HYDROGEOLOGY AND SIMULATION OF WATER FLOW IN THE KOOTENAI AQUIFER OF THE JUDITH BASIN, CENTRAL MONTANA

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4146

Helena, Montana
September 1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

The following factors can be used to convert inch-pound units in this report to the International System of Units (SI):

Multiply inch-pound unit	By	To obtain SI unit
acre	4047	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	square meter per day
gallon per day (gal/d)	3.785	liter per day
gallon per minute (gal/min)	0.06309	liter per second
inch	25.40	millimeter
mile	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Fahrenheit (°F) or degrees Celsius (°C) by the following equations:

$$°F = 9/5\ (°C) + 32$$
$$°C = 5/9\ (°F - 32)$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

HYDROGEOLOGY AND SIMULATION OF WATER FLOW IN THE KOOTENAI

AQUIFER OF THE JUDITH BASIN, CENTRAL MONTANA

by

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ABSTRACT

The hydrogeology of five Jurassic and Cretaceous geologic formations in the Judith basin of central Montana was investigated to improve the understanding of water flow in the Kootenai aquifer. A three-dimensional digital model of flow in the aquifer was constructed from existing data. A steady-state model was calibrated and evaluated using a parameter-estimation procedure.

The geologic units considered in this study are, in ascending order, the Upper Jurassic Swift Formation, the Upper Jurassic Morrison Formation, the Lower Cretaceous Kootenai Formation, and the Lower and Upper Cretaceous Colorado Shale combined with the Upper Cretaceous Telegraph Creek Formation. The Swift, the lower two-thirds of the Kootenai, and several sandstone beds in the Colorado are confined aquifers in this area, whereas the intervening Morrison and upper one-third of the Kootenai are confining layers.

Potentiometric maps of the three aquifers all show recharge from precipitation in the mountains bordering the basin and discharge as underflow along the northern basin boundary. Anomalies in this pattern may be due to subsurface faulting and fracturing.

The major identifiable sources of recharge to the Kootenai aquifer are infiltration of precipitation and upward leakage of water from the Swift aquifer. The major sources of discharge are upward leakage of water into the Colorado Shale, outflow along the northern basin boundary, and withdrawal of water from wells.

Values of transmissivity for the Kootenai aquifer obtained from the calibrated model range from 137 to 364 feet squared per day. Recharge in the form of precipitation on the outcrop is about 2 percent of total precipitation or 5.44 cubic feet per second. The other component of net recharge is 32.48 cubic feet per second of vertical leakage from the Swift aquifer. The cumulative rate of discharge from all known wells penetrating the aquifer is about 0.84 cubic foot per second, or 2.2 percent of total discharge from the aquifer. Other components of net discharge are 1.83 cubic feet per second of underflow and 35.25 cubic feet per second of vertical leakage to the Colorado aquifer. Estimates of vertical hydraulic conductivity are 2.15×10^{-2} foot per day for the lower confining layer, and 3.16×10^{-3} and 1.33×10^{-4} foot per day for the upper confining layer.

The difference between values of computed and observed hydraulic heads is less than 20 feet in 28 percent of the modeled area; 20 to 50 feet in 30 percent; and 50 to 100 feet in 34 percent. All but one node in the model was calibrated to within 200 feet of the observed water level.

INTRODUCTION

The increasing demand for water resulting from continuing development of energy resources, power generation, industry, irrigation, and domestic and municipal water supplies in the northern Great Plains area of Montana, Wyoming, North Dakota, and South Dakota probably will require that additional ground-water supplies be used in the future. Consequently, in 1978 the U.S. Geological Survey began a 4-year study of aquifers of Mesozoic and Cenozoic age to define and quantify the hydrologic system, to determine the availability and chemical quality of ground water, and to describe the complexities within the hydrologic system on a regional scale. In conjunction with the regional study, selected aquifers or areas of interest in the individual States were studied in greater detail. Common to all these analyses was the use of digital modeling techniques to evaluate the aquifers.

Purpose and scope

The Judith basin in central Montana is an area where the need for additional water supplies is likely to occur in the future as a result of potential coal development, increased irrigation, and population growth. The purpose of this report is (1) to describe the flow system within the Kootenai Formation, which is the principal aquifer, and (2) to describe the interaction between the Kootenai and overlying and underlying Mesozoic aquifers.

Data gathered from many sources were synthesized into a conceptual model of the Judith basin. Information on basin boundaries was obtained from geologic maps by Vine (1956), Gardner (1959), Zimmerman (1966a), and Feltis (1973, 1977). Geologic data obtained from Feltis (1973, 1977), Zimmerman (1966b), Feltis and others (1981), and Levings and Dodge (1981) provided the basis for the final interpretation of the subsurface structural configuration of the Kootenai Formation. Historic water-level data supplemented by data from a 1980 well inventory were used to construct steady-state potentiometric-surface maps of the pertinent aquifers. This information is currently retrievable from the U.S. Geological Survey's Ground-Water Site Inventory (GWSI) data base. Other miscellaneous sources of useful data are discussed in appropriate places in the text.

Finally, the conceptual model was tested by construction of a three-dimensional finite-difference digital flow model (Trescott, 1975) aided by the use of a two-dimensional finite-difference parameter-estimation program by S. P. Larson and J. V. Tracy (U.S. Geological Survey, written commun., 1979). Refinements were made during the calibration process until a satisfactory match was achieved between observed data and simulated results.

Geographic setting

The Judith basin of central Montana lies approximately between 46°40' to 47°30' north latitude and 109°15' to 110°40' west longitude (fig. 1). It is a structural and topographic basin of more than 3,500 mi^2 that is bounded by the Big Snowy Mountains on the southeast, the Little Belt Mountains on the southwest, the Highwood Mountains on the northwest, and the Judith and North Moccasin Moun-

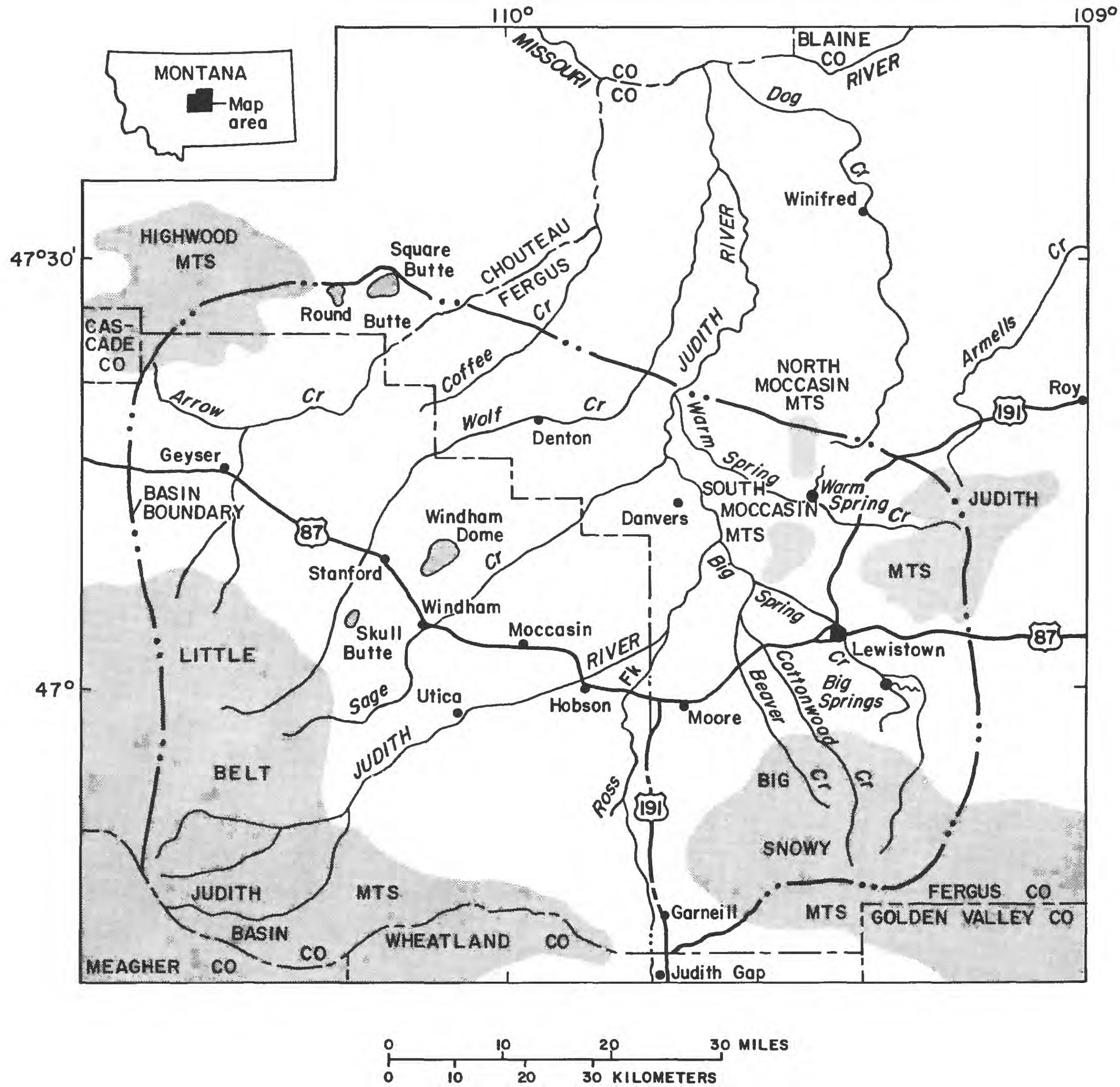


Figure 1.--Location of study area.

tains on the east. The arbitrary northern boundary coincides roughly with a line drawn from Square Butte southeast to the North Moccasin Mountains.

The topography of the study area consists of foothills grading into gently sloping plains and exhibits a total relief of 2,000 feet. The plains are topped with ancient stream terrace gravels and are frequently dissected by steep-sided stream valleys. In the northern Judith basin, Arrow Creek and its tributaries have eroded so deeply into the landscape that this area has characteristics typically associated with badlands topography. The foothills exhibit moderate relief due to differential erosion of the inclined strata. Prominent topographic features in the Judith basin include Round Butte and Square Butte east of the Highwood Mountains, Skull Butte south of Stanford, and North Moccasin and South Moccasin Mountains north of Lewistown.

Runoff from the Judith basin and surrounding highlands eventually flows into the Judith River or Arrow Creek and thence into the Missouri River north of the study area. Arrow Creek receives runoff intermittently from the Highwood Mountains and the Little Belt Mountains. The Judith River receives runoff from the Judith, Big Snowy, Little Belt, North Moccasin, and South Moccasin Mountains. Two tributaries of the Judith River, Big Spring Creek and Warm Spring Creek, receive water from two first-magnitude springs (fig. 1). The discharge of Big Springs varies from about 110 to 130 ft^3/s and the discharge of Warm Spring varies from about 130 to 150 ft^3/s.

The Judith basin is characterized by a continental climate that is modified somewhat by mountain-induced wind patterns. The average annual precipitation ranges from 13.7 inches in the basin near Moccasin, Mont., to about 40 inches in the uppermost reaches of streams in the Big Snowy and Little Belt Mountains. Approximately one-half of the annual precipitation falls during the 14-week frost-free growing season, which extends on the average from early June through mid-September.

