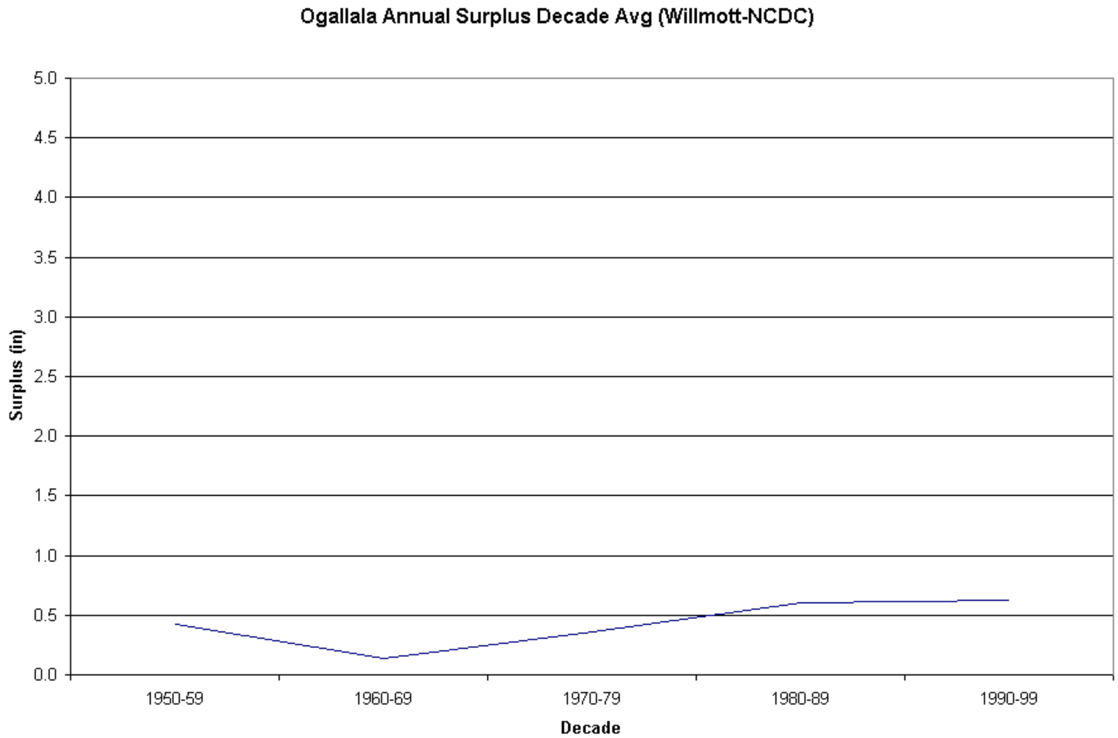


Ogallala Annual Surplus 10-yr Running Avg (Willmott-NCDC)

