Comparative review and synthesis of ground-water recharge estimates for the Great Bend Prairie aquifer of Kansas

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Abstract In this report I briefly outline the importance of and difficulties involved in estimating aquifer recharge and compare reported recharge estimates for the Great Bend Prairie aquifer of central Kansas and associated alluvial-valley aquifers of the Pawnee River and Walnut Creek. Results from 20 studies are reported, including ongoing recharge-related projects. These studies were conducted by three different state agencies, a federal agency, a Kansas University department, and a private consulting firm. The recharge estimates are classified into site-specific, countywide, subregional, and regional estimates. Estimates are consistent among all four spatial scales. The average of all estimates is approximately 2 in./yr (50 mm/yr), with an average recharge range of 1.7–2.5 in./yr (43–64 mm/yr).

Quantification of the rate of natural ground-water recharge is a basic prerequisite for efficient ground-water resource management. It is particularly vital in semiarid to subhumid regions with large demands for ground-water supplies, such as the Great Bend Prairie, where such resources are the key to economic development. An essential requirement for developing a natural resources management policy is the definition of ground-water recharge mechanisms and characteristics, so that policymakers can determine whether long-term exploitation involves "mining" of an essentially "fossil" resource or withdrawal from a dynamic supply. If uncontrolled overdevelopment of an aquifer occurs because of false assumptions about ground-water recharge (especially when evaluating water-rights applications), serious consequences often arise. These consequences vary widely with hydrogeologic conditions but can include (1) increased pumping costs, yield reductions, and even complete failure of wells, (2) encroachment of deeper-lying saline water into fresh-water aquifers, (3) streamflow depletion and ecosystem disruption, and (4) land subsidence resulting from settlement of underconsolidated aquifers. In addition to its basic importance in ground-water management, knowledge of recharge rates is also crucial in assessing minimum-risk waste disposal locations, for developing efficient pollution prevention plans, and in assessing artificial recharge potential.

Digital ground-water flow simulation models are increasingly used in making ground-water management decisions. One of the most sensitive (crucial) parameters in the construction and application of these simulation models is the amount of natural recharge to the aquifer system along with its areal and temporal distribution. Incorrect assumptions about these parameters can invalidate the predictions made by such numerical models.

The Ground-Water Management District 5 (GMD5), which encompasses most of the Great Bend Prairie region of Kansas, uses an estimate of recharge as an integral part of its safe yield formulas to process ground-water rights. Better estimates of recharge would make safe yield calculations more accurate when administering water-rights applications. This is of particular importance in areas of moderate precipitation that face considerable ground-water declines and water-quality degradation problems, such as the Great Bend Prairie of Kansas. Here, especially, it is likely that there are appreciable amounts of recharge that need to be quantified and appropriately managed in the sense of wise use of this renewable resource. However, ground-water recharge is a highly complex process, making quantitative determinations unusually difficult. The rate of aquifer recharge is one of the most difficult and uncertain factors to measure in the evaluation of ground-water resources.

The main techniques that can be used specifically to estimate ground-water recharge rates can be divided into physical methods and chemical methods. The physical methods are (1) hydrometeorologic and soil-crop data processing to determine the soil-water balance or hydrologic balance of an area; (2) hydrologic data interpretation, including water table fluctuation analysis and differential streamflow or streamflow separation (baseflow) analysis; and (3) soil-physics-based analysis, including estimation of water fluxes beneath the root zone using unsaturated hydraulic conductivity functions and the gradients in water potential, the zero-flux plane method, and lysimetry. The chemical methods include chemical and isotopic analyses of pore fluids from the saturated and unsaturated zones, with the results significantly affected by the mechanisms of infiltration. Chemical methods, which may offer only an indirect measure of recharge, are usually employed in arid zones.

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Estimates of recharge, by whatever method, are normally subject to large uncertainties. In addition, recharge exhibits such a high spatial and temporal variability and process nonlinearity that there is no established practical methodology to satisfactorily regionalize point recharge estimates. To reduce such uncertainties, we need to monitor aquifer behavior on a continuous or periodic basis to ensure that adequate data, and hence representative averages of the spatially and temporally varying recharge processes, are obtained. The application of several independent or different ground-water recharge estimation methods can complement one another, and using several methods is likely to improve our knowledge of aquifer recharge, provided that an adequate hydrogeologic database exists.

To measure how accurate the estimate of the mean value of a variable (such as recharge) is, we can compute its standard deviation from the mean, most often referred to as standard error (SE) (Glantz, 1981). The term *standard error* is a statistical term for the degree of uncertainty inherent in estimating a mean value. The standard error quantifies the reliability of the estimate of the population (true) mean from a sample drawn randomly from the population. Because the certainty with which the mean can be estimated increases as the sample size increases, the standard error of the mean decreases as the sample size increases. Conversely, the more variable the original population, the more variable the possible mean values of samples. Because the population of all sample means follows a normal distribution at least approximately, the true mean of the original population lies within two standard errors of the sample mean about 95% of the time. With this information we can construct an interval that represents the range of values over which the mean can be expected to vary.

Purpose and scope

Because of the importance of ground-water recharge in the Great Bend Prairie region and associated major river valleys (e.g., Pawnee River and Walnut Creek), a number of recharge-related studies have been conducted or are going on in the region. My purpose here is to bring together and compare the reported estimates and the results of ongoing studies of ground-water recharge to the unconsolidated aquifers of the region so that a more representative average recharge estimate and range can be obtained. These estimates are divided into (1) site-specific estimates based on field measurements of recharge-related variables, (2) countywide estimates, (3) subregional recharge estimates for specific river valleys, smaller watersheds, or portions of watersheds, and (4) regional recharge estimates for the whole Great Bend Prairie or the entire Rattlesnake Creek watershed. Regional recharge estimates are also derived from averaging countywide and site-specific estimates. Figure 1 depicts the entire area for which recharge estimates are presented in this report; it also includes the locations of all recharge assessment sites in the GMD5.

Site-specific recharge estimates

According to the just completed (as of December 1992) GMD5-KGS (Kansas Geological Survey) recharge assessment project (Sophocleous, 1989; 1991a,b; 1992a), in which recharge-related variables are monitored in the field on a year-round basis at 10 sites distributed throughout the GMD5 area (fig. 1), ground-water recharge was highly variable both from year to year and from one area to another. The methodology used in quantifying recharge for the region consisted of combining the hydrologic or soil-water balance on a storm-by-storm year-round basis with the resulting water table rises. Each recharge assessment site was equipped with a weighing and recording rain gauge, a neutron-probe access tube for measuring the soil-profile water content, a water table well with a water-level recorder, and two deeper piezometers. Two of the sites were also equipped with weather stations that recorded solar radiation, air temperature, relative humidity, barometric pressure, and wind speed. Using the data collected at these sites and detailed weather data from the Sandyland Experiment Station, just south of St. John (fig. 1), the soil-water balance for each recharge-producing storm period was calculated. By associating the result with the consequent water table rise, which is tied to specific precipitation events, reliable effective recharge values for different storm periods were obtained (Sophocleous, 1991a).