Temperatures in the Judith basin are marked by extremes. The highest temperature on record is 105°F for Lewistown. The lowest temperature on record is -48°F near Moccasin. Summer temperatures rise above 90°F for about 12 days in an average year. Temperatures fall to 0°F or below for an average of 27 days during the winter months. However, severe cold spells rarely last more than a few days before being moderated by chinook winds from the west.

Previous investigations

Comprehensive geologic reports describe the structure and stratigraphy of the North Moccasin Mountains (Blixt, 1933), South Moccasin Mountains (Miller, 1959), and Big Snowy Mountains (Reeves, 1931). Witkind (1971) published a geologic map of the Barker quadrangle in the Little Belt Mountains. In conjunction with recent RARE II studies, a reconnaissance geologic map by Lindsey (1980) and aeromagnetic and Bouguer gravity maps by Long (1981a,b) have recently been released for the proposed Big Snowy Wilderness Area in the Big Snowy Mountains.

The most comprehensive geologic report of nearly all but the eastern part of Judith basin resulted from the study by Vine (1956). Gardner (1959) published a geologic map of the southeastern part of the basin and the northern flank of the Big Snowy Mountains. Calvert (1909) details the structural features evident along the flanks of the Big Snowy, Judith, and South Moccasin Mountains, and along the Little Belt Mountains southeast of Utica. Reeves (1929) discusses the occurrences of thrust faulting in the northwestern part of the study area adjacent to the Highwood Mountains. The remaining unmapped segments of the Judith basin study area were mapped by Zimmerman (1966a) and Feltis (1973, 1977) in conjunction with their water-resources studies. Structure-contour maps by Feltis (1980b,c) show the configuration of the top of the Madison Group in the Judith basin north of 47° north latitude.

Perry (1932) first described the ground-water resources of the study area. Detailed accounts of the water resources were given by Zimmerman (1966a,b) for the southern and western parts, by Feltis (1973) for the eastern part, and by Feltis (1977) for the northern part of Judith basin. Other information released for the area includes a hydrogeologic map report by Feltis (1980a) that emphasizes the Madison aquifer and a report by Levings and Dodge (1981) that tabulates the hydrogeologic data currently available for the area.

Well and spring numbering system

In this report, locations are numbered according to geographic position within the rectangular grid system used by the U.S. Bureau of Land Management (fig. 2). The location number consists of as many as 14 characters. The first three characters specify the township and its position north (N) of the Montana Base Line. The next three characters specify the range and its position east (E) of the Montana Principal Meridian. The next two characters are the section number. The next one to four characters designate the quarter section (160-acre tract), quarter-quarter section (40-acre tract), quarter-quarter-quarter section (10-acre tract), and quarter-quarter-quarter-quarter section (2 1/2-acre tract), respectively, in which the well or spring is located. The subdivisions of the section are designated A, B, C, and D in a counterclockwise direction, beginning in the northeast quadrant. The last two characters form a sequence number: 01 for the first well or spring inventoried in a tract, 02 for the second, and so forth. For example, as shown in figure 2, well 15N14E16DCDD01 is the first well inventoried in the SE1/4 SE1/4 SW1/4 SE1/4 sec. 16, T. 15 N., R. 14 E.

Acknowledgments

Appreciation is expressed to the landowners and public officials who permitted access to their land for the inventory and sampling of their wells. Thanks also are extended to the personnel of the Montana Department of Natural Resources and Conservation and the Montana Bureau of Mines and Geology who supplied drillers' logs and other information pertinent to the report. The author also wishes to acknowledge O. C. Thatcher and George Singley, two local well drillers, for the benefit of their observations on the water-bearing formations in the Judith basin.

GEOLOGY

Stratigraphy

The sedimentary strata exposed in the Judith basin and adjacent mountains range in age from Cambrian to Holocene. The stratigraphy of the complete sedimen-

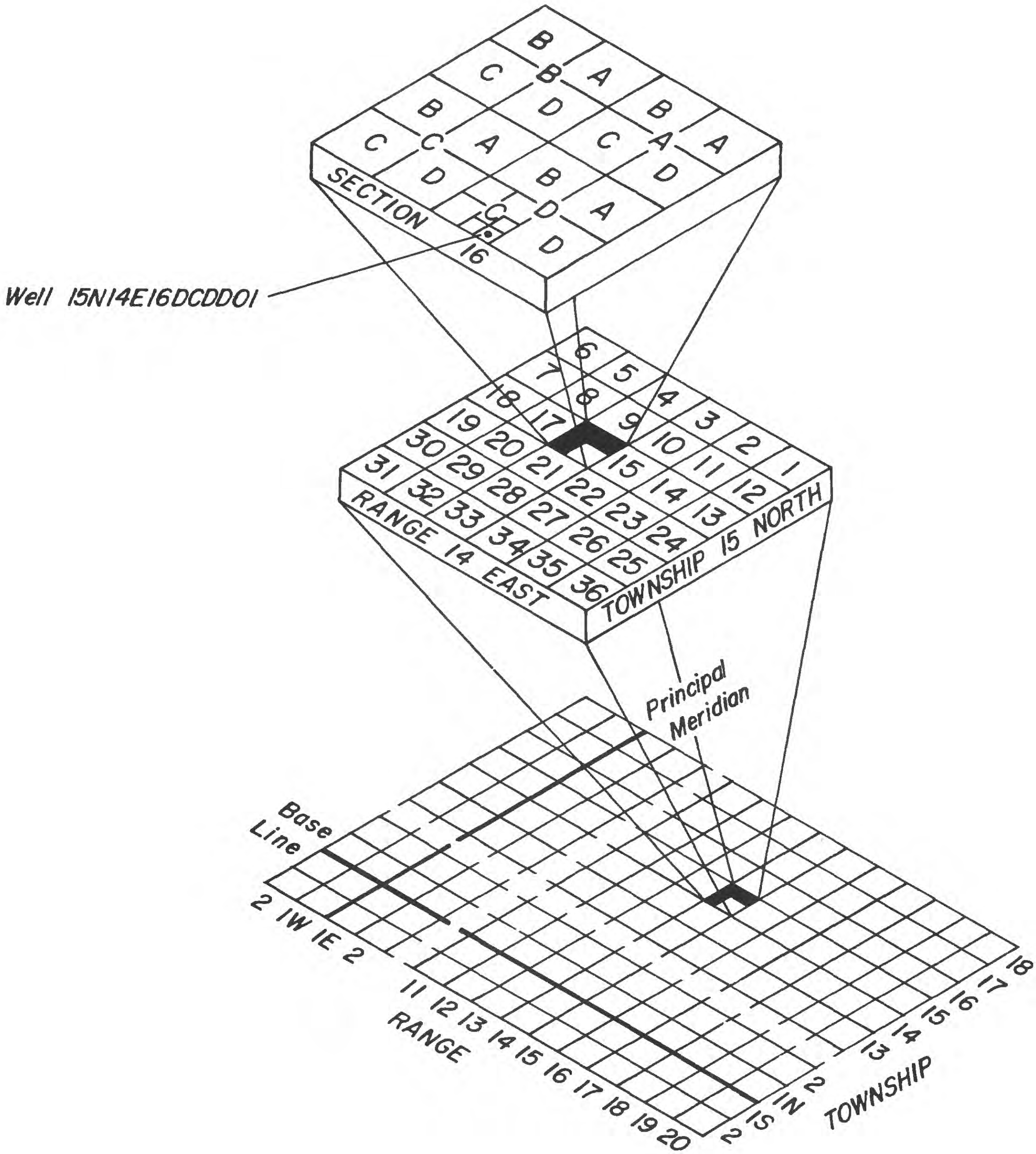


Figure 2.--Well and spring numbering system.

tary column has been described by Vine (1956) and Gardner (1959). The formations pertinent to this modeling study are, in ascending order: the Swift and Morrison Formations of Jurassic age and the Kootenai Formation, Colorado Shale, and Telegraph Creek Formation of Cretaceous age (fig. 3). A description of the lithologic characteristics of these units follows.

The Upper Jurassic Swift Formation, the topmost formation of the Ellis Group, is a medium- to coarse-grained brown to orange glauconitic marine sandstone with interbeds of shale. The Swift Formation is more extensive than the underlying formations of the Ellis Group. In places, it rests unconformably on Paleozoic rocks of the Amsden, Big Snowy, and Madison Groups. The Swift Formation ranges in thickness from 45 to 280 feet.

The Upper Jurassic Morrison Formation conformably overlies the Swift. It consists mainly of 50 to 300 feet of nonmarine variegated shale and siltstone, thin nodular limestone, white and brown lenticular sandstone, and black shale. A coal bed with an aggregate thickness of 3 to 6 feet is an easily identifiable marker commonly at or within a few feet of the erosional surface at the top of the formation.

The Lower Cretaceous Kootenai Formation unconformably overlies the Morrison. Thickness of the Kootenai in measured stratigraphic sections reported in the literature ranges from 316 to 580 feet. The average thickness in the subsurface based on numerous geologic well reports from oil test holes and drillers' logs is about 550 feet.

The basal part of the Kootenai Formation consists of a thick crossbedded fine- to coarse-grained "salt and pepper" fluvial sandstone and chert-pebble conglomerate with a few shale breaks. It forms a prominent ledge in outcrop over long distances. The Third Cat Creek sandstone[1] is typically 20 to 120 feet thick, except locally where it may thin and disappear. Feltis (1982) used geophysical logs to identify a definitive northeast-trending zone about 12 miles wide along the southeastern edge of the Highwood Mountains, where this unit is less than 50 feet thick in the subsurface. Equivalent units in adjacent areas are the Sunburst Sandstone Member of the Kootenai Formation in northwestern Montana, the Pryor Conglomerate Member of the Kootenai Formation of south-central Montana, and the Lakota Sandstone of eastern Montana.

The middle part of the formation, the Second Cat Creek sandstone, contains fine- to coarse-grained brown and gray sandstone lenses interspersed with siltstones and shales similar to those in the upper part. These lenses range in thickness from 0.5 to about 20 feet. The nonuniformity in thickness and the lenticular nature of the sandstone beds make correlation of the sequence of beds over a large area unfeasible. However variable the sequence itself may be, it is generally present.

---

[1]The First, Second, and Third Cat Creek sandstones are beds in the basal Colorado Shale and Kootenai Formation. This terminology is used to distinguish between sandstone sections penetrated during oil exploration in the Cat Creek oil field of Petroleum and Garfield Counties about 40 miles east of the study area.

