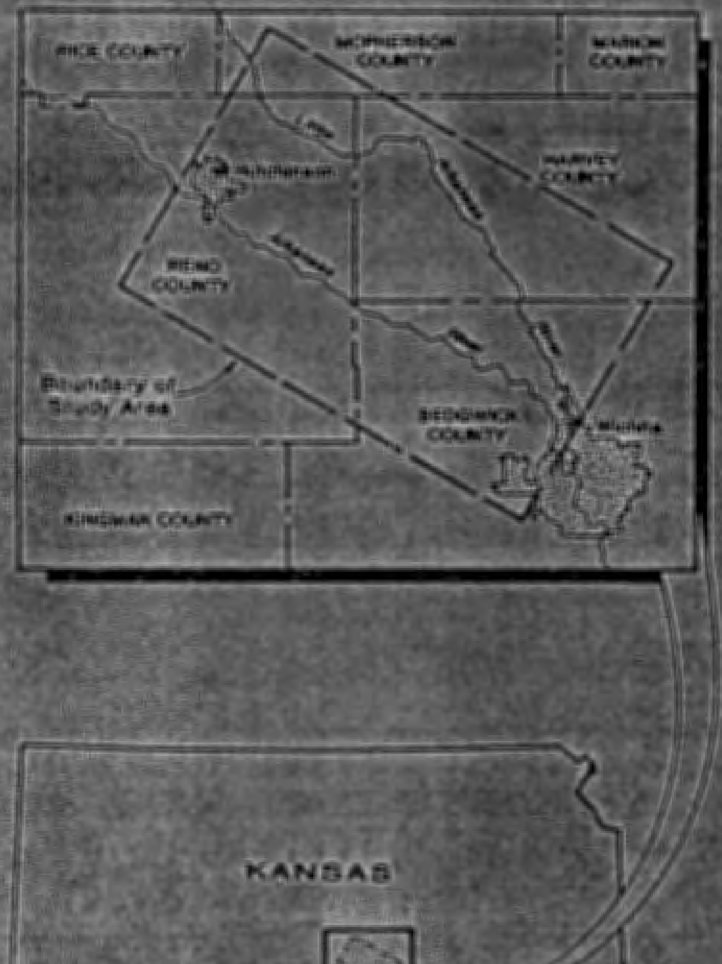
EXHIBIT J

Arkansas River Water Management Improvement Study

Modeling of Chloride Transport in the Equus Beds Aquifer

Technical Report



United States Department of the Interior

Bureau of Reclamation

November 1993

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American [illegible]

ABSTRACT

The Arkansas River Water Management Improvement Study is a joint effort by the Kansas Water Office, Equus Beds Groundwater Management District No. 2, the U.S. Geological Survey, and the Bureau of Reclamation (Reclamation). Reclamation's portion of the study used ground-water flow and chloride transport models of the Equus Beds aquifer system to investigate management strategies and issues about water-quality degradation of the aquifer.

Models used were a flow model of the Equus Beds system which uses the three-dimensional, finite-difference, flow model program (MODFLOW) and a transport model, developed and calibrated to simulate 1940-1989 chloride conditions in the Equus Beds aquifer.

The study considered three sources of salinity present in the aquifer: chloride from Arkansas River water entering the aquifer, deep natural saltwater, and brine from oil field operations.

ACRONYMS AND ABBREVIATIONS

ARWMIS	Arkansas River Water Management Improvement Study
gpm	gallons per minute
GMD2	Equus Beds Groundwater Management District No. 2
KWO	Kansas Water Office
mg/L	milligrams/liter
m.s.l.	mean sea level
MT3D	A modular three-dimensional transport model program
MODFLOW	Three dimensional, finite difference flow model program
Reclamation	Bureau of Reclamation
USGS	U.S. Geological Survey
WATSTORE	A USGS data base

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Summary

In 1988, the Arkansas River Water Management Improvement Study (ARWMIS) was formed to examine the hydrogeology and water quality of the Arkansas River-Equus Beds aquifer system. As a part of this study, Bureau of Reclamation (Reclamation) modeled the Equus Beds aquifer to investigate management issues regarding water quality degradation of the Equus Beds aquifer. The modeling examined ground-water flow and the transport of chloride[1] in the aquifer.

The Equus Beds aquifer provides most of the fresh and usable water in south-central Kansas. Ground-water withdrawals from the Equus Beds aquifer between Hutchinson and Wichita in Kansas have been increasing since the 1940's. The city of Wichita's principal water supply, Wichita well field, is located in the Equus Beds aquifer east of Burrton.

Salinity Sources

The quality of the ground water in the area is generally good, although salinity from natural and manmade sources has entered the ground water. Naturally occurring sources include Arkansas River water and natural saltwater located in the deepest part of the aquifer around a bedrock low, or trough, near the course of the Arkansas River. Brine from oil field operations, evaporation-pan brine from salt-refining activities, and the possible migration of saltwater around disposal wells or poorly cased boreholes completed in or below the Wellington Formation are sources of salinity from human activities.

Models

The study used two numerical models:

- A flow model of the Equus Beds system using a three-dimensional, finite-difference, flow model program (MODFLOW) that was developed by the U.S. Geological Survey (USGS) (Myers et al., in review). This model was used as the basis for the investigation of chloride transport in the aquifer. The flow model was modified by increasing the resolution of the

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[1] In this report, chloride serves as an indicator of the salinity in the ground water.

finite-difference grid and was used in conjunction with a transport model (Papadopulos and Associates, Inc., 1992).

- A transport model developed and calibrated to simulate 1940-1989 chloride conditions in the Equus Beds aquifer. The transport model was used to characterize the movement of chloride from specific sources[2] during the calibration period (1940-1989) and the projection period (1990-2049). Additional simulations were made to investigate potential management strategies.

Results

Field data and results from these simulations indicate that chloride plumes are migrating from the Arkansas River and Burrton Oil Field area toward the Wichita well field area. The transport model predicts that chloride concentrations would be as high as 400 milligrams per liter (mg/L) in the south part and 300 mg/L in the extreme northwest part of the well field by 2049.[3] The saltwater plume originating in the Burrton Oil Field area would contribute the largest amount of chloride to the Wichita well field area until about 2010, when the Arkansas River would become the largest contributor.

The increasing pumpage from the aquifer is primarily responsible for the contribution of chloride from the Arkansas River as well as the oil field saltwater plume's movement toward the well field. Withdrawals from the aquifer have also induced significant vertical movement of chloride from the upper and middle layers into the lower part of the Equus Beds aquifer.

Maintaining present withdrawals or further developing the aquifer could accelerate chloride migration from these salinity sources to areas of development.

Management Strategies

The study investigated potential management strategies and concerns regarding chloride degradation of the Equus Beds aquifer.

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[2] The Arkansas River, natural saltwater located deep in the aquifer, and brine from the Burrton Oil Field.

[3] The secondary drinking water standard for chloride is 250 mg/L.

- Applying recharge water between the Arkansas River and the Wichita well field area appears to inhibit the movement of chloride from the river to the aquifer.
- Installing withdrawal wells in areas of high chloride concentration appears to minimize the impact of the Burrton Oil Field saltwater on the Wichita well field area.
- Reducing pumping within the Wichita well field area decreases the impacts from each of the salinity sources considered, the Arkansas River, deep natural saltwater, and the Burrton Oil Field brine.
- Eliminating flow in the Arkansas River significantly decreases heads and demonstrates the importance of the river serving as a water supply to recharge the aquifer.
- Eliminating agricultural pumping near the Arkansas River because of poor quality water would have minimal impacts on ground-water flow and quality in the aquifer.

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Chapter 1: Introduction

Introduction

In 1988, the Arkansas River Water Management Improvement Study (ARWMIS) began as a joint effort of the Kansas Water Office (KWO), the Equus Beds Groundwater Management District No. 2 (GMD2), the U.S. Geological Survey (USGS), and the U.S. Bureau of Reclamation (Reclamation). One of Reclamation's principal tasks was to investigate strategies to effectively manage the Equus Beds aquifer.

This report presents the results of transport model simulations of chloride in the stream-aquifer system and the Equus Beds. This work is largely based on the flow model developed by USGS as a portion of the ARWMIS study. Calibration simulations have been performed for chloride transport for the period 1940-1989. In addition, model simulations are used to predict the movement of chloride in the Equus Beds aquifer.

This report also discusses the modeling results of simulations investigating management concerns regarding water quality degradation of the Equus Beds aquifer.

Background

The Equus Beds aquifer provides most of the fresh and usable water in south-central Kansas. Ground-water withdrawals from the Equus Beds aquifer between Hutchinson and Wichita in Kansas have been increasing since the 1940's. The city of Wichita's principal water supply, Wichita well field, is located in the Equus Beds aquifer east of Burrton.

The quality of the ground water in the area is generally good, although salinity, indicated by the presence of chloride, has entered the aquifer from several sources. This portion of the ARWMIS study examined the following sources.

- **Arkansas River water**—generally saline through the project area from salinity sources upstream from Hutchinson, Kansas.
- **Natural saltwater located in the deepest part of the aquifer** around a bedrock low, or trough, near the course of the Arkansas River. High concentrations of

natural chloride have probably intruded from the underlying Wellington Formation into the deepest portions of the Equus Beds.

- **Brine from Burrton Oil Field activities**—oil field brine contamination from the Burrton Oil Field area has rendered water unsuitable for most uses in portions of the Equus Beds aquifer near Burrton.

Other sources that were not examined include:

- **Brine from Hollow-Nikkel Oil Field activities**.
- **Evaporation-pan brine** from salt-refining activities.
- **Possible migration of chloride** via poorly cased boreholes or disposal wells completed in or below the Wellington Formation.

Maintaining present withdrawals or further developing the aquifer could accelerate migration of saltwater from these salinity sources to areas of development.

Understanding the hydrologic and hydrochemical aspects of the stream-aquifer system could lead to improved management of the available water resources in the study area.

Purpose

The purpose of Reclamation's Modeling Management Strategies portion of the ARWMIS is to examine water management strategies and issues regarding water quality degradation of the Equus Beds aquifer. The primary objective is to determine how aquifer use affects the distribution of chloride from the main sources of chloride within the aquifer.

Description of Study Area[4]

The study area is located in south-central Kansas in parts of Reno, Harvey, McPherson, and Sedgwick Counties (figure 1). Principal cities in the area are Hutchinson, Newton, and Wichita. Towns and water features in the area are shown in figure 2.

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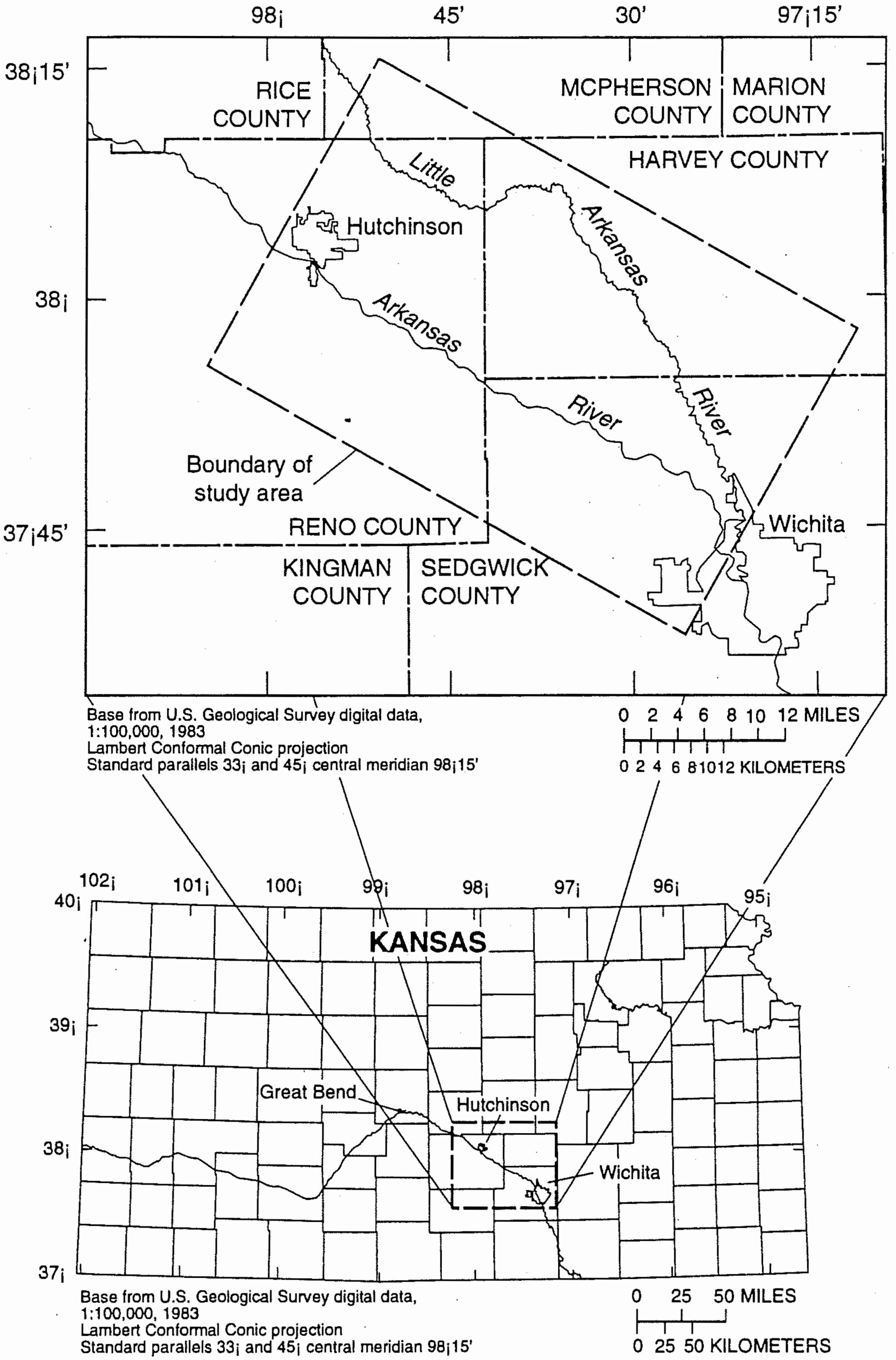
[4] This section was extracted and modified from Myers et al., in review.



