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THE HYDROLOGIC IMPACT OF THE GREAT FLOOD OF 1993 IN THE GREAT BEND PRAIRIE OF SOUTH-CENTRAL KANSAS

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Abstract

We evaluate the hydrologic impact of the Great Flood of 1993 on the Great Bend Prairie aquifer of South-central Kansas. During the summer of 1993, rainfall totals surpassed 200% of normal in the northern portion of the study area. At the same time temperature and evapotranspiration were below normal levels during the same period of time. Employing the results of the hybrid water-fluctuation method of Sophocleous (1991) in estimating ground-water recharge at four recharge index sites resulted in an average recharge of 178 mm (from January to July 1993). Employing the recharge-estimation multiple-regression equation of Sophocleous (1992) for the area based on 1985–1990 data resulted in a recharge estimate of 145 mm. Both estimates are higher than the maximum annual recharge observed at the recharge index sites during the 1985–1992 period. A January to July 1993 hydrologic balance analysis for a major portion of the study area resulted in a total recharge of 130 mm. The southern portion of the study area was outside the brunt of the summer storms. The flooding impact of the 1993 precipitation in south-central Kansas was serious but not catastrophic. The recharge amounts caused by the flood in the study area were 3 to more than 4 times the previous 8-year average estimates.

Key Terms

Groundwater Hydrology; Great Flood of 1993; groundwater recharge; hydrologic balance; precipitation patterns; streamflow and baseflow; water table; Rattlesnake Creek, Kansas.

Introduction

In this note we describe and demonstrate the hydrologic impact of the Great Flood of 1993 in the Great Bend Prairie of south-central Kansas (fig. 1). During the summer of 1993, towns throughout central Kansas were battling floodwaters, as persistent and widespread summer storm systems dumped heavy rains on much of the state, and area streams were cresting well above flood stage. The primary data sources we used are daily climatic data from the National Weather Service (NWS) and the Kansas State University Weather Data Library, data from the NOAA Weekly Weather and Crop Bulletin, daily streamflow data from the USGS, and recorded ground-water-level data from the Big Bend Groundwater Management District no. 5 (GMD5). A recharge assessment study of the area (Sophocleous, 1992; 1993a; 1993b) forms the background of this study. The NWS climatic stations in the area, the USGS streamgaging stations, and recharge assessment sites in GMD5 are shown in fig. 1.

The Flood Precursors and the Summer 1993 Rains

Since the drought of 1988, persistent soil-profile moisture-storage declines and depressed ground-water levels resulted in significantly diminished aquifer recharge in south-central Kansas (Sophocleous, 1993a). This water-deficiency trend was halted in 1992 when a wet spring, summer, and late fall resulted in above-normal annual precipitation (figs. 2 and 3) and long overdue soil-profile-moisture replenishment throughout south-central Kansas. Since June 1992, the Palmer Drought Severity Index (PDSI), a meteorological drought index based on the principles of a balance between moisture supply and demand, and used to assess the severity of a wet (positive values) or dry (negative values) spell, exceeded the 1.0 mark, indicating mild wetness, and by August 1992, exceeded the 2.0 mark, indicating moderate wetness (fig. 4a). These wet conditions were followed by extremely wet winter months (January–February 1993, figs. 2 and 3, with the PDSI reaching extreme wetness conditions), which set the stage for early (starting in February 1993) aquifer recharge with the first snowmelt. This early recharge resulted in the initiation of significant water-table rises which continued on the same trend until midspring (early May 1993, see fig. 13 later on). The 1993 first trimester above-normal wet period and spring snowmelt moistened soils to near saturation and raised many stream levels to bankfull conditions. By the beginning of April 1993, the PDSI for south-central Kansas was well above 4.0 (fig. 4a), which indicates extremely moist conditions. Nineteen ninety-three was the wettest year for the region since the 1920's, even wetter than the flooding year of 1951 (fig. 4b). Because the surficial soils in the area were nearly saturated, the potential for additional heavy precipitation to infiltrate the soil was low, and therefore the area was more susceptible to flooding. Thus the stage was set for flooding in the area well before major flooding actually developed in June and July 1993. Since May 1993, persistent, repetitive storm systems of broad areal extent struck central and eastern Kansas with copious rainfall amounts, which culminated during mid-June through late July 1993, generating record flooding throughout central and eastern Kansas. During the summer (June–August 1993), rainfall totals surpassed 510 mm in Chase, Claflin, Hudson, Larned, and Burdett stations (figs. 2 and 3). These amounts were approximately 200% or more above normal precipitation. At the same time, temperatures were below normal up to the beginning of August 1993; this fact in combination with increased cloud cover and moisture in the lower atmosphere reduced seasonal solar radiation and hence evapotranspiration to below normal levels (fig. 5).

Climate of south-central Kansas and the 1993 annual precipitation

Two climatic controls contribute to the precipitation pattern in south-central Kansas. The Rocky Mountains form a massive barrier, blocking maritime air masses that frequently move in from the Pacific Ocean in fall, winter, and spring, thus producing a "rain shadow" over western Kansas. The Gulf of Mexico is the principal source of moisture for precipitation in the area. From east to west, the average annual amount of precipitation received decreases about 25 mm for every 27 km of distance (Bark, 1961). The 30-year (1961–1990) normal precipitation pattern in the area is shown in fig. 6, where a generally increasing precipitation pattern from west to east is evident. However, the 1993 precipitation pattern (fig. 7) differs significantly from the normal, with the deviations plotted in fig. 8. Note the extremely high precipitation amounts in a west to east direction from Burdett through Larned to Hudson and from there in a northeast direction from Hudson to Ellsworth and beyond. Note also that the south and southwest portion of the Great Bend Prairie received the least amounts of precipitation in 1993, although still well above normal.

Weather Patterns during the Great Flood of 1993

To understand the 1993 precipitation patterns in south-central Kansas, a knowledge of the highly anomalous and persistent atmospheric patterns over the U.S. during 1993 is required. An unusually rich supply of north Pacific energy and a stalwart ridge of high pressure over the Southeast combined to produce rare summer flooding in the upper Mississippi River basin and northern and central Great Plains (NOAA, 1994). By the summer of 1993, a low-pressure trough was located near the Gulf of Alaska and below-normal sea-level pressures covered the western U.S. At the same time a high-pressure air mass (Bermuda high) expanded into the southeastern U.S. and stalled, thus creating a persistent and strong trough-ridge couplet (fig. 9a). The clockwise circulation of the Bermuda high system brought warm, moist air from the Gulf of Mexico into the upper Midwest. The energetic trough, fueled by a strong north Pacific jet stream, which had plunged farther south than usual, allowed cool Canadian air to converge with this moist air over the upper Midwest (fig. 9a), bringing record cold to the Northwest and delivering record rainfall to many areas within the upper Mississippi River basin and northern and central Great Plains for most of the summer (fig. 10, Parrett et al., 1993; NOAA, 1993). The mean position of the jet stream had become firmly established in the summer of 1993 over the northern portion of the Mississippi River basin with a southwest to northeast orientation (fig. 9a, NOAA, 1994). To the northwest lay a deep trough of low pressure, while an unusually strong, clockwise circulation, associated with the Bermuda high, lay over the southeastern states. Hot and dry conditions were characteristic of the surface conditions beneath the ridge. Records of July 1993 dryness were established in scattered locations across much of the U.S. southern frontier from Arizona to the Carolinas. In parts of central and eastern Texas, no measurable rain fell during the month of July 1993. But farther north, Concordia, KS, broke its July rainfall record by more than 127 mm, while in Great Bend, central Kansas, July rainfall exceeded its norm by more than 230 mm.

By late July and early August 1993, a dramatic shift in the weather pattern (fig. 9b; NOAA, 1994) brought drier conditions to the Midwest as the trough shifted eastwards, simultaneously increasing rainfall and decreasing temperature in the East, while warmer weather returned to the Pacific Northwest (NOAA, 1994).

Great Bend Prairie aquifer responses to the Great Flood of 1993

As a result of this above-normal 1993 precipitation, aquifer water levels rose significantly in the Great Bend Prairie, as shown by the January 1993 to January 1994 ground-water-level change map (fig. 11). As can be seen in that map, most of the ground-water-level rises occurred in the eastern portion of the Great Bend Prairie, around the Rattlesnake Creek and Quivira National Wildlife Refuge, which constitute the natural ground-water-discharge region of the Great Bend Prairie aquifer and are characterized by shallow water-table elevations. A January 1994 depth to water table map is shown in fig. 12.

An analysis of daily precipitation and recorded ground-water levels at several recharge-monitoring sites in the area (Sophocleous, 1991, 1992, 1993b) revealed a number of ground-water-recharge producing precipitation events resulting in significant water-table rises (fig. 13). The first such event occurred in May 7–11, 1993, the second in June 17–20, 1993, and the third (combined event) in July 8–23, 1993. The spatial distribution of precipitation for those three major events is shown in figs. 14, 15, and 16. The May 1993 pattern resembles the expected normal precipitation pattern with precipitation amounts increasing from west to east. The June 1993 pattern shows localized heavy precipitation amounts exceeding 127 mm paralleling the Rattlesnake Creek in a southwest to northeast direction across Stafford and Rice counties. Note that southern, southwest, and northwest south-central Kansas received much less precipitation than the rest of the region. The July 1993 pattern shows three maxima: one around Greensburg with more than 8 inches of precipitation, one around Burdett and Alexander with more than 9 inches of precipitation, and one around Hudson and Claflin with more than 8 inches of precipitation. Recharge sites 8, 9, and 10, which since their establishment in 1988 had shown practically continuous water-level declines (Sophocleous, 1993b), for the first time showed continuous water-level rises throughout 1993.

Employing the results of the hybrid water-fluctuation method of Sophocleous (1991) in estimating ground-water recharge at the four recharge index sites (1, 2, 3, and 5), i.e. multiplying the average effective storativity derived for each site using the combined soil-water balance and water-table fluctuation procedures by the corresponding water-table rise associated with specific precipitation events, resulted in the recharge values shown in table 1. Sites 2 and 3 which received the highest precipitation also received the highest recharge, while the southern GMD5 sites (1 and 5), which were located outside the brunt of the big storms, did not reach maximum values estimated in previous years (column 7 in table 1). Employing the recharge-estimation multiple-regression equation (3) of Sophocleous (1992) based on 1985–1990 data from the GMD5, which had a multiple correlation coefficient of 0.87, and using available measured soil profile water-storage data from the wettest year of the 1985–1990 period and summer (instead of spring) water levels, resulted in the second recharge estimate (column 6 of table 1). The annual recharge estimates (columns 5 and 6 in table 1) are in satisfactory agreement except for site 2, which the regression equation underestimates by a factor of approximately 2. During 1993, site 2 witnessed a January to July water-table rise of almost 19 ft, the highest observed among all recharge sites since their establishment in 1985 (Sophocleous, 1991, 1992, 1993a, 1993b).

The 1993 areal precipitation, based on the Thiessen polygon approach, in south-central Kansas, specifically in an area of more than 19,500 km^2 encompassing the GMD5, totaled 874 mm, which is approximately 226 mm above the 30-year (1961–1990) normal areal precipitation over the same region (648 mm). As a result of this precipitation, the 1993 estimated average aquifer recharge based on the four recharge index sites is 178 mm (column 5, table 1); the recharge estimate based on regression equation (3) of Sophocleous (1992, p. 128) is 145 mm (column 6, table 1). Both estimates are higher than the average maximum recharge observed at the recharge index sites during the 1985–1992 period (column 7, table 1), and much higher than the 1985–1992 average annual recharge based on the same sites (column 8, table 1).

Streamflow response to the Great Flood of 1993

Figures 17–19 show daily streamflow hydrographs of area streams with baseflow separated using the local minimum technique (see next section), as well as daily precipitation plotted on the same vertical scale for relative comparisons. The identified recharge-causing precipitation events also produced identifiable streamflow peaks. Of interest is the fact that the southern area streams at Pratt, Kinsley, and Macksville show relatively minimal peaks (Kinsley practically none), confirming that precipitation was much more intense in northern south-central Kansas. If we consider the 150% of normal precipitation isoline, shown in fig. 10, as the boundary of intense rainfall, we see that the southern portion of the Great Bend Prairie was outside the brunt of the summer storms, thus explaining the low observed streamflows of the streams in that part of the Great Bend Prairie. This is also confirmed by analyzing the number of precipitation days (exceeding 0.3 mm) at different climatic stations shown in table 2. The table shows that the number of precipitation days generally increases as one moves from south to north. It should be noted that none of the extreme streamflow records in the region has been exceeded in 1993. (The maximum streamflow for the period of record for the Rattlesnake Creek was reached in October 1973 [515.4 m^3/s at the Zenith gaging station]; for Arkansas River in the area on June 1965 [1,410.3 m^3/s at Kinsley]; and for Pawnee River in July 1958 [461.6 m^3/s near Larned].)