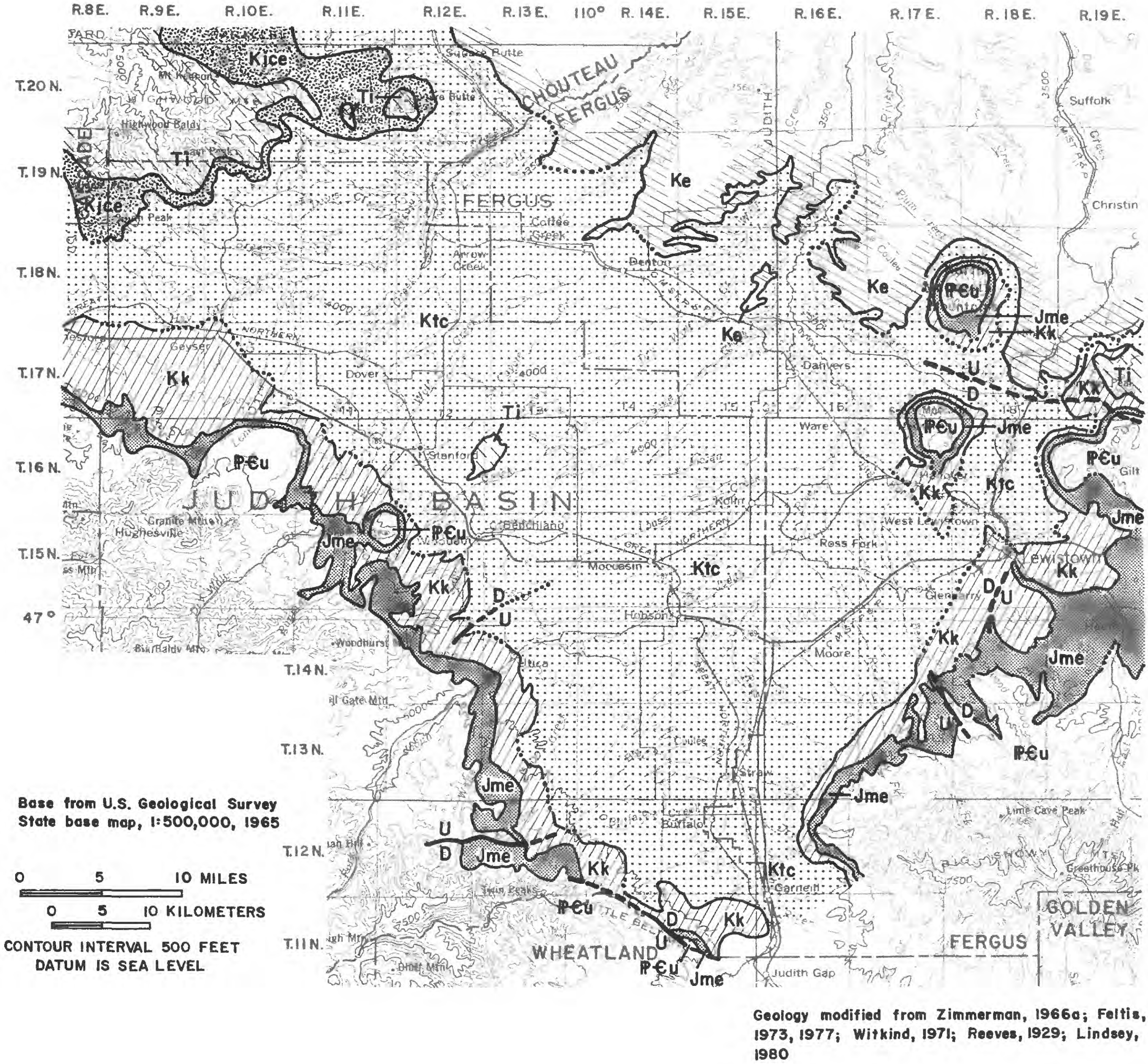


Figure 3.--Generalized geology.

The upper third of the Kootenai consists primarily of red, purple, lavender, brown, and gray shale and siltstone. The upper contact is easily distinguishable by the conspicuous color change from the black and gray marine shales and yellow and brown fine-grained sandstones of the Colorado Shale to the continental "red-beds" of the Kootenai.

The Lower and Upper Cretaceous Colorado Shale crops out in large areas of the Judith basin (fig. 3). It consists of 1,500 to 2,000 feet of primarily fissile,

CORRELATION OF MAP UNITS

Ti			TERTIARY
Ke	Kjce	Upper Cretaceous	CRETACEOUS
Ktc			
Kk		Lower Cretaceous	
Jme		Upper and Middle Jurassic	JURASSIC
P€u			PENNSYLVANIAN TO CAMBRIAN

DESCRIPTION OF MAP UNITS

Ti	Tertiary igneous rocks. Intruded Tertiary dikes and sills not identified
Kjce	Judith River Formation, Claggett Shale, and Eagle Sandstone, undivided
Ke	Eagle Sandstone
Ktc	Telegraph Creek Formation and Colorado Shale, undivided
Kk	Kootenai Formation
Jme	Morrison Formation and Ellis Group (includes Swift Formation in upper part), undivided
P€u	Pennsylvanian to Cambrian rocks, undivided
———·····	CONTACT--Dotted where concealed
U/D ———–– ···	FAULT--Dashed where approximately located; dotted where inferred. U, upthrown side; D, downthrown side

easily weathered, dark-gray to black marine shale interspersed with sandstone and bentonite beds. Near the base of this unit is a very fine grained sandstone with thin yellow and brown laminae called the First Cat Creek sandstone. Several isolated very fine grained sandstone beds interbedded with shale occur elsewhere in the lower 850 feet of the Colorado Shale.

The Telegraph Creek Formation consists of the Upper Cretaceous transitional beds between the underlying Colorado Shale and overlying Eagle Sandstone. It consists of about 160 feet of yellow-weathering dark-gray to dark-brown shale and sandy shale. This unit is included with the Colorado Shale (fig. 3) because of the difficulty of identifying its basal contact.

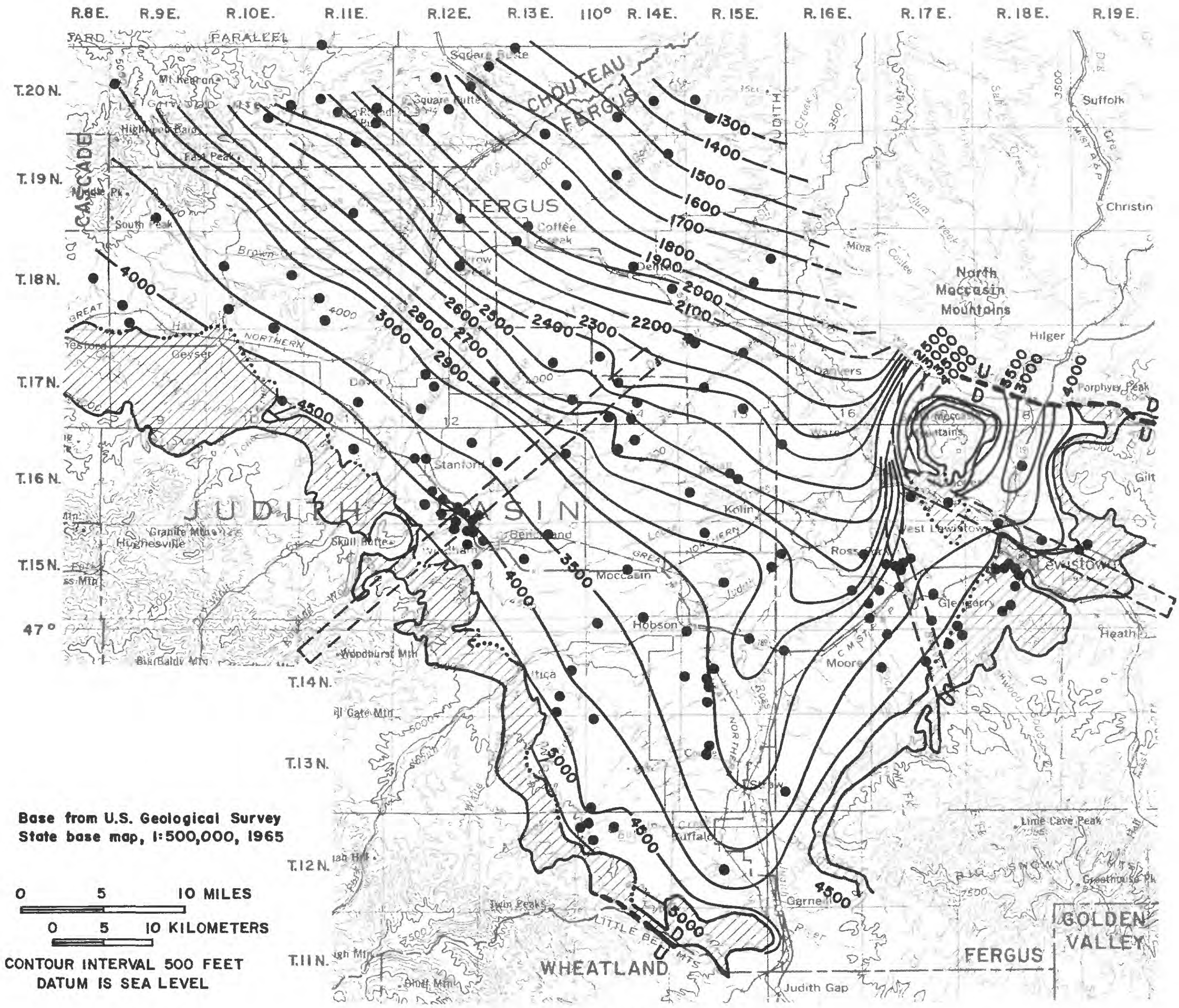
Pleistocene terrace deposits from 0 to 20 feet thick cover large areas of the basin. Thus, most exposures of the Colorado Shale are restricted to stream valleys and much of the contact between the Kootenai and Colorado Formations is concealed. Terrace deposits have been omitted from the geologic map (fig. 3) so they do not obscure the underlying geology. Holocene alluvium in stream valleys has also been omitted.

Structure

The structural Judith basin is enclosed by the Little Belt, Big Snowy, Judith, and North Moccasin Mountains. Because the Highwood Mountains have produced little structural arching, the general strike of the sedimentary strata is northwest, which parallels the regional structural trend of central Montana. The dip is northeast toward the open end of the basin. The altitude and configuration of the top of the Kootenai Formation are shown in figure 4. The depth to the top of the Kootenai is the altitude of land surface minus the altitude of the top of the formation.

Faults along the margins of the Judith basin commonly trend northwest or northeast. Faults with possible basinward extensions that may have some bearing on the hydrogeologic boundaries of, or flow patterns in, the Kootenai Formation are shown on the geologic map (fig. 3). Three areas where the configuration of the top of the Kootenai indicates possible zones of weakness or faulting are shown in figure 4. The area near Lewistown is also supported by anomalously large concentrations of sulfate (Henderson, 1982) in water from three wells completed in the Third Cat Creek sandstone near the trace of Big Spring Creek northwest of Lewistown. The area along Beaver Creek in Tps. 14-15 N., R. 17 E., has more tenuous support. A Bouguer gravity anomaly (Long, 1981a) along the fault paralleling Beaver Creek in Tps. 13-14 N., Rs. 17-18 E. (fig. 3), indicates that displacement evident at the surface extends into the subsurface. A topographic scarp along the west side of Beaver Creek from the edge of the basin near the Big Snowy Mountains to Big Spring Creek is also an indication that the fault in the foothills extends into the basin (R. D. Feltis, U.S. Geological Survey, oral commun., 1980).