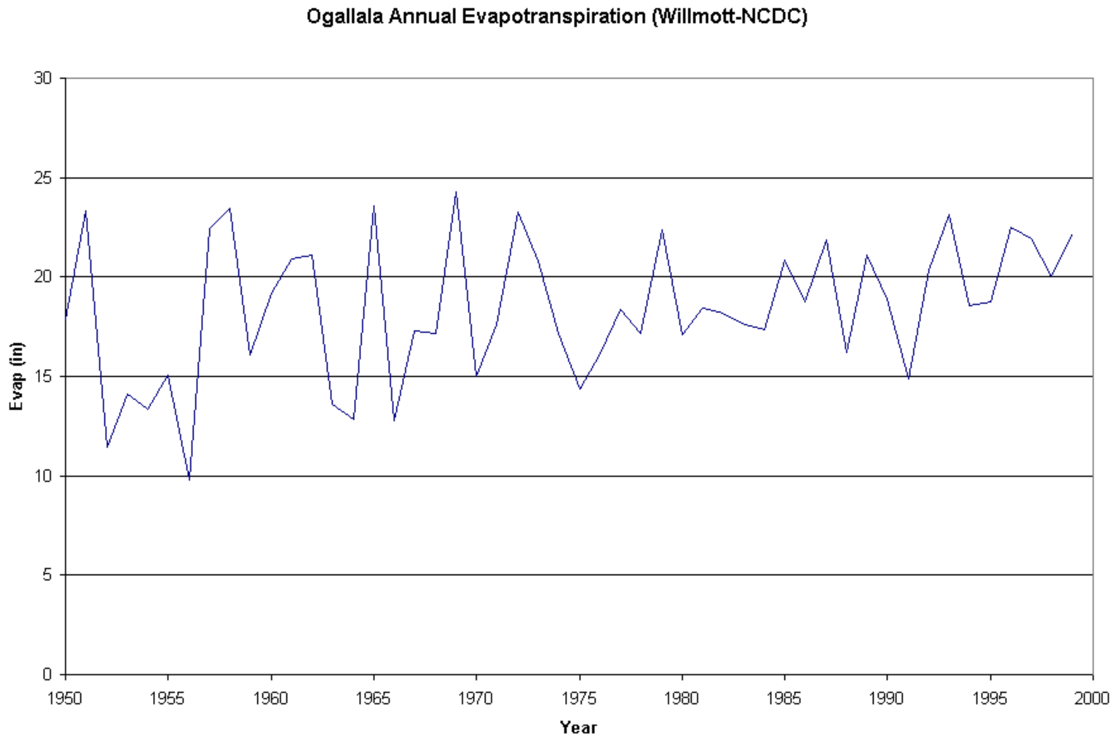


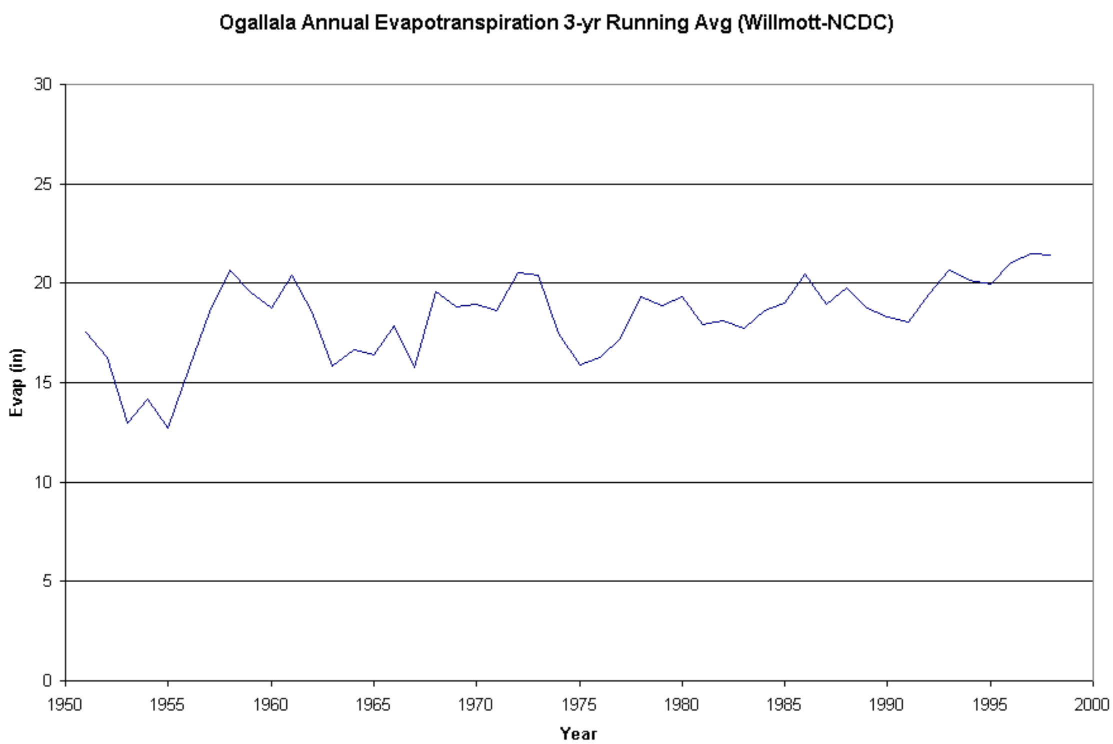

Ogallala Annual Surplus 20-yr Running Avg (Willmott-NCDC)
Surplus (in)
Year
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000


Ogallala Annual Surplus Half-Decade Avg (Willmott-NCDC)
Surplus (in)
Half Decade
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1950-54
1955-59
1960-64
1965-69
1970-74
1975-79
1980-84
1985-89
1990-94
1995-99