Table 1. Ground-water recharge estimates at sites in Great Bend Prairie during 1993

(1) Site No. and Precip. sta.	(2) Precip. event 1993	(3) Precip. amount (mm)	(4) Water table rise (m)	(5) Recharge[1] (mm)	(6) Recharge[2] (mm)	(7) Recharge[3] mm (year)	(8) Recharge[4] (mm)
1. Trousdale	(0) March 2–May 7	125	0.51	23			
	(1) May 8–11	50	0.31	14			
	(2) June 19–20	98	0.46	21			
	(3) July 12–21	109	0.94	44			
	Site yearly total	855		105	130	140 (1987)	36
2. Sandyland	(0) March 2–May 6	136*	0.83	51			
	(1) May 7–11	62	1.02	62			
	(2) June 17–19	170	1.76	107			
	(3) July 11–18	154	2.01	123			
	Site yearly total	951*		343	163	99 (1987)	41
3. Hudson	(0) March 2–May 6	136	1.01	35			
	(1) May 8–11	86	0.33	11			
	(2) June 18–19	139	0.56	20			
	(3) July 8–23	203	2.18	76			
	Site yearly total	985		142	160	71 (1985)	23
5. Pratt	(0) Feb. 11–May 7	7.90	0.83	48			
	(1) May 8–11	4.73	0.35	21			
	(2) June 19	1.30	0.31	18			
	(3) July 12–21	4.11	0.53	31			
	Site yearly total	845		121	125	150 (1985)	71
Annual Average				178	145	115	43

1. Recharge estimate based on the hybrid water fluctuation method.
2. Yearly recharge estimate based on multiple regression equation (3) of Sophocleous (1992); $R = -9.3727 + 0.2459\ PCP_T - 0.0819 S_{max} - 5.2387\ WL_{max}$, where R = annual recharge (mm), PCP_T = total annual precipitation (mm), S_{max} = spring–average maximum soil-water storage (mm) in upper 2.75 m of soil profile and WL_{max} = spring–average shallowest depth to water table (m).
3. Maximum yearly recharge estimate at the indicated sites during the 1985–1992 period.
4. Average annual recharge at the indicated sites during the 1985–1992 period.

* The missing first three months of 1993 were replaced by the corresponding ones from the nearby Hudson station.

Table 2. Number of days with precipitation exceeding 0.3 mm during several months of 1993 in south-central Kansas

Precipitation Station	May	June	July	August
Pratt	9	5	7	5
Trousdale	14	6	9	9
Hudson	12	8	11	11
Larned	11	12	14	11
Great Bend	15	9	14	11

Generalized hydrologic balance of the Lower Rattlesnake Creek watershed during the Great Flood of 1993

In order to account for the mass balance of the Great Flood of 1993 in the study area, we selected a portion of the lower Rattlesnake Creek watershed between the Macksville and Zenith streamgaging stations (fig. 1) for which we know the incoming and outgoing streamflow, and for which precipitation at the Hudson climatic station, and other climatic data from the Sandyland Experiment Station (fig. 1) are representative. The total drainage area for the Zenith streamgaging station is 2,724 km^2 of which only 1,380 km^2 are contributing surface runoff to streamflow, whereas the Macksville streamgaging station drainage area is 2,030 km^2 of which only 1,108 km^2 are contributing (Geiger et al., 1994). Thus we focus on a total drainage area of (2,724–2,030 =) 694 km^2 between the two streamgaging stations.

The hydrologic balance for a certain period over an area can be represented in a simplified manner by the following equation:

$$R = P - ET - RO - \Delta S \qquad (1)$$

where P is precipitation, R is groundwater recharge, ET is actual evapotranspiration, RO is runoff, both surface and subsurface, and ΔS is the change in soil-water storage in the vadose zone, all quantities expressed as a height of water. From the hydrologic budget eq. (1), one can appreciate that aquifer recharge is dependent on meteorologic, soil, vegetation, physiographic characteristics, and properties of the geologic material through which water flows. Therefore, to understand the recharge process more fully, we need a fundamental knowledge of all these factors.

The hydrologic budget approach has a large data demand and, given the nature of routinely available data, does not usually provide very accurate results. The fact that the calculated recharge is the result of the difference in measurements that are themselves subject to significant errors leads to comparatively high recharge estimation error in many cases. Sophocleous (1991) outlined procedures which minimize or reduce the hydrologic budget-based recharge-estimation errors. Because evapotranspiration estimated from routine climatalogical measurements, and surface runoff estimated from streamflow separation techniques are usually understood to be accurate over relatively long periods of time, a monthly time step was adopted for this analysis. Furthermore, as a result of the extreme soil wetness and the high frequency of rainfall during 1993, the masking impact on recharge by the averaging effect of monthly input data (Sophocleous, 1991) is minimized.

As a result of the prevailing extremely wet soil-profile conditions (fig. 4), we can justify the assumption of nearly constant and saturated soil-water storage levels in the vadose zone, resulting in $\Delta S = 0$ in eq. (1). Also, because of the near flatness of the topography and high soil-profile moisture levels, subsurface (lateral) runoff can be assumed negligible. However, because of the high intensity and amounts of rainfall, surface (overland) runoff cannot be safely ignored. Surface runoff was obtained by separating baseflow from stream hydrographs at Zenith and Macksville streamgaging stations using the HYSEP2 program (White and Sloto, 1990) with the local minimum method of separation, and obtaining the difference between total streamflow and estimated baseflow. *ET* is estimated using the complementary relation areal evapotranspiration (CRAE) method (Morton, 1983; Morton et al., 1985). This methodology permits areal *ET* to be estimated from its effects on the routinely observed temperatures, humidities, and insolation, thereby avoiding the complexities of the soil-plant system, and the need for locally calibrated coefficients.

The January to July 1993 precipitation in that portion of the watershed between the Macksville and Zenith streamgaging stations totaled 817 mm, the areal *ET* over the same interval totaled 607 mm, and the direct surface runoff totaled 80 mm, thus resulting in a total recharge (eq. 1) of 130 mm. The 1993-estimated *ET* is the lowest estimated value since solar radiation records were established at the Sandyland Experiment Station (fig. 5). The 1993-estimated surface runoff is more than four times the average annual runoff for the Rattlesnake Creek Watershed (18 mm; Hedman and Engel, 1989). The January to July 1993 estimated recharge of 130 mm, although somewhat lower than the previous recharge estimates (columns 5 and 6 of table 1), is certainly of the same order of magnitude and thus satisfactory, given the uncertainties of such estimations. This amount of estimated recharge resulted in an average water-table rise in Stafford County of approximately 1.65 m (fig. 11). It should be noted that the January to July 1993 estimated baseflow contribution to streamflow in the Macksville to Zenith reach of the Rattlesnake Creek (using the local minimum method in the HYSEP2 program) is 20 mm, which is less than 15.5% of the hydrologic balance-estimated recharge amount, with the remainder of the estimated recharge going into ground-water storage and causing the observed water table rises (fig. 11). The average 1993 recharge in the lower Rattlesnake Creek watershed, practically representing Stafford County, is probably the average of the site-estimated values (178 mm), regression-estimated values (145 mm), and hydrologic balance-estimated value (130 mm), resulting in 151 mm.

Concluding comments

In conclusion, despite the severity of the 1993 flood in the upper Mississippi River basin and northern and central Great Plains, which resulted in the most catastrophic of flood disasters to occur in U.S. history, justifying the name "The Great Flood of 1993" (NOAA, 1994), the flooding impact of the 1993 precipitation events in south-central Kansas was serious but not catastrophic. Total precipitation in the area did not exceed the 1973 flooding year rainfall in any climatic station within the GMD5. Streamflows did not exceed their observed maxima over the last 20–40 years. However, the recharge impact of the Great Flood of 1993 on the Great Bend Prairie aquifer was remarkable, causing the highest water-table rises since the flood of 1973 and recharge amounts three to more than four times the previous eight year-average (1985–1992) estimates.

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References

Bark, L.D., 1961. Rainfall patterns in Kansas. Kansas Agricultural Experiment Station, Manhattan, KS, Reprint No. 9, 4 p.

Geiger, C.O., Lacock, D.L., Schneider, D.R., Carlson, M.D., and Dague, B.J., 1994. Water Resources Data, Kansas Water Year 1993. U.S. Geological Survey, Water-Data Report KS-93-1, Lawrence, KS, 497 p.

Hedman, E.R., and Engel, G.B., 1989. Flow characteristics for selected streams in the Great Plains subregion of the Central Midwest regional aquifer system and selected adjacent areas—Kansas and Nebraska, and parts of Colorado, Iowa, Missouri, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. U.S. Geological Survey, Hydrologic Investigations Atlas HA-708.

Morton, F.I., 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. Journal of Hydrology 66(1/4):1–76.

Morton, F.I., Fogarasi, S., and Ricard, F., 1985. Operational estimates of areal evapotranspiration and lake evaporation—Program WREVAP. NHRI paper no. 24, National Hydrology Research Institute, Inland Waters Directorate, Environment Canada, Ottawa, Ontario.

National Oceanic and Atmospheric Administration (NOAA), 1993. Weekly Weather and Crop Bulletin. U.S. Department of Commerce.

_____, 1994. The Great Flood of 1993. Natural Disaster Survey Report. U.S. Department of Commerce.

Parrett, C., Melcher, N.B., and James, R.W., Jr., 1993. Flood discharges in the Upper Mississippi River Basin, in: Floods in the Upper Mississippi River Basin, 1993. U.S. Geological Survey Circular 1120-A, 14 p.

Sophocleous, M.A., 1991. Combining the soil-water balance and water-level fluctuation methods to estimate natural groundwater recharge: Practical aspects. Journal of Hydrology, vol. 124, p. 229–241.

_____, 1992. Groundwater recharge estimation and regionalization: The Great Bend Prairie of central Kansas and its recharge statistics. Journal of Hydrology, v. 127, p. 113–140.

_____, 1993a. A comparative review of ground-water recharge estimates for the Great Bend Prairie of central Kansas. in: Current Research on Kansas Geology, Kansas Geological Survey, Bulletin 235, p. 41–54.

_____, 1993b. Pictorial synthesis of 2,922 days (1985–1992) of continuous water-related data recording for the Big Bend Groundwater Management District No. 5 of south-central Kansas. Kansas Geological Survey, Open-file Report 93-22, 32 p.

White, K.E., and Sloto, R.A, 1990. Base-flow-frequency characteristics of selected Pennsylvania streams. U.S. Geological Survey, Water-Resources Investigations Report 90-4160, 67 p.

List of Figures

Fig. 11 Ground-water-level changes from January 1993 to January 1994 in Groundwater Management District No. 5. Circles indicate measurement points. Contours in feet; contouring interval 2 feet. To convert feet to meters multiply by 0.3048.

Fig. 12 Configuration of the depth to water table as of January 1994 in Groundwater Management District No. 5. Contours in feet; contouring interval 10 feet. To convert feet to meters multiply by 0.3048.

Fig. 13 Daily precipitation and water-table hydrographs for recharge-monitoring sites (a) 1, (b) 2, (c) 3, and (d) 5. To convert inches to mm multiply by 25.4; feet to meters by 0.3048.

Fig. 14 Spatial distribution of precipitation (in inches) for May 7–11, 1993. To convert inches to mm multiply by 25.4.

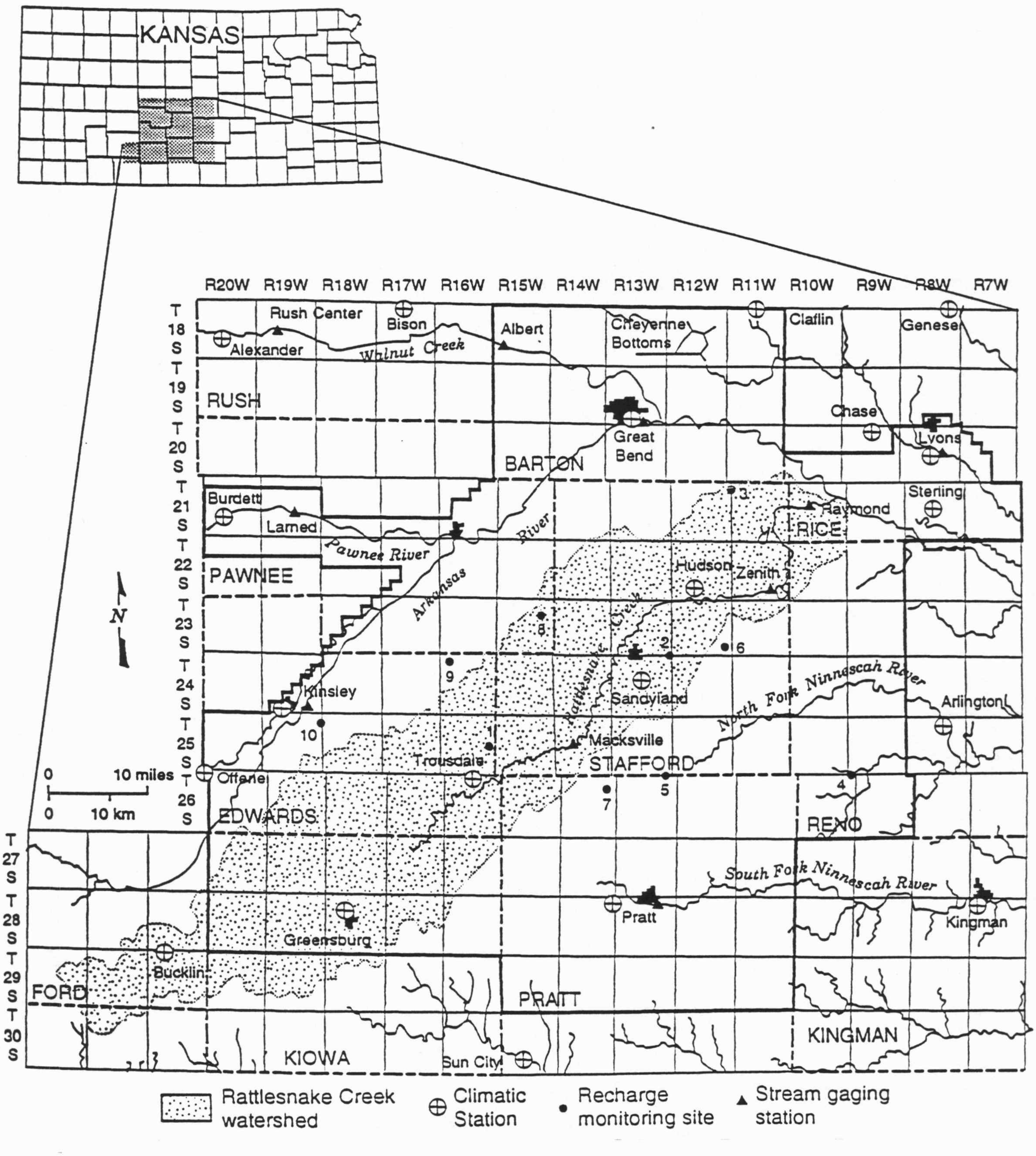
Fig. 15 Spatial distribution of precipitation (in inches) for June 17–20, 1993. To convert inches to mm multiply by 25.4.