The fault along Warm Spring Creek in T. 17 N., Rs. 17-19 E. (fig. 3), emerges from the Judith Mountains south of Porphyry Peak. Seeps in valley-fill material appear along the fault trace. Warm Spring issues from a small dome cut by this fault in sec. 19, T. 17 N., R. 18 E. Nearby, adjacent outcrops of Third Cat Creek sandstone and Swift Formation are indicative of about 200 feet of displacement. The primary source of water supplied to Warm Spring is considered to be cavernous limestone of the Mississippian Madison Group (Feltis, 1973).



EXPLANATION

OUTCROP OF KOOTENAI FORMATION

CONTACT--Dotted where concealed by alluvium or terrace deposits

—2000— STRUCTURE CONTOUR--Shows altitude of the top of the Kootenai Formation. Dashed where approximately located. Contour intervals 100 and 500 feet. Datum is sea level

U/D FAULT--Dashed where approximately located. U, upthrown side; D, downthrown side

POSTULATED ZONE OF WEAKNESS OR FAULTING

• DATA SITE

Figure 4.--Altitude and configuration of the top of the Kootenai Formation.

Reeves (1929) has mapped thrust faults southeast of the Highwood Mountains and igneous dikes around the mountain perimeter. Because he concludes that the thrust faults involve only the upper one-half of the Colorado Shale and younger rocks, they were omitted from the generalized geologic map. Numerous dikes radiating outward from the Highwood Mountains are exposed in T. 19 N., R. 9 E., and in the northwest quarter of T. 18 N., R. 9 E. These dikes (and sills) extend into the subsurface, as verified by the 60 feet of igneous rock penetrated 250 feet below land surface in a well drilled in sec. 10, T. 17 N., R. 8 E. Drillers' logs of wells in sec. 8, T. 17 N., R. 9 E., and in sec. 18, T. 17 N., R. 10 E., refer to layers of "rock" and "hard rock" at depth that may be igneous rocks or sedimentary rocks altered by the heat of intrusion. Other northeast-trending igneous dikes have also been mapped in the vicinity of Stanford and Windham in the southwest quarter of T. 17 N., R. 13 E., the northwest quarter of T. 15 N., R. 13 E., and the west half of T. 16 N., R. 14 E.

Several domes occur around the perimeter of the Judith basin. The northeast-trending zone of weakness or faulting (fig. 4) connects Skull Butte and Windham Dome in sec. 18, T. 16 N., R. 13 E., with anomalies in T. 17 N., Rs. 13 - 14 E., which may be the subsurface expression of buried domes. Smith (1965) postulates the existence of west-northwest-trending megashears and associated northeast-trending tensional fracture zones in central and western Montana. He concludes (p. 1408) that "The tensional stress field produced by lateral movement along these megashears would provide relatively easy access for magmatic materials into the upper levels of the crust along northeast-trending zones."

GROUND WATER

In the Judith basin, the Swift and Kootenai Formations and the Madison Group are the most productive and widespread aquifers from which to obtain a reliable water supply. For the most part, water in the Swift and Kootenai aquifers and in the individual sandstone lenses of the Colorado Shale is under artesian pressure, except near their respective outcrops. Water under water-table conditions is also obtainable from the discontinuous alluvial and terrace deposits throughout the basin, although these supplies are prone to contamination. In addition, the productivity of the terrace deposits is hampered by the limited thickness of the unit coupled with a limited source of recharge.

Water in the Quaternary deposits will not be given further consideration in this report in keeping with the scope of the project. Despite its availability, water in the Paleozoic Madison Group falls under the same restriction and is treated in separate reports by Downey (1982), Miller (1976), and MacCary and others (1981).

Use and occurrence

Water for domestic and stock uses is obtained from some wells completed in the Swift Formation near its outcrop area. The water commonly contains dissolved iron in concentrations exceeding the limit of 0.3 mg/L (milligrams per liter) recommended by the U.S. Environmental Protection Agency (1979) for public water supplies. The large concentration is due in part to the decomposition of the iron-bearing silicate mineral glauconite in the sediments. Few wells in the basin are completed in the Swift in areas where a reliable supply of water for domestic and stock use can be extracted from the overlying Kootenai Formation at a lesser cost.

The potentiometric surface of water in the Swift shown in figure 5 is based on 29 water-level measurements, most of which are from wells located near the perimeter of the basin. Therefore, this map is most reliable near the outcrop area.

The Kootenai Formation is the most widely used aquifer in the Judith basin. It supplies water for domestic and stock needs from both the Second and the Third Cat Creek sandstones. A composite potentiometric-surface map of water from these sandstone beds is shown in figure 6. Note that areas where water-level measurements are scarce are limited to the northern edge of the basin extending approximately from the Highwood mountain front on the west to the North Moccasin mountain front on the east.

An attempt to separate water levels in the Second and Third Cat Creek sandstones into two distinct potentiometric surfaces proved fruitless for several reasons. First, because wells are rarely drilled deeper than the first water-yielding sandstone, drillers' logs commonly describe only part of the section of the Kootenai. Second, the formation as a whole and the basal Third Cat Creek sandstone within it range greatly in thickness over the basin so that knowledge of depth to the formation top is not sufficient to separate aquifers. Finally, no other unique horizon or continuous sequence of beds distinguishes one layer from the other, except for the basal sandstone, which is identified by the underlying erosional unconformity, and the coal bed at the top of the Morrison Formation. Thus, where the depth to the base of the Kootenai is unknown, it is difficult to assign an isolated water-bearing sandstone to either layer with any confidence.

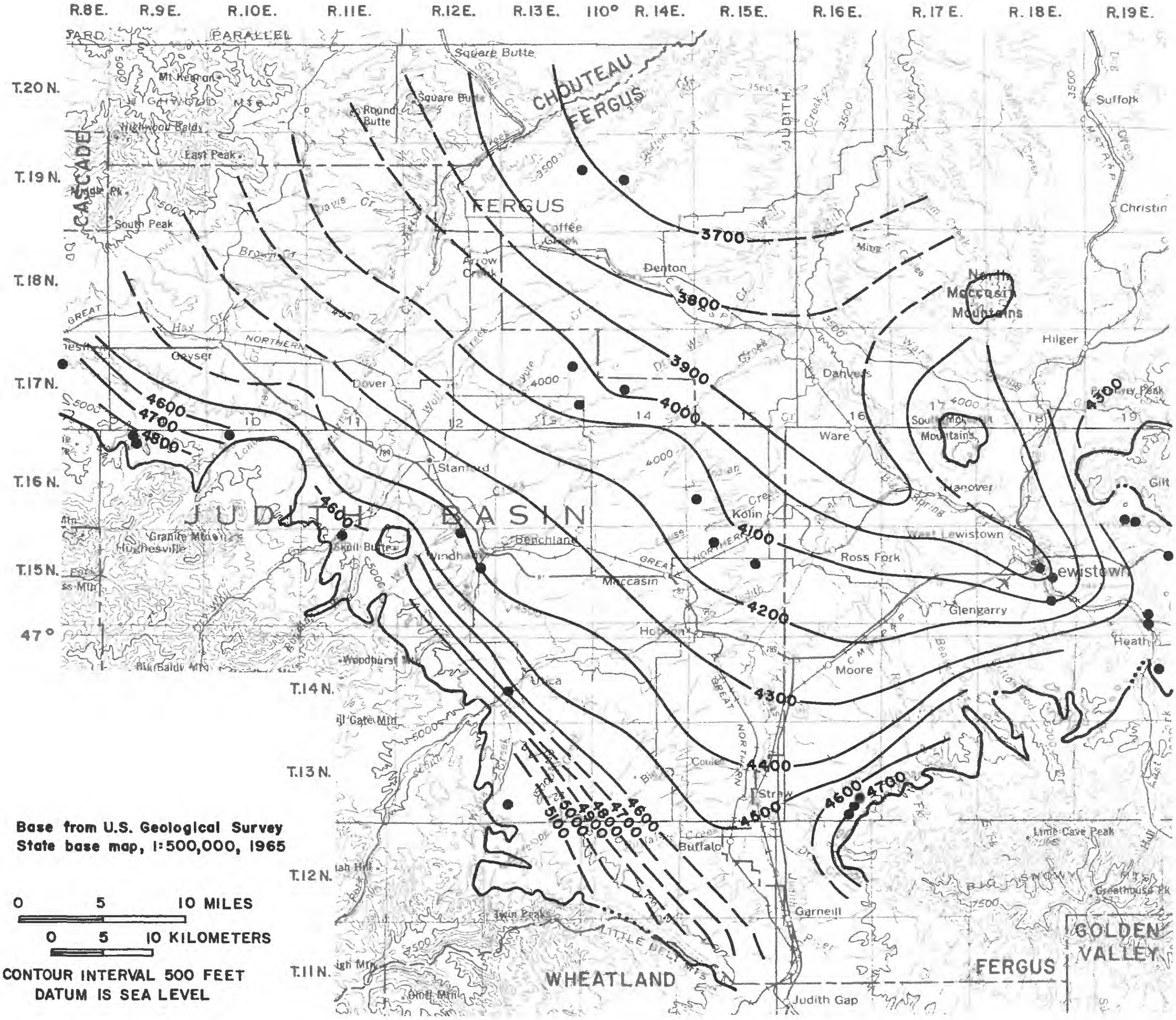
In the basin, water can be obtained from sandstone beds in the lower part of the Colorado Shale. However, its availability, quality, and quantity are more variable than other aquifers discussed. Where the water is not suitable for domestic consumption, it is used primarily for livestock watering.

A composite potentiometric-surface map of water in the sandstone lenses of the Colorado Shale is shown in figure 7. As the thickness of the Colorado Shale increases, so do the number of sandstone beds that are represented by the composite surface. The map is most accurate near the margins of the basin because that is where it is representative of the fewest number of sandstone lenses.

Potentiometric-surface maps can be used to show hydraulic gradients. They are also useful for determining areas of ground-water inflow and outflow. For instance, the general flow patterns in figures 5, 6, and 7 result from recharge to the aquifers in the Little Belt, Big Snowy, North Moccasin, and Judith Mountains. The Swift and Kootenai aquifers may benefit from a small amount of recharge from the South Moccasin Mountains as well. After vertical leakage, the major outflow is underflow to the north along the northern boundary of the basin. Another source of outflow is discharge to wells. The elongate depression near Lewistown (fig. 6) is undoubtedly due in part to withdrawal of water from wells, although its coincidence with the postulated zone of weakness (fig. 4) roughly in line with Big Spring Creek may also have some bearing on the existence of this feature.

Aquifer properties

Estimates of the values of certain aquifer properties are needed to prepare a ground-water model. For the steady-state model described in this report the transmissivity of the Kootenai aquifer and the leakage coefficient of the confining layers above and below it were most important.



