Kansas Geological Survey

Mineral Intrusion: Geohydrology of Permian Bedrock Underlying the Great Bend Prairie Aquifer in South-Central Kansas

David P. Young

Kansas Geological Survey Open-File Report 92-44

GEOHYDROLOGY

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EXECUTIVE SUMMARY

The Great Bend Prairie aquifer is the primary source of fresh water in the Big Bend Groundwater Management District (GMD5). Water quality in portions of this alluvial aquifer is threatened by salt-water intrusion from underlying bedrock of Permian age. As part of the Mineral Intrusion Study, this report describes Permian bedrock formations in the study area, their hydrologic relation to the overlying aquifer, and the mechanisms for mineral (or salt-water) intrusion.

East of a line roughly coincident with U.S. Highway 281, Permian bedrock directly underlies the Great Bend Prairie aquifer. Highly mineralized waters from the Permian formations discharge into the fresh-water aquifer in this area. Ground-water quality generally deteriorates east of U.S. 281.

The Permian formations in the study area are known to contain salt water. Permian bedrock units include the Cedar Hills Sandstone, the Salt Plain Formation, and the Harper Sandstone. Below these units are the Stone Corral Formation and the Ninnescah Shale. In some locations, Permian hydraulic heads are higher than overlying fresh-water heads, a condition that favors upward leakage of salt water. At certain sites, there is evidence that Permian heads have become higher than deep alluvial aquifer heads for increasingly longer periods as pumping reduces fresh-water heads. The implication is that Permian waters may have an increasing tendency to intrude into the fresh-water aquifer.

Little information is available on the hydrogeologic properties of the Permian formations. Estimates of hydraulic conductivity have ranged from about 0.006 to 14.7 feet per day. Estimates of salt-water discharge from the Cedar Hills Sandstone to the fresh-water aquifer have been roughly 700 to 14,000 acre-feet per year. Due to lack of detailed knowledge about aquifer

hydrogeologic properties and hydraulic relationships, a precise estimate of total leakage from Permian bedrock can not be made at this time. Features such as clay lenses, fractures, and unplugged wells and boreholes further complicate the salt-water movement.

Based on an estimated partial water budget for the aquifer area in contact with the Cedar Hills formation, the amount of water entering the Great Bend Prairie aquifer from the bedrock may be of the same magnitude as that entering as recharge from precipitation. This suggests that under natural conditions there may be a dynamic balance between these two sources of recharge to the Great Bend Prairie aquifer. Mineral intrusion may therefore be a serious threat to the water quality of the fresh-water aquifer in the area if ground-water withdrawals disrupt the balance of recharge sources.

The Cedar Hills Sandstone and other shallow formations have been used for oil-field brine disposal. Ground-water contamination from oil-field brines has been confirmed at at least one site in the study area, and at others to the west. Disposal may also have altered the hydraulic heads, and hence the discharge distribution, of the Cedar Hills formation relative to the Great Bend Prairie aquifer.

INTRODUCTION

The Great Bend Prairie aquifer is the primary source of fresh water in the Big Bend Groundwater Management District (GMD5). The water quality of part of this alluvial aquifer is threatened by mineral intrusion from underlying bedrock of Permian age, which contains ancient brines. Mineral (or salt-water) intrusion is a natural process in the eastern portion of GMD5, but its rate and extent can be altered by human activities. Leakage of salt water from bedrock already has rendered ground water unusable for most purposes in parts of eastern GMD5. This report describes the Permian bedrock formations in the study area (Figure 1), their hydrologic relation to the overlying aquifer, and the mechanisms for salt-water intrusion. A companion report (Whittemore, 1993) discusses the geochemistry of ground waters in the study area.

GEOLOGIC OVERVIEW

The Great Bend Prairie aquifer overlies bedrock of Cretaceous and Permian age. The geology of the region is described by Latta (1950), Layton and Berry (1973), Fader and Stullken (1978), and Cobb (1980). The geologic units are illustrated in Figure 2 and their physical character and water-bearing properties are described in Table 1.

In the west the bedrock is composed of Undifferentiated Lower Cretaceous rocks, including the Cheyenne Sandstone, the Kiowa Shale, and locally, the Dakota Formation. The Cretaceous unit consists of interbedded sandstones and shales and is generally considered a confining or leaky confining layer that separates the unconsolidated Great Bend Prairie aquifer from the highly mineralized waters of the Permian rocks below. Watts (1989) gives estimates of hydrogeologic and chemical properties of the Lower Cretaceous units in southwestern Kansas.

Although the remainder of this discussion will be concerned with Permian bedrock and its relation to the overlying fresh-water aquifer, it is worth noting that the Cheyenne Sandstone, which contains highly mineralized water, may also be a source of salt water to the fresh-water aquifer. In parts of western Stafford County the Cheyenne Sandstone may be hydraulically connected with the Permian Cedar Hills Sandstone (Cobb, 1980), and may be in direct contact with the Quaternary

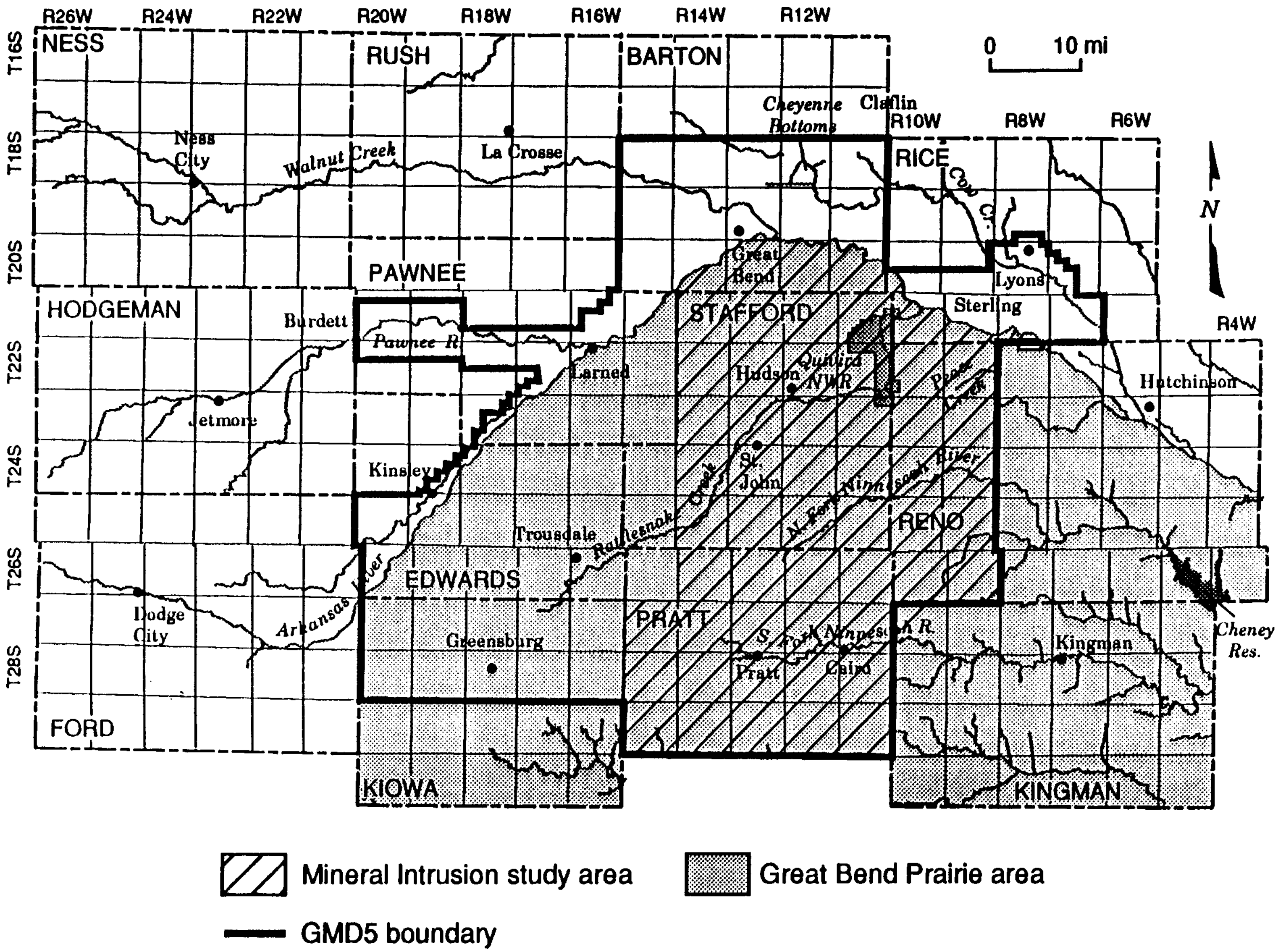


Figure 1. Map of the Big Bend Groundwater Management District (GMD5) showing the major features of the region and the area of primary interest to this study.

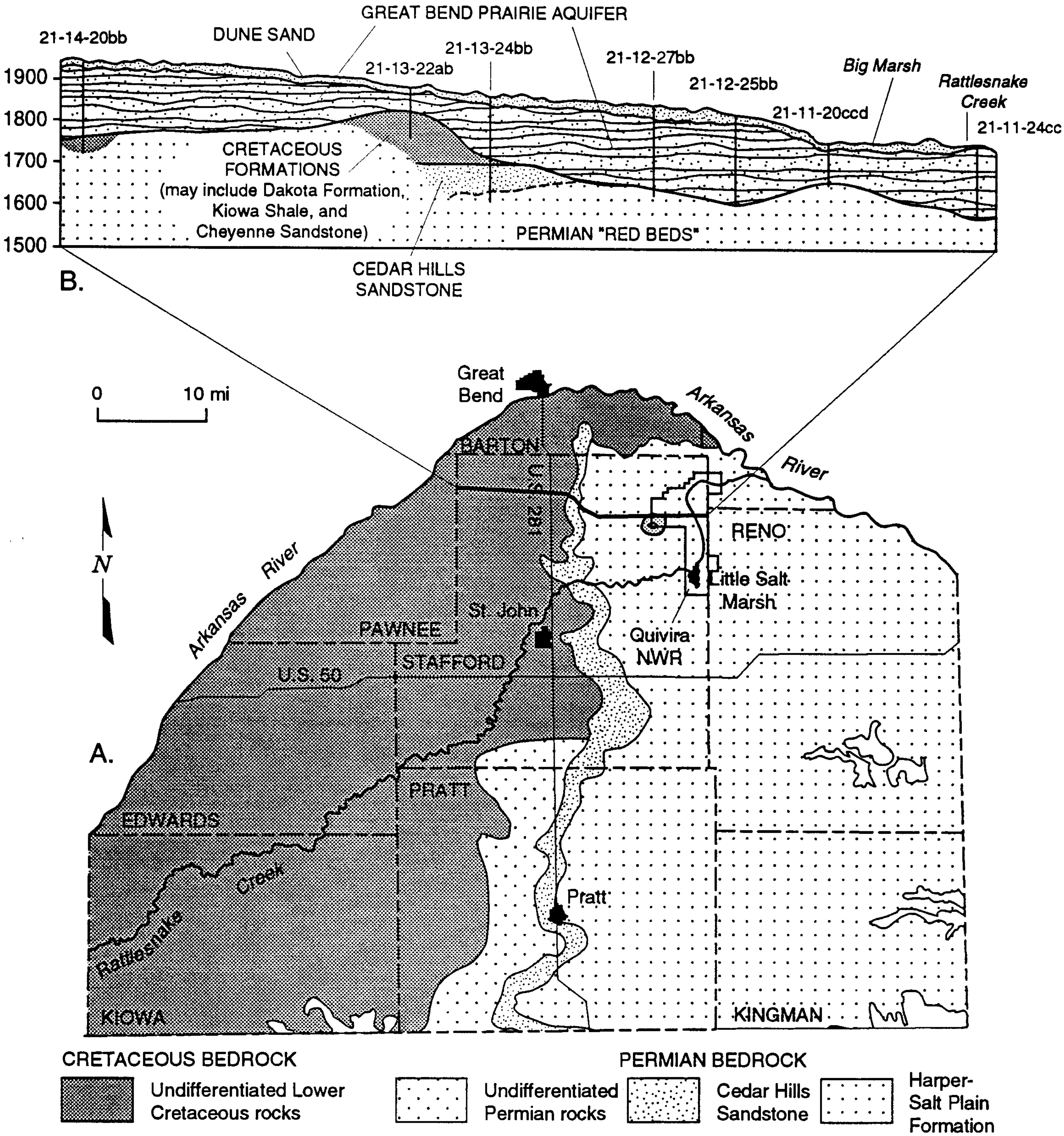


Figure 2. A. Map of the bedrock beneath the Great Bend Prairie aquifer showing the areas in which the Permian formation has the potential to contribute salt water to the overlying aquifer (adapted from Fader and Stullken, 1978). B. Vertical section from west to east across the region, showing the relation of the alluvial Great Bend Prairie aquifer to the underlying Cretaceous and Permian formations (adapted from Latta, 1950).

Table 1. Generalized columnar section of geologic units in the Great Bend Prairie area and their water-bearing properties (adapted from Fader and Stullken, 1978).

