The Declining Ground-Water Resources of Alluvial Valleys: A Case Study

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ABSTRACT

The use of ground water increased rapidly in the Pawnee Valley, Kansas, during the last two decades, causing ground-water levels to decline and streamflow to diminish. Therefore, this study was undertaken to evaluate the impact of present and future ground-water withdrawals in the region. This report documents the depleting water resource of the area and calculates a preliminary hydrologic budget for the region. It also adapts, automatically calibrates, and applies a mathematical model that adequately simulates the operation of the hydrogeologic system for the purpose of evaluating several schemes for managing the ground-water resource. Two different estimates of regional ground-water recharge in the area indicated that the average natural recharge is approximately 0.5 inch per year. On the other hand, it was found that the amount of appropriated ground water in the area exceeded the natural recharge figure by about 11 times. Digital simulations of the aquifer system indicated that, even without any additional development or with very wet periods, water-level declines will continue indefinitely, since ground-water withdrawals in the Pawnee Valley are of such magnitude. One option put forth for consideration is to prolong the life of the ground-water resource through the application of all the following recommendations: concerted efforts to reduce water wasting and to increase efficiency of water use; implementation of not more than a 40 percent saturated-thickness depletion allowance for the next several years; imposition of a freeze on the number of irrigation wells to the present levels; and engagement in an artifical-recharge program.

Additional Index Words: ground-water recharge; water balance; streamflow; baseflow; modulated soil-moisture budget; water-level declines; numerical simulation; parameter estimation; automated calibration; steepest descent; management options; Pawnee River Valley, Kansas.

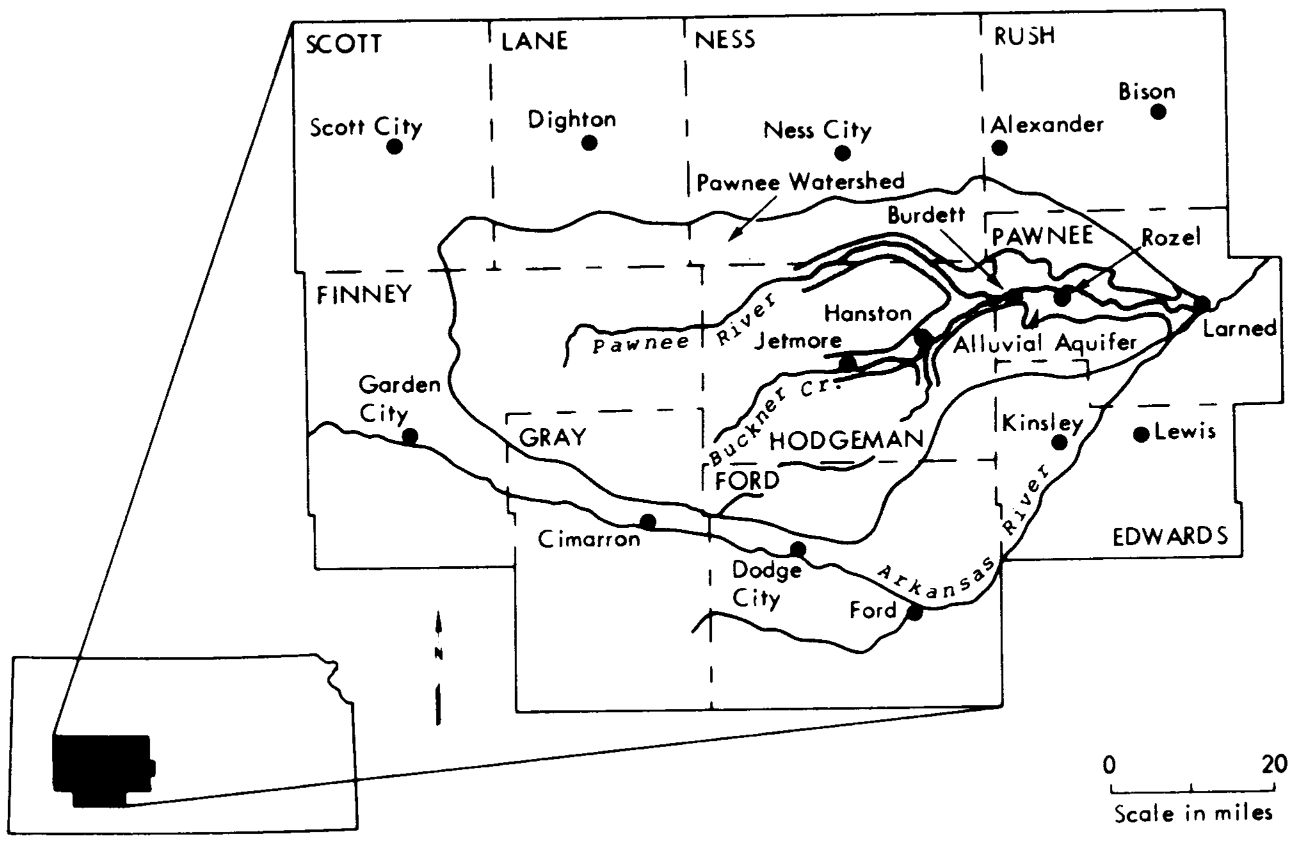

Fig. 1. Area and location map.

INTRODUCTION

The rapid development of ground-water-based irrigation in many alluvial valleys in central and western Kansas during the last two decades has caused ground-water levels to decline and streamflows to diminish. Although similar conditions exist in other areas, this paper concentrates on only one such valley, the Pawnee River Valley of west-central Kansas (Figure 1). The results and conclusions presented, however, are generally applicable to many areas of similar conditions. Because of the severity of ground-water declines in the Pawnee River Valley, a moratorium on new irrigation wells was declared in part of that valley, pending public hearings on the matter. For this reason, the Kansas Geological Survey was asked to undertake a short-term investigation of the alluvial aquifer in the Pawnee River Valley and to evaluate the impact of present and future ground-water withdrawals in that region. The author was faced with two major problems in dealing with the dwindling ground-water resources of such areas. The first was to persuade local residents that the problem exists, and the second was to recommend acceptable measures to deal effectively with the problem.

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Discussion open until September 1, 1981.

In this paper, the following aspects of the problem are dealt with. First, the existence of the problem is briefly documented; second, a preliminary water balance is presented; third, a simulation of the alluvial aquifer system is made, and an automated calibration procedure based on parameter estimation techniques performed; and fourth, a number of predictive simulations or management options are presented. Some concluding remarks follow. (For an expanded treatment of most of the above aspects, the reader is referred to Sophocleous, 1980.)

DOCUMENTATION OF THE DECLINING WATER RESOURCE AND PRELIMINARY WATER-BALANCE ESTIMATES

The area overlying the alluvial aquifer of the Pawnee Valley (Figure 1) is used for agricultural purposes. The growth of irrigated acreage is shown in Figure 2 for Pawnee and Hodgeman counties, where the dramatic increase in irrigated acreage since the mid-sixties is clearly evident. A tenfold increase in irrigated acreage since the forties is observed in Pawnee County, while a fivefold increase is shown for Hodgeman County. The major source of irrigation water in the Pawnee Valley is ground water; therefore, the increase in irrigated acreage has a significant effect on that source. The historic growth of well registration in Pawnee and Hodgeman counties is shown in Figure 3. It is worth noting that, in Pawnee County, growth is exponential, closely matching that of the irrigated acreage growth. A similar growth of well registration, but of a smaller scale, is also observed in Hodgeman County. The arrows in Figures 2 and 3 point to the time when ground-water-based irrigation started

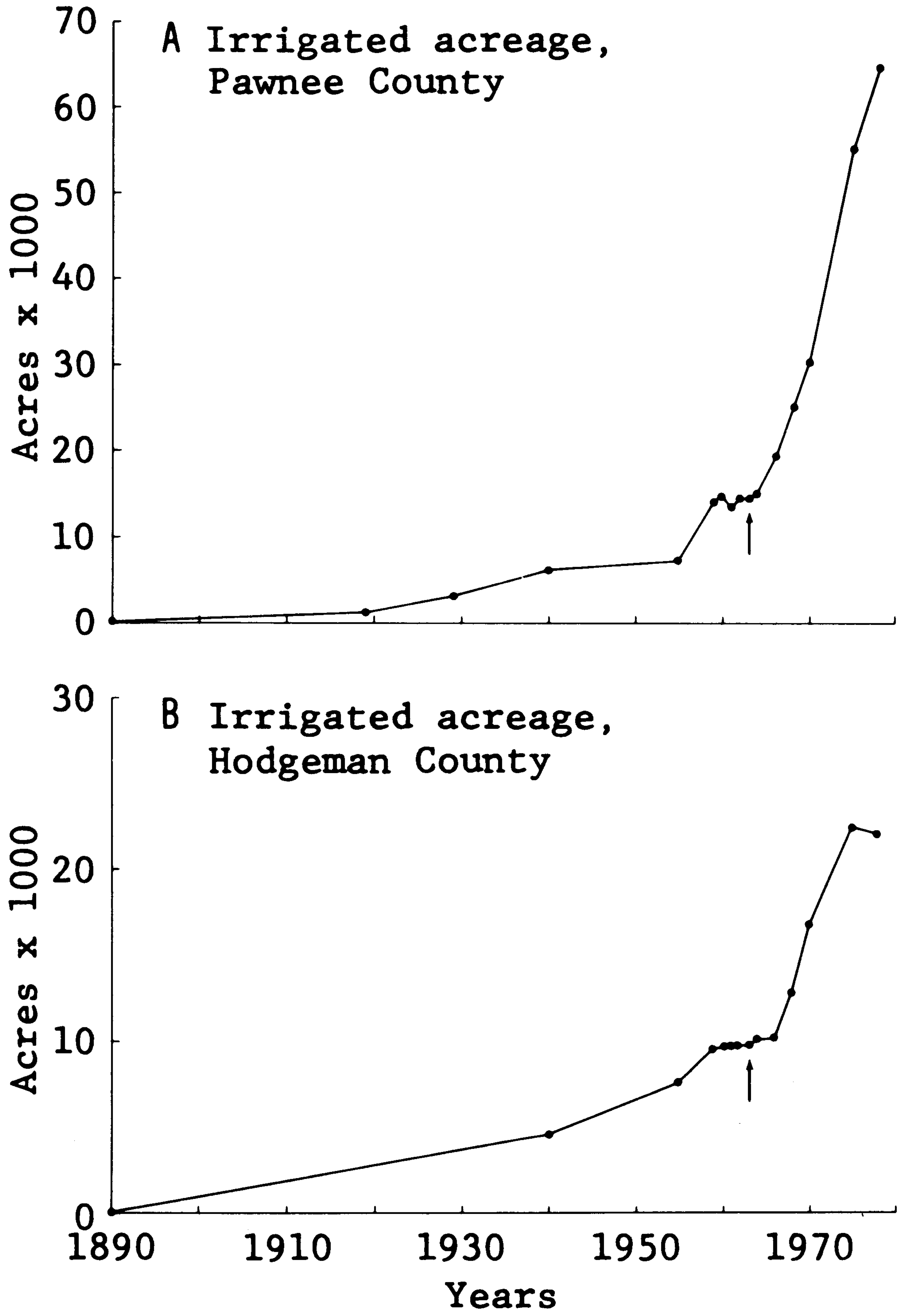


Fig. 2. Irrigated acreage of (a) Pawnee County and (b) Hodgeman County from 1890 to 1978 (refer to text for explanation of arrows).

