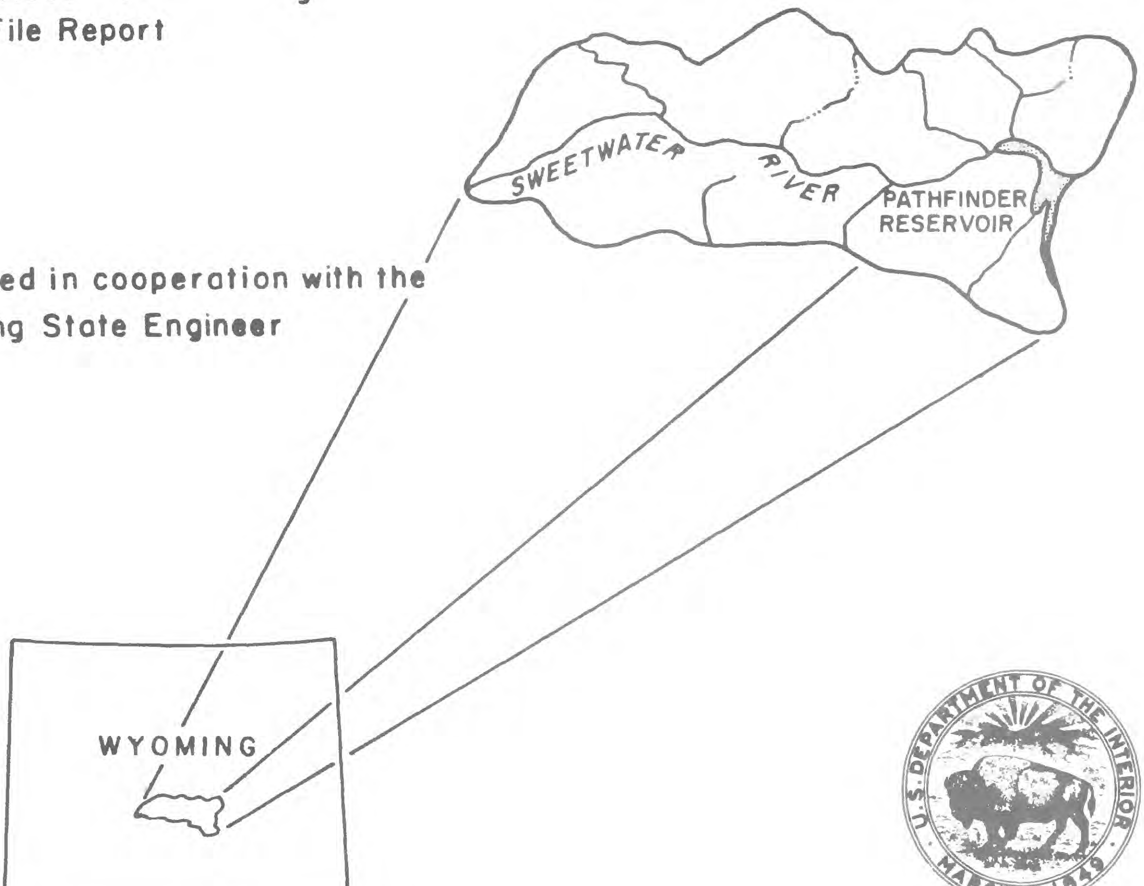
PRELIMINARY DIGITAL MODEL OF THE ARIKAREE AQUIFER IN THE SWEETWATER RIVER BASIN, CENTRAL WYOMING

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 77-107
Open-File Report

Prepared in cooperation with the
Wyoming State Engineer



BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle PRELIMINARY DIGITAL MODEL OF THE ARIKAREE AQUIFER IN THE SWEETWATER RIVER BASIN, CENTRAL WYOMING			5. Report Date September 1977 6.
7. Author(s) William B. Borchert			8. Performing Organization Rept. No. USGS/WRI 77-107
9. Performing Organization Name and Address U.S. Geological Survey, Water Resources Division 2120 Capitol Avenue P. O. Box 1125 Cheyenne, Wyoming 82001			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey, Water Resources Division 2120 Capitol Avenue P. O. Box 1125 Cheyenne, Wyoming 82001			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes
Prepared in cooperation with the Wyoming State Engineer

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17. Key Words and Document Analysis. 17a. Descriptors

*Computer model/ *surface-ground-water relationships/ *aquifer characteristics/ *Wyoming/ hydrogeology/ ground water/ streamflow/ hydraulic conductivity/ aquifer/ recharge/ discharge/ simulation.

17b. Identifiers/Open-Ended Terms

Sweetwater River basin/ Arikaree aquifer/ central Wyoming.