System	Geologic unit	Maximum thickness (ft)	Physical character	Remarks
Quaternary	Undifferentiated Pleistocene deposits	360	Unconsolidated deposits of sand and gravel with interbedded lenses of clay, silt, and caliche. Windblown silt (loess) and dune sand occur at the surface over most of the area. Stream-laid deposits (alluvium) of late Quaternary age ranging from clay to gravel occur along the principal stream valleys.	Comprises principal aquifer. Water generally is of good chemical quality* but may be of poor chemical quality in the northeastern part of the area and in deep buried valleys in the southeastern part. Yields as much as 2,000 gal/min to wells.
Cretaceous	Undifferentiated Lower Cretaceous rocks	380	Upper unit (Dakota Formation) brown to gray fine- to medium-grained sandstone interbedded with gray sandy shale and varicolored shale. Middle unit (Kiowa Shale) dark-gray to black shale interbedded with tan and gray sandstone. Lower unit (Cheyenne Sandstone) gray and brown fine- to medium-grained sandstone interbedded with dark-gray shale.	Water probably of poor chemical quality. Yields 10–100 gal/min to wells locally in the western part of the area.
Permian	Undifferentiated Permian rocks	350	Interbedded reddish shale, siltstone, and sandstone with some beds of dolomite and anhydrite. Includes in descending order, Whitehorse Formation, Dog Creek Formation, Blaine Formation, and Flower-pot Shale.	Water generally of poor chemical quality. May yield as much as 10 gal/min to wells.
	Cedar Hills Sandstone	200	Fine grained sandstone, siltstone, shale, and silty shale.	Sandstone may contribute highly mineralized water to the principal aquifer where the two units are in contact.
	Salt Plain Formation	300	Reddish-brown sandy siltstone and fine-grained sandstone.	May contribute highly mineralized water to the principal aquifer where the two units are in contact
	Harper Sandstone	250	Brownish-red siltstone and silty shale with a few thin beds of silty sandstone. Kingman sandstone member is near the top of the formation.	Water may be of poor chemical quality. May yield no water or as much as 100 gal/min to wells in the eastern part of area.
	Stone Corral Formation	20	White and light-gray anhydrite and dolomite.	Not known to yield significant amounts of water to wells in the area.
	Ninnescah Shale	400	Red and grayish-green shale, siltstone, and very fine grained silty sandstone. The "Ninnescah salt" member, when present, is in the upper part of the formation.	May yield water of fair to poor chemical quality to wells in the outcrop areas.
	Wellington Formation	550	Calcareous gray and blue shale containing several thin beds of limestone, gypsum, and anhydrite. The Hutchinson Salt Member, when present, is near the middle of the formation.	Not known to yield significant amounts of water to wells in the area.

*Chemical quality of water is classed as good if the concentration of dissolved solids is less than 500 mg/L or the concentrations of chloride and sulfate are less than 250 mg/L, fair if dissolved solids are 500–1,000 mg/L or chloride and sulfate are 250–500 mg/L, and poor if dissolved solids are greater than 1,000 mg/L or chloride and sulfate are greater than 500 mg/L.

alluvial deposits of the Great Bend Prairie aquifer. Cobb (1980) states that water-quality information from two sites in Stafford County indicates that low-quality water, probably from the Lower Cretaceous units, is leaking upward into the fresh-water aquifer. Both the Cheyenne Sandstone and the Cedar Hills Sandstone have been used as disposal zones for oil-field brines. As of 1986, brines were still being injected into Permian formations to the west of and in the study area (see Appendix).

The geologic history since the Cretaceous Period is complex. Before the Quaternary sediments were deposited, erosion had removed all the Cretaceous rocks and the upper part of the Permian in parts of the study area (Latta, 1950). This erosion left Cretaceous rocks exposed west of a line roughly coincident with U.S. Highway 281, and Permian rocks exposed east of that line (Figure 2). The eroded surface was irregular, consisting of hills and valleys as shown by the contours in Figure 3. This erosional surface was later covered by the Quaternary sands, gravels, silts, and clays that make up the Great Bend Prairie aquifer.

The Permian formations that underlie the Great Bend Prairie aquifer are known to contain salt water. The subcropping Lower Permian rocks in the study area are collectively termed red beds. These include the Cedar Hills Sandstone, the Salt Plain Formation, and the Harper Sandstone. Below these units, and subcropping to the east, are the Stone Corral Formation and the Ninnescah Shale (see Table 1). Undifferentiated Permian rocks (Whitehorse Formation, Dog Creek Formation, Blaine Formation, and Flower-pot Shale) occur as subcrops mainly in Pratt County (Figure 2).

Permian red beds and evaporites are thought to have been deposited in "shallow brackish-saline seas subject to periodic influxes of marine water from the south" (Holdoway, 1978, p. 2). Holdoway (1978) and Cobb (1980) note the ubiquity of halite (NaCl) in the Lower Permian rocks. Halite is present as cement (Cedar Hills), as discrete crystals, and as large bedded units (Ninnescah, Harper-Salt Plain, Flower-pot, and Blaine).

The Permian-age rocks consist of reddish-brown siltstone, shale, and fine-grained sandstone with lesser amounts of halite, gypsum, dolomite, and anhydrite. In the study area they

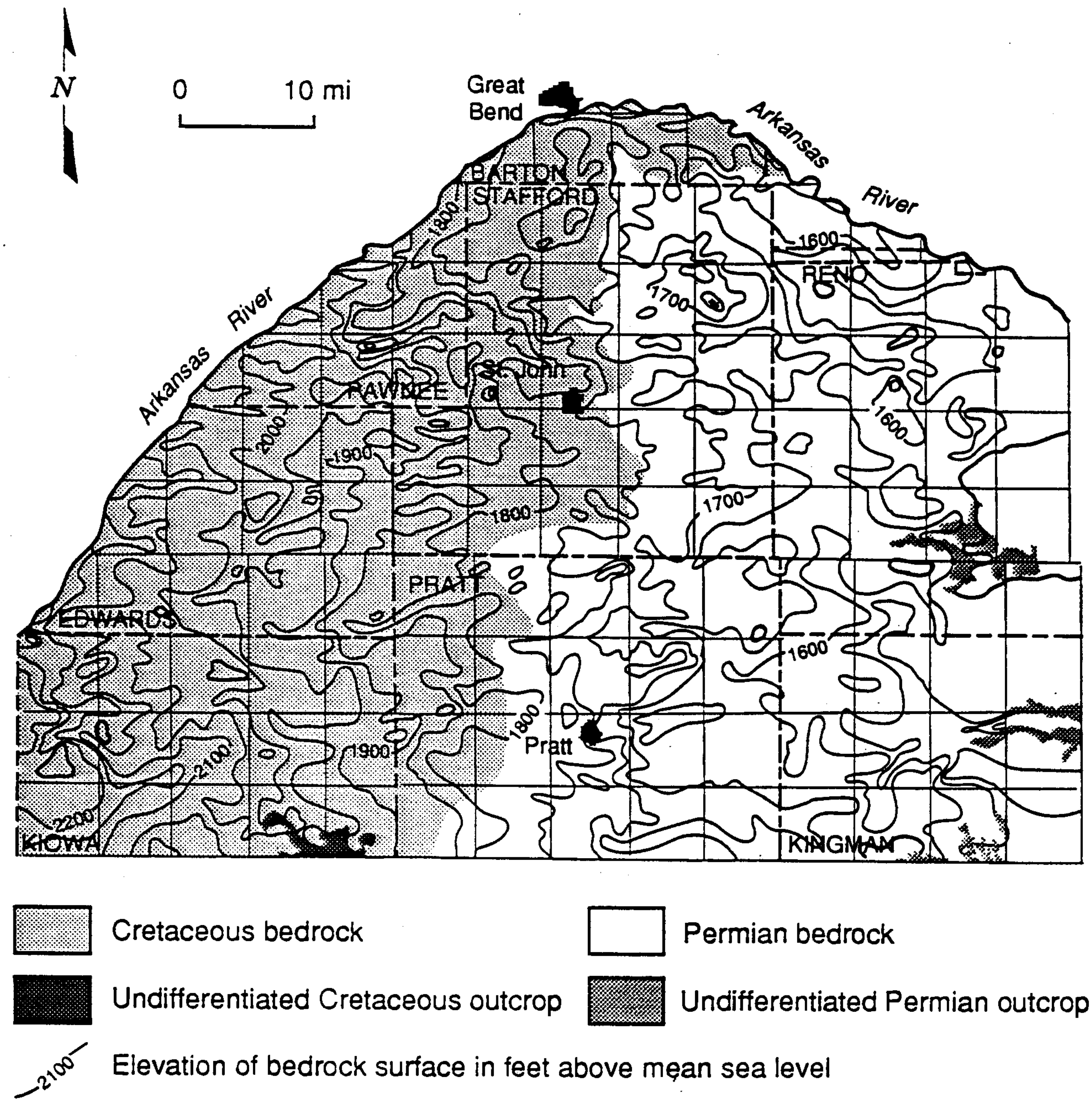


Figure 3. Configuration of the pre-Cenozoic bedrock surface in the Great Bend Prairie area (from Sophocleous et al., 1990).

are encountered at depths ranging from approximately 34 to 258 feet below land surface (Whittemore, 1993). Following is a brief description of the individual units that underlie the fresh-water aquifer in the study area, including their estimated thickness at outcrop. The information is based on reports by Swineford (1955), Zeller (1968), and Cobb (1980).

Harper Sandstone (180-220 feet)

The formation at outcrop is roughly composed of 70% siltstone, 25% silty shale to shale, and 5% sandstone.

Salt Plain Formation (265 feet)

Lithologic analysis indicates 65% siltstone, 25% shale to silty shale, and 10% sandstone. In the subsurface, the Salt Plain is difficult to distinguish from the Harper or the Cedar Hills (Cobb, 1980). Swineford (1955) states that the Harper-Salt Plain boundary is an artificial and unmappable one that should be revised or eliminated.

Cedar Hills Sandstone (180 feet)

The Cedar Hills formation consists of brownish-red massive very fine-grained sandstones and sandy siltstones separated by beds of clayey siltstone and silty shale. The composition at outcrop is about 70% sandstone, 25% siltstone, and 5% shale and silty shale. The top and base of the formation are marked by beds of white fine-grained sandstone. Individual beds of the Cedar Hills Sandstone are traceable for long distances.

Being the most porous Permian bedrock formation in the study area, the Cedar Hills Sandstone is often considered the main source of salt water to the overlying alluvial aquifer. On the other hand, Swineford (1955) states that the Harper, Salt Plain, and Cedar Hills formations are so similar in well cuttings that they are not commonly differentiated. Based on careful examination of wire-line geophysical logs, Cobb (1980) concluded that, at least in Stafford County near the Cretaceous-Permian contact, the Cedar Hills Sandstone is hydrologically undifferentiable from the lower Salt Plain-Harper formation. Where sandstone is present in the top of the Salt Plain Formation, the Salt Plain-Cedar Hills Sandstone functions as a single hydrostratigraphic unit (P. A. Macfarlane, personal communication, 1992).

Undifferentiated Permian Rocks

The Flower-pot Shale consists of reddish-brown gypsiferous shale and silty shale (80%) with a few thin beds of sandstone and siltstone (20%).

The Blaine Formation is composed of massive gypsum, thin dolomite, and brownish-red shale. At outcrop the formation is 65% anhydrite or gypsum, 30% shale to silty shale, and 5% carbonates.

The Dog Creek Shale is approximately 75% shale to silty shale, 15% siltstone, and 5% sandstone; evaporites constitute less than 5% of this formation.

The Whitehorse Formation is the basal unit of the Upper Permian Series. At outcrop it is composed primarily of poorly cemented sandstone, siltstone, and shale.

WATER QUALITY

The Permian bedrock units in the study area are of considerable hydrologic importance because they are known aquifers containing salt water (Cobb, 1980). These units are in direct contact with the Great Bend Prairie aquifer and constitute a serious threat to the water quality of this major fresh-water aquifer.

The most complete general description of water quality in the Permian bedrock is given by Whittemore (1993). The report is based on data obtained from a monitoring-well network constructed by the Kansas Geological Survey (KGS) and GMD5, which is described in the report. Locations of the monitoring wells and site numbers are shown in Figure 4. A more detailed study of water quality and water levels along the South Fork Ninnescah River in Pratt County has been conducted by Gillespie et al. (1991).

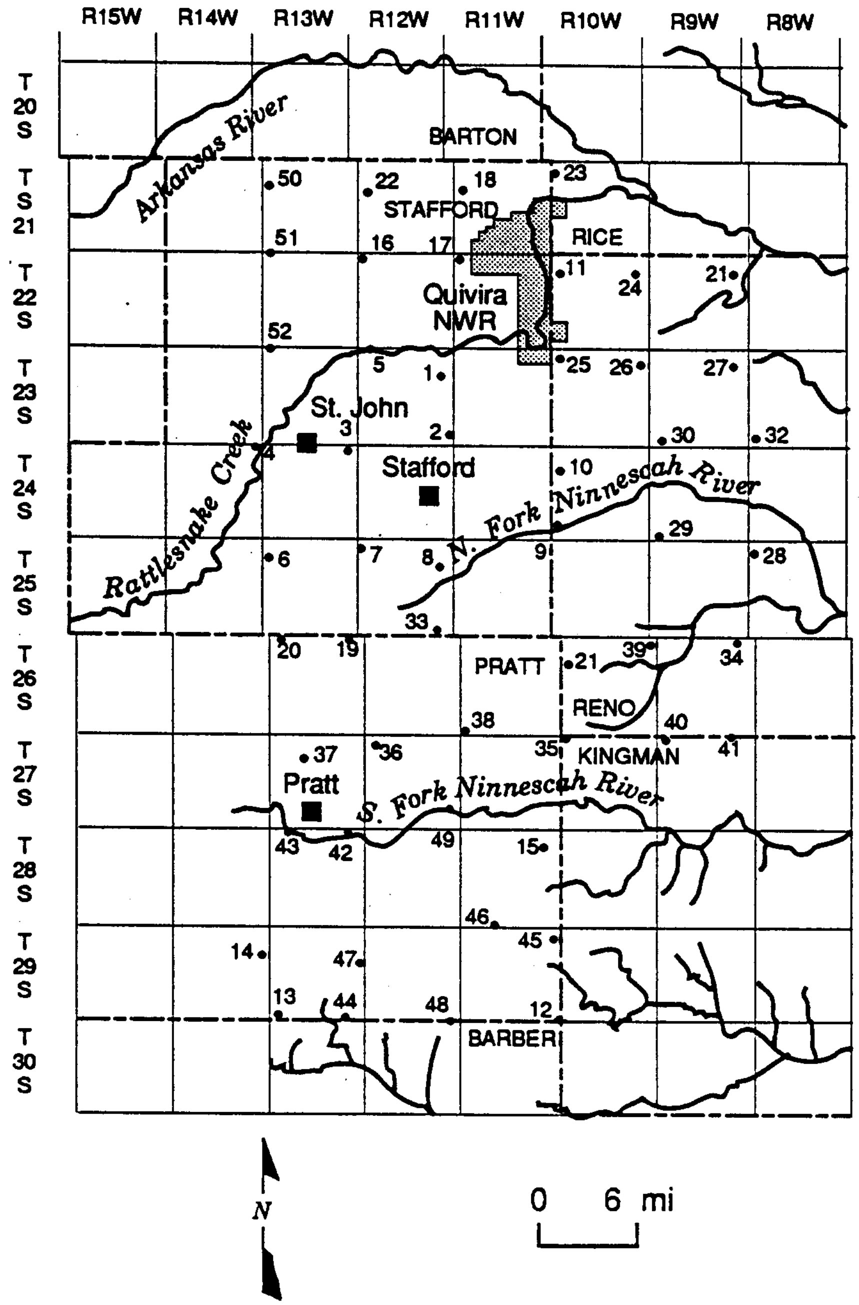


Figure 4. Locations and site numbers of observation wells in the KGS/GMD5 monitoring-well network.