Base from U.S. Geological Survey digital data,
1:100,000, 1983
Lambert Conformal Conic projection
Standard parallels 33¡ and 45¡ central meridian 98¡15'

Base from U.S. Geological Survey digital data,
1:100,000, 1983
Lambert Conformal Conic projection
Standard parallels 33¡ and 45¡ central meridian 98¡15'

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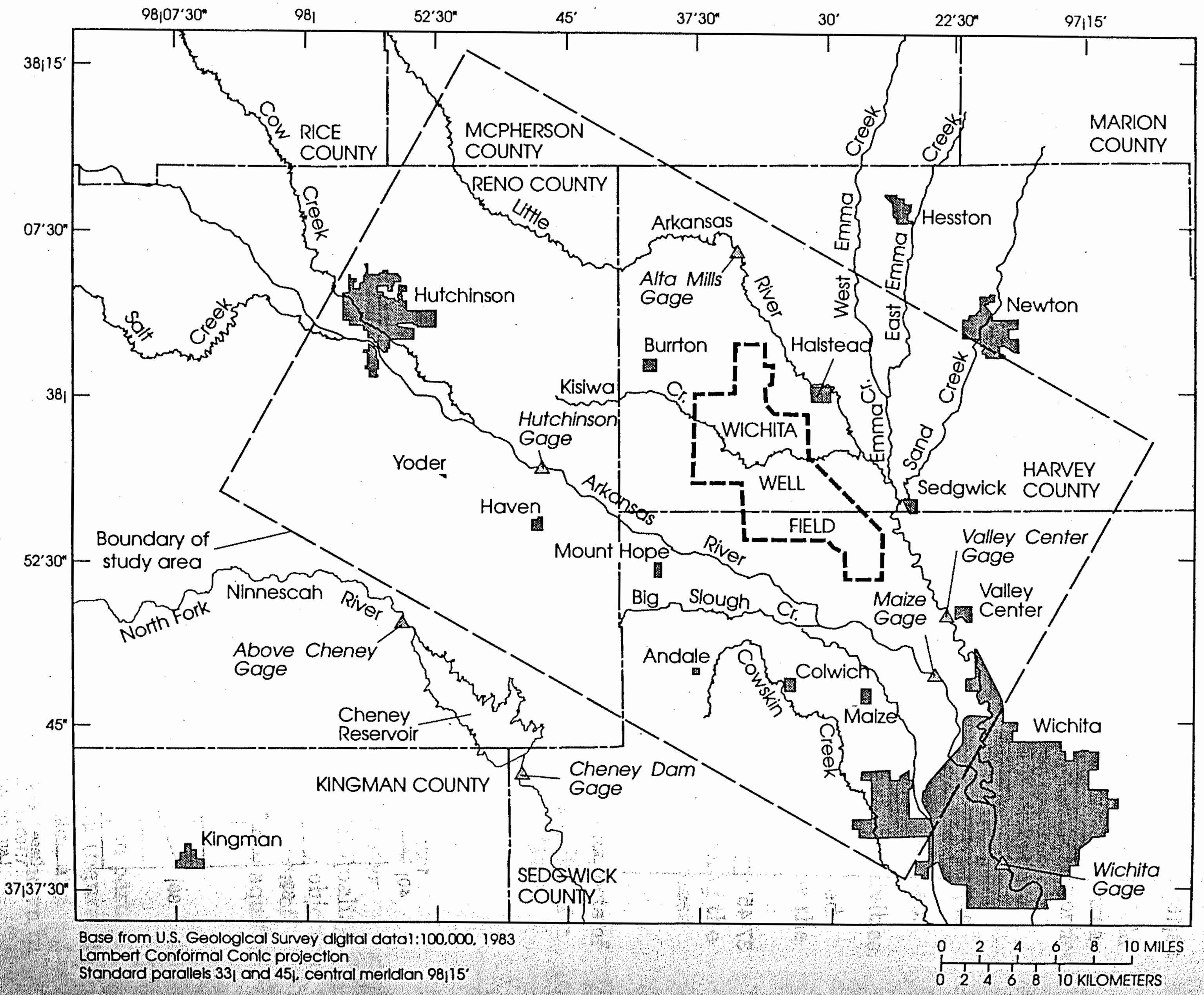
Figure 1.—Location of study area.



Base from U.S. Geological Survey digital data1:100,000, 1983
Lambert Conformal Conic projection
Standard parallels 33| and 45|, central meridian 98|15'

Figure 2.—Principal features in and around the study area.

The Equus Beds study area is in a subhumid portion of south-central Kansas. Annual precipitation averages about 30 inches per year from rainfall in spring and summer and snowfall typically from December through March. Temperatures vary widely throughout the year with average July highs in the mid-90's degrees Fahrenheit and lows in the upper 60's. Average January temperatures range from the mid-40's to the low 20's.

There is very little topographic relief over the study area except for an area of sand dunes near Hutchinson. Mostly, the land surface slopes gently toward the major streams in the area.

The Arkansas River and the Little Arkansas River are the major streams in the study area (figure 1). The Arkansas River flows southeast in a fairly straight, slightly braided channel. The Arkansas River channel is entrenched 5 to 10 feet below the adjacent land surface. In contrast, the Little Arkansas River meanders as it flows east and southeast to its confluence with the Arkansas River in Wichita. The channel of the Little Arkansas River is entrenched 15 to 20 feet below the adjacent land surface. Several small creeks flow into the Arkansas and Little Arkansas Rivers in the study area (figure 2).

USGS Contributions to the Study

USGS prepared the *Hydrologic and Chemical Interaction of the Arkansas River and the Equus Beds Aquifer between Hutchinson and Wichita, South-Central Kansas* (Myers et al., in review) as part of the ARWMIS. This report presents the results of a hydrogeologic and water quality study of the Arkansas River-Equus Beds aquifer system using flow modeling and particle tracking simulations of the river-aquifer system between Hutchinson and Wichita. Simulations of ground-water flow for calibration purposes cover the period 1940-1989. Model simulations are used to project the effects of natural and human-induced stresses on the river-aquifer system. The report also discusses sources and movement of chloride in the Equus Beds aquifer.

Methods of Study

For this portion of the ARWMIS study, Reclamation investigated management concerns by modeling flow and chloride transport.

Reclamation used the USGS flow model as a starting point and foundation for investigating the impacts of management concerns in the stream-aquifer system and the Equus Beds. The USGS flow model was accepted as a reasonable representation of the aquifer system within the study area. Any significant changes in the flow model would demand considerable time and effort in recalibration. However, a finer spaced finite-difference grid was necessary to adequately define the velocity flow field for the transport model, which required regridding. Reviewing these results indicated that the regridded flow model was an acceptable representation of the original flow model and required no further calibration.

Previous transport modeling studies were used to establish transport parameters and initial concentrations of chloride in the aquifer. Historical chloride data obtained from USGS and the GMD2 were used for transient calibration of the transport model. Transport model data were refined during calibration of the transient model to approximate graphs of chloride concentration versus time at sites within the study area.

Simulations were made to characterize the transport of chloride from specific sources during the calibration period (1940-1989) and the projection period (1990-2049). These chloride sources are: the Arkansas River, deep natural saltwater, and saltwater from the Burrton Oil Field. Simulations were also performed to investigate potential management strategies and issues.

Previous Studies[5]

The Equus Beds aquifer is an important source of water for cities, industries, and farms. The importance of this water source and high chloride concentrations in parts of the aquifer, streams, and adjacent rocks have made the Equus Beds aquifer a center of academic attention. Many

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[5] This section was extracted and modified from Myers et al., in review.

hydrogeologic, water quality, ground-water flow model, and solute-transport studies concerning this aquifer have been completed.

- Williams and Lohman (1949) wrote an extensive work on the geology and ground-water resources of the Equus Beds.
- Williams (1946) studied ground-water conditions near Hutchinson.
- Williams and Lohman (1947), Stramel (1956, 1962a, 1962b, and 1967), and Petri et al. (1964) studied the aquifer in the Wichita well field area.
- Bayne (1956), Lane and Miller (1965), and Bevans (1988) described the geology and hydrology of Reno and Sedgwick Counties.
- Green and Pogge (1977), McElwee et al. (1979), and Spinazola et al. (1985) developed ground-water flow models of all or part of the Equus Beds.
- Gogel (1981) and Spinazola et al. (1985) modeled the underlying Wellington aquifer.
- Sophocleous (1983), Spinazola et al. (1985), and Heidari et al. (1986) developed solute-transport models to predict the movement of chloride in the Equus Beds, particularly in relation to the Wichita well field.

Many investigations have focused on water quality, salinity in particular:

- Leonard and Kleinschmidt (1976) studied the occurrence of saline water in the Little Arkansas River basin.
- Hathaway et al. (1981) studied the chemical quality of irrigation water in the Equus Beds area.
- Williams (1946) discussed the origin of large concentrations of chloride in the aquifer near Hutchinson.
- Gogel (1981) discussed the potential for discharge of saltwater from Permian rocks to the Equus Beds.
- Whittemore (1982-1990) and Whittemore and Basel (1982) identified sources of saltwater brines in the Equus Beds using chloride-iodide and chloride-bromide ratios.

Physiography

The major part of the study area is located in the Osage Plains section of the Central Lowland Province in the Physical Divisions of the United States as determined by Fenneman (1931). The Arkansas River section described by Schoewe (1949) is equivalent to the Osage Plains section. These areas are composed of sands, silts, and clays over bedrock.

This area is composed of old scarped plains with entrenched streams. Part of the area is located in the Great Plains Province which is described as a submaturely to maturely dissected plateau and is characterized by flat to gently rolling terrain. Surface elevations range from about 1200 feet mean sea level (m.s.l.) in the southeast near Wichita to about 1650 feet m.s.l. near Hutchinson to the north.

Wind-blown sand and silt form a major belt of sand dunes between the northern edge of the Arkansas River Valley and the Little Arkansas River. These sand belts extend southeastward from Rice County across Reno County. The eastern end is northeast of Burrton in Harvey County, Kansas. Small, isolated sand dune areas also occur locally in the area.

Soils in the area include:

- Excessively drained soils with loamy or silty subsoil on the uplands.
- Well-drained soils with clayey subsoil on ridges and side slopes.
- Imperfectly drained and loamy soils with clayey subsoil and well-drained sandy soils on level plains.
- Deep loamy soil over sandy or gravelly material in the breaks and along alluvial lands.

Some of the uplands and breaks are used for rangeland, but cultivated crops (mainly wheat, alfalfa, and grain sorghum) are grown on the majority of the lands.

Geology

Bedrock in the study area consists mainly of limestones and shales of the Chase Group as well as shales, thin sandstones and siltstones, and evaporites of the overlying Sumner Group. Both the Chase and Sumner Groups are Permian, and the Chase Group is thicker than the Sumner in the study area. Included in the Sumner Group is the Wellington Formation, which has lower, middle, and upper members. The lower member (Lower Anhydrite) consists of gray shale with some dolomite and many thin gypsum and anhydrite beds. The middle member (Hutchinson Salt) consists of salt, interbedded with minor shale, gypsum, and anhydrite. The Hutchinson Salt Member occurs about 650 feet below ground level in the Hutchinson, Kansas, area and is mined at that location. The upper member (Upper Shale) consists of mainly gray shale with minor amounts of gypsum, anhydrite, dolomite, and siltstone (figure 1 in appendix A).

The Wellington Formation is up to 750 feet thick, but the thickness is an average of 250 feet. Natural dissolution of the Hutchinson Salt Member and subsequent subsidence and collapse of overlying rock has resulted in as much as 350 feet of Tertiary and Quaternary sediment accumulation. This accumulation is known as the Equus Beds Formation (figure 2 in appendix A). Because the Equus Beds Formation is permeable, most of this formation acts as an aquifer.

Tertiary and Quaternary age alluvium, known as the Equus Beds Formation, consists of sand and gravel, interfingered with lenses of silt and clay. The Equus Beds Formation overlies most of the bedrock in the study area. Maximum thickness of these sediments occurs in a north-south-trending buried valley known as the McPherson Channel in McPherson, Harvey, and northern Sedgwick Counties and in the southeasterly trending Arkansas River bedrock valley in Reno and Sedgwick Counties. The bedrock surface is low near the course of the Arkansas River (figure 3 in appendix A). Saltwater from the Hutchinson Salt Member of the Wellington Formation may be entering the Equus Beds aquifer around this bedrock low, or trough.

The study divided the Equus Beds Formation into layers: lower, middle, and upper on the basis of the characteristics of the sediment accumulation that makes up the Equus Beds Formation. The lower and upper layers contain mostly sand and gravel with interbedded clay or silty clay. The middle layer contains more fine-grained material. The model of the aquifer contained three layers to reflect the relative permeability and other properties of the three layers of the Equus Beds Formation.

Areas of continued subsidence are indicated by a linear trend of water-filled depressions and sinkholes. Subsidence and collapse, together with pre-Quaternary subaerial erosion, has resulted in a very irregular bedrock surface (figure 3 in appendix A).

Also included in the Sumner Group and conformably overlying the Wellington Formation is the Ninnescah Shale, which consists of alternating beds of brownish-red silty shale and siltstone interbedded with thin beds of gray-green shale and siltstone and very thin layers of satinspar gypsum. The Wellington Formation crops out in the east part of the study area while the Ninnescah Shale crops out in the western part of the study area. Figure 3 shows the contact of the aquifer with Permian bedrock.

Dune sands overlie formation rock near Hutchinson and overlie the Equus Beds east of Hutchinson. The dunes consist of fine-grained, tan sand with interbedded buried soil zones. Maximum thickness of the dune sand is about 150 feet. Wind-blown silt deposits (loess) about 30 feet thick occur on uplands southwest of the Arkansas River, but they thin rapidly toward the river (figure 1 in appendix A).

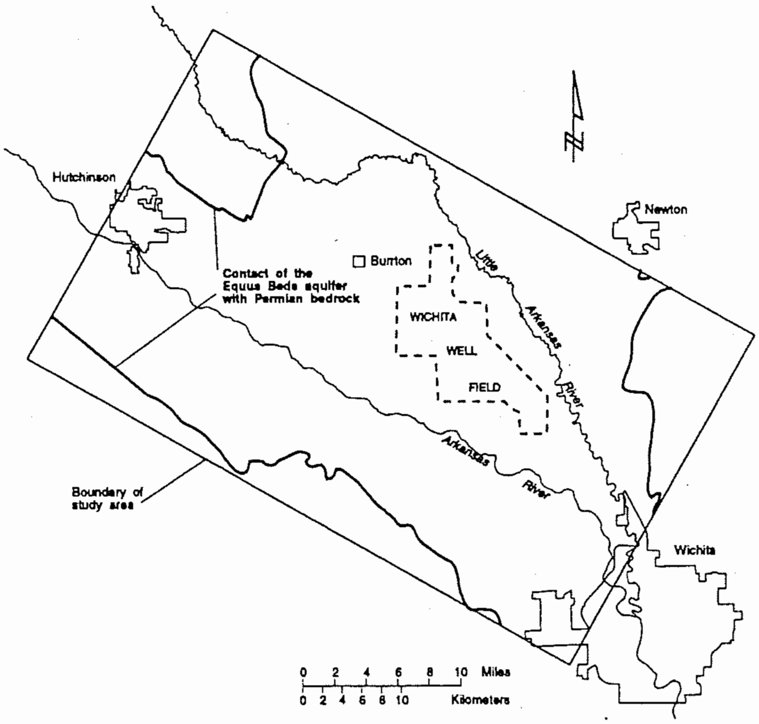

Figure 3.—Contact of Equus Beds aquifer with Permian bedrock within the study area.

Water Resources

Hydrology

About 11 percent of the 1.2 million acres of agricultural land in Harvey, McPherson, Reno, and Sedgwick Counties use supplemental irrigation, primarily from the ground-water supply (Equus Beds Groundwater Management District No. 2, 1990). Various investigators estimate that recharge to the ground-water supply is in the range of 4 to 6 inches per year, or about 20 percent of the 30 inches of annual precipitation in the Equus Beds area (Spinazola et al., 1985).

