UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

DISCHARGE OF SALTWATER FROM PERMIAN ROCKS TO MAJOR STREAM-AQUIFER SYSTEMS IN CENTRAL AND SOUTH-CENTRAL KANSAS

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ABSTRACT

Saline-water inflow from Permian rocks has resulted in the degradation of freshwater systems in several areas of central and south-central Kansas. Solution of evaporite beds has occurred along the eastern edge of the Wellington Formation, chiefly within the Hutchinson Salt Member and associated gypsum units. The solution, caused by leakage of freshwater primarily from overlying unconsolidated deposits, has resulted in formation of a discontinuous zone of solution cavities and collapsed beds. This zone, which extends southward from Salina to near Wellington, contains large quantities of saltwater and is termed the Wellington aquifer.

The generalized potentiometric surface of the Wellington aquifer is determined from water-level measurements in observation wells and from digital model studies. A ground-water divide is indicated on this surface east of Hutchinson where the gradient slopes northward toward the Smoky Hill River valley and southeastward toward eastern Sumner County in the Arkansas River valley.

The digital model and field evidence indicate that there are several major areas where the potentiometric surface of the Wellington aquifer is above the water table of the overlying freshwater deposits. This difference in head provides a mechanism for the upward leakage of saline water. Areas of saline-water encroachment to freshwater systems are near Belle Plaine, Adamsville, and Geuda Springs in south-central Kansas and in the Smoky Hill River valley east of Salina. Another area of possible saline-water contamination is southeast of Hutchinson. Owing to erosion of most of the intervening shale layers, the Wellington aquifer may be in hydraulic connection with the aquifer in the unconsolidated deposits.

Regression analyses and measurements of seepage and salinity were used to determine the amount of saltwater discharge and chloride-load increase to the Arkansas River and its tributaries between Derby and Arkansas City during 1970-74. These analyses indicate that approximately 0.60 cubic foot per second of saltwater is entering the freshwater system in this area and that the average increase in chloride load is about 229 tons per day.

Possible methods of alleviating saline-water intrusion include desalinization, dilution, evaporation, and diversion. Interception may be accomplished by installation of wells in the Wellington aquifer or at the base of the unconsolidated deposits or by construction of collection systems at land surface in areas of seeps and springs. Following interception, possible methods of saline-water disposal include: (1) injection into the Arbuckle Group of Cambrian and Ordovician age, (2) dilution with freshwater in streams during high-flows, or (3) evaporation from surface ponds.

INTRODUCTION

Degradation in the chemical quality of freshwater in streams and aquifers has adversely affected the suitability of water for public use in several areas of central Kansas. This degradation commonly occurs as a result of the natural discharge of saline water from the Wellington Formation* of Permian age. The contaminating water is generated as a result of differential solution of salt by circulating freshwater. The dissolution occurs along the eastern edge of the Hutchinson Salt Member and associated gypsum units of the Wellington where they are in proximity to freshwater systems. Dissolution of the salt has resulted in the formation of a discontinuous zone of solution cavities and collapsed beds. This zone, which extends southward from Salina toward the Oklahoma State line, is termed the Wellington aquifer.

The hydrologic conditions that control the flow from saltwater systems into freshwater systems is not fully understood, and the severity of degradation has not been accurately documented.

In this report, water is classified generally in terms of dissolved-solids concentrations in mg/L (milligrams per liter). Freshwater is defined as having less than 1,000 mg/L dissolved solids, saline water is 1,000 to 35,000 mg/L, and brine is more than 35,000 mg/L.

* The classification and nomenclature of the rock units used in this report are those of the Kansas Geological Survey and differ somewhat from those of the U.S. Geological Survey.

Purpose and Scope

Saltwater inflow from the Wellington aquifer has resulted in degradation of freshwater systems in several areas of central and south-central Kansas. Contamination of the freshwater systems has deleteriously affected their use for industrial, municipal, irrigation, and domestic purposes.

The purpose of this study, made in cooperation with the Kansas Geological Survey, is to: (1) describe the general geohydrologic relationships between saltwater from the Wellington aquifer and freshwater in the major unconsolidated aquifers in central and south-central Kansas, (2) determine the location, extent, and severity of the naturally occurring saline-water inflow into the major stream-aquifer systems, and (3) provide an assessment of possibilities for alleviation or control of the pollution in each of the stream-aquifer systems.

The geohydrologic relationships between saltwater and freshwater aquifers are described by structure, thickness, and potentiometric-surface maps and geohydrologic cross sections. A steady-state digital model of ground-water flow was constructed as an aid in understanding the hydraulic characteristics of the Wellington aquifer and determining if the observed, or conceptual, potentiometric surface was mathematicaly feasible. Seepage and salinity measurements were made on several streams to delineate areas of saline-water intrusion. Methods available to alleviate degradation of the freshwater aquifers are discussed.

Location and Extent of Area

FIG 1 → (near here)

The area of investigation comprises about 1,500 square miles and includes parts of Saline, McPherson, Reno, Harvey, Sedgwick, Sumner, and Cowley Counties, Kansas (fig. 1). Freshwater supplies produced in this area serve approximately 400,000 people.

Figure 1.--Map of Kansas showing area of investigation.

Previous Investigations

Many reports have been published on the geology and hydrology of the area. The reader is referred to Lane and Miller (1965) for a complete listing of these works. Comprehensive reports on the geohydrology of the area that were most referred to by the author are mentioned here. Kulstad (1959) reported on the Hutchinson Salt Member of the Wellington Formation. Williams and Lohman (1949) published a comprehensive report on the hydrogeology of McPherson County and parts of Reno, Harvey, and Sedgwick Counties. Latta (1949) reported on the ground-water conditions in Saline County. Stramel (1956, 1967) published progress reports on the ground-water hydrology of the "*Equus* beds" area. Petri and others (1964) reported on the water resources of the Wichita area. Walters (1961) discussed the geology and ground-water resources of Sumner County. Lane and Miller (1965) discussed the geohydrology of Sedgwick County, and Leonard and Kleinschmidt (1976) reported on saline water in the Little Arkansas River basin.

Methods of Investigation

Electrical logs were used to construct maps of the top and thickness of the eastern part of the Hutchinson Salt Member of the Wellington Formation. Twenty-five observation wells, screened in the Wellington aquifer, were installed between Salina and Wellington. An aquifer test of the Wellington aquifer was conducted in April 1977 using the facilities of Home Petroleum Company, Conway, Kansas.

Water samples were collected from selected wells for complete chemical analyses, including determination of bromide, iodide, and lithium concentrations. A solid salt sample was collected from the Interpace Mine, Hutchinson, Kansas. Prior to analysis, this sample was dissolved with deionized water until the chloride concentration was comparable with the average chloride concentration of water samples collected from the Wellington aquifer.

In an attempt to locate areas and estimate quantities of saline-water inflow to streams, seepage and salinity measurements were made on the Ninnescah River and Slate and Salt Creeks in Sumner County. Water samples collected during this investigation were analyzed by the Kansas Department of Health and Environment or the U.S. Geological Survey.

A water-table map of the freshwater deposits and a potentiometric-surface map of the Wellington aquifer were prepared. Control for these maps was based on water-level measurements of approximately 250 wells made in April 1977. The Kansas Water Resources Board, the City of Wichita, and the U.S. Geological Survey cooperated in this effort.

A steady-state digital model of ground-water flow was constructed as an aid in understanding the hydrologic system of the Wellington aquifer. Data for the model consisted of water-level measurements and aquifer-test data.

Acknowledgments

Appreciation is expressed to the many individuals and companies who supplied information incorporated in this investigation. Special acknowledgment is made to John Mooney, Home Petroleum Company, Conway, Kansas, for making his facility available for a 24-hour aquifer test of the Wellington aquifer and for allowing installation of a permanent recorder on one of the company observation wells. The author is also grateful to Messrs. William Biegler and Ralph O'Connor, Kansas Department of Health and Environment, for providing data and for their suggestions. Mr. Michael Withrow, City of Wichita Water Department, was most helpful in providing necessary data and in assisting with the mass water-level measurement in April 1977.

Well-Numbering System

The system of numbering wells and test holes in this report is based on the U.S. Bureau of Land Management's system of land subdivision. The first number indicates the township, the second indicates the range west or east of the sixth principal meridian; and the third indicates the section in which the well is located. The first letter denotes the quarter section or 160-acre tract; the second, the quarter-quarter section or 40-acre tract; and the third, the quarter-quarter-quarter section or 10-acre tract. The letters are designated A, B, C, and D in a counterclockwise direction beginning in the northeast quarter of the section. Where there is more than one well in a 10-acre tract, consecutive numbers are added in the order in which the wells are inventoried.

FIG 2 (near here)

For example, 20-4W-4AAD indicates a well in the southeast quarter of the northeast quarter of the northeast quarter of sec. 4, T. 20 S., R. 4 W. (fig. 2).

Conversion to Metric Units

For those readers who may prefer to use metric units rather than the inch-pound units, the conversion factors for International System (SI) units and abbreviations for terms used in this report are given below:

Inch-pound units	Multiply by	SI units
Foot (ft)	0.3048	Meter (m)
Mile (mi)	1.609	Kilometer (km)
Square mile (mi^2)	2.590	Square kilometer (km^2)
Gallon per minute (gal/min)	6.309×10^{-2}	Liter per second (L/s)
Cubic foot per second (ft^3/s)	.0283	Cubic meter per second (m^3/s)
Barrel (bbl)	.1590	Cubic meter (m^3)

Figure 2.--System of numbering wells and test holes in Kansas.

PLATE 1 → FIG 3 → (near here)

GEOLOGIC SETTING

Permian Rocks

Rocks of Permian age that crop out in the area of investigation include the Nolans Limestone of the upper part of the Chase Group and the Wellington Formation and Ninnescah Shale of the Sumner Group (pl. 1 and fig. 3).

The Nolans Limestone is the lowermost unit exposed in the study area (pl. 1). These rocks, which average about 35 feet in thickness, crop out in extreme southeastern Sumner County and western Cowley County.

Wellington Formation

The Wellington Formation forms the bedrock unit underlying the major part of the unconsolidated deposits in the study area (pl. 1). The Wellington, which dips gently westward and southwestward, can be divided into three distinct units in the subsurface of central Kansas. The lower Wellington member, the "anhydrite beds" of Ver Wiebe (1937), consists of gray shale and some dolomite alternating with many thin anhydrite and gypsum beds (Lee, 1956). Thickness of the lower Wellington ranges from 150 feet in Saline County to almost 250 feet in Sumner County, and averages about 200 feet.

The middle unit of the Wellington Formation is the Hutchinson Salt Member. In Reno County, where no dissolution has occurred, the unit averages 300 feet in thickness and consists of salt interbedded with minor amounts of shale, gypsum, and anhydrite.

The upper Wellington member consists mainly of gray shale with minor amounts of gypsum, anhydrite, dolomite, and siltstone. Thickness of the Wellington averages 250 feet, but the contact with the overlying Ninnescah Shale is indefinite because of lithologic similarities between the two units (Leonard and Kleinschmidt, 1976).

Plate 1.--Map showing surficial geology and configuration of Permian bedrock surface in area of Wellington aquifer, central Kansas.

Figure 3.--Part of gamma ray-neutron log of well in 16-4W-22DAB showing stratigraphic relationship of bedrock units discussed in this report.

Ninnescah Shale

The Ninnescah Shale conformably overlies the Wellington Formation and crops out in the extreme western part of the area of investigation. The Ninnescah also forms the bedrock surface under the unconsolidated deposits in Tps.18, 19, and 21 through 23 S., R.4 W. and Tps.24 through 26 S., Rs.3 and 4 W. The Ninnescah consists of alternating beds of brownish-red silty shale and silt-stone interbedded with some thin beds of gypsum. A few thin beds of gray-green silty shale occur in the lower part (Lane and Miller, 1965).

Cretaceous Rocks

The Kiowa Formation of Cretaceous age unconformably overlies the Ninnescah Shale or the Wellington Formation along parts of the Smoky Hill River valley in northern McPherson and Saline Counties. The Kiowa Formation consists of light- to dark-gray and black clay and shale with thick lenticular beds of iron-stained quartzitic sandstone. Owing to their greater resistance to erosion, the sandstone beds are the most conspicuous feature of the Kiowa because these beds cap all the high hills bordering the Smoky Hill River valley (Latta, 1949).

Undifferentiated Tertiary and Quaternary Deposits

Unconsolidated deposits of Tertiary and Quaternary age overlie much of the bedrock units throughout the area of investigation (pl. 1). Undifferentiated Pliocene deposits of Tertiary age occupy a small area in northern McPherson County. Undifferentiated Pleistocene deposits of Quaternary age, which contain the principal aquifers, underlie the major valleys of the area. The aquifers include the "*Equus* beds" in McPherson, Reno, Harvey, and Sedgwick Counties (Stramel, 1956); the Arkansas River alluvium in Reno, Sedgwick, and Sumner Counties; the Ninnescah River alluivum in Sedgwick and Sumner Counties, and the Smoky Hill River alluvium in Saline County. The deposits consist of sand and gravel interfingered with lenses of silt and clay.

Subsidence in the underlying Wellington Formation, as a result of salt dissolution and the subsequent subsidence and erosion of overlying beds, has influenced the depositional patterns of Pleistocene streams in the study area. The McPherson channel, which trends southward from near Lindsborg, was a major drainageway in the area prior to being filled with Pleistocene deposits. This channel contains nearly 250 feet of saturated deposits. The Arkansas River channel contains nearly 300 feet of saturated deposits.

