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Best Estimates of Aquifer Recharge: Magnitude and Spatial Distribution

By

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With contributions from other authors in the report series

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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.

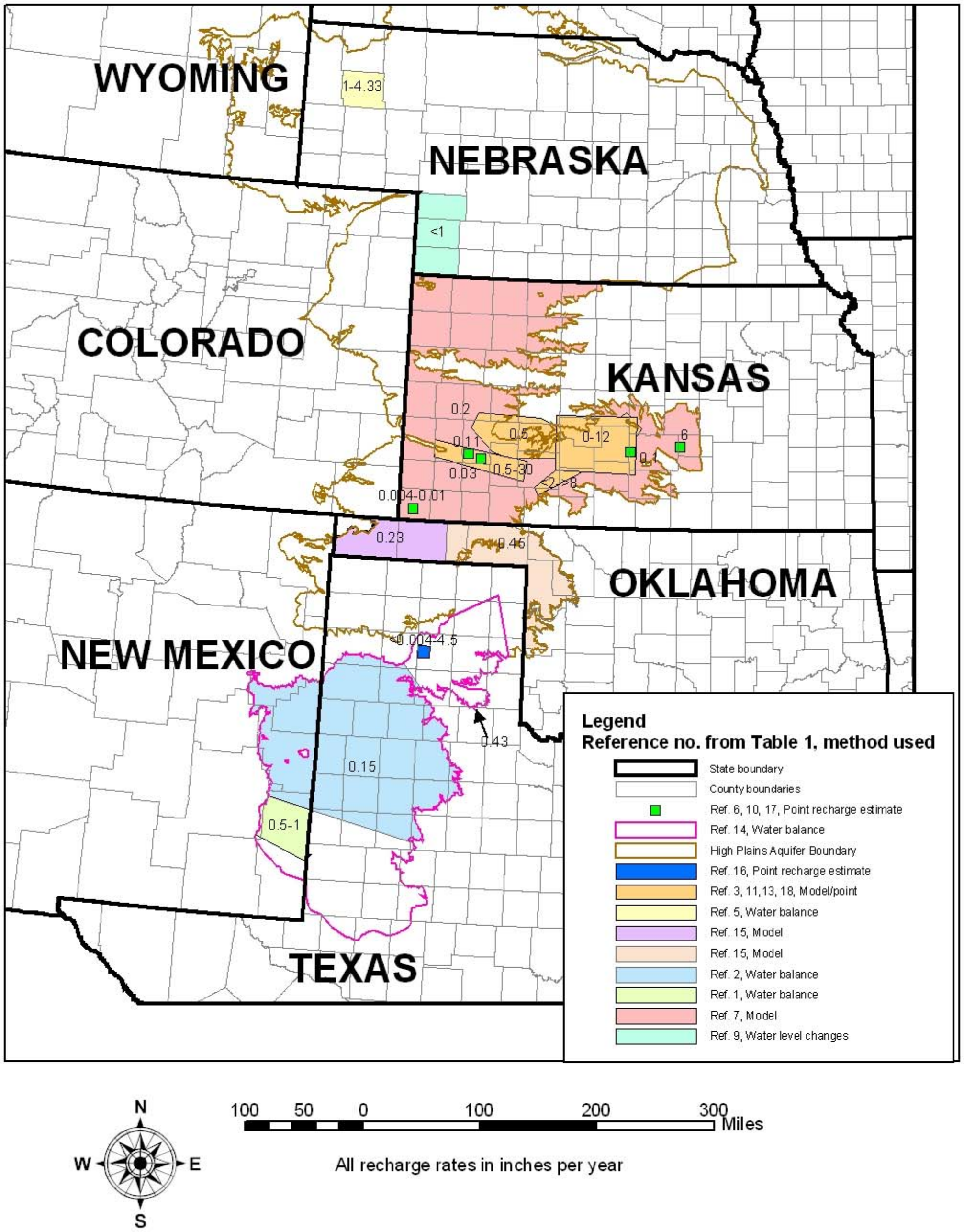
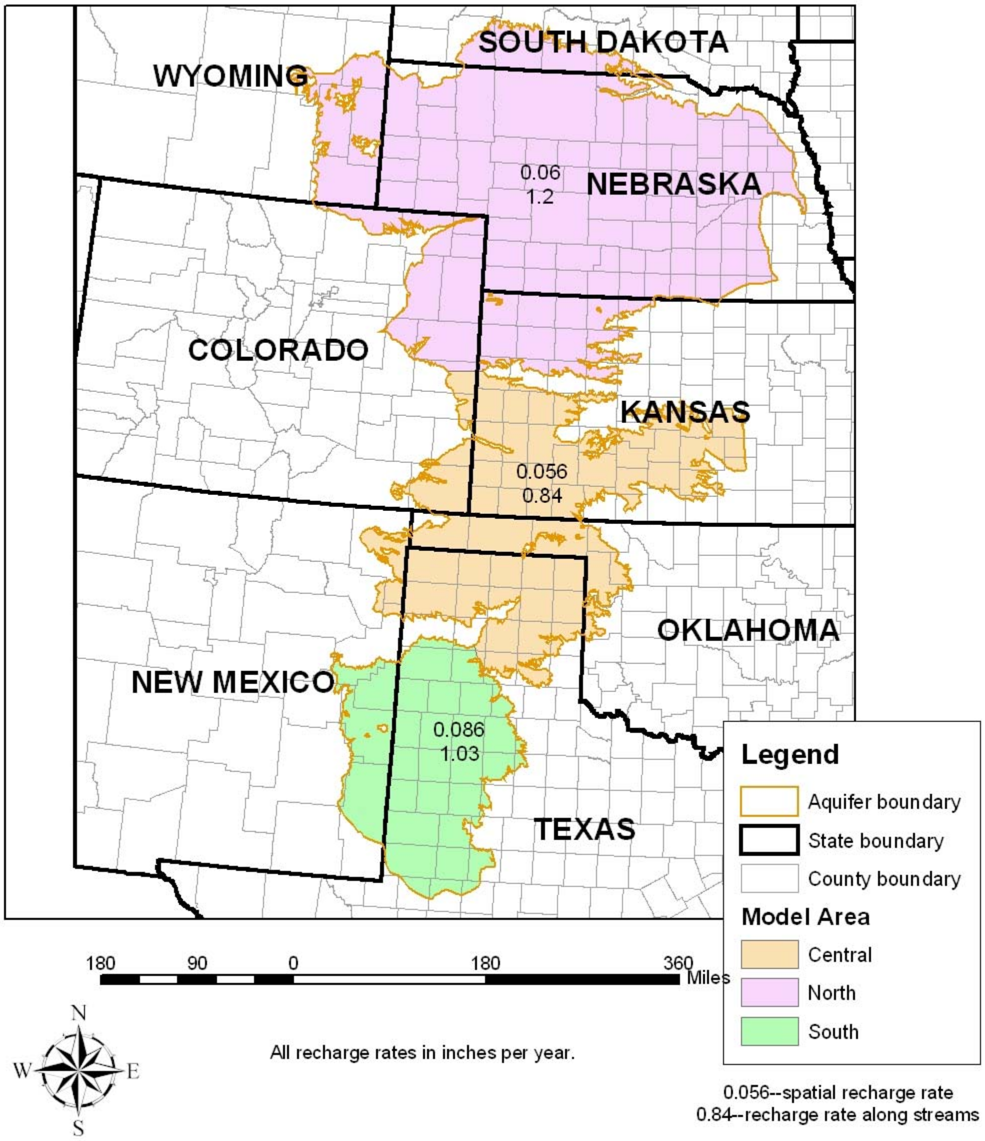