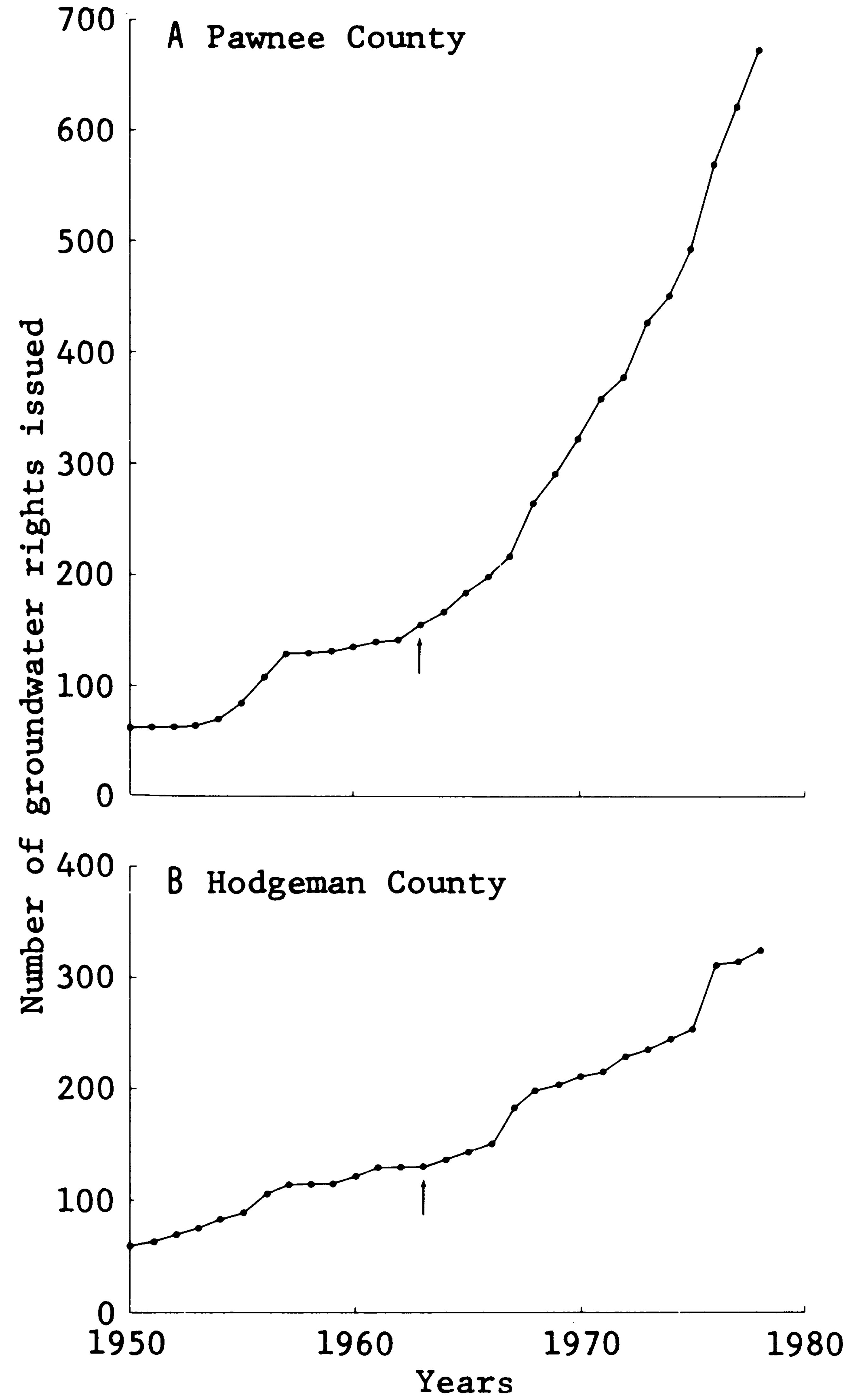


Fig. 3. Cumulative number of ground-water rights issued in (a) Pawnee County and (b) Hodgeman County from 1950 to 1978 (refer to text for explanation of arrows).

accelerating rapidly, which correlates well with significant decreases in the baseflow regime of the Pawnee River, as is pointed out further on.

The runoff from the Pawnee watershed is measured at the Pawnee River near Larned (Figure 1). The streamflow records for the Larned station have been analyzed for the period 1945-78 (Sophocleous, 1980). In order to more clearly distinguish the streamflow and baseflow data trend from the wildly fluctuating streamflow and precipitation records, a simple seven-year moving average time-trend analysis is applied to these data as shown in Figure 4. Baseflow data were obtained from streamflow records following the hydrograph separation procedures outlined by Busby and Armentrout (1965). A continuous streamflow and baseflow decline is evident from these data, although average areal precipitation over the same period of record does not decrease. This fact indicates that an increase in ground-water use is probably one major cause of this streamflow decline. It should be noted that because of the unreliability and small volumes of flow of the Pawnee River, especially during the recent years when the stream is dry or the flow is less than one to two cubic feet per second for long periods of time, surface-water-based irrigation in the Pawnee Valley is very limited.

A steeper decline in baseflow than in streamflow is observed during the period of record as shown in Figure 4, providing further evidence of heavy ground-water withdrawals. In order to examine this observation further, a double mass analysis of cumulative baseflow versus cumulative precipitation for the study period was performed (Figure 5). Effects of the drought in the early fifties are evident. The number of ground-water rights issued in the Pawnee Valley increased significantly during the drought period (Figure 3), thus enabling irrigated acreage growth. The trend of increasing ground-water rights issued leveled off only after the end of the drought period in 1957. An examination of that double mass diagram reveals that an apparent change in baseflow regime occurs in the mid-sixties. Average baseflow for 1945 through 1963 is 15.8 cubic feet per second—cfs (0.447 cubic meters per second—cms), while the average for 1963 through 1978 is 1.5 cfs (0.042 cms), which indicates a drastic reduction in baseflow after the mid-sixties. This break in slope of the mass curve after 1963—indicated by an arrow in Figure 5—coincides with a significant increase in the development of ground water for irrigation, as is shown by the increase in irrigated acreage (Figure 2) and the increase in well registrations (Figure 3). Reduced precipitation is not a cause of depletion of the flow in the stream since 1963 (Figure 4). The only remaining reasonable causes of the depletions are capture by irrigation wells of water normally discharged to streams and changes in land-use practices. Among other changes, the latter include construction of terraces on land, contour farming, summer fallowing, stubble mulching, use of more efficient machinery and chemicals (all resulting in higher crop yields, which contribute to greater soil-moisture depletion and consequent decrease of

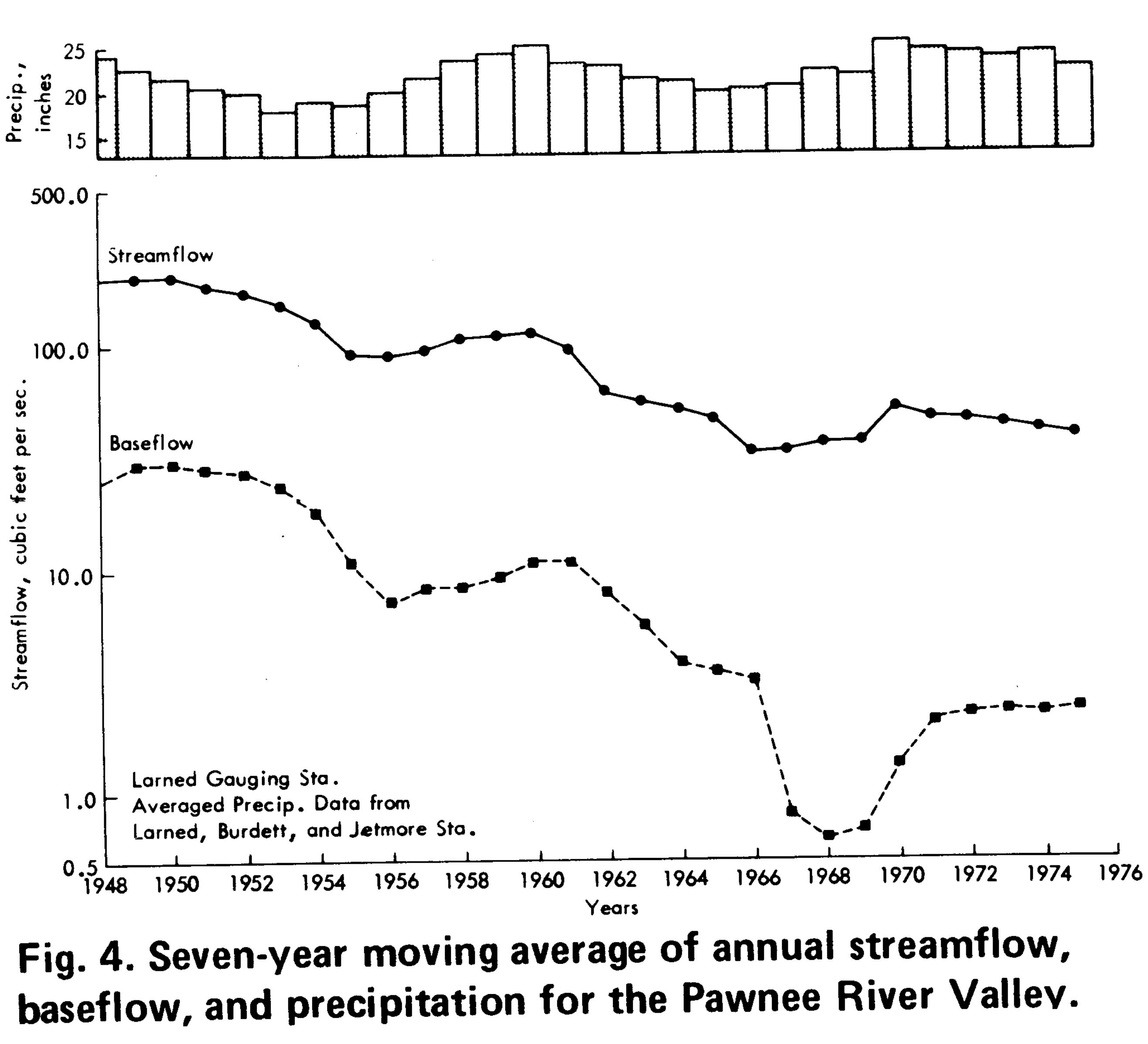


Fig. 4. Seven-year moving average of annual streamflow, baseflow, and precipitation for the Pawnee River Valley.