The quality of ground waters from monitoring wells screened in bedrock ranges from fresh to very salty. Chloride concentrations range from 4 to 43,800 mg/L. Permian waters with the highest salinities occur in the northwest and central portion of the monitoring-well network (Figure 5). A more detailed map showing chloride concentration contours is in Whittemore (1993). Bedrock along the southern part of the area contains fresh water. Fresh water is also obtained from the bedrock well at site 34. Of the 49 Permian wells, all but eight yield waters of Na-Cl type. Samples from the other eight wells contain fresh water (Whittemore, 1993).

It has been recognized for some time that Permian-derived salt water naturally rises and increases the water salinity of the Great Bend Prairie aquifer in the eastern portion of GMD5 (Latta, 1950; Fader and Stullken, 1978; Cobb, 1980; Macfarlane and Ackerman, 1983; Sophocleous, 1992a; among others). In fact, a salt-water/fresh-water interface or transition zone has been identified and monitored in parts of the study area (Sophocleous and Perkins, 1992).

The effects are most pronounced in areas of natural ground-water discharge, such as the lower reaches of Rattlesnake Creek (east of Highway 281), Big and Little Salt Marshes, and the South Fork Ninnescah River near Cairo (Figure 1) in Pratt County (Layton and Berry, 1973; Cobb, 1980; Bidleman, 1983; Gillespie et al., 1991; Sophocleous, 1992a; Whittemore, 1993). In these areas, which receive natural discharge from both the unconsolidated aquifer and the underlying bedrock aquifers, upward leakage of salt water has resulted in widespread contamination of both ground and surface waters. Figures 6 and 7 show evidence of salt water rising in the vicinity of Rattlesnake Creek.

Ground waters in the unconsolidated aquifer and the Permian bedrock aquifers flow to the east. The fresh-water aquifer west of U.S. 281 is believed to be protected by the underlying Cretaceous confining unit. Highly mineralized waters are thought to discharge into the fresh-water aquifer east of this approximate line. Water quality in the Great Bend Prairie aquifer generally deteriorates east of Highway 281. Ground water in most of northeastern Stafford County has been classified as generally unsuitable for irrigation by Fader and Stullken (1978).

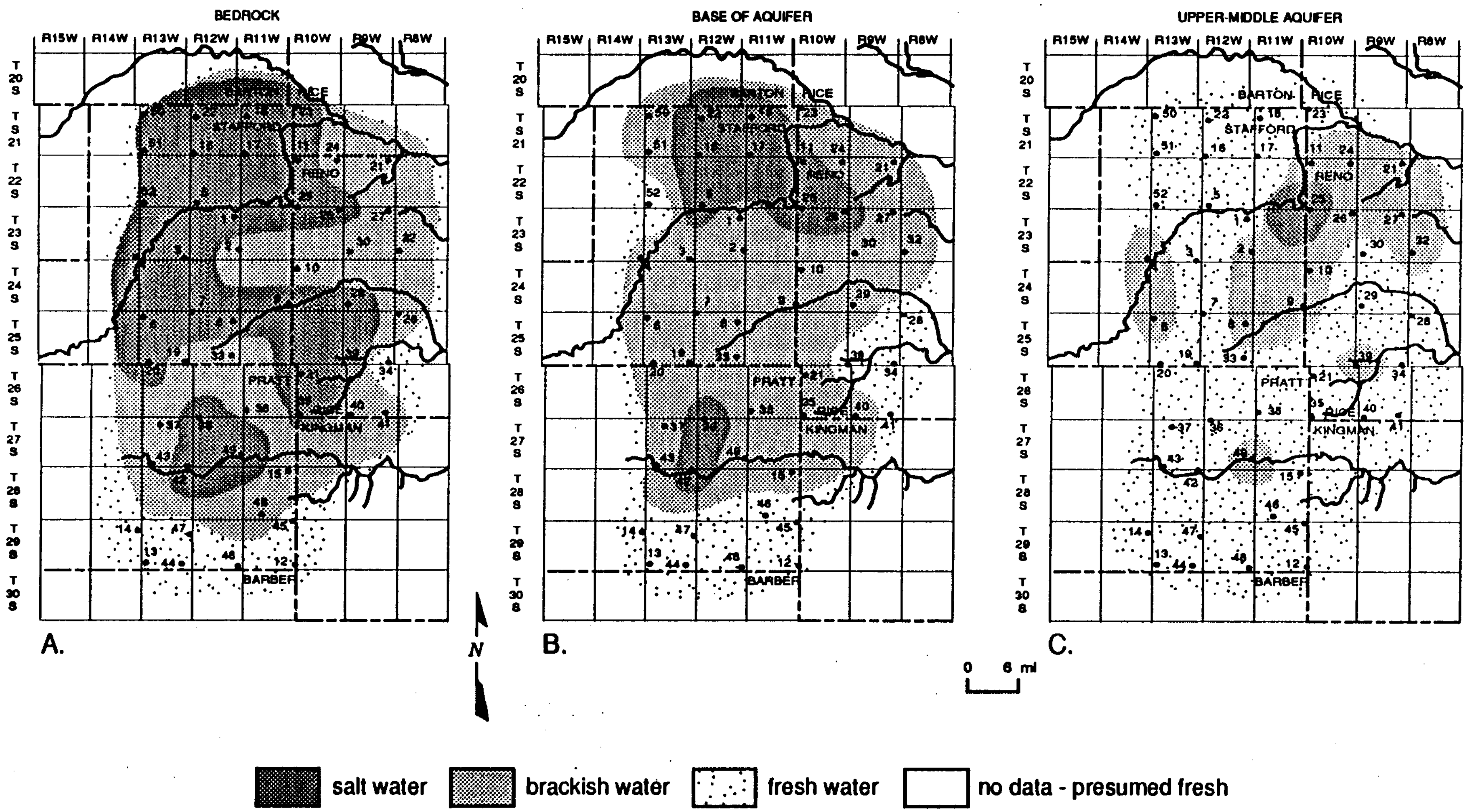


Figure 5. Maps showing categories of ground-water quality based on conductivity measurements at the numbered monitoring network sites; wells are identified as fresh (less than 1000 µS, or less than about 600 mg/l total dissolved solids (TDS)), brackish (1000-10000 µS, or 600-6000 mg/l TDS), or saline (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.

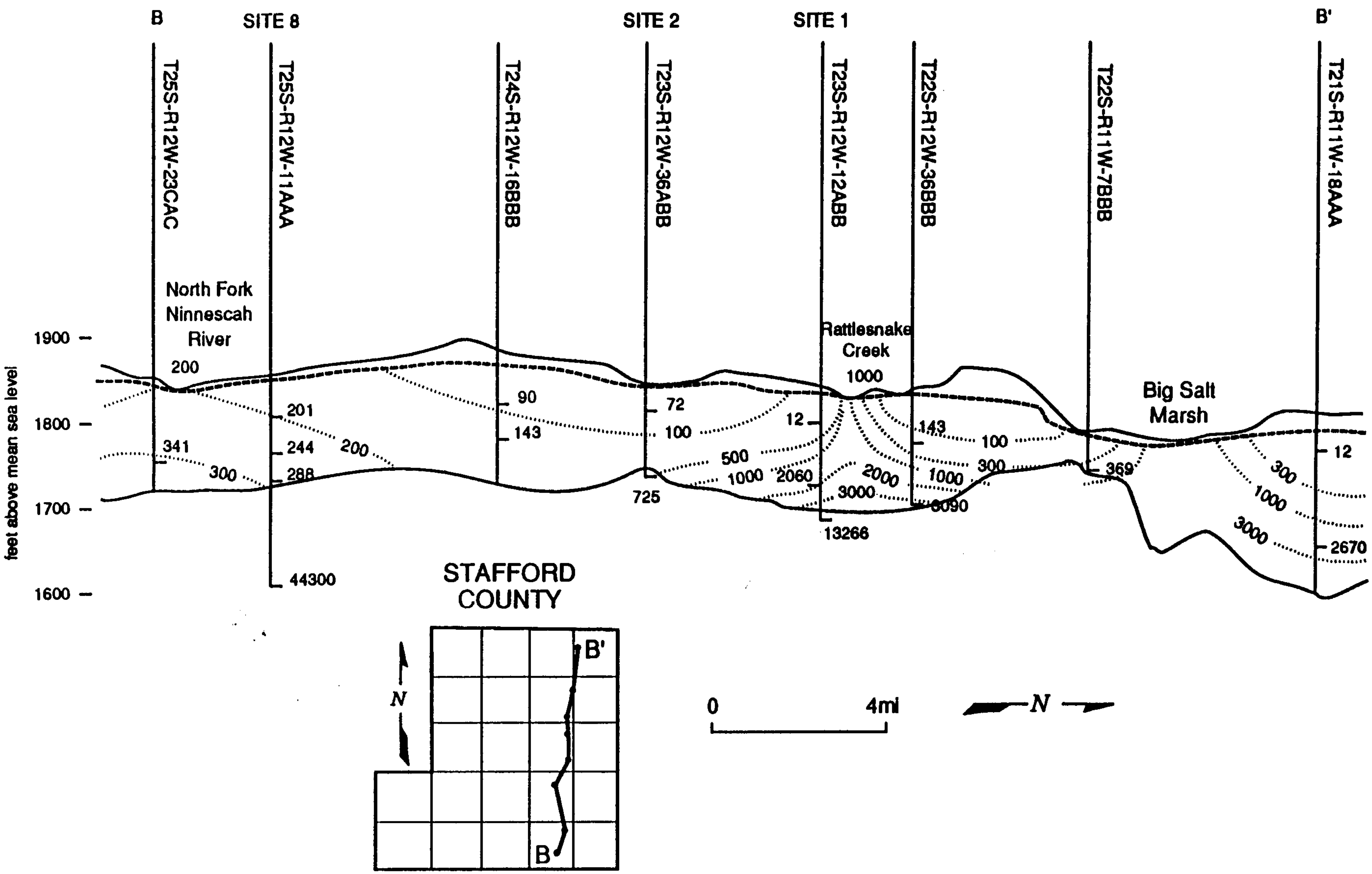


Figure 6. Cross section B-B' showing the position of the December 1973 water table and the inferred distribution of chloride (mg/L) in the major streams and aquifers (from Cobb, 1980). Isochlors are based on samples from wells at locations indicated by the vertical lines.

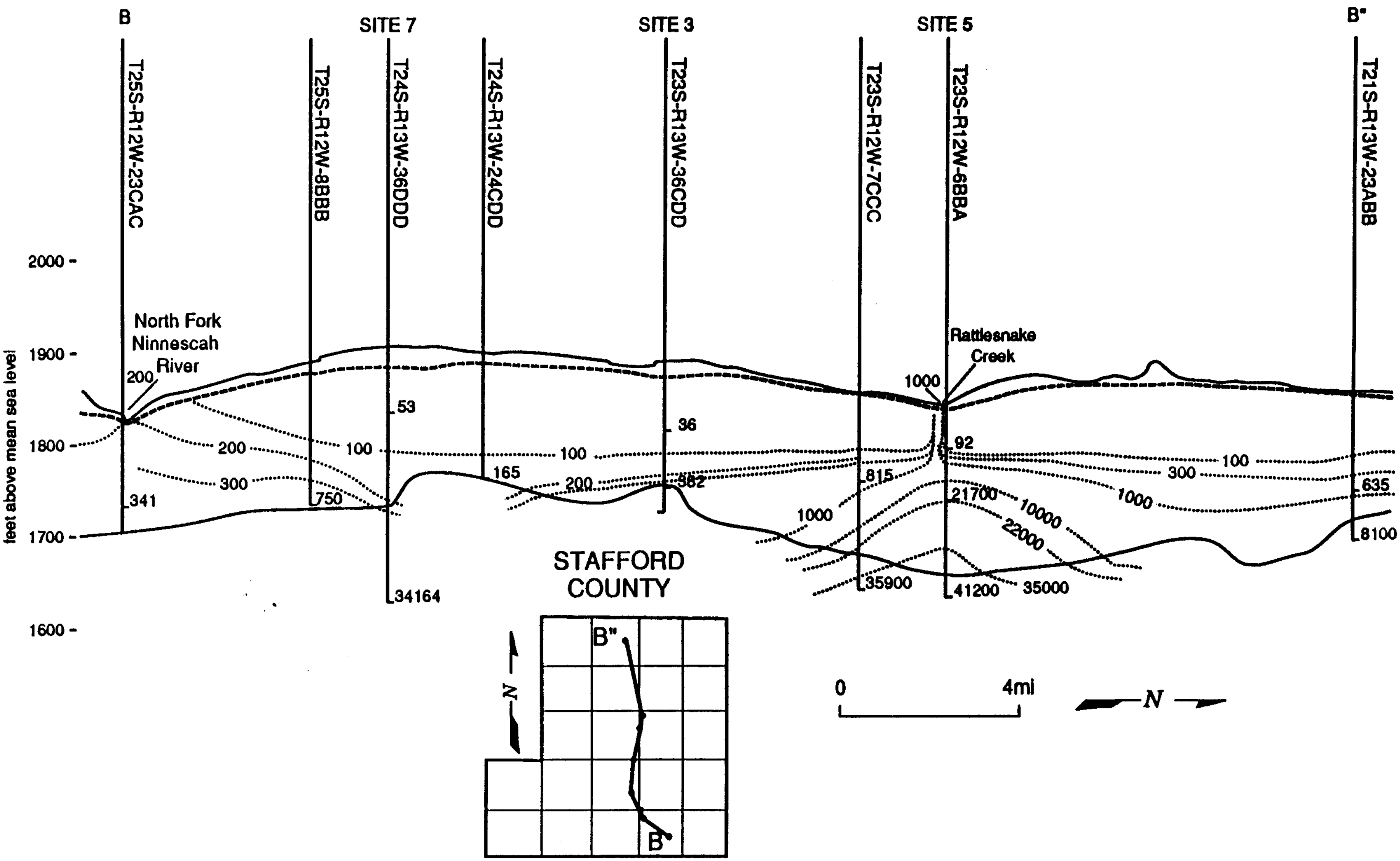


Figure 7. Cross section B-B" showing the position of the December 1973 water table and the inferred distribution of chloride (mg/L) in the major streams and aquifers (from Cobb, 1980). Isochlors are based on samples from wells at locations indicated by the vertical lines.

