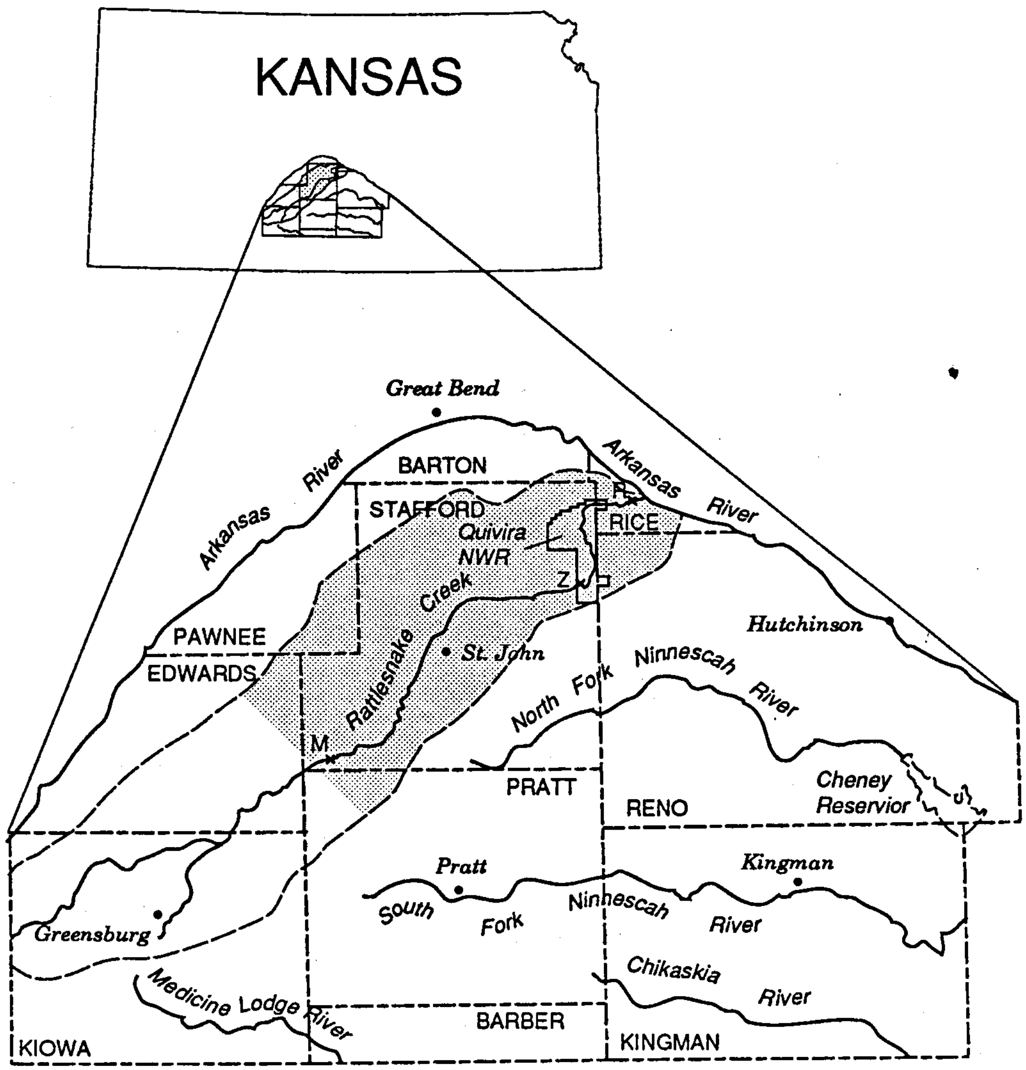
Kansas Geological Survey

Stream-aquifer modeling of the lower Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge



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Principal Investigator

Open-File Report 92-10

GEOHYDROLOGY

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Report Outline

I. Statement of the problem

Many regions of western and central Kansas have experienced significant ground-water and streamflow declines, especially during the last two decades (Sophocleous, 1981; Sophocleous and McAllister, 1987, 1990; among others). According to the Kansas Water Office (KWO), extensive ground-water appropriations in the Great Bend Prairie have contributed to extremely low flows in the Arkansas River and Rattlesnake Creek (Water Research Needs Conference, Wichita, Nov. 14, 1984). Also, according to the Kansas Department of Wildlife and Parks, fish and wildlife resources in and along the Arkansas River, the Smoky Hill River, the Pawnee River, Rattlesnake Creek, and other streams in western and south-central Kansas have been significantly affected because of losses of baseflows (Water Research Needs Conference, Wichita, Kansas, Nov. 14, 1984).

In 1983 the Kansas legislature passed the minimum instream flow law, which requires that minimum desirable streamflows be maintained in different streams in Kansas, including Rattlesnake Creek. Implementation of this law certainly requires a better understanding of the stream-aquifer system. According to the Division of Water Resources (Water Research Needs Conference, Wichita, Kansas, Nov. 14, 1984), a more thorough understanding of this stream-aquifer relationship would allow quantitative determination of the effect of ground-water withdrawals on streamflows and would be valuable in the administration of the minimum desirable streamflow program.

The two major central Kansas wetlands—the Cheyenne Bottoms Wildlife Area and the Quivira National Wildlife Refuge, both of which are classified as "outstanding natural resource areas of unique significance" [KAR 28-16c(3)]—are being threatened because of decreasing water supplies and deteriorating water quality. The quality of ground and surface waters is deteriorating mainly because of increased natural nonpoint mineral intrusion from underlying geologic formations; this increased mineral intrusion is considered to be a consequence of freshwater declines in the Quaternary alluvial aquifers of central Kansas. Natural conditions, such as low streamflows and mineral intrusion, result in violations of the dissolved oxygen, chloride, fluoride, and metals criteria for streams during the summer months in several parts of Kansas. According to the Kansas Department of Health and Environment (Fromm and Wilk, 1988), streams in central Kansas overlying Permian red beds and the Wellington Formation have elevated levels of metals and selenium. In addition to natural conditions, past and current oil and gas production activities have increased the mineral content of some streams..

The Quivira National Wildlife Refuge, which covers approximately 21,280 acres in northeast Stafford County (see cover page), is a major stopover point for migratory birds in the Central Flyway. The refuge was established in 1955 and obtained a permit to divert 22,000 acre-ft of water per year from Rattlesnake Creek. The average annual streamflow in the Rattlesnake Creek at the entrance to the refuge (Zenith gaging station, Z in the cover page) during the 1981–1990 decade was 19,625 ac-ft/yr. The stream hydrograph for the period of record at the Macksville and Zenith gaging stations (designated as M and Z in the cover page, respectively) together with the annual precipitation at Hudson (in northeast Stafford County) are shown in fig. 1.

A review of existing water rights in Rattlesnake Creek basin as of December 31, 1966 (Stramel, 1967), indicated that more water rights had already been filed in the basin than there was water in the stream, and the applications for irrigation rights were increasing. A recent (1990) review of the ground-water rights appropriations in the lower Rattlesnake Creek basin (from near the Macksville stream-gaging station, southwestern Stafford County, to the confluence with the Arkansas River) indicated that the appropriated ground-water pumpage in that area totaled approximately 96,300 acre-ft. The 1990 ground-water rights in the Groundwater Management District No. 5 (GMD5), which encompasses the study area, are shown in fig. 2.

II. Objectives and study area

This study was undertaken to address some of the mentioned water issues affecting the Quivira National Wildlife Refuge. Specific objectives of the overall research program include:

1. Analysis of the effects of overall regional ground-water appropriations on stream baseflows and aquifer water levels and analysis of the effects of mineral intrusion from underlying geologic formations.

2. Evaluation of the outlook for available surface-water and ground-water supplies to the Quivira National Wildlife Refuge, the impact of droughts and floods on those supplies, and development of strategies to maintain or enhance these supplies.

3. Evaluation of the hydrologic effectiveness of management alternatives, including the determination of protective corridors around Rattlesnake Creek for possible water rights restrictions if streamflows fall below established minima or if drought conditions develop.

The study area encompasses an approximately 560 square mile area of the lower Rattlesnake Creek watershed (shaded area on cover page illustration) predominantly in Stafford

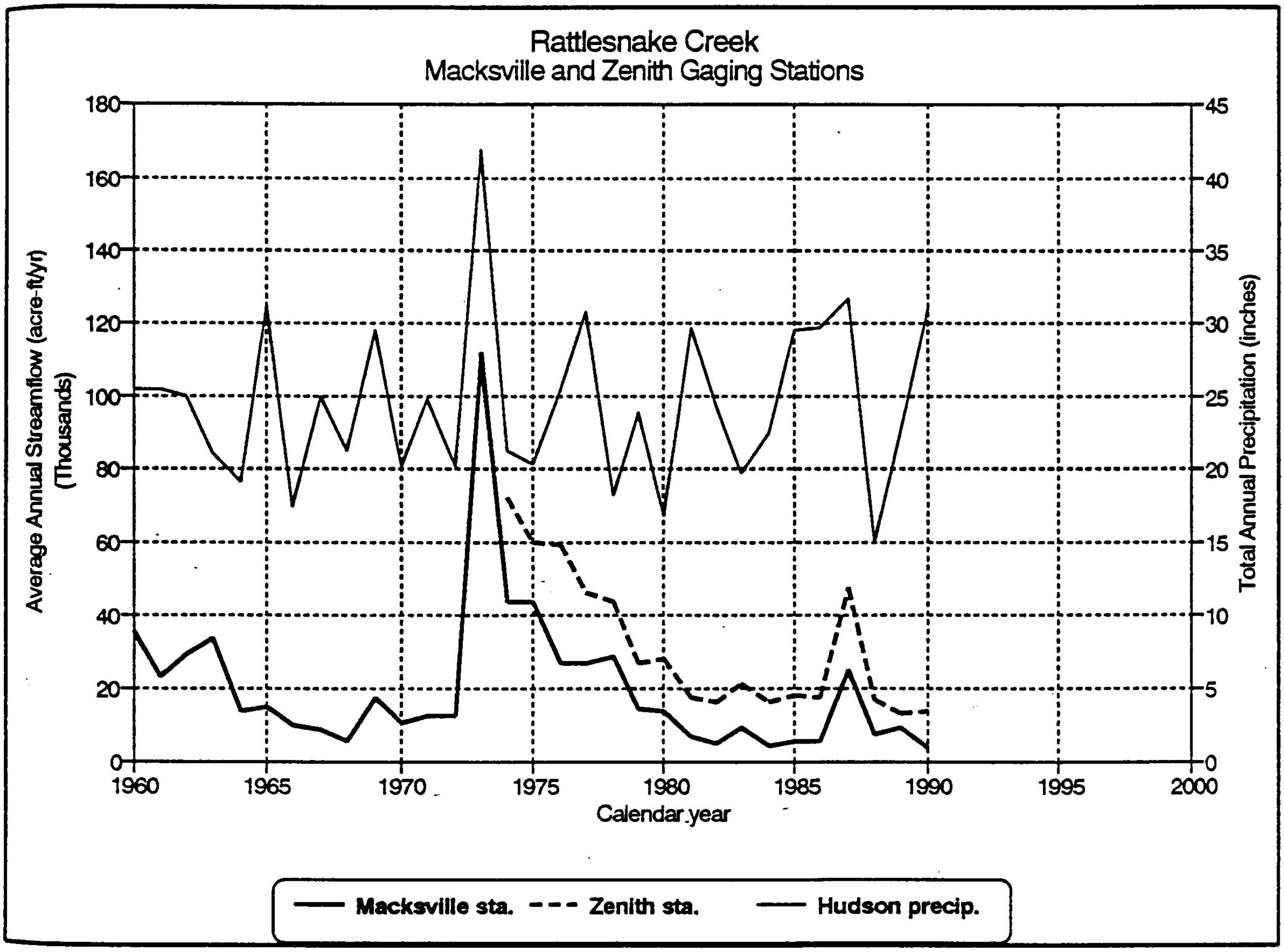

Figure 1. Average annual streamflows of Rattlesnake Creek at the Macksville and Zenith gaging stations, and annual precipitation at Hudson, west of the Little Salt Marsh.