Rainfall runoff and irrigation return flows feed the Arkansas River in the Equus Beds area. Snowmelt from the Rocky Mountains is a relatively minor factor in the seasonal runoff patterns observed. Snowmelt greatly influences regulated releases from reservoirs far upstream, but very few substantial releases from snowmelt reach the study area. The Arkansas River generally loses water to the ground-water system during extended periods of flow. However, at times, gains in the river from the ground-water supply in this reach can also be substantial, but this is not a consistent pattern.

Surface Water

Principal surface water features are shown in figure 2. The most important tributary to the Arkansas River in this area is the Little Arkansas River, fed primarily by irrigation return flow and, at times, by rainfall runoff. The Little Arkansas River joins the Arkansas River just downstream of the study area and consistently gains water from the aquifer.

Peak flows in terms of both instantaneous rates and monthly runoff volumes can occur at various times of the year. However, these most commonly occur in the rainy months of spring and early summer. Minimum flows are usually reached in the late summer, fall, and early winter after the seasonal irrigation withdrawals.

The Water Resources Data publications of USGS provide complete annual summaries of the measured data. Several stations in these publications are useful to verify model results.

The primary gauging stations on the main stem are:

- *Location:* The Arkansas River near Hutchinson.
  Drainage area: 38,910 square miles—7,186 square miles probably noncontributing.
  Record: From October 1959 to the present.
  Average annual discharge: 386,900 acre-feet.

- *Location:* The Arkansas River near Maize.
  Drainage area: 39,110 square miles—7,186 square miles probably noncontributing.
  Record: From March 1987 to the present.

The period of record for the Maize station is so short that an average annual discharge cannot be compared reliably to other stations on the river.

Other stations near the study area on the Arkansas River are:

- *Location:* The Arkansas River at Wichita.
  Drainage area: 40,490 square miles—7,263 square miles probably noncontributing.
  Record: From July 1934 to the present.
  Average annual discharge: 745,500 acre-feet.

- *Location:* The Arkansas River at Derby.
  Drainage area: 40,830 square miles—7,263 square miles probably noncontributing.
  Record: From October 1968 to the present.
  Average annual discharge: 802,700 acre-feet.

The two stream gauges on the Little Arkansas River are:

- *Location:* The Little Arkansas River at Alta Mills.
  Drainage area: 736 square miles—55 square miles probably noncontributing.
  Record: From June 1973 to the present.
  Average annual discharge: 147,100 acre-feet.

> *Location:* The Little Arkansas River at Valley Center.
Drainage area: 1,327 square miles—77 square miles probably noncontributing.
Record: From June 1922 to the present.
Average annual discharge: 208,700 acre-feet.

Detailed information about the extremes at all stations is available in Equus Beds (Groundwater Management District No. 2, 1990) and also in the Water Resources Data publications.

While outside of the study area, two gauges on the North Fork of the Ninnescah River also provide further insights into the hydrology of the general region:

> *Location:* North Fork Ninnescah River above Cheney Reservoir.
Drainage area: 787 square miles—237 square miles probably noncontributing.
Record: From July 1965 to the present.
Average annual discharge: 107,200 acre-feet.

> *Location:* North Fork Ninnescah River at Cheney Dam.
Drainage area: 901 square miles—237 square miles probably noncontributing.
Record: From October 1964 to the present.
Average annual discharge: 85,490 acre-feet. (Evaporation losses and diversions for water supply from Cheney Reservoir may account for, at least in part, the reduced flow at this station.)

Additional tributaries and their locations within the study area are given in Equus Beds (Groundwater Management District No. 2, 1990).

The only major reservoir in the study area is Reclamation's Cheney Reservoir. However, the reservoir is outside the study area at the extreme south end of the Equus Beds District and minimally affects the surface water situation in the study area. Its total storage capacity is 566,300 acre-feet. The reservoir is a multiple purpose facility which provides water supplies for municipal, industrial, fish and wildlife, and recreational purposes. A substantial portion of the storage is reserved for flood control.

Ground water[6]

The generally shallow depth to the water table and the large saturated thickness make Equus Beds sediment an important source of ground water. Near the Arkansas River, the water table may be as little as 10 feet below the surface, depending on the altitude of the land and the amount of drawdown induced by pumping wells. Data collected indicate that the maximum saturated thickness within the study area, about 300 feet, occurs near the course of the Arkansas River where the bedrock surface is low (figure 3 in appendix A).

The Arkansas and Little Arkansas Rivers, to a large extent, control the direction of ground-water flow in the study area, as indicated by potentiometric-surface maps based on water-level data collected during 1940 and 1989 (figures 4 and 5 in appendix A). Near the Arkansas River, ground water flows southeast and generally parallels the direction of riverflow with very little vertical flow. Near the Little Arkansas River, ground water flows toward the river. Southwest of the Arkansas River near Hutchinson, ground water flows to the northeast. Except for the Wichita well field area, the direction of ground-water flow in the 1980's is generally unchanged from that in the 1940's. Water-level data from nested observation wells along the Arkansas River show that the overall direction of ground-water flow is similar in the upper, middle, and lower layers.

The sand dune area near Hutchinson contains zones of perched water as indicated by water levels in nearby wells that differ by as much as 27 feet (Williams and Lohman, 1949, table 37, wells 375 and 376). The sand dunes also contain interdune ponds (Williams, 1946) and springs (Williams and Lohman, 1949). Nevertheless, the sand dunes are an effective precipitation-capture area and probably recharge a larger percentage of precipitation than other areas in the study area (Williams, 1946). A mound of ground water in Equus Beds sediment under and near the southern edge of the sand dunes attests to the recharge capacity of the dunes.

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[6] This section was extracted and modified from Myers et al., in review.

Water Use[7]

Well water withdrawals are a significant source of discharge from the Equus Beds aquifer. Prior to 1940, water was withdrawn from the Equus Beds near the cities of Hutchinson and Wichita and used mainly for municipal and industrial purposes (Spinazola et al., 1985). The Wichita well field (initially holding 25 wells in 1940 and increasing to 55 wells in 1992) helped develop water withdrawals. Municipal water use increased rapidly from 1940 to about 1952 (figure 4). Water withdrawals from the aquifer were fairly constant throughout the 1950's. However, in the late 1950's and early 1960's, agricultural and industrial water uses began increasing. Agricultural water use was fairly uniform in distribution over the study area, including the Wichita well field. Industrial water use was limited to local areas. In the mid-1970's, agricultural water use increased substantially and has been the single largest use of water since the early 1980's (figure 4).

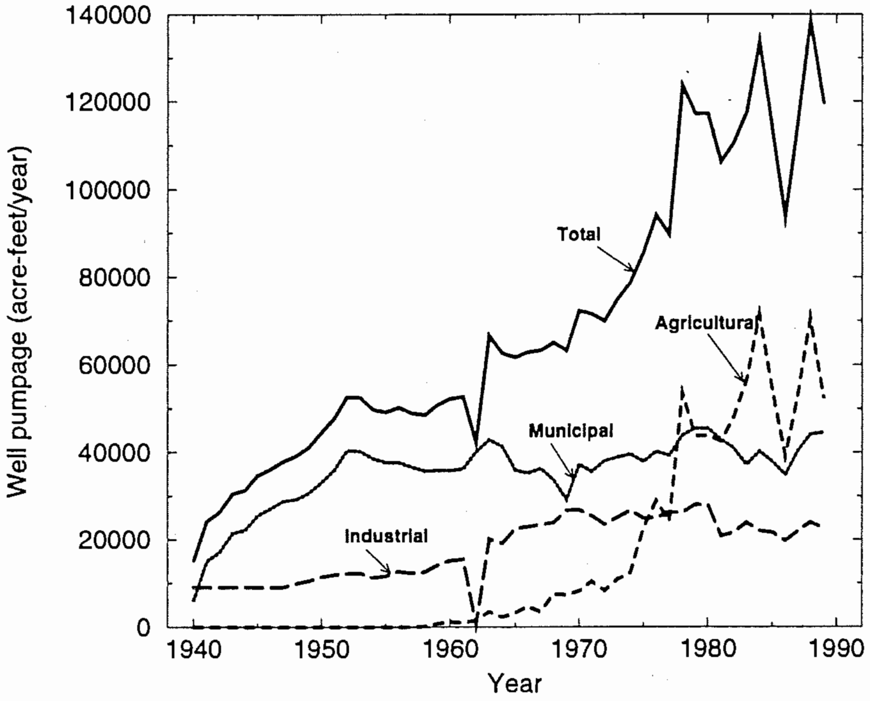

Figure 4.—Industrial, municipal, agricultural, and total pumpage from the Equus Beds aquifer in study area for 1940-1989 (Myers et al., in review).

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[7] This section was extracted and modified from Myers et al., in review.

Most of the municipal wells in the Wichita well field produce water from the middle and lower layers of the Equus Beds aquifer. Irrigation wells near the Arkansas River usually produce water from the upper and middle layers because of the large chloride concentrations found in the bedrock lower layer that parallels the river. Irrigation wells farther from the river may produce water from all three layers. Industrial wells may also produce water from all three layers.

Water Quality

This portion of the ARWMIS study focused on salinity in the Equus Beds aquifer as indicated by the presence of chloride. To provide a reference comparison, the secondary drinking water standard for chloride is 250 milligrams per liter (mg/L). This standard reflects the acceptability of the water to the public and is primarily based on taste or undesirable effects on various domestic uses.

Salinity Sources

Geochemical characterization of ground waters in the alluvial aquifer of the Arkansas River valley from Hutchinson to Wichita suggests there may be five different sources of salinity (Whittemore, 1990). Naturally occurring sources include Arkansas River water and natural saltwater located in the deepest part of the aquifer around a bedrock low, or trough, near the course of the Arkansas River. Salinity sources introduced by human activities include brine from oil field operations, evaporation-pan brine from salt-refining activities, and migration of saltwater through disposal wells or poorly cased boreholes from the Wellington Formation.

Chloride originating from the Arkansas River.—The salinity in the Arkansas River is primarily attributed to Permian saltwater entering the river upstream of the study area (Whittemore, 1990). Measured chloride concentrations ranged between 363 and 907 mg/L at the Hutchinson station between 1961 and 1978 (Spinazola et al., 1985). A median chloride concentration of 630 mg/L was found in samples collected near the towns of Hutchinson, Haven, Mt. Hope, Bentley, and Maize (Myers et al., in review). In general, as flows in the river increase, the chloride concentration decreases (Myers et al., in review).

Deep Natural Saltwater.—Natural saltwater is located in the deepest part of the aquifer around a bedrock low, or trough, near the course of the Arkansas River (figure 5). The origin of this saltwater is not definitely known. Whittemore (1990) reports "the predominant source of salinity [is] the natural intrusion of saltwaters from Permian strata underlying the aquifer, both within and upstream of the study area." This sources includes the probable intrusion of high concentrations of chloride from the Wellington Formation in the deepest portions of the Equus Beds within the study area. Most notably, this chloride is thought to be intruding into the bedrock low, or trough, that parallels the Arkansas River. Figure 6 shows how saltwater from the Wellington Formation possibly intrudes from the collapsed Hutchinson Salt Member through fractures in the upper shale member of the Wellington Formation into the Equus Beds aquifer.

The chloride concentration from wells in the Wellington Formation averaged about 150,000 mg/L in 15 water samples from the Wellington Formation (Gogel, 1981). This chloride is attributed to the natural dissolution of evaporite deposits in Lower Permian rocks and the injection of oil field brine (Spinazola et al., 1985). Chloride in the Equus Beds alluvial

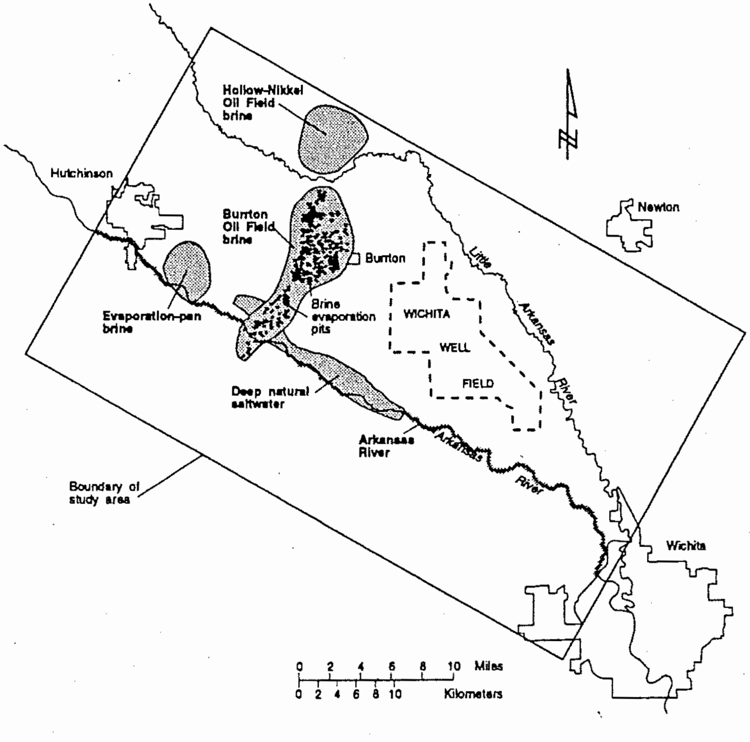

Figure 5.—Salinity sources.