The reader is referred to Williams and Lohman (1949) and Lane and Miller (1965) for a more complete discussion of the Pleistocene drainage and depositional history of the area.

FIG 4
(near here)

HYDROLOGIC SETTING

Figure 4 shows conceptual block diagrams depicting the ground-water flow pattern which led to the formation of the Wellington aquifer. Originally the depositional edge of the salt probably was several miles farther east where salt interfingered with shale that was washed into the Permian basin from low-lying border areas. During and following removal of most of the Cretaceous and the upper part of the Permian rocks by erosion, fresh ground water from surficial deposits was able to penetrate to the salt body. This resulted in differential dissolution of large parts of the salt and consequent westward migration of the edge of the salt body.

PLATE 2

Owing to the west-southwestward dip of rocks in the area, the lower Wellington member generally subcrops beneath the undifferentiated Pleistocene deposits east of the salt body, as depicted in a series of cross sections on plate 2. Circulating ground water also has caused large-scale dissolution of gypsum and anhydrite in the lower Wellington. The dissolution of gypsum and anhydrite appears to be best developed in the Smoky Hill River valley and in the area between Belle Plaine and Geuda Springs.

Fracturing, slumping, and collapsing of overlying deposits in the Wellington Formation occurred coincidently with the solution of salt, gypsum, and anhydrite at many locations along the solution trend. These mechanisms also influenced the depositional patterns of Pleistocene streams resulting in accumulation of unconsolidated deposits as mentioned earlier. This process has altered the normally impermeable unit into one that is capable of transmitting large quantities of water at a few locations. This permeable unit has been named the Wellington aquifer; the solution zone in the salt and the solution zones in the gypsum and anhydrite are termed, respectively, the "salt-dissolution zone" and the "gypsum-dissolution zone."

Figure 4.--Conceptual block diagrams near Lindsborg showing geologic development, mechanism of dissolution of the Hutchinson Salt Member, and development of Wellington aquifer between Cretaceous time (A) and present (B).

Plate 2.--Hydrogeologic cross sections showing relation of Hutchinson Salt Member and Wellington aquifer to unconsolidated deposits, central Kansas.

Ground water in the Wellington aquifer moves downgradient in two directions from a potentiometric "high" east of Hutchinson. One vector indicates northward movement of saltwater through the salt-dissolution zone and discharge through the gypsum-dissolution zone into the Smoky Hill River alluvium between New Cambria and Solomon. The other vector indicates southeastward movement of saltwater through the salt-dissolution zone and discharge through the gypsum-dissolution zone in the vicinity of Belle Plaine, Adamsville, and Geuda Springs.

The degree of permeability development in the Wellington aquifer is indicated by the frequency that drillers report a rapid loss of drilling fluid into voids as they penetrate the dissolution interval that comprises the aquifer. As a result, drillers have applied the name "lost-circulation zone" to the interval. The degree of permeability development in the Wellington aquifer was examined on the basis of drillers' logs of wells in the area. The logs indicate that there are many more reports of "lost-circulation" in the area from Salina to Wichita than in the area south of Wichita. The former area is associated with thick sections of salt which are subject to the dissolution and collapse that greatly increase permeability. The latter is near the depositional edge of interbedded salt and shale where dissolution would cause less significant collapse and increased permeability.

PLATE 3

PLATE 4

The thickness of the Hutchinson Salt Member is shown on plate 3; the altitude and configuration of the top of the member is shown on plate 4. As shown in plate 3, the Hutchinson Salt Member generally thickens southward and southwestward from about 200 to 500 feet. Along the eastern edge of the member, the abrupt decrease in thickness of as much as 200 feet coincides with the dissolution zone. The trend of this zone, which corresponds with the Wellington aquifer, extends from northwest of Salina through central Saline, western McPherson, western Harvey, eastern Reno, central Sedgwick, and central Sumner Counties. Another area of apparent salt solution, as indicated by abrupt thinning, occurs east and south of Wellington.

The shaded part of plate 3 denotes areas where thick salt beds are present. In adjacent areas, data from electric logs indicate the presence of thin salt layers interbedded with shale suggesting a sequence representative of the original depositional edge of the salt. However, the salt layers in adjacent areas also may represent numerous outliers remaining after widespread dissolution occurred.

The top of the Hutchinson Salt Member, as shown on plate 4, has a regional dip that ranges from westerly in the northern part of the area to southwesterly in the southern part. Plate 3 also shows the rapid thinning of the top of the salt along the eastern margin, as evidenced by local reversals in dip.

Depths below land surface to the salt-dissolution zone range from 205 feet in the area northwest of Salina to about 550 feet in the area southeast of Hutchinson near the Arkansas River. Southeastward from this area the depths below land surface to the salt-dissolution zone are about 220 feet near Clearwater and 120 feet at Belle Plaine.

Plate 3.--Map showing thickness of the eastern part of the Hutchinson Salt Member, central Kansas.

Plate 4.--Structure-contour map of top of Hutchinson Salt Member, central Kansas.

Depths to the gypsum-dissolution zone in the Smoky Hill River valley range from about 200 feet in the area immediately east of the salt-dissolution zone to about 60 feet (at the base of the alluvium) in the New Cambria-Solomon area. Depths to the gypsum-dissolution zone in the southern part of the study area range from about 200 feet in the area northeast of Wellington to land surface near Geuda Springs, where saline water is present in the form of seeps and springs.

The Wellington aquifer is located in an area that has undergone intensive exploration for oil and gas trapped in deeper horizons. Prior to implementation of pollution protection standards by the State of Kansas, the aquifer was used extensively for disposal of brine produced in association with oil and gas. Many disposal wells have been drilled, and the general limits of the aquifer are defined by their location. Figure 5 shows where disposal wells were, or are located, and where circulation was reportedly lost during drilling. Elsewhere, the limits of the Wellington aquifer are nebulous and are defined mainly by topographic and geologic evidence as discussed later.

FIG 5 → (near here)

Figure 5.--General outline of Wellington aquifer as denoted by areas of sinks and undrained depressions, locations of disposal wells, and areas where lost circulation was reported.

Uses of Ground Water in Wellington Aquifer

Ground water in the Wellington aquifer has been used for several purposes. On the west side of the McPherson channel near Conway, brine is withdrawn from wells in the aquifer and used to displace LPG (liquified petroleum gas) that is stored in "jugs" or cavities in the Hutchinson Salt Member. These jugs are formed by dissolving the salt with freshwater pumped from the "*Equus* beds." During summer months the brine is displaced from the jugs as LPG storage occurs. The brine is either stored in lined surface pits, disposed into deeper horizons such as the Arbuckle Group of Cambrian and Ordovician age, or occasionally returned to the Wellington aquifer. Between summer 1968 and winter 1974-75 almost 26 million barrels of brine were withdrawn from the Wellington aquifer and more than 27 million barrels were injected into the aquifer (John Mooney, oral commun., 1976).

FIG 6 → (near here)

Figure 6 is a hydrograph of well 19-4W-34BDA completed in the Wellington aquifer near Conway. The hydrograph depicts a generally rising potentiometric surface on which is superimposed the effects of barometric pressure changes, pumping, and injection. Pumping from the aquifer extended from September 19-23, 1977, and from October 11-14, 1977. Pumping began again on January 10, 1978; the ending date is unknown owing to lack of record but probably occurred about January 25, 1978. Injection into the aquifer occurred from September 7-10, 1977. Minor fluctuations in the potentiometric surface are due to changes in barometric pressure.

Figure 6.--Hydrograph of well 19-4W-34BDA showing fluctuation of potentiometric surface of Wellington aquifer in response to changes in barometric pressure, pumping, and injection.

Southwest of Wichita, near Clearwater, large quantities of brine were formerly withdrawn for industrial purposes. However, because of economic factors and excessive quantities of calcium, manganese, and sulfate, removal of brine from the Wellington aquifer was curtailed in about 1955 in favor of solution mining of the salt. The brine wells continued to be used as disposal wells until they became plugged with slurry containing carbonates and hydroxides of calcium and magnesium (Leonard and Kleinschmidt, 1976).

Brine is withdrawn at a rate of about 1,000 barrels per day from the Wellington aquifer and used for secondary recovery operations in an oilfield in southern Saline County.

PLATE 5A

Hydraulic Characteristics of the Wellington Aquifer

In an attempt to determine the hydraulic characteristics of the Wellington aquifer, 23 observation wells were completed in the aquifer between Solomon and Geuda Springs (pl. 5A). Fifteen wells were completed in the salt-dissolution zone and eight in the gypsum-dissolution zone. The installation of these observation wells illustrates the discontinuity of the Wellington aquifer. Circulation was lost in salt- or gypsum-solution cavities at 10 sites. The remaining wells were screened in intervals that were believed to be stratigraphically equivalent to the Wellington aquifer and that appeared permeable based upon drilling time, drilling-fluid loss, sample appearance, and increase in specific conductivity of drilling fluid.

Upon completion, attempts were made to remove drilling water by pumping the wells so that formation water would be obtained when the wells were sampled for chemical analysis. The observation wells that were screened in solution cavities were easily pumped and formation water was obtained. Also, water levels recovered rapidly. However, at the sites where circulation was not lost, pumpage could not be sustained due to the exceedingly low hydraulic conductivity of the formation. In these cases, water was pumped from the well to ascertain if the water level would recover, thereby indicating that hydraulic connection existed between the well and the aquifer. Water levels recovered to static levels in all wells in 2 days. Repeated evacuation of the wells and subsequent water-level recovery indicate that hydraulic connection does exist between the wells and the Wellington aquifer.

Plate 5A.--Map of the Wellington aquifer showing grid nodes in the modeled area, central Kansas.

Another indication of hydraulic connection between the wells and the aquifer is the fact that as more drilling water was removed, the water became significantly more concentrated with chloride. The increase in chloride concentration varied from one site to the next. However, chloride concentrations approached saturation levels (180,000-190,000 mg/L chloride) only in the wells that were completed in solution cavities. Additionally, the potentiometric surface defined by the water levels measured in observation wells is continuous, indicating that hydraulic connection exists throughout the Wellington aquifer system.

Because water in the Wellington aquifer has very high concentrations of dissolved solids (high density), water levels are lower than comparable levels of freshwater. Thus, water-level measurements in the aquifer have been adjusted to equivalent freshwater levels. The equivalent, or calculated water levels, comprise the control for the potentiometric map of the Wellington aquifer. For example, measurements near Buhler show that the altitude of the potentiometric surface in the Wellington aquifer is 1,449 feet above mean sea level in well 22-4W-19BBB (fig. 7). If the top of the screened interval in the well is used as datum (1,070 feet), the hydraulic head (h_w) of the brine is 379 feet. The altitude of the measured water level in a well in 22-5W-13DAD, completed in the freshwater aquifer, is 1,461 feet. Thus, the hydraulic head (h_f) above the same datum is 391 feet, or 12 feet (Δh) above the potentiometric surface of the Wellington aquifer. If the head in well 22-4W-19BBB is adjusted for density of 1.026 (measured from chemical analysis), the calculated head (h_{calc}) of an equivalent freshwater column is given by:

IG 7 →
ear here)

$$h_{calc} = 1.026 \times h_w$$
$$= 1.026\ (379)$$
$$= 389 \text{ feet.}$$

Figure 7.--Comparison of measured and calculated water levels near Buhler.

Thus, the observed freshwater head is only 2 feet higher in altitude than the calculated head of an equivalent freshwater column above datum. This residual difference (h_r) is the part of Δh not accounted for by density differences and probably represents head loss across intervening beds.

Hydraulic Connection Between
Wellington Aquifer and Overlying Unconsolidated Aquifers

Topographic evidence of hydraulic connection between the unconsolidated desposits and the Wellington aquifer is present in the form of hundreds of sinkholes that have developed in the unconsolidated deposits (fig. 5). These sinkholes, which range in area from 10 ft^2 to more than 4 mi^2 (Big Basin, west of McPherson), have been formed by dissolution of the underlying salt, resulting collapse of the overlying shale, and settling of the unconsolidated deposits. The fact that many sinks have developed since the area has been populated adds support to the hypothesis that salt solution is still continuing.

Where the salt section is intact, the thickness of the upper Wellington member is relatively uniform. Based on this assumption of uniformity, if the top of the intact portion of the salt is projected eastward, the Hutchinson Salt Member, lower Wellington member, or collapsed portion of the Wellington aquifer subcrops at the base of the unconsolidated aquifers in several areas (pl. 2). Thus, there exists a direct avenue of hydraulic communication between unconsolidated aquifers and the Wellington aquifer. If the collapsed portion of the Wellington aquifer is permeable, freshwater from the unconsolidated deposits could move downward into the Wellington aquifer. However, if the head in the Wellington aquifer is higher than the head in the unconsolidated deposits, potential exists for saltwater to move from the Wellington aquifer upward into the unconsolidated deposits.

Changes in the chloride concentration of water from wells completed in the Wellington aquifer suggest localized connections with overlying freshwater aquifers. When pumping begins, water from wells in the Conway area is about 85 percent saturated with salt (Leonard and Kleinschmidt, 1976). With continued pumping, the water soon becomes saturated. During nonpumping periods, a relatively small amount of fresh ground water infiltrates through the collapsed shale overlying the Wellington aquifer and occupies a position overlying the saltwater. When pumping begins, stratification is destroyed by mixing, and the fresher water is removed early during the pumping period.