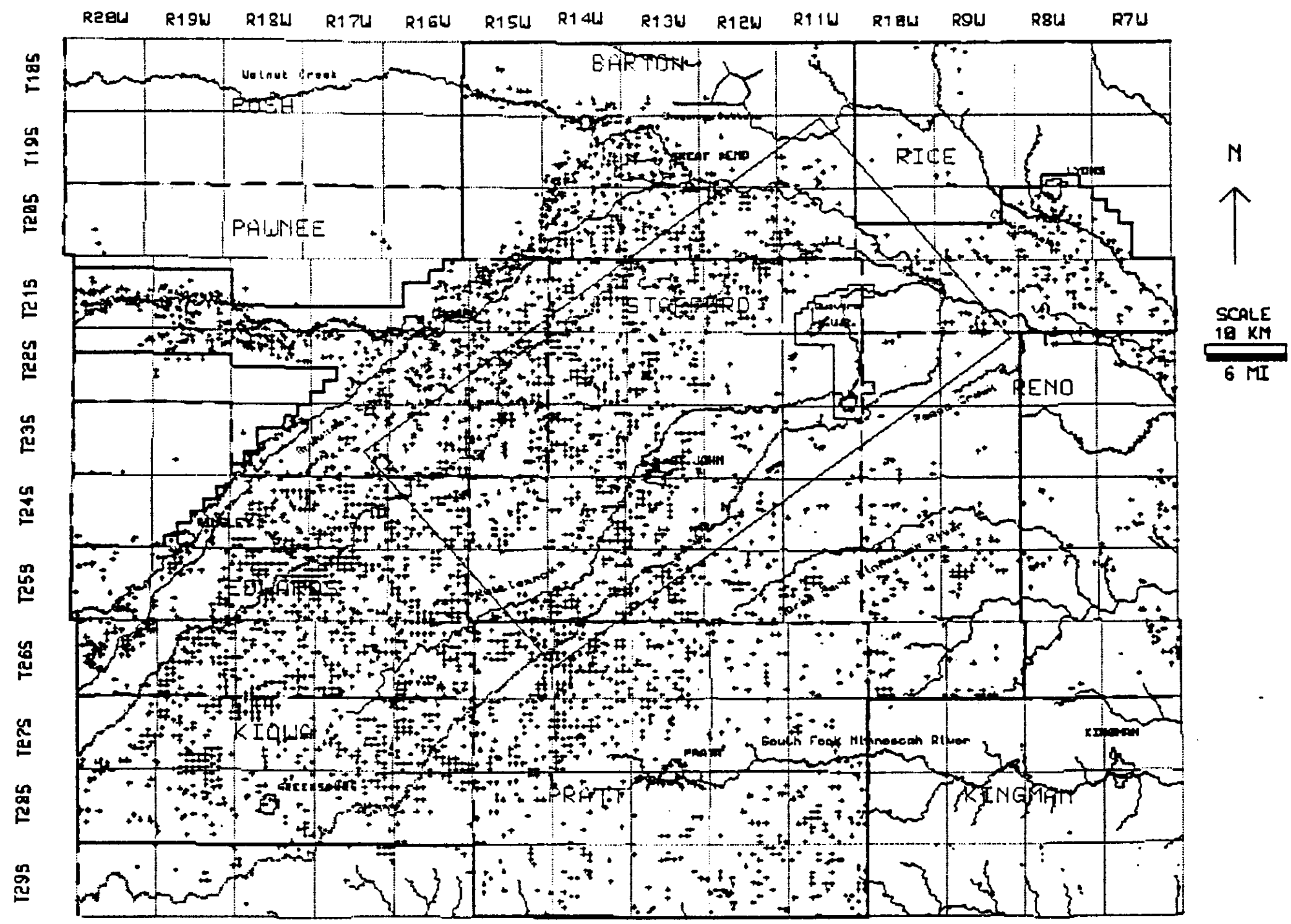

Figure 2. Ground-water rights in the Great Bend Prairie region. The gray thick line denotes the Rattlesnake Creek basin boundary, and the rectangle isolates the lower portion of the basin under study.

County but also includes portions of other counties, such as Pawnee, Barton, Rice, and Reno (fig. 3). The study area encompasses all three existing stream-gaging stations on Rattlesnake Creek, namely, the Macksville, Zenith, and Raymond stations.

This report summarizes progress toward project objectives completed through March 1992. For further details, the reader is referred to Sophocleous and Perkins (1992).

III. Hydrogeology of the Great Bend Prairie and the mineral intrusion problem

The Great Bend Prairie, which encompasses the Rattlesnake Creek basin, is covered with a veneer of loess deposits and sand dunes, with underlying Pleistocene alluvium forming the major aquifer of the area (Latta, 1950; Fader and Stullken, 1978). This alluvium was deposited by the ancestral Arkansas River and a small number of local streams and is composed of undifferentiated Pleistocene sediments (interbedded lenses of unconsolidated gravel, sand, silt and clay; caliche is common throughout the formation). The Pleistocene alluvium overlies Cretaceous and Permian bedrock. A bedrock geology map of the region is shown in fig. 4. The lower reaches of Rattlesnake Creek and the Quivira refuge represent a natural ground-water discharge area of both the unconsolidated Great Bend Prairie aquifer and the underlying bedrock aquifers; the depth to the water table is shallow there—less than 10 ft.

Rocks of Cretaceous age form the bedrock surface in the western part of the Great Bend Prairie. These rocks consist of interbedded shales, sandy shales, and fine- to coarse-grained sandstones, and form a confining layer that separates the underlying Permian fluids from the Great Bend Prairie aquifer in western GMD5.

The Permian formations in the area, known as red beds, consist of reddish-brown sandstone, siltstone, shale, salt, gypsum, anhydrite, and limestone. The Permian bedrock subcrops along an approximately north-south trend near US–281. East of that line it is hydraulically connected with the Great Bend Prairie aquifer and constitutes a source of poor-quality (saline) water in northeast Stafford County (fig. 4). This Permian-derived saline water rises

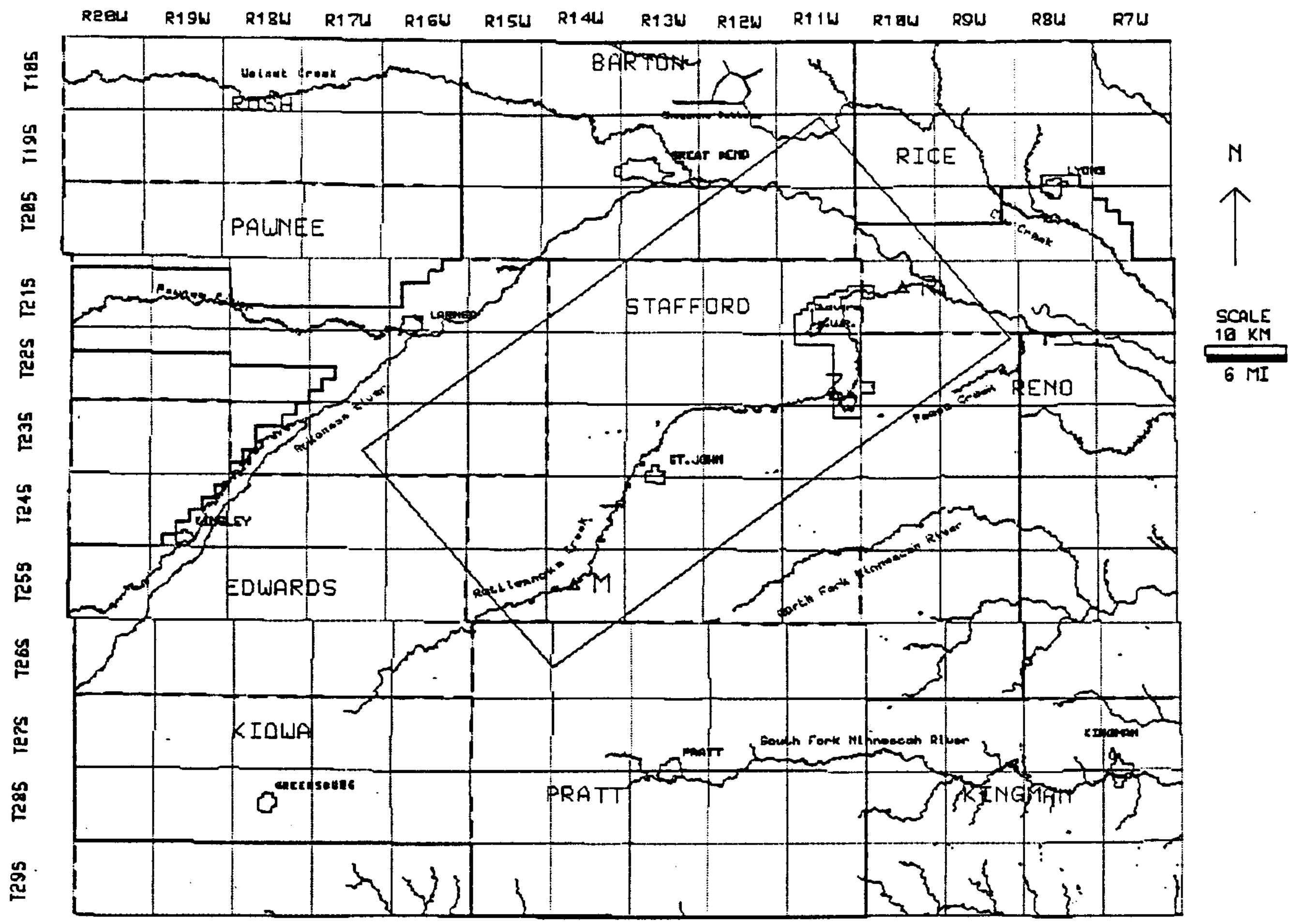

Figure 3. Study area. The rectangle encloses the lower Rattlesnake Creek basin under study. The Quivira National Wildlife refuge boundaries are also shown. Triangles denote stream-gaging stations (Macksville–M, Zenith–Z, and Raymond–R).