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 19
No restriction on distribution.	20. Security Class (This Page) UNCLASSIFIED	22. Price

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

U.S. Geological Survey
2120 Capitol Avenue
P.O. Box 1125
Cheyenne, Wyoming 82001

CONTENTS

PLATES

ILLUSTRATION

PRELIMINARY DIGITAL MODEL OF THE ARIKAREE AQUIFER IN THE SWEETWATER RIVER BASIN, CENTRAL WYOMING

By William B. Borchert

ABSTRACT

Potentially large supplies of ground water are available in the Sweetwater River basin from the Arikaree aquifer, which consists of the upper part of the White River Formation (conglomerate and sandstone) of Oligocene age, the Arikaree Formation (sandstone) of early Miocene age, and the Ogallala Formation (thin beds of limestone, sandstone, claystone, and tuff) of late Miocene age. The Arikaree aquifer underlies an area of about 1,500 square miles that is approximately bisected by the Sweetwater River. The aquifer is divided into the western, northeastern, and southeastern areas in this report. Gain and loss studies during November 1975 indicate that the river gains about 17 cubic feet per second between the gaging station near Sweetwater Station and the gaging station near Alcova. The gain in streamflow in this reach is assumed to be the total discharge from the Arikaree aquifer in the western area. The recharge from precipitation to the aquifer is assumed to be about 2 percent of the estimated mean annual precipitation of 8.5 inches. Along the southern boundary, the Arikaree aquifer is assumed to receive additional recharge from greater precipitation near the mountains and from creeks flowing off the mountains into the study area.

A preliminary digital model was developed for the Arikaree aquifer using a small amount of poorly distributed data, an estimated distribution of recharge, and a conceptual model of the Arikaree aquifer flow system. Calibration of the model was based on the reproduction of the potentiometric surface and the base flow of the Sweetwater River in November 1975. Calculated steady-state hydraulic heads were within 50 feet of the observed heads in about 98 percent of the nodes. The calculated leakage from the Arikaree aquifer to the Sweetwater River in the western area was within about 12 percent of the leakage determined by gain and loss studies. Observed data are not available to estimate leakage to the river from the northeastern and southeastern areas. In order to develop a comprehensive digital model that would respond to hydraulic stress in nearly the same manner as the actual aquifer flow system, measured responses of the aquifer to stress are needed. Also needed are additional data for aquifer characteristics, recharge to the aquifer, and stream-aquifer relationships.

INTRODUCTION

This investigation was made by the U.S. Geological Survey between August 1975 and October 1976 in cooperation with the Wyoming State Engineer. The study area consists of about 1,500 square miles and includes parts of Fremont, Natrona, and Carbon Counties in central Wyoming (fig. 1).

The Sweetwater River basin is an area of major uplift extending from the northern edge of the Green, Ferris, and Seminoe Mountains on the south to the Beaver Rim, an escarpment overlooking the Wind River Basin on the north (pl. 1). This area of major uplift has been referred to by Van Houten (1964, p. 11) as the Sweetwater uplift. The displacement of this crustal block occurred during two major episodes of movement along the north and south Granite Mountains fault systems. Although Love (1970, p. C9) named this area of uplift the Granite Mountains area, the term Sweetwater River basin is used in this report to emphasize the hydrologic importance of the Sweetwater River to this area.

Ground water in the Sweetwater River basin is used predominantly for stock and domestic purposes. However, potentially large supplies of ground water may be obtained from an unconfined sandstone and conglomerate aquifer, referred to as the Arikaree aquifer in this report. The Sweetwater River, the principal stream in the study area and a major tributary to the North Platte River, is closely associated with the aquifer. Before ground water in the Arikaree aquifer is extensively developed, there is a need to know the relationship between water in the Sweetwater River and water in the Arikaree aquifer. Water administrators also would like to know the feasibility of developing a digital model that would simulate water-level changes resulting from groundwater pumping and the effects of this pumping on the flow of the Sweetwater River.