Recent water-quality information collected by GMD5 in northern Stafford County (Hudson Saltwater Study) supports these phenomena (GMD5, unpublished data). With one exception, sampled irrigation wells located clearly to the west of the Cedar Hills subcrop (Figure 2) in township 22-range 13W (T22-R13W) consistently yield fresh water (water with chloride concentrations less than 250 mg/L). In the same township, chloride concentrations of all irrigation wells located near or over the subcrop increase to more than 300 mg/L during the growing (pumping) season.

Hathaway et al. (1978) analyzed samples of irrigation well waters from the 36-square-mile area of T24-R13W, which is centered on Highway 281. They reported that ground waters in the aquifer are a $Ca\text{-}HCO_3$ type in the western half of this area and undergo transition toward a Na-Cl type in the eastern half. Data from one well suggest that a chloride source other than Na-Cl from Permian bedrock is contributing to the chloride load. A possible source of the excess chloride at this location, and at others, is oil brine (Whittemore and Hathaway, 1983; Whittemore, 1993). (See Appendix.)

The distribution of chloride with depth is variable, but trends are generally consistent. Chloride concentrations increase with depth in the fresh-water aquifer at all monitoring-well sites. Concentrations increase from the aquifer to the bedrock at all sites except sites 19 and 25. Hathaway et al. (1978) also reported a general deterioration of water quality with depth. Fader and Stullken (1978) reported that highly mineralized ground water in Pratt, Kingman, and southern Stafford counties is apparently limited to deeper bedrock channels.

However, some studies (Hathaway et al., 1978; Cobb, 1980; Sophocleous and McAllister, 1990) report that in certain areas water near bedrock seems to improve in quality and that better quality water is observed in inferred bedrock channels. The inconsistent relationship of water quality to depth indicates the complex nature of the aquifer system. The lithology of the Great Bend Prairie aquifer is not uniform. While the main water-bearing units are sands and gravels, relatively impermeable silt-clay layers or lenses are scattered throughout. These silt-clay units, which affect the movement and distribution of saline water, will be discussed in a following section: Salt Water in the Great Bend Prairie Aquifer.

The inconsistent relation of water quality to depth also suggests that mixing of salt water and fresh water has been and is occurring. Some natural mixing occurs, but this can be exacerbated by ground-water pumping. Intensive pumping can result in enhanced mixing of fresh and salt waters, increases in the amount of leakage from bedrock, and increasing chloride concentrations in individual wells. Water-quality information collected for the Hudson Saltwater Study reveals dramatic chloride increases in many irrigation wells during pumping seasons (GMD5, unpublished data).

GEOHYDROLOGY

Understanding the upward movement of saline water requires some comprehension of ground-water hydrology. The term hydraulic head, or head, is used to indicate potential energy at a point. The water level in a well expresses the potential energy averaged over the screened interval (Cobb, 1983). Comparison of water levels or heads in different wells can indicate ground-water flow direction. (Systems containing variable-density fluids require other considerations, which will be discussed later in this section.) Water tends to move from regions of higher head to regions of lower head. Figure 8 illustrates how this method can be used to determine both vertical and horizontal directions of ground-water flow.

If water-level elevations in wells tapping the same aquifer are plotted on a map and contoured, the result is a map of hydraulic head in the aquifer. For an unconfined aquifer, such as the Great Bend Prairie aquifer, the surface is called the water table. For a confined aquifer it is called the potentiometric surface.

Ground-water flow is downgradient in a direction perpendicular to the water-level contours. Thus the water-table contours in Figure 9 show that in the unconsolidated aquifer, ground water flows to the east. Figure 10 illustrates that ground water in the Cedar Hills Sandstone flows in a similar direction in the study area.

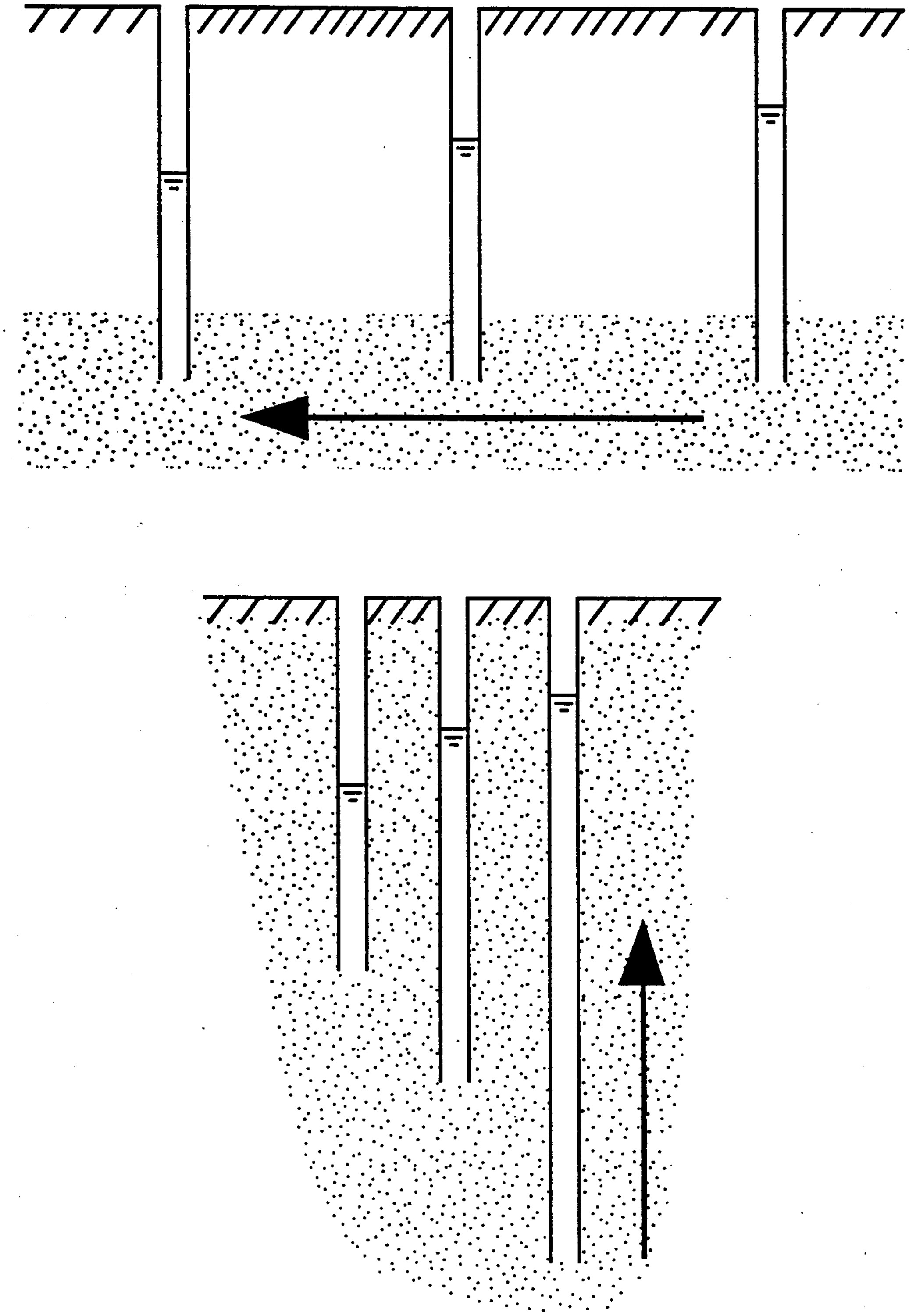


Figure 8. Determination of horizontal and vertical ground-water flow directions based on differences in hydraulic heads.

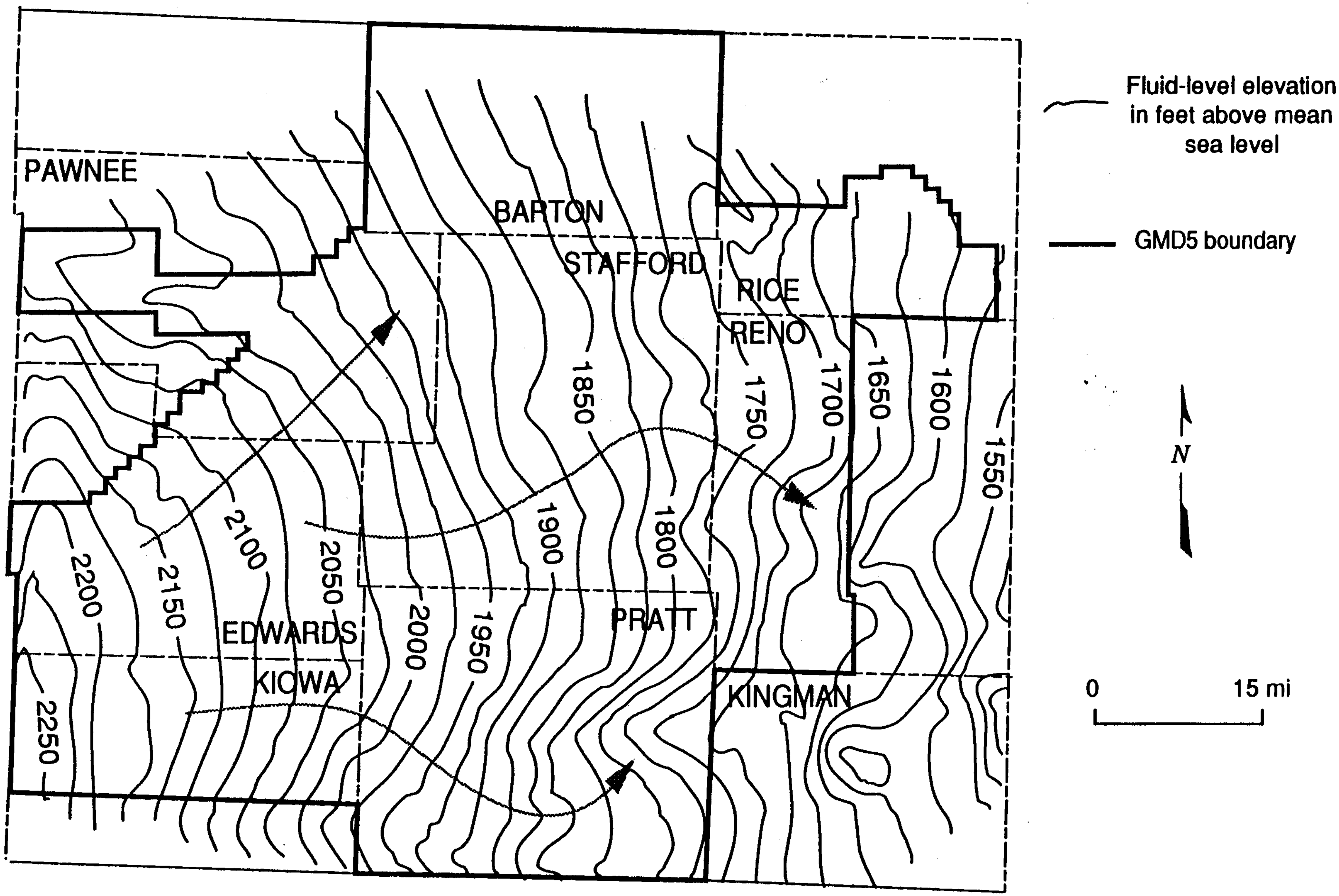


Figure 9. Contours of 1991 water elevations for GMD5. Ground-water flow is perpendicular to the contour lines, as shown by the arrows (from Sophocleous, unpublished map, 1992).