Lane and Miller (1965) observed a general increase in chloride concentration with depth in the alluvium of the Arkansas River valley southeast of Hutchinson. The observed trend could be the result of: (1) poor sampling methods, (2) saline water derived from surface contamination and consequent settling toward the base of the unconsolidated deposits owing to the higher density of the chloride, or (3) upward leakage from the Wellington aquifer.

Although many water samples have been collected for analyses, the methods of collection and analysis have varied widely. For example, many sampling locations and depths are poorly documented. Thus, a comprehensive description of water quality in this area based on existing data is not possible. Moreover, the reach of the Arkansas River and adjacent alluvium from Hutchinson to Wichita has received localized contamination in the past from oilfield activities, from brine emitted from salt plants, and, in a few places, by inadequately treated sewage (Bayne, 1956).

The ancestral Arkansas River has eroded much of the confining layer between the alluvial aquifer and the Wellington aquifer along the reach southeast of Hutchinson. In T.24 S., Rs.3 and 4 W. and T.25 S., R.3 W., less than 100 feet of shale is present between the two aquifers (pl. 1 and section E-E', pl. 2). The possibility exists that there is upward flow of saltwater into the alluvial aquifer in this area.

Additional evidence of hydraulic connection is the relationship between the water table in the freshwater deposits and the potentiometric surface of the Wellington aquifer. Plate 6 depicts the contours of the water table in the freshwater aquifers where they overlie the Wellington aquifer. The water table of an aquifer reflects the influence of geology, hydrology, and topography. The shape of the water table, as shown by contour lines, indicates the slope and direction of ground-water movement.

PLATE 6

The water-table "high" in the area just east of Hutchinson reflects the combined factors of a relatively high bedrock surface (pl. 6) and dune sand deposits on the land surface. The linear area of dune sand, which extends about 16 miles eastward from Hutchinson to the Little Arkansas River, affords an excellent catchment for precipitation. Thus recharge to the shallow water table probably is greater than that in surrounding areas and contributes to local mounding. A ground-water divide is present about 4 miles south of McPherson. Ground water flows southward and southeastward from the divide toward the Little Arkansas and Arkansas River valleys and northward toward the Smoky Hill River valley.

Plate 6.--Map showing water-table contours of freshwater deposits where overlying the Wellington aquifer, central Kansas, April 1977.

Water-table contours indicate that the Arkansas River between Hutchinson and Wichita is essentially in equilibrium with the alluvial aquifer, neither gaining water from nor losing water to the alluvium. Contours flex sharply upstream as they cross the Smoky Hill, Little Arkansas, and Ninnescah Rivers, the Arkansas River below Wichita, and Slate and Salt Creeks. These flexures indicate ground water is discharging to these streams during low-flow conditions. Other ground-water discharge from the alluvium include wells, streams, springs, evapotranspiration, subsurface outflow from the area, and downward leakage to the underlying Permian rocks.

The water-table gradient is markedly steeper on the west side of the unconsolidated deposits between Lindsborg and Hutchinson and on the southwest side of the Arkansas River valley, west of Wichita. In these areas, the water moves from bedrock terrain through thin, silty residual material before entering the thick, highly permeable sand and gravel in the valley.

Recharge to the alluvial aquifer is principally by precipitation and subsurface inflow from outside the area of investigation. Recharge to the deposits in the vicinity of the Wichita well field is estimated at 20 percent of precipitation (Williams and Lohman, 1949). This value probably is a reasonable estimate for the entire study area. The principal areas of subsurface inflow are in the Saline, Arkansas, and Smoky Hill River valleys; minor amounts of subsurface inflow occur in the Little Arkansas and Ninnescah River valleys.

PLATE 5B

Plate 5B shows the observed potentiometric surface of the Wellington aquifer and the potentiometric surface calculated by the steady-state model (discussed later). Owing to lack of control, the potentiometric surface of the Wellington aquifer is more generally defined than the water table of the freshwater aquifers. However, a comparison of plates 5B and 6 shows that the two surfaces are similar in form. This similarity provides additional evidence that ground water in the Wellington aquifer results from downward leakage of freshwater from the overlying deposits. Plate 5B shows: (1) an area east of Hutchinson with a relatively high potentiometric surface bounded on the north and southeast by two areas of steep hydraulic gradient and (2) gradual hydraulic gradients north and southeast toward outflow areas in the Smoky Hill River valley and in the Belle Plaine-Adamsville-Geuda Springs area, respectively.

There are three major areas where observed potentiometric heads in the Wellington aquifer are higher in altitude than observed water levels in the freshwater deposits (pl. 6). Thus, there is potential for upward leakage of saltwater from the Wellington aquifer to the overlying freshwater systems. Two of these areas are synonymous with the saline-water outflow areas in the Smoky Hill River valley and in the Belle Plaine-Adamsville-Geuda Springs area.

The outlined areas show only where there is potential upward leakage. In addition to the necessity for heads in the Wellington aquifer being higher in altitude than heads in the water table of the freshwater aquifers, hydraulic connection must exist between the two aquifers. The confining bed overlying the Wellington aquifer in the northern and southern areas has been subjected to fracturing and slumping concurrent with dissolution and removal of salt and gypsum. Moreover, the confining bed is relatively thin in both areas, ranging from 50 feet to 150 feet. The fact that saline-water inflow to the freshwater system does occur in these areas indicates that hydraulic connection exists between the two systems.

Plate 5B.--Map showing observed and calculated potentiometric surfaces of Wellington aquifer, central Kansas, April 1977.

The third major area of higher observed potentiometric heads is east of Hutchinson. The potentiometric surface in observation well 23-4W-30ABB, completed in the Wellington aquifer, is higher in altitude than the water table in the alluvial aquifer when density corrections are made as previously described. However, the thickness of shale in the upper Wellington member in this area averages about 300 feet. Even with the noted head reversals, it is doubtful that the head differential is great enough to overcome the flow-retardation effects of such a thick confining layer. A more probable area of possible saline-water inflow is the Arkansas River valley to the south, as discussed earlier.

It is emphasized that saline-water inflow to the freshwater system probably does not occur throughout the entire shaded areas in plate 6. Owing to the lack of control, the contours of the observed and calculated potentiometric surface are very generalized. With added control, the areas denoting saline-water inflow could be defined to a much greater degree.

DIGITAL MODEL OF WELLINGTON AQUIFER

A two-dimensional finite-difference steady-state digital ground-water flow model developed by Trescott, Pinder, and Larson (1976) was used as an aid in understanding the hydraulic characteristics of the Wellington aquifer and determining if the observed, or conceptual, potentiometric map was mathematically feasible. The modeled area, which exceeds 1,500 mi^2, was subdivided into a variably spaced rectangular finite-difference grid of 22 rows and 69 columns (pl. 5A).

It is believed that the Wellington aquifer system does not have horizontal outflow. Instead, discharges are vertically upward from the saltwater aquifer into overlying freshwater deposits. (The method of determining the rate of natural discharge from the Wellington aquifer is described in the "Water Quality" section.) Because the model was intended to be a simplified method of simulating the observed discharge and potentiometric surface, constant head nodes were placed at the upgradient end of the areas where discharge occurs (pl. 5A). The altitudes assigned to the constant head nodes were derived from the observed potentiometric map.

Aquifer Properties

Occurrence of ground water in the Wellington aquifer evidently is the result of leakage from overlying unconsolidated deposits through the upper Wellington member. Because the member is a relatively impermeable confining bed, leakage must be through fractures and slumping that resulted from dissolution of salt and collapse of overlying beds. Thus, the vertical-leakage rate through the confining bed is calculated at each node in the model by solution of the equation

$$q' = \frac{k'}{m} (h_1 - h_o),$$

where

q' = leakage per unit area through the confining bed, in feet per second;

k' = hydraulic conductivity of the confining bed, in feet per second;

m = thickness of the confining bed, in feet;

h_1 = head at the top of the confining bed, in feet; and

h_o = head in the Wellington aquifer at the start of the simulation period, in feet.

The rate of vertical leakage through the confining bed was calculated by the digital model to equal 0.7 ft^3/s, as explained in the section, "Results of Digital Model Simulation."

The Home Petroleum Company at Conway reports that during the summer 1968 through winter 1974-75, 25,878,201 bbl of saltwater were removed from the Wellington aquifer and 27,052,278 bbl were injected. This was a net increase for the period of 1,174,077 bbl or an average of 460 bbl per day (0.03 ft^3/s). Also the Kansas Department of Health and Environment reports that, as of 1975, there were 30 wells through which disposal of saltwater to the Wellington aquifer was allowed. The total allocated disposal rate was 9,336 bbl per day (0.61 ft^3/s). This equals a maximum of 0.64 ft^3/s of saltwater disposal through all wells into the system. The wells were represented by 18 nodes in the model. The amount of disposal allocated per node was based on the number of wells and disposal rate per node. About 90 percent of the disposal occurs between Salina and McPherson.

Data indicating the transmissivity of the Wellington aquifer in the vicinity of Conway is available from one aquifer test performed by the U.S. Geological Survey at the Home Petroleum Company in May 1977. The average transmissivity derived from this test was 0.0289 ft^2/s. The Wellington aquifer in this local area may be very cavernous and well developed owing to the cyclical pumpage and injection of saline water in conjunction with the aforementioned LPG operations. Thus, the transmissivity value may be relatively large when compared with the remainder of the aquifer system. Transmissivity values were adjusted in other areas as discussed later.

Calibration of Model

To ascertain whether the digital model of the Wellington aquifer is a viable simulation, water-level measurements from the field should be compared with corresponding output from the model.

It was assumed that the potentiometric surface defined by water-level measurements represents a steady-state flow system. The model then computes a potentiometric surface based upon the input data on aquifer properties, boundaries, and hydraulic stresses.

One objective of the calibration procedure is to minimize differences between the observed and computed potentiometric surfaces by manipulating input data (aquifer properties, boundary conditions, and hydraulic stresses). Obviously, many interrelated factors affect ground-water flow; thus, the manipulation of this data is highly subjective. The degree of adjustment of any parameter is relative to the uncertainty of its value; i.e., the disposal rates into the Wellington aquifer (0.64 ft^3/s) and natural discharge from the aquifer (1.36 ft^3/s) are reasonably determined, and thus were not adjusted. (The method of determining the rate of natural discharge is discussed in the "Water Quality" section.) However, the values for aquifer transmissivity and hydraulic conductivity of the confining bed are poorly known, and various values were assumed during the calibration of the model. All changes in parameters were made uniformly over an area, rather than on a node-to-node basis, to arrive at an acceptable match between calculated and observed heads.

Development of the final model simulation was an evolutionary process in which adjustments to the model were based on results of previous simulations. Initially, a uniform transmissivity and zero hydraulic conductivity (zero leakage) of the confining bed was assumed. Use of these criteria, however, showed little agreement between the calculated head distribution and discharge rate from the system and those from observed conditions.

Several simulations were made using values of hydraulic conductivity for typically impermeable shale (1.0×10^{-10} to 1.0×10^{-12} ft/s) in conjunction with transmissivity values that ranged from 0.0116 ft^2/s to 0.0578 ft^2/s (approximately one-half and two times the transmissivity value derived from the aquifer test). These values were applied uniformly over the modeled area or variably over major areas. It was found that a value of 3×10^{-11} ft/s for hydraulic conductivity of the confining layer and values of transmissivity of about 0.03 ft^2/s in the northern half of the study area and 0.01 ft^2/s in the southern half generally gave results in which calculated and observed values of head distribution and discharge were relatively agreeable (pl. 5A).

One notable exception to the general agreement occurs in the three-township area east of Hutchinson. The calculated head distribution was on the order of 80 to 100 feet below the observed head distribution. It is evident from the very steep ground-water gradients and the lack of similarity between calculated and observed aquifer characteristics that some anomalous conditions occur within this area.

There is no evidence of faulting in the shallow subsurface in this area that could cause a discontinuity of the ground-water flow pattern. It is possible that the two areas of steep hydraulic gradient may represent zones of exceedingly low hydraulic conductivity in the aquifer, which may be the result of minor dissolution, poor interconnection of solution cavities, and little settling and compaction of thick overlying shales. This also may be true in other areas, but may not be evident owing to the sparse control and consequent lack of definition of the observed potentiometric surface.

Assuming that poor hydraulic connection did exist across the zones of steep gradient, these zones were assigned very low values of transmissivity ranging from 0.0001 ft^2/s to 0.0022 ft^2/s (pl. 5A). Using this approach, a reasonable match was generated between the observed and calculated potentiometric surfaces (pl. 5B) and the observed and calculated discharge (1.36 ft^3/s and 1.46 ft^3/s, respectively).

Another objective of calibrating the digital model is to determine the sensitivity of the model to various combinations of aquifer parameters. By using sensitivity analysis, it is possible to judge which factors most affect groundwater flow in the aquifer system.