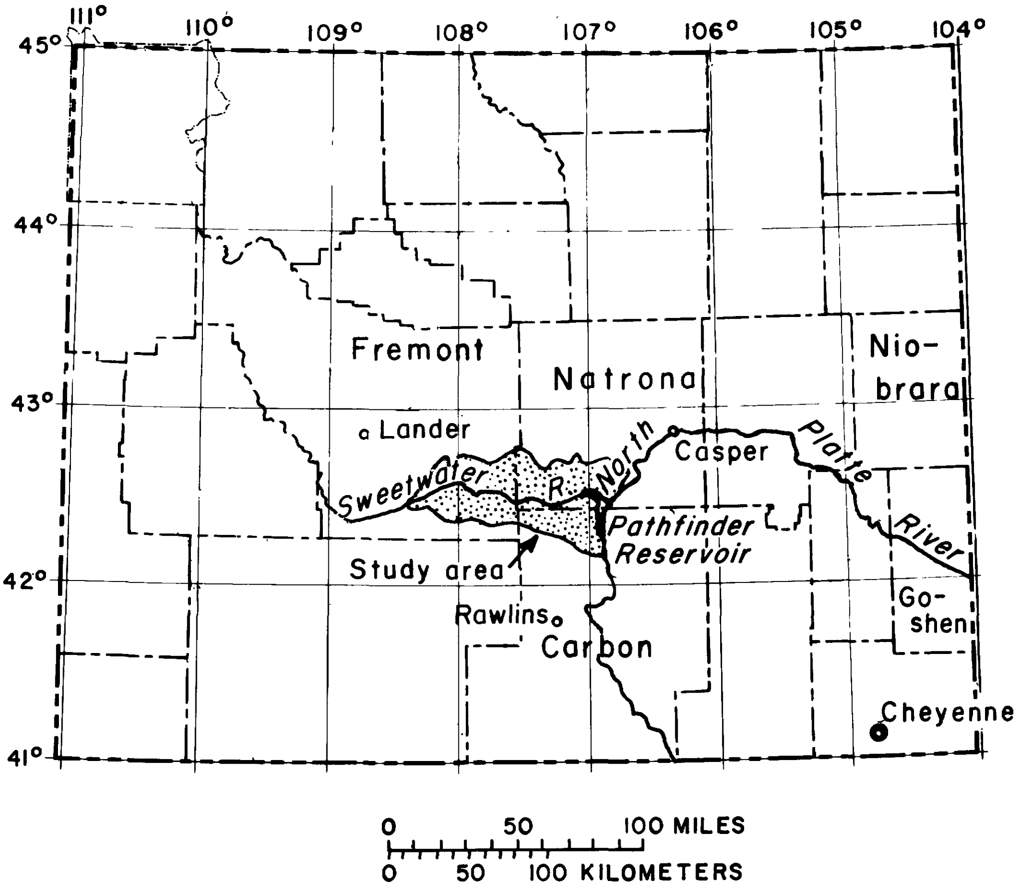

Figure 1.—Location of the study area.

For those readers interested in using the metric system, the following table may be used to convert English units of measurement used in this report to metric units:

English	Multiply by	Metric
Acres	0.4047	hectares (ha)
Feet (ft)	.3048	meters (m)
Square feet (ft^2)	.0929	square meters (m^2)
Feet per mile (ft/mi)	.1894	meters per kilometer (m/km)
Cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
Cubic feet per day per square foot $(ft^3/d)/ft^2$	.3048	cubic meters per day per square meter $(m^3/d)/m^2$
Inches (in)	25.40	millimeters (mm)
Miles (mi)	1.609	kilometers (km)
Square miles (mi^2)	2.590	square kilometers (km^2)

Purpose of the Investigation

The purpose of this investigation was to develop a preliminary digital model of the Arikaree aquifer in the Sweetwater River basin and to define the existing stream-aquifer relationship. Results from the preliminary digital model were used to evaluate the feasibility of developing a comprehensive digital model of the hydrologic system for the Sweetwater River basin.

Previous Investigations

The ground-water resources of the Sweetwater River basin were described as part of the study of the ground-water resources and geology of the Wind River Basin by Whitcomb and Lowry (1968). Most of the eastern half of the study area was included in a study of the ground-water resources of Natrona County by Crist and Lowry (1972).

Numerous studies of the geology in and near the Sweetwater River basin have been made and include: Cenozoic geology of the Granite Mountains area by Love (1970); Tertiary geology of the Beaver Rim area, Fremont and Natrona Counties by Van Houten (1964); and Geology and uranium deposits at Crooks Gap, Fremont County by Stephens (1964).

Acknowledgments

The author appreciates the cooperation of the landowners who allowed access to the Sweetwater River for discharge measurements. The cooperation of personnel from the Wyoming Water Planning Program for providing aquifer test information is gratefully acknowledged.

HYDROGEOLOGY

Precambrian Rocks

Rocks of Precambrian age comprise the knobs and masses of the Granite Mountains, a conspicuous topographic feature extending across most of the area. Precambrian rocks are exposed along most of the eastern half of the southern boundary. Stratigraphic and structure sections of Love (1970, pls. 1, 3, and 4) show Precambrian rocks comprising the basement beneath the White River and Arikaree Formations in areas north of the eastern end of the Green Mountains, north of the Ferris Mountains, and in areas near the Granite Mountains.

The Arikaree Aquifer

The Arikaree aquifer (pl. 1), as used in this report, includes saturated rocks in the upper part of the White River Formation of Oligocene age, the Arikaree Formation of early Miocene age, and the Ogallala Formation of late Miocene age. Rocks of these formations were originally assigned to the Split Rock Formation (now abandoned) and its subdivisions by Love (1961). However, Denson (1965, p. A70-A75) assigned most of the rocks referred to as the Split Rock Formation in the Granite Mountains area to the Arikaree Formation. Furthermore, he assigned rocks previously included in the uppermost part of the Split Rock to the Ogallala Formation and rocks in the lowermost part of the Split Rock to the upper part of the White River Formation. These three formations are considered one aquifer in this report because they seem to be in hydraulic interconnection and to have similar hydraulic characteristics.

The lower part of the Arikaree aquifer, which is the upper part of the White River Formation, consists predominantly of conglomerate and sandstone. The conglomerate consists of pebbles, cobbles, and boulders of Precambrian rocks in a gray, coarse-grained, poorly cemented sandstone matrix. Many beds of gray, medium- to coarse-grained sandstone are interbedded with the conglomerate (Love, 1961, p. 10). This part of the Arikaree aquifer is as much as 600 feet thick.

The part of the Arikaree aquifer with the largest areal extent is the Arikaree Formation that was described by Denson (1965, p. A74) as consisting predominantly of windblown, fine- to medium-grained tuffaceous sandstone with thin interbeds of limestone, tuff, and conglomerate. The Arikaree Formation is the thickest part of the Arikaree aquifer, averaging about 1,000 feet in thickness.

The upper part of the Arikaree aquifer, the Ogallala Formation, occurs mostly in the area south of the Sweetwater River. The rocks comprising the Ogallala consist mostly of thin beds of relatively pure white pumicite, pumiceous limestone, sandstone, claystone, and tuff. These beds grade mountainward into fanlike deposits of coarse-grained sandstone, conglomerate, and gravel (Denson, 1965, p. A72). This part of the Arikaree aquifer is estimated to be as much as 800 feet thick (Crist and Lowry, 1972, p. 70).