Fig. 16 Spatial distribution of precipitation (in inches) for July 8–23, 1993. To convert inches to mm multiply by 25.4.

Fig. 17 Daily precipitation and streamflow (and baseflow) hydrographs for Rattlesnake Creek near (a) Macksville, (b) Zenith, and (c) Raymond. To convert inches to mm multiply by 25.4; cfs to m^3/s by 0.028.

Fig. 18 Daily precipitation and streamflow (and baseflow) hydrographs for (a) Pawnee River near Larned, and (b) Arkansas River near Great Bend.To convert inches to mm multiply by 25.4; cfs to m^3/s by 0.028.

Fig. 19 Daily precipitation and streamflow hydrographs for (a) South Fork Ninnescah River near Pratt, and (b) Arkansas River near Kinsley. To convert inches to mm multiply by 25.4; cfs to m^3/s by 0.028.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Sterling
Raymond
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PRATT
KINGMAN
KIOWA
Sun City
Rattlesnake Creek watershed
Climatic Station
Recharge monitoring site
Stream gaging station

Fig. 1

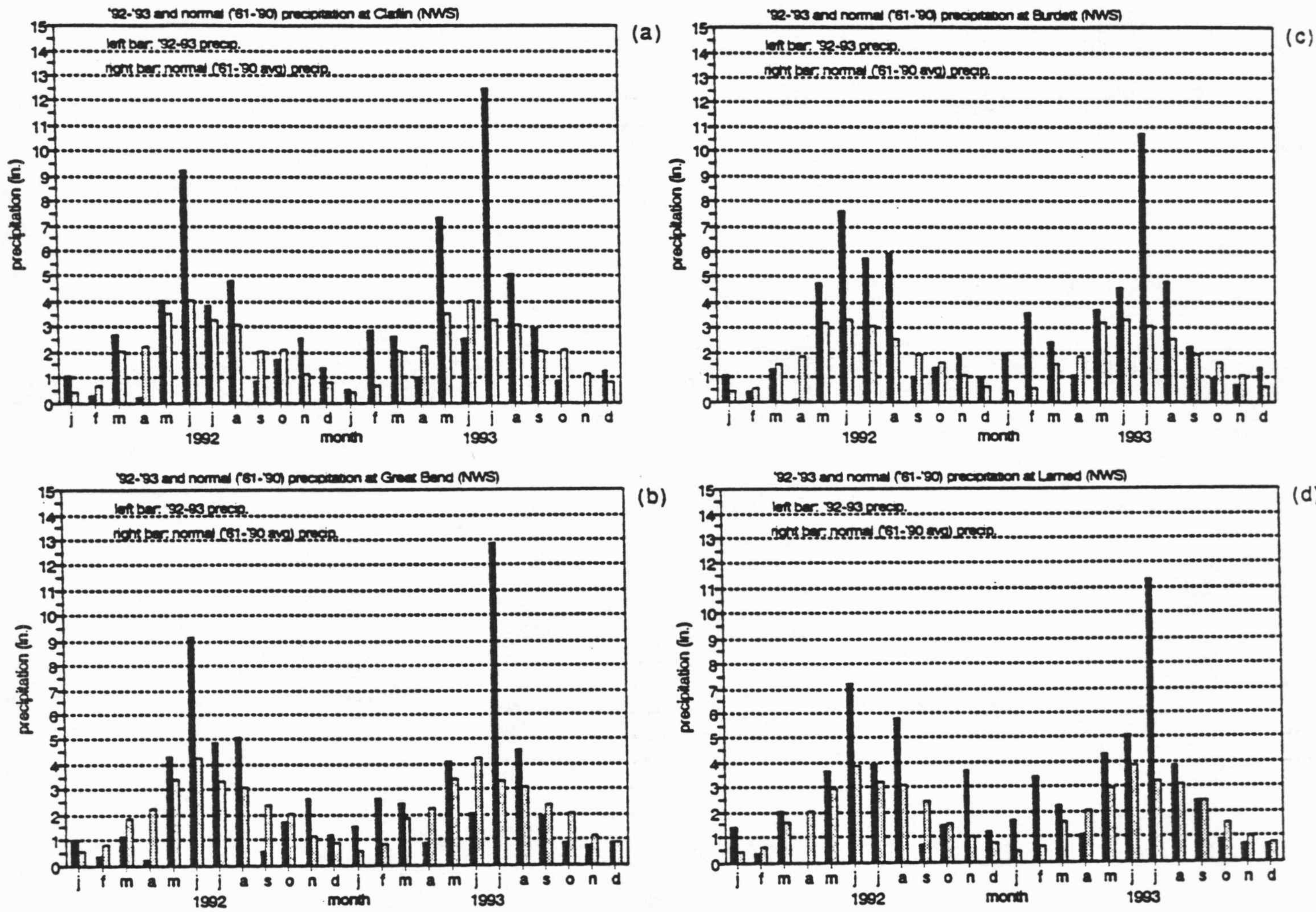
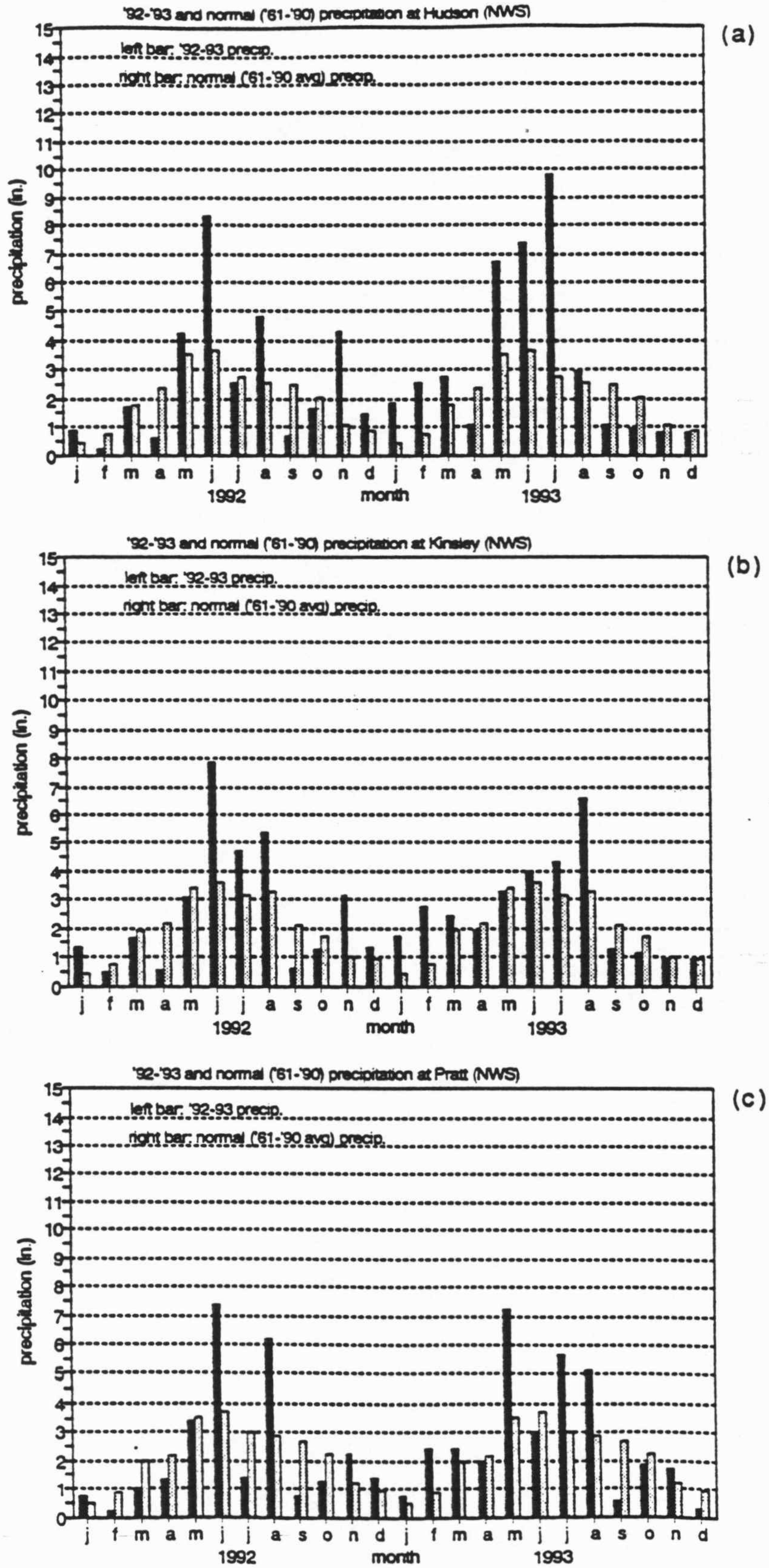

'92-'93 and normal ('61-'90) precipitation at Claflin (NWS)
(a)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
j f m a m j j a s o n d j f m a m j j a s o n d
1992
month
1993
'92-'93 and normal ('61-'90) precipitation at Burdett (NWS)
(c)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
1992
month
1993
'92-'93 and normal ('61-'90) precipitation at Great Bend (NWS)
(b)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
1992
month
1993
'92-'93 and normal ('61-'90) precipitation at Larned (NWS)
(d)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
1992
month
1993

Fig. 2


'92-'93 and normal ('61-'90) precipitation at Hudson (NWS)
(a)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
j f m a m j j a s o n d j f m a m j j a s o n d
1992
month
1993
'92-'93 and normal ('61-'90) precipitation at Kinsley (NWS)
(b)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
j f m a m j j a s o n d j f m a m j j a s o n d
1992
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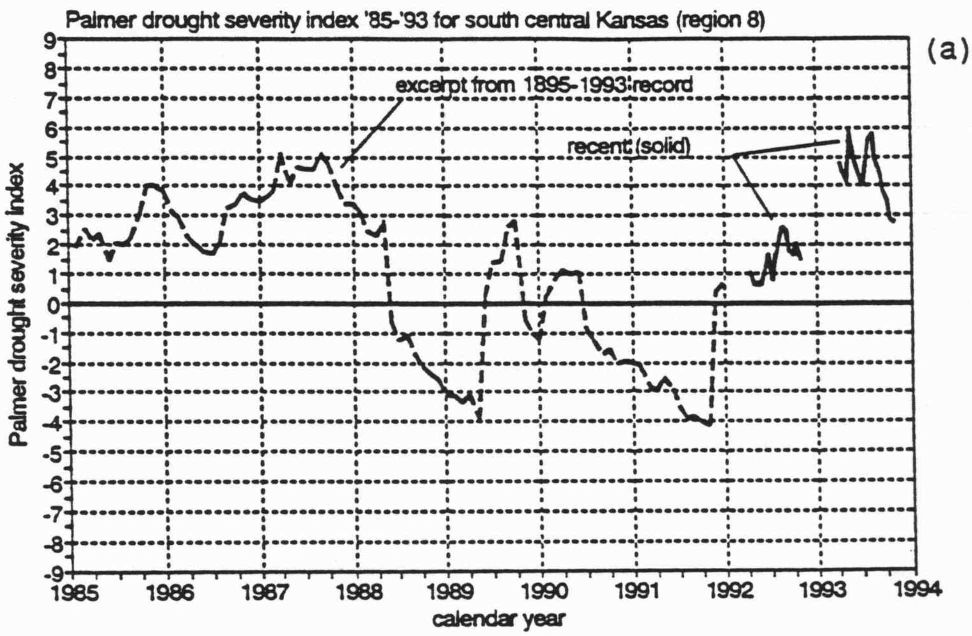
'92-'93 and normal ('61-'90) precipitation at Pratt (NWS)
(c)
left bar: '92-93 precip.
right bar: normal ('61-'90 avg) precip.
precipitation (in.)
j f m a m j j a s o n d j f m a m j j a s o n d
1992
month
1993

Fig. 3


Palmer drought severity index '85-'93 for south central Kansas (region 8)
(a)
excerpt from 1895-1993 record
recent (solid)
Palmer drought severity index
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
calendar year