Table 1 gives the estimated annual recharge values, measured precipitation, and depth to water table for all the sites and for all the years for which measurements have been collected. For the original recharge sites 1 through 5 data have been collected since 1985, whereas for sites 6 through 10 data exist only since 1988. Table 1 also includes the Zenith recharge site (Reno County) results from an earlier KGS-USGS (U.S. Geological Survey) recharge study (Sophocleous and Perry, 1984, 1985, 1987). Figure 2 presents a histogram of the annual precipitation and recharge values for the 1985–1992 period. As can be seen in table 1 and fig. 2, similar yearly rains produced different recharge amounts; this can be attributed to differences in the timing of rains. Spring rains are the most effective in recharging the aquifer. The unusually high recharge estimates for site 4 in Reno County, which received the highest precipitation among all sites, are due to the site being located on the streambank of a tributary to Wolf Creek where the depth to the water table is very shallow, approximately 2–4 ft (0.6–1.2 m). Also, note the drought effect of 1988, which resulted in the lowest overall amount of recharge over the measurement period. Sites 8, 9, and 10 received no detectable recharge during the 1988–1992 period of record. The 1991 estimated recharge at each site was well below the 1985–1992 average, resulting in the lowest ground-water levels in the 1985–1992 period of continuous ground-water

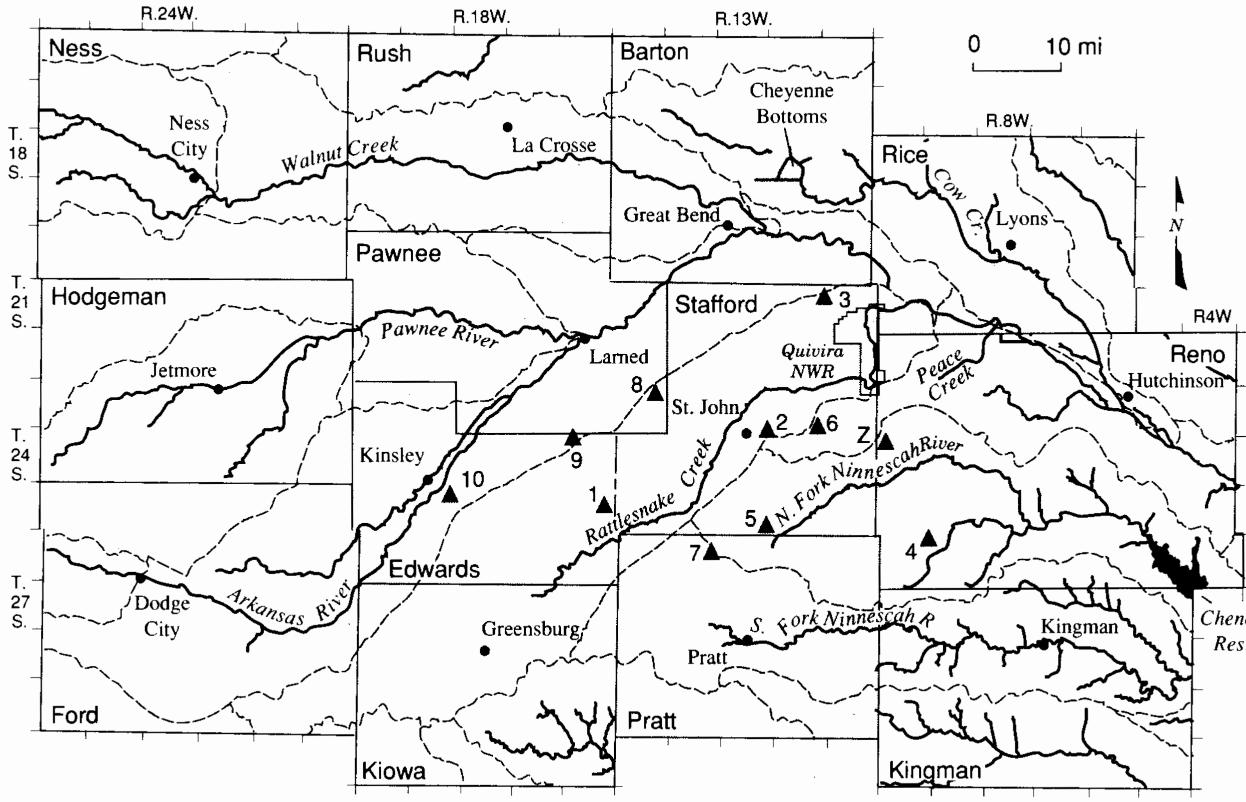

Figure 1. Ground-water recharge assessment area and recharge study sites (traingles) (Z is Zenith site). Shaded area denotes GMD5. River basins are outlined with dashed lines.

level record (fig. 3, sites 1 through 10). Despite above average precipitation during 1992 (fig. 2), aquifer recharge estimates for 1992 were in general somewhat below the 1985–1992 average (table 1), most probably because of the lowered ground-water levels and the persistent soil-profile water deficits from previous drier years.

Countywide recharge estimates

In 1967 the Kansas Water Resources Board (KWRB) prepared a comprehensive report on the historical and potential development of irrigation in Kansas in which "indirect analyses have been made of the magnitude of recharge in some areas of Kansas" (KWRB, 1967, p. 14). Stuart W. Fader of the USGS was acknowledged for providing information on natural recharge.

Subsequently, in an administrative report to the U.S. Army Corps of Engineers, Tulsa District, Fader and Morton (1972) presented a compilation of available ground-water data for the middle Arkansas River basin on a county basis. This report was based on previous reports and on the files of the USGS and cooperating state agencies with "few additional data collected for this investigation" in which "the estimated annual recharge to the unconsolidated aquifers in Kansas was modified from a report by the KWRB (1967)" (Fader and Morton, 1972, p. 14).

Layton and Berry (1973) in a hydrogeologic study of Pratt County estimated ground-water recharge in Pratt County to be 5–10% of the average annual precipitation [of 24.04 in. (611 mm), based on 68 years of climate records from Pratt] "with the higher percentage occurring in areas that are underlain by dune sand. Recharge from precipitation in Pratt County probably averages 62,000 acre-ft (7.65×10^{-2} km^3) of water annually" (Layton and Berry, 1973, p. 13). Furthermore, "the percentage of the applied irrigation water that returns to the ground-water reservoir probably is similar to the percentage recharge from precipitation" (Layton and Berry, 1973, p. 13).