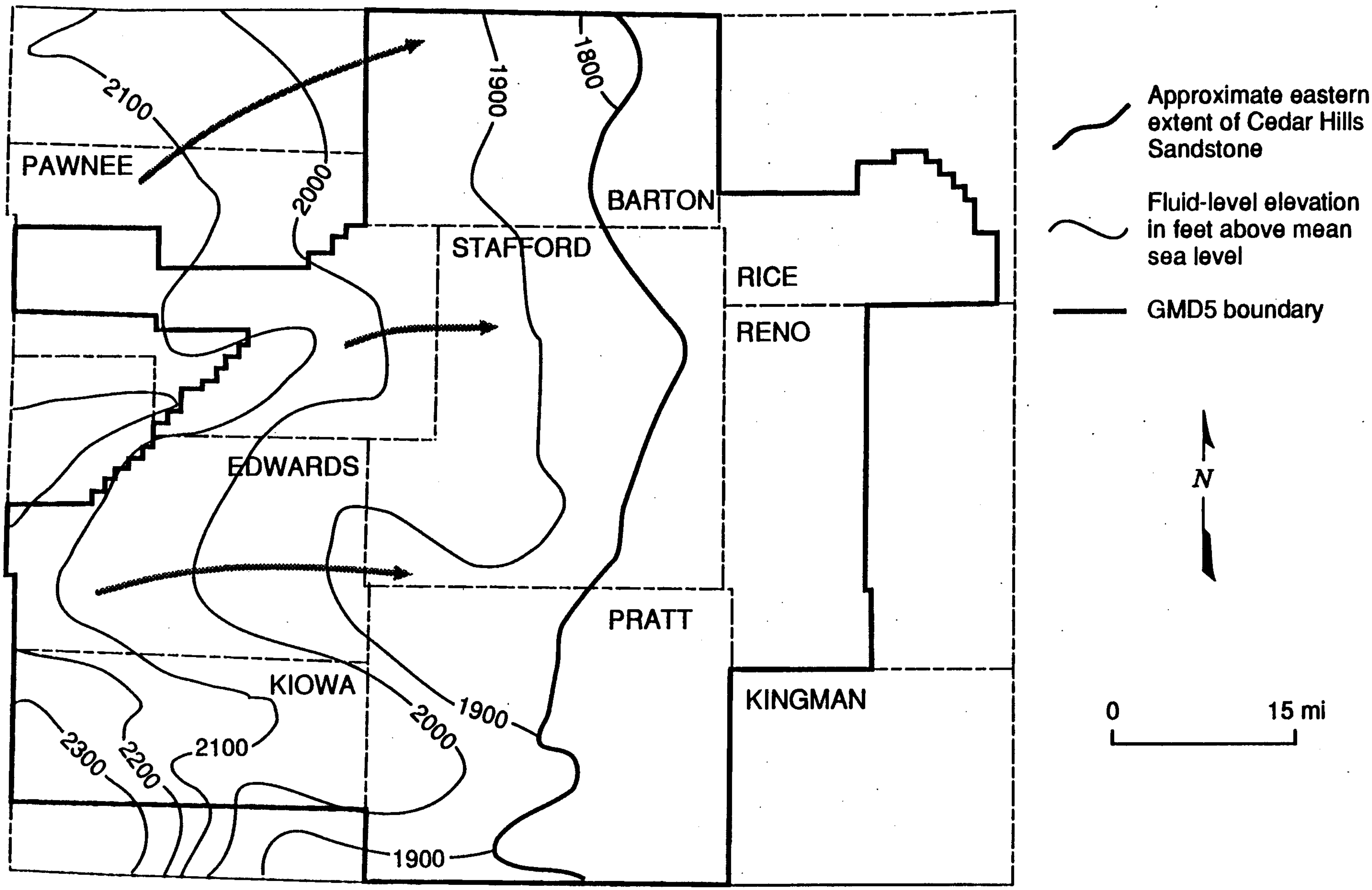


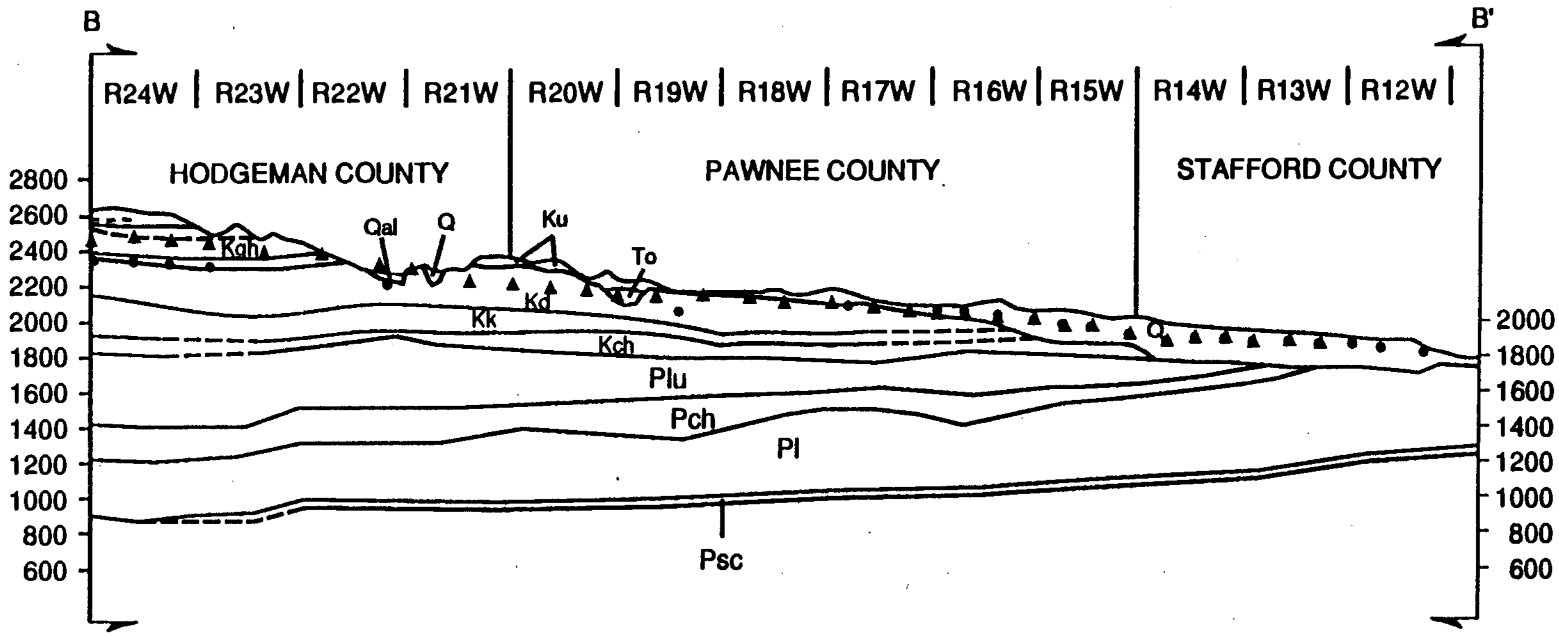
Figure 10. Potentiometric surface map of the Cedar Hills Sandstone: circa 1975 (from Macfarlane and Chen, unpublished map, 1992). Ground-water flow is perpendicular to the contour lines as shown by the arrows.

The geologic cross sections (Figures 11 and 12) show that the potentiometric surface of the Cedar Hills Sandstone is fairly well matched with that of the overlying fresh-water aquifer (Kansas Corporation Commission, 1986). In the study area the hydraulic gradient of the Cedar Hills Sandstone ranges from about 7.2 feet per mile in Stafford County to about 8.5 feet per mile in Pratt County. The hydraulic gradient of the Great Bend Prairie aquifer is similar, generally ranging between 7 and 9 feet per mile.

Where fresh-water heads are higher than heads in bedrock wells, fresh water tends to keep lower salt water contained. Conversely, if Permian heads are higher, salt water may move upward if hydrologic conditions are otherwise opportune. However, this scenario is complicated by variable densities of the fresh and salt waters. Salt water is denser (or heavier) than fresh water.

When determining flow direction in such a system, it is necessary to consider the implications of fluids of different densities. Hydrologists and others commonly have tried to account for the effects of variable density by converting salt-water heads to equivalent fresh-water heads. Unfortunately, this technique can lead to erroneous interpretation of directions of ground-water flow. Jorgensen et al. (1982) and Davies (1987) give insightful discussions concerning methods of determining the occurrence and direction of flow in variable-density aquifers and identify potential errors in using equivalent fresh-water heads. For the remainder of this report, the terms "fluid level" and "head" will refer to a water level not adjusted for density; "adjusted head" or "head adjusted for density" will refer to a water level adjusted to an equivalent fresh-water head.

In some locations hydraulic heads in the Permian bedrock are higher than the fresh water table, a condition that favors upward leakage of Permian waters. Data from the KGS/GMD5 monitoring-well network indicate that Permian heads are normally higher than fresh-water heads at sites 2, 4, 5, 15, 41, and 49. Gillespie et al. (1991) reported these conditions in T27-R11W and other locations near the South Fork Ninnescah River. In some places Permian heads are above the land surface, creating flowing artesian conditions when tapped.



Q - Undifferentiated Quaternary Deposits
Qds - Quaternary Dune Sand
Qal - Quaternary Alluvial Deposits
To - Ogallala Formation
Ku - Undifferentiated Upper Cretaceous Rocks
Kgh - Greenhorn Limestone
Kd - Dakota Formation
Kk - Kiowa Formation
Kch - Cheyenne Sandstone
Plu - Undifferentiated Lower and Upper Permian Rocks
Pch - Cedar Hills Sandstone
Pl - Undifferentiated Lower Permian: Harper-Salt Plain Formation
Psc - Stone Corral Formation

● Fresh water table
▲ Cedar Hills potentiometric surface
Geologic contact - *dashed where approximately located*
Vertical scale is exaggerated
Datum is sea level

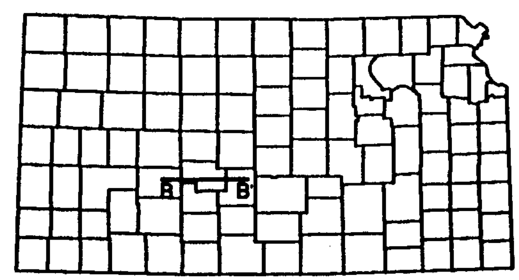
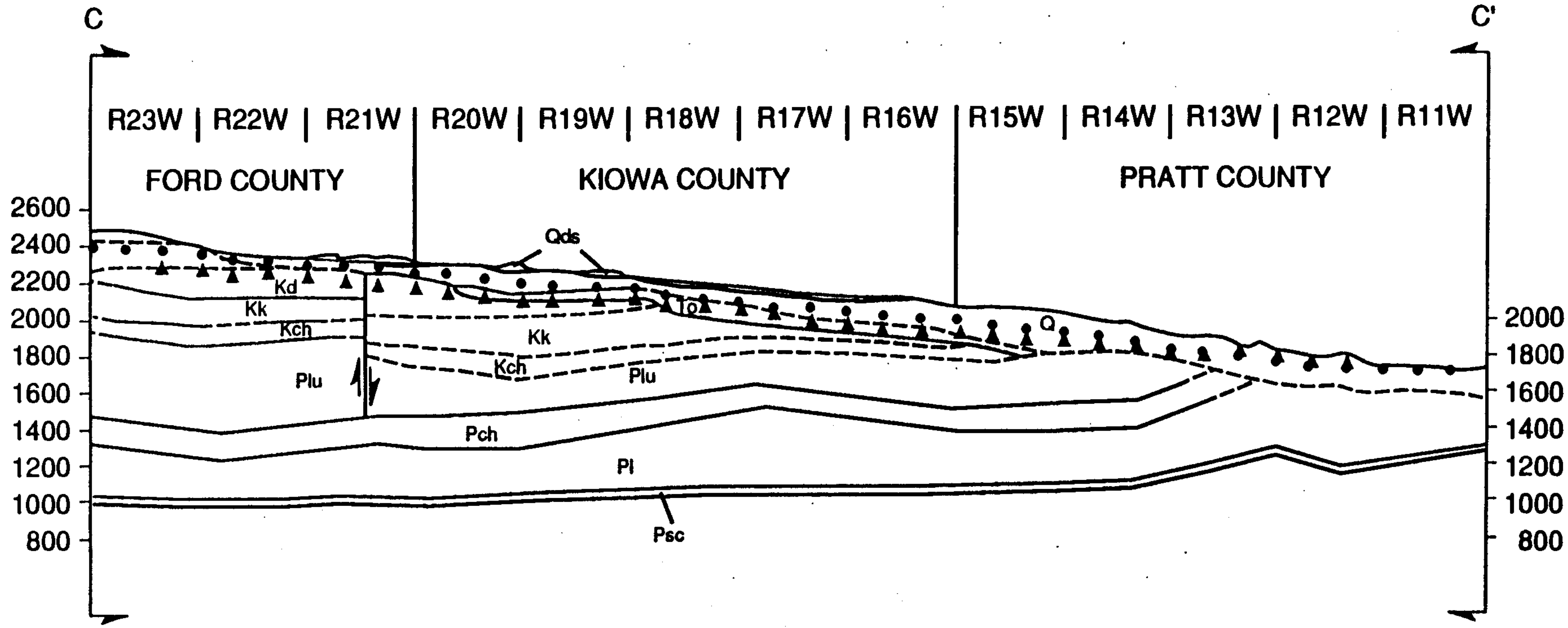


Figure 11. Geologic cross-section B-B' showing the fresh water table and the Cedar Hills potentiometric surface (adapted from KCC, 1986).



Q - Undifferentiated Quaternary Deposits
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To - Ogallala Formation
Kd - Dakota Formation
Kk - Kiowa Formation
Kch - Cheyenne Sandstone
Plu - Undifferentiated Lower and Upper Permian Rocks
Pch - Cedar Hills Sandstone
Pl - Undifferenіated Lower Permian: Harper-Salt Plain Formation
Psc - Stone Corral Formation

• Fresh water table
▲ Cedar Hills potentiometric surface
| Concealed fault
Geologic contact - *dashed where approximately located*
Vertical scale is exaggerated
Datum is sea level

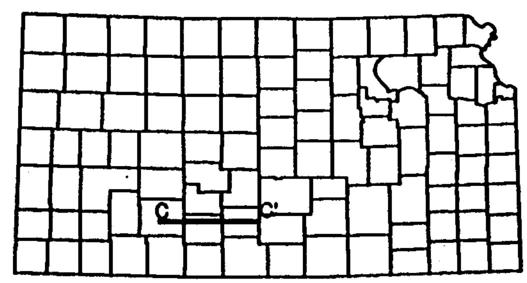


Figure 12. Geologic cross-section C-C' showing the fresh water table and the Cedar Hills potentiometric surface (adapted from KCC, 1986).

Sophocleous (1992b) recognized that at monitoring-well sites 18 and 19, Permian heads have become higher than deep alluvial aquifer heads for increasingly longer periods as pumping reduces the fresh-water heads (see Figure 13). The implication is that Permian waters have an increasing tendency to intrude into the fresh-water aquifer. Head changes in both the fresh-water and (the shallow portion of the) bedrock aquifers appear to correlate with annual pumpage from and recharge to the aquifer (Cobb, 1980).

Aquifer Hydrogeologic Properties

The rate of ground-water flow is influenced by differences in hydraulic heads and by aquifer properties such as permeability or hydraulic conductivity. Coarse-grained materials (sands and gravels) are more permeable than fine-grained materials (silts, clays, and most rocks). Therefore they can transmit more water than fine-grained materials. Table 2 lists ranges of hydraulic conductivity of different materials.

Little information is available on the hydrogeologic properties of Permian formations. Fader and Stullken (1978) state that wells in rocks of Early Permian age may yield from about 10 to 100 gallons per minute (gpm), however the waters are highly mineralized. Using particle sizes from cuttings, Cobb (1980) correlated the Permian units to a "poor aquifer." The range of hydraulic conductivity (K) for this group is given as 0.00013 to 1.3 feet per day (ft/day). The hydraulic conductivity in the Great Bend Prairie aquifer, including the Arkansas River alluvium, has been estimated to range from 20 to 280 ft/day (Fader and Stullken, 1978; Sophocleous and Perkins, 1992).