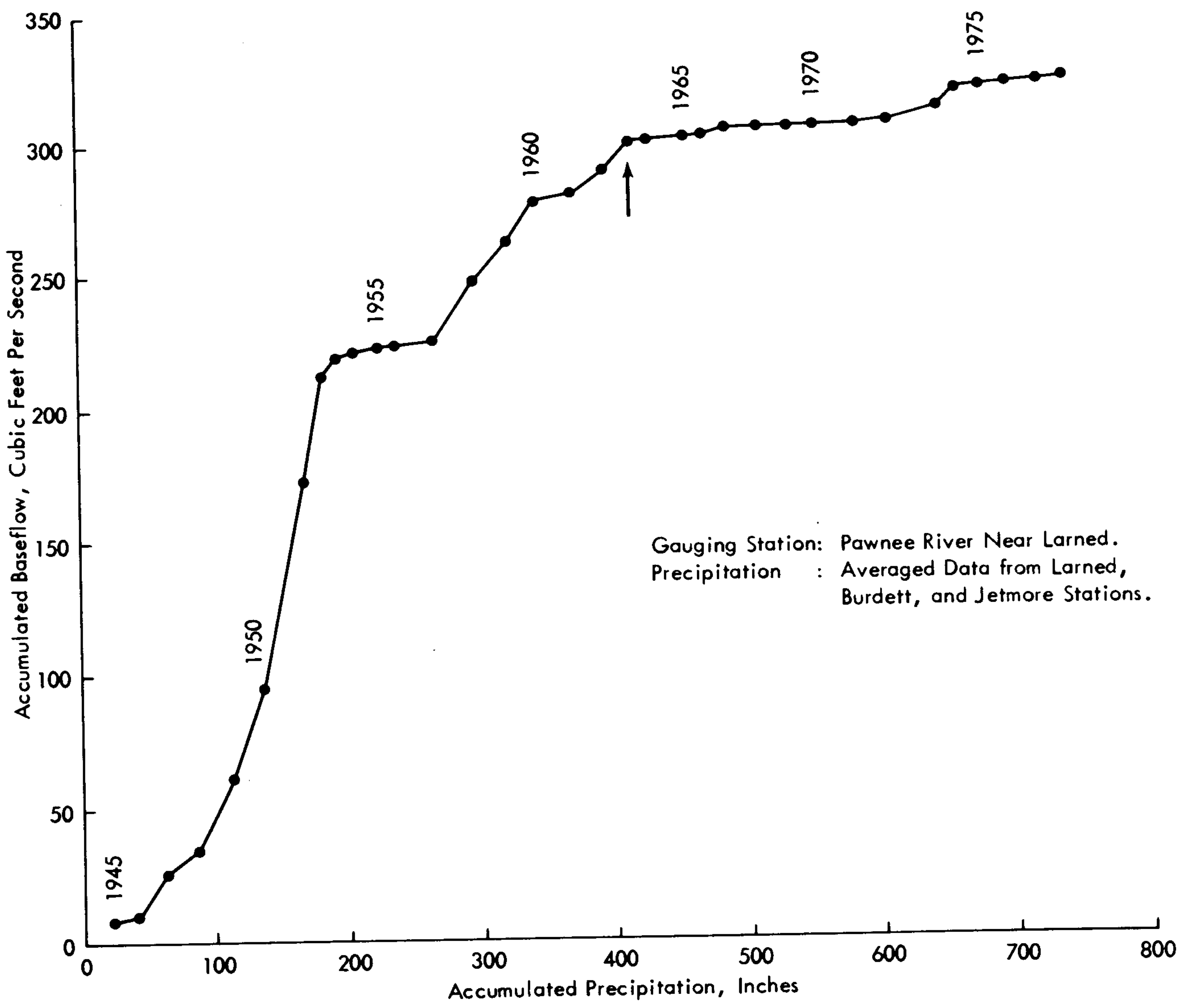
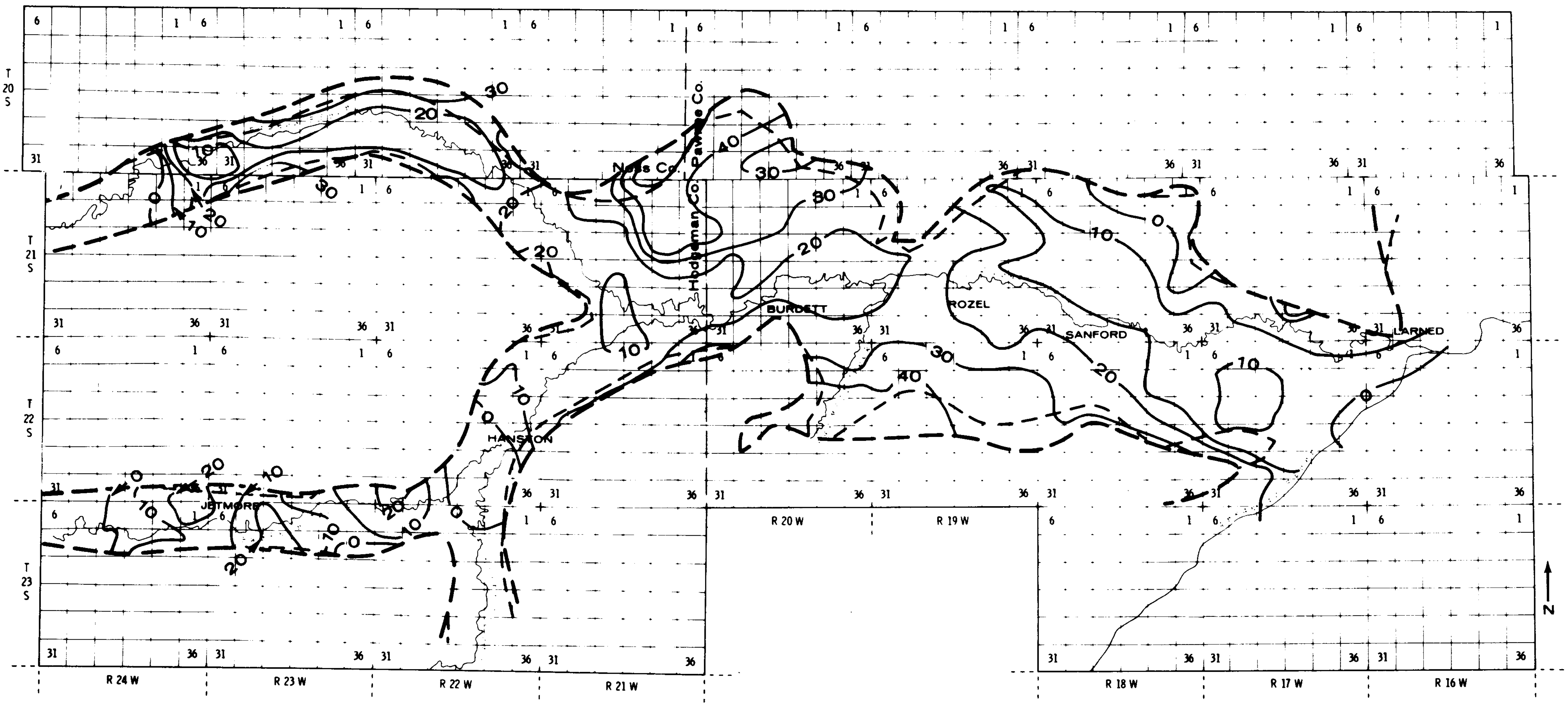


Fig. 5. Accumulated baseflow versus accumulated precipitation for Pawnee River from 1945 to 1978 (refer to text for explanation of arrow).



EXPLANATION

—20— Water-level decline contours in feet.
Contour interval 10 feet.
— — — Approximate extent of the alluvial aquifer during 1945-47.
- - - - Approximate extent of the alluvial aquifer during 1979-80.
Approximate scale: 1:125,000

Fig. 6. Water-level decline map of Pawnee Valley, Kansas, alluvial aquifer from 1945-47 to 1979-80.

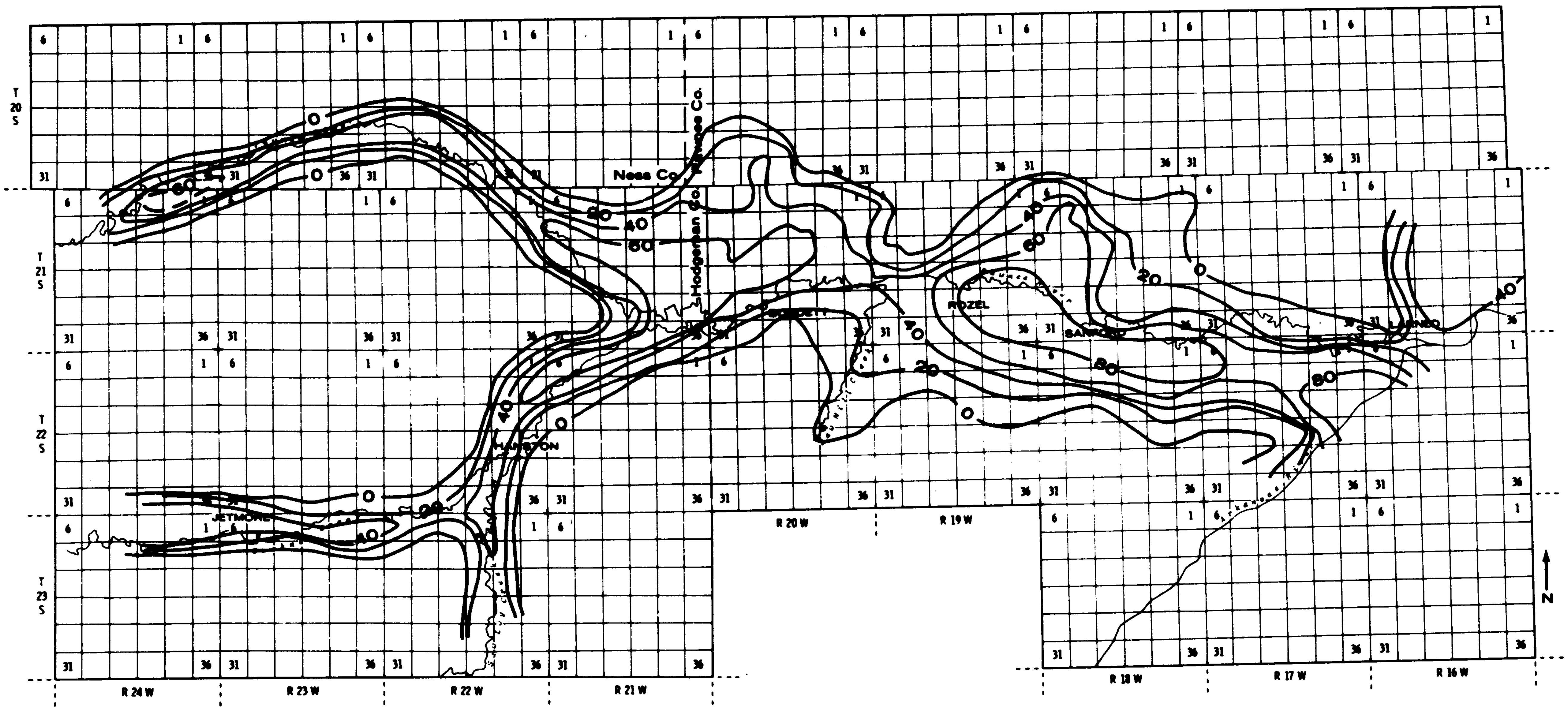
runoff to streams), and construction of small dams.