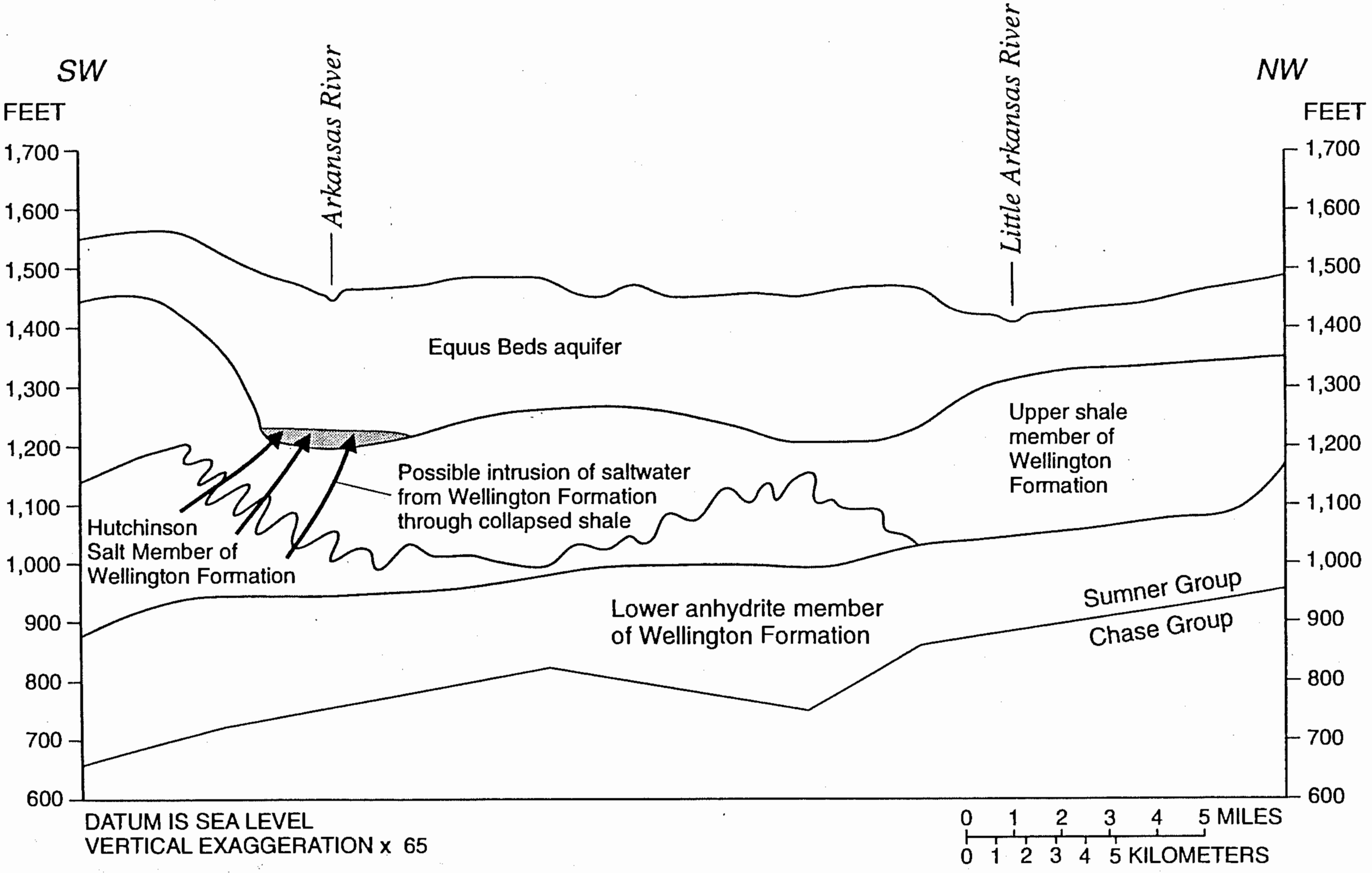

Figure 6.—Possible intrusion of saltwater from the Wellington Formation into the Equus Beds aquifer.

aquifer thought to have intruded from the Wellington Formation has been measured at concentrations as high as 4,000 mg/L in deep wells installed along the Arkansas River (Whittemore, 1990).

Oil Field Brine from Oil Field Activities.—Another primary salinity source comes from pollution from oil field brines (Burrton and Hollow-Nikkel Oil Fields). Brine was disposed of in surface pits in the Burrton Oil Field area mainly during the 1930's to 1940's (Whittemore, 1990) (figure 5). Five brine analyses from the oil field in 1943 indicated an average chloride concentration of around 120,000 mg/L (Schoewe, 1943). In the early 1950's, ground-water chloride concentrations over 7,000 mg/L were measured in the area of the surface pits. More recently, measured concentrations in the same areas are generally less than 2,000 mg/L. The concentrations decrease as the initial mass of chloride is mixed with larger volumes of water and diluted by recharge from precipitation.

Waste Brine from Evaporation Pans.—Waste brine from evaporation pans used in the late 1890's and early 1900's by salt companies in Hutchinson have been identified as a significant salinity source (Whittemore, 1990). The evaporation pans contained brine from salt-solution mining of the Hutchinson Salt Member of the Wellington Formation (figure 5). The contamination is most concentrated in the intermediate and deep portions of the Equus Beds with concentration contributions of 200 to almost 1,900 mg/L chloride at 13 out of the 16 wells at 5 sites (Whittemore, 1990).

Human-Caused Sources from the Wellington Formation.—Permian saltwater together with oil field brine that flowed up around disposal wells or poorly cased boreholes from the Wellington Formation may be another source of salinity (Whittemore, 1990). Oil brines were disposed of in the Wellington Formation prior to the accepted practice of deep well injection (Whittemore, 1990). In some areas in the Wellington Formation, the potentiometric surface has a higher altitude than the water table of the overlying Equus Beds aquifer (Gogel, 1981). Boreholes may allow a small flow from the Wellington Formation to the Equus Beds aquifer.

This study considers three of these sources:

- Saltwater originating in the Arkansas River.
- Deep natural saltwater.
- Oil field brine from the Burrton Oil Field activities.

Surface Water[7]

Arkansas River water becomes increasingly salty downstream of Great Bend, Kansas. Most of this salt probably comes from salt marshes upstream of Hutchinson (Williams, 1946). Within the study area, Arkansas River water contains enough chloride to be classified as brackish or salty (Williams, 1946). Williams and Lohman (1949) reported that concentrations of chloride in Arkansas River water samples collected during the winter of 1934-1935 ranged from 392 to 460 and 750 to 1,895 mg/L at two sampling sites near Hutchinson. The chloride concentrations from 750 to 1,895 mg/L were downstream from a sewage outlet (Williams and Lohman, 1949). Chloride concentrations taken at the same location were generally over 1,000 mg/L and reached as high as 1,400 mg/L during low riverflows in the fall of 1937 (Williams and Lohman, 1949).

From August 1988 to July 1991, samples of Arkansas River water were collected at sites along the river near the towns of Hutchinson, Haven, Mt. Hope, Bentley, and Maize. Median chloride concentrations for these five sites ranged from 620 to 640 mg/L. The median chloride concentration for all of these samples is 630 mg/L. Generally, flow in the river and chloride concentration are inversely related (figures 6a-b in appendix A). The chloride load in the river (figure 6c in appendix A), a function of flow and concentration, fluctuates. The chloride load depends on the chloride concentration in water sources that supply flow to the river.

The Little Arkansas River also is known to have carried salty water, although generally not in as large concentrations as in the Arkansas River. Leonard and Kleinschmidt (1976) reported that chloride concentrations at Valley Center ranged from 56 to 220 mg/L in water samples collected during

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[7] This section was extracted and modified from Myers et al., in review.

1960-1972. The maximum chloride concentrations in the Little Arkansas River occurred near the mouths of tributaries that drain oil fields (Leonard and Kleinschmidt, 1976).

Ground Water

Ground-water quality in the study area is generally good, although chloride contamination has occurred from the sources previously described (figure 5). Chloride concentration data[8] at various well locations show areas of the aquifer that have been contaminated by these sources (figure 7). Because the model predicted values for 1989 while the measured data for 1989 might be lacking, the concentrations displayed in figure 7 were obtained by averaging measured data collected between 1986 and 1992. Also, wells had to be assigned a layer number that the measured data could represent. Many wells lacked complete information, making the assignment of a layer number impossible. Therefore, the data presented is processed and has a moderate degree of uncertainty associated with it.

Arkansas River water and the deep natural saltwater are naturally occurring sources of chloride. Measured chloride concentrations are generally higher along the Arkansas River. Concentrations are very high in the deepest portion of the aquifer below the Arkansas River where the deep natural saltwater resides.

Brine from oil field operations and evaporation-pan brine from salt-refining activities are among human-caused sources of chloride. High chloride concentrations are found in the Burrton Oil Field, Hollow-Nikkel Oil Field, and evaporation-pan brine areas in all three layers (figures 5 and 7).

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[8] Data collected by the USGS during this study and data from the GMD2 and USGS WATSTORE databases.

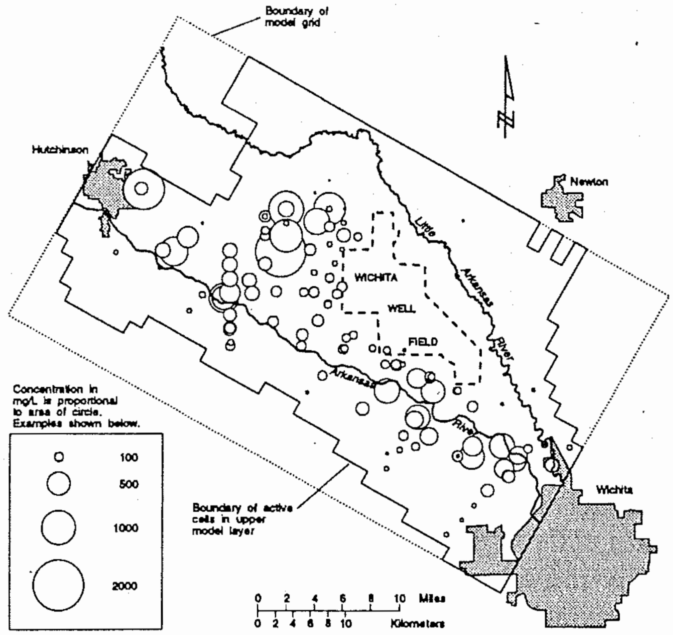

Figure 7a.—Average chloride concentrations of measured data (1986-1992) in the Equus Beds aquifer, upper layer. Chloride concentration in mg/L is proportional to the areas of the circles. The center of the circle indicates where the measurement was taken.

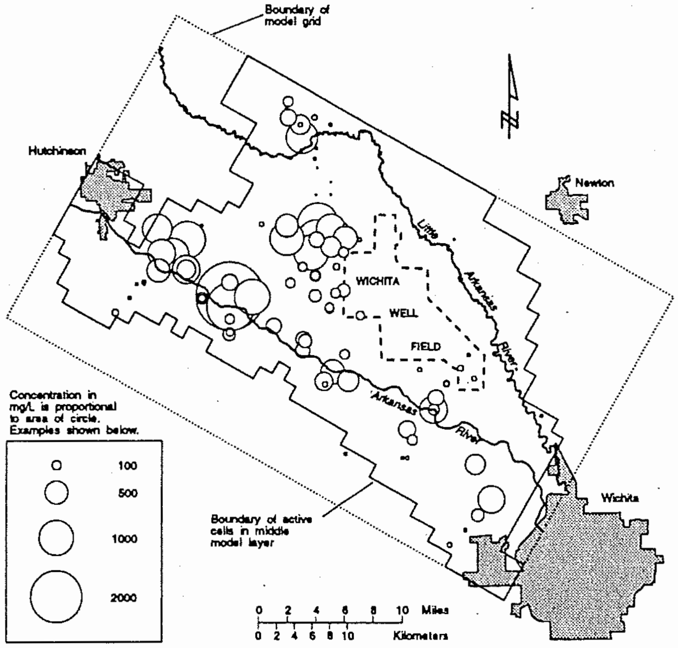

Figure 7b.—Average chloride concentrations of measured data (1986-1992) in the Equus Beds aquifer, middle layer. Chloride concentration in mg/L is proportional to the areas of the circles. The center of the circle indicates where the measurement was taken.

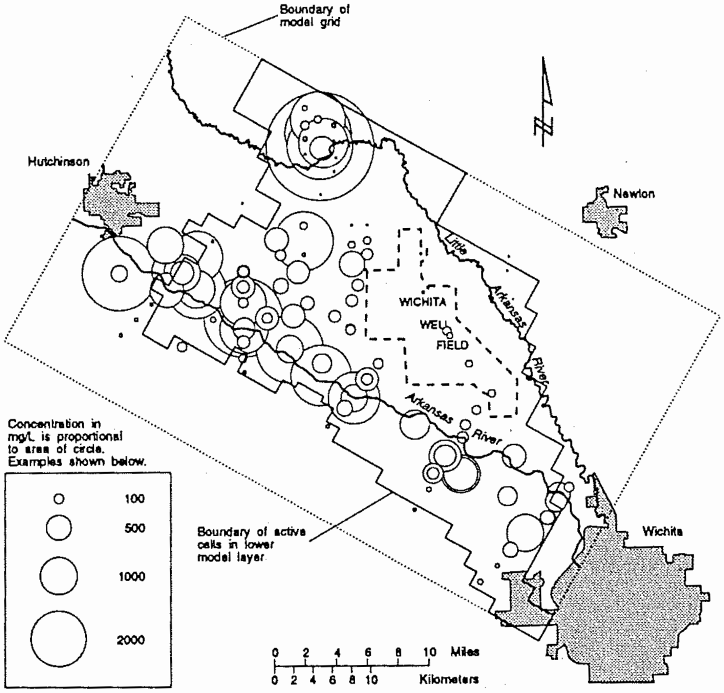

Figure 7c.—Average chloride concentrations of measured data (1986-1992) in the Equus Beds aquifer, lower layer. Chloride concentration in mg/L is proportional to the areas of the circles. The center of the circle indicates where the measurement was taken.

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Chapter 2: The Models

Ground-Water Flow Model

The USGS developed a ground-water flow model using MODFLOW—a three-dimensional, finite-difference, flow model program (McDonald and Harbaugh, 1988). This program was used to simulate the stream-aquifer system and the Equus Beds aquifer. Both steady-state and transient simulations were performed. A detailed discussion of the model geometry, aquifer properties, stresses, calibration, and sensitivity analysis is given in the USGS report (Myers et al., in review).

The transport model program used in this study uses MODFLOW to solve the flow equation. The USGS flow model was modified by reducing the spacing of the finite-difference grid. This was necessary to adequately define the flow field for transport modeling in areas of interest. The resulting flow model was determined to be an acceptable representation of the original USGS flow model.

USGS Flow Model

The USGS data sets that comprise the steady-state and transient models are based on a model geometry of 34 rows, 42 columns, and 3 layers (figure 8). The grid was oriented with variably spaced rows parallel to the Arkansas River. The grid spacing was smaller near the river. No-flow boundaries were simulated where Permian bedrock provides a natural barrier to ground-water flow. Clay layers within the Equus Beds aquifer are accounted for by varying vertical and horizontal hydraulic conductivity in the model layers. Constant-head boundaries were used to represent areas where the Equus Beds aquifer extends beyond the model boundaries. Layer thicknesses near the Arkansas River were determined from lithologic and gamma logs of drill holes. Away-from-the-river thicknesses were determined from lithologic descriptions only (Myers et al., in review). The primary source of aquifer-property data was a previous study by Spinazola et al. (1985). Myers et al. (in review) contains a detailed discussion of model geometry, boundary conditions, properties, stresses, and results. Maps from this USGS report that display much of this information are in appendix B.

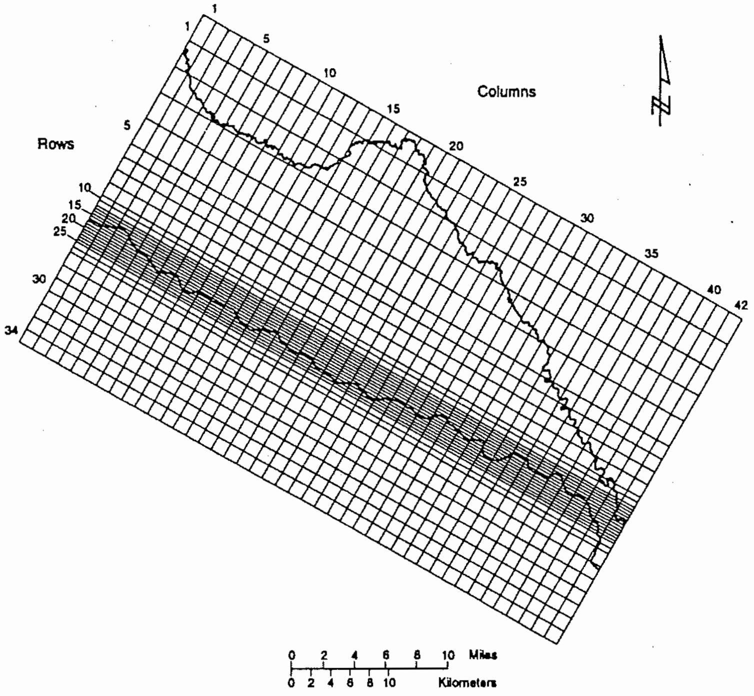

Figure 8.—Model grid (34 rows X 42 columns) from USGS flow model.