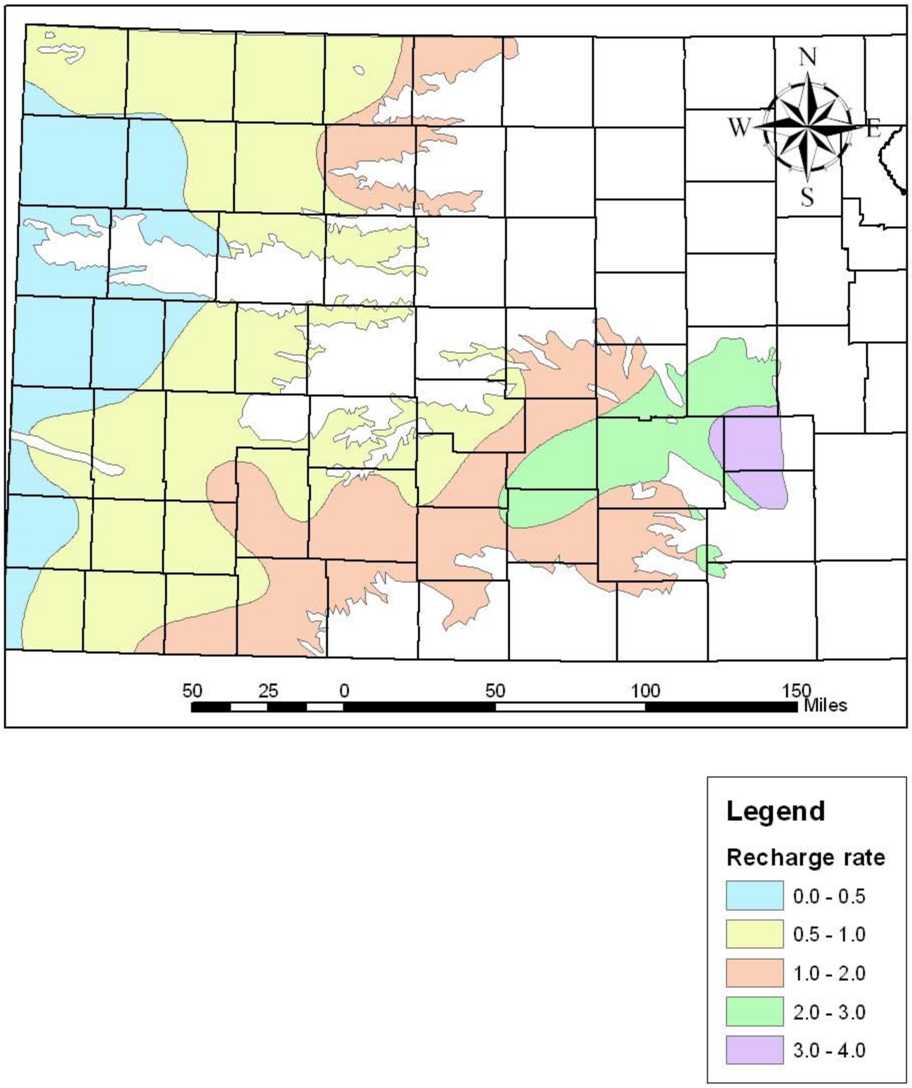
Figure 1. Spatial variability of High Plains aquifer recharge estimates.