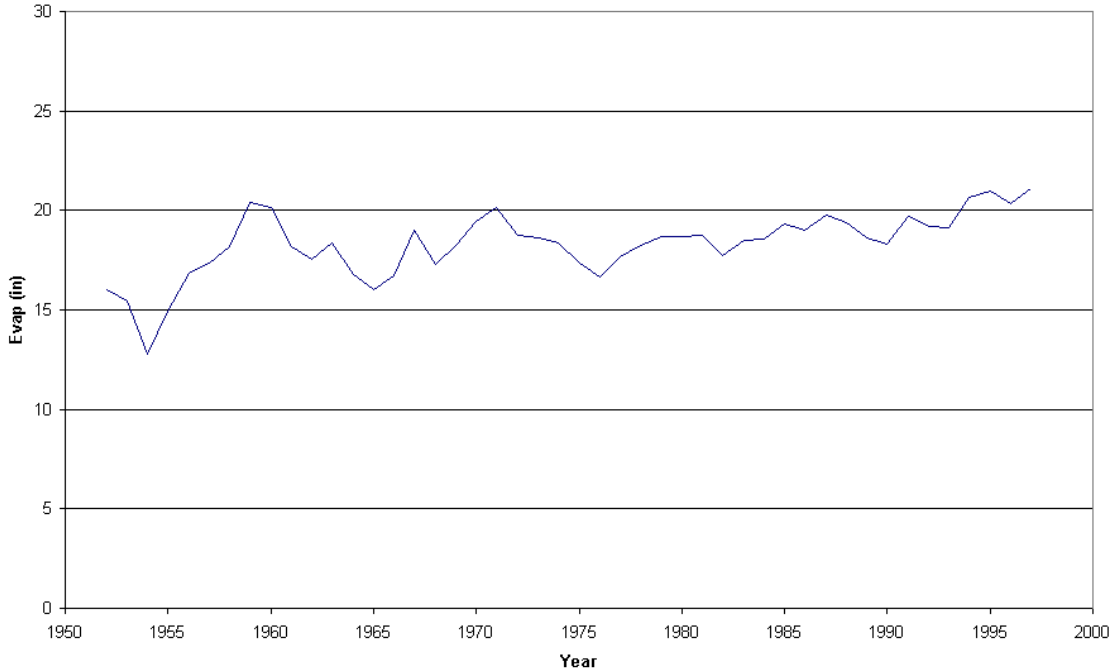

Ogallala Annual Surplus Decade Avg (Willmott-NCDC)
Surplus (in)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 2.3. Evapotranspiration (Willmott and Matsuura, 2001)

