Kansas Geological Survey

Mineral Intrusion:

Investigation of Salt Contamination of Ground Water in the Eastern Great Bend Prairie Aquifer

R. W. Buddemeier, M. A. Sophocleous, and
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Open-File Report 92-25

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GEOHYDROLOGY

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EXECUTIVE SUMMARY

In the eastern portion of Groundwater Management District No. 5, a brine-containing formation underlies and is connected with the Great Bend Prairie aquifer, the primary source of freshwater in the area. Concerns about water table declines and decreasing stream flow in this area are intensified by the possibility that freshwater withdrawals will increase the rate of saltwater intrusion and reduction of water quality. The Kansas Water Office has funded a major study by the Kansas Geological Survey to describe the natural process of mineral intrusion and to determine how these processes might be altered by human-induced changes in the water budget of the area. The expected results include descriptions and models that can be used by water planning and management agencies to address issues such as the safe yield of the aquifer under various conditions.

Proposed research includes field studies to determine the geohydrologic characteristics of the brine-containing formation and freshwater aquifer, regional characteristics of the saltwater-freshwater interface and its variation over time, and the extent of local salt-water upconing that may result from high-volume pumping. Vertical models of the salt-water interface and its response to water table changes, and larger-scale models of the water and salt budgets for the entire area will be developed and calibrated against existing data. A system of management, technical advisory, and public information and advisory committees will be established to ensure that the research approach is of the highest possible quality and responsive to local needs.

INTRODUCTION

This report describes the background, issues, and objectives of the Mineral Intrusion Study, a research project undertaken by the Kansas Geological Survey (KGS) with funding from the Kansas Water Office (KWO). The purpose of this report is to provide information for other agencies and the interested public to facilitate both effective interagency coordination and an improved general understanding of the water resource issues of south-central Kansas.

The focus of the study is the present and possible future contamination of fresh ground-water resources by natural saltwater in the eastern portions of Groundwater Management District No. 5 (GMD5), shown in Figure 1. South of the Arkansas River and east of US–281, there is no effective separation of the Great Bend Prairie aquifer from the underlying Permian "red beds" that contain ancient brines (Figure 2). Saltwater is therefore free to move upward into the freshwater aquifer. There is concern that withdrawal of fresh water and lowering of the water table may reduce the confining pressure of the freshwater head and increase the flow of saltwater into the Great Bend Prairie aquifer. In addition, intensive local pumping may cause vertical mixing of the saltwater even in areas where there is no long-term net decline in the water table. Although we have no detailed knowledge of the geographic extent or rate of salt intrusion at

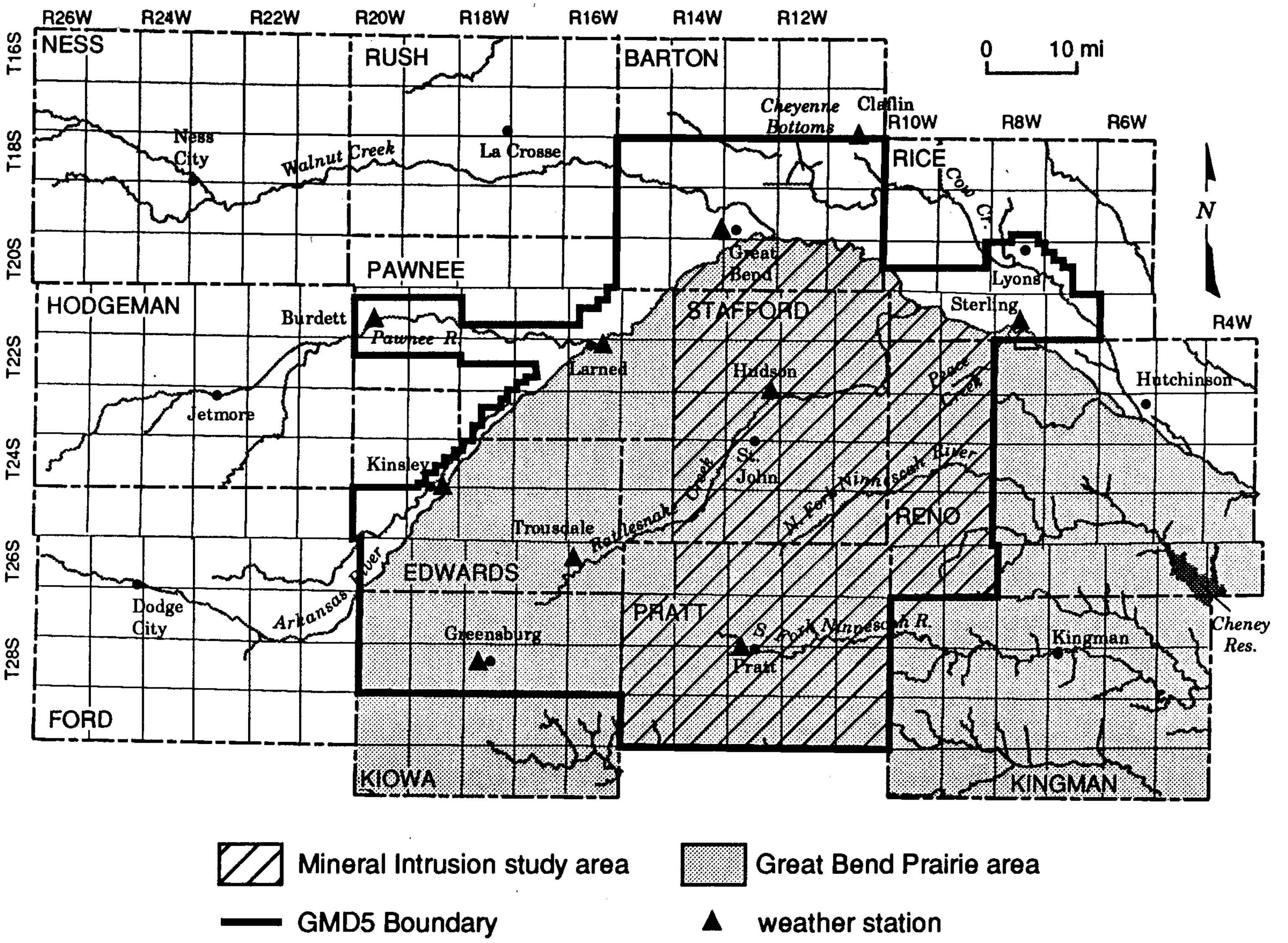


Figure 1. Map of Groundwater Management District No. 5, showing the major features of the region and the area of primary interest to this study. Locations of long-term weather stations within GMD5 are also shown.

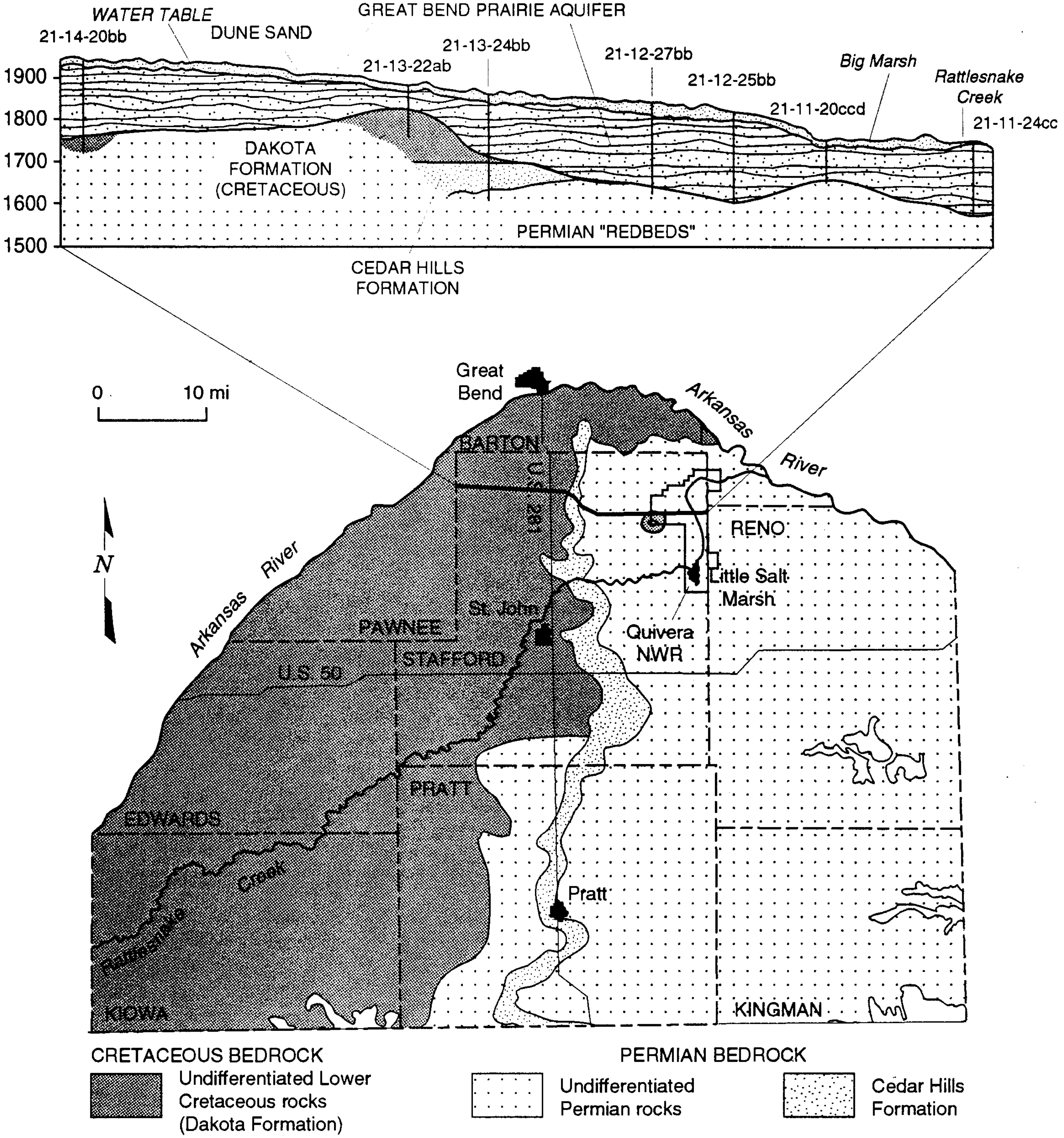


Figure 2. A. Map of the bedrock beneath the Great Bend Prairie Aquifer showing the areas in which the Permian formation has the potential to contribute saltwater to the overlying aquifer. B. Vertical section from west to east across the region, showing the relation of the alluvial Great Bend Prairie Aquifer to the underlying Dakota and Permian formations.

present, increasing salt concentrations in some of the wells of the region indicate that the problem is real and must be considered in management plans and in the determination of safe yields.

In this report we first discuss the environmental setting and water resources background of the study, address some general principles of hydrologic research and ground-water management that are relevant to the research, and then describe the experimental approach and expected outcomes of the study. Supporting documents provided by the KWO, GMD5, and the Division of Water Resources (DWR) that provide further information on the planned study and the concerns of the agencies most directly involved are attached as appendixes.

BACKGROUND

Geology and General Hydrology

Over the past 1.7 million years, the ancestor to our present-day Arkansas River and its tributaries gradually developed its drainage across south-central Kansas. This process left behind what we now know as the Great Bend Prairie aquifer—interleaved layers of sand, gravel, silt, and clay, mostly derived from ancient streams, stream cutoffs, and ponds but with some of the silt and sand layers deposited by wind. The aquifer deposits range from a few tens of feet to over 200 feet in thickness and lie atop the preexisting bedrock. The nature of the bedrock varies across GMD5. In the west the bedrock, of Cretaceous age (65–144 million years old), is generally known as the Dakota Formation. This formation contains both aquifer units and relatively impermeable layers, and it effectively blocks hydraulic connection between the Great Bend Prairie aquifer and the underlying water-bearing units. However, east of a line that roughly coincides with US–281 (Figure 2), the Dakota formation is not present, and the surface aquifer lies directly on formations of Permian age (245–286 million years old) that contain and transmit water, much of which has a high salt content.

The freshwater of the surface aquifer comes from local recharge, mostly from precipitation that infiltrates from the land surface to the water table. Many studies have attempted to estimate the recharge of all or parts of the GMD5 area; these are summarized by Sophocleous (1992a). The average of all these estimates is approximately 2 inches per year, with a most probable range of 1–3 inches per year, values that agree with the most recent efforts to measure recharge. A current subject of research is determining how the rates and patterns of recharge vary across GMD5 (Sophocleous, 1992b). Because groundwater can occupy only the 15–20% of the total aquifer volume that is not solid material, the recharge (or withdrawal) of 2 inches of free water causes a change in ground-water elevation of about 1 foot.

The water table, or the surface of the saturated part of the aquifer, slopes gently downward from west to east, reflecting the behavior of the bedrock and surface topography.