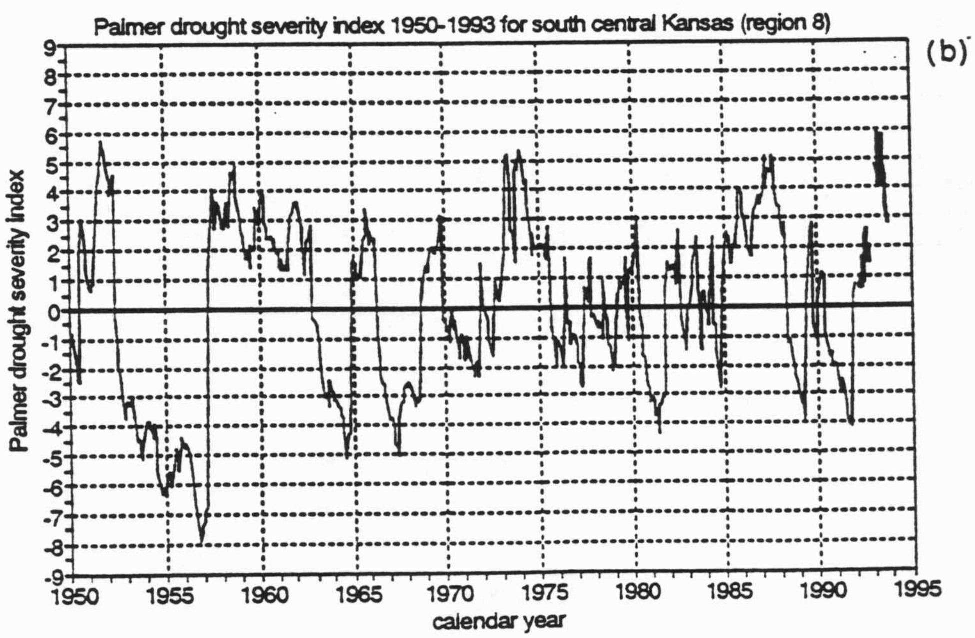

Palmer drought severity index 1950-1993 for south central Kansas (region 8)
(b)
Palmer drought severity index
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
calendar year

Fig. 4

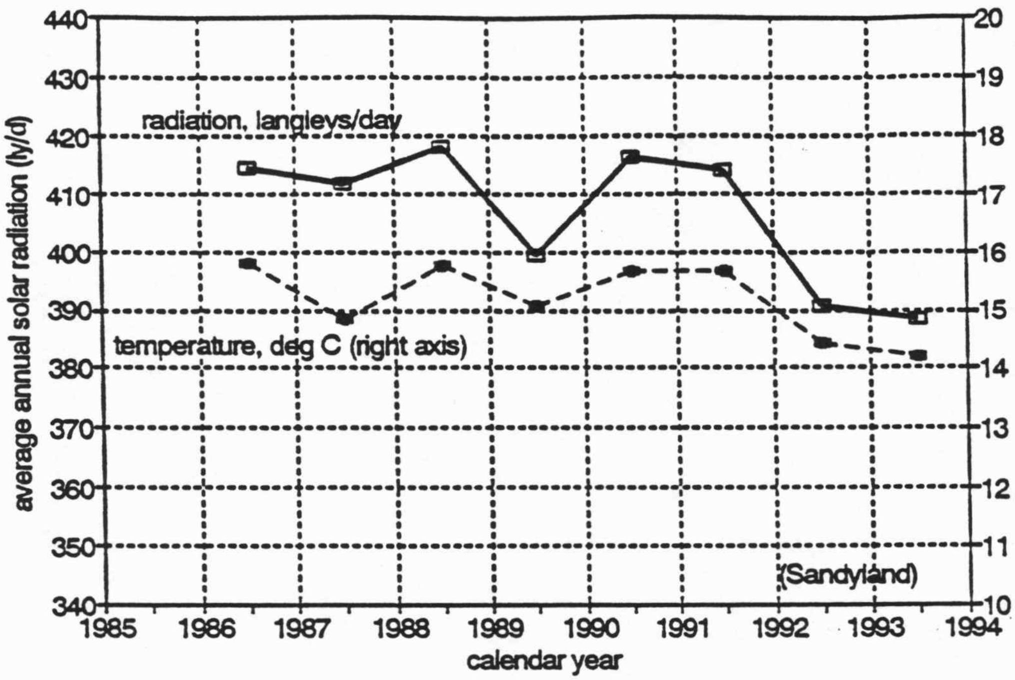
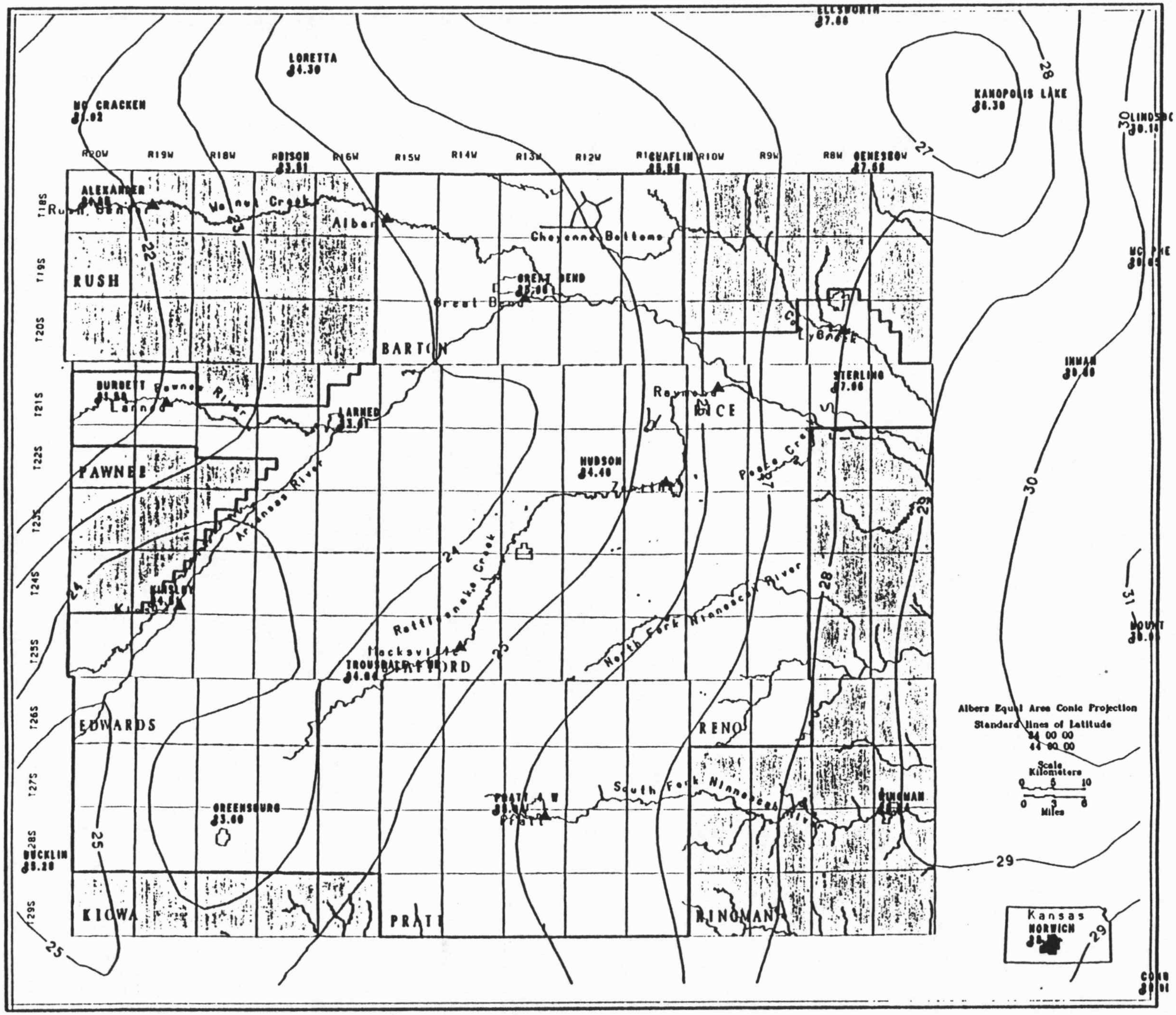
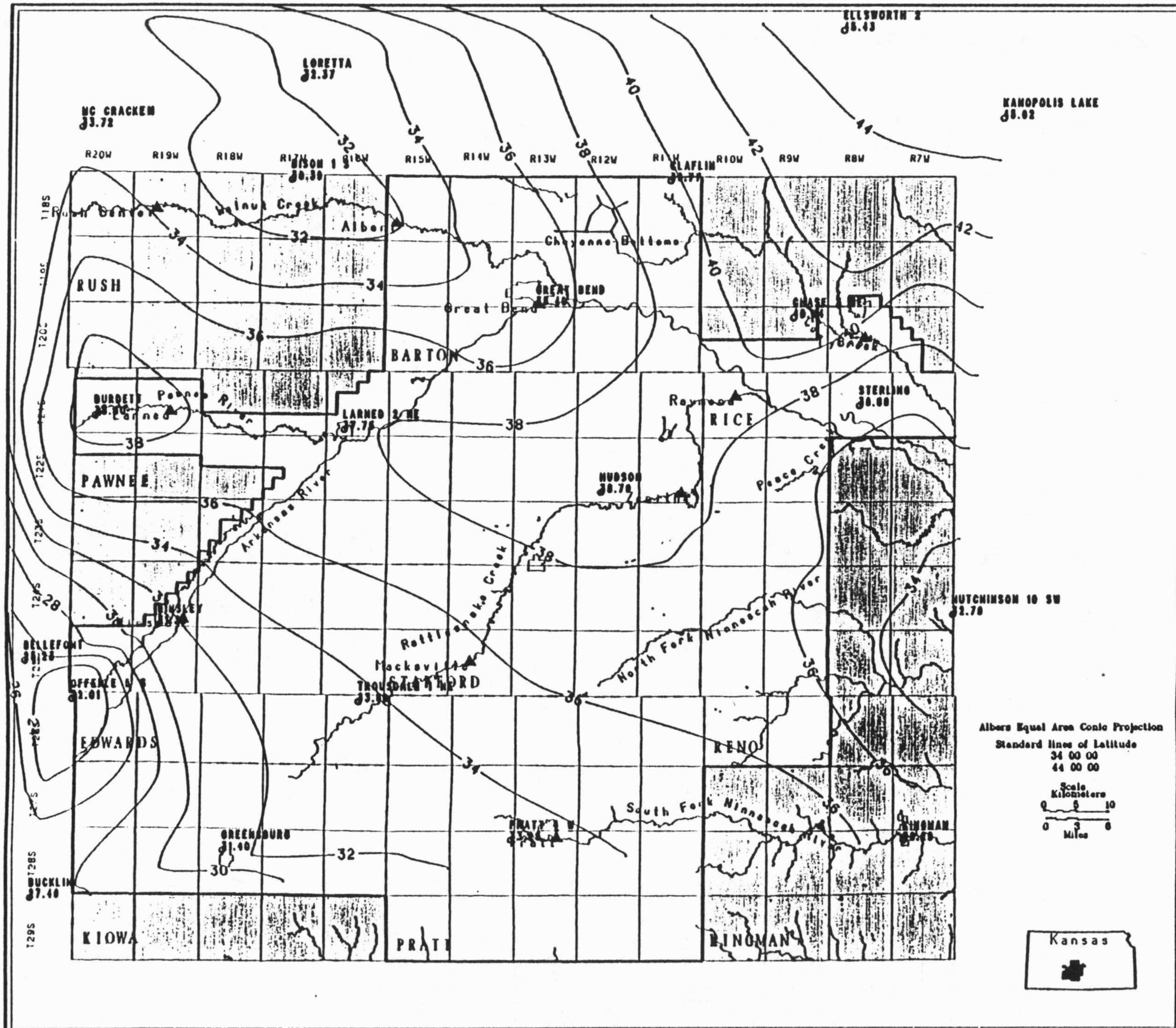

radiation, langleys/day
temperature, deg C (right axis)
(Sandyland)
average annual solar radiation (ly/d)
average annual temperature (deg C)
calendar year
440
430
420
410
400
390
380
370
360
350
340
20
19
18
17
16
15
14
13
12
11
10
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994