All recharge rates in inches per year.

0.056--spatial recharge rate
0.84--recharge rate along streams

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.

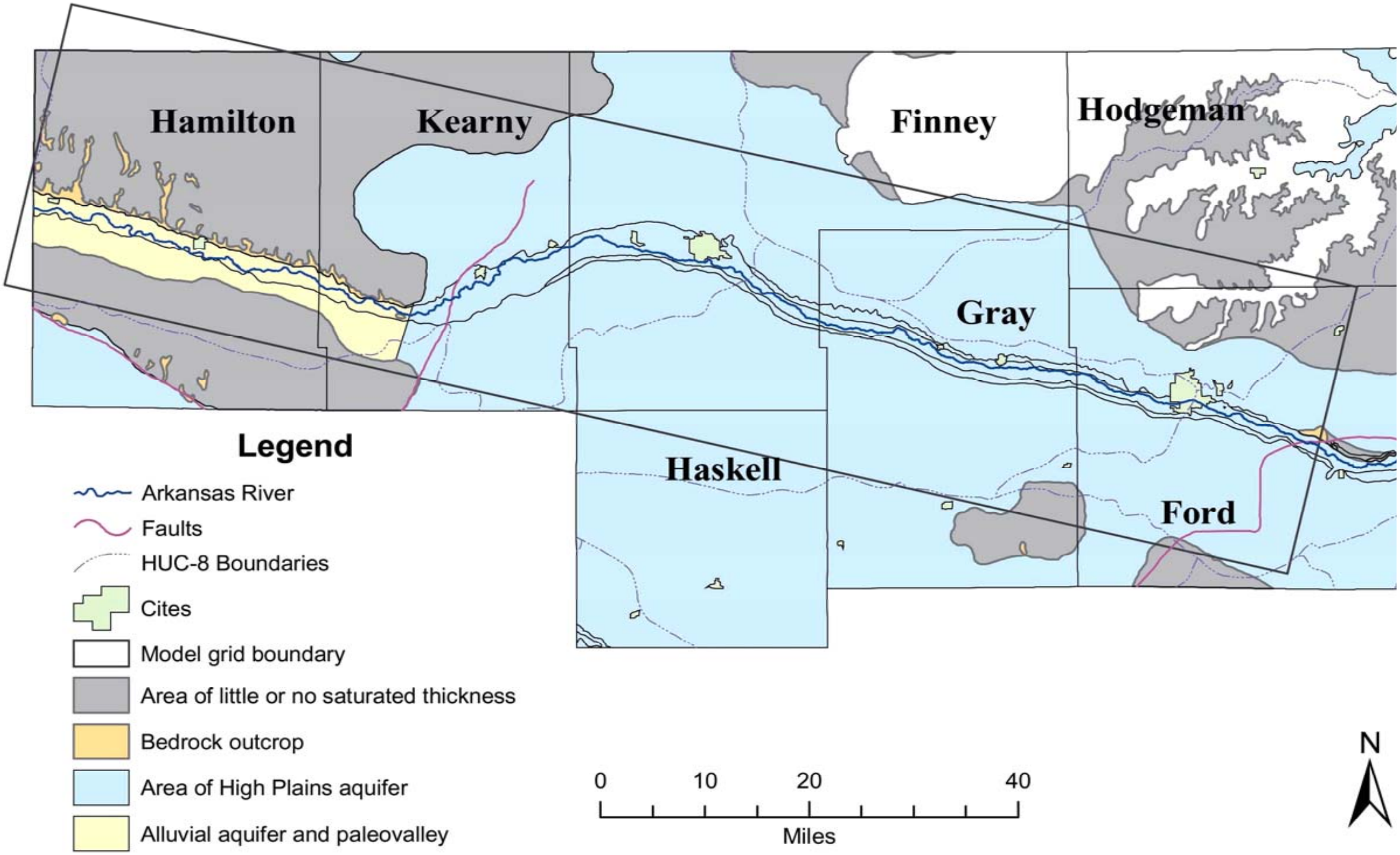


Figure 4. The location of the regional model of the upper Arkansas River corridor in southwest Kansas. The boundary of the model grid extends from the Colorado-Kansas border through parts of Hamilton, Kearny, Finney, Haskell, Gray, Hodgeman, and Ford counties to where the Crooked Creek–Fowler Fault zone 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, 1.66×10^8 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