Calibration.—The steady-state and transient models were calibrated by comparing simulated head distributions to measured head distributions for the years 1940 (steady-state), 1971, 1980, and 1989 (Myers et al., in review). Also, simulated streamflow was compared to measured streamflow and simulated heads were compared to well hydrographs for the transient calibration.

Sensitivity Analyses.—Myers et al. (in review) performed sensitivity analyses that indicated the models are most sensitive to hydraulic conductivity and recharge.

Stresses.—Stresses simulated in the steady-state and transient flow models include recharge, evapotranspiration, streamflow, stream leakage, and pumpage by wells (Myers et al., in review).

Recharge Values.—Recharge values reported by Spinazola et al. (1985) were adjusted through calibration resulting in values ranging from 0.1 to 5.5 inches per year for the steady-state model. Recharge values for the transient model were adjusted based on average precipitation for each stress period.

Evapotranspiration Rate.—Evapotranspiration rate was determined through calibration with a maximum rate of 3.5 inches per year with the water table at land surface and a linear decrease to 0 where the water table is 10 feet or more below the land surface for both the steady-state and transient models (Myers et al., in review).

Streamflow and Leakage.—Streamflow and stream leakage were simulated using a stream-routing module (Prudic, 1988) in the MODFLOW program.

Pumpage.—Well pumpage developed by Spinazola et al. (1985) was used for the first five stress periods. Myers et al. (in review) developed pumpage data for the sixth stress period and prorated pumpage among the model layers.

Reclamation's Adaptation of the USGS Flow Model

The finite-difference grid was modified by reducing the grid spacing and making grid cells more square shaped in the areas where transport is important. The original grid had a geometry of 34 rows and 42 columns (figure 8). This grid was subdivided (figure 9) so that the resulting grid has a geometry of 54 rows and 84 columns. The new grid is simply a subdivision of the USGS grid and includes the original grid lines.

A reduced grid spacing better defines the flow field, thus improving the accuracy of transport modeling. Square-shaped grid cells minimize numerical errors in particle tracking procedures used in transport modeling.

The steps taken in regridding the flow model were intended to preserve the USGS flow model to avoid recalibrating a new flow model.

Method of Regridding.—The USGS flow model data sets were converted to data sets that represented an equivalent flow model based on a grid geometry of 54 rows and 84 columns.

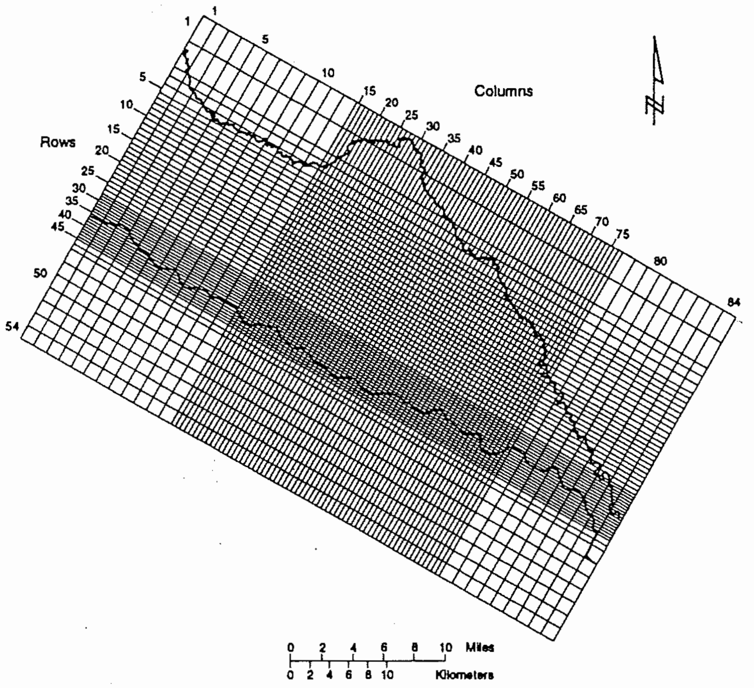

Figure 9.—Model grid (54 rows X 84 columns).

All spatial data (i.e., model input that varies with geographic position) had to be reprocessed. The two types of spatial data input to the flow model are:

1. A value for every grid cell, or a matrix of values (e.g., aquifer porous media properties, elevations, recharge, and boundaries).
2. A value for a single grid cell (e.g., pumping rate or streambed conductance).

In the regrid procedure, each cell in the USGS grid (supercell) was subdivided into a number of smaller cells (subcells). Spatial data of type 1 were processed by simply assigning the supercell value to the corresponding subcells. For type 2 data, the value of the supercell was prorated to the corresponding subcells by the fraction of the area that the subcell is relative to the original supercell area.

Results of Grid Modification.—Predicted heads and the overall water budget were used to evaluate the validity of the regridded flow model.

Predicted Heads.—The predicted heads for each of the model layers were compared with results from the USGS model for both the steady-state and transient simulations (figures 7 and 8 in appendix A show comparisons of these predicted heads). In each comparison, the predicted heads are almost identical.

Water Budget.—The water budget at the end of the steady-state and transient simulations was compared for both models. The overall budget comparison was reasonable, but some significant differences were found in the stream leakage term. The regridded model shows a net increase in leakage from streams to the aquifer of 2 percent for the steady-state case and 7 percent for the transient case.

Stream Leakage.—The leakage for each stream supercell in the USGS model (34 X 42) was compared to the net leakage for the corresponding subcells in the regridded model. At this detailed level, the leakage may vary significantly between the two models. But as more supercells are considered, the difference in cumulative leakage between the two models decreases.

The differences in the stream leakage can be attributed to the method used to convert data in the stream package resulted in roughly three times the number of grid cells representing streams in the regridded model as compared to the USGS model. Relatively large grid cells (supercells) are used to represent the Arkansas and Little Arkansas Rivers in the USGS model. Thus, regridding allows each original stream supercell to be represented by numerous subcells. This approach was taken to produce an equivalent model rather than to improve on resolution of stresses and boundaries. An equivalent model does not have to be recalibrated. An improved model would represent the streams with only the grid cells necessary but would require further calibration.

Solute-Transport Model

To simulate the movement of chloride in solution from 1940 to 2049 and to predict the effects of management alternatives on chloride movement in part of the Equus Beds aquifer, the study used a modular three-dimensional transport model program, MT3D (Papadopulos and Associates, Inc., 1992).

The MT3D transport model is a computer program used to simulate advection, dispersion, and chemical reactions of contaminants in ground-water flow system (Papadopulos and Associates, Inc., 1992). It was developed for use with any block-centered finite-difference flow model, such as MODFLOW.

Governing Equation

The governing partial differential equation describing three-dimensional transport of contaminants in ground water can be written as follows (Papadopulos and Associates, Inc., 1992):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial \chi_i} \left(D_{ij} \frac{\partial C}{\partial \chi_j} \right) - \frac{\partial}{\partial \chi_i} (\nu_i C) + \frac{q_s}{\theta} C_s + \sum_{k=1}^{N} R_k$$

where

C	is the concentration of contaminants dissolved in ground water, ML^{-3}
t	is time, T
x_i	is the distance along the respective Cartesian coordinate axis, L
D_{ij}	is the hydrodynamic dispersion coefficient, L^2T^{-1}
ν_i	is the seepage or linear pore water velocity, LT-1
q_s	is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative), T^{-1}
C_s	is the concentration of the sources or sinks, ML^{-3}
θ	is the porosity of the porous medium, dimensionless
$\sum_{k=1}^{N} R_k$	is a chemical reaction term, $ML^{-3}T^{-1}$
M	is the fundamental unit of mass
L	is the fundamental unit of length
T	is the fundamental unit of time

The four terms on the right-hand side of the equation are, from left to right: the dispersion term, the advection term, the sink/source term, and the chemical reaction term.

Dispersion.—Hydrodynamic dispersion, represented by the first term in the governing equation, is the process of solution mixing due to the variation of ground-water velocity around the mean advective velocity. It reflects the heterogeneity of the aquifer on a smaller scale than the scale associated with the measurement of analysis of advection (McWhorter, 1992). Parameters representing hydrodynamic dispersion can be considered ignorance factors which depend on the scale of heterogeneity. The transport model uses the following parameters to account for this process:

- Longitudinal dispersivity.
- The ratio of transverse to longitudinal dispersivity.
- The ratio of vertical to longitudinal dispersivity.

Advection.—Advection, represented by the second term in the governing equation, is the tendency for the chemical to be carried along by the water in which it is dissolved. Advection is characterized by the magnitude and direction of ground-water flow, which depends on the hydraulic gradient, the hydraulic conductivity, and the effective porosity in the aquifer (McWhorter, 1992). The hydraulic conductivity distribution is input, and the hydraulic gradient is represented in the output of the USGS flow model. The transport model uses the output of the flow model together with the aquifer's effective porosity in solving the advective part of the transport equation.

Sink/Source.—The third term in the governing equation is referred to as the sink/source term. It represents chemicals dissolved in water entering the simulated domain or system through sources, or chemicals dissolved in water leaving the simulated domain through sinks (Papadopulos and Associates, Inc., 1992). The sinks and sources considered in this study include wells, rivers, and recharge.

Chemical Reaction.—The fourth term in the governing equation is referred to as the chemical reaction term. In this study, chloride is the contaminant being considered. Chloride is a conservative ion and does not readily participate in chemical reactions. Hem states:

> "*Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces and play few vital biochemical roles.*" (Hem, 1970, p. 172)

Therefore, chemical reactions need not be considered for this study.

Solution Techniques

The MT3D transport model provides four options in solving the three-dimensional governing equation:

- The method of characteristics.
- The modified method of characteristics.
- A hybrid of these two methods.
- The pure finite-difference method.

Papadopulos and Associates (1992) provides a detailed discussion of these solution techniques. This portion of the ARWMIS study explored these options and decided to use the pure finite-difference method.

The method of characteristics technique was implemented in the USGS two-dimensional solute transport model (Konikow and Bredehoeft, 1978). That model has been used extensively in field studies. The method of characteristics technique solves the advection term of the governing equation with a set of moving particles. Also, it solves the dispersion term with an explicit version of the block-centered finite-difference method.

The pure finite-difference method solves all terms in the transport equation using the finite-difference scheme, solving the unexpanded advection term and the sink/source directly based on an upstream weighing scheme (Papadopulos and Associates, Inc., 1992).

Assumptions for Applying the Transport Model

The transport model requires the following assumptions about the Equus Beds aquifer:

- Darcy's law is valid, and hydraulic-head gradients are the only significant driving mechanism for fluid flow.
- The porosity and hydraulic conductivity of the aquifer are constant with time.

- Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.
- No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties.
- Ionic and molecular diffusion are negligible contributors to the total dispersive flux.

Boundary Conditions

Boundary conditions regarding transport include active concentration cells and constant concentration cells. All cells which were active cells in the regridded flow model were considered to be active concentration cells. Constant concentration cells were located in the lower layer below the Arkansas River (figure 10) to represent deep natural saltwater, indicated by chloride, that resides in the area of a bedrock low, or trough (Whittemore, 1990).

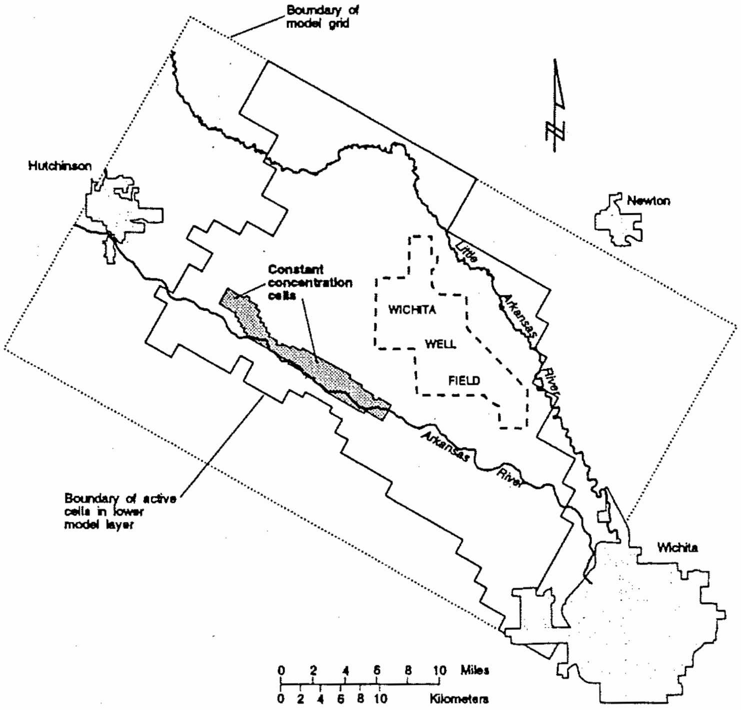

Figure 10.—Constant concentration boundaries for lower model layer.

Initial Conditions

Initial Concentration.—The initial concentration of chloride in the study area for 1940 was determined by combining data from work by Spinazola et al. (1985) and data obtained by the USGS during this portion of the ARWMIS study. Reclamation considered several sources of chloride: oil field brine from the Burrton Oil Field, saltwater from the Arkansas River, and deep natural saltwater.

Oil Field Brine.—A mass-balance approach was used to estimate the initial concentration of chloride from oil field brine (Spinazola et al., 1985). This involved estimating the mass of chloride produced from oil production operations during 1932-1943 and distributing this chloride in areas where the brine surface pits were located. These pits functioned as recharge pits as the brine was recharged to the shallow ground water. By 1944, 95 percent of the brine was disposed of through injection wells into deep zones below the Equus Beds (Williams and Lohman, 1949).

Reclamation estimated the mass of chloride by using the following procedure (Spinazola et al., 1985). Oil production from 1932-1943 was compiled for the Burrton Oil Field from records at the Kansas Geological Survey. The volume of brine produced was determined by multiplying the total oil volume by a brine-to-oil ratio (table 1). Based on the average of five chloride analyses by Schoewe (1943), the total volume of brine disposed into the surface pits was assumed to have a chloride concentration of 120,000 mg/L, resulting in a total mass of approximately 1.3 million tons of chloride introduced into the Equus Beds aquifer.