Fig. 5

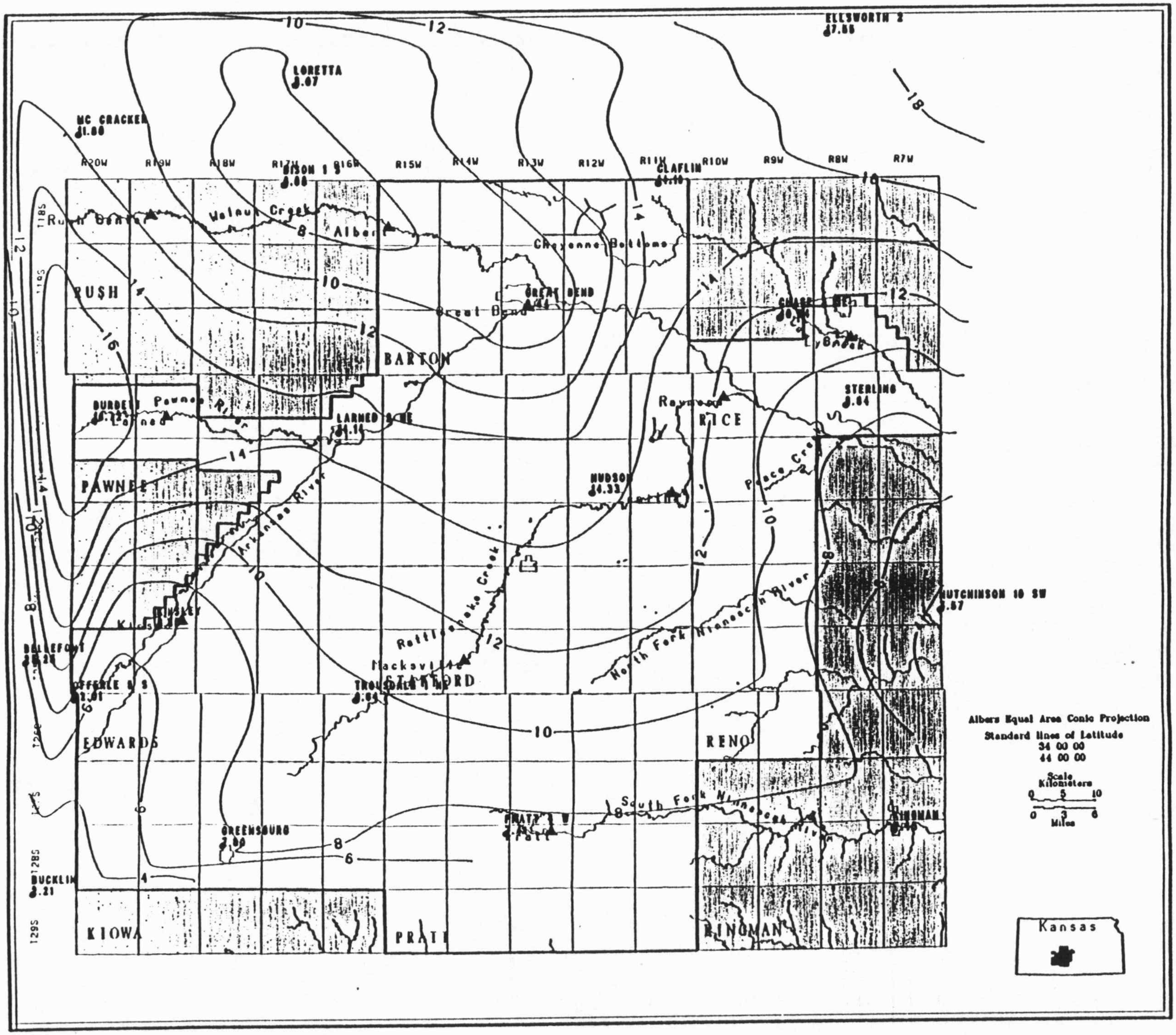


ELLSWORTH
LORETTA
MC CRACKEN
KANOPOLIS LAKE
LINDSBORG
ALEXANDER
Rush Center
Walnut Creek
Albert
Cheyenne Bottoms
GREAT BEND
Great Bend
RUSH
BARTON
BURDETT
Larned
LARNED
PAWNEE
Arkansas River
KINSLEY
Kinsley
Rattlesnake Creek
Macksville
TROUSDALE
STAFFORD
HUDSON
STERLING
RICE
Peace Creek
North Fork Ninnescah River
South Fork Ninnescah River
EDWARDS
RENO
GREENSBURG
PRATT
Pratt
KIOWA
PRATT
KINGMAN
BUCKLIN
INMAN
MOUNT
Albers Equal Area Conic Projection
Standard lines of Latitude
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas
NORWICH

Fig. 6



ELLSWORTH 2
LORETTA
MC CRACKEN
KANOPOLIS LAKE
R20W
R19W
R18W
R17W
R15W
R14W
R13W
R12W
R10W
R9W
R8W
R7W
CLAFLIN
T18S
Rush Center
Walnut Creek
Cheyenne Bottoms
RUSH
GREAT BEND
Great Bend
BARTON
BURDETT
Pawnee River
Larned
LARNED 2 NE
STERLING
Raymond
RICE
PAWNEE
HUDSON
Peace Creek
Arkansas River
Rattlesnake Creek
North Fork Ninnescah River
HUTCHINSON 10 SW
BELLEFONT
Macksville
STAFFORD
EDWARDS
RENO
South Fork Ninnescah River
GREENSBURG
Pratt
BUCKLIN
KIOWA
PRATT
KINGMAN
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0
5
10
0
3
6
Miles
Kansas



ELLSWORTH 2
LORETTA
MC CRACKEN
BISON 1 S
CLAFLIN
R20W
R19W
R18W
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
R8W
R7W
Walnut Creek
Albert
Cheyenne Bottoms
RUSH
GREAT BEND
Great Bend
BARTON
Lyons
STERLING
Pawnee River
LARNED
Larned
RICE
PAWNEE
HUDSON
Arkansas River
Peace Creek
Rattlesnake Creek
North Fork Ninnescah River
HUTCHINSON 10 SW
KINSLEY
Kinsley
BELLEFONT
OFFERLE
Macksville
STAFFORD
EDWARDS
RENO
South Fork Ninnescah River
PRATT
Pratt
GREENSBURG
BUCKLIN
KIOWA
KINGMAN
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas

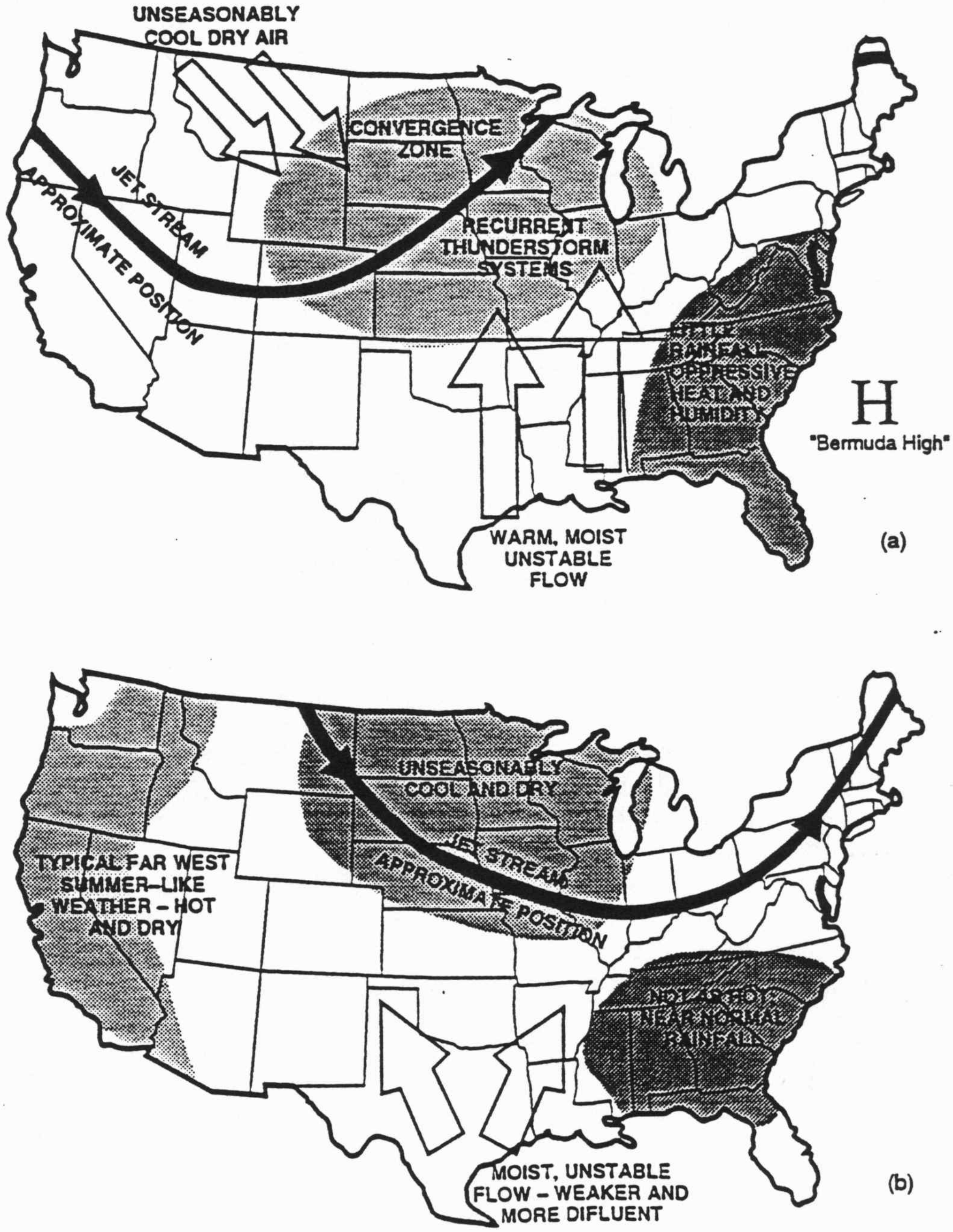
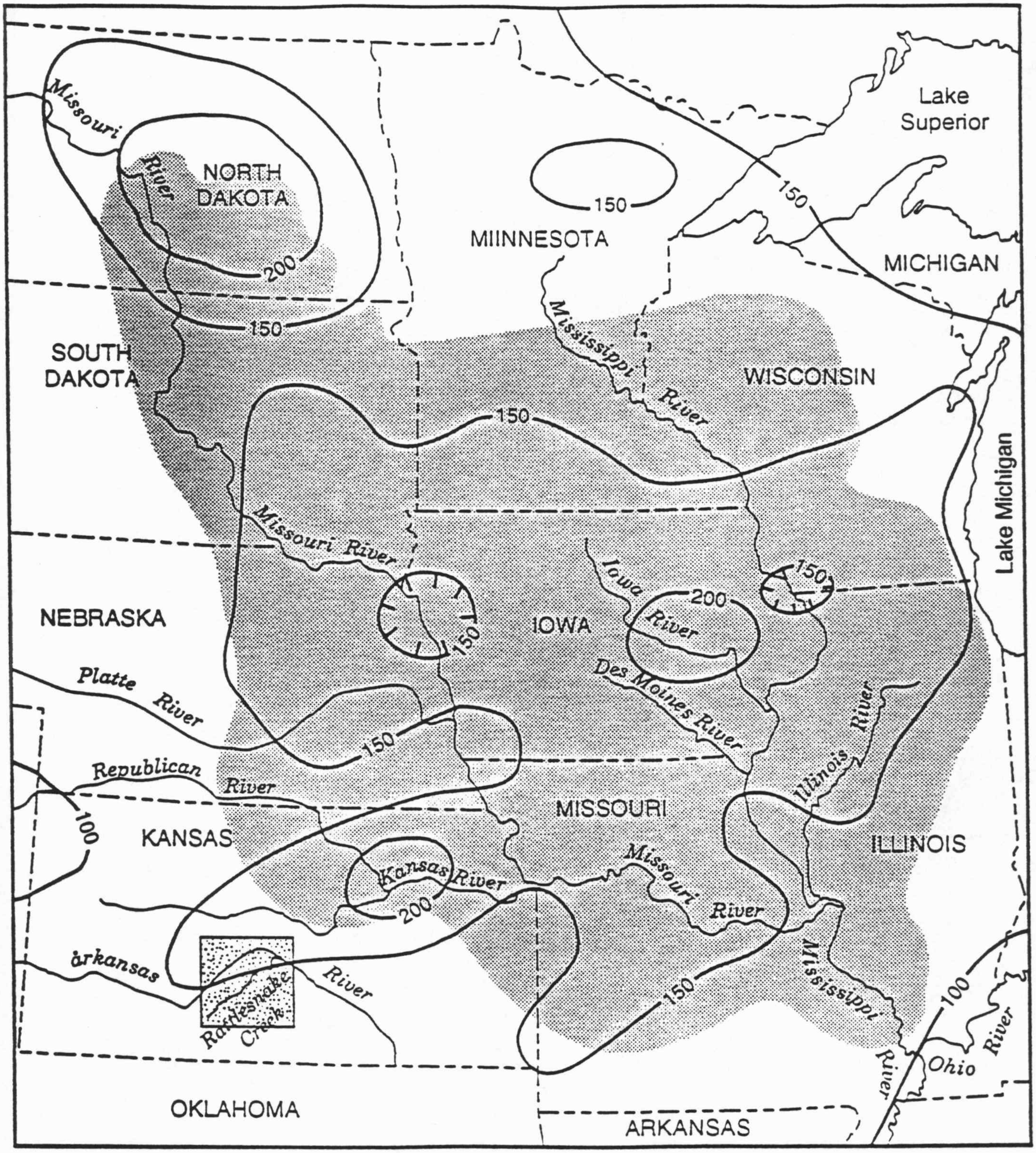

UNSEASONABLY COOL DRY AIR
CONVERGENCE ZONE
JET STREAM
APPROXIMATE POSITION
RECURRENT THUNDERSTORM SYSTEMS
H
"Bermuda High"
WARM, MOIST UNSTABLE FLOW
(a)
UNSEASONABLY COOL AND DRY
JET STREAM
APPROXIMATE POSITION
TYPICAL FAR WEST SUMMER-LIKE WEATHER - HOT AND DRY
MOIST, UNSTABLE FLOW - WEAKER AND MORE DIFLUENT
(b)