Figure 3 shows our best available estimate of the water table in 1991, with flow lines superimposed on the water elevation contours. The water table slope (or "gradient") and the permeability of the aquifer permit us to estimate the rate of flow; the linear velocity of a particle of groundwater over much of the area is about 1 foot per day (calculated values range from a few tenths of a foot to several feet per day). Although this is a rapid flow by ground-water standards, it is slow compared with surface water and most human uses of water and has some important consequences that will be discussed later. Eastward across GMD5, depths to water tend to decrease and there are areas of groundwater discharge (return of groundwater to the surface or to the rooting zone of plants), especially in the vicinity of the Quivira Mmarsh. Other discharge occurs in the form of baseflow in streams such as the Arkansas River downstream from Great Bend and Rattlesnake Creek. Flow in these streams depends strongly on the elevation of the water table in the vicinity of the streambeds.

As opposed to ground-water movement in the Great Bend Prairie aquifer, groundwater movement in the Permian formations is controlled by the water's interactions with other deep formations extending hundreds of miles to the west to probable recharge areas in Colorado. Because of the extent of the formation and its isolation from surface effects, the groundwater head in the Permian strata is usually considered nearly constant. However, one particular unit of the Permian, the Cedar Hills Sandstone, has been extensively used to receive waste oil-field brines injected to the west of the mineral intrusion study area in GMD5, and these practices may have altered the pressure and flow patterns of the aquifer over historic time.

The Permian formations also have some similarities to the surface aquifer, however. The flow of water is generally from west to east, and the eastern part of GMD5 is a discharge area for saltwater as well as freshwater, especially around the salt marshes of the Quivira National Wildlife Refuge. Other salt discharges can be found in localized areas, such as specific reaches of the South Fork of the Ninnescah River (Gillespie et al., 1991).

Hydrogeochemistry

The distribution of the Permian brine is by no means uniform. Figure 4 summarizes present understanding based on the monitoring well network installed and monitored between 1978 and 1987 as a cooperative project between GMD5 and the KGS. Figure 4 is designed to give a large-scale overview and does not incorporate the more detailed findings of Gillespie et al. (1991) along the South Fork of the Ninnescah River. More than 50 multiple-well monitoring sites have been studied; in most cases these consist of a bedrock (Permian) well, a well near the bottom of the Great Bend Prairie aquifer, and a shallow well. Chemical analyses have shown that, although there are minor salt contributions from oil-well brine or evaporative concentration at some locations, the high salinities are mostly caused by Permian brines. The pattern of salt

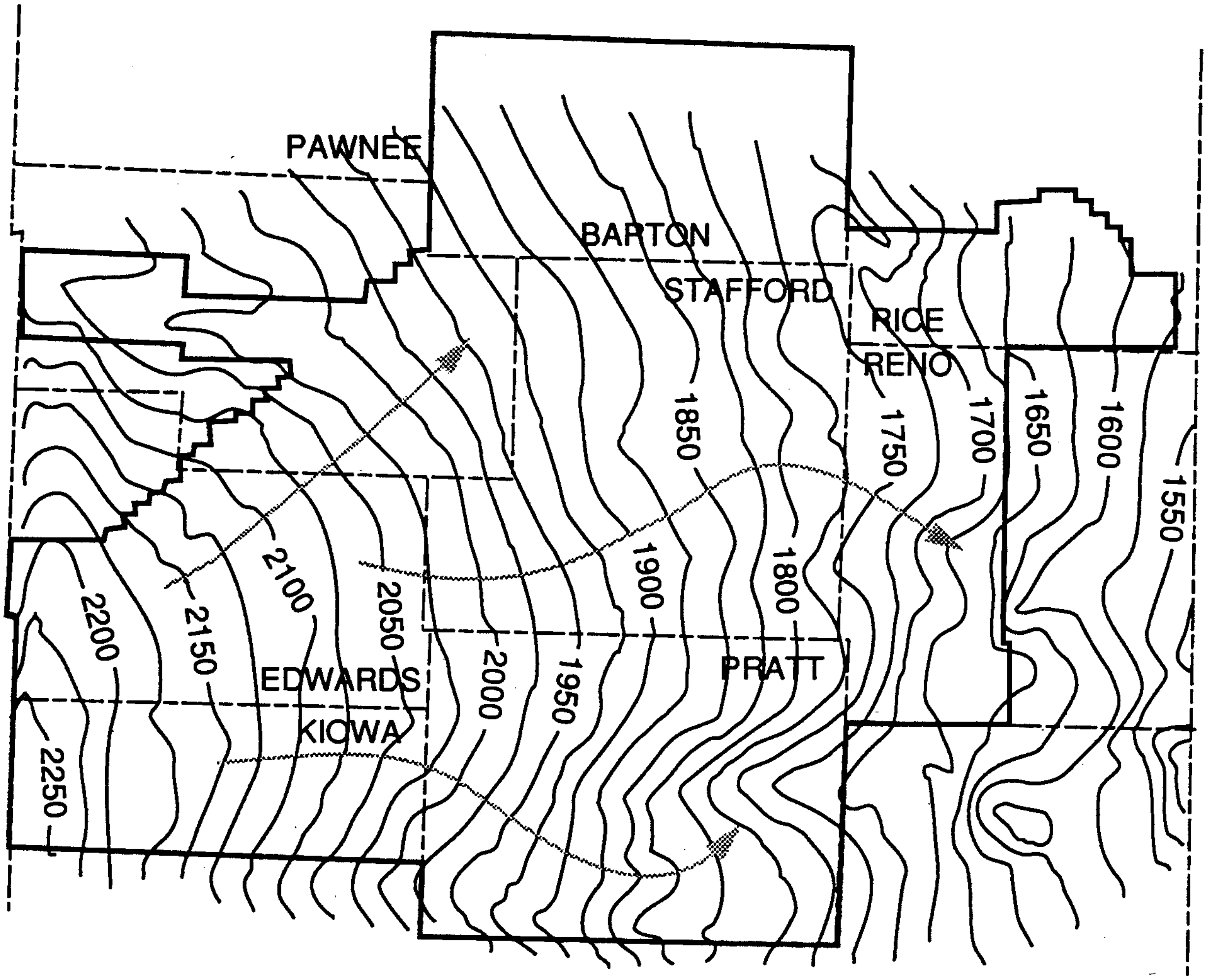


Figure 3. Contours of 1991 water elevations for GMD5. Groundwater flow is perpendicular to the contour lines, as shown by the arrows.

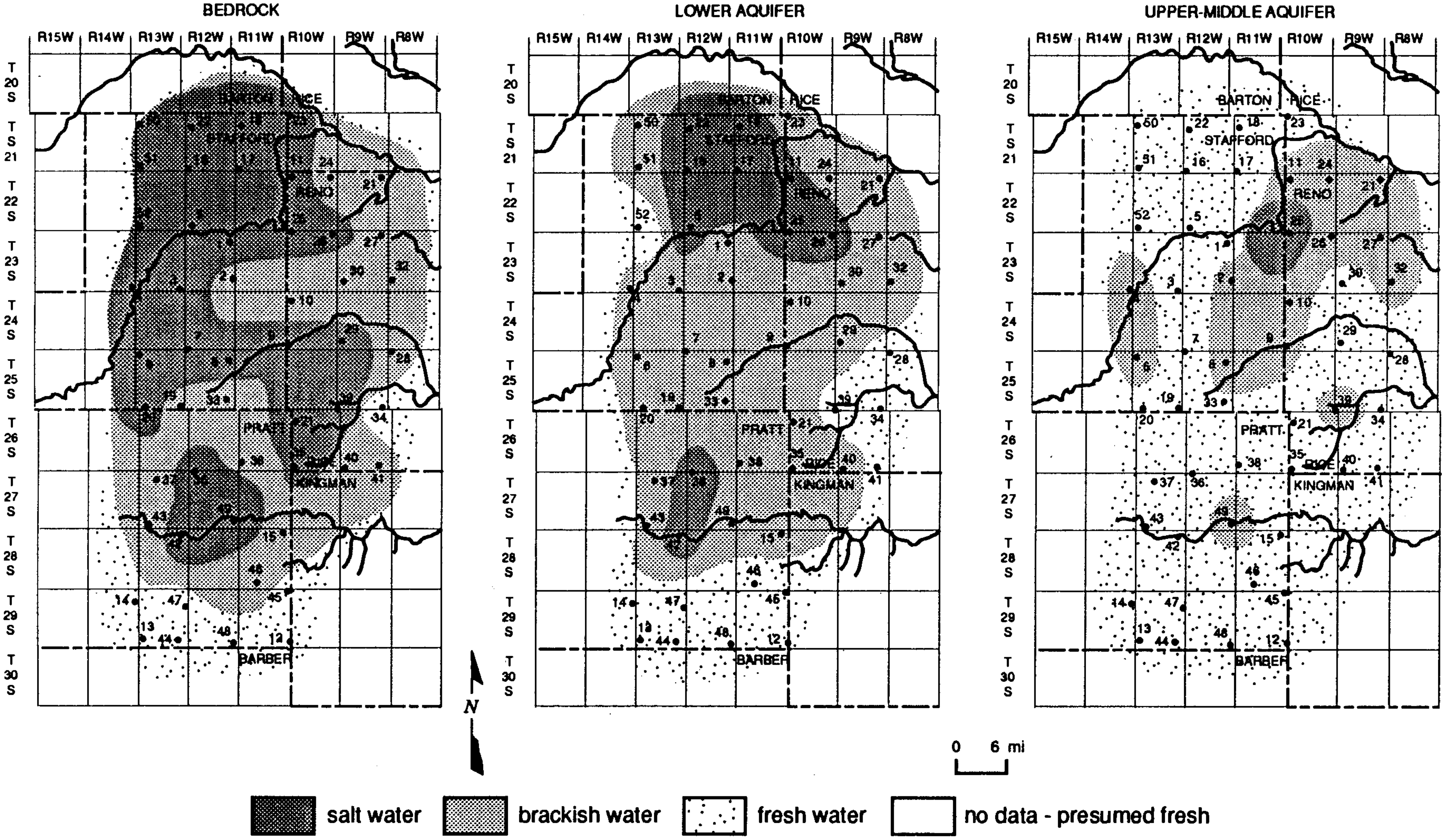


Figure 4. Maps showing categories of groundwater quality based on conductivity measurements at the numbered monitoring network sites; wells are identified as fresh (less than 1000 µS, or less than about 600 mg/l total dissolved solids (TDS)), brackish (1000-10000 µS, or 600-6000 mg/l TDS), or saline (greater than 10000 µS or 6000 mg/l TDS). Boundaries are for purposes of illustration only. A: Bedrock (Permian) wells; B: Deep wells in the Great Bend Prairie Aquifer; C: Shallow and intermediate-depth wells.

occurrence is consistent. In the bedrock all but the southernmost wells have significant salt content. Freshwater occurs in both the bedrock and the aquifer in the southern area near the outcrop area of the Permian rocks. Recharge from the overlying Great Bend Prairie aquifer has flushed the saltwater from the bedrock, discharging to the tributaries of the Medicine Lodge River where they cut through the Permian. This represents the expression in Kansas of a larger regional pattern (Johnson, 1981).

Reflecting the lack of effective separation between the bedrock and the aquifer, the deep alluvial wells in the Great Bend Prairie aquifer show a salinity pattern similar to the bedrock wells, although salt-affected wells are fewer in number and salt concentrations tend to be somewhat lower. At present the shallow and intermediate-depth wells show serious salt effects only in the north-central GMD5 and in local areas of the central parts of the region.

There are 47 observation network sites with wells screened at the base of the Great Bend Prairie aquifer and 51 sites with wells at shallow to intermediate in depth. The maximum recommended limit for chloride in drinking water (250 mg/l) is exceeded at the aquifer base at 31 sites and in the upper and middle portions of the aquifer at 11 sites. Aquifer waters at many of the sites are also unsuitable or marginal for irrigation use. There are about as many sites with at least a medium salinity hazard for field crops as there are sites that exceed the drinking water standard. However, an even greater number of sites have water that represents at least a medium sodium hazard for soils (Cooperative Extension Service, 1975) because the high salinities are caused mainly by elevated concentrations of sodium and chloride.

In addition to chemical analyses, heads (the elevation of the free-water surface) have been measured in some of the monitoring wells over time. Water tends to flow from higher to lower head, so where the elevation of water in the shallow well is higher than the elevation in the bedrock well, the freshwater tends to move downward, containing the brine. On the other hand, if pressure in the underlying aquifer becomes higher than that in the freshwater, saltwater may move upward to shallower depths if the hydrologic conditions are otherwise favorable. Figure 4 indicates that this has happened in some areas, and a further example is seen in Figure 5. Rattlesnake Creek is a gaining stream, fed mostly by groundwater discharge. Along its course salinity remains low until the creek flows across the boundary of the unconfined Permian formation. In that vicinity the salt content of the water increases, indicating that the flow system of the aquifer is mixing saltwater upward into the groundwater discharging into the stream.