This mass of chloride was distributed to the aquifer in areas where the brine evaporation pits were located. Figure 5 shows the pit locations within the Burrton Oil Field produced from aerial photography taken when the pits were active (Burrton Task Force, 1984). The total mass of chloride was equally divided and distributed to the pits identified on this map. The concentration of chloride for cells containing pits was determined by mixing the mass of chloride for that cell with the volume of water in storage beneath the cell in the upper and middle model layers, since most of the chloride originating from the evaporation pits is in the shallow and intermediate depths of the aquifer (Whittemore, 1990). The

Table 1.—Calculated brine production from the Burrton Petroleum Field, 1932-1943[1]

Year(s)	Oil production (millions of barrels)	Brine-to-oil ratio	Brine production (millions of barrels)	Percentage of brine production disposed into evaporation pits	Brine disposed into evaporation pits (millions of barrels)
1932-37	21.4	2	42.8	90	38.52
1938	3.5	3	10.5	60	6.3
1939	3.1	5	15.5	40	6.2
1940	2.6	6	15.6	30	4.68
1941	2.5	6	15	20	3
1942	2	6	12	10	1.2
1943	3.3	6	19.8	5	.99
Total					60.89

[1] Table 1 is taken from Spinazola et al., 1985, p. 56.

amount of chloride applied to each layer was adjusted during calibration with 20 percent of the chloride applied to the upper layer and 80 percent applied to the middle layer.

Although the surface pits were completed in the upper layer of the aquifer, the higher density of the brine appears to result in a high percentage of chloride sinking to the lower permeability layers of the middle layer. The model code does not account for density. Valid model results can be expected only after the concentrations drop to levels where density has minimal effects. Mixing the mass of chloride with the volume of water in storage yields maximum concentrations of around 18,000 mg/L—well below the level where density is a significant factor in transport.

Other Chloride Distribution.—The chloride distribution in areas of the model not affected by oil field brine was determined from historical water quality data provided by the USGS (WATSTORE data base) and from a 1940 chloride-distribution map of the Equus Beds aquifer by Williams and Lohman (1949). Figure 11 displays the contour maps of the resulting initial chloride concentrations used in the modeling.

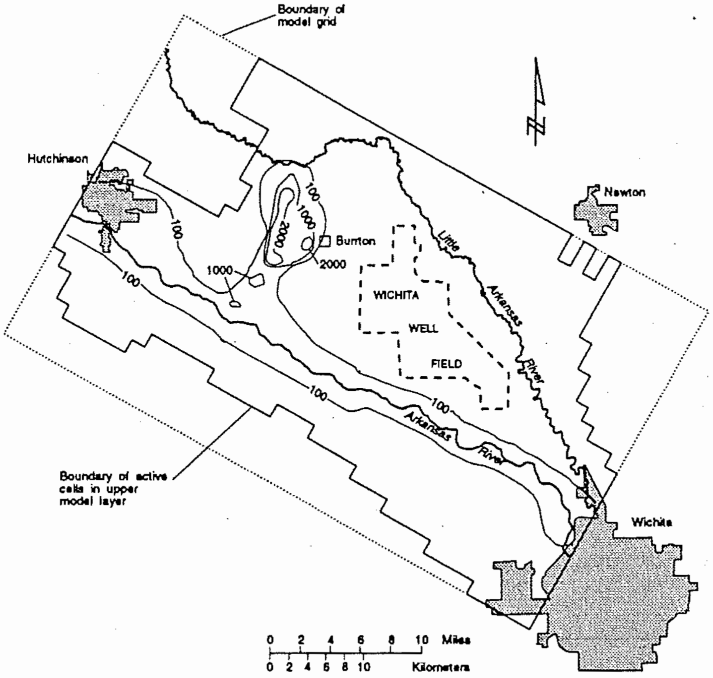

Figure 11a.—Distribution of chloride representing initial conditions for upper model layer, 1940.

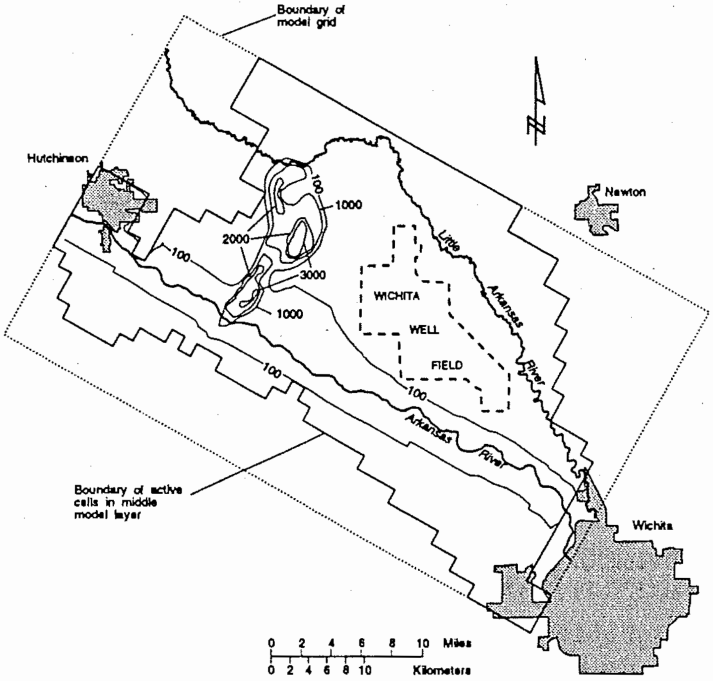

Figure 11b.—Distribution of chloride representing initial conditions for middle model layer, 1940.

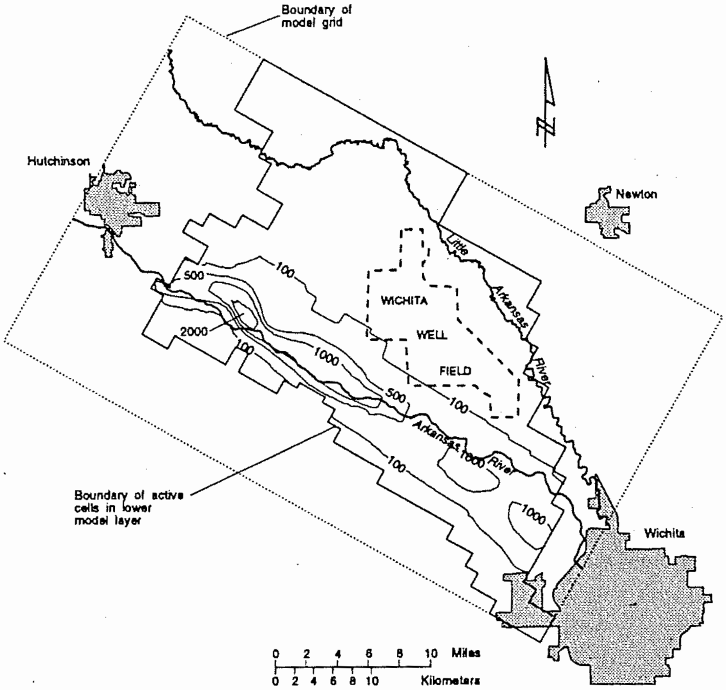

Figure 11c.—Distribution of chloride representing initial conditions for lower model layer, 1940.

Evaporation-Pan and Hollow-Nikkel Oil Field Brine.—These sources were not considered in calibration because of the location of the contamination and lack of data. Waste brine from evaporation pans used in the late 1890's and early 1900's by salt companies in Hutchinson is another significant salinity source (Whittemore, 1990). These pans contained brine from salt-solution mining of the Hutchinson Salt Member of the Wellington Formation and were located southeast of Hutchinson and just north of the Arkansas River (figure 5).

The Hollow-Nikkel Oil Field is located near the edge of the model grid where accurate modeling could not be expected. The location and estimated extent of salinity from these sources make these sources much less of a threat than salinity from the Arkansas River or Burrton Oil Field. In addition, little information is available concerning the volumes and concentrations of brines that were introduced into the aquifer. This makes determining initial conditions difficult.

Arkansas River as a Chloride Source

The Arkansas River was modeled as a continuous source of chloride. During a simulation, reaches of the river that lose water would contribute chloride to the aquifer at a given concentration. Reclamation determined this concentration, which varied from 480 mg/L to 630 mg/L from historical data (table 2). Historical data (USGS WATSTORE database) was available from 1961 to the present. The concentration for the first two stress periods was assigned the same value as the third stress period.

Table 2.—Average chloride concentrations from 1940 to 1989

Stress period	Chloride concentration (mg/L)
1940-1952	480
1953-1958	480
1959-1963	480
1964-1970	520
1971-1979	600
1980-1989	630

Transport Parameters

The necessary transport parameters describe the advection and dispersion processes. The model inputs required are:

- Effective porosity.
- Longitudinal dispersivity.
- The ratio of transverse to longitudinal dispersivity.
- The ratio of vertical to longitudinal dispersivity.

Laboratory analysis of porosity from samples of the aquifer materials ranged from 24.1 to 60.2 percent (Williams and Lohman, 1949). The higher porosity values are typically associated with clays that have high porosities but low effective porosities. The **effective porosity** is the pore space which water is able to flow through, whereas the porosity is a measure of the total pore space. A previous study representing the aquifer as a single layer used a value of 25 percent for effective porosity determined through calibration (Spinazola et al., 1985).

Values of **effective porosity** for the three-layer model used in this study were determined through the calibration process. The resulting effective porosity values used in the transport model are 30 percent for the upper and lower layers and 20 percent for the middle layer. A smaller value for effective porosity results in faster movement of the water and, thus, the contaminant in the aquifer. These values were determined by comparing predicted chloride breakthrough curves with measured values at various locations in the study area. A smaller effective porosity value for the middle layer may be attributed to more poorly sorted materials. Myers et al. (in review) reports the middle layer consists of clay or silty clay interbedded with sand and gravel and has generally more fine-grain material than the lower and upper layers.

Spinazola et al. (1985) determined that values of 100 feet for **longitudinal dispersion** and 0.3 for the **ratio of transverse to longitudinal dispersion** resulted in a best-fit between model results and measured data. These values were adopted for the transport model. The **ratio of vertical to longitudinal dispersion** was assumed to be negligible, based on sensitivity runs.

Transient Calibration

Method of Characteristics.—The transport method originally used was the method of characteristics. The method exhibited numerical problems during projection (1990-2049) simulations. These problems were manifested in large mass balance errors and unreasonable predicted chloride concentrations. A possible source of these problems is that the flow model was vertically discretized using a deformed mesh. The deformed vertical discretization can introduce numerical discretization errors (Papadopulos and Associates, Inc., 1992). Because of the numerical problems experienced with the method of characteristics during predictive runs, the pure finite-difference method was used.

However, the method of characteristics was reasonably stable during the transient calibration period (1940-1989). During this period, the pure finite-difference method compared reasonably with the method of characteristics. Figure 12 shows the predicted chloride distribution using the pure finite-difference method.

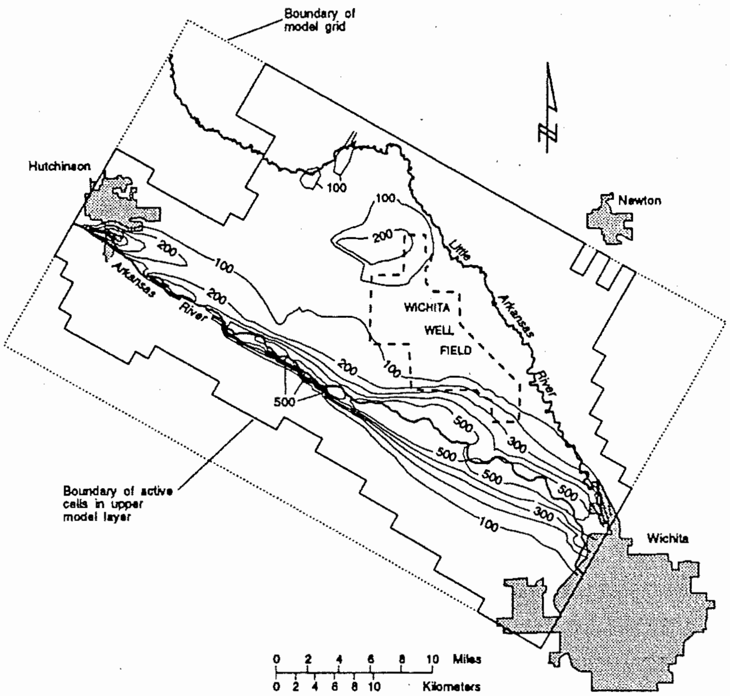

Figure 12a.—Predicted chloride distribution in 1989 for upper model layer.

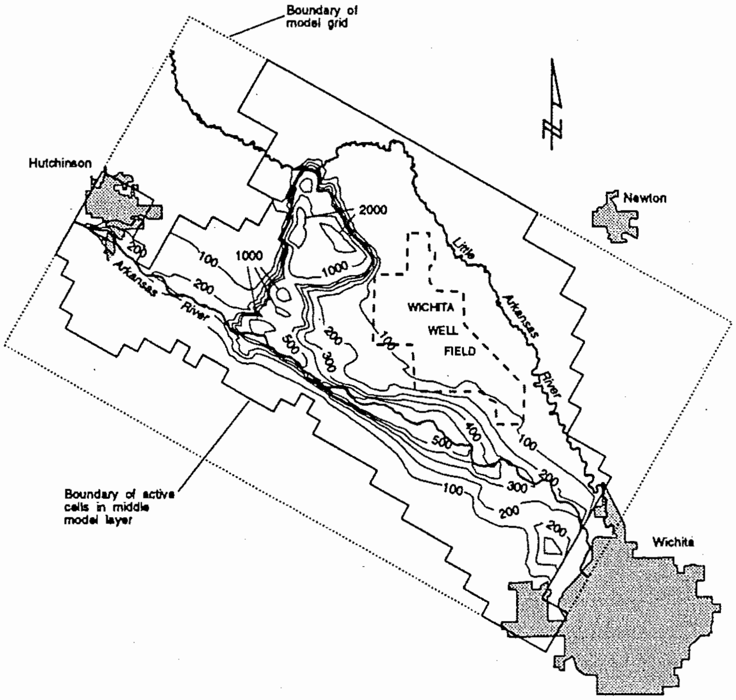

Figure 12b.—Predicted chloride distribution in 1989 for middle model layer.

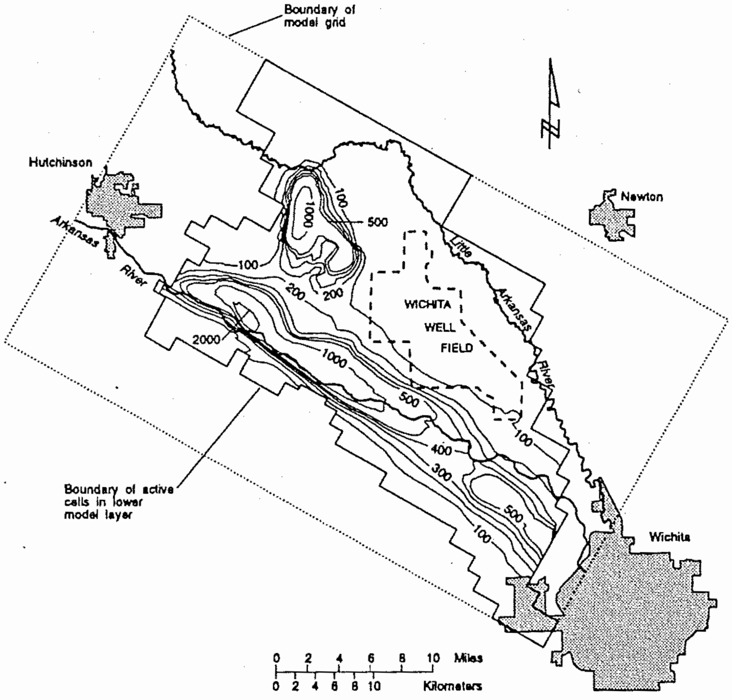

Figure 12c.—Predicted chloride distribution in 1989 for lower model layer.