Finally, the USGS (Hansen, 1991; Kansas Water Office, 1987) presented some estimates of mean annual potential natural recharge for the 1951–1980 period in Kansas. Potential natural recharge was defined as "the amount of water from precipitation that infiltrates across the water table to … an aquifer that directly underlies the soil at land surface" (Hansen, 1991, p. 39). The rate of potential natural recharge was estimated by a computer model from soil, vegetative, and climatic data. The report concluded that "estimates of poten-

Table 1. 1985–1992 Site-specific ground-water recharge estimates for GMD5

Site number	Location	Total precipitation (in./yr)	Minimum and maximum depth to water table (ft)	Estimated ground-water recharge (in./yr)
1	Edwards County, sec. 13, T. 25 S., R. 16 W. (land owned by Grizzell)			
	1985	23.30	18.2–20.2	1.3
	1986	26.54	18.5–20.5	1.1
	1987	34.05	9.8–18.5	5.5
	1988	14.91	14.2–19.6	0.2
	1989	21.90	17.3–19.6	1.5
	1990	20.17	18.3–21.2	0.5
	1991	20.78	20.7–22.5	0.5
	1992	25.22	20.3–22.3	0.8
	8-yr avg. (1985–1992) and SE	23.36 (2.0)		1.4 (0.6)
	5-yr avg. (1988–1992)	20.60		0.7
2	Stafford County, sec. 36, T. 23 S., R. 13 W. (land owned by Bliss)			
	1985	26.42	24.2–26.7	2.8
	1986	27.81	24.0–26.5	1.7
	1987	26.10	19.2–24.1	3.9
	1988	14.52	22.3–26.8	0.3
	1989	20.50	26.2–27.3	1.0
	1990	21.19	25.4–28.2	1.3
	1991	16.47	27.3–29.7	0.8
	1992	28.96	28.5–29.8	0.9
	8-yr avg. (1985–1992) and SE	22.75 (1.9)		1.6 (0.4)
	5-yr avg. (1988–1992)	20.33		0.9
3	Stafford–Barton counties, sec. 7, T. 21 S., R. 11 W. (land owned by Schlockterneier)			
	1985	29.83	16.4–23.0	2.8
	1986	22.53	15.9–19.4	0.7
	1987	28.11	14.6–18.3	1.3
	1988	15.66	15.5–21.9	0.0
	1989	21.80	21.5–24.5	0.6
	1990	21.26	20.9–25.0	0.3
	1991	18.94	21.6–26.8	0.2
	1992	27.61	21.5–26.1	1.6
	8-yr avg. (1985–1992) and SE	23.22 (1.7)		0.9 (0.3)
	5-yr avg. (1988–1992)	21.05		0.5
4	Reno County, sec. 1, T. 25 S., R. 9 W. (land owned by Bradshaw and Sherow)			
	1985	31.19	2.4–4.9	6.8
	1986	32.96	2.6–4.7	8.5
	1987	37.09	0.5–3.3	11.9
	1988	18.00	1.6–5.7	3.7
	1989	27.39	3.6–5.0	6.1
	1990	25.65	1.9–5.8	4.8
	1991	20.97	1.7–6.4	3.9
	1992	30.04	2.8–5.2	6.3
	8-yr avg. (1985–1992) and SE	27.91 (2.2)		6.5 (1.0)
	5-yr avg. (1988–1992)	24.41		5.0
5	Stafford–Pratt counties, sec. 36, T. 25 S., R. 13 W. (land owned by Harrison)			
	1985	30.15	10.1–14.6	5.9
	1986	32.51	10.4–13.7	3.8
	1987	30.69	6.2–10.5	3.8
	1988	14.95	8.6–14.4	0.9
	1989	23.86	11.7–14.8	2.9

Table 1 (continued)

Site number	Location	Total precipitation (in./yr)	Minimum and maximum depth to water table (ft)	Estimated ground-water recharge (in./yr)
	1990	23.09	10.9–16.6	1.5
	1991	22.56	12.0–17.9	1.5
	1992	25.91	15.2–17.5	2.2
	8-yr avg. (1985–1992) and SE	25.47 (2.0)		2.8 (0.6)
	5-yr avg. (1988–1992)	22.07		1.8
6	Stafford County, sec. 36, T. 23 S., R. 12 W. (land owned by Wendelburg)			
	1988	16.27	10.0–22.8	0.5
	1989	22.49	9.9–22.8	1.7
	1990	23.43	10.2–23.7	1.1
	1991	13.79	14.4–26.7	0.0
	1992	28.50	12.6–21.1	1.1
	5-yr avg. (1988–1992) and SE	20.90 (2.6)		0.9 (0.3)
7	Pratt County, sec. 11, T. 26 S., R. 14 W. (land owned by Moore)			
	1988	14.95[a]	15.1–26.5	0.5
	1989	22.53	21.9–26.8	4.7
	1990	20.86	22.6–29.2	3.7
	1991	27.60	24.8–29.4	1.0
	1992	28.82	25.1–29.7	2.4
	5-yr avg. (1988–1992) and SE	22.95 (2.5)		2.4 (0.8)
8	Pawnee County, sec. 14, T. 23 S., R. 15 W. (land owned by Tranbarger)			
	1988	14.36	23.6–26.3	0.0
	1989	20.77	26.3–27.2	0.0
	1990	23.99	27.3–27.8	0.0
	1991	19.00	28.0–29.0	0.0
	1992	26.55	29.1–29.8	0.0
	4-yr avg. (1988–1992) and SE	20.93 (2.1)		0.0
9	Edwards County, sec. 5, T. 24 S., R. 16 W. (land owned by Schwartz)			
	1988	14.73	29.3–31.9	0.0
	1989	18.37	31.5–33.1	0.0
	1990	20.97	32.7–34.4	0.0
	1991	16.51	33.8–35.3	0.0
	1992	28.07	35.2–35.5	0.0
	5-yr avg. (1988–1992) and SE	19.73 (2.3)		0.0
10	Edwards County, sec. 1, T. 25 S., R. 19 W. (land owned by Olsen)			
	1988	15.02	46.7–48.7	0.0
	1989	21.54	48.5–50.2	0.0
	1990	22.05	50.0–51.3	0.0
	1991	11.34	50.7–52.5	0.0
	1992	23.27	52.2–53.2	0.0
	4-yr avg. (1988–1991) and SE	18.64 (2.3)		0.0
Arithmetic avg., sites 1–10 ($N = 65$) and SE		23.03 (0.71)		1.9 (0.30)
Arithmetic avg., sites 1–7 ($N = 50$) and SE		24.02 (0.80)		2.5 (0.35)
Zenith	Reno County, sec. 6, T. 24 S., R. 10 W. (land owned by Krey)			
	1983	19.77[b]	16.6–17.4	0.1

a. Precipitation taken from site 5 (the nearest site).

b. Precipitation taken from Hudson, approximately 13 mi northwest of the Zenith site.