A study of the hydrographs of a number of irrigation and observation wells in the study area (Sophocleous, 1980) indicated nearly continuous water-level declines, especially since the mid-sixties. Such declines are the direct result of increased discharge from the aquifer to supply the consumptive use of irrigated crops. In order to evaluate the extent of these water-level declines, a water-level decline map was constructed based on an existing 1945-47 water-level survey and a recently completed one (1979-80). Declines of greater than 20 to 30 feet are measured or calculated for various parts of the Valley (Figure 6). An approximate 15 percent shrinkage of the Pawnee Valley aquifer from 1945-47 to 1979-80 is a result of increased pumpage, indicated by the zero saturated-thickness contour outline. Comparison of the 1945-47 volume of water in the saturated deposits of the alluvial aquifer with that calculated during 1979-80 indicated an average depletion of water in storage of more than 35 percent during that period (Sophocleous, 1980). It should be noted that the Pawnee Valley aquifer—consisting of alluvium and terrace deposits containing sand and gravel with silt and clay—is thin and shallow, with current maximum saturated thickness of 80 to 90 feet (24 to 27 m) or less (Figure 7).

The mean annual precipitation for the last 20-year period (1959-1978) for the Larned station (Figure 1) is 24.2 inches (61.5 cm), while for the Jetmore station (Figure 1) it is 21.2 inches (53.8 cm). No direct measurements of evaporation or evapotranspiration are available for the Pawnee watershed.

As an approach to the problem of estimating potential evapotranspiration, the empirical method of Thornthwaite (1948) has been applied to the data from the stations at Larned and Jetmore, representing the two opposite ends of that part of the Pawnee watershed studied in detail in this report (Figure 1). The minimum amount of meteorological data required for this method and its simplicity were the factors considered in choosing this method, although the results are only a rough approximation of evapotranspiration. The average annual potential evapotranspiration from these two stations is approximately 32 inches (81.3 cm).

The measured precipitation and the calculated potential evapotranspiration values have been used together with the Holmes and Robertson (1959) modulated soil-moisture budget technique to determine the monthly and annual actual evapotranspiration and the moisture surplus available for runoff and ground-water recharge (see also Meyboom, 1966). Although other similar but more sophisticated

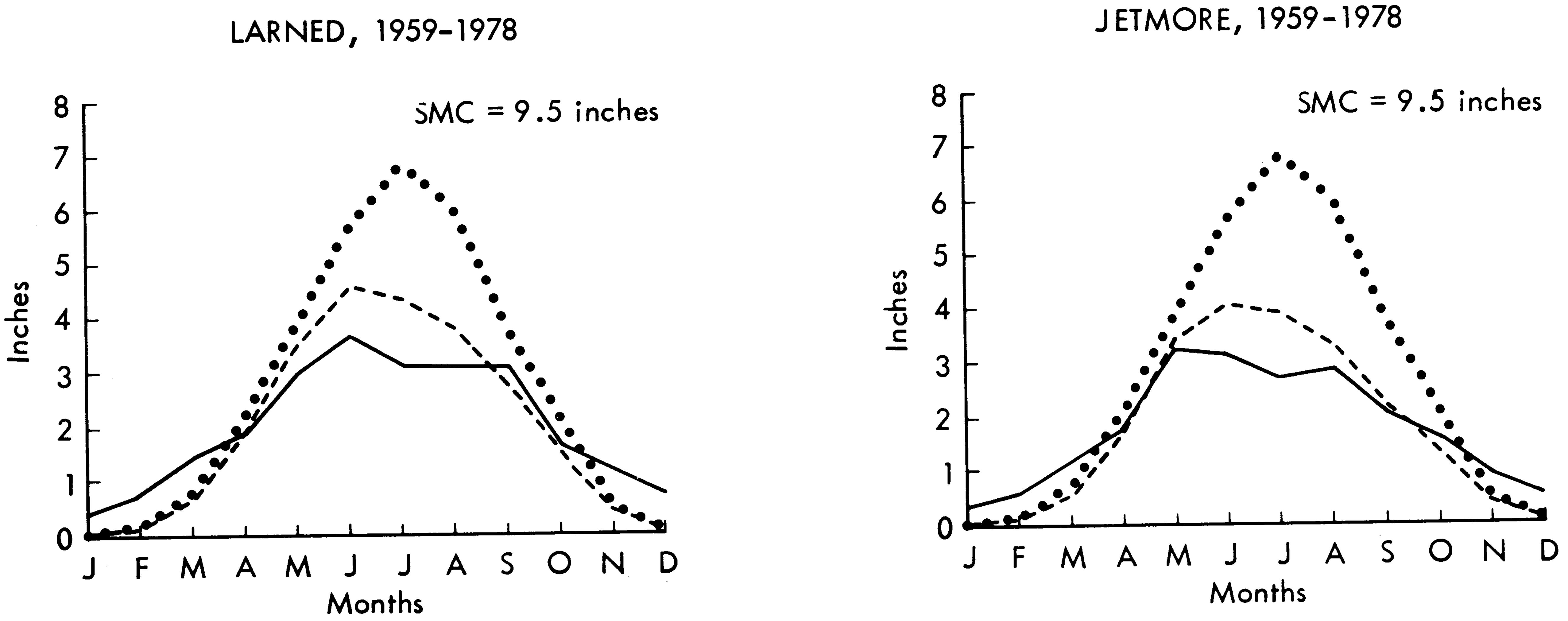


EXPLANATION

—40 – Saturated-thickness contours in feet.
Contour interval 20 feet.
Approximate scale: 1:125,000

Fig. 7. Saturated-thickness map of Pawnee Valley, Kansas, alluvial aquifer during 1979-80.

techniques, such as Baier and Robertson's (1965) versatile soil-moisture budget technique, are available, the available data are not sufficient to justify their use. With the aid of a computer program (Freeze, 1967) suitably modified, the analysis was carried out for six different soil-moisture capacities ranging from 2.5 to 10.5 inches (6.3 to 26.7 cm). These soil-moisture capacity values cover the range of values observed in the watershed area. The results of this analysis, based on 20-year means (1959-78) for a typical soil moisture capacity in the area, are shown in a water-balance diagram (Figure 8). Such a diagram compares potential and actual evapotranspiration with the



	——— Precipitation	• • • • • Potential ET	- - - - - Actual ET
Larned	24.16*	32.11	23.78
Jetmore	21.15	31.95	21.15

*Twenty-year average values in inches

Fig. 8. Water-balance diagrams for Larned and Jetmore, Kansas (1959-1978).

amount of precipitation, on a monthly basis. This comparison then gives information on the amount of deficit or surplus water available during different seasons. One can see in the water-balance diagram that the 20-year average actual evapotranspiration is less than the 20-year average precipitation for the Larned station and equal to it for the Jetmore station.

All previous data analysis concentrated on the estimation of subsurface-water discharge from the soil and alluvial aquifer system and related effects therein. To complete the ground-water balance, two different methods were employed in estimating regional ground-water recharge. First, streamflow records at the discharge end of the flow system were interpreted for this purpose, and second, soil-moisture budget analysis was employed based on soil and hydrometeorological data.

The long-term average recharge to the alluvial aquifer was assumed to equal the long-term average ground-water outflow during the early times of irrigation development in the Pawnee Valley. According to Fishel (1952), there were 35 irrigation wells in the Pawnee Valley in 1925 and 132 in 1945. The average annual baseflow during the period of 1925 to 1945 was 5.04 cfs (0.143 cms) or 3,649 acre-feet of water per year—ac-ft/yr (4,500,975 m^3/yr). Assuming that each irrigation well pumped about 90 ac-ft/yr (111,013 m^3/yr), the average amount of ground water pumped during that period was approximately 7,515 ac-ft/yr (9,269,616 m^3/yr). Making the further assumption that approximately 10 percent of that water returned to the aquifer by deep percolation (H. Dickey, Soil Conservation Service, 1979, oral communication), the net amount of pumpage during that period was 6,763 ac-ft/yr (8,343,271 m^3/yr). Thus, the total ground-water outflow (baseflow plus pumpage) for the period 1925 to 1945 was about 10,413 ac-ft/yr (12,844,246 m^3/yr), which—under the assumption of equilibrium—represents the amount of ground-water recharge. As the area of the Pawnee Valley alluvial aquifer during 1945 (Figure 6) was approximately 325 square miles (842 km^2), that quantity of recharge represents 0.6 inches (1.5 cm) per year over the aquifer area.