Geologic maps of all or part of the Sweetwater basin are in reports by Crist and Lowry (1972), Love (1970), Rich (1962), Stephens (1964), and Van Houten (1964). These maps show the complex geology along the boundary of the Arikaree aquifer. However, formations outside this boundary are not pertinent to this study because most of the hydrologic boundary of the Arikaree is assumed to be impermeable.

Boundaries of the Arikaree aquifer do not coincide everywhere with the boundaries of the Sweetwater River basin (pl. 1). In the extreme western and northern part of the basin north of the Sweetwater River and west of the Granite Mountains, the Arikaree aquifer is either not saturated or is missing.

Potentiometric Surface

Contours showing the configuration of the potentiometric surface in the Arikaree aquifer are shown on plate 1. This potentiometric surface is referred to in this report as the observed potentiometric surface. These contours are based on altitudes of water levels measured in 1964 and 1965 by Whitcomb and Lowry (1968) and on altitudes along perennial streams. Where water-level altitudes are not available, the contours are approximately located. The configuration of the potentiometric surface indicates that ground-water movement in most of the area is primarily toward the Sweetwater River except in the eastern part of the area where it is toward Pathfinder Reservoir and the North Platte River.

Saturated Thickness

The saturated thickness of the Arikaree aquifer, as shown on plate 2, was calculated as the difference between the observed potentiometric surface and the base of the aquifer. Altitudes of the base of the Arikaree aquifer were estimated using a map showing thickness of the former Split Rock Formation (Love, 1970, pl. 5) and using altitudes of the base of the Split Rock determined by Love (1970, p. C20-C29) from wells and core holes. The data from Love (1970) were available for most of the area south of the Sweetwater River. However, north of the river, data were available only in parts of T. 30 N., R. 84 W.; T. 31 N., Rs. 84, 85, 86, 90, and 91 W.; and in T. 32 N., R. 89 W.

Saturated thickness of the aquifer in most of the area south of the Sweetwater River ranges from about 500 to 3,000 feet. The areas of greatest saturated thickness are along the axis of the Split Rock syncline. South of the Sweetwater River this syncline trends west-northwest and is about 80 miles long with a steep south side. Saturated thickness of the aquifer north of the Sweetwater River ranges from 200 to 600 feet. Saturated thickness was assumed to be less than 400 feet in areas north of the river where data are lacking.

Hydraulic Conductivity

The hydraulic conductivity of an aquifer is a measure of the ability of the aquifer to transmit water. It can be expressed as the rate of flow in cubic feet per day through a cross-sectional area of one square foot under a hydraulic gradient of one foot per foot. Hydraulic conductivities for the Arikaree aquifer of 0.05 and 5.2 $(ft^3/d)/ft^2$ were determined by M. A. Crist (written commun., 1976) from aquifer tests made in the northeastern part of the area during the Natrona County study (Crist and Lowry, 1972). These hydraulic conductivities are approximate values because the saturated thickness of the aquifer at the test sites was estimated. A hydraulic conductivity of 5.4 $(ft^3/d)/ft^2$ was estimated for the Arikaree aquifer from hydraulic characteristics determined by the Wyoming Water Planning Program (A. J. Mancini, oral commun., 1975) from an aquifer test of a well south of Jeffrey City.

Data on the hydraulic conductivity determined from aquifer tests of the Arikaree Formation in various parts of eastern Wyoming have been published by Morris and Babcock (1960, p. 53); Weeks (1964, p. 40); Whitcomb (1965, p. 48); Lines (1976, p. 7); and Borchert (1976, p. 12). The hydraulic conductivities from the above reports ranged from 0.2 to 50 $(ft^3/d)/ft^2$. Hydraulic conductivities estimated from three aquifer tests made by M. E. Lowry (written commun., 1973) in Niobrara County in eastern Wyoming ranged from 1.9 to 10 $(ft^3/d)/ft^2$. The wide range in hydraulic conductivity for the Arikaree Formation is due to the variability of several factors from one test site to another. Some of these factors include the differences in sand grain size and degree of cementation, the presence of fracture zones, and the variation in thickness of aquifer penetrated by the wells used in the test. The hydraulic conductivity determined from a test using a well that partially penetrates the aquifer may not be representative of the entire saturated thickness of the aquifer. Whitcomb (1965, p. 48 and 51) reported a hydraulic conductivity of 8.6 $(ft^3/d)/ft^2$ as being representative of the entire saturated thickness of the Arikaree Formation in Niobrara County. M. A. Crist (written commun., 1977) used a range of hydraulic conductivity from 0.17 to 60 $(ft^3/d)/ft^2$ in a digital model of the Arikaree Formation in Niobrara and Goshen Counties in eastern Wyoming. The Arikaree aquifer in the Sweetwater River basin is assumed to have hydraulic conductivities similar to those of the Arikaree Formation in eastern Wyoming.