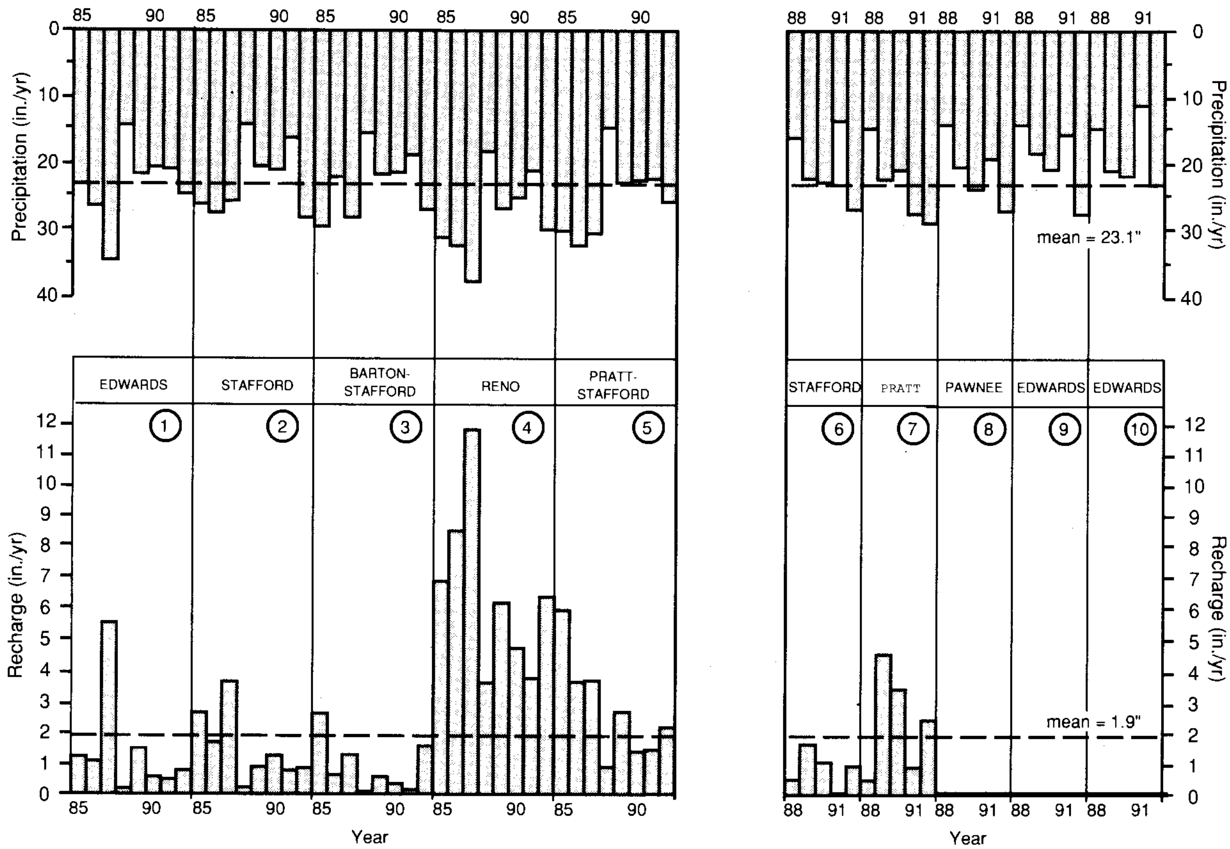

Figure 2. Annual recharge and precipitation at each site for the period 1985–1992.

tial natural recharge made by this study tend to be somewhat larger than those made by previous studies [e.g., Stullken et al. (1985)], especially in western Kansas. The actual rate of natural recharge may be somewhere between previous estimates and the ones made by this study" (Hansen, 1991, p. 40).

Table 2 presents all three recharge estimates (KWRB, Kansas Water Office, USGS) together with some derived average estimates for the region. It is evident from the table that the original recharge estimates were overestimated and that subsequent studies based on additional data revised those estimates downward.

Subregional recharge estimates

Sophocleous et al. (1992), in an ongoing study of the Kinsley to Great Bend reach of the Arkansas River and associated valley, calibrated a numerical stream-aquifer flow model (MODFLOW with stream routines; McDonald and Harbaugh, 1988; Prudic, 1989) using inverse modeling techniques (MODINV; Doherty, 1990) covering the 1955–1990 period. A 1-mile (1.6-km) finite-difference grid was employed. The model area covered 470 mi^2 (1,220 km^2). The derived tentative 1955–1990 recharge to the combined Arkansas River alluvium and Great Bend Prairie aquifer in that region was 1.8 in./yr (46 mm/yr) [with a standard error of 0.1 in./yr (2.5 mm/yr)].

Sophocleous and Perkins (1992) and Sophocleous (1992b) engaged in a study of the lower Rattlesnake Creek watershed from immediately west of the Macksville stream-gaging station to the confluence with the Arkansas River, an area of more than 560 mi^2 (1,450 km^2). Using a 1-mile (1.6-km) finite-difference grid, they also calibrated a numerical stream-aquifer flow model (MODFLOW with stream routines; McDonald and Harbaugh, 1988; Prudic, 1989) using inverse modeling techniques (MODINV; Doherty, 1990) covering the 1955–1990 period. The derived 1955–1990 average recharge to the Great Bend Prairie aquifer in that region ranged from 1.5 to 1.9 in./yr (34–48 mm/yr) [with a standard error of 0.2 and 0.3 in./yr (5 and 8 mm/yr, respectively)], resulting in an average recharge of 1.7 in./yr (43 mm/yr).

In a hydrogeologic study of the Pawnee River valley, Sophocleous (1980, 1981) estimated regional ground-water recharge in that valley using two different methods:

1. Interpretation of streamflow records at the discharge end of the flow system and of pumping data from the 1925–1945 period for which near-equilibrium conditions can be

assumed. This analysis resulted in a recharge rate of 0.6 in./yr (15 mm/yr) over the studied 325-mi^2 (842-km^2) aquifer area.

2. Analysis of a modulated soil-moisture budget based on hydrometeorologic and soil data of the composite Pawnee River watershed. This analysis, based on 20 years of hydrometeorologic data (1959–1978), resulted in a value for regional ground-water recharge of 0.4 in./yr (10 mm/yr).

The average annual precipitation over the same 20-yr period (1959–1978) was 22.7 in./yr (577 mm/yr). Thus the average estimated regional ground-water recharge for the Pawnee River valley was 0.5 in./yr (13 mm/yr), which represents less than 2.5% of the average annual precipitation. Sophocleous (1980, 1981) indicates that by 1978–1979, the Pawnee River valley aquifer had been depleted by 37% compared to 1945–1947. Also, the ground-water appropriations in the Pawnee River valley aquifer by 1978–1979 amounted to 11 times the amount of estimated ground-water recharge.