The second method for estimating regional ground-water recharge in the Pawnee Valley is the soil-moisture budget technique. Table 1 presents the calculated average monthly moisture surpluses for the Larned and Jetmore stations, together with the frequencies at which surpluses occurred during the 1959-1978 period. The table indicates that in the Pawnee Valley, and for the predominant soil-moisture capacity of 9.5 inches (24 cm), moisture surpluses occur 15 percent or less of the time from January to March; five percent or less of the time during April, September, November, and December; and never during May, June, July, August, and October. Column number 3 of that table shows the total average moisture surplus, which constitutes potential ground-water replenishment. Column number 4 shows the same amount as a percentage of the average total annual precipitation from 1959 to 1978. In Table 1, the moisture surplus for the two predominant soil moisture capacities representative of Pawnee Valley soils is listed for the two meteorological stations mentioned previously. A soils association map for the entire Pawnee watershed has been constructed and interpreted in terms of

Table 1. Average Monthly Soil-Moisture Surplus for 1959-1978 Calculated from Year to Year for Different Soil-Moisture Capacities According to the Modulated Soil-Moisture Budget Technique of Holmes and Robertson (1959) for Two Stations in the Pawnee Valley

SOIL MOISTURE CAPACITY= 8.50

Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		PERIOD	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
Larned, KS	0.19	15	0.10	15	0.40	15	0.07	5	0.	0	0.	0	0.	0	0.	0	0.04	5	0.	0	0.01	5	0.12	10	0.94	3.9
Jetmore, KS	0.17	5	0.02	5	0.32	15	0.06	5	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.57	2.7

SOIL MOISTURE CAPACITY= 9.50

Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		PERIOD	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
Larned, KS	0.01	10	0.08	15	0.39	15	0.07	5	0.	0	0.	0	0.	0	0.	0	0.03	5	0.	0	0.01	5	0.12	5	0.70	2.9
Jetmore, KS	0.	5	0.02	5	0.28	15	0.06	5	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.36	1.7

**EXPLANATION OF COLUMNS:

1. Average monthly moisture surplus (in.) for 1959-1978.
2. Percentage of years during 1959-1978 in which moisture surplus occurred during the month indicated.
3. Total average moisture surplus from Jan to Dec (in.).
4. Total average moisture surplus from Jan to Dec expressed as percentage of average total annual precipitation 1959-1978.

the percentage of the effective drainage area covered by soils representing each of the soil-moisture capacities (Sophocleous, 1980).

If 20 years of record (1959-1978) at the Larned and Jetmore stations are at all representative of the average conditions in the Pawnee Valley, moisture budgets indicate that the average potential annual ground-water replenishment in this watershed varies from 0.28 inches (0.7 cm) (soil moisture capacity 10.5 inches; Jetmore hydrometeorological conditions) to 1.27 inches (3.2 cm) (soil moisture capacity 6.5 inches; Larned hydrometeorological conditions). Or, in other terms, the potential annual recharge in this area lies between 1.3 and 5.3 percent of the average total annual precipitation. Reference to Table 1 shows that, as the soil-moisture capacity increases, the percentage of the available water that is actually evapotranspired increases at the expense of the moisture surplus.

Applying the percentages of the effective drainage area covered by soils representing each of the soil-moisture capacities to the average moisture surplus over the basin for each soil-moisture capacity gives rise to an average annual surplus of 0.64 inches (1.6 cm) in the Pawnee watershed. The moisture surplus must, however, satisfy the surface runoff as well as ground-water recharge. The average total runoff from the Pawnee watershed, as measured at the gauging station west of Larned during the 1959-78 period for which the moisture budget is performed, is 0.27 inches or 45.10 cfs (0.7 cm or 1.28 cms). Of this, 0.02 inches or 3.75 cfs (0.05 cm or 1.17 cms) represents baseflow from ground-water discharge. Subtracting this from the total runoff yields a surface runoff value of 0.25 inches per year or 41.34 cfs (0.6 cm or 1.17 cms) over the effective watershed drainage area up to the gauging station west of Larned (i.e., 2,290 mi^2 or 5,931 km^2). This figure, when subtracted from the average annual surplus, results in a value for regional ground-water recharge of 0.39 inches (1.0 cm) per year. This value is of the same order of magnitude as the one calculated from baseflow measurements.

Thus, the average estimated regional ground-water recharge for the Pawnee Valley is about 0.5 inches (1.3 cm) per year, which represents only 2.5 percent of the average annual precipitation. During 1978-79, the ground-water appropriations in the Pawnee Valley alluvial aquifer (which reached at least 84,000 aft or 103,612,470 m^3) amounted to about 11 times the amount of estimated natural ground-water replenishment for the Pawnee Valley.

SIMULATION OF THE ALLUVIAL AQUIFER SYSTEM

In order to evaluate the impact of present and future ground-water withdrawals in the region and to assist the ground-water management districts responsible for the area in their decisions on ground-water resources, a numerical simulation of the relevant hydrogeologic system was undertaken. Through this modeling effort we sought to determine, in a general way, how rapidly the resource is being depleted, where and when water-level declines will seriously affect existing investments, and what impacts alternative developments or management practices will have on the system.

The mathematical equation describing the two-dimensional ground-water flow through an areally extensive aquifer is given by the following partial differential equation (Bittinger, *et al.*, 1967).

$$\frac{\partial}{\partial x}[Kb\frac{\partial H}{\partial x}] + \frac{\partial}{\partial y}[Kb\frac{\partial H}{\partial y}] = S_y\frac{\partial H}{\partial t} + \frac{Q}{\Delta x \Delta y}$$

where

K = hydraulic conductivity [L/T],

b = saturated thickness [L],

H = hydraulic head [L],

S_y = storativity or specific yield,

Q = net withdrawal flow rate [L^3/T],

$\Delta x, \Delta y$ = incremental distances,

x, y = space directions, and

t = time.

A computer simulation program based on the above-mentioned equation as applied to a rectangular model system (Knowles, *et al.*, 1972) and suitably modified to conform to our own requirements is used to simulate the alluvial aquifer system in the Pawnee Valley. The modeled area has approximate dimensions of 49 miles (79 km) by 19 miles (31 km). A nonuniform grid spacing ranging from one to three miles (1.6 to 4.8 km) was chosen. Although a shorter nodal spacing would seem more appropriate, the lack of adequate data, the cost limitations and the objective of obtaining only generalized results for the area were the principal factors involved in the grid size selection process. While the Arkansas River flowing at the eastern end of the Pawnee Valley (Figure 7) was simulated as a constant head boundary, the Pawnee River, a much smaller stream, was not, because of the extended periods of time that stream runs dry or with insignificant amount of flow, especially during the recent years, as was mentioned previously. However, the amounts of ground-water recharge calculated from the Pawnee River streamflow records in combination with the soil-moisture budget have been incorporated into the model. For details on the implementation of the model in the Pawnee Valley, the reader is referred to Sophocleous (1980).

There are many alternatives available if a well runs dry, e.g., turning the pump off, reducing the pumpage to match the aquifer capabilities, shifting pumpage to other wells, or using some combination of these. In this study, it is conservatively and arbitrarily assumed that the wells are able to pump their original appropriation until the saturated thickness declines to 8 feet (2.4 m) or less in which case the well is shut down; the same well does not resume pumping until the saturated thickness is built up to 15 feet (4.6 m) or more. Another option employed consists of allowing the well to deplete not more than 40 percent of the initial saturated thickness, in which case the well is shut down; the same well is assumed to resume pumping when the saturated thickness is built up to 62 percent or more of the original saturated thickness.

PARAMETER ESTIMATION OR MODEL CALIBRATION

Before an appropriate model selected for the area of interest can be used as a predictive or problem-solving device, it must be "calibrated" by using data from the physical system to be simulated. The two primary objectives of calibration are: (1) to adjust the model's input data (i.e., aquifer properties, sources and sinks, boundary, and initial conditions) so that it best approximates the physical system; and (2) to determine the sensitivity of the model to the input variables (Huntoon, 1974). In practice, the calibration of a ground-water model is frequently accomplished through a trial-and-error adjustment of the model's input data to modify the model's output. Because a large number of interrelated factors affect the output, this may become a highly subjective procedure. Recent advances in parameter estimation procedures (Seinfeld and Lapidus, 1974) help eliminate some of the subjectivity in model calibration.

Parameter estimation procedures provide a tool for determining aquifer parameters for a set of points in an aquifer by treating initial estimates of those parameters as terms to be adjusted on the basis of some criterion of "goodness of fit." The key point in the adjustment of parameters is the determination of the computer-model sensitivity to changes of the parameters. The sensitivity is indicated by the extent to which the simulated water levels react to a change in an aquifer parameter.

The procedure used for adjusting the aquifer parameters is the method of steepest descent, also known as the method of gradients (Knowles *et al.*, 1972). This procedure obtains the minimum of a function by determining the changes of the independent parameters that will result in the greatest rate of reduction of the function. The function to be minimized is the difference between the simulated and measured water levels. The independent parameters are the hydraulic conductivity, storativity, and net withdrawal rates or fluxes. These parameters were constrained by upper and lower bounds based on the hydrogeologic regime of the area (Sophocleous, 1980).

The parameter adjustment procedure is as follows. First, a simulation is performed of the water levels for the year or years during which measured water levels are available. The measured water levels are used as starting points for each year's simulation, and the original estimates of hydraulic conductivity, storativity, and net withdrawal rates or fluxes are used for each node. Second, the values of the coefficients and constants for all the sensitivity equations are determined. The sensitivity of any node's simulated water level with respect to one of the parameters may be expressed by the partial derivative expression of water level with respect to the parameter of interest. For further details on the derivation and application of the equations involved in such sensitivity analysis, the reader is referred to Knowles *et al.* (1972). Third, the aquifer parameters are adjusted according to the steepest descent algorithm (Vemuri and Karplus, 1969), using constraints on storativity, hydraulic conductivity, and fluxes:

$$\phi^{m+1} = \phi^{m} - \lambda(\partial H/\partial \phi)$$

where

ϕ	is an aquifer parameter (hydraulic conductivity, storativity, or fluxes—vertical or lateral),
$\partial H/\partial \phi$	is the sensitivity of the water level with respect to parameter ϕ,
λ	is a scalar such that $\lambda > 0$, and
m	is an interation index.

