Kansas Geological Survey

Open-file Report series 2002-25

Technical Support for Ogallala Aquifer Assessment, Planning, and Management

2002-25A: The Kansas water context: Background, description, and summary of work. R. W. Buddemeier, B. B. Wilson, D. O. Whittemore, T. Huntzinger, T. Alder, E. Lewis and S. Stover

2002-25B: Best estimates of aquifer recharge: magnitude and spatial distribution. G. R. Hecox, D. O. Whittemore, R. W. Buddemeier, and B. B. Wilson

2002-25C: Calculation of yield for High Plains aquifer wells: relationship between saturated thickness and well yield. G. R. Hecox, P. A. Macfarlane, and B. B. Wilson

2002-25D Exploring relationships between water-table elevations, reported water use, and aquifer lifetime as parameters for consideration in aquifer subunit delineations. B. B. Wilson, D. P. Young, and R. W. Buddemeier

2002-25E: Climatic variation: implications of long-term records and recent observations. D. P. Young and R. W. Buddemeier

2002-25F: Scale, uncertainty, and the relationships among basic data, information, and management perspectives. R. W. Buddemeier, B. B. Wilson, J. Mosteller, and G. Hecox

2002-25G: Information Sheets and Supplementary Documents. M. A. Townsend, D. O. Whittemore, D. P. Young, G. Hecox, P. A. Macfarlane, M. A. Sophocleous, and R. W. Buddemeier

A final report of fiscal year 2002 activities by the Kansas Geological Survey supported by contracts with the Kansas Water Office and the Kansas Department of Agriculture

Kansas Geological Survey Open File Report 2002-25

GEOHYDROLOGY

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Kansas Geological Survey

Open File Report 2002-25A

The Kansas water context: Background, description, and summary of work

By

R. W. Buddemeier, B. B. Wilson, and D. O. Whittemore
(Kansas Geological Survey)

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GEOHYDROLOGY

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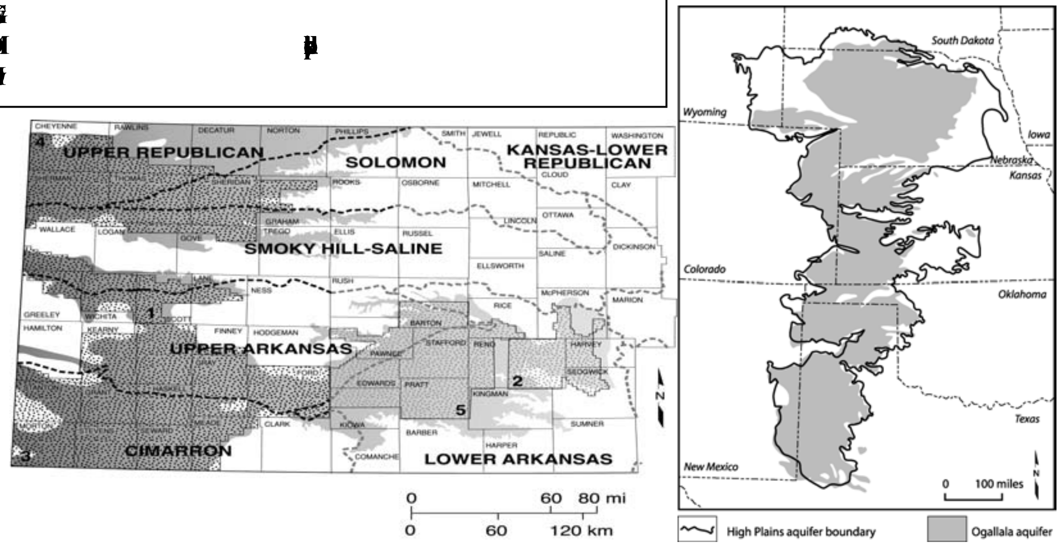
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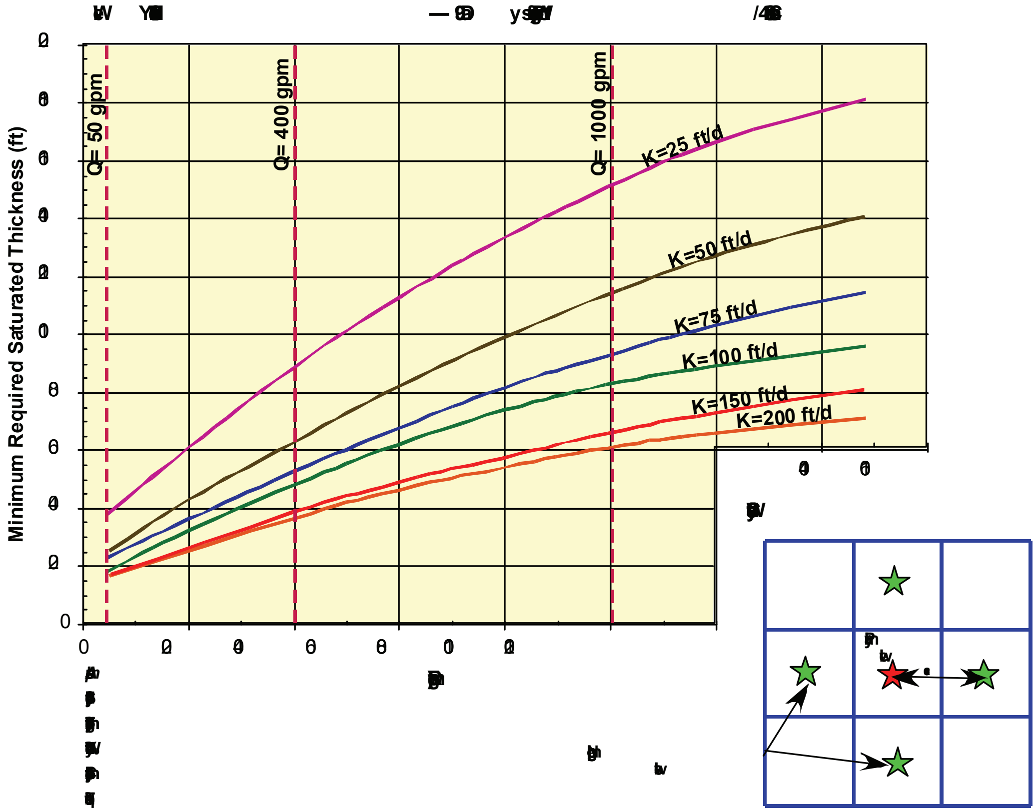
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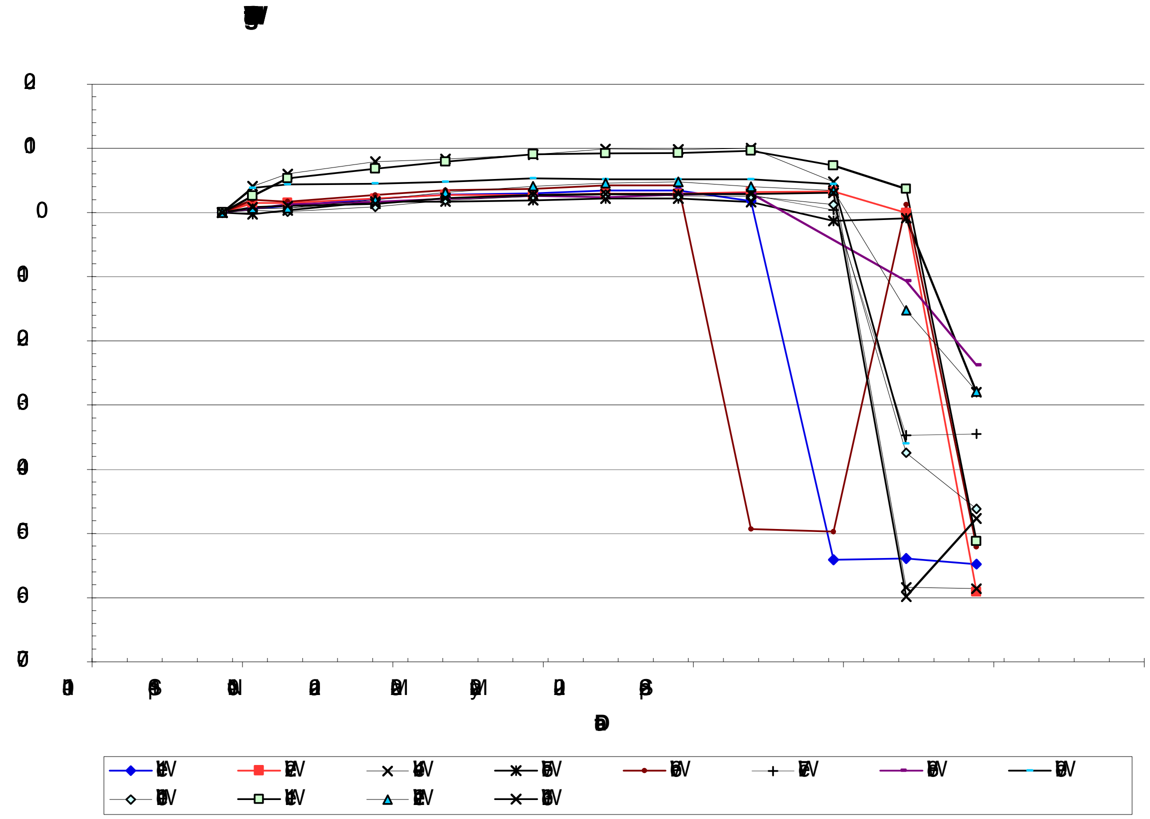
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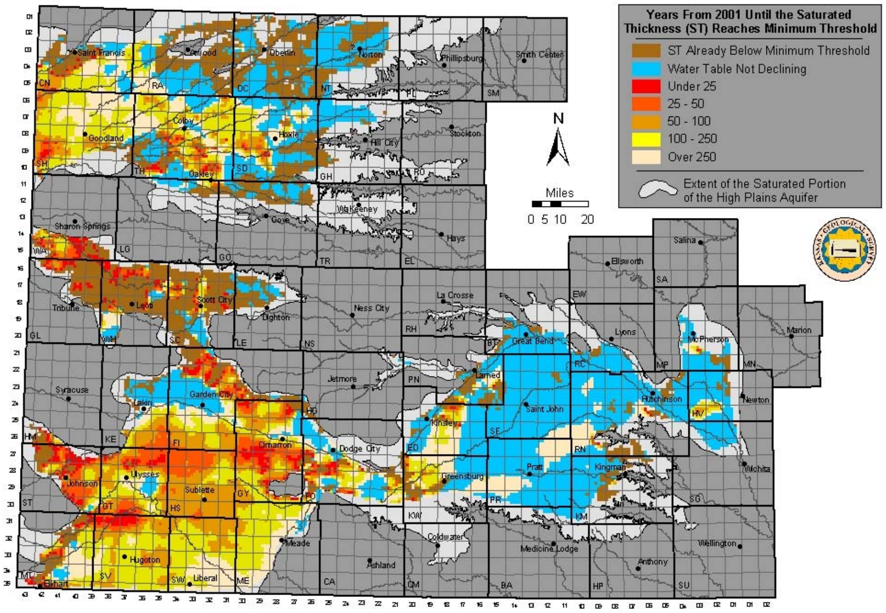
Estimated Usable Lifetime for the High Plains Aquifer in Kansas
(Based on ground water trends from 1991 to 2001 and the minimum saturated thickness required to support well yields at 400 gpm under a scenario of 90 days of pumping with wells on 1/4 section)



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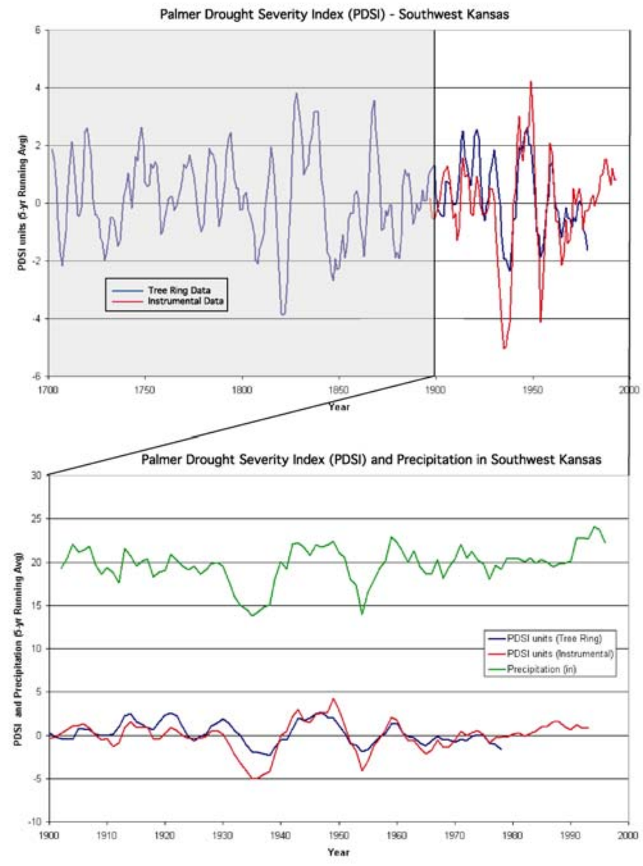
Palmer Drought Severity Index (PDSI) - Southwest Kansas
PDSI units (5-yr Running Avg)
6
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2000
Year
Tree Ring Data
Instrumental Data
Palmer Drought Severity Index (PDSI) and Precipitation in Southwest Kansas
PDSI and Precipitation (5-yr Running Avg)
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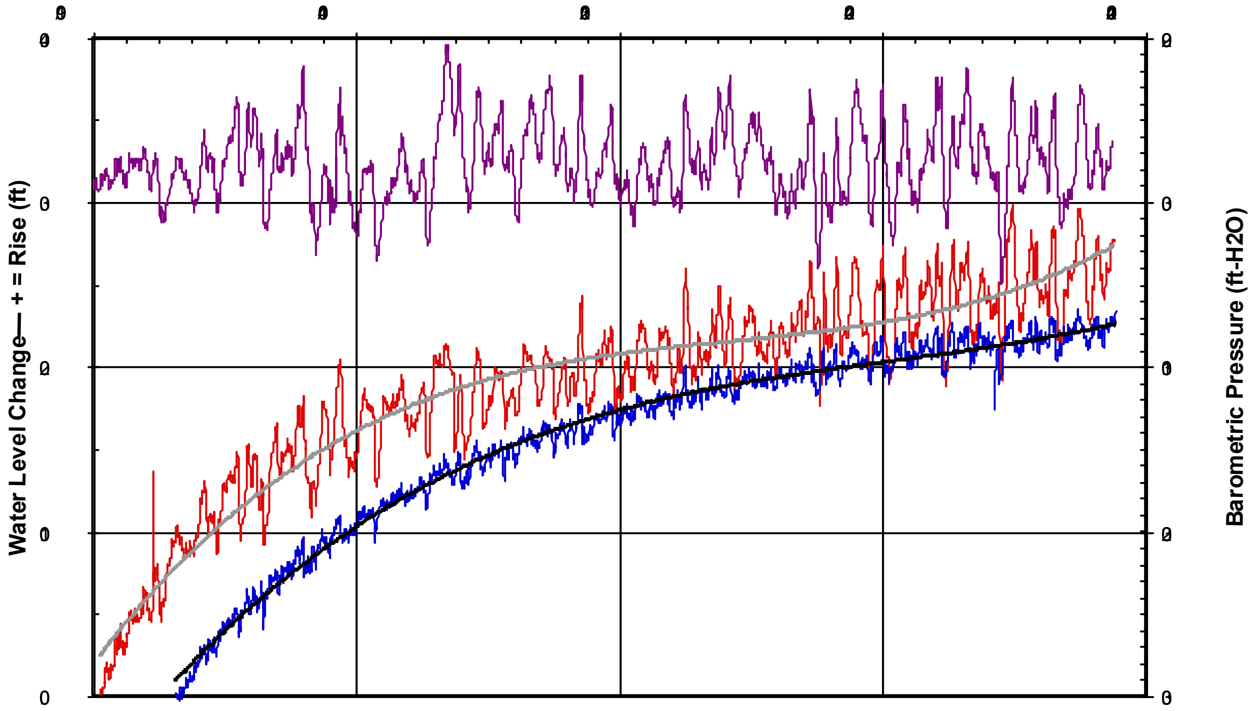
Water Level Change— + = Rise (ft)
Barometric Pressure (ft-H2O)

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Kansas Geological Survey

Open File Report 2002-25B

Best Estimates of Aquifer Recharge: Magnitude and Spatial Distribution

By

G.R. Hecox, D.O. Whittemore, R.W. Buddemeier, and B.B. Wilson

With contributions from other authors in the report series

A component of the Technical Report series 2002-25: Technical Support for Ogallala Aquifer Assessment, Planning, and Management

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KGS OFR 2002-25B. Best estimates of aquifer recharge from a magnitude and spatial sense

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KGS OFR 2002-25B.
Best estimates of aquifer recharge magnitude and spatial distribution
By G.R. Hecox, D.O. Whittemore, R.W. Buddemeier, and B.B. Wilson

1. Introduction

This report on exploring relationships between water table elevations, reported use, and aquifer lifetime as parameters for consideration in aquifer subunit delineations (OFR 2002-25D) 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.

The data presented were compiled from multiple sources. These references were obtained by querying various on-line databases and following citations referenced in the respective publications. For this evaluation, attempts were made to separate those values that are attributed to natural recharge as compared to those that result from anthropogenic (man-made) recharge sources. The methods of determining recharge varied from detailed measurements in the vadose zone above the water table (e.g. Sophocleous et al., 2002), water table fluctuations (e.g. Heimes et al., 1987), water balance groundwater models (Stullken et al., 1985) and detailed numerical groundwater flow simulations (e.g. Luckey et al., 1986). Also included is a case study of recharge determined for the upper Arkansas River corridor by a recent KGS study (section 3).

1.1 Methods for estimating recharge rates

Scientists using various techniques have developed recharge values tabulated in this review:

- Point measurements—Using several methods for measuring the values for various groundwater parameters and chemistry in the vadose zone above the water table, it is possible to calculate site-specific recharge rates and quantities at specific locations. Sophocleous (1992a and b, 1993), Scanlon and Goldsmith (1997), and Sophocleous et al. (2002) present examples of various instrumentation methods used to determine recharge rates at point locations. These methods typically use modified forms of Darcy's law (Freeze and Cherry, 1979; Fetter, 2001) to calculate the recharge flux (volume of water per unit of time) to the water table.
- Water balance—Also known as water budget methods, water balance methods are based on measurements and calculations of different components such as precipitation, streamflow, irrigation diversions, surface water evaporation, evapotranspiration from evapotranspiration rates and distribution of vegetation. The basic premise for all water balance methods is that the water flowing into an aquifer has to equal to the sum of the water flowing out of the aquifer and the change in water stored within the aquifer. Heimes et al. (1987) present an application of water balance methods for determining recharge rates. A Kansas example is presented in section 2.2 of KGS OFR 2002-25G (this report series).
- Ground-water flow model—Ground-water numerical models, also referred to as numerical simulations, can be viewed as sophisticated water balance methods when used to determine recharge. Because recharge is an important component in the development of ground-water models, recharge rates generally have to be

estimated during the model calibration process. Ground-water modeling methods can be used to separately estimate the various components of recharge including areal recharge, stream losses, irrigation returns, and pond infiltration. Unfortunately, the ground-water model calibration process does not necessarily result in unique hydrogeologic values (Zheng and Bennett, 1995). Inaccuracies can be large in some models because calibration can introduce error into initial recharge estimates for nodes or cells to match hydraulic heads. Stullken et al. (1985), Luckey et al. (1986) and Whittemore (2002) provide examples of the use of ground-water models for estimating recharge.

1.2 Recharge components

Ground-water recharge can be separated into natural components and anthropogenic (human-related) components that include various sources of water that infiltrate into the soil column, flow below the root zone, and eventually reach the water table. This distinction is important because the anthropogenic factors can increase the recharge rate in an area by several times compared to the natural recharge rate. Although in the few cases where this separation was made (Luckey et al., 1986; Heimes et al., 1987; Luckey and Becker, 1999; and Sophocleous et al., 2002) the importance of this distinction was very apparent, for most of the studies reviewed, separation of the recharge rates in an area into these two major classifications was not possible.

Factors included in natural recharge are:

- Areal infiltration of precipitation on upland and sloping areas not within stream drainages and pond areas. This type of natural recharge usually has the lowest rate in a given area. The areal precipitation can be divided into two types, one over grassland and the other over dryland cultivation.
- Infiltration of surface-water runoff through streambeds. This includes recharge of alluvial aquifers in stream and river valleys by high stream or river flows followed by leakage of water from the alluvial aquifer to the underlying aquifer. Streambed infiltration recharge rates are usually an order of magnitude (10x) or more greater than the areal infiltration rate in areas where the water-level elevation in the High Plains aquifer is below the baseflow elevation of the stream. The streambed recharge is the net infiltration of water after subtraction of return flow from bank storage following high flow.
- Infiltration of accumulated surface water through the bottoms of ponds, playas, and other significant standing bodies of water. Like streambed recharge rates, recharge through pond infiltration can be over an order of magnitude greater than the areal recharge rates.

From the literature review, several anthropogenic parameters are identified that have enhanced recharge to the High Plains Aquifer compared to predevelopment conditions. These include:

- Farming cultivation—under certain conditions, areas that have been plowed where the soil is furrowed and the native grasses removed will have higher recharge than native grasslands. Reduced surface runoff and direct exposure of the cultivated soil to precipitation are the major factors contributing to this increase. Luckey and Becker (1999) stated that the recharge enhancement probably occurred when the fields are fallow. They used a factor of 3.9% times mean 1961-1990 precipitation (equivalent to 0.64 in/yr) for recharge due to dryland cultivation for their ground-water simulation of a development period in comparison with a factor ranging from 0.37% to 4.0% for precipitation recharge (equivalent to 0.068-0.69 in/yr) in a predevelopment-period simulation.

- Irrigation return flows—the infiltration of irrigation water to the water table has been determined to be a significant recharge component in several studies including Pettijohn and Chen (1984), Luckey et al. (1986), Heimes et al. (1987), Sophocleous and McAllister (1987), Luckey and Becker (1999), and Sophocleous et al. (2002). This factor includes return flow of the sprinkler or flood irrigation water plus leakage from irrigation diversion canals and ditches. Whereas Sophocleous et al. (2002) quantified recharge measurements illustrating the differences between native land and irrigated land, the basic rationale used in the other studies was that recharge through irrigation returns had to be occurring at a significant rate otherwise the observed water level declines would have been much larger than those observed. For the time period from 1960 through 1980, Luckey et al. (1986) estimated the irrigation return flow at 36% of the pumpage for the Nebraska and northern Kansas portions of the High Plains Aquifer. Heimes et al. (1987) estimated that between 28 and 76% of the irrigation water pumped returned to the aquifer for a three county area in South-central Nebraska in the period from 1975–1983. Luckey and Becker (1999) used values of irrigation-return flow in their simulation that averaged 24% of pumpage for the 1940's and 1950's, averaged 14% for the 1960's, averaged 7% for the 1970's, averaged 4% for the 1980's, and averaged 2% for the 1990's. They assumed that recharge was greater for flood irrigation and much smaller for well managed, precision application systems. No published literature was found that quantified the effect these changes in irrigation practices have had on the percentage of pumped irrigation water that returns to the water table.
- Declining ground-water levels—as the water level declined in the Ogallala High Plains Aquifer from the predevelopment condition to those observed today, infiltration from surface water streams and ponds has increased. Attempts to quantify this increase were made by Luckey et al. (1986) who estimated approximately a 100% increase in recharge from enhanced stream infiltration caused by water-level declines. The declining water levels and subsequent enhanced streambed infiltration is one of the reasons given for the disappearance of most perennial streams in the Kansas portion of the Ogallala High Plains Aquifer (Sophocleous and Wilson in Schloss et al. (2000)). The streambed with the largest increase in recharge from lower water tables in western Kansas is the Arkansas River valley (Whittemore, 2002).

While it is not practical to quantify the impact that each of these factors has had on the increase in anthropogenic recharge from predevelopment to present day, several studies have attempted to estimate the net increase in recharge rate from one or more of these factors. Luckey et al. (1986) estimated that the combined effect of these factors was to increase the recharge rate by about 400% for the Nebraska and northern Kansas portion of the High Plains Aquifer. Sophocleous et al. (2002) measured recharge rates at irrigated sites to be 6-10 times that measured at a native grassland site. Section 3 below quantifies recharge related to anthropogenic factors along the Arkansas River valley. It should be noted that in a water balance, anthropogenic recharge does not represent new water that is introduced to the system. Rather, it is an accounting factor that needs to be considered in evaluating the water discharge term in the water balance equation.

1.3 Temporal and spatial changes in recharge rates

Only one of the studies reviewed, Sophocleous (1992 a and b, 1993), quantified the changes in recharge over a period of time (six years). In this study, the annual measured recharge varied by over an order of magnitude from one year to the next. At several of the locations tested, some areas recorded no recharge while another location recorded recharge rates consistently greater than three inches per year over the course of the study.

Several of the studies illustrated this spatial variation in recharge including Pettijohn and Chen (1984), Luckey et al. (1986), Scanlon and Goldsmith (1997), Sophocleous (1992 a and b, 1993), and Sophocleous et al. (2002). Spatial variations in recharge can be over an order of magnitude in relatively short distances. Such spatial variations are typically integrated in the water balance or ground-water modeling estimates of recharge.

The effect that long-term climatic changes may have on recharge rate could not be quantitatively evaluated from the publications reviewed. As presented by Wood and Sanford (1995), Scanlon and Goldsmith (1997), Sophocleous (1992 a and b, 1993), and Sophocleous et al. (2002), the interaction between precipitation infiltration (including stream and pond infiltration) and groundwater recharge is a complex interaction of many parameters, and changes in one parameter may or may not result in a change in the recharge rate. The technology and databases required to estimate the effects that a major reduction or increase in precipitation would have on the overall recharge to the High Plains Aquifer are not available.

2. Results of Review

Summary results of the literature review of recharge estimates are presented in Figures 1-3 and Table 1. The values for the High Plains aquifer range from values less than a millimeter per year to over 30 inches per year in areas affected by large irrigation-related return flows. Generally, most of the natural areal recharge values not affected by anthropogenic factors are less than one inch per year with several areal recharge values being less than a half inch per year. As with most hydrogeologic parameters, a scale-dependent effect on the recharge estimates was generally observed, with the point estimates having lower recharge rates than the spatially distributed methods such as those derived from models.

Table 1. References used.

Citation number	Year	Reference	Notes
1	1966	Havens J S, *Recharge Studies On The High Plains In Northern Lea County, New Mexico*, US Geological Survey Water-Supply Paper 1819-F	1/2 to 1 inch per year using Theis method
2	1975	Brutsaert W; Gross G W; McGehee R M, *C. E. Jacob's Study On The Prospective And Hypothetical Future Of The Mining Of The Ground Water Deposited Under The Southern High Plains Of Texas And New*	0.15 inch/year regional

Citation number	Year	Reference	Notes
		Mexico, Ground Water; V13 N6; P492-505	
3	1981	Sophocleous, M.A., The Declining Groundwater Resources in Alluvial Valleys—A Case Study, Ground Water; V19, N2, P. 214–226	0.5 inches per year for Pawnee River Basin
4	1983	Koelliker, J.K., *Groundwater recharge study with terraces in Kansas*, In, Proceedings of the tenth annual conference, Groundwater Management Districts Association, pp. 54-63, Groundwater Management Districts Association, East Tulsa, OK, 144 pages	1.7 inches per year through artificial terraces
5	1984	Pettijohn R. A.; Chen H. H., *Hydrologic Analysis Of The High Plains Aquifer System In Box Butte County, Nebraska*, US Geological Survey Water-Resources Investigations Report 84-4046	0.06–4.33 inches per year using water balance modeling
6	1985	Sophocleous, M.A.; and Perry, C.A., *Experimental Studies In Natural Ground Water-Recharge Dynamics: The Analysis Of Observed Recharge Events,* Journal Of Hydrology; V81 N3/4; P297-332	0.1 to 6 inches per year based on site point measurements at Zenith and Burton sites
7	1985	Stullken, L.E., Watts, K.R., and Lindgren, R. J., Geohydrology of the High Plains Aquifer, Western Kansas, US Geological Survey Water-Resources Investigations Report 85-4198	0.2 inches per year based on steady-state groundwater model, original source for Hansen, 1991 report
8	1986	Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J. B., *Digital Simulation of Ground-Water Flow in the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, Regional Aquifer-System Analysis*, U.S. Geological Survey Professional Paper 1400-D, 57 p.	Spatial estimates of recharge for the entire High Plains Aquifer
9	1987	Heimes, H.J., Ferrigno, C., Gutentag, E.D., Luckey, R.R, Stephens, D., and Weeks, J. D., *Comparison Of Irrigation Pumpage With Change In Ground-Water Storage In The High Plains Aquifer In Chase, Dundy, And Perkins Counties, Nebraska*, US Geological Survey Water Resources Investigation Report 87-4044	<1 inch per year from cultivated land, 28 to 79% of irrigation pumpage returned to aquifer as return flow
10	1987	Sophocleous, M.A.; and Perry, C.A.,	Burton and Zenith site

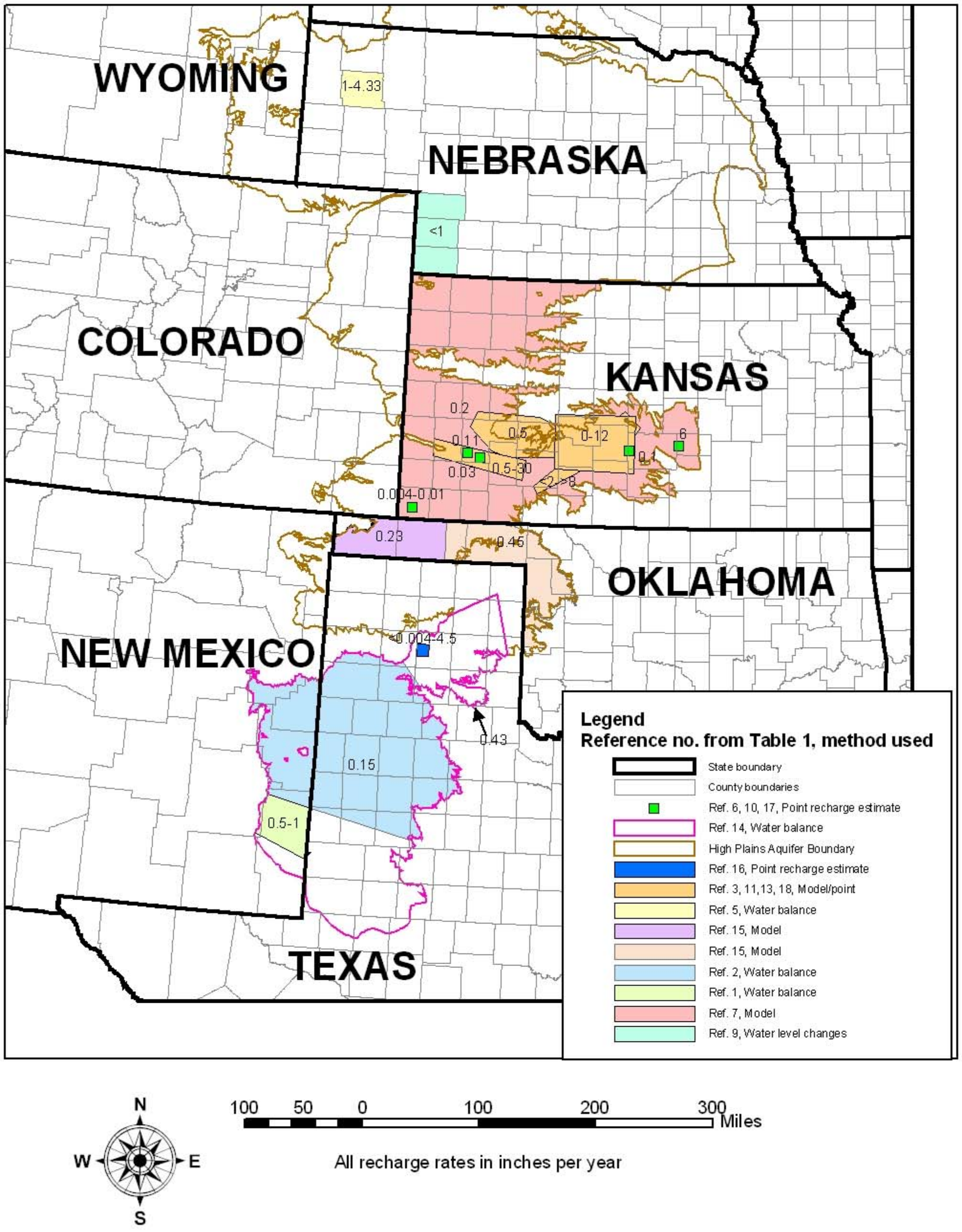
Citation number	Year	Reference	Notes
		Measuring and computing natural ground-water recharge at sites in south-central Kansas, U.S. Geological Survey, Water-resources Investigations, no. 87-4097, 48 pages	results (see reference 5)
11	1987	Sophocleous M.A. and McAllister J.A. *Basin Wide Water-Balance Modeling With Emphasis On Spatial Distribution Of Ground Water Recharge*, Water Resources Bulletin; V23 N6; P997-1010	<2 to over 8 inches per year for Rattlesnake Creek basin in central Kansas
12	1991	Hansen, C.V., *Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas*, U.S. Geological Survey, Water-resources Investigations, No. 87-4230, 100 pages	Kansas portion of the Ogallala-High Plains Aquifer, 0.5 to 1 inch per year based on work of Stullken, et al (1985) and Luckey, et al (1986)
13	1992	Sophocleous, M.A., Groundwater Recharge estimation and regionalization: the Great Bend Prairie of Kansas and its recharge statistics, Journal of Hydrology, v. 137, p. 113–140 and Sophocleous, M.A., A Quarter-Century of Ground-Water Recharge Estimates for the Great Bend Prairie Aquifer of Kansas (1967–1992), Kansas Geological Survey open-file report 92-17, 22 p.	Great Bend Prairie aquifer with estimates from 0 to 12 inches per year. Annual estimates from point stations.
14	1995	Wood W. W. and Sanford W. E.; *Chemical And Isotopic Methods For Quantifying Ground-Water Recharge In A Regional, Semiarid Environment*, Ground Water; V33 N3; P458-468	0.43 inches per year using chloride mass-balance
15	1996	Becker, C.J., Runkle, D., and Rea, A., Digital recharge rates for the High Plains aquifer in western Oklahoma, US Geological Survey Open-file report 96-451, GIS metafile data	0.23 and 0.45 inches per year from groundwater model studies
16	1997	Scanlon, B.R. and Goldsmith, R.S. Field Study of Spatial Variability in unsaturated flow beneath and adjacent to playas, Water Resources Research, V.33, N10, p. 2239-2252	<0.04 –4.5 inches per year in vicinity of playas in Texas
17	2002	Sophocleous, M.A., Kluitenberg, G.,	Estimated recharge

Citation number	Year	Reference	Notes
		Healey, J., Dennehy, K., Ellett, K., and McMahon, P., *Southwestern Kansas High Plains Unsaturated Zone Pilot Study to Estimate Darcian-Based Groundwater Recharge at Three Instrumented Sites*, Kansas Geological Survey Open-file report 2001-11, 46 p.	from 0.004–0.11 inches per year from detailed data collection program
18	2002	Whittemore, D.O., *Recharge in the upper Arkansas River corridor*, Kansas Geological Survey Open-File Report 2002-30.	0.5 to 30 inches per year from groundwater model study

For the entire High Plains aquifer, the values developed by Luckey et al. (1986) (Figure 2) are considered the most spatially and long-term temporally representative of overall natural recharge values for the aquifer. These values were based on modeling and included the effects of natural recharge, stream-flow losses, and irrigation return flows. With the developments in groundwater modeling technology over the last 20 years, it is possible to use the same general techniques used by Luckey et al. (1986) to substantially improve the estimates of recharge, stream losses, and irrigation return flows. This would be especially productive for the Kansas portion of the aquifer because an additional 20 years of water level and 11 years of reasonably high-quality data for pumping volume would be added to the calibration dataset. Currently an update of the Luckey modeling has not been done nor is any update currently proposed.

For the Kansas portion of the High Plains aquifer, the often-cited (e.g. Schloss et al., 2001) Kansas-wide values presented by Hansen (1991) (Figure 3) may be reasonable for current recharge rates. As Hansen cites in her report, she based the values for the majority of the High Plains aquifer on the published work of Stullken et al. (1985) and a follow up communication in 1986 with him concerning the fact that water levels have not declined as much as the original Stullken values might predict. She therefore used rates of between 0.5 and 1 inch per year as compared to the Stullken et al. (1985) value of 0.2 inch per year. Hansen (1991) makes no statement about whether she accounted for irrigation return flows in her updated recharge values but her updated values may reflect the aforementioned anthropogenic changes in recharge rates.

The data presented by Scanlon and Goldsmith (1997), Sophocleous et al 2002, and Whittemore (2002) illustrate the variability in the analysis of recharge in small areas when detailed measurements or evaluations are conducted. These studies illustrate that the observed recharge rate can vary by an order of magnitude or more over relatively short distances. These types of studies may be more likely to detect small-area and short time-frame variations in recharge. However, the ability of the technologies used in these studies to detect such changes has not been demonstrated in the literature.



All recharge rates in inches per year

Figure 1. Spatial variability of High Plains aquifer recharge estimates.

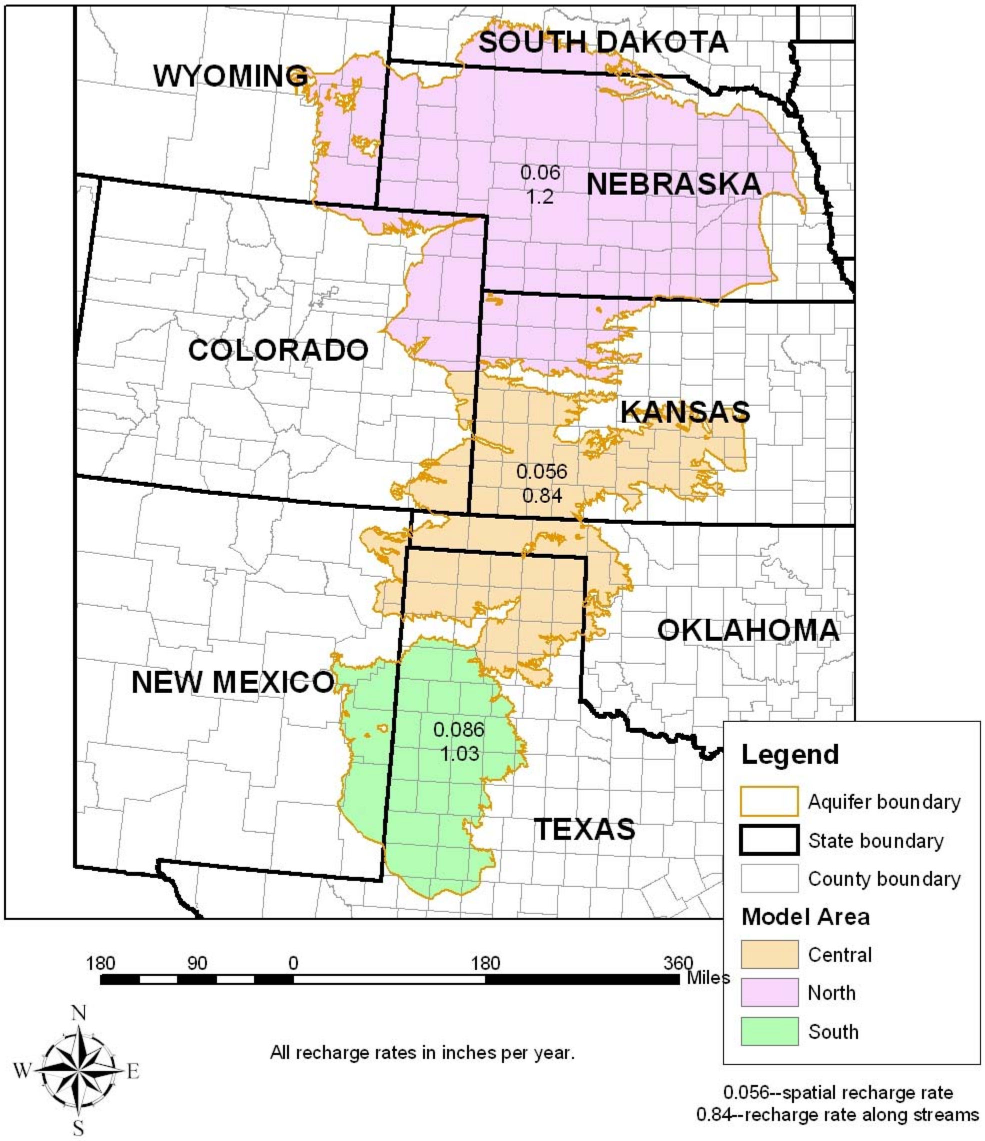
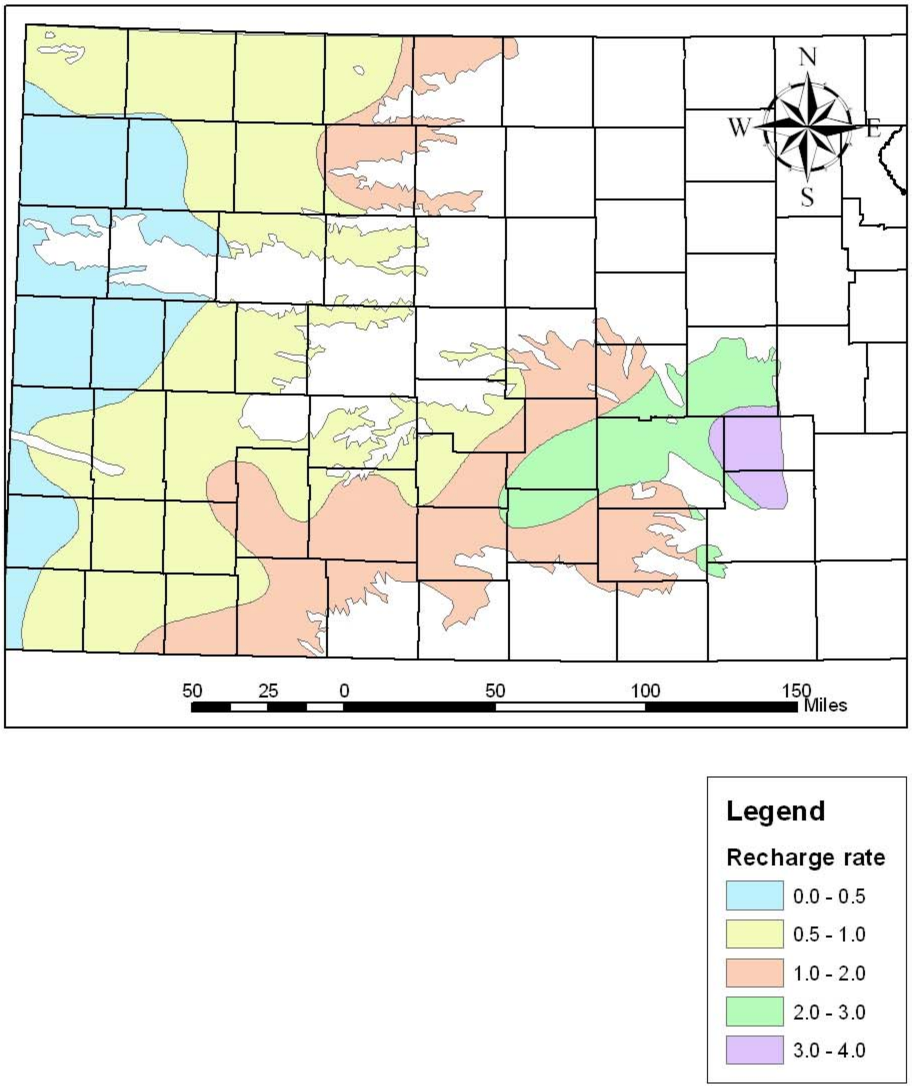


Figure 2. Recharge estimates from Luckey, et al (1986) from regional High Plains aquifer modeling.



Recharge rate in inches per year.

Figure 3. Hansen (1991) recharge estimates.

3. Case study – Ground-Water Recharge in the Upper Arkansas River Corridor of Southwest Kansas

Spatial and temporal variations in ground-water recharge are substantial in the upper Arkansas River corridor of southwest Kansas. Average annual recharge to the High Plains aquifer ranges from a fraction of an inch on non-irrigated upland, to several inches underlying flood irrigated fields, to over a foot as leakage from the overlying alluvial aquifer of the upper Arkansas River, and up to two feet in areas with canals diverting river water and adjacent ditch laterals. The year-to-year annual recharge for each of these different types of areas varies greatly depending on such factors as the amount and temporal distribution of rainfall, the temperature and humidity, the amount of irrigation water use and, in the case of the upper Arkansas River, the precipitation and water use in Colorado that affect the flow into Kansas. Long-term changes in climate, land and water use, and agricultural practices have caused variations in the average annual recharge rates.

Research conducted during the Upper Arkansas River Corridor Study, a Kansas Water Plan project, gives some insight into these recharge variations at the regional scale. Information on recharge used in the study was based on previous investigations, publications, calculations using river flow and water-use data, and conceptual and numerical models of ground-water flow and river-aquifer interactions (Whittemore, 2000a; Whittemore et al., 2000, 2001). Figure 4 shows the location of the High Plains aquifer within the boundary of the regional numerical model in the study area. The following sections are a summary of a longer document (Whittemore, 2002) on ground-water recharge in the upper Arkansas River corridor written for the FY 2002 Ogallala Aquifer Support Study.

3.1 Surface recharge from precipitation on non-irrigated land

Areal recharge to the High Plains aquifer from precipitation on non-irrigated land was estimated by Dunlap et al. (1985) to be less than 0.5 inch/yr (1.3 cm/yr) in the river corridor. A slightly greater initial value of 0.6 inch (1.5 cm) of surface recharge over non-irrigated land was used in the numerical models of Whittemore et al. (2001) for ground-water flow in the upper Arkansas River corridor. This value was not altered in most of the non-irrigated areas as a result of calibration of the models.

3.2 Surface recharge on irrigated land

Recharge over irrigated land is substantially greater than from precipitation over non-irrigated areas because the water applied produces conditions of high soil moisture that can lead to drainage more frequently. For example, heavy rainfall falling on soils moist from irrigation can rapidly produce saturated conditions that lead to effective recharge. Flood irrigation has greater recharge than from center pivot applications because water must saturate the shallow soils underlying the furrows to flow completely across the field. Arkansas River water is diverted across portions of both the alluvial valley and the upland in Kearny and Finney counties and used as flood irrigation. Seepage from the unlined canals used to carry the water from the river and ditches that distribute the water to fields can provide substantial localized recharge. A small, shallow reservoir (Lake McKinney) used to store diverted river water in east-central Kearny County also provides localized recharge.

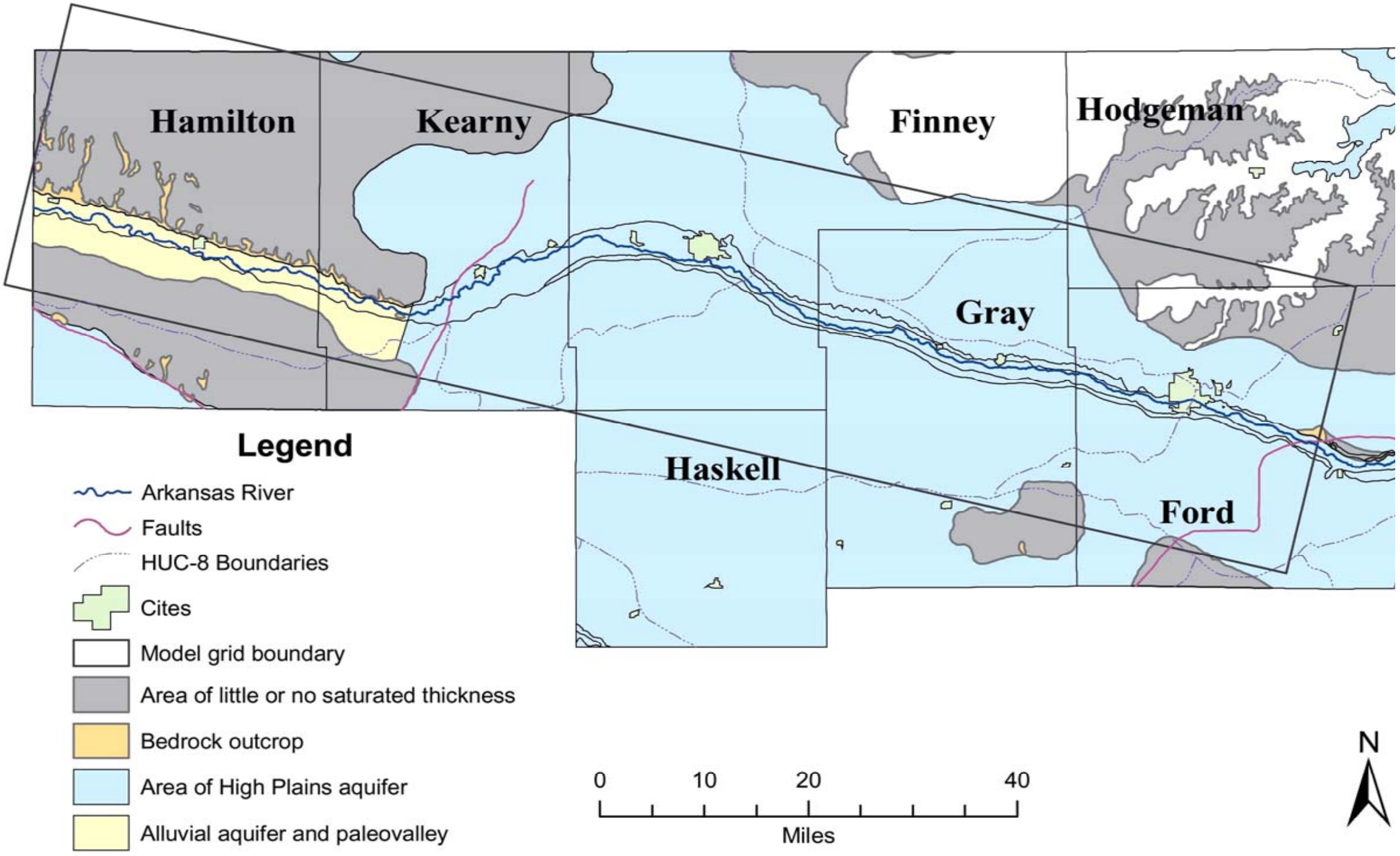


Figure 4. The location of the regional model of the upper Arkansas River corridor in southwest Kansas. The boundary of the model grid extends from the Colorado-Kansas border through parts of Hamilton, Kearny, Finney, Haskell, Gray, Hodgeman, and Ford counties to where the Crooked Creek–Fowler Fault zone crosses under the Arkansas River. The thin black lines on both sides of the Arkansas River delineate the boundaries of the alluvial valley and terrace deposits.

The initial value of canal seepage was estimated at 1% per mile of the diversion flow for the ground-water models. Within each ditch service area, the irrigation return flow was distributed over the existing water rights in proportion to the irrigated area associated with each water right. The initial values of recharge for the water applied to fields for irrigation were calculated as 25% of the surface water spread by ditches and the ground water pumped from irrigation wells within the ditch services area based on Meyer et al. (1970). Up to 2 ft of recharge resulted for areas with canals diverting river water, adjacent ditch laterals, and flood irrigated fields. The mean annual flow diverted from the Arkansas River for irrigation during 1989-1998 was approximately 63,000 acre-ft/yr. An estimate of 25% seepage below canals, ditches, and fields irrigated with the river water equates to a volume of 16,000 acre-ft/yr of recharge to the alluvial and High Plains aquifers underlying the canals and ditch service area.

3.3 Recharge from the Arkansas River to the alluvial aquifer

Before wells began to pump substantial amounts of ground water from the High Plains aquifer in the upper Arkansas River corridor, the river gained flow along nearly all of its length in southwest Kansas. The water levels in the High Plains aquifer were usually slightly higher than in the adjacent alluvial aquifer, thus, ground-water discharge generally increased baseflow downstream. The discharge was derived primarily from areal precipitation recharge. The installation and pumping of large-capacity wells in the High Plains aquifer, especially during the 1950’s through the mid-1980’s, caused declines in ground-water tables. The vertical head gradients that were generated caused water to seep from the alluvial aquifer into the underlying High Plains aquifer. With this reverse in the ground-water table gradients, water from the Arkansas River then recharged the alluvial aquifer. After the 1970’s, the river changed progressively downstream from a system of average net increases in baseflow to net flow decreases even after accounting for the diversions for ditch irrigation. Today, the location where baseflow typically adds to the river flow is east of Dodge City.

The average annual decrease in river flow from the Colorado-Kansas border (gaging station near Coolidge) to Dodge City was 152,000 acre-ft/year (210 acre-ft/day, 1.66 x 10^8 gal/day, 243 cfs) for the ten-year period of 1989-1998. The mean annual flow diverted from the river for irrigation during the same period was 63,000 acre-ft/yr. The estimated amount of water lost from the surface of the river to evaporation was about 6,000 acre-ft/yr based on lake evaporation rates and an approximation of the average surface area of flow in the river from Coolidge to Dodge City. Up to 20,000 acre-ft/yr of water from the alluvium could be consumed by phreatophytes in the river valley based on water consumption data for a study in southwestern U.S. and an investigation of phreatophytic density in the upper Arkansas River corridor. Some of this water would be derived from river flow and the rest of the phreatophytes' consumption would be from infiltration of precipitation into the soil of the floodplain. By difference, the amount of water that seeped from the river channel and recharged ground water during 1989-1998 averaged 73,000 acre-ft/yr if approximately half of the phreatophyte consumption was from river flow. The total recharge from the ditch diversion system and the river channel is estimated to have averaged nearly 90,000 acre-ft/yr during the period. The amount of recharge during the high flow years of the late 1990’s is greater than the 10-year average. Annual recharge of Arkansas River water into the alluvial aquifer in southwest Kansas substantially exceeded 100,000 acre-ft during 1995-2000.

Most of the flow losses between the state line and Garden City occur from the western edge of the High Plains aquifer underlying the river valley (near the former town of Hartland) to Garden City. The distances along the Arkansas River between Hartland and the stream gaging station at Garden City and between the stations at Garden City and Dodge City are approximately

22 miles and 53.3 miles, respectively. If the width of the active river channel where seepage occurs averages 0.05 mile, the areas of the channel between Hartland and Garden City and between Garden City and Dodge City are 1.1 sq miles and 2.7 sq miles, respectively. Mean flow losses of 52 cfs and 77 cfs for the two streams reaches in the 1990's translate to annual recharge rates of 642 inch/yr (53.5 ft/yr, 1.8 inch/day) and 392 inch/yr (32.7 ft/yr, 1.1 inch/day), respectively, for these channel areas. Not all of this recharge seeps to the underlying High Plains aquifer due to evapotranspiration and pumping losses from the alluvial aquifer.

3.4 Leakage from the alluvial aquifer to the underlying High Plains aquifer

Leakage from the alluvial aquifer to the underlying High Plains aquifer begins at the western extent of the High Plains aquifer in southwest Kansas near the former town of Hartland. The length of the alluvial valley from Hartland to Dodge City is about 78 miles. The width of the alluvial aquifer ranges from 1.5 to 4 miles. The total surface area of the alluvial valley from Hartland to Dodge City is about 184 square miles, which is equivalent to 118,000 acres. An average net recharge of 73,000 acre-ft from the Arkansas River to the alluvium followed by leakage into the underlying High Plains aquifer during 1989-1998 would be equivalent to a recharge rate of about 7.4 inches per year over the entire area of the alluvial valley. During 1995-2000 when the river flows and recharge were much greater, the recharge would have been over 100,000 acre-ft, meaning recharge rates of over one foot per year across the entire alluvial valley. Local rates of recharge from the alluvium to the underlying High Plains aquifer probably exceed 2 ft/year where the geology of the aquifer sediments allows a good hydraulic connection between the aquifers.

3.5 Impact of recharge on ground-water levels

Before development of the High Plains aquifer in the Arkansas River corridor, ground-water tables to the north and south of the river were generally higher than in the river. After substantial ground-water development, water levels in the High Plains aquifer dropped substantially in much of southwest Kansas. Pumping caused the ground-water levels to the north and south of the river to drop below the streambed surface during the 1970's. During 1974 through 1979, the flow in the Arkansas River and, thus, the amount of water available for surface-water irrigation diversion were particularly low. Extensive amounts of ground water were pumped from the High Plains aquifer within the ditch service areas because the amount of diverted river water was substantially less than the long-term mean. Arkansas River flows at the state line increased during 1980 through 1982 but were still below the long-term average. Ground-water levels continued to drop in the ditch service area.

River flows were above average for 1983 through 1988 and exceeded three times the mean in 1987. The quantity of water diverted from the river for irrigation also was above the long-term mean for 1983-1988. The water levels for wells within the ditch service areas to the north of the river began to increase during this period, reflecting substantial recharge from the river water diverted in canals and spread over fields and a decline in the amount of ground water needed for irrigation. River flow and diversion volumes were also above average in 1995-1999. Recharge for this period is also indicated by the water-levels rises in the High Plains aquifer wells in the ditch area north of the river.

Water levels in the High Plains aquifer wells south of the river continued to drop at a substantial rate during the 1980's and 1990's. In general, the farther the distance of the well location from the river, the steeper was the rate of decline. The farther a well is from the river and alluvial aquifer, the smaller is the recharge water volume that flows in the subsurface to the well.

Figure 5 displays the distribution of water-level changes in the High Plains aquifer between 1991 and 2000 across the area of the regional model of the upper Arkansas River corridor. The water-level rises to the north of the Arkansas River in east-central Kearny County and west-central Finney County represent the effect of the surface recharge from much of the area irrigated by diverted river water. The south-central part of the model area in Figure 5 shows that there are substantial water-level declines across a large region and that the declines increase to the south. The Arkansas River valley lies between the water-level rise and decline areas. The water levels in the High Plains aquifer underlying the valley do not vary much from year to year because leakage of water from the alluvial aquifer maintains the levels.

3.6 Impact of recharge on ground-water quality

The salinity of ground waters in the High Plains aquifer has increased substantially during the last half of the 20th Century in the Arkansas River corridor as a result of saline recharge derived from the river. The recharge occurs along the river channel and moves into the alluvial aquifer and then into the underlying High Plains aquifer. Recharge also occurs from irrigation canals, ditches, and fields irrigated with the river water. The migration of saline recharge from the river into the High Plains aquifer could be considered as a depletion of water usable (without treatment) for public water supply, drinking water for young stock, and industrial supplies requiring low dissolved solids. This would be a different type of depletion from the actual loss of water but one that is appropriate to consider in evaluating the various management considerations and the impacts of human activities on the aquifer resources.

Dissolved solids contents in low flows of the Arkansas River water can exceed 4,000 mg/L at the Colorado-Kansas state line. The dissolved constituent in greatest concentration in the river water is sulfate. Sulfate concentration has ranged from 700 to 2,600 mg/L and averaged between 1,900 and 2,000 mg/L during the last couple of decades (Whittemore, 2000b). Sulfate concentration ranges from less than 30 mg/L in the freshest ground waters to over 2,700 mg/L in the most saline ground waters in the river corridor (Whittemore, 2000a). The recommended maximum concentration for dissolved sulfate and chloride in drinking is 250 mg/L sulfate. However, adults can tolerate over 500 mg/L without noticeable short-term effects. Sulfate concentrations of several hundred mg/L have been found to cause problems for many young livestock. The value of 500 mg/L was selected as a useful upper limit for designating whether water is useable or unusable without treatment for a drinking-water supply (Whittemore, 2002).

The distribution of sulfate concentration in the High Plains aquifer has been mapped based on analyses of water samples collected primarily from 1990 to 2000 (Whittemore, 2000a). Figure 6 displays the area with greater than 500 mg/L sulfate content in the High Plains aquifer in the river corridor. The figure also shows the area into which ground water with greater than 500 mg/L sulfate content is predicted to flow during the next 40 years in the High Plains aquifer based on the results of a transient flow simulation assuming average 1990’s water use remains constant (Whittemore et al., 2001). The additional area of the High Plains aquifer into which the saline water will move by 2040 is located mainly to the south of the river valley from south-central Kearny County to western Ford County, and to the east of the high sulfate area north of the river in western Finney County. The width of the additional saline area south of the river is up to a few miles. Substantial reductions in ground-water pumping from the High Plains aquifer would be necessary to appreciably decrease the migration distance of the saline water.

4. Data limitations and applications

Based on the review of recharge publications for the Kansas portion of the High Plains aquifer, research has been done that allows for estimates of large-area recharge rates and illustration of the small-area variations in recharge. There is one study (Sophocleous, 1993) that illustrates how small-area or point values may be scaled up to cover larger areas. However, for the majority of the High Plains aquifer in Kansas, such point measurements are not available. Therefore, for evaluations requiring large-area recharge rates (on the order of the size of a county and larger), the original values developed by Stullken et al. (1985) or Luckey et al. (1987), possibly with the adjustments made by Hansen (1991), are the only values available.

There are only a few research studies that indicate how to separate the natural recharge components (precipitation infiltration and stream losses) from the anthropogenic influences (cultivation, irrigation return flow, and induced surface water infiltration). This problem is especially important if future predictions are to be made for changes in water level-decline rates resulting from modifications of irrigation practices. The available literature demonstrates quite conclusively that irrigation return flow is an important and substantial recharge component in irrigated areas of the High Plains. Research is not available to make an assessment of how the irrigation changes made in the western Kansas portion of the Ogallala High Plains aquifer have or will affect the rates of water level declines. If, as suggested by Luckey and Becker (1999) and Sophocleous et al. (2002), past flood irrigation practices resulted in much higher irrigation return flow than that from current low-pressure sprinkler practices, the current rate of water-level decline may actually increase as the volume of irrigation return declines in response to more efficient irrigation practices if the water use remains constant. Unfortunately, other than Sophocleous et al. (2002), there have been no studies that would allow a determination of the effect of irrigation efficiency changes on irrigation-return recharge.

Thus the question is, what can be concluded about the rate of recharge in the Kansas portion of the Ogallala High Plains aquifer? The literature review indicates that the large-area spatial value of recharge in less than one inch and probably less than one-half inch per year. If the modeling of Luckey et al. (1986) is correct, the natural areal recharge could be less than 0.1 inch. Locally, recharge values ten times these values are possible but determination of such values across the entire Kansas Ogallala High Plains aquifer is not possible because of a lack of data.

Lack of applicable research precludes even qualitative assessments about the effects of changes in one or more of the recharge components. For example, it is not possible to determine, even qualitatively, what effect a climatically induced reduction in precipitation will have on the recharge to the aquifer. This is because naturally occurring precipitation is only a minor contributor to present-day recharge. Another example is presented above about the effects irrigation efficiency changes have on recharge and ultimately the rate of water level decline. There is only a minor bit of anecdotal data (Sophocleous et al., 2002) that would allow a comparison of the recharge effects of flood irrigation compared to highly efficient low-pressure, drop-head irrigation return flows. There is extremely limited research available that can be used to qualitatively assess what the current irrigation return rate is or allow for the comparison to historical irrigation return rates and no data that would allow for the quantitative assessment.

Based on the research reviewed, the conclusion is that the average areal recharge rate to the whole High Plains aquifer and the Kansas portion in general, is small but greater than zero. The quantity is large as a volume summed over the aquifer but very small relative to the quantity of

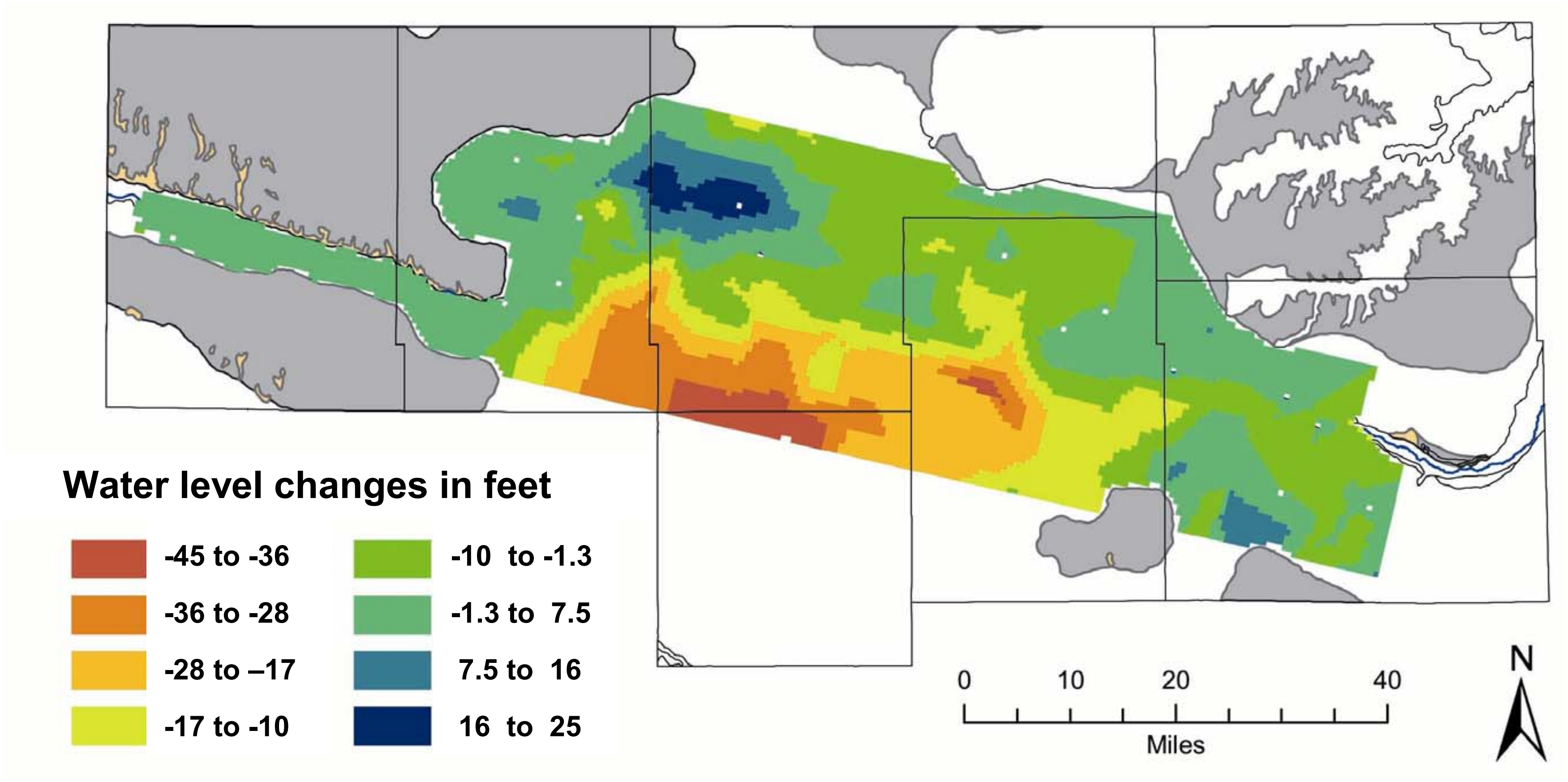


Figure 5. Change in the water-level surface between 1991 and 2000 represented as color-shaded intervals in the area of the regional model of the upper Arkansas River corridor. The intervals range from a maximum water-level decline of 45 ft to a maximum water-level rise of 25 ft.

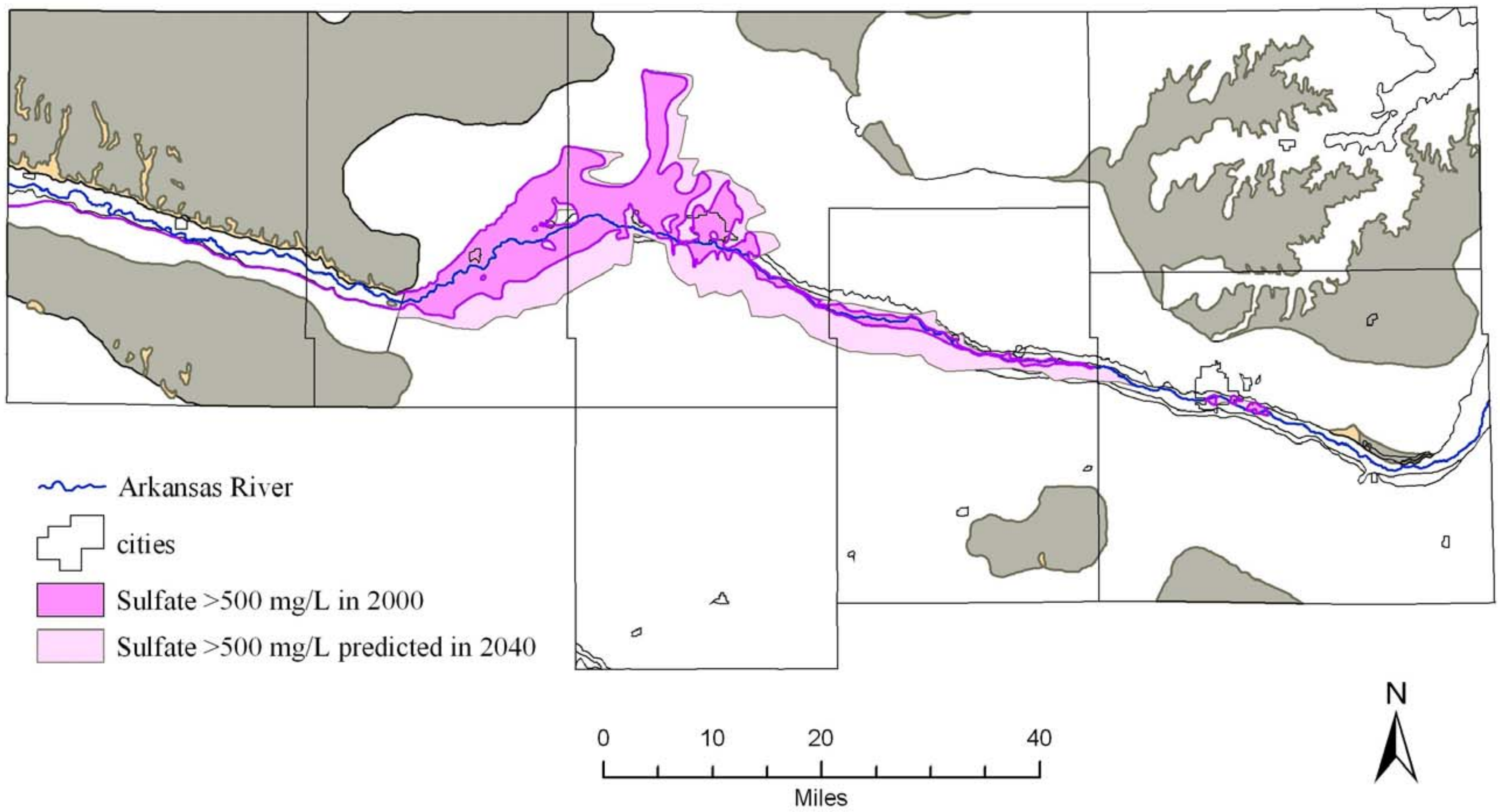


Figure 6. Distribution of high sulfate concentration (>500 mg/L) in 2000 from observations and predicted in 2040 from a 40-year transient simulation of ground-water flow based on average 1990's water use in the High Plains aquifer. See Figure 4 for explanation of additional features of the map.

water withdrawn. Only in stream valleys and under ditch diversions and some irrigated fields is the recharge substantial relative to the volume of water pumped from the aquifer. The Arkansas River valley and the ditch irrigation area in the river corridor stand out as a subregion of substantially greater recharge than other areas of the Ogallala High Plains aquifer in Kansas. Further definition beyond these general statements requires substantial investment in resources and it is not yet clear how much more definitive the resulting values could be than those already published by the U.S. Geological Survey (Stullken et al., 1985, Luckey et al., 1987, and Hansen, 1991).

5. Policy and management implications

Given the limitations outlined in this report on establishing a sound and defensible value for recharge to the High Plains aquifer, specific values of recharge should not be used as a primary or principle parameter when developing water management policies or aquifer subunit delineations. Rather the probable differences or potential ranges in recharge over time and space should be considered. In addition, the factors that influence effective recharge, such as land use, soil types, and other parameters, have been better documented and digitally represented with greater levels of accuracy and confidence. By accounting for these types of parameters, management techniques or processes for aquifer subunit delineations can be tailored to enhancing or protecting areas most likely to have effective recharge rates.

Existing information could also be used to indicate limiting values and inherent error for recharge if considered for future policy, management or aquifer subunit approaches that are based on safe yield or sustainable yield for the aquifer. Sophocleous (1998) defined safe yield "…as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge." In a natural system undisturbed by human activities, the long-term recharge to an aquifer is balanced by the long-term discharge. Thus, substantial pumping from an aquifer under a safe-yield policy cannot be based solely on recharge values because the pumping withdrawals and natural discharge are outflow that exceed the recharge inflow. However, if the pumping decreases water levels to a point that ground-water derived baseflow in streams is no longer a significant discharge from an aquifer region, essentially all of the recharge is "captured" within the region. Such a case is approximated in most of the Ogallala portion of the High Plains aquifer. If ground-water inflow and outflow from the Ogallala region roughly balance each other, the total surface and stream valley recharge could possibly be used as a guide for future safe yield and sustainable policies.

6. Potential for improved current High Plains aquifer recharge estimates

The first alternative to improve the recharge estimates would involve the use of modeling methods such as those published by Stullken et al. (1985), Luckey et al. (1986), or Whittemore (2002), which are viable methods available to refine the existing overall High Plains aquifer recharge rate estimates. The model could use the Ogallala-High Plain aquifer water levels, streamflow, and irrigation-pumpage volume data that have been collected since 1980—the last year of data use in the Luckey et al. (1986) modeling. Such a modeling effort could estimate current recharge rates, improve estimates for irrigation return flows, and benefit from 21 additional years of water-level and 10 years of irrigation pumpage changes that have been observed and documented. This model would benefit from the recent developments in groundwater modeling technology (e.g. Harbaugh et al., 2000; Environmental Simulations, 2001) that have substantially improved the productivity and reduced the costs associated with the development of groundwater flow models. Such a model would also provide a tool for prediction of the effects that groundwater use or management changes may have a long-term viability on the High Plains aquifer. An important point in using the modeling approach is that the design and objective of the simulation must obtain recharge values rather than ground-water flow. Thus, the calibration of the model must be performed in a manner in which error is primarily minimized in the recharge distribution rather than in other parameters.

The second alternative method for improving recharge estimates would involve the use of environmental tracers to estimate the recharge flux. This would be done in a manner similar to what was done by Wood and Sanford (1995), by Scanlon and Goldsmith (1997), or McMahon and Sophocleous (2002). While the use of tritium is becoming problematic because of the decay of tritium over time, other environmental tracers could be used such as chloride, nitrate, atrazine, or chlorofluorocarbons to estimate recharge. Furthermore, this could be done in conjunction with the ongoing agricultural monitoring performed by Kansas State University to improve the estimates of current recharge and irrigation return flows in irrigated areas. Such an effort would involve installation and monitoring of unsaturated zone monitoring devices and wells, sampling of existing wells, and recording devices. Such an effort could dramatically improve the current estimates of recharge plus return flow in irrigated areas and address the large uncertainty associated with the magnitude of irrigation return flow compared to natural recharge.