Surface Water

The discharge of the Sweetwater River, a perennial stream that meanders across the basin at an average gradient of less than 10 ft/mi, is measured at two gaging stations in the study area. The gaging station Sweetwater River near Sweetwater Station is about 4.4 miles southwest of Sweetwater Station. This gaging station has been operated since October 1973. During water year 1976 (October 1, 1975 to September 30, 1976), daily mean discharge ranged from a minimum of 17 ft^3/s in January to a maximum of 898 ft^3/s in May. The other gaging station in the area, Sweetwater River near Alcova, is about 13 miles upstream from the high-water line of Pathfinder Reservoir. This gaging station has been operated from August 1913 to September 1924 and from October 1938 to the current year (1977). Since 1973, winter records from October through March are not available except for water year 1976. Daily mean discharge during water year 1976 ranged from a minimum of 17 ft^3/s in September to a maximum of 699 ft^3/s in May.

Most of the small creeks that perennially flow into the Sweetwater River basin have changing gradients causing them not to flow into the Sweetwater River or Pathfinder Reservoir. Creeks flowing north have segments of their reaches south of the south Granite Mountains fault system with gradients that average more than 200 ft/mi. Segments from the fault system to the axis of the Split Rock syncline have gradients of about 85 ft/mi and from the axis to the Sweetwater River a gradient of about 35 ft/mi. Several major creeks, such as Crooks Creek, have such a low gradient north of the axis of the syncline that they become ponded and lose water to the underlying porous sandstone. Not even a flood channel of Crooks Creek reaches the Sweetwater River (Love, 1970, p. C9). Creeks flowing south have an average gradient of about 45 ft/mi and do not have the gradient variability as do the creeks flowing north.

Tracts of native hay and alfalfa along the Sweetwater River and some of the tributaries are irrigated by surface water and by subirrigation. After a survey for the State Engineer of adjudicated water rights in the Sweetwater River basin, Ken Bower (oral commun., 1976) estimated about 10,000 acres is currently being irrigated by water diverted from the Sweetwater River and its tributaries.

PRELIMINARY DIGITAL MODEL

The theoretical development, documentation, and computer program for the model used to simulate ground-water flow is explained by Trescott, Pinder, and Larson (1976). D. T. Hoxie of the U.S. Geological Survey made minor modifications to the model program, primarily in data input and in the output.

The computer model used in this study solves the partial differential equation of ground-water flow in an unconfined aquifer for the head distribution in the aquifer. It is assumed that vertical flow within the aquifer may be neglected, that the head at any location is equal to the altitude of the potentiometric surface at that location, and that the aquifer is nonhomogeneous and isotropic with respect to its hydrologic properties.

Simulation of the Arikaree aquifer flow system is accomplished by dividing the modeled area into a grid of rectangular cells, referred to as a finite-difference grid (pl. 3). The aquifer properties are assumed to be uniform within each cell although they may vary from cell to cell. The center point in each cell is referred to as a node. The flow equation is written as a finite-difference equation for each node, and the resulting set of algebraic equations is solved iteratively on a digital computer using the strongly implicit procedure (SIP).

The finite-difference grid used to model the Arikaree aquifer consists of 45 rows and 79 columns. Variable grid spacing is used in order to provide better detail along the Sweetwater River. Dimensions of the cells ranged from 2,640 feet by 5,280 feet along the Sweetwater River to 5,280 feet by 13,200 feet along the northeastern and southeastern boundaries of the model area.

Data Requirements

In order to simulate the aquifer system under steady-state conditions (no change in head with time), the following data must be provided:

1. Area of each cell in the grid. The area of each cell is calculated by the computer using the grid spacing in the X and Y directions in the finite-difference grid.

2. Altitude of the observed potentiometric surface in the aquifer. These altitudes were estimated for each node from the map on plate 1 showing the potentiometric surface prepared from the altitudes of water levels measured in 1964 and 1965 (Whitcomb and Lowry, 1968). In several areas where control for the potentiometric surface was not available, altitudes were assumed.

3. Average hydraulic conductivity. A range of values of hydraulic conductivity was estimated from three aquifer tests in the study area and from aquifer tests in eastern Wyoming. Average values within the estimated range were assumed for each node.

4. Altitudes of the base of the Arikaree aquifer. Control data for the base were available from Love (1970) for most of the area south of the Sweetwater River. However, for most of the area north of the river, altitudes of the base were assumed.

5. Recharge to the ground water from precipitation. Recharge from precipitation was assumed to be about 2 percent of the mean annual precipitation for the area. A mean annual precipitation of 8.5 inches was adopted for the basin based on 25 years of precipitation records for the Oregon Trail Crossing station at Sweetwater Station (U.S. Dept. of Commerce, 1951-75).

Data required for the model to simulate stream-aquifer relationships are discussed in the following section of the report. Additional data are needed in order to model the aquifer system under transient (head changes with time) conditions.

Stream-Aquifer Relationship

The potentiometric contours shown on plate 1 indicate that the Sweetwater River and several creeks are gaining water from the Arikaree aquifer. However, potentiometric contours indicate that Willow Creek is losing water to the aquifer. Gain and loss studies consisting of streamflow measurements at five sites on the Sweetwater River between the two gaging stations, plus streamflow measurements at each gaging station were made in November 1975. The results of these studies and the analyses of streamflow records at each gaging station indicate that the reach of the river between the two gaging stations in the study area gains about 17 ft^3/s, plus or minus 15 percent. Actually, the Sweetwater River gains water mostly from the alluvium which in turn gains water from the Arikaree aquifer. However, because the alluvium is thin and narrow, it is treated in the model as part of the Arikaree aquifer.