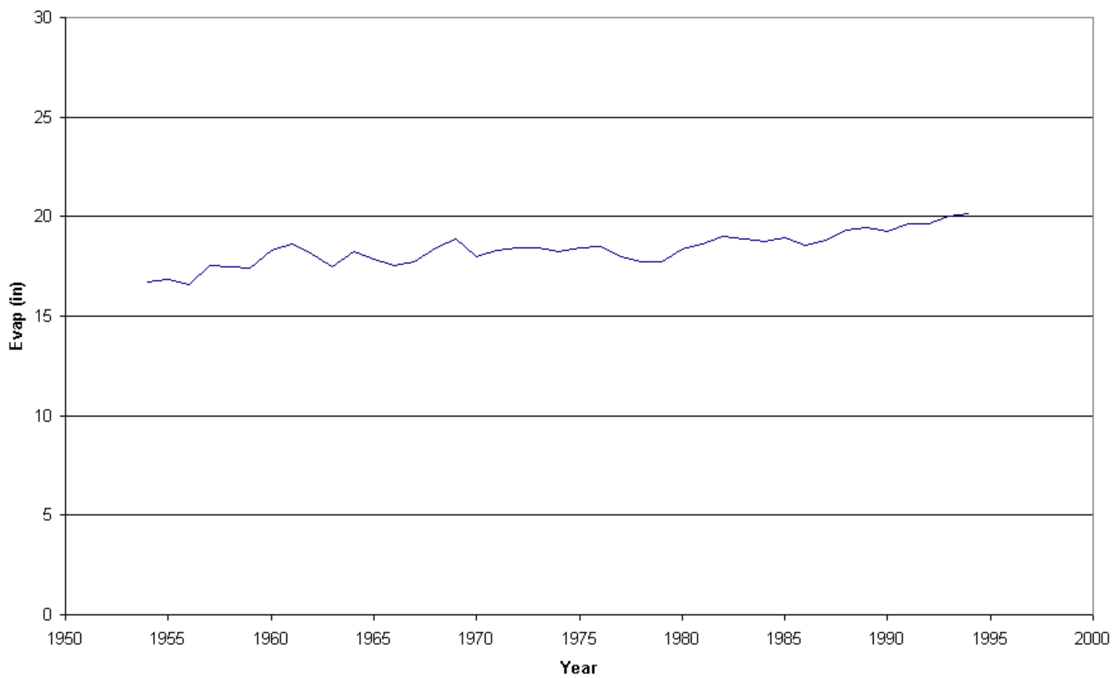


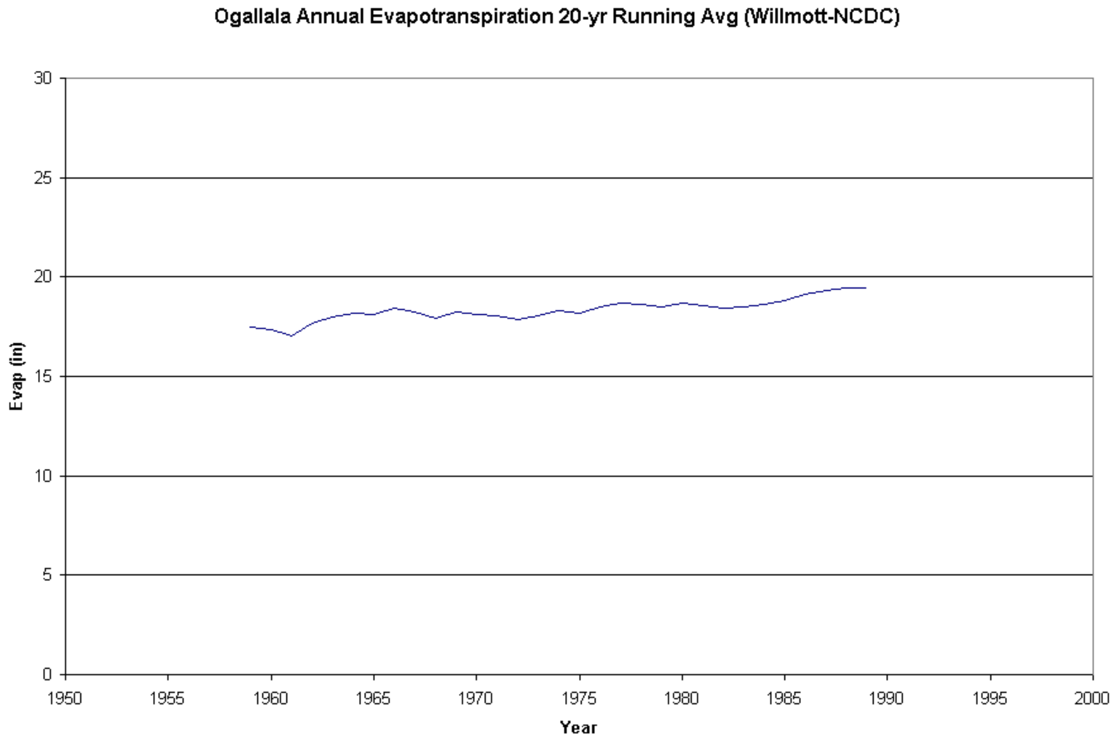


Ogallala Annual Evapotranspiration 5-yr Running Avg (Willmott-NCDC)

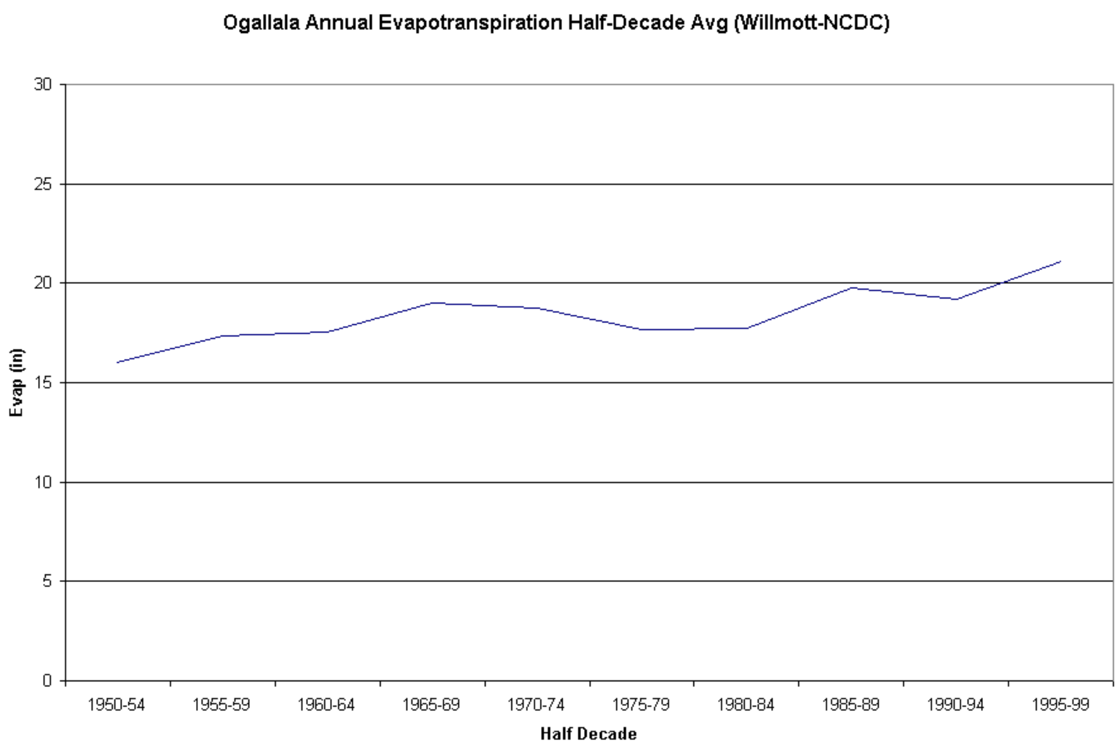


Ogallala Annual Evapotranspiration 10-yr Running Avg (Willmott-NCDC)