At least three studies (Olsen, circa 1981; Cobb et al., 1982; KCC, 1986) have attempted to estimate hydraulic properties of Permian formations in the study area. These reports were based on very limited data from slug tests performed on wells in the KGS/GMD5 monitoring-well network. Estimates for hydraulic conductivity (K), storage coefficient (S), and vertical hydraulic gradient (*i*) are listed in Table 3.

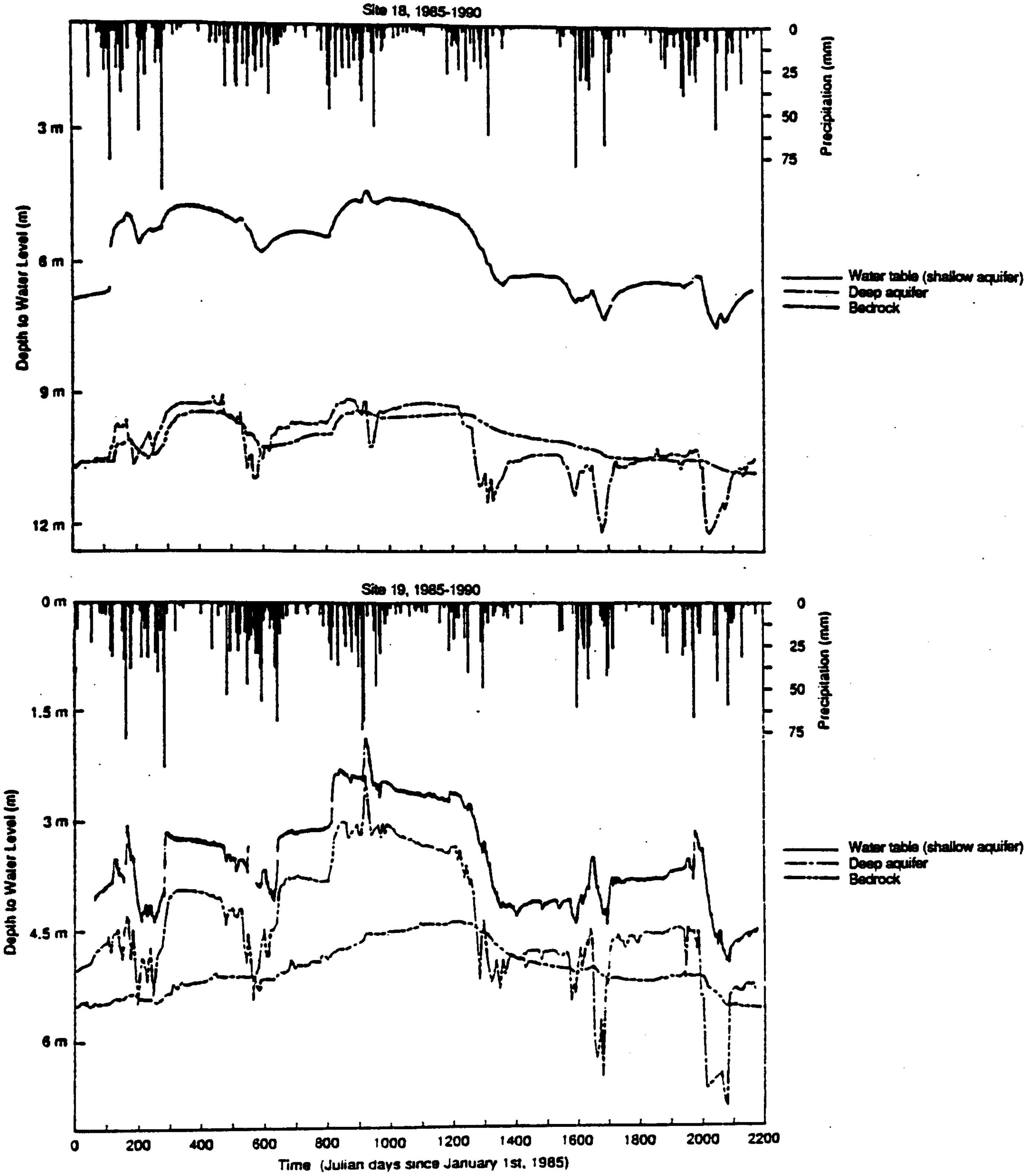


Figure 13. Daily precipitation and multiple depth ground-water-level time series for sites 18 and 19 for the period 1985-1990 (from Sophocleous, 1992b).

Table 2. Range of values of hydraulic conductivity
(adapted from Freeze and Cherry, 1979; and Todd, 1959).

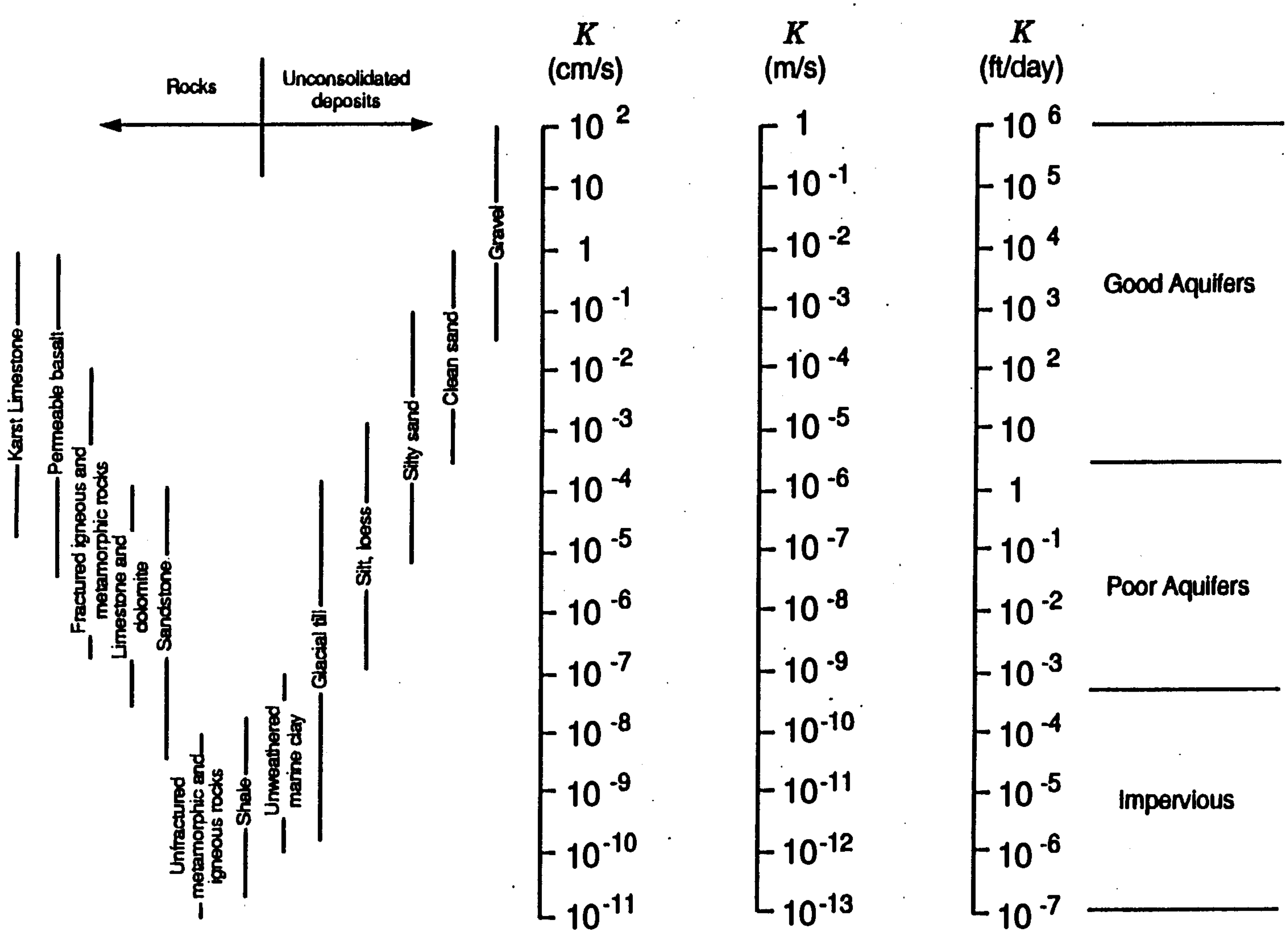


Table 3. Estimates of hydraulic conductivity (K), storativity (S), and vertical hydraulic gradient (i) compiled from KCC (1986), Olsen (circa 1981), and Cobb et al. (1982).

Site	Location	Geologic Unit	K (ft/day)	i*	S
1	NE NE NW12-23S-12W	Salt Plains	14.7	-0.11	
5	NW NW NW6-25S-12W	Cedar Hills	4.9	-0.89	
6	NW SW NW6-25S-13W	Undiff. Permian	0.03	-0.47	$10^{-2} - 10^{-4}$
			0.04		
7	SE SE SE6-24S-13W	Cedar Hills/Undiff.	0.2	-0.01	
			0.5		$10^{-4} - 10^{-6}$
8	NE NE NE11-25S-12W	Cedar Hills	0.35	-0.07	$10^{-3} - 10^{-5}$
10	SE SW SW6-24S-10W	Salt Plains	1.0	0.01	
			9.4		$10^{-5} - 10^{-7}$
15	NE NE NE1-28S-11W	Salt Plains	0.01		
			0.01		$10^{-1} - 10^{-3}$
17	SE SE SE36-21S-12W	Salt Plains	0.009		
18	NW NW NW7-21S-11W	Salt Plains	0.006		
19	SE SW SW36-25S-13W	Cedar Hills	0.008		
**	NE 35-22S-23W	Cedar Hills	1.5		1×10^{-4}
			0.04		0.166

* Vertical hydraulic gradients calculated by Cobb et al. (1982). Calculations were based on heads adjusted for density. These values may greatly overestimate the actual gradients.
** From KCC (1986).

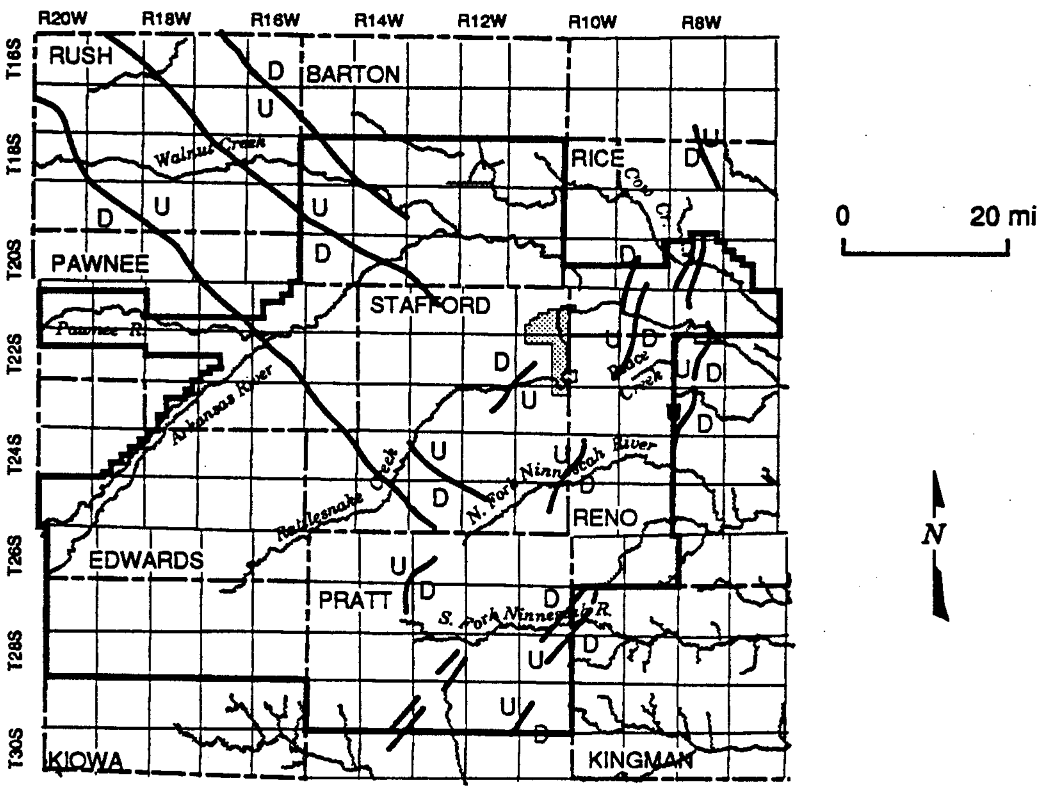
Permian K estimates ranged from 0.006 to 14.7 feet per day. Olsen (circa 1981) concluded that the hydraulic conductivity of the Permian rock, within 25 feet of the interface with the overlying aquifer, is generally about 10^{-6} cm/sec (0.003 ft/day). This estimate was based on data from only five wells which, according to Olsen, were clearly completed and sealed in the red rock. Based on inspection of cores and familiarity with the slug tests, a Permian K value of this magnitude is reasonable (T. J. McClain, personal communication, 1992).

The KCC (1986) report used data from existing disposal wells along with slug-test data from Permian observation wells to make estimates of the hydraulic properties of the Cedar Hills Sandstone. This report maintains that the most realistic hydraulic conductivity value is on the order of 1.5 to 2.0 ft/day. Using these values for K and assuming a saturated thickness of 100 feet, a transmissivity (T) value ranging from 150 to 200 ft^2/day was obtained.

Cobb et al. (1982) preferred a K value of 4.93 ft/day, but made the distinction that the calculated K values (listed in Table 3) may actually represent the horizontal hydraulic conductivity, not the vertical. Cobb et al. indicated that these values may therefore overestimate the vertical K by several orders of magnitude. They also emphasized that, because of the limited data available, only very sketchy hypotheses could be constructed concerning the distribution of hydraulic conductivity and the regional salt-water inflow.