Pure Finite-Difference Method.—The pure finite-difference method can lead to significant numerical dispersion for some problems. Numerical dispersion is caused by the finite-difference approximation of the first-order derivatives (advection term), which involves errors of the order of magnitude of the second-order derivative (dispersion term) (Bear and Verruijt, 1987). Predicted results at the completion of the transient calibration using the pure finite-difference method were compared with those predicted by the method of characteristics. The predicted chloride distributions in 1989 for the two methods compare reasonably. This was assumed to indicate that numerical dispersion was not a prohibitive factor for the problem being studied.

Calibration.—For this portion of the study, Reclamation calibrated the transient transport model by attempting to match graphs of measured chloride concentrations versus time with predicted chloride concentrations versus time at various well locations within the study area. These wells were assigned layer numbers corresponding to layers in the model by comparing completion information with layer elevations. Most of the wells used for calibration are located between the chloride sources (Arkansas River and brine evaporation pits) and the Wichita well field area (figure 9 in appendix A). Special attention was given to matching measured well data that exhibited a trend of increasing chloride concentration (breakthrough of chloride). Calibrating to measured chloride concentrations over time permits trends rather than just magnitudes of chloride concentration at a given time to be considered.

Comparing graphs of measured and predicted chloride concentration versus time (appendix C) provide a measure of how well the flow and transport models are calibrated. The best data for calibration is located between the Burrton Oil Field and the Wichita well field where breakthrough curves could be seen in the measured data from numerous wells.

Calibration Results.—The transport model predicts concentration curves that are relatively smooth and gradually changing, while the measured data may be more erratic (see the data for well 212 in appendix C as an example). The transport model is based on averaged conditions and is unable to account for local variability around a given well site. Predicted values are also output at regular intervals. The measured data is often not sampled at regular intervals and may contain bad readings resulting from sampling technique, laboratory procedures, or other problems. These potential errors may account for many of points that appear to be outlier values (such as well 312 around 1985).

The bulk of the brine from oil field operations was placed in the middle layer of the model when establishing initial conditions. The graphs of predicted chloride concentration which show breakthrough of this chloride toward the Wichita well field display a good approximation of actual conditions (see appendix C, wells 392, 412, 441, 672, 675, and 798).

The model appears to somewhat overpredict the rate of chloride movement in the upper layer. This is especially evident between the Arkansas River and the Wichita well field (well numbers 121, 122, 150, 152, and 626). Detailed adjustment of effective porosity values within reasonable ranges did not improve the calibration, indicating that additional work on the flow model may be necessary to make further improvements. For this reason, it was decided that assigning uniform values for each layer was a more realistic approach than trying to tweak the model to make detailed improvements.

1989 Chloride Distribution.—The 1989 predicted distribution of chloride compared to actual measurements provides useful insights into the strengths and weaknesses of the model (figure 10 in appendix A), although this comparison may not be as indicative of the validity of the model as the comparison of predicted and measured concentrations values over time.

Some areas of high measured chloride concentrations were not considered in the model (figure 7). These areas include the evaporation-pan area and the Hollow-Nikkel Oil Field area. (See the "Salinity Sources" discussion in the "Water Quality" section.)

Definition of Zones for Interpreting Model Results

Model results were processed to produce graphs of average chloride concentration, mass of chloride, and average water level versus time for specific areas within the model grid. Specific areas were defined where chloride transport was considered to be important. This process was intended to simplify the interpretation of model results and to allow easy comparison of different simulations. For example, the average chloride concentration within a given area can be plotted versus time.

This type of plot allows trends to be easily identified and the results of different simulations, such as management alternatives, to be easily compared for that area. These tasks can often be difficult when using contour maps to display results. Typically, contour maps of chloride distribution would be used to evaluate model results. In identifying trends or variations in predicted concentrations over time for a given simulation, numerous chloride distribution maps would have to be produced, including a map for each model layer at different times. To interpret these results, the investigator would need to compare these maps. In addition, comparing multiple simulations would require repeating this process for each simulation, rapidly increasing the number of maps that need to be considered and the complexity of interpreting the results. By producing graphs of average concentration for particular areas, this process can be greatly simplified.

Three areas to evaluate the model results over time were designated to reflect the major areas of concern: transport of chloride toward the Wichita well field from the Burrton Oil Field area, the Arkansas River, and the deep natural saltwater (figure 13). These are:

- **River zone**—defined to evaluate the transport for chloride primarily originating in the Arkansas River and from the deep natural saltwater.
- **Brine zone**—defined to evaluate results for chloride which originated as oil field brine from the Burrton area.
- **Well field zone**—defined to evaluate the impacts of all chloride sources on the area where the Wichita well field is located.

The results of calibration, projection, and management simulations were processed and presented as graphs of average chloride concentration, mass of chloride, and average water level versus time within the defined areas. The average concentration for each layer in an area was computed as the mass of chloride divided by the volume of water in storage for

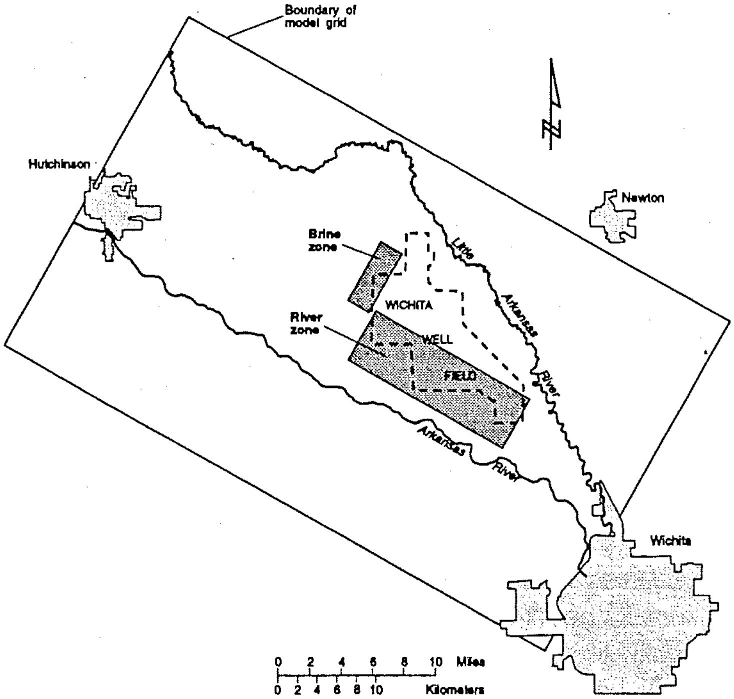

Figure 13a.—Areas used in evaluating model results, brine and river zones.

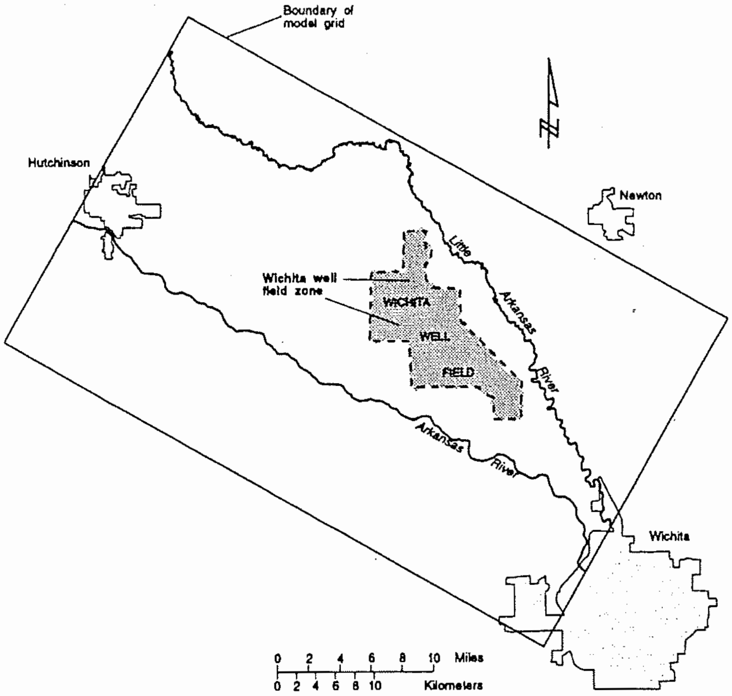

Figure 13b.—Areas used in evaluating model results, Wichita well field zone.

that layer and area. Viewing these graphs permits results to be evaluated in a transient sense and to look at specific concerns, such as transport of saltwater to the Wichita well field from the Arkansas River.

Transport Model Projection

Projections of chloride transport were made for the period 1990 through 2049. The projections were made assuming stresses and chloride concentration in the Arkansas River for the final stress period of the calibrated model would remain constant throughout the projection simulation. The predicted change in water level in 1989 and 2049 from 1940 conditions shows the impact of withdrawals from the aquifer. A cone of depression would be centered over the Wichita well field (figure 14). The predicted distribution of chloride in 1989 and 2049 when compared with the initial conditions reflects how the chloride distribution has changed and is estimated to change over time (figures 11, 12, and 15).

Predicted distributions of chloride concentration indicate the movement of a chloride plume from the Arkansas River toward the Wichita well field. Graphs of chloride mass and

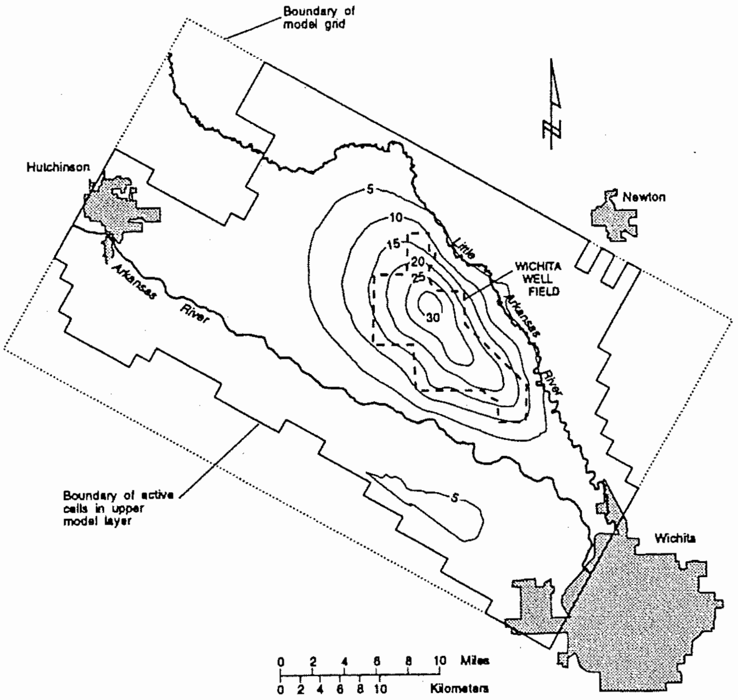

Figure 14a.—Predicted drawdown since 1940 in 1989.

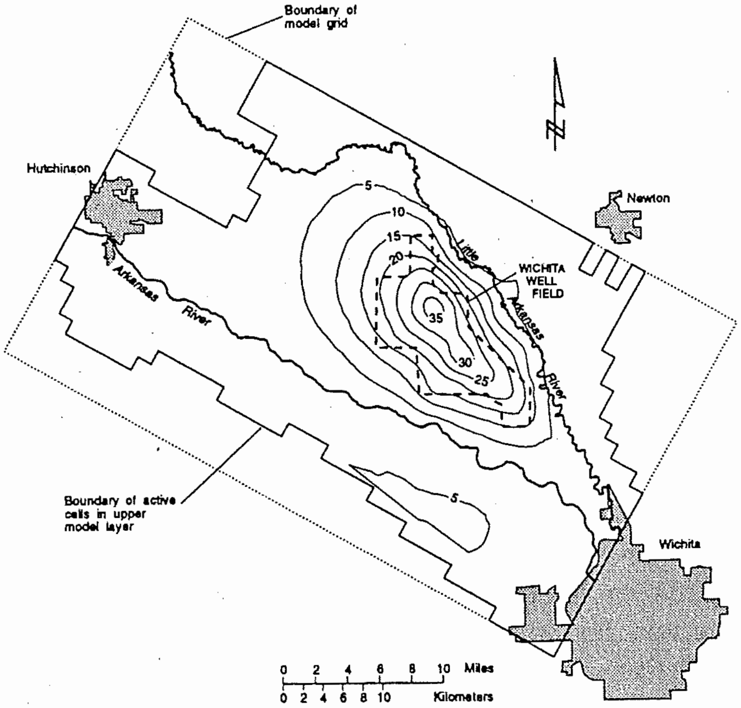

Figure 14b.—Predicted drawdown since 1940 in 2049.

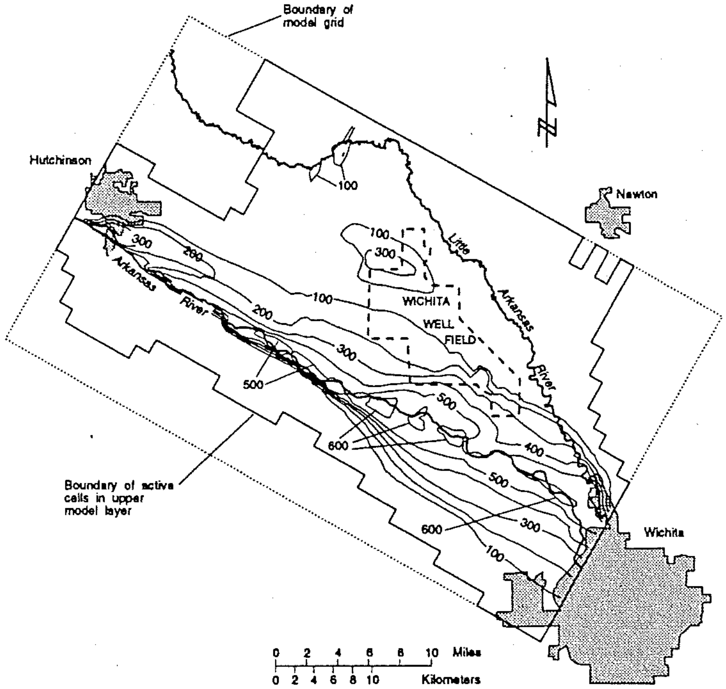

Figure 15a.—Predicted chloride distribution in 2049 for upper model layer.