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Calculation of Yield for High Plains Wells: Relationship between saturated thickness and well yield

By

G.R. Hecox, P. A. Macfarlane and B. B. Wilson
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A component of the Technical Report series 2002-25: Technical Support for Ogallala Aquifer Assessment, Planning, and Management

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$$s_{aquifer} = \frac{Q}{4\pi T}\left[-\text{[illegible]} - \ln\left(\frac{r^2 S}{4Tt}\right)\right]$$

[illegible] *aquifer*:

$$u = \left(\frac{r^2 S}{4Tt}\right)$$

$$s_{aquifer} = \frac{Q}{4\pi T}\left[-\text{[illegible]} - \ln u + \text{[illegible]}\, u - \text{[illegible]}\, u^2 + \text{[illegible]}\, u^3 - \text{[illegible]}\, u^4 + \text{[illegible]}\, u^5 \right]$$

[illegible]

$$s_{well} = s_{aquifer} + \text{[illegible]}\, s_{aquifer}).$$

[illegible]

[illegible]

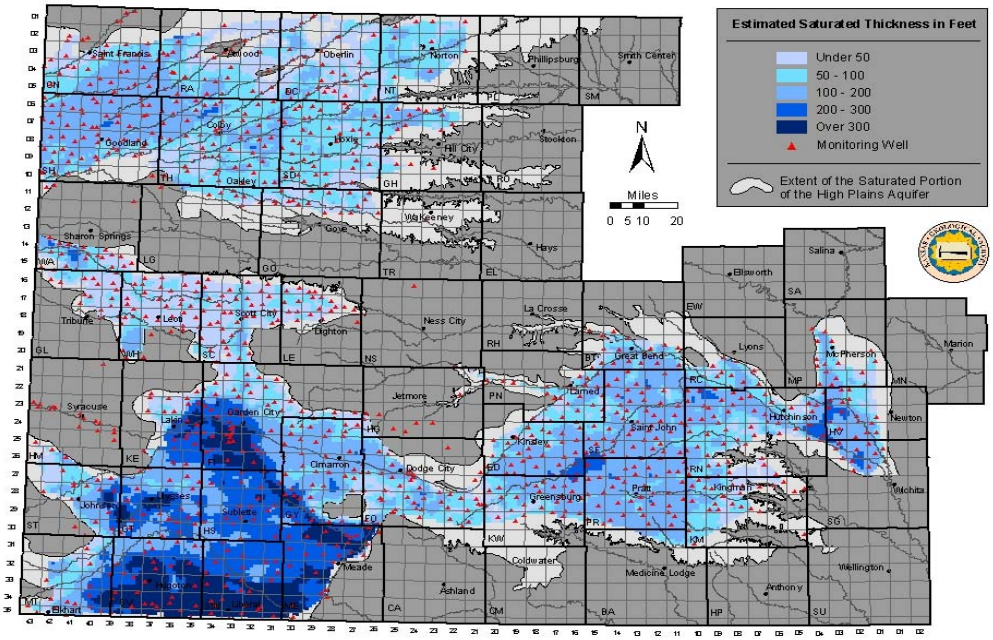
$$Ent.Vel. = \frac{Q}{\text{[illegible]} \times \text{[illegible]} \times (screen\ open\ area)}$$

[illegible]

[illegible]

2 [illegible]

[illegible]

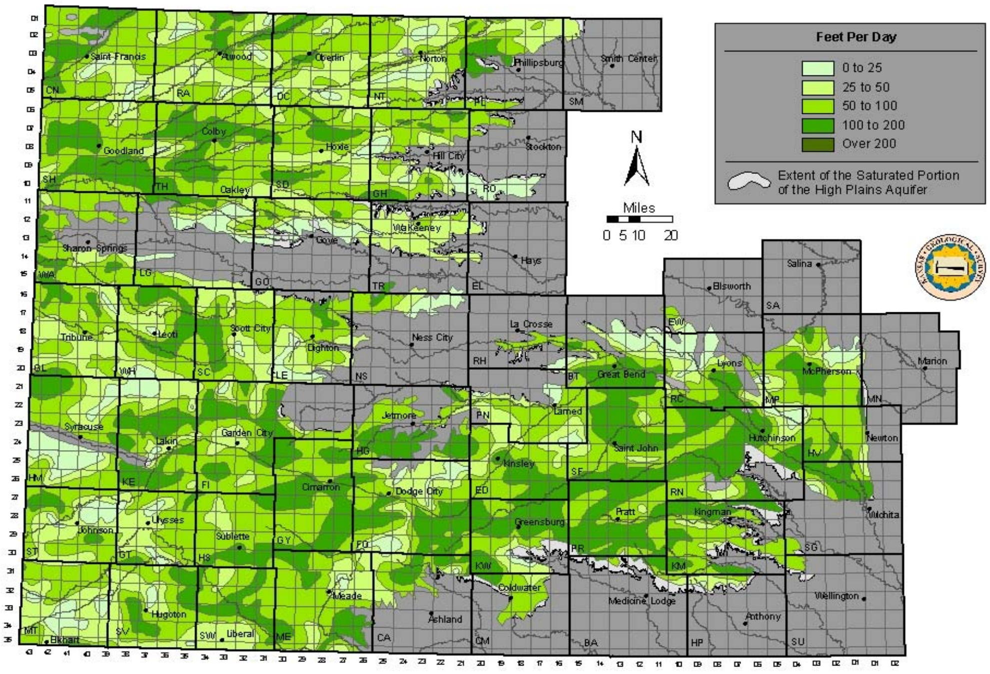

Average 2000 - 2002 Saturated Thickness for the High Plains Aquifer in Kansas

[illegible] [illegible]

[illegible] [illegible] [illegible]

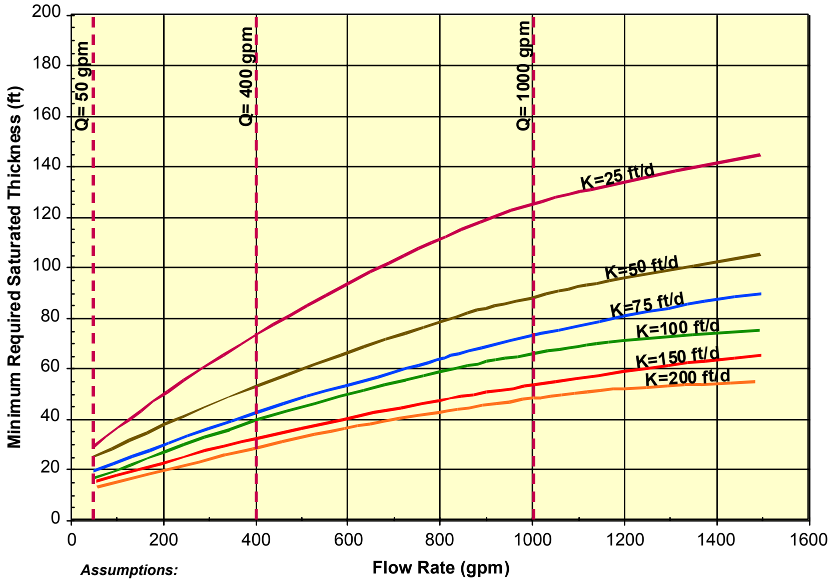
[illegible] [illegible] [illegible]

[illegible] [illegible]


Estimated Hydraulic Conductivity in the Kansas High Plains Aquifer
USGS Open File Report 98-548

[illegible] [illegible]

[illegible]



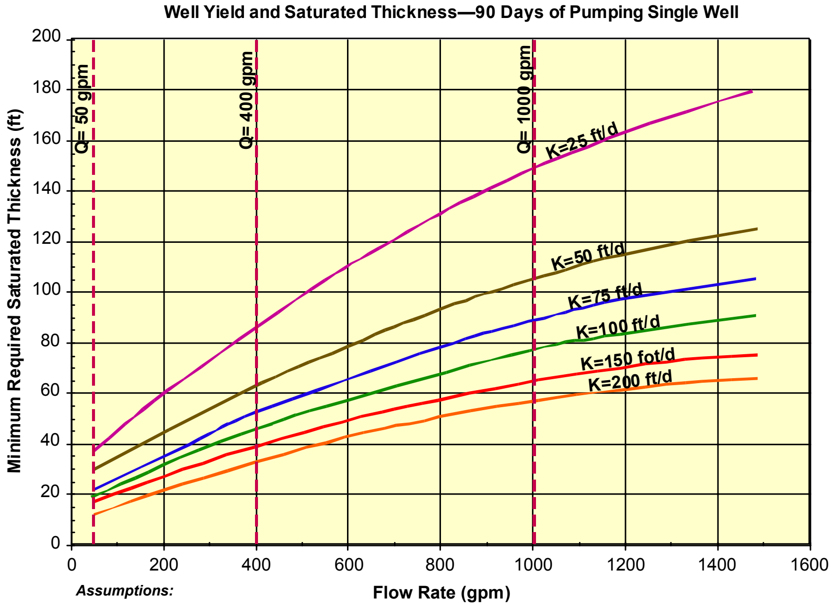
Assumptions:

1. Specific yield = 0.1

2. Time of pumping = 90 days

3. Well efficiency = 50%

4. Cooper-Jacob approximation of Theis equation used for calculations.



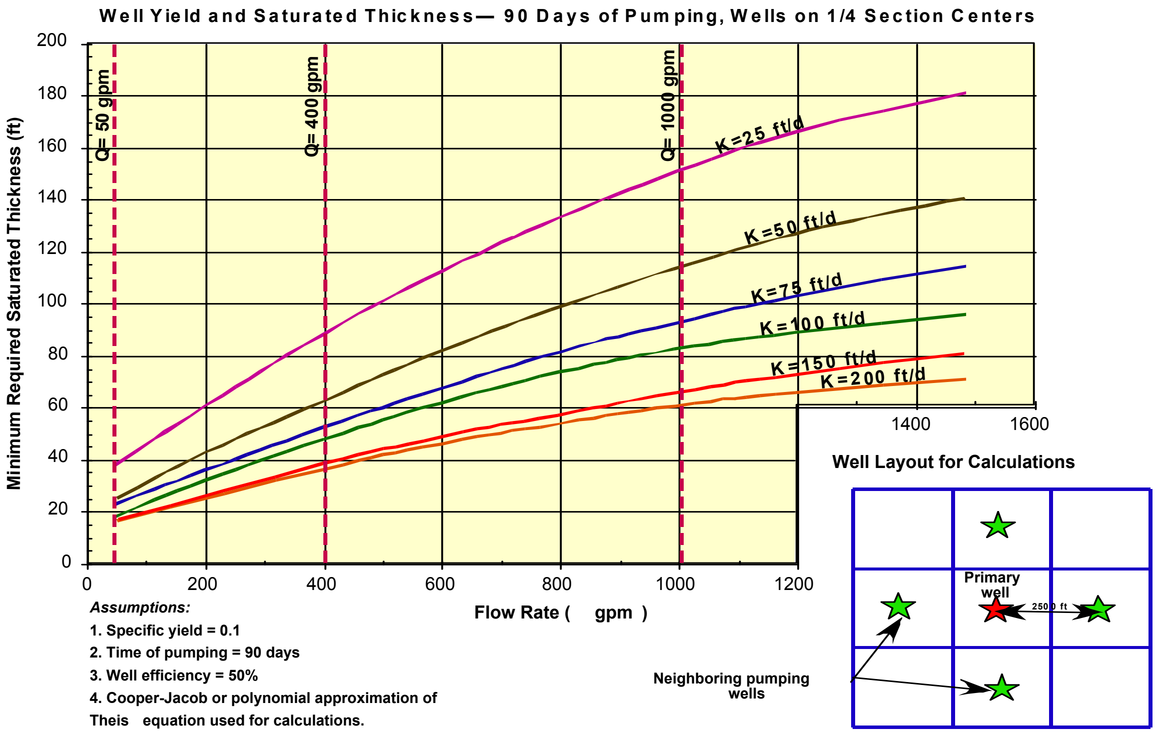
Assumptions:

1. Specific yield = 0.1

2. Time of pumping = 90 days

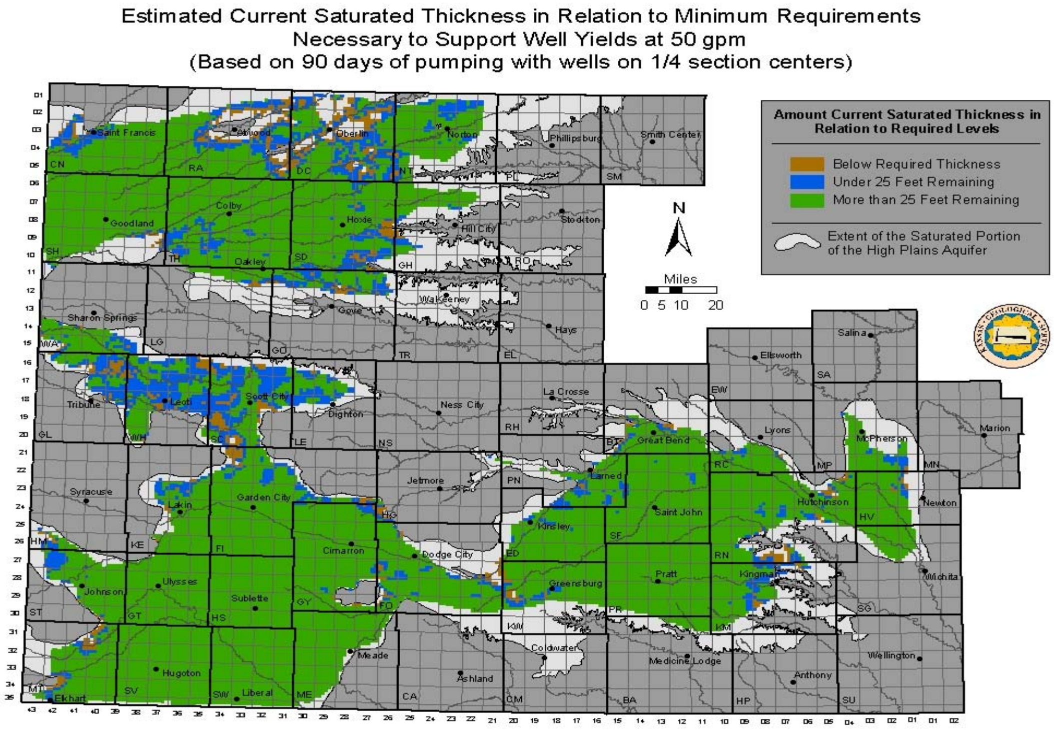
3. Well efficiency = 50%

4. Cooper-Jacob approximation of Theis equation used for calculations.


Well Yield and Saturated Thickness— 90 Days of Pumping, Wells on 1/4 Section Centers
Minimum Required Saturated Thickness (ft)
0
20
40
60
80
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
1600
Flow Rate (gpm)
Q= 50 gpm
Q= 400 gpm
Q= 1000 gpm
K=25 ft/d
K=50 ft/d
K=75 ft/d
K=100 ft/d
K=150 ft/d
K=200 ft/d
Assumptions:
1. Specific yield = 0.1
2. Time of pumping = 90 days
3. Well efficiency = 50%
4. Cooper-Jacob or polynomial approximation of Theis equation used for calculations.
Well Layout for Calculations
Primary well
2500 ft
Neighboring pumping wells

[illegible] [illegible]

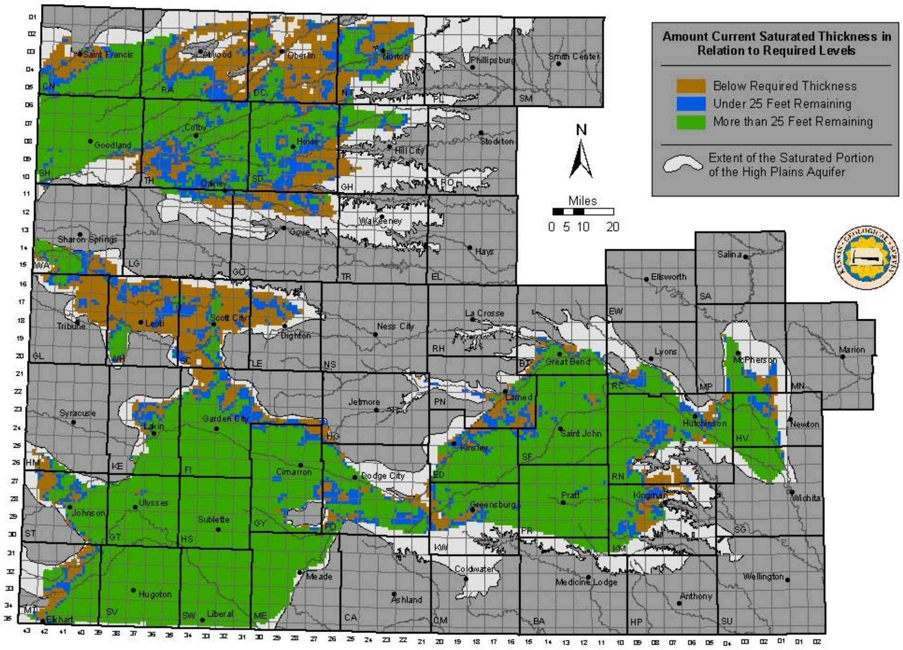
[illegible]


Estimated Current Saturated Thickness in Relation to Minimum Requirements
Necessary to Support Well Yields at 50 gpm
(Based on 90 days of pumping with wells on 1/4 section centers)
Amount Current Saturated Thickness in Relation to Required Levels
Below Required Thickness
Under 25 Feet Remaining
More than 25 Feet Remaining
Extent of the Saturated Portion of the High Plains Aquifer
N
Miles
0 5 10 20
Saint Francis
Atwood
Oberlin
Norton
Phillipsburg
Smith Center
Goodland
Colby
Hoxie
Hill City
Stockton
Oakley
Wakeeney
Gove
Hays
Sharon Springs
Tribune
Leoti
Scott City
Dighton
Ness City
La Crosse
Great Bend
Ellsworth
Salina
Lyons
McPherson
Marion
Syracuse
Lakin
Garden City
Jetmore
Larned
Saint John
Hutchinson
Newton
Kinsley
Cimarron
Dodge City
Greensburg
Pratt
Kingman
Wichita
Johnson
Ulysses
Sublette
Hugoton
Liberal
Elkhart
Meade
Ashland
Coldwater
Medicine Lodge
Anthony
Wellington

[illegible] [illegible]

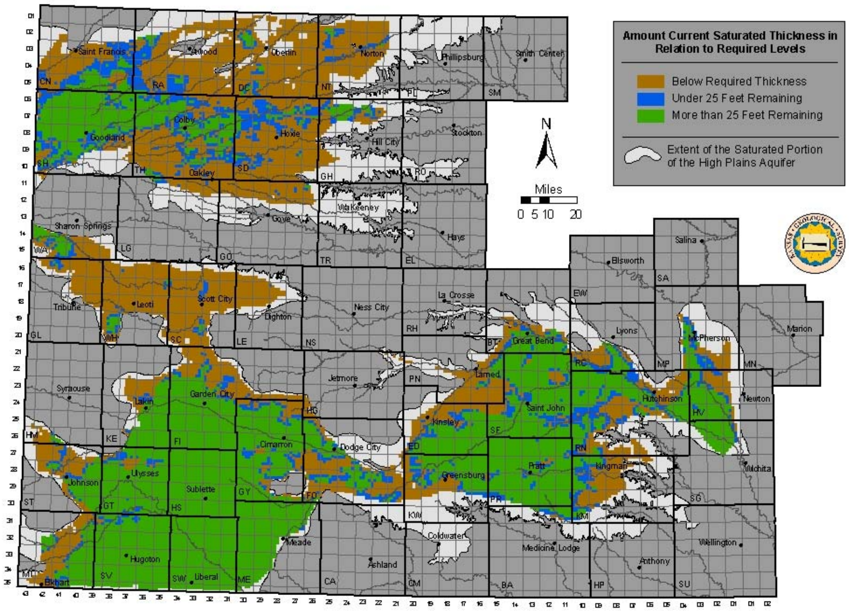
[illegible]

Estimated Current Saturated Thickness in Relation to Minimum Requirements
Necessary to Support Well Yields at 400 gpm
(Based on 90 days of pumping with wells on 1/4 section centers)



[illegible] [illegible]

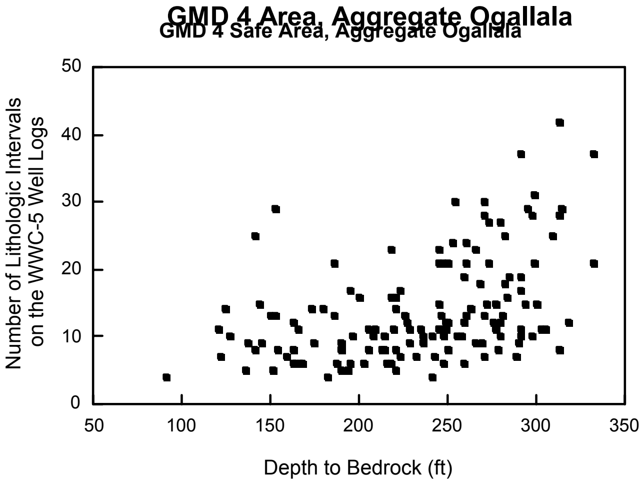
Estimated Current Saturated Thickness in Relation to Minimum Requirements
Necessary to Support Well Yields at 1000 gpm
(Based on 90 days of pumping with wells on 1/4 section centers)



[illegible] [illegible]

[illegible]

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]


GMD 4 Area, Aggregate Ogallala
GMD 4 Safe Area, Aggregate Ogallala
Number of Lithologic Intervals on the WWC-5 Well Logs
Depth to Bedrock (ft)
0
10
20
30
40
50
50
100
150
200
250
300
350

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

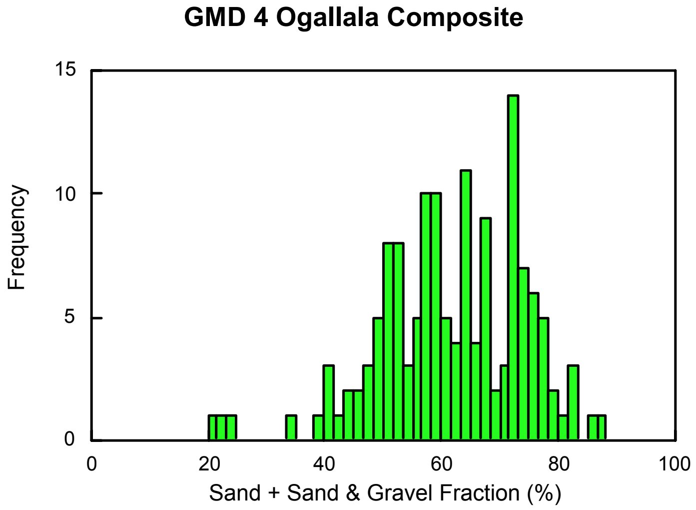
[illegible]

[illegible]

[illegible]

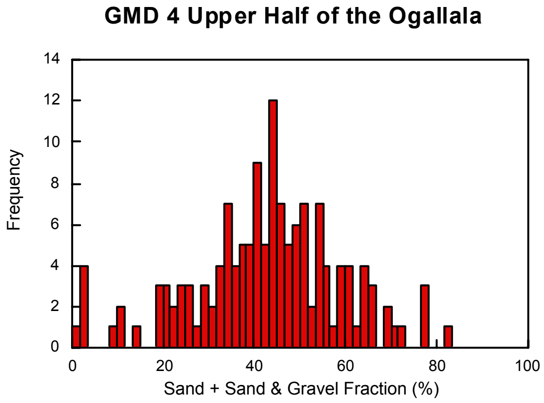
[illegible]

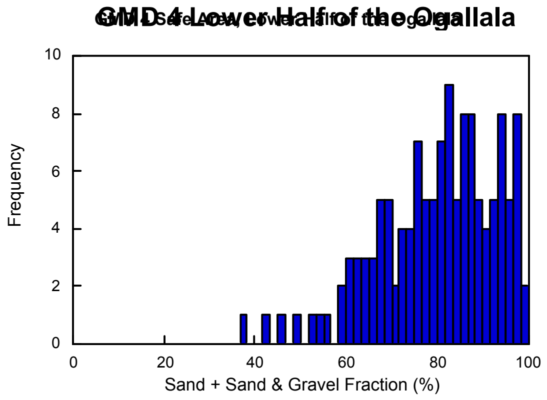
[illegible]


GMD 4 Ogallala Composite
Frequency
0
5
10
15
0
20
40
60
80
100
Sand + Sand & Gravel Fraction (%)

[illegible]

[illegible]

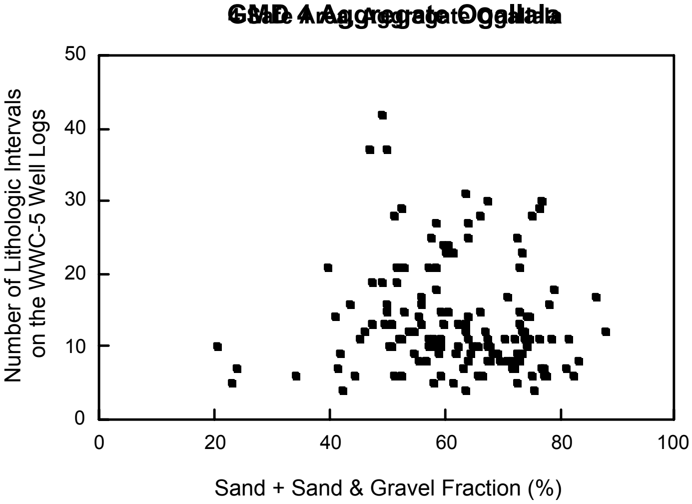

GMD 4 Upper Half of the Ogallala
Frequency
0
2
4
6
8
10
12
14
0
20
40
60
80
100
Sand + Sand & Gravel Fraction (%)


GMD 4 Lower Half of the Ogallala
Frequency
0
2
4
6
8
10
0
20
40
60
80
100
Sand + Sand & Gravel Fraction (%)

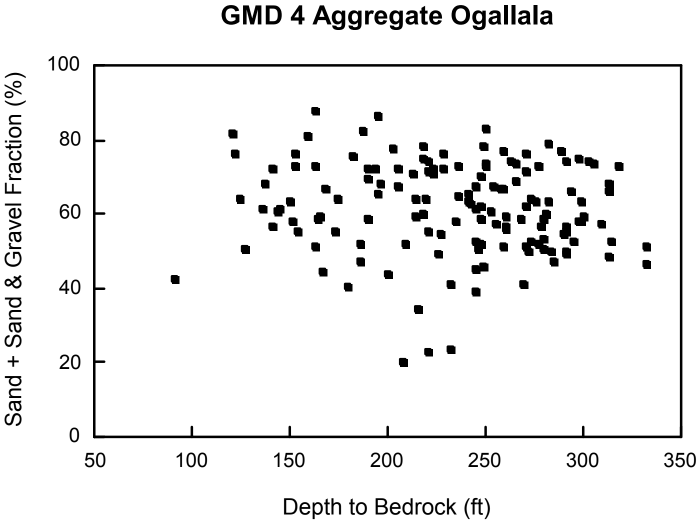
[illegible]

[illegible]

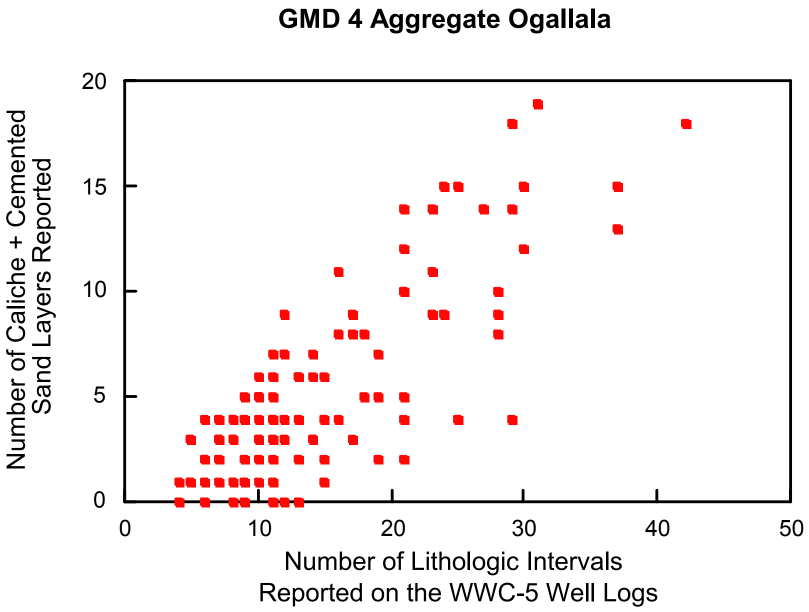
[illegible]


GMD 4 Aggregate Ogallala
Number of Lithologic Intervals on the WWC-5 Well Logs
0
10
20
30
40
50
0
20
40
60
80
100
Sand + Sand & Gravel Fraction (%)

[illegible] [illegible]


GMD 4 Aggregate Ogallala
Sand + Sand & Gravel Fraction (%)
0
20
40
60
80
100
50
100
150
200
250
300
350
Depth to Bedrock (ft)

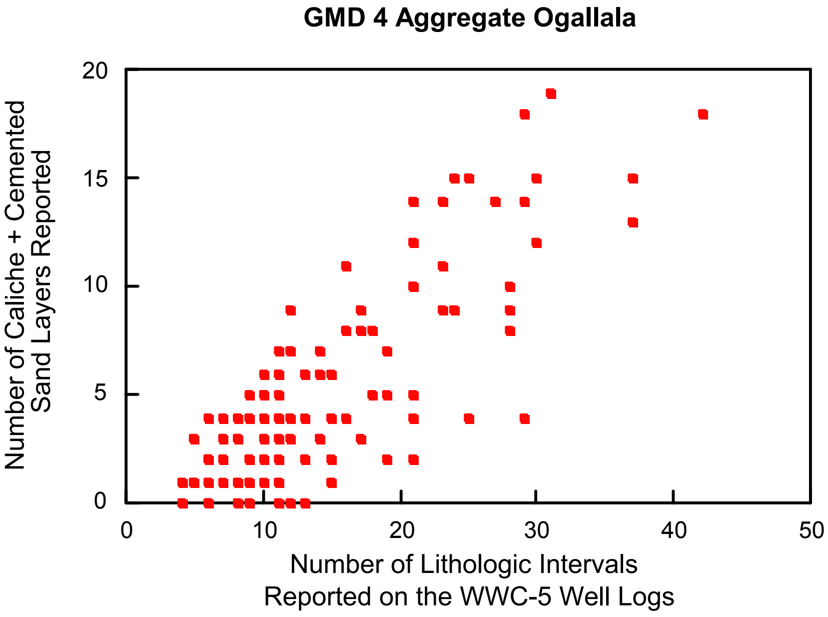
[illegible] [illegible]


GMD 4 Aggregate Ogallala
Number of Caliche + Cemented Sand Layers Reported
Number of Lithologic Intervals Reported on the WWC-5 Well Logs
0
5
10
15
20
0
10
20
30
40
50

[illegible] [illegible]

[illegible] [illegible]

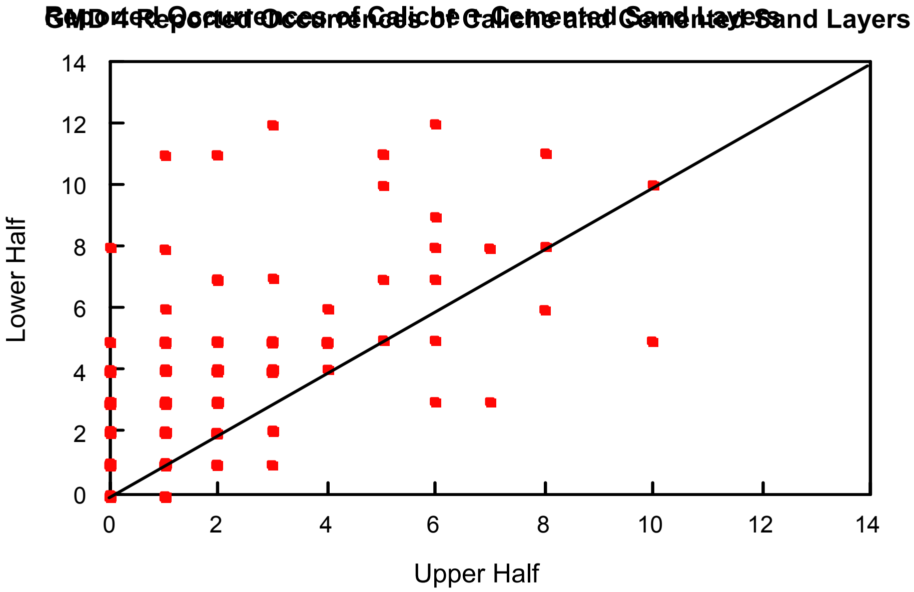
[illegible]


GMD 4 Aggregate Ogallala
Number of Caliche + Cemented Sand Layers Reported
Number of Lithologic Intervals Reported on the WWC-5 Well Logs
0
5
10
15
20
0
10
20
30
40
50

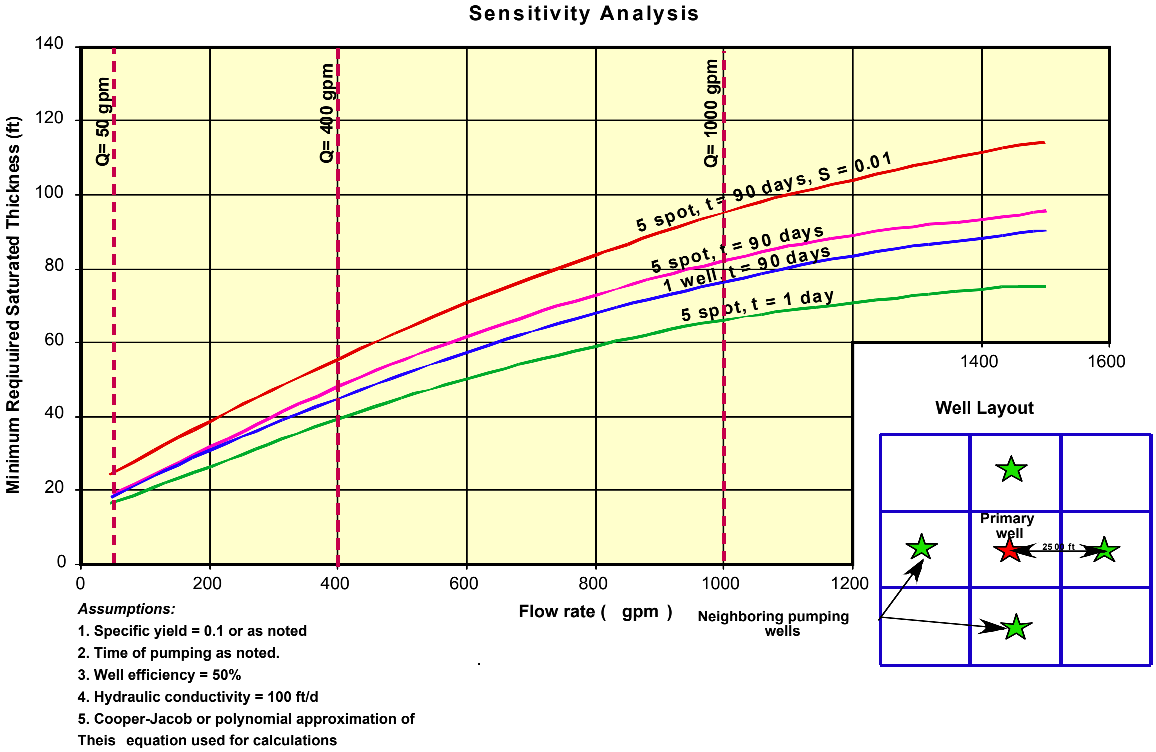
[illegible] [illegible]

[illegible]

[illegible]


Reported Occurrences of Caliche – Cemented Sand Layers
GMD 4 Reported Occurrences of Caliche and Cemented Sand Layers
Lower Half
Upper Half
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
14

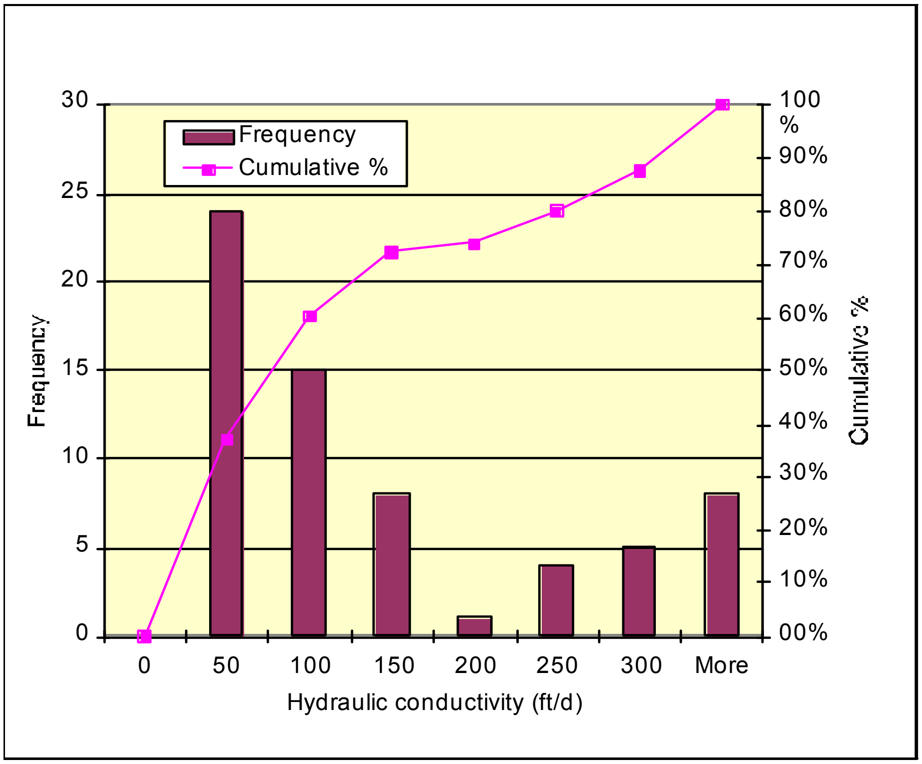
[illegible]



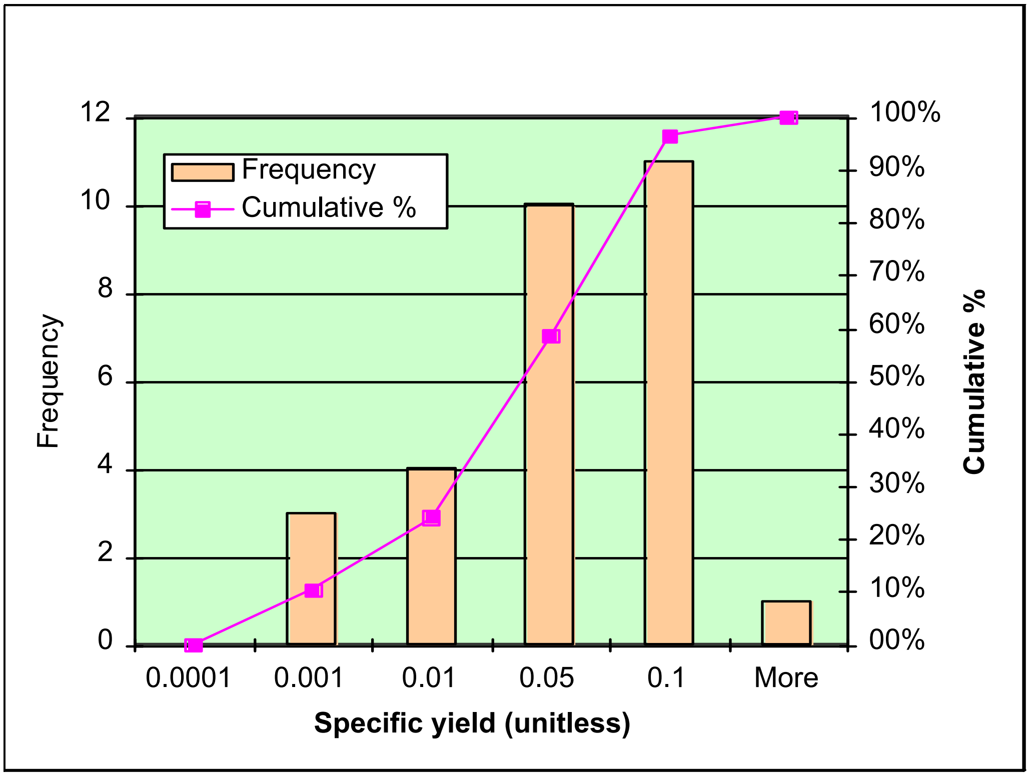
Assumptions:

1. Specific yield = 0.1 or as noted
2. Time of pumping as noted.
3. Well efficiency = 50%
4. Hydraulic conductivity = 100 ft/d
5. Cooper-Jacob or polynomial approximation of Theis equation used for calculations

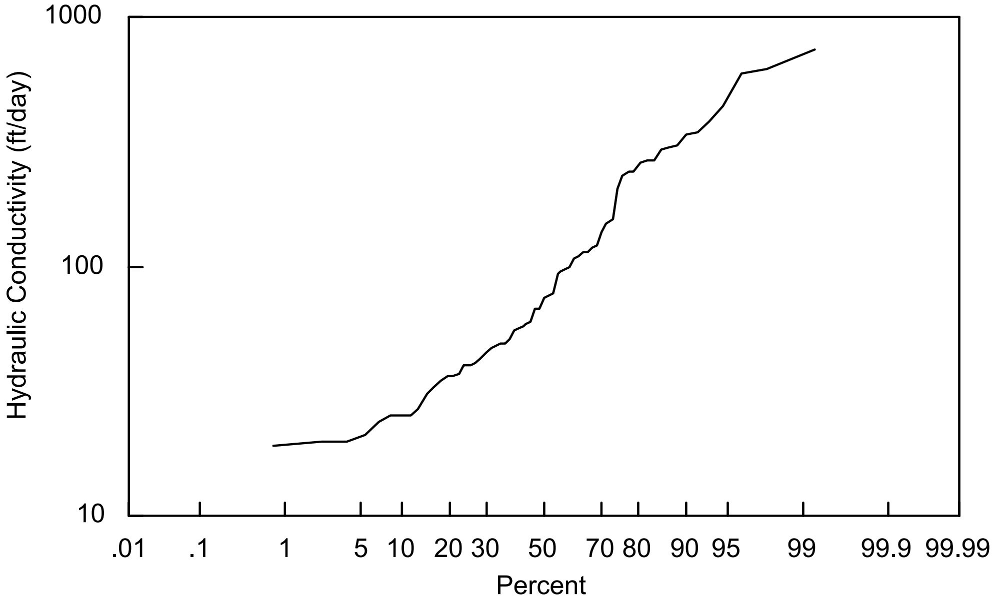
[illegible] [illegible]



[illegible]


12
10
8
6
4
2
0
Frequency
Cumulative %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
00%
Cumulative %
Frequency
0.0001
0.001
0.01
0.05
0.1
More
Specific yield (unitless)

[illegible] [illegible]
[illegible] [illegible]


1000
100
10
Hydraulic Conductivity (ft/day)
.01
.1
1
5
10
20
30
50
70
80
90
95
99
99.9
99.99
Percent

[illegible] [illegible]
[illegible]

[illegible]

- [illegible]
- [illegible]
- [illegible]
- [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

- [illegible]

[illegible]

Well Number	CTY 3/	Principal Aquifer 1/	Depth of Well (ft) 2/	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) 4/	Hydraulic conductiv-ity (ft/d) 4/	Storage Coefficient (Specific Yield) 4/	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
1-26-17caa	DC	Qal	50	19	31	105	7	15.0	68	2,273	119				5/10/66
1-29-30bdd	DC	Qal	75	46	29	1450			24	13,369	303	0.02		1700	1962
1-38-2cdc	CN	Qal	41	18	23	485	9	53.9	73	14,706	735	0.07		1050	4/7/67
2-27-7dca	DC	Qal	75	36	39	960	11	87.3	3	10,027	294	0.06		1250	4/13/67
2-31-9bda	RA	Qal	40	29	11	440	24	18.3	48	8,690	348	0.01		2800	7/25/67
2-36-18ccb	RA	To	300	76	222	445	37	12.0	123	6,016	78	0.05			7/8/66
3-28-32bca	DC	To	205	70	134	435	53	8.2	44	1,337					7/27/67
3-29-21bad	DC	Qal	62	39	22	1500			24	16,043	382	0.02			8/1/62
3-33-3dcc	RA	Qal	68	37	25	625	27	23.1	190	7,353	230	0.015	.01-.02	450	4/16/68
3-36-27cbb	RA	To	299	129	167	1000	56	17.9	1150	5,682	43			1700	3/29/67
3-40-28abc	CN	Qal, To	24	17	7	165	15	11.0	Many Days	5,080	299				1965
4-26-8ddd	DC	Qal	70	38	32	460	18	25.6	168	5,882	155	0.004		1450	6/26/68
4-37-17aac	CN	To	342	138	187	850	53	16.0	90	3,476	25	0.08			5/31/66
4-38-4bac	CN	To	330	115	212	810	54	15.0	815	3,877	33	0.02			7/22/67
4-39-21dbd	CN	To	268	122	145	640	56	11.4	288	2,807	24	0.09		700	7/12/67
4-41-16daa	CN	Qal	38	20	18	235	33.8	7.0	141	6,818	341	0.006		1300	7/3/68
4-42-26bda	CN	Qal, To	50	28	22	560	27	20.7	6	7,353	267				9/15/50
4-42-26dbc	CN	Qal, To	36	29	7	630	12	52.5	5	17,112	590				8/5/65
4-42-26dbc	CN	Qal, To	36	29	7	630	12	52.5	5	18,048	623				
4-42-27add	CN	Qal, To	54	27	27	235	10	23.5	18	4,011	148				1965
4-42-27add	CN	Qal, To	54	33	21	235	10	23.5	18	4,011	122				
5-28-5dcd	SD	Qal	58	29	22	800			24	9,358	267	0.03			1962
5-33-29bda	TH	To	115	96	19	600	25	24.0	360	5,348	56	0.03		940	3/14/68

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductiv- ity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
5-40-27aba	SH	To	333	158	174	925	35	26.4	610	3,075	20	0.06			7/1/66
5-40-27bba	SH	To	327	148	176	900	31	29.0	65	7,353	49				6/29/66
5-41-12adc	SH	To	315	115	198	680	62	11.0	112	5,573	48				4/18/67
6-27-3dbd	SD	Qal	92	63	27	195	20	9.8	23	2,005	31				5/13/66
6-29-5dcb	SD	To	212	89	121	725			240	8,690	95	0.02			7/5/66
6-30-14ccd	SD	To	205	100	103	470	76	6.2	47	2,941	27	0.07			6/2/66
6-32-29cdb	TH	To	204	92	112	820	69	11.9	17	10,027	110				4/4/66
6-33-33cab	TH	Qal	38	25	13	637	15.4	41.4	3	6,016	241				10/20/43
6-35-26acd	TH	To	260	113	147	485	?		1390	7,353	67	0.12			7/9/66
6-37-3bcc	SH	To	280	121	157	780			210	8,021	67				3/11/68
6-39-33bdd	SH	To	314	176	133	840	84	10.0							6/??/64
6-42-26baa	SH	To	303	108	195	870	41	21.2	120	4,947	45	0.08			6/24/66
7-26-28cab	SD	To	247	93	150	880	25	35.2	98	8,690	94				8/1/66
7-28-21aba	SD	To	254	122	130	1040	32.5	32.0	242	9,358	76	0.08		1950	7/3/68
7-31-26ccc	TH	To	177	72	105	588	42.1	14.0	3	7,086	99				10/19/43
7-32-7aca	TH	To	135	62	72	1021	18.1	56.6	3						10/16/43
7-33-10cbd	TH	To	195	67	127	295	26.3	11.2	4	4,011	60				10/18/43
7-33-35add	TH	To	265	133	132	970	28	34.6							7/21/67
7-34-25dbb	TH	To	197	99	98	600	22	27.3	340	11,364	115				8/27/66
7-36-17dad	TH	To	275	135	139	1080	80	13.5	725	5,348	40				3/28/67
7-39-20bad	SH	Qal, To	139	118	21	1170	16	73.1	4	52,941	441			220	7/29/49
7-40-6adb	SH	To	345	193	150	1080	70	15.4	625	8,690	49	0.08	.03-.13	4900	3/27/68
7-42-27aab	SH	To	321	180	141	770	33	23.3	950	4,144	25	0.03			3/9/67
8-26-16cdd	SD	Qal	72	35	35	270	6	45.0	44	8,690	241				5/16/66
8-26-21bab	SD	Qal	72	37	35	225	7	32.1	24	7,353	205				5/16/66

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductiv-ity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
8-28-9abc	SD	To	206	114	119	403	63	6.4	8	6,684	59				10/8/52
8-30-13bba	SD	To	268	144	120	1100	41	26.8	2	6,684	47				4/21/66
8-33-2cda	TH	To	265	137	126	1800	51	35.3	1414	14,706	108	0.08		4600	2/14/67
8-33-34bcc	TH	To	227	110	117	1090	58	18.8	71	5,348	55				4/11/66
8-34-1bcb	TH	To	270	142	128	950									9/15/71
8-34-13cbd	TH	To	245	88	157	1000	18	55.6	170	12,032	136				4/25/66
8-37-28abc	SH	To	243	122	116	820	60.5	13.6	390	6,417	51	0.09		1100	6/29/68
8-39-15ccc	SH	To	254	127	127	640	32	20.0	10	4,545	36				8/4/49
8-39-15ccc	SH	To	254	127	127	640	32	20.0	4						
8-40-12dba	SH	To	247	117	122	315	9	35.0	4	4,813	41				7/27/49
8-40-12dbb	SH	To	306	162	140	710	68	10.4	175	12,032	75	0.005			7/7/66
8-40-29bbb	SH	To	280	193	85	290	44	6.6	28	6,684	35	0.001			7/16/66
8-40-35cbb	SH	To	274	140	132	600	27	22.2	140	3,610	25				6/25/66
8-42-19abb	SH	To	317	184	126	970	33	29.4	25	6,684	36				8/24/55
9-32-29adc	TH	To	220	105	110	720	63	11.4	190	5,348	58				8/18/66
9-35-32daa	TH	To	238	48	187	390			620						4/1/67
9-41-31aba	SH	To	265	148	112	830	49	16.9	290	17,380	114	0.0003		740	6/27/68
9-42-16cdd	SH	To	296	174	117	655	58	11.3	670	7,019	40	0.00055	.0003-.0008		7/14/65
10-27-20bcd	GO	Qal	68	23	45	380	18	21.1	168	3,342	98	0.02		?	1/25/68
10-31-28bcc	GO	To	185	109	74	1080	45	24.0	10	2,273	21				8/18/66
10-32-11baa	LG	To	185	79	106	290	49	5.9	69	1,471	19				8/3/66
10-39-25cca	SH	Qal	40	21	19	220	8	27.5	217	5,214	261				5/11/66
10-42-13acc	SH	To	203	95	82	1010	85	11.9	90	3,610	37				6/28/66

Well Number	CTY *3/*	Principal Aquifer *1/*	Depth of Well (ft) *2/*	Saturated Thickness (ft)	Depth to Water (ft)	Average Pumping Rate (gpm)	Drawdown (ft)	Specific Capacity (gpm/ft)	Duration of Pumping (hours)	Transmissivity (ft^2/d) *4/*	Hydraulic conductiv-ity (ft/d) *4/*	Storage Coefficient (Specific Yield) *4/*	Range of storage values	Apparent Radius of Influence (ft)	Date of Test
10-42-24bba	SH	To	205	119	83	1030	75	13.7	20	2,406	20				6/28/66
11-26-4cdc	GO	To	167	130	60	700									7/2/70
Average Values:								24.1		7737	140	0.043			

FOOTNOTES:

1/ = Geologic Source: Qal = Alluvium; To = Ogallala Formation

2/ All depths are feet below ground surface

3/ CTY= Counties, CH= Cheyenne, DC=Decatur, GO=Gove, LO=Logan, RA=Rawlins, SD=Sheridan, SH=Sherman, TH=Thomas

4/ =Average value for test results

Kansas Geological Survey

Open File Report 2002-25D

Exploring Relationships Between Water Table Elevations, Reported Water Use, and Aquifer Lifetime as Parameters for Consideration in Aquifer Subunit Delineations

By

B. B. Wilson, D.P. Young and R.W. Buddemeier

With contributions from other authors in the report series

A component of the Technical Report series 2002-25: Technical Support for Ogallala-High Plains Aquifer Assessment, Planning, and Management

A final report of Fiscal Year 2002 activities by the Kansas Geological Survey supported by contracts with the Kansas Water Office and the Kansas Department of Agriculture

Kansas Geological Survey Open File Report 2002-25D

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KGS OFR 2002-25D. Exploring Relationships Between Water Table Elevations, Reported Water Use, and Aquifer Lifetime as Parameters for Consideration in Aquifer Subunit Delineations

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KGS OFR 2002-25D.

Exploring Relationships Between Water Table Elevations, Reported Water Use, and Aquifer Lifetime as Parameters for Consideration in Aquifer Subunit Delineations

By B. B. Wilson, D.P. Young and R.W. Buddemeier

1. Introduction

This report on exploring relationships between water table elevations, reported use, and aquifer lifetime as parameters for consideration in aquifer subunit delineations (OFR 2002-25D) 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.

The concept of aquifer subunits is a relatively new approach for planning enhanced management activities in the Ogallala-High Plains Aquifer. The Kansas Water Authority's Ogallala Management Advisory Committee (MAC) and Technical Advisory Committee (TAC) final report, which was adopted into the FY 2004 Kansas Water Plan, recommends the delineation of aquifer subunits in which specific water use goals could be tailored to areas containing similar aquifer characteristics (Ogallala, 2001). This approach recognizes that a "one-size fits all" management policy or program is not applicable for the entire Ogallala-High Plains aquifer region. Excerpts from this recommendation are contained in Section 3, KGS OFR 2002-25G.

This report is focused on a review of possible techniques and methodologies that could be used to identify and characterize aquifer subunits within the Ogallala-High Plains aquifer (the western region of the High Plains Aquifer). The first method is based on the estimated usable life of the Ogallala-High Plains aquifer where past rates and trends in the water table are projected into the future until the saturated thickness of the aquifer reaches a certain level. These estimates provide a simple classification of the amount of time remaining until the amount of water in storage for a subunit area is projected to reach resource exhaustion and large volume ground-water pumping becomes impractical.

The second aquifer subunit delineation process evaluated in this report is the use of geo-statistical cluster processes to spatially classify similar areas of the aquifer based on a series of selected aquifer parameters, specifically, the amount of reported water use, the change in the water table, and the current saturated thickness. The geo-statistical clustering process is based on both unsupervised and supervised clustering routines similar to methods used to classify remotely-sensed satellite data images.

2. Estimated Usable Lifetime of the Ogallala-High Plains Aquifer

2.1. Methodology

In published maps of the Atlas of the Kansas High Plains Aquifer (Schloss et al., 2000), the heterogeneity of the aquifer is well documented, both in terms of resource available and water demands. The spatial distribution of the amount of water in storage, water right development, climatic features, and the changes in the water table elevations over time has been and continues to be extremely nonuniform. In addition, different methods used to estimate the usable lifetime of the Ogallala-High Plains aquifer provide very different answers to the question of whether the ground-water resource is sustainable and if not, how long until necessary transitions will occur.

Usable lifetime was estimated using the methods of Schloss et al. (2000), but incorporating more recent data on water level trends (1991-2001) and additional time classifications. The estimates were made by projecting established recent rates of water level declines into the future until a certain saturated thickness threshold was reached. Note that these are projections of recent water level trends, not predictions. Consistent with Schloss et al. (2000), a saturated thickness of thirty feet has been assumed by state agencies and local water users to be the approximate minimum thickness needed to support large volume water demands. The 30 feet saturated thickness threshold is used in this report to facilitate comparisons with the estimated usable lifetime maps originally portrayed in the Atlas of the Kansas High Plains Aquifer. Sections 2.2 and 2.3 below describe usable lifetime projections using the 30 foot threshold value and 5 and 10 year water level trend values.

However, recent results from the well yield portion of this report series (KGS OFR 2002-25C) suggest that the minimum thickness is actually substantially greater than thirty feet; these issues are addressed in section 2.4 of this report.

To calculate the recent rates of water level change, data were extracted from the KGS Water Information Storage and Retrieval Database (WIZARD). Monitoring wells selected from WIZARD were required to be screened within the geologic formations of the High Plains aquifer and to have at least one depth to water measurement during the winter months (December, January, and/or February) in a three-year time window around each year of 1991, 1996, and 2001. For example, the 1991 water level data subset represents wells measured at least once during the winters of 1990, 1991, or 1992. If more than one measurement was available, the average of all the winter measurements over the three-year time period was used. Under these selection criteria, a total of 1,115 monitoring wells in the High Plains aquifer were identified.

The rates of water level change for the periods 1991-2001 (Figure 1), 1991-1996 (Figure 2), and 1996-2001 (Figure 3) were then established for every well in the data set by dividing the total change in the water table by the number of years in the time period. For example, if the water table at a monitoring well declined by 10 feet from 1991 to 2001, the annual rate of change was calculated to be 1 foot per year. The annual rates of change were then used for spatial interpolation of the average annual rate of change across the High Plains aquifer region and assigned to section-centers. By classifying the rates of change into five year intervals of 1991 to 1996 and 1996 to 2001, comparisons can be made during conditions when the overall precipitation levels where higher (early 1990s), compared to when they were normal or lower (later 1990s). Information from WIZARD data can be access free of charge via the internet at http://www.kgs.ku.edu/Magellan/WaterLevels/index.html.

The estimated saturated thickness, defined as the vertical thickness of the aquifer in which the pore spaces are filled (saturated) with water, was calculated from the interpolated section-center values of the water table elevation from the 2001 WIZARD data subset, by subtracting the estimated elevation of the bedrock or base of the aquifer at each location. Bedrock elevation estimates were derived from Hansen and Juracek (1995); these data can be obtained free of charge from the Data Access and Support Center via the internet at http://gisdasc.kgs.ku.edu/. The estimated 2001 saturated thickness (Figure 4) was then used as the starting point from which the annual rate of change for a given time period was used to calculate the number of years until the aquifer reaches a saturated thickness of thirty feet or less.

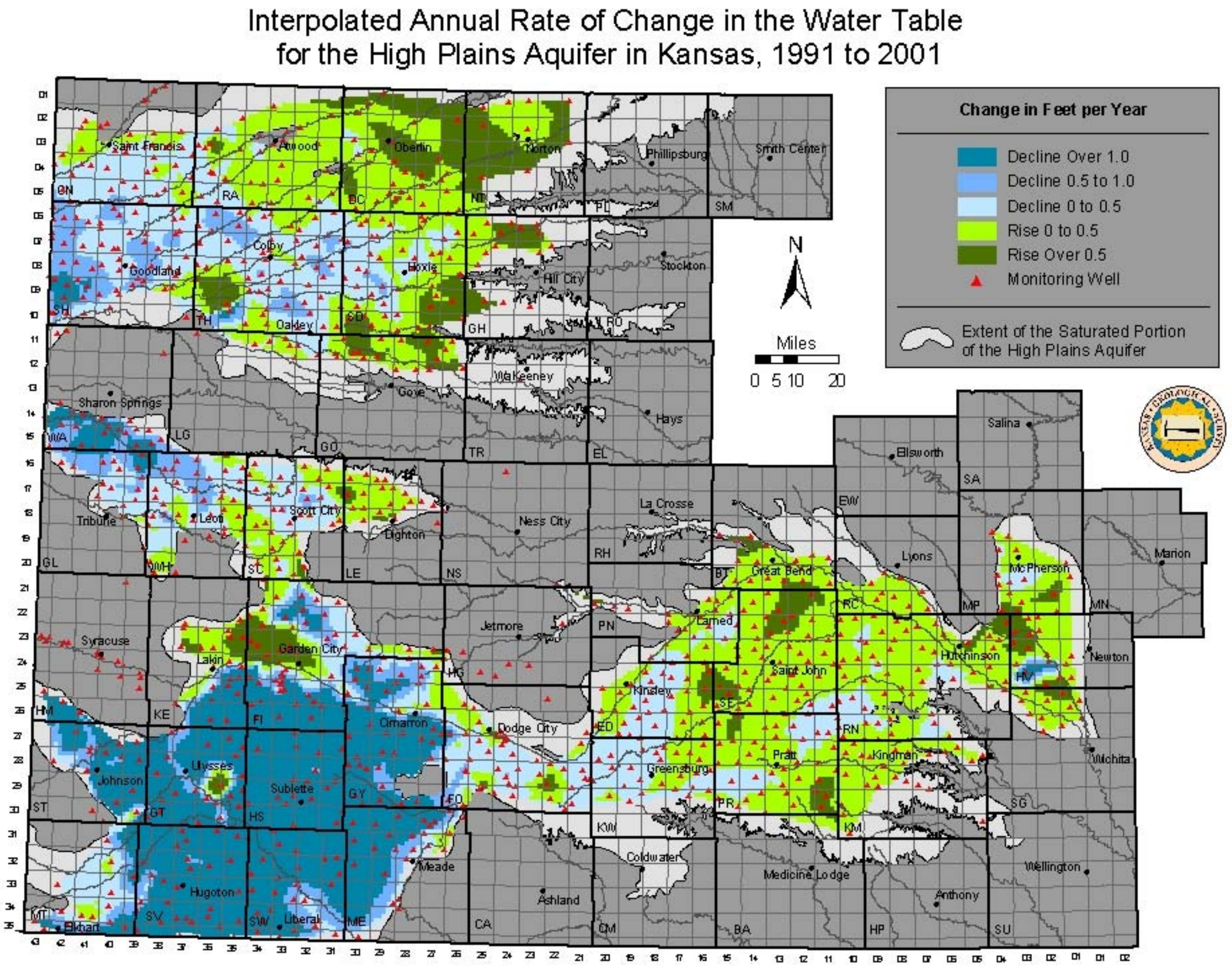


Figure 1- Interpolated annual rate of change in the water table for the High Plains aquifer in Kansas, 1991 to 2001.

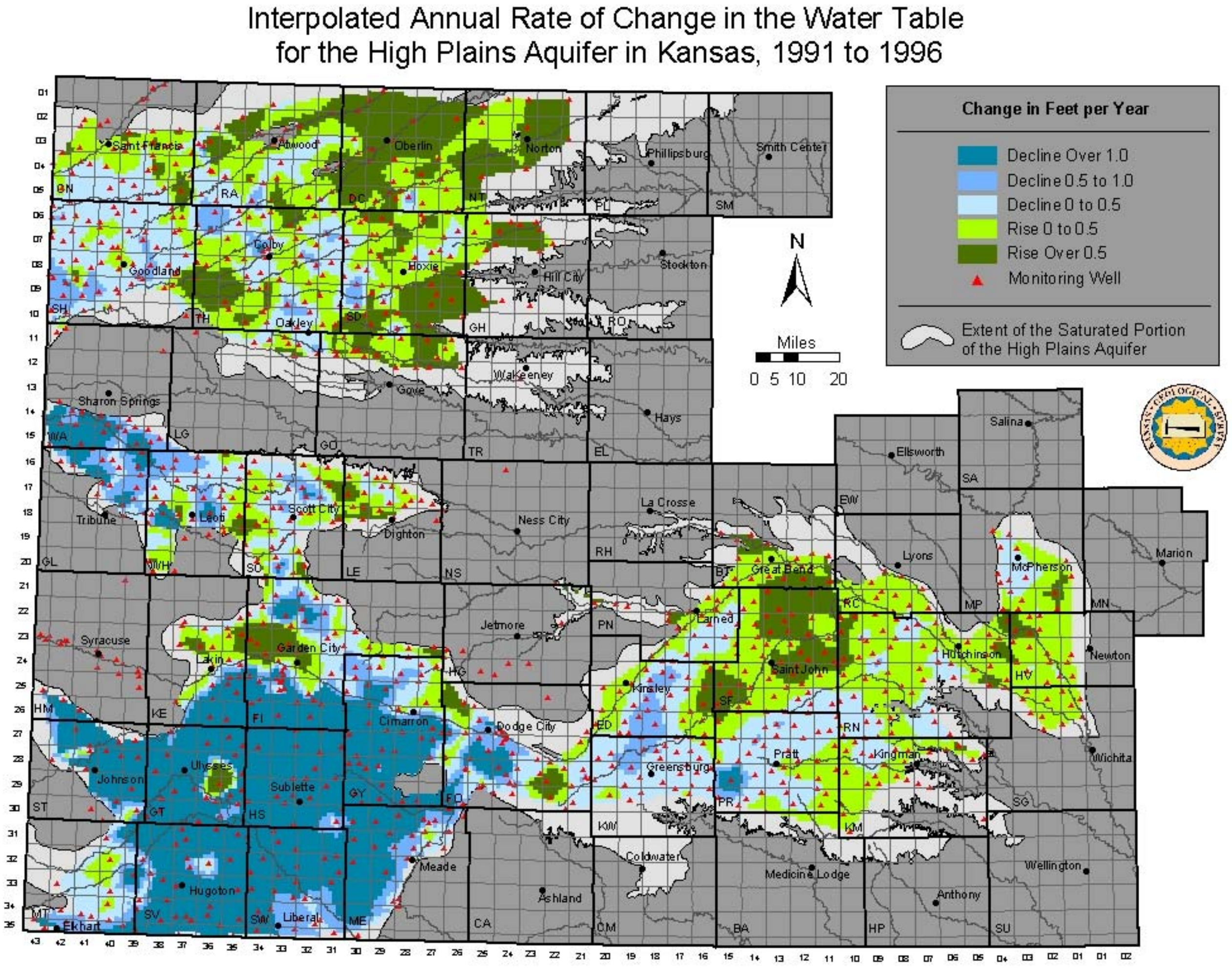


Figure 2- Interpolated annual rate of change in the water table for the High Plains aquifer in Kansas, 1991 to 1996.

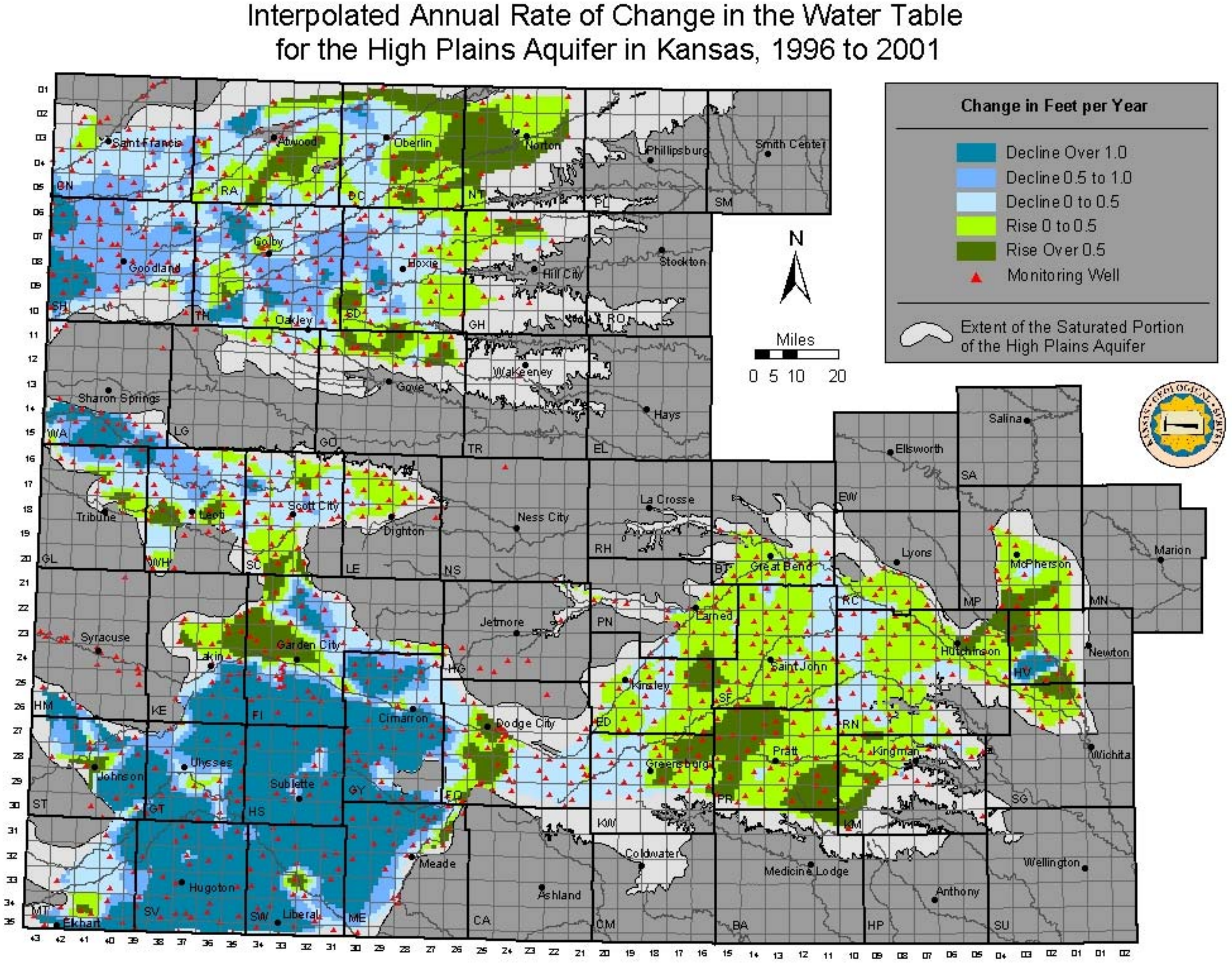


Figure 3- Interpolated annual rate of change in the water table for the High Plains aquifer in Kansas, 1996 to 2001.

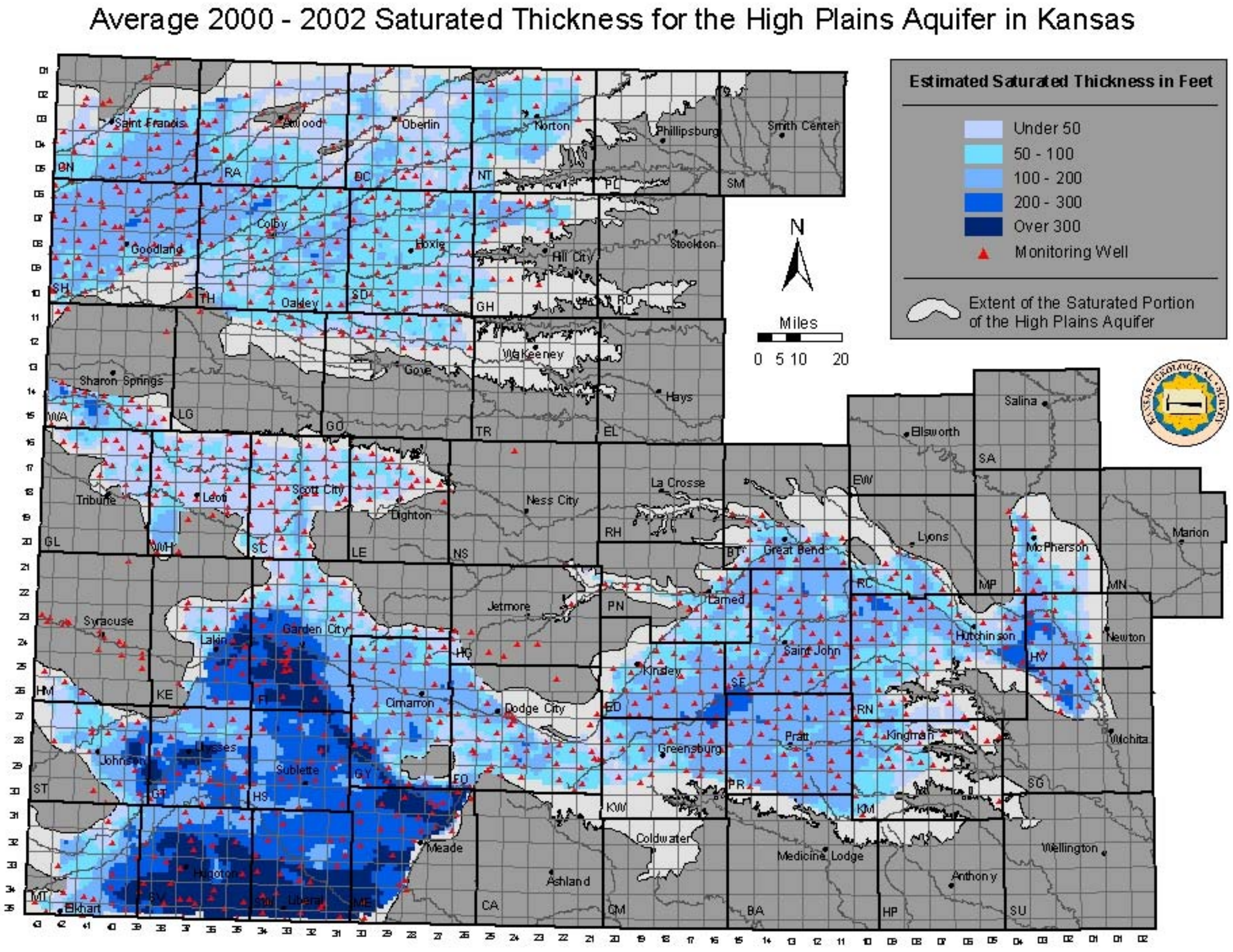


Figure 4- Estimated 2001 saturated thickness for the High Plains aquifer in Kansas. The 2001 saturated thickness is based on the difference in the average 2000-2002 water table elevation and the estimated bedrock elevation.

The usable lifetime estimates are presented in a variety of formats based on differing time intervals, classifications, and minimum required saturated thicknesses . The intervals initially used are the same intervals used in the Atlas of the Kansas High Plains Aquifer (Schloss et al., 2000): under 25, 25-50, 50-100, 100-250, and over 250 years (see section 2.2). Under the contract scope of work developed for this report, the estimated usable lifetime classification schemes were further refined to 10-year time intervals (see section 2.3). Finally, the estimated usable lifetime calculations were repeated using the Atlas classifications based on the minimum required saturated thickness thresholds for varying wells yields outlined in KGS OFR 2002-25C (see Section 2.4).

2.2. Results Using Atlas Intervals

The new estimates of the usable lifetime of the High Plains aquifer were classified for comparison purposes using the same intervals initially used in the Atlas of the Kansas High Plains Aquifer (Schloss et al., 2000). The estimated lifetime based on ground-water trends from 1991 to 2001 can be seen in Figure 5, with estimates based on trends from 1991 to 1996 and from 1996 to 2001 being shown in Figures 6 and 7, respectively.

Results from this evaluation using more recent data reveal both similar and dissimilar regional patterns when compared with the aquifer lifetime estimates in the Atlas. West-central Kansas consistently shows areas at or within 25 years of resource exhaustion, defined here as a saturated thickness of thirty feet or less. The estimates for southwest Kansas also show similar patterns, although at the township scale there is greater variability between the different time periods used. It is interesting to note the area of localized recharge occurring in Kearny and Finney counties. This is probably caused primarily by the operation of surface ditch irrigation systems where surface water is seeping back into the aquifer; the area is further discussed in OFR 2002-25B.

The area that shows the greatest variability in the usable lifetime estimates occurs in the northwest region of the aquifer. Within this region, the areas classified as being within 25 or 25 to 50 years change considerably depending on the water level change time-period used. It should be noted, however, that northwest Kansas has been subject to greater influences from climatic factors than the other regions of the Ogallala- High Plains; precipitation levels were higher than normal in 1993, and there was an untimely freeze event in 1994. Both events had notable effects on the amount of water used and resulted in decreases in the water level declines for those years.

Results from this assessment further demonstrate that there is great variability in the Ogallala-High Plains aquifer. This variability supports the idea of management approaches based on specific aquifer subunit characteristics, and illustrates one possible approach to their identification based on sub-regional lifetime classifications using the amount of and trends in the water resources for a given area.