FIG 8 (near here)

Figure 8 shows results of the sensitivity analysis that was performed on the digital model of the Wellington aquifer. A "best fit" was attained between the observed and calculated head distributions as previously discussed. Then values of transmissivity were increased and decreased 50 percent to ascertain the effect on: (1) the absolute value of the sums of the drawdown residuals and (2) on the calculated discharge from the system. The absolute value of the sums of the drawdown residuals was determined by summing the differences between the observed head and the head calculated by the digital model at each node. Figure 8A shows that, as transmissivity in the system was lowered by 50 percent, the absolute value of the sums of the drawdown residuals increased from 4,535 to 16,310, and discharge decreased from 1.46 ft^3/s to 1.15 ft^3/s. Conversely, as transmissivity was increased by 50 percent, the absolute value of the sums of the head residuals increased from 4,535 to 12,485, and discharge increased from 1.46 ft^3/s to 1.85 ft^3/s.

Figure 8B shows the results of the sensitivity analysis when transmissivity was held constant and the hydraulic conductivity of the confining bed was changed by 50 percent. As the hydraulic conductivity was increased from 3×10^{-11} ft/s to 4.5×10^{-11} ft/s, the absolute value of the sum of the drawdown residuals increased from 4,535 to 6,517, and discharge increased from 1.46 ft^3/s to 1.57 ft^3/s. Conversely, when hydraulic conductivity of the confining bed was decreased to 1.5×10^{-11} ft/s, the absolute value of the sum of the drawdown residuals increased from 4,535 to 5,033, and the discharge decreased from 1.46 ft^3/s to 1.31 ft^3/s.

Figure 8.--Relation between (A) percentage change in transmissivity and (B) hydraulic conductivity versus the absolute value of the sums of the drawdown residuals and discharge from the Wellington aquifer.

Figure 8 shows that changes in transmissivity over a range of 100 percent have more effect on discharge than corresponding changes in hydraulic conductivity of the confining bed. Thus, the model is more sensitive to changes in transmissivity than to changes in hydraulic conductivity of the confining bed.

Also, the effect on the absolute value of the sum of the drawdown residuals of positive or negative changes in transmissivity over a range of 100 percent is greater than the effect of such changes in hydraulic conductivity. Conversely, when considering the effects of changes in hydraulic conductivity on the absolute value of the sum of the drawdown residuals, figure 8B shows that an increase of 50 percent in hydraulic conductivity of the confining bed causes a larger increase in the absolute value of the sum of the drawdown residuals than a 50 percent decrease in the hydraulic conductivity of the confining bed.

Results of Digital Model Simulation

The steady-state potentiometric surface of the Wellington aquifer calculated by the calibrated digital model is shown on plate 5B. The major features of the observed potentiometric surface generally are well matched by results from the digital model. The calculated surface shows: (1) the relatively high potentiometric surface in the area just east of Hutchinson, which is bounded on the northeast and southeast by two zones of steep hydraulic gradient and (2) gradual hydraulic gradients north and southeast of these zones toward outflow areas in the Smoky Hill River valley and in the Belle Plaine-Adamsville-Geuda Springs area, respectively.

The observed and calculated head distributions do not agree along the western edge of the Wellington aquifer in the area west of Belle Plaine. In this area, the calculated heads are lower than the observed heads. A constant value for hydraulic conductivity was assigned to each node in the model. Perhaps an increase in the leakage rate through the confining layer in this area would allow a better match between the observed and calculated potentiometric surfaces. Alternatively, the transmissivity values used in this part of the digital model may be greater than in the physical system. Decreasing the values of transmissivity would tend to elevate the calculated heads.

During the calibration process, a mass balance for each simulation was computed to check the numerical accuracy of the solution. Incorporated in the mass balance is the net flux contributed by each hydrologic component of the model. These fluxes are tabulated as part of the hydrologic budget. The hydrologic budget for the calibrated steady-state simulation run consists of: (1) injection of saline water into the Wellington aquifer via wells, (2) recharge of fresh water to the Wellington aquifer via leakage from the freshwater-bearing deposits through the overlying confining bed, and (3) discharge of saline water from the Wellington aquifer to the various freshwater systems. This hydrologic budget can be written in the form:

$$R_w + R_l = -Q ,$$

where

R_w = recharge via wells,

R_l = recharge via areal leakage, and

Q = discharge from the Wellington aquifer.

Observed discharge from the Wellington aquifer is estimated to be 1.36 ft^3/s, and the discharge calculated by the digital model is 1.46 ft^3/s. Recharge to the aquifer via wells is estimated to be 0.64 ft^3/s. Using the hydrologic budget outline above, recharge to the aquifer via areal leakage through the confining bed should be about 0.7 ft^3/s. The areal leakage calculated by the digital model was 0.6 ft^3/s, indicating a reasonably good match.

The reasonable match between observed and calculated heads, between observed and calculated discharges and between the areal leakage derived from the hydrologic budget and the calculated areal leakage indicate that the conceptual model is numerically possible and hydrologically valid.

WATER QUALITY

Owing to the large amounts of saline-water disposal that has occurred and the subsequent mixing of water from several geologic units, it is not feasible to "type" the ground water in the Wellington aquifer. Table 1 gives the results of chemical analyses of ground-water samples derived from the Wellington aquifer and of a whole salt sample procured from the mine operated by Interpace Salt Co., Hutchinson, Kansas. This sample was dissolved in deionized water until a chloride concentration of 180,000 mg/L was attained. Analyses were made by the Water and Sewage Laboratory of the Kansas Department of Health and Environment and the U.S. Geological Survey.

TABLE 1 → (near here)

The analyses indicate that the water in the Wellington aquifer is of a sodium-chloride type. The relatively low chloride concentration in the sample collected from well 16-3W-3CDC is a result of the well being located less than one-quarter mile from an active oilfield-brine disposal well. Saline water pumped from a deeper horizon in association with oil production is injected into this disposal well. The chloride concentration of the injected water is lower than the chloride concentration thought to be representative of undiluted water from the Wellington aquifer.

Table 1.--Chemical analyses of brine from Wellington aquifer.

[Dissolved constituents and hardness given in milligrams per liter. Analyses by Kansas Department of Health and Environment, except as noted.]

Well location	Date of collection	Temperature (°C)	Dissolved silica (SiO_2)	Total iron (Fe)	Dissolved manganese (Mn)	Dissolved calcium (Ca^{++})	Dissolved magnesium (Mg^{++})	Dissolved sodium (Na^{+})	Dissolved potassium (K^{+})	Carbonate ($CO_3^{=}$)	Bicarbonate (HCO_3^{-})	Dissolved sulfate ($SO_4^{=}$)	Dissolved chloride (Cl^{-})	Total Bromide (Br^{-})	Total Iodine (I^{-})	Total Lithium (Li^{+})[1/]	Nitrate (NO_3^{-})	Fluoride (F^{+})	Dissolved solids residue at 180°C	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Specific conductance (micromhos/cm at 25°C)	pH	Ratio of sodium to chloride
13-3W-4DCC	9-10-76	--	--	--	--	--	--	--	--	--	--	6,500	110,000	--	--	--	--	--	189,700[2/]	--	--	176,000	--	--
13-3W-33BCC	9-10-76	--	--	--	--	--	--	--	--	--	--	4,900	190,000	--	--	--	--	--	327,600[2/]	--	--	214,000	--	--
14-3W-27BBB	7-26-76	--	--	--	--	--	--	--	--	--	--	7,100	120,000	--	--	--	--	--	206,900[2/]	--	--	185,000	--	--
15-3W-19AAA	8-9-76	--	--	--	--	--	--	--	--	--	--	5,700	170,000	--	--	--	--	--	293,100[2/]	--	--	212,000	--	--
16-3W-3CDC	9-9-76	--	--	--	--	--	--	--	--	--	--	3,100	41,000	--	--	--	--	--	70,700[2/]	--	--	94,200	--	--
17-3W-8CCB	9-8-76	--	--	--	--	--	--	--	--	--	--	4,700	190,000	--	--	--	--	--	327,600[2/]	--	--	214,000	--	--
18-3W-7BBB	5-21-76	--	--	--	--	--	--	--	--	--	--	5,875	187,500	--	--	--	--	--	323,300[2/]	--	--	23,700	--	--
18-4W-8DDD	8-10-76	--	2.4	2.3	0.4	1,080	804	120,000	232	0.0	139	5,340	181,000	300[3/]	0.58[3/]	160[3/]	0.4	0.4	313,000	6,000	6,000	--	7.0	0.66
19-4W-27	3-21-73	--	--	7.4	--	1,550	360	116,000	100	0.0	240	4,380	181,000	--	--	--	--	--	304,000	5,350	5,150	--	6.4	0.64
19-4W-28CDC	4-15-77	--	5.5	--	--	1,350	556	101,000	190	0.0	195	4,800	162,000	0.0[3/]	0.44[3/]	160[3/]	0.0	0.0	--	5,650	5,490	--	--	0.62
	1-11-78	--	--	--	--	--	--	--	--	--	209	--	167,000	--	--	--	--	--	286,000	--	--	202,000	--	--
22-4W-19BBB	7-29-76	--	--	--	--	--	--	--	--	--	--	--	22,000	--	--	--	--	--	--	--	--	55,800	--	--
29-1W-7[4/]	11-5-57	--	16	1.0	--	690	920	94,000	--	0.0	33	3,520	146,000	52	--	--	--	--	--	--	--	--	6.8	0.64
29-2W-26[4/]	6-18-57	27.9	0.05	3.5	--	985	1,250	122,000	--	--	80	6,660	188,000	--	--	--	--	--	319,000	--	--	--	6.1	0.65
31-1E-3BBB	6-7-77	--	--											41[3/]	0.44[3/]	1,200[3/]	--	--	--	--	--	--	--	--
	7-27-77	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1,000[3/]	--	--	--	--	--	--	--	--
	3-14-78	--	2.0	--	--	660	1,400	120,000	140	0.0	54	9,800	180,000	--	1.30[3/]	1,600[3/]	--	0.2	315,000	7,400	7,400	192,000	6.3	0.66
Cargill Salt Mine[3/]	3-30-78	--	0.8	--	--	750	73	100,000	63	--	2	1,900	150,000	17	1.0	50	--	--	296,700	2,200	2,200	195,000		

1/ Analyses in micrograms per liter.

2/ Computed based on average ratio of Cl^- to dissolved solids when both parameters are available.

3/ Analyses by U.S. Geological Survey.

4/ H. V. Coates, Jr., Vulcan Materials Co., Oatville, Kansas, oral commun., 1973.

FIG 9 (near here)

A series of seepage and salinity measurements were made on major streams in the southern part of the study area in an attempt to determine the magnitude of saline-water discharge from the Wellington aquifer to freshwater streams (fig. 9). Except for the Ninnescah River, which is regulated by Cheney Reservoir (located about 40 miles upstream from Belle Plaine), the measurements were made during low-flow conditions. There had been no precipitation for about 2 weeks prior to the measurements.

Water quality, with respect to chloride, is marginal in the Ninnescah River upstream from the area where the stream flows over the Wellington aquifer (fig. 9). The Kansas Department of Health and Environment recommends a maximum concentration of 250 mg/L chloride in drinking water. The Kansas Water Resources Board reports that chloride concentration in the Ninnescah River at the Peck gaging station (about 10 miles upstream from the area of saline-water inflow) is greater than 250 mg/L 33 percent of the time and that the maximum recorded chloride concentration was 421 mg/L at a discharge of 43 ft^3/s (J. D. Hargadine, oral commun., 1977). The source(s) of chloride in the Ninnescah River at this location is attributed to inflow of saline water from Permian-age evaporite deposits in areas to the west of the study area.

Figure 9.--Measuring sites for seepage-salinity measurements (November 1977), surface-water gaging stations, and areas of saline-water contamination.

Walters (1961) reported on the high chloride concentrations in the alluvium in a 2-mi^2 area west of Belle Plaine where the Ninnescah River flows over the Wellington aquifer. Analyses of water samples from several augered test holes and wells screened in the basal part of the alluvium in this area indicated chloride concentrations ranging from 1,700 to 160,000 mg/L. The source of chloride gained in the reach between site N-2 and site N-3A (11 ft^3/s) evidently is from the Wellington aquifer where chloride concentrations are about 180,000 mg/L (table 1).

The seepage and salinity measurements along this reach of the Wellington aquifer indicate an increase in chloride load from 95 tons per day at site N-2 to 115 tons per day at site N-7 (a 14 mile reach) (fig. 9 and table 2).

TABLE 2 (near here)

Slate Creek contains water of good quality upstream from the saline-water inflow area. Results of the seepage and salinity measurements mentioned earlier showed increases in chloride concentrations along the reach of saline-water inflow from 78 mg/L (0.78 tons per day) at site S-1 to 3,540 mg/L (44 tons per day) at site S-3. The overall net gain in chloride load in the reach from site S-1 to site S-5 was 35.5 tons per day, while the net increase in discharge was 0.68 ft^3/s (fig. 9 and table 3). Also, there are several large seeps in the area (secs. 4, 9, 15, 22, 26, and 27, T.33 S., R.2 E.) where saline-water outflow from the Wellington aquifer has formed moderate-sized lakes and has denuded large areas of land. The chloride concentrations of water samples taken from a lake in 33-2E-16AB and from a sink-hole in 33-2E-26BB were 11,300 mg/L and 16,600 mg/L, respectively.

TABLE 3 (near here)

Table 2.--Results of seepage and salinity measurements on Ninnescah River, November 1976.