Gain and loss studies were not made on any of the creeks flowing in the study area. Creeks indicated by the potentiometric contours to be gaining or losing (pl. 1) are simulated by the model as gaining or losing at an assumed rate, which varies for each creek and in each of the stream cells representing the creek. These creeks shown on plate 1 as intermittent along their lower reaches are modeled to lose all their flow to the Arikaree aquifer before reaching the Sweetwater River. The assumed rates of gain or loss of these creeks show a net total loss to the aquifer of about 3 ft^3/s. The creeks included in the model are treated as partially penetrating and are shown on plate 3 as stream cells.

Most of the creeks outside the study area along the southern boundary flow into the Sweetwater River basin from the northern flanks of the Green, Ferris, and Seminoe Mountains. After many of these creeks flow across the south Granite Mountains fault system into the basin, they probably lose their flow to the Arikaree aquifer. The rate of recharge to the Arikaree aquifer from these creeks is not known. It is treated in the model as part of the total recharge distributed along the southern boundary as necessary to balance the recharge-discharge relationship in the model. This total recharge derived from surface water and precipitation is about 10 ft^3/s along the southern boundary.

In addition to the data required in the model at each node as previously described, the following data are required for each stream cell:

1. The head in the stream. This is the altitude of the stream surface at the cell node and is held constant during steady-state and transient simulations.

2. Leakance. The leakance is defined as the ratio between the vertical hydraulic conductivity in the streambed and the thickness of the streambed. The leakance was estimated for each stream cell by using the observed or estimated total gain of

water in the stream cell, the area of the stream cells, an assumed difference of 1 foot between the head in the aquifer and the head in the stream (hydraulic gradient), and an assumed streambed thickness of 1 foot.

The leakage between the aquifer and the stream is modeled as a function of the difference between heads in the stream and the aquifer under the stream cells.

Boundary Conditions

Two boundary conditions are assumed for the model of the Arikaree aquifer, a boundary using no-flow cells and a boundary using constant head cells, as shown on the finite-difference grid on plate 3. The no-flow boundary around the entire border of the model in plate 3 is used in the computer program as a computational expediency (Trescott and others, 1976, p. 30). The constant-head boundary is placed inside this border of the model. For simplicity, where constant-head boundaries are not used, the no-flow boundary is used also for the no-flow model boundary necessary to represent the hydrologic conditions in the aquifer.

The model boundary for most of the Arikaree aquifer is assumed to be impermeable. Cells representing the impermeable boundaries are designated in the model as no-flow cells through which ground water neither moves into nor out of the aquifer system. The no-flow boundary cells were assigned where the saturated thickness of the Arikaree aquifer was zero, which includes areas where Precambrian outcrops were present, and along the north and south Granite Mountains fault systems.

Pathfinder Reservoir and the North Platte River form part of the eastern boundary of the Arikaree aquifer in the Sweetwater River basin. Cells representing this boundary are designated in the model as constant-head cells in which the hydraulic head in the aquifer does not change with time. Depending upon the hydraulic gradient and transmissivity in the aquifer, constant-head cells allow the movement of ground water either into or out of the aquifer system.

Assumptions Used in the Model

The steady-state model is an approximation of the hydrologic system operating within the Arikaree aquifer. The approximation is based on the following assumptions that simplify the field conditions and allow for the limited amount of data:

1. The aquifer parameters assigned to each cell are representative average values for the whole cell.

2. The digital model is simulating the hydrologic system at a point in time representative of the conditions as they existed in November 1975. This assumption is necessary because no long-term or seasonal information is available.

3. The potentiometric surface prepared from the altitudes of water levels measured in 1964 and 1965 is representative of the steady-state head distribution in the Arikaree aquifer during November 1975.

4. There is no evapotranspiration loss from ground water.

5. The Arikaree aquifer can be separated into three areas--northeastern, southeastern, and western--each having its own recharge-discharge relationship. The northeastern area is the area east of the ground-water barrier (pl. 1) and north of the Sweetwater River and Pathfinder Reservoir. The southeastern area is the area east of the ground-water divide (pl. 1) and south of the Sweetwater River and Pathfinder Reservoir. The western area is the remainder of the total area of the Arikaree aquifer west of the northeastern and southeastern areas.

6. The total discharge from the Arikaree aquifer in the western area in November 1975 is about 17 ft^3/s and is approximately equal to the gain in flow of the Sweetwater River between the two gaging stations. This gain in streamflow is considered to be the net leakage from the Arikaree aquifer to the Sweetwater River.

7. Recharge to the Arikaree aquifer is about 2 percent of the precipitation except (1) adjacent to the granite knobs, where it is slightly higher assuming runoff from the granite, and (2) along the southern boundary where additional recharge is included to simulate greater precipitation near the mountains and recharge from creeks flowing off the mountains.

Model Calibration

Purpose and Procedure

In this report, calibration refers to the process whereby the input hydrologic parameters to the model are adjusted until the difference between the observed and the calculated steady-state potentiometric surfaces is within an acceptable degree of accuracy.

In order to obtain this calibration, hydraulic conductivity was adjusted at most nodes in the model. Adjustment of this parameter was justified because of the limited amount of data for hydraulic conductivity. The range of hydraulic conductivity used in the calibrated model was from 0.1 to 9 $(ft^3/d)/ft^2$.