2.3. Results Using 10-Year Intervals

Under the contract scope of work developed for this report, the estimated usable lifetime classification schemes were further refined to 10-year time intervals. Within this classification format, the estimated lifetime values for an area are portrayed in a manner more compatible with the time periods associated with short-term bank loans and some owner-tenant agreements. Figures 8, 9 and 10 show the same estimates of the usable lifetime of the aquifer, characterized by 10 year time periods, based on rates of water level change during 1991 to 2001, 1991 to 1996, and 1996 to 2001 respectively.

Although these figures further illustrate the great variability of the aquifer, in some areas it is clear that adjacent small areas with different aquifer classifications reflect the influence of water level measurements from individual monitoring wells. Given the water level measurement uncertainties discussed in OFR 2002-25F, this level of spatial resolution is not justified for establishing trends on a ten-year time interval on the basis of currently available data.

Additionally, the classification areas are too small to conform effectively to the township-scale size target for manageable subunits. However, it could be argued that a 10-year time period classification on the lifetime estimates does have application in prioritizing possible water use goals based on larger areas identified as having a short time period (10, 20 or possibly 30 years) of adequate saturated thickness remaining. Classifying the estimated usable lifetime of the aquifer to 10-year time intervals at local (e.g., section) scales exceeds the temporal resolution of data now being acquired from the existing monitoring well network, and should probably not be used as a management target at local (sub township) levels unless the monitoring data are significantly enhanced (see OFR 2002-25F).

2.4. Estimated Usable Lifetime Based on Required Saturated Thickness/Well Yield Estimates

One of the products of the well yield portion of this series (KGS OFR 2002-25C) is estimates of the minimum amount of saturated thickness required to support different well yields under a variety of pumping and hydrogeologic property scenarios. These relationships between saturated thickness and well yield indicate that the minimum saturated thickness required to support large volume water demands is substantially greater than thirty feet for most scenarios. Based on the scenario of 90 days of pumping with five wells on adjacent ¼ sections, the estimated 2001 saturated thickness (Figure 4) and the estimated hydraulic conductivity shown in Figure 11 (Cedarstrand and Becker, 1998) were used to establish a new minimum required saturated thickness threshold for the estimates of the usable lifetime of the aquifer. The estimates replace the previously used 30 feet threshold with the minimum saturated thickness needed to support well yields of 50, 400 and 1000 gpm under this scenario. The results of the estimated usable lifetime based for well yields of 50, 400, and 1000 gpm under the 90 day pumping scenario can be seen in Figures 12, 13, and 14 respectively, and are based on annual ground-water trends from 1991 to 2001.

The estimates of the usable lifetime of the aquifer for the various pumping rates illustrate that in general there are adequate water reserves to support all of the selected well yields and the associated minimum saturated thicknesses under the 90 day pumping scenario in much of southwest Kansas, and to a lesser extent in northwest Kansas (particularly Sherman county) for at least 25 years if not longer. However, by using the minimum saturated thickness thresholds for the 90 day pumping scenario, the overall lifetime estimates have shortened, and the total area and spatial distribution of areas classified as being within 25 years of, or areas already below, the minimum saturated thickness, have increased from the initial estimates based on the 30 feet threshold.

The lifetime estimates required for 50 gpm well yields (Figure 12) has characteristics most similar to the initial lifetime estimates presented in the Atlas of the High Plains Aquifer and its updated version shown in Figure 5. This should be expected since the original saturated thickness of 30 feet was chosen based on discussion with other state agencies and local water users to

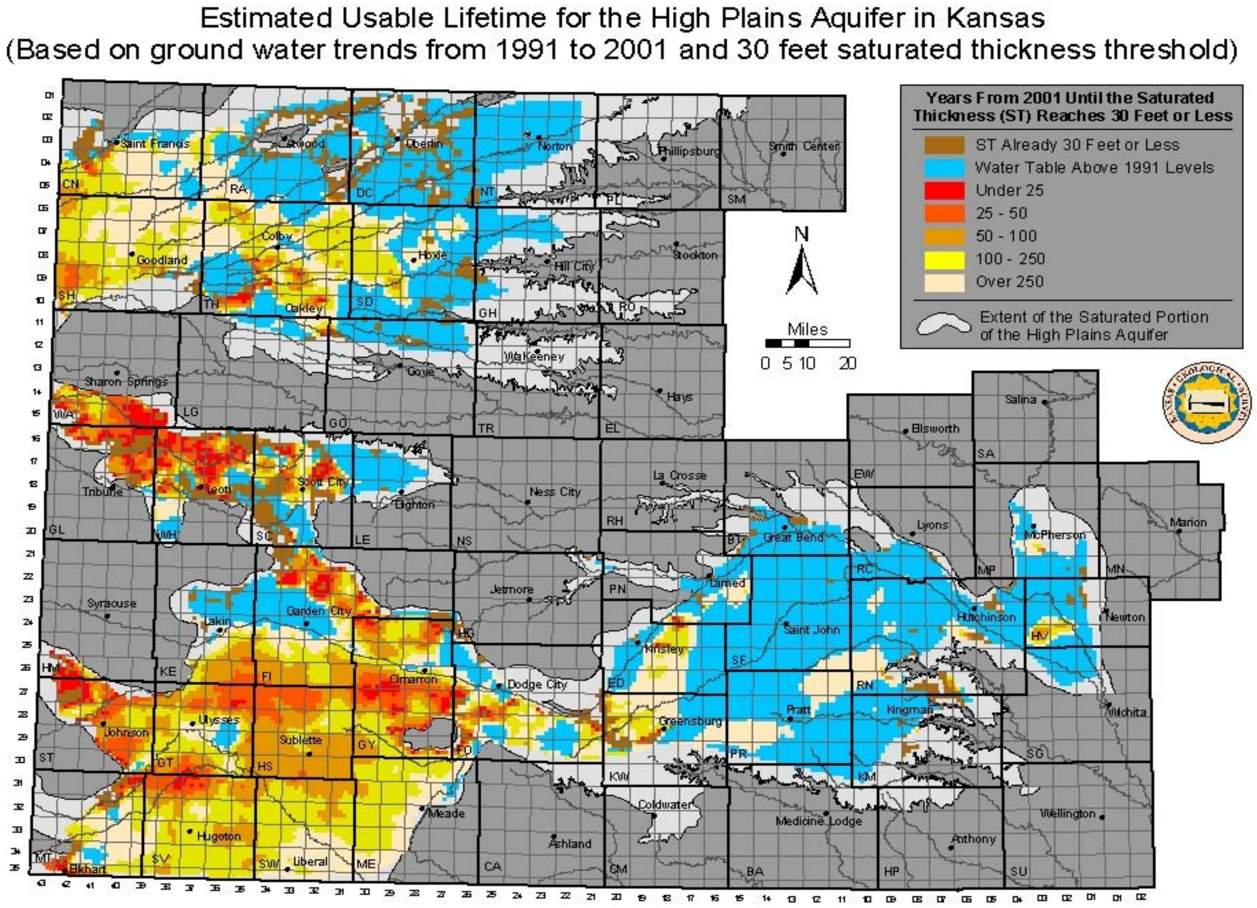


Figure 5- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1991 to 2001 and a 30 feet saturated thickness threshold.

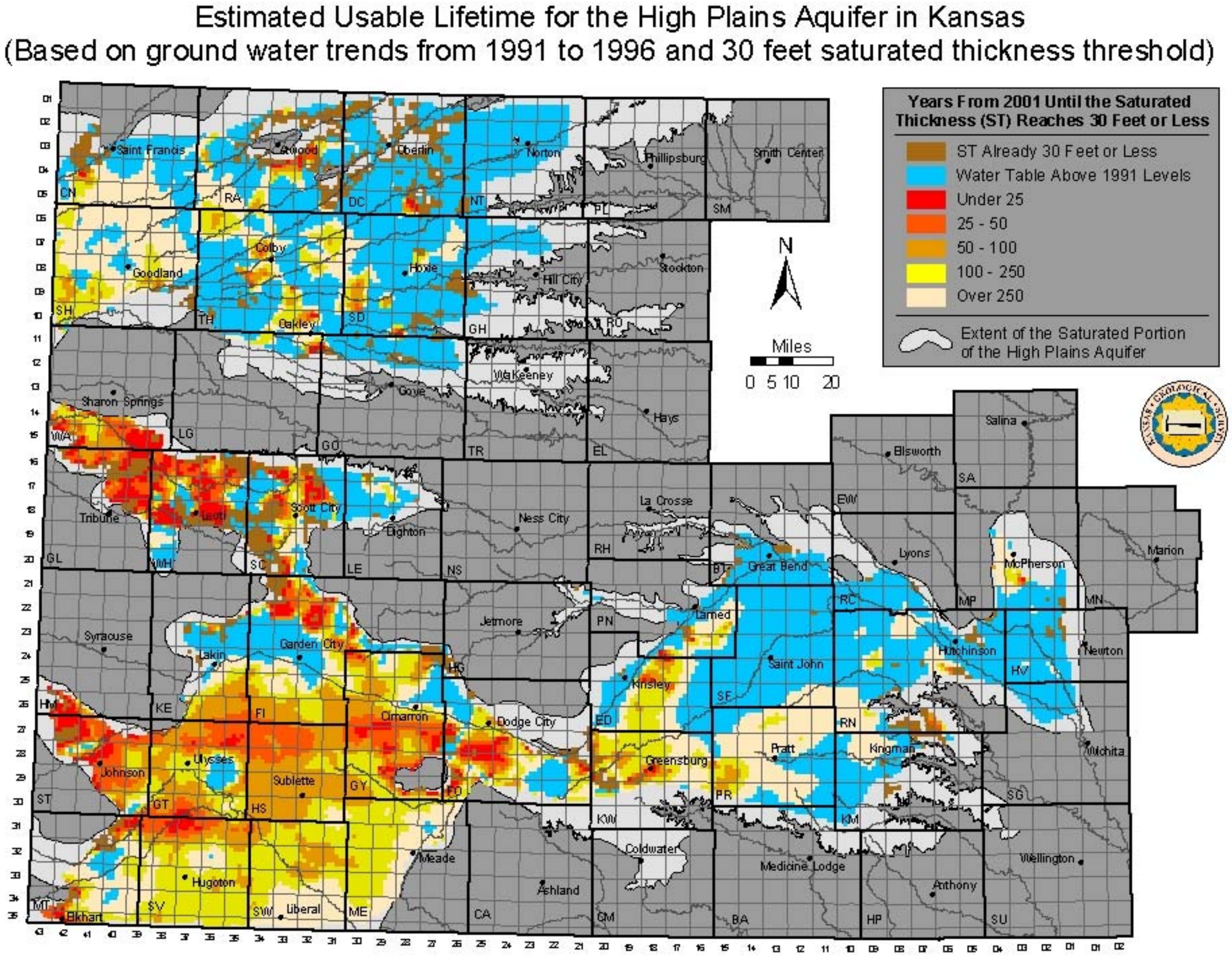
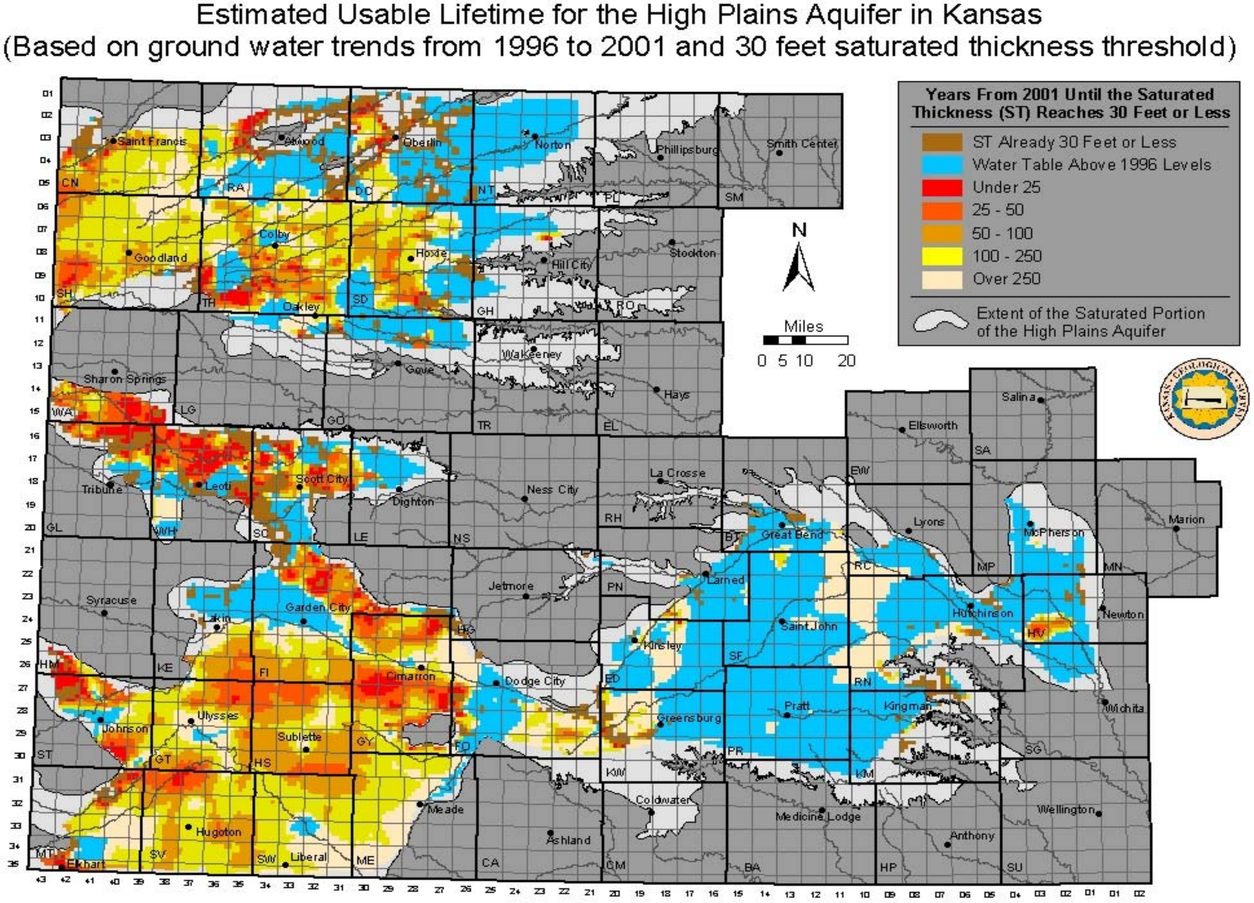


Figure 6- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1991 to 1996 and a 30 feet saturated thickness threshold.



Estimated Usable Lifetime for the High Plains Aquifer in Kansas
(Based on ground water trends from 1996 to 2001 and 30 feet saturated thickness threshold)

Figure 7- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1996 to 2001 and a 30 feet saturated thickness threshold.

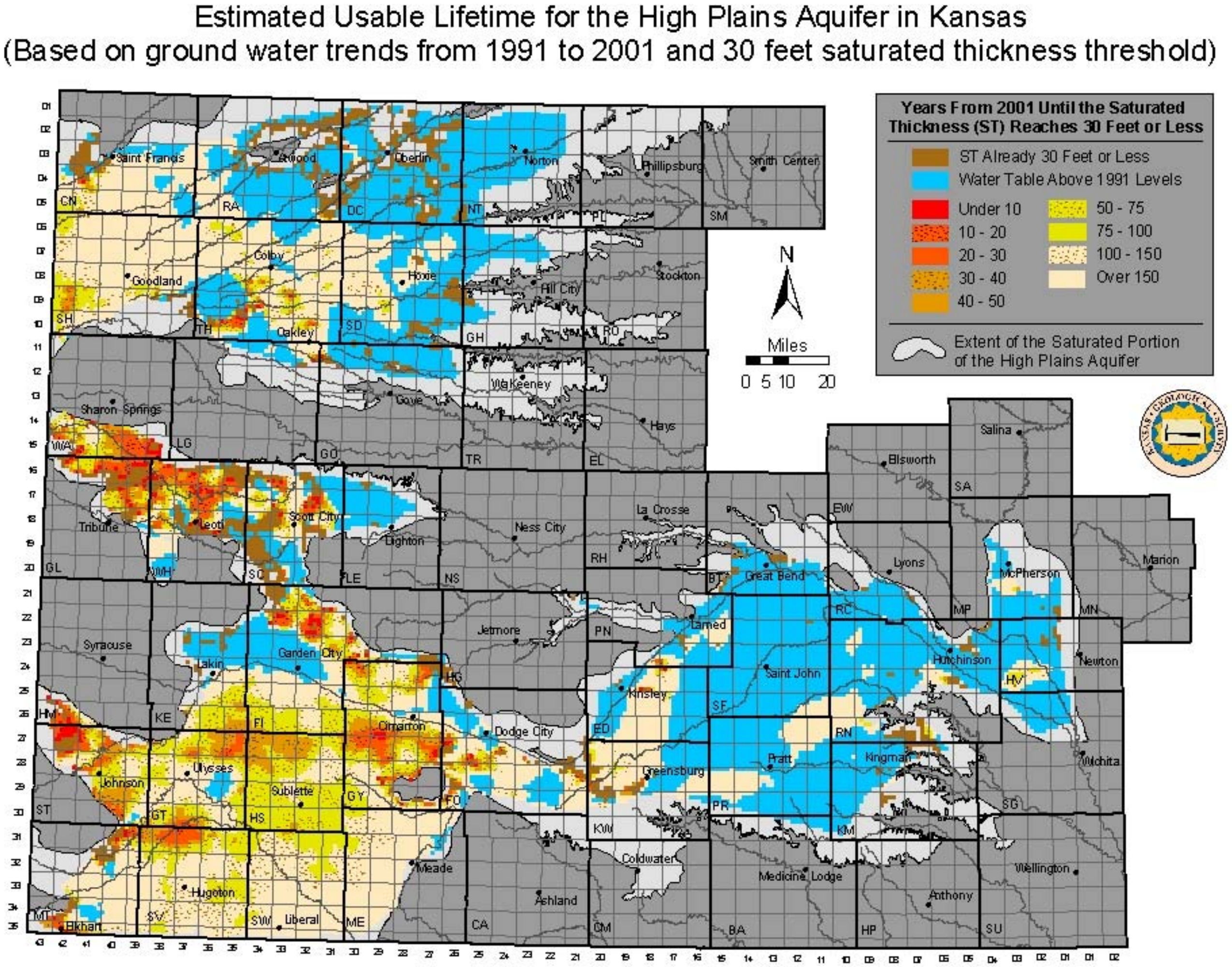


Figure 8- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1991 to 2001 and a 30 feet saturated thickness threshold.

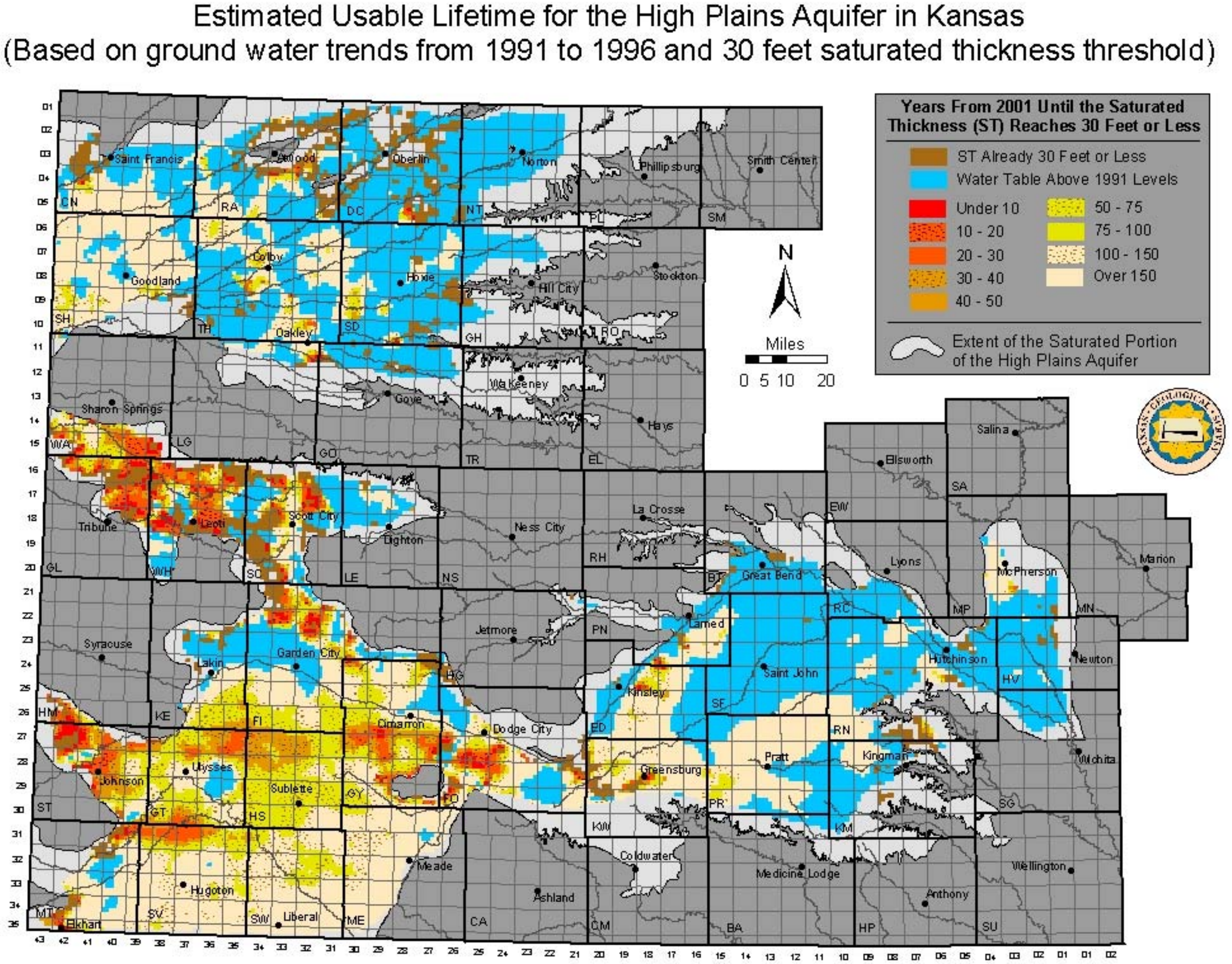


Figure 9- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1991 to 1996 and a 30 feet saturated thickness threshold.

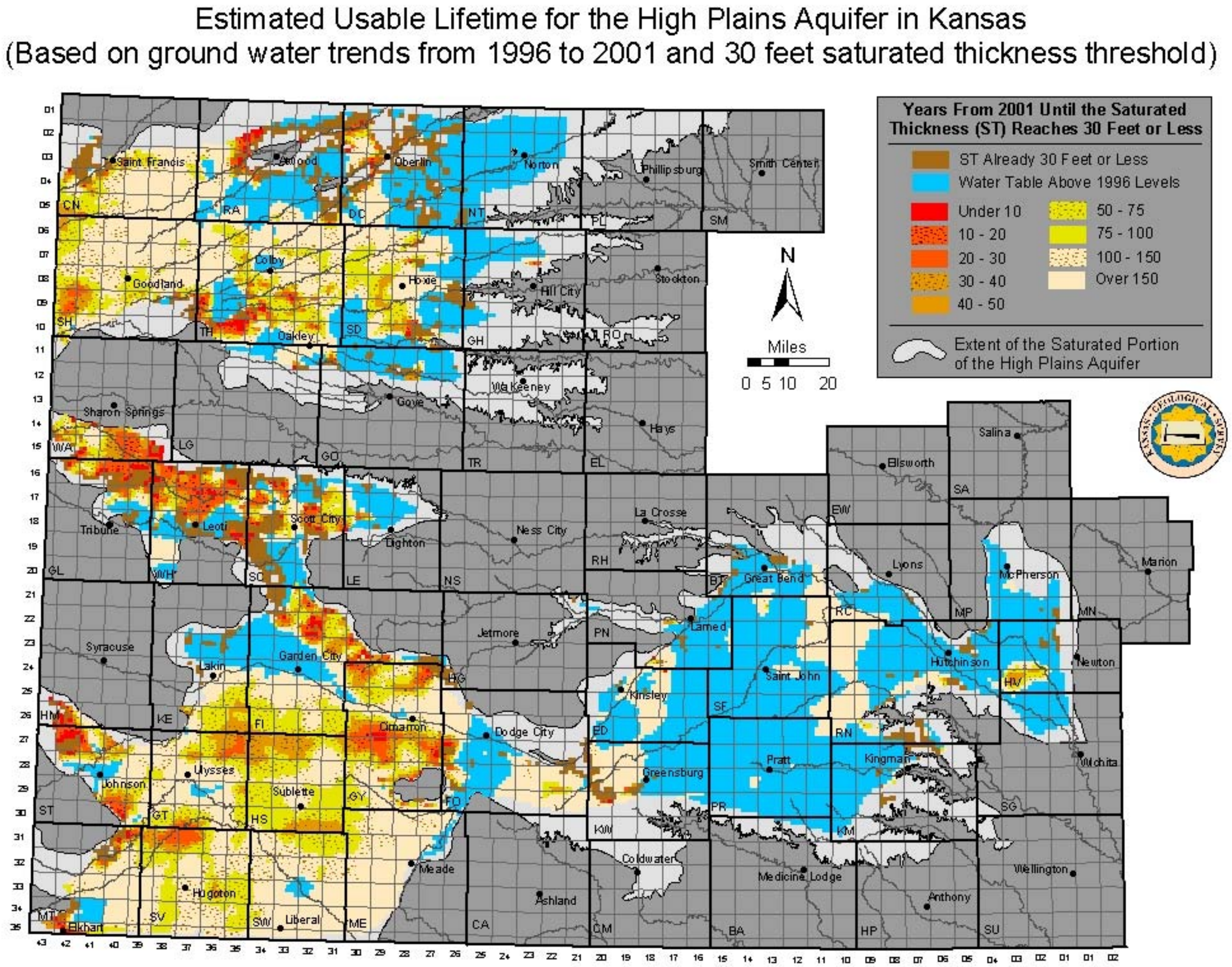
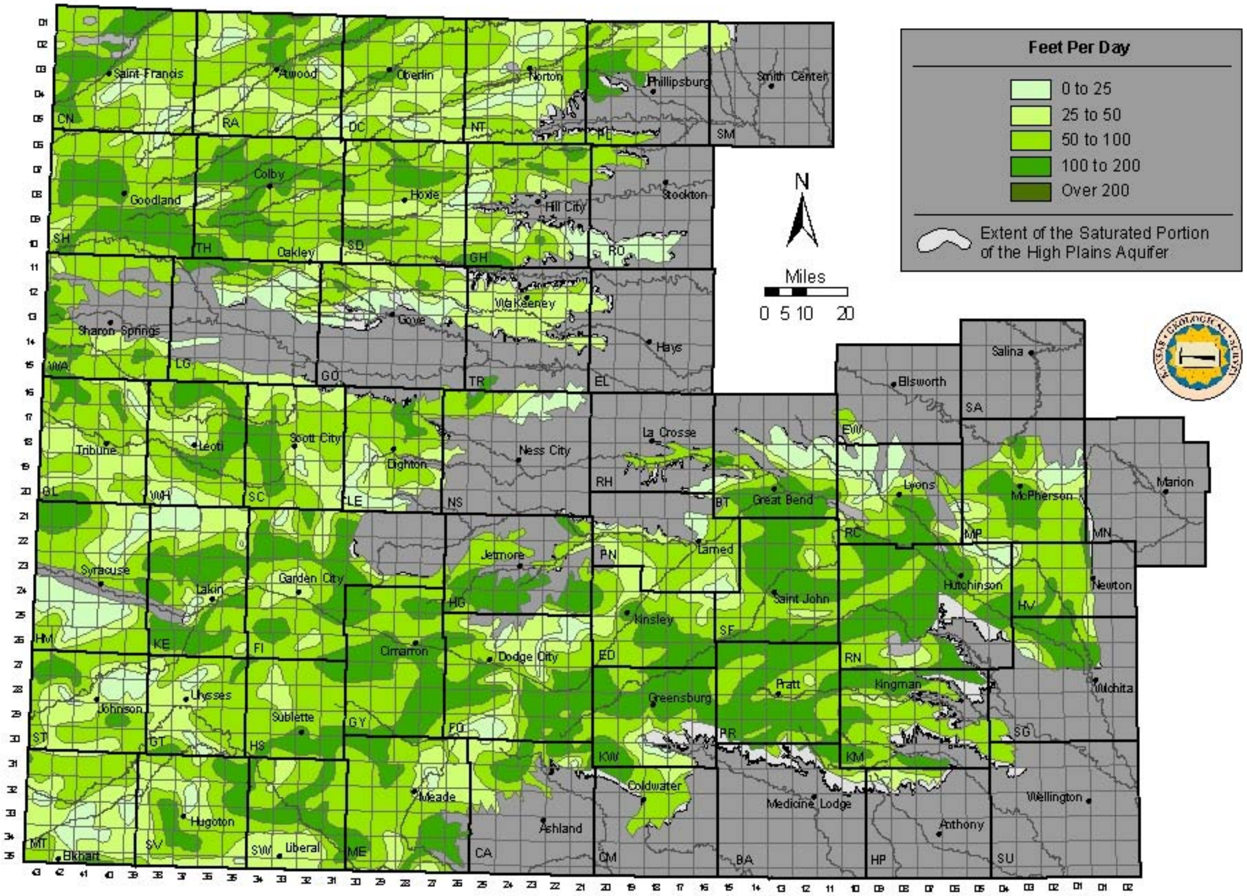

Estimated Usable Lifetime for the High Plains Aquifer in Kansas
(Based on ground water trends from 1996 to 2001 and 30 feet saturated thickness threshold)

Figure 10- Estimated usable lifetime for the High Plains aquifer in Kansas based on ground-trends from 1996 to 2001 and a 30 feet saturated thickness threshold.



Estimated Hydraulic Conductivity in the Kansas High Plains Aquifer
USGS Open File Report 98-548

Figure 11 - Estimated hydraulic conductivity in the Kansas High Plains Aquifer. USGS Open File Report 98-548.

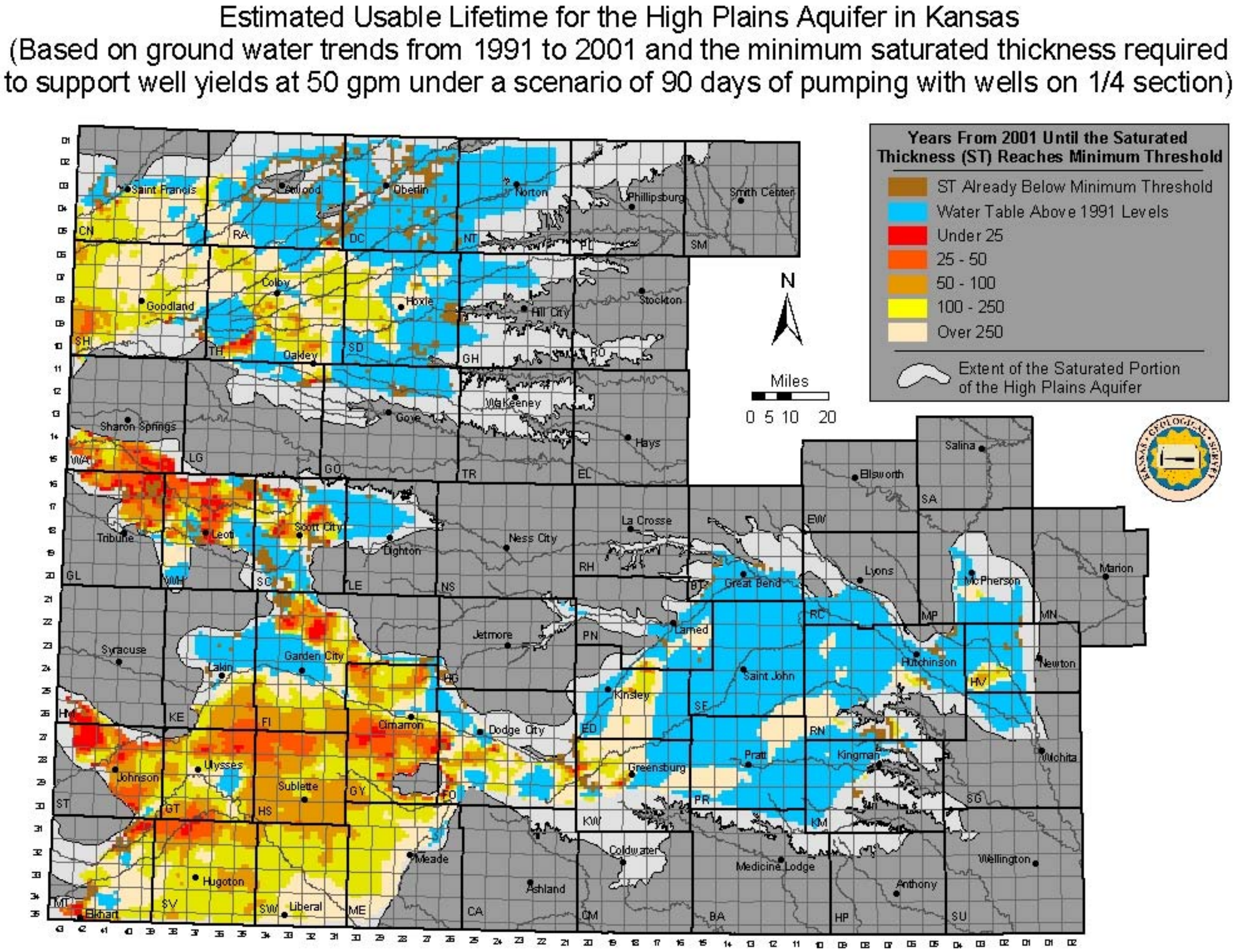

Estimated Usable Lifetime for the High Plains Aquifer in Kansas
(Based on ground water trends from 1991 to 2001 and the minimum saturated thickness required to support well yields at 50 gpm under a scenario of 90 days of pumping with wells on 1/4 section)

Figure 12- Estimated usable lifetime for the High Plains Aquifer in Kansas based on ground water trends from 1991 to 2001 and the minimum required saturated thickness required to support well yields at 50 gpm under a scenario of 90 days of pumping with wells on ¼ section.

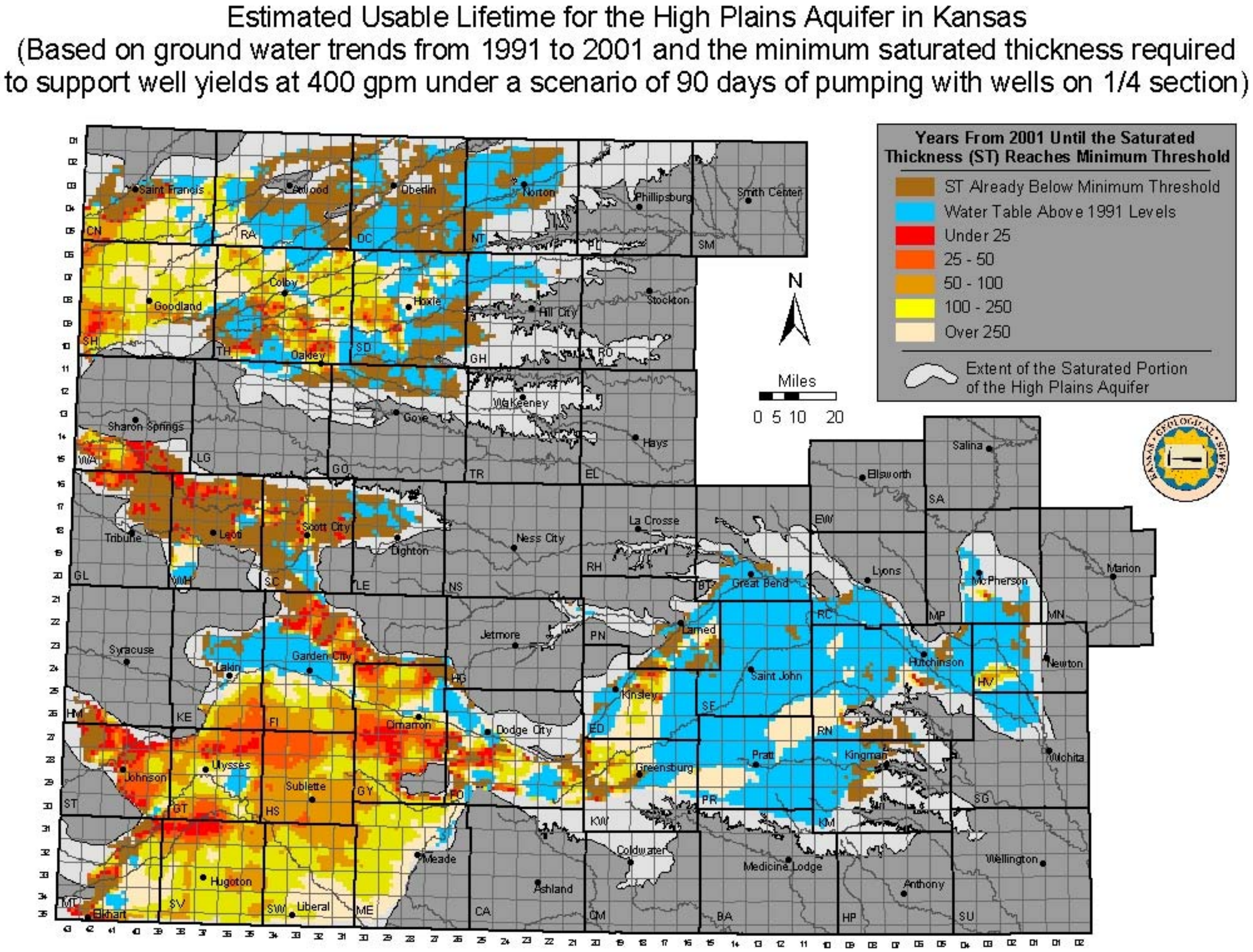


Figure 13- Estimated usable lifetime for the High Plains Aquifer in Kansas based on ground water trends from 1991 to 2001 and the minimum required saturated thickness required to support well yields at 400 gpm under a scenario of 90 days of pumping with wells on ¼ section.

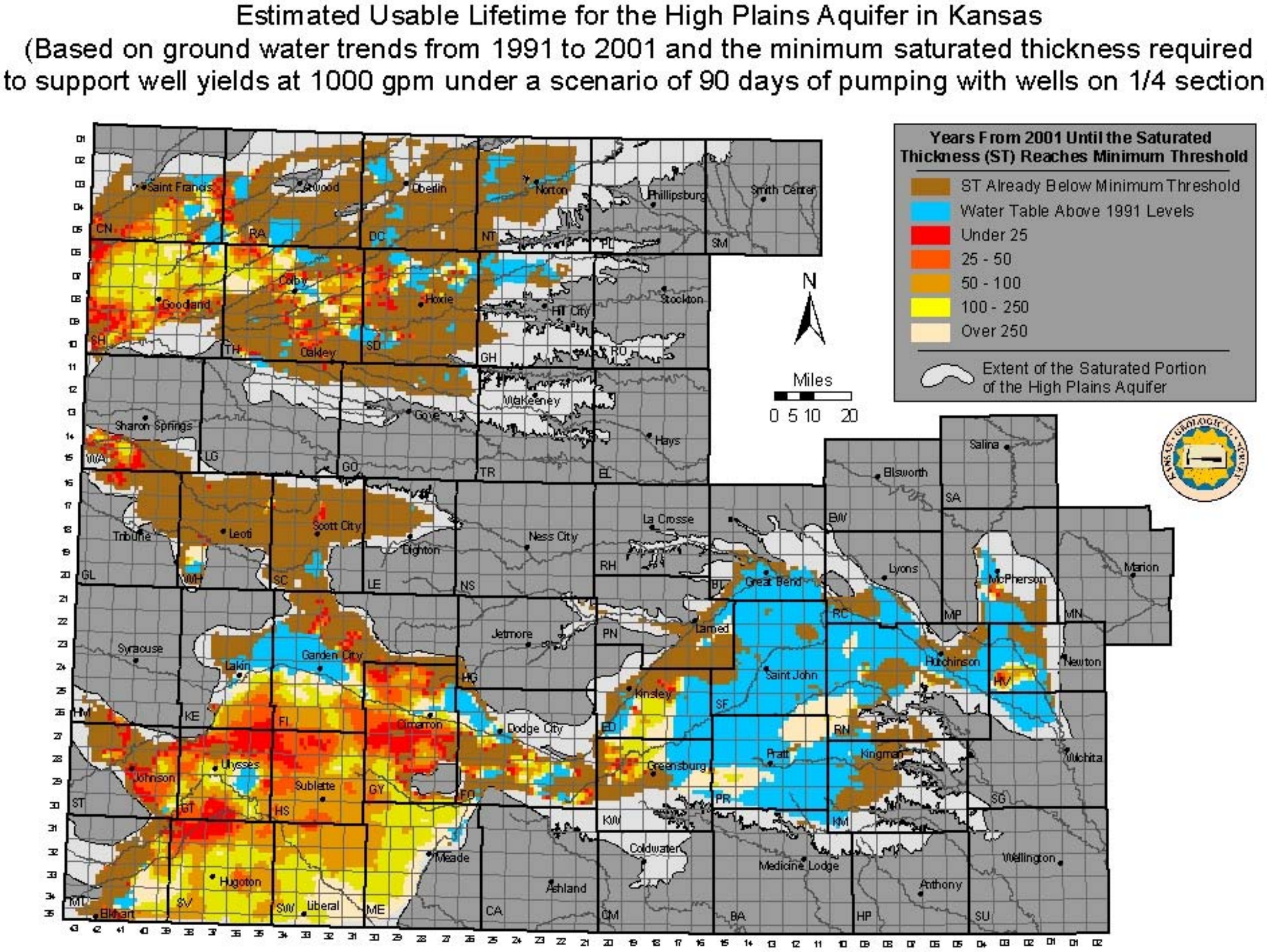

Estimated Usable Lifetime for the High Plains Aquifer in Kansas
(Based on ground water trends from 1991 to 2001 and the minimum saturated thickness required
to support well yields at 1000 gpm under a scenario of 90 days of pumping with wells on 1/4 section)

Figure 14- Estimated usable lifetime for the High Plains Aquifer in Kansas based on ground water trends from 1991 to 2001 and the minimum required saturated thickness required to support well yields at 1000 gpm under a scenario of 90 days of pumping with wells on ¼ section

represent an approximate value for low well yields. The lifetime estimates required for 1000 gpm (Figure 14) shows the greatest difference, particularly in terms of areas identified as already being below the minimum saturated thickness threshold. This is particularly true in the west central portions of the Ogallala-High Plains Aquifer and in the fringe areas of the aquifer in the northwest portion of the region where there historically has been less water right development.

A pumping rate of 400 gpm is used as an approximate value to represent the minimum flow required to operate a low-pressure sprinkler irrigation system. Comparison of the minimum required saturated thickness for 400 gpm identified in KGS OFR 2002-25C (Figure 13) and the 30 feet threshold (Figure 5) shows some interesting patterns. Overall, the two maps show similar patterns, but the most notable difference is in areas identified as already being below the minimum requirements, especially in the west central portions of the Ogallala-High Plains aquifer. The similarity and variability is expected given that the two figures are both based on the same estimates of saturated thickness and annual trends in the water table but use differing minimum saturated thickness thresholds. It is also interesting to note that the fringe areas of the northwest portion of the Ogallala-High Plains region where the water table is shown as not declining tend to be the same general areas where the saturated thickness is below required levels to support yields at 400 gpm.

3. Exploratory Geo-statistical Clustering Exercises

3.1 Unsupervised Classifications

Geostatistical clustering techniques, using the LoiczView web-based software (Maxwell and Buddemeier, 2002; www.palantir.swarthmore.edu/loicz/help), were employed to explore various ways to first subdivide the Ogallala aquifer portion of the High Plains aquifer and then based on those units, establish regression equations that can determine the change in the water table as a function of the amount of ground-water reported pumped each year. The clustering techniques were based on two data parameters consisting of section-centered values for the changes in the water table from 1991 to 2001 (Figure 1) and the density of average reported ground water use from 1991 to 2000 (Figure 15c).

Past clustering exercises involving reported water use resulted in very spotty cluster groupings caused by the nonuniform nature of water right development over the High Plains aquifer region. The concept of representing reported use as measure of density helps to regionalize the reported water use values. To create the maps shown in Figure 15 a-c, a 500x500 meter grid network was overlain across the region. Then for each grid cell, the average reported ground water use per square mile occurring within 2, 5, and 10 miles (Figures 15a, 15b, and 15c, respectively) of the cell was calculated. The goal of the water use density plots for this application is not to identify actual water use quantities per square mile, but rather to regionalize the influence of ground water pumping across an area. That regional characterization can then be used to compare the reported use within specific areas with corresponding changes in the water table. For the purposes of this report, the 10 mile water use density (Figure 15c) was selected for the clustering exercise.

Each of the Groundwater Management District areas of the Ogallala- High Plains, including the fringe areas surrounding each district, was clustered separately into 5 groupings. Since variance within and between data sets is the primary factor used by the k-means clustering algorithm, clustering the districts separately helps to focus relationships between the data parameters to better represent the conditions within each district area. Once the cluster groups were identified, the total reported ground water use and the average depth to water for all monitoring wells was calculated for each year between 1990 to 2000 for each subunit area.

Linear regression equations were then generated for each unit area to establish how total annual reported use in each year explains the variation in the changes in the water table. This process yields a factor, the R^2 value, that assesses the strength of the relationship tested. The higher the R^2 value, the stronger the correlation between water use and decline; values greater than about 0.8 represent an extremely strong relationship, and values greater than 0.5 - 0.6 are significant but weaker.

Results from this exercise are encouraging and can be seen in Figure 16, which shows the cluster groups for each GMD area and the resulting R-square value for the unit areas. Since each GMD area was clustered separately, the common colors between the GMD areas do not signify a relationship; they simply represent a unique area in terms of reported water use and changes in the water table within each GMD.

In general, the R^2 values are better in the GMD 1 and GMD 3 areas, and show weaker statistical relationships in the GMD 4 area. This may be caused by the spatial extent and size of each area, the number of water rights and monitoring wells within each area, the percentage of wells that reported metered water use (which is lower in GMD4), and the influence of other factors such as streamflow or surface water diversions, or the influence on recharge of topography, depth to water, land use, or streamflow (see OFR 2002-25B). Overall, where the R^2 values are high (> 0.8), it indicates that water withdrawals are the primary influence on ground water levels, which in turn accounts for the strong relationships to changes in the water table. Areas where the R^2 values are lower indicate the influence of other parameters such as the presence of surface water flow, higher local or regional recharge amounts, or data quality considerations (e.g. metered water use).

3.2 Supervised Classifications

The LoiczView software provides the option to conduct supervised clustering routines on data sets where unique areas within a region are identified as core or “type” areas. Similar to satellite classifications, the clustering routine associates other areas that contain data parameters that best match or fit the data variations within the core area. The Western Kansas GMD #1 was selected as a test case to explore various clustering exercises. This district was chosen for similar exploratory exercises with the Ogallala Technical Advisory Committee’s work, which resulted in several clustering examples and unique data sets that are not yet available for the other western Ogallala-High Plains districts.

The GMD1 Manager was asked to identify some geographic areas that might serve as type specimens for regions or classes of conditions. He selected seven blocks of sections that were approximately township size, including: two in Scott County from the Scott-Finney depression area (area 1 has adequate quantity, somewhat questionable quality, and concerns about over appropriation; 2 has good quantity and quality); three that were considered representative of their general geographic regions in terms of hydrology and water use (locations 3, 4, and 7 in Lane, Wichita and Wallace Counties, respectively); one (Area 5 in Greeley County) where there are concerns about overdevelopment, and one (Area 6 in Wallace County) that is considered unique and unlike the rest of the District in overall hydrology.

The supervised classification function of Loiczview was used to cluster the district into areas that best fit the characteristics of the core areas initially identified by the GMD #1 Manager. For comparison purposes, a separate unsupervised classification routine was run as well. For this particular exercise, the clustering procedures were based on changes in the water table from 1991 to 2001 (Figure 1), the 2001 saturated thickness (Figure 4), and the 10 mile reported ground water use density (Figure 15c).

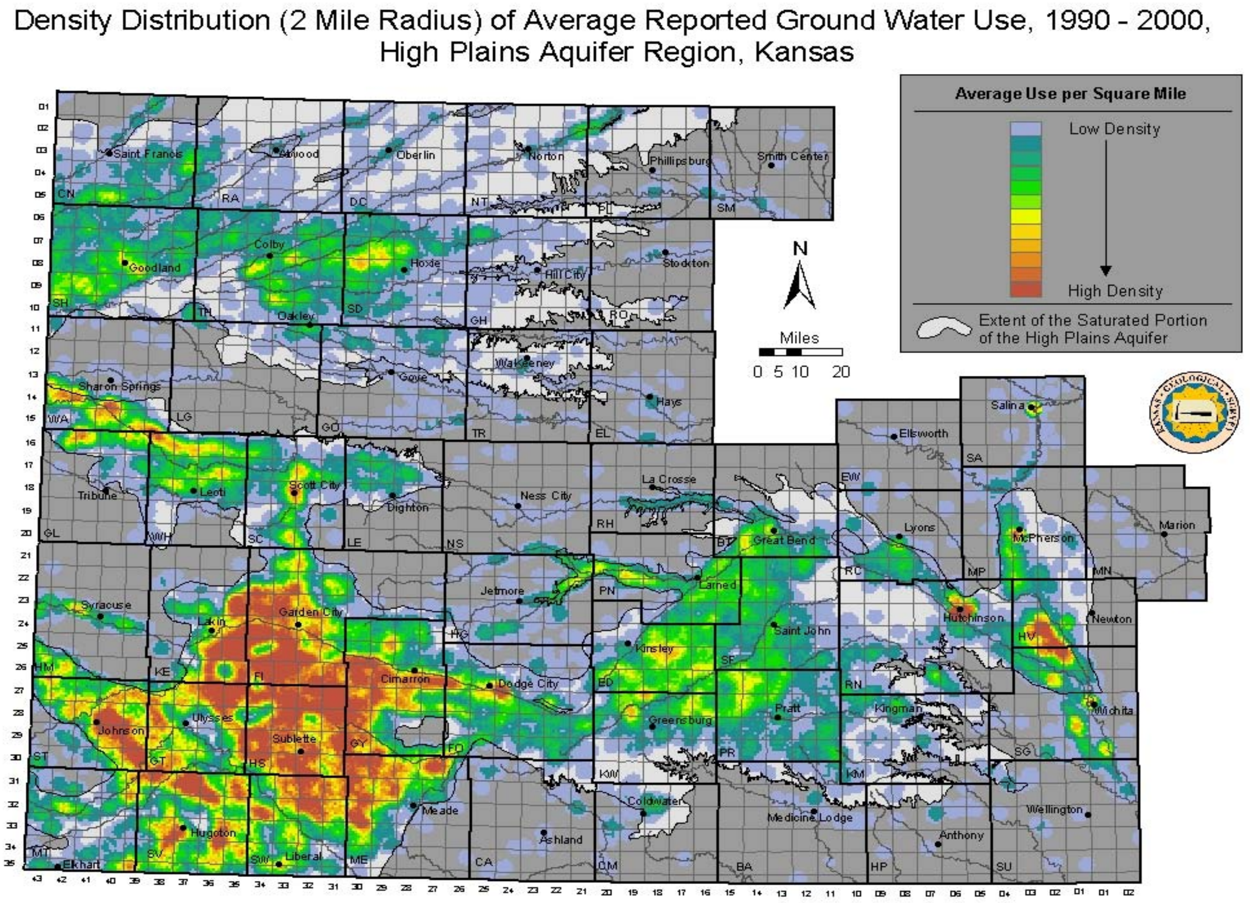


Figure 15a- Density Distribution (2 Mile Radius) of Average Reported Ground Water Use, 1990-2000, High Plains Aquifer Region, Kansas

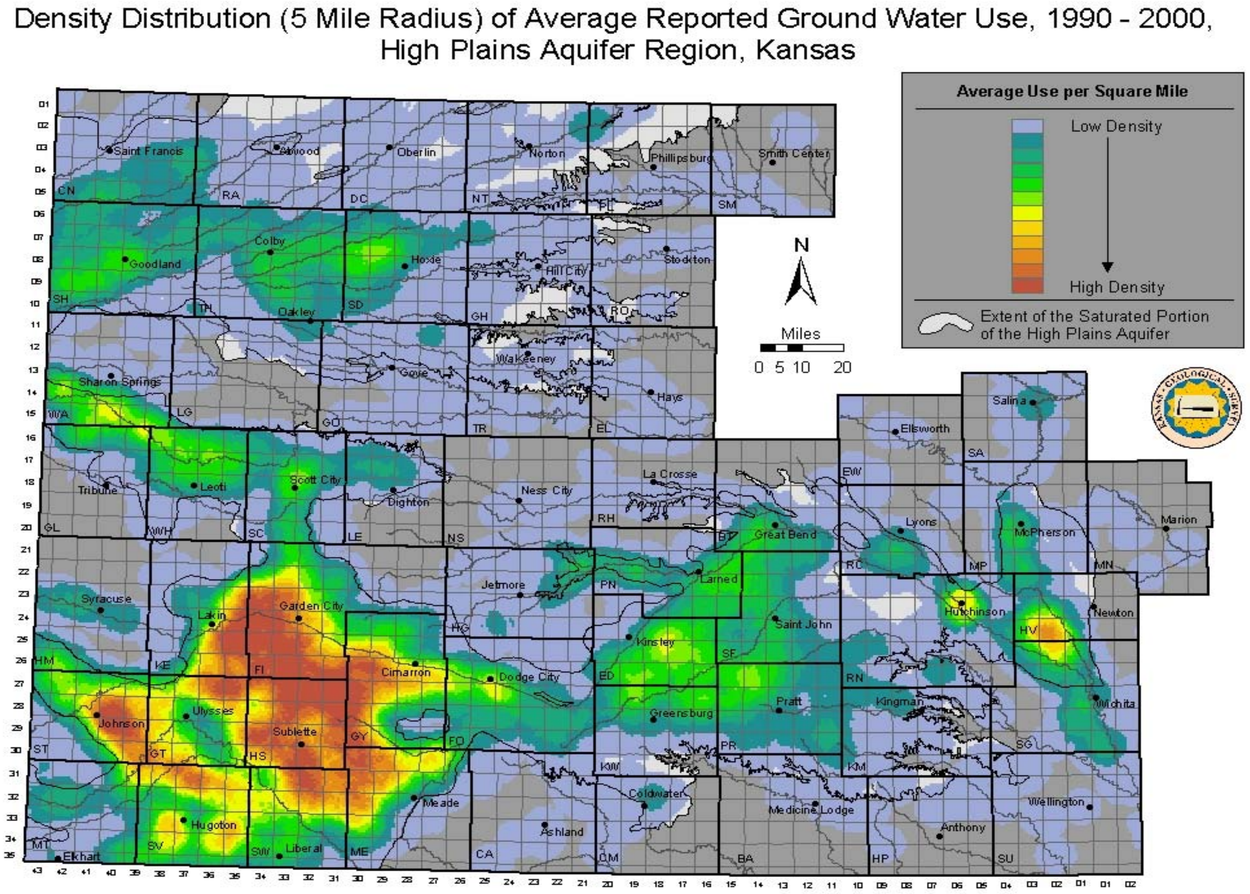


Figure 15b- Density Distribution (5 Mile Radius) of Average Reported Ground Water Use, 1990-2000, High Plains Aquifer Region, Kansas

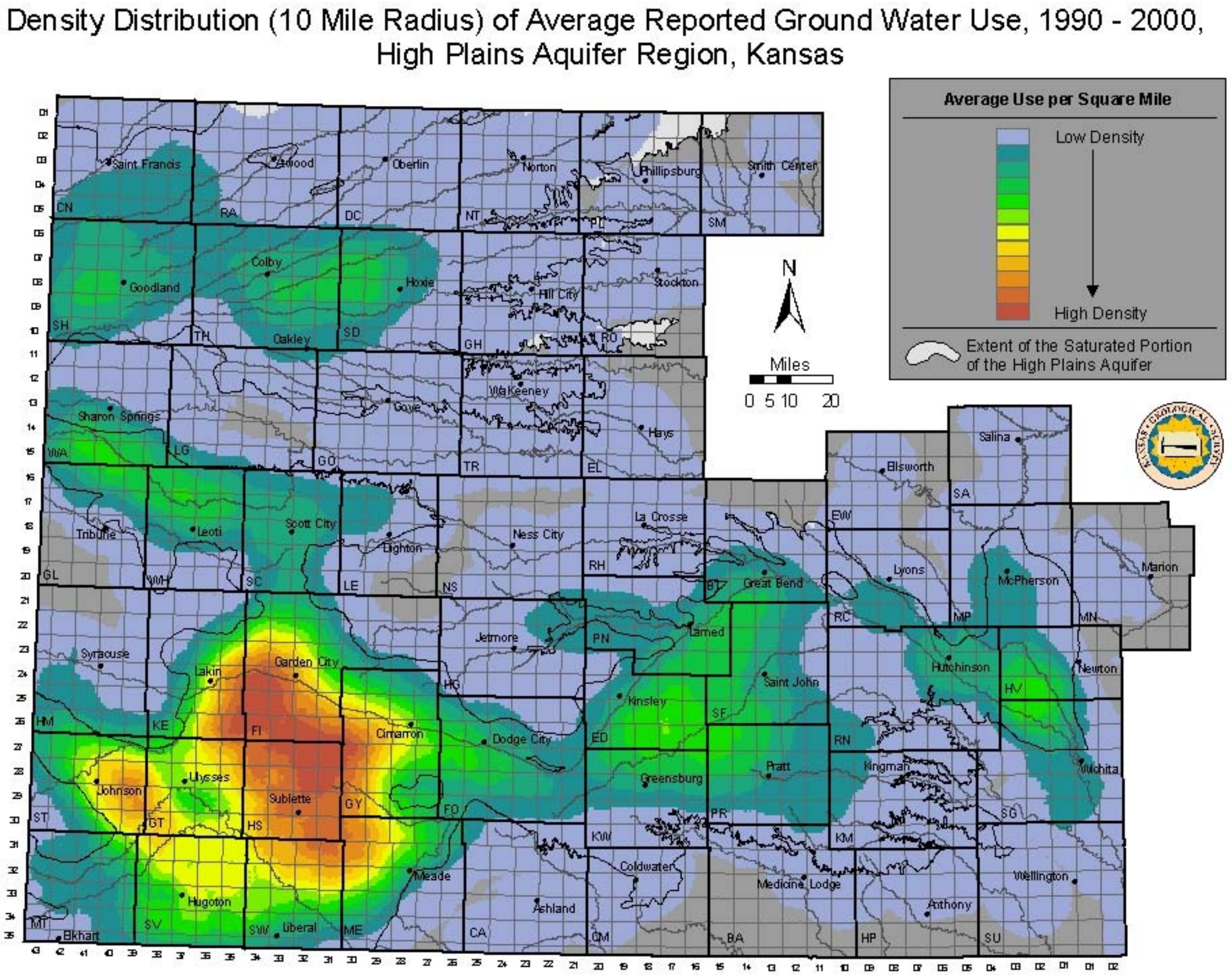


Figure 15c- Density Distribution (10 Mile Radius) of Average Reported Ground Water Use, 1990-2000, High Plains Aquifer Region, Kansas

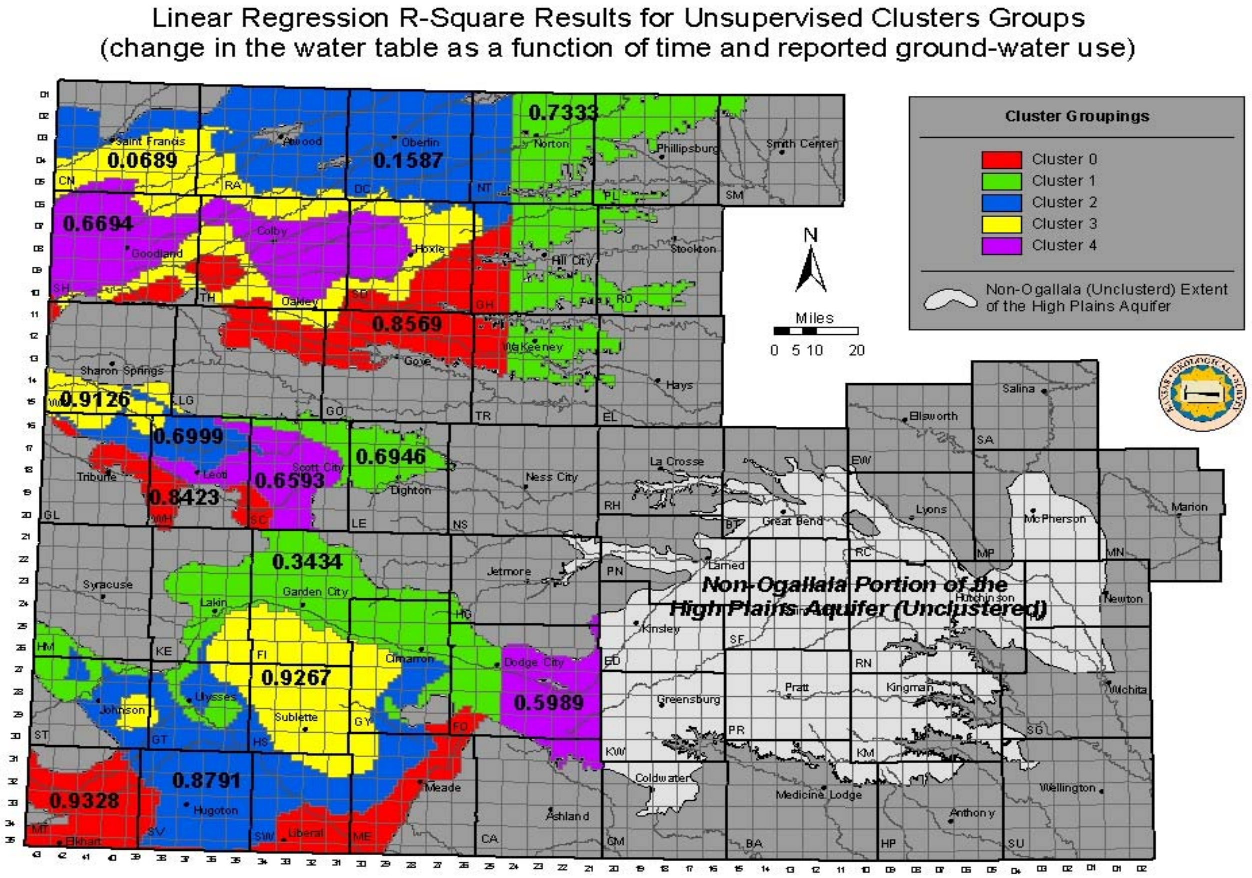
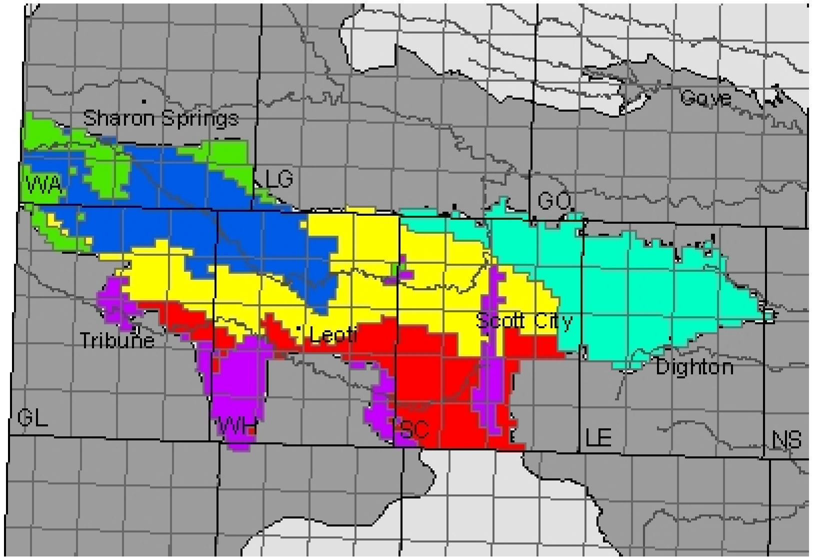


Figure 16- Linear regression R-square results for unsupervised cluster groups. Each GMD area of the Ogallala-High Plains, including the fringe areas surrounding each district, was clustered into five groupings. The common color schemes between the district areas have no relationships to one another.

Comparison of Unsupervised vs Supervised LoiczView Clustering Groups, GMD #1

Unsupervised



Supervised

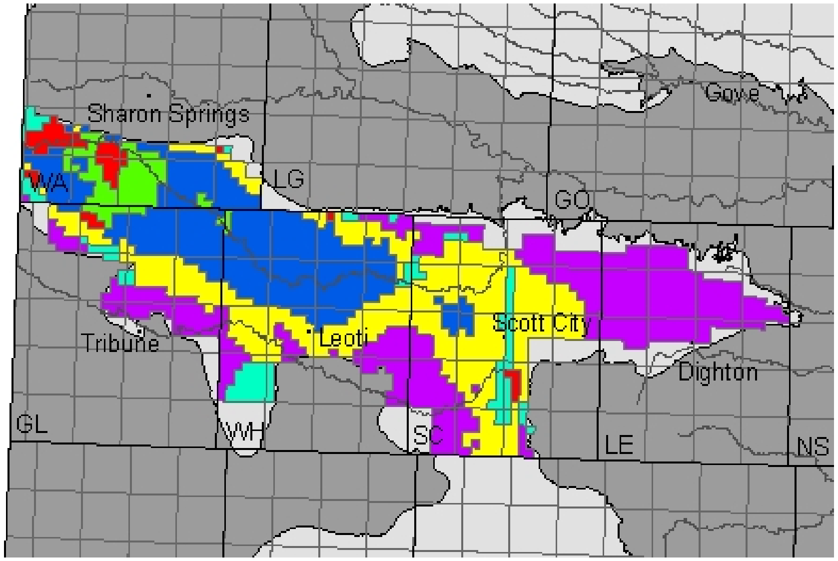


Figure 17- Comparison of Unsupervised vs Supervised LoiczView Clustering Groups, GMD #1.

The results of this comparison between unsupervised and supervised clustering routines can be seen in Figure 17. Overall, both the unsupervised and unsupervised methods produced similar groupings. The advantages of the supervised clustering applications for the purpose of identifying aquifer subunits is that local expert knowledge and judgment can used as the initial input to the clustering process. This allows managers to identify other areas within a region that may have similar characteristic to areas of known aquifer properties, and to test the results of unsupervised clustering against local expertise. The primary advantage of the unsupervised clustering routines is that data relationship that may not be well known or recognized can be identified. The common colors between the clustering groups do not signify a common relationship between unsupervised and supervised methods; they simply represent a unique area in terms of the 2001 saturated thickness, density of reported water use and changes in the water table within each GMD. The unique areas that are identified spatially do represent a common relationship such as can be seen in Lane County in the eastern portion of the district.

4. Data Limitations and Applications

4.1 Estimated Usable Lifetime

The estimated usable lifetime maps are a unique way to classify ground water changes in the aquifer. However, they are based simply on estimates of past rates of change and how that change, if it is accurately assessed and continued unabated into the future, would impact the existing aquifer storage. The results of KGS OFR 2002-25C indicate that the minimum saturated thickness required to support large-volume demands is substantially greater than the thirty foot value originally used to estimate the usable lifetime. Considering the great variations that occur in climatic factors (OFR 2002-25E), pumping amounts, and other economic considerations, there is considerable uncertainty in those estimates. This is particularly true for the longer time estimates (50 years or more).

Lifetime estimates based on well yield are dependent on the data quality and level of detail available for aquifer characteristics such as hydraulic conductivity and specific yield. Although the available maps provide a basis for classification and management planning, detailed management implementation will need to take into consideration the issues of aquifer heterogeneity raised in OFR 2002-25C.

The annual rates of change used to estimate the usable lifetime of the aquifer are based on the differences in elevations from the start to end of a given time period. If the water table over a ten-year time period dropped ten feet, the annual rate of change is calculated as 1 foot per year. This approach does not account for the various possible conditions of how that change actually took place; the water table could have dropped 11 feet in one year and then risen one foot over the remaining nine years. The conditions under which this pattern of change can be projected into the future are very different from the scenario where the water table gently declined 1 foot a year over a 10 year time period. Detailed observations show that the water table fluctuates significantly over both time and space (see OFR 2002-25F). The trend uncertainties caused by these variations and calculation assumptions suggest that classifying the estimated usable lifetime of the aquifer at 10-year intervals should be approached with caution. However, regardless of classification, the estimated usable lifetime maps do outline areas that are subject to potential resource exhaustion, and provide relative comparisons among different areas.

4.2 Geo-statistical Clustering

The use of geo-statistical clustering techniques is showing strong promise in identifying areas of the aquifer that share common parameters and association. The limitations in the process are generally the limitations imposed by the data, and how those data are portrayed, interpolated, or classified. For example, past attempts at using reported water use at the section level were probably not suitable for identifying larger homogenous areas. Using techniques such as a reported use density helps smooth out the data, and provides a better representation of the influence of the parameter at spatial and temporal scales comparable to water level and other data collected on a larger scale.

5. Policy and Management Implications

Both the estimated usable lifetime concept and geo-statistical clustering methods show promise as tools to develop the protocols necessary for the delineation of aquifer subunits and to further evaluate potential management concepts within subunit areas. Areas of similar characteristics could be defined as a subunit. For a given set of conditions and data relationships, management scenarios could be developed and further evaluated.

The maps portraying the estimated usable lifetime of the Ogallala-High Plains aquifer are based on changes in the water table elevations in a manner that can be readily understood by most individuals. In the past, data and maps showing only changes in the ground water, although informative, did not account for how that change relates to the amount of water in storage. Relating the change in the water table to a specified storage level allows management and policy development that can be better related to the implications of ground water changes for future planning and socioeconomic issues. Regardless of the uncertainties involved with the methodology, this technique of portraying ground-water changes identifies the relative vulnerability of areas to resource exhaustion in terms of large volume water demands.

The use of geo-statistical clustering procedures shows great promise for identifying potential aquifer subunit areas with common characteristics. Relationships between different data parameters can be further identified and examined, and clustering with projected characteristics can show how proposed management concepts might impact the water resource and the nature of the subunits. The use of expert judgment in identifying unique areas for the supervised clustering approach allows local knowledge to be incorporated into the statistical processing procedure, permitting the clustering focus to be tailored to unique characteristics of the individual management areas.

6. Potential for Improved Data or Applications

In view of the prospects for aquifer subunit identification and future management focus on smaller target areas, a review of the state's cooperative monitoring well program should be undertaken (see OFR 2002-25F for a more detailed discussion). The initial network (see section 2.5, OFR 2002-25G) was established for a particular purpose and need, which may not suffice for the management approaches of the near future. The program goals and objective should be evaluated to insure the resources used for this program are focused on the overall planning and management effort of the State.

Well log and local pump tests can be used to refine estimates aquifer of characteristics at higher resolution in selected regions. The procedures and results of OFR 2002-25C can be used to further refine and improve usable lifetime estimates. In addition, climatic factors

(OFR 2002-25E) and reported water use should be explored as potential parameters to include and account for when making lifetime estimates of the aquifer.

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Kansas Geological Survey

Open File Report 2002-25E

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

By

D.P. Young and R.W. Buddemeier

With contributions from other authors in the report series

A component of the Technical Report series 2002-25: Technical Support for Ogallala Aquifer Assessment, Planning, and Management

A final report of fiscal year 2002 activities by the Kansas Geological Survey supported by contracts with the Kansas Water Office and the Kansas Department of Agriculture

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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KGS OFR 2002-25E: Climate Variation:
Implications of Long-Term Records and Recent Observations
By D.P. Young and R.W. Buddemeier

> *"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:

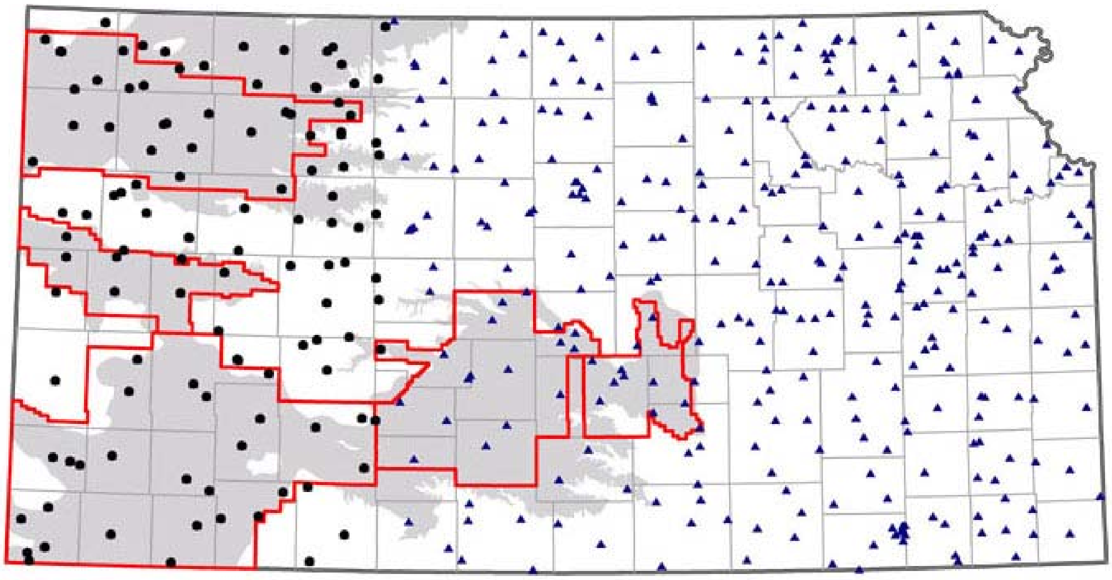


Figure 1. Location of NCDC stations in Kansas. Circles are stations used in the Ogallala climate analysis. Also shown are GMD and county boundaries and the extent of the High Plains aquifer.

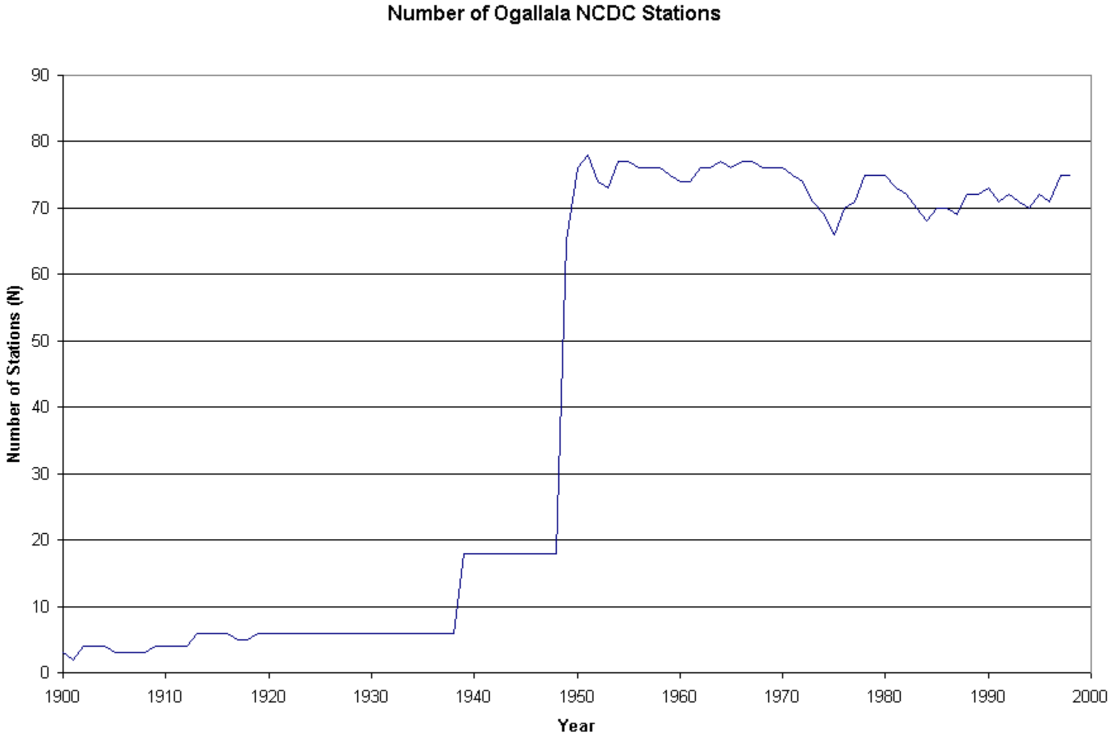


Figure 2. Number of NCDC weather stations in the Ogallala region of Kansas.