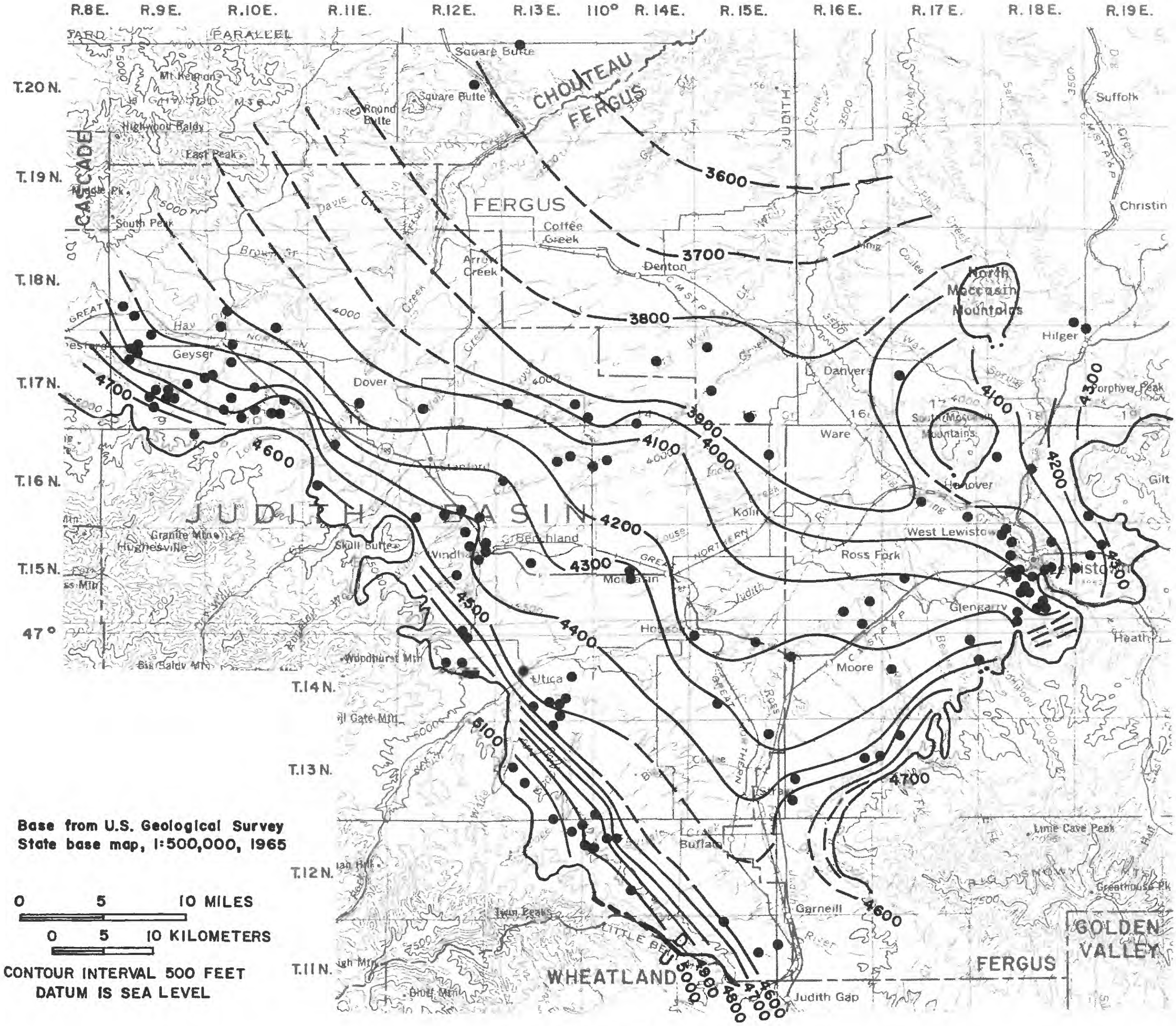
EXPLANATION

——4000— —GENERALIZED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells completed in the Swift aquifer, 1980. Dashed where approximately located. Contour interval 100 feet. Datum is sea level

● WELL

————..... CONTACT--Shows lower contact of Ellis Group (fig. 3), which in most places corresponds to base of Swift Formation of the Ellis Group. Dotted where concealed by alluvium or terrace deposits

Figure 5.--Potentiometric surface of water in the Swift aquifer.



EXPLANATION

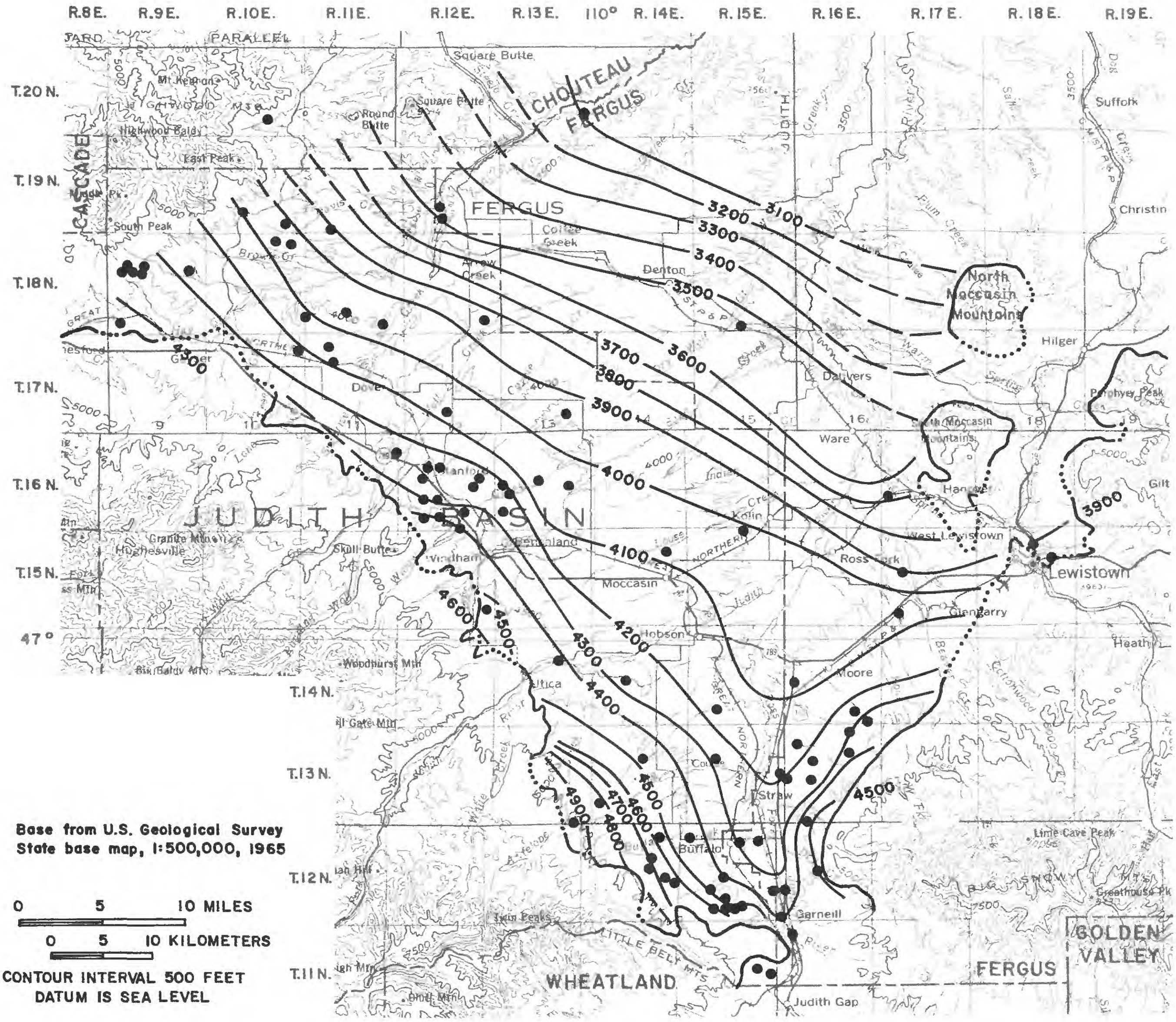
——4000—— — GENERALIZED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells completed in the Kootenai aquifer, 1980. Dashed where approximately located. Contour interval 100 feet. Datum is sea level

● WELL

————···· CONTACT--Shows lower contact of Kootenai Formation. Dotted where concealed by alluvium or terrace deposits

U/D — — FAULT--Dashed where approximately located. U, upthrown side; D, downthrown side

Figure 6.--Potentiometric surface of water in the Kootenai aquifer.



EXPLANATION

——3600—— — GENERALIZED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells completed in the Colorado Shale, 1980. Dashed where approximately located. Contour interval 100 feet. Datum is sea level

● WELL

————···· CONTACT--Shows lower contact of Colorado Shale. Dotted where concealed by alluvium or terrace deposits

Figure 7.--Composite potentiometric surface of water in the Colorado Shale.

Values of transmissivity determined from aquifer tests of the Kootenai Formation are moderately small. All known published values of transmissivity derived from pump or flow tests in Kootenai wells in the Judith basin are given in table 1. In all but one test, the thickness and composition of the tested interval were unknown. These values represent at least the minima for the aquifer. The transmissivity of 100 ft^2/d for well 2 is representative of 233 feet of an uncased sandstone and shale sequence in the middle and lower part of the Kootenai. The uppermost 227 feet of the formation in this hole consists mostly of shale and is cased. The aquifer might extend as much as 100 feet deeper than the bottom of the hole.

Table 1.--*Transmissivity of the Kootenai Formation*

Well number	Location	Transmissivity (feet squared per day)	Published source
1	15N12E23BA02	23	Zimmerman, 1966a
2*	15N14E16DCDD01	100	Feltis, 1977
3	16N11E36BA01	249	Zimmerman, 1966a
4	16N12E35AC01	77	Zimmerman, 1966a
5	16N18E08CAA01	15	Feltis, 1973
6	17N10E16BB01	116	Zimmerman, 1966a
7	17N10E33AA02	184	Zimmerman, 1966a