More recently the hydraulic conductivity of the Salt Plain Formation was estimated from aquifer tests utilizing recovery or slug-test analyses in five monitoring wells near Cairo (J. B. Gillespie, personal communication, 1992). Hydraulic conductivity values ranged from about 0.2 to 0.7 ft/day, with an average of 0.5 ft/day. According to Gillespie, K values could be greater locally because of fracturing.

The area around Cairo has been active geologically. Pre-Permian faults trend northeasterly across eastern Pratt County and northwestern Kingman County (Figure 14). An earthquake registering 4.4 on the Richter scale occurred in 1956; the epicenter was located in western Kingman County (Gordon, 1988). It is probable that deformation and movement along the fault



U = Upthrown side
D = Downthrown side

Figure 14. Pre-Permian faults in GMD5 (adapted from Merriam, 1963).

zones have caused fracturing in the friable Permian siltstone, sandstone, and shale (J. B. Gillespie, personal communication, 1992).

The hydraulic conductivity of the bedrock may decrease with depth. Cobb (1980) hypothesized that if the Permian formations are weathered in their upper zones, then their permeability may be altered. The degree of alteration would decrease with depth. This situation could account for a water-quality gradient in the bedrock. Fresh-water penetration into the Permian bedrock may be enhanced in the altered regions of higher permeability. In the southern part of the study area, for example, fresh water could dilute and flush low-quality water from the shallow zone of the bedrock. Thus the occurrence of fresh water in the shallow bedrock would not preclude the occurrence of low-quality water deeper in the bedrock.

Upward Leakage from the Permian Bedrock

The amount of water that discharges from the Permian formations into the fresh-water aquifer has been estimated. Estimates of leakage (Olsen, circa 1981; Cobb et al., 1982; KCC, 1986) from the Cedar Hills Sandstone subcrop (Figure 2) range from about 700 acre-feet/year to about 14,000 acre-feet/year. All estimates were based on the Darcy equation:

$$Q = KiA,$$

where

Q is the amount of discharge or leakage (volume/time);
K is the hydraulic conductivity (length/time);
i is the hydraulic gradient (length/length or dimensionless); and
A is the area across which leakage occurs.

Discharge at the Cedar Hills subcrop was estimated to be about 700 acre-feet/year in the KCC (1986) report. This estimate was based on the following parameters: K = 1.5 ft/day, i = 0.00133, and A = 1,000 acres. Apparently, the hydraulic gradient used was the horizontal gradient, roughly 7 feet per mile, and the area was a vertical cross section of the Cedar Hills.

Fader and Stullken (1978) estimated inflow from bedrock to be 5,000 to 10,000 acre-feet/year. This estimate was based on the assumptions that "the Cedar Hills Sandstone is the major contributor; the hydraulic gradient in the formation is virtually equal to and in the same direction as in the overlying unconsolidated deposits; and the hydraulic conductivity of the Cedar Hills Sandstone is about 25 feet per day."

Cobb et al. (1982) estimated upward leakage from the Cedar Hills Sandstone to be about 14,000 acre-feet/year, using a K value of 4.93 ft/day, a vertical hydraulic gradient of -0.1 (a negative gradient indicates upward movement of fluid), and an area of 28,800 acres. The 28,800-acre area used corresponds to the Cedar Hills subcrop area from approximately the Barton County line to about U.S. Highway 50 (Figure 2). Using these numbers, however, Cobb et al. should have calculated a discharge of 14,000 acre-feet *per day,* not per year. This would represent an annual discharge on the order of 5 million acre-feet. As alluded to in the two reports just mentioned, the maximum horizontal flow that could be sustained in the Cedar Hills Sandstone in the study area is on the order of 10,000 acre-feet per year. It is virtually inconceivable that an annual supply of millions of acre-feet from a portion of the Cedar Hills subcrop would be sustainable.

Cobb et al. (1982) used some assumptions that would tend to maximize leakage estimates. First, as was mentioned previously, the (horizontal) K value used to estimate upward leakage may overestimate the vertical hydraulic conductivity by orders of magnitude. Second, the vertical hydraulic gradient used may greatly overestimate the average vertical gradient.

Vertical hydraulic gradients calculated by Cobb et al. (Table 3) were based on heads adjusted for density at six monitoring well sites. The observed Permian fluid level was consistently higher than the deep aquifer fluid level at only one of these sites (site 5), and intermittently higher at only one other (site 6). However, after adjusting for density, calculated hydraulic gradients were negative at five of the six sites, thus giving a much greater indication of upward flow than would the observed heads. There is no convincing evidence that the value of -0.1 accurately represents the average vertical gradient. This value, used to estimate leakage, may greatly overestimate the average vertical hydraulic gradient. Cobb et al. (1982) recognized that the vertical hydraulic gradient is not negative at all locations. A positive gradient suggests that bedrock may also accept a certain amount of water from the unconsolidated fresh-water aquifer.

Considering this inspection of the vertical *i* and K values used, it seems obvious that Cobb et al. (1982) may have overestimated leakage by at least two or three orders of magnitude. If the leakage estimate of 5 million acre-feet per year were reduced by two or three orders of magnitude, values would fall closer to or within the range of values given by Fader and Stullken (1978) and KCC (1986).

Table 4 was constructed to put the Cedar Hills leakage estimates in perspective. Many of the numbers in this table are only rough estimates based on limited data obtained in and around the Cedar Hills subcrop area (Figure 2). Therefore this table should be used for relative comparisons only. Importantly, the numbers seem to indicate that the amount of water entering the Great Bend Prairie aquifer from the bedrock may be of the same magnitude as the amount entering as recharge from precipitation. This suggests that under natural conditions there may be a dynamic balance between these two sources of recharge to the Great Bend Prairie aquifer. The implication is that mineral intrusion is indeed a serious threat to the water quality of the fresh-water aquifer in the area, especially if ground-water withdrawals disrupt the balance.

The table also indicates that the amount of water discharged from the aquifer by pumpage, and the amount of storage loss (calculated from water-table declines), are of the same magnitude as the recharge and leakage estimates. It should be noted that there is not a consistent trend in water-table declines. In some areas the water table stays fairly constant with time, and in some areas it appears to be rising. In other words, pumpage does not seem to cause long-term water-table declines in all areas. However, even where water-table declines are not evident, increases in pumpage may be counterbalanced by increasing amounts of salt-water leakage from the bedrock.

Many researchers assume that the Cedar Hills Sandstone is the major source of salt water to the alluvial aquifer. However, because the subsurface hydraulic relationships between the formations are not clearly understood, it is important to consider other possibilities. For example, it is unclear whether or not the Cedar Hills contributes substantially more salt water than other subcropping Permian formations (Figure 2) or deeper Permian formations (Table 1). Also, the relative importance of the Cheyenne Sandstone is not well understood.

Table 4. Partial water budget for the Great Bend Prairie aquifer in the vicinity of the Cedar Hills subcrop. [Some values are rough estimates. Table should be used for relative (order of magnitude) comparisons only.]

	Flow (acre-ft/yr)	Area (acres)	Flow/Area (acre-ft/acre/yr)	Recharge (in/yr)	Discharge (in/yr)	Storage Loss (in/yr)
Salt-water leakage						
KCC (1986)	**700**[a]	90,000[b]	0.008	0.1	–	–
Fader and Stullken (1978)	**5,000–10,000**	90,000	0.06–0.1	0.7–1.3	–	–
Cobb et al. (1982)	**≥5,000**[c]	28,800[d]	≥0.2	≥2.0	–	–
Recharge from precipitation						
	7,500–22,500	90,000	0.08–0.25	**1–3**[e]	–	–
	2,400–7,200	28,800	0.08–0.25	**1–3**	–	–
Pumpage						
	18,000	90,000	**0.2**[f]	–	2.4	–
	5,800	28,800	**0.2**	–	2.4	–
Water table decline						
	≤7,500	90,000	**≤0.08**[g]	–	–	≤1
	≤2,400	28,800	**≤0.08**	–	–	≤1

a. Bold-faced values are primary; other values in each row have been calculated from these using area listed in each row.
b. Approximate area of Cedar Hills subcrop (Figure 2) in Stafford and Pratt counties.
c. See text for explanation.
d. Approximate area of Cedar Hills subcrop from Barton County line to about U.S. 50, as estimated by Cobb et al. (1982).
e. Sophocleous (1992b).
f. Calculated from data in 1990 Kansas Irrigation Water Use Report. Some 5 to 15% of water pumped for irrigation may return to the ground-water reservoir.
g. Based on water-level declines of 0 to 10 feet in 20 years, and assuming a porosity of 0.17.

A number of hypotheses exist on how saline ground water discharges to the South Fork Ninnescah River. One hypothesis is that the source of saline water near Cairo is the dissolution of salt in the Permian Ninnescah Shale, about 600 feet below land surface. Subsidence and collapse into salt cavities may have caused fracturing in the overlying siltstone, fine sandstone, and shale (J. B. Gillespie, personal communication, 1992). Brine may move upward through the Permian aquifer and discharge into the alluvial aquifer and the river.

Assuming that the water in the Permian aquifer has a chloride concentration of approximately 33,000 mg/L, and taking into account the chloride discharge to the river of about 63 tons per day, the rate of briny ground-water discharge to the alluvial aquifer along a five-mile reach near Cairo has been estimated to be about 300 gallons per minute or about 500 acre-feet per year (J. B. Gillespie, personal communication, 1992).

Layton and Berry (1973) reported that the increase in the flow and in the concentration of dissolved solids in the South Fork Ninnescah River near Cairo could result from leakage from Permian rocks of about 1,500 acre-feet annually.

A reliably accurate estimate of total leakage from Permian bedrock can not be made at this time. In addition to unknown aquifer hydrogeologic properties and hydraulic relationships, features such as unplugged wells and boreholes, sinkholes, and fractures may provide pathways for more rapid contaminant transport (see Appendix). It is possible that discharge from the Cedar Hills Sandstone alone accounts for an appreciable percentage of the total natural recharge into the eastern Great Bend Prairie aquifer. Leakage from other Permian formations would of course increase the percentage.

Salt Water in the Great Bend Prairie Aquifer

The principal water-bearing units in the Great Bend Prairie aquifer are sands and gravels, which transmit large quantities of water. The formation also contains clay layers or lenses of varying thickness and lateral extent. These relatively impermeable clay units act as controls on the upward movement of saline water.

It is not uncommon, particularly in northern Stafford County, to encounter fresh water overlying a clay unit and mineralized water below the clay. Monitoring-well data are indicative of this phenomenon. Fader and Stullken (1978) mentioned that clay layers, where present, may separate highly mineralized waters below from water suitable for irrigation above. According to Rosner (1988), the driller of an irrigation well near monitoring-well site 23 noted that below a silt-clay lens the water was too saline for irrigation. The water overlying that silt-clay lens, however, was suitable for irrigation. Cobb (1983) observed that in areas where deeper ground waters are plagued with salt water problems, shallow fresh water is often underlain by a relatively thin, but extensive clay unit.

Rosner (1988) lists 44 locations in the study area where silt-clay lenses directly overlie the bedrock, including observation well sites 1, 6, 9, 16, 25, and 51. These lenses may serve as confining layers, separating the fresh-water aquifer from underlying salt water. It is well established that if saline water and then fresh water come in contact with silt-clay, the permeability of the silt-clay is significantly reduced.

At least one author (Cobb, 1983) envisioned a (fairly) continuous clay layer separating the upper and lower portions of the Great Bend Prairie aquifer. Figure 15 is a schematic showing Cobb's (1983) idea of the typical configuration of the aquifer along with various possible scenarios for salt-water movement. Cobb maintained that the shallow aquifer is generally in the 100-foot depth range and the deep aquifer is often from 150 to 180 feet below land surface.

The idea of an upper and a lower aquifer separated by a confining layer is supported by the fact that heads are sometimes higher in the lower part of the aquifer. This condition exists at 16 sites in the monitoring-well network. However, there is little if any evidence that (deep) confining layers are extensive. It is more likely that silt-clay lenses act as confining or semiconfining units locally.

Although a continuous confining layer at depth is unlikely, Layton and Berry (1973) and Rosner (1988) identified a fairly continuous near-surface silt-clay layer. The silt-clays extend from the surface to the bedrock at locations north and west of the study area. Relatively thick silt-clays

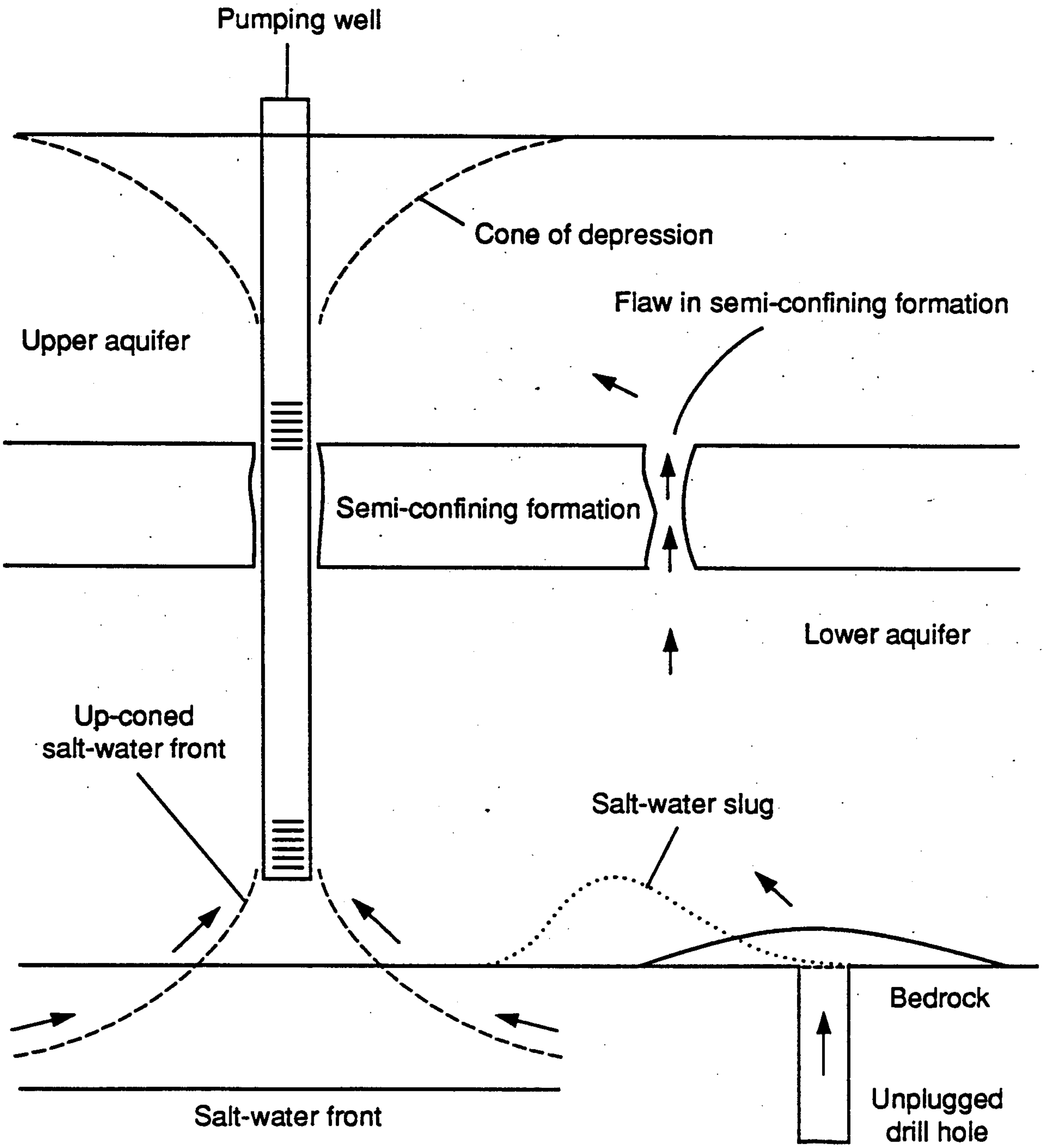


Figure 15. Schematic showing a possible configuration of the Great Bend Prairie aquifer and possible scenarios for salt-water movement (adapted from Cobb, 1983). Arrows represent direction of water flow. When salt water is under greater pressure (i.e., higher head) than overlying fresh water, the salt water may move upward where pathways exist.