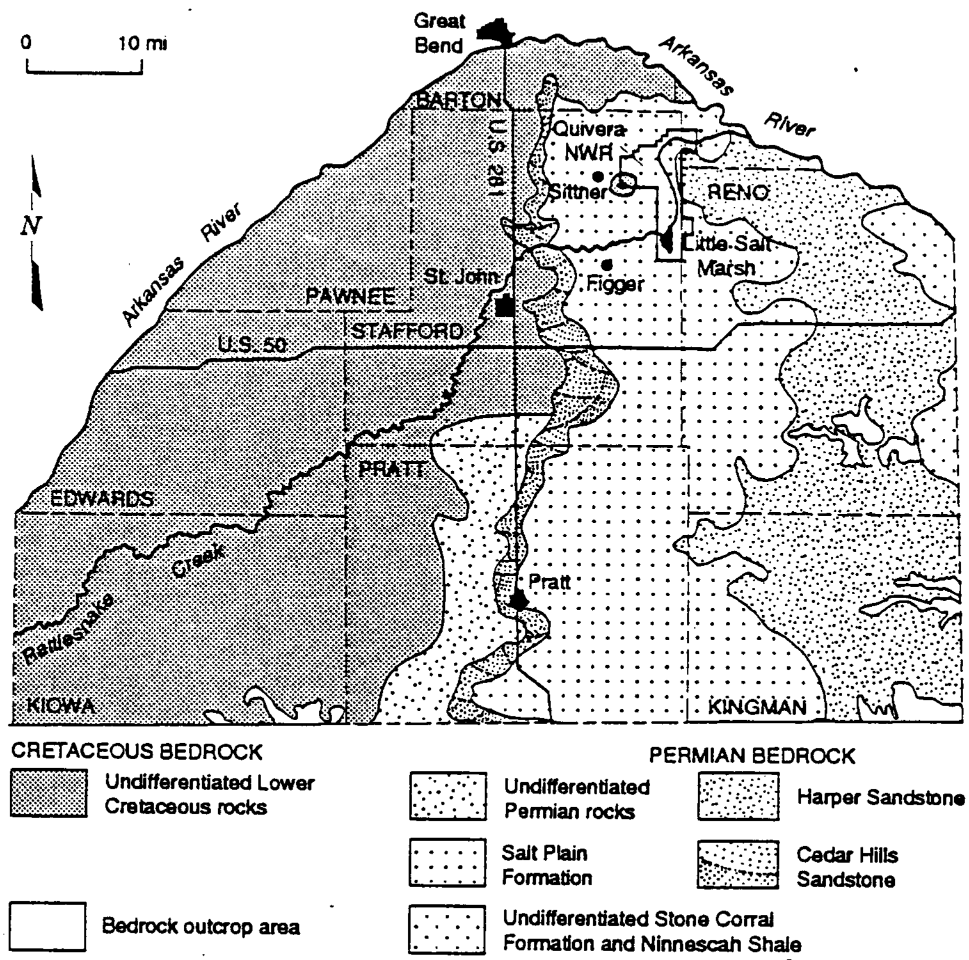

Figure 4. Bedrock geology of the Great Bend Prairie (adapted from Fader and Stullken, 1978). The locations of the two monitoring wells (Figger and Sittner) are also shown.

upward and increases the water salinity of the unconsolidated Great Bend Prairie aquifer in the lower reaches of Rattlesnake Creek, in particular, the Quivira refuge area.

The mechanical details of the subsurface hydraulic relationships of the consolidated and unconsolidated deposits are not clearly understood. The water near the salt marshes is believed to be a natural occurrence of artesian saltwaters encountered deeper to the west. The saltwater flows from the edges of the bedrock formation into the overlying sediments and rises to the surface in the low areas, primarily along Rattlesnake Creek. The upper reaches of Rattlesnake Creek yield fairly good quality water (350–625 µS/cm) with little saline pollution from natural sources as indicated in a 1983 salinity survey of Rattlesnake Creek (fig. 5). An abrupt rise in water specific conductance (a measure of water salinity) was observed 1 mi east of where Rattlesnake Creek crosses US–281, with values leveling off at 3,000–4,000 µS/cm (fig. 5). Where the creek enters the Quivira National Wildlife Refuge, another rise in conductivity occurs, with an abrupt increase to values exceeding 20,000 µS/cm. Before discharging into the Arkansas River, however, the creek's conductivity drops to 3,150 µS/cm.

Two conductivity recording probes were installed in two specially constructed monitoring wells (Sophocleous and Perkins, 1992) in the area to monitor the saltwater-freshwater interface in the Great Bend aquifer resulting from brine intrusion from the directly underlying Permian formations. The two 5-inch monitoring wells, drilled down to Permian (red siltstone) bedrock, and known as the Sittner and Figger wells, are both in northeastern Stafford County (fig. 4) a few miles west of the Quivira Refuge. Results from the saltwater-freshwater interface monitoring sites

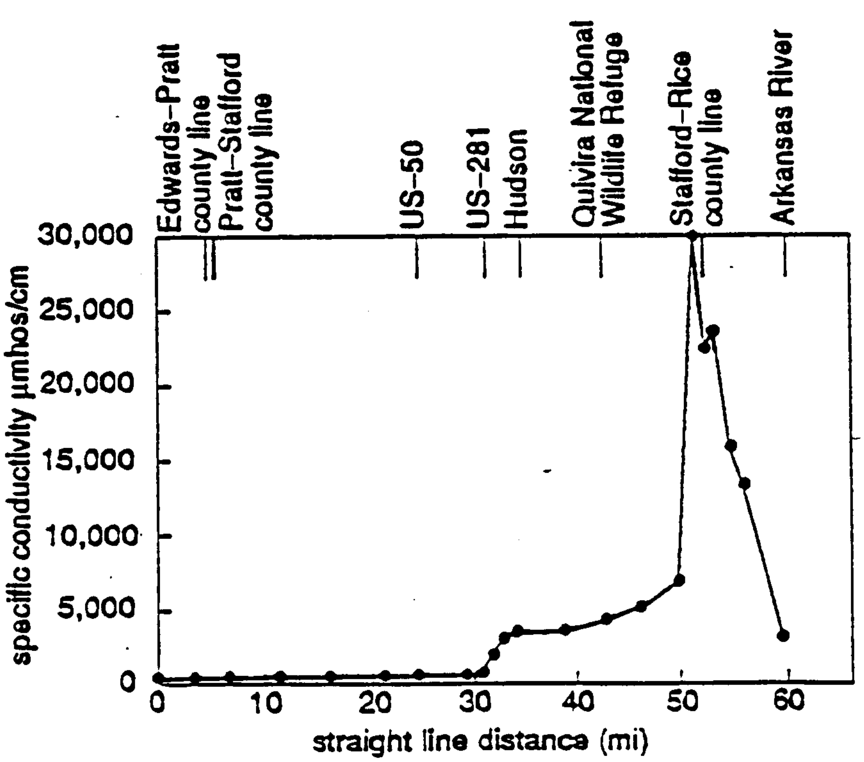

Figure 5. Specific conductance survey along Rattlesnake Creek (adapted from Bindleman, 1983).

indicate that the interface is extremely sharp at the Sittner site west of the Big Salt Marsh (within 1 ft the specific conductance increases from 700 μS/cm to 24,000 μS/cm; fig. 6) and fluctuates appreciably (ranging from 55 ft to 90 ft below ground surface) with very small changes in the water-table levels (less than 0.5 ft in most cases; fig. 7). The saltwater-freshwater interface at the Figger monitoring site west of the Little Salt Marsh and near Rattlesnake Creek is more diffuse (fig. 6) and does not fluctuate as much as at the Sittner site. These results indicate that the behavior of the saltwater-freshwater interface in the study area is complex and not well understood; thus more detailed study of saltwater behavior in the region is needed.

IV. Numerical modeling of the study area

The major thrust of this study is to implement and analyze an appropriate stream-aquifer numerical model for the study area so that future baseflows and ground-water levels in the area under a variety of conditions can be predicted. The simulation model chosen to evaluate the lower Rattlesnake Creek stream-aquifer system is a modified two-dimensional version of the popular U.S. Geological Survey modular finite-difference ground-water model (MODFLOW) with streamflow routing capabilities. A parameter estimation model (MODINV) was also implemented to optimize model parameters during model calibration.

Model implementation and calibration

Model implementation requires that the study area be divided into grid cells—in this case, cells of 1-square-mile area are employed, as shown in fig. 8. Model implementation also requires that the period of simulation be divided into a series of stress periods, represented by the increasing number of ground-water pumping wells in the model area, as shown in fig. 9, and by the varying incoming streamflows into the model area as measured at the Macksville stream-gaging station (fig. 1).