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).

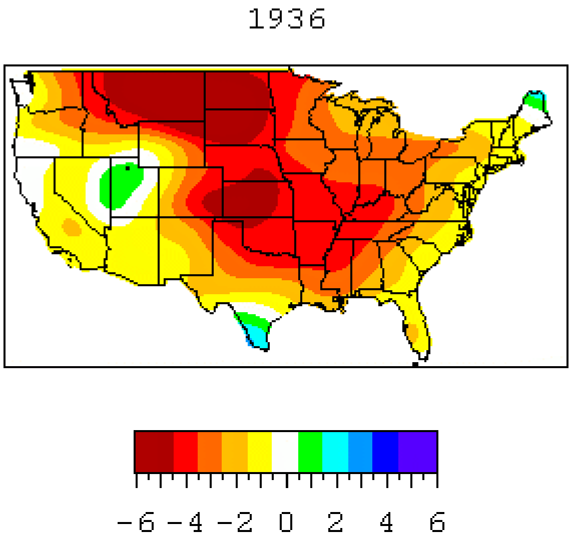
This section looks at past climate, focusing on dry spells or droughts, at two scales: 1) the period of instrumental record (the past hundred years) and 2) the paleoclimatic record (the early historic and pre-historic period of the past several hundred years or more).

3.1 The Period of Instrumental Record

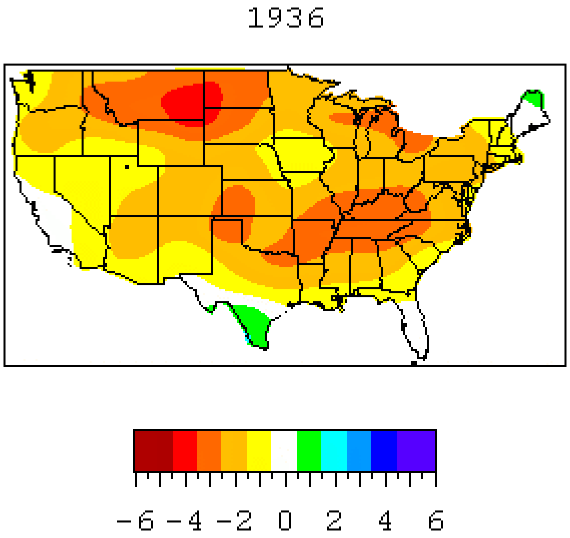
3.1.1 The Data

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

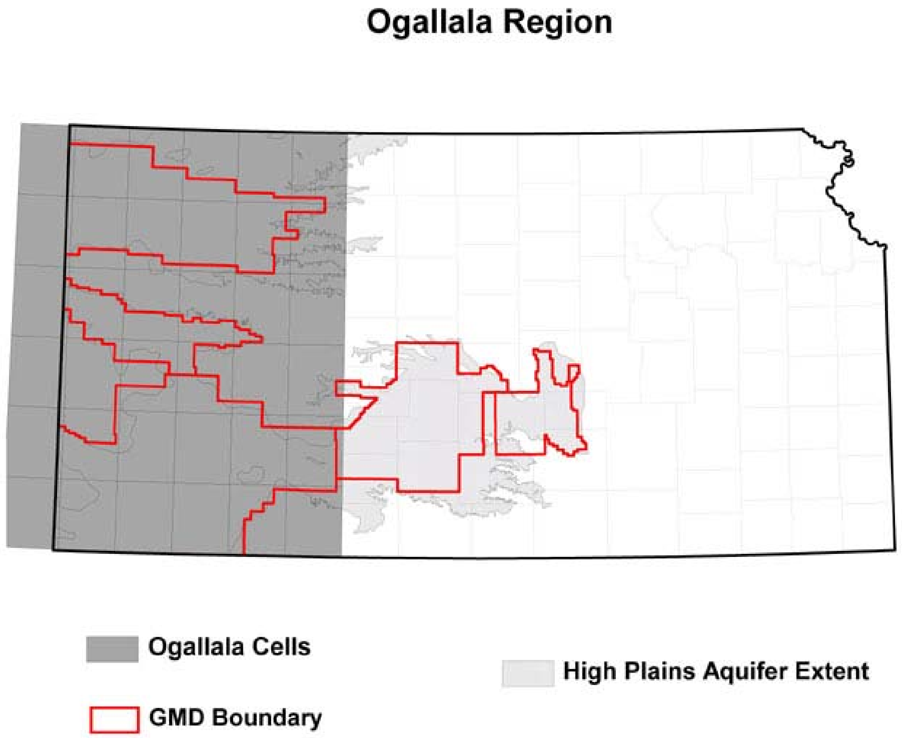


Figure 4. Half-degree cells (n = 36) covering the Ogallala region are shown by the gray - bordered rectangular boxes underlying the shaded area.

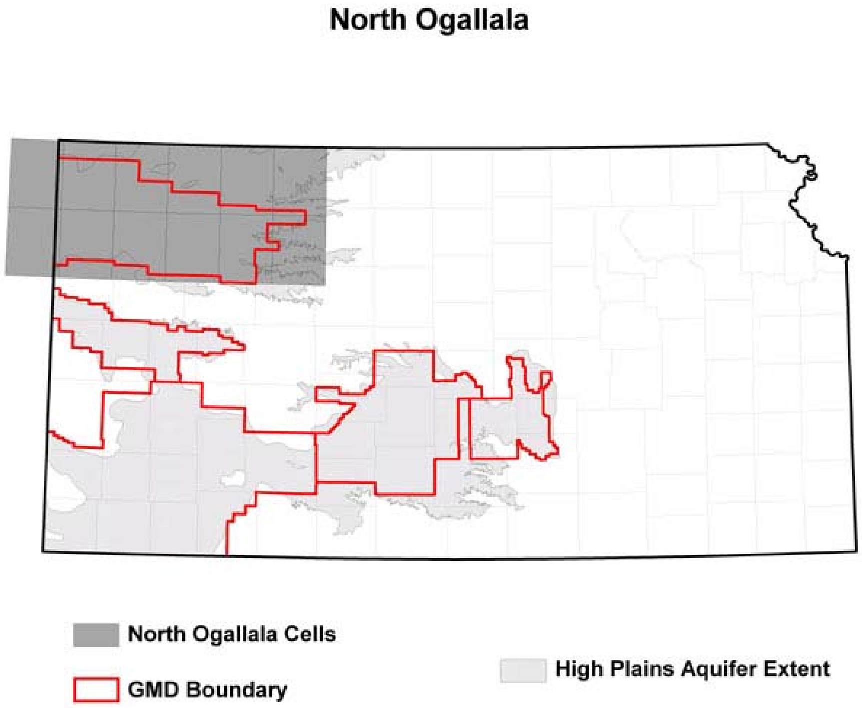


Figure 5. Half-degree cells covering the North Ogallala region.

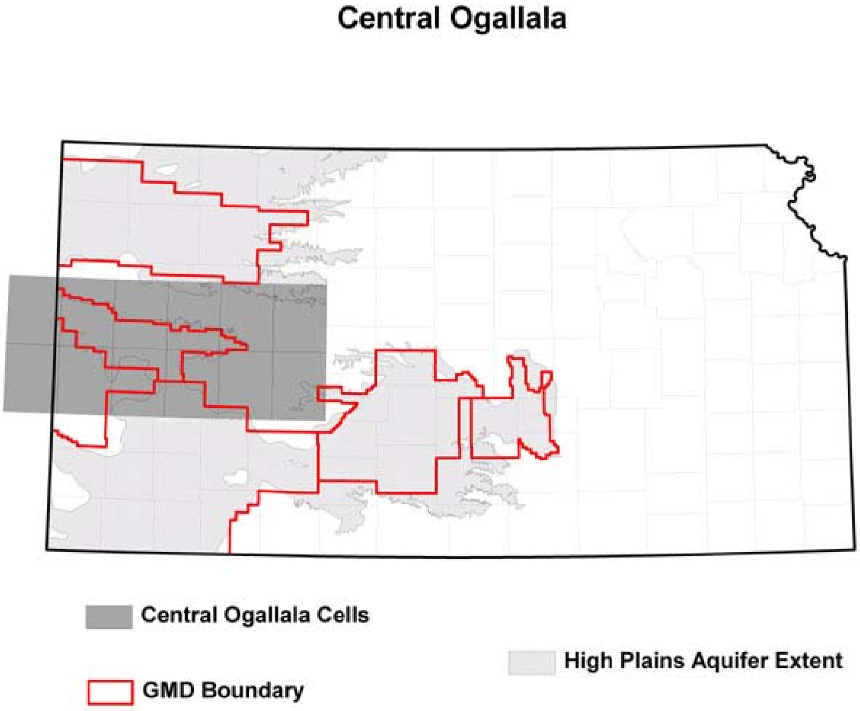


Figure 6. Half-degree cells covering the Central Ogallala region.

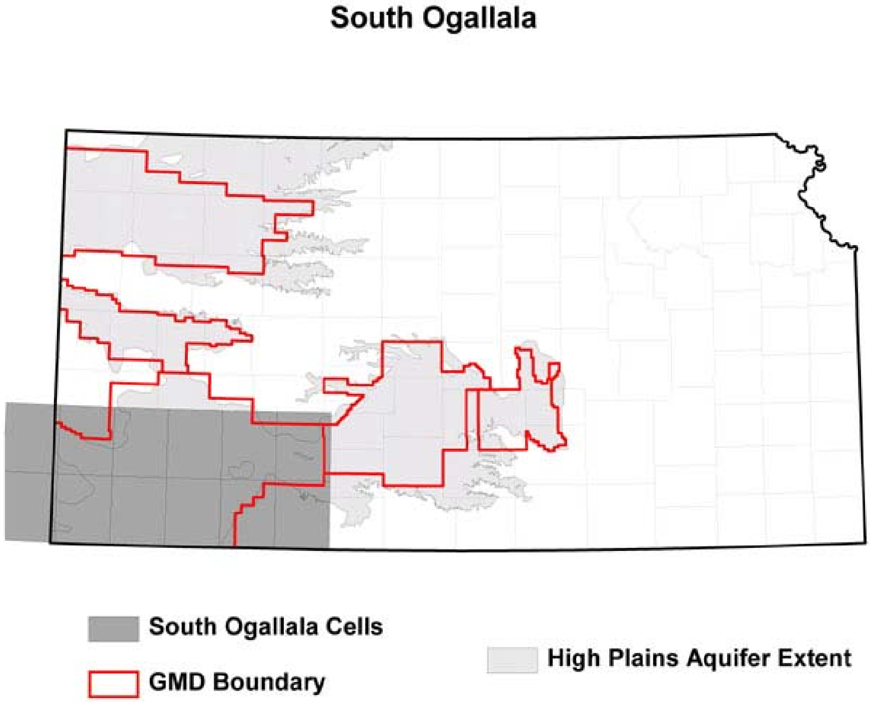


Figure 7. Half-degree cells covering the South Ogallala region.

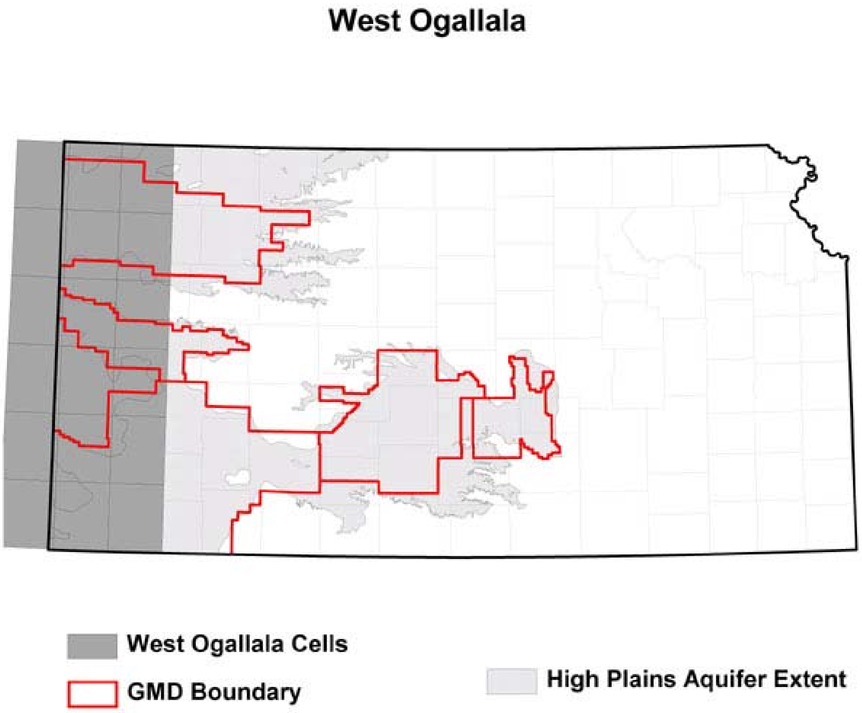


Figure 8. Half-degree cells covering the West Ogallala region.

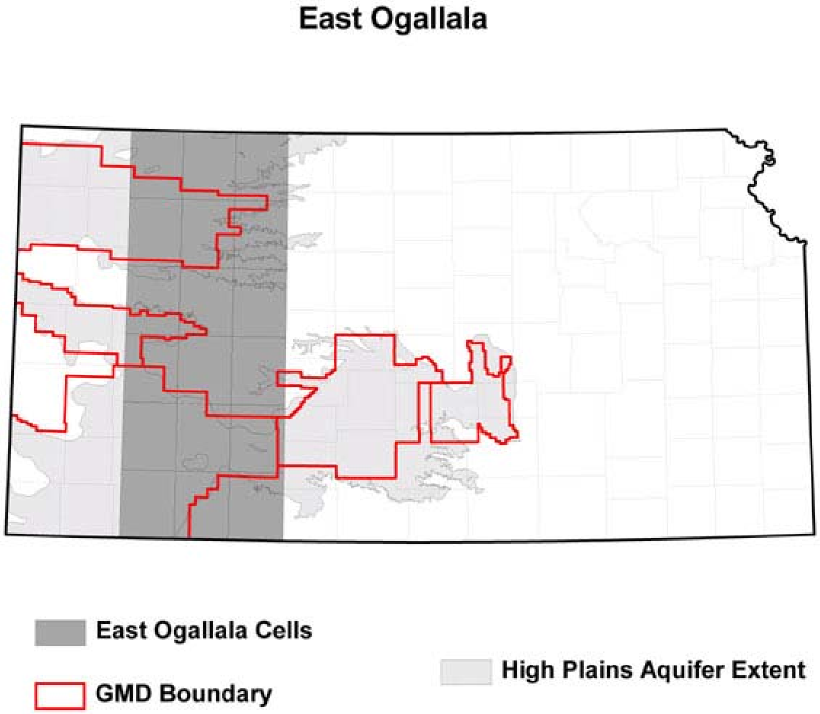


Figure 9. Half-degree cells covering the East Ogallala region.

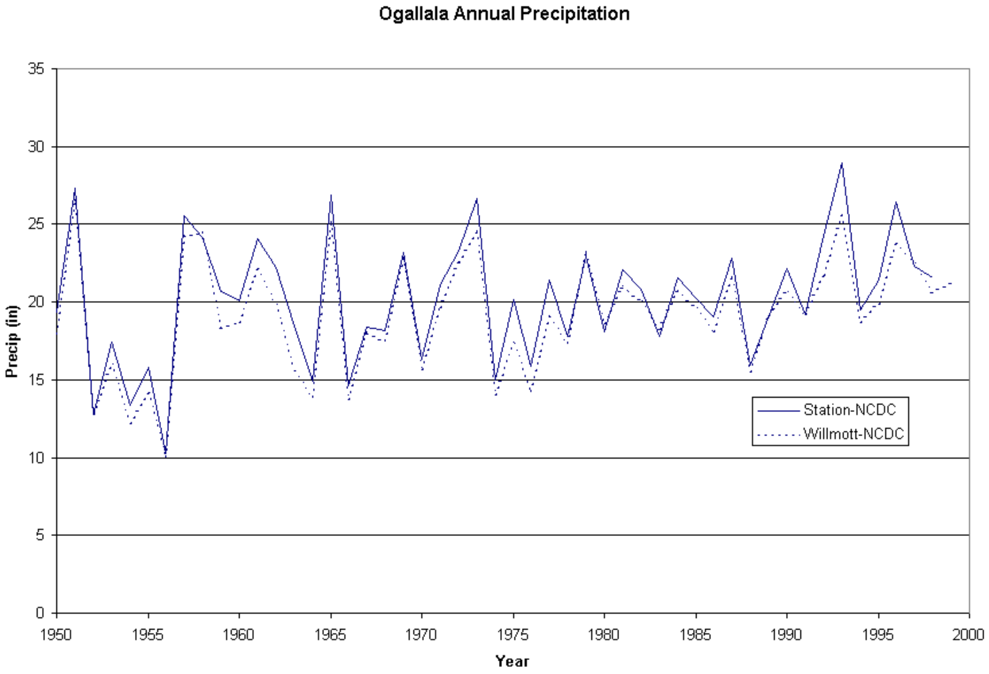


Figure 10. Ogallala precipitation: comparison between Station-NCDC and Willmott-NCDC data.

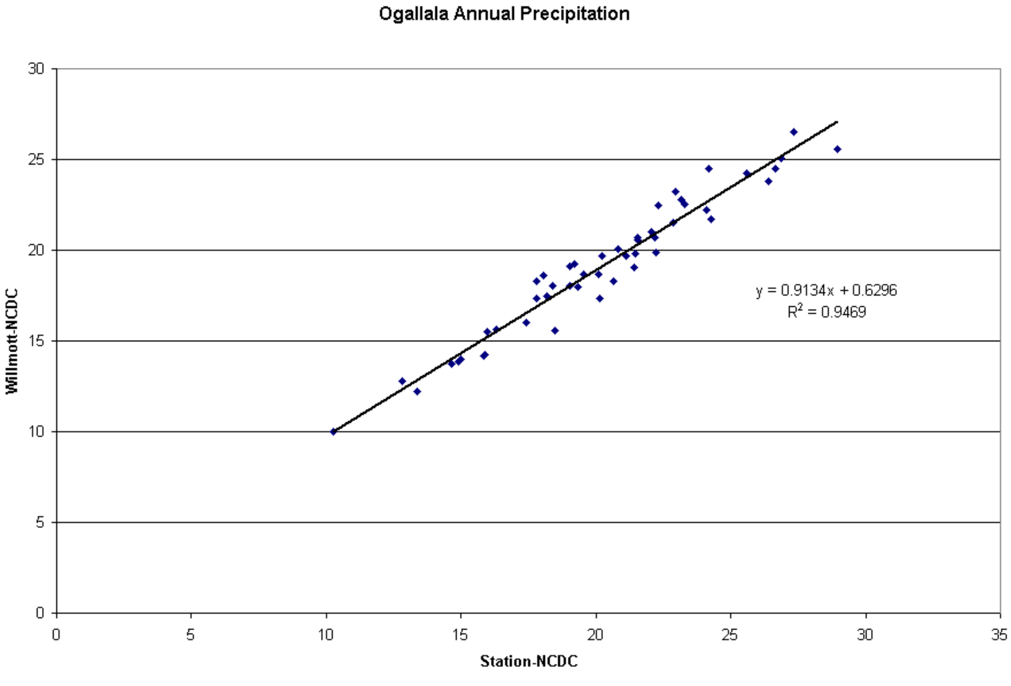


Figure 11. Correlation between Willmott-NCDC and Station-NCDC precipitation data.

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.

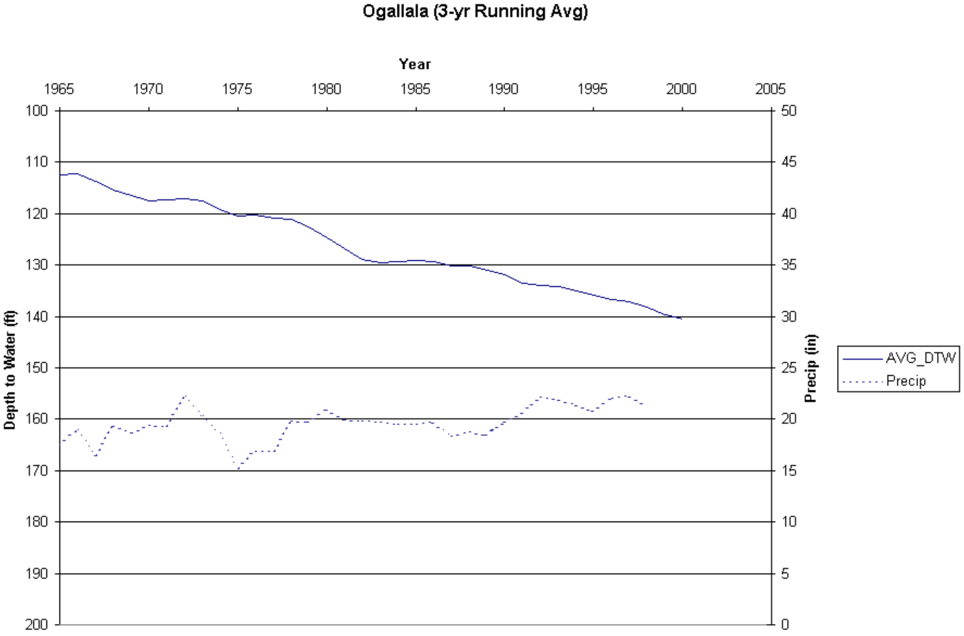


Figure 12. Comparison of water level and precipitation trends for the Ogallala region.

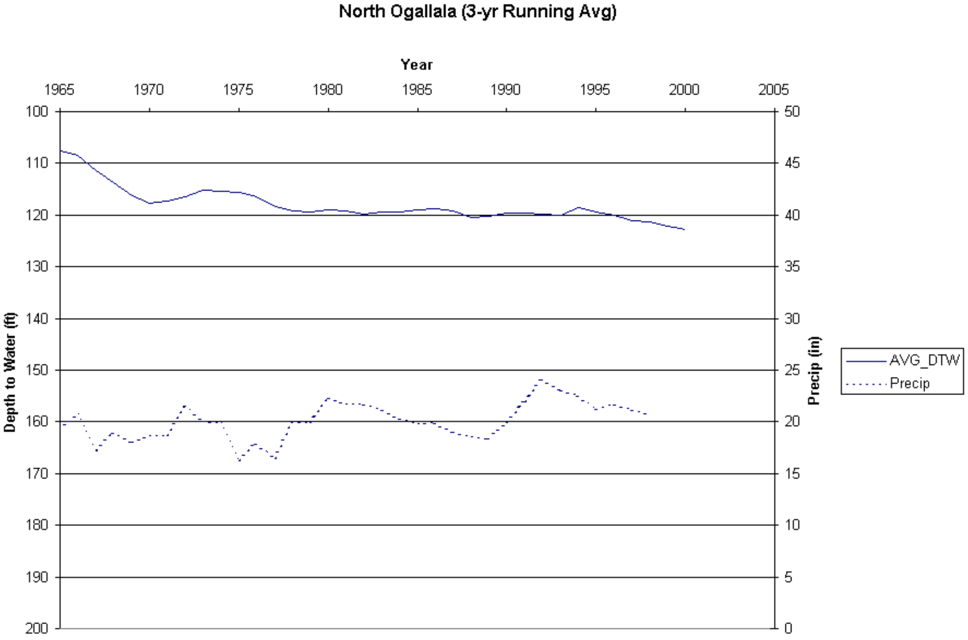


Figure 13. Comparison of water level and precipitation trends for the North Ogallala region.

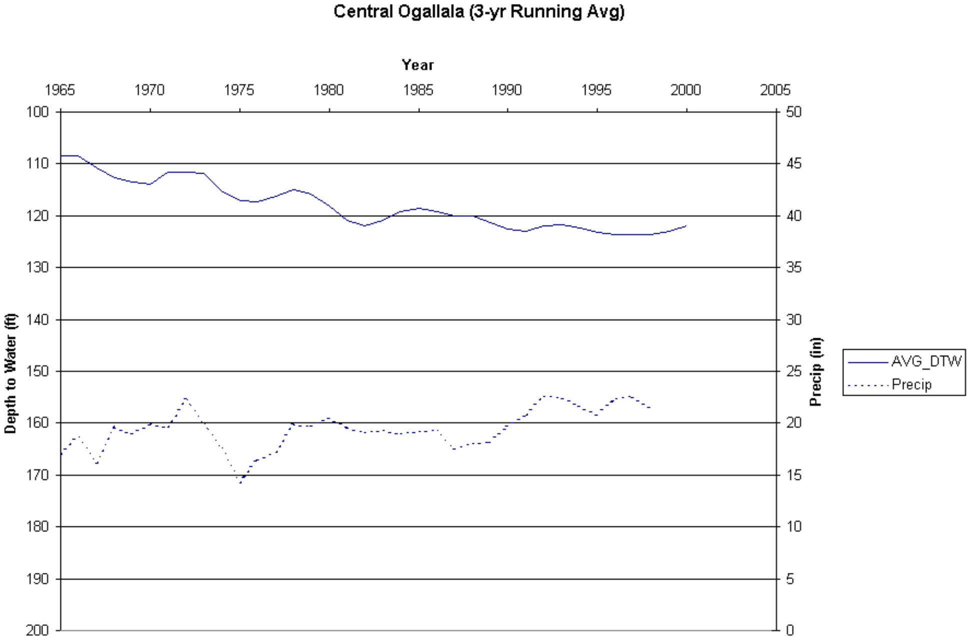


Figure 14. Comparison of water level and precipitation trends for the Central Ogallala region.

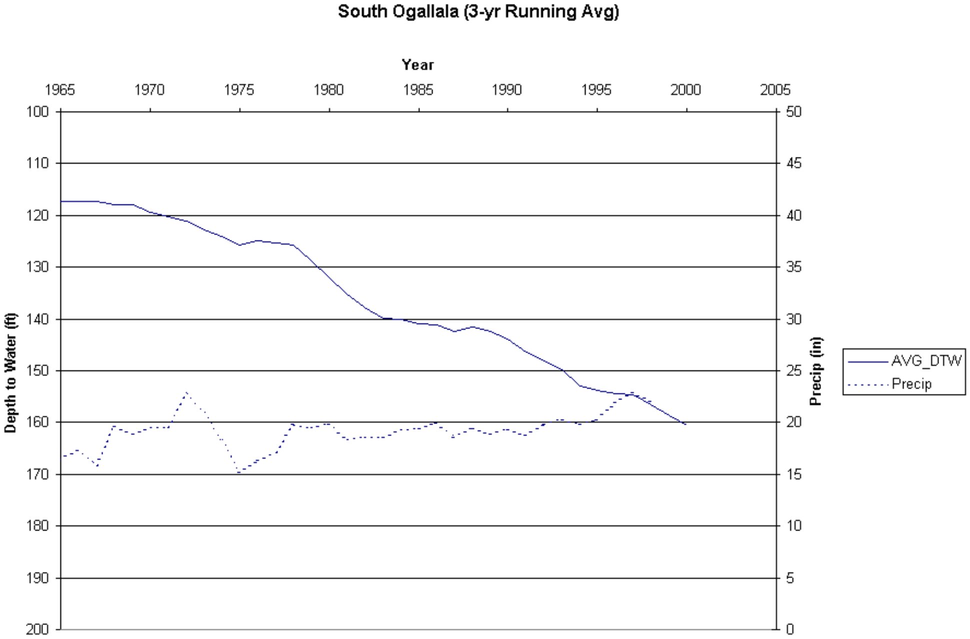


Figure 15. Comparison of water level and precipitation trends for the South Ogallala region.

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 actual cost or benefit, but it does provide a quantitative criterion for discussing and ranking threats and costs.

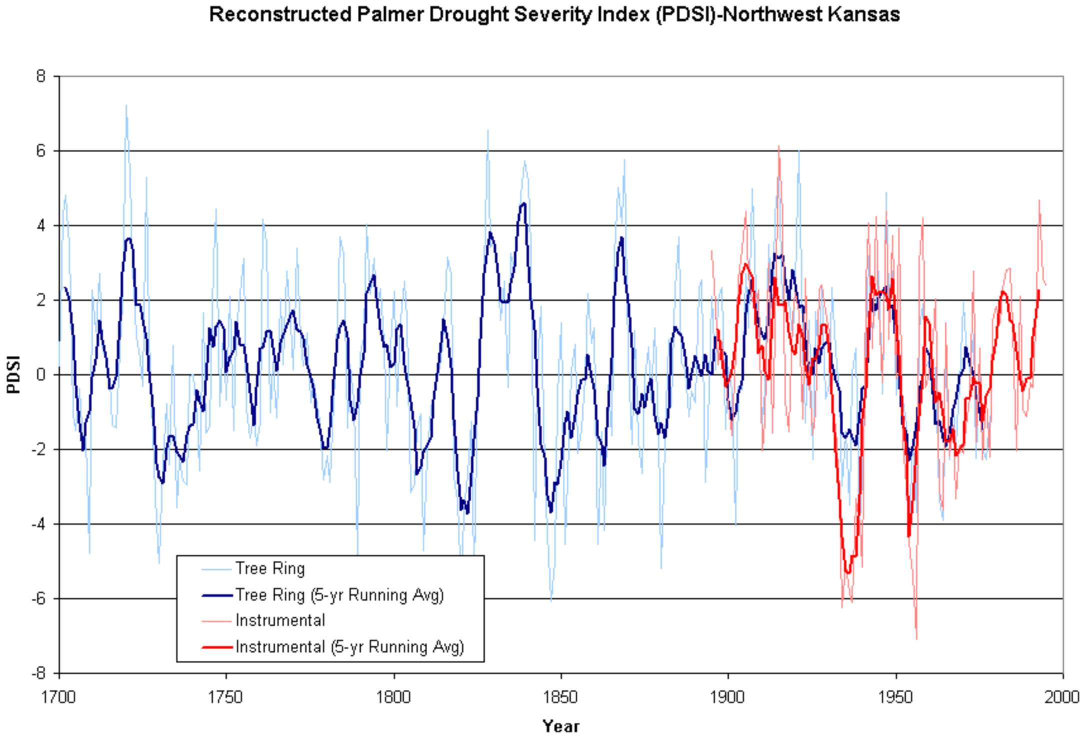


Figure 16. Reconstructed Palmer Drought Severity Index (PDSI) - Northwest Kansas.

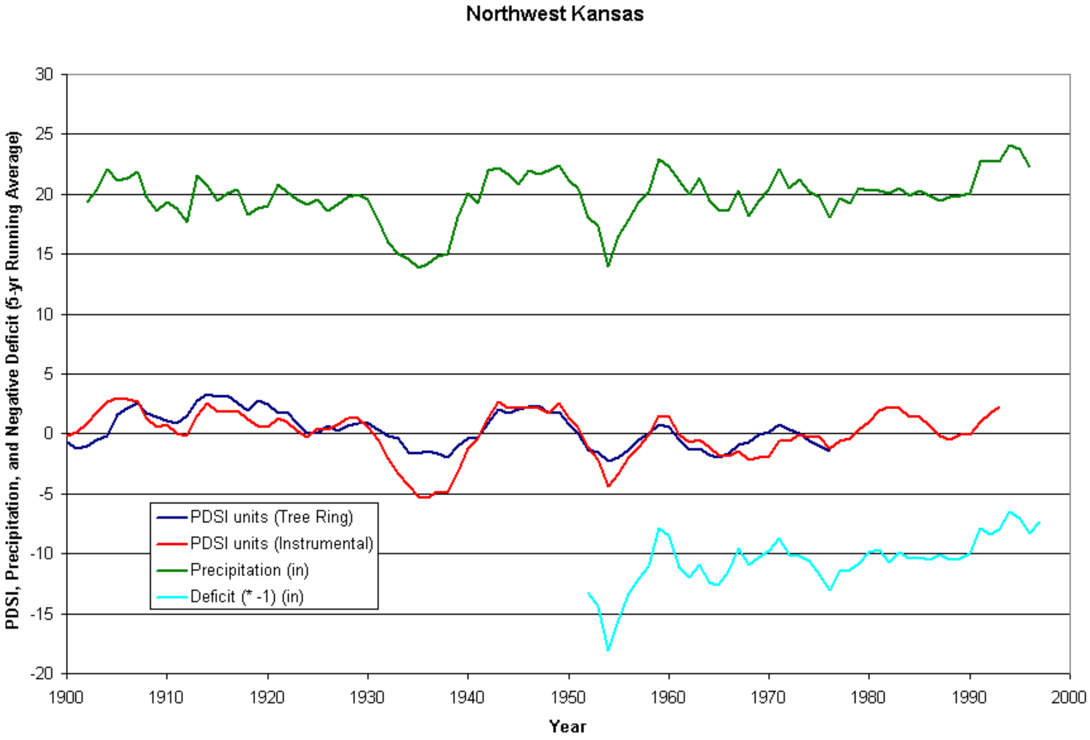


Figure 17. Comparison of some raw and derived climatic indicators - Northwest Kansas.

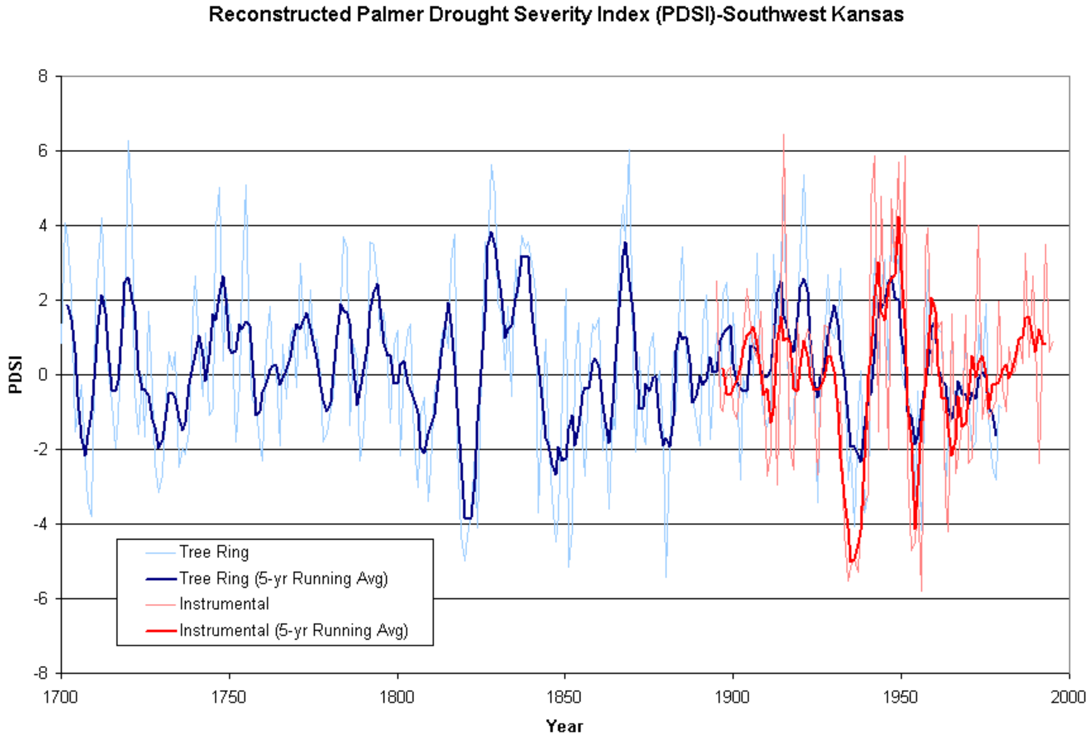


Figure 18. Reconstructed Palmer Drought Severity Index (PDSI) - Southwest Kansas.

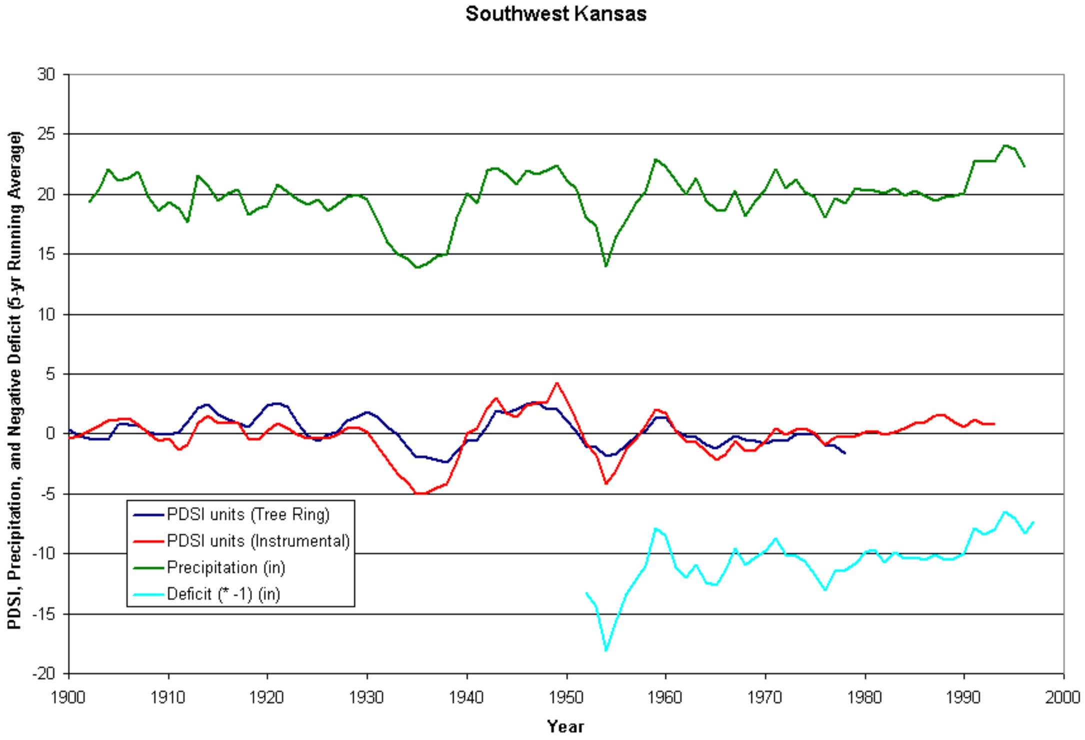


Figure 19. Comparison of some raw and derived climatic indicators - Southwest Kansas

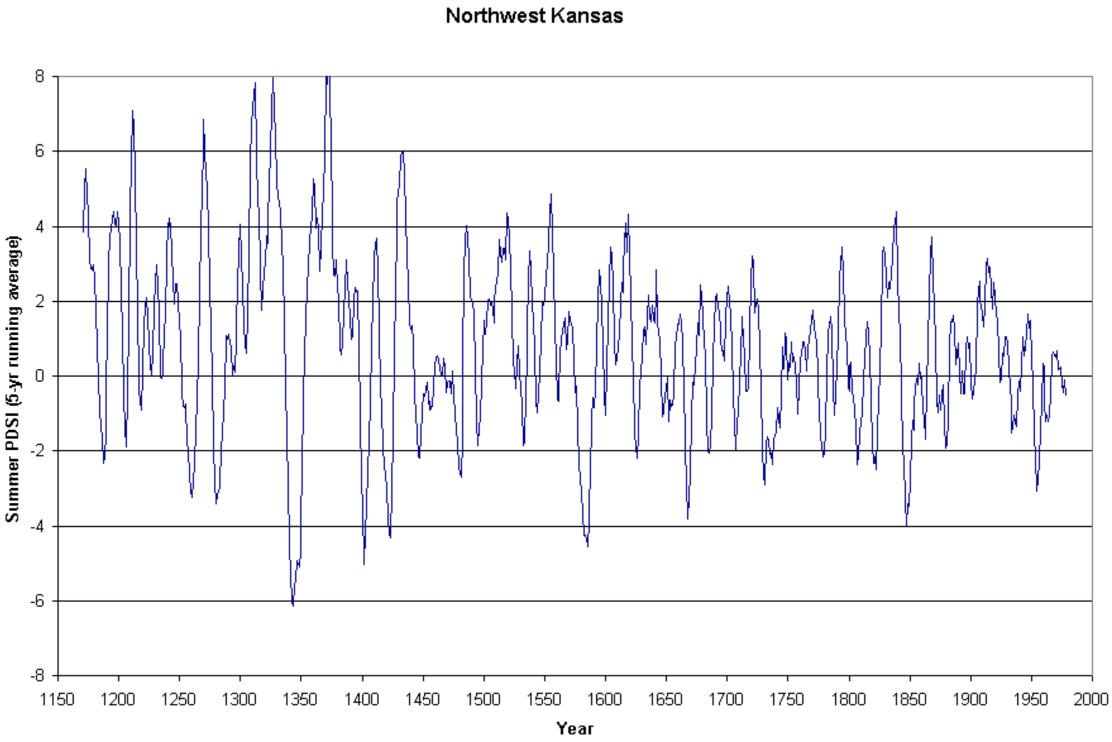


Figure 20. Northwest Kansas PDSI reconstructions (5-yr running average).

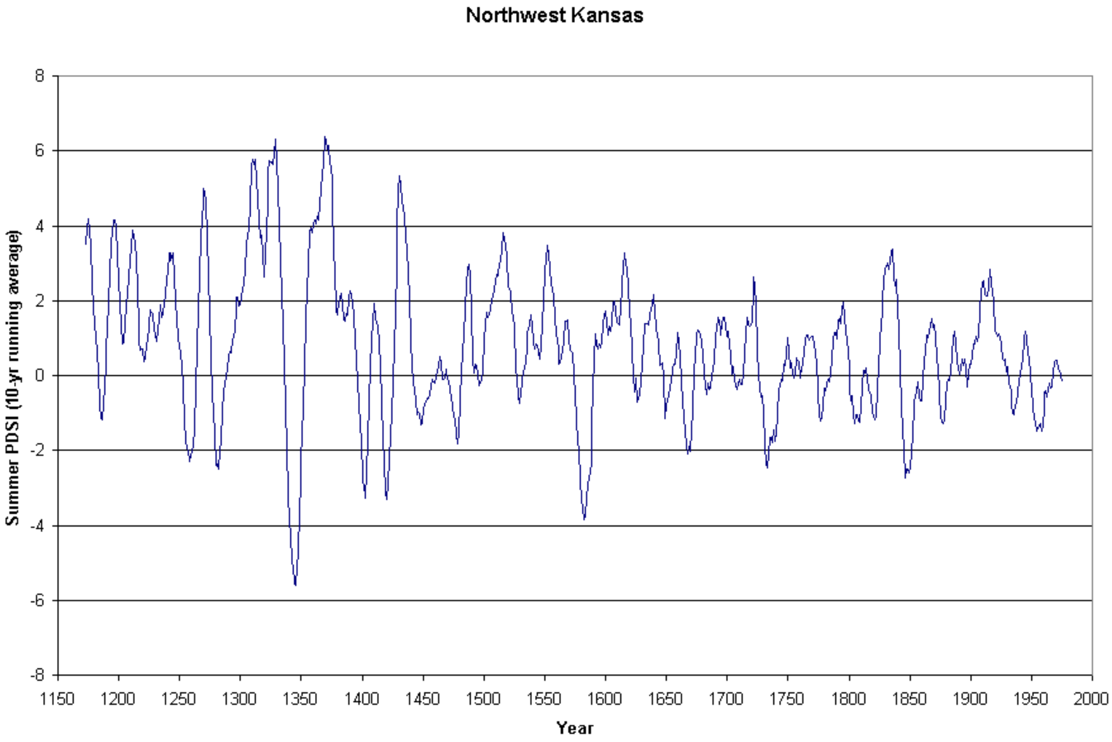


Figure 21. Northwest Kansas PDSI reconstructions (10-yr running average)

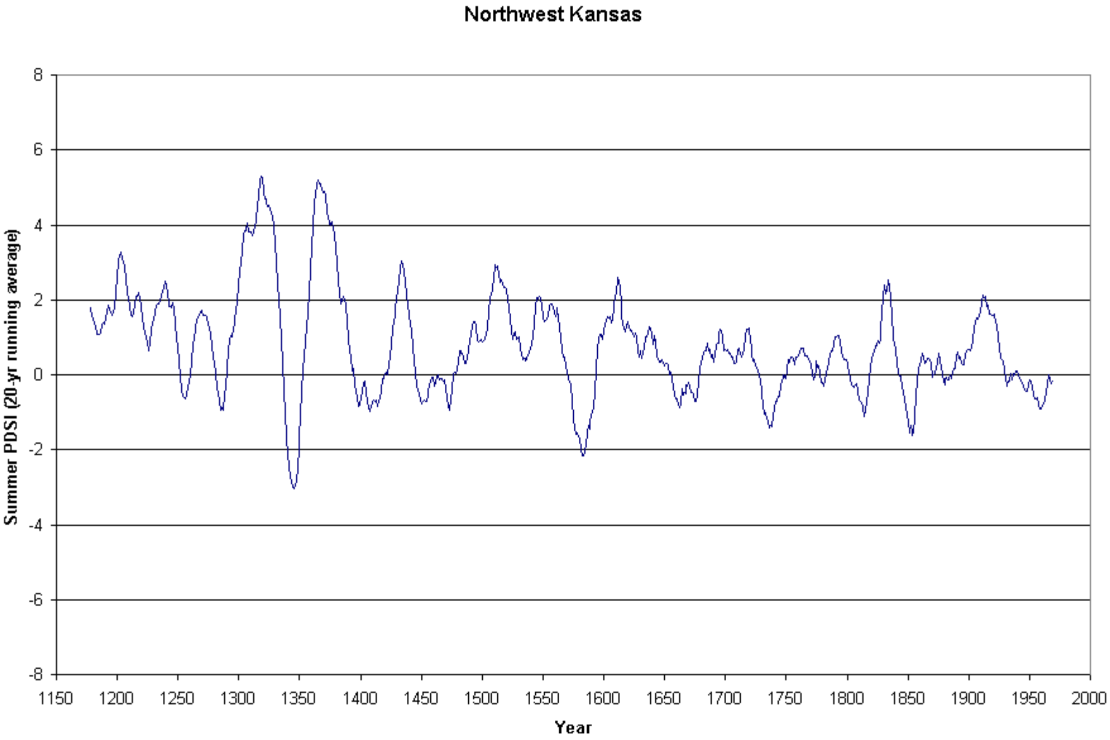


Figure 22. Northwest Kansas PDSI reconstructions (20-yr running average).

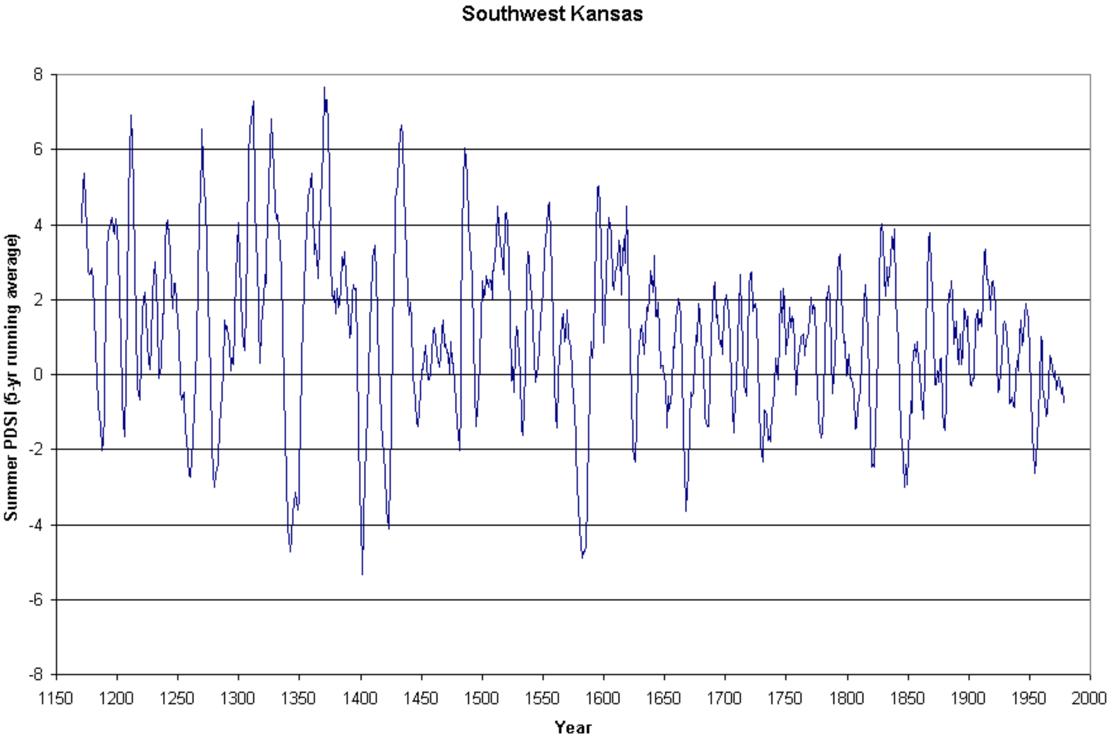


Figure 23. Southwest Kansas PDSI reconstructions (5-yr running average).

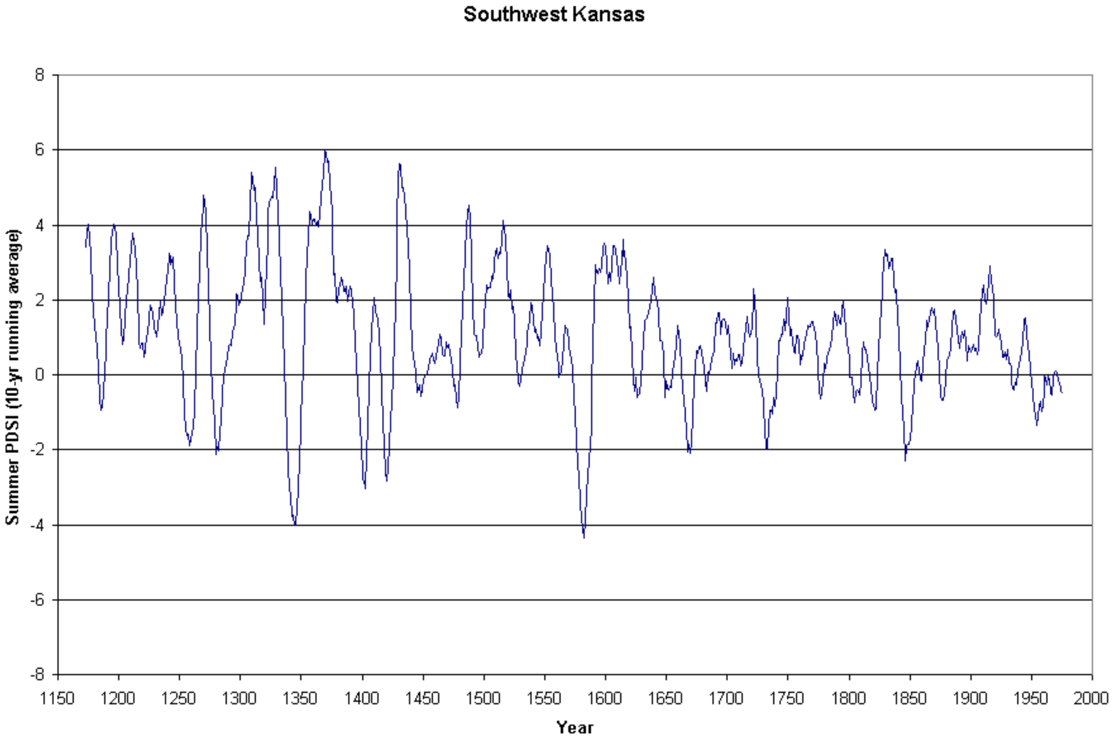


Figure 24. Southwest Kansas PDSI reconstructions (10-yr running average).

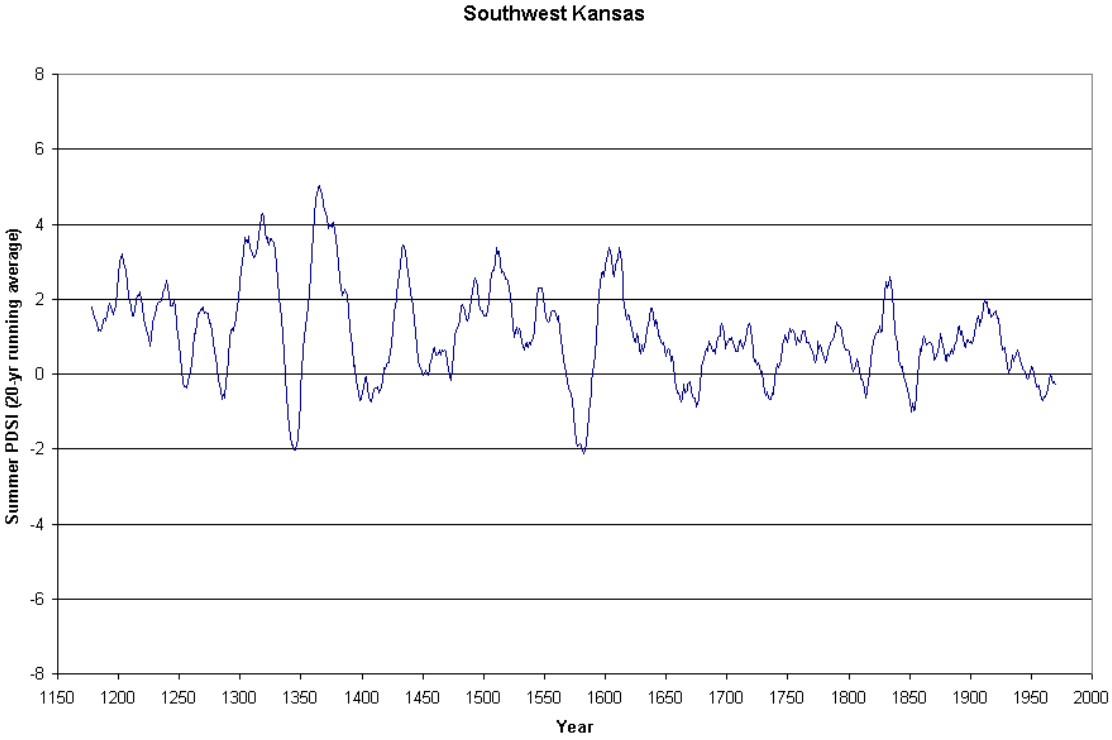


Figure 25. Southwest Kansas PDSI reconstructions (20-yr running average).

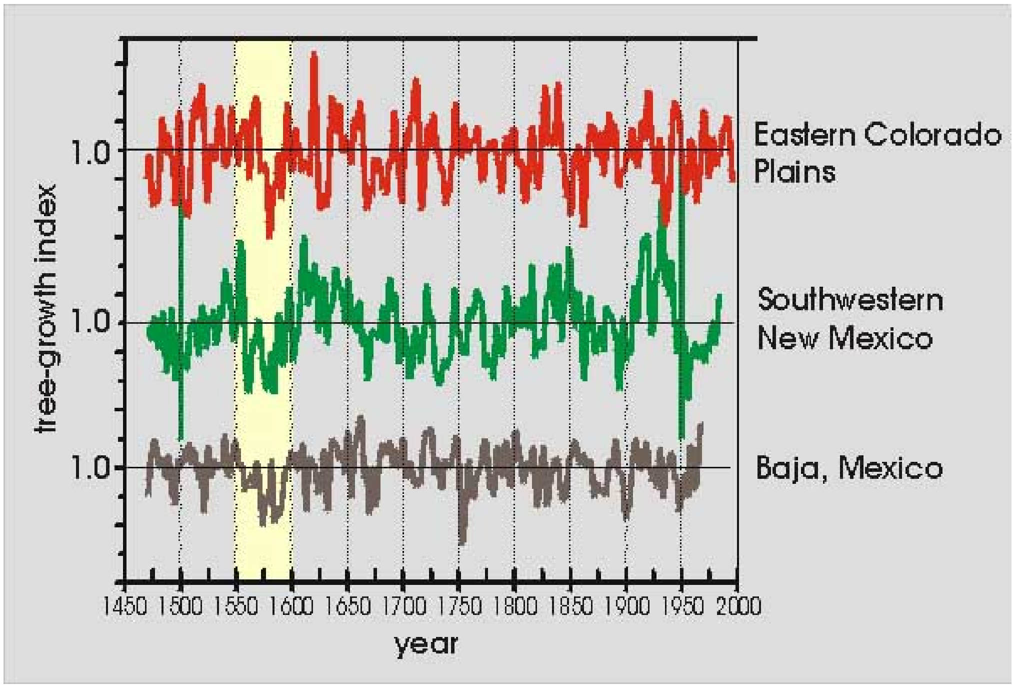


Figure 26. Coincident droughts, or the same drought, in the eastern Colorado plains, southwestern New Mexico, and Baja, Mexico (from http://www.ngdc.noaa.gov/paleo/drought/drght_500years.html).

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

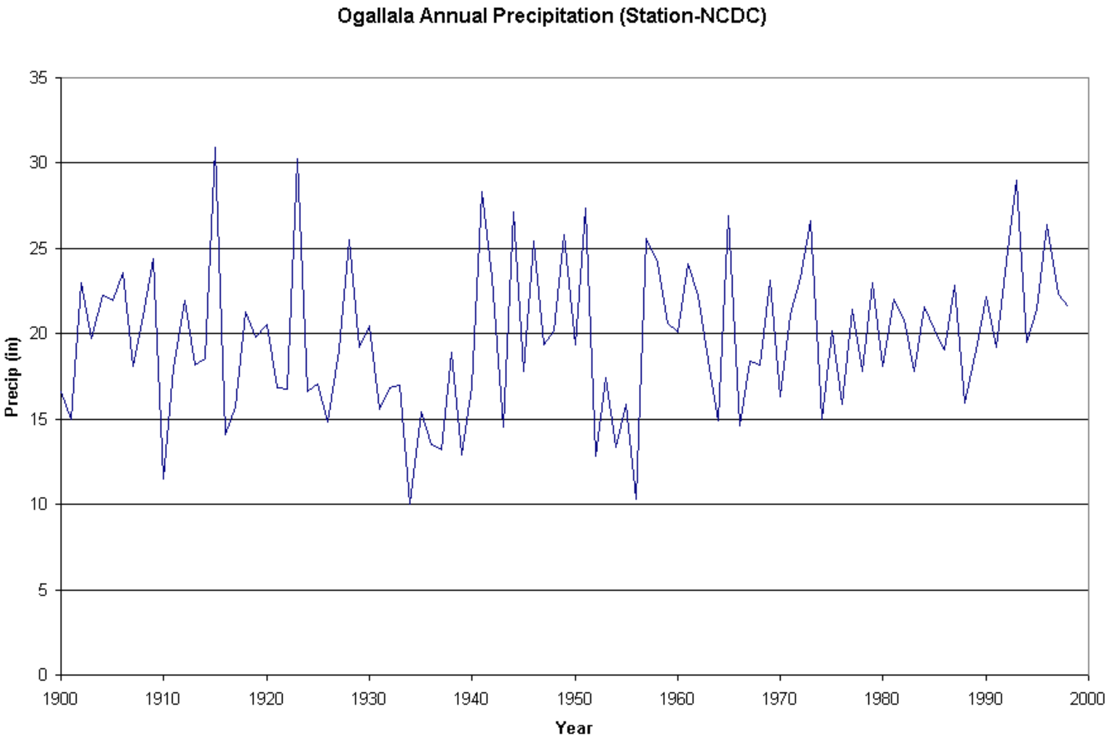
Station-NCDC data are the NCDC weather station point data, which are available since about 1900. The Willmott-NCDC data set contains spatially-interpolated Station-NCDC data, beginning in 1950.

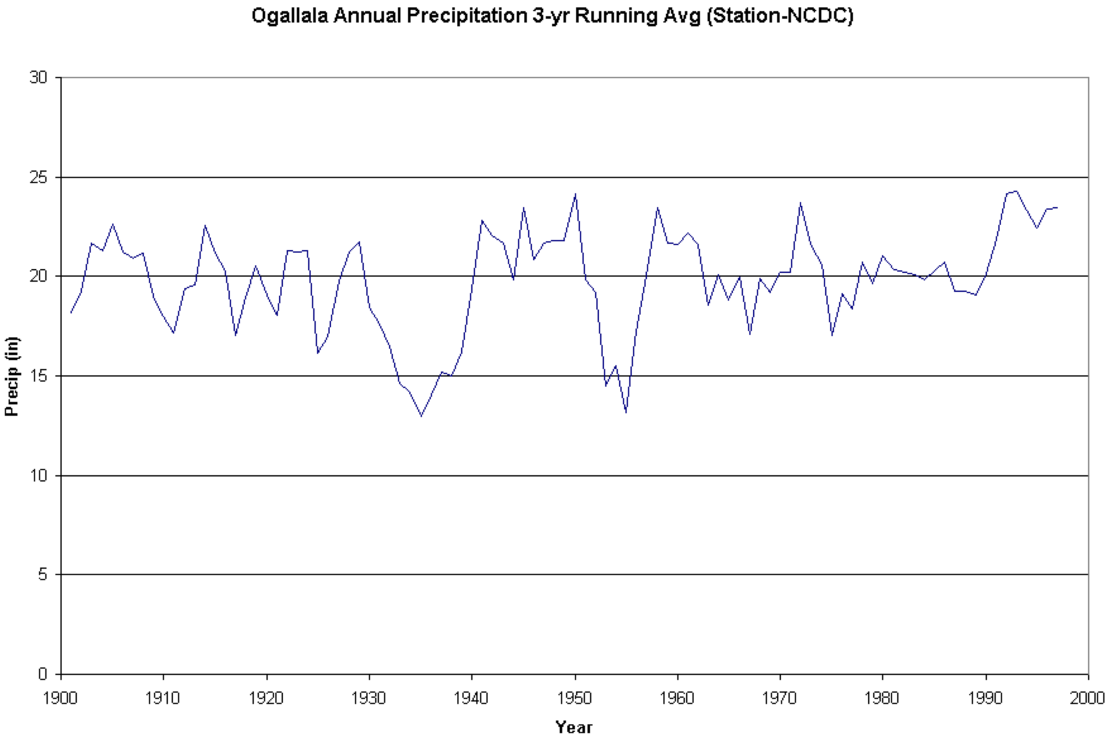
Data plotted are the regional annual averages, which are the sums of monthly values for the year of interest averaged over all the Willmott-NCDC half-degree cells in the designated region (Figures 4-9).

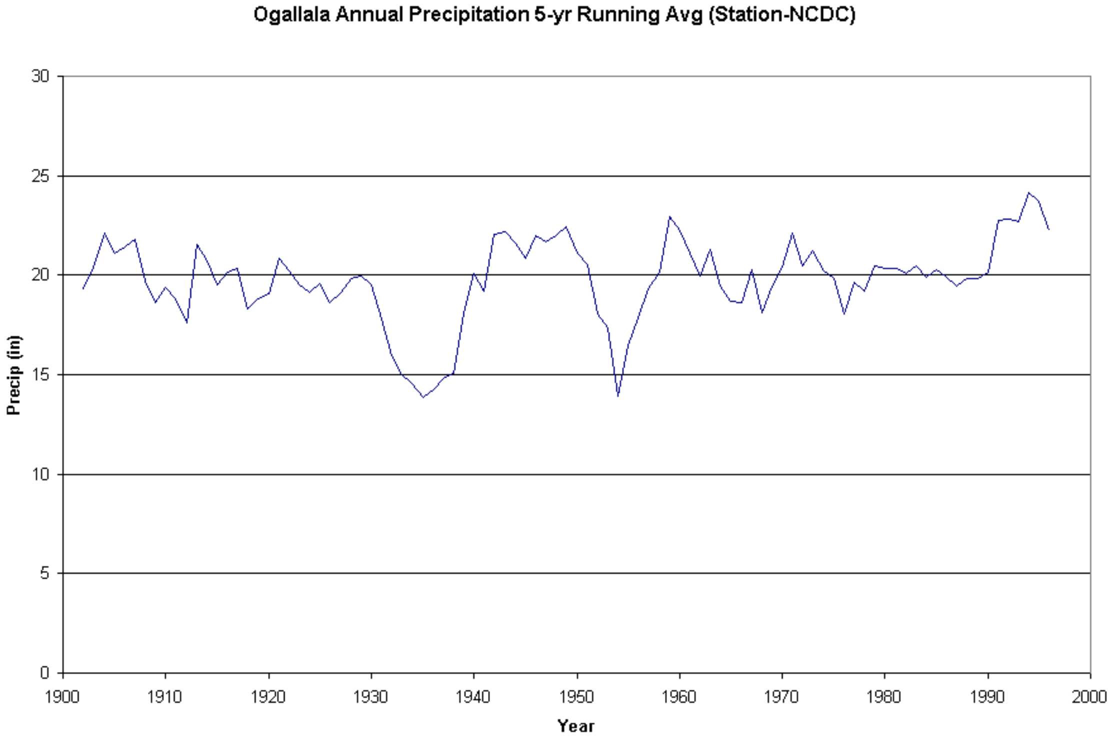
Values are plotted as individual year totals and as running averages (also called "boxcar" averages) of the annual totals over 3, 5, 10, and 20 year time periods. In this presentation, the 3-year average for 1990, for example, is the average of values for 1989, 1990, and 1991. This averaging has the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

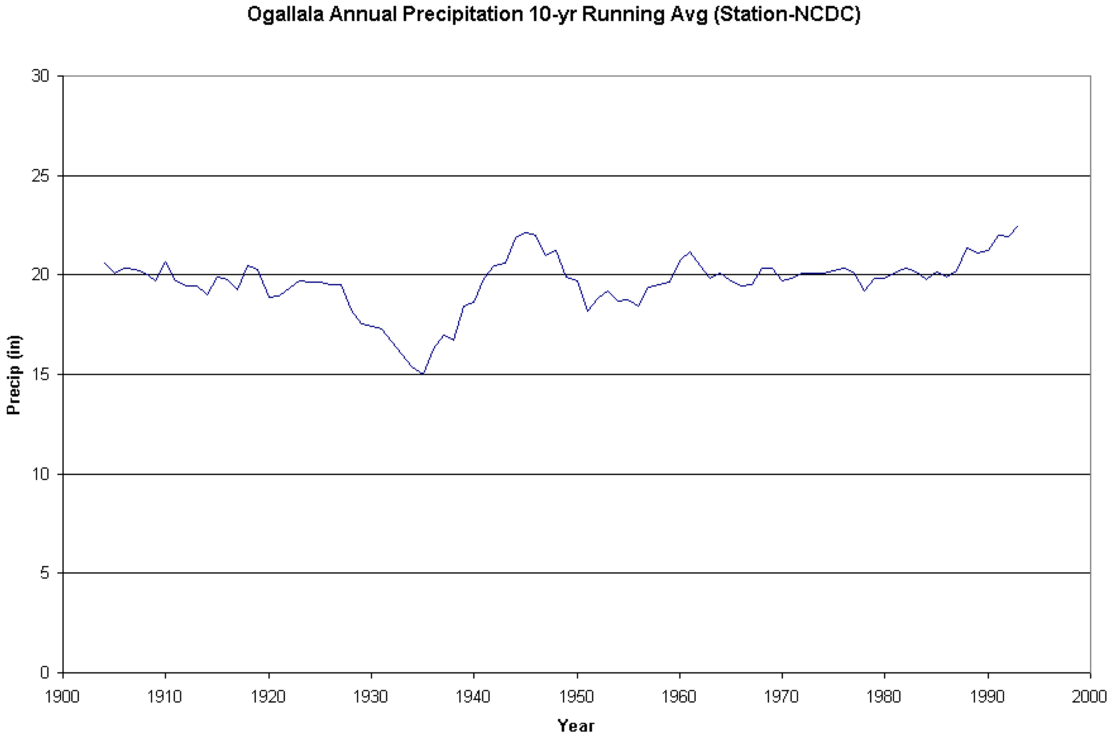
Contents

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






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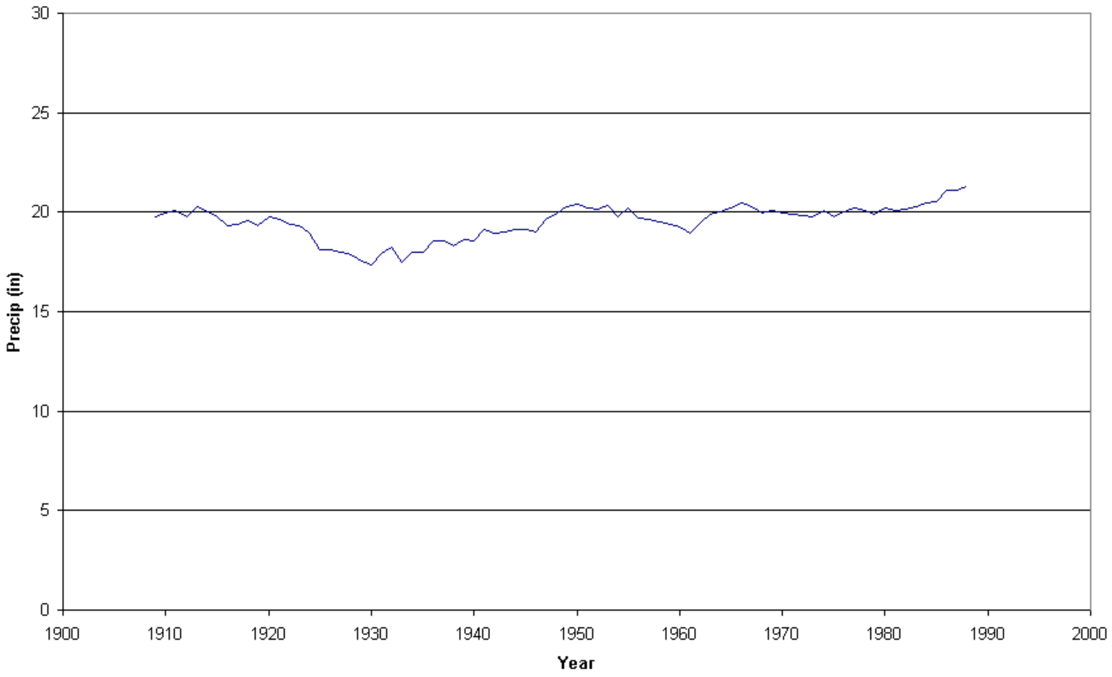
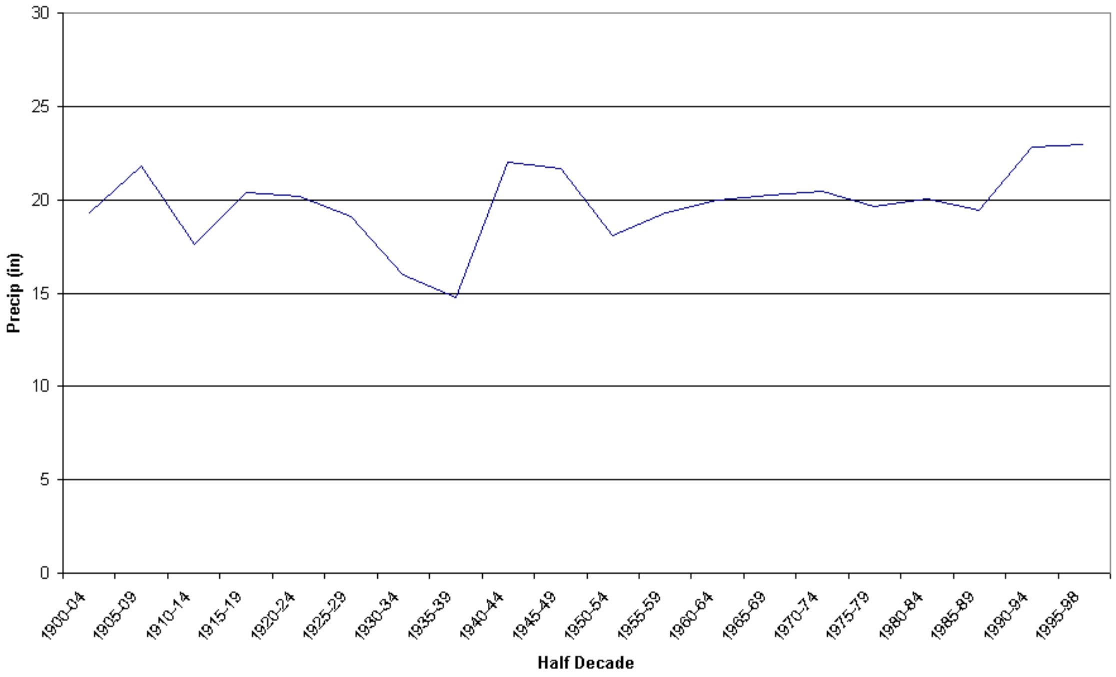
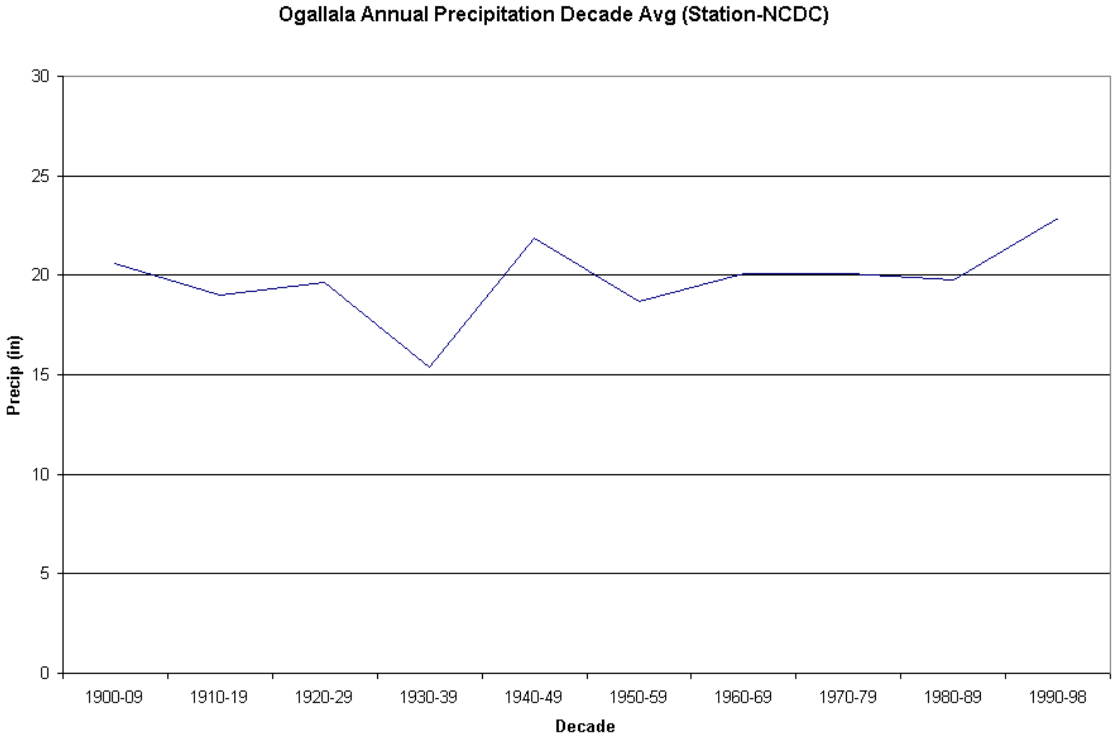
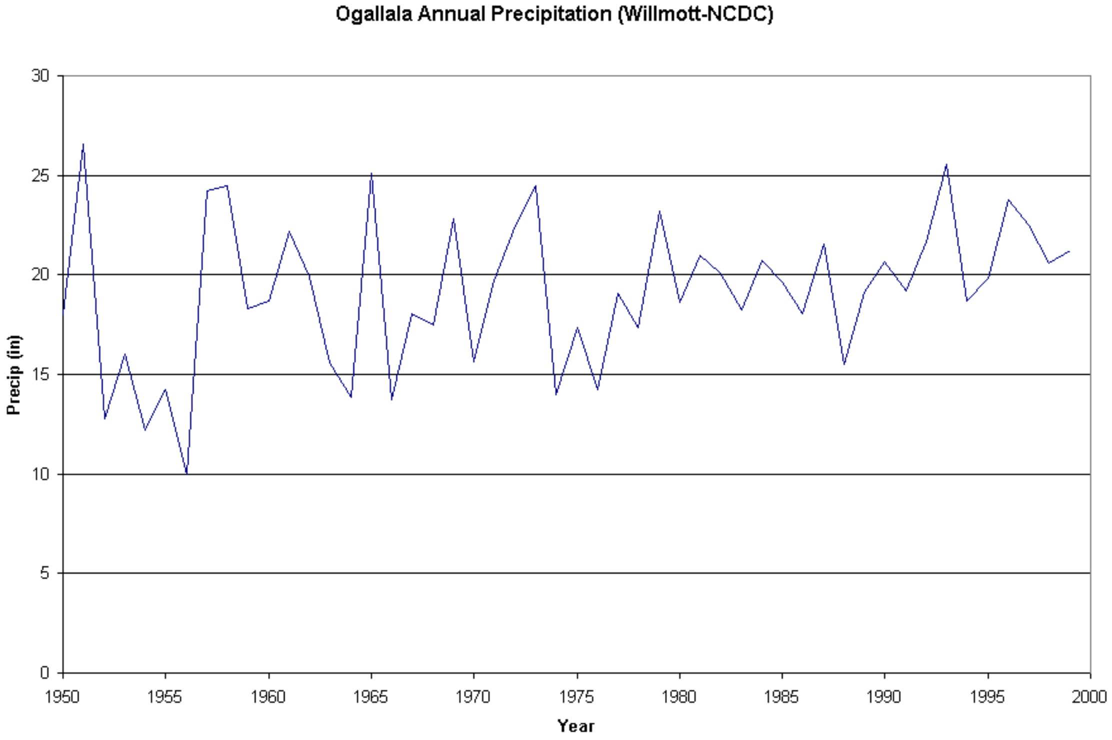
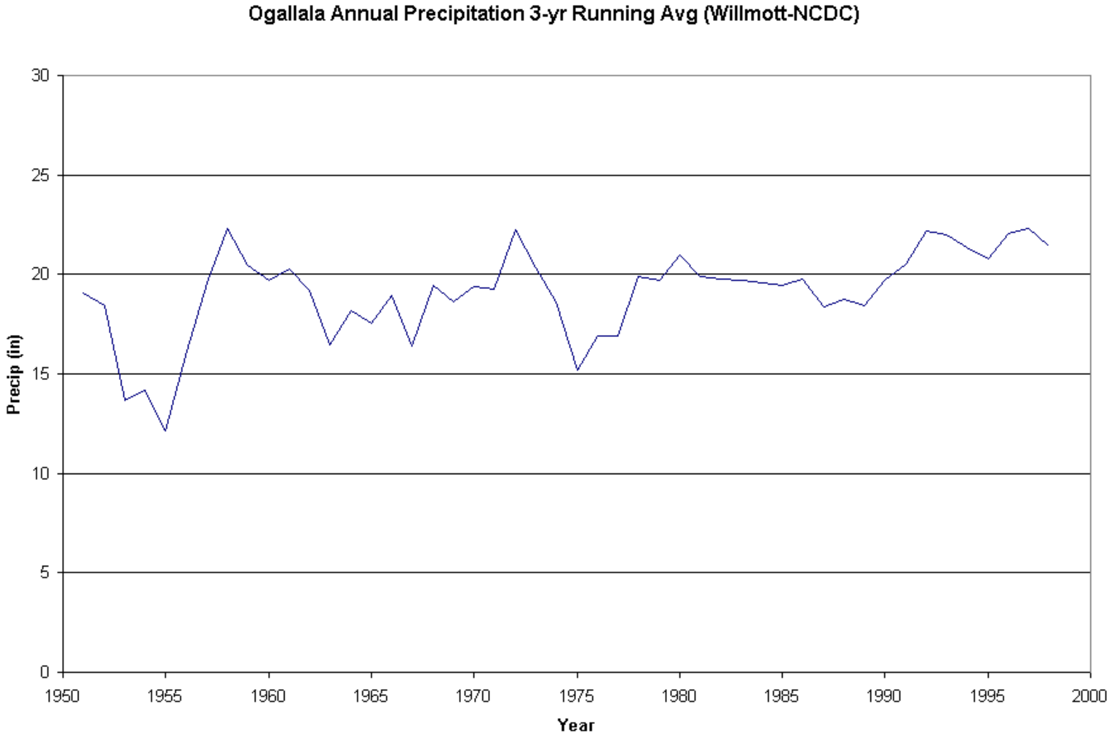