Sophocleous and McAllister (1990), in a comprehensive but short-term soil-water balance analysis of the entire Rattlesnake Creek watershed, estimated that the 1982–1983 recharge to the lower Rattlesnake Creek watershed from near the Macksville gaging station to the confluence with the Arkansas River was 2.9 in./yr (74 mm/yr).

Kemblowski and Moya [see Moya (1985)], formerly of the Kansas Geological Survey, conducted a stream-aquifer modeling study of the South Fork Ninnescah River basin (Pratt County), an area of more than 420 mi^2 (1,088 km^2). The model [integrated finite-difference model by Kemblowski (1982)] was calibrated by trial-and-error techniques from 1964 to 1984, resulting in a (sub)regional natural recharge of 3.5 in./yr (89 mm/yr).

Gillespie and Slagle (1972), of the USGS, in a ground-water recharge study of Wet Walnut Creek valley from Bazine to Albert, estimated the average annual recharge to the aquifer for 1965–1969 to be 13,000 acre-ft/yr (1.6×10^{-2} km^3/yr). If we approximate the study area to be 64,000 acres (100 mi^2; 259 km^2), this recharge value converts to an estimate of 2.4 in./yr (61 mm/yr).

Nuzman (1990) conducted a numerical modeling study of the Walnut Creek valley from near Ness City to Great Bend, an area of 124,160 acres (194 mi^2; 502 km^2), using the USGS MODFLOW program (McDonald and Harbaugh, 1988) and a grid of 1 mi. A trial-and-error calibration resulted in a recharge estimate of 10% of an average of 22 in. (559 mm) of annual precipitation [i.e., 2.2 in./yr (56 mm/yr)].

Finally, as a result of the 1990–1991 public hearings on the designation of an Intensive Ground-Water Use Control Area (IGUCA) in Barton, Rush, and Ness counties, Kansas, the chief engineer concluded, regarding long-term ground-water recharge in the Walnut valley, "that the long-term sustainable yield of the aquifer within the boundaries of the proposed control area as set forth in Conclusion No. 8 [i.e., an area of 348,800 acres (1,412 km^2)] is no more than approximately 22,700 acre-ft per year (2.8×10^{-2} km^3/yr)" (Division of Water Resources, 1992, p. 96). This translates to 0.8 in./yr (20 mm/yr). However, the declared IGUCA encompasses areas beyond the Walnut Creek alluvium. Considering that the Walnut Creek alluvial aquifer area from near Ness City to the confluence at Great Bend is approximately 128,000 acres (200 mi^2; 518 km^2), the sustainable yield figure of 22,700 acre-ft/yr (2.8×10^{-2} km^3/yr) translates to a perhaps more representative long-term recharge estimate of 2.1 in./yr (53 mm/yr).

All these subregional recharge estimates for the region are summarized in table 3.

Regional recharge estimates

Fader and Stullken (1978), both with the USGS at that time, evaluated the ground-water resources of the Great Bend Prairie in south-central Kansas by combining

> data from previous studies and other records with current information obtained in the area.... The work consisted of (1) making an inventory of about 1,500 wells, (2) measuring the water level in a network of about 290 wells, (3) measuring the discharge and rate of fuel consumption for 53 randomly sampled irrigation wells, (4) collecting about 150 ground-water samples for chemical analysis, (5) determining the flow-duration curves of 20 small streams in the area, (6) analyzing about 2,000 logs of oil, gas, and water tests to prepare maps of the geology of the bedrock and the altitude and configuration of the bedrock surface, and (7) evaluating the hydrologic properties of the unconsolidated aquifer. (Fader and Stullken, 1978, p. 3)

Fader and Stullken (1978) estimated ground-water recharge for the combined drainage area of about 2,460 mi^2 (6,371 km^2) above the stream-gaging stations of Raymond (Rattlesnake Creek), Arlington (North Fork Ninnescah River), and Murdock (South Fork Ninnescah River), where average annual precipitation was estimated to be 25 in./yr (635 mm/yr). The ground-water drainage area above the three stations was estimated to be 2,280 mi^2 (5,905 km^2) based on a December 1973 potentiometric surface map of the region. Fader and Stullken's recharge estimate by precipitation to the above ground-water drainage area was 2 in./yr (51 mm/yr). Accordingly, "the combined ground-water contribution to streamflow at these stations is about 110,000 acre-ft/yr (0.14 km^3/yr), which is equivalent to about 45% of the average annual recharge [2 in./yr (51 mm/yr)] to the ground-water drainage area above the (streamgaging) stations" (Fader and Stullken, 1978, p. 11).

Fader and Stullken (1978) state that recharge to the ground-water reservoir is principally by direct infiltration of precipitation on the land surface throughout the area plus underflow laterally from the west and leakage upward from the bedrock.