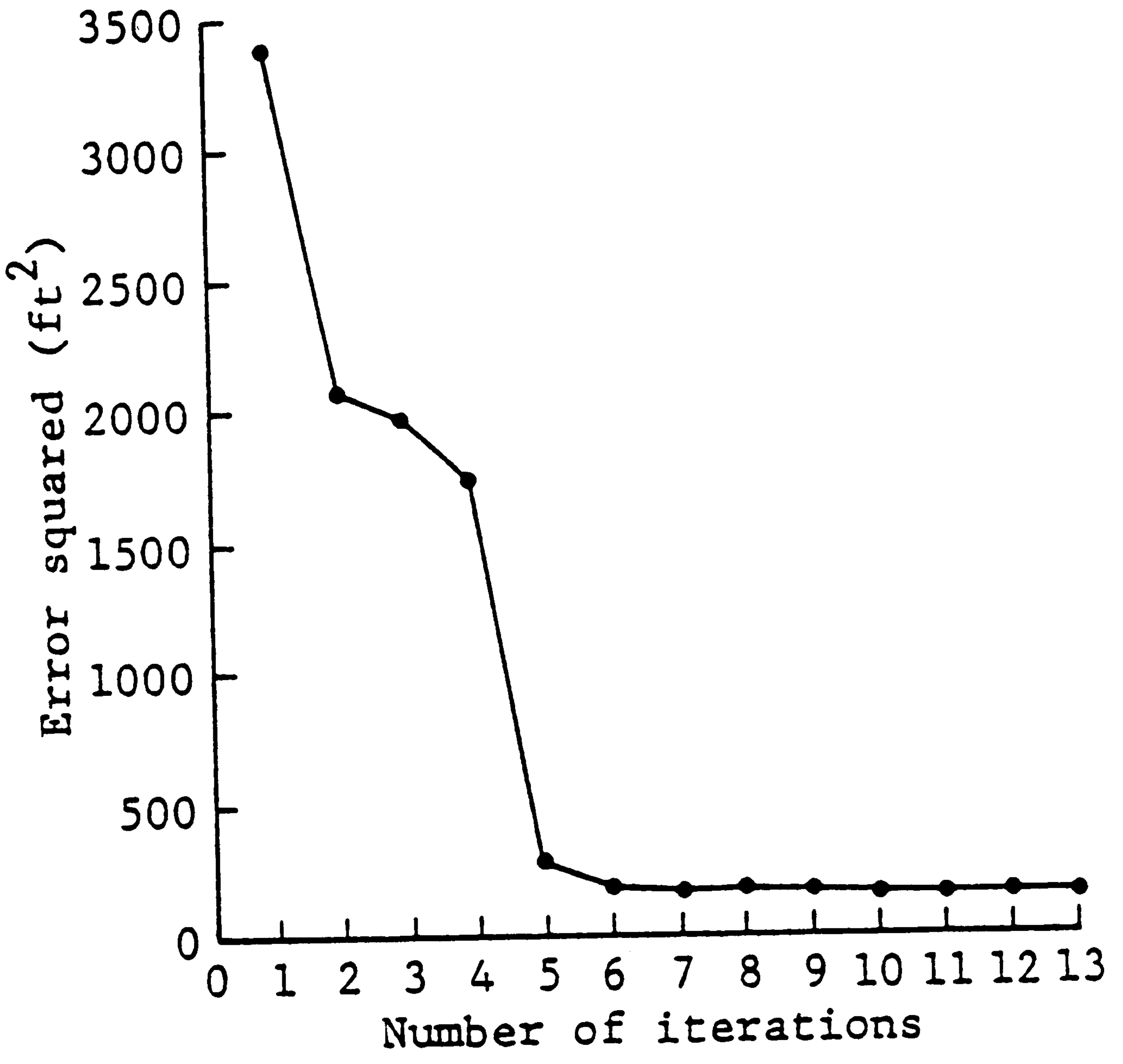


Fig. 9. Plot of sum of errors squared versus number of iterations.

As shown in Figure 9, the sum of the errors squared between observed and calculated water levels decreased as successive simulation tests were made. This figure indicates that the parameter adjustment procedure effectively reduced the magnitude of the error. After about 10 tests, additional adjustments produced only very small improvements in the fit between observed and computed water levels.

Another objective of the calibration procedure is to determine the sensitivity of the model to factors that affect ground-water flow. Evaluating the importance of each factor helps determine which data must be defined more accurately and which data are already adequate or require only minimal definition. If additional data cannot be collected, then the sensitivity tests can help to assess the reliability of the model by demonstrating the effect of a given range of uncertainty or error in the input data on the output of the model. The relative sensitivities of the parameters that affect flow will vary from problem to problem. Figure 10 shows the effects of changes in hydraulic conductivity, storativity, and fluxes on the simulated water levels at a randomly selected node near Rozel (Figure 1). From these figures it is concluded that the computed head is more sensitive to values of storativity and fluxes (both vertical and lateral) than to hydraulic conductivity values. The high sensitivity of computed hydraulic head to storativity is important because this property is the least well known at a given point in space and time. While the sensitivity of hydraulic head to fluxes is constant (linear), the sensitivity to hydraulic conductivity deceases with increasing hydraulic conductivity (Figures 10b and c).

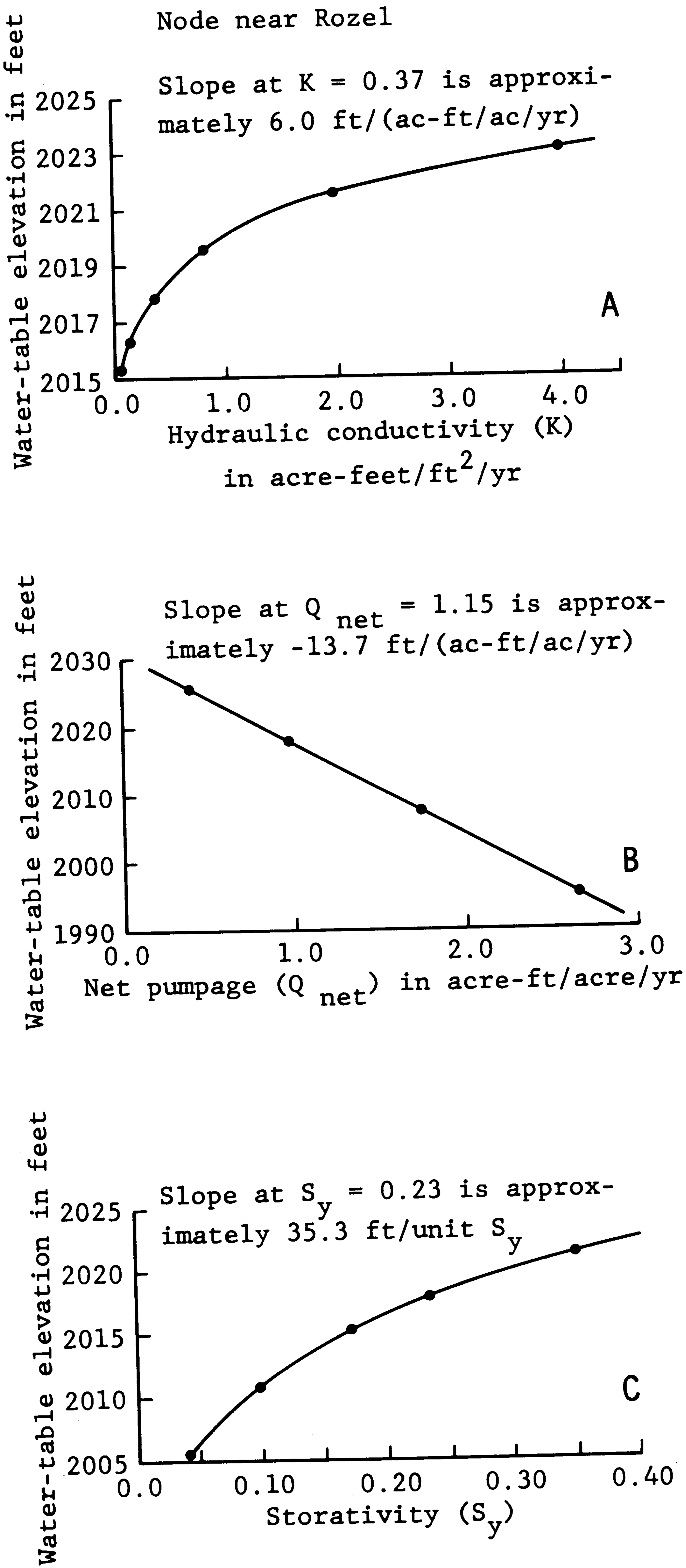


Fig. 10. Effect of changes in (a) hydraulic conductivity, (b) net pumpage, and (c) storativity on simulated water level of a node.

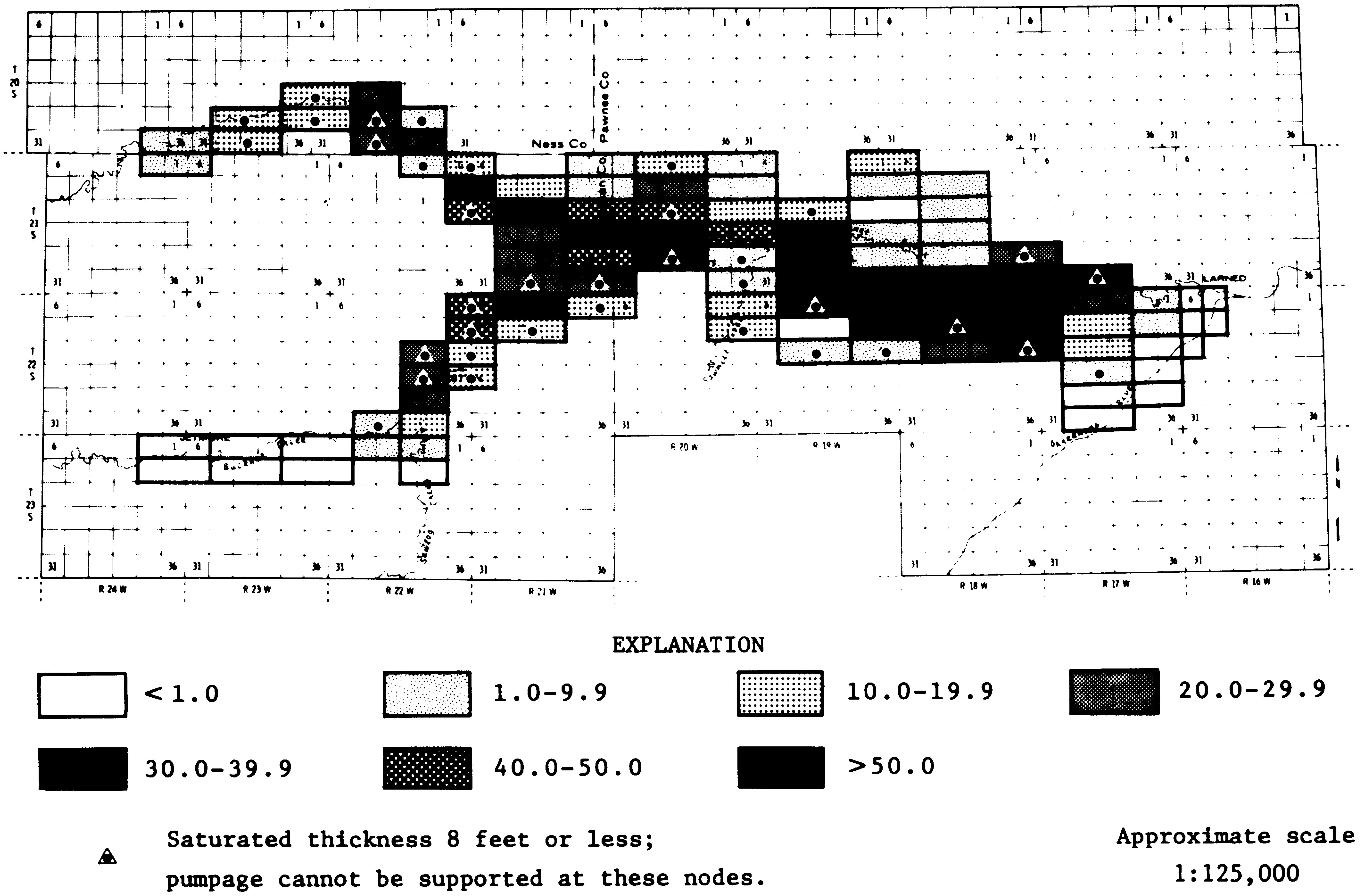


Fig. 11. Projected average water-level declines, in feet, from 1979-80 to 1999-2000 under a moratorium on new wells for the prediction interval.