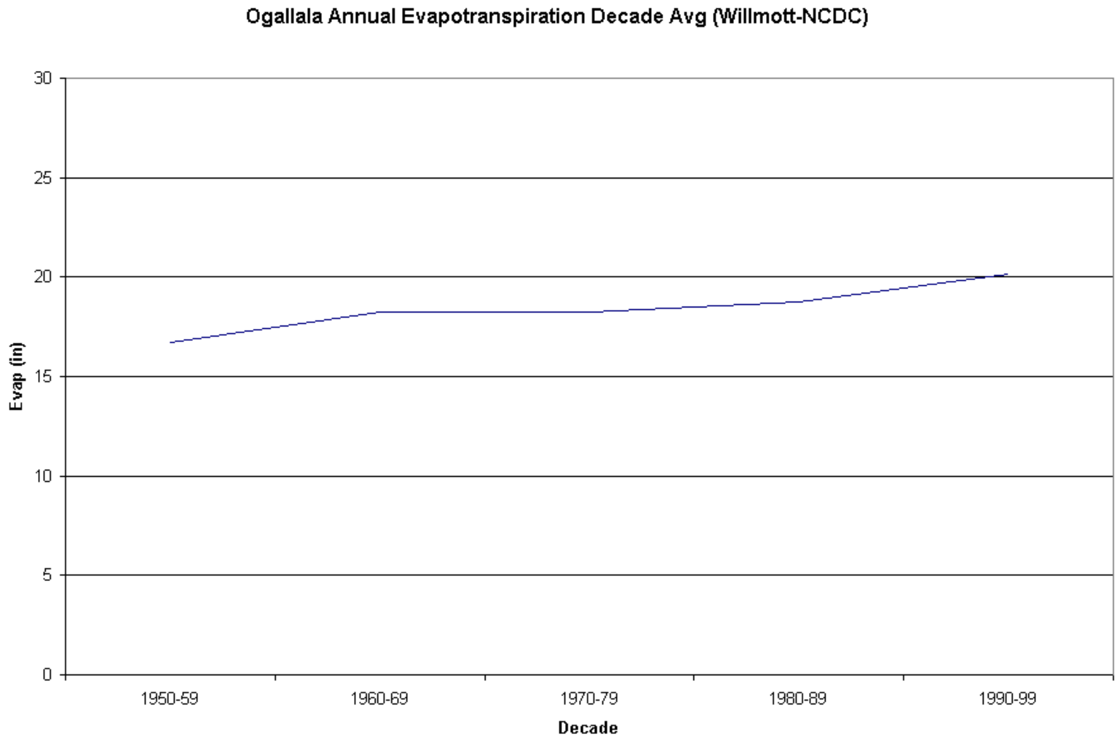




Ogallala Annual Evapotranspiration 20-yr Running Avg (Willmott-NCDC)
30
25
20
15
10
5
0
Evap (in)
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year

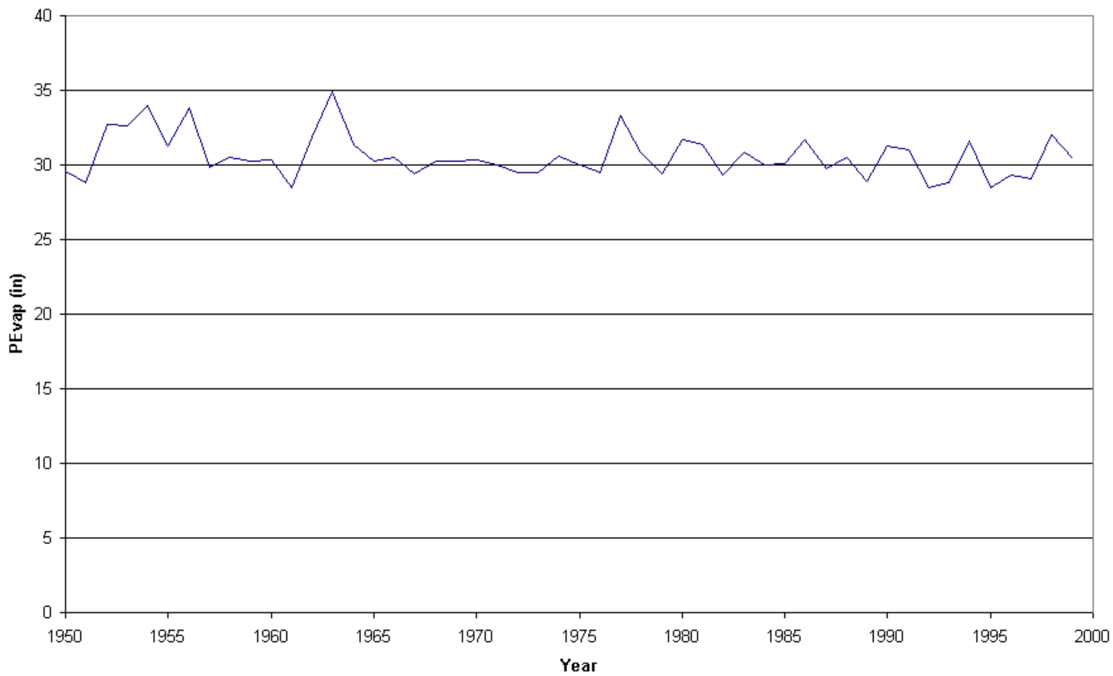


Ogallala Annual Evapotranspiration Half-Decade Avg (Willmott-NCDC)
30
25
20
15
10
5
0
Evap (in)
1950-54
1955-59
1960-64
1965-69
1970-74
1975-79
1980-84
1985-89
1990-94
1995-99
Half Decade