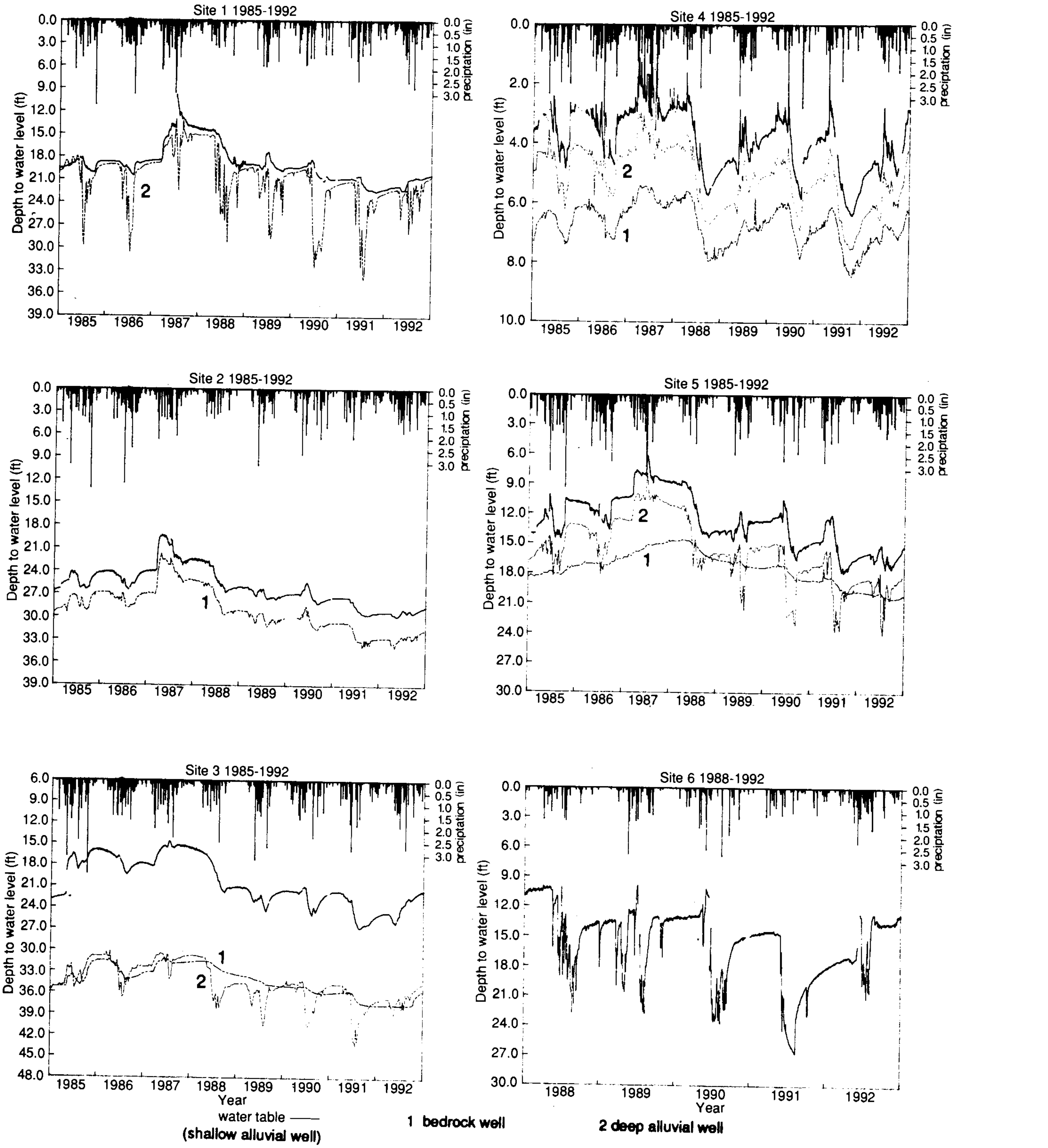

Figure 3. Daily precipitation and multiple ground-water-level time series for recharge study sites 1–10 for the period 1985–1992.

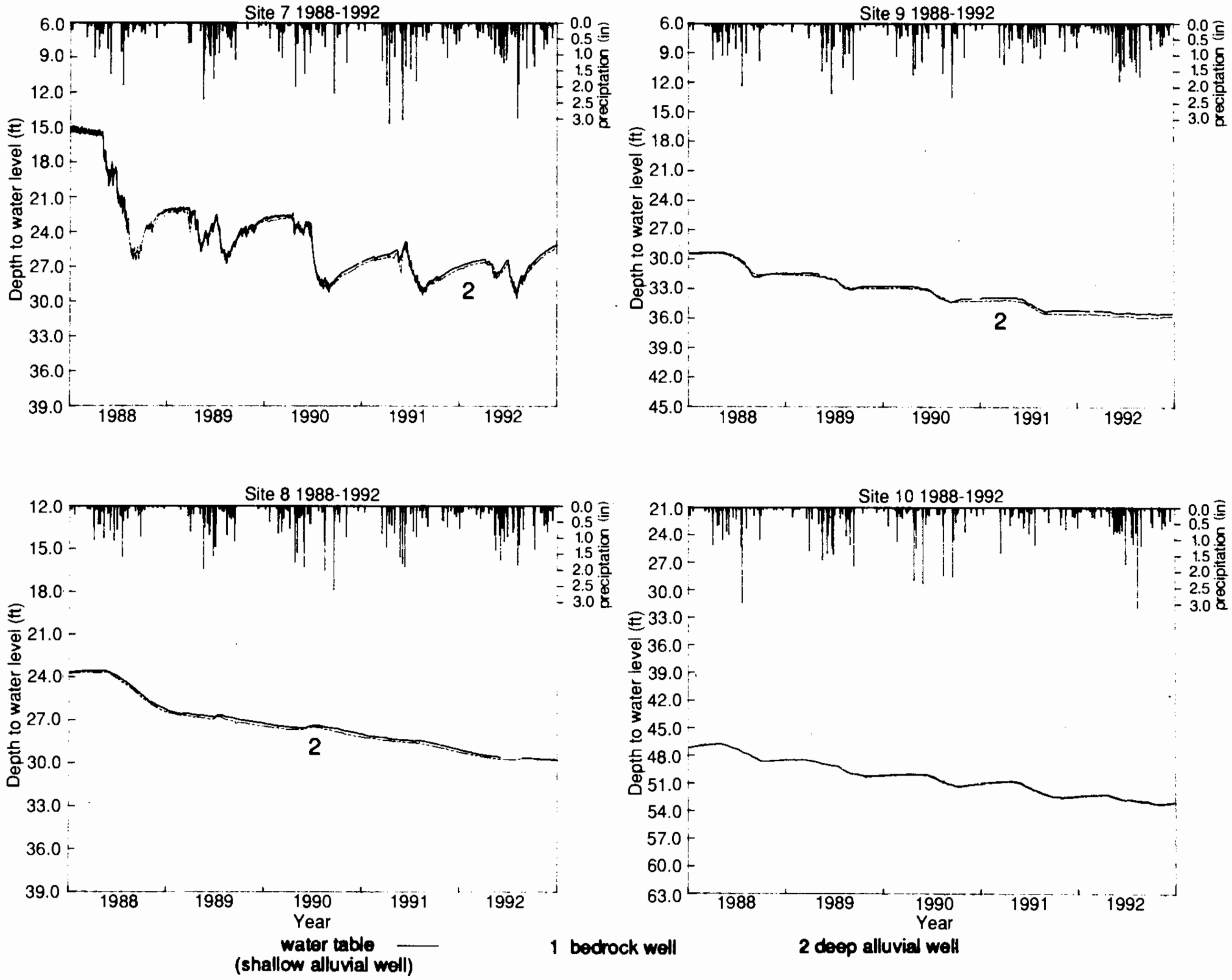

Figure 3 (continued)

Also,

> recharge to the area by underflow occurs only across the western Kiowa County line and is estimated to be 500 to 1,000 acre-ft/yr [6.2 $\times$ 10^{-4} to 1.2 $\times$ 10^{-3} km^3/yr]. The inflow from the bedrock is estimated to be 5,000 to 10,000 acre-ft/yr [6.2 $\times$ 10^{-3} to 1.2 $\times$ 10^{-2} km^3/yr] based on the assumptions that the Cedar Hills Sandstone is the major contributor, the hydraulic gradient in the formation is virtually equal to and in the same direction as in the overlying unconsolidated deposits, and the hydraulic conductivity of the Cedar Hills Sandstone is about 25 ft/day [7.62 m/day]. (p. 11)

Fader and Stullken (1978) estimated that 900,000 acre-ft (1.11 km^3) of water was withdrawn by wells through the Great Bend Prairie during 1952–1971, of which 680,000 acre-ft (0.84 km^3) was for irrigation and 220,000 acre-ft (0.27 km^3) was for municipal and industrial use. Sixty-two percent of the wells recorded in May 1974 were within the ground-water drainage area above the stream-gaging stations near Raymond, Arlington, and Murdock.