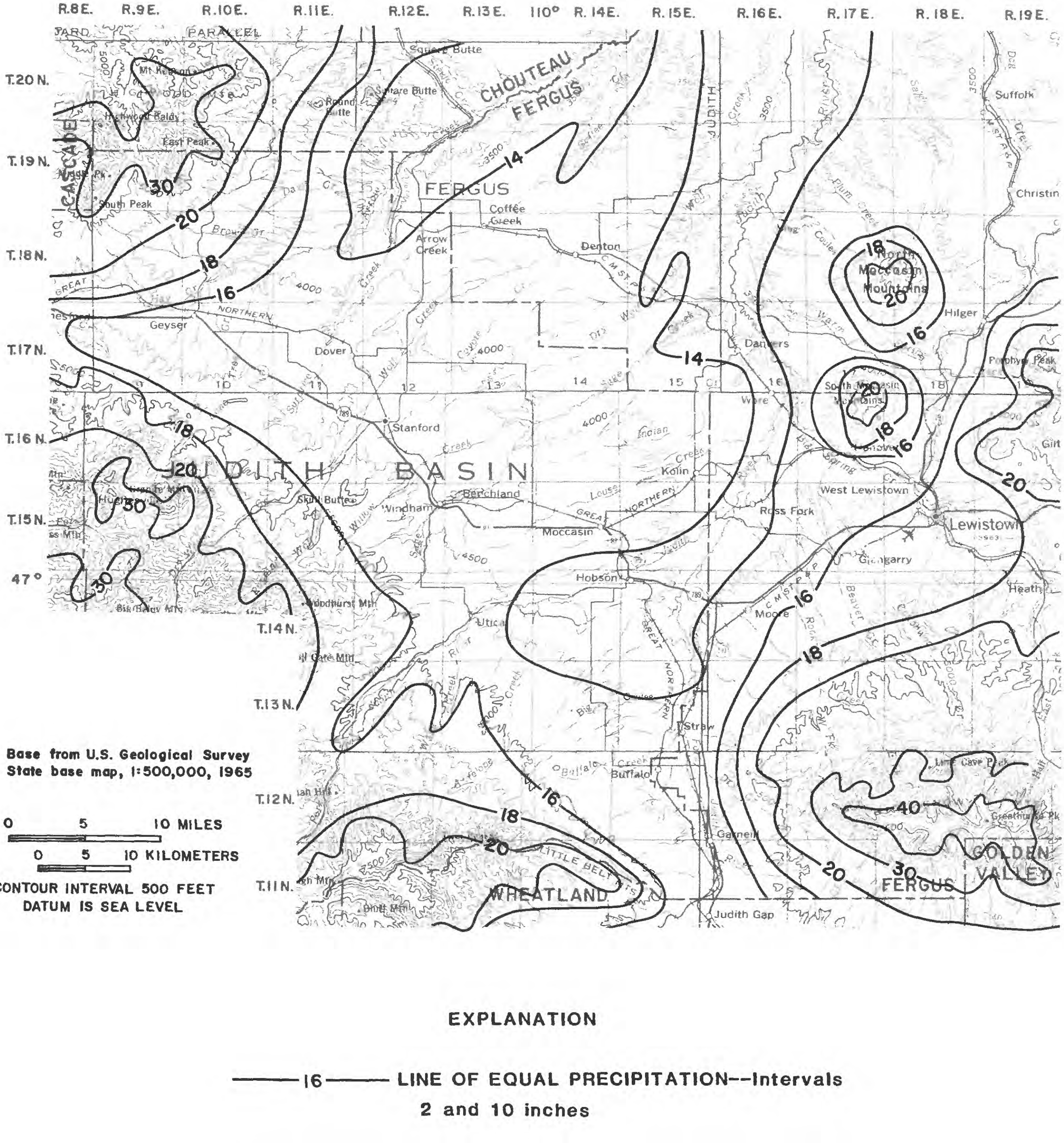
* Tested interval is 233 feet thick.

The specific-capacity information that is available for selected wells completed in the Kootenai (Levings and Dodge, 1981) is generally based on test-period durations of 1 hour or less. Many of these tests are representative of wells that only partly penetrate the aquifer. The specific capacities of a group of 30 wells in T. 15 N., R. 18 E., were converted to transmissivities by a method described by Meyer (1963). These equivalent transmissivities ranged from 25 to 1,650 ft^2/d with a median transmissivity of about 250 ft^2/d.

Determination of the leakage coefficient, K'/m, of a confining layer requires knowledge about the unit's vertical hydraulic conductivity and its thickness. No test data are available on the vertical hydraulic conductivities of the Morrison Formation, the upper shale member of the Kootenai Formation, or the Colorado Shale for the Judith basin. However, data on the thickness of the Morrison, and the combined thicknesses of the upper part of the Kootenai with the Colorado Shale, are available at many locations.

CONCEPTUAL FLOW MODEL

The major sources of recharge to the Kootenai aquifer include the direct infiltration of precipitation on the outcrop and the upward leakage of water from the Swift Formation. Figure 8 is an excerpt for the Judith basin of an unpublished U.S. Soil Conservation Service precipitation map compiled from data collected between 1953 and 1967. Between 1 and 3 percent of the precipitation that falls on



EXPLANATION

——16—— LINE OF EQUAL PRECIPITATION--Intervals 2 and 10 inches

Figure 8.--Average annual precipitation. Map from U.S. Soil Conservation Service.

the outcrop area is estimated to recharge the deeper ground-water system of the Kootenai. The rest either is consumed by evapotranspiration, flows overland to streams, or contributes to a local, shallow ground-water system discharging to springs on the outcrop.

The direction and quantity of vertical leakage to one aquifer from another depend not only on the hydrogeologic properties of the connecting confining layer, but also on the vertical hydraulic gradient between the aquifers (fig. 9). If the potentiometric-surface map of the Kootenai aquifer (fig. 6) were superimposed on the map of the Swift aquifer (fig. 5), it would be evident that a potential exists for water from the Swift to leak upward through the Morrison Formation and recharge the Kootenai aquifer. Similarly, by superimposing the composite potentiometric-surface map of the Colorado Shale (fig. 7) over the map of the Kootenai aquifer (fig. 6), one would see that a potential exists for water to discharge from the Kootenai aquifer by upward leakage into the sandstone beds of the Colorado Shale. Neither the vertical hydraulic conductivity of the overlying and underlying confining layers nor the volume of vertical flow to or from the Kootenai aquifer has heretofore been measured or estimated. Besides vertical leakage, other sources of discharge from the Kootenai aquifer in the Judith basin include minor withdrawals of water from wells and outflow along the arbitrary northern basin boundary.

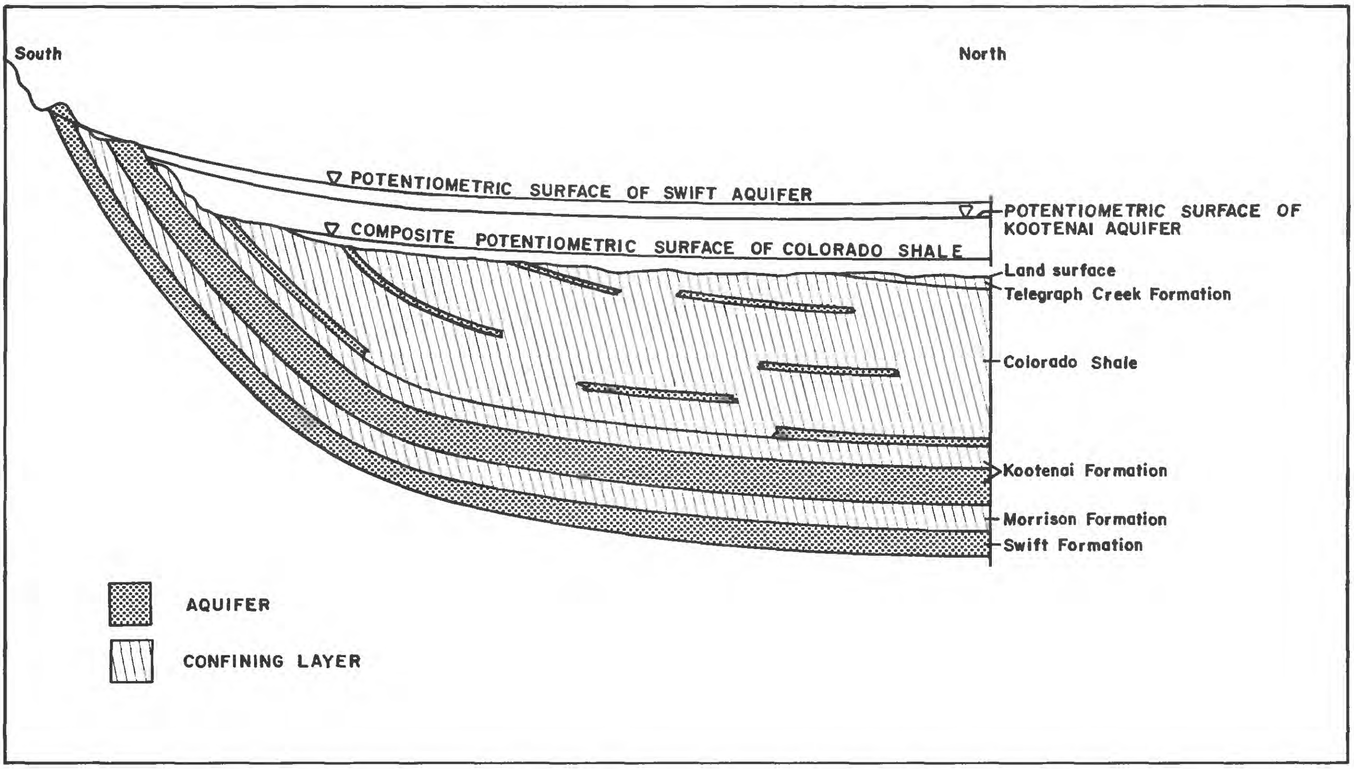


Figure 9.--Schematic section showing hydraulic gradients of the aquifers.

DIGITAL SIMULATION MODEL

The documentation and theoretical development of the three-dimensional finite-difference model that was used to simulate ground-water flow in the Judith basin are described by Trescott (1975) and Trescott and Larson (1976). The model is capable of computing the hydraulic head at any time or designated location in an aquifer if the hydraulic properties, boundaries, and stresses to the model area are known.

Assumptions

Some simplifying assumptions are always necessary in constructing a digital ground-water model of the real hydrologic system with all its complexities. Other assumptions stem from the theory behind the governing equations of ground-water flow on which the model is based and from the need to design a solution technique and program code with reasonable cost and data input criteria. The simplifying assumptions for this model include:

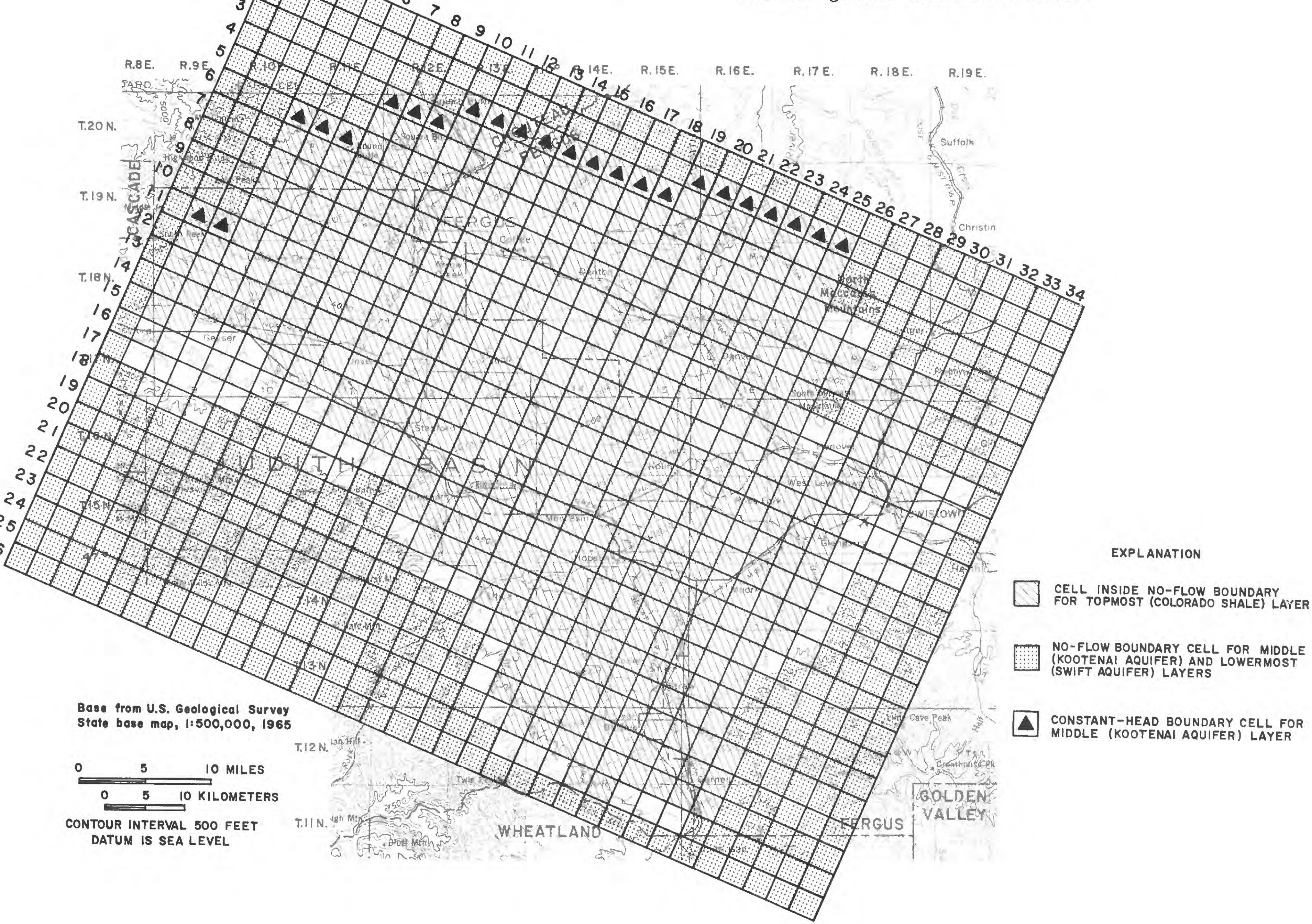
(1) Ground-water flow obeys Darcy's law.
(2) The Kootenai is an isotropic artesian aquifer.
(3) Recharge to the Kootenai is instantaneous and constant with time.
(4) Point discharge from wells occurs at a constant rate. [Because the effective radius of a cell (model unit) is larger than that of a pumped well, the computer drawdown is not an accurate measure of true drawdown from an individual pumped well].
(5) Water in the Swift aquifer and in the water-bearing sandstone beds of the Colorado Shale has a constant hydraulic head, so that only water levels in the Kootenai aquifer are explicitly modeled.
(6) Horizontal components of flow in the intervening confining layers and vertical components of flow in the aquifers are negligible.
(7) The potentiometric surface of water in the Kootenai aquifer is currently in a state of equilibrium.

Finite-difference grid

The ground-water model was constructed by superimposing a square grid over the study area and by orienting the grid so that the principal axes coincide roughly with the direction of flow and with the underlying regional structural grain in the area. The program solves for hydraulic head at all nodes, which are located by convention at the center of each cell, or square compartment within the grid. Nodes that lie within the study area boundary will be referred to as active nodes in this report. Hydraulic-head, hydraulic-stress, and aquifer-property values must be input at each active node within their respective data arrays.

This model consists of three layers each with 26 rows and 34 columns of nodes. With a node spacing of 2 miles throughout the area, the grid translates to a 52-by 68-mile nodal network (fig. 10). The layers represent the Swift and Kootenai aquifers, and the water-bearing sandstone beds in the Colorado Shale in ascending order.

Figure 10.--Finite-difference grid and boundary conditions for the ground-water flow model.



Boundary conditions

The limits of the modeled area were selected to coincide closely with the structural boundaries of the Kootenai Formation, except along the northern boundary. This boundary was arbitrarily modeled as impermeable, and placed beyond the area thought likely to be affected to any great extent by ground-water development in the basin.

The model has the capability of simulating three types of boundary conditions: no flow, constant flow, and constant head. No water enters or leaves the model along a no-flow boundary. Water enters or leaves the model at a specified constant rate along a constant-flow boundary. At a constant-head boundary, the water level is kept constant and the rate of discharge or recharge to the node is determined by the head gradient within the model.

Except for the northern edge, the lateral boundaries of the middle layer (Kootenai aquifer) of the model are of the no-flow type (fig. 10). Along the mountain fronts to the southwest and east, the boundary is representative of the outcrop of the Kootenai Formation where it has been truncated by erosion. At the northwestern edge, the boundary closely approximates a ground-water flow line for the Kootenai aquifer, which implies no transverse flow out of the basin for the current steady-state condition. The southern boundary is represented by a ground-water divide in the vicinity of Judith Gap. The boundary between rows 5 and 6, columns 28-30 (fig. 10) that coincides roughly with the fault paralleling Warm Spring Creek has been designated "no-flow" in accordance with the assumption that flow across the fault is negligible.

The constant-head boundary along the northern edge of the model (fig. 10) simulates underflow out of the Judith basin. The Swift layer is the lower boundary of the model and the Colorado layer is the upper boundary. All active nodes in these layers have constant heads based on the assumption that the horizontal components of flow within these aquifers and the vertical components of flow between aquifers are in a steady-state condition. They are treated in this way as their primary function was to aid in simulating vertical leakage into and out of the Kootenai layer. The top layer (fig. 10) conforms to the outline of the outermost edge of the Colorado Shale (fig. 3). Although the Swift is present over a larger area than the Kootenai, this bottom layer is simulated only as large as the Kootenai layer, so that a vertical-leakage connection is available to any node in the middle layer.

Hydrologic stresses

Precipitation

Recharge to the Kootenai aquifer from precipitation was simulated by selecting a value from the precipitation map (fig. 8) at any node whose cell overlaps the Kootenai outcrop and then decreasing it by an amount equal to the areal percentage of outcrop in the cell that is receiving recharge. Finally, these data were varied overall by a factor that represents the percentage of precipitation recharging the aquifer. Rahn and Gries (1973) have estimated recharge to be 3.5 percent of total precipitation for the Pahasapa (Madison) Limestone in a Black Hills watershed characterized by intermittent streamflow, and 30 percent for the Pahasapa in another Black Hills watershed with perennial streamflow. An estimate of recharge from precipitation at the small end of this range, less than 3.5 percent, seems probable for the Kootenai aquifer because its overall permeability is on the average at least an order of magnitude less than that of the limestone.

Well pumpage

The determination of withdrawals of water from wells was a multistep process. First, a list of all wells inventoried by the U.S. Geological Survey in the Judith basin deriving water from the Kootenai aquifer was compiled according to water use from a data report by Levings and Dodge (1981).

Domestic wells were assigned a consumptive-use value of 700 gal/d, or 200 gal/d per person for a household with an average of 3.5 members. The population served by public water wells completed in the Kootenai was obtained from the Water Quality Bureau, Montana Department of Health and Environmental Sciences. The total usage for such a well was computed on the basis of 200 gal/d per individual served.

Very few irrigation wells exist in the Judith basin because most crops are dry-farmed. These wells were assigned an average-use value of 0.5 gal/min, or the equivalent of 0.8 acre-foot per year. This value is reasonable considering the generally small measured well yields and the shortness of the season when irrigation is necessary.

Stock wells were assigned an average-use value of 2.0 gal/min, or 2,880 gal/d. This value represents both pumped and flowing wells, including those flowing wells that have no control of discharge.

All this information was tabulated and input to the model as constant discharge wells. (Withdrawals were summed in instances where more than one well was situated within a single cell.) The assumptions inherent in the tabulation are that all existing wells completed in the Kootenai aquifer have been inventoried, all these wells are currently in use, and the average water-use values closely represent actual conditions in the Judith basin.

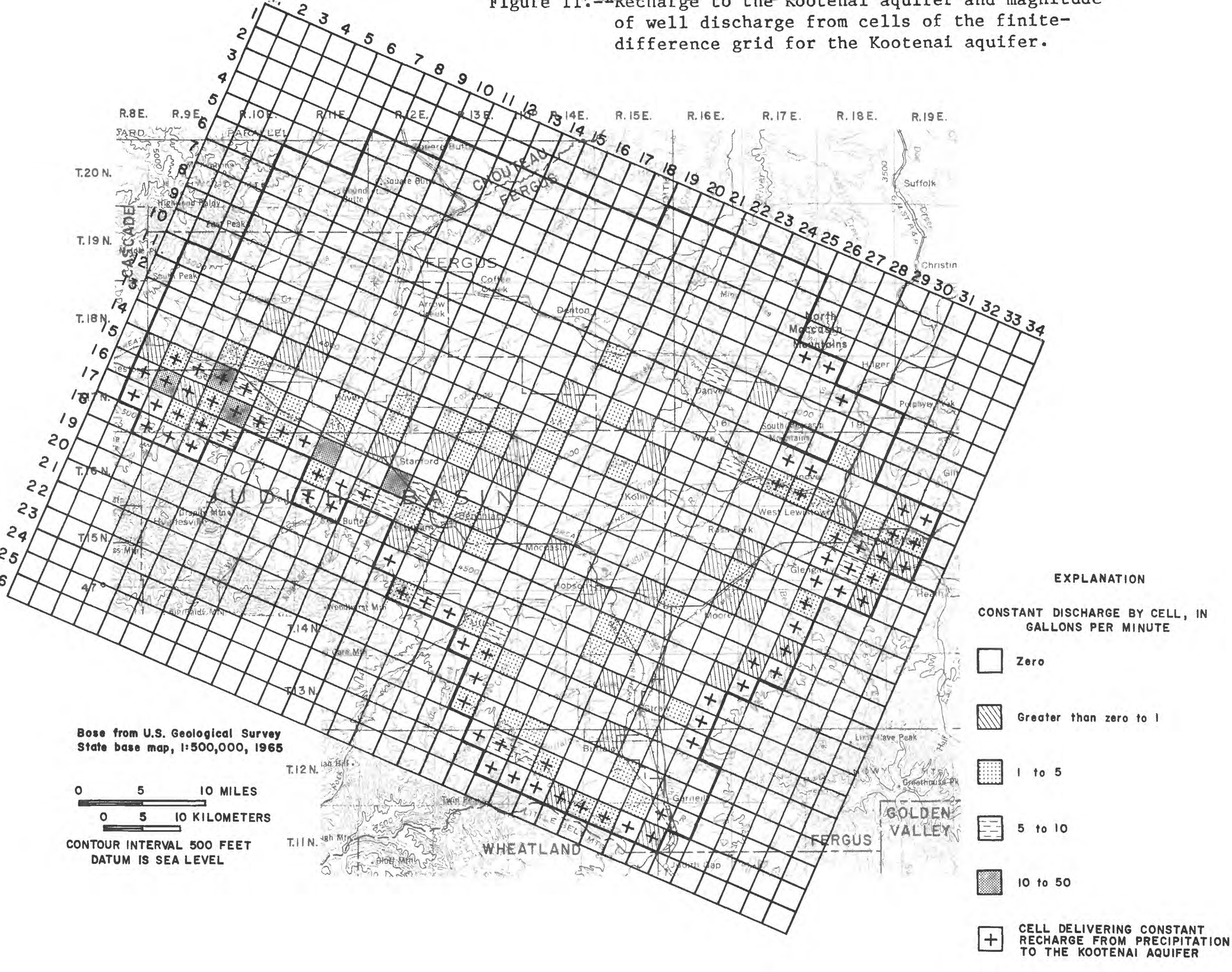
The magnitude of withdrawal from each cell of the finite-difference grid is shown in figure 11. These values are probably within 100 percent of being correct, because of the manner in which they were obtained. However, discharge due to pumping represents less than 2 percent of the total flow in the final version of the calibrated model.