Fig. 9



Area of flooding streams

study area

0 100 200 miles

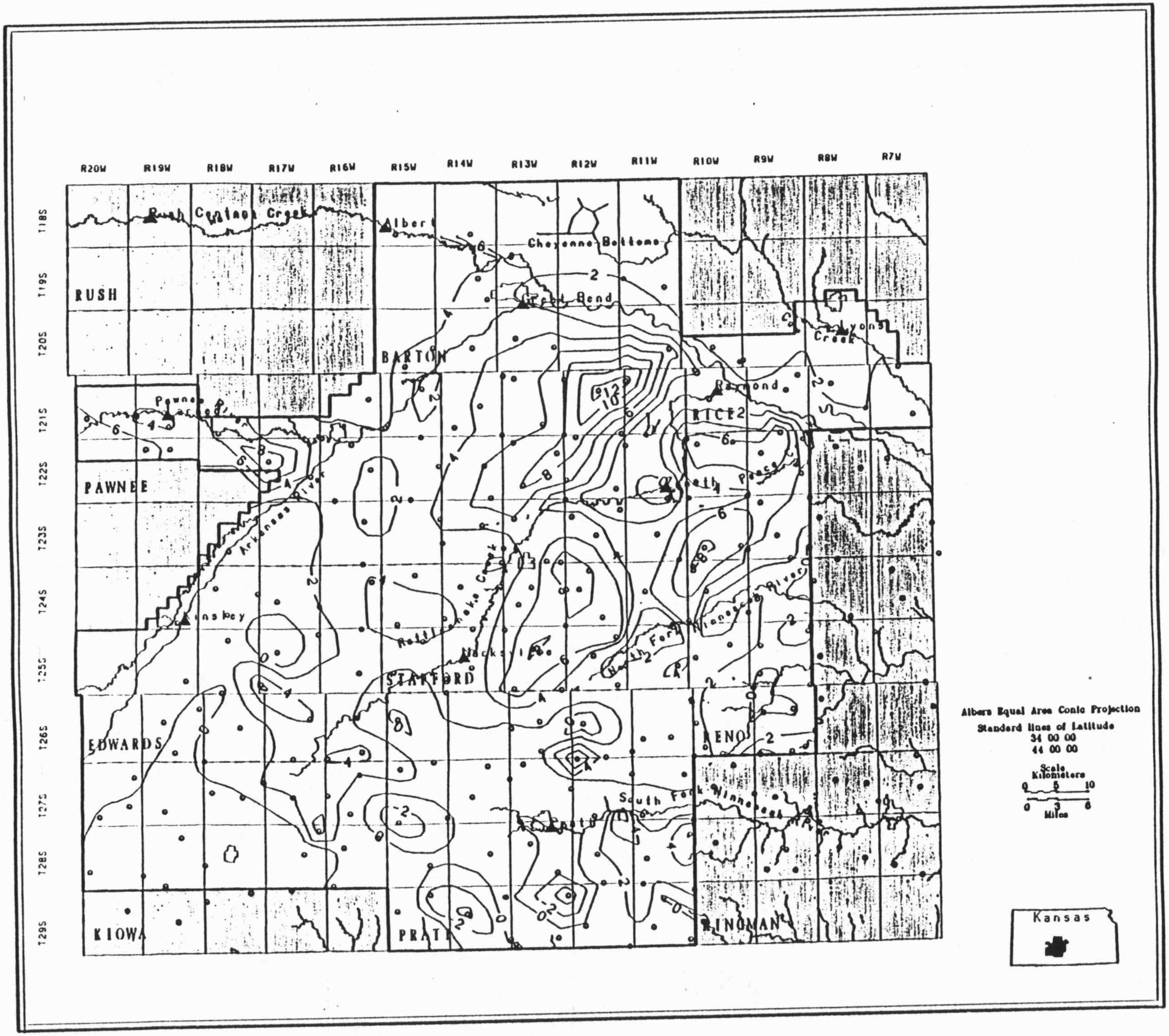
0 100 200 km

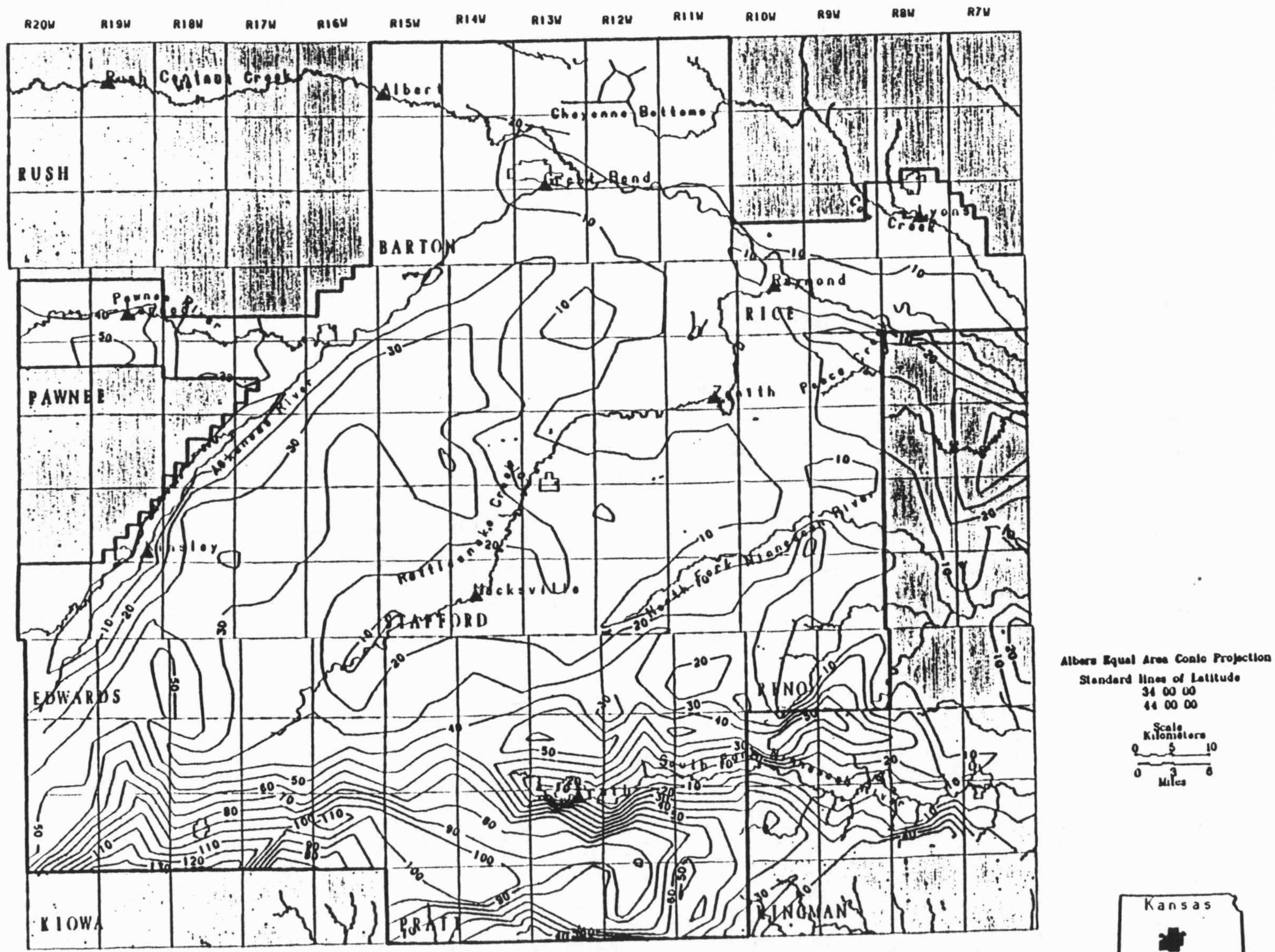
N

—200— Line of equal total precipitation for January through July, 1993 as percentage of the 30-year precipitation normal for January through July, 1961-1990

Hachures indicate closed areas of lesser precipitation. Interval 50 percent

Fig. 16


R20W
R19W
R18W
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
R8W
R7W
T18S
T19S
T20S
T21S
T22S
T23S
T24S
T25S
T26S
T27S
T28S
T29S
RUSH
BARTON
PAWNEE
RICE
STAFFORD
EDWARDS
RENO
KIOWA
PRATT
KINGMAN
Cheyenne Bottoms
Great Bend
Albert
Raymond
Lyons
Kinsley
Rattlesnake Creek
Arkansas River
Pawnee River
South Fork Ninnescah River
North Fork Ninnescah River
Macksville
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas


R20W
R19W
R18W
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
R8W
R7W
T18S
T19S
T20S
T21S
T22S
T23S
T24S
T25S
T26S
T27S
T28S
T29S
RUSH
BARTON
PAWNEE
RICE
STAFFORD
EDWARDS
RENO
KIOWA
PRATT
KINGMAN
Albert
Cheyenne Bottoms
Great Bend
Lyons
Raymond
Macksville
Rattlesnake Creek
Arkansas River
North Fork Ninnescah River
South Fork Ninnescah River
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas

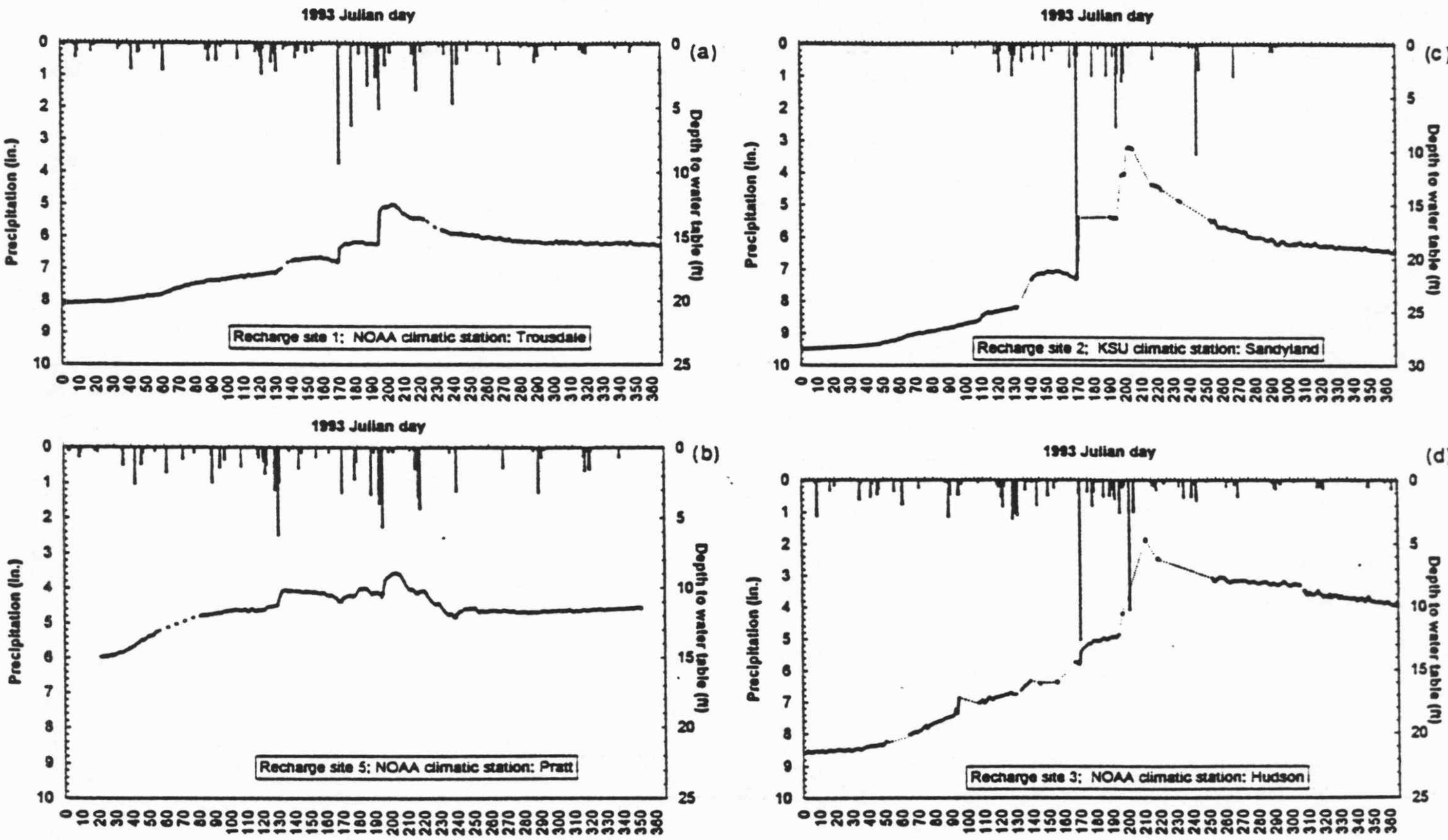

1993 Julian day
Precipitation (in.)
Depth to water table (m)
(a)
Recharge site 1; NOAA climatic station: Trousdale
(c)
Recharge site 2; KSU climatic station: Sandyland
(b)
Recharge site 5; NOAA climatic station: Pratt
(d)
Recharge site 3; NOAA climatic station: Hudson