Cobb et al. (1983), previously of the Kansas Geological Survey, calibrated (by trial and error) the Trescott et al. (1976) USGS two-dimensional finite-difference flow model using a grid spacing of 15,000 ft (4.6 km) throughout the Great Bend Prairie region. The resulting average recharge was 0.75 in./yr (19.1 mm/yr).

Luckey et al. (1986), of the USGS, calibrated (by trial and error) a regional flow model for the High Plains aquifer, which was divided into three parts (southern High Plains, central High Plains, and northern High Plains) with each part simulated separately. For the simulations Luckey employed the Trescott et al. (1976) USGS two-dimensional finite-difference flow model using a grid spacing of 10 mi (16 km). The estimated predevelopment long-term average recharge rate for the Great Bend Prairie was 0.28 in./yr (7 mm/yr).

Table 2. Countywide annual recharge estimates to unconsolidated aquifers

County	Area (acres)	Area weights[a]	KWRB (1967) acre-ft/yr	in./yr	USGS (Fader and Morton, 1972) acre-ft/yr	in./yr	KWO, 1987; USGS (Hansen, 1991) acre-ft/yr	in./yr	KGS (Layton and Berry, 1973) acre-ft/yr	in./yr
Barton	575,360	0.1220	83,100	1.7	60,000	1.3	33,800	0.7		
Edwards	396,160	0.0840	84,000	2.5	50,000	1.5	33,100	1.0		
Kingman	553,600	0.1174	201,600	4.4	150,000	3.3	62,700	1.4		
Kiowa	460,800	0.0977	99,600	2.6	50,000	1.3	50,000	1.3		
Pawnee	483,200	0.1025	52,600	1.3	24,000	0.6	18,800	0.5		
Pratt	466,560	0.0989	169,000	4.3	150,000	3.9	77,800	2.0	62,000	1.6[b]
Reno	807,680	0.1713	276,400	4.1	270,000	4.0	143,000	2.1		
Rice	464,000	0.0984	74,800	1.9	75,000	1.9	43,000	1.1		
Stafford	508,800	0.1079	187,500	4.4	190,000	4.5	80,400	1.9		
Total	4,716,160	1.000	1,228,600	27.35	1,019,000	22.20	542,600	11.96		
Average and SE				3.0 (0.4)		2.5 (0.5)		1.3 (0.2)		
Weighted avg. and SE				3.1 (0.4)		2.6 (0.5)		1.4 (0.2)		

a. Fraction of total 9-county area represented by the indicated county.
b. Range of 1.2–2.4 in./yr based on 5–10% of normal annual precipitation of 24.04 in./yr.

Table 3. Subregional recharge estimates

Subregion	Reference	Area (acres)	Recharge time period	Recharge (in./yr)	Avg. recharge (in./yr) for subregion	Recharge range (in./yr)
Kinsley–Great Bend, Arkansas R. valley	Sophocleous et al., 1992	302,100	1955–1990	1.8		
Lower Rattlesnake Creek basin	Sophocleous & Perkins, 1992	362,000	1955–1990	1.5	2.3 (combined)	
	Sophocleous, 1992b	362,000	1955–1990	1.9		
	Sophocleous and MacAllister, 1990	745,000	1982–1983	2.9		
South Fork Ninnescah River basin	Moya, 1985	270,000	1964–1984	3.5		
Great Bend Prairie					2.5	1.5–3.5
Pawnee River valley	Sophocleous, 1980, 1981	208,000	1925–1945	0.6	0.5	0.4–0.6
		208,000	1959–1978	0.4		
Walnut Creek valley	Gillespie and Slagle, 1972	64,000	1965–1969	2.4	2.2	2.1–2.4
	Nuzman, 1990	124,200	1982	2.2		
	Division of Water Resources, 1992	128,000	long term	2.1		

Luckey et al. (1986) estimated the overall mean long-term predevelopment recharge rate for the central High Plains, which covers approximately 48,500 mi^2 (125,615 km^2) between the Canadian River in Texas and the Smoky Hill River in Kansas, to be 0.14 in./yr (3.5 mm/yr).

Sophocleous and McAllister (1987, 1990) conducted a daily soil moisture budget for the entire Rattlesnake Creek watershed during the 1982–1983 year, taking into account climate, soil, crop, and land use (crop rotations, irrigated and dryland agriculture) factors. The irrigated acreage was estimated to be 21% of the total watershed area. The following irrigation amounts per irrigation season were considered: winter wheat, 6 in. (152 mm); soybean, 12 in. (305 mm); sorghum, 12.5 in. (318 mm); corn, 15 in. (381 mm); and alfalfa, 23.5 in. (597 mm). Average precipitation during the 1983 water year was approximately 21 in. (533 mm). The total average recharge from precipitation and irrigation was estimated to be 4.3 in./yr (109 mm/yr) during the study period.

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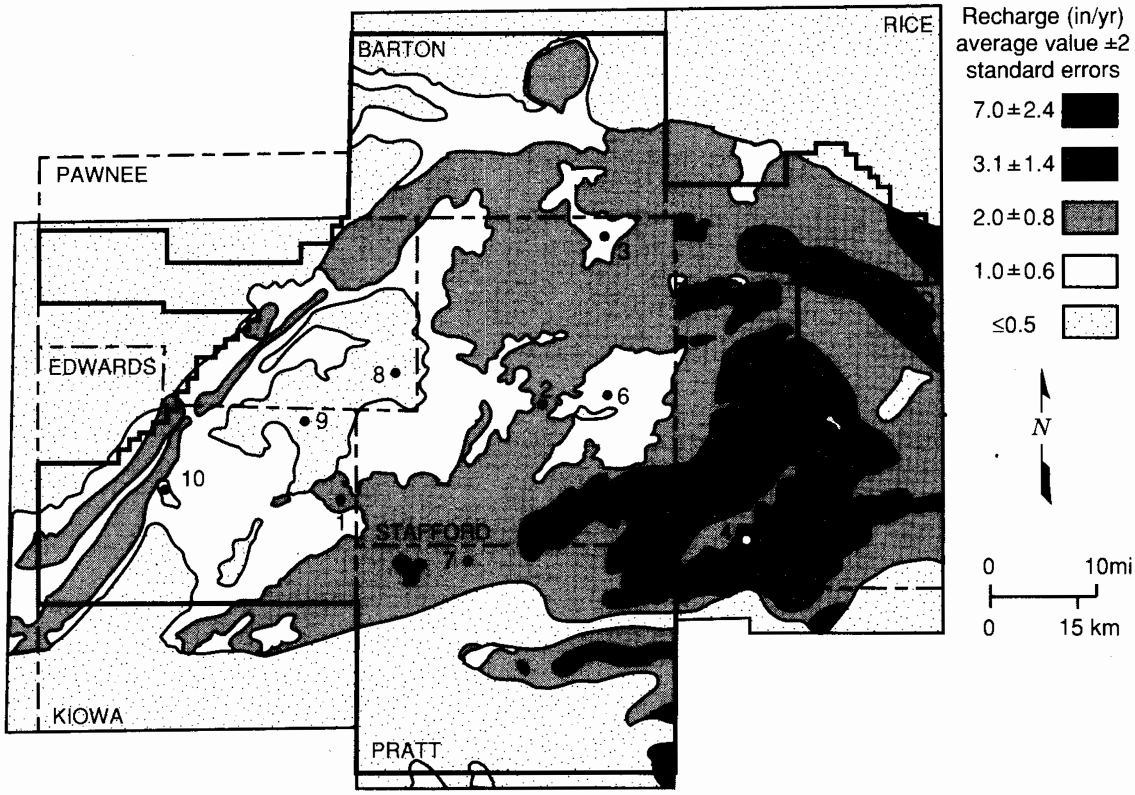