As discussed earlier, the discharge of saltwater to the surface is a natural process in this part of Kansas; at six of the monitoring well sites (wells 2, 4, 5, 15, 41, and 49; see Figure 4) the head in the Permian aquifer is higher than the head of freshwater in the overlying aquifer, and at 16 sites wells at the base of the aquifer have higher heads than the shallow wells. However, there are also solid reasons for concern that groundwater pumping may alter the pattern and increase

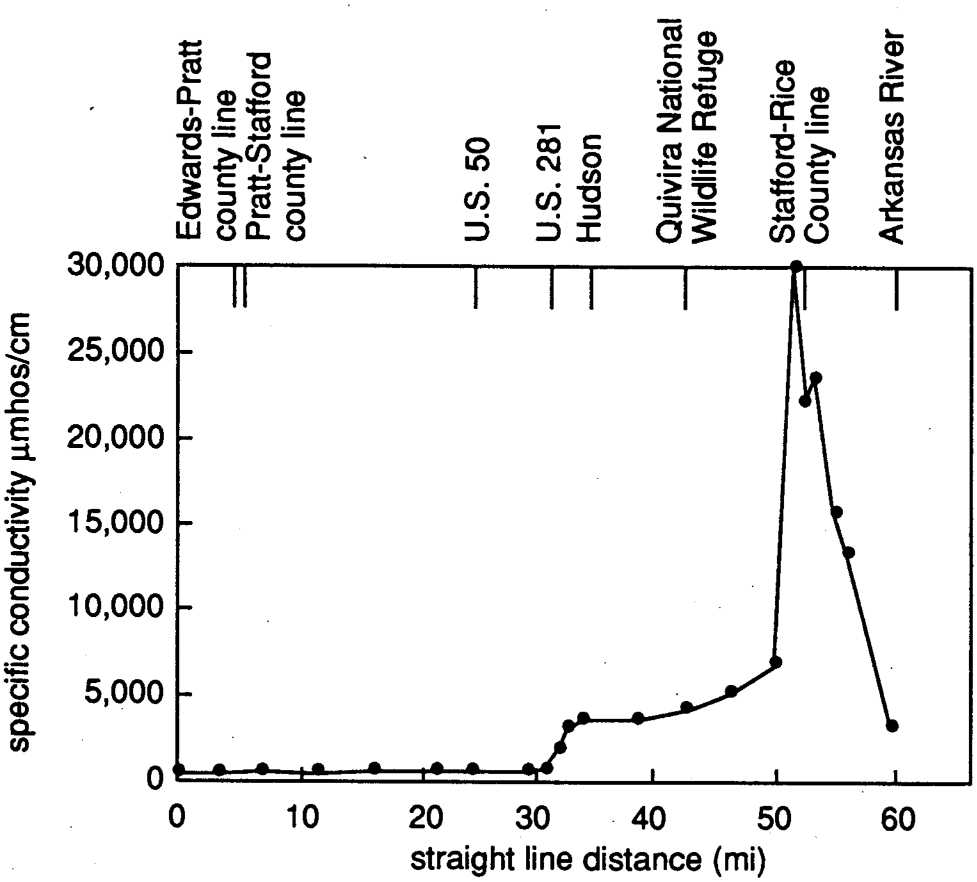


Figure 5. Specific conductance survey along the Rattlesnake Creek (adapted from Bindleman, 1983).

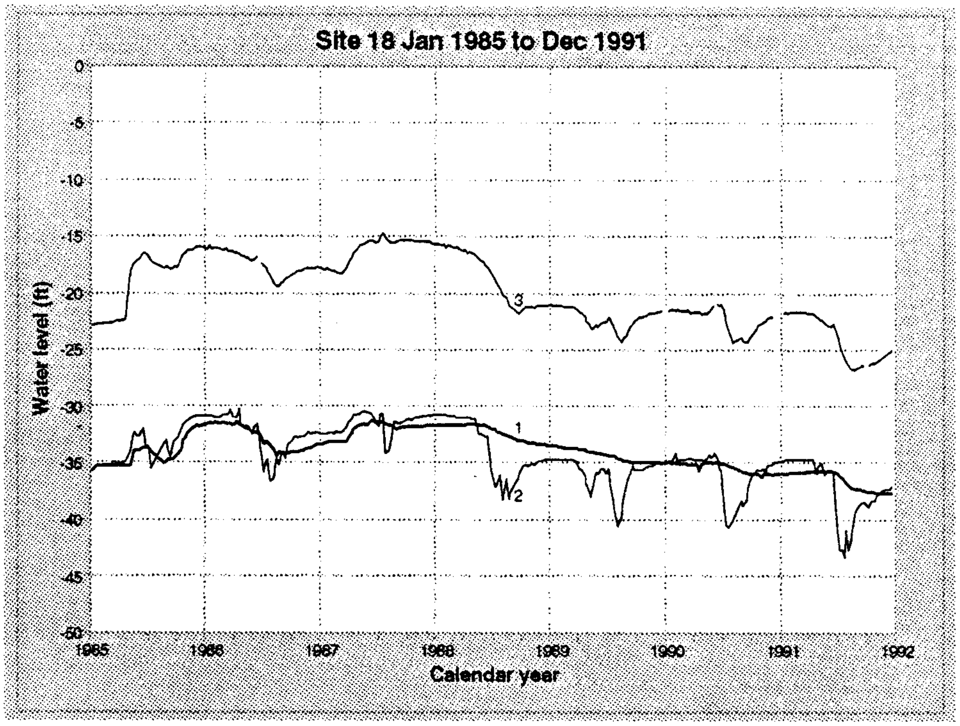
the rate of natural saltwater intrusion into the freshwater aquifer. One is illustrated in Figure 6, where at some sites the drop in the water table during the irrigation season brings the heads in the deeper portion of the freshwater aquifer below those in the bedrock aquifer. This may permit the upward movement of the saltwater-freshwater interface. Although site 19 is within half a mile of an irrigation well, site 18 is approximately a mile away from irrigation wells in several directions and probably reflects a more regional water table effect..

In 1990, GMD5 began conducting preliminary investigations into irrigation-water-quality changes resulting from the operation of large-capacity wells in north-central Stafford County (approximately that area covered by the Hudson NW quadrangle—U.S. Geological Survey 7.5 minute topographic map series). Samples of water have been collected from selected irrigation wells at intervals throughout the growing (pumping) season. In some cases the chloride levels of the water pumped continued to increase the longer the wells were in operation. However, once the pumps were stopped for an extended time, chloride levels decreased. For the 23 wells in which multiple samples were taken during a growing season, the distribution of chloride level increases over the season was +0 to 20 mg/l in six wells, +20 to 100 mg/l in eight wells, +100 to 200 mg/l in six wells, and more than 200 mg/l in three wells. These data indicate that in this area the pumping (and resulting drawdown) from some large-capacity wells has a direct effect on the movement of saline water in the aquifer.

A potential source of the local problems suggested by GMD5 studies is saltwater upconing in the immediate vicinity of high-capacity wells. This problem is common and well understood in coastal environments and on oceanic islands where freshwater is underlain by ocean water. The cone of depression of the pumping well creates a region of lowered head that acts to "pull up" a matching cone of saltwater below the well. This is illustrated in Figure 7; the exact situation depends on the extent of low-permeability layers between the well and the saltwater-freshwater interface. Local deterioration of water quality as a function of either the rate or cumulative volume of pumping is reason to suspect upconing.

Salinity changes in the aquifer are also affected substantially by climatic variations. Little to no recharge combined with continued natural discharge during extended periods of drought will decrease water levels appreciably. Saline water upconing from pumping wells can be especially severe during drought. The effect lags behind the beginning of the drought and can extend beyond the end of the drought. For example, the chloride content in the municipal water supply for both Stafford and Turon in the Great Bend Prairie area increased substantially from 1956 to about 1961 because of the severe drought of 1953–1956 (Whittemore et al., 1982, 1989).

Although the examples given are temporary disturbances of the water table, they are a concern even in situations where there is no long-term net change in the average water table



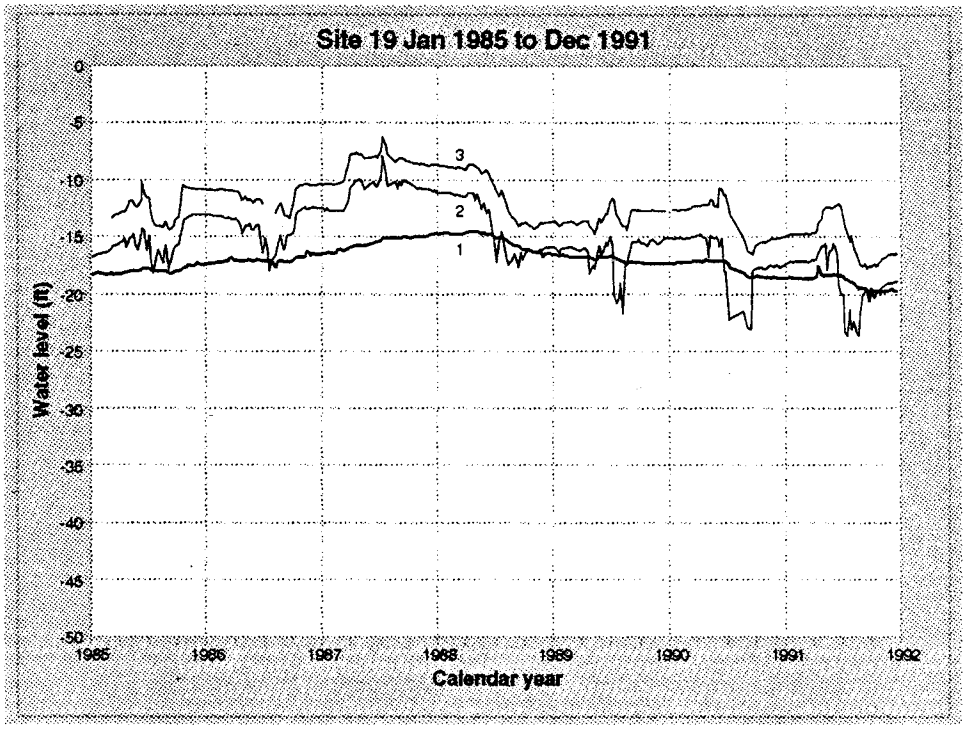


Figure 6. Time histories of heads at two recharge study sites in Stafford County (adapted from Sophocleous, 1992a). Line 1 is the bedrock well, line 2 is the deep aquifer well, and line 3 is the shallow aquifer well. The fraction of time that the bedrock head has exceeded the deep alluvial aquifer head has been increasing over time, suggesting increased potential for upward movement of salt water.

SALINE WATER UPCONING

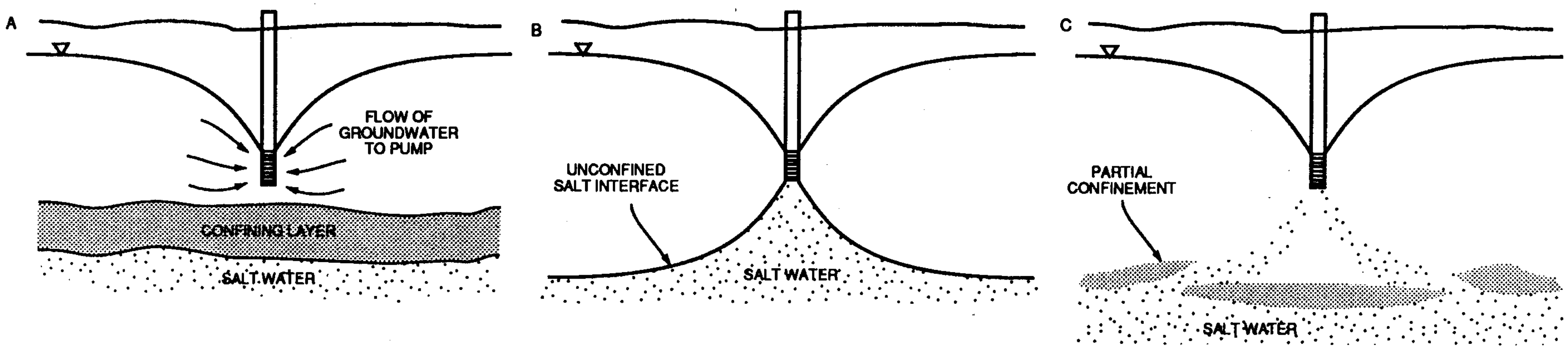


Figure 7. Saltwater upconing in response to pumping stress. A: The "confined" case, where a thick clay layer ("confining layer") inhibits response. B: The "unconfined" case, where saltwater migrates freely toward the pumping well. C: The "semi-confined" case, where discontinuous clay stringers impede but do not completely block the upward movement of saltwater.

elevation. Once the saltwater-freshwater interface moves into a previously freshwater region of the aquifer, the salt is never perfectly flushed out when the interface moves back to its original position. With repeated intrusions, the salt load gradually builds up until the fluctuating part of the aquifer becomes permanently brackish rather than alternating between saltwater and freshwater. Figure 8 gives an example of one of the mechanisms by which this occurs; the effect is one of the reasons for the enormous expenses and marginal success associated with efforts to clean up contaminated groundwater by pumping or flushing. Part of the lag in the decrease of salinity in the Stafford and Turon water supplies after the 1950's drought may be due to the slow flushing of the aquifer.