Ogallala Annual Precipitation 20-yr Running Avg (Station-NCDC)


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

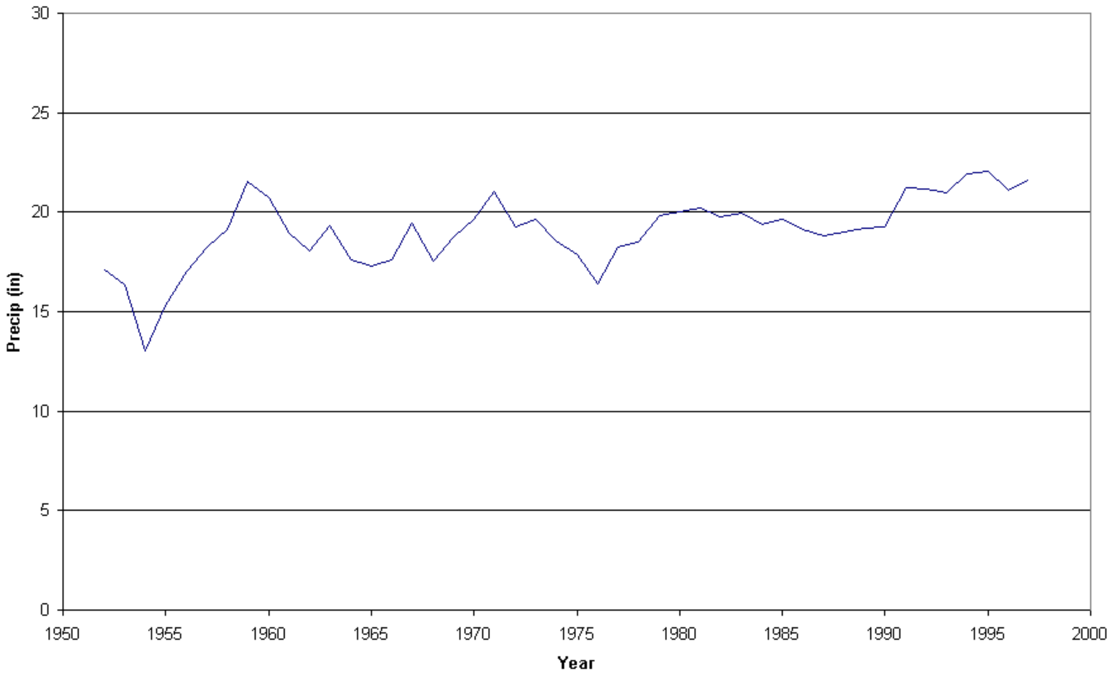

Ogallala Annual Precipitation Decade Avg (Station-NCDC)
Precip (in)
30
25
20
15
10
5
0
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-98
Decade

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

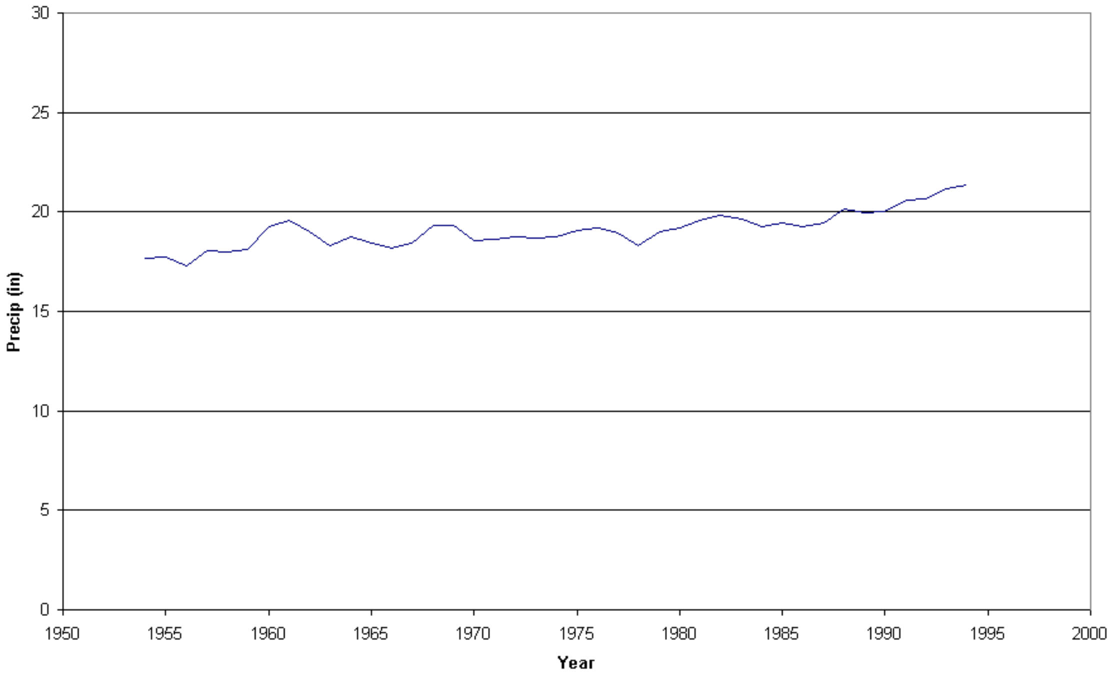




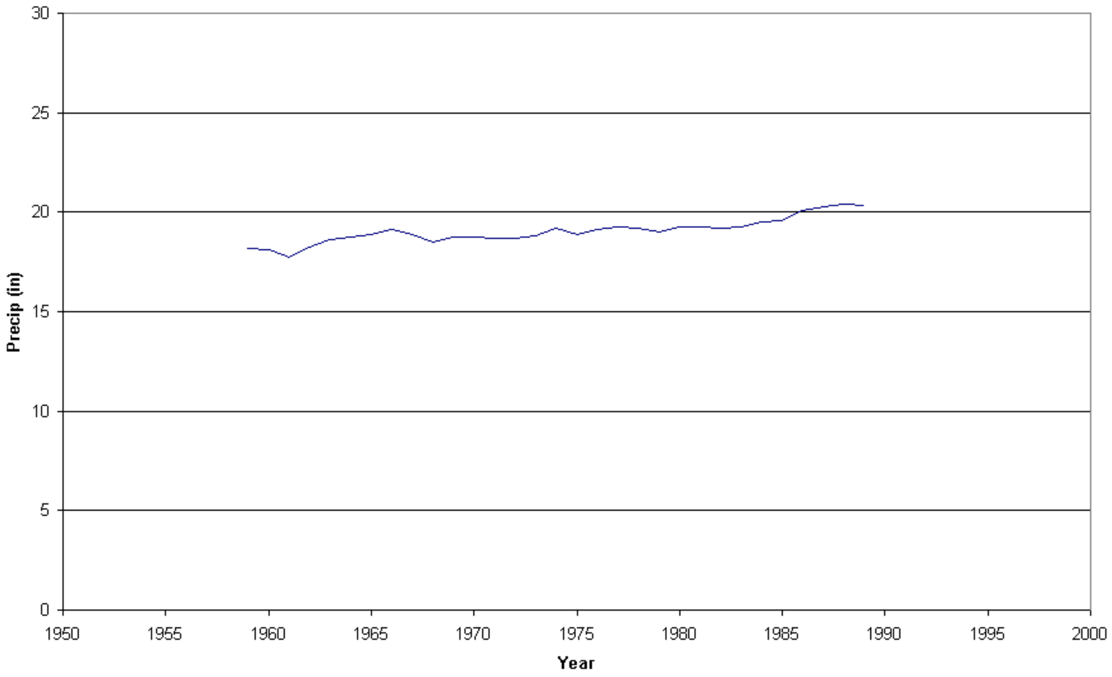
Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



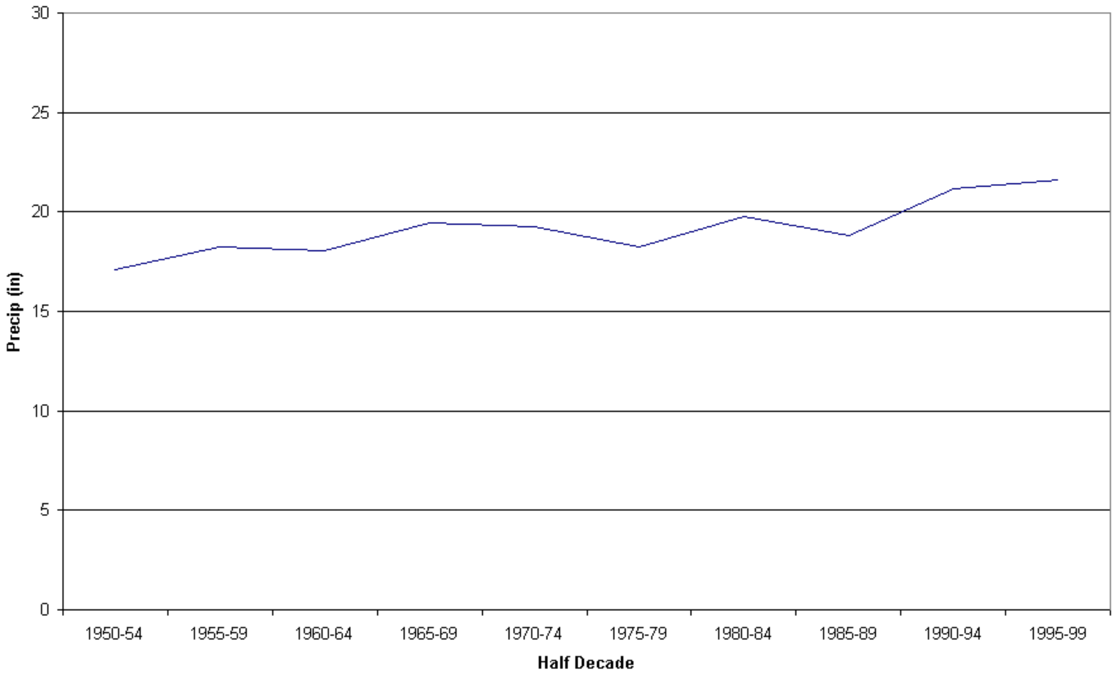
Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

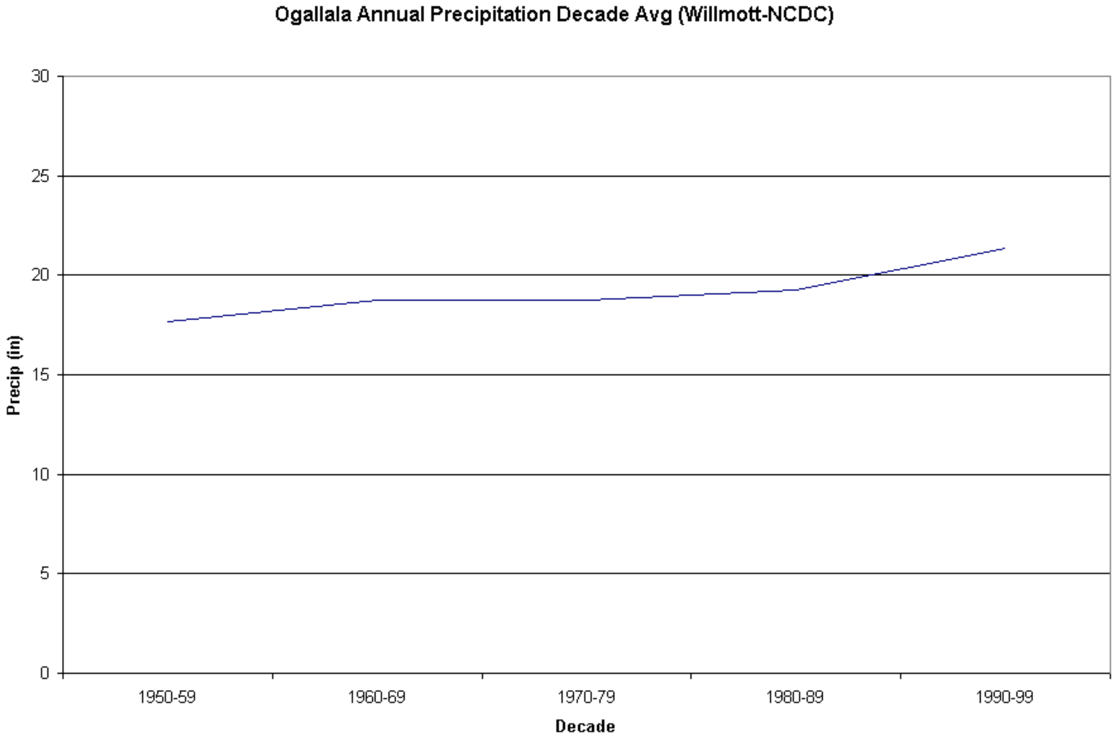


Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

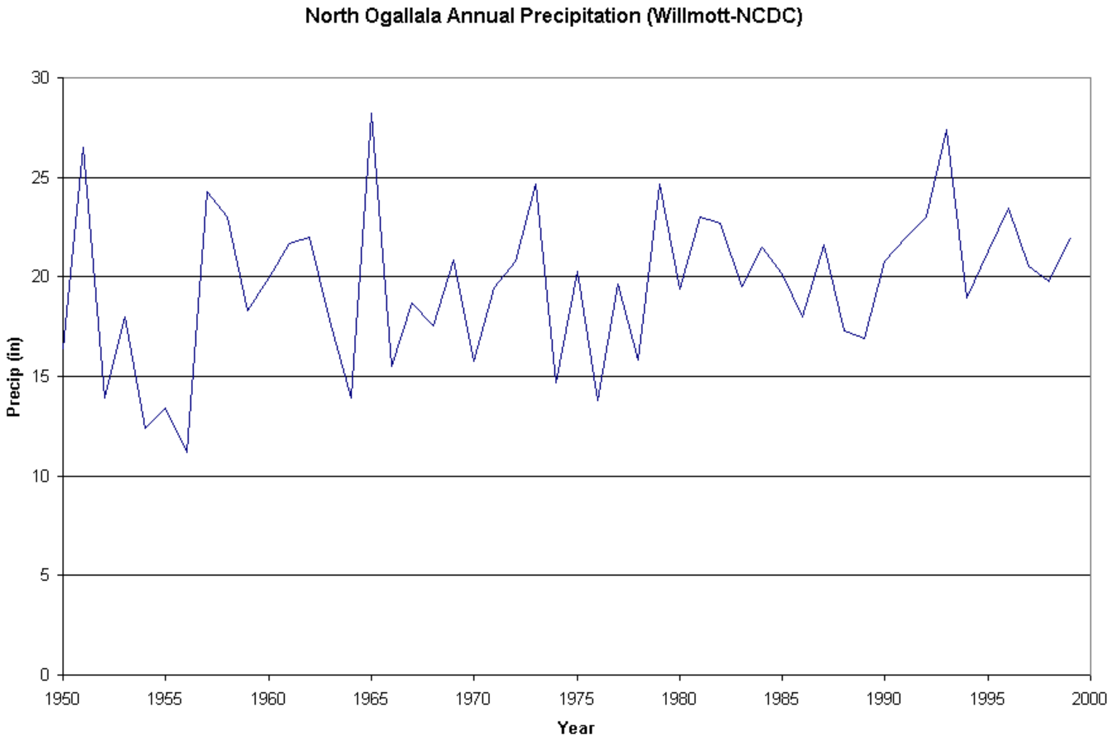


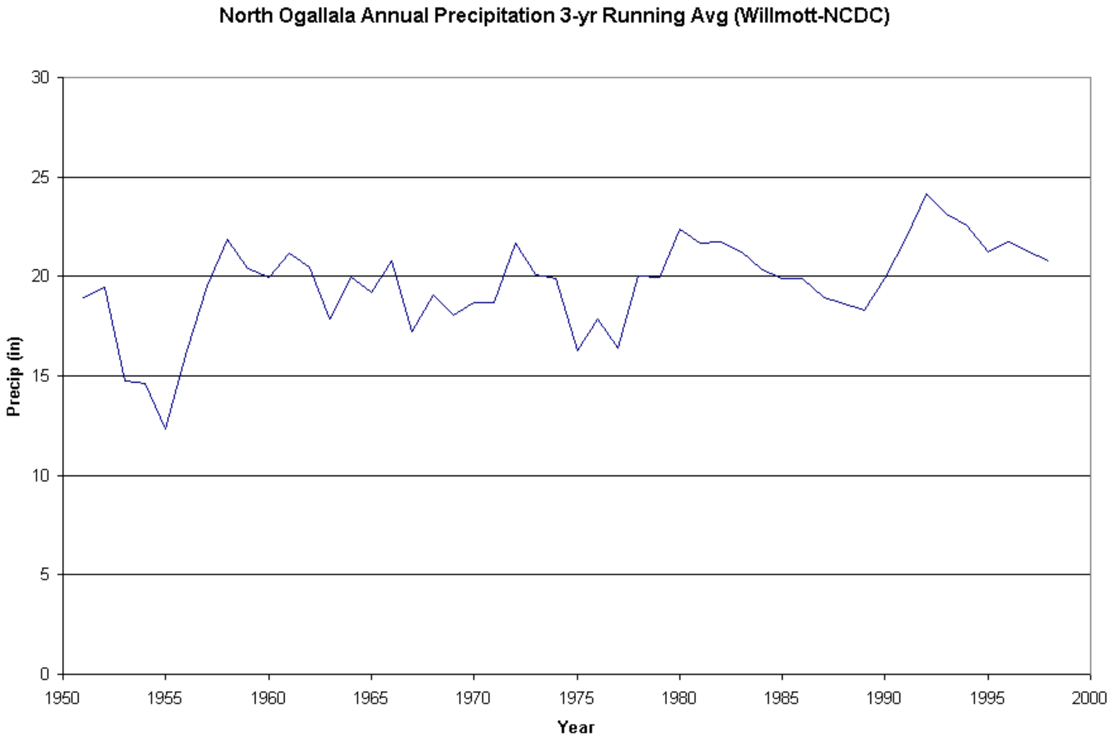
Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)



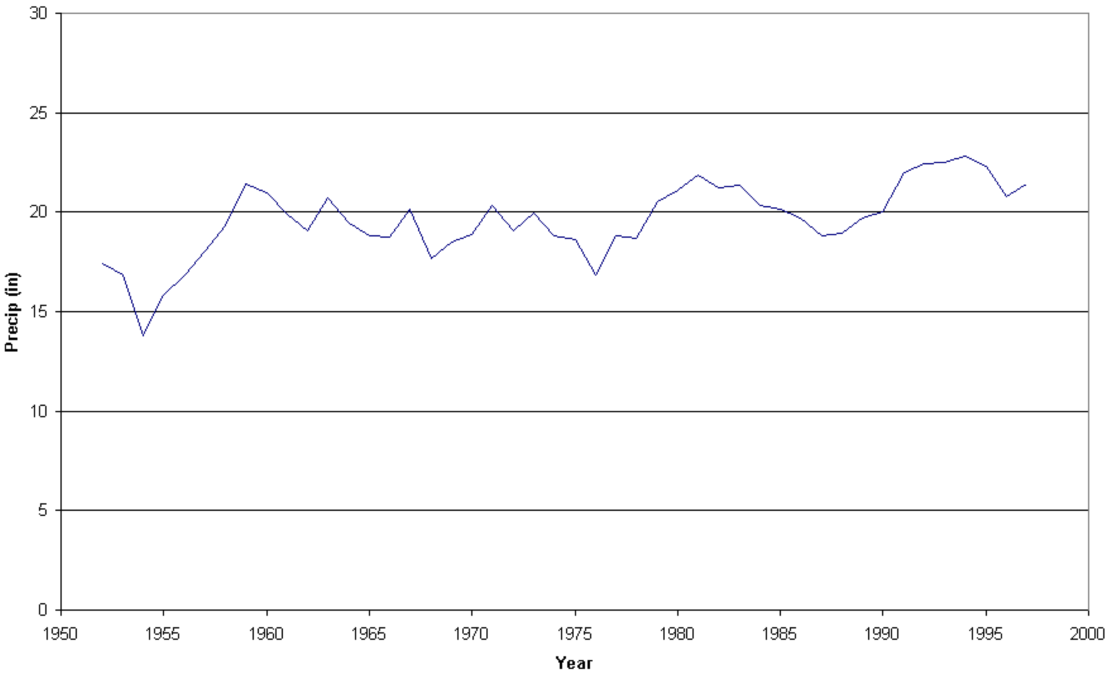

Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.3. North Ogallala (Willmott-NCDC)

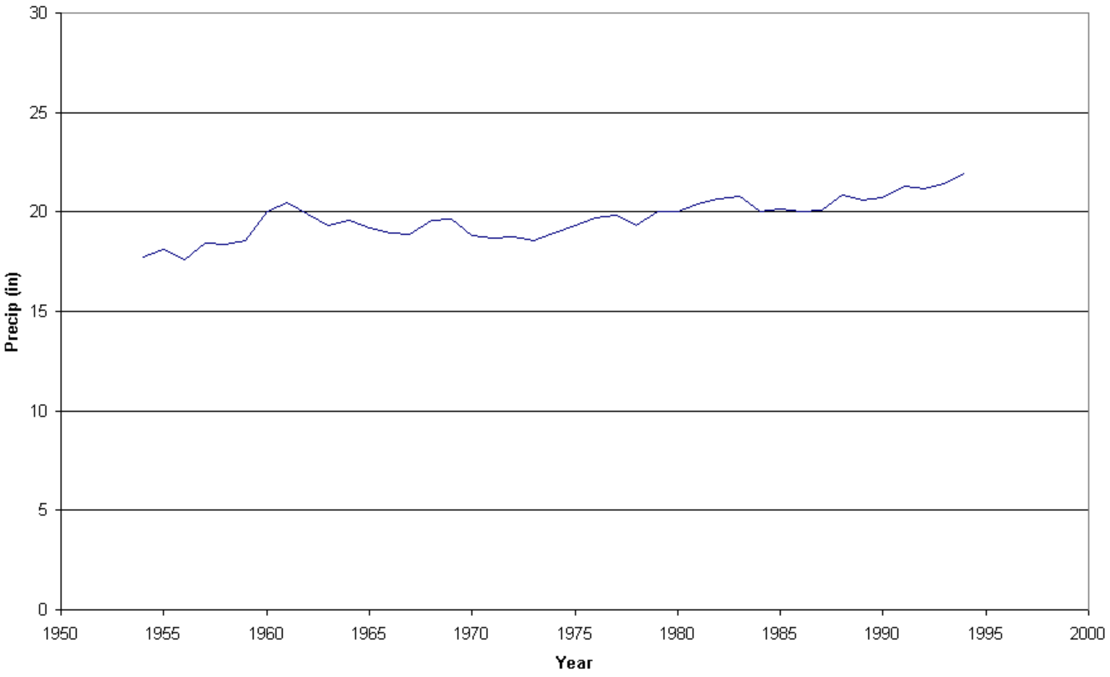




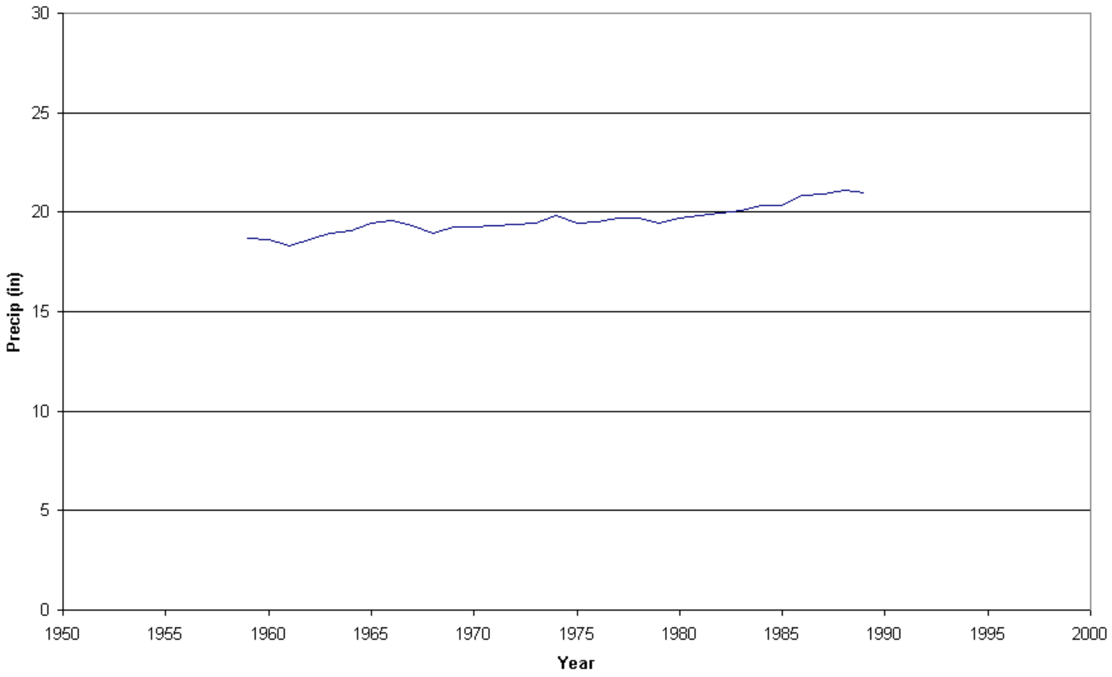
North Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



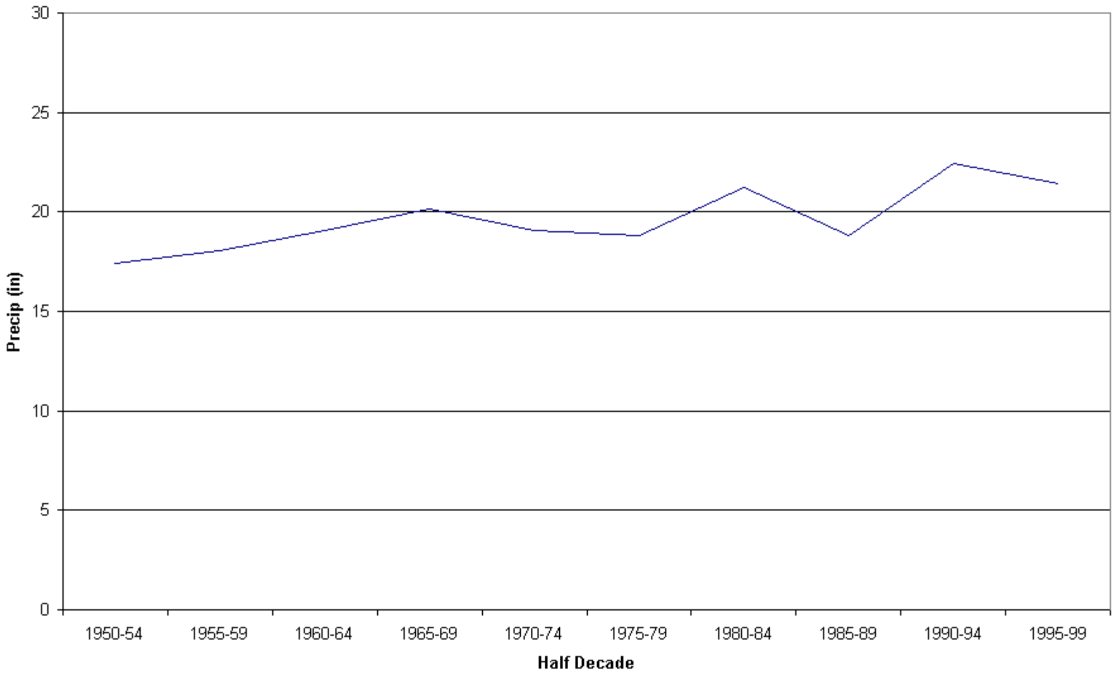
North Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

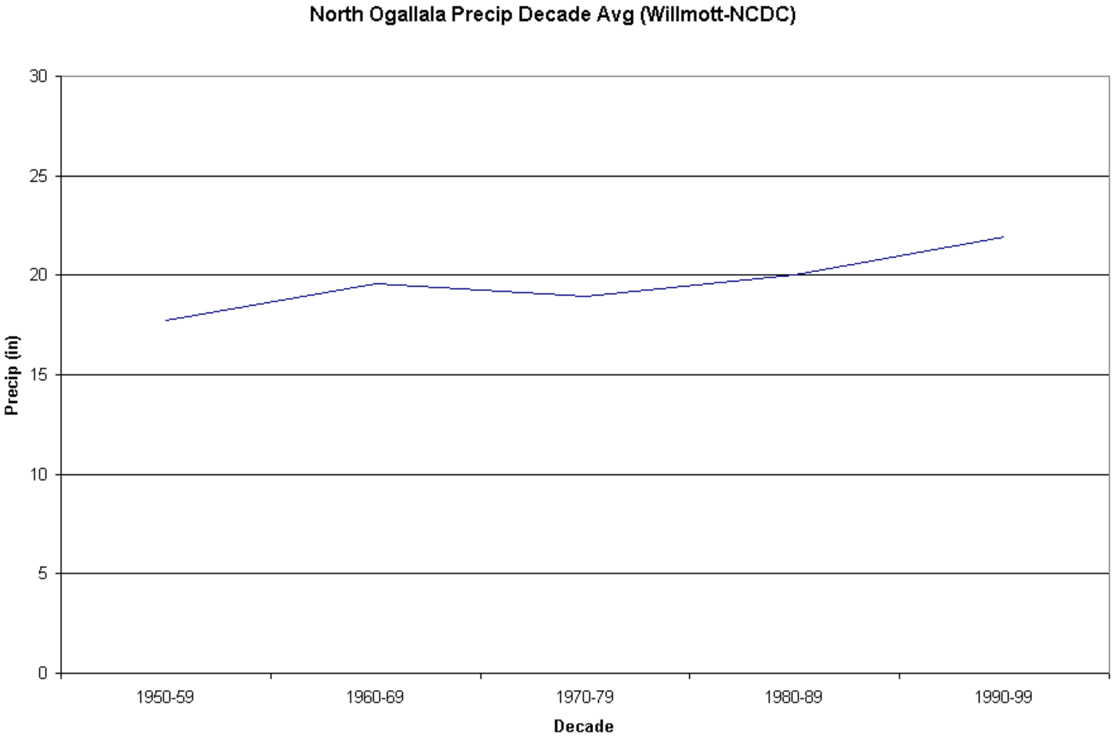


North Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

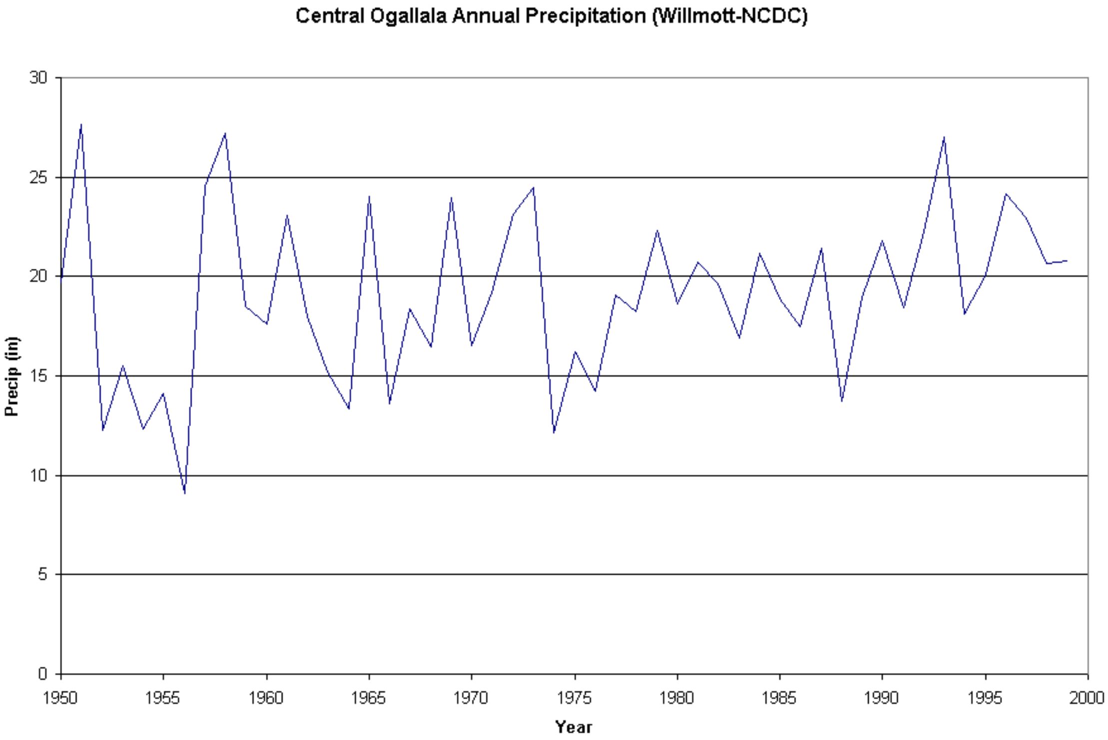


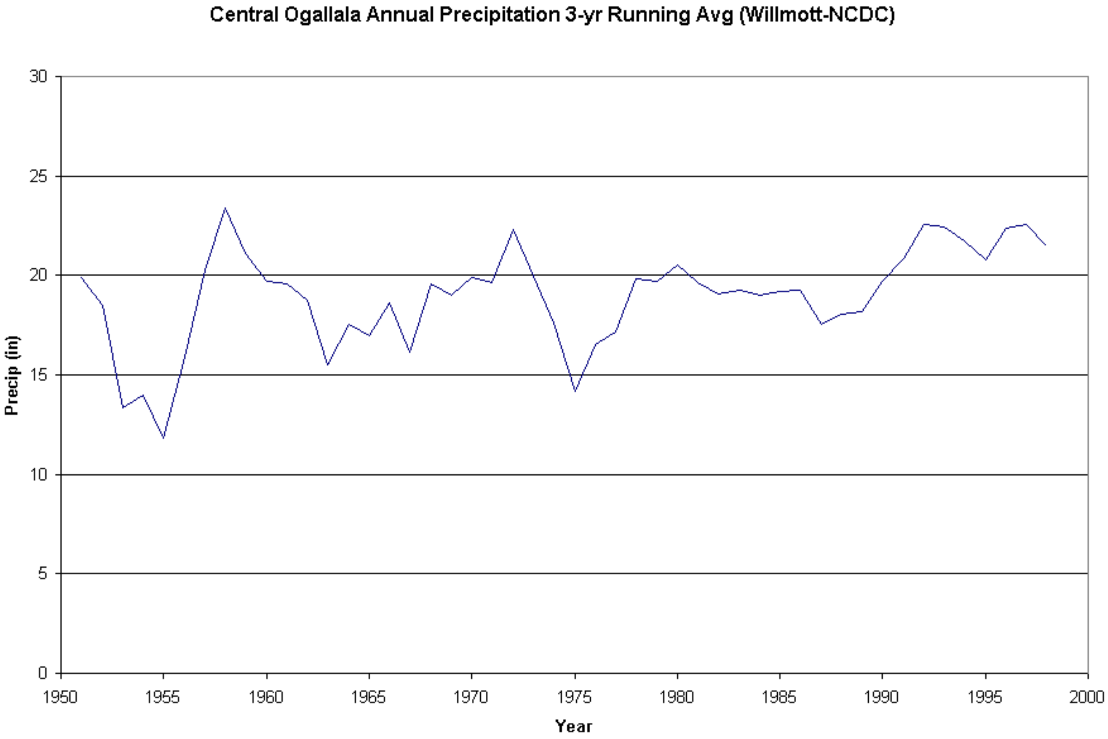
North Ogallala Annual Precipitation Half-Decade Average (Willmott-NCDC)



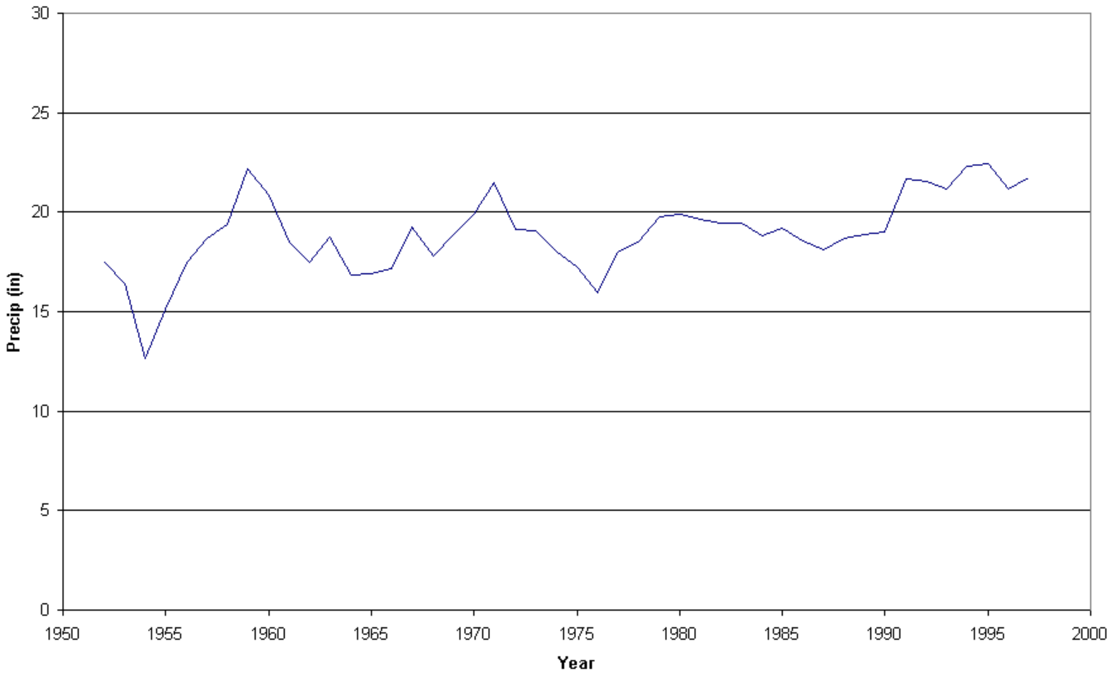

North Ogallala Precip Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.4. Central Ogallala (Willmott-NCDC)

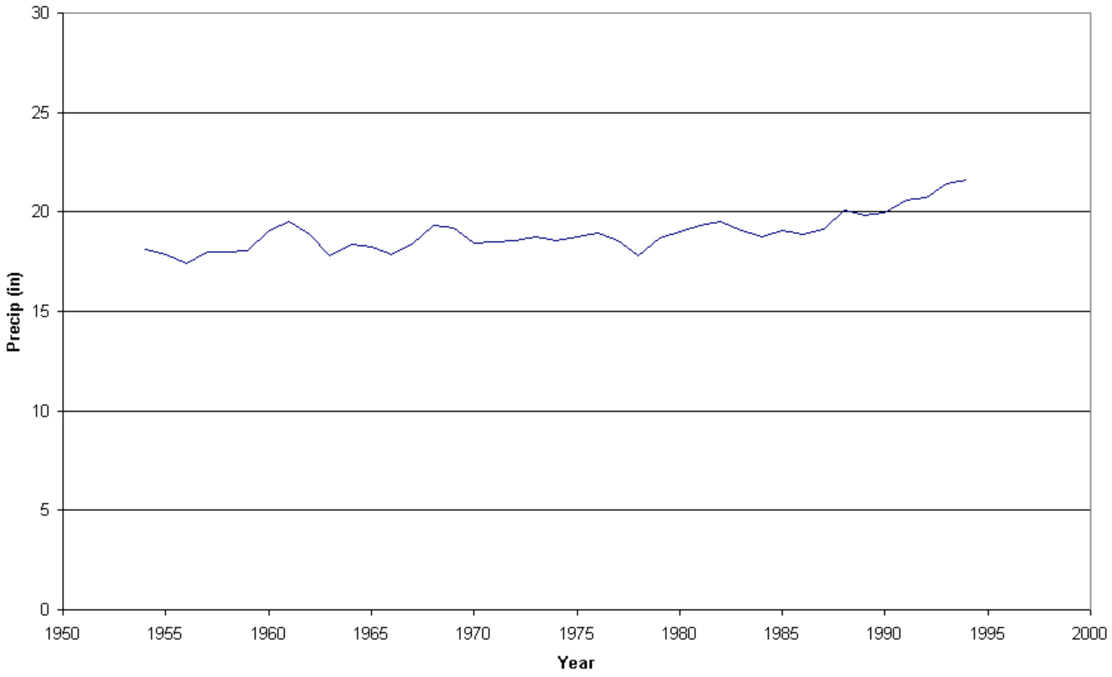


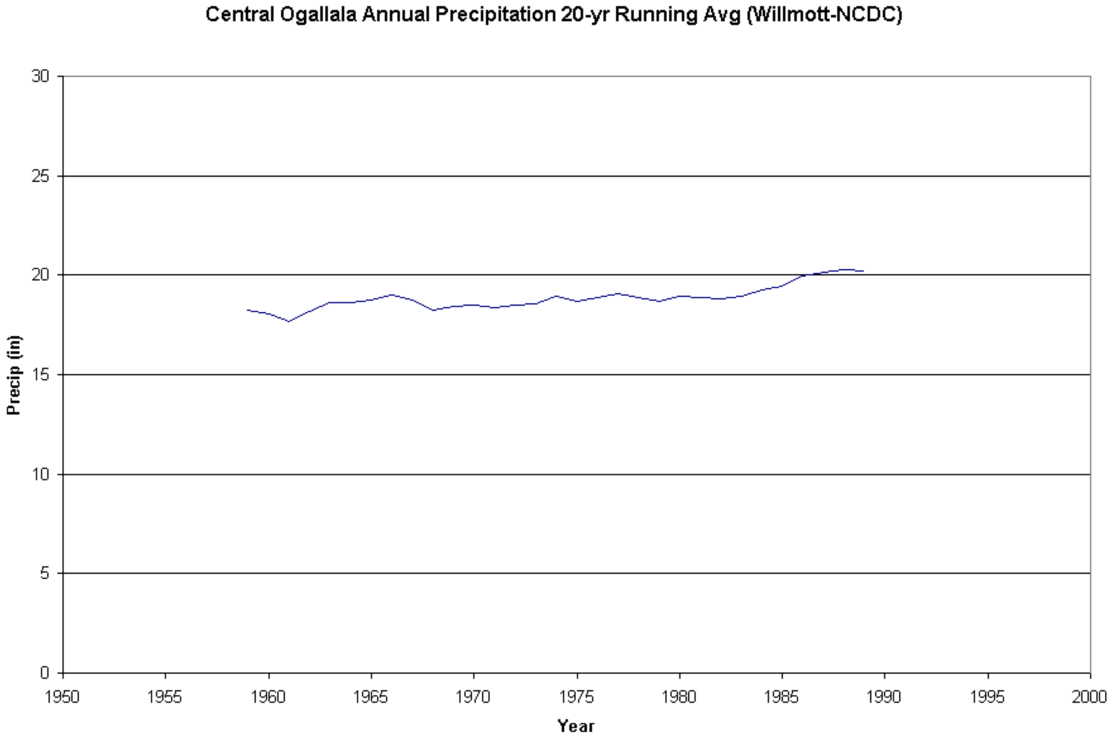


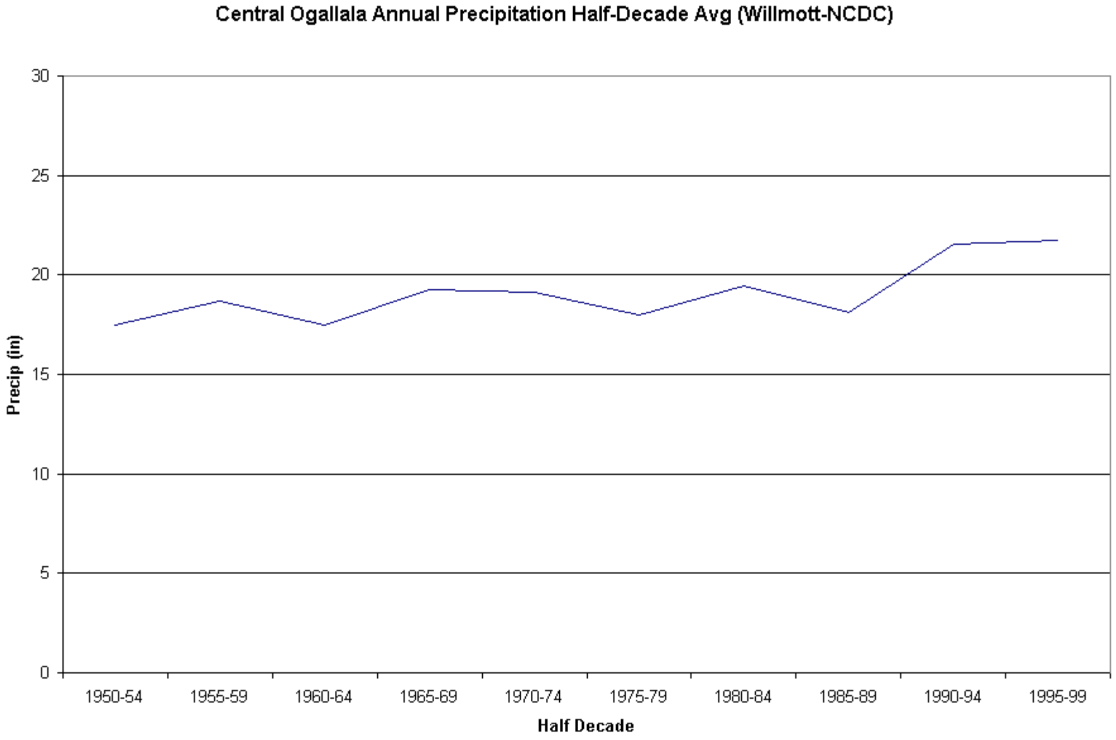
Central Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



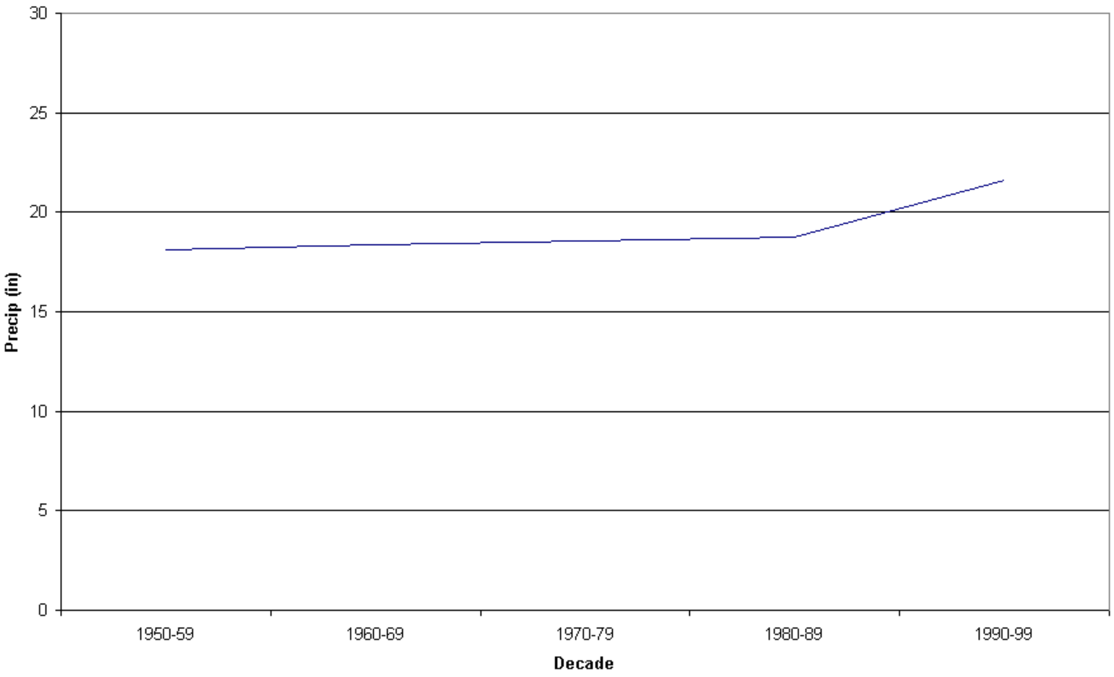
Central Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)



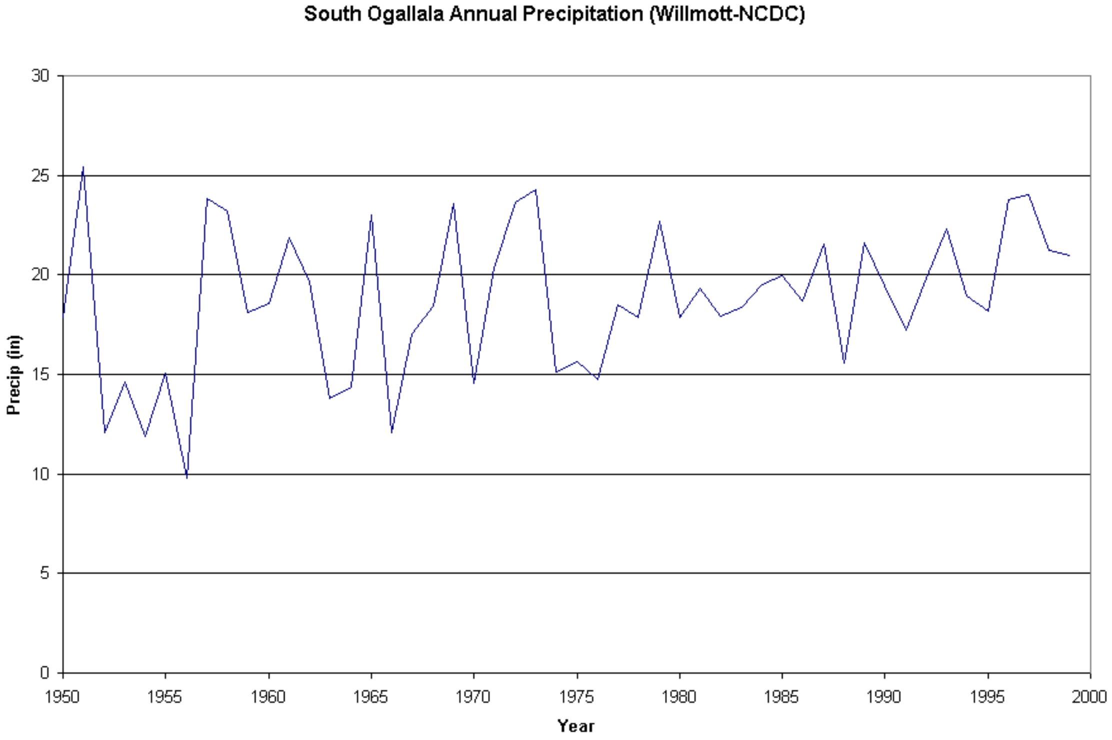

Central Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)

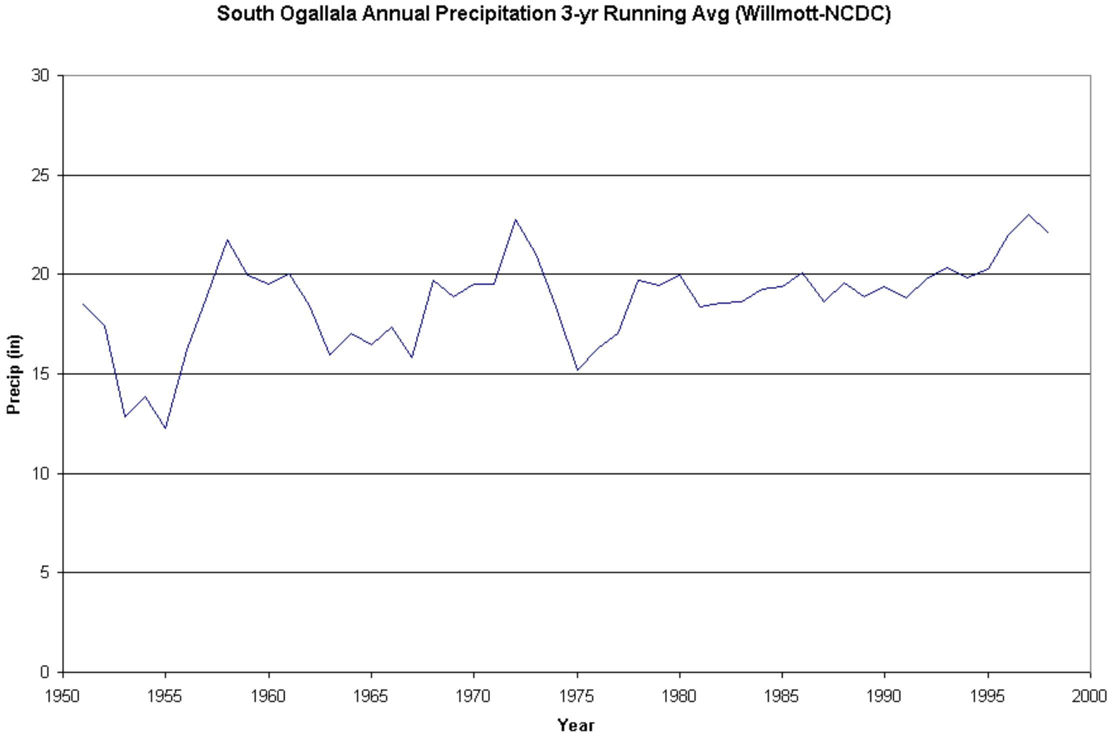

Central Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)

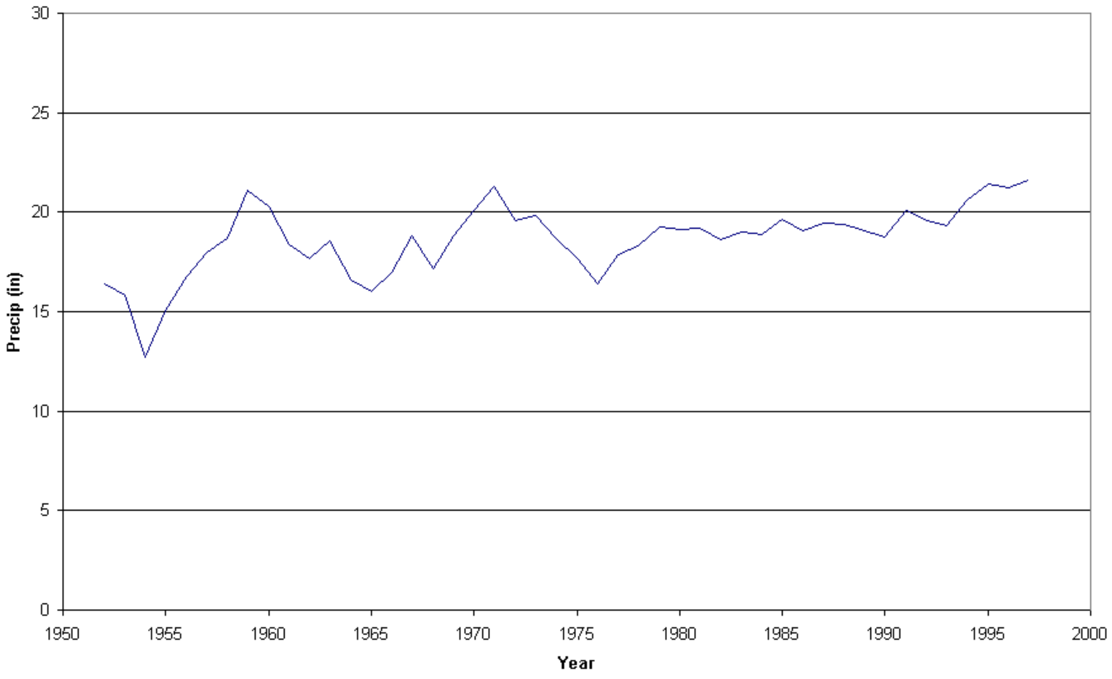
Central Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)



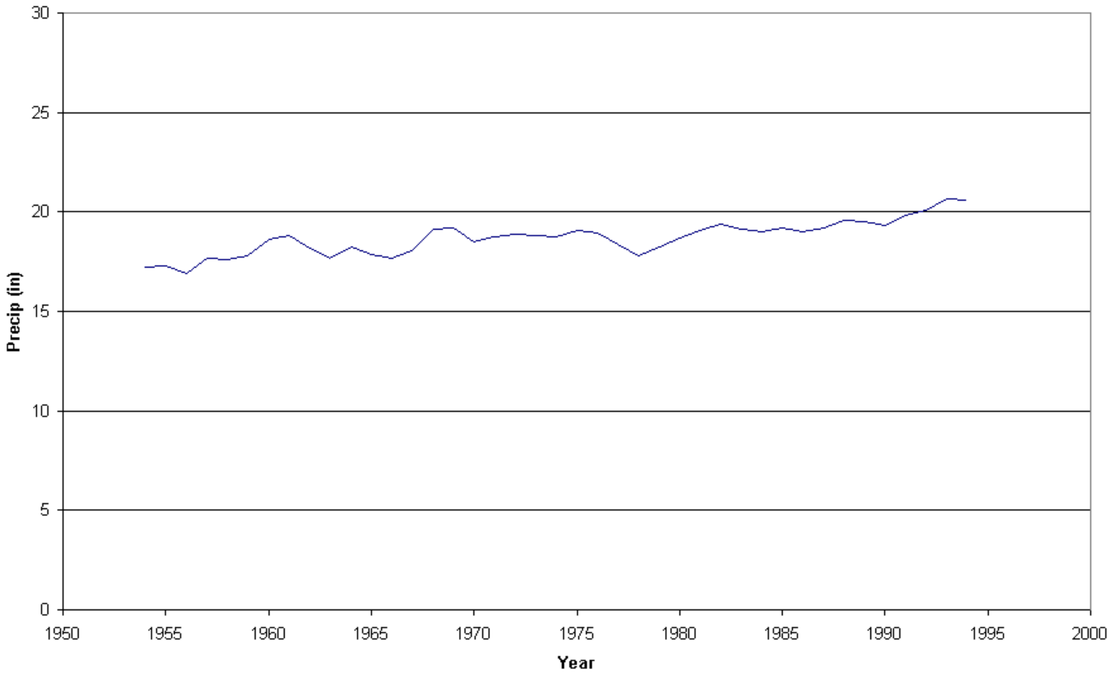
Appendix Figures 1.5. South Ogallala (Willmott-NCDC)



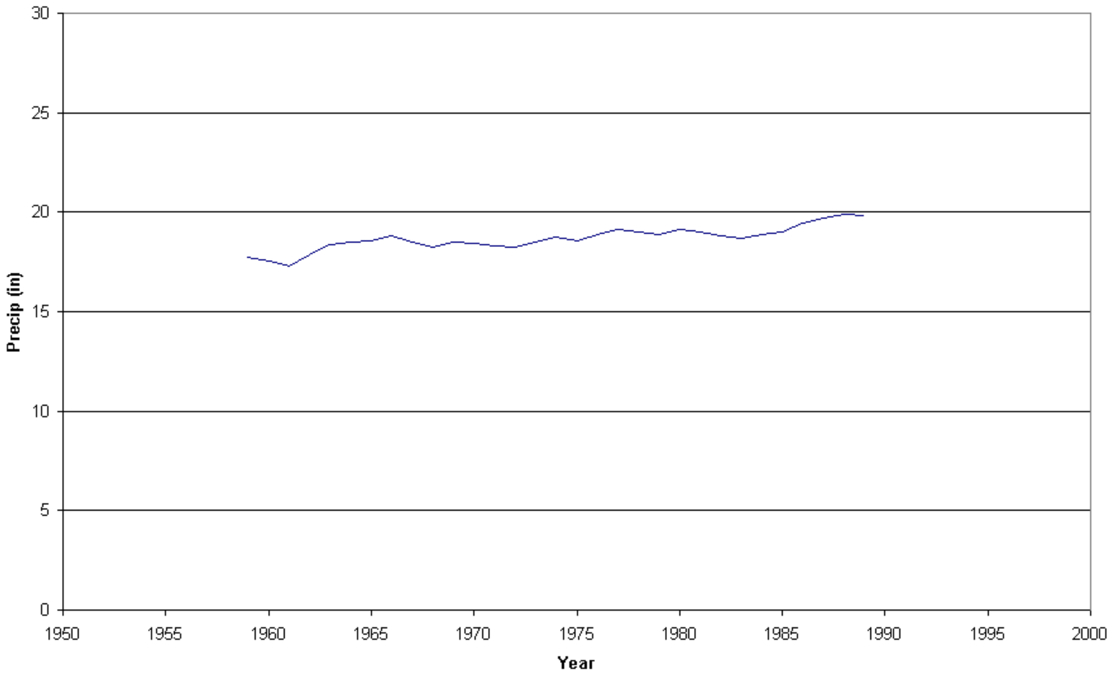




South Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



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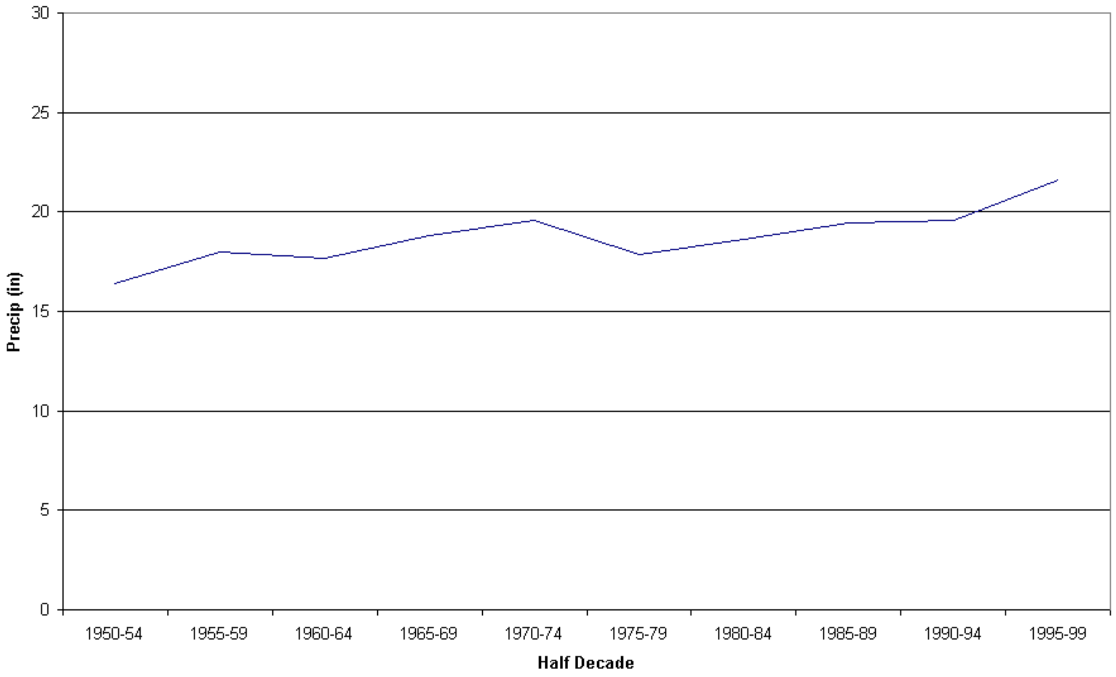
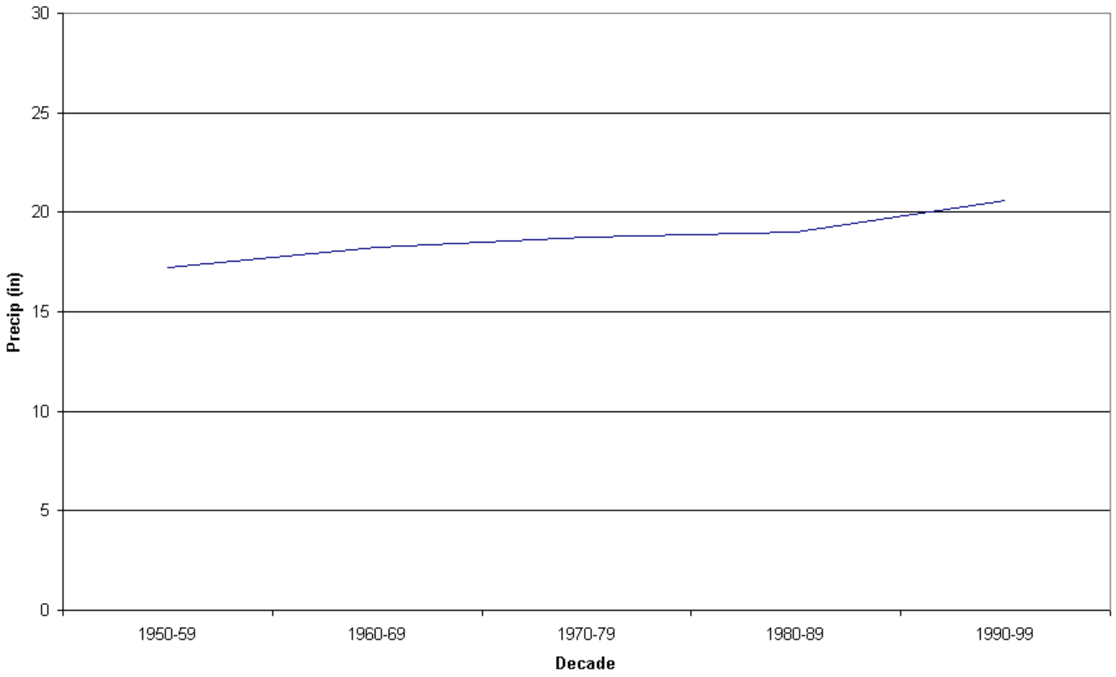
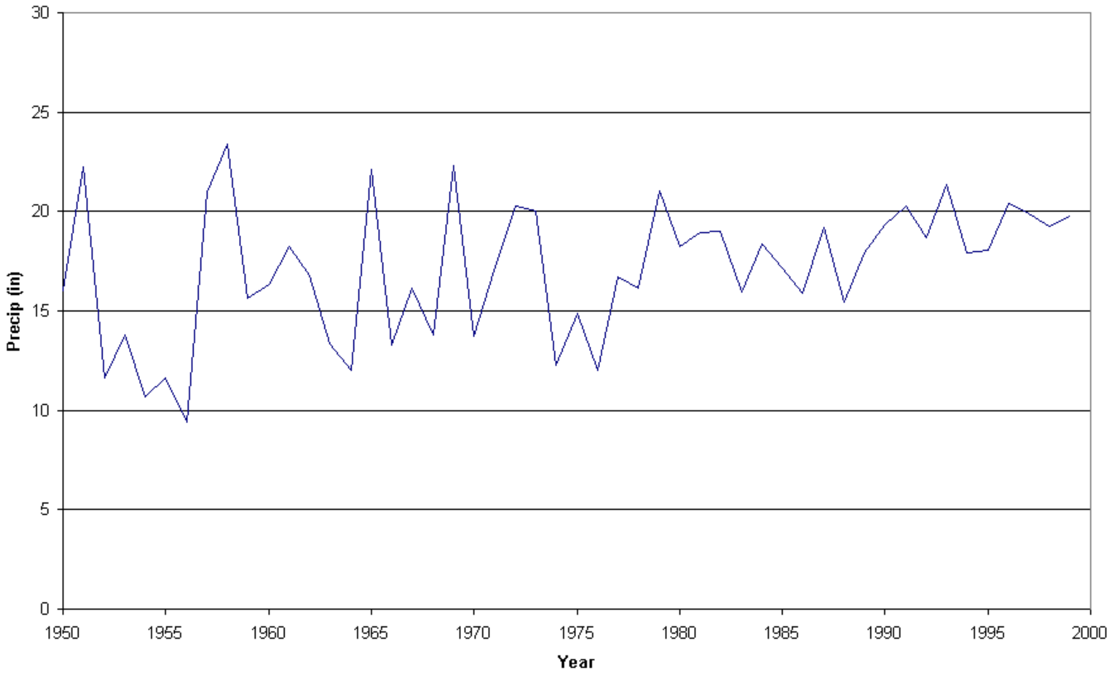
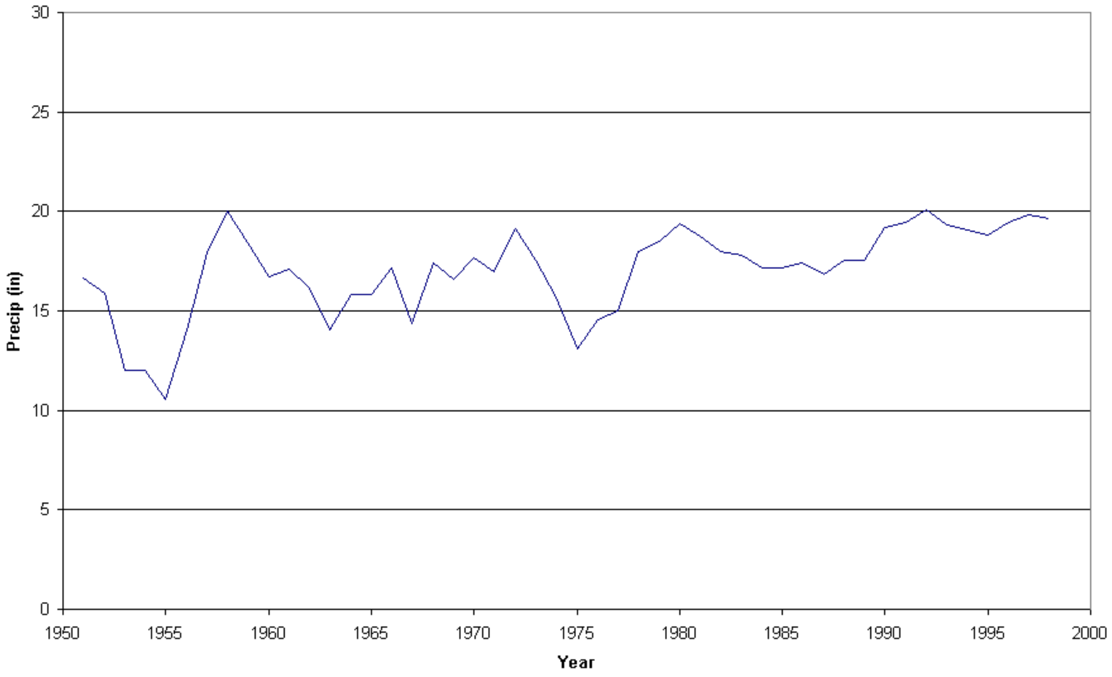

South Ogallala Annual Precipitation Half-Decade Avg (Willmott-NCDC)