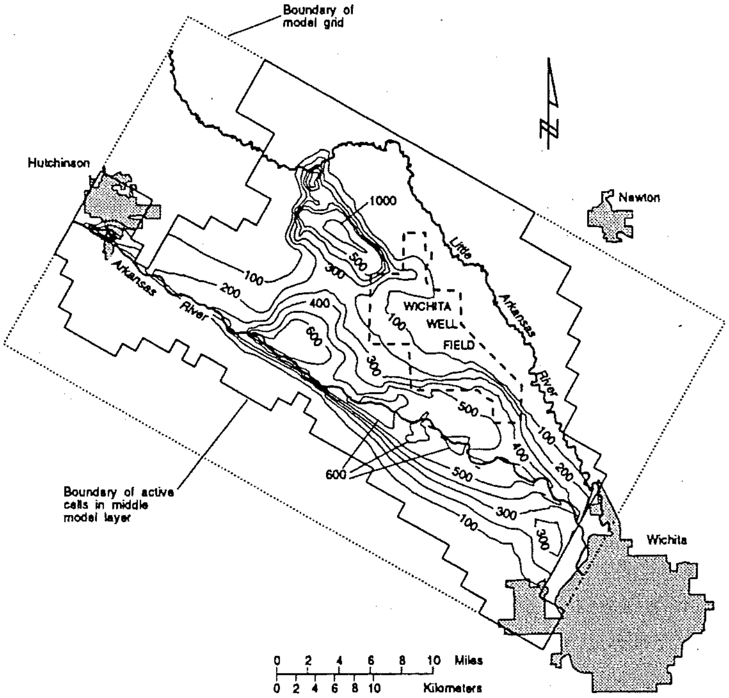

Figure 15b.—Predicted chloride distribution in 2049 for middle model layer.

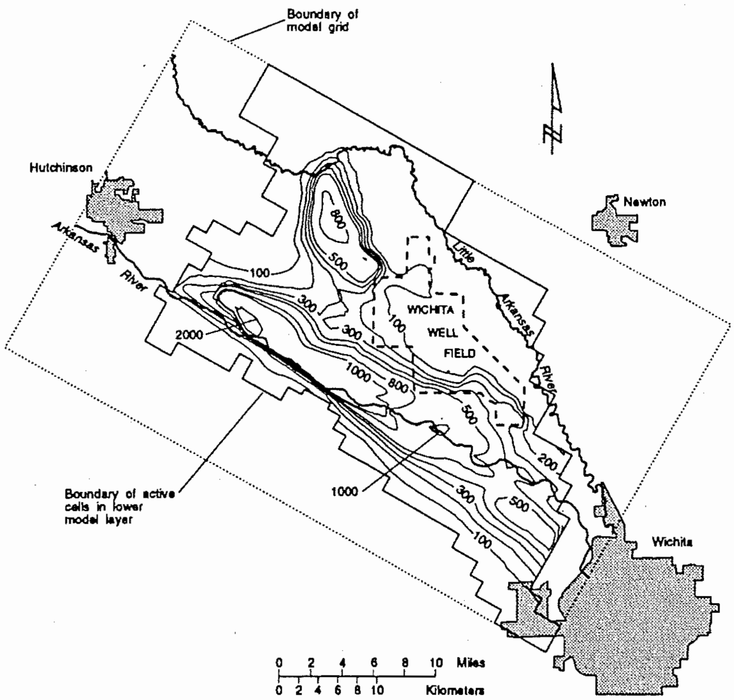

Figure 15c.—Predicted chloride distribution in 2049 for lower model layer.

average concentration versus time represent the movement of this plume in each layer through the river zone (figure 16). In general, the oil field saltwater plume originating in the Burrton area would disperse and move to the east, toward the Little Arkansas River and the Wichita well field. The oil field saltwater would also move vertically to the lower layer from above. Graphs for the brine zone illustrate changes for this plume in mass and concentration from 1940 through 2049 (figure 17). A more detailed discussion of these results is presented in a later section.

Reference Simulation

The reference simulation is a combination of the calibration simulation (1940-1989) and the base projection simulation (1989-2049) to provide a continual model period from 1940-2049.

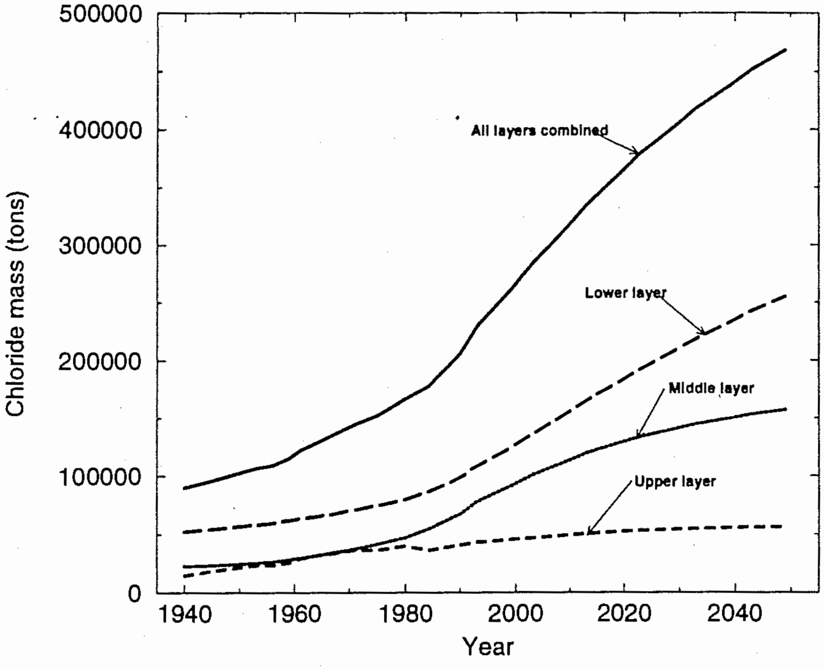

Figure 16a.—Predicted chloride mass for the river zone, 1940-2049.

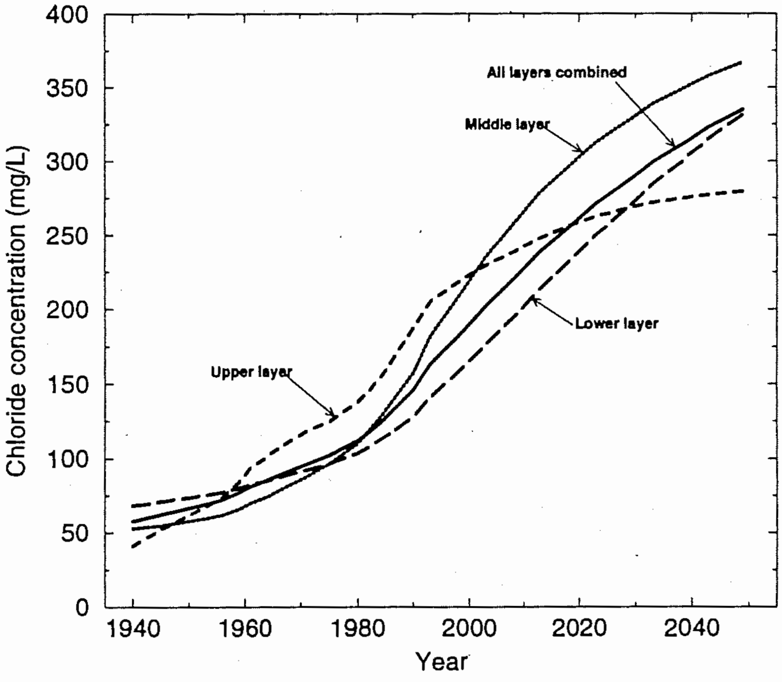

Figure 16b.—Predicted chloride average concentration for the river zone, 1940-2049.

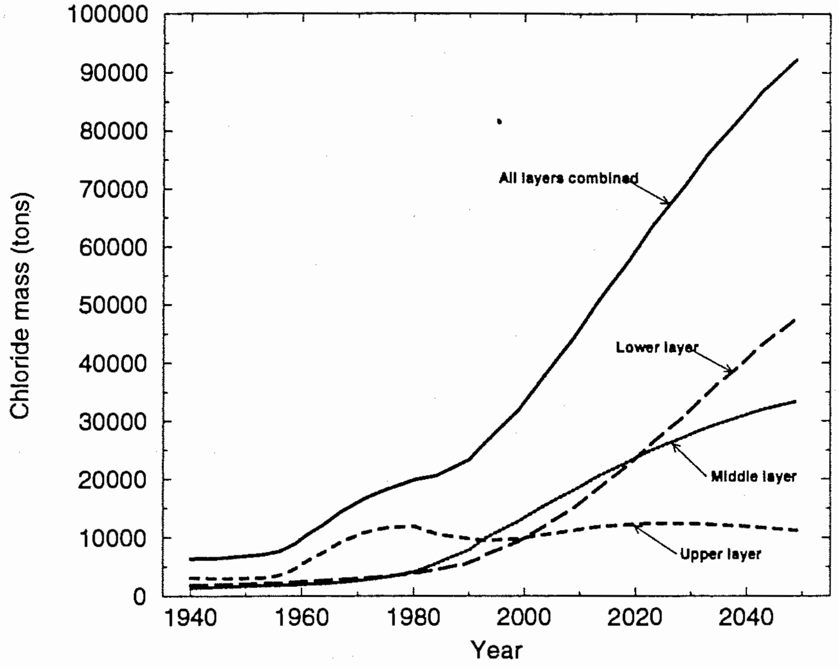

Figure 17a.—Predicted chloride mass for the brine zone, 1940-2049.

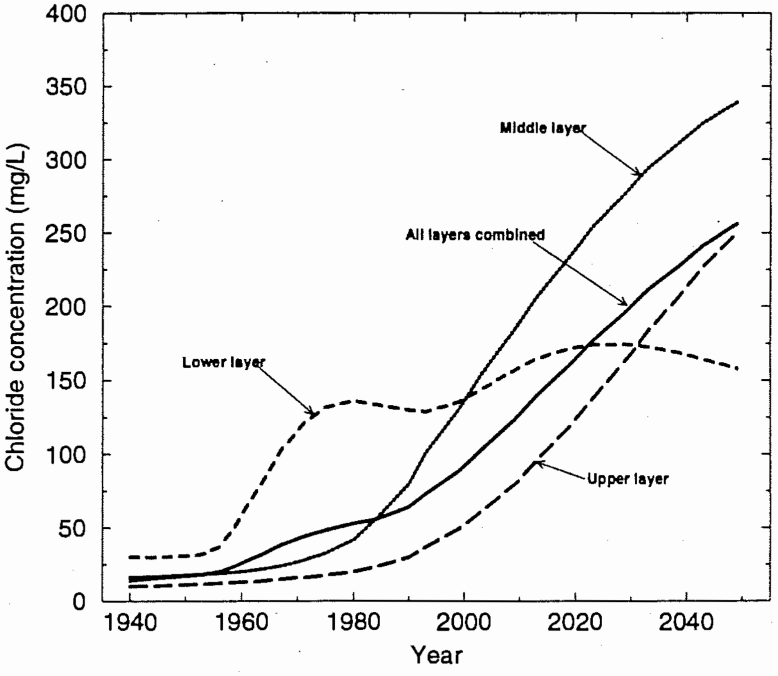

Figure 17b.—Predicted chloride average concentration for the brine zone, 1940-2049.

The base projection was made assuming that stresses and the chloride concentration in the Arkansas River for the final stress period of the calibrated model (1980-1989) would remain constant throughout the projection simulation period.

The results from the following simulations were evaluated by comparing them with the results from the reference simulation:

- Sensitivity.
- Simulations of individual sources.

Results from management simulations were compared with results from the base projection simulation to cover the same time period (1990-2049).

Results from the reference simulation indicate that chloride plumes are migrating from the Arkansas River and Burrton Oil Field area toward the Wichita well field area. The transport model predicts that chloride concentrations would be as high as 400 mg/L in the south part and 300 mg/L in the extreme northwest part of the well field by 2049. The predicted movement of these plumes is considered to be reasonable, while more uncertainty exists concerning the predicted arrival times.

Sensitivity Analysis

Sensitivity analyses were performed by varying effective porosity and hydrodynamic dispersion coefficients. For each sensitivity simulation, one of the parameters was increased or decreased a proportionate amount from the accepted or calibrated value. This increase or decrease was then applied uniformly over the entire model grid. The impact on predicted chloride concentration was evaluated by comparing the predicted average concentrations from the sensitivity simulations with that of the reference simulation in areas of interest.

The transport model is most sensitive to effective porosity and relatively insensitive to values representing hydrodynamic dispersion for the three areas defined.

Sensitivity to Effective Porosity

River Zone.—For the river zone, the concentration graphs deviate steadily from those for the reference simulation (1940-2049) (figure 11a in appendix A). The Arkansas River provided a continuous source of chloride, the primary source that impacts the river zone. Varying effective porosity values impacts the travel time of chloride from the river into the river zone and affects the appearance of the breakthrough curve.

Brine Zone.—The source of chloride impacting the brine zone is primarily oil field brine from the Burrton Oil Field. Movement of oil field saltwater into this zone is sensitive to effective porosity throughout the reference simulation (figure 11b in appendix A). This source is noncontinuous and has initial conditions that are not uniformly distributed. Consequently, slugs or pockets of higher chloride concentrations break through at different times. The result is a more variable concentration graph that is more pronounced for smaller effective porosity values (figure 11b in appendix A).

Well Field Zone.—The chloride concentration graphs for the well field zone indicate influence from both chloride sources, the Arkansas River and oil field brine, based on similarities with both the graph for the river zone and the graph for the brine zone (figure 11c in appendix A).

Sensitivity to Dispersion Parameters

Values representing hydrodynamic dispersion include longitudinal dispersivity and lateral dispersivity. The predicted average chloride concentrations are relatively insensitive to these parameters for the defined areas (figures 12 and 13 in appendix A).

Comparison of Zones and Parameters

The relative sensitivity of predicted chloride concentrations to a parameter can also be evaluated by observing the percent change in concentration as a function of the percent change in the parameter. The absolute percent change in average predicted chloride concentration for all layers combined in an area can be plotted against the percent change in the parameter.

Sensitivity to porosity evaluated at the end of the calibration period is very similar for the different areas. The brine zone displays the greatest sensitivity for a negative percent change in porosity (figure 14a in appendix A). A similar analysis for longitudinal dispersivity indicates that the brine zone is significantly more sensitive to longitudinal dispersivity than the river zone or the well field zone (figure 14b in appendix A).

The sensitivity to porosity is relatively much higher than the sensitivity to longitudinal dispersivity for the three defined areas (figure 14c in appendix A).

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Chapter 3: Simulations

Summary of Simulations

Table 3 describes some of the simulations run under this study, with a brief discussion of the general results from each simulation. When not stated otherwise, the management simulation used the same boundary conditions, initial conditions, and stresses as the base projection. The data for these boundary conditions, initial conditions, and stresses are taken from data used in the last stress period in the calibration simulation (1980-1989). Section "Solute-Transport Model" provides more information on how these data were obtained and used. Initial conditions are those predicted by the calibrated model in 1989 as reflected in figure 12. The sections following this table—"Basic Simulations," "Simulations of Individual Sources," and "Management Simulations"—provide an overview of the simulations and results.

The reference simulations are further described in "Transport Model Projection."

Table 3 is also reproduced in appendix A for readers who wish to consult the table while reading about the further details of these simulations discussed in the following sections.