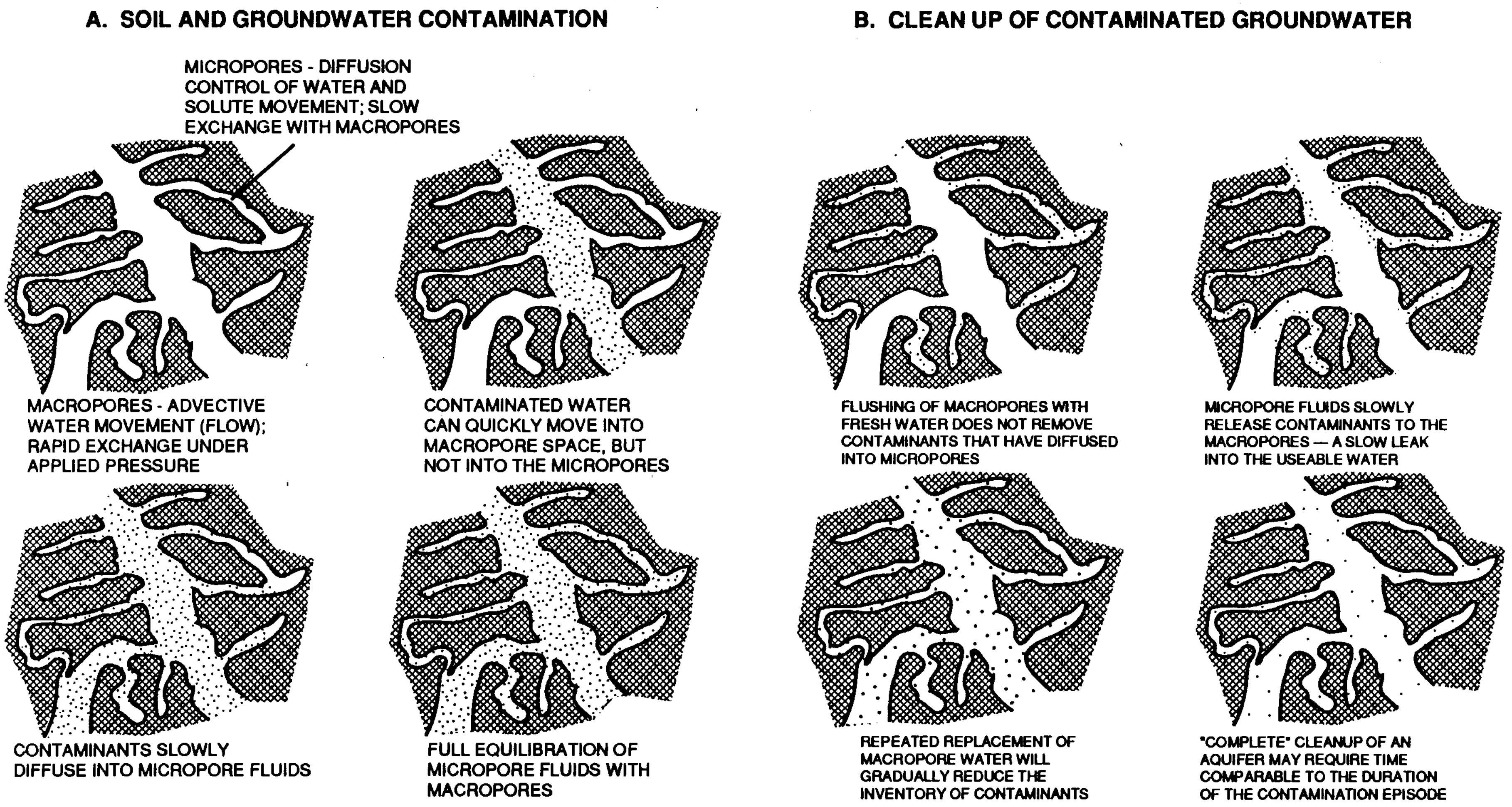
Groundwater Use and Management

The largest amount of groundwater used in GMD5 is for irrigation; stock, domestic, and municipal wells represent only a minor amount of the total pumpage. Figure 9 shows the distribution of appropriated ground-water rights in the district. In parts of the mineral intrusion study area, little or no groundwater is used. This reflects in part the salinity of the groundwater and local knowledge about the availability of freshwater. However, in the western part of the study area reasonably high densities of wells are above the Permian bedrock formations. Water-rights appropriations and irrigation in the district have increased steadily from the later 1960's into the 1980's (Figure 10).

GMD5 was formed in 1976. Initially, a recharge rate of 9 inches per year was used as the basis for appropriations; this was lowered to 4.5 inches per year in 1984. Since 1990 the district has been under a moratorium on appropriations, enacted because of concerns about groundwater depletion in the western part of the district and water quality issues in the east.

Water agencies have been concerned about ground-water and streamflow depletion in the area for decades (Stramel, 1967, Hargadine et al., 1979). In presentations at the Kansas Water Research Needs Conference (Wichita, Nov. 14, 1984), the KWO stated that extensive ground-water appropriations have contributed to extreme low flows in the Arkansas River and Rattlesnake Creek, and the Kansas Fish and Game Commission asserted that fish and wildlife resources in south-central Kansas were significantly affected by loss of baseflows. The Kansas Water Plan (KWO 1988) stated that "the safe yield policy of Groundwater Management District No. 5 has not protected low flows in the [Rattlesnake] Creek". Over the years the lower Arkansas basin subsection of the Kansas Water Plan has consistently ranked water supply and water quality concerns as high-priority items, and ground-water depletion in the Rattlesnake basin has been identified as an issue by the Basin Advisory Committee.

The history of water table variations in the district depends on location (Figure 11). In the southern part of GMD5 water tables have been stable or rising over time. However,



A. SOIL AND GROUNDWATER CONTAMINATION

MICROPORES - DIFFUSION CONTROL OF WATER AND SOLUTE MOVEMENT; SLOW EXCHANGE WITH MACROPORES

MACROPORES - ADVECTIVE WATER MOVEMENT (FLOW); RAPID EXCHANGE UNDER APPLIED PRESSURE

CONTAMINATED WATER CAN QUICKLY MOVE INTO MACROPORE SPACE, BUT NOT INTO THE MICROPORES

CONTAMINANTS SLOWLY DIFFUSE INTO MICROPORE FLUIDS

FULL EQUILIBRATION OF MICROPORE FLUIDS WITH MACROPORES

B. CLEAN UP OF CONTAMINATED GROUNDWATER

FLUSHING OF MACROPORES WITH FRESH WATER DOES NOT REMOVE CONTAMINANTS THAT HAVE DIFFUSED INTO MICROPORES

MICROPORE FLUIDS SLOWLY RELEASE CONTAMINANTS TO THE MACROPORES — A SLOW LEAK INTO THE USEABLE WATER

REPEATED REPLACEMENT OF MACROPORE WATER WILL GRADUALLY REDUCE THE INVENTORY OF CONTAMINANTS

"COMPLETE" CLEANUP OF AN AQUIFER MAY REQUIRE TIME COMPARABLE TO THE DURATION OF THE CONTAMINATION EPISODE

Figure 8. Example of how advective (physical) and diffusive (chemical) movement of contaminants in an aquifer combine to make contamination a persistent condition.