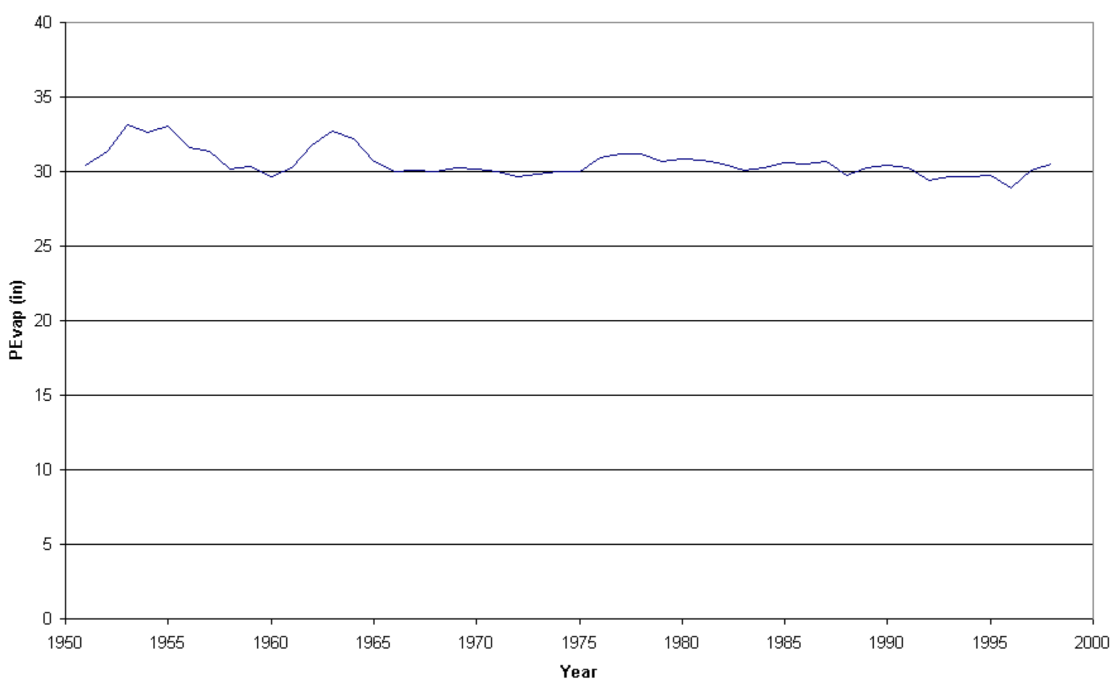

Ogallala Annual Evapotranspiration Decade Avg (Willmott-NCDC)
Evap (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 2.4. Potential Evapotranspiration (Willmott and Matsuura, 2001)

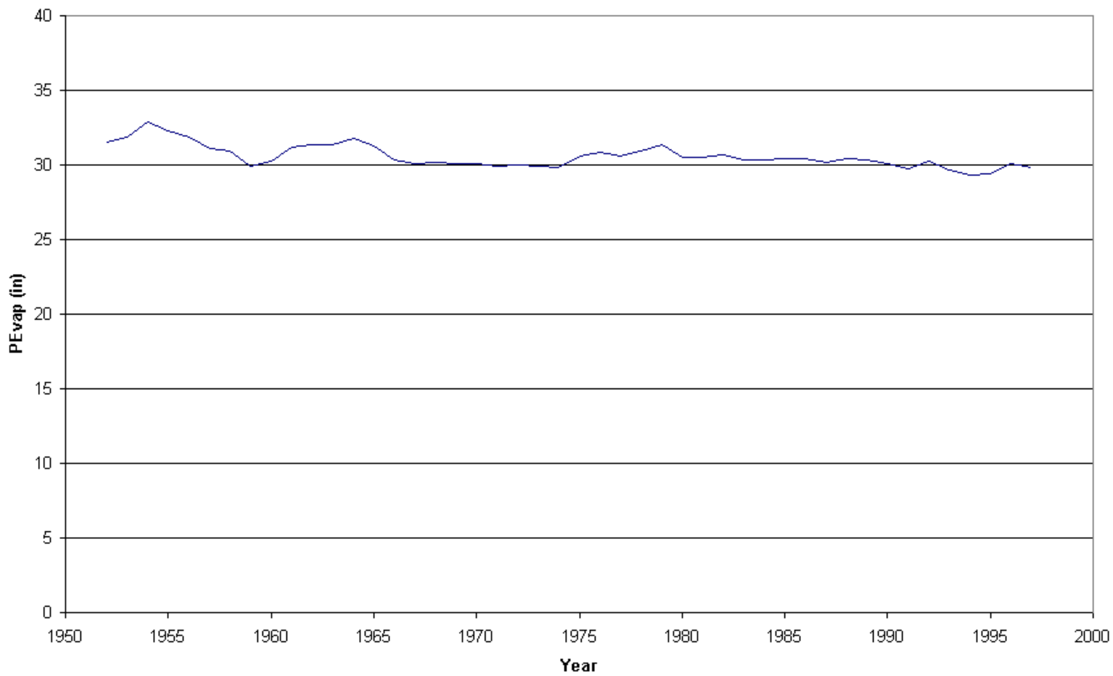
Ogallala Annual Potential Evapotranspiration (Willmott-NCDC)