Location*	River mile upstream from mouth	Measured discharge (ft^3/s)	Gain or loss (ft^3/s)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Sodium load (tons/day)	Chloride (mg/L)	Chloride load (tons/day	Sodium/chloride ratio
N-1	17.0	120	----	78	15	196	63.5	291	94	0.67
N-2	15.5	122	2.0	77	15	191	62.9	289	95	.66
N-3	14.6	126	4.0	77	15	194	66.0	291	99	.67
N-3A	13.8	131	5.0	80	15	199	70.4	307	109	.65
N-4	11.6	130	-1.0	78	16	202	70.9	303	106	.67
N-5	9.6	132	2.0	78	17	201	71.6	307	109	.65
N-6	6.6	133	1.0	80	15	199	71.4	302	108	.66
N-6A	4.7	130	-3.0	83	13	199	69.8	304	107	.65
N-7	1.2	141	11.0	80	16	200	76.1	301	115	.66
	Overall net gain		21.0						21	

* See figure 9.

Table 3.--Results of seepage and salinity measurements on Slate Creek, November 1976.

Location*	River mile upstream from mouth	Measured discharge (ft^3/s)	Gain or loss (ft^3/s)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Sodium load (tons/day)	Chloride (mg/L)	Chloride load (tons/day)	Sodium/chloride ratio
S-1	14.5	3.73	----	91	41	71.0	0.72	78.0	0.78	0.91
S-2	11.6	3.82	0.09	139	48	340	3.51	500	5.18	.68
S-3	9.3	4.58	0.76	259	80	2,350	29.1	3,540	43.8	.66
S-4	5.9	4.08	-0.50	246	79	2,160	23.8	3,300	36.3	.65
S-5	3.5	4.41	0.33	250	77	2,000	23.8	3,050	36.3	.66
Overall net gain			0.68				23.8		35.52	
33-2E-16AB	lake	----	----	496	142	7,300	----	11,300	----	.65
33-2E-26BB	lake	----	----	1,264	186	10,800	----	16,650	----	.65

* See figure 9.

TABLE 4 (near here)

Salt Creek west of Geuda Springs is a small stream that contributes very little chloride load to the Arkansas River (fig. 9 and table 4). Seepage and salinity measurements during low-flow conditions in November 1976, indicated an increase in chloride load from .10 tons per day at site R-1 upstream from the saline-water inflow area to 2.2 tons per day at site R-3 just north of Geuda Springs and an increase in discharge from 0.10 ft^3/s to 0.46 ft^3/s.

Leonard (1964) states that in Kansas oilfield brines the ratio of sodium plus potassium to the concentration of chloride is virtually constant despite wide differences in dissolved-solids concentration. The sodium-to-chloride ratio of water containing oilfield brine is normally less than 0.60. In brines from the Wellington aquifer, the ratios are slightly higher than 0.60, and in sewage effluent they are normally even higher. Excluding potassium, the ratios would be slightly lower.

Sodium-to-chloride ratios for samples from the Wellington aquifer are given in table 1, and sodium-to-chloride ratios of water samples collected during the seepage and salinity measurements are given in tables 2, 3, and 4. The ratios in water samples collected from the Ninnescah River are similar to the ratios in water from the Wellington aquifer (table 2).

Sodium-to-chloride ratios in water from Slate Creek, with the exception of site S-1, also are similar to ratios in water from the Wellington aquifer (table 3). Site S-1 is upstream from the saline-water inflow area.

Table 4.--Results of seepage and salinity measurements on Salt Creek, November 1976.

Location*	River mile upstream from mouth	Measured discharge (ft^3/s)	Gain or loss (ft^3/s)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Sodium load (tons/ day)	Chloride (mg/L)	Chloride load (tons/ day	Sodium/ chloride ratio
R-1	4.1	0.10	---	628	123	201	0.05	390	0.10	0.52
T-1**	2.5	0.06	---	860	184	410	0.07	1,440	0.23	.28
R-2	2.0	0.32	0.16	744	140	410	0.35	990	0.86	.41
R-3	1.2	0.46	.14	744	135	960	1.19	1,780	2.2	.54
Overall net gain			.30				1.14		2.1	

* See figure 9.

** Tributary measuring site.

Sodium-to-chloride ratios in water samples collected from the seepage and salinity measurements along Salt Creek indicate that at least part of the salt contamination is due to oilfield activities. Although Salt Creek basin drains an area in which there is oilfield activity, the author toured the entire drainage of Salt Creek and could find no obvious evidence of present contamination due to these activities. However, it is possible that some ground-water inflow into the tributary reflects contamination that has occurred in the past.

High concentrations of calcium and magnesium chloride are indicative of brine produced in association with oil in Kansas. The analysis for site T-1 shows a magnesium concentration of 184 mg/L compared with 123 mg/L, 140 mg/L, and 135 mg/L for sites R-1, R-2, and R-3, respectively (table 4). These values also are high compared with magnesium concentrations of water samples collected from Ninnescah River and Slate Creek (tables 2 and 3).

Although some of the saline water in Salt Creek may be due to past contamination from oilfield activities, it is evident that the Wellington aquifer contributes saline-water inflow to the stream. Numerous salt seeps and saline water in Salt Creek were noted before oilfield activities commenced in the 1920's. Thus, possible contamination owing to past oilfield activities may be masking the contamination resulting from saline-water inflow from the Wellington aquifer.

The mean daily natural saltwater discharge and chloride-load gain in the Arkansas River and its tributaries between Derby and Arkansas City during 1969-74 was computed by regression analysis procedures. A computer program developed by J. M. McNellis (oral commun., 1977) calculates the first-degree log regression equation formed by regressing the dependent variable, instantaneous chloride concentration, against the independent variable, and instantaneous discharge. The derived regression equation is of the form:

$$10^I \times RC \times \log Q = 0,$$

where I = intercept, in log units,

RC = regression equation, and

Q = instantaneous discharge.

The derived regression equation is used with mean daily stream discharge to derive mean daily chloride concentrations in milligrams per liter. If it is assumed that the saltwater moving through the Wellington aquifer is saturated (180,000 mg/L), the mean daily chloride concentrations and mean daily discharges can be used in the following equation to calculate the average chloride load in tons per day:

$$\text{load (tons per day)} = .0027 \times Cl^-(\text{mg/L}) \times Q(\text{ft}^3/\text{s}),$$

where .0027 is a conversion factor, and Q = mean daily discharge.

The net mean daily increase in chloride load attributable to ground-water inflow to the Arkansas River can be estimated by subtracting the calculated chloride loads at the Derby and Peck gaging stations from the load calculated at the Arkansas City station (fig. 9). A. M. Diaz (oral commun., 1977) states that about 90 percent of the increase in chloride load between Derby and Arkansas City is attributable to ground-water inflow. The remaining load is derived from various municipal waste-treatment facilities and oilfield operations.

Slate Creek downstream from Wellington also exhibits an increase in chloride load due to ground-water inflow from the Wellington aquifer (fig. 8 and table 3). However, because chloride analyses were not available for Slate Creek, the chloride load was determined in a different manner. Salinity and seepage measurements were made during low-flow conditions in November 1976, along the reach of Slate Creek where water high in chloride and sulfate concentration flows from the gypsum-dissolution zone of the Wellington aquifer into the stream.

The average mean daily discharge for the nearest upstream gaging station, Slate Creek near Wellington, during 1970-74 was 60.1 ft^3/s. The chloride concentration of 78 mg/L obtained at the upper end of the seepage run was assumed to represent an average concentration for the stream. Also, it was assumed that any increase in chloride concentration downstream from this point was due to ground-water inflow to the stream (there is no indication of contamination from oilfield operations). Thus, the chloride load already in the stream above the area of saline-water inflow was computed to average 12.66 tons per day. This value also was subtracted from the chloride load computed at the Arkansas City station.

TABLE 5 (near here)

Table 5 lists the parameters derived for substitution into the first-degree log equation that is used to compute the chloride concentrations at the various stations. Table 5 also lists the computed chloride load that is believed due to ground-water inflow from the Wellington aquifer. Based on these criteria, the amount of chloride-load gain into the Arkansas River and its tributaries between Derby and Arkansas City averaged 294 tons per day. J. B. Gillespie (personal commun., 1978) reports that for the water years 1974-77 an average of 369 tons per day of saltwater entered the Smoky Hill River between New Cambria and Solomon. Thus, the total amount of chloride load contributed to the freshwater system as a result of natural inflow from the Wellington aquifer is about 663 tons per day.

If it is assumed that the water in the Wellington aquifer is saturated (180,000 mg/L), the mean daily saltwater discharge to the streamflow system may be calculated by the equation:

$$Q(\text{ft}^3/\text{s}) = \frac{\text{chloride load (tons/day)}}{.0027 \times 180{,}000 \text{ mg/L}} .$$

Thus, the rate of saltwater inflow would be 0.60 ft^3/s to the Arkansas River and 0.76 ft^3/s to the Smoky Hill River.

Table 5.--Parameters used to determine chloride load due to ground-water inflow to the Arkansas River between Derby and Arkanasas City.

Station	Number of chloride analyses (1969-74)	Mean daily discharge (ft^3/s)	Cl^--Q* correlation coefficient	Intercept (I)	Cl^--Q regression coefficient (RC)	Cl^- load (tons/day)
Arkansas River at Arkansas City (Sta. No. 08146500)	238	2,428	-.827	4.14	-.537	1,226
Arkansas River at Derby (Sta. No. 08144550)	78	1,609	-.874	4.11	-.560	727
Ninnescah River nr Peck (Sta. No. 08145500)	60	521	-.837	3.23	-.400	160
Slate Creek blw Wellington	---	60	---	---	---	12.66
		Total chloride load increase - - - - - - - - - - - - - -				326.34
		Chloride load increase due to ground-water inflow- - - -				293.7**

* Q = discharge, cubic feet per second.

** Total chloride load increase x .90 (A. M. Diaz, personal commun., 1977).

ALLEVIATION OF CHLORIDE CONTAMINATION

Several control measures possibly could be utilized to alleviate the chloride contamination problem in the study area. These include desalinization, dilution, evaporation, and diversion.

Desalinization costs have decreased in recent years but are still prohibitively expensive. The cost of producing freshwater by desalinization, exclusive of collection and effluent disposal cost, is in the range of $0.50 to $1.00 per 1,000 gal (U.S. Army Engineer District, Tulsa, 1965). Other methods of controlling salt contamination would certainly be less expensive.

Dilution of contaminated water with good-quality water is another viable alternative and probably the most commonly used method of contamination abatement. Large storage areas are required so that dilution water can be available during periods of low flow. This method is currently being used in the Kansas River system whereby water is released from reservoirs during low-flow periods to improve water quality in the Kansas River at Topeka, Lawrence, and other municipalities where the water is used for public supply.

Implementation of lined evaporation basins is another alternative that should be considered. The mean annual precipitation in the study area is about 32 inches per year, and the average pan evaporation is 58 inches per year. In addition, salt evaporation operations were successfully undertaken in the late 1800's east of Salina. Evaporation may be a viable alternative in areas where the water introduced to the evaporation basins is highly saturated with respect to sodium chloride. Interception of highly saturated saline water by wells completed in the Wellington aquifer, followed by spreading of the water in basins, would be an example of this method. It should be noted, however, that the use of evaporation ponds also may provide a potential source of groundwater contamination.

Diversion of freshwater around a salt-source area or of saline water out of a system via injection wells or transportation from the area is not a control plan in itself but must be used with other brine collection and control systems.

Discussion of measures that possibly could be implemented to control pollution caused by flow of highly mineralized water from the Wellington aquifer into freshwater stream-aquifer systems will be limited to the southern emission area; i.e., the area between Belle Plaine and Geuda Springs.

Because the saline-water inflow area is fairly limited, alleviation of the inflow to the Ninnescah River alluvium possibly could be accomplished by installation of interception wells screened in the Wellington aquifer. The saline water could be injected into disposal wells completed in the Arbuckle Group, which in this area is a highly permeable unit and often used for disposal of brines produced with oil and gas. The Arbuckle is found at depths of about 3,900 feet in this area. Another possible method of disposal is implementation of evaporation ponds as mentioned earlier.

Alternatively, a series of wells could be screened in the contaminated part of the alluvium. These wells could be pumped during high-flow periods, and the saline water could be diluted with river water and removed from the area.

The saline-water emission area is more diverse in the Slate Creek basin than in the Ninnescah alluvium, and interception of saline water in the subsurface is infeasible. Thus, alleviation would require construction of a collection system whereby the saline water could be gathered at the surface and transported via pipeline to disposal wells completed in the Arbuckle Group. The Arbuckle in this area occurs at depths ranging from 3,100 to 3,600 feet.

Because of the small quantities of contaminated water involved, probably the most feasible method of chloride alleviation in Salt Creek would be by dilution. Possibly an inflatable dam could be constructed that would store the saline water until the occurence of a high-flow event. Then, when the stage in the stream reaches a predetermined level, the dam could be deflated to allow the diluted water to flow into the Arkansas River.

RECOMMENDATIONS FOR FUTURE STUDIES

The "*Equus* beds" aquifer northwest of Wichita is the principal source of water for public supply for the city and also yields large supplies of ground water for irrigation. Increased withdrawals and continued uncontrolled development could result in mining of ground water, reduced well yields, and possible deterioration of water quality as a result of saline-water inflow from the Wellington aquifer and that part of the "*Equus* beds" in the Burrton-Buhler area that is presently contaminated.