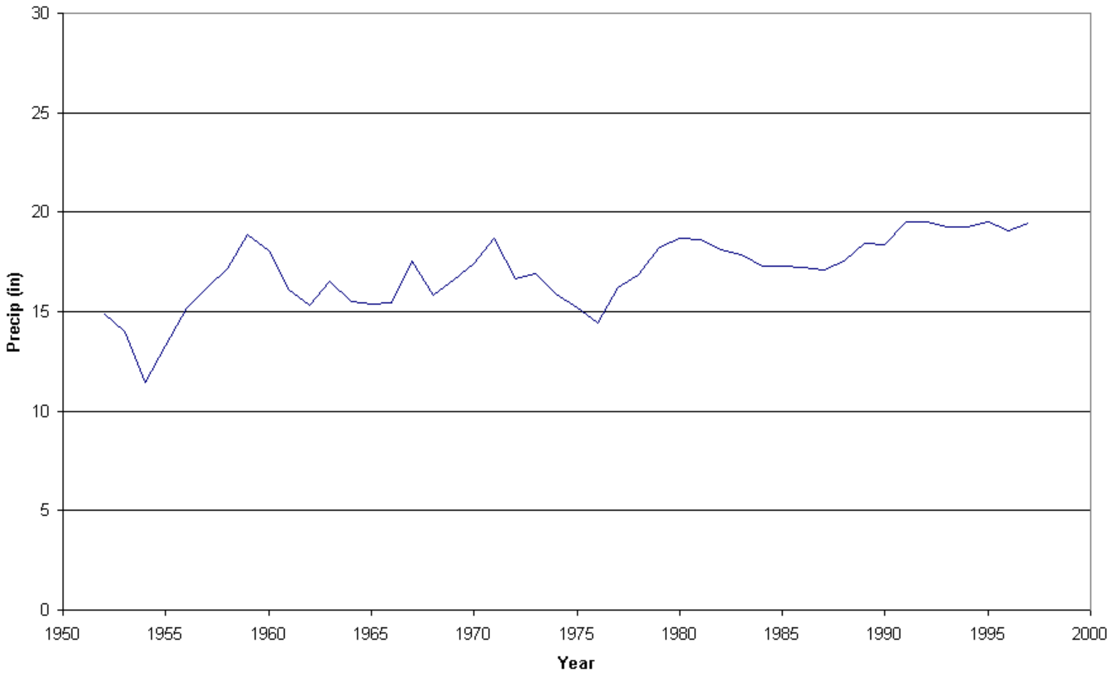
South Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)

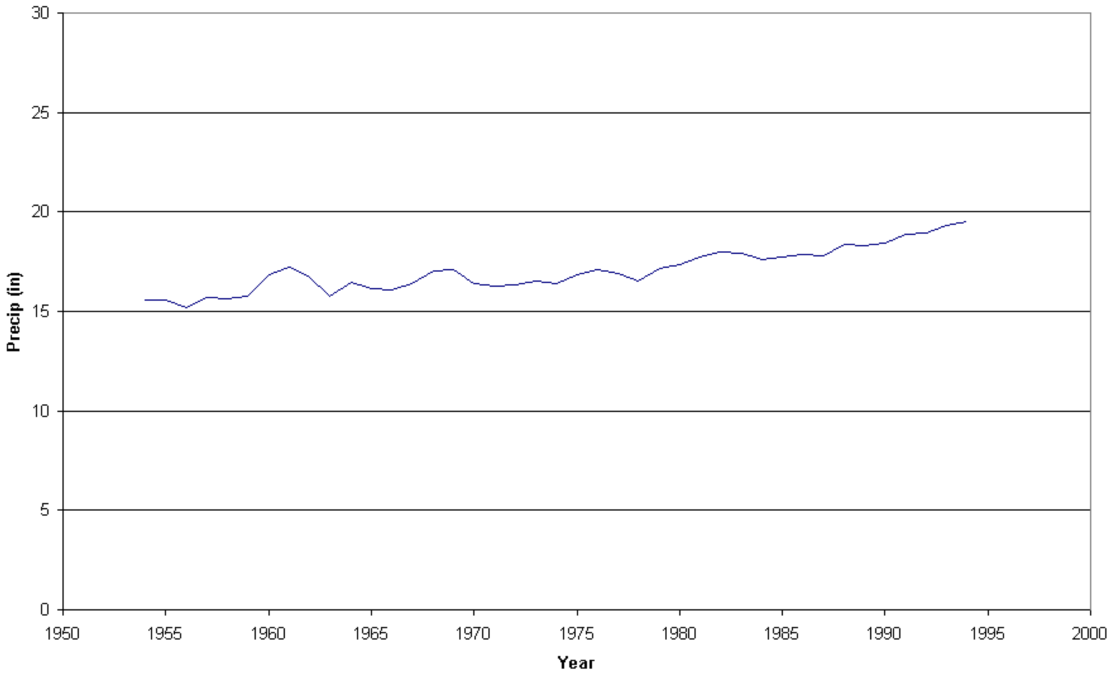


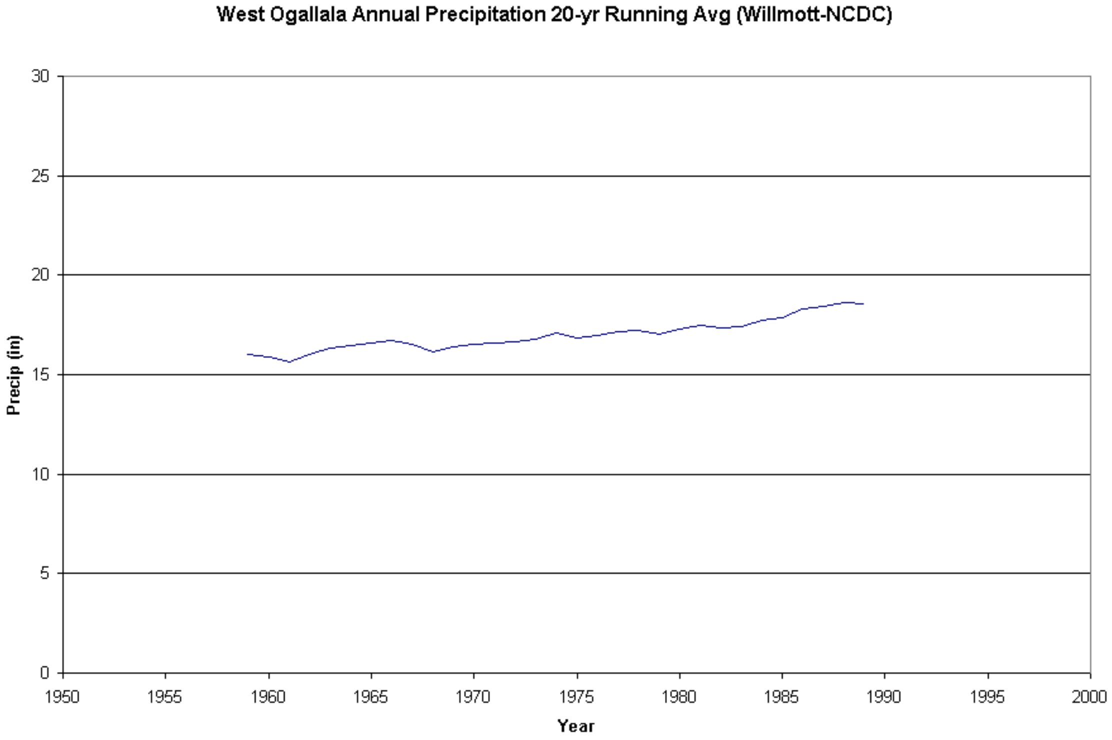
Appendix Figures 1.6. West Ogallala (Willmott-NCDC)

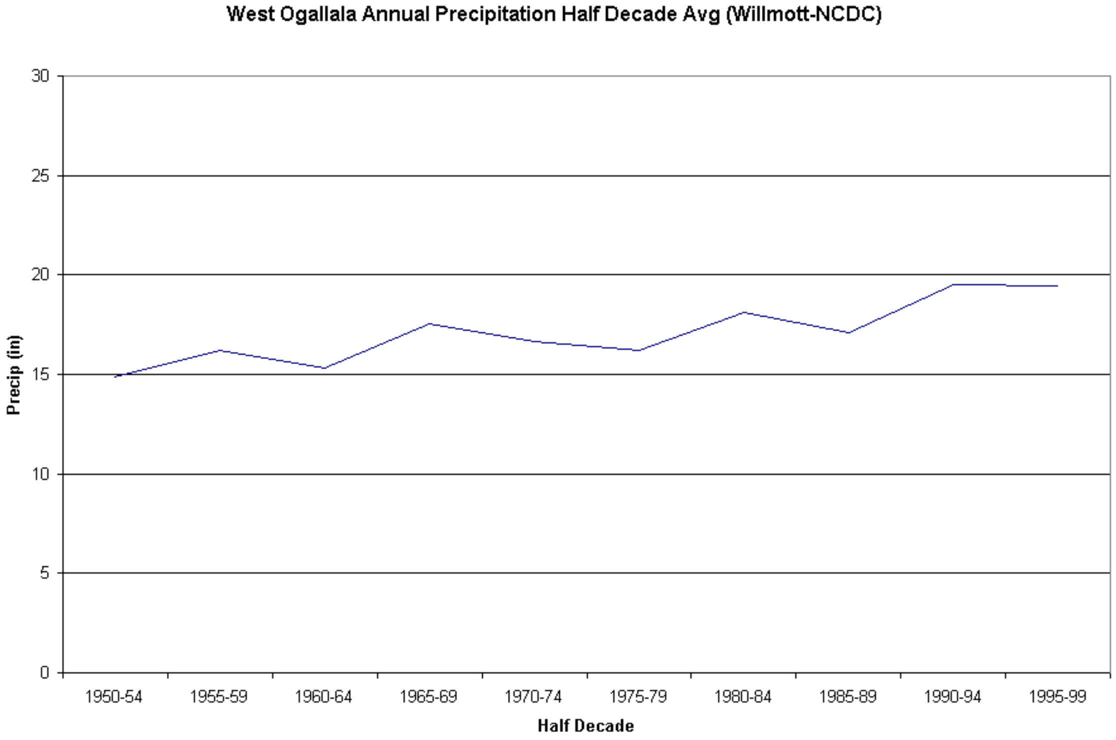

West Ogallala Annual Precipitation (Willmott-NCDC)

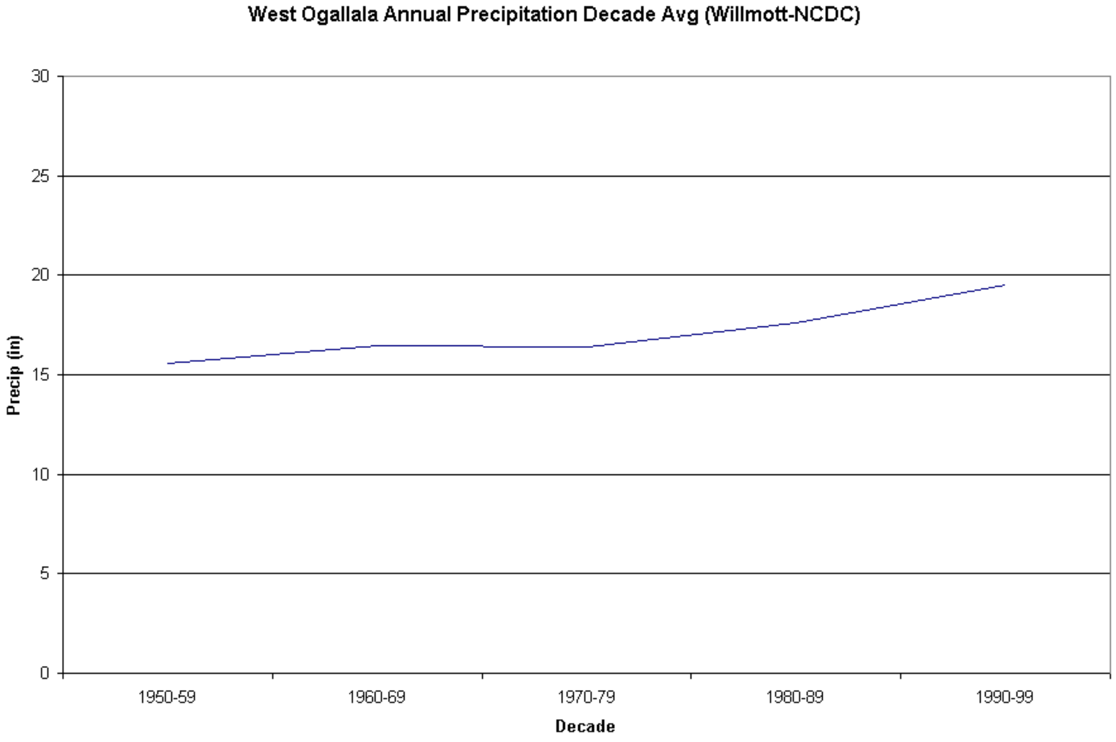

West Ogallala Annual Precipitation 3-yr Running Avg (Willmott-NCDC)


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

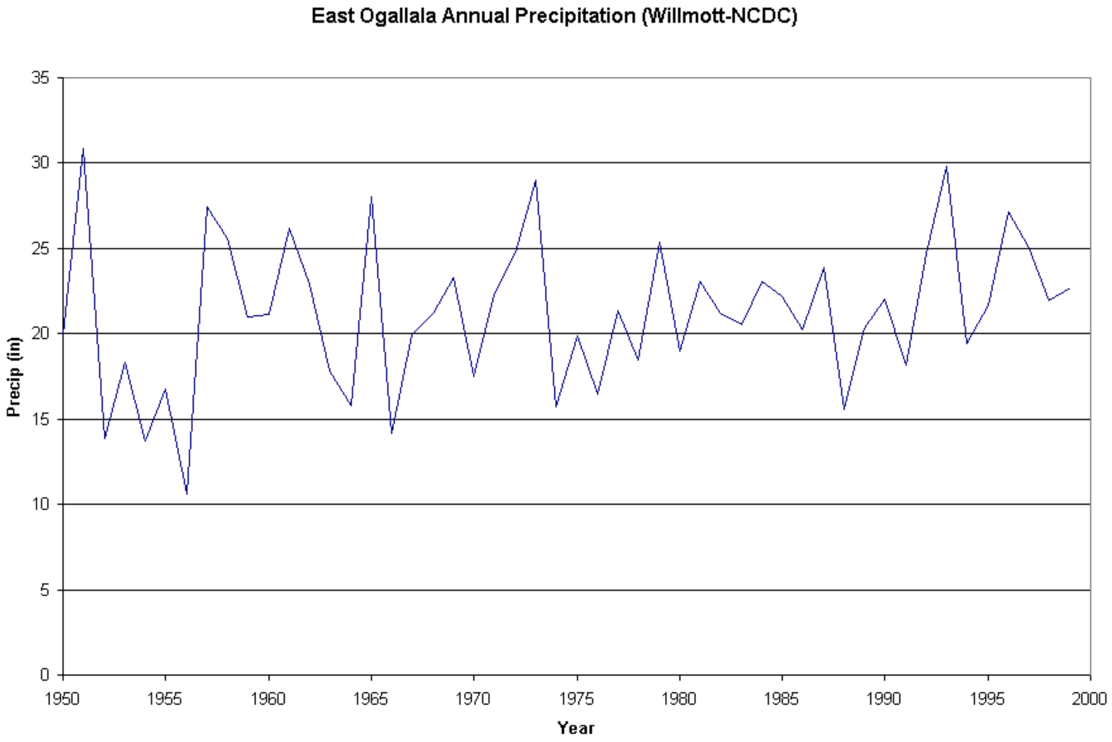

West Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)

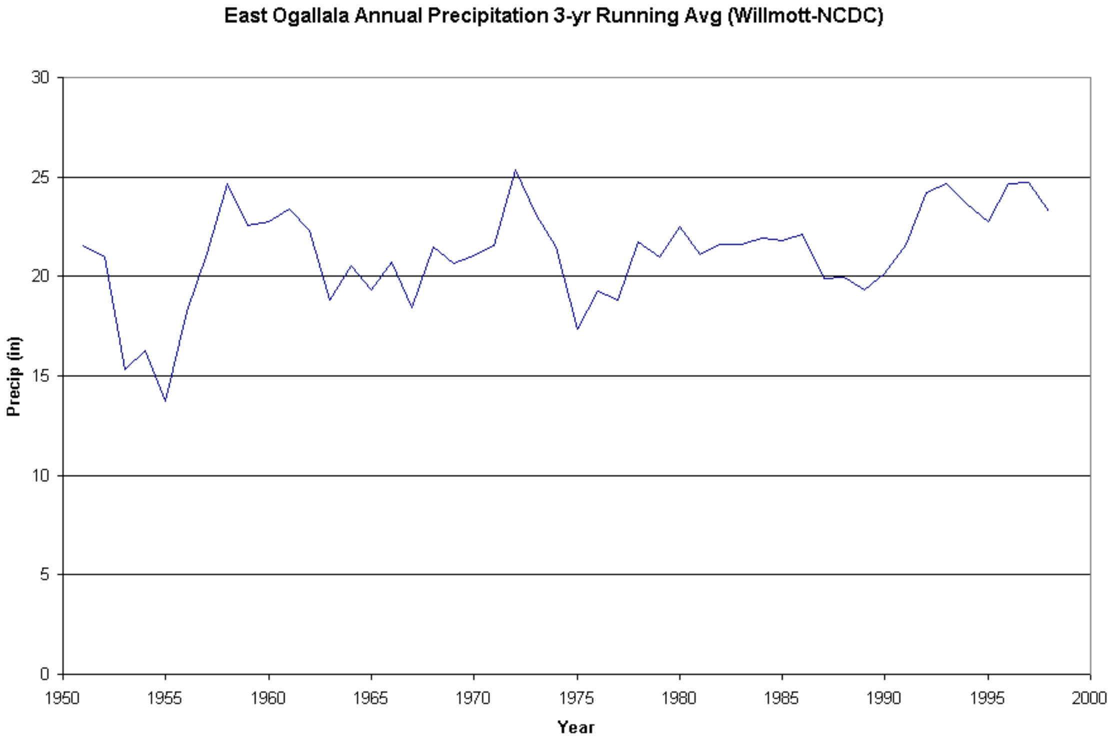

West Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year


West 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

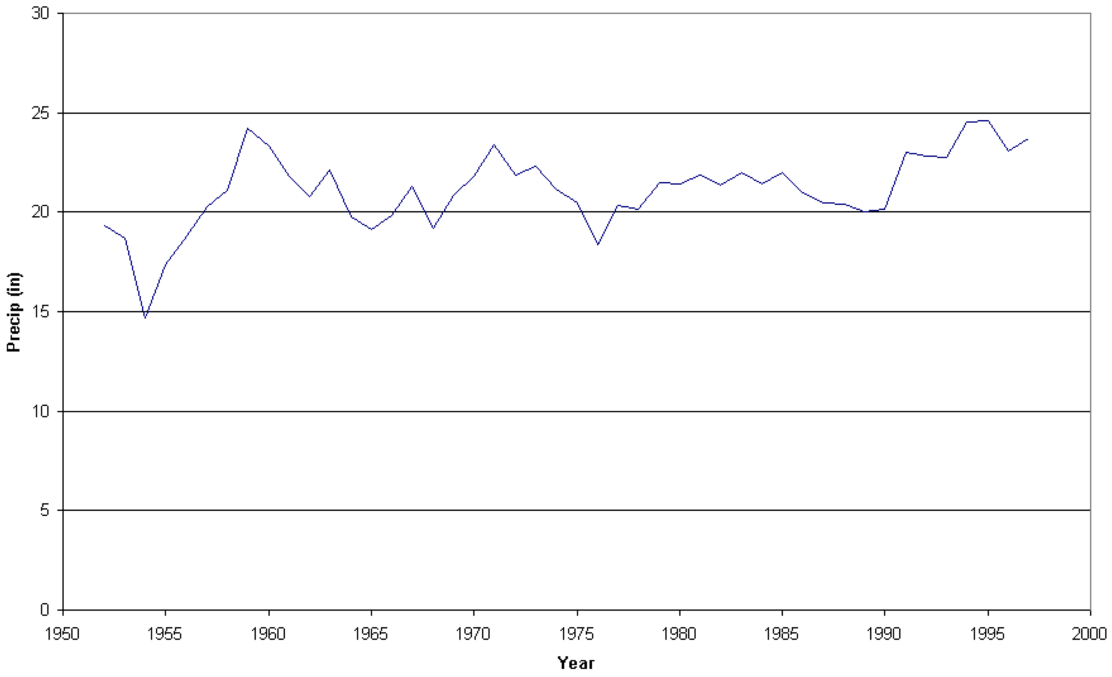

West Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)
Precip (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

Appendix Figures 1.7. East Ogallala (Willmott-NCDC)

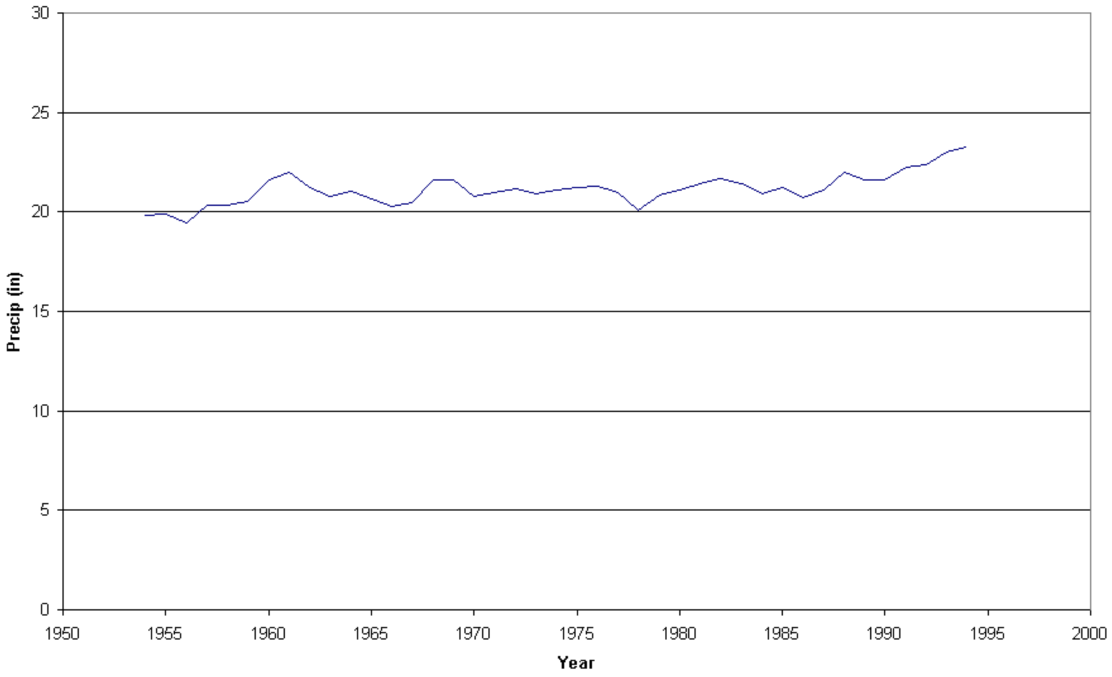




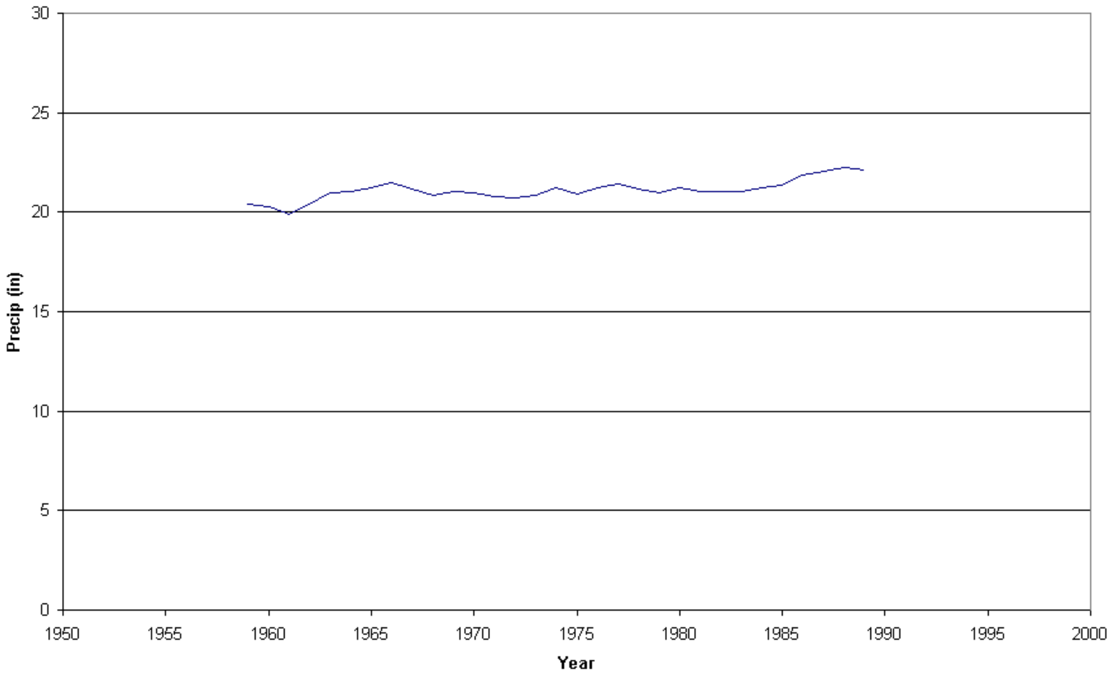
East Ogallala Annual Precipitation 5-yr Running Avg (Willmott-NCDC)



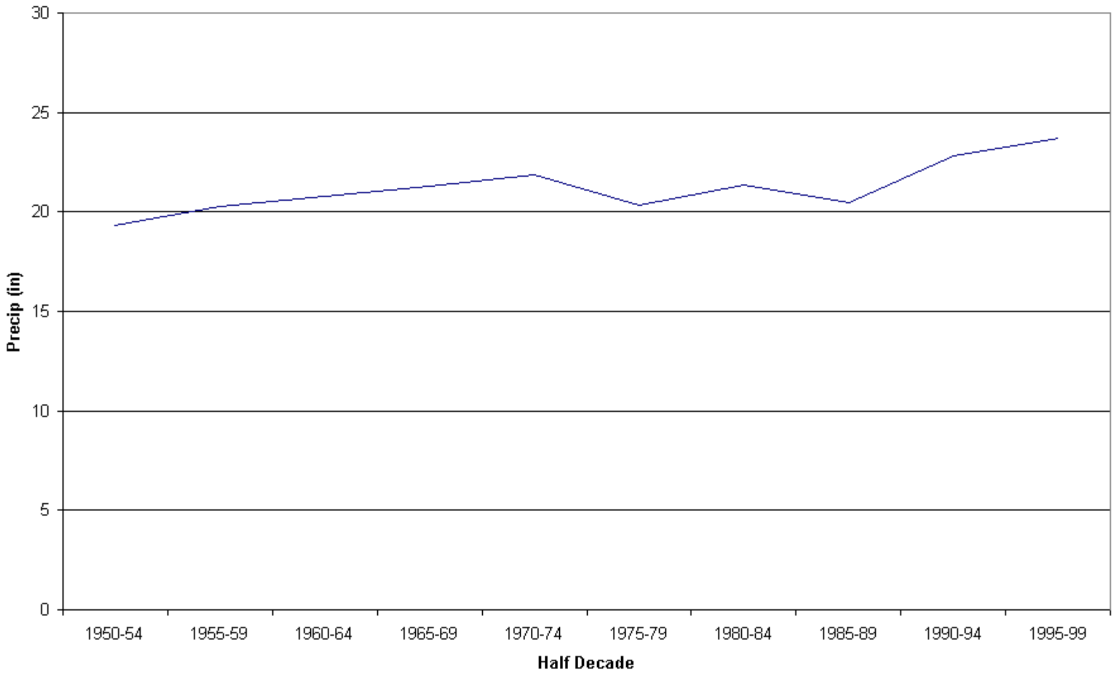
East Ogallala Annual Precipitation 10-yr Running Avg (Willmott-NCDC)



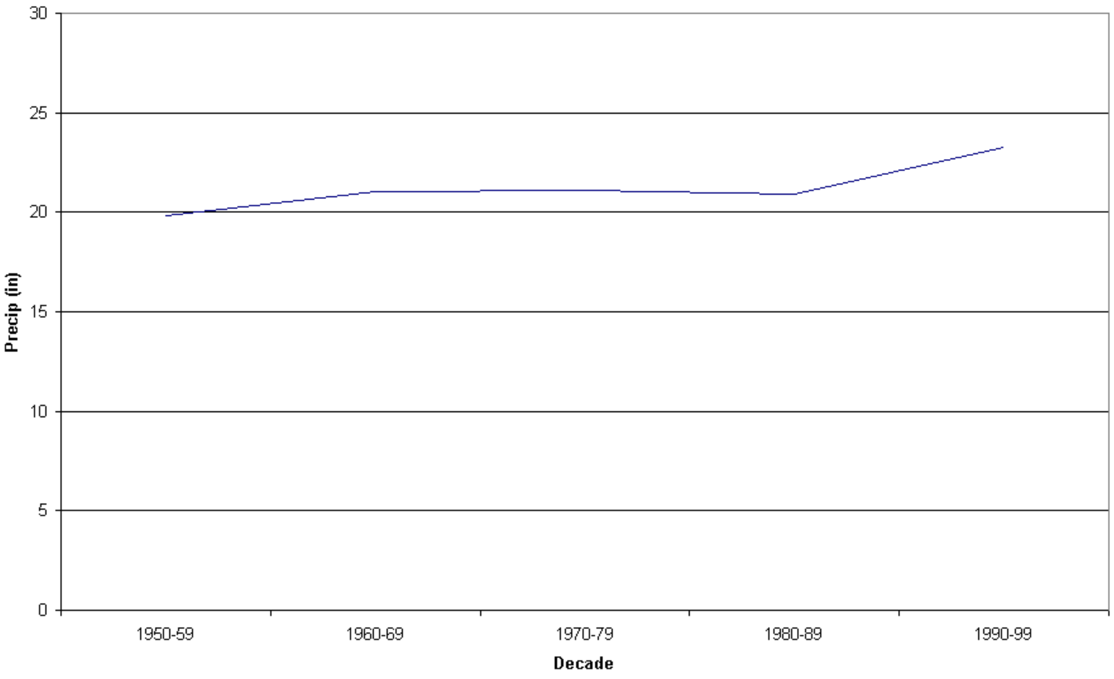
East Ogallala Annual Precipitation 20-yr Running Avg (Willmott-NCDC)



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



East Ogallala Annual Precipitation Decade Avg (Willmott-NCDC)



Appendix 2. Derived Water Balance Plots

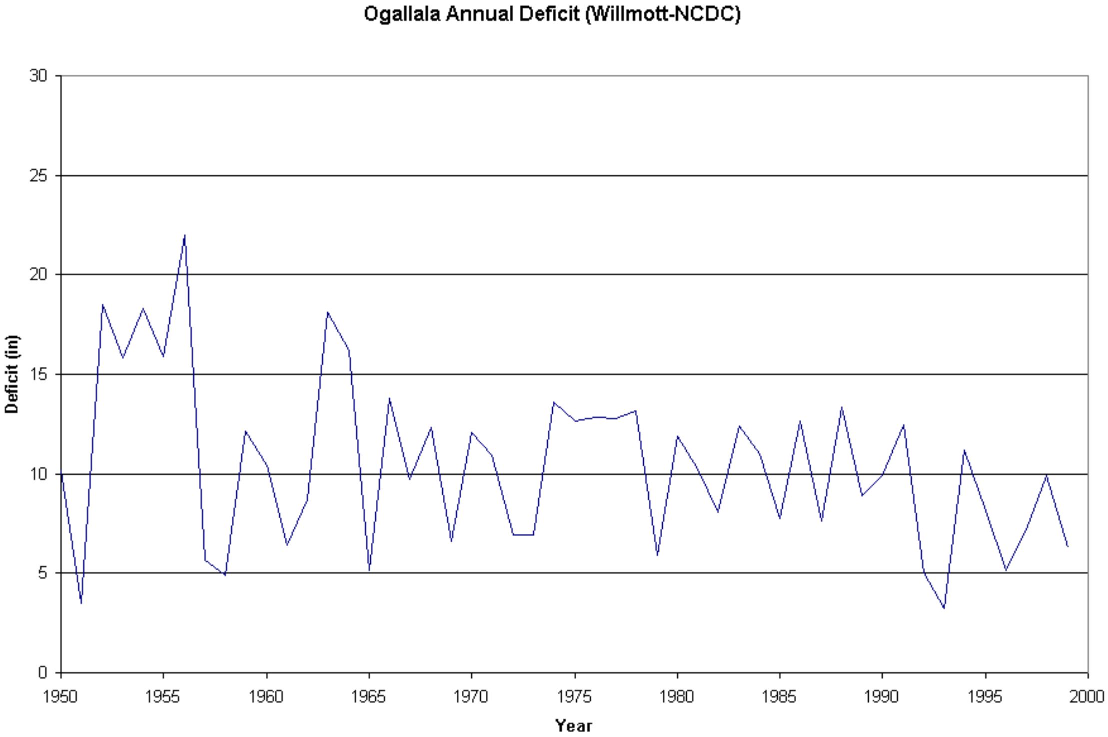
Data plotted are the regional annual averages, which are the sums of monthly values for the year of interest averaged over all the Willmott-NCDC half-degree cells in the designated region (Figure 4).

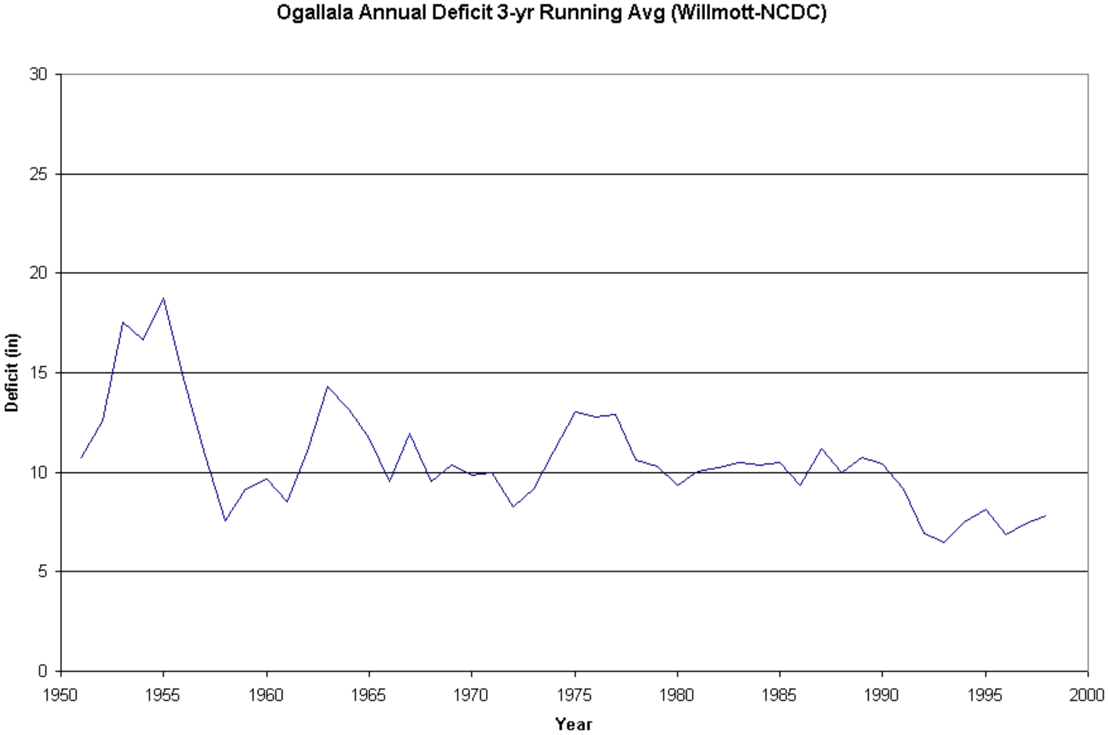
Values are plotted as individual year average totals and as running averages (also called "boxcar" averages) over 3, 5, 10, and 20 year time periods. In this presentation, the 3-year average for 1990, for example, is the average of values for 1989, 1990, and 1991. This averaging has the effect of making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

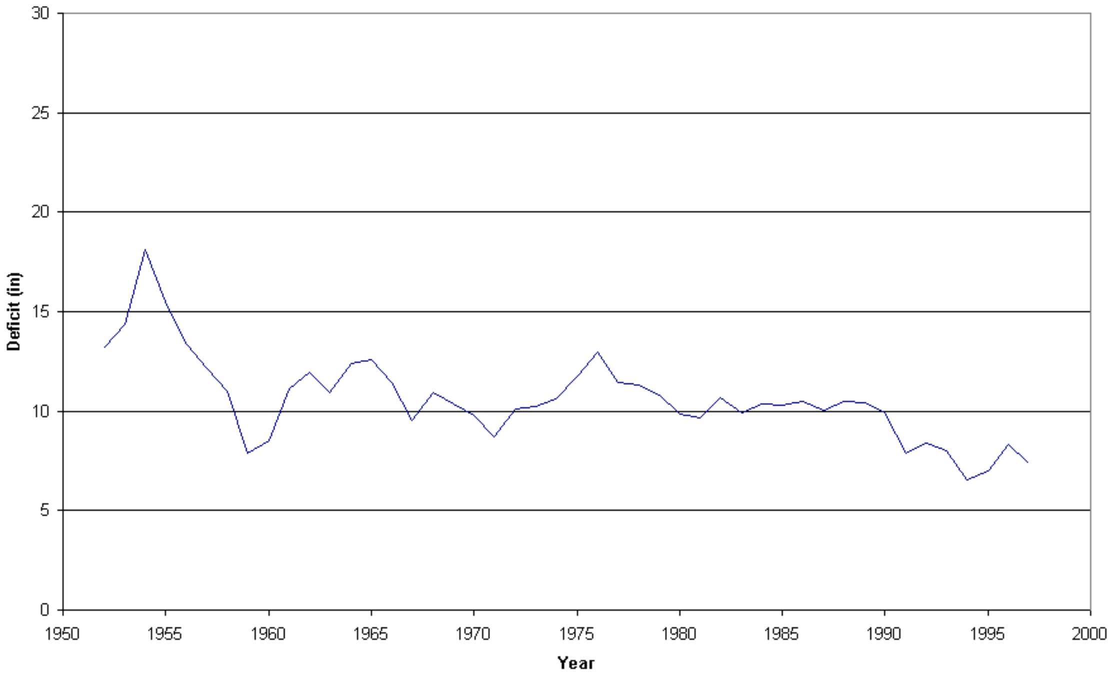
<u>Contents</u>

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

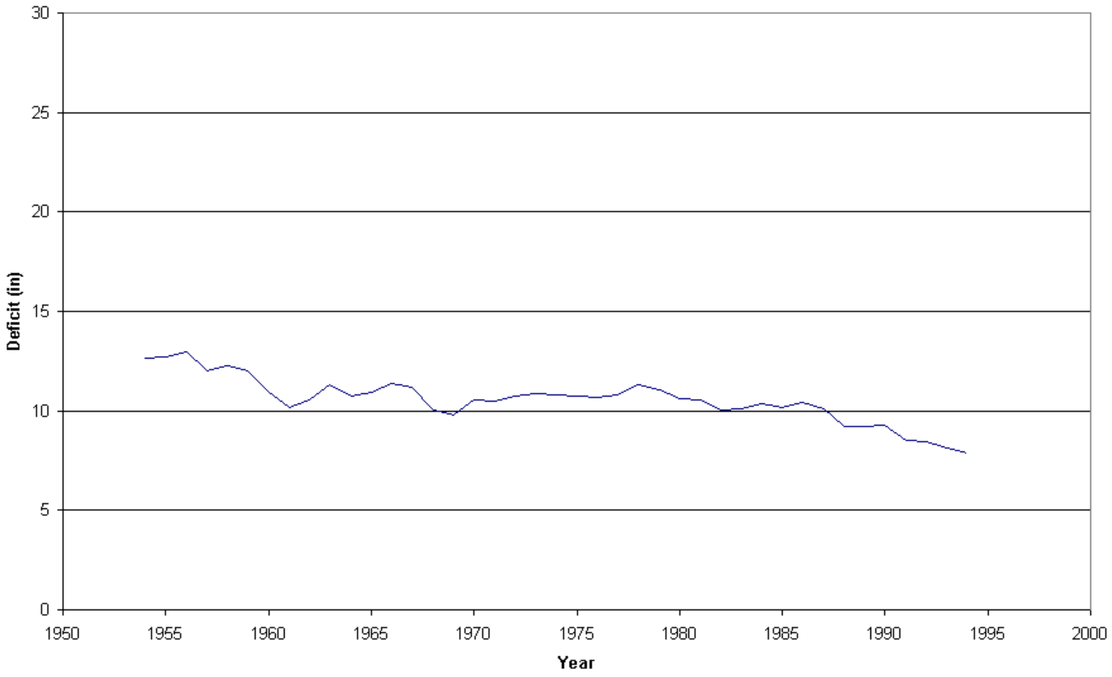


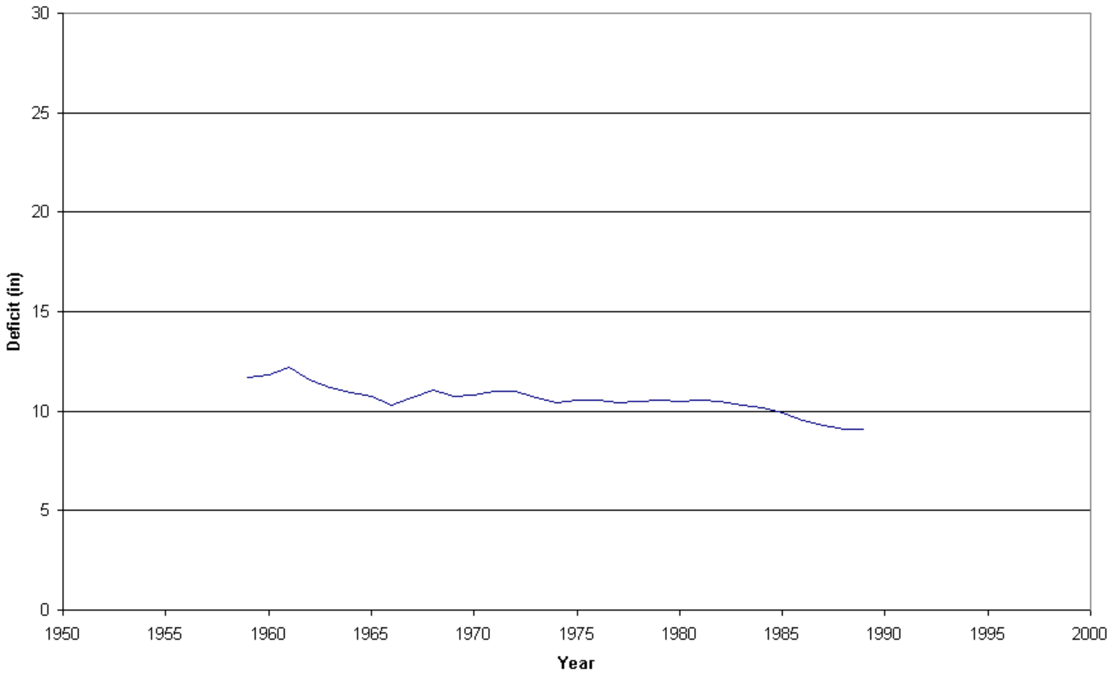


Ogallala Annual Deficit 5-yr Running Avg (Willmott-NCDC)

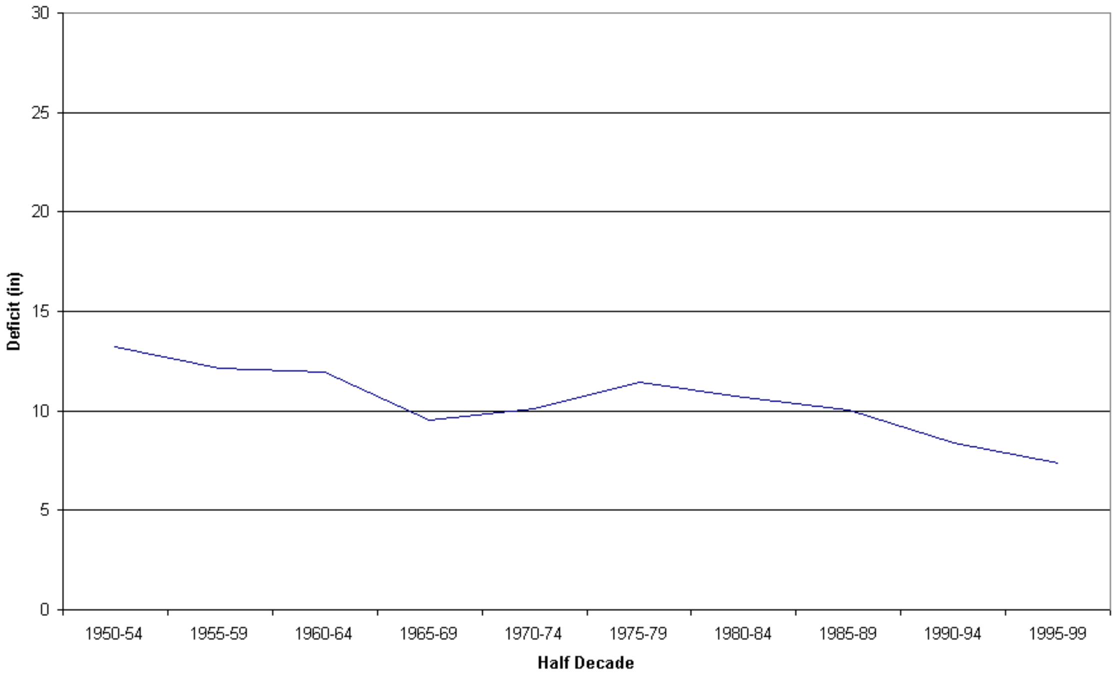


Ogallala Annual Deficit 10-yr Running Avg (Willmott-NCDC)

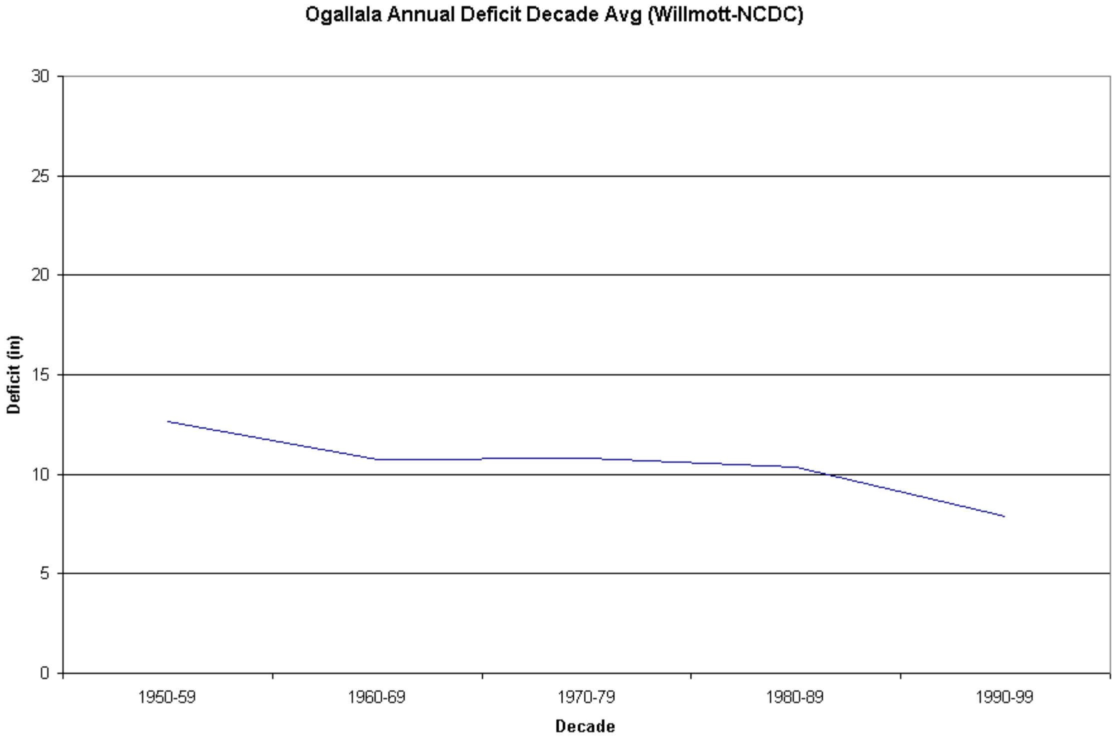




Ogallala Annual Deficit 20-yr Running Avg (Willmott-NCDC)

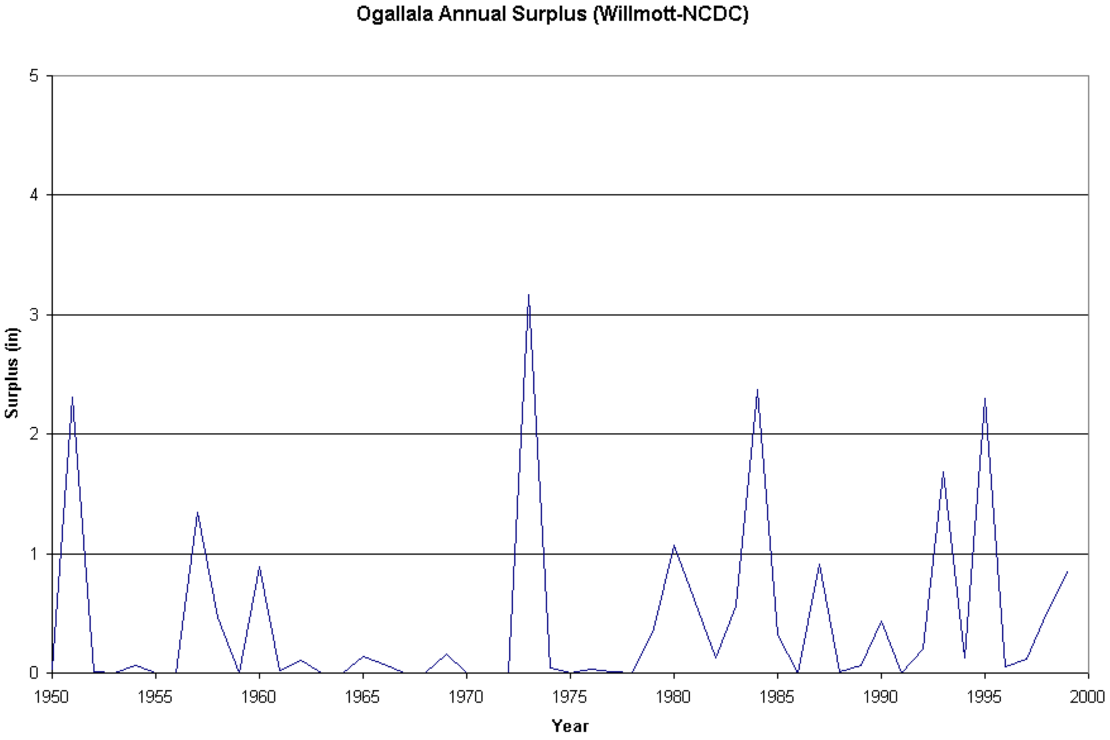


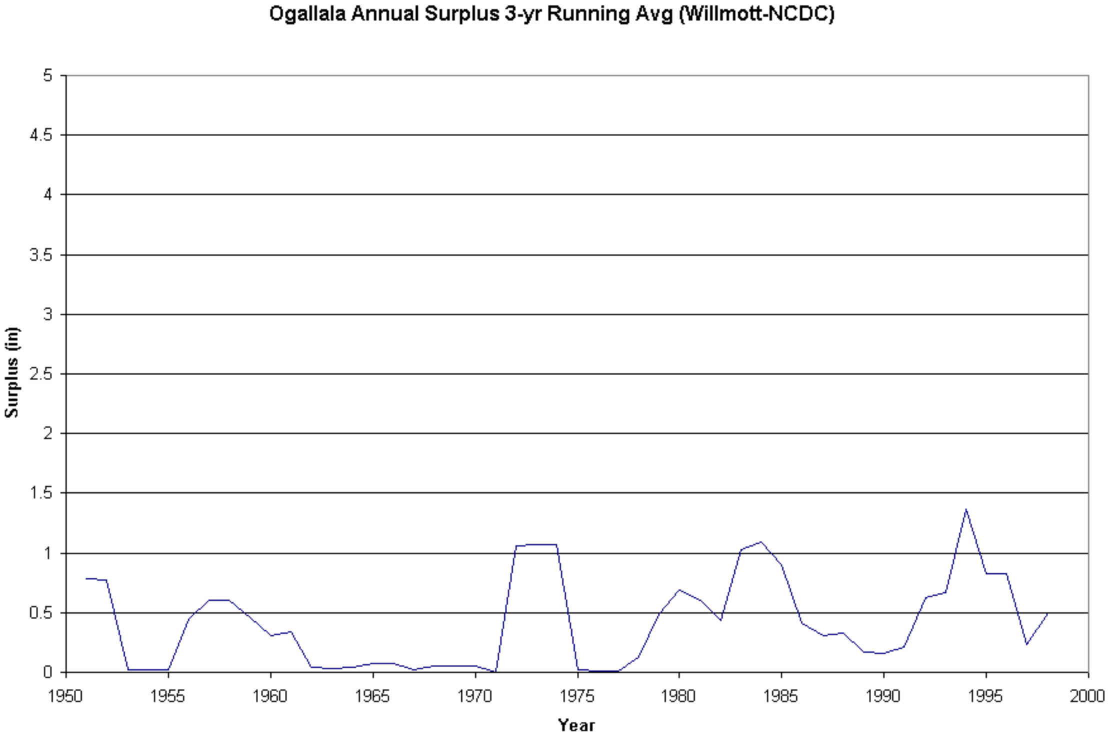
Ogallala Annual Deficit Half-Decade Avg (Willmott-NCDC)



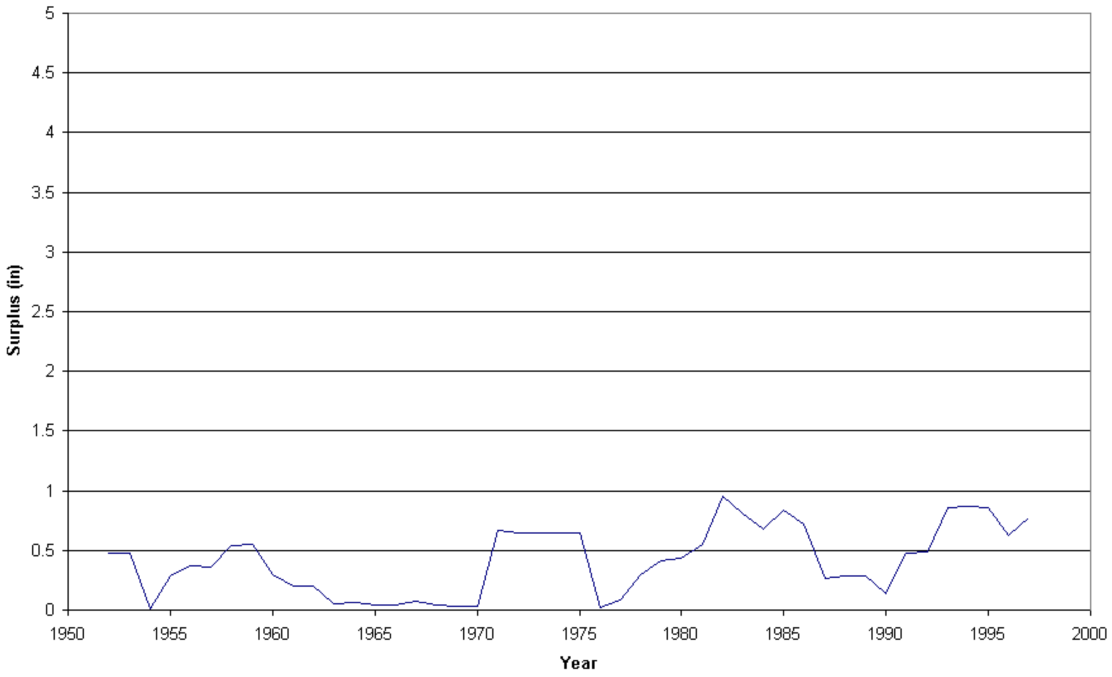
Ogallala Annual Deficit Decade Avg (Willmott-NCDC)
Deficit (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

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

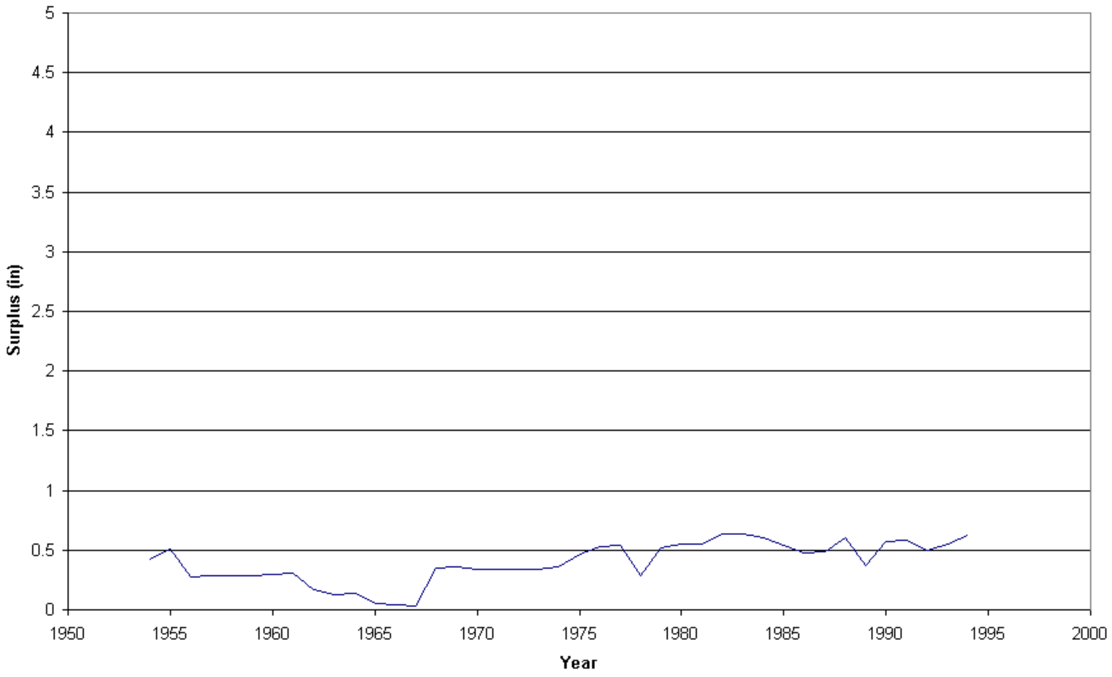


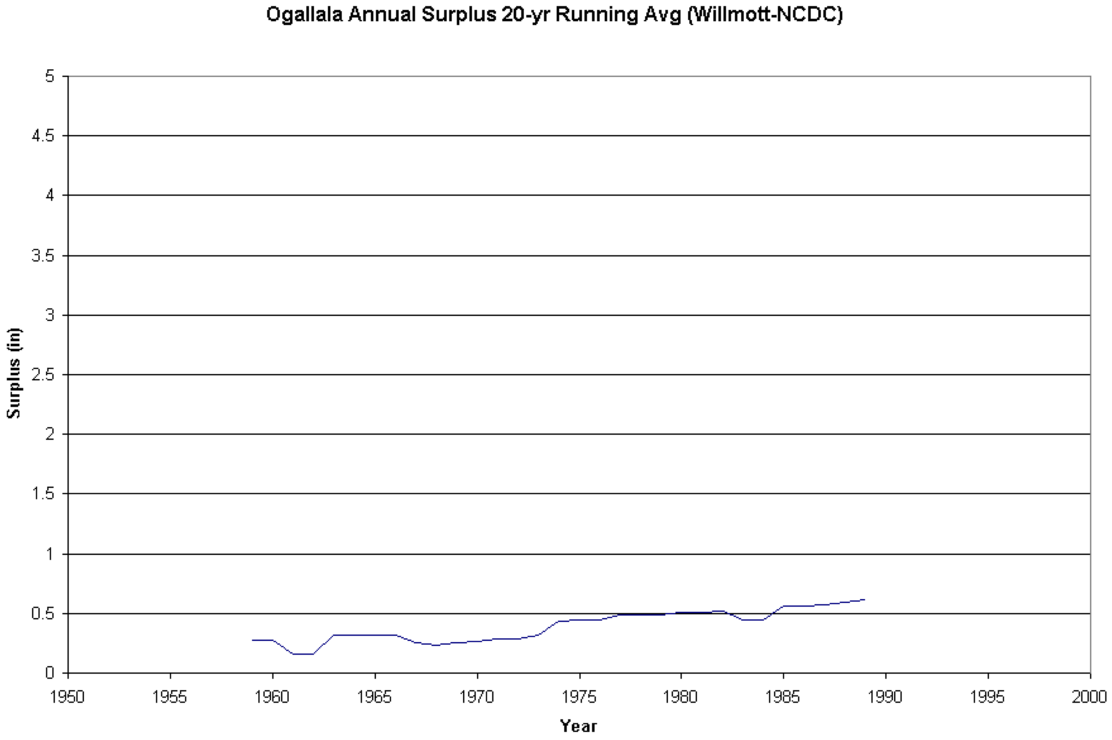


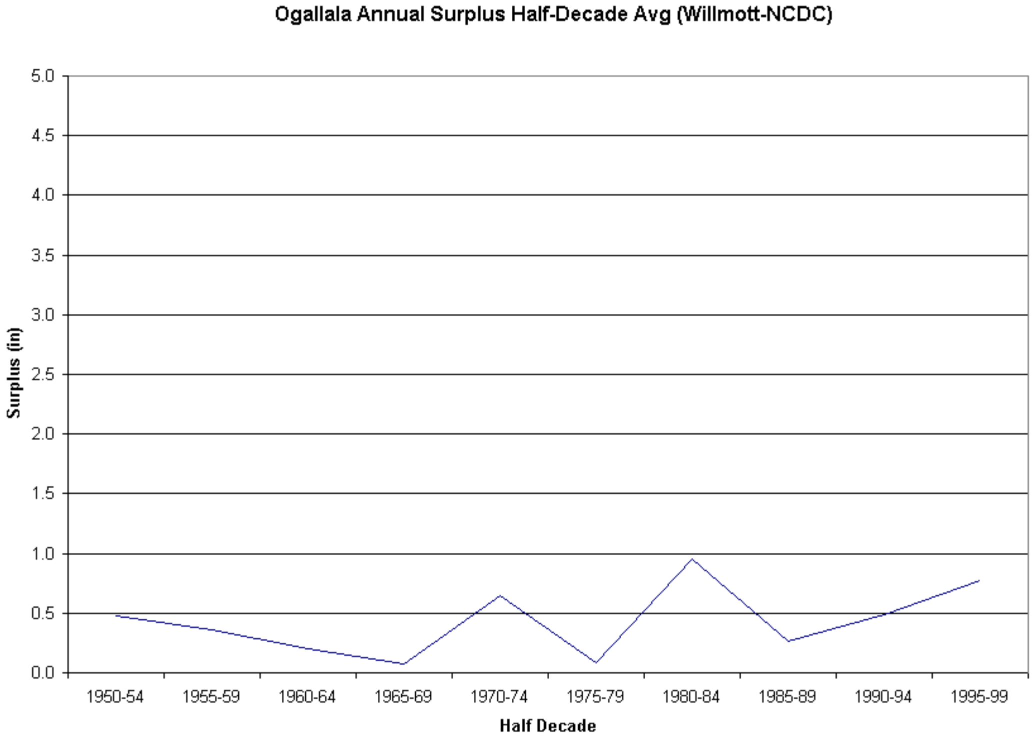
Ogallala Annual Surplus 5-yr Running Avg (Willmott-NCDC)

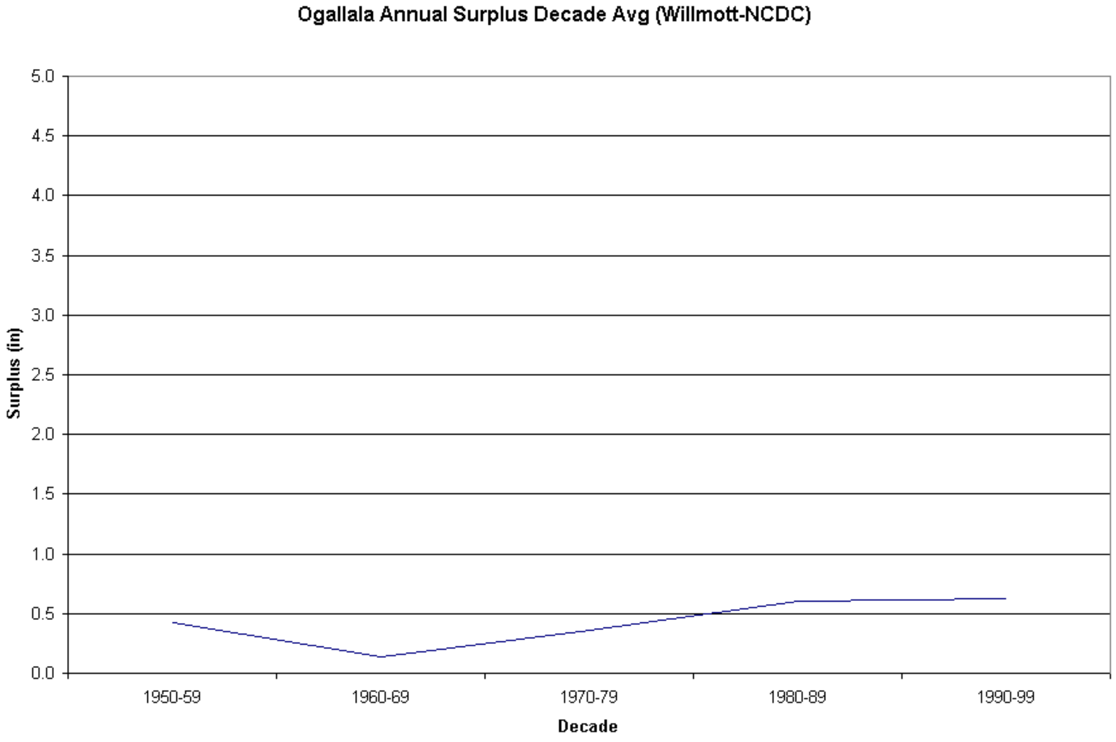


Ogallala Annual Surplus 10-yr Running Avg (Willmott-NCDC)

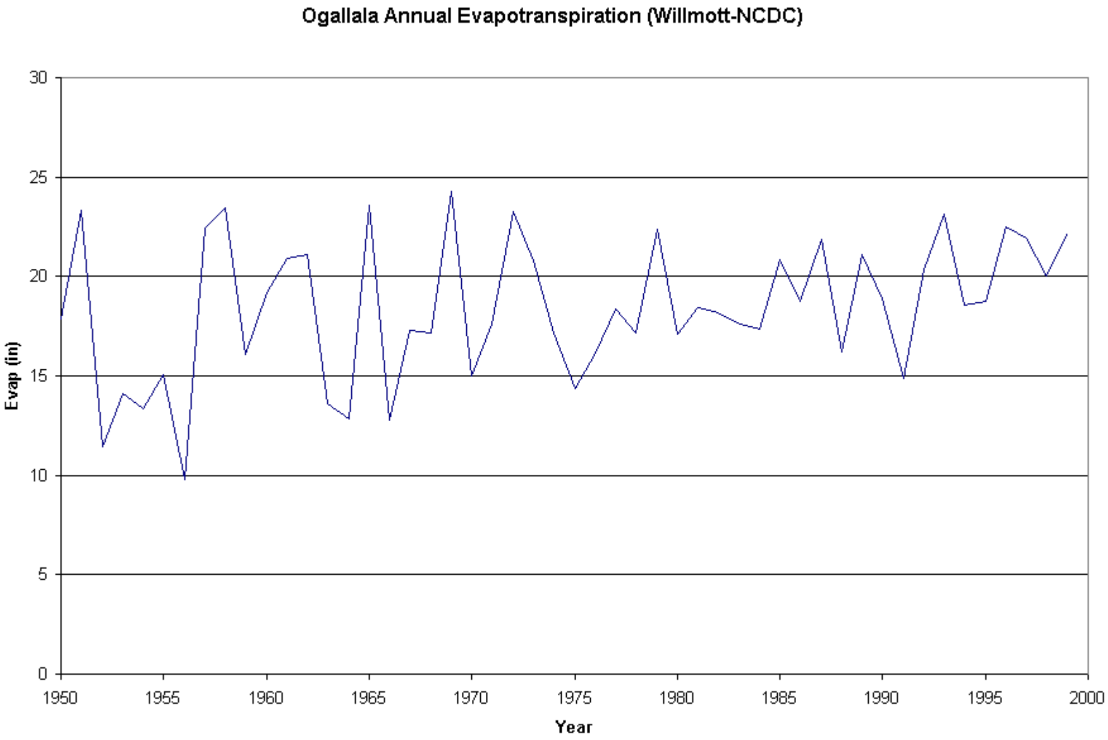


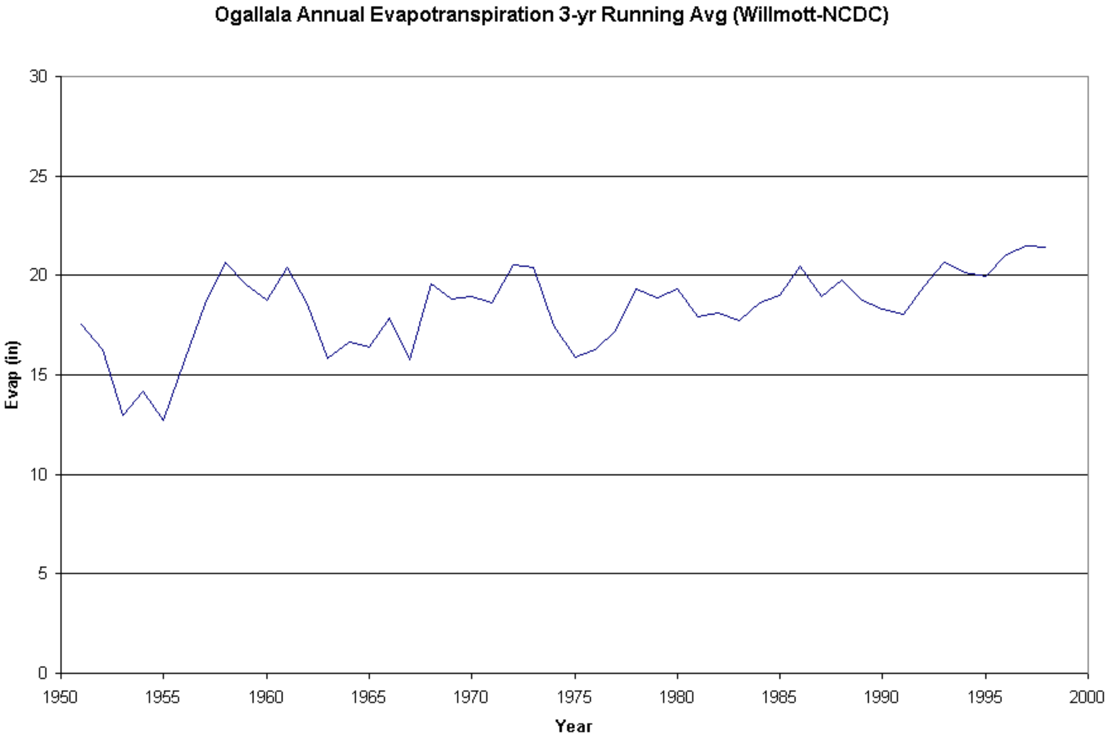

Ogallala Annual Surplus 20-yr Running Avg (Willmott-NCDC)
Surplus (in)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year


Ogallala Annual Surplus Half-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
1950-54
1955-59
1960-64
1965-69
1970-74
1975-79
1980-84
1985-89
1990-94
1995-99
Half Decade