Fig 13

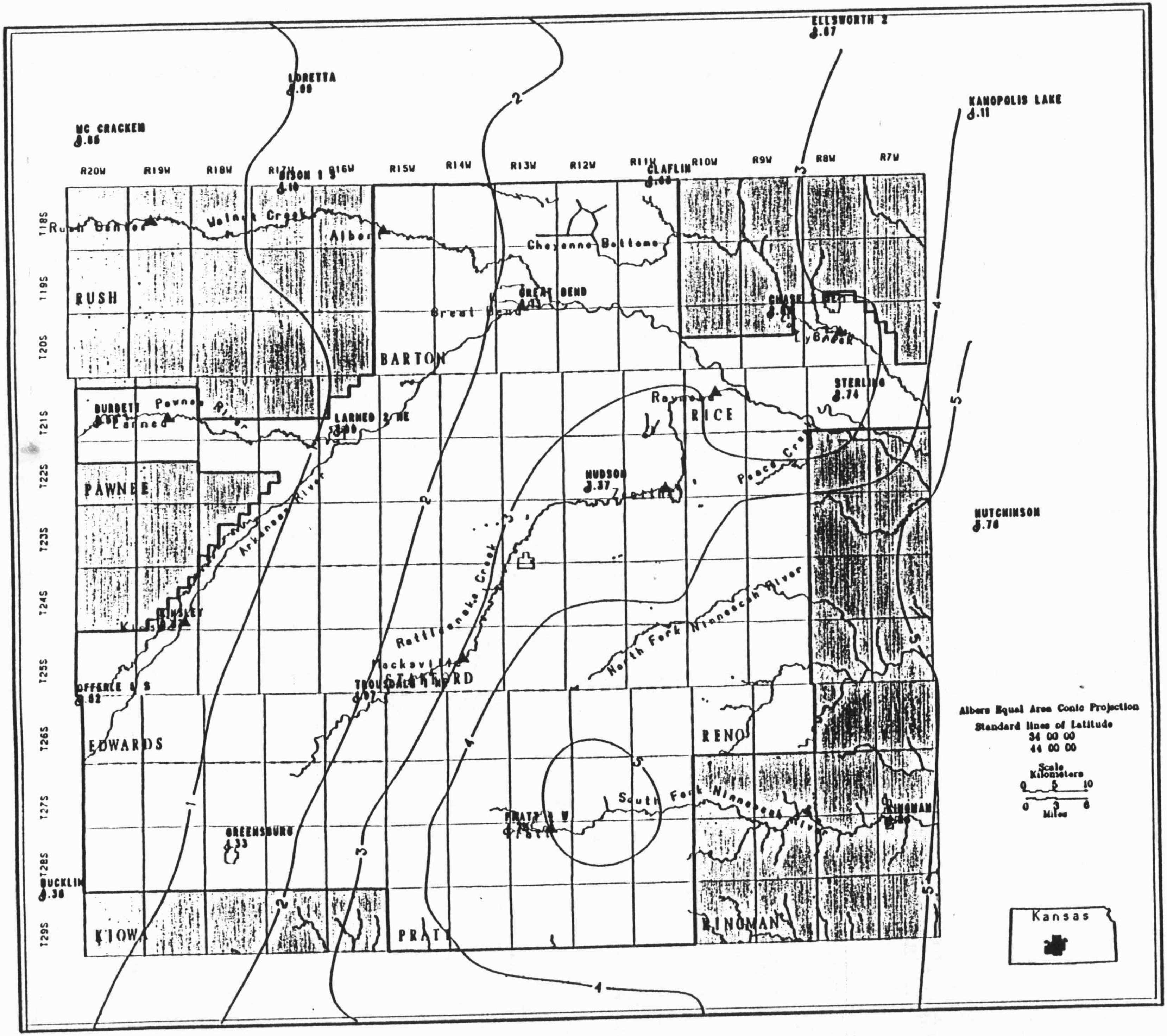

ELLSWORTH 2
.87
LORETTA
MC CRACKEN
KANOPOLIS LAKE
.11
R20W
R19W
R18W
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
R8W
R7W
CLAFLIN
T18S
T19S
T20S
T21S
T22S
T23S
T24S
T25S
T26S
T27S
T28S
T29S
Rush Center
Walnut Creek
Cheyenne Bottoms
RUSH
GREAT BEND
Great Bend
BARTON
STERLING
.74
BURDETT
Pawnee River
Larned
LARNED 2 NE
RICE
Peace Creek
HUDSON
.37
PAWNEE
Arkansas River
HUTCHINSON
.76
Rattlesnake Creek
North Fork Ninnescah River
KINSLEY
Kinsley
Macksville
STAFFORD
OFFERLE 6 S
.62
TROUSDALE 1 NE
EDWARDS
RENO
South Fork Ninnescah River
GREENSBURG
.33
PRATT 3 W
Pratt
KINGMAN
BUCKLIN
.38
KIOWA
PRATT
KINGMAN
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas
1
2
3
4
5

Fig. 14

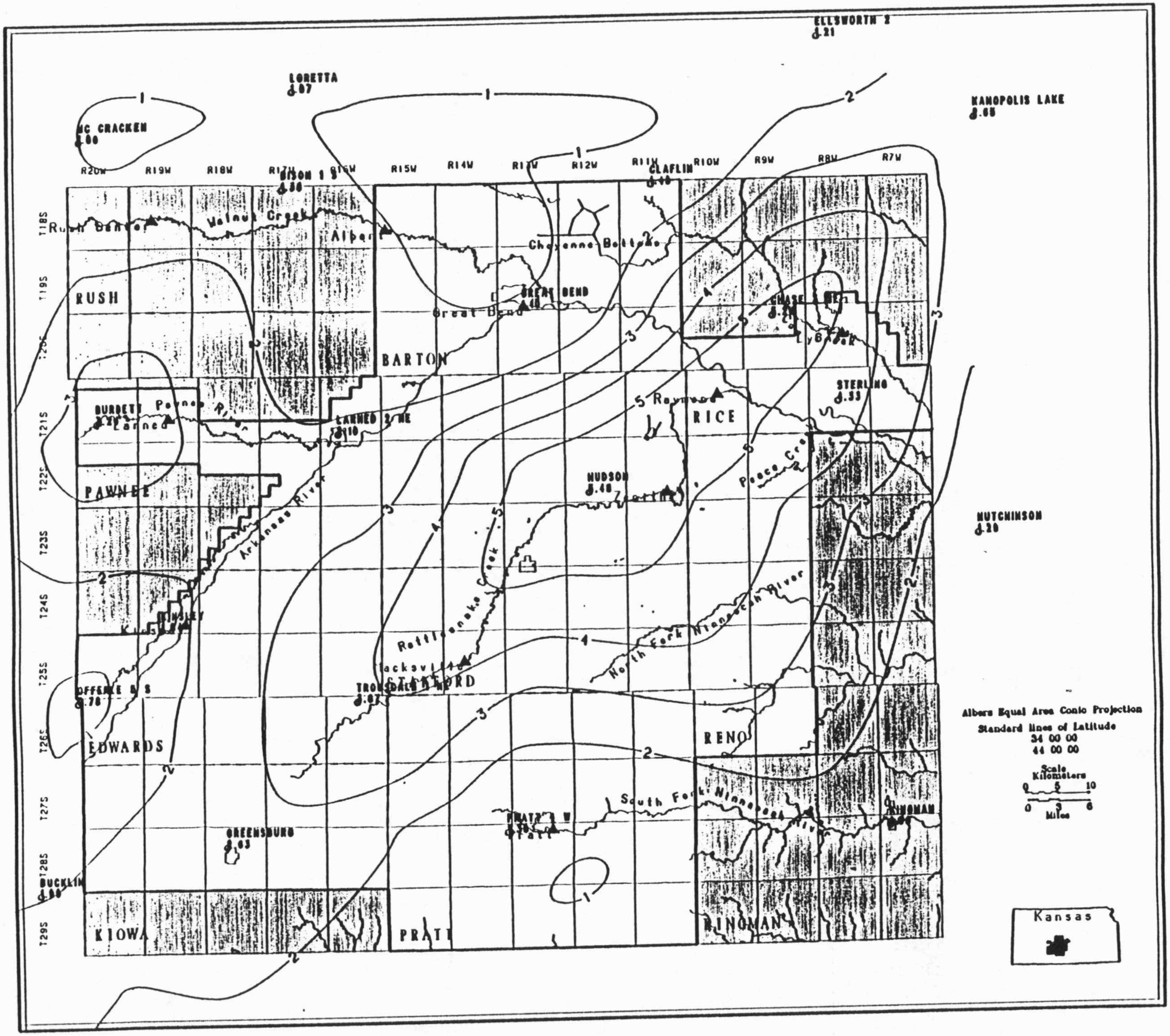
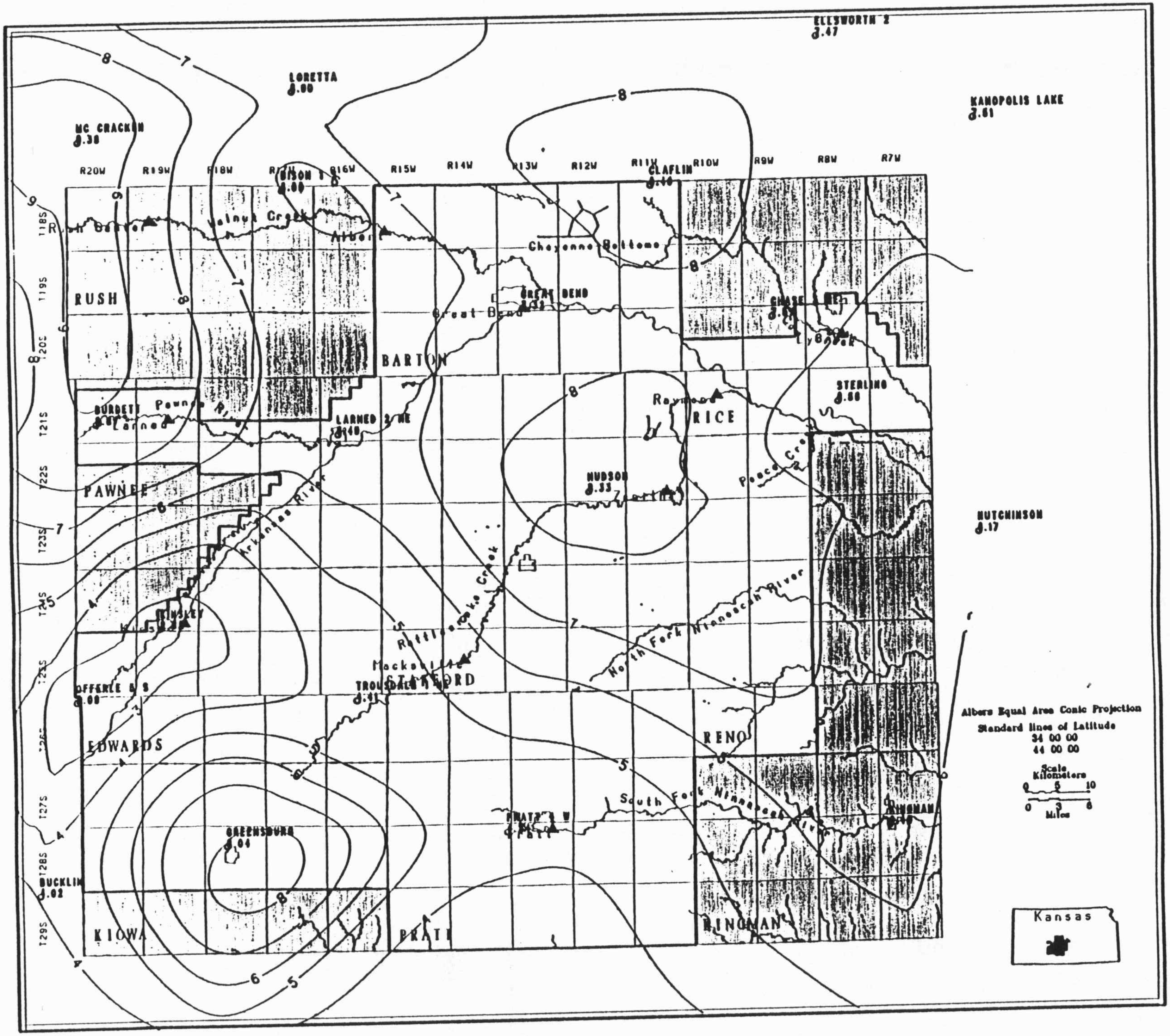

ELLSWORTH 2
.21
LORETTA
.07
KANOPOLIS LAKE
.65
MC CRACKEN
.00
R20W
R19W
R18W
R17W
R16W
R15W
R14W
R13W
R12W
R11W
R10W
R9W
R8W
R7W
BISON 1 S
.36
CLAFLIN
T18S
T19S
T21S
T22S
T23S
T24S
T25S
T26S
T27S
T28S
T29S
Walnut Creek
Albert
Cheyenne Bottoms
RUSH
GREAT BEND
Great Bend
CHASE
BARTON
BURDETT
Pawnee River
Larned
LARNED 2 NE
Raymond
RICE
STERLING
.33
PAWNEE
HUDSON
.46
Arkansas River
Peace Creek
HUTCHINSON
.20
Rattlesnake Creek
North Fork Ninnescah River
KINSLEY
OFFERLE
.78
STAFFORD
TROUSDALE
.07
EDWARDS
RENO
South Fork Ninnescah River
GREENSBURG
.03
PRATT
Pratt
KINGMAN
BUCKLIN
.00
KIOWA
PRATT
KINGMAN
Albers Equal Area Conic Projection
Standard lines of Latitude
34 00 00
44 00 00
Scale
Kilometers
0 5 10
0 3 6
Miles
Kansas
SWAKHYDRO
08/31/1994 09:40 AM