The study should include reevaluation of existing hydrologic and chemical-quality data using up-to-date techniques. Additional test drilling is needed to define the relation of the "*Equus* beds" aquifer to the Wellington aquifer. Solute transport digital models would then be used to simulate ground-water flow in the "*Equus* beds" as a result of stresses applied via increased pumpage and to determine the potential for movement of saline water from the Wellington aquifer into the "*Equus* beds" aquifer and the Wichita well field.

Deterioration of the alluvial aquifer in a small area west of Belle Plaine has occurred as a result of saline-water inflow from the Wellington aquifer. In this area, the head in the Wellington aquifer is above the head in the unconsolidated deposits. A detailed study is needed to describe the geohydrologic relationships between the freshwater alluvial aquifer and the Wellington aquifer; to determine the extent, severity, and direction of movement of saline water in the aquifer; and to assess possible means of alleviation or control of the contamination.

The study should include installation of observation wells screened at the base of the alluvium and in the Wellington aquifer. Water-level measurements from these wells and radioactive logs could be used in conjunction with electrical logs from local oil tests to gain an understanding of the local geohydrologic relationships between the alluvial aquifer and the Wellington aquifer. The wells should be sampled periodically to determine water type and monitor chemical changes that may occur, as well as to ascertian areas of saline-water inflow to the alluvial aquifer.

A variable-density digital flow model could be used to aid in determination of the quantity, source(s), and direction of movement of saline water that is entering the alluvial aquifer.

SUMMARY

Degradation of chemical quality in freshwater streams and aquifers in central and south-central Kansas has adversely affected their suitability for public use. The degradation occurs as a result of natural discharge of saline water from the Wellington aquifer. The contaminating water is derived from differential solution of the eastern edge of the Hutchinson Salt Member and associated gypsum units of the Wellington Formation where they are in close proximity to freshwater systems.

The dissolution of salt and gypsum has resulted in formation of a discontinuous zone of solution cavities and collapsed beds (termed the Wellington aquifer) which trends from Salina southward toward the Oklahoma stateline.

The generalized potentiometric surface of the Wellington aquifer was determined through measurements of water levels in wells completed in the Wellington aquifer and by results of a steady-state digital model of ground-water flow.

Comparison of maps of the potentiometric surface of the Wellington aquifer and the water table of the overlying freshwater deposits indicates that the ground water enters the Wellington aquifer from downward leakage of freshwater (pls. 5B and 6). Also indicated on the potentiometric maps is a ground-water divide east of Hutchinson. The potentiometric surface slopes north to the Smoky Hill River valley where, between New Cambria and Solomon, the head of the potentiometric surface of the Wellington aquifer is higher than the water table of the unconsolidated deposits. Saline-water inflow to the alluvium and stream occurs in this area.

Another major direction of flow from the potentiometric high is southeast toward the Belle Plaine-Adamsville-Geuda Springs area where the head in the Wellington aquifer is higher than the head in the freshwater deposits and where saline water is emitted to stream valleys and onto the land surface in the form of springs and seeps.

The potentiometric head in the Wellington aquifer is also higher than the head in the freshwater deposits in the area just east of Hutchinson. However, the confining layer between the Wellington aquifer and freshwater deposits is about 300 feet thick in this area, and it is doubtful that the head differential is great enough to overcome the flow-retardation effects of such a thick confining bed.

Another area of possible upward flow of saline water to the freshwater deposits is in the Arkansas River valley between Hutchinson and Mt. Hope. In this area, the confining layer has been eroded by the ancestral Arkansas River so that there is less than 100 feet of shale between the Wellington aquifer and the freshwater deposits. Unknown quantities of saline water may be entering the freshwater system in this area.

Seepage and salinity measurements and regression-analysis methods were used to estimate the quantity of saline water that is entering the Arkansas River and its tributaries between Derby and Arkansas City as a result of ground-water inflow from the Wellington aquifer. These methods indicate that about 294 tons of chloride per day are entering the freshwater system in this area. J. B. Gillespie (personal commun., 1978) reports that about 369 tons of chloride per day are entering the Smoky Hill River between New Cambria and Solomon. The concentrated saltwater discharge into the two systems is about 0.60 ft^3/s and 0.76 ft^3/s, respectively.

Possible methods of alleviation of the saline-water contamination include interception by wells of the saline water in the Wellington aquifer before it enters the freshwater systems, interception by wells at the base of the freshwater deposits where they are present, and collection at land surface in areas of seeps and springs. Subsequent to interception, methods of disposal include injection to the Arbuckle Group, dilution with fresh stream water during high-flow events, and evaporation in ponds.

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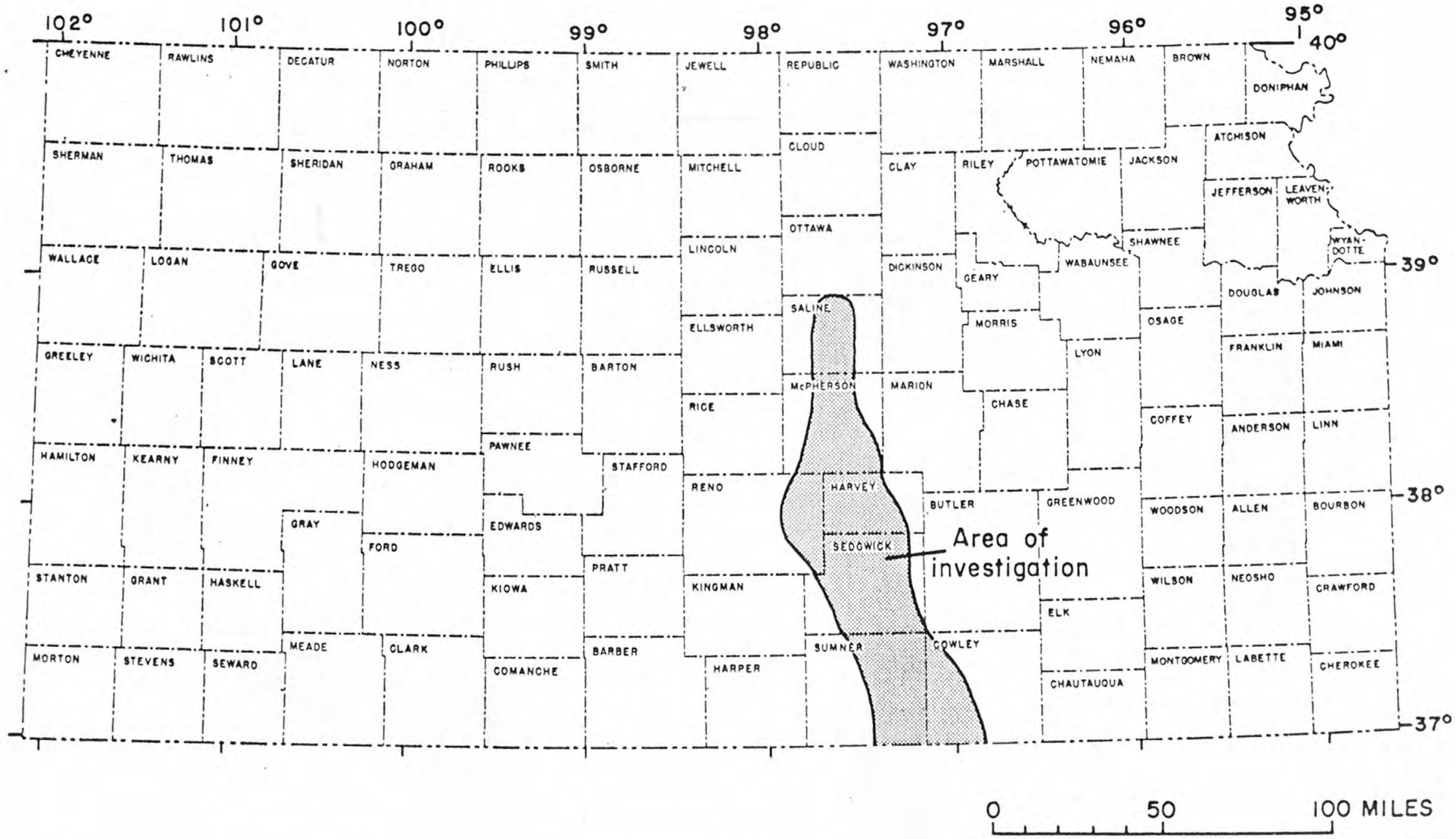


Figure 1.--Map of Kansas showing area of investigation.

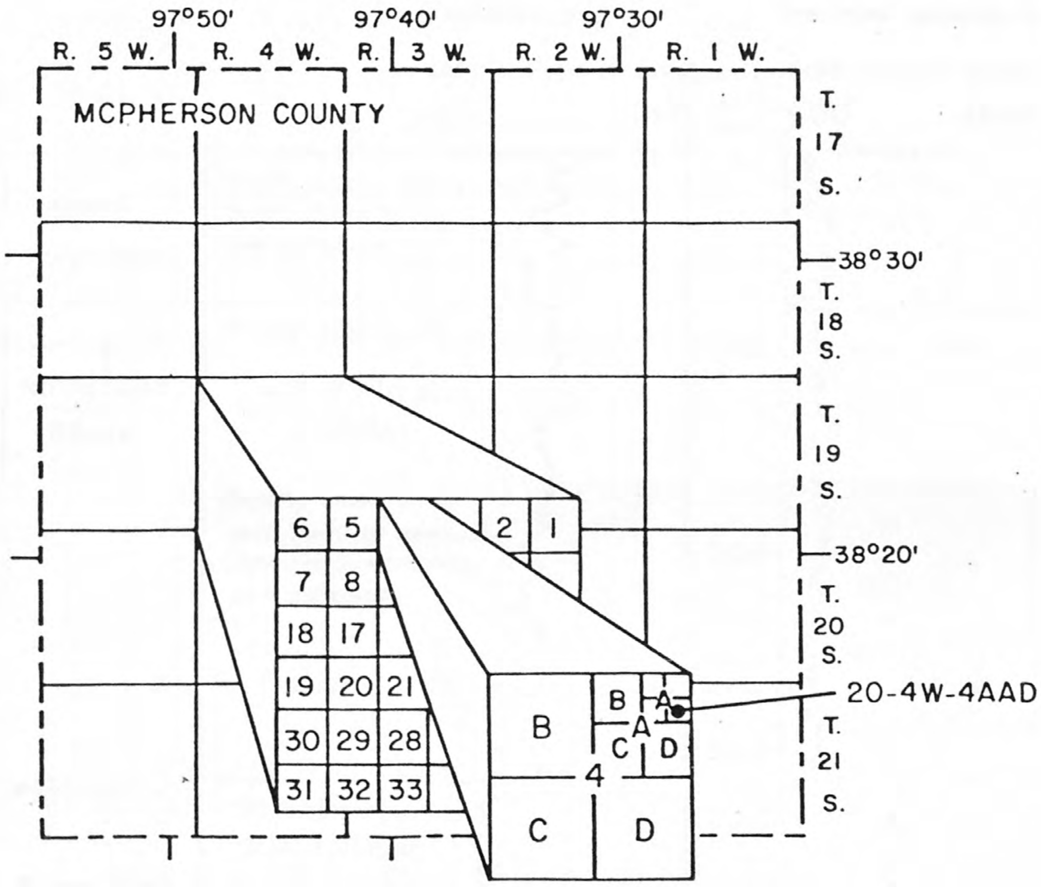


Figure 2.--System of numbering wells and test holes in Kansas.