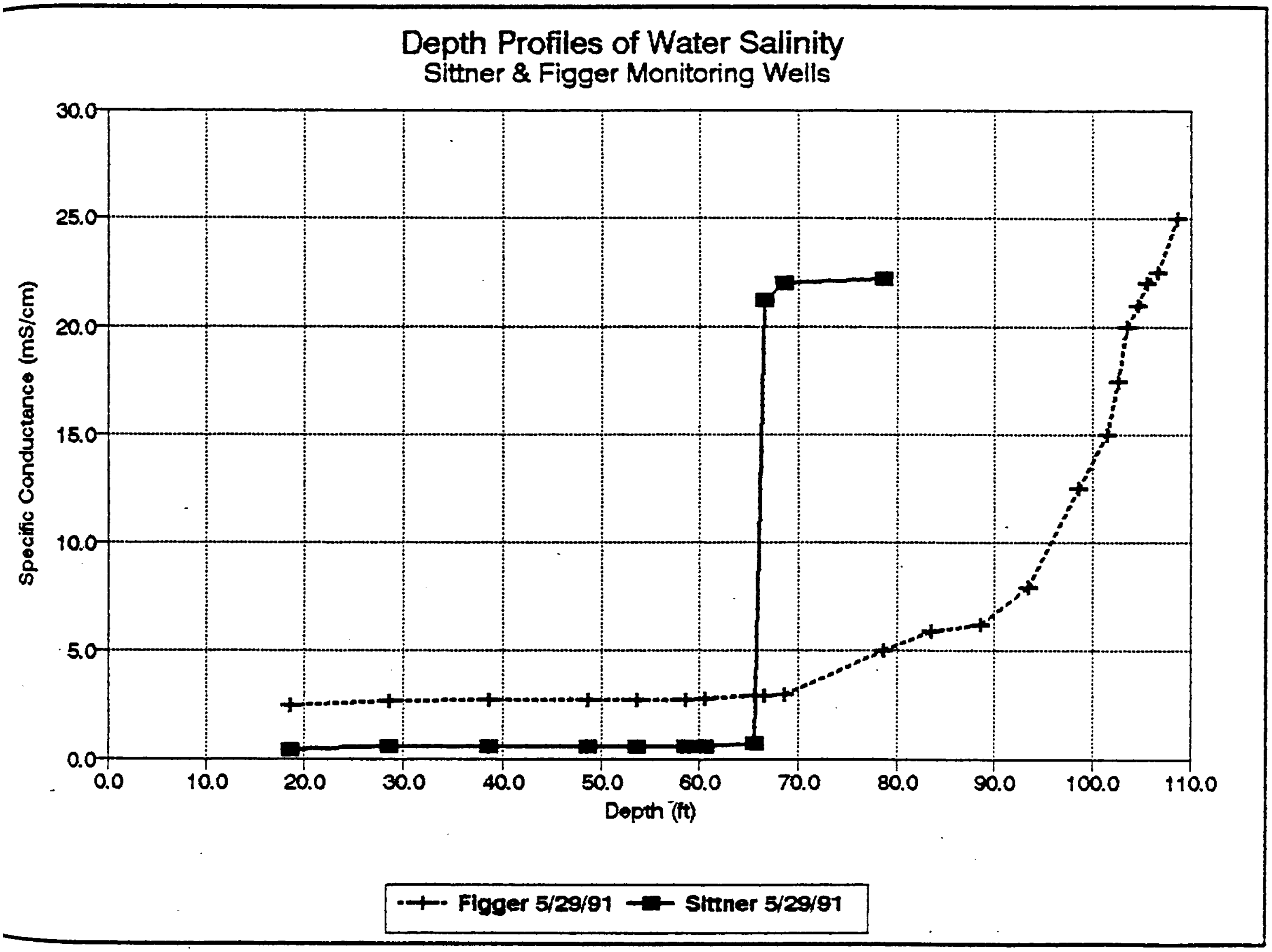

Figure 6. Specific conductance depth profiles at the Figger and Sittner wells.

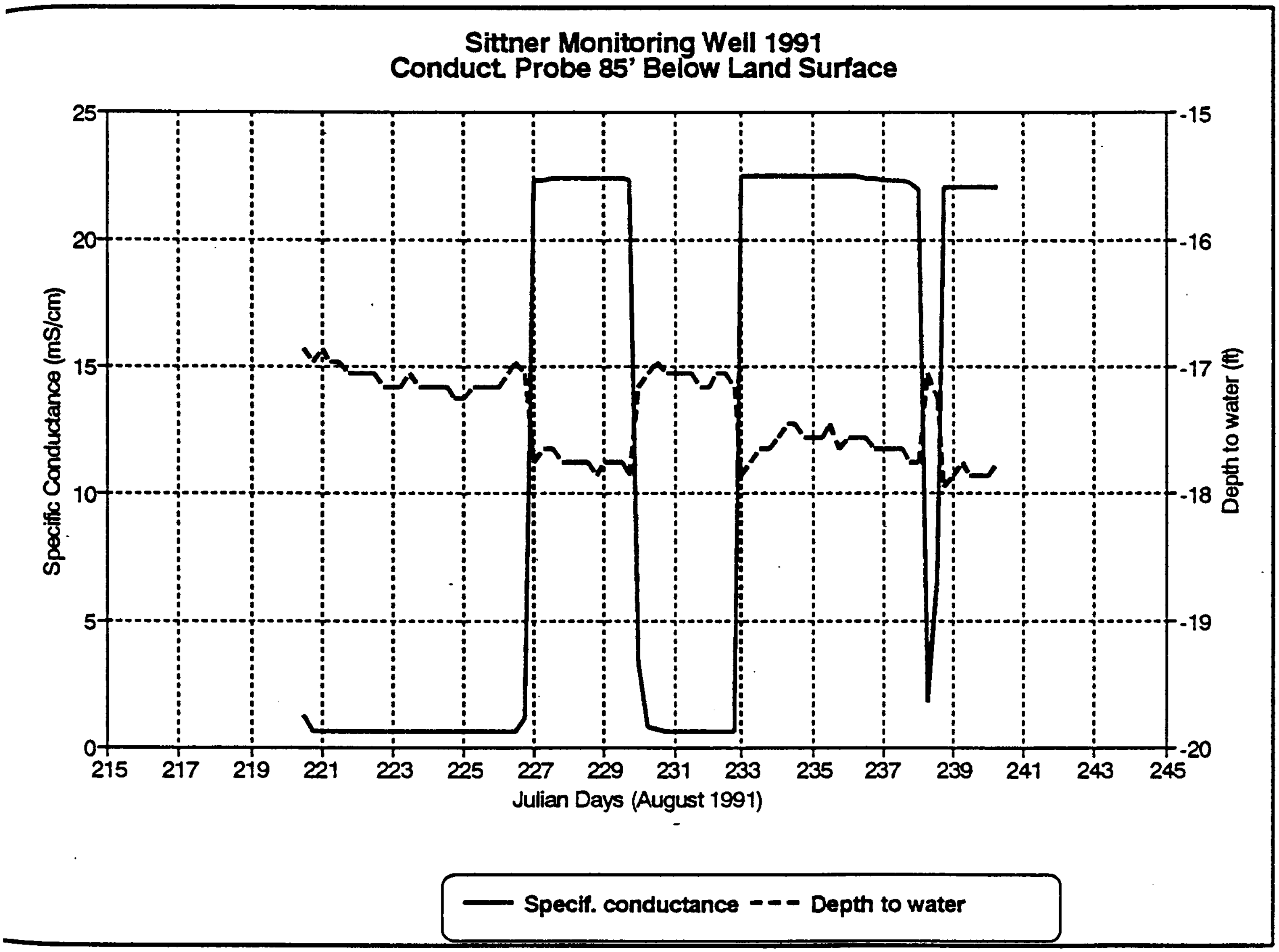

Figure 7. Depth to water table and specific conductance time series near the saltwater-freshwater interface in the Sittner well.

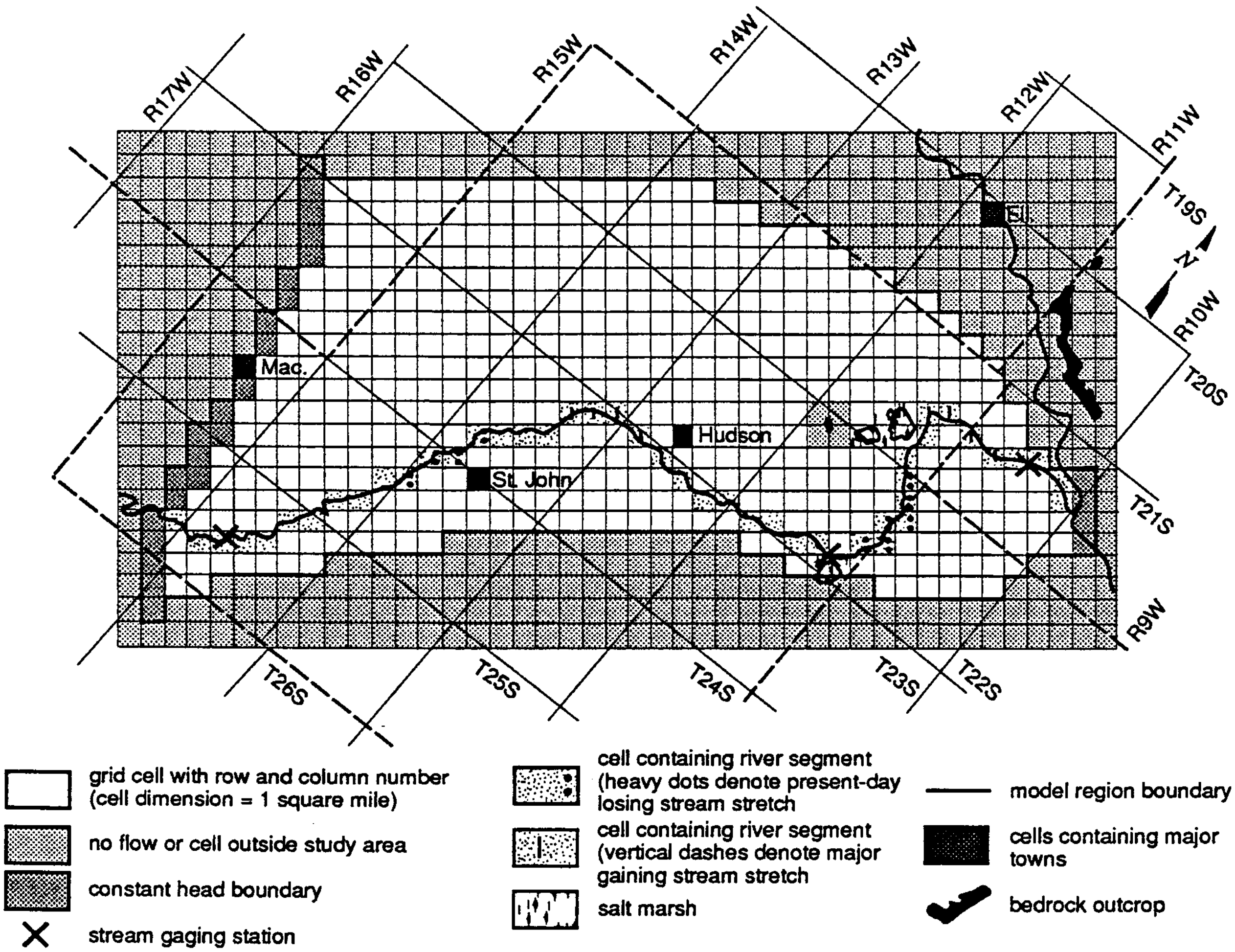

Figure 8. Finite difference grid of the model area. Present-day losing stream stretches are indicated.