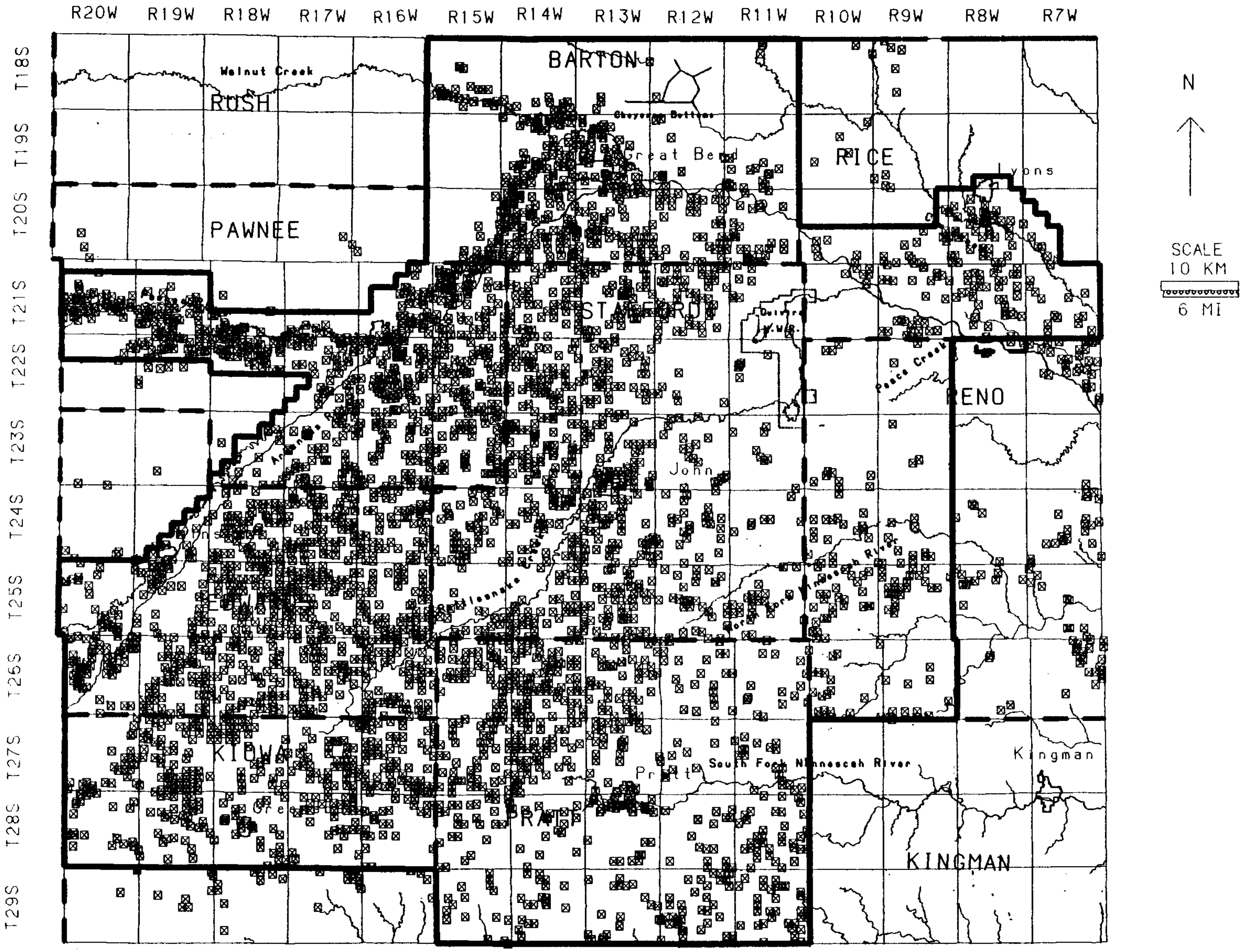


Figure 9. Map of groundwater rights in GMD5

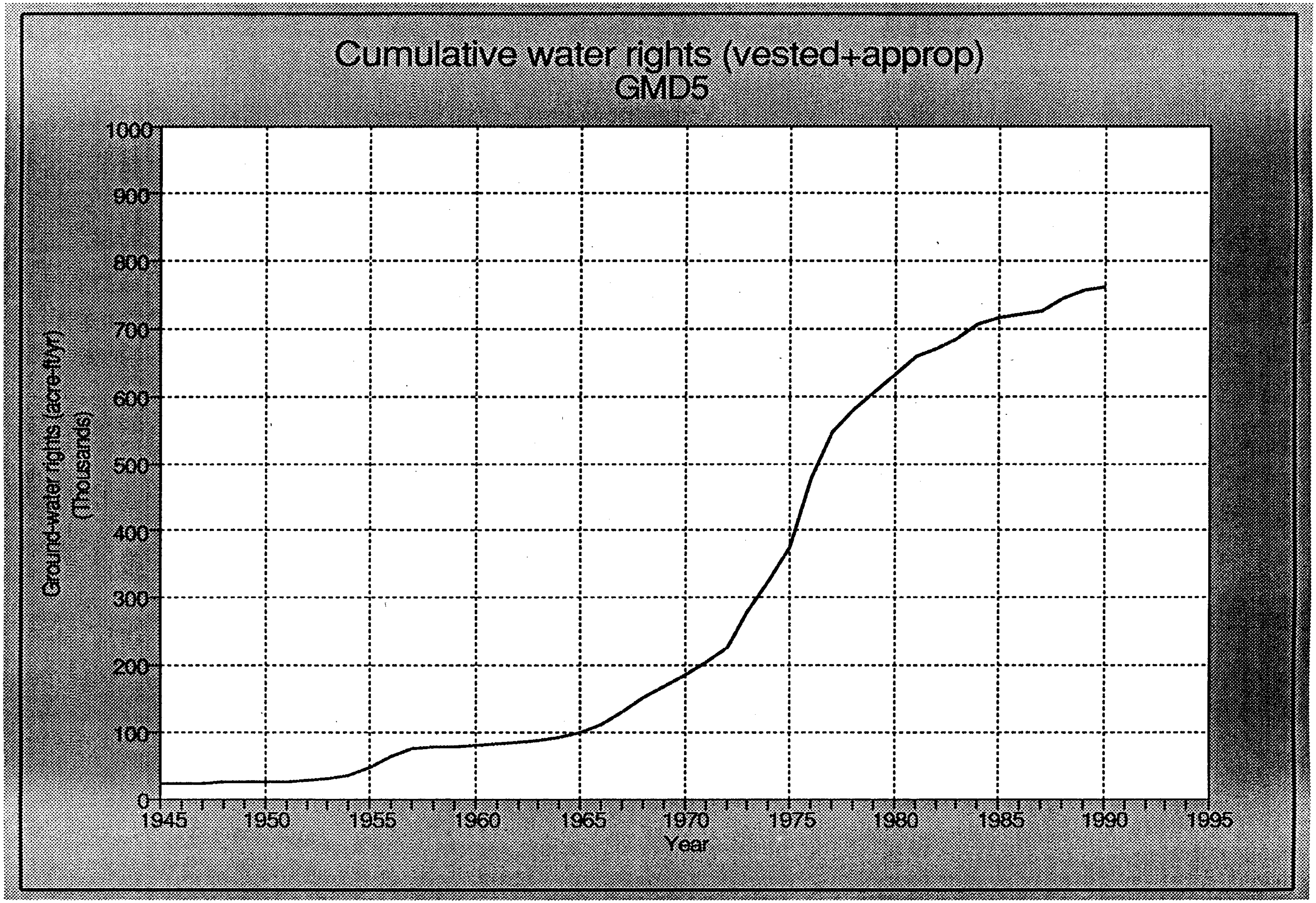


Figure 10. Groundwater rights in GMD5 as a function of time

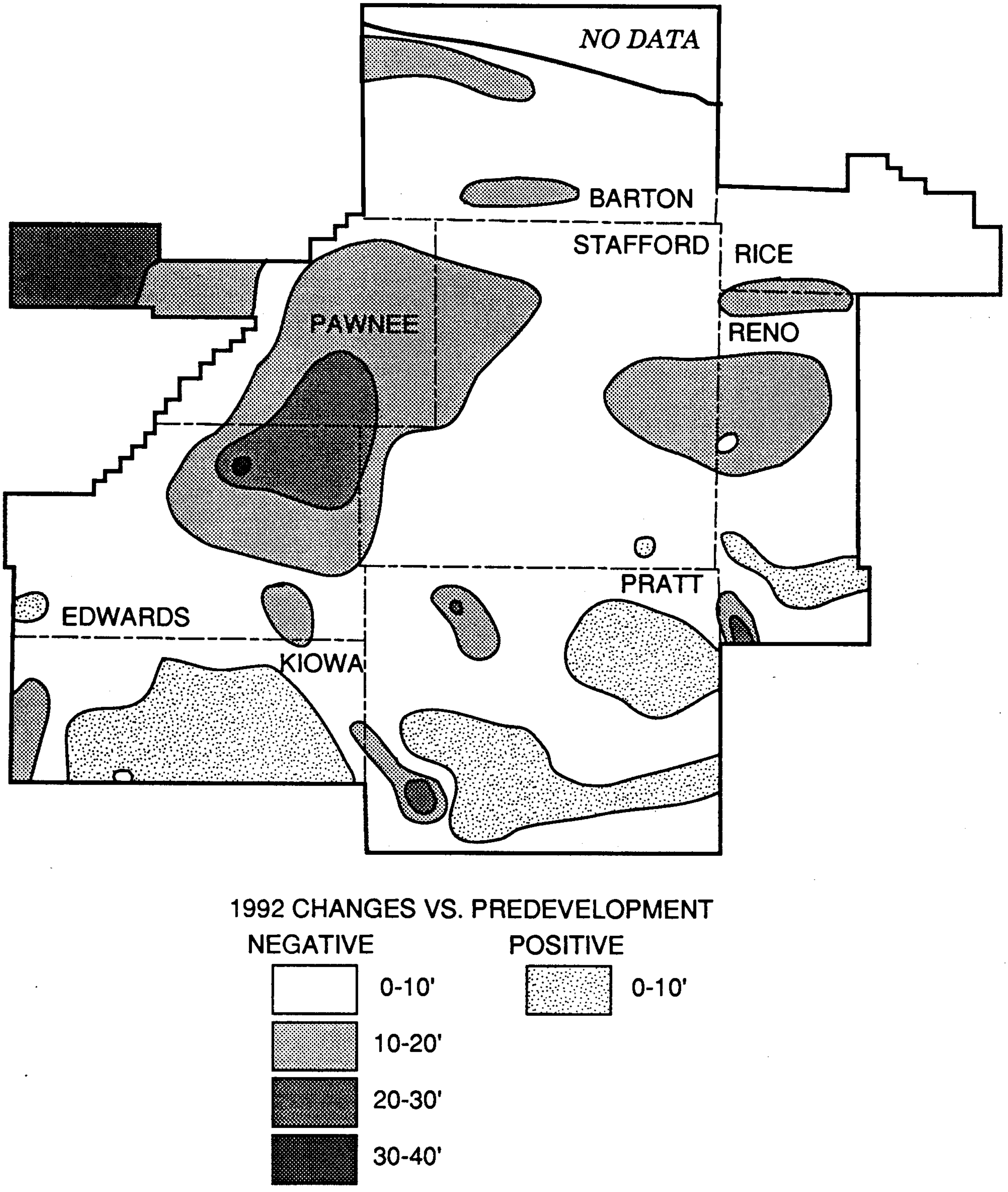


Figure 11. Generalized groundwater elevation changes, predevelopment to 1992, for GMD5. Contours are in feet of elevation change. Figure adapted from a map prepared by GMD5 (Groundwater Hi-Lites, GMD5, May 1992).

water table declines are significant in the northwest and are appreciable even in some of the eastern areas where pumping is relatively low (see Figure 9 for comparison of water-rights distributions).

Concerns about streamflow are illustrated in Figure 12, which compares the total streamflow of the Rattlesnake Creek at the Macksville gauging station (on the western boundary of the study area) with the recommended minimum desirable flow contained within the Kansas Water Appropriations Act. To focus attention on concerns about low flows, flow rates are plotted on a logarithmic scale. This deemphasizes the high flows and gives a more detailed view of the lows. The steadily increasing occurrence of low flows near or below the recommended minimums clearly shows the reasons for concern. The state has viewed the perceived streamflow declines as symptomatic of ground-water depletion, which is considered the paramount water management issue for this region.

CONCEPTS AND ISSUES

Safe Yield

The term "safe yield" (or "sustainable yield") is often used to describe the amount of water that can be removed from a natural hydrologic system, such as an aquifer or a river, without unacceptable consequences.

It is important to understand that "safe yield" is fundamentally not a scientific concept. Artificial withdrawal of water from a natural system alters that system. Hydrologists can often analyze or predict the alteration that will occur, but the determination of whether the consequences are or are not acceptable is basically a political (or economic or management) decision.

Figure 13 provides an example. A common definition of "safe yield" for a ground-water system is a withdrawal rate that equals average long-term recharge, although this definition has consistently been challenged by hydrologists (Bredehoeft et al., 1982). If a groundwater system is naturally in equilibrium (hydrologists use the term "steady-state"), then average long-term recharge is approximately balanced by average long-term discharge (springs, seeps, baseflow in streams, etc.). If an amount equal to average recharge is pumped from the system, then initially the loss of water from the system is equal to approximately twice the average recharge—one recharge equivalent lost to natural discharge and one to pumping. This additional loss must initially be supplied from the water in storage in the system, and the water table elevation decreases. As the water table is lowered, natural discharge to springs, streams, and wetlands is decreased; if pumping continues, eventually a new equilibrium water level will be reached at which all or most of the original natural discharge will have been converted to artificial withdrawal, with loss of wetlands, springs, and perennial streams. In Figure 13 this is illustrated

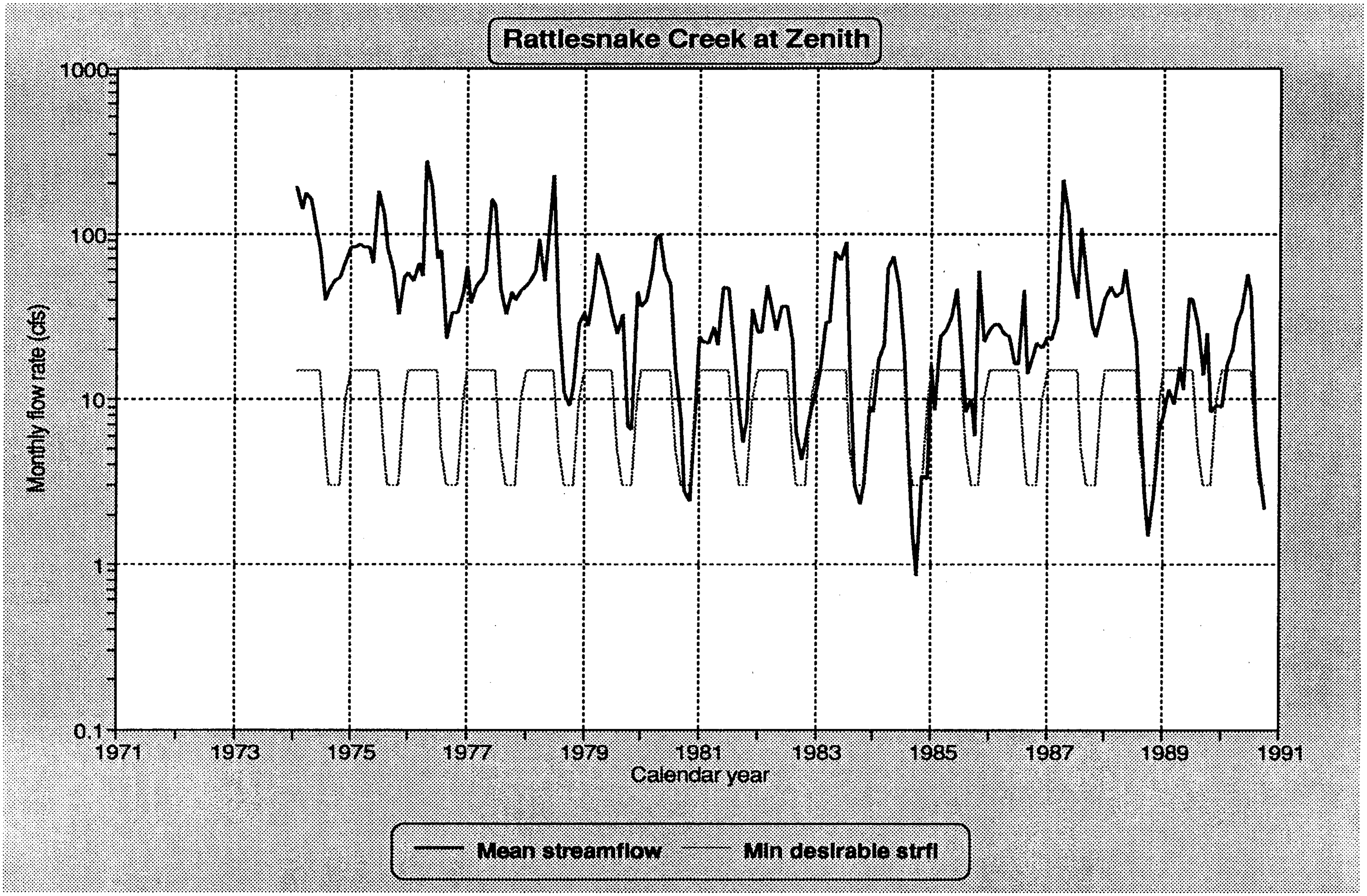
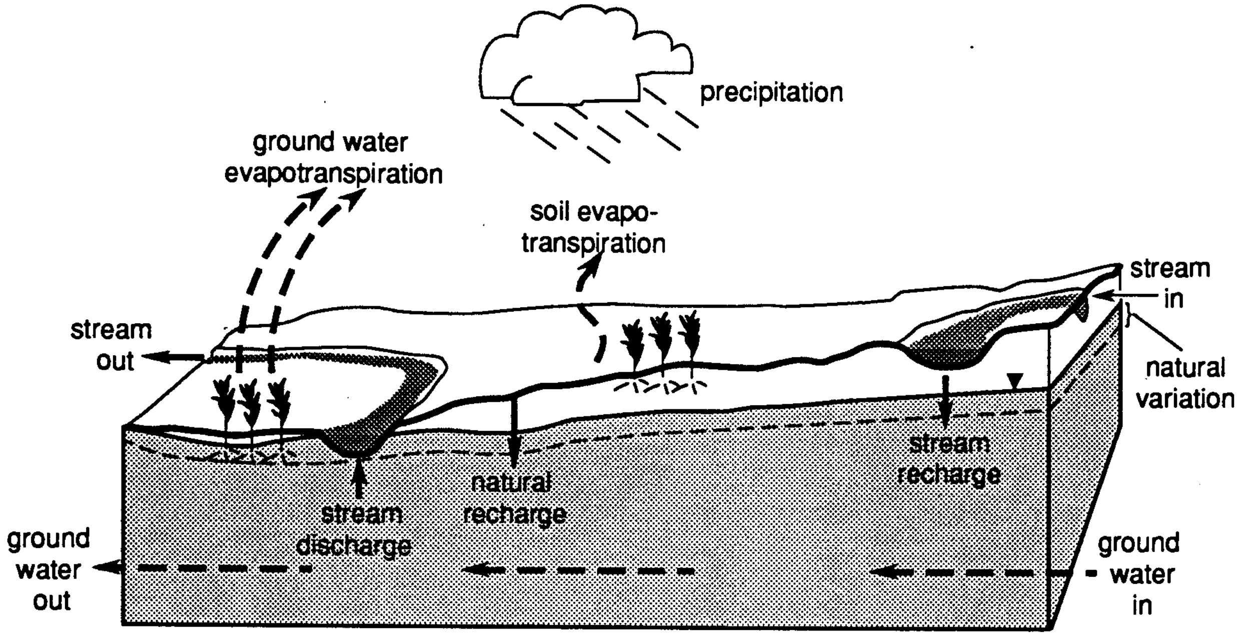


Figure 12. Streamflows in the Rattlesnake creek at the Macksville gaging station,plotted with the recommended minimum streamflow values. In order to present a clear picture of low-flow conditions, flows are plotted on a logarithimic scale that de-emphasizes high-flow conditions.