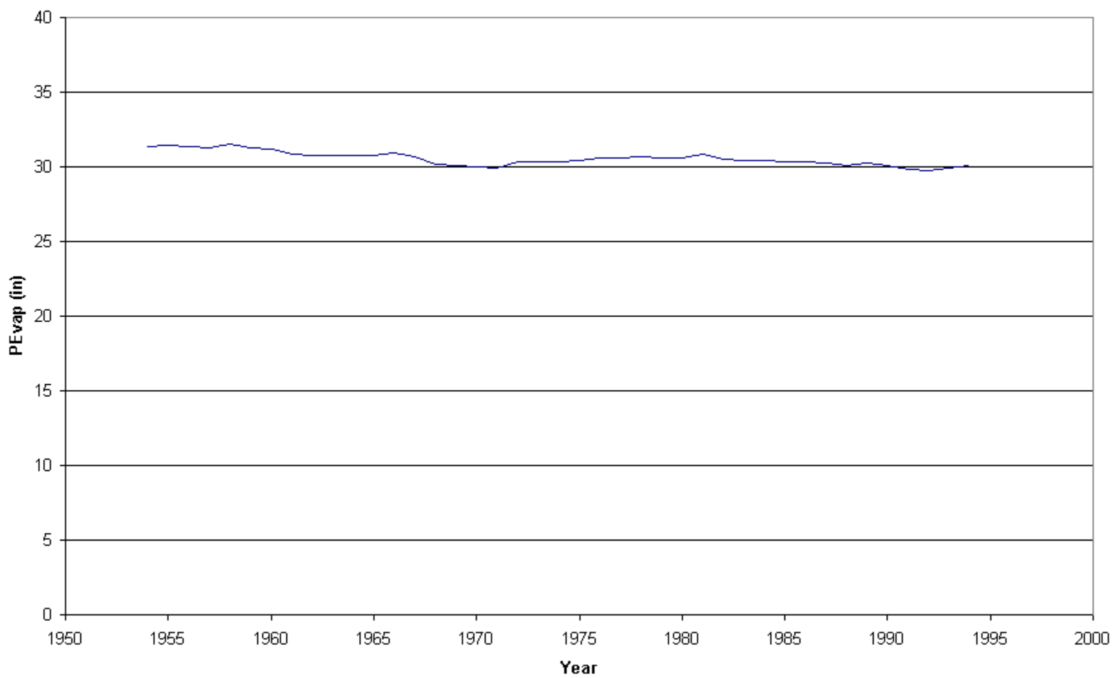
Ogallala Annual Potential Evapotranspiration 3-yr Running Avg (Willmott-NCDC)



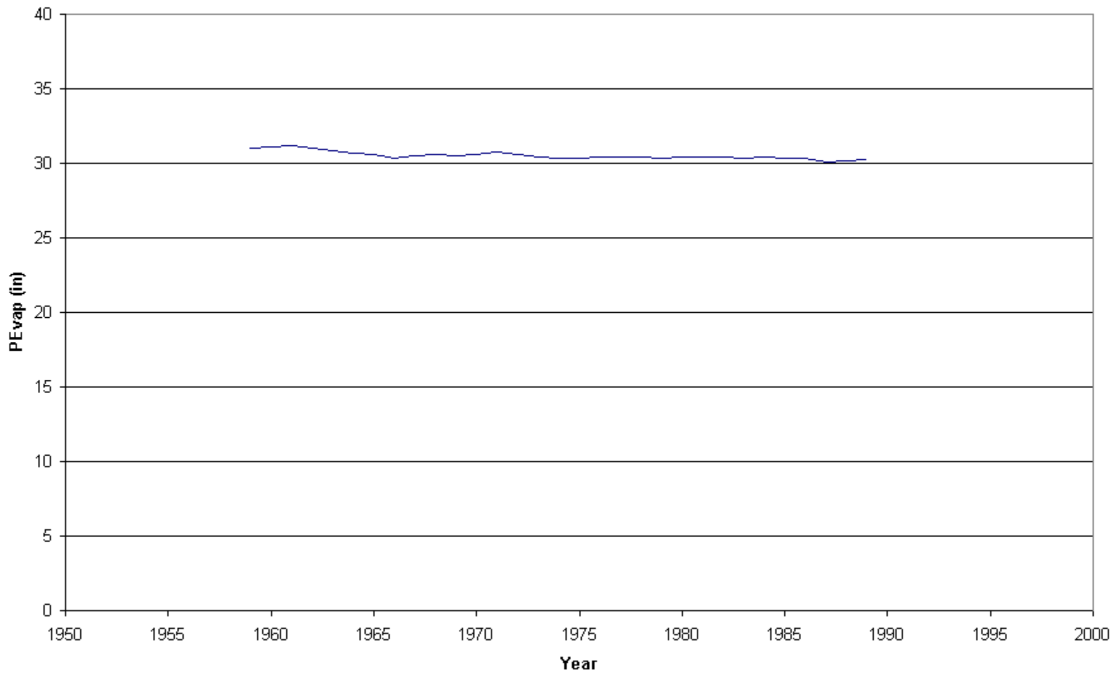
Ogallala Annual Potential Evapotranspiration 5-yr Running Avg (Willmott-NCDC)