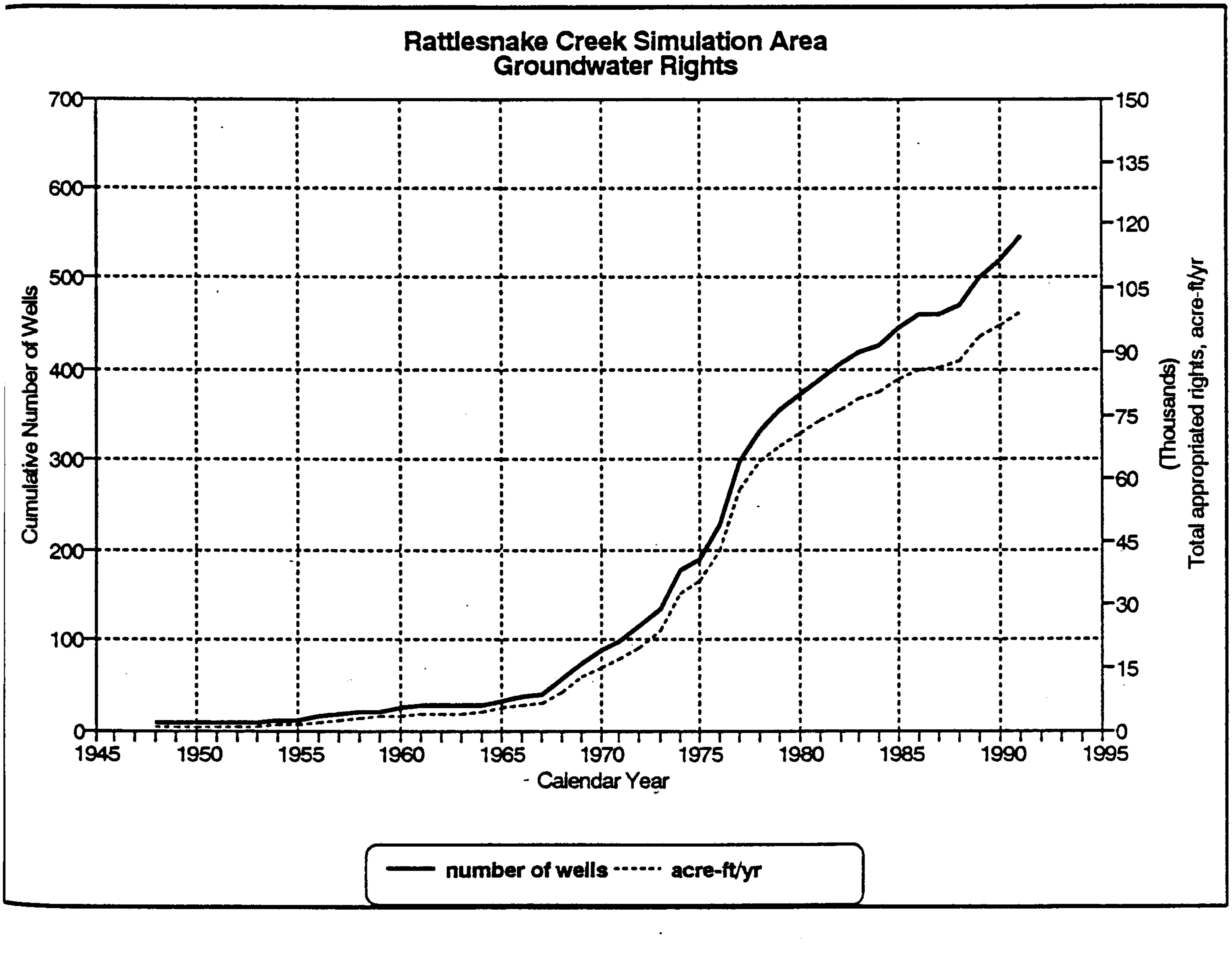

Figure 9. Number and amount of appropriated ground-water rights issued in the study area versus time.

Numerous aquifer and stream-related input data required to run the model were compiled from previous studies and data for the region and from other ongoing KGS-GMD5 cooperative studies in the area, and are outlined in Sophocleous and Perkins (1992).

One of the most important steps in setting up a numerical model is calibration. Development of a computer model as a predictive tool is based on the premise that, if historic hydrologic phenomena can be satisfactorily approximated by the model, then so should future conditions. Calibration involves adjusting model input parameters, based on field data, to obtain reasonable agreement with measured water-level and streamflow data.

The task of manually calibrating a numerical model is an arduous one, time consuming and expensive, oftentimes resulting in non-optimal solutions or sometimes in no answer. To avoid these problems, we used a sophisticated parameter estimation model (MODINV) that uses the MODFLOW program as its forward processor to obtain an optimum set of parameter values as well as measures of their reliability, given the observed ground-water level data that is used in the calibration. In addition, the model provides for measures of overall goodness of fit of the model and means for examining the validity of various model assumptions.

The model was calibrated for both steady-state (predevelopment) and transient-state conditions (from the mid-1950's to the present). In the transient-state runs the ground-water pumpage was held at 80% of the appropriated amounts. We judged that 80% of the appropriated water rights was closer to the one actually used, and therefore all transient-state runs were performed under this assumption (This assumption was confirmed by comparing water use reports with appropriated amounts in the GMD5.) Calibration results (Sophocleous and Perkins, 1992) indicate good overall fit of the model to the observed data, relatively low standard errors of determined parameters, and data that verify the correctness of the numerical model we implemented for the area.

V. Simulation results and model analysis

Predevelopment (steady-state) conditions

The results of the steady-state analysis are shown in fig. 10, in which a comparison of observed and model simulated water table contours indicates a satisfactory match.

A summary of all inflows and outflows to a region is generally called a water budget. Because in the model program the water budget is calculated independently of the equation solution process, it provides independent evidence of a valid solution. The difference between total inflow and outflow is given as a percent error. If the model equations are solved correctly, the percent error should be negligibly small, as was actually the case. The volumetric water budget for the model area under both predevelopment (c. 1955) and present-day conditions is shown in fig. 11. The convention followed in MODFLOW is that flow into or out of aquifer storage is considered part of the overall budget inasmuch as accumulation in aquifer storage effectively removes water from the flow system and storage release effectively adds water to the flow, even though neither process in itself involves the transfer of water into or out of the ground-water regime. It is evident from the figure that the bulk predevelopment input to the stream-aquifer system was ground-water recharge and that the largest outflows from the system were evapotranspiration losses from the Quivira refuge and the region surrounding it (where the depth to the water table was less than approximately 10 ft) and ground-water (baseflow) contributions to streamflows. Note that the irrigation pumpage was a minor element of total system outflow for the predevelopment period.

Transient-state simulations

The results of the transient-state simulations from 1955 to 1990 are shown in fig. 12, where the observed and model-predicted water-table contours are in satisfactory agreement.

The overall volumetric water budget for the model area during the 1955–1990 transient-state simulation is also presented in fig. 11. In contrast to what was the case during the 1950's and early 1960's, the present-day dominant outflow component from the aquifer is ground-water

Observed and predicted predevelopment water levels

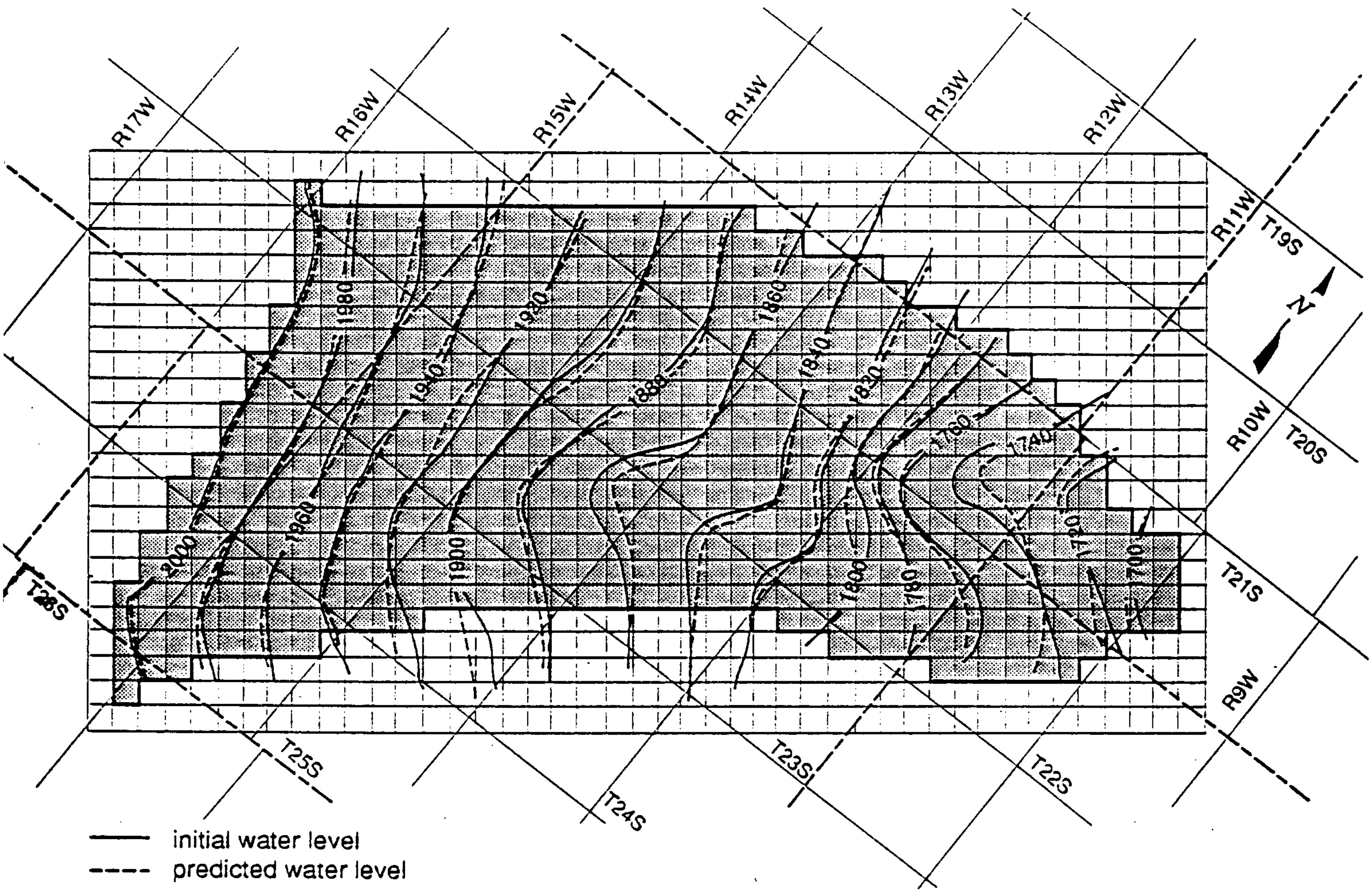

Figure 10. Comparison of observed and simulated predevelopment water table contours.