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

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





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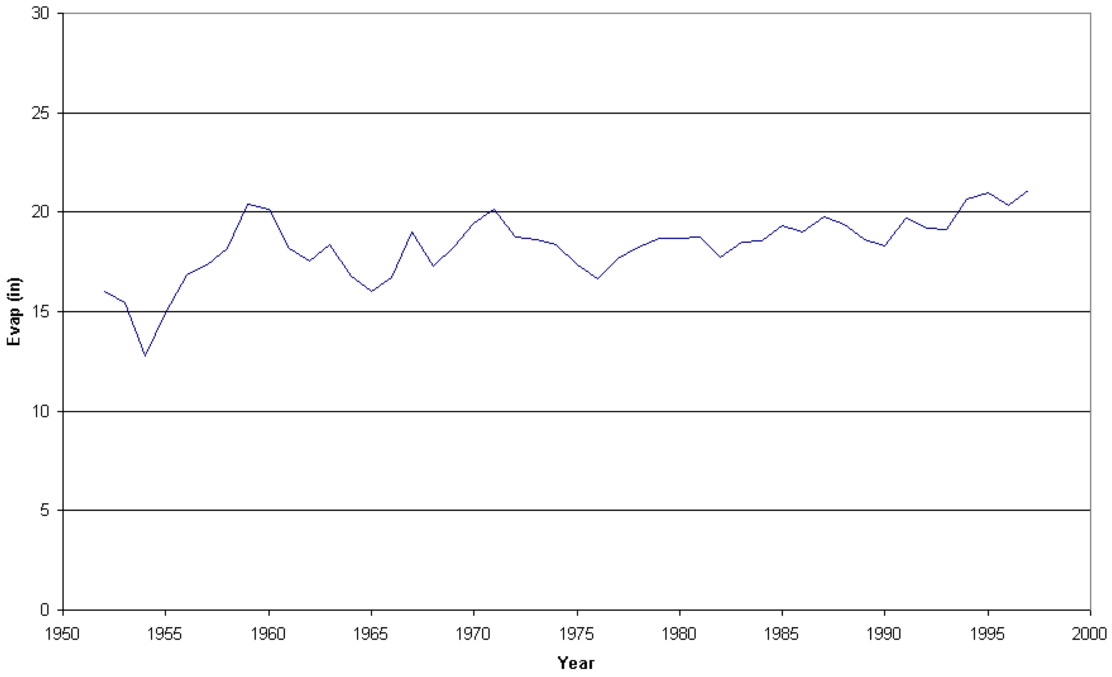
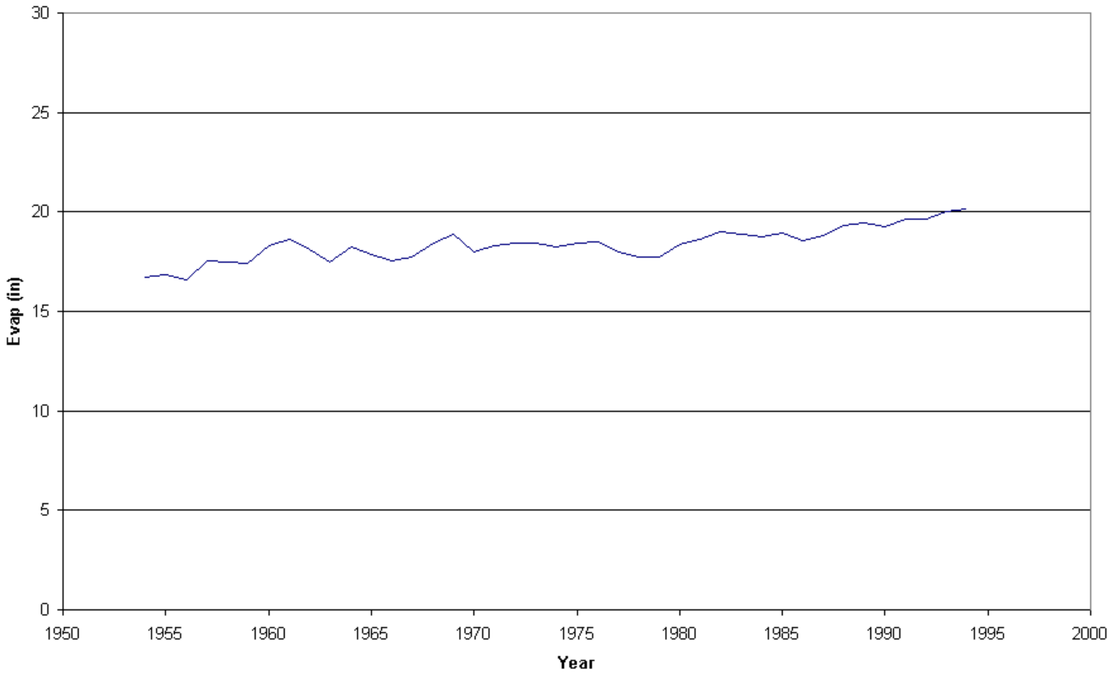
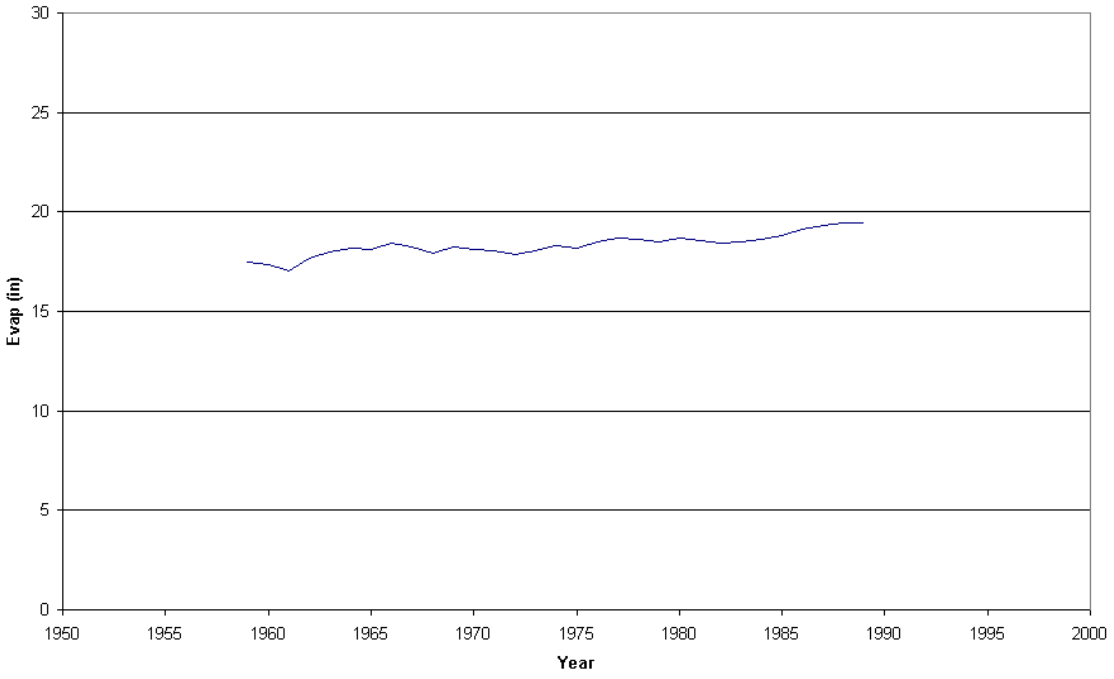
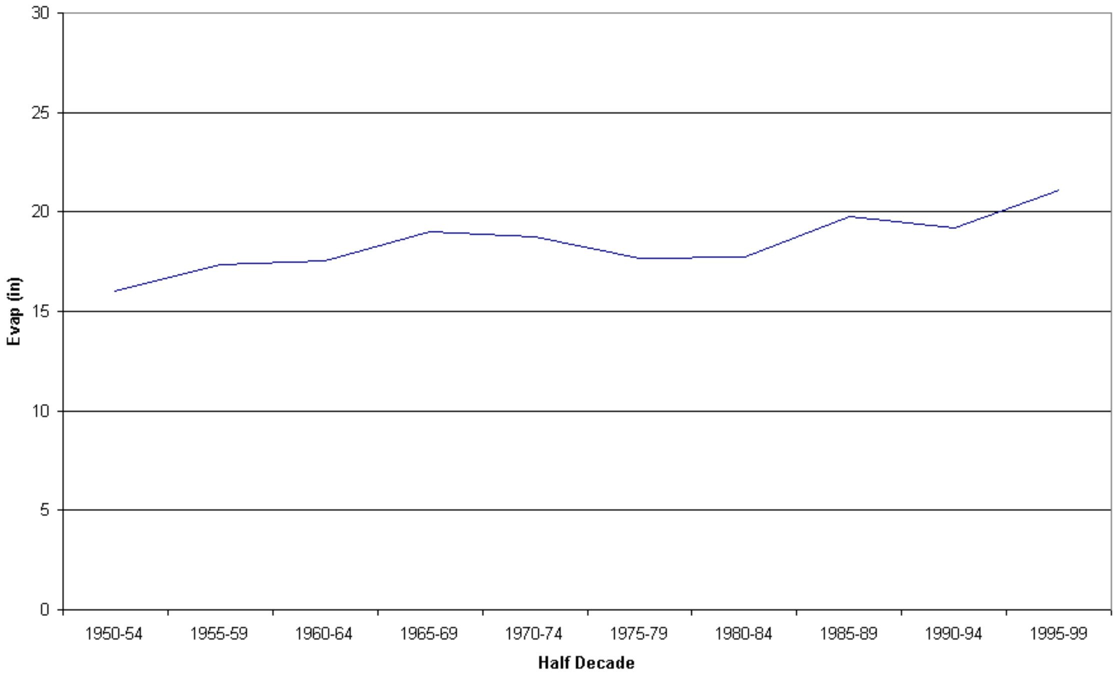
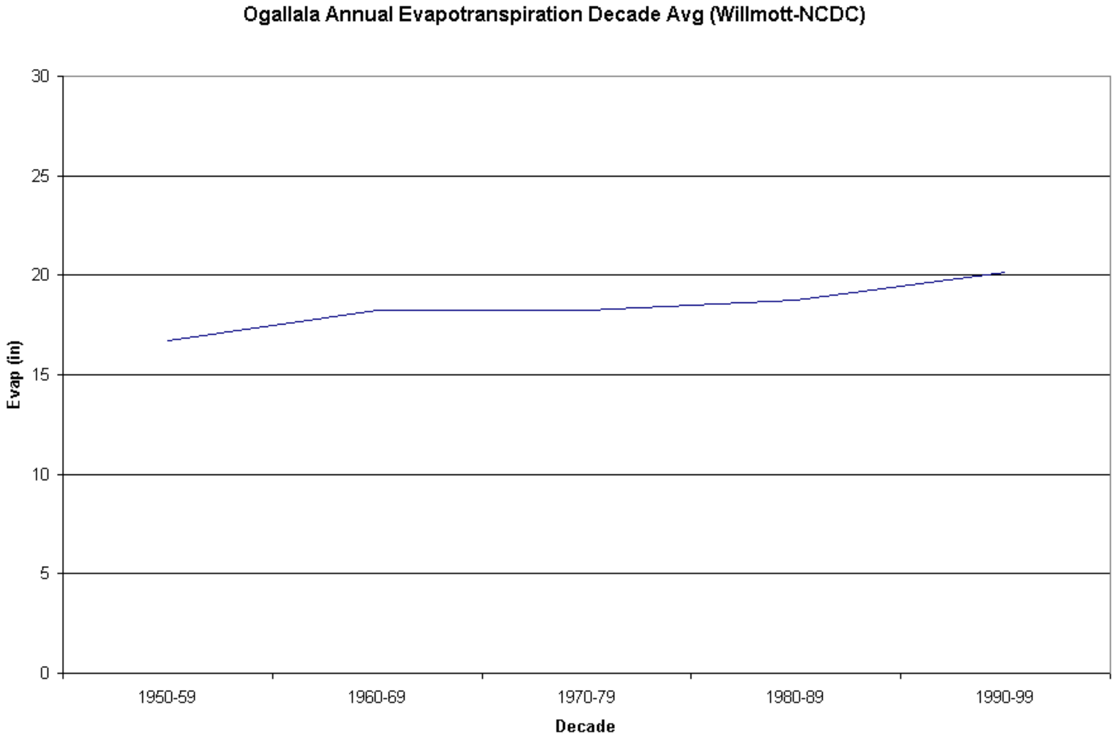


Ogallala Annual Evapotranspiration 10-yr Running Avg (Willmott-NCDC)

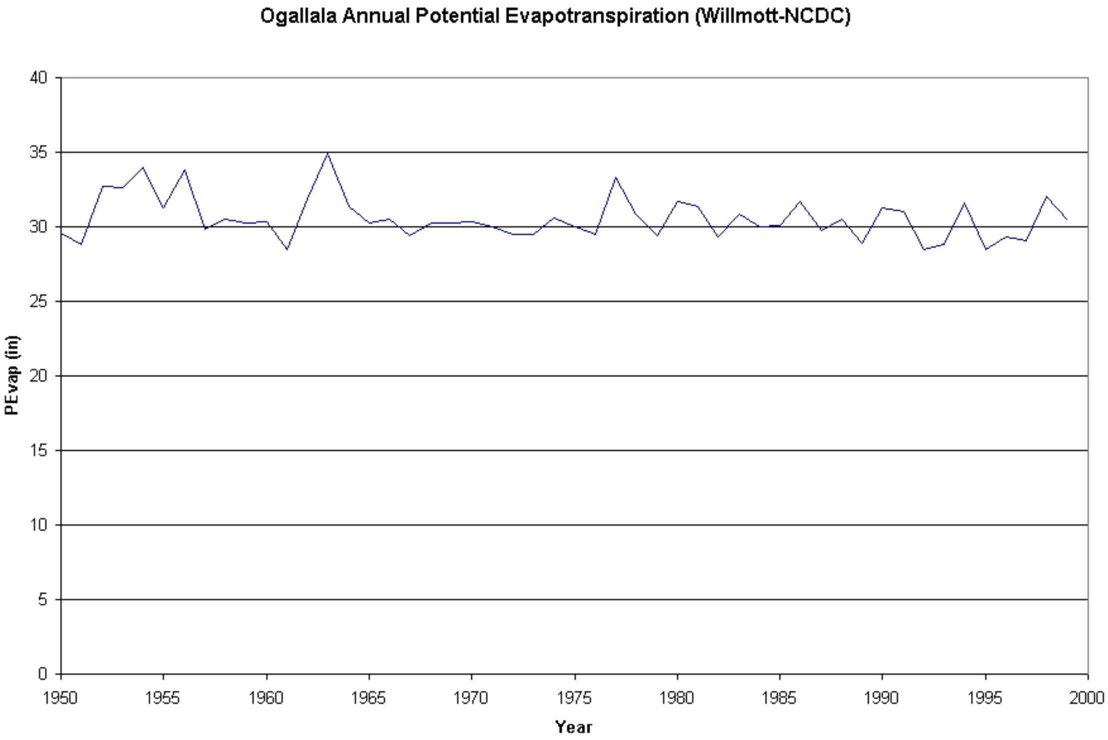


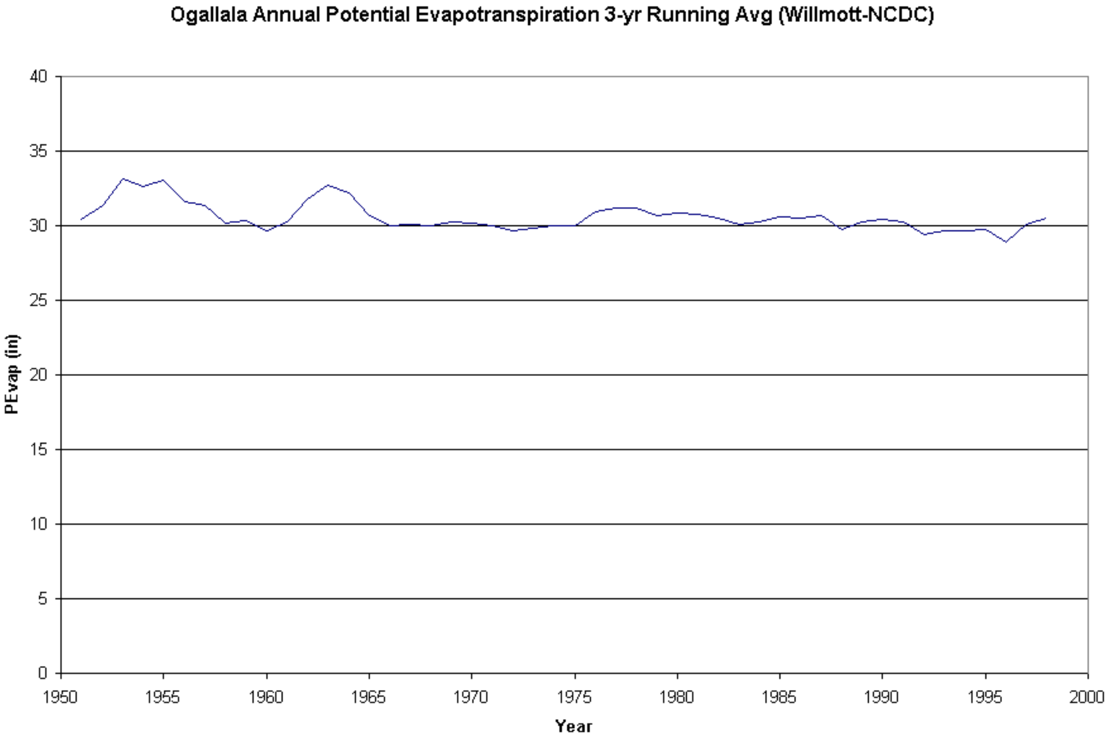

Ogallala Annual Evapotranspiration 20-yr Running Avg (Willmott-NCDC)


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

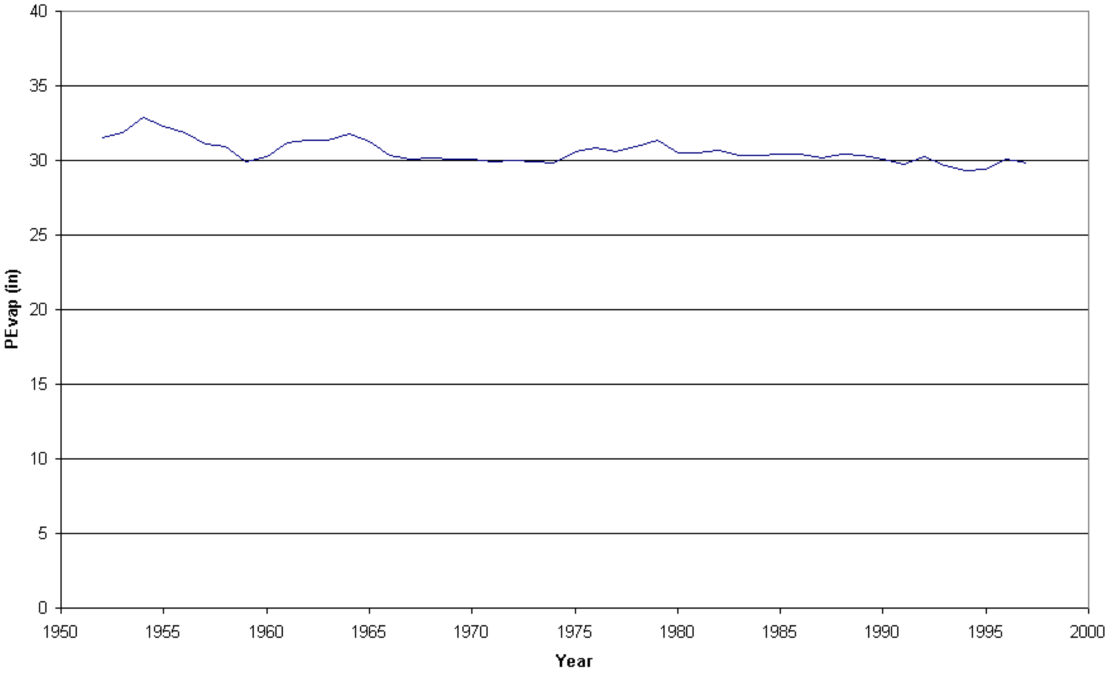

Ogallala Annual Evapotranspiration Decade Avg (Willmott-NCDC)
Evap (in)
30
25
20
15
10
5
0
1950-59
1960-69
1970-79
1980-89
1990-99
Decade

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

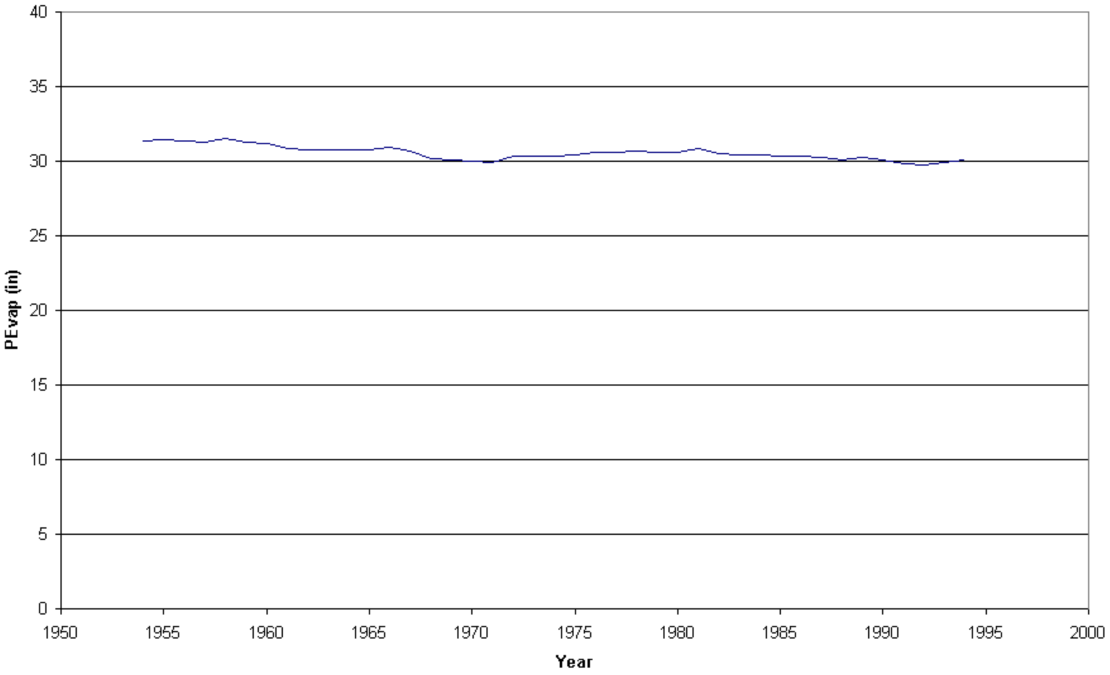




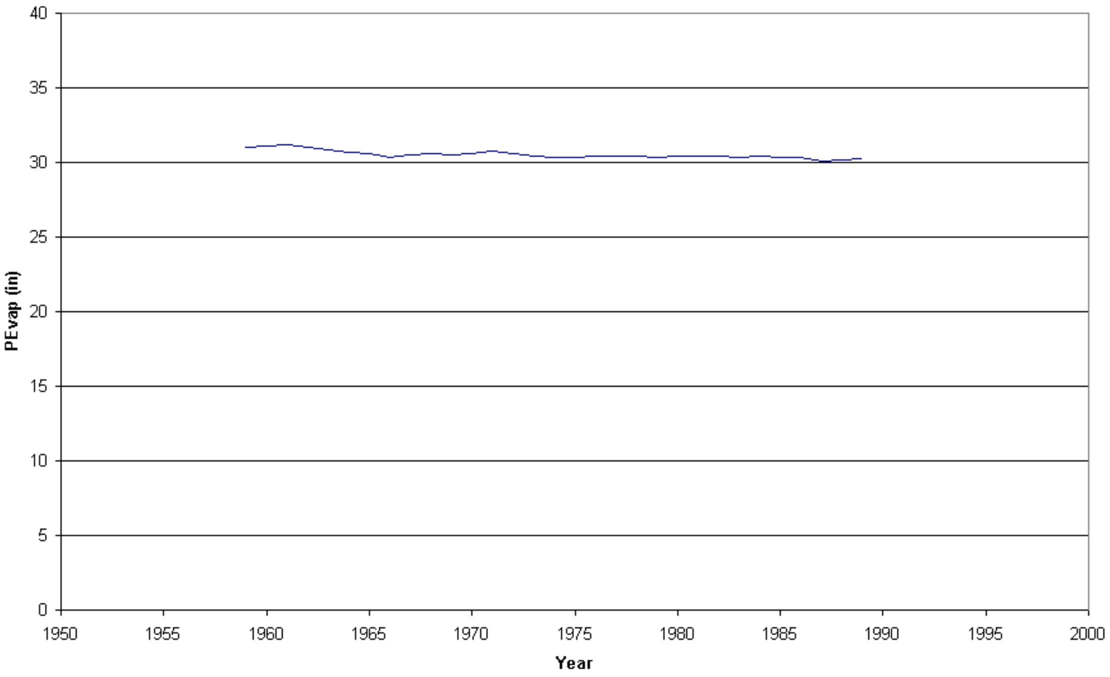
Ogallala Annual Potential Evapotranspiration 5-yr Running Avg (Willmott-NCDC)



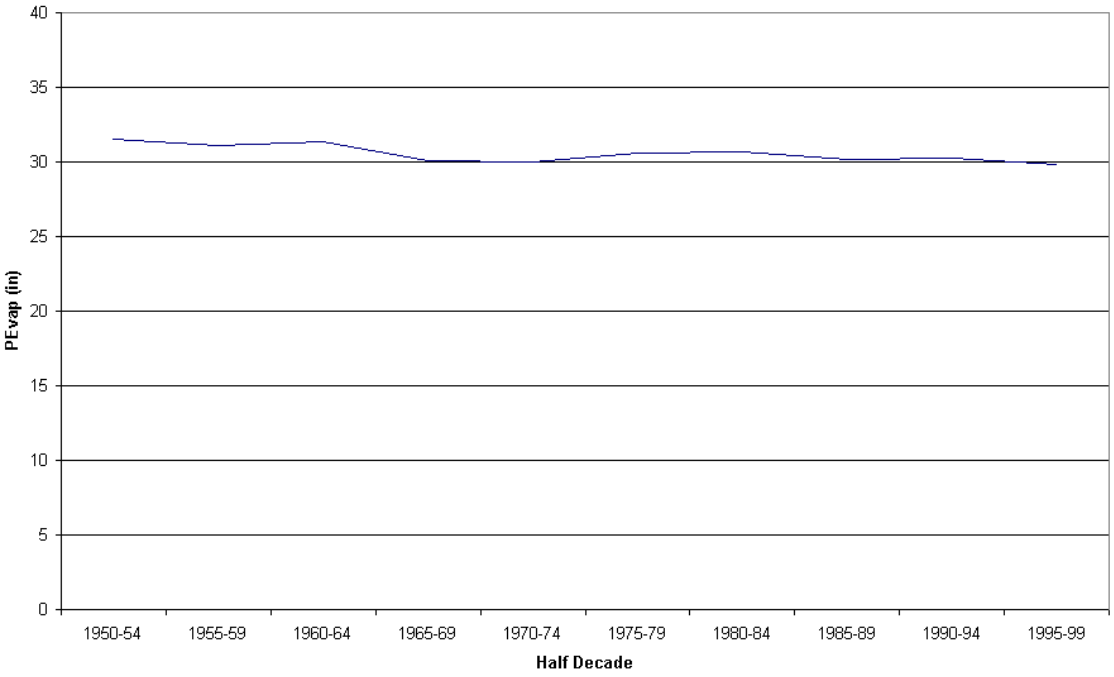
Ogallala Annual Potential Evapotranspiration 10-yr Running Avg (Willmott-NCDC)

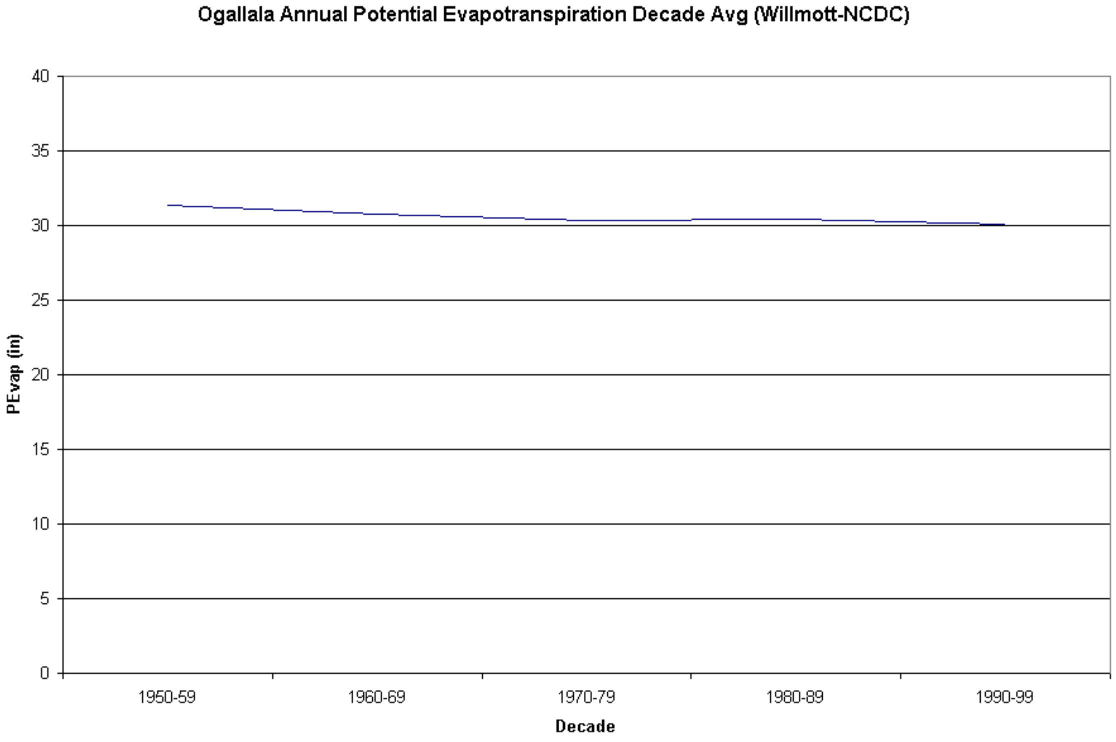


Ogallala Annual Potential Evapotranspiration 20-yr Running Avg (Willmott-NCDC)



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




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

Kansas Geological Survey

Open File Report 2002-25F

Scale, uncertainty, and the relationships between basic data, information, and management perspectives

By

R. W. Buddemeier, B. B. Wilson, J. Mosteller, and G. R. Hecox

With contributions from other authors in the report series

A component of the Technical Report series 2002-25: Technical Support for Ogallala Aquifer Assessment, Planning, and Management

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Kansas Geological Survey Open File Report 2002-25F

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KGS OFR 2002-25F. Scale, uncertainty, and the relationships between basic data, information, and management perspectives

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KGS OFR 2002-25F.
Scale, uncertainty, and the relationships between basic data, information, and management perspectives
By R. W. Buddemeier, B. B. Wilson, J. Mosteller, and G. Hecox

1. Introduction

1.1 Objectives:

This report addresses information relevant to two slightly different formulations of the same issue addressed as the final substantive point in both the KWO and KDA contracts (Appendix A, KGS OFR 2002-25A). KWO: “The appropriate scale of use and precision of data sets identified during the quarterly meetings.” KDA: “Data reflecting the appropriate balance or interface in scale between basic data (sub township) and basic information (township) and management perspective.”

These issues have been grouped under two general headings. ‘Scale’ refers to the size of an interval of either space (distance, area or volume) or of time. The scales of models or measurements are important in considering appropriate applications, or in combining different kinds of information. For example, the information acquired by making a measurement at hourly or daily intervals is quite different from that obtained by monthly or annual observations. Similarly, knowledge of the same parameter based on observations at the scale of miles, tens of miles and hundreds of miles are related, but can be quite different in their accuracy, precision, and potential applications. ‘Uncertainty’ is the technical term used to discuss ways to deal with the fact that all knowledge is imprecise or uncertain at some level; measuring or estimating uncertainties (which are often a function of scale) is an important step in deciding how to use data and information. It should be recognized that all measured data are simply representations of or provide a model for natural conditions and/or phenomena. As such, data will always have some level of uncertainty in their representation. The question then becomes, is that uncertainty at a level that changes the goals or implementation of management and analysis considerations.

The purpose of the discussions presented in the following sections is to provide some basic background on terms, concepts, and available data, and then to examine their application to specific issues related to the identification and management of aquifer subunits that can be selected on the basis of internal similarity and the expected lifetime of the water resources. An important component of evaluating data quality and uncertainty is knowledge about the data and how it was acquired or processed. The information providing this knowledge is often called ‘metadata’ and is also described and discussed in this report.

1.2 Scientific and management scales

Human decisions are implemented on the basis of legal and political boundaries, while scientific characterization follows natural boundaries and gradients that often do not coincide with social conventions. How can these two approaches be reconciled in developing a more scientifically based approach to managing groundwater resources? The boundaries of the Groundwater Management Districts provide an example; because the hydrogeologic limits of the aquifer formation do not coincide with county boundaries, township and section boundaries are used to approximate the aquifer extent in terms of units that are well defined by the Public Land Survey System (PLSS).

Hydrologists, geologists, and geographers commonly use grid systems to describe and calculate spatially distributed characteristics. To be effective, a grid-system used should be fine enough (that is, have small enough grid cells or 'boxes') so that it can adequately represent the highest resolution data set or application. In the case of ground-water resources, pumping wells have zones of influence that typically extend a half-mile or more in all directions from the well (see section 4.3 below). This defines a distance of about a mile, or an area of about one section, as a practical lower limit of resolution for most purposes. A grid based on PLSS sections is not exactly identical to a perfect square-mile grid, but it is close enough so that scientific conclusions are not significantly distorted by treating it as a square-mile grid, and its use ensures that results are presented in a form that is directly recognizable and usable for public information and management.

The KGS has developed a section-based grid for presenting and analyzing water and hydrogeologic data that has been used in a variety of research and analysis projects such as the Atlas of the Kansas High Plains Aquifer (http://www.kgs.ukans.edu/HighPlains/atlas/). This internet-accessible database is described, along with information on accessible point-data and time series databases, in section 2.1 below. Section-level data is a convenient, consistent medium for exchanging and applying information, and provides the basic 'building blocks' for addressing larger areas. Some data are available at the section level or even finer – water use, elevation, and soil type, for example. Other data, such as depth to bedrock and precipitation, may be available or appropriate to use at that resolution in some areas, but not everywhere. Many types of data are available from much coarser resolution observations that must be interpolated or aggregated from point sources to obtain section level values between the measuring sites (examples include climate data, discussed in OFR 2002-25E, and water-level data, considered in section 4 of this report).

Because of the variety of the data sets available at this present date that contribute to the section-level database, and the uncertainty at the section level of those values that are interpolated from much more widely-spaced observations, there is general agreement that management applications of the data should be at the scale of tens of square miles. This is referred to as the township level, since a 36 square mile township is about the minimum size appropriate for application of some of the present data sets. However, this term is not meant to imply that legal township boundaries should be used. Rather, an assembly of similar, contiguous sections adding up a total area of that magnitude (or greater) should be the goal of subunit definition on the basis of the existing data.

2. Data and Metadata

2.1 Data availability and applicability, present and potential

2.1.1 Tools and access

The Kansas Geological Survey, and the closely associated Data Access and Support Center, have a long-term goal of making electronic data and information readily available to the citizens and agencies of Kansas. Beginning with the production of the High Plains Atlas (Schloss et al., 2000), a database of water-related variables gridded by legal section has been under development and has been available on line in prototype form. The present version can be accessed from the "section-level data" link at http://www.kgs.ukans.edu/HighPlains/data_access.html. It permits selection of geographic areas by GMD or latitude-longitude (plans are in place to add extended spatial query capabilities such as township-range-section), visualization of data selections to determine completeness and range and distribution of values, mathematical transformation or filtering of data sets, correlation analysis, and data download or cluster analysis in the electronically linked LoiczView on-line program (http://www.palantir.swarthmore.edu/loicz/help).

In addition to this consistently gridded spatial data set, another prototype development makes time-series data available at the individual well and legal section level. These are available from the prototype access page accessible at (http://www.kgs.ukans.edu/HighPlains/Dywix_intro.htm) (or via the “Time-Series Data” link on the High Plains data access page). The database can be searched by GMD, county, township-range-section, or latitude and longitude, but in the present version the data can be accessed only via individual well records, one well (or the corresponding legal section) at a time.

2.1.2 Data availability

2.1.2.1 Time series

The data access tool (http://www.kgs.ukans.edu/HighPlains/Dywix_intro.htm) is based around the KGS Wizard database; it provides time-series plots (or data downloads) of water level measurements on selected wells, plus access to the other aquifer and well information contained in the Wizard database. In addition, linked databases provide concurrent download and visualization of water use and irrigation summary data (extracted from the WRIS database for the period 1990-1999; see section 2.2 below) for the section identified, and monthly water balance data from the Wilmott-NCDC data set (Wilmott and Matsuura, 2001) described in report OFR 2002-25E (1950 through 1999 precipitation, potential evapotranspiration, evapotranspiration, surplus, deficit, and soil mosture).

The individual well water levels and well-based information are usable at the local (section or smaller) level, as are the water use data. The climatic water balance data are appropriate for annualized estimates at the township-to-section scale.

The inclusion of temporal statistics in the geospatial database (see below), such as range and standard deviation of the values over a given period, provides additional insight into the temporal variability of the parameters.

2.1.2.2 Gridded section-scale databases

Table 1 is based on the variable selection list from the High Plains Aquifer database website. It presents current data availability in ordinary text, and lists feasible additions (that, is data presently available or readily obtainable on a time scale of a year or less) in **Impact** type font. The variables are coarsely grouped together into common themes and types of variables.

Column A indicates time scale of potential availability: 0 = presently contained in database; 1 = could be included on a time scale of 3-4 months or less; 2 = could be included on a time scale of 6-8 months or less; 3 = could be included within one year. It is important to note that these times refer to **individual variable additions**; the combined effort associated with all items listed as 1 is far too great to update the database with all of them on a time scale of 3-4 months with presently available resources. Another important factor is the need to select a relatively small number of scenarios for implementation; for example, the choice of a wide range of pumping rates and hydraulic conductivities could result in an unmanageable number of yield-based lifetime estimates.

Column B indicates the appropriate analysis scale for application of the data; although all are presented as section-level values, many are derived from data sets with coarser resolution, and should only be used to assemble aggregated measurements at larger scales. T and S stand for Township and Section scales, used in the sense outlined in section 1.2 above and discussed in more detail in section 3 below. The + and – symbols indicate a variable that is intermediate in applicability; a T- evaluation indicates that the underlying data support higher resolution that a township, but not as fine as a section. A variable rated S+ might be appropriate for application to a two mile circle, but not an individual section, for example. These rankings are based on a combination of the metadata (see sections 2.1.2.3 and 2.2 below) and the professional experience of KGS staff in working with the data sets.

In the interests of conciseness, possible variable additions or updates that are the same as or closely related to existing variable are indicated in the same data row, using the distinguishing type face. New variables that are qualitatively different from those already available are shown in separate lines.

Table 1.1: Data gridded at section level presently **and potentially available from KGS**

Column A – availability code; see text for explanation

Column B -- Appropriate (smallest) scale of application: see text for explanation

A	B	Column Name	Variable	Select
Geographic and Geomorphic variables				
0	S	LONGITUDE	Section center Longitude (HPA)	☐
0	S	LATITUDE	Section center Latitude (HPA)	☐
1	**S**	**TOWNSHIP_RANGE_SECTION**	**PLSS identity of section**	
1	**S-**	**GROUND_ELEVATION (mean, max., min., std. dev.)**	**Section elevation statistics (USGS DEM) – *multiple entries, ft and m***	
0 **1**	S	TOTALAREA **[add square miles]**	Total area of section in square meters	☐
Hydrogeology and Aquifer Characteristics				
0	T-	SPEC_YLD	Specific yield (USGS)	☐
o 1	T-	HYDR_COND **[update with new interpolation routine]**	Hydraulic conductivity (USGS)	☐
0	T-	BDRK_ELEV	Bedrock elevation (USGS with minor WWC5 enhancements by the KGS)	☐
2	**S+**	**AVG_MIN_SOIL_PERM [other variables available]**	**Section average permeability of least permeable soil layer (NRCS/KGS)**	
2-3+	**S**	**LOCAL_BDRK_ELEV [GMD or subunit level]**	**New or enhanced bedrock surveys**	
Note: spec_yld and hyd_cond may also be upgraded in selected areas, but probably not within a year				

Water Budget variables				
0 **1**	T-	TOTAL_PRECIP_MM **[update, w/statistics – mean, min., max., and std. dev.]**	Total Annual Precipitation, mm (HPA) [1950-1999]	☐
0	T-	TOTAL_PRECIP_IN	Total Annual Precipitation, inches (HPA)	☐
0	T-	PRECIP_NRM (would be replaced by statistics)	The calculated normal precipitation (1961 - 1990) (HPA)	☐
0 **1**	T-	PRECIP_SNL **[update, w/statistics – mean, min., max., and std. dev.]**	The (HPA) calculated normal seasonal precipitation (Mar-Oct),1961 - 1990)	☐
0 **1**	S	WUSE_AVG90 **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of water reported diverted from 1990 to 1999 (DWR-KGS) **[to most recent year available]**	☐
0	S	G_WUSE_AVG **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of ground water reported diverted from 1990 to 1999 (DWR-KGS)	☐
1	**S-T**	**Groundwater Use Density**	**Multiple values: 2, 5, and 10 mi smoothing**	
0	S	S_WUSE_AVG **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of surface water reported diverted from 1990 to 1999 (DWR-KGS)	☐
0	T+	USGS_RECHARGE	Recharge, estimated actual (USGS)	☐
?	**?**	**Aquifer discharge (not yet defined)**	**Apportionment of groundwater and surface water discharge across relevant aquifer units**	
0	T+	ST_PRE	Saturated thickness, predevelopment (HPA)	☐
0 **1**	T	ST_98 **[update to 2001 value]**	Saturated thickness, 1998 (HPA)	☐
0	T-	STOR_PRE	Water in storage, predevelopment (HPA)	☐
0 **1**	T	STOR_98 **[update to 2001 value]**	Water in storage, 1998 (HPA)	☐
0 **1**	T	DTW_98 **[update to 2001 value]**	Depth to water, 1998 (HPA)	☐
0	T	INV_DTW_98 [*drop – online calculation available*]	Depth to water inverse (1/ft), 1998 (HPA)	☐
0	T+	WLE_PRE	Water level elevation, predevelopment (HPA)	☐
0 **1**	T	WLE_98 **[update to 2001 value]**	Water level elevation, 1998 (HPA)	☐
Groundwater Dynamics – changes and trends				
0	T	WL_CHG_PRE_98	Water level change (ft), predev – 1998	☐

1		**[update to 91-01, 91-96, 96-01 values]**	(HPA)	
0 **1**	T	ATREND_88_98 **[update to 91-01, 91-96, 96-01 values]**	Water level annual trend (ft/yr) 1988-1998 (HPA)	☐
0	T	INV_ATREND_88_98 [*drop – online calculation available*]	Water level inverse trend (yr/ft) 1988-1998 (HPA)	☐
0	T	ATREND_78_88	Water level annual trend (ft/yr) 1978-1988 (HPA)	☐
0	T	INV_ATREND_78_88 [*drop – online calculation available*]	Water level inverse trend (yr/ft) 1978-1988 (HPA)	☐
0 **1**	T	ST_CHG_FT **[update to 2001 value]**	Saturated thickness change (ft), predev-1998 (HPA)	☐
0 **1**	T	ST_CHG_PCT **[update to 2001 value]**	Saturated thickness change (%), predev-1998 (HPA)	☐
0 **1**	T	STOR_CHG **[update to 2001 value]**	Water in storage change, predevel-1998 (HPA)	☐
2	**T**	**STOR_CHG_[91_01]** **[or period to match water use data]**	**Calculated change in water in storage, 1999-2001 [or other selected period]**	
Administrative, Planning and Management variables				
0	#	DWR_RECHARGE	Recharge, administrative (DWR)	☐
0 **1**	T*	FT_TO_DEPLETE (1998) **[update to 2001 value]**	Feet to depletion (Saturated thickness - 30') (HPA)	☐
1-2	**T**	**YIELD_FT_TO_DEPLETE**	**Feet above minimum sat. thick. per selected OFR 2002-25C scenarios**	
0 **1**	T*	YRS_DEPL_88_98 **[Update to, or add, 91-01 & 96-01 values]**	Years to depletion (1988-1998 trend) (HPA)	☐
0	T*	YRS_DEPL_78_88	Years to depletion (1978-1988 trend) (HPA)	☐
2	**T**	**YRS_DEPL_YIELD**	**Years to depletion based on selected trends and YIELD_FT_TO_DEPLETE**	
0	S	AUTH_QTY	The amount of water authorized to be pumped annually (as of June 25, 2001) (DWR-KGS)	☐
0	S	G_AUTH_QTY	The amount of ground water authorized to be pumped annually (DWR-KGS)	☐
0	S	S_AUTH_QTY	The amount of surface water authorized to be pumped annually (DWR-KGS)	☐
0	S	VNUM	The number of vested water rights within the section (DWR-KGS)	☐
0	S	G_VNUM	The number of vested ground water rights within the section (DWR-KGS)	☐
0	S	S_VNUM	The number of vested surface water rights within the section (DWR-KGS)	☐

0	T	AVAIL	Availability index (HPA)(1998)	☐
0	T	ACCESSIB	Accessibility index (HPA)(1998)	☐
Land Use and Land Cover (as of early 1990s)				
0	S+	OPEN_WATER	Percent section classed Open Water in USGS KS LULC	☐
0	S+	LOW_INTENS_RES	Percent section classed Low Intesity Residential in USGS KS LULC	☐
0	S+	HIGH_INTENS_RES	Percent section classed High Intesity Residential in USGS KS LULC	☐
0	S+	COMMERCIAL_INDUST_TRANS	Percent section classed Commerical/Industrial/Transportation in USGS KS LULC	☐
0	S+	BARE_ROCK_SAND_CLAY	Percent section classed Bare Rock/Sand/Clay in USGS KS LULC	☐
0	S+	QUARRIES_STRIP_GRAVEL	Percent section classed Quarries/Strip Mines/Gravel Pits in USGS KS LULC	☐
0	S+	TRANSITIONAL	Percent section classed Transitional in USGS KS LULC	☐
0	S+	DECID_FOREST	Percent section classed Deciduous Forest in USGS KS LULC	☐
0	S+	EVERGREEN_FOR	Percent section classed Evergreen Forest in USGS KS LULC	☐
0	S+	MIXED_FOREST	Percent section classed Mixed Forest in USGS KS LULC	☐
0	S+	SHRUBLAND	Percent section classed Shrubland in USGS KS LULC	☐
0	S+	GRASSLANDS_HERBAC	Percent section classed Grasslands/Herbaceous in USGS KS LULC	☐
0	S+	PASTURE_HAY	Percent section classed Pasture/Hay in USGS KS LULC	☐
0	S+	ROW_CROPS	Percent section classed Row Crops in USGS KS LULC	☐
0	S+	SMALL_GRAINS	Percent section classed Small Grains in USGS KS LULC	☐
0	S+	FALLOW	Percent section classed Fallow in USGS KS LULC	☐
0	S+	URBAN_REC_GRASSES	Percent section classed Urban/Recreational Grasses in USGS KS LULC	☐
0	S+	WOODY_WETLANDS	Percent section classed Woody Wetlands in USGS KS LULC	☐
0	S+	EMERG_HERBAC_WETLND	Percent section classed Emergent	☐

			Herbaceous Wetlands in USGS KS LULC	▨

2.1.2.3 Supporting information and development plans

The water- and geology-related data in the databases described are largely derived from the Wizard and WRIS databases, the metadata for which are discussed in section 2.2. Derived variables produced for the High Plains Atlas are described by Schloss et al. (2000), and the metadata for the Wilmott-NCDC climate data are given by Wilmott and Matsuura (2001).

Because the data sets come from disparate sources with a wide range in the quality and format of metadata and background information, a common-format, user-friendly metadata inventory will take substantial effort to develop. Ultimately, it is hoped that resources will be available to develop database access tools that have built-in links to standardized metadata; for an example, go to (http://www.kgs.ukans.edu/Hexacoral/Envirodata/envirodata.html) and login to the data base to see examples of access to multiple related databases, and source and variable metadata links from the selection table.

Also under development by funded projects are new tools and database 'front ends' that could be adapted to refine the High Plains prototypes. A particularly relevant project is construction of an expanded front end for the Wizard database, with expanded capabilities. Expected to be on line sometime in Fall, 2002, this version of the WIZARD database access web page will include new GIS capabilities as well as additional water level data processing and statistical review tools. By enabling the spatial characteristics of the WIZARD data, a potential expansion of this project is to adapt it to access the variables listed in Table 1 based on the selection results from the WIZARD front end. This would allow users the ability to incorporate actual well data and water level time series with additional data parameters. This is turn provides a better understanding of those trends in relation to each other and other characteristics of that location.

2.2 Metadata

The concept or term of "metadata" can best be described as data about data. Metadata is a collection of information that describes the content, quality, condition and other characteristics of data sets. It enables organizations to record and maintain important information about data, which in turn facilitates the sharing and understanding of that data by outside users. Metadata also serves as the mechanism to outline how or where the data were acquired, potential use limitation, recommended scales of use, and other unique parameters for not only the data set itself, but also the individual data elements within the data set.

As discussed before, every data set has some level of uncertainty associated with it; however, many data sets also have a particular set of "business" or relationship rules that must be followed when conducting analyses or calculations on that information. Unfortunately in many cases, the person charged with maintaining a particular data set is often the only one who is familiar with or recognizes these conditions. Personnel changes can lead to this information being lost if it is not systematically and accessibly maintained.

The Federal Geographic Data Committee (FGDC) is a federal interagency committee organized in 1990 to promote the coordinated use, sharing, and dissemination of geo-spatial data on a national level. From this effort a set of FGDC metadata standards was developed in 1994, which serves as the primary guidelines for metadata posted in many data clearinghouses throughout the country. There are several objectives and benefits behind having standards for metadata specifically. For example, a set of metadata standards provide a common set of terminologies and definitions for documents, help organize and maintain an organization's investment in data, and provide information to process and interpret data received by external sources.

Many of the data elements stored in the KGS section-level database came from a series of principal data sets maintained by state agencies. Specifically, the Water Information Storage and Retrieval Database (WIZARD) represent the primary repository on ground water level measurements in Kansas, the Water Well Completion Records (WWC5) Database contains information from records submitted by water well drillers to the Kansas Department of Health and Environment, and the Water Rights Information System (WRIS) contains information associated with water rights administered by the Kansas Department of Agriculture's Division of Water Resources.

These particular data sets were the foundation for the bulk of information currently stored in the KGS section-level database. For example, saturated thickness and changes in the water table over time were interpolated from data housed in WIZARD and WWC5, while reported water use and annual allocation information was obtained from WRIS. Maps like the estimated usable lifetime of the High Plains aquifer are products of analyses of data from these sources.

Given the importance and level of use of these data sets in understanding the aquifer system, FGDC compliant metadata was either created or updated for the WIZARD, WWC5, and WRIS data sources. The metadata files for WIZARD and WWC5 databases can be viewed at (http://www.kgs.ku.edu/Magellan/WaterLevels/wizard_fgdc.html) and (http://magellan.kgs.ukans.edu/WaterWell/wwc5_fgdc.html) respectively. Information pertaining to the data stored in the Water Information Management and Analysis System (WIMAS), which represent a commonly used subset of WRIS, is available at (http://gisdasc.kgs.ukans.edu/metadata/wimas.html). A more detailed metadata file on the actual water rights data is stored within the WIMAS application.

With developed metadata files for these primary data sets, users have a resource that addresses several key questions and use requirements. Question that can be answered from the metadata files include: how and by whom were the data collected, when and here were the data collected, why were the data collected, and how and at what scale should they be used.

3. Spatial and temporal scales and variability

3.1 Background information

3.1.1 Notes on terminology:

1. The word "scale" has two different uses, which can generate confusion. We use the commonly understood definition of a "large-scale" feature as something that covers a lot of space and/or time (the Ogallala formation, for example) and a "small-scale" feature as something very local (like a specific location where a section of the Ogallala is exposed) or of short duration. However, in mapping (cartographic) terminology, the terms are reversed because they are applied to the 'scale' or display ratio of the map.

A 1:10,000,000-scale map is considered a small-scale map because ten million inches on the ground are represented by only one inch on the map (a small distance relative to what it represents). A 1:10:000 scale map is a large-scale map, because one inch on the map represents only 10,000 real inches -- a much larger scaling ratio. The idea is internally consistent, but the confusion arises because the small-scale map is used to portray large-scale features (e.g., the continent) while the large-scale map provides a much more detailed view of small-scale features (such as a county). To avoid confusion between large- and small-scale maps, think of an example map where the scale is 1:1. Although one is a small number, a theoretical map of Kansas at a scale of 1:1 (**large** scale) would be actual size of the state (one mile = one mile) and represent an exceptional **large** map. A safe policy is to be careful and ask for definitions if maps are being explicitly described or discussed in considerations of scale.

2. Scales are human inventions for dividing up and classifying nature, which is continuous. As a result, there is no one "right" classification of scales -- these have to be user-dependent, which requires some level of definition and agreement. They also have inherently "soft" boundaries; a block of land that is a few square miles in area could be considered either ‘section-scale’ or ‘township-scale’ -- or both. Although specific applications may require specific definitions, general discussions can use the kind of fuzzy definitions given below for classifying features and processes. Table 1 provides some examples of terms, concepts and values associated with a range of space and time scales. Note that the unit ranges are approximate and that there are gaps and overlaps in the numbers given -- this reflects the "soft boundaries" and common usage; it is a guideline, not a standard.

3.1.2 Spatial scale and variability

In ground water issues important to Kansas, horizontal spatial scales of importance are usually in miles to tens of miles, or perhaps a hundred – while vertical spatial scales, those of soil and aquifer layers and ground water bodies, are measured in feet to hundreds of feet. Nothing is absolutely uniform, but large horizontal features generally tend to vary rather gradually; however, gradual horizontal variations on the scale of the geologic unit can include local changes that are quite abrupt on the scale of the vertical measurements used to determine ground water inventories. To make estimates from relatively few sampling or measurement points over large regions requires the application of the concept of continuity for features like aquifer properties. This is a powerful, economical, and widely used approach, but it puts limits on the confidence of the interpolated values that are far from measurement points. These limits represent the **uncertainty** of the estimate, which is determined largely by the small-scale **variability** of the large-scale feature. In such cases, the uncertainty in the actual measurements (see uncertainty section for discussion of accuracy and precision) is usually minor compared to the uncertainty introduced by variability and problems of representative sampling over a large area.

Quantitative variability -- both spatial and temporal -- has two important components: the magnitude (the total or maximum amount of change) and the frequency (the rate of change per unit distance, area, time, etc.). Driving across a series of speed bumps exemplifies low-magnitude, high frequency elevation change while driving east to west across Kansas is a moderately high-magnitude but very low frequency change in elevation. Continuing to drive west across the continental divide brings an experience that is high-magnitude and moderately high-frequency change. Qualitative variability occurs, but we more commonly express it in quantitative terms -- a change in the nature of the aquifer unit, for example, usually corresponds to a quantitative change in hydraulic conductivity, water quality, or some other measurable characteristic.

Table 3.1: Examples of spatial and temporal scales

Spatial Scales				Temporal Scales		
Unit	**Term**	**Feature example**		**Unit**	**Term**	**Process examples**
<0.5 mi <0.25 mi^2	local, field-scale	Point observations (e.g., wells)		Min-hour	instantaneous	water level measurement
~0.5-5 mi ~0.5-20+ mi^2	section-scale	pumping well zone of influence; measurement densities in well-studied areas		days (~0.5-15)	days	fluctuations in precipitation, pumping, barometric pressure, etc.
~5-10 mi ~20-50 mi^2	township-scale	typical level of generalization supported by statewide data sets		months (~0.5-6)	months (seasonal, intra-annual)	crop and pumping cycles, precipitation patterns, water table recovery
~10-50 mi ~50-300 mi^2	county-scale	Some climatic parameters such as evaporation		years (~0.5-5)	years (annual, inter-annual)	management and regulatory cycles, short-term variability averaging
30-100 mi 300-10,000 mi^2	Regional (e.g. GMD-scale)	Nation-wide, generalized data sets like NRCSSTATSGO soils data		decades (~0.5-2+)	decades	planning, economic cycles, long-term variability averaging
>100 mi >1000 mi^2	Aquifer-scale	Very long-term processes; climatic and geologic time scales		long-term (>~25 yr)	long-term	natural groundwater flow and recharge

In the horizontal dimension, ground water, like surface water, represents a special case because it is a fluid -- which means that it will fill available openings, seek a common surface level under the influence of gravity, and is mobile (that is, will ‘run downhill’). This means that ideally, an undisturbed ground-water surface would be a nearly horizontal plane with a slope determined by the tilt of the land and the local water balance. This is a very powerful and useful model, and water resource assessment and management would be vastly more difficult without it. However, it is not perfectly accurate. Even under natural settings, recharge, discharge, and other physical aquifer characteristics cause variations in water level that can become even greater when large quantities of water are pumped from the system. In the case of water-level measurements, our interpretations have uncertainties caused by variability of the system, but in this case variations over time (**temporal variability**) are likely to be at least as important as spatial variability. These are discussed in the following section.

3.1.3 Temporal scale and variability

Most geologic features can be treated as invariant on human scales -- natural features on the landscape change rapidly only in rare catastrophic events (floods or earthquakes) or by direct and focused human intervention. If we measure the depth to bedrock at points A and B, we can go back and measure points at C, D, and E a week or a year from now with great confidence that A and B will not have changed in the meantime. This gives us the relative luxury of being able to take our time to decide how much information we need about the feature; we can go back and expand our store of knowledge when, where, and how we wish.

By contrast, water features are not so cooperative or accommodating. First and foremost, if we are concerned about trends in a changing system, we cannot "go back" in time to take measurements we later decide that we need (although we can sometimes tease more information out of the measurements we did take). Secondly, ground-water levels in many (but not all!) locations can be somewhat dynamic in response to other factors. For example, ground water level can fluctuate in response to barometric pressure changes (at frequencies of hours to days), and may also respond rapidly to nearby ground-water withdrawals or to major recharge events (floods or major storms). Recovery from perturbation can be much slower -- it takes many months for wells to recover from the irrigation-pumping season, and in some areas they probably never regain full equilibrium before the pumping season starts again. Finally, the natural time constants of ground-water systems are very long by human standards. For example, the best estimates of natural ground-water flow rates (undisturbed by pumping) in the Ogallala aquifer are about one foot per day (with a range of 0.1-10'/day). That means a gallon of water might take 10 years to get from one side of a section of land to another -- but if that gallon and a few million others are pumped out over the course of a few months, changes occur much more rapidly.

For an overview of examples of some of these features, see the instrumental hydrographs from some wells in GMD4 (Figure 4.3 below). This record illustrates barometric fluctuations (very strong in one well, less so in the other) and protracted recovery curves in both. These records are discussed and explained in more detail in section 4 (below) on Uncertainty.

4. Uncertainty

4.1 Types and sources of uncertainty

Uncertainty is a fundamental aspect of all experiential knowledge, and is a central theme of science. Scientific progress occurs through the identification, explanation, and reduction of uncertainty. This seems counter to the popular view of science as the source of confidence and certainty; the apparent paradox is resolved by realizing that many (but far from all!) scientific projects work at reducing uncertainties that are already small compared to issues that the general public worry about.

The words used to describe scientific and technical uncertainty sometimes provoke misunderstanding. In particular, two terms that have moral connotations in ordinary speech are used in a value-neutral way in science. "Error" is a term used to describe certain kinds of uncertainties in a measurement or set of measurements, and "bias" describes the amount and direction of a consistent difference between the measured value and the true value. Although we work to reduce both, neither term indicates failure, negligence, or a bad attitude.

Uncertainty can arise from two sources -- one is the quality (accuracy) of the measurement or observation, and the other is our use or interpretation of the measurement. The second category is far broader, and in most large or complex systems (such as hydrology and water resources) is usually the critical issue. It includes not only interpretation of data, but also the design of experiments and observations -- where, when, and how should we make measurements, and what will they represent? This requires some appreciation of the purpose and uses of the data by those who make the measurements, which in turn requires articulation of the management needs and desires.

In complex systems, uncertainties interact and combine. Scientist and engineers have mathematical formulas for 'propagation of uncertainty' from multiple factors, but an important practical point is identification of the limiting uncertainty or uncertainties for the final information product. We often spend considerable time and effort improving techniques that are already much better than the 'weakest link' in the process, producing no real gain in the overall quality of information. The discussion in this section focuses on the issue of water-level determination, which is one of the more complex components of understanding the hydrologic system, and which provides excellent examples of most of the points previously discussed.

4.2 Data uncertainties

Uncertainties in actual measured values have a long history of study and definition. A measurement technique is considered accurate if the average value obtained by repeated measurements of the same thing is close to the 'true' value (how we evaluate that is beyond the scope of this discussion -- but there are ways, even though we can't exactly know what the true value is). Everybody is familiar, however, with situations where this statistical definition of accuracy seems unhelpful in the individual case:

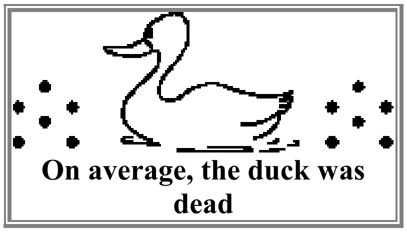

Figure 4.1. The average location of all of the pellets is right on target – but none of the actual locations are.

A further characterization of measurements is in terms of precision as well as accuracy; precision is the degree to which repeated measurements agree with each other, rather than with the "true" value. Precision and accuracy are related, but are not the same:

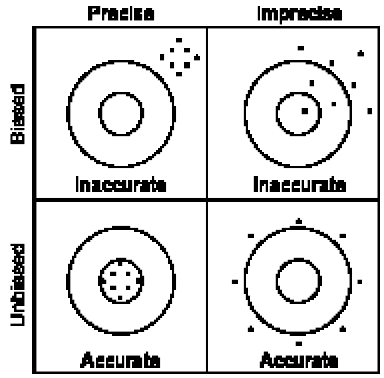

Figure 4.2. The need for both precision and accuracy depends on the scale of the application and the scale of the measurement.

A consistently biased measurement is just as good as an unbiased measurement if it is a **difference** that is being determined. This is important to water-level measurements because the absolute elevation of the well is often only approximately known. The difference between any two measurements made in the same well is not affected by this, however, since any error in absolute elevation is canceled when the difference is taken. All that is required is that the bias be consistent -- and that the measurements continue in the same well.

4.3 Combination and comparison of data with uncertainties

Understanding and estimating the uncertainties of our primary numbers are only part of the process – we always want to look at calculated results (for example, changes), or to compare different measurements across space or time. How do we assess the uncertainties in the calculated values or comparisons?

Standard formulas used in the physical sciences and engineering permit us to evaluate the uncertainty in a sum, difference, product or quotient if we know the uncertainties in the component numbers. An example of applying this approach to the water level differences calculated from a single well over different time periods and with different assumed individual measurement uncertainties is given in Table 4.3. These assume the same decline and the same uncertainty in each year, and solve for the number of years required to generate a water level difference that is at least twice the magnitude of the calculated uncertainty in the difference. For example, suppose that we feel that a given well is being measured under conditions that lead us to assign a value of one foot to the uncertainty in any individual measurement. If that is the case, we will need to take a water level difference over a period of about 6 years in order to measure an actual water table decline of 0.5'/year (or a total of 3 feet in six years) with reasonable accuracy. In this case the result would be a calculated change rate of 0.5 ± 0.23 feet/year.

Table 4.3: Years required for WL decline ≥ 2x uncertainty

True decline rate, ft/yr	Annual water level measurement uncertainty, feet				
	0.1	**0.5**	**1.0**	**1.5**	**2.0**
0.1	3	14	28	42	56
0.2	2	7	14	21	28
0.5	**1**	**3**	**6**	**9**	**12**
1.0	1	2	3	5	6
1.5	1	1	2	3	4

An uncertainty of 0.1' is approximately that of the individual measurement, and is unobtainable as a regionally integrated (calculated) result. The value of 0.2' is only marginally less unrealistic, and is included in the table to illustrate the progression of the requirements as a function of the factors considered. Uncertainty values in the range of 0.5-1.0' are probably realistically obtainable by redesign and careful operation and interpretation of an improved measurement network (see section 4.4 and the Appendix 1). With an averaging period of 5-10 years, this would be adequate to determine trends down to the level of about 0.5'/yr, or to about half that minimum at a 10-year period. Under present conditions of water level uncertainty, decade-scale trend analyses are probably adequate for use at the township scale and large and for decline trends in the 0.3-0.4'/year range – which is essentially the same conclusion arrived at in report OFR 2002-25D by examination of mapping and clustering results. Areas with lower rates of change should probably be assessed using alternative criteria. Table 4.3 highlights the uncertainty-trend combinations that would require more than a 10-year observation period.

Note that the above analysis is approximately valid for a spatially distributed network of occasional (e.g., annual) measurements in wells of opportunity, where the measurement wells are unchanged. If water level changes are calculated by direct combination of records from different wells, uncertainties in the ground elevation have to be considered and may greatly expand the overall uncertainty. For different approaches, such as continuous (recorder) measurements of water level, and/or the use of specifically designed or selected index wells, both the assumptions of uncertainty levels and the nature of the analysis would be substantially different.

4.4 A case study of uncertainties – water level measurements

It can be helpful to understand the sources of uncertainties – and how to reduce or work around them – by considering some actual examples. The water level database and measurement program provide a useful case study example; it is the source of our knowledge of, and concerns about aquifer depletion, it is an important source of information for planning and management, and water level observations are subject to a variety of possible influences and interpretations.

Report OFR 2002-25D demonstrated that township- and decade-scale water level trends provide a practical means of regionalizing lifetime estimates, and that for many regions of the Ogallala-High Plains there is a strong relationship between water use data and water level trends. These conclusions about the utility of the data for subunit identification and prioritization are supported by some of the calculation estimates in section 4.3 above.

While supporting the use of existing data for the establishing subunits and considering management options, 2002-25D and the uncertainty considerations also raise questions about needs that may arise for data needed to implement detailed subunit management. It was noted that at the local (subtownship) scale, time periods on the order of 25 years are needed to provide regionally smooth trend maps, and that in some regions, the relationship between use and water level trend was unexpectedly weak. Considering possible sources of uncertainties may help to understand and improve the data base.

An important fundamental question not discussed above is the basic issue of whether the measurements taken represent what is actually expected or intended. The State of Kansas is in a transition period from viewing the aquifer as a whole to taking a much more focused approach to specific areas. The water level measurement program currently in effect (described briefly in section 2.5 of OFR 2002-25G) was designed on the basis of assumptions that the aquifer is uniform and homogeneous, and there is no significant difference in either importance or measurement-related hydrogeology. The results have served well for questions asked in that context, but as more and more attention is focused on the differences rather than the similarities within the aquifer, problems arise.

The annual water-level measurement program has for many years determined water levels during the winter, operating on the assumption that these measurements are reasonably free from interference, provide a reasonable approximation of the recovered equilibrium water table, and can be used to estimate the water remaining in the aquifer. As these assumptions come under closer scrutiny, more detailed measurements are being examined to consider how best to monitor water levels in the future. Two components of these considerations are examined below: the issue of the time and frequency of well measurements, and the question of well interference.

4.4.1 Measurement time and frequency

Two wells in the GMD4 area that have been fitted with downloadable pressure transducers provide information on water level behavior over time scales ranging from minutes to months. In addition, GMD4 staff has made available monthly manual measurements of numerous other wells in the vicinity of the instrumented wells. These are providing valuable information to help understand well monitoring issues.

Figure 4.3 shows plots of the water levels from shortly after the end of irrigation in Fall 2001 to just before the onset of irrigation in Spring 2002; Figure 4.4 shows effects of the onset of irrigation on water levels in the monthly wells.

The curves of figure 4.3 address the assumption of a recovered water table. Annual measurements were made in the first week of January, and both of the recorder wells showed water level rises of about 0.5 feet over the succeeding two months - and do not appear to have been fully leveled off at that point. These observations are supported by the measurements in the monthly wells (http://www.kgs.ukans.edu/HighPlains/GMD4.htm). Water level exhibits continued variability on time scales of months; this creates an uncertainty not in the measured elevation, but in what that measurement represents in terms of the program objective (understanding changes in the equilibrated water table).

One of the wells shown in figure 4.3 has a strong barometric pressure response, with observed water level changes in excess of 0.5 feet on a time scale of a few days. The fitted curve presumably represents the trend line of the water table, and is what measurements should be expected to determine. However, individual measurements (even if repeated at the well head over a few days) can produce values that deviate in either direction from the trend line by >0.5' (while the trend line itself is > 0.5' below the assumed full-recovery water level). This is a level of uncertainty imposed by short-term (high frequency) variations in the condition measured. Again, it is not an uncertainty in the instantaneous measurement value, but in what that represents in terms of the average (in this case over periods of days) water-level response.

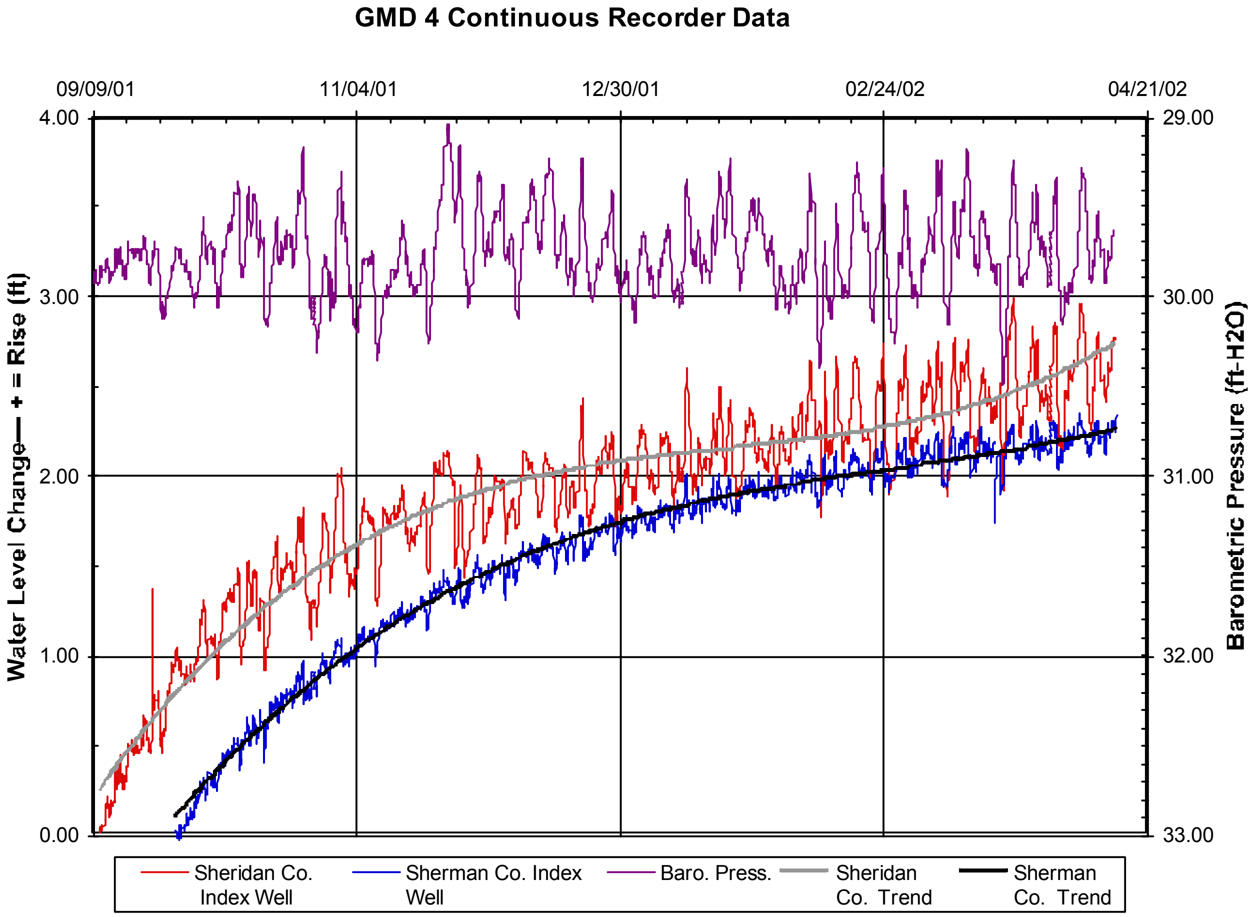

Figure 4.3. Transducer water level measurements at two wells in GMD4 for the recovery period prior to pumping. The middle plot is for a well in eastern Sheridan County, a region of high decline; the lower plot is for a well in western Sherman County, a region with lower decline rates. Also shown are the trend lines averaging the individual recorder measurements and the barometric pressure record from Goodland, Kansas (top plot). See figure 4.4 for the effects of pumping.

At least as significant is the fact that a high barometric efficiency in well water indicates **confined or semi-confined aquifer** behavior. The Ogallala-High Plains aquifer system is generally regarded as an unconfined aquifer system (also known as a phreatic or water table aquifer -- one in which the ground water surface is in pressure equilibrium with the atmosphere). We know that it contains areas where the aquifer is confined or semi-confined, but because the apparent water levels and water level changes in confined systems have different meanings than water table elevations in an unconfined aquifer, observations from the two types of wells of systems should be combined or compared carefully, if at all.

The data in figure 4.4 illustrate the drawdown occurring in wells during the irrigation season that will affect the long-term viability of a given irrigation well in a given area. All wells are operating the same types of center pivots, and most pump at about the same flow rate of approximately 500–600 gpm. These drawdown plots illustrate the points made in OFR 2002-25C, and in section 4.5 of this report (below).

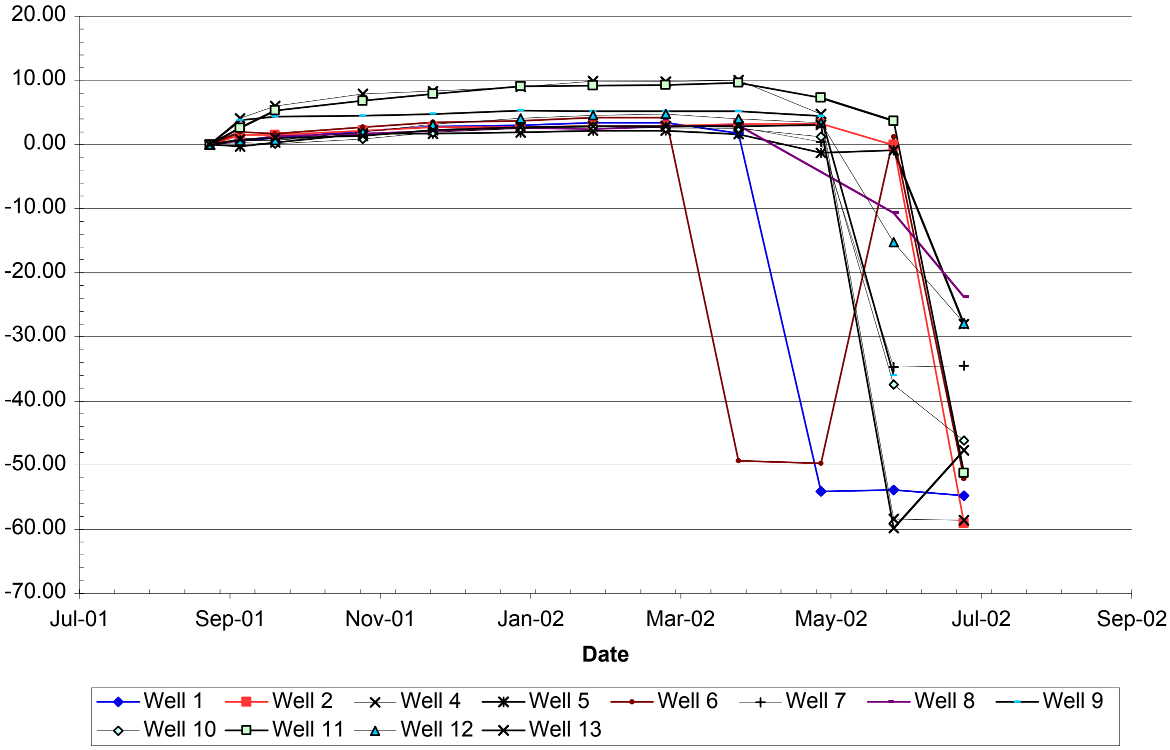

Figure 4.4: Monthly measurements of water level in central GMD4 wells (Sherman-Thomas-Sheridan counties). Note that early in the pumping season drawdowns range from near zero to over 60 feet; four of the wells show prompt initial drawdowns of more than 30 feet.

Almost all monthly wells experienced a significant change in water level between early January (the time of the annual program measurements) and mid-March. The amount of that change was not consistent, ranging from <0.2 to >1.0 feet, but the most common amount of change was in the vicinity of 0.5', as was seen in the recorder wells. The period of late December through early January generally exhibits much higher and more variable (between wells) rates of change than does the (February-March) period, suggesting that measurements later in the winter season will be more consistently representative of the desired condition than the standard early January measurement time.

Several wells show up-and-down responses or breaks in the slope of the recovery curve. These features could be due to either pumping patterns in the measured well, local well interference (nearby pumping), or the effects of having measured successive points at opposite extremes of the barometric response pattern. The latter possibility can be checked by detailed comparison with barometric pressure records; the issue of pumping interferences is discussed in section 4.5 of this report.

It is important to note that the uncertainties discussed in this section can be significantly reduced or eliminated. Testing of wells for barometric response would permit replacement of wells that are locally confined or semi-confined, and identification of larger areas that need to be monitored and managed as a confined aquifer subunit. This would create a more consistent network of water table wells that would provide measurements with less short-term variability and are more representative of the intended aquifer measurements. Moving the measurement period later in the recovery season could significantly reduce the effects of incomplete recovery on intermediate-term variability. Continuous monitoring of more wells would provide the information needed to assess the regional degree of recovery and identify possible anomalies. These and other issues are addressed in an initial set of recommendations for measurement program refinement, presented as Appendix 1 of this report.

4.5 Uncertainties due to human interference.

The uncertainties discussed in the preceding section (barometric responses and recovery from pumping) are natural hydrologic responses, and can be predicted if aquifer characteristics and forcing functions (pumping drawdown and barometric pressure) are known. The preceding section also illustrated the magnitude of the effect of pumping on measured local water levels.

Local well interaction – the response of neighboring wells to water table drawdown from nearby pumping – is another source of uncertainty in well measurements. Although irrigation pumping generally does not occur in the winter, irrigation wells may be pumped for a variety of reasons (system testing and repair, chemigation, ‘pre-irrigation’ soil conditioning, etc.), and there are a substantial number of non-irrigation wells (e.g., municipal and industrial) that are pumped at least occasionally on a year-around basis. Recent pumping in a measured well, or nearby pumping (within a radius of a few miles) of other wells, can affect water levels by a significant amount that will depend on the location, duration, and rate of pumping and the local aquifer characteristics.

Drawdown from pumping wells alters (lowers) the water table in a variable area surrounding the pumped well, depending on the rate and duration of pumping and the aquifer characteristics (especially the Transmissivity, T). Figures 4.5 and 4.6 show plots of the radius of the effects of pumping at two different rates, 250 and 1000 gpm, for a range of transmissivity values. Calculations were made using SuprPump. Additional calculations (not shown) were also made for 50 gpm and 20870 gpm (the highest authorized rate contained in the WIMAS database).

By determining the potential distance range of drawdown effects at the uncertainty threshold of 0.1’ we are able to identify some standard radii of influence for wells, depending on their authorized pumping rate. These radii can be further adjusted if aquifer characteristics are known (see also the OFR 2002-25C report on Yield for discussion of drawdown from the standpoint of local water availability). Figure 4.7 is a map of the locations and sizes of these estimated circular zones of influence, and Table 4.2 summaries the statistics on the absolute and relative areas involved in each of the major groundwater management units.