Components of a water budget
a.) Predevelopment Conditions



Components of a water budget
b.) System with groundwater pumpage

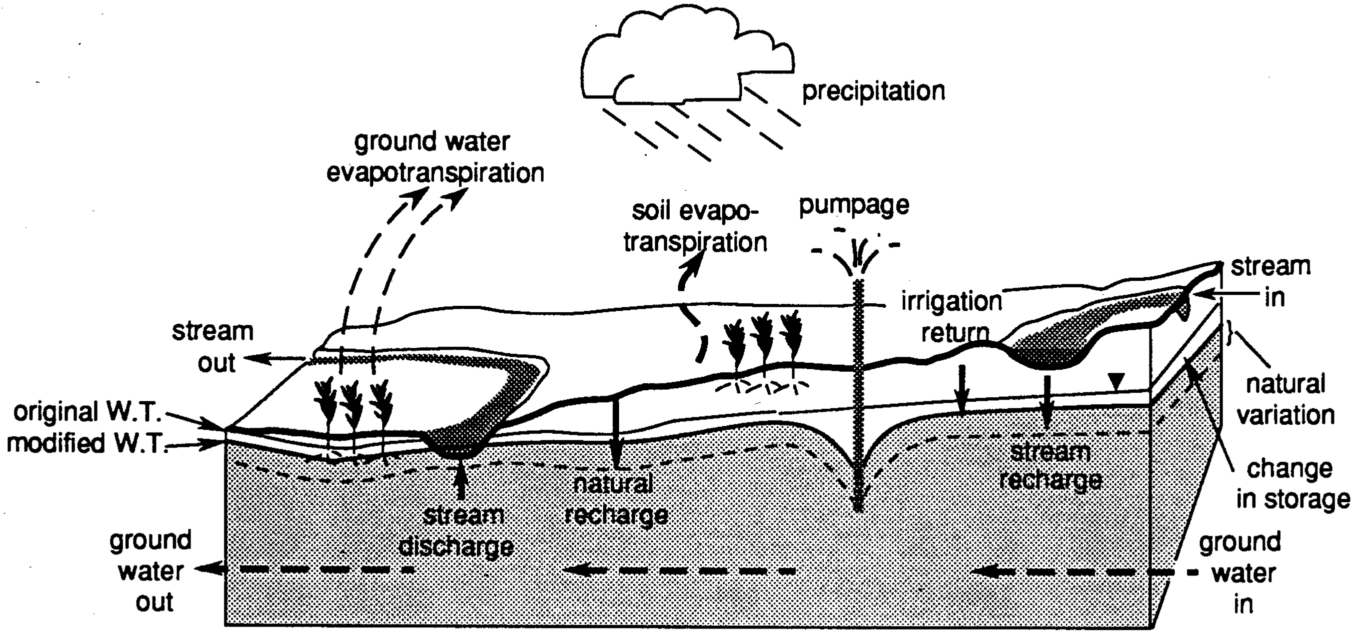


Figure 13. Comparisons of dynamic water budgets showing the major terms and features under unaltered conditions and after groundwater development. If the water table is lowered, stream base flow and evapotranspiration due to shallow water tables are all reduced.

by lowering the water table relative to the channel of the gaining stream and the rooting depth of plants in the discharge area.

The rate at which artificial discharge (pumping) reduces natural recharge depends on the size of the system and the distance between pumping and discharge points. In a large hydrologic unit, such as the Ogallala aquifer, re-equilibration may take many centuries, whereas in small alluvial aquifers such as the Walnut Creek or Pawnee River valleys, effects are evident in a few decades (Sophocleous, 1981). Once the new equilibrium is reached, such a groundwater yield is "safe" in terms of pumpage; production can be maintained indefinitely as long as recharge remains approximately the same. Obviously, however, it is not "safe" in terms of sustained streamflow or other water uses that depend on discharge or on a water table higher than the new equilibrium level.

If pumpage is less than long-term average recharge, an intermediate equilibrium will be established where natural discharge is reduced but not completely eliminated. This example can be used to develop a simple equation for a discussion of safe yield.

There are the following inputs and outputs:

R = predevelopment average recharge (water input to the system); and

D= predevelopment average discharge (water loss from the system).

When they are in equilibrium, $R = D$, so

$$R - D = 0. \qquad (1)$$

If some pumping occurs:

Q = the net artificial withdrawal from the system; this is another loss term, and if irrigation is the primary water user, Q will equal the gross amount pumped minus the amount of return flow.

With increased rate of water removal, some natural adjustments will occur:

r = the change in natural recharge caused by lowering the water table (usually a small increase resulting from slow dewatering of previously saturated sediments and to more effective removal of infiltrating water from the zone of evapotranspiration), and

d = the change in natural discharge (a decrease).

If pumping Q is less than recharge R, then a new (lower) equilibrium water table elevation will be established, the new discharge will be $(D - d)$, and the new recharge will equal $(R + r)$. Because the system is at equilibrium, inflow must equal outflow; thus:

$$(R + r) - (D - d) - Q = 0. \qquad (2)$$

Because $R - D = 0$, we can remove these from the new steady-state equation and see that

$$r + d - Q = 0. \tag{3}$$

A simple rearrangement gives:

$$Q = r + d. \tag{4}$$

The quantity $(r + d)$ is called the "capture" of the system, and it provides an alternative definition of safe yield if a decision can be made about what amount of discharge depletion or water table decline is acceptable. In the extreme, if $d = D$, then natural discharge has disappeared and the largest sustainable amount of pumpage is $Q = (R + r)$. Because r is usually only a small fraction of R, this means that the maximum sustainable yield (without consideration of what it is "safe" for) is just a bit more than the average annual recharge.

This argument addresses only the issue of water quantity in the ground and in discharge areas. When water use affects water quality, either by increased salinity in irrigation return flow or (as is the concern in the eastern GMD5) by drawing a larger quantity of naturally saline water into the freshwater aquifer, the determination of safe yield takes on a new aspect—the question of whether the water resource will be effectively depleted because it is no longer usable even though a substantial volume of water may remain.

The process of defining safe yield is complicated for at least two reasons. One is that many of the effects are not immediate—because of the time and space scales of groundwater movement (discussed elsewhere in this report), it may take decades or even centuries for the effects of pumping to be felt at distances of miles to tens of miles. The second complication is uncertainty. The natural variability of climate and of aquifer characteristics and the uncertainties associated with water use and demand all combine to make it difficult for scientists to make large-scale, long-term hydrologic predictions that are both detailed and accurate. Accurate analyses tend to be averaged over several years and/or over large geographic areas, while detailed understanding is usually limited to small areas or specific subjects. Predictions are probabilistic or dependent on assumptions. Decision making under conditions of uncertainty is one of the major challenges facing managers and planners, and explaining or reducing that uncertainty is a major task for the research agencies.

In dealing with questions of "safe yield," the question, "Safe for what?" has already been asked. The question, "Safe for how long?" is also an important one. Ground-water management strategies may be different if the view is of ground-water resources only and a time scale of years or a few decades than if surface-water resources and the water supply of future generations are considered.

A primary goal of the Mineral Intrusion study is to determine whether there are threshold values of water table declines or ground-water pumpage (quantity) that, if exceeded, could cause or greatly accelerate the contamination of fresh groundwater by natural saltwater (quality). An important secondary goal is to incorporate this knowledge into stream-aquifer water budgets that describe the relationships among pumpage, water level, and natural discharge of both salt and water. These results should enable planning and management agencies to make more complete and accurate determinations of what should be considered a "safe yield" policy and how water resources can best be managed.

Variability, Uncertainty, and Scale

Whether in research or in management, hydrologists must cope with the fact that they do not have and usually cannot obtain the certainty of understanding or prediction that they would like to have. Closely related to this frustration is the need to identify appropriate scales of time and space for study or planning.

As one example, consider the rainfall records shown in Figure 14. All three graphs are based on the same data—the average of the annual precipitation at the 10 long-term weather stations located within GMD5 boundaries (see Figure 1 for locations). The first graph illustrates individual yearly values. These are highly variable; if long-term average rainfall is used to predict next year's precipitation, it could easily be off by 25–30% and possibly by as much as 50%! The second graph gives a picture of possible predictions of the average precipitation for the next 5 years based on history—a much lower variability, but still with the possibility of changes in excess of 10% of the long-term average. 20-year averages, however, have good predictability, with deviations of only a few percent from the long-term average. Because of the high year-to-year uncertainty, the staff of the KWO, the DWR, and GMD5 have agreed that two time frames should be addressed in modeling and predictive studies. The primary concern is the five-year interval; processes and trends occurring over 20 years are secondary concerns.

These time scales—fairly long by human standards—translated into distances of ground-water movement, give somewhat surprising results. Recall that typical groundwater flow rates are about 1 foot per day. At that rate, 5 years is less than 1 mile, and 20 years is not enough to cross a township! Changes in head (or pressure) may be much more rapid and extensive than this, but the actual flow of water and dissolved salt is retarded by the resistance of the aquifer material. This means that management on 5– or 20–year time scales needs to consider small areas and that the more distant parts of a multicounty district will not normally exchange water or

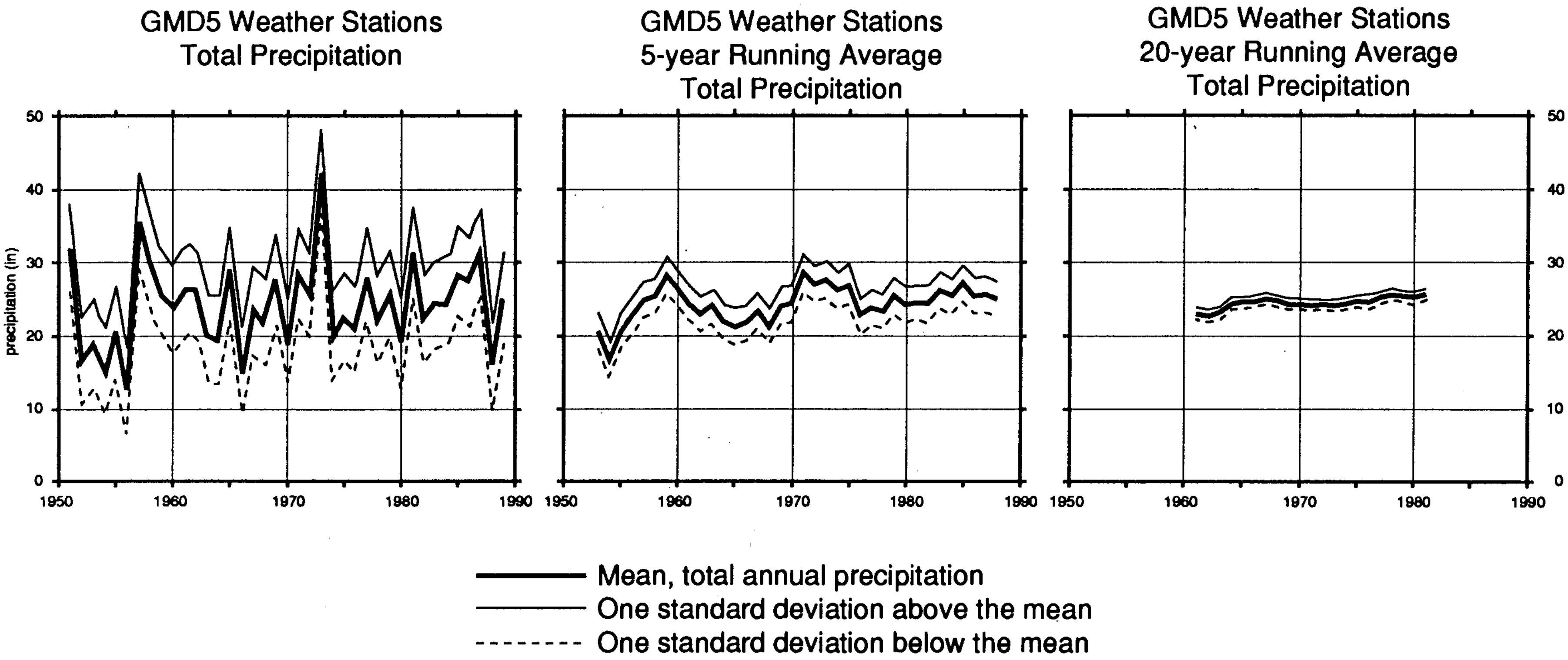


Figure 14. A: Annual precipitation for GMD5, based on the average and standard deviation of 10 weather stations for individual years. B: Same as A, but with the data presented as a 5-year running mean (i.e., each point is an average of that year and two years on either side of it). C: Same as A, but with the data treated as a 20-year running mean. Points or lines above and below the central line represent one standard deviation of the mean.

salt on any time scale relevant to the lives of individual humans. It also helps to explain why controversies about the effects of irrigation are arising two or three decades after the beginning of intensive pumping—it takes that long for the effects to be detectable over substantial distances and above the background of natural variability.