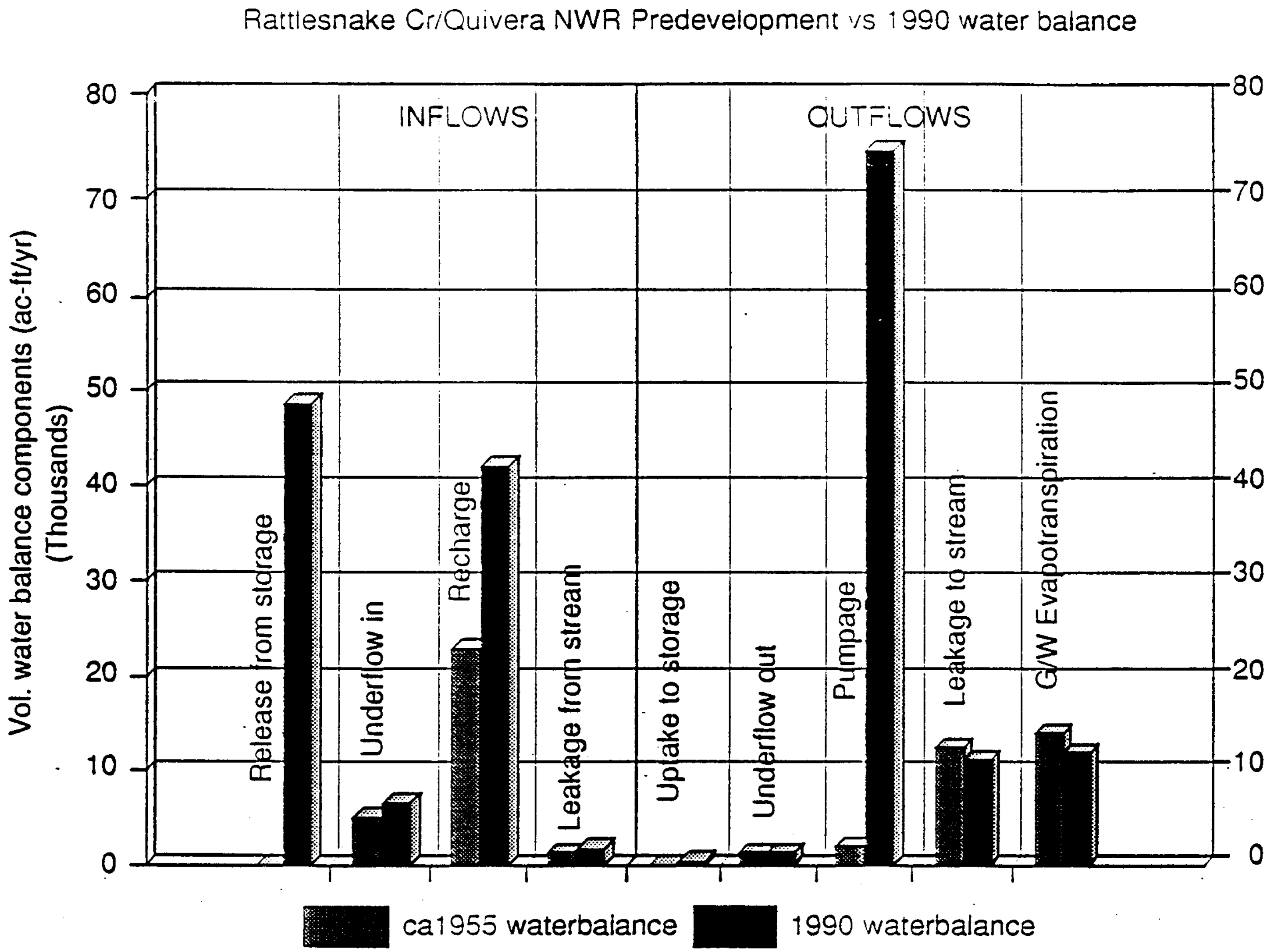

Figure 11. Water budget bar graph for predevelopment (c. 1955) and present-day conditions in the model area.

Observed and Predicted water levels (Jan 1991)

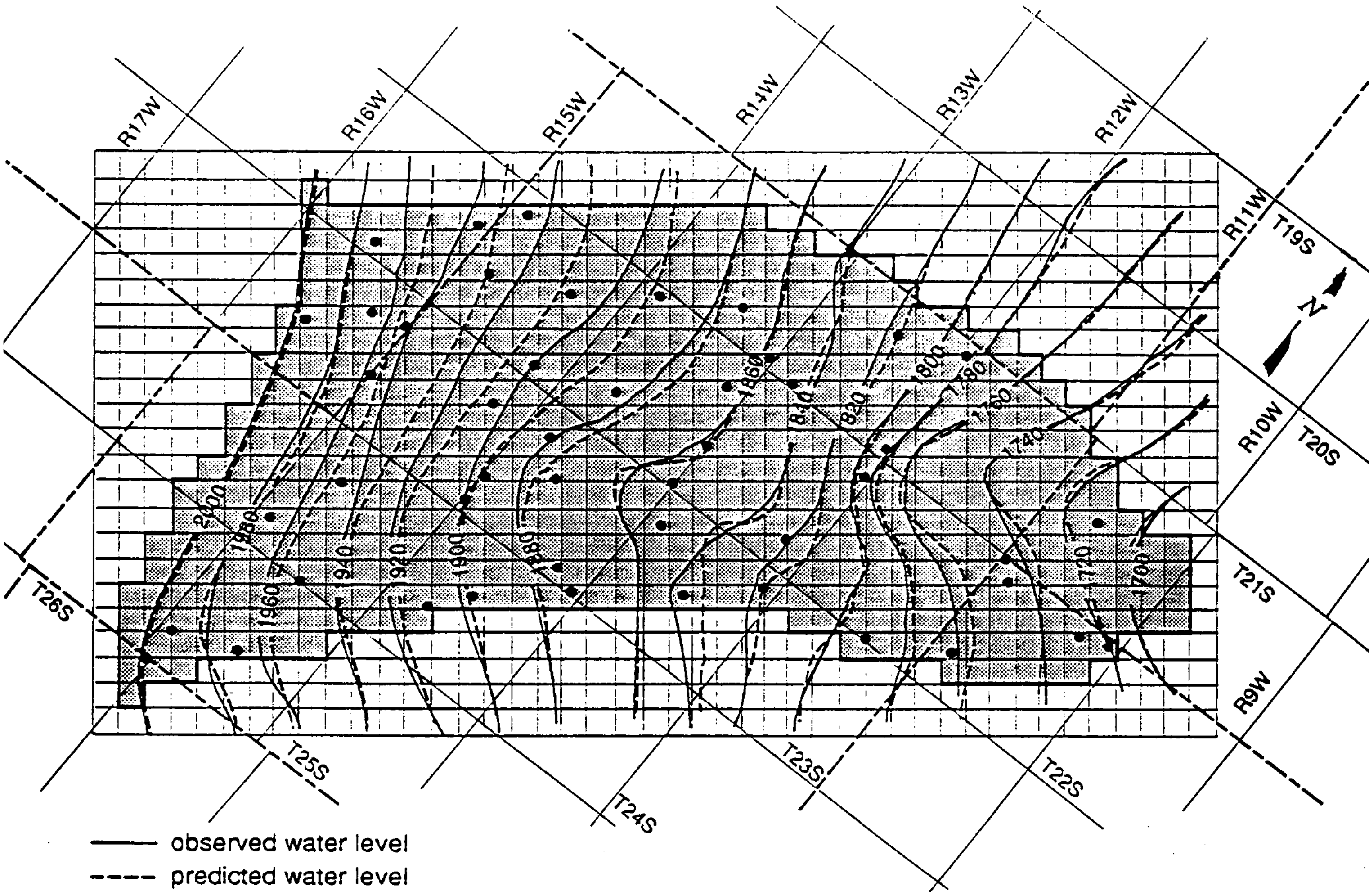

Figure 12. Comparison of observed and model-predicted January 1991 water table contours.

pumpage for irrigation, which is a new discharge superimposed on the predevelopment (steady-state) system. The irrigation pumpage must be balanced by (1) an increase in the aquifer recharge (by increased induced leakage from streams, drainage of the dewatered aquifer sediments, irrigation return flows, capture of previously "rejected" recharge as surface runoff by increased hydraulic gradients between recharge areas and areas with significant irrigation well development, and increased recharge from below, i.e., from saltwater intrusion from the Permian formations), (2) a decrease in the old natural discharge (by decreased baseflow contributions to streams, decreased outflows to seeps and springs, decreased ground-water evapotranspiration), (3) loss of water storage in the aquifer as manifested by long-term ground-water-level declines, or (4) a combination of these changes. Indeed, a combination of all three types of change is indicated in the water budget of the model area (fig. 11), which shows an increase in recharge, a loss of water in storage, and a decrease in baseflow contributions to streamflows and decreased evapotranspiration losses compared to the predevelopment water budget.

Comparison of predicted groundwater discharge and observed average annual streamflow for the 1955–1990 simulation period near the Zenith stream-gaging station also shows a satisfactory match, as indicated in fig. 13. As can be seen from that figure, the model underpredicts ground-water discharge during periods of high streamflow because the model does not simulate overland runoff. During periods of low flow, however, most streamflow is derived from ground-water discharge.

During predevelopment times, the part of Rattlesnake Creek within the study area was entirely a gaining stream. At present, however, the model results indicate that the stream has both gaining and losing stretches. The major losing stretches (fig. 8) are (1) between the Little Salt Marsh and the RCA structure, that is, in T. 22 S., R. 11 W., and (2) from south of US–50 to northwest of St. John. The major gaining stretches of Rattlesnake Creek (fig. 8), according to our model results, are (1) after the juncture with Salt Creek exiting the Big Salt Marsh and (2) from the confluence with Wild Horse Creek up to southeast of Hudson.