Fig 15



name: SMARHYDRO
time: 08/31/1994 10:11 AM

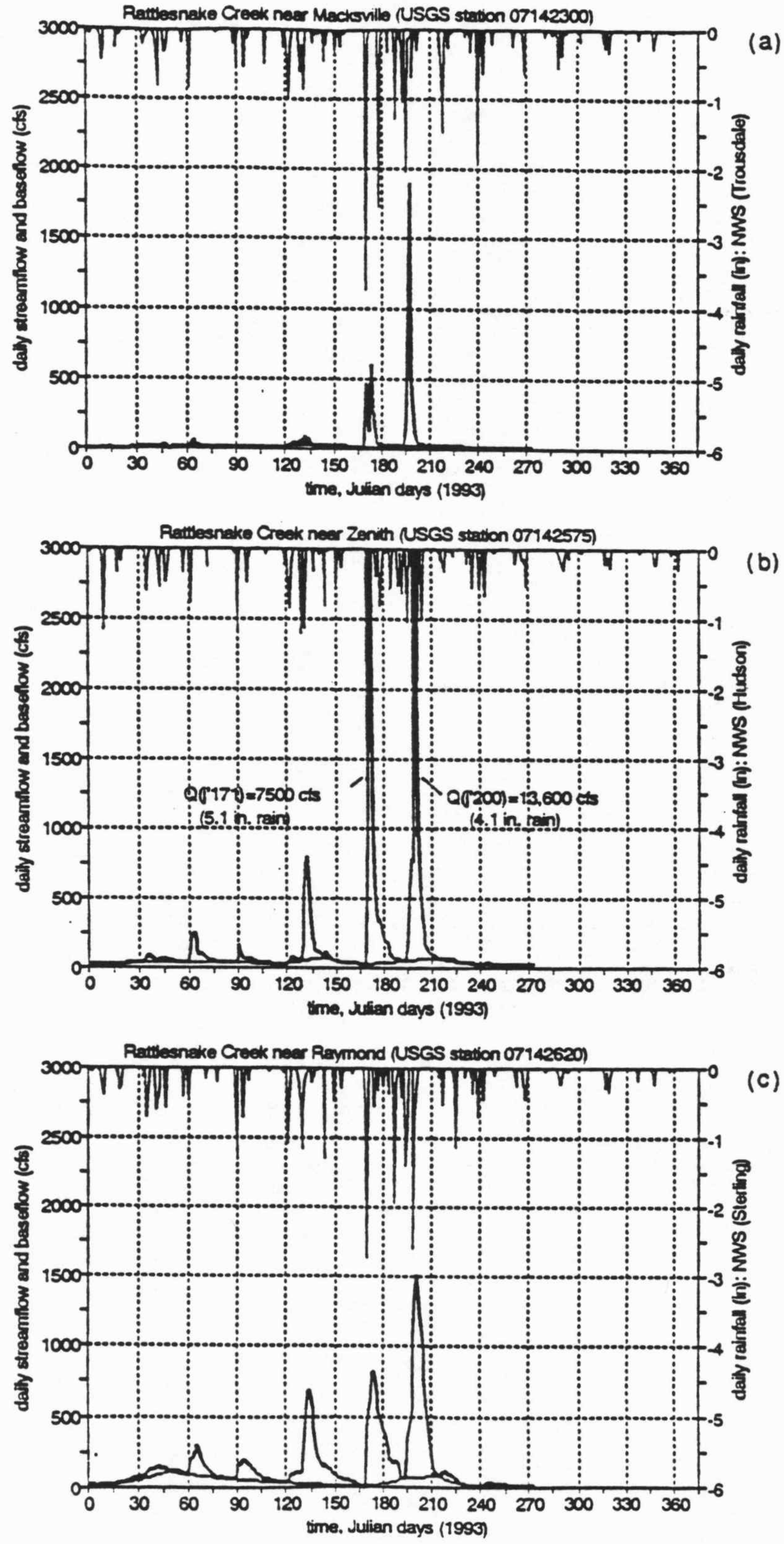
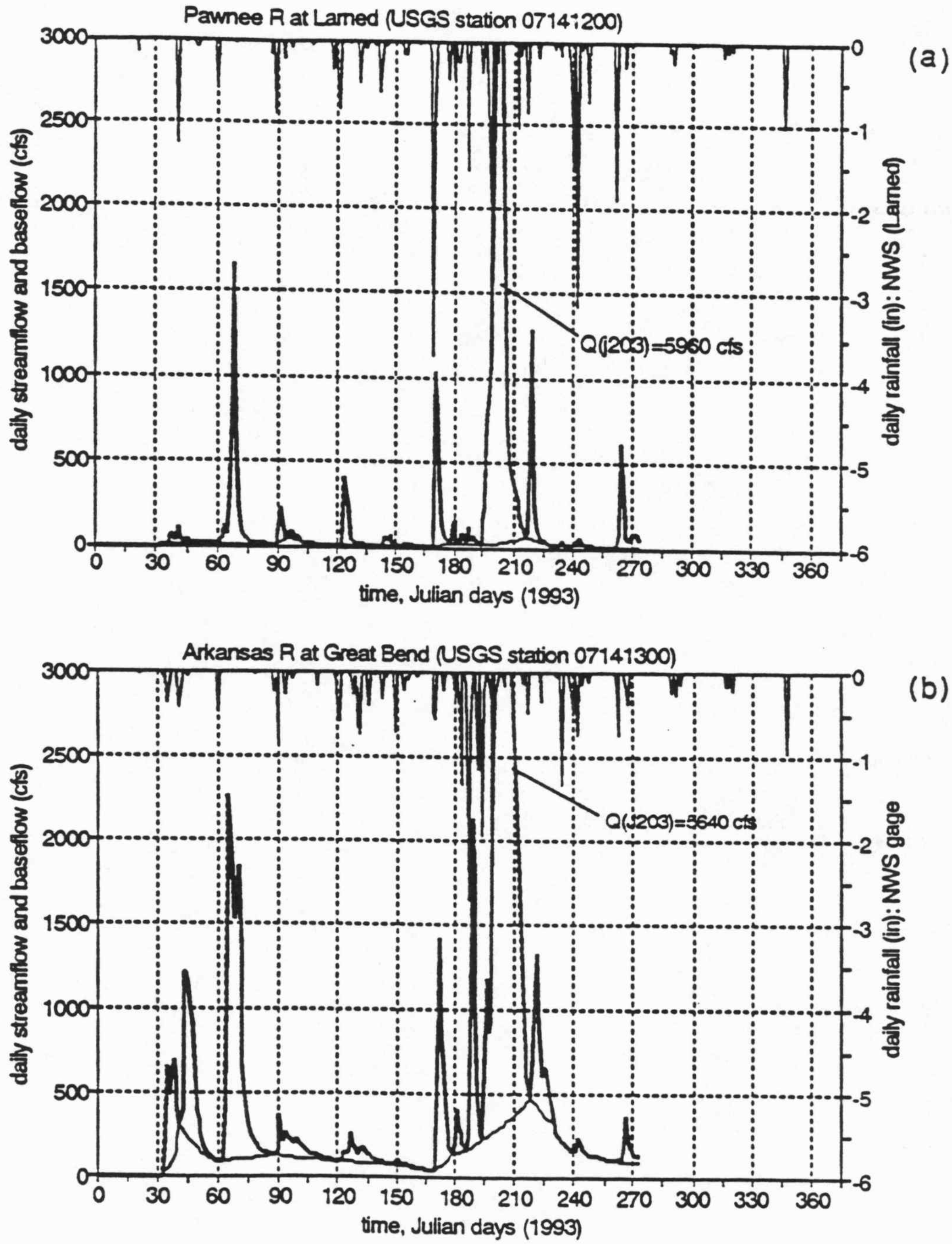

Rattlesnake Creek near Macksville (USGS station 07142300)
(a)
daily streamflow and baseflow (cfs)
daily rainfall (in): NWS (Trousdale)
3000
2500
2000
1500
1000
500
0
0
-1
-2
-3
-4
-5
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
time, Julian days (1993)
Rattlesnake Creek near Zenith (USGS station 07142575)
(b)
daily streamflow and baseflow (cfs)
daily rainfall (in): NWS (Hudson)
Q('171)=7500 cfs
(5.1 in. rain)
Q('200)=13,600 cfs
(4.1 in. rain)
3000
2500
2000
1500
1000
500
0
0
-1
-2
-3
-4
-5
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
time, Julian days (1993)
Rattlesnake Creek near Raymond (USGS station 07142620)
(c)
daily streamflow and baseflow (cfs)
daily rainfall (in): NWS (Sterling)
3000
2500
2000
1500
1000
500
0
0
-1
-2
-3
-4
-5
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
time, Julian days (1993)

Fig. 15



Pawnee R at Larned (USGS station 07141200)
(a)
daily streamflow and baseflow (cfs)
daily rainfall (in): NWS (Larned)
Q(j203)=5960 cfs
time, Julian days (1993)
Arkansas R at Great Bend (USGS station 07141300)
(b)
daily streamflow and baseflow (cfs)
daily rainfall (in): NWS gage
Q(J203)=5640 cfs
time, Julian days (1993)

Fig. 18

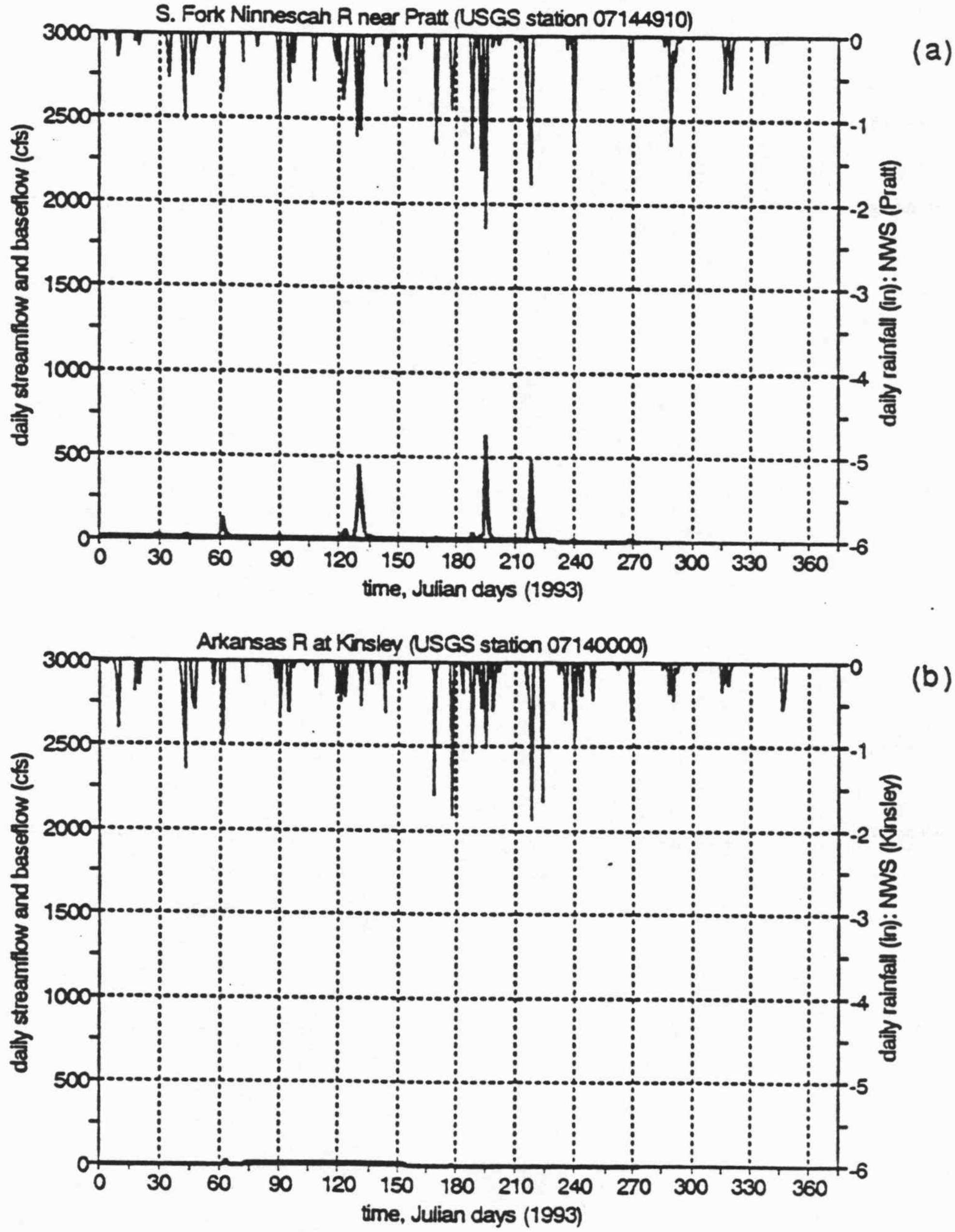

S. Fork Ninnescah R near Pratt (USGS station 07144910)
(a)
daily streamflow and baseflow (cfs)
3000
2500
2000
1500
1000
500
0
daily rainfall (in): NWS (Pratt)
0
-1
-2
-3
-4
-5
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
time, Julian days (1993)
Arkansas R at Kinsley (USGS station 07140000)
(b)
daily streamflow and baseflow (cfs)
3000
2500
2000
1500
1000
500
0
daily rainfall (in): NWS (Kinsley)
0
-1
-2
-3
-4
-5
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
time, Julian days (1993)

Fig 19