To investigate and describe a process such as mineral intrusion that occurs with substantial variability over an area comparable to more than two counties, conditions must be studied concurrently at more than one scale. At local sites we observe saltwater changes intensively and establish the relationship to local geology and hydrology. At the same time we investigate how these geologic and hydrologic factors are distributed across much larger areas, which permits us to make inferences about the related distribution of saltwater and its behavior. Finally, we use models and simulations to combine scales and test our regional "predictions" against large-scale behavior and long-term records, such as water levels, stream flows, water quality, and other observations sensitive to the regional budget of water (or salt).

THE RESEARCH APPROACH

Overall objectives

Appendix A contains the contract between the KGS and the KWO for the first year of the Mineral Intrusion Study, with an attachment outlining our present understanding of future work over the projected four-year duration of the study. The purpose of this section of the report is to summarize those goals and to outline briefly the approach to achieving them.

The basic objective (from Attachment A to Appendix A of this report) is "Determination of how naturally and artificially induced brine intrusion affects the 'safe yield' of groundwater in that part of GMD5 in which the Permian formation is hydraulically coupled to the Great Bend Prairie Aquifer, [and] develop[ment of] information or guidelines suitable for use by managers, planners, and policy makers." Although "safe yield" is not a fixed concept, there is no doubt that water quality affects the use of groundwater and little doubt that ground-water use in turn affects water quality in the region considered by this study. A basic understanding of these interactions and how they can be modified or controlled will be essential to ground-water management, whatever the local definition of "safe yield," and will help in the development of the sub-basin water resource management plan proposed by the DWR.

In addition to a specific understanding of the role of mineral intrusion in the hydrologic cycle and its effects on water resources, other study objectives are to develop coordination between research efforts in GMD5 area and to present and develop the results in ways that assist the agencies in addressing other and more general concerns in the area. Letters outlining the concerns and interests of GMD5 and the DWR are contained in Appendixes B and C, respectively. As the project evolves, the experimental design, reports, and other products will be directed toward effectively addressing these larger issues to the maximum extent compatible with available resources.

Literature and Data Review

The Great Bend Prairie aquifer has been the subject of investigation for a long time and has been studied from many standpoints. The Kansas Geological Survey and other agencies and investigators alone have produced numerous studies of all or part of the mineral intrusion area [see references cited by Sophocleous and Perkins (1992), Sophocleous (1992a), and Gillespie et al. (1991)]. In spite of this attention, none of the previous studies has investigated the water and salt budgets and distributions over the time and space scales demanded by this research. The first order of business is therefore to assemble, evaluate, and interpret the scattered information available on the salt distributions and the hydrogeologic characteristics of the bedrock aquifer system (the freshwater aquifer has been much more systematically studied). Reviews of these two topics will be prepared by early 1993 and will guide experimental design and the interpretation of the field work to be carried out subsequently.

Field Experiments

As alluded to in the previous paragraph, the research is designed to determine the salt effects on two different scales and to link them together for a complete understanding. On a scale of miles to tens of miles, the study will depend initially on the existing monitoring well network and will use logging techniques supported by chemical analysis to map the distribution and characteristics of the saltwater-freshwater interface, to determine its changes on time scales of years, and to understand its geologic and hydrologic correlations. During the first year, all the existing monitoring wells will be logged before the start of irrigation to establish a baseline, and subsequent annual remeasurement will permit measurement of systematic changes. Figure 15 shows a schematic view of the focused electromagnetic logging tool and a simplified illustration of how its output relates to the conductivity (and therefore salinity) of the water in the formation. Because this device is most sensitive to the characteristics of a region 1.5 feet away from the tool itself, the determination is essentially independent of the quality of the water in the well itself and avoids most of the potentially complicating factors of borehole disturbance. We are confident that the method has sufficient sensitivity and accuracy to measure the location of and significant changes in the saltwater-freshwater interface.

On a much more detailed scale, we will identify one or more specific sites to monitor intensively over time the variations in water level and salinity in the various aquifer units and to develop a more detailed understanding of the geologic features influencing water table and saltwater-freshwater interface variations.

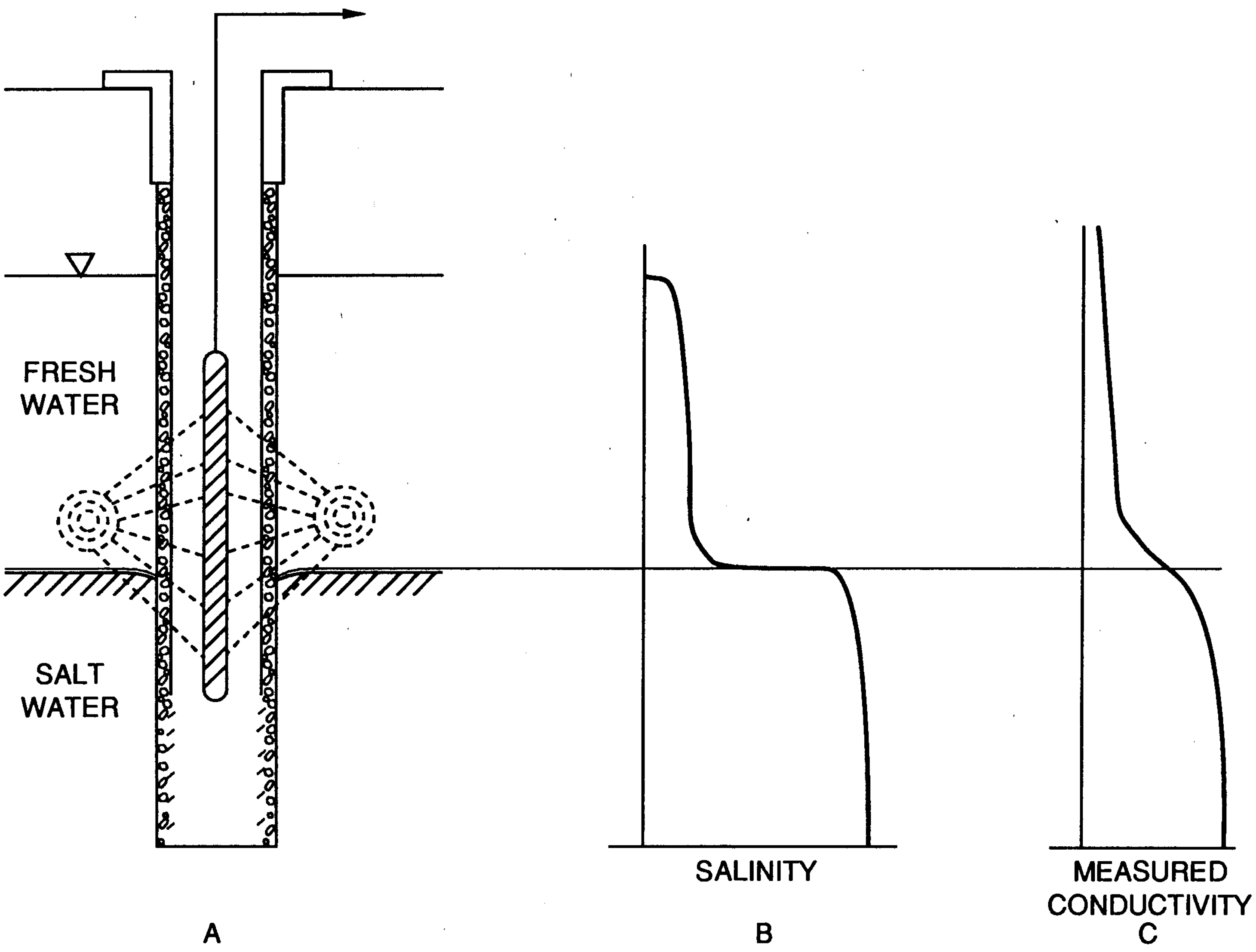


Figure 15. Schematic representation of focused-induction logging. A: the tool is designed to be sensitive to the response of the aquifer to electromagnetic fields at a distance outside of borehole disturbances. If a homogeneous aquifer contains a salt-water interface as shown in B, then the logging process will produce a record that looks likes C.

Modeling

The use of models, simulations, and such tools as Geographic Information Systems are essential to integrating our findings across various time and space scales and to testing the predictions and management recommendations we may develop.

The KGS has performed several studies that involved modeling all or significant parts of the Great Bend Prairie aquifer (Cobb et al., 1983; Sophocleous and McAllister, 1990; Sophocleous, 1992c). Although these studies did not specifically address the mineral intrusion issue, they provide a basis for understanding the water budget and can serve as a basis for extending the work to models more specifically designed for the local situation (Sophocleous and Birdie, 1990).

Large-scale modeling will not be initiated until later in the project. However, vertical modeling studies to predict and simulate the movement of the saltwater-freshwater interface under various hydrologic and geologic conditions will be undertaken during the first year. This will guide the design and interpretation of the detailed site studies and prepare for regional simulation of interface movement.

Management, advice, and review

Technical direction and management of the Mineral Intrusion Study will be provided by the KGS, with the advice and review of a steering committee composed of representatives of the KGS and the agencies with statutory authority for water planning and management: GMD5, KWO, and DWR. To maximize understanding, review, and input, this steering committee will also assemble two other bodies: a technical advisory committee that will consist of technical representatives of the other federal, state, and local agencies with water-related concerns or responsibilities in the area and a public advisory committee that will provide a forum for information exchange with interested individuals, nongovernmental organizations, or other agencies.

ACKNOWLEDGMENTS

This report was prepared with the advice, review, and financial support of the Kansas Water Office. We gratefully acknowledge the assistance of the staff of Groundwater Management District No. 5, and of our colleagues at the Kansas Geological Survey in providing information and reviews. All or part of this manuscript has been reviewed by T. J. McClain, P. A. Macfarlane, and R. Buchanan (KGS) and by B. Falk (DWR); we appreciate their assistance in improving the document, but responsibility for the views and information presented ultimately resides with the authors. The production assistance of M. Schoeneweis and A. Kraxner made timely preparation possible.

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LIST OF FIGURES

Figure 13: Comparisons of dynamic water budgets showing the major terms and features under unaltered conditions and after groundwater development. If the water table is lowered, storage, stream base flow, and evapotranspiration due to shallow water tables are all reduced.

Figure 14: A: Annual precipitation for GMD5, based on the average and standard deviation of 10 weather stations for individual years. B: Same as A, but with the data presented as a 5-year running mean (i.e., each point is an average of that year and two years on either side of it). C: Same as A, but with the data treated as a 20-year running mean. Points or lines above and below the central line represent one standard deviation of the mean.

Figure 15: Schematic representation of focused-induction logging. A: the tool is designed to be sensitive to the response of the aquifer to electromagnetic fields at a distance outside of borehole disturbances. If a homogeneous aquifer contains a salt-water interface as shown in B, then the logging process will produce a record that looks like C.

Appendix A

KWO-KGS Contract for Year 1, Mineral Intrusion Project, With Attachment Outlining Expected Longer-Term Activities and Progress.

I. PROJECT TITLE

This contract effective July 1, 1992, and entered into by the Kansas Water Office (KWO) and the Kansas Geological Survey (KGS) shall be know as the "Big Bend Aquifer Mineral Intrusion Study." All references to this agreement shall include this title and the Kansas Water Office agreement number.

II. SCOPE OF WORK

The KGS will furnish the personnel, all materials, services, computer facilities, office space and equipment and laboratory space and equipment required for the first year of study, as described in the Overall Study Scope (Attachment A) including:

1. Determine the salt source characteristics under the Big Bend Aquifer.
2. Determine the present condition of the saltwater interface and apparent variations or trends.
3. Investigate the effects on the interface by variations in climatic conditions or local pumping stresses.
4. Integrate this study with ongoing data and operations existing within the Groundwater Management District No. 5 region.

III. DELIVERABLES

The KGS shall deliver to the Director, Kansas Water Office, 109 SW 9th Street, Suite 300, Topeka, Kansas, the following items listed below:

Item	Description	Delivery Date
1.	A report detailing the statement of the problem and the background underlying the issues, including consideration of time and space scales of the interface.	September 30, 1992
2.	A progress report on the available data related to the interface, including historic water level fluctuations, water quality values and trends, hydraulic head within the Permian formations and the expected quality of water within the Permian formations.	December 31, 1992

Item	Description	Delivery Date
3.	A progress report describing the elevation and transitional characteristics of the interface, basic maps of the study area, suggested monitoring strategies for the study period, preliminary log data within the aquifer, slug tests of the Permian formations, progress on simulation of the vertical transport of salt within the aquifer and a preliminary water budget for the study area.	June 30, 1993
4.	In regard to each deliverable, the KGS will conduct a meeting of a technical advisory committee for this study, including KWO, Division of Water Resources, Groundwater Management District No. 5, as well as appropriate interested parties.	

IV. COMPENSATION

The Kansas Water Office agrees to pay the Kansas Geological Survey the lesser of $130,000 or the total expenditures required to complete this contract as detailed in the budget estimate (Attachment B). Payment shall be made in installments after delivery of each deliverable item 1 through 3 and upon receipt of an interfund voucher for the total expenditures incurred by the KGS, subject to the limitation that the final 25 percent shall be payable upon satisfactory completion of this contract by the KGS as described in Section V.

V. COMPLETION OF THE CONTRACT

This contract shall be completed prior to July 1, 1993. The contract will be successfully completed upon KWO receipt of the progress reports described in Section III.