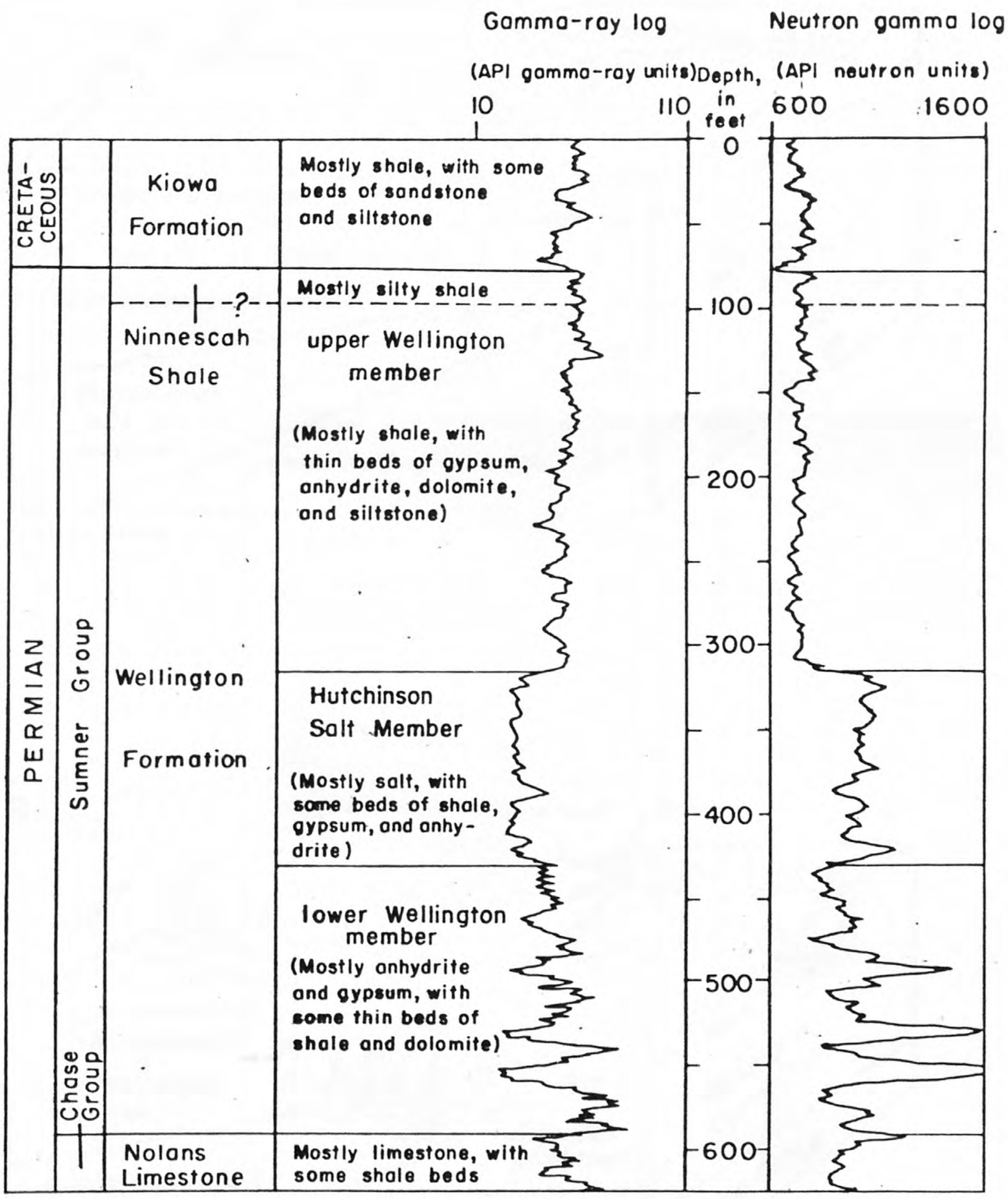
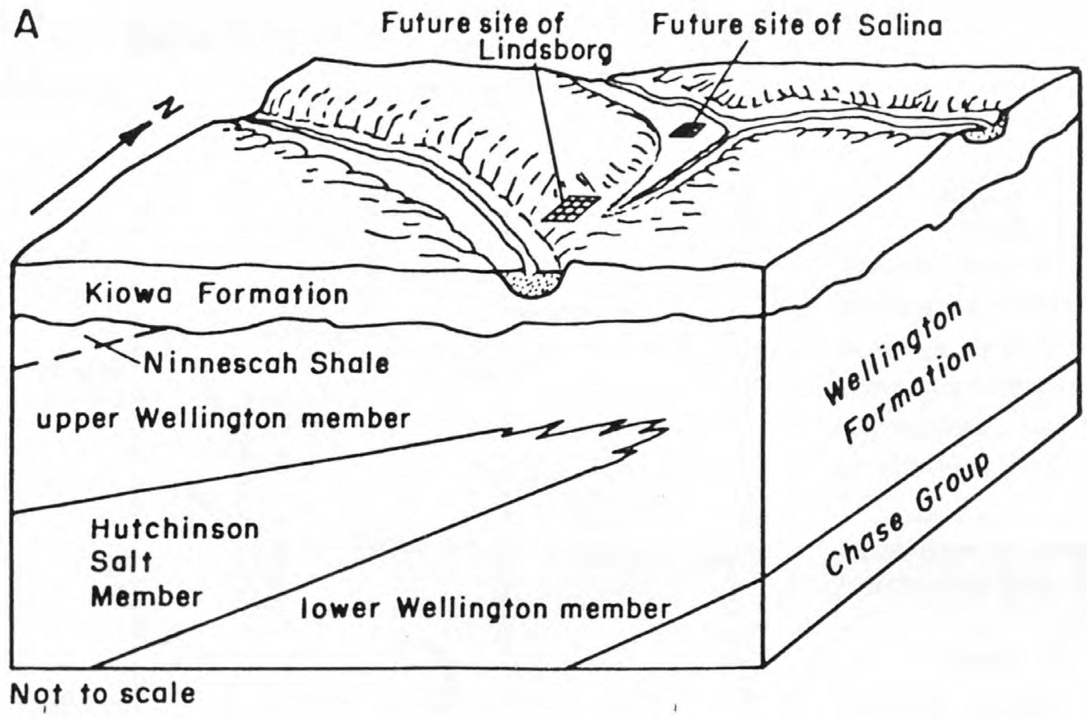


Figure 3.--Part of gamma ray-neutron log of well in 16-4W-22DAB showing stratigraphic relationship of bedrock units discussed in this report.



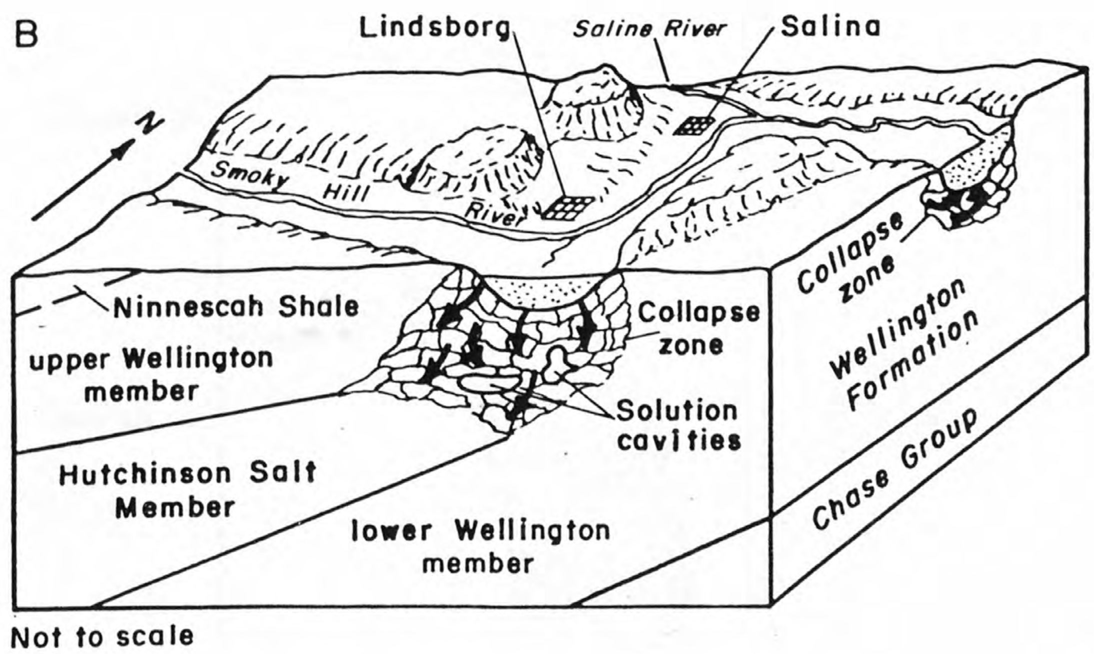


Figure 4.--Conceptual block diagrams near Lindsborg showing geologic development, mechanism of dissolution of Hutchinson Salt Member, and development of Wellington aquifer between Cretaceous time (A) and present (B).

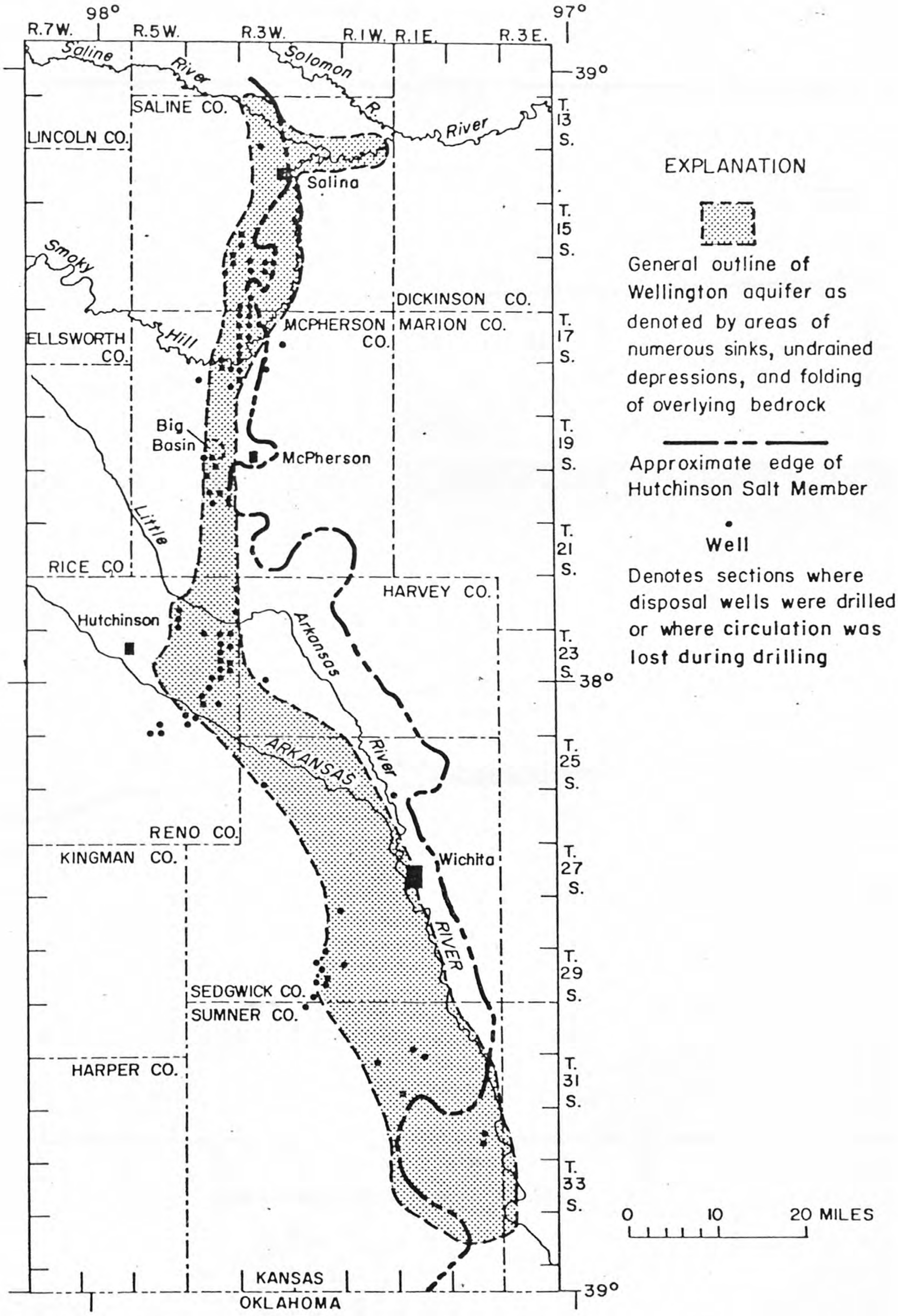
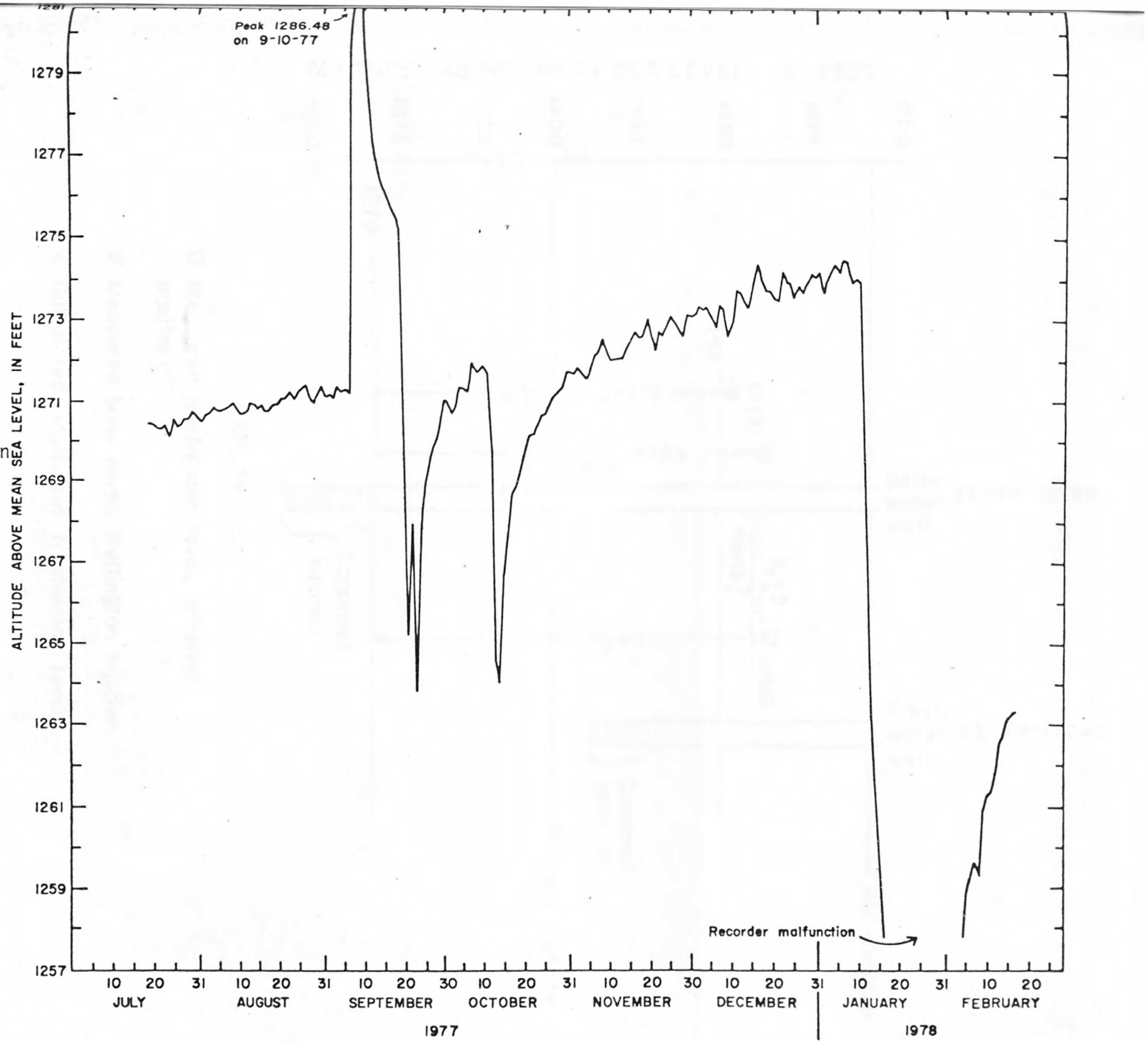


Figure 5.--General outline of Wellington aquifer as denoted by areas of sinks and undrained depressions, locations of disposal wells, and areas where lost circulation was reported.