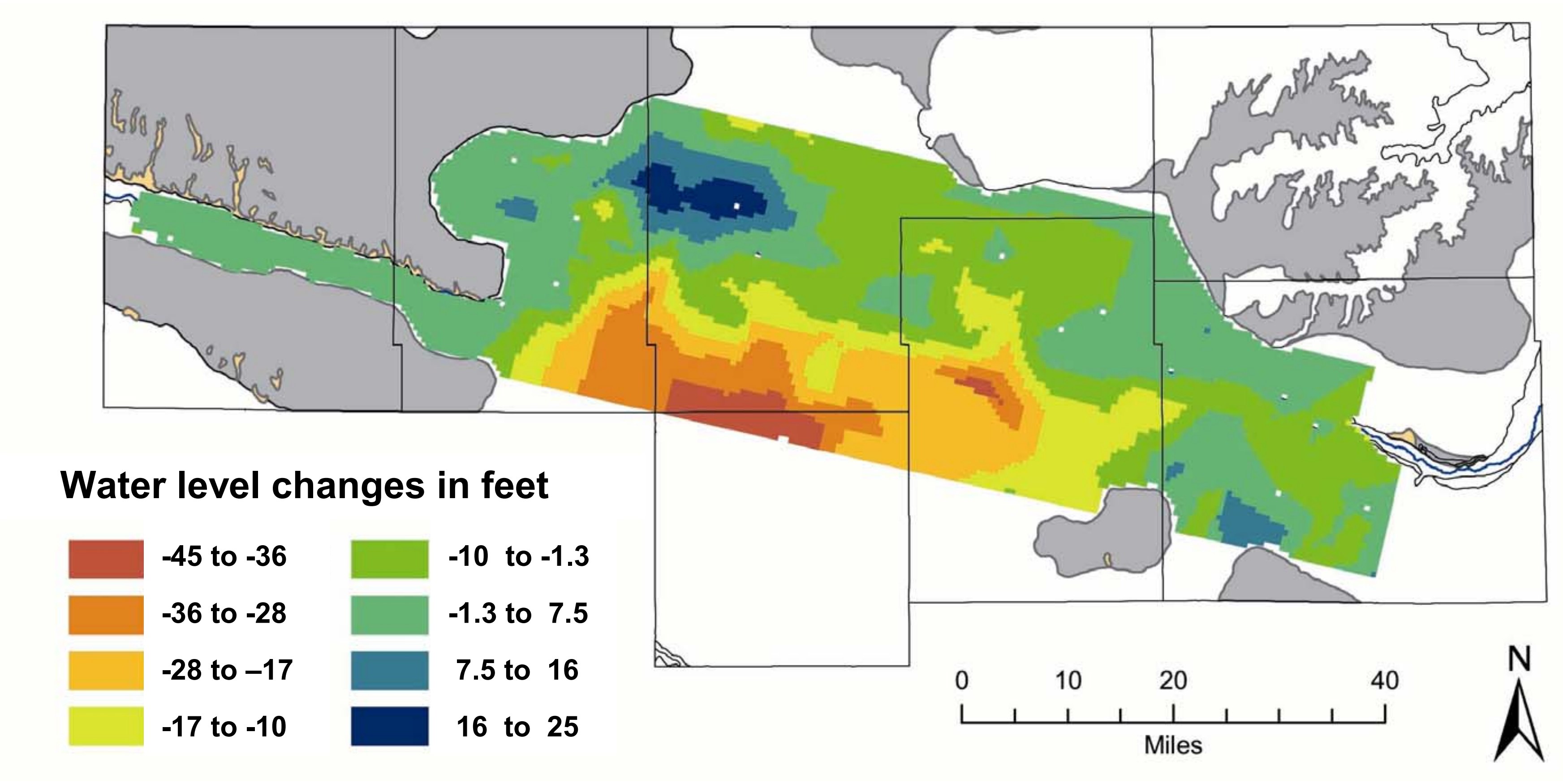


Figure 5. Change in the water-level surface between 1991 and 2000 represented as color-shaded intervals in the area of the regional model of the upper Arkansas River corridor. The intervals range from a maximum water-level decline of 45 ft to a maximum water-level rise of 25 ft.