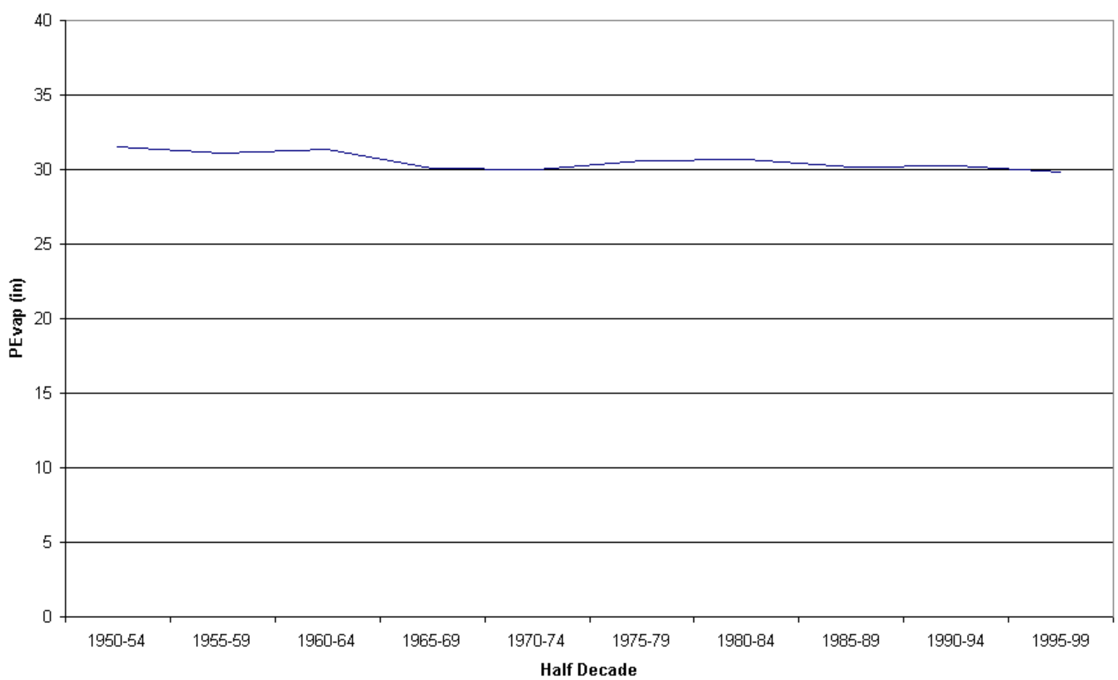
Ogallala Annual Potential Evapotranspiration 10-yr Running Avg (Willmott-NCDC)

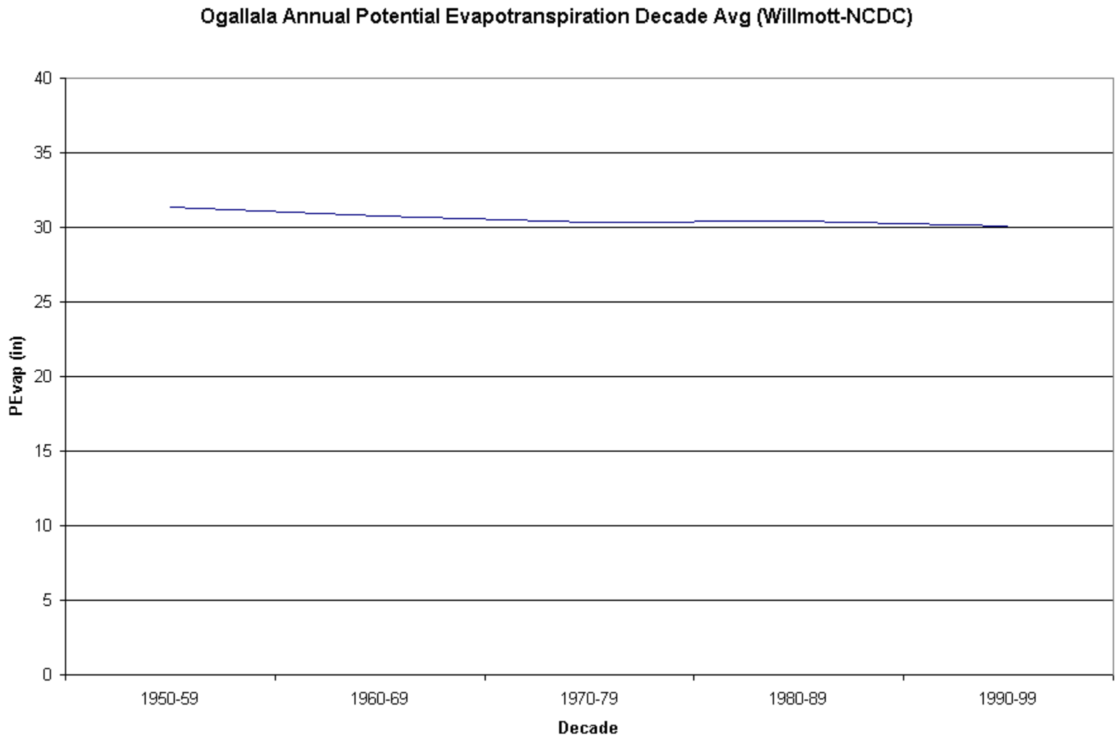


Ogallala Annual Potential Evapotranspiration 20-yr Running Avg (Willmott-NCDC)



Ogallala Annual Potential Evapotranspiration Half-Decade Avg (Willmott-NCDC)




Ogallala Annual Potential Evapotranspiration Decade Avg (Willmott-NCDC)
40
35
30
25
20
15
10
5
0
PEvap (in)
1950-59
1960-69
1970-79
1980-89
1990-99
Decade