Figure 6.--Hydrograph of well 19-4W-34BDA showing fluctuation of potentiometric surface of Wellington aquifer in response to changes in barometric pressure, pumping, and injection.



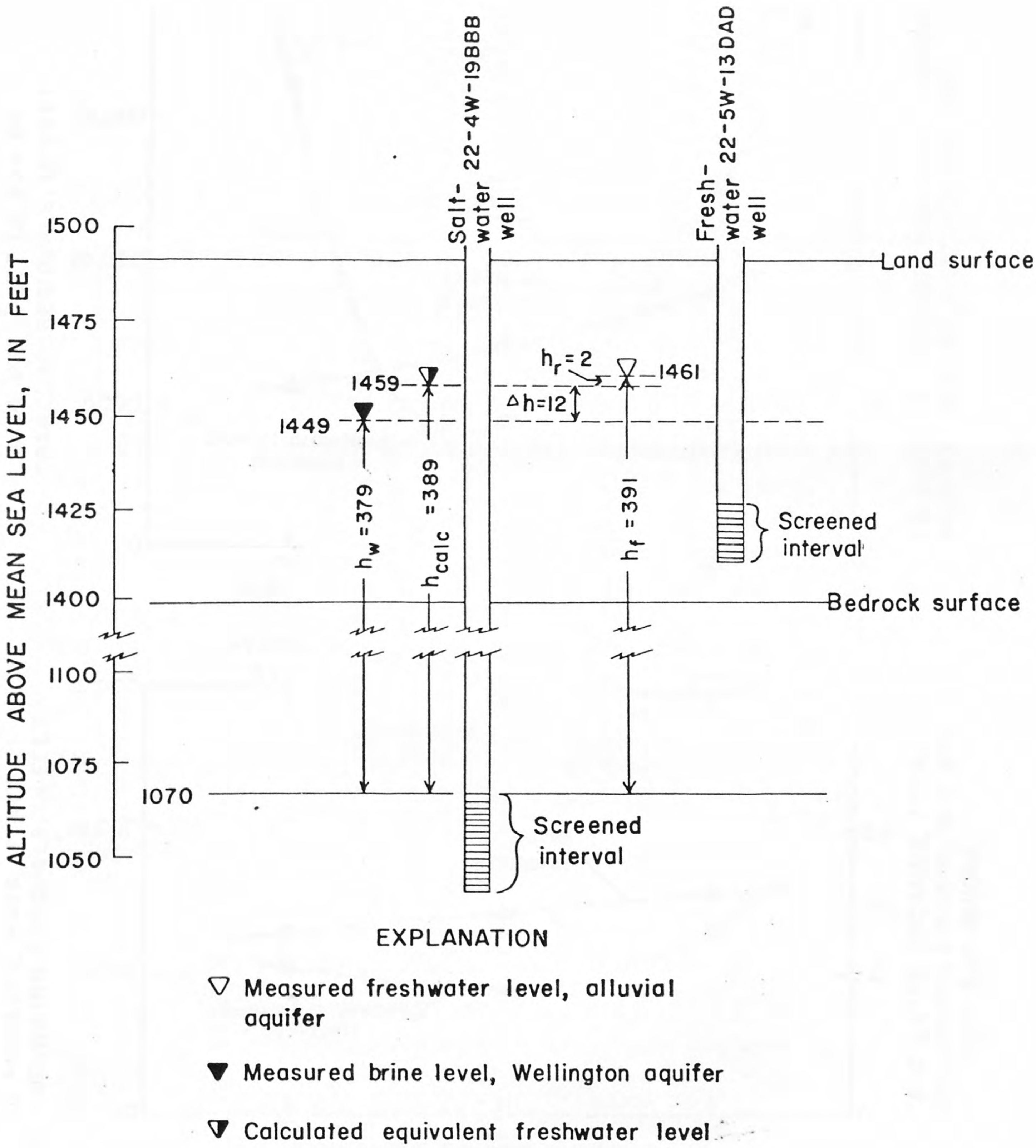


Figure 7.--Comparison of measured and calculated water levels near Buhler.

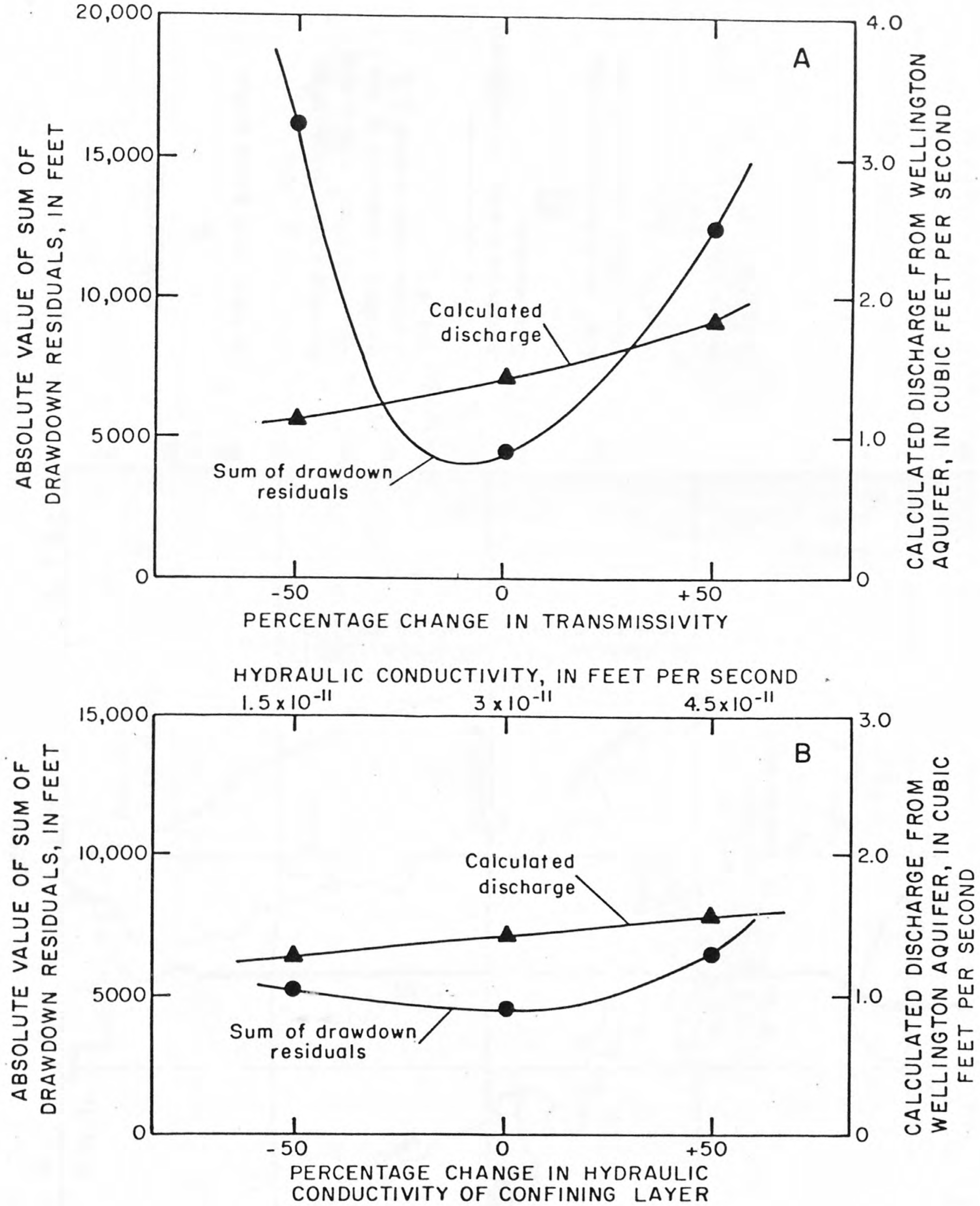


Figure 8.--Relation between (A) percentage changes in transmissivity and (B) hydraulic conductivity versus the absolute value of the sum of the drawdown residuals and discharge from the Wellington aquifer.

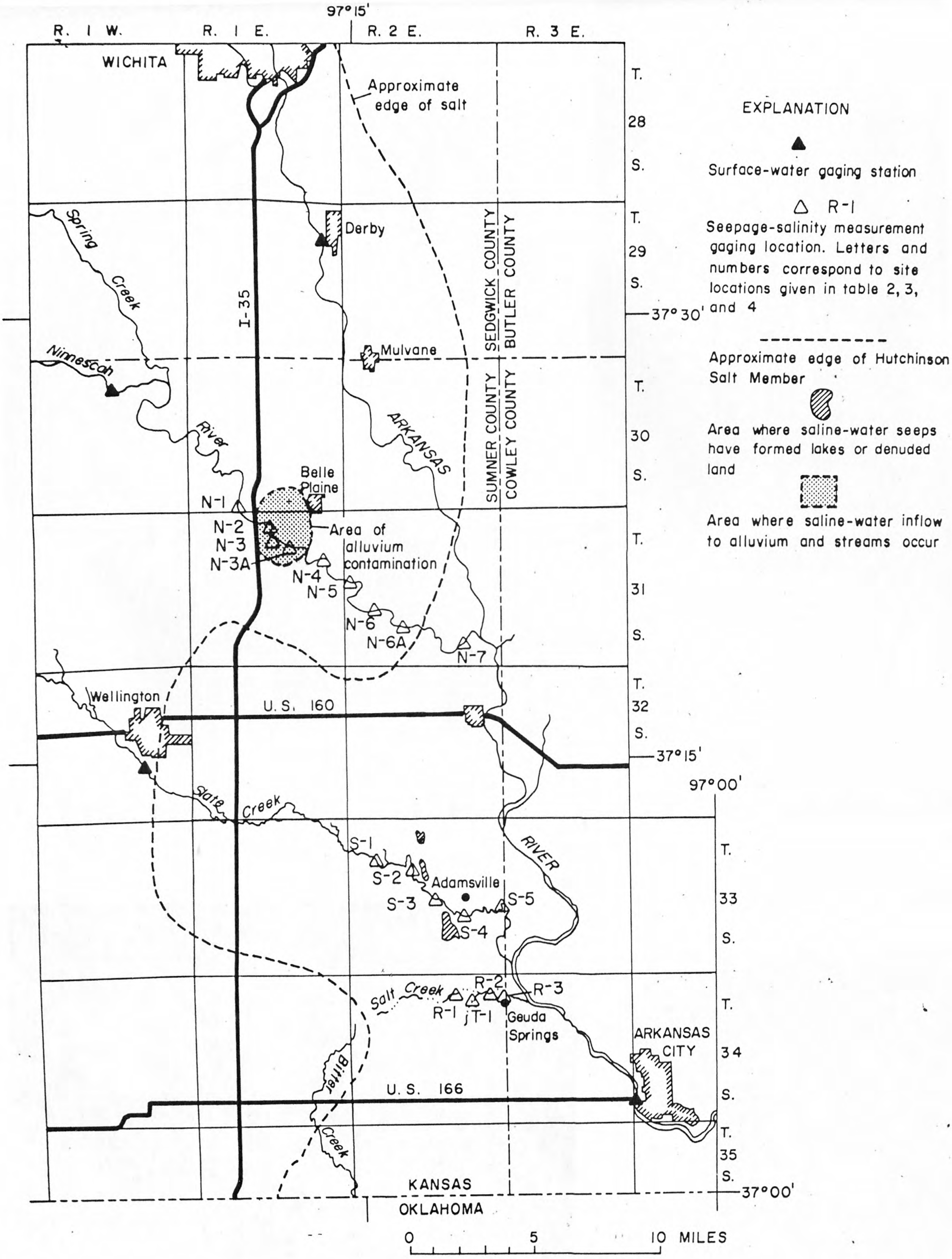


Figure 9.--Measuring sites for seepage and salinity measurements (November 1977), surface-water gaging stations, and areas of saline-water contamination.

Plate 1.--Map showing surficial geology and configuration of Permian bedrock surface in area of Wellington aquifer, central Kansas