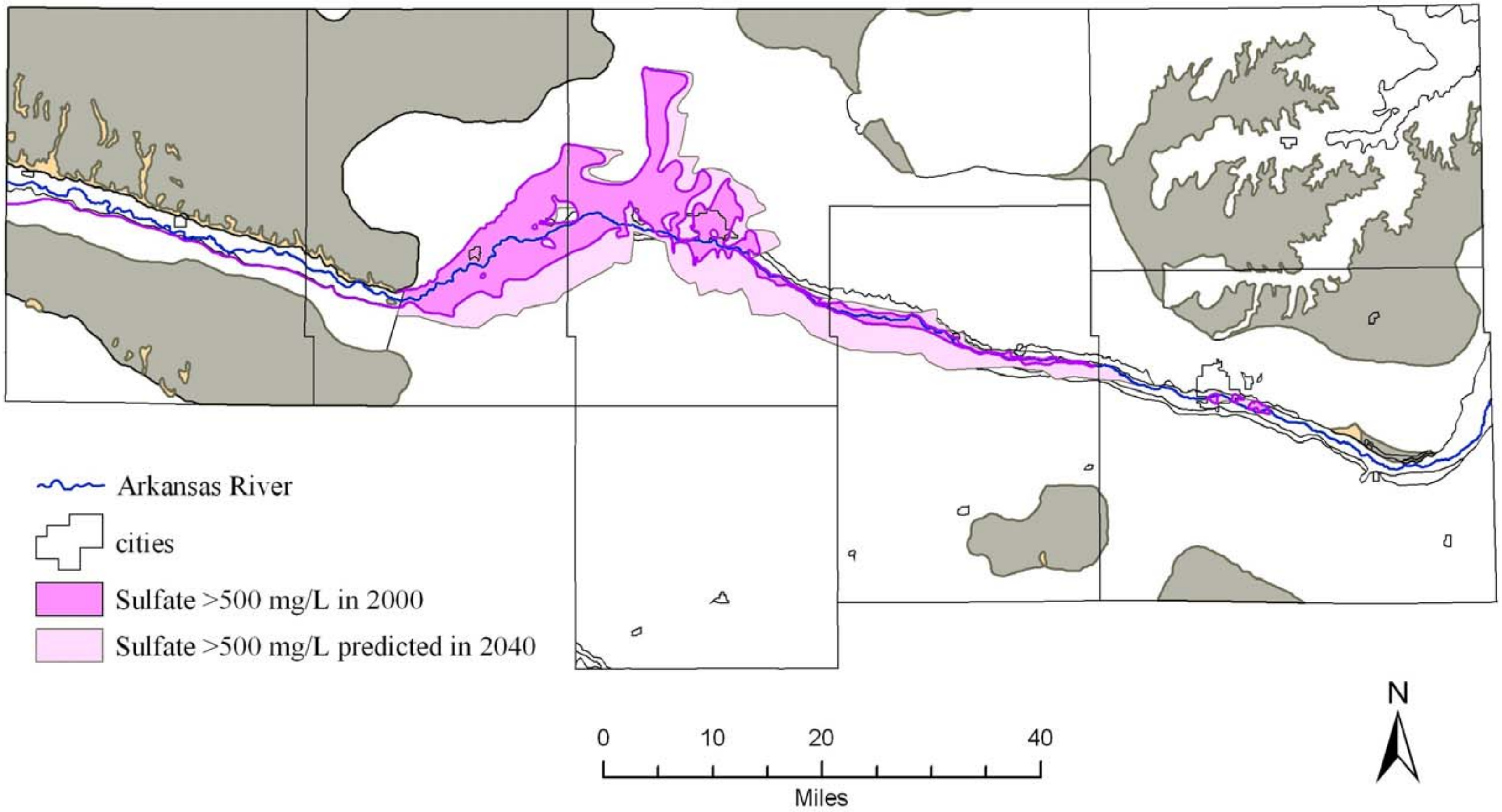


Figure 6. Distribution of high sulfate concentration (>500 mg/L) in 2000 from observations and predicted in 2040 from a 40-year transient simulation of ground-water flow based on average 1990's water use in the High Plains aquifer. See Figure 4 for explanation of additional features of the map.

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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