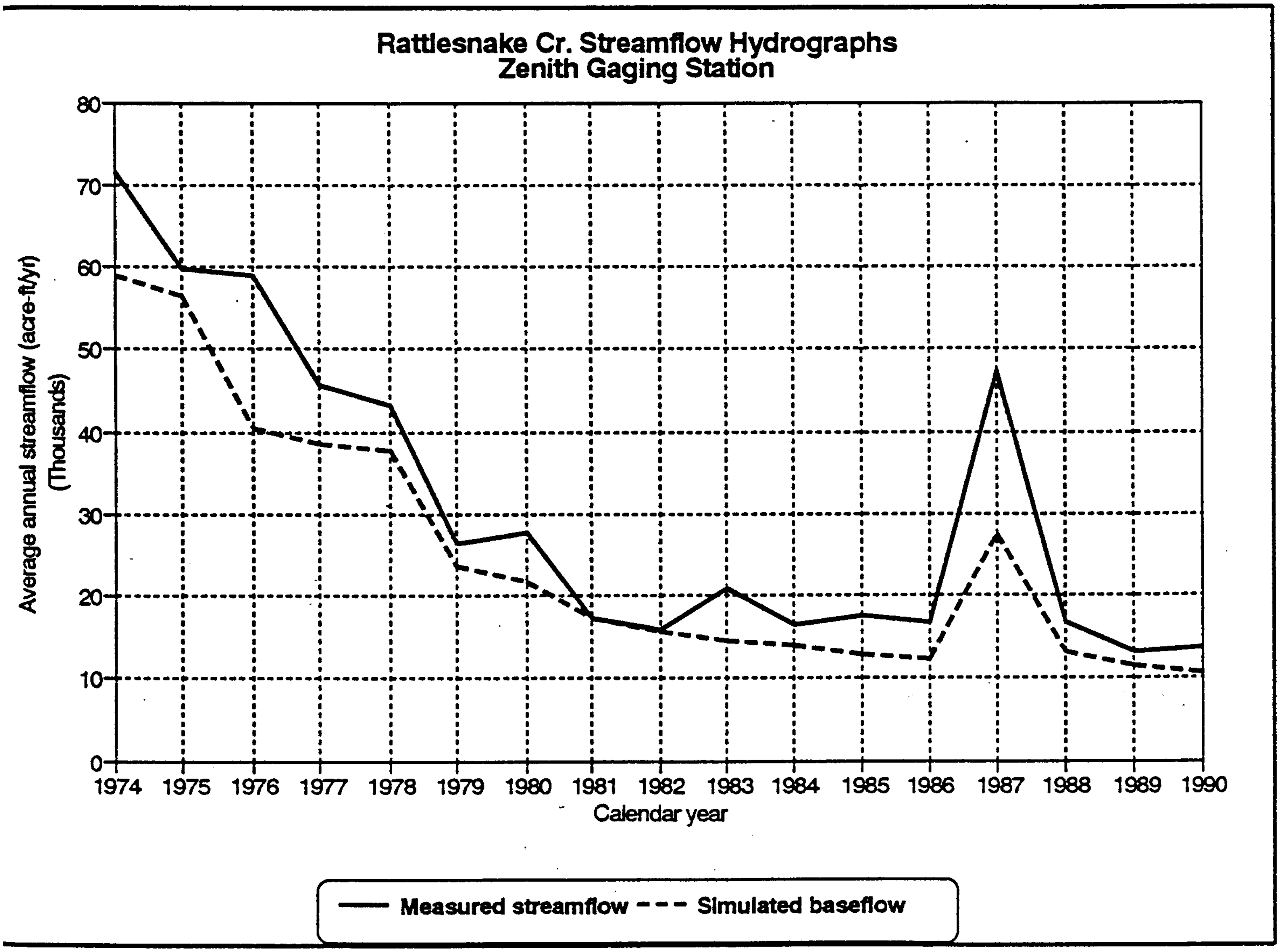

Figure 13. Comparison of predicted Rattlesnake Creek baseflow and measured streamflow at the Zenith gaging station versus time.

Sensitivity analysis and predictive runs

Sensitivity analysis, which quantifies the model's response to input parameter changes, gives insight into mechanisms and dependencies. Therefore an analysis was made to determine the sensitivity of the model to variations in the values of selected parameters on both the aquifer and the stream. The input and aquifer parameters considered were pumpage, recharge, hydraulic conductivity, and storativity. The stream parameters considered were conductance of the streambed, Manning's roughness coefficient, stream slope, and stream width. Sensitivity to each parameter was determined by running the model in a predictive mode from 1990 to 2010 with the optimized parameters for 1990 and by varying (increasing and decreasing) each parameter by 50%. Corresponding changes in ground-water levels or drawdown and in streamflow were observed, tabulated, and graphed at selected nodes within the model area.

Sensitivity analysis of ground-water levels to changing aquifer and input parameters indicates that ground-water pumpage (fig. 14a) has the largest effect on aquifer water levels (note that the 50% change in pumpage is taken over the assumed 80% water appropriation use). The water levels are also highly sensitive to the amount of ground-water recharge (fig. 14b), followed by aquifer storativity (fig. 14c), aquifer hydraulic conductivity, and groundwater evapotranspiration. However, different parts of the aquifer respond differently in absolute amount to changing parameters, with the relative significance of some parameters altered in some instances. For example, in the area north of the Zenith gaging station and southeast of the Cretaceous bedrock outcrop (located southwest of the Big Salt Marsh), where irrigation pumping is nonexistent and the depth to the water table is shallow, water levels are most sensitive to recharge (fig. 15a) and evapotranspiration (fig. 15b) followed by hydraulic conductivity (fig. 15c) and storativity with no sensitivity to pumpage (Sophocleous and Perkins, 1992).

Sensitivity analysis of streamflows to changing aquifer, input, and stream parameters indicates that, similar to what was observed with regard to ground-water levels, streamflows respond differently to various parameters. The aquifer and aquifer input-related parameters in this case have a much more pronounced effect on streamflows than do stream-related parameters. For

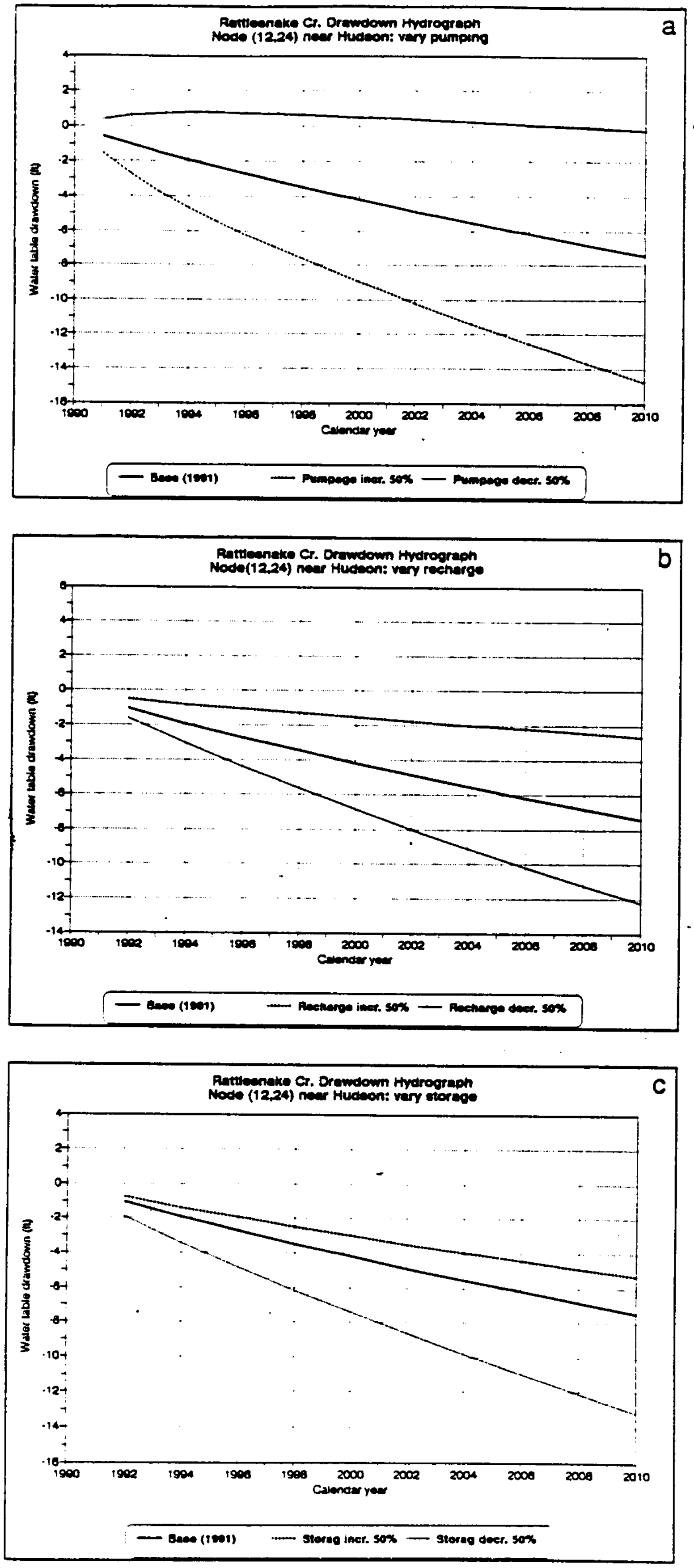

Figure 14. Sensitivity plots of water-table drawdown with changing ground-water pumpage (a), recharge (b), and storativity (c) at a grid cell near Hudson.

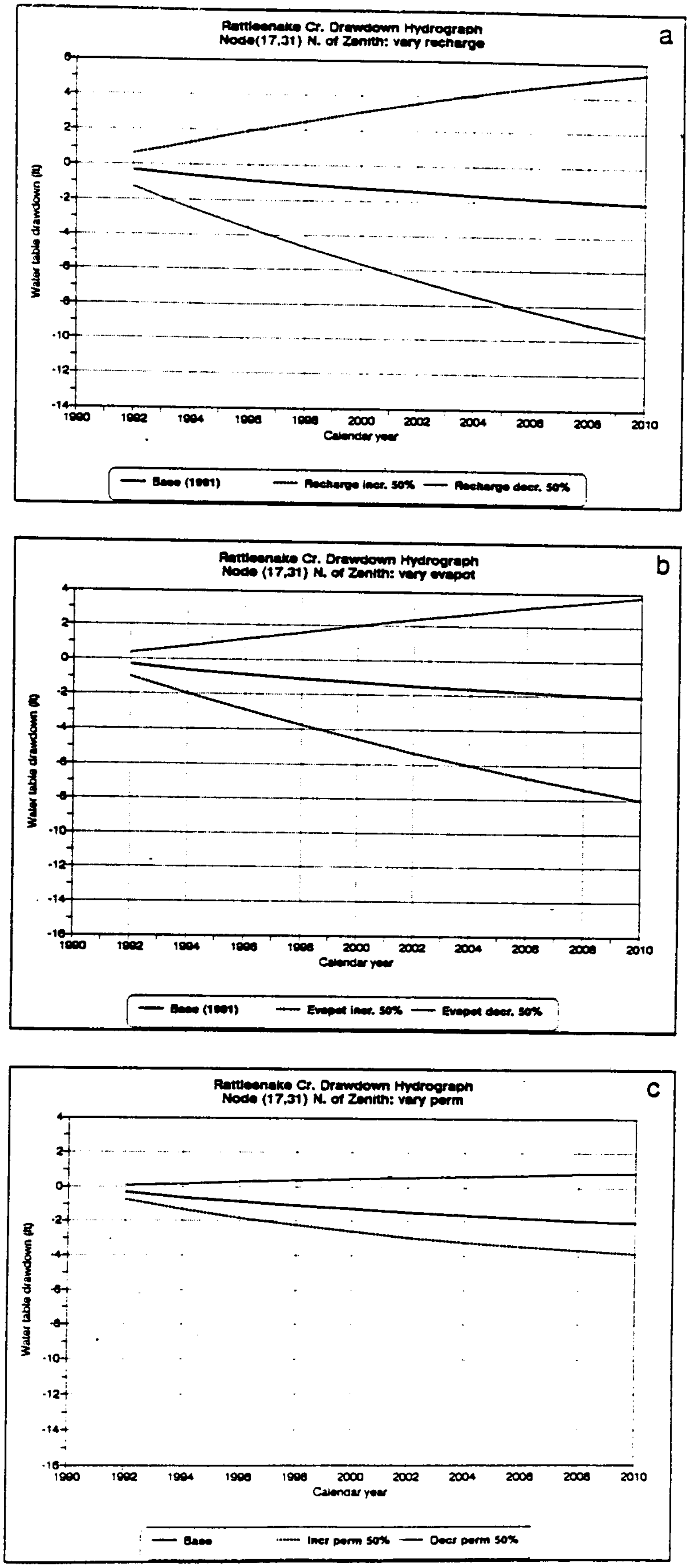

Figure 15. Sensitivity plots of water-table drawdown with changing recharge (a), evapotranspiration (b), and hydraulic conductivity (c) at a grid cell north of the Zenith stream-gaging station.

example, ground-water pumpage (fig. 16a) and recharge (fig. 16b) are more sensitive parameters than aquifer storativity, hydraulic conductivity, or aquifer evapotranspiration, but all these aquifer variables are much more sensitive parameters than streambed conductance (fig. 16c), Manning's roughness coefficient, stream slope, or stream width. Plots of responses to all stream-aquifer parameters may be found in Sophocleous and Perkins (1992).