Vertical leakage

Although vertical leakage to and from the Kootenai aquifer has not been previously measured, estimates can be obtained during the modeling process. Values of the reciprocal of confining-layer thickness were input at each node for the leakage-coefficient array, TK, of the confining layers. These arrays are then multiplied by a parameter card value (Trescott, 1975, Appendix III), which in this instance contained a value for vertical hydraulic conductivity. Estimates of vertical hydraulic conductivity, and hence vertical leakage, can then be obtained using a parameter-estimation procedure to be described in a subsequent section of this report.

The confining unit below the Kootenai aquifer is the Morrison Formation. The confining unit above the Kootenai aquifer is the relatively impermeable upper one-third of the Kootenai Formation, generally about 200 feet thick, and the entire overlying Colorado Shale. The composite potentiometric surface of water in the Colorado Shale, which is the upper constant-head boundary in the model, does not

Figure 11.--Recharge to the Kootenai aquifer and magnitude of well discharge from cells of the finite-difference grid for the Kootenai aquifer.



represent an aquifer at land surface nor at any one distinct layer at depth. Owing to the somewhat abstract nature of this boundary, the thickness of the upper confining unit is probably overestimated. The advantage, however, is that the confining unit thickness depends on the depth to the top of the Kootenai throughout the structural basin, a fact that agrees with the premise that progressively downdip in the basin, the data used to construct this constant-head boundary represent water levels from sandstone beds that are successively higher in the Colorado Shale sequence.

Model modifications

A few minor modifications have been made to Trescott's (1975) original program listing. To aid in the interpretation of the model output, the printout format of the input arrays of data has been standardized to facilitate comparison of data values at a particular node. An iteration parameter was included to aid in maximizing the rate of convergence where necessary. Signs were added to the printout of maximum hydraulic-head changes for each iteration so that the direction of the change could be easily ascertained. When the ITKR option is specified in the program, an internal search is activated that checks for non-zero hydraulic heads above and below all non-zero values in the TK array. The constant recharge from precipitation option (RECH) has been modified to include recharge in all layers of the model so that simulations of flow in sedimentary basins whose aquifers crop out in the surrounding highlands can be represented more accurately. Finally, to aid in the calibration effort, a statistical subroutine was added to the program that calculates and prints the average hydraulic-head difference and the standard deviation between the starting and ending hydraulic-head distribution of active nodes for every layer.

Steady-state calibration

Calibration is the process whereby the initial aquifer properties, boundaries, and stresses input to the model are adjusted within the physically reasonable limits implied by the conceptual model and by the degree of certainty with which these individual parameters are known. The adjustments are made to minimize the difference between computed and observed hydraulic heads. The closeness of fit between observed and calculated heads that can be expected from model calibration depends upon the accuracy of the interpretation of the potentiometric surface from observed head data and the conceptual flow model. Revisions and improvements to either one would require recalibration. In this instance, calibration was ultimately achieved by using an objective approach--the parameter-estimation method of Cooley (1977)--after several subjective approaches were used.

Much of the data for the potentiometric-surface map of the Kootenai aquifer came from a 1980 well inventory of the Judith basin (Levings and Dodge, 1981). In areas where 1980 water levels could be compared with water levels measured during previous years in the same or nearby wells, no temporal pattern of drawdown or buildup was detected. Because most of the major hydraulic stresses in the aquifer have existed for years with little or no change, the potentiometric surface was assumed to be in equilibrium (steady state). The calibration of a steady-state model is independent of storage properties of the aquifer.

The steady-state model was developed in stages, with each additional stage contributing to a better overall match of computed and observed hydraulic-head data. The first stage of development was a two-dimensional model of the Kootenai aquifer with a uniform transmissivity of 150 ft^2/d and no well discharge or vertical leakage. This transmissivity value was calculated by determining the hydraulic conductivity at the second well in table 1 to be 0.43 ft/d and then by multiplying it by an average aquifer thickness of 350 feet. A recharge of about 1 percent of precipitation at the outcrop provided sufficient inflow. However, the fit was poor. Computed heads were hundreds of feet too low near the perimeter of the basin and too high in the deeper parts.

The next stage of development included adjusting transmissivities for the effects of viscosity and for cells containing only partial areas of outcrop. Kinematic viscosity is a temperature-dependent function. Bottom-hole temperature data and formation picks for geophysical well logs in the Montana part of the northern Great Plains were obtained from a report by Feltis and others (1981). Assuming a mean annual surface temperature of 8°C, a linear relationship of temperature versus depth was developed for holes drilled in the Judith basin. Then, a map showing lines of equal depth to the midpoint of the Kootenai aquifer was prepared. Values of temperature for each active node in the model were chosen from the temperature-depth relationship and applied to the relationship in figure 12 to obtain corre-

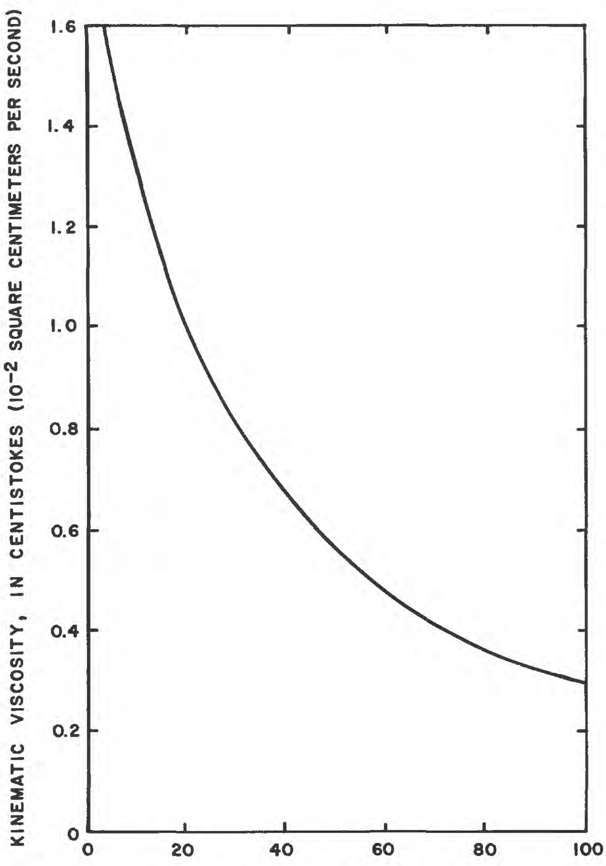


Figure 12.--Relationship between kinematic viscosity and temperature of water. Diagram modified from Konikow (1976, p. 19).

sponding values of kinematic viscosity. As transmissivity is directly proportional to temperature, and temperature increases with increasing depth, a 50-percent increase in transmissivity values for the Kootenai aquifer was calculated between its shallowest and deepest sections in the Judith basin.

Cells containing only partial areas of outcrop were adjusted by using a simple proportion to determine the probable thickness of the unit at the midpoint (node) of every affected cell. The assumptions were that the formation had a constant dip and that, on the average, the aquifer consisted of only the lower 350 feet of the 550-foot-thick formation. Although these adjustments resulted in an improvement of the overall match, the calculated heads were still hundreds of feet too high in the eastern part of the model area and several hundred feet too low near the edge of the Little Belt and Big Snowy Mountains.

The next stage involved the incorporation into the model of any known well withdrawals from the Kootenai. The distribution and magnitude of these withdrawals are shown in figure 11. The addition of these stresses significantly decreased the calculated heads in the eastern part of the model. Unfortunately, it also decreased heads along the Little Belt Mountains and compounded the low-head problem in that area.

One way to improve the match along the Little Belt mountain front would be to reduce the transmissivities there. The reduction would imply the existence of a fault in the subsurface with sufficient offset to have created a substantial barrier to flow. To date, no evidence exists to support this hypothesis. Neither the structure contours reflecting the configuration of the top of the Kootenai (fig. 4), nor those for the top of the Madison Group (R. D. Feltis, U.S. Geological Survey, written commun., 1981), show any justification for a fault in that area.

Another hypothesis that could very likely account for the steep water-level gradient is increased vertical leakage due to enhanced fracturing in formations where the flexure in their bedding planes is most severe. However, owing to the lack of any vertical hydraulic conductivity data for the confining layers overlying and underlying the Kootenai aquifer, and to some degree of uncertainty already present in the choice of model values of transmissivity and recharge, it seemed appropriate to evaluate this last complexity and finish the calibration by switching to an objective, statistical approach for estimating these parameters.

Parameter-estimation procedure

Description

Cooley (1977) developed a method to estimate parameters using a nonlinear least-squares regression technique applicable to two-dimensional steady-state ground-water flow problems. This method forms the basis of the parameter-estimation program (S. P. Larson and J. V. Tracy, U.S. Geological Survey, written commun., 1979) used in this study. Because horizontal components of flow were neglected in the confining layers and vertical components were neglected within the Kootenai aquifer, the three-dimensional model of the Kootenai is essentially a two-dimensional aquifer model linked on its vertical boundaries by one-dimensional leakage terms. Thus, the two-dimensional nature of the parameter-estimation program did not preclude its use in this instance.

Data input is designed for a lattice grid (fig. 13), wherein hydraulic-head data are input at the intersection of grid lines and flow data are input at the center of every cell created by intersecting grid lines. Thus, flow data from the digital flow model were reformulated for input between the head data. A slight modification was made to the program so that vertical leakage from an overlying and underlying confining layer could be estimated.

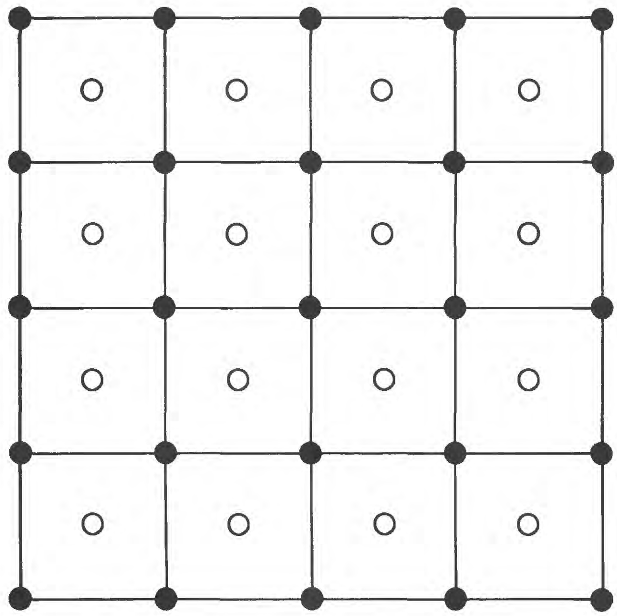