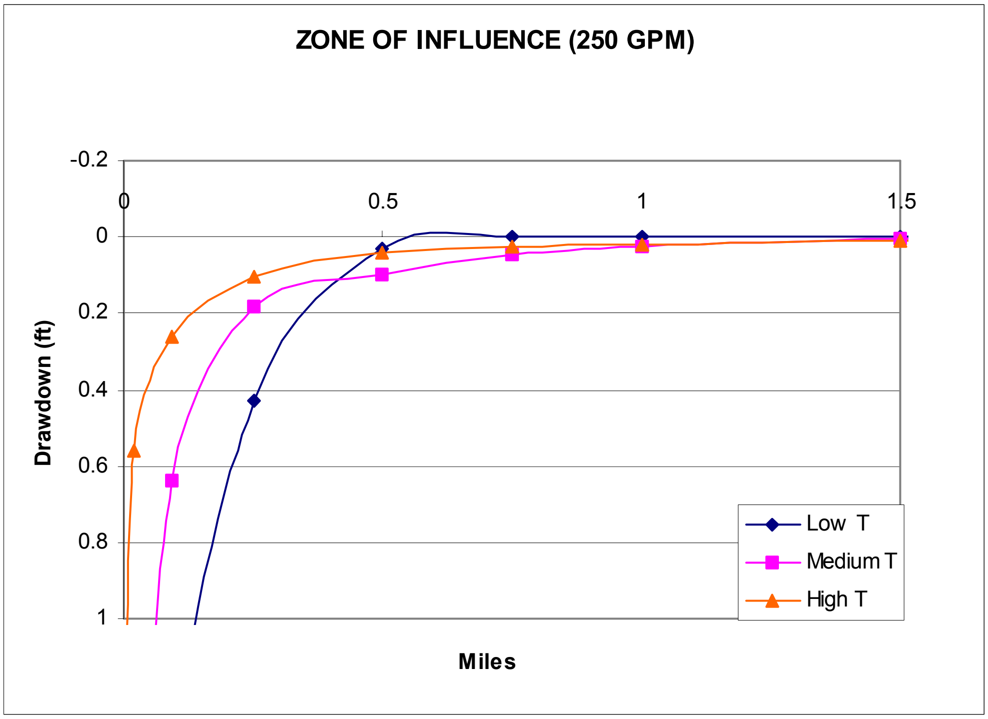

Figure 4.5. Observed drawdown as a function of distance from pumping well for high, low and medium, transmissivity values and a pumping rate of 250 gpm.

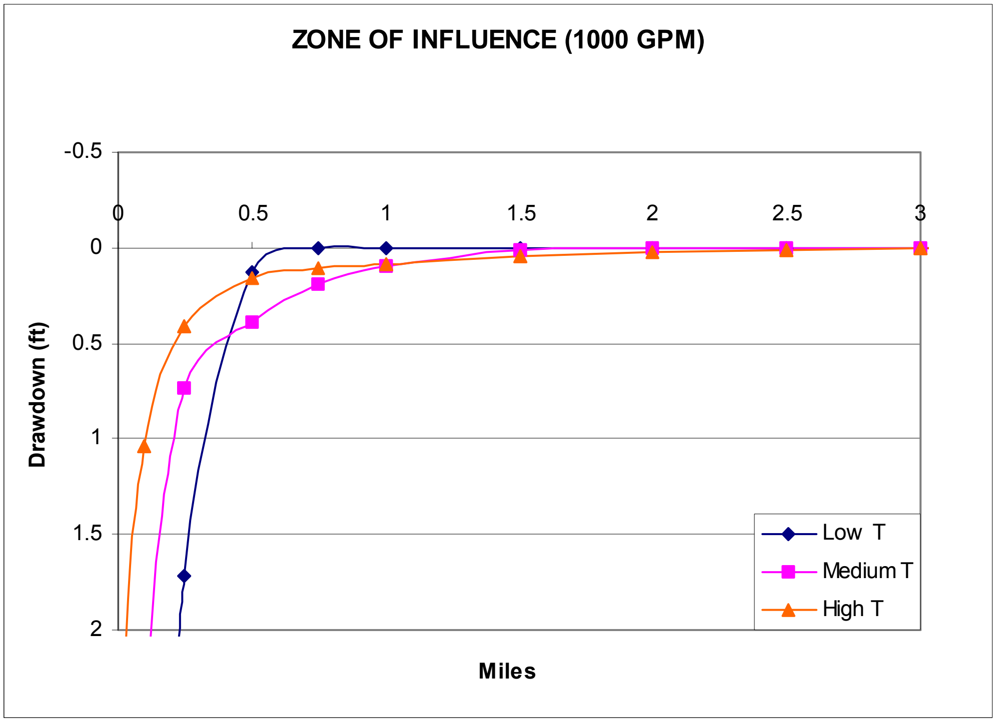

Figure 4.6. Observed drawdown as a function of distance from pumping well for high, low and medium, transmissivity values and a pumping rate of 1000 gpm.

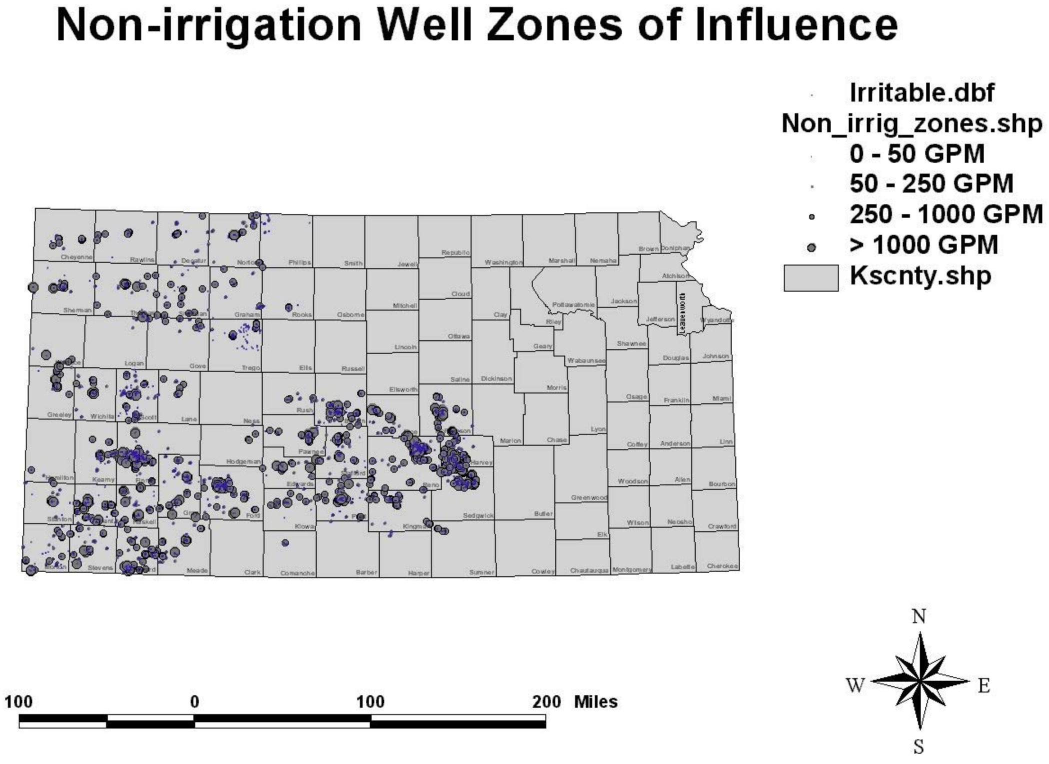

Figure 4.7. Map of non-irrigation water rights in the High Plains aquifer system. Each well is surrounded by a buffer zone, the radius of which is estimated on the basis of authorized pumping rate. See Table 4.2 for the fraction of the total area within the possible zone of influence (ZI) of non-irrigation well.

Table 4.2: Areas potential influenced by non-irrigation wells

Areas associated with non-irrigation well zones of influence (ZI)						
GMD #	**Non-irrigation wells**	**Total GMD area (mi^2)**	**Area inside total ZI (mi^2)**	**Area inside total ZI (mi^2)**	**% Area inside ZI**	**% Area outside ZI**
1	222	1827.44	471.85	1355.59	25.82	74.18
2	534	1369.86	778.67	591.18	56.84	43.16
3	1233	8338.91	2091.96	6246.95	25.09	74.91
4	271	4873.06	654.51	4218.55	13.43	86.57
5	461	3906.76	1132.56	2774.21	28.99	71.01
No GMD	526					
Total	3247	20316.03	5129.55	15186.48	25.25	74.75

An extreme example of interference is illustrated by Figure 4.8, showing the water level measurements from irrigation well (USGS ID number 375540097320901), located in southwestern Harvey County. The maximum difference in repeated water level measurements made during each winter period (December, January and February) was graphed for the years 1959-2000. During 25 of the years, the maximum deviations between measurements taken during the same winter season were less than 6 feet. However, during 16 of the years the deviation between measurements was between 30 and 45 feet. Only one year, 2000, had a measurement between 6 and 30 feet. Thus, the graph reflects two distinct water level ranges. Upon further investigation, it was found that this irrigation well was located within 200 feet of a municipal well belonging to the city of Wichita that has an authorized water right pumping rate of 20870 gallons per minute. It appears that during the sixteen years with the high levels of deviation, at the time a measurement was taken, the municipal well was either actively pumping or had recently been pumping.

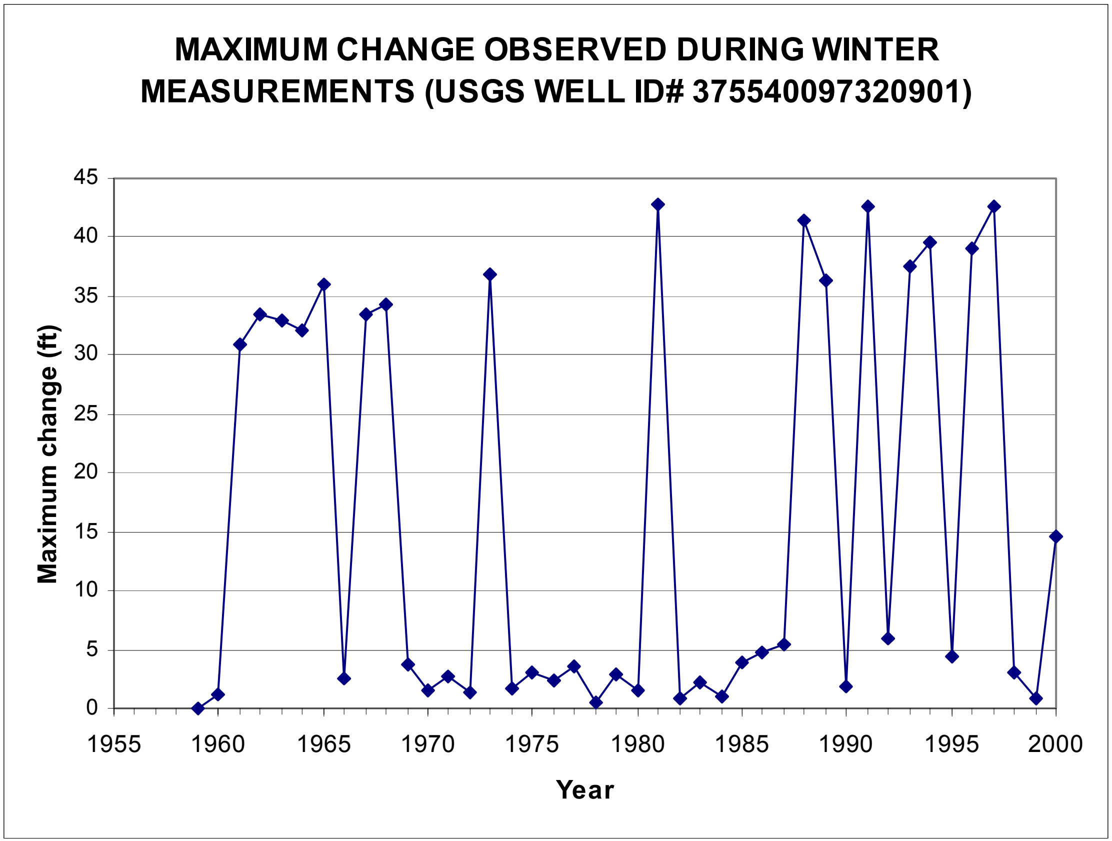

Figure 4.8: Variability of winter water level measurements in well 375540097320901, located in southwestern Harvey County – in close proximity to a high volume municipal supply well.

Contrast the situation shown in Figure 4.8 with that of an irrigation well (USGS ID number 373422098063301) in central Kingman County (Figure 4.9). The maximum difference in water level measurements during each winter period for this well was graphed for the available years 1979-1996. During this time period, the maximum winter measurement water level difference never exceeded one foot. The closest non-irrigation well is a municipal well for the city of Kingman, 2.6 miles away. This municipal well has an authorized pumping rate of only 700 GPM. All other non-irrigation wells are over 3 miles away. Thus, it appears that this relatively isolated irrigation well produces winter water level measurements that are unlikely to be greatly affected by neighbor well interference.

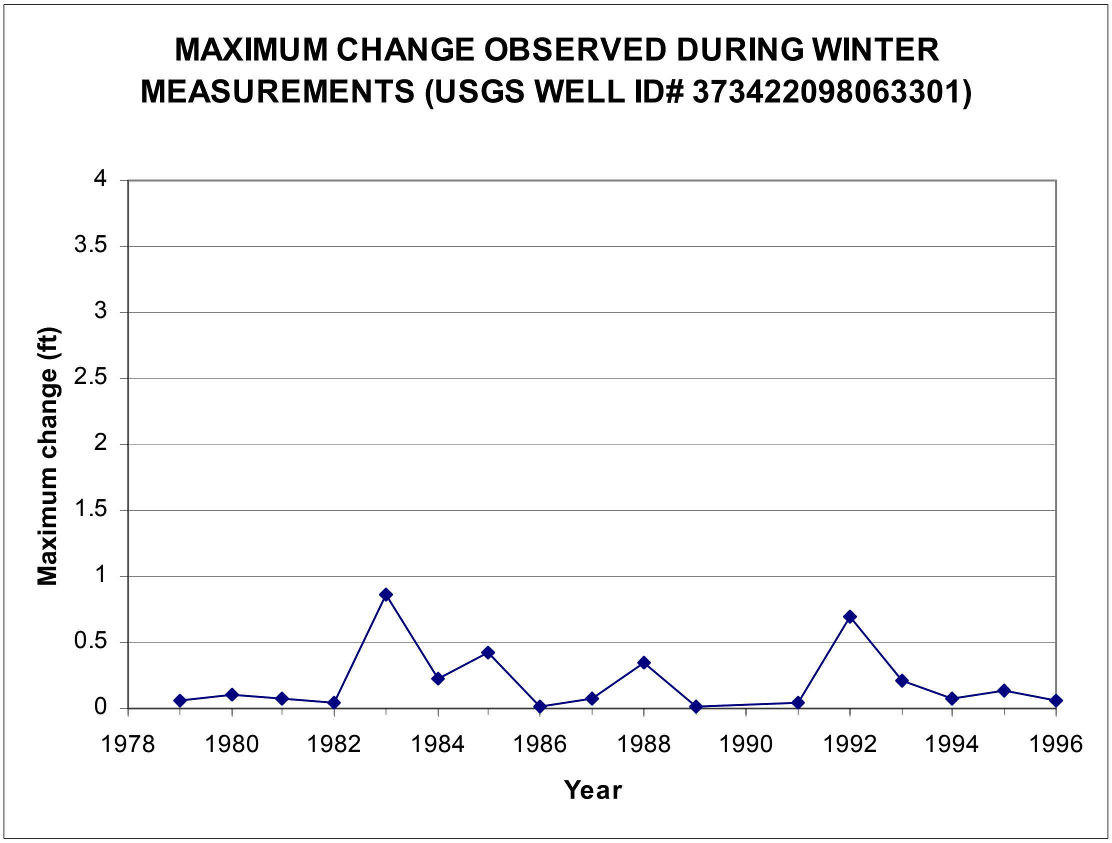

Figure 4.9: Differences in winter water level measurements for a Kingman County irrigation well distant from any significant non-irrigation pumping.

Figure 4.7 illustrates the potential for interference in water level measurements -- and this does not include interference resulting from off-season pumping of irrigation wells or of non-permitted (e.g., domestic) wells. Uncertainties from this source are probabilistic; therefore they cannot be assessed rigorously on a site-specific basis without actual experimental measurements, but sites and measurement times can be selected to minimize the probability of interference (see section 4.5).

5. Data limitations and applications

- A section-based grid system provides the most flexible, recognizable and consistent way of presenting and analyzing data. However, present limitations in some of the databases mean that the appropriate scale of management application is limited to subunits comparable to or larger than a township in size.

- Present water-level trend information is limited in scope to interpretation at the township scale in core regions of the aquifer, and to interpretation of trends over time periods of a decade or longer. Data are adequate for subunit identification and prioritization, but will probably require refinement for detailed management of priority units.

- Depending on the management strategy adopted, priority units may also require additional hydrogeologic aquifer characterization as part of a long-term management plan.

6. Policy and management implications

- The section-centered database provides a means for matching hydrogeologic and management boundaries at the finest scale supported by the data.

- Data and tools can be assessed in terms of their reliability and precision; they are presently adequate for subunit identification, prioritization, and development of initial management options.

- Proposed management strategies need to be evaluated at the level of uncertainty that is known about a particular data source to determine if the uncertainty is at a level that would change the management strategy's goals or objectives

- Refinement of databases and analyses to provide additional support for protocols, evaluations, and management approaches is practical

7. Potential for improved data or applications

- Lithologic and stratigraphic characteristics of the aquifer that do not vary over time can be further assessed and measured as needs and resources dictate to improve the knowledge base for refined local management. Such characterizations include:

    - ♦ Determination of the bedrock surface underlying the aquifer. The primary sources of are information for improving the characterization are water-well logs (WWC-5 records, and older logs in publications and kept by drillers for wells drilled previous to 1975), and geophysical logs from oil and gas well drilling. Additional information could be obtained from observation well drilling at selected sites of special interest.

    - ♦ Interpretation of the lithologic data for the aquifer, based on mathematical processing and knowledge of sedimentary depositional systems, is important for better characterization of the horizontal and vertical distribution, and probably hydraulic connection, of fine-grained, low permeability and coarse-grained, high permeability zones.

- Time-varying measurements, such as water-table elevation, can be refined and improved for specific local areas as illustrated by the results of the case studies and considerations reported in this and the companion OFRs. Among the improvements possible are:

    - ♦ Evaluation and minimization of the potential for pumping interference with water levels in measurement wells.

  - Establishing criteria for ensuring that measurements represent as nearly as possible the average elevation of the recovered water table, and that probable biases are understood and evaluated (see section 4 and report Appendix).
  - Determination of whether the water-level measurements represent water-table conditions in an unconfined portion of the aquifer or a potentiometric surface in a confined area (as described in uncertainty subsection 4.4 above).
- Access to and understanding of the available data and information by water users and managers can be improved by expanding the inventory of user-friendly data and tool sources, as discussed in section 2 above.

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Schloss, J. A., Buddemeier, R. W., and Wilson, B. B. (eds.), 2000. An Atlas of the Kansas High Plains Aquifer, http://www.kgs.ukans.edu/HighPlains/atlas/, and also published as Educational Series 14, Kansas Geological Survey, Lawrence, KS, 90 pp.

Willmott, C. J. and Matsuura, K., 2001. Willmott, Matsuura, and Collaborators' Global Climate Resources Pages: http://climate.geog.udel.edu/~climate/index.shtml

Appendix 1. Recommendations for Improving and Adapting the Annual Water Level Measurement Program for Aquifer Subunit Management Requirements

Potential uncertainties (other than the accuracy of the measurement itself, which is usually not the limiting uncertainty) in individual well measurements include:

- Incomplete regional recovery from the stress of the previous pumping season;
- Short-term local variations around the mean water level due to barometric pressure fluctuations;
- Systematic differences in confined and unconfined aquifer water levels (pressure variation suggests confinement); and
- Possible transient or sustained perturbation due to pumping of nearby wells.

In addition, there are other uncertainties that come into play in comparison of water level changes using multiple wells, especially if the records from different wells are combined over time.

The following items represent suggested options for reducing or controlling uncertainties and undesirable effects on applications of the data.

Preliminary draft recommendations, Water level measurement program upgrade (items 1-4 can be implemented under present program arrangements; 5-6 would require reorganization)

1. Ground (datum) elevation surveys (better than 0.5’ accuracy) to be made on all replaced/replacement well pairs, from now on, and retrospectively to ’95 as resources permit.

Rationale: this is required to make the replacement well a true replacement in terms of water level/difference measurements – without this, well changes may introduce up to several feet of instantaneous offset into the region represented by the well.

Note 1 – this is a cost item, but is critical component of improving absolute accuracy and precision of change measurements.

Note 2 – This is one of the few possibilities for retrospectively improving the quality of measurements in the past decade, where previously measured wells still exist and can be surveyed along with their replacements.

2. Wells to be evaluated for proximity to non-irrigation wells (present and recent past network wells) that might produce winter-season interferences.

Note: this is readily done as a GIS exercise.

3. Develop criteria and priorities for investigating and replacing network wells with high probability of interference, and/or questionable representativeness.

3.1. Wells to be evaluated for barometric pressure response/confined aquifer characteristics.

Note 1: Although this involves some cost and effort, it is fairly easily achieved by rotating movable transducer units through wells (when they are not being pumped) for time periods of a few days to a week.

Note 2: This can and should be prioritized according to the sensitivity/importance of the well data (e.g., classification of subunit and area represented by well)

3.2 Develop criteria and priorities for replacing and/or measuring high variability wells, and for identifying the geographic extent and characteristics of confined or semi-confined aquifer subunits.

4. Shift measurement times to as late in the non-irrigation season as is feasible to maximize recovery.

Note 1: Synoptic measurements are NOT necessary; local variations in (e.g.) cropping or pre-irrigation practices may actually make for more efficient use of personnel and equipment by spreading the measurement period over a longer time.

Note 2: An initial transition period of doing both standard early January and late-season measurements, at least in some regions, might be desirable as cross checks on the effects of the transition – this would be a cost item.

5. Redesign measurement system to conform to and support high priority management subunits – Develop an orderly evolution from the present system that maintains and improves existing data source, into a management-oriented system that includes:

5.1. One or more continuously monitored (non-pumping) index wells per unit

5.2. A network of hand-measured wells (and/or additional recorder wells) with schedule/frequency keyed to index well data and local pumping practices to supplement the existing network.

5.3. Options for including owner-participant contributed measurements into the centralized (Wizard or Wizard-derived) database for easy access and analysis of all available data (possible MOU or other mechanism) – subject to review and quality control

5. Develop more involvement of GMD’s and DWR field offices to maximize local relevance of and participation in the program; retain KGS/DWR design oversight, data storage, data evaluation/interpretation, and data dissemination to maintain credibility and accessibility.

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Kansas Geological Survey

Open File Report 2002-25G

Information Sheets and Supplementary Documents

By

M. A. Townsend, D. O. Whittemore, D. P. Young, G. Hecox, P. A. Macfarlane,
M. A. Sophocleous, and R. W. Buddemeier

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Kansas Geological Survey Open File Report 2002-25G
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KGS OFR 2002-25G. Information Sheets and Supplementary Documents

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KGS OFR 2002-25G.
Information Sheets and Supplementary Documents
By M. A. Townsend, D. O. Whittemore, D. P. Young, G. Hecox, P. A. Macfarlane, M. A. Sophocleous, and R. W. Buddemeier

1 Introduction

This report contains supporting and supplementary information documentes relating to the design, conduct, and output of the projects reported on in the overall OFR 2002-25 series.

The technical content (section 2) consists of the seven information sheets developed by the KGS for the Ogallala aquifer management and technical committes. These sheets were developed in response to specific questions or requests from the committees or committee staff, and are intended to provide brief summaries understandable by a lay audience. These information sheets are included since they document work performed under the contract, and contain pertinent information related to the Ogallala-High Plains aquifer. They also present possible issues and parameters for further consideration in subunit delineation and the development of potential management options. They are presented as originally distributed, and have not been edited to conform to subsequent findings.

Information sheet 2.1 relates primarily to report part 25B; 2.2 relates to 25B and 25C; 2.3 relates to 25D and 25F; 2.4 relates to 25C; 2.5 relates to 25F and 25D. Information sheets 2.6 and 2.7 are responses to questions about issues not directly addressed by the contract reports.

Section 3 contains excerpts from the Ogallala committee report, providing information on the motivation for identification and prioritization of aquifer subunits as an approach to managing the watrer resources in areas of present or potential depletion.

Section 4 presents copies of the two contracts under which the reports were generated and some of the work discussed was supported.

2 Technical information sheets developed in response to committee requests

2.1 Recharge- Recharge amounts (accuracy, precision, uncertainty)

1. Focused question: What is the amount of annual recharge to a selected region?

2. General applications question: What is the reliability and utility of recharge estimates for water resource planning and management?

Summary responses:

1. Recharge values are necessarily estimates, based on some combination of model-based calculations with observations of other variables (such as groundwater elevation, stream baseflow, precipitation, soil moisture, etc.). As such, they represent estimates of the relatively long-term average amount of water that penetrated below the rooting zone.

In Kansas, the most widely accepted regional recharge estimate is that prepared by the USGS. This has been used, for example, by KGS in preparing the relevant sections of the High Plains Atlas. Based on the USGS maps, the western third of Kansas can be estimated to have a total (including aquifer and non-aquifer) area of about 30,000 sq. mi., and an average annual recharge of about one inch -- with lower values in the west and higher in the east. This would correspond very approximately to 1.6 million AF/year. However, the 'recharge' that appears to occur where there is no aquifer and little or no groundwater use is of no real resource significance. That can be somewhat refined by looking, for example, at the recharge estimates for the total areas of the GMDs, or for those parts of the GMDs that have relatively low saturated thickness and therefore might be priority management areas. Considering only the GMD areas brings the recharge estimate down by factor of 3; considering only the areas depleted or at risk reduces the total by a factor of about 10.

Western GMDs, Recharge estimates from High Plains Atlas (MAF/yr) based on USGS

	GMD4	GMD1	GMD3	Total
Total Recharge	0.16	0.05	0.33	0.54
Where ST<50’	0.04	0.03	0.06	0.13

However, even these refined figures may be of little significance in management by aquifer subunits defined on the basis of hydrology and water use. This is because the rates of groundwater flow and exchange are slow, and recharge on one side of a GMD -- or a county, or even perhaps a township -- will not have a noticeable effect on the other side for decades or longer. Estimating specific recharge values at the subunit level are subject to the problems discussed below.

2. Recharge is an important process, and an important concept in water resource management. Its estimates provide important constraints on, and general inventories of, water availability. However, it is one of the most variable, uncertain, and difficult hydrologic

parameters to measure or calculate accurately. Recharge values generally do not make good practical management tools, for the following reasons:

a. Time lags and variations -- in relatively arid regions with thick unsaturated zones, recharge may occur in only a few years per decade, and the water may be delayed up to decades in its progress from the surface to the water table. By contrast, alluvial valleys in the same region will be much more responsive.

b. Recharge is sensitive to land use, treatment and cover -- and therefore subject to change as farming practices, urbanization, etc., change.

c. Even without human intervention, recharge quite variable over space, even at the field scale.

d. Recharge is dependent not only on climate parameters such as precipitation and average water balance, but on the details such as the timing, frequency and intensity of rainfall -- which studies have shown have changed significantly over past decades.

e. Because of the above relationships and uncertainties, estimated recharge values not only change as a result of actual recharge change, but also are subject to alteration as measurements and models evolve.

Comments and general information:

An appreciation of the magnitude of ground-water recharge and of the factors controlling it is critically important to general water resource planning and management. Not only do the approximate values provide some boundaries for the possible ranges of sustainable use, but knowledge of the mechanisms and controls can lead to land use and other management techniques that can enhance or protect natural recharge, or identify areas or aquifer subunits most likely to have significant replenishment rates.

Because of variability and uncertainty in the absolute magnitudes of recharge, however, it is generally more practical to manage groundwater on the basis of direct measurements of use and supply (for example, pumping, stream discharge, and water level or saturated thickness) within a framework based on the approximate values for recharge.

2.2 GMD #1 Water Balance

The approach to the water balance was to quantify the volume of groundwater withdrawn from the GMD1 groundwater system over the period from 1990-1999 and compare that to the volume of water that may be accounted for by various forms of recharge and storage depletion. The time period was selected because these are the 10 years for which the groundwater use data were compiled for the document "An Atlas of the Kansas High Plains Aquifer" (the Atlas; Schloss, et al, 2000). Once the various variables were identified and quantified the water balance is simply a comparison of the water removed and the water inflow plus storage depletion. The basic equation used is:

The variables required for use in the water balance were compiled from various public datasets and databases and are summarized in Table 1.

After all of the variables required to conduct the water balance were compiled, a statistical evaluation was conducted to check for outliers and anomalous values. For purposes of the water balance, it was decided to perform the water balance calculations using the arithmetic average, minimum and maximum values for each of the Table 1 Inflow variables (Table 2).

Table 1. Water balance variables and data sources.

	Variable	Water Balance Use	Data Source
Outflow	Reported Groundwater Use	Groundwater Outflow	**wuse_90_99_raw2.dbf. Compiled by Brownie Wilson from DWR water use reports.**
Inflow	Irrigation Return Flow	Irrigation returns	**Calculated as percentage of irrigation water use: 15% of flood irrigation and 5% of sprinkler irrigation.**
	Area of GMD 1 evaluated	Storage depletion Recharge inflow	**Secpols coverage file, variable is *Acres.* This is an ArcInfo file available through KGS.**
	Specific yield	Storage depletion	**Secpols coverage file, variable is *Spec_yld.***
	Water level decline rate	Storage depletion	**Secpols coverage file, variable is *Acres.***
	Natural recharge rate	Recharge	**Secpols coverage file, variable is *Usgs_recharge.***
	Hydraulic conductivity	Groundwater inflow	**Secpols coverage file, variable is *Acres.***
	Hydraulic gradients	Groundwater inflow	**Secpols coverage file, variable is *Acres.***
	Saturated thickness	Groundwater inflow	**Secpols coverage file, variable is *Acres.***
	Cross-sectional width	Groundwater inflow	**Measurement across *Hp_saturated* polygon.**
	Steam flow	Surface water infiltration	**USGS database at** http://ks.water.usgs.gov/ for Smokey Hill and Ladder Creek

Table 2. Groundwater variables and values used in water balance calculations

Variable	**Units**	**Min**	**Max**	**Mean**	**Relative Uncertainty**
Specific Yield	fraction	0.10	0.25	0.17	Low
Annual rate of water level change	feet/year	-2.17	1.85	-0.42	Low
USGS Recharge	in/year	0.50	0.70	0.53	Moderate
Area of GMD 1	acres	–	–	1,026,000	Negligible
Hydraulic gradient	foot/foot	–	–	0.002	Low
Hydraulic conductivity	feet/day	–	–	100	Moderate
Saturated Thickness	feet	–	–	80	Moderate
Cross-sectional width of flow path	feet	–	–	64,000	Low
Inflow from Recharge	Acre-feet	428,000	599,000	453,000	Moderate
Inflow from Storage Depletion	Acre-feet	431,000	1,077,000	733,000	Low
Groundwater Inflow from west (total in 10 years)	Acre-feet	90,000	90,000	90,000	Moderate

The Outflow variable, Reported Groundwater Use, is presented on Figure 1, along with irrigated acres and calculated irrigation return flow volumes. For the Outflow variable, it was decided that the Reported Use volume would be treated as a maximum Outflow value and an arbitrary 75% of the Reported Use would be used as a minimum possible Outflow volume for illustration purposes.

The results of the water balance are presented on Table 2 and Figure 2. It is concluded that the available data for the GMD 1 area, with all of the inherent variability and uncertainty discussed in such data, could be used to develop a reasonable understanding of the groundwater flow conditions in this area. A reasonable dataset is available to begin development of quantitative groundwater resource management tools for the GMD 1 area.

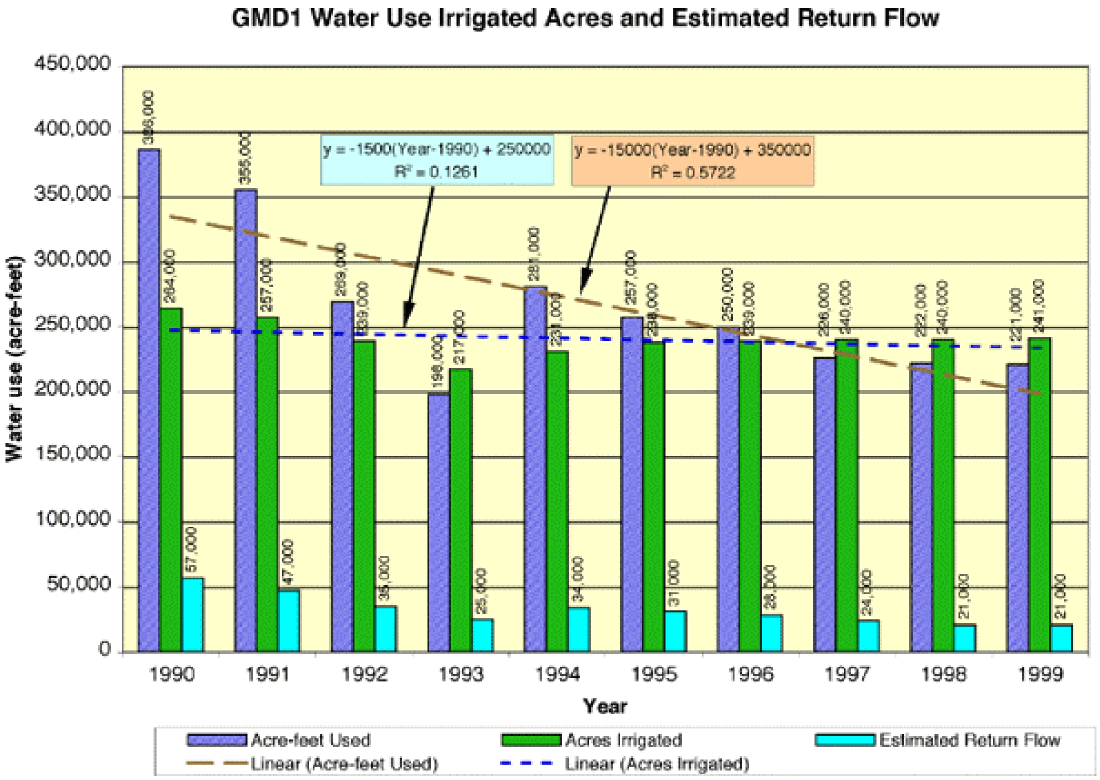


Figure 1. Groundwater use, irrigated acres, and irrigation return flow volumes.

Table 3. Water balance results

	Production Volume		***Inflow Volumes***		
Variable	Reported Use (AF)	Minimum Use (AF)	Average Inflow (AF)	Minimum Inflow (AF)	Maximum Inflow (AF)
Groundwater Use	2,665,000	1,999,000			
Storage Depletion			733,000	431,000	1,077,000
USGS Recharge			453,000	428,000	599,000
Irrigation Return Flow			323,000	162,000	646,000
Ladder Creek streamflow			34,000	10,000	140,000
Groundwater inflow			90,000	90,000	90,000
Total Volumes	2,665,000	1,999,000	1,543,000	1,121,000	2,552,000
Water Balance Inflow Deficit (Acre-feet)			1,122,000	1,545,000	113,000
Water Balance Inflow Deficit (%)			42	58	4

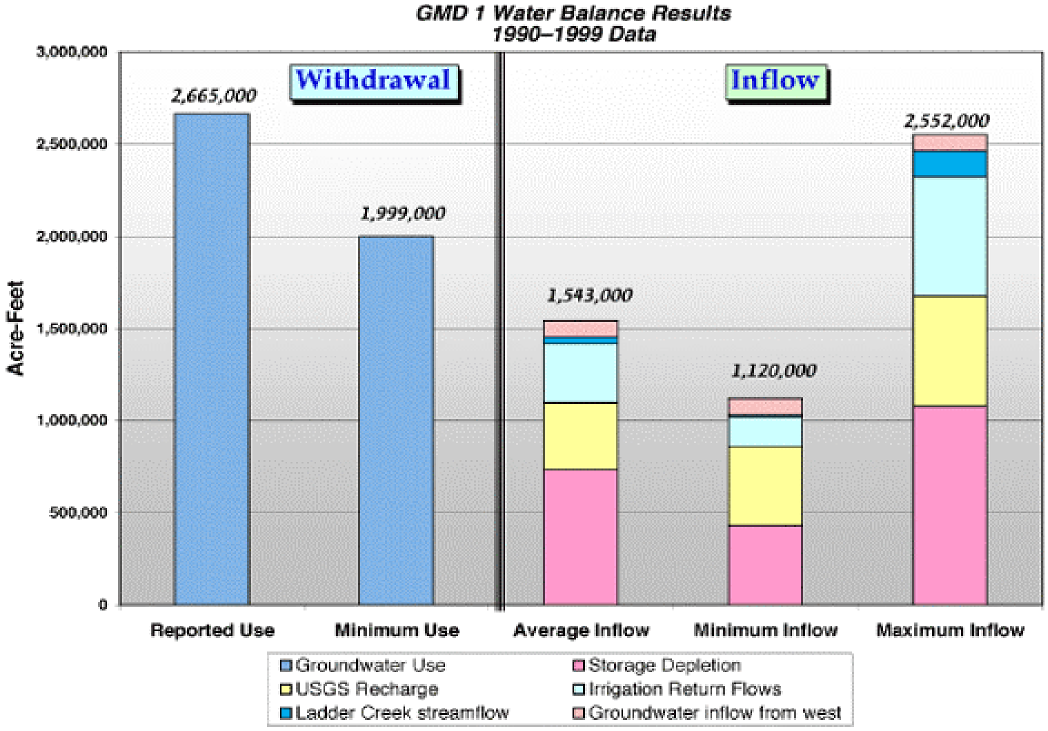


Figure 2. Water balance results for GMD-1.

2.3 Quality (accuracy, precision, uncertainty) of water level measurements

1. Focused question: What is the quality of the annual measurements of depth to water?

2. General applications question: What is the reliability and utility of water level change information derived from these measurements?

Summary responses:

1. The field measurements of the annual water level program have been developed and tested, and are applied, under a rigorous program of quality control that includes standardized procedures, training and cross-checks for technical staff, and statistical analysis of the measurements. The original procedure design, and the results of annual assessments, are published in a series of reports available from the KGS. The specific depth-to-water measurements and their recording are of high quality, and subject to continuing review and monitoring to maintain that quality. In practical terms, this means that the large majority of the measurements are within 0.1' of the "true" values of depth to water at the time and place measured.

2. The utility of these high-quality point measurements of depth-to-water depends on how well they can be used to calculate the net change of elevation in the water table over an extended area. An underlying assumption is that the depth-to-water measurements can be used to represent the absolute elevation of a fully-recovered, equilibrium water table. This is an approximation that has numerous uncertainties:

> a. The standardized measurement period in early January is significantly before many of the wells have recovered fully from pumping -- either in the measurement well or in the surrounding region -- during the previous irrigation season. The recovery is not only incomplete, but its extent varies from year to year. At specific sites, this can introduce 'noise' into the record that is on the scale of feet.
>
> b. Related to factor (a) is the point that well selection in the program to date has not taken into consideration distance to other wells that may affect how well the measurement represents a regional equilibrium. This is a particular issue in the case of municipal and industrial wells that may be pumping during the period of measurement.
>
> c. The water table elevation is calculated by combining precise depth-to-water measurements with land elevation values that are, in most cases, estimated from a topographic map and necessarily have uncertainties comparable to the map contour intervals (plus or minus 2-3 feet). This does not affect comparisons of water levels at the same well, but it introduces significant uncertainties in comparing levels at different wells, especially when a measurement well is replaced in the network.

These compound uncertainties have been recognized and reflected in the standard caution in the KGS Technical Series publications on annual water levels, that individual annual and local changes should not be considered reliable but that trends observed over a period of years and areas observed by multiple wells can be used with confidence. Additional comments are presented below.

Comments and general information:

Recent expanded interest in assessing, managing, and conserving the Ogallala aquifer resources place demands on the water level data base which the measurement system was not designed to meet. KGS, with contributing support from KWO, KDA, and individual GMDs, has an ongoing program to review and assess options for improving the interpretations of existing measurements and for identifying potential improvements in the program (see, for example, KGS Open-file Report 2000-29B, viewable at http://www.kgs.ukans.edu/HighPlains/2000-29B/Decdir.htm)

There are a significant number of cost-effective steps that can be taken to not only improve future measurements, but also retrospectively improve our interpretation of existing data. These need not be accomplished for the entire aquifer at once, but can be phased in on the basis of selected case studies or priority areas. Among the more promising possibilities are:

a. GPS elevation surveys of present and past measurement wells would improve the accuracy of comparisons between wells, retrospectively as well as in the future.

b. Detailed comparison of the water use, water level and water budget data that has recently been made possible by electronic database assembly and access improvements has the potential to greatly improve our interpretation of the degree of recovery and general reliability of individual well measurements.

c. Use of water level recording devices, at least on selected sub-regional index wells, will provide a basis for design and interpretation of measurements in the future, as well as insights into past observations.

d. Where recording is not a convenient option, manual measurements can be scheduled and/or performed on the basis of knowledge of local pumping practices and potential interferences in a given aquifer subunit, with individual subunits measured as late in the recovery season as possible to better approximate the equilibrium water table.

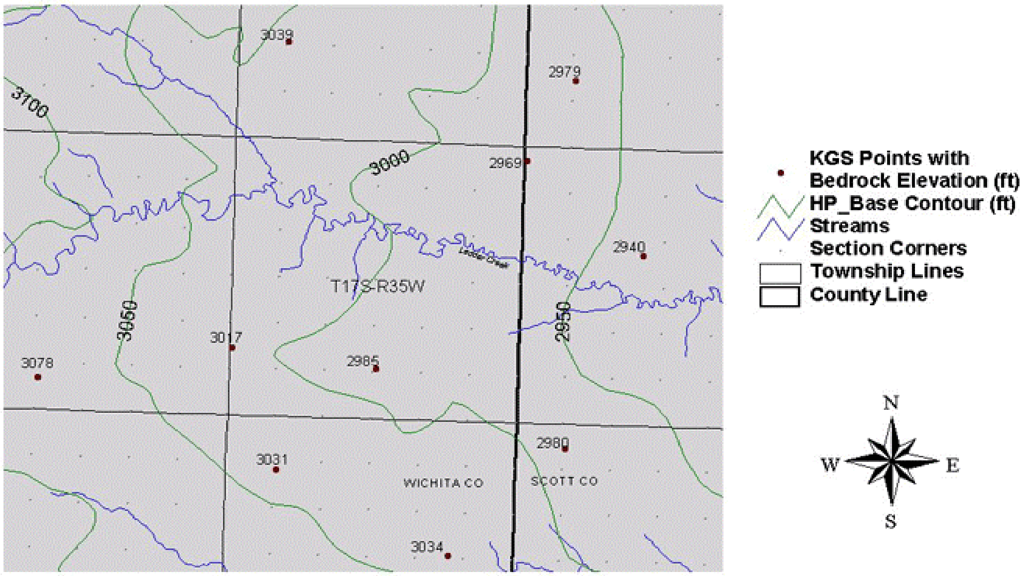
e. Well selection criteria can be modified to consider not only additional hydrologic considerations (e.g., to minimize potential interference), but also specific management needs and priorities in designated aquifer subunits.

2.4 Bedrock – Preliminary Analysis of Bedrock Surface Estimates and Data Sources

A preliminary analysis of available bedrock elevation estimates was undertaken in a randomly-chosen township in GMD1. The selected township is T17S-R35W in Wichita County.

The USGS Base of High Plains (HP_Base) contours were compared with the KGS point data used to create the bedrock surface used in the High Plains Atlas (Fig. 1). Also, a limited amount of readily-available point data was compiled and compared with the USGS contours and KGS point data (Fig. 2). The only additional data sources used in this initial exercise were WWC-5 forms and the county bulletin (Prescott et al., 1954).

Fig 1. USGS HP_Base Contours and KGS Bedrock Point Data
in and Around T17S-R35W

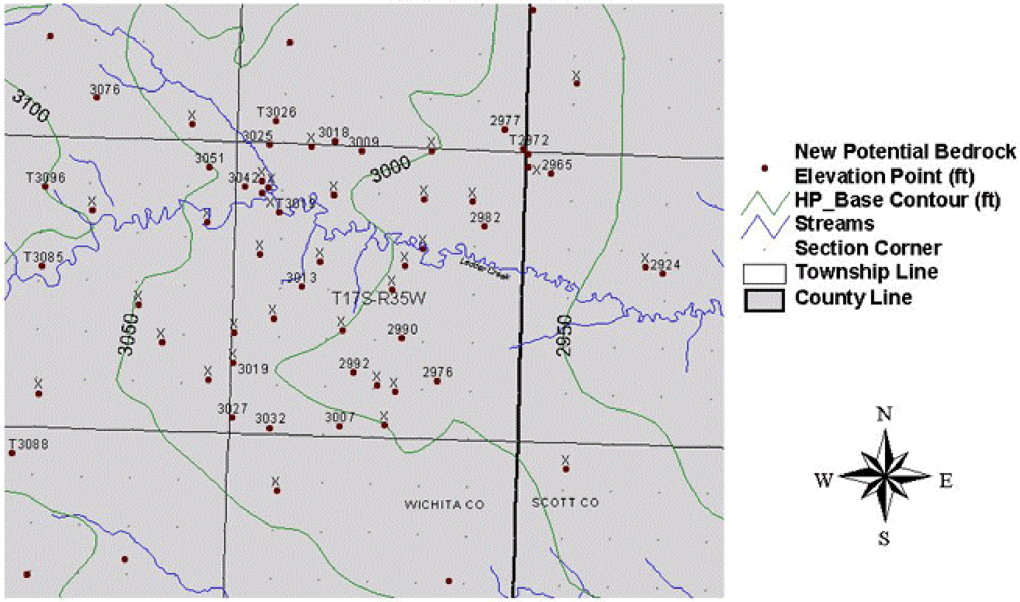


- The USGS Base of High Plains (HP_Base) map provides 50-ft interval contours developed from 1:500,000-scale source information. USGS point data for the HP_Base contour map are not available.

- KGS bedrock elevation point data (used for HP Atlas bedrock surface) were obtained from the KGS WIZARD (Water Information Storage and Retrieval Database). However, not all bedrock data available from WIZARD were used.

Fig 2. Potential Additional Bedrock Elevation Points in and Around T17S-R35W

X indicates location on log was questionable and/or surface elevation could not be picked with confidence
T indicates published log of test hole



- Generally, the both the WIZARD points and the additional point data agreed well with the USGS contours. Point density was improved substantially by using additional data. Potentially, the bedrock surface could be mapped with a contour interval of 25 ft or less, but no significant changes in the present average values would be expected *in this area*.

- Other untapped sources of bedrock data could further refine the bedrock surface and reduce uncertainties. Potential sources include: GMDs and other agencies, local drillers and landowners, Kansas Department of Transportation files, oil and gas logs, and other published and unpublished data.

- Surveyed locations and elevations of selected wells, especially using a high-accuracy Global Positioning System (GPS), would improve the absolute accuracy of bedrock surface, as well as water table estimates.

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Prescott, G.C., Branch, J.R., and Wilson, W.W. (1954). Geology and ground-water resources of Wichita and Greeley counties, Kansas. Kansas Geological Survey Bulletin 108.

2.5 Monitoring Well Network

In 1982 the USGS water level monitoring network was evaluated by the KGS staff to determine the "optimum" sampling design and needed enhancements to minimize the number of wells needing to be measured and to minimize the standard error of the water level measurement (Olea, 1982). The work was done using the 1795 water-level wells in use at that time.

- The error in the water level for the High Plains aquifer uses the average of the water-level values from the whole water-level network.
- There is no separation of areas based on variation in hydrology, geology, or geography.
- A hexagonal monitoring network was found to be the most efficient method of well placement (figure 1).

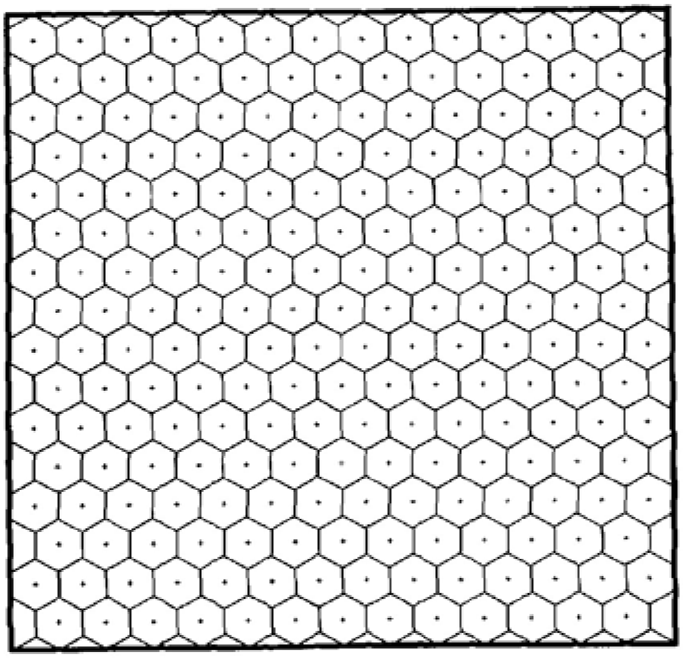

Figure 1. Hexagonal pattern used to place one observation well inside each polygon, which is 16 square miles in area.

- The values in Table 1 indicate that there is not a large difference in average standard error between a straight hexagonal pattern and a stratified hexagonal and stratified square pattern (figure 2).
- The stratified pattern means that one available sampling point is selected to represent the space within the hexagon surrounding a point. If more than one point falls within a given hexagon only one of those points is used.

- The results of the study indicated that due to cost considerations and the desire to use existing wells with long-term records a stratified hexagonal or square pattern would improve the sampling grid that existed (figure 2).
- The standard error in the existing water level measurement program is ± 10 ft.

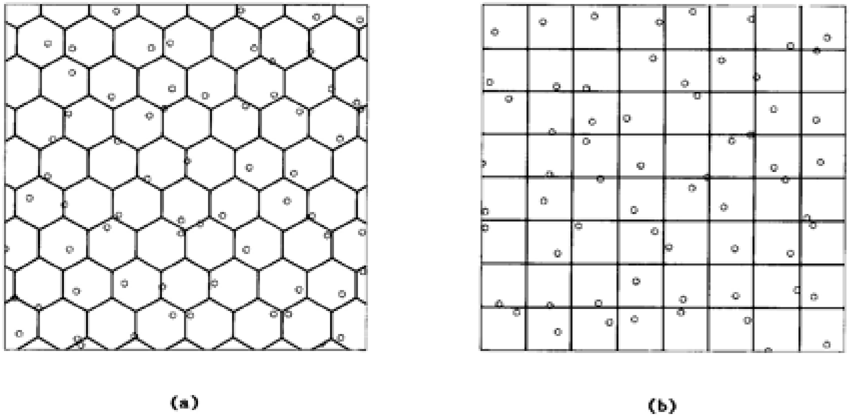

Figure 2. Sampling mechanism for stratified patterns. (a) One point is selected randomly from inside each hexagon. (b) One point is selected randomly from inside each square.

Table 1. Sampling Efficiency Indices for Different Sampling Patterns

Pattern	**Average Std. Error**	**Maximum Std Error**
Hexagonal	0.63	0.72
Square	0.64	0.74
Triangular	0.66	0.80
Hexagonal Stratification	0.69	0.86
Square Stratification	0.69	0.86

If the state of Kansas wishes to design and drill a monitoring well network for water level measurements the hexagonal pattern clearly has the lowest standard error and is most efficient (figure 1, table 1). However, if the desire is to decrease the standard error of the actual measurements and increase the level of accuracy in the estimation of the water table, the number of wells that would be needed in such a pattern becomes quite large (figure 3). The cost of drilling such a large number of wells also becomes a factor.

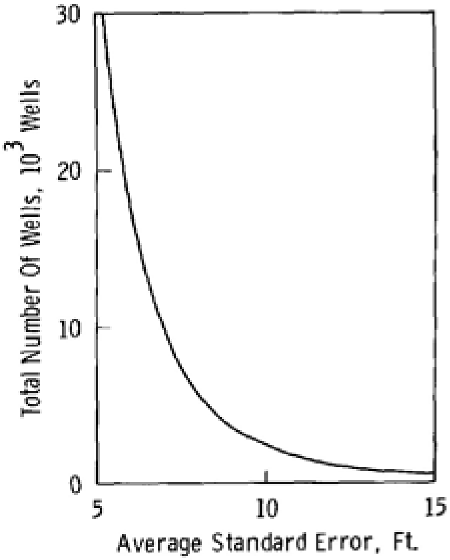

Figure 3. Network size as a function of level of accuracy in the estimation of water-table elevations in the High Plains aquifer in Kansas. Sampling is assumed to follow a hexagonal stratification.

The above discussion assumes that each new measurement point is perfect and that no known information exists between the two points. This is obviously not correct. One idea has been proposed to divide the High Plains area into "like subunits" in order to maximize similarities of hydrology and geology.

- The error in water level measurements would be typical of that area and would not use the "average error" calculated for the whole High Plains aquifer.
- Subunits could be selected by "intuitive" observation, such as northern Kansas with GMD4 and GMD1 areas, southwest Kansas (GMD3), and south-central Kansas (GMDs 2 and 5) or by use of the clustering technique as illustrated by Brownie Wilson's work.
- The error in the water level measurements would increase dramatically in southwest Kansas because of the large variation in areas with declining water levels
- The error would probably decrease in south-central and northern Kansas areas.
- Developing a monitoring network utilizing the subdivisions would probably result in a varying number of wells to be installed within each sub-area. This kind of analysis has not been done at present.
- The advantage of establishing a monitoring net by sub-area is that it would permit more efficient use of information within each sub-area for selecting future areas for drilling.

2.6 Review of USGS Water Quality Report

Below is a review of the U.S. Geological Survey's water quality study of the High Plains aquifer, for consideration by the Ogallala Aquifer Management Advisory Committee. Results of this study have made it into recent news reports, noting that nitrate and other contaminants have been detected in the Ogallala aquifer.

Litke, D. W., 2001, Historical Water-Quality Data for the High Plains Regional Ground-Water Study Area in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1930-98. USGS Water-Resources Investigations Report 00-4254,65 p.

The report is an overall compilation of water-quality data from the High Plains states being investigated in the USGS NAWQA (**Na**tional **W**ater **Q**uality **A**ssessment) program. Evaluation of the data was done on a subunit basis or time interval basis rather than by state boundaries. The aquifer subunits pertinent to Kansas include:

- Ogallala North (includes northern Kansas and parts of Nebraska, Wyoming, and Colorado)
- Ogallala Central (includes west-central and southwest Kansas as well as Oklahoma and northern Texas),
- Kansas Quaternary deposits (south-central Kansas), and
- Valley-fill alluvium (includes Platte River, Republican River, and Arkansas River).

The report evaluated nitrate, dissolved solids, pesticides and other constituents as major categories of interest. My review is of the analysis of nitrate, dissolved solids, and atrazine. The USGS analysis of nitrate and dissolved solid concentration changes with time is based on data from all aquifer units lumped together.

Nitrate

The U.S. EPA drinking water standard for nitrate is 10 mg/L. Where levels are above this amount, the water may cause health problems for infants or young animals.

From 1930 to 1998 an increasing trend in nitrate values was observed:

- Valley-fill alluvial deposits -1.5 ppm in 1930 to 5.5 ppm by 1998.
- Kansas Quaternary deposits - 3.5 ppm in 1940s to 4.5 by 1998.
- Central Ogallala - general range of 2 ppm during the 1940s to 1998.
- Northern Ogallala –1.8 in1930s to 3.5 ppm by 1998.

  The range of reported nitrate values and number of samples evaluated:
- Northern Ogallala – less than 1.1 to greater than 8.9 ppm (1,787 samples)

- Central Ogallala – less than 0.6 to greater than 5.6 ppm (1,468 samples)
- Kansas Quaternary deposits – less than 0.1 to greater than 15.7 ppm (302 samples)
- Valley-fill alluvium – less than 0.1 to greater than 20 ppm (2,544 samples)

These values indicate the wide variability present in the High Plains aquifer depending upon such factors as depth to water, well construction, land use, fertilizer use, and type of well use (municipal, irrigation, industrial, etc.). The higher values indicate that throughout the High Plains (not just in Kansas) there is a potential for nitrate problems.

- Land use was a significant factor in the Kansas Quaternary deposits and the Ogallala Central areas (as well as other parts of the study area).
  - Nitrate concentrations were smaller under rangeland than under agricultural areas (no values were given in the text).
- Irrigation intensity showed a significant but weak relationship in areas with shallow water table (Kansas Quaternary deposits).
  - Irrigation intensity was not correlated with nitrate values in either the Ogallala north or central areas.

Salinity

A recommended secondary standard for total dissolved solids (salinity) is 500 mg/L. Above this level water hardness; chemical deposits; corrosivity; colored water; staining; and salty taste may be noticed in the water.

- Variable salinity occurs throughout the entire High Plains aquifer.
- The range of dissolved solids in the Kansas Quaternary deposits and Ogallala central area was between 300 and 350 ppm from 1930s to 1998
- The alluvial areas and the northern part of the Quaternary deposits had a range of values from 501 to 1,000 ppm prior to 1980.
- After 1980 more hot spots of salinity values greater than 1,000 ppm occurred.
- Land use evaluation showed that urban areas in the three Ogallala areas had larger dissolved solids concentrations that the other units.
- Areas such as the Arkansas River valley have higher dissolved solids and sulfate concentrations than other portions of Kansas.
- The underlying Cretaceous units in Kansas caused larger dissolved solids concentrations in those areas than in other portions of the High Plains aquifer.

Pesticides

- About 75% of pesticide data came from sites in Nebraska and central Kansas
- Atrazine detections were larger in areas of agricultural land that produced corn or sorghum

- Shallow aquifers, such as the Platte River alluvium in Nebraska, were most susceptible to pesticide contamination
- Pesticides were detected in the deeper High Plains aquifer but not as frequently as in the shallower portion of the aquifer.
    - Presence of pesticides in the deeper aquifer indicates that contamination pathways exist and may pose a potential future problem.

Summary

- Overall the report indicates that contamination of the High Plains aquifer has occurred primarily due to agricultural practices over the years.
- Certain parts of the High Plains aquifer in Kansas (mostly areas with shallow water tables) have nitrate above the drinking water limit and increasing salinity problems at present.
- The presence of nitrate and pesticide in the deeper portions of the aquifer (including parts of Kansas) indicate that pathways exist for future movement of contaminants into the aquifer.
- The slow movement of water through the unsaturated zone to the ground-water table indicates that the potential for long-term contamination exists.

2.7 Question of blending of oil and gas brine with Ogallala aquifer water

During the June 28, 2001 meeting, one of the members of the Ogallala Management Advisory Committee raised the issue of using brine from oil and gas production and blending it with Ogallala ground water to extend the life of the aquifer. The following document reports the typical salinity levels (both chloride and total dissolved solids concentrations) in oil and gas brines in western Kansas and in the Ogallala portion of the High Plains aquifer. These values were used to calculate the volumes of brine and Ogallala aquifer water that would bring mixtures of the two waters to recommended standards for drinking water and upper limits for use of irrigation water.

Chemical Characteristics of Oil and Gas Brines in Western Kansas

Oil and gas brines in western Kansas are sodium–chloride type waters. Chloride is the dissolved constituent in highest concentration in the brines. Sulfate concentration in the brines is typically around one tenth or lower of the chloride concentration. The typical chloride concentration ranges from about 19,000 mg/L (close to that of seawater) up to 100,000 mg/L. (A mg/L is essentially the same as a ppm in freshwater but is slightly greater than a ppm in brine due to the greater density of the brine than of freshwater.) The typical concentration of total dissolved solids (TDS) ranges from 35,000 mg/L (close to that of seawater) up to 160,000 mg/L. Some brine in the deep Arbuckle Group can have chloride concentrations as low as about 10,000 mg/L and TDS contents as low as 20,000 mg/L. Some brine in other formations can have chloride and TDS concentrations as high as 200,000 mg/L and 340,000 mg/L, respectively. For comparison, seawater contains chloride and TDS contents of 19,400 mg/L and 35,800 mg/L, respectively.

Chemical Characteristics of Ground Waters in the Ogallala Aquifer

Ground waters in the Ogallala portion of the High Plains aquifer in western Kansas are usually fresh and are calcium, magnesium–bicarbonate in chemical type. Chloride and TDS concentrations are typically in the ranges 5-50 mg/L and 250-600 mg/L, respectively. The chloride and TDS contents average approximately 20 mg/L and 380 mg/L, respectively, if the ground waters affected by saline Arkansas River water are not included.

Water for Drinking and Irrigation Use

The recommended standards for drinking use are 250 mg/L for chloride and 500 mg/L for TDS concentration. Although the chloride level that different crops can withstand ranges depending on the crop and soil type, concentrations greater than about 350 mg/L begin to cause reductions in yield. The usual definition of the division between freshwater and saline water, 1,000 mg/L TDS content, is the effective upper limit of sodium–chloride type water that can be used for irrigation water use before yield reductions occur. Crops can withstand greater concentrations of sulfate and TDS in sodium–sulfate type water than of chloride and TDS in sodium–chloride type water.

Blending of Brines and Ogallala Aquifer Water

The amount of oil and gas brine that could be blended with ground water from the Ogallala aquifer to produce a mixture that could still be used would depend on the chemistry of both the brine and the aquifer water. The chemical type of water that would result from blending of a brine and Ogallala aquifer water to produce a mixture at a use limit would range from calcium, sodium–bicarbonate, chloride to sodium–chloride, depending on the amount of brine in the mixture. Table 1 lists the volume percentages of brine and Ogallala water in various blends based on different ranges of typical brine chemistry, average Ogallala composition, and water-use limits.

The volume percentage of Ogallala aquifer water that would be necessary to dilute oil and gas brine to a usable level ranges from about 98% to over 99.1% of the mixture. The volumes are mainly dependent on the chloride and TDS concentrations in the starting Ogallala water and the salinity of the brine. For illustration, it would take about 100 acre-ft or more of average water from the Ogallala aquifer to dilute one acre-ft of average oil and gas brine to a usable level. The volume of brine that could contaminate fresh Ogallala ground water to over limits recommended for use ranges from less than 2% to as low as less than 0.1% of the mixture. This shows why a small volume of oil brine can contaminate a large amount of freshwater. The unit usually used by the petroleum industry for volumes of oil and saltwater is the barrel, which is equivalent to 42 gallons. There are 7,758 barrels in an acre-ft of water. The amount of an average oil and gas brine from western Kansas that would contaminate an acre-ft of fresh Ogallala ground water to chloride and TDS levels greater than recommended for use would usually be less than 100 barrels.

The computations indicate why oil and gas brine in western Kansas would not be a suitable source of water to use to extend the life of the Ogallala aquifer. If marginal quality water were to be used in western Kansas to blend with Ogallala aquifer water, a more appropriate source would be slightly saline water from the Dakota aquifer with a TDS content of 1,000-2,000 mg/L in west-central Kansas.

Table 1. Volumes of Oil and Gas Brine and Ogallala Aquifer Water in Mixtures at Usable Limits for Drinking and Irrigation Use.

Average Ogallala aquifer content, mg/L	Oil and gas brine content, mg/L	Brine and Ogallala water mixture, mg/L	Percent volume of Ogallala water in mixture	Percent volume of brine in mixture	Volume of Ogallala water to dilute one acre-ft of brine, acre-ft	Volume of brine to contaminate one acre-ft of Ogallala water, barrels
Mixtures based on chloride concentration for drinking water use						
20	19,000	250	98.79	1.21	82	95
20	100,000	250	99.77	0.23	434	18
Mixtures based on chloride concentration for irrigation water use						
20	19,000	350	98.26	1.74	57	137
20	100,000	350	99.67	0.33	302	26
Mixtures based on TDS concentration for drinking water use						
380	35,000	1,000	99.65	0.35	288	27
380	160,000	1,000	99.925	0.075	1,329	5.8
Mixtures based on TDS concentration for irrigation water use						
380	35,000	1,000	98.21	1.79	55	141
380	160,000	1,000	99.61	0.39	256	30

3. Relevant excerpts from the report to the Kansas Water Office *"Discussion and Recommendations for long-term management of the Ogallala Aquifer in Kansas"*, by the Ogallala Management Advisory Committee
http:// /www.kwo.org/Reports/ogallala_mgt__rpt_.htm

(Excerpts from the body of the report, section II, Recommendations)

1. ***Delineate the Ogallala Aquifer into aquifer subunits to allow management decisions in areas of similar aquifer characteristics.***
Each Groundwater Management District, and the Division of Water Resources for areas outside of GMDs, should delineate these subunits. The Kansas Geological Survey, Division of Water Resources, Kansas State University, and Kansas Water Office should cooperate and assist through the water planning process.
1. ***The GMDs and DWR should identify each aquifer subunit in decline or suspected decline and establish water-use goals to extend and conserve the life of the Ogallala Aquifer.***
Setting water-use goals in aquifer subunits helps define the enormous challenge of managing this large, extremely valuable resource today and into the future. In areas where ample supplies remain either no reductions will be necessary or modest reductions may be recommended to help extend and conserve the life of the aquifer and reduce stress on nearby subunits. In a subunit with a rapid decline and a short estimated usable lifetime, a more aggressive goal should be set. Assistance programs would be targeted to those areas to help reach the water-use goals. Variables to consider in setting the water-use goal include the estimated volume of water available, recharge, amount of annual water use, estimated usable life of the aquifer, public input and others should be determined by the GMDs and DWR.
2. ***Identify aquifer subunit priorities to extend the life of the aquifer and sustain the vitality of western Kansas.***
Base priority on rate of decline, the estimated time before an area must transition to less water use due to declines and the potential socio-economic impact of the decline and other factors. High priority aquifer subunits should be candidates for acquiring additional information necessary to implement plans, assistance programs and/or other actions deemed necessary by the GMDs and DWR. If incentive and voluntary plans are unsuccessful, then strict administration of existing water law should be applied.

(Excerpts from Appendix A to the report, Menu of Options)

II. Management of Aquifer Subunits

A. *Develop a protocol to define criteria to a) identify preliminary aquifer subunits, b) establish preliminary water use goals for each subunit, and c) classify aquifer subunits as high, medium, or low priority, using existing data and tools recommended by the Technical Advisory Committee. The GMDs and DWR, with assistance and cooperation from the KWO, KGS, and KSU, are to establish the protocols and report them to the Kansas Water Authority by July 2003. The GMDs, and DWR for Ogallala aquifer areas outside the GMDs, are to identify preliminary aquifer subunits and preliminary water use goals.*
B. *The GMDs and DWR should set timelines to achieve sections C through H of the management proposal by July 2003. The progress made towards the aquifer subunit goals is to be reported to the Kansas Water Authority every 2 years, beginning in 2004.*
C. *The GMDs and DWR are to establish criteria to identify aquifer subunits as high, medium, or low priority, and then assign priority to each subunit in their areas. Consider factors such as rate of decline, the estimated time before an area must transition to less water use due to declines, legal (water right) criteria in each subunit, the economics, and potential socio-economic impact of the declines. High priority aquifer subunits would be targeted for additional data if needed, assistance, and possibly enhanced management.*

D. Identify aquifer subunits based on aquifer characteristics and other key parameters that can be used in water resource management. Each GMD is to identify the aquifer subunits within their district, and DWR is to identify the Ogallala aquifer subunits outside of the districts. The KGS, DWR, KWO and KSU should cooperate and assist. The Technical Advisory Committee has recommended several tools for delineating aquifer subunits. An aquifer subunit can later be redefined, based on new data or management needs.

E. For high priority aquifer subunits, enhanced water management plans should be considered by the GMDs. These enhancements can be developed with input from water users in the subunit about management approaches outside of strict water administration. The Chief Engineer must determine that these approaches are not in conflict with the water appropriation act and are in the public interest. If GMDs choose not to implement enhanced management plans the Chief Engineer may initiate them in response to the public interest to protect the resource.

F. Analyze additional data as needed to verify high priority aquifer subunit conditions, and as needed for proposed management strategies.

4 Copies of contracts

4.1 KWO-KGS Contract:

OGALLALA AQUIFER SUPPORT STUDY

I. PROJECT TITLE

This contract, effective August 15, 2001, between the Kansas Water Office (KWO) and the University of Kansas Center for Research, Inc. (CRINC, FEIN#480680117, 2385 Irving Hill Road, Lawrence, KS 66044) on behalf of the Kansas Geological Survey (KGS), shall be known as the "Ogallala Aquifer Support Study". All references to this contract shall include this title and the Kansas Water Office contract No. 02-114.

This contract shall be effective for the period of August 31, 2001, through June 30, 2002.

II. KANSAS WATER PLAN REFERENCE

WATER RIGHTS MANAGEMENT SECTION: Implementation of H.S. for S.B. 287 Report Recommendations.

III. KANSAS WATER PLAN 2010 OBJECTIVES

By 2010, reduce water level decline rates within the Ogallala Aquifer and implement enhanced water management in targeted areas.

IV. SCOPE OF WORK

Item	Description
1.	**Data Support:** The KGS agrees to collect and provide to the KWO specific data and information regarding the Ogallala Aquifer for the purpose of policy determination by the Management and Technical committees established by the Kansas Water Office.
2.	**Provide preliminary data and information needs as follows:** a. Best estimates of aquifer recharge from a magnitude and spatial sense, including the range of values of the estimates spatially and among scientific sources. b. Identify the potential relationships between saturated thickness and well yield both in magnitude and spatially distribution. c. Data reflecting the relationship between ground water levels, estimated usable lifetime for large volume pumping and water usage and whether that relationship can be represented spatially by a decade representation

	of time for selected water use options that will be identified during the quarterly meetings. d. Data reflecting climatic variations experience of current generation of irrigators as compared to long term climatic variations. e. The appropriate scale of use and precision of data sets identified during the quarterly meetings. f. Other data needs determined by the Ogallala Management and Technical Advisory Committees under the approval of both the KWO and the KGS.

V. DELIVERABLES

The KGS shall submit to the Kansas Water Office, 901 South Kansas Avenue, Topeka, Kansas, 66612-1249, the following items:

Item	Description	Delivery Date
1.	A progress report on items listed in the Scope of Work outlined in Section IV	October 12, 2001 January 11, 2002 April 12, 2002
2.	Final report and posted web page(s) on items listed in the Scope of Work outlined in Section IV	June 30, 2002

VI. COMPENSATION

The Kansas Water Office agrees to pay the KGS a total of $37,500 for the anticipated costs of accomplishing the Scope of Work outlined in Section IV and providing the deliverables listed in Section V. Payments will be made within 30 days, upon receipt of a billing from the KGS under the following schedule, and the receipt and acceptance by KWO of the indicated deliverables listed in Section V. It is understood that this contract is consistent in scope and purpose with the Kansas Department of Agriculture's and Kansas Geological Survey contract, dated June 12, 2001 and the Kansas Geological Survey's water plan fund appropriation from Senate Bill 57.

Item	Deliverable	Payment Amount	Payment Schedule

1.	Upon contract execution	$18,750	August 31, 2001
2.	Satisfactory completion of item 1 in Section V	$9,375	January 11, 2002
3.	Satisfactory completion of this contract.	$9,375	June 30, 2002

VII. COMPLETION OF THE CONTRACT

This contract shall be completed no later than June 30, 2002, unless otherwise modified in writing by mutual agreement of all parties. This contract shall be successfully completed upon review and approval by the Kansas Water Office of all deliverables as described in Section V. All items received may be used by the KWO upon receipt.

VIII. MODIFICATION AND EXTENSION OF CONTRACT

This contract may be modified or extended at any time upon written approval of all parties, but not later than 30 days prior to the aforementioned completion date.

IX. CONTACT PERSONS

The Kansas Geological Survey will be represented by Bill Harrison, Deputy Director and Chief Geologist, (785) 864-2070. The Kansas Water Office will be represented by Earl Lewis, Professional Engineer, (785) 296-0875.

X. KANSAS CONTRACT PROVISIONS ATTACHMENT

The provisions found in Contract Provisions Attachment (Form DA-146a - Attachment B), which is attached hereto, are hereby incorporated in this contract and made a part thereof.

XI. ACKNOWLEDGMENT

All products resulting from this contract shall acknowledge that this contract is funded (in part) by the State Water Plan Fund.

4.2: KDA-KGS Contract

AGREEMENT
Between
THE KANSAS DEPARTMENT OF AGRICULTURE
And
THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH INC.

This agreement is entered into on this _12____, day of June, 2001, by and between THE KANSAS DEPARTMENT OF AGRICULTURE (KDA) and THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.(KUCR) on behalf of the KANSAS GEOLOGIC SURVEY(KGS).

In consideration of the covenants contained herein, KUCR/KGS agrees to collect and provide to KDA specific data regarding the Ogallala aquifer for the purpose of policy determination by Management and Technical committees established by the Kansas Water Office. The specifics for the data required will be established and refined by discussions between the parties at 1 or more coordination meetings to be held in June of 2001.

Preliminary data needs could include; but shall not be limited to:

Best estimates of aquifer recharge from a magnitude and spatial sense, including the range of values of the estimates spatially and among scientific sources.

B. Data related to the relationship between saturated thickness and well yield in magnitude spatially.

C. Data reflecting the relationship between time to deplete and selected water use options, and whether that relationship can be represented spatially by a decade representation of time.

D. Data reflecting climatic variation experience of current generation of irrigators as compared to long term climatic variations.

E. Data reflecting the appropriate balance or interface in scale between basic (data sub-township), basic information(township) and management perspective (community, county, GMD, sub-area of decade) time to deplete.

Both parties recognize that the deliverables of this contract are part of a more extensive project. Both parties agree that this contract may be amended after the coordination meetings outlined above. Any such amendment(s) shall be in writing, shall be formalized by both parties in the same manner as this agreement, and shall be attached to and become a part of this agreement.

4. The time-frame for completion of the deliverables shall be not later than June 30, 2002, unless an alternative date is established to the agreement of both parties.

In consideration of the covenants contained herein, KDA agrees to pay KUCR/KGS as compensation for the performance as specified in this agreement the sum of $37,500. This amount shall be paid in three installments; $18,750, upon execution of this agreement, $9,375 upon 50% completion, and the remaining $9,375 upon satisfactory completion of the project.

TERM OF AGREEMENT. The term of this agreement shall commence upon execution and shall continue through full performance by both parties.

EQUIPMENT. KUCR/KGS shall provide or arrange for all equipment necessary for this project.

RELATIONSHIP OF PARTIES. During the term of this agreement, it is mutually understood by the parties hereto that the KUCR/KGS will be deemed to be an independent contractor and is in no way an employee or agent of KDA.

ASSIGNMENT. Neither this agreement nor the subject matter thereof nor any portion thereof may be sold, assigned or transferred in any manner by the KUCR/KGS, without first obtaining written permission from KDA.

SUCCESSORS IN INTEREST. This agreement shall be binding upon the respective parties, their successors and assigns.

11. **TERMINATION.** Failure by either to perform any of it's duties as specified in this agreement or as specified in further discussion by the parties, shall be sufficient cause for termination of this agreement by KDA. In addition, either party may terminate this agreement upon 30 days notice to the other party. Upon termination of agreement pursuant to this provision, all unexpended funds paid by KDA in the hands of the KUCR/KGS**,** shall be returned to KDA immediately.

1. The provisions contained in Contractual Provisions Attachment form (DA-146a) which is attached hereto, are hereby incorporated in this contract and made a part hereof. Whenever the term State or Agency or words of like effect is used in the form DA-146a, such reference shall be deemed to apply to KDA. The term contractor shall mean the KUCR/KGS.

KANSAS DEPARTMENT OF AGRICULTURE	THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
(Signed- 6-12-01)	*(Signed- 6-08-01)*
Jamie Clover Adams Secretary of Agriculture	Joanne Altieri, Director Contract Negotiations and Research Compliance