At some nodes, observed hydraulic head, recharge, or saturated thickness were also adjusted within the degree of allowable adjustment of the data. The degree of allowable adjustment of a parameter generally is directly proportional to the uncertainty of the value of the parameter.

For example, at nodes where control data were available, heads were not adjusted in the model. But where little or no control data were available, heads were adjusted by as much as 100 feet during calibration. Recharge from precipitation was another parameter that had an uncertain value. The estimate of 2 percent of the mean annual precipitation was made for recharge to the aquifer because this amount of recharge was approximately equal to the discharge in the western area. However, the distribution of greater recharge along the southern boundary was highly subjective. Thus, the degree of allowable adjustment of the recharge parameter was as much as an order of magnitude at some nodes.

Results

The steady-state potentiometric surface calculated by the model is shown on plate 4. The calculated steady-state hydraulic heads are within 50 feet of the observed heads in about 98 percent of the nodes. The match between the calculated and observed potentiometric surface is judged to be satisfactory, considering the quality, quantity, and distribution of the available data.

The reproduction of the observed heads to within 50 feet by the steady-state model is only an indication of how accurately the combination of parameters in the model simulate the observed aquifer conditions. The observed aquifer conditions are described by parameters determined from meager, uncertain, and poorly distributed data. Some of the parameters were assumed from a conceptual model of the Arikaree aquifer. The conceptual model consists of the author's understanding of the flow system, including variations in aquifer properties, the physical and functional nature of the hydrologic boundaries, sources of recharge and discharge, and the relation of surface water to the aquifer. Therefore, although the accuracy of the calibrated model in defining the conceptual model is acceptable, the accuracy of the calibrated model in defining the actual aquifer flow system is not known. This accuracy could be determined if observed conditions of aquifer response to hydraulic stress were compared with calculated response of the model to the same stress. This modeling process is called verification. Verification of this model is not possible because sufficient stress, such as pumping, has not been applied to the aquifer.

Other than calibrating the model with respect to the observed potentiometric surface, the model is calibrated with respect to the observed leakage from the aquifer to the Sweetwater River. At the end of the calibration of this model, the calculated leakage from the Arikaree aquifer to the Sweetwater River in the western area was within about 12 percent of the observed leakage determined by gain and loss studies. The observed leakage to the river from the southeastern and northeastern areas was not available. The accuracy of the simulation of the observed leakage is acceptable because it is within the limits of the field data.

Hypothetical Model Application

A model must be verified before it can be used as a reliable predictive tool. Although verification of this model was not possible, a hypothetical example of the model's use as a predictive tool is presented.

Assuming that the digital model of the Arikaree aquifer is calibrated and verified to an acceptable accuracy, the model could then be used to predict future effects of pumping (hydraulic stress) on the flow system. A specific yield of 15 percent is assumed, and the model is used to simulate the response of the aquifer to pumpage from 60 wells for 3 years. The specific yield of the aquifer defines the volume of water that the aquifer yields by gravity drainage as the head in the aquifer is lowered. Each year is divided into two periods of 6 months. The wells pump continuously for 6 months; then are turned off and allowed to recover during the next 6 months. Each well pumps enough water during the 6 months to irrigate 135 acres with 1.5 ft of water per acre. The model assumes each discharge cell represents one discharging well that fully penetrates the aquifer. Therefore, the total pumpage from a discharge cell is equal to the sum of the pumpages from wells that are located within that cell. The hydraulic head calculated after pumpage represents an average hydraulic head for the cell.

Pumpage from the 60 wells was simulated in the model by 25 discharge cells located in three groups south of the Sweetwater River (pl. 3). The total pumpage for the 3 years was the same from each group of discharge cells. After 3 years of simulated pumping, hypothetical drawdowns occurred in the discharge cells as follows: The western group, about 15 to 20 feet; the central group near the river, about 10 to 20 feet; the eastern group, about 25 feet. Drawdowns in cells adjacent to the western and central groups were less than 10 feet and adjacent to the eastern group were less than 1 foot. The leakage between the aquifer and the stream was modeled as a function of the difference between heads in the stream and the aquifer under the stream cells. The heads in the stream were held constant, but a change in the heads in the aquifer because of pumping resulted in a change in the leakage to the Sweetwater River. The leakage of ground water from the aquifer to the Sweetwater River in the western area was decreased by about 2 ft^3/s at the end of this hypothetical simulation.

FEASIBILITY OF DEVELOPING A COMPREHENSIVE DIGITAL MODEL

The calibrated digital model is considered to simulate the observed steady-state flow system in the Arikaree aquifer to an acceptable degree of accuracy and to illustrate that the Arikaree aquifer could be modeled satisfactorily. However, this model is considered preliminary because several parameters used in the model were based on a small amount of poorly distributed data and because the model was based on a conceptual model of the Arikaree aquifer and on an estimated distribution of recharge. In order to develop a comprehensive digital model, one that would respond to hydraulic stress in nearly the same manner as the actual aquifer flow system, additional data are necessary to refine the preliminary model to a better approximation of the actual aquifer flow system.

Part of the additional data necessary for a comprehensive model would be altitudes of the potentiometric surface and altitudes of the base of the Arikaree aquifer, particularly in areas where data are not now available. The observed potentiometric surface is an important basis for the calibration procedure. The accuracy of the calibration depends on the accuracy of the observed potentiometric surface. The better the observed data approximate the actual conditions in the aquifer, the closer the simulation of the flow system will be to the actual flow system.