VI. EXTENSION

Contingent upon funding of this agreement, the parties may agree to extend the investigation beyond the termination date for an additional period under terms provided for in writing and approved by all parties. Such agreement must be reached 30 days prior to the original termination date.

VII. KANSAS CONTRACTUAL PROVISIONS ATTACHMENT

The provisions found in contractual provision attachment Form DA-146a (Attachment C), which is attached hereto and executed by the parties to this agreement, are hereby incorporated in this contract and made a part hereof.

KANSAS GEOLOGICAL SURVEY

Lee C. Gerhard, Director

KANSAS WATER OFFICE

Stephen A. Hurst, Director

UNIVERSITY OF KANSAS

Kim Moreland

Kim Moreland, Director 8-16-92
Research Support and Grants Administration

ATTACHMENT A

Big Bend Mineral Intrusion Project - Scope of Study

Basic objective: Determination of how natural and artificially induced brine intrusion affects the "safe yield" of groundwater in that part of GMD5 in which the Permian formation is hydraulically coupled to the Great Bend Prairie Aquifer, develop information or guidelines suitable for use by managers, planners and policy makers.

Subsidiary objectives:

1. Determine salt source characteristics. (Distribution and variation in head, water quality, hydraulic conductivity, etc. for Permian)
2. Determine present elevation and hydrogeologic associations of salt water interface; measure or infer variations and trends.
3. Determine regional salt-water interface response to climatic variations (recharge effects on water table) and regional groundwater depletion. (Relates to and combines 2 & 4).
4. Determine local effects of pumping on salt-water interface (upconing of salt, residual salinization of aquifer in transition zone), and their relationship to geology (e.g., thickness, depth, areal extend of clay layers).
5. Establish water and salt budget for eastern GMD5 (and/or for specific selected subregions), including stream-aquifer and recharge effects.
6. Integrate and where possible coordinate the data and operations already existing or to be produced by other projects involving KGS, GMD5, and/or other cooperating agencies.

Summary of Tasks and Deliverables: The following are specified for the entire 4-year project, but emphasis on definition and specification of deliverables is given to those with major efforts or products during the first year.

Task 1: Define problem and background. Prepare a report detailing in non-technical terms (but with scientific basis, references) the issues and problems of "safe yield" definition and determination, need for specification of time and space scales under consideration, local identification of objectives and hydrologic system. Define assumptions and objectives of study.

Product -- Report to be submitted by 30 September 92. Agencies (KWO, DWR, GMD5) will provide to KGS by 30 July 92 identification of specific issues, time and space scales of concern, and specific subareas to focus on.

Task 2: Determine present/past salt water interface and intrusion situations.

a. Publish data and basic interpretation of history of measurements on monitoring well network.
b. Compile and/or summarize other relevant water quality data (GMD5,?) -- either separately or as part of (a).
c. Measure elevation, and to the extent possible the sharpness and geologic associations of the salt-water interface by borehole electromagnetic induction and

gamma logging of monitoring well network, plus other suitable wells that may be available. If feasible, complete logging by start of 93 irrigation season.

d. Design future monitoring strategy to detect changes over the course of the project. This will be started during FY93, but probably not fully completed until after results of 2a-c are fully interpreted in cooperation with GMD5.

Products -- 2a: Report to be submitted by 30 December 1992. 2b: Report to be completed by 30 June 1993 (earlier if possible); as most of these data are collected and possessed by GMD5, the exact schedule and format of reporting will have to be negotiated. 2c: Data report, possibly with basic maps, sections, first-cut observations by end of CY93. 2d: No formal deliverables until FY94.

Task 3: Hydrogeologic characterization of Permian formations.

a. Review of literature, analysis of head data and available formation tests from monitoring wells.

b. Slug tests of Permian formation monitoring wells. Will have to be preceded by review of well construction, condition, logs, and head/geochemical data and completion of logging. Some preliminary results may be available for FY93 report.

c. Drilling and testing (vertical gradient within Permian; slug or pump tests for hydraulic conductivity) of Permian wells. Depending on the results of Task 2 and 3a-b, 1-3 wells or well nests may be constructed in FY93 or 94.

Products -- 2a: Report to be submitted (probably in combination with 2a and/or 2b) by 31 December 92. 2b: Available results will be included in the FY 93 report to be published by 30 June 93: however, complete reports and analyses should be available by the end of FY93. 2c: No formal deliverables until FY94.

Task 4: Local aquifer and aquifer response characterization.

a. Interface migration under pumping stress -- time-dependent logging of water table drawdown and saltwater upconing in monitoring wells tied to an irrigation well that is known or suspected to produce water quality degradation.

b. Hydrologic characterization of aquifer and of in-situ clay layers -- Slug or pump tests on selected wells to improve our knowledge of the hydraulic conductivity of the fresh-water aquifer is regarded as a contingency effort if sensitivity analyses show that we need better or more specific data.

c. Clay layer characteristics -- This may involve either or both undisturbed sampling of the layer and laboratory tests, or field tests involving pump or slug tests across or within a clay layer (4b). Sampling and testing will be guided by sensitivity analyses from the modeling efforts (below), although samples of opportunity may be taken during early drilling operations.

Products -- 2a: Preparations in FY93 or FY94; initial results reported by FY95 (earlier if available). 2b-c: Activities and reporting in later project years.

Task 5: Vertical transport modeling/simulation.

Set up or develop computer simulation model(s) that will permit modeling of both water flow and chemical transport (both upward and lateral or downward migration of brine or other salts) at both of the scales needed -- individual well effects (100-1000 m) and subregional studies (10-100 km). Develop capability to simulate and model the effects of clay layer geometry on both recharge and salt transport, and the effects of both natural variations and pumping stresses on water table and the salt water interface. Use in designing field studies as well as interpreting results.

Products -- set up and testing will be started in FY93, with a report on progress to be included in the FY93 annual report (30 June 93); however, substantive results will not be reported until FY94 and later

Task 6: Overall water and salt budget modeling and simulations.

Initial assessments will be based on expansion of the MODFLOW models developed for Kinsley-Great Bend and Rattlesnake budgets, which will require refinement of the surface processes and addition of aquifer-aquifer interactions. Depending on initial evaluations, a full 3-d model may prove necessary.

Products -- Reports on progress and plans will be included in regular annual reports for FY93 and FY94, with reporting of results beginning in FY95.

Task 7: Study coordination.

Coordinate project with existing data collection and analysis activities of DWR and GMD #5. Create a technical advisory committee to review project progress and findings. Conduct meetings with appropriate interested parties to discuss study.

Appendix B

GMD5 Issue Paper on Mineral Intrusion Project

MINERAL INTRUSION PROJECT
ISSUE PAPER
AUGUST 1992
BIG BEND GMD #5

STUDY: SALINE-FRESHWATER INTERACTION: The cause and effects of Permian saline-water intrusion into the freshwater, for that portion of the Great Bend Prairie Aquifer which lies within the eastern region of Big Bend Groundwater Management District #5.

ISSUE: The research objectives, directions of approach, and time frames necessary to: better define all aquifer parameters for this region (both saline and freshwater); to better understand the mechanisms of saline-freshwater interaction and effects of external influences; and to develope management options that will insure long-term availability of the freshwater resource.

A major responsibility of GMD #5 is the management and protection of the groundwater resource. In order for the District to formulate groundwater management policy, it requires the collection and analysis of an adequate base of data. This is especially true in the eastern portion of the District where natural mineral intrusion occurs. This natural saline water intrusion problem presents a difficult task in defining workable management options. Because of the complexity of the problem, there is the possibility that any management program developed for this area would be large in scope, and relate to all water users. It is the hopes of the District that all parties, be they local, state, or federal, could come to a cooperative partnership in working to solve the many problems. This opportunity to present the issues, as they relate to the District's wants and needs for this study, is an important first step towards that end. It is to the benefit of all to achieve an early understanding of goals and data requirements.

The area of concern to be studied is defined by the existence of a direct contact between the deeper saline Permian formations, and the upper sands and gravels of the freshwater Great Bend Prairie Aquifer. Historically, this is an area where natural saltwater intrusion has existed in varying degrees. However, with increasing demands being placed upon the freshwater resource, there is a greater need to determine all the physical characteristics, as well as the present condition, of the aquifer (both saline and freshwater).

The following is a generalized outline of the data requirements that will be needed to answer some of the major questions. Although broken down into categories, there will be some overlapping data needs among the different sections. There is certainly some priority in data acquisition, but a portion of it is field work related and may take substantial time to carrying it through.

I) DEFINING AND MAPPING THE INTERFACE

- A) Geophysical survey
  - 1) Location, elevation, and character (i.e. dilute vs. sharp) This creates a base from which to work, and would allow the continued monitoring for subsequent changes.
    - a) monitor yearly for larger regional changes
    - b) monitor local site specific during pumping (would require installation of observation wells).

II) DETERMINATION OF AQUIFER PARAMETERS

- A) Freshwater aquifer
  - 1) Thickness
    - a) saturated
    - b) freshwater vs.. saltwater
  - 2) Stratigraphy
    - a) geophysical survey, determine depth, thickness and extent of clays (effects as barrier to intrusion)
  - 3) Lithologic variability (as it relates to)
    - a) storitivity
    - b) hydraulic transmissivity
    - c) hydraulic conductivity [permeability of aquifer will require some type of testing, slug or pump.]
  - 4) waterlevels
    - a) hydraulic head variation
- B) Permian aquifer
  - 1) Water Quality
    - a) salinity concentration and distribution [may be necessary to distinquish between oil-brine contamination.]
  - 2) Water levels
    - a) hydraulic head variation
  - 3) lithologic variability
    - a) hydraulic transmissivity and conductivity (cores would be nice but expensive, most likely by slug testing)
    - b) need to consider differences among the Cedar Hills, Salt Plain

        and Harper formations
    - c) may need to consider subcrop erosional surface on west edge of contact

III) NEED TO GENERATE A COMPLETE WATER BUDGET
- A) Aquifer gains
    - 1) recharge from precipitation (has been questions raised on accuracy of existing data)
    - 2) recharge from stream flow or storm-event runoff
    - 3) upwelling of Permian saltwater
    - 4) regional subsurface flow west to east
    - 5) irrigation return flows
- B) Aquifer losses
    - 1) evapotranspiration (native, dryland and irrigation)
    - 2) baseflow
        - a) also Permian flows into Rattlesnake creek
    - 3) regional subsurface flow west to east
    - 4) pumpage
        - a) dealing with appropriated vs.. reported vs.. actual use
    - 5) "ghost water" is it large enough to be considered (domestic, stockwater, recreation -- occur in both groundwater and surface water). Also artesian flows (both saline and fresh)
- C) Consideration: a regional scope vs. doing it by basin or sub-basin

IV) Mechanisms of saline-freshwater interaction
- A) From data above
- B) Effects of external influences
    - 1) natural
        - a) recharge
        - b) drought
    - 2) human
        - a) pumping
        - b) changing landuse practices

V) Stream-aquifer interaction
- A) Regional groundwater vs. streamflow
    - 1) effects of natural climate
    - 2) effects of pumping
- B) By basin
    - 1) same as above
- C) Rattlesnake
    - 2) relationship of aquifer change with change in surface flow quality

Appendix C

DWR Statement of Issues for Mineral Intrusion Project

KANSAS STATE BOARD OF AGRICULTURE

SAM BROWNBACK, Secretary
DIVISION OF WATER RESOURCES
DAVID L. POPE, Chief Engineer-Director
TOPEKA • • KANSAS

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June 30, 1992

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RECEIVED
KANSAS WATER
OFFICE

Tom Stiles
Kansas Water Office
Mills Building, 109 SW 9th, Suite 300
Topeka, Kansas 66612-1249

RE: Mineral Intrusion Study

Dear Mr. Stiles:

Thank you for allowing me to participate and provide input at the recent meeting at Groundwater Management District No. 5, in which the Mineral Intrusion Study was discussed. The meeting proved to be not only interesting, but also thought provoking.

You requested that I submit a written list of concerns that would benefit the Division of Water Resources if they are addressed in some manner in the completed study. It was also suggested that these items be incorporated into the Groundwater Management District recommendations but scheduling problems have prevented this. I am sure that our needs will parallel each other quite closely anyway. From a regulatory view point it is felt that the study should at least encompass the following:

1. If current pumping conditions are maintained, what effects can be expected to take place on the salt water interface itself and water quality in surrounding areas. This should be predicted in five year increments for up to 25 years, or more, if possible.

2. Expected impairment of existing water rights, including domestic uses, due to contamination under current conditions. This should also be in five year increments for up to 25 years into the future.

3. Expected effects of current conditions on streamflow quality and quantity over the next 25 years.

4. Steps that can be taken to maintain groundwater quality at its current conditions or if possibilities exist that might actually improve water quality in some areas.

5. Pinpoint any areas that might exist where further appropriation might be possible, without contributing to groundwater quality degradation or lowered water levels.

6. Suggestions of other studies that may add to our understanding of the complete system.

The six items listed above will probably prove to be an oversimplification of the problems that may face us all in the future. I am sure that the completed Mineral Intrusion Study will prove to be one more very important piece to our complicated environmental puzzle.

Sincerely,

M Bruce Falk

M. Bruce Falk
Water Commissioner

MBF:jmw