A model prediction of baseflows, assuming that present conditions (pumpage, recharge, evapotranspiration, incoming streamflows at the Macksville gaging station) persist throughout the 1990–2010 period, is shown in fig. 17 for three Rattlesnake Creek locations near Macksville, St. John, and the Zenith gaging station. In all three areas future baseflows will be declining, with the steepest decline of approximately 40% by the year 2010 occurring at the Zenith gaging station near the entrance to the Quivira National Wildlife Refuge.

VI. Management alternatives to be tested and further work

The predictive capabilities of the calibrated model permit hypothetical conditions to be explored by simply changing the data input to emulate the desired situations. After further checks on model sensitivity and reliability analyses, the following initial set of scenarios are proposed for testing:

1. How would ground-water levels and streamflows respond to increased incoming streamflows from Rattlesnake Creek?

2. What effect do climatic fluctuations (i.e., sequence of flooding and drought years) have on the stream-aquifer system?

3. What effect do changing pumping patterns, including water conservation and improved irrigation efficiency, have on the stream-aquifer system?

4. How can specified minimum desirable streamflows be maintained throughout the Rattlesnake Creek basin?

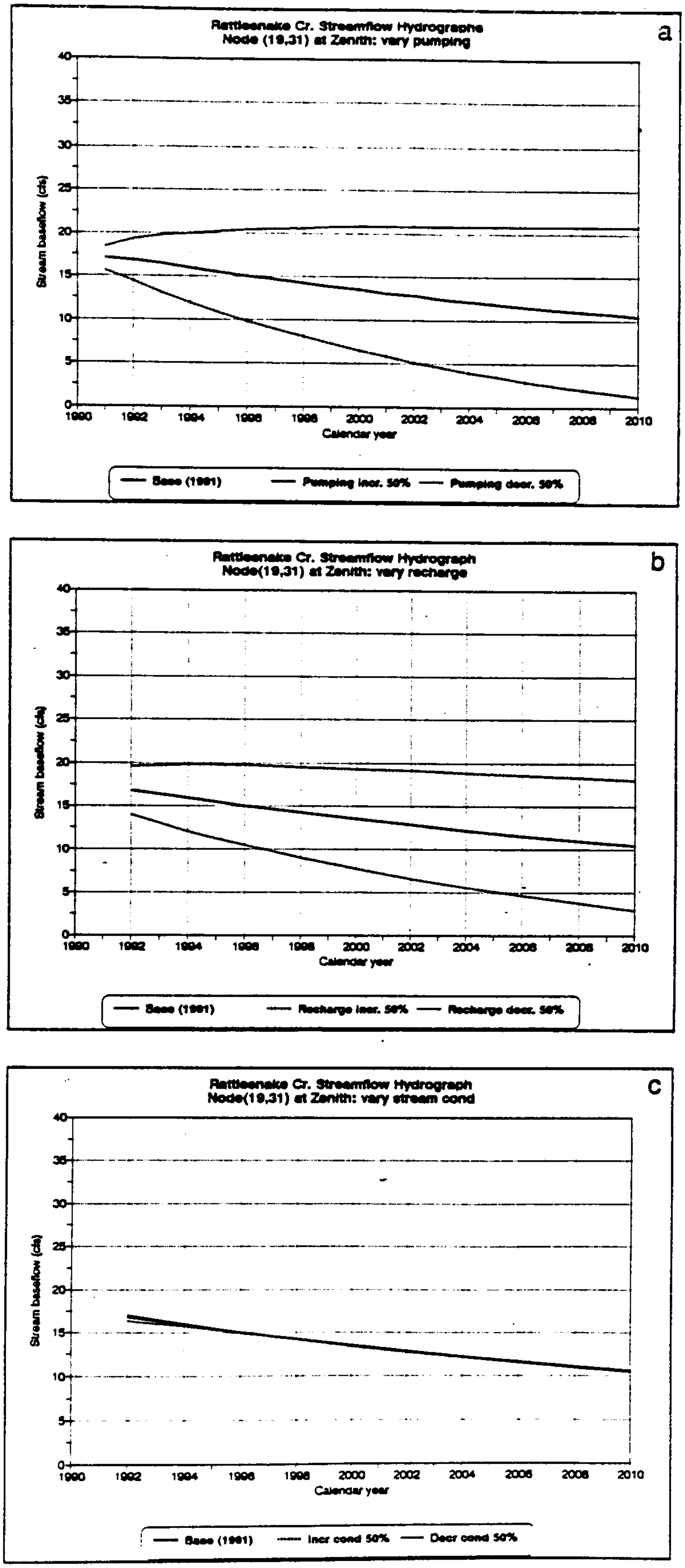

Figure 16. Sensitivity plots of stream baseflow with changing ground-water pumpage (a), recharge (b), and streambed conductance (c) at a grid cell by the Zenith stream-gaging station.

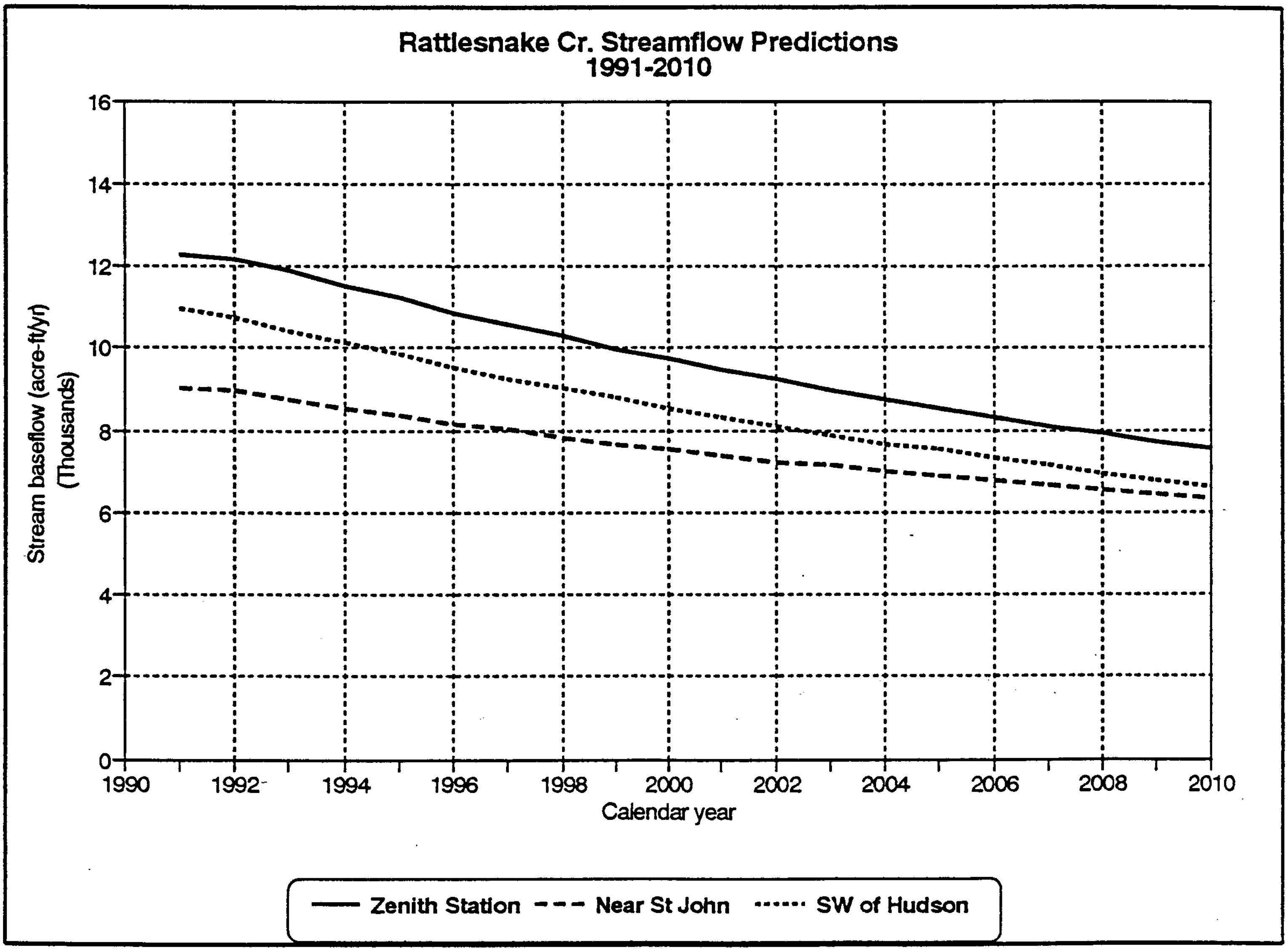

Figure 17. Model-predicted stream baseflow declines during the 1991–2010 period.

5. What effect would protective stream corridors of different sizes have on streamflows?

6. In case of drought, what is the most vulnerable subregion of the study area, and what ameliorating options are available?

A number of additional work elements are required to answer important questions or problems in the area:

- Separation of climatic from anthropogenic (irrigation and land use) influences on the water balance of the area is an important question which needs to be addressed.
- A detailed water balance modeling of the Quivira Refuge proper, taking into account climate, soils, vegetation, surface and ground-water hydrology, is important for better management of the refuge.
- Additional fieldwork is required to characterize the spatial and temporal distribution of the saltwater-freshwater interface and of the Permian brine influxes into the Great Bend Prairie aquifer so that saltwater intrusion processes can be adequately modeled and predicted.

Acknowledgments

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