Hydraulic conductivity and saturated thickness are used in the model to calculate transmissivity, which is used in the flow equations. Therefore, once better control data are available for saturated thickness, a better definition of areal variation in transmissivity of the Arikaree aquifer is possible. The areal variation of hydraulic conductivity could be verified by making aquifer tests. The hydraulic conductivities determined from these aquifer tests would provide control to guide the adjustment of hydraulic conductivity during calibration of the comprehensive digital model.

In order for the comprehensive model to be verified and used under transient conditions, a value for specific yield is required at each node. Specific yield and storage coefficient are approximately equal for an unconfined aquifer such as the Arikaree aquifer. Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storage coefficient can be determined from aquifer tests, and specific yield can be determined from laboratory analyses of formation samples. These data combined with hydrologic judgment could be used to estimate specific yield values that may be adjusted during the verification process.

The distribution of recharge from precipitation to the Arikaree aquifer used in the preliminary model was estimated mostly from a conceptual model of the hydrologic system. Data from recording rain gages at selected sites could be used to define the distribution of precipitation in the basin. These additional data probably would refine the value for recharge from precipitation to the aquifer used in the comprehensive model.

Creeks flowing into the basin and within the basin probably provide recharge to the Arikaree aquifer. The quantity and timing of streamflow should be determined for the creeks that lose their flow after crossing into the basin from the mountains along the southern boundary. The seasonal variability of flow and the gains and losses of flow should be measured for the creeks south of the Sweetwater River that flow perennially in only part of their reaches and apparently lose their flow to the Arikaree aquifer before reaching the Sweetwater River. From these data, more reliable estimates of recharge to the aquifer could be made for the comprehensive model than were estimated for the preliminary model.

Because the Sweetwater River is gaining water from the Arikaree aquifer, better definition of the head in the river and the leakance is necessary for the comprehensive model to realistically simulate the stream-aquifer relationship. Additional gain and loss studies should be made on the Sweetwater River, and the gaging stations near Sweetwater

Station and near Alcova should be operated full time so that the baseflow period can be determined. Approximations of the base flow (discharge from the aquifer) could then be determined for periods when evapotranspiration is minimal and could be neglected.

Before the comprehensive model can be used to predict how the flow system will respond to the stresses from long-term development, it must be verified. Verification of the model will determine the accuracy with which the model is simulating the actual flow system. Thus, other than additional data, the feasibility of developing the comprehensive digital model ultimately depends on the Arikaree aquifer being stressed and on the measurement of the response of the aquifer to this stress.

SUMMARY AND CONCLUSIONS

Potentially large supplies of ground water are available in the Sweetwater River basin from the upper part of the White River, the Arikaree, and the Ogallala Formations. These formations are assumed to act as one hydrologic unit referred to in this report as the Arikaree aquifer.

The unconfined flow system in the Arikaree aquifer and its relation to surface water, most importantly the Sweetwater River, is simulated by a digital model. The steady-state hydraulic heads calculated by the model were within 50 feet of the observed heads in about 98 percent of the model nodes. The calculated steady-state leakage from the Arikaree aquifer to the Sweetwater River in the western area was within about 12 percent of the leakage estimated from gain and loss studies. Observed data are not available to estimate leakage to the river from the northeastern and southeastern areas. Because the hydraulic heads and leakage from the aquifer calculated by the model are within the accuracy of the field data, the model is considered to be calibrated for steady-state conditions. The accuracy with which the calibrated model simulates the actual aquifer flow system is not known.

This digital model is considered preliminary because several parameters used in the model were based on a small amount of poorly distributed data and because the model was based on a conceptual model of the Arikaree aquifer and on an estimated distribution of recharge. Because of the lack of long-term or seasonal streamflow records at the two gaging stations in the area, leakage from the aquifer to the Sweetwater River was determined only for November 1975, when the stream gained about 17 ft^3/s. The potentiometric surface in November 1975 was assumed to be represented by the surface prepared from altitudes of water levels measured in 1964 and 1965. Assumed values for the altitudes of water levels and the base of the Arikaree aquifer were used in areas where measured values were not available. Mean annual precipitation was estimated to be 8.5 inches for the basin. Recharge from precipitation was assumed to average about 2 percent of the mean annual precipitation. Along the southern boundary, additional recharge was modeled to simulate greater precipitation near the mountains and surface-water recharge from creeks flowing off the mountains.

The calibration of this preliminary digital model was based on the observed potentiometric surface and the observed leakage from the Arikaree aquifer to the Sweetwater River. The calibrated model simulates the observed flow system in the Arikaree aquifer to an acceptable degree of accuracy considering the quality, quantity, and distribution of the available data and illustrates that the Arikaree aquifer could be modeled satisfactorily.

It would be feasible to develop a comprehensive digital model that would respond to hydraulic stress in nearly the same manner as the actual aquifer flow system with additional data for aquifer characteristics, recharge to the aquifer, and stream-aquifer relationships. However, the feasibility of the comprehensive digital model being verified and used as a predictive tool depends ultimately on the Arikaree aquifer being stressed by discharging wells and on the measurement of the response of the aquifer to that stress. The accuracy with which the model simulates the actual flow system will be determined by the adequacy of the verification.

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