Figure 4. Recharge zonation for the Great Bend Prairie region. Numbers indicate recharge sites.

(precipitation) change were also analyzed by Sophocleous and McAllister (1990). Thus, had the Rattlesnake Creek watershed been covered entirely by prairie grasses, as it probably was during predevelopment times, and had the 1982–1983 precipitation pattern and amount prevailed, the overall watershed recharge would have been 1.1 in. (28 mm) compared with 0.2 in. (5 mm) if alfalfa had been planted exclusively in the watershed. If the entire watershed had been planted with dryland wheat under 1982–1983 precipitation conditions, the overall watershed recharge (deep drainage) would have been 5.1 in. (130 mm).

Taking the average of all counties in the Great Bend Prairie region (table 2) results in a long-term regional recharge estimate of (1) 3.1 in./yr (79 mm/yr) if the KWRB (1967) report is followed, (2) 2.6 in./yr (66 mm/yr) if the Fader and Morton (1972) report is followed, and (3) 1.4 in./yr (36 mm/yr) if the Hansen (1991) report is followed. [Note that the Layton and Berry (1973) recharge estimate (table 2), which would have further lowered these recharge estimates, was not taken into account in this averaging.] Because the Fader and Morton (1972) study is an updated version of the KWRB (1967) study, the Fader and Morton report is favored in obtaining average recharge values for the region.

Based on the GMD5-KGS recharge assessment study (table 1), the arithmetic average recharge from all sites (1–10) for all years for which data are available (1985–1992) is 1.9 in./yr (48 mm/yr). [Note that the 1983 Zenith recharge estimate (table 1), which would have further lowered this average recharge estimate, was not taken into account in this averaging.] The overall average recharge for the sites for which ground-water recharge has been detected (i.e., sites 1–7) is 2.5 in./yr (64 mm/yr).

Sophocleous (1992a), using a combination of statistical (forward stepwise regression) analysis and GIS overlay analysis, identified the portion of the GMD5 area that each recharge site or cluster of sites represents (fig. 4) and derived an area-weighted average recharge for the GMD5 of 1.4 in./yr (36 mm/yr) based on the 1985–1990 recharge site data, as shown in table 4.

All the regional recharge estimates for the Great Bend Prairie aquifer are summarized in table 5.

Finally, table 6 compares all four types of recharge estimates (site, county, subregional and regional) for the Great Bend Prairie aquifer. Combining all these estimates, it is calculated that *the overall recharge estimate for the aquifer is 2 in./yr (51 mm/yr) with a recharge range of 1.7–2.5 in./yr (43–64 mm/yr).* It is worth noting the similarity of the average recharge estimates for the Great Bend Prairie aquifer across both spatial and temporal scales.

Table 4. Recharge zonation of GMD5 based on GIS overlay analysis

Recharge zone	Approximate area within GMD5 (mi^2)	Percentage of GMD5 area	Recharge sites within zone	1985–90[a] average annual recharge (in.) from within zone
1	1,313	33.3	8, 9, 10	0[b], 0.5[c]
2	830	21.1	3, 6	1 (0.3)[d]
3	1,398	35.4	1, 2, 7	2 (0.4)[d]
4	401	10.2	5	3 (0.7)[d]
5	2	0.1	4	7 (1.2)[d]
Area-weighted average recharge: 1.4 in./yr				

a. 1988–1990 for sites 6–10.
b. Three-year average based on recharge sites.
c. Twenty-year average based on Pawnee River valley study (Sophocleous, 1981).
d. Standard error of zonal recharge (in./yr).

Table 5. Regional recharge estimates for the Great Bend Prairie aquifer

Investigator(s)	Period	Recharge (in./yr)	Average recharge (in./yr)	Recharge range (in./yr)
Fader and Stullken (1978)	1951–1971	2.0		
Cobb et al. (1983)	1950–1975	0.75	1.9	0.3–4.3
Luckey et al. (1986)	1950–1980	0.28		
Sophocleous and McAllister (1990)	1982–1983	4.3		
USGS-KWO				
1967 report	long term	3.1[a]		
1972 report	long term	2.6	2.0	1.4–3.1
1991 report	long term	1.4		
Sophocleous (1992a)				
Arithmetic average of site results	1985–1992	1.9	1.7	1.4–1.9
GIS area-weighted average of site results	1985–1990	1.4		

a. Not considered in averaging (see text).

Table 6. Summary recharge estimates for the Great Bend Prairie aquifer

Recharge estimate	Average recharge (in./yr)	Average recharge range (in./yr)	Source
Site estimates (KGS)	1.7	1.4–1.9	Tables 1 and 4
County estimates (USGS-KWO)	2.0	1.4–3.1	Table 2
Subregional estimates (KGS)	2.5	1.5–3.5	Table 3
Regional estimates (USGS-KGS)	1.8	0.3–4.3	Table 5
Overall average	2.0	1.7–2.5	

Conclusion

Few areas of the world have had the benefit of such detailed and comprehensive recharge assessments as the Great Bend Prairie of Kansas. The assessment techniques used are state-of-the-art and combine both local and regional scales and an adequate span of time scales. Although no recharge methodology is free of uncertainties, the recharge-site-based techniques used by Sophocleous and associates are believed to be the most detailed and probably the most accurate. The average recharge for the region is estimated to be approximately 2 in./yr (50 mm/yr), and this estimate is found to be surprisingly robust across spatial and temporal scales and across different estimation methodologies. Given the recharge-estimation uncertainties, I recommend this estimated average annual recharge rate for developing management and conservation plans for the region.

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