PREDICTED WATER-LEVEL DECLINES—MANAGEMENT OPTIONS

A number of predictive simulations or management options were examined using the model previously described. The first set of simulations includes predictions of average water-level declines under the following three options: a moratorium on new wells is imposed for the next 20 years; an immediate 20 percent increase in the appropriated pumpage is assumed for the planning horizon of 20 years; and an immediate 20 percent decrease in the appropriated pumpage is simulated for the next 20 years. The second set of management simulations involves allowing only 40 percent reduction of the present saturated thickness for the next 20 years, while maintaining the amount of appropriated pumpage at the current levels. The policy of 40 percent saturated thickness reduction allowance for the next 20 years has already been adopted by some ground-water management districts in western Kansas. The third set of simulations deals with the effects of extended droughts or wet periods on water levels. A five-year wet or drought period is assumed to have occurred just before the middle of the 20-year projection period. Historically, the droughts in Kansas have varied from one to ten years in duration (Flickinger, 1967); therefore, a five-year average period is considered justified. The wet period is simulated by reducing by half the appropriated pumpage from the wells; at the same time natural ground-water recharge is doubled uniformly over the region. The exact opposite is assumed for the drought period.

Under the first set of simulations, the important question is whether, after an initial adjustment, the water levels will stabilize to the existing pumping regime if no additional wells are installed. Figure 11 summarizes the results of this simulation and illustrates that water levels will continue to decline despite a cessation of development in 1979. Even a 20 percent decrease in the amount of appropriated pumpage will not result in a stabilization of water levels.

From all options considered, the second set of simulations produces the least amount of water-level decline in 20 years. However, the number of subregions where the saturated thickness is reduced to the 60 percent level with the consequent shut-down of wells is so numerous that irrigated agriculture in most of the Pawnee Valley would have to cease by the year 2000. However, for the next decade, this policy will not result in such a prohibitive situation for the Pawnee Valley, as shown in Figure 12. Therefore, the beneficial results from this policy for the next several years should be considered carefully in any management decision.

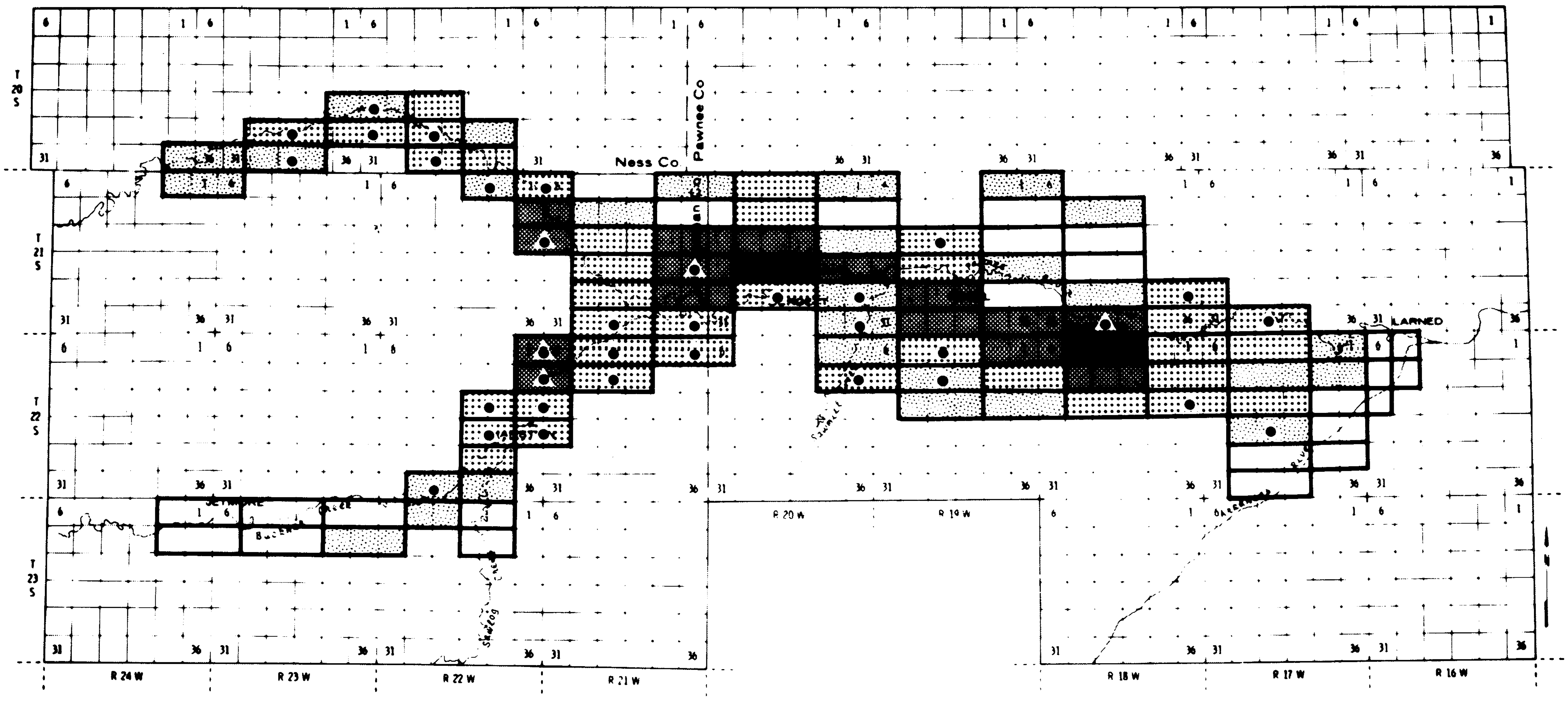
The third set of simulations examines the behavior of the aquifer under sustained periods of extreme climatic conditions. While the effects of the wet periods are temporary, the effects of an extended drought are very severe, as shown in Figures 13 and 14, respectively.

CONCLUSIONS AND RECOMMENDATIONS

Ground-water withdrawals in the Pawnee Valley are currently of such magnitude that even without any additional development, water-level declines will continue indefinitely, exceeding 40 to 50 feet in many parts of the valley by the year 2000.

Wet periods, which reduce the pumpage demand and increase the rate of natural recharge, would benefit the ground-water system; however, even extremely wet periods would not reverse water-level declines resulting from any anticipated level of development. Even if no further development occurs, the beneficial effects of such wet periods would be felt mainly during those periods or shortly thereafter; in other words, they would be temporary.

Data presented in this report indicate a rather bleak future for ground-water supplies in a large part of the study area unless the ground-water management districts of the area soon make important decisions regarding their water supply. Over-irrigating would probably completely dry the streams in the valley—streamflows are already significantly reduced—and increase water losses through summer evapotranspiration. The argument that lowering the ground-water levels through over-irrigation will increase recharge to the aquifer cannot stand because there is simply not much water in the Valley to recharge the aquifer. One option for consideration is to prolong the life of the ground-water resource through concerted efforts to reduce water wasting and to increase efficiency of water use. However, such practices alone will not solve the problem because the current level of development is such that the water supply eventually will approach exhaustion. In addition to concerted



EXPLANATION

☐ <1.0

░ 1.0-9.9

▒ 10.0-19.9

▓ 20.0-29.9

■ 30.0-39.9

▲ Saturated thickness 60% of original thickness or less; further pumpage not permitted at these nodes.

Approximate scale 1:125,000

Fig. 12. Projected average water-level declines, in feet, from 1979-80 to 1989-1990 under a 40 percent saturated-thickness depletion allowance.