lie on or near bedrock highs in the southern part of the study area. Site 49 is the only location in the monitoring-well network where the near-surface silt-clay may be absent (Rosner, 1988). Because the permeability of the near-surface silt-clay layer could be reduced by salt-water contact, recharge to the aquifer could be affected by such contact.

As mentioned previously, heavy ground-water pumpage may increase the rate of natural salt-water intrusion into the Great Bend Prairie aquifer. This is true on a local scale (one well) and on a regional scale. It is particularly risky to drill or pump an irrigation well that is too deep (for example, a well screened beneath a deep clay layer and/or near the Permian bedrock or the fresh-water/salt-water interface). In such cases, increasing salt concentrations may rapidly render the water unsuitable for irrigation. In addition to high chloride concentrations, ground waters in much of eastern GMD5 have medium to very high sodium hazards. The result of pumping such water could range from reduced crop yields or loss of the present crop to field damage sufficient to impair or prohibit future crops.

Figure 16 represents salt-water upconing in the vicinity of a high-capacity well. The exact situation depends on the occurrence and extent of confining layers between the well and the fresh-water/salt-water interface. If no confining layer exists between the well screen and the salt water, the cone of depression of the water table acts to "pull up" a matching cone of salt water below the well (Figure 16B). Confining or semiconfining layers of low permeability (silt-clay) may inhibit or impede the upward movement of salt water.

On a larger, more regional scale, heavy pumpage may result in lowering of the water table (lower fresh-water head), particularly during periods of drought (see Figure 13). Lower fresh-water heads probably result in increases in the rate and amount of salt-water intrusion from the Permian bedrock, for reasons discussed previously.

As mentioned earlier, heavy pumpage does not seem to be causing water-table declines in all areas. Nevertheless, ground-water withdrawals may be counterbalanced by upward leakage of salt water. In effect, this also may increase the rate and amount of salt-water intrusion and result in an upward movement of the salt-water/fresh-water interface.

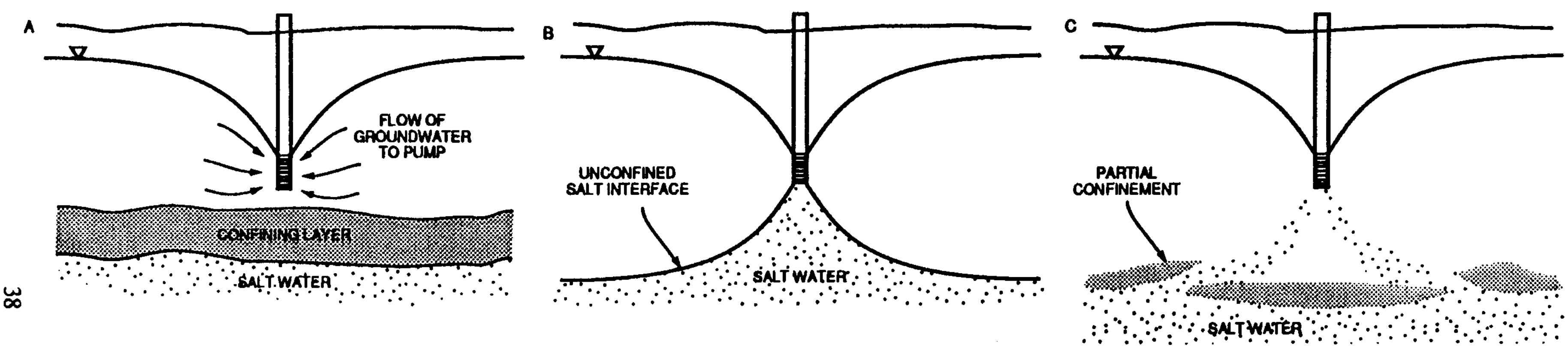


Figure 16. Salt-water upconing in response to pumping stress. A: The "confined" case, where a thick clay layer ("confining layer") inhibits response. B: The "unconfined" case, where salt water migrates freely toward the pumping well. C: The "semi-confined" case, where discontinuous clay stringers impede but do not completely block the upward movement of salt water.

Once the salt-water/fresh-water interface rises into a previously fresh water portion of the aquifer, the salt water is never perfectly flushed from the system, even if the interface returns to its original position. With repeated intrusions, a residual builds up until the water is eventually unusable for most purposes.

APPENDIX:
Disposal of Oil-Field Brines and Other Sources of Local Salt-Water Contamination

Local ground-water contamination may result from a number of sources, including human and livestock wastes, road salts, and evaporation of irrigation water, which results in the concentration of salts or solutes (see Whittemore, 1993). One practice that may represent a prominent source of salt-water pollution is the disposal of waste oil-field brines.

Disposal of oil-field brine is much better regulated than in the past; however, problems still exist, many resulting from practices that occurred decades ago (Cobb, 1983). Ground-water contamination from oil-field brine has been confirmed for at least one site in the study area (Whittemore and Hathaway, 1983) and is suspected at others. Sources of contamination from oil and gas activities include surface disposal ponds, disposal or injection wells, and unplugged or improperly plugged boreholes.

For a few decades oil-field brines were commonly disposed of in surface ponds or pits. Actually, brines were sometimes simply disposed of on the land. Obviously, these practices could result in contamination of soil and ground water. Surface disposal has resulted in major contamination in some areas in Kansas such as the Burrton area of the Equus Beds aquifer, but surface contamination is only local in the GMD5 study area.

Disposal of oil-field brines in injection wells warrants concern for a number of reasons. The most obvious threat to the water quality of the Great Bend Prairie aquifer is shallow disposal, which has been practiced since the 1930's. Although present restrictions prohibit new disposal wells above the base of the Stone Corral Formation in most of the study area, preexisting shallow wells may still operate. As of 1986, oil-field brines were still being disposed of into the Cedar Hill Sandstone and other Permian formations that underlie the Great Bend Prairie aquifer. Table A.1 lists the locations and characteristics of known shallow Permian disposal wells in Stafford and Pratt counties that were operating as of 1986.

Table A.1. Shallow disposal wells in Stafford and Pratt counties (from KCC, 1986).

Legal Location	Disposal zone	Disposal interval (feet)	Land surface elevation (feet)	Static fluid level (feet)	Elevation of fluid level (feet)	Wellhead pressure	Daily water volume in bbls (gallons)	Chloride concentration (mg/L)	Comments
STAFFORD COUNTY									
SENE 19-22-13W	Wellington Salt and Ft. Riley	549–2,069	1,905	–19	1,886	2 lb.	40 (1,680)	NA	
NENE 31-24-14W	Cedar Hills	392–450	1,996	–56	1,940	Gravity	2 (84)	87,000	Abandoned and plugged in late 1985
SESE 25-24-15W	Cedar Hills	532–850	2,002	–35	1,967	Gravity	120 (5,040)	39,000	
NE 19-24-15W	Cedar Hills	505–535	2,042	–84	1,958	Gravity	110 (4,620)	118,000	
SW 10-25-15W	Cedar Hills	500–590	2,032	–90	1,942	Gravity	35 (1,470)	117,500	
PRATT COUNTY									
SESE 4-26-14W	Permian Red Beds	710–803	1,999	–138	1,861	Gravity	80 (3,360)	122,000	
NWNW 4-27-14W	Cedar Hills	520–790	1,994	–133	1,861	Gravity	400 (16,800)	132,000	
E/2NE 6-28-11W	Permian Red Beds	400–700	1,749	–33	1,716	Gravity	30 (1,260)	73,000	
NWSW 23-28-13W	Stone Corral Anhydrite	814–834	1,950	–138	1,812	Gravity	40–60 (2,100)	69,000	
NW 36-28-14W	Harper/Ninnescah	830–1,006	1,984	+895	2,879	500+	72 (3,024)	62,000	
NW 23-29-13W	Cedar Hills	550–798	1,895	+2	1,897	90	320 (13,440)	69,000	
SWSE 33-29-13W	Ninnescah	750–800	1,909	–53	1,856	Gravity	330 (13,860)	61,000	
NWSE 28-29-13W	Permian Red Beds	675–750	1,865	–208	1,657	NA	NA		Idle since 1977

Recharge to the Cedar Hills aquifer is mostly from injection of oil-field brines; some underflow from the west also occurs (P. A. Macfarlane, personal communication, 1992). Discharge in the study area is primarily to the Great Bend Prairie aquifer. Adding more brine will inevitably result in more brine discharge, particularly if disposal wells are located in or near subcropping areas, and especially if pressure injection is used.

Disposal into shallow formations may enhance salt-water intrusion into the Great Bend Prairie aquifer by increasing the pressure (or head) in the disposal zone. Localized pollution in overlying unconsolidated aquifers by upwelling of salt water around casings of some wells was recognized as early as the late 1930's (Leonard and Kleinschmidt, 1976). Northwest of the study area, the Cedar Hills potentiometric surface has been affected by injection and shows the effect of fluid pressure build up. Some fluid levels may have risen 100 feet since the 1970's (Macfarlane et al., 1988). The Dakota aquifer, which overlies the Cedar Hills to the northwest, is thought to have been affected by disposal in some areas.

There are probably more than 500 Cedar Hills disposal wells in central and western Kansas. The average rate of disposal is around 550 barrels (23,000 gallons) per day per well (Macfarlane et al., 1988). Using the values of T, K, and S estimated by the KCC (1986), the KCC report suggested that, theoretically, the radius of influence of a Cedar Hills disposal well may be as much as 20 miles after one year, and as great as 75 miles after 10 years of disposal.

Another concern is that pressure injection may cause fracturing of the disposal zone. Fluid-level and injection-pressure data suggest that, at least theoretically, hydraulic fracturing of the Cedar Hills aquifer may take place during injection at some disposal sites (Macfarlane et al., 1988). Fractures may facilitate upward movement of brines.

In addition to shallow disposal, ground-water contamination may be associated with injection wells disposing into deeper formations. Leakage may occur from deep disposal wells with corroded or faulty casing. Often, old abandoned oil wells have been converted to disposal wells by perforation of the casing opposite permeable zones. Because oil-field brines are corrosive to metals, disposal wells with leaky casings are probably not uncommon. Problems with disposal wells are usually not discovered until water quality has been impaired. Of related concern are unplugged or improperly plugged abandoned wells or boreholes, which may serve as conduits between different aquifers.

Where connections between aquifers exist, fresh water may move down or salt water may move up, depending on hydrologic conditions. The former case represents loss of fresh water and the latter may represent contamination of the fresh water. If fresh water enters a salt formation, dissolution of the salt may occur. Similarly, disposal of brines undersaturated with respect to chloride may dissolve salt formations. The manifestation of such dissolution is often subsidence or sinkholes on the land surface.

Solution of salt formations by injected brine or by leakage of fresh water apparently has caused sinkholes at a number of disposal sites. Some huge sinkholes exist at disposal sites in the Great Bend Prairie area. In fact, virtually all sinkholes in the study area are at disposal well sites. Walters (1978, p. 31) maintained that the "rare instances of land subsidence due to salt dissolution associated with oil and gas activity have all been caused by the disposal of produced oil-field brines, undersaturated as to sodium chloride, by reinjecting them into deep aquifers through salt water disposal wells with corroded or faulty casing allowing uncontrolled dissolution of salt."

Injected brine has a large capacity to dissolve more salt. The high energy input and large volumes of water undersaturated with respect to chlorides have the potential for appreciable salt dissolution. Generally, with abandonment and proper plugging of oil wells and disposal wells in an oil field, "the energy input is curtailed, circulation is terminated, dissolution ceases, and subsidence at the land surface declines..." (Walters, 1978, p. 32).

Important exceptions occur where the Cheyenne Sandstone and Cedar Hills Sandstone are present above a salt formation. These aquifers were not required to be isolated by surface casing, and have been used for disposal. Connections such as improperly plugged boreholes permit undersaturated brines to flow downward, continually dissolving salt (Walters, 1978).

Again, if Permian heads are higher than fresh-water heads, the naturally occurring and disposed brines may flow upward into the Great Bend Prairie aquifer. Permian heads can be naturally higher, or can become higher because of 1) declines in fresh-water levels or 2) injection into Permian formations. The upward movement may be facilitated by pathways such as boreholes, abandoned wells, and fractures.

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