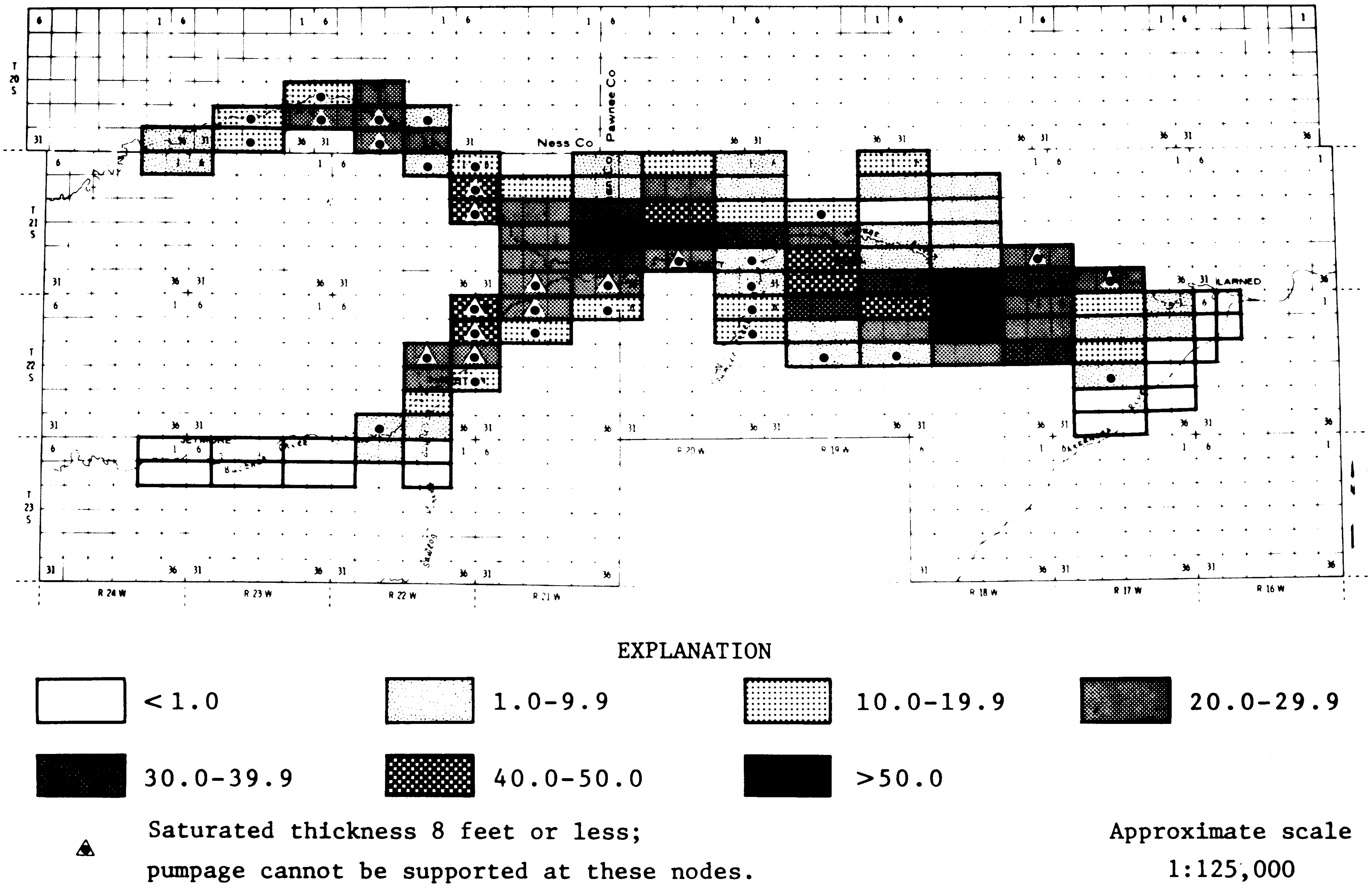


Fig. 13. Projected average water-level declines, in feet, from 1979-80 to 1999-2000 under the wet-period case.

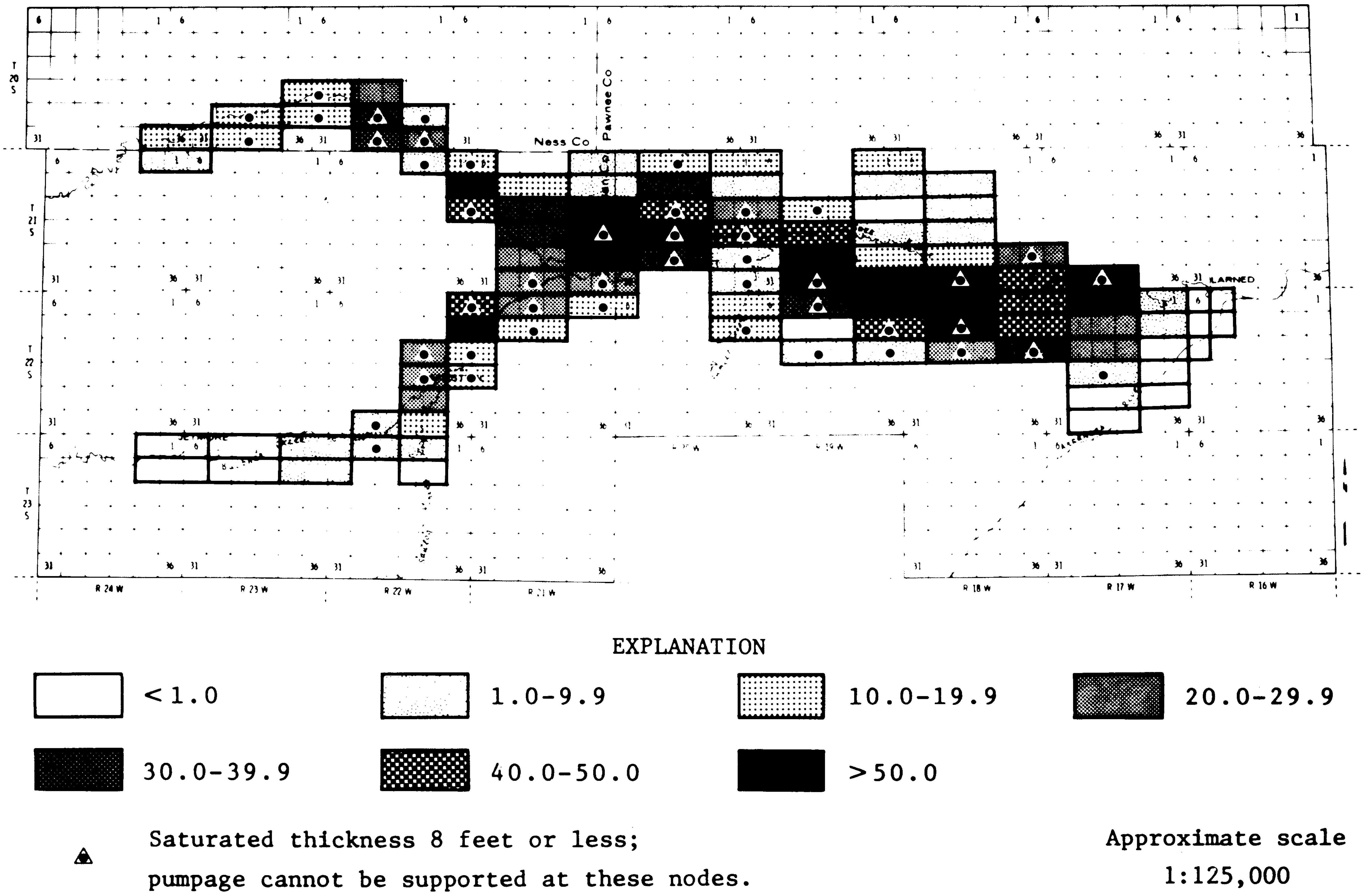


Fig. 14. Projected average water-level declines, in feet, from 1979-80 to 1999-2000 under the drought-period case.

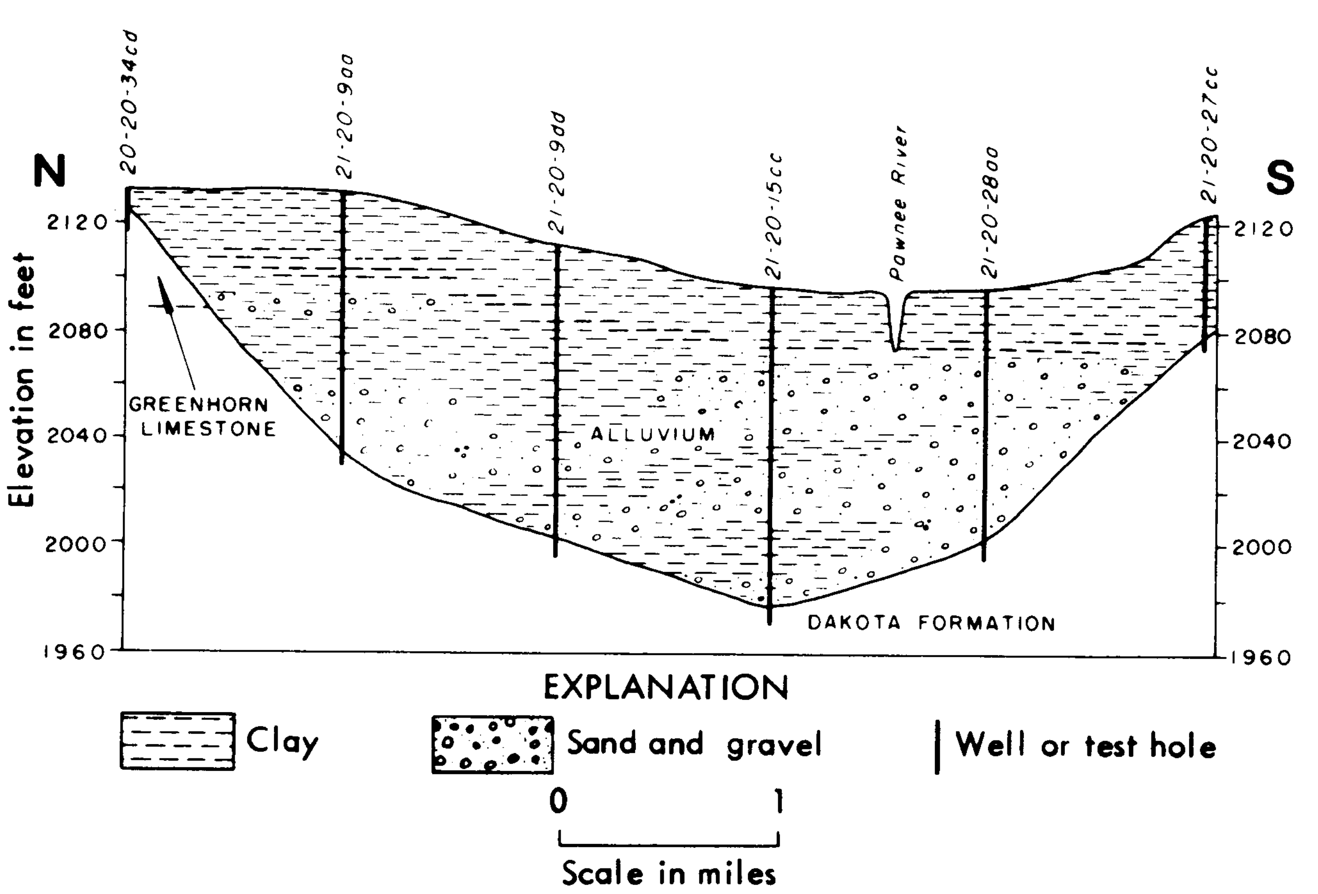


Fig. 15. Geologic north-south cross section of Pawnee Valley near Burdett, Kansas. The well or test hole numbers give locations according to the U.S. Bureau of Land Management's system of land subdivision. (Adapted from Fishel, 1952.)

efforts to conserve water and to increase the efficiency of water use, development of artificial recharge systems provides an option that may prolong the life of the ground-water reserves.

The cost of an adequate recharge scheme would probably be very high and presumably would increase with time. The clayey nature of the surficial materials between the land surface and water table in large parts of the Pawnee Valley is not well suited for artificial recharge through recharge basins, seepage canals, or surface-spreading systems. In support of this argument, a fairly typical cross section of the Pawnee Valley is shown in Figure 15. More expensive means such as recharge wells may offer better opportunities for success in many areas. Detailed studies of the availability of adequate water supplies and of recharge potential over the Valley may provide an estimate as to the feasibility of such endeavor. It should be kept in mind, however, that water is not plentiful in the area, and that the amounts of estimated natural ground-water recharge are very small. In the meantime, the benefits resulting from putting a freeze on new irrigation wells and the implementation of not more than 40 percent saturated-thickness depletion allowance encompassing both old and new wells for the next several years is worth pursuing. At the same time, a detailed monitoring system of the water resources of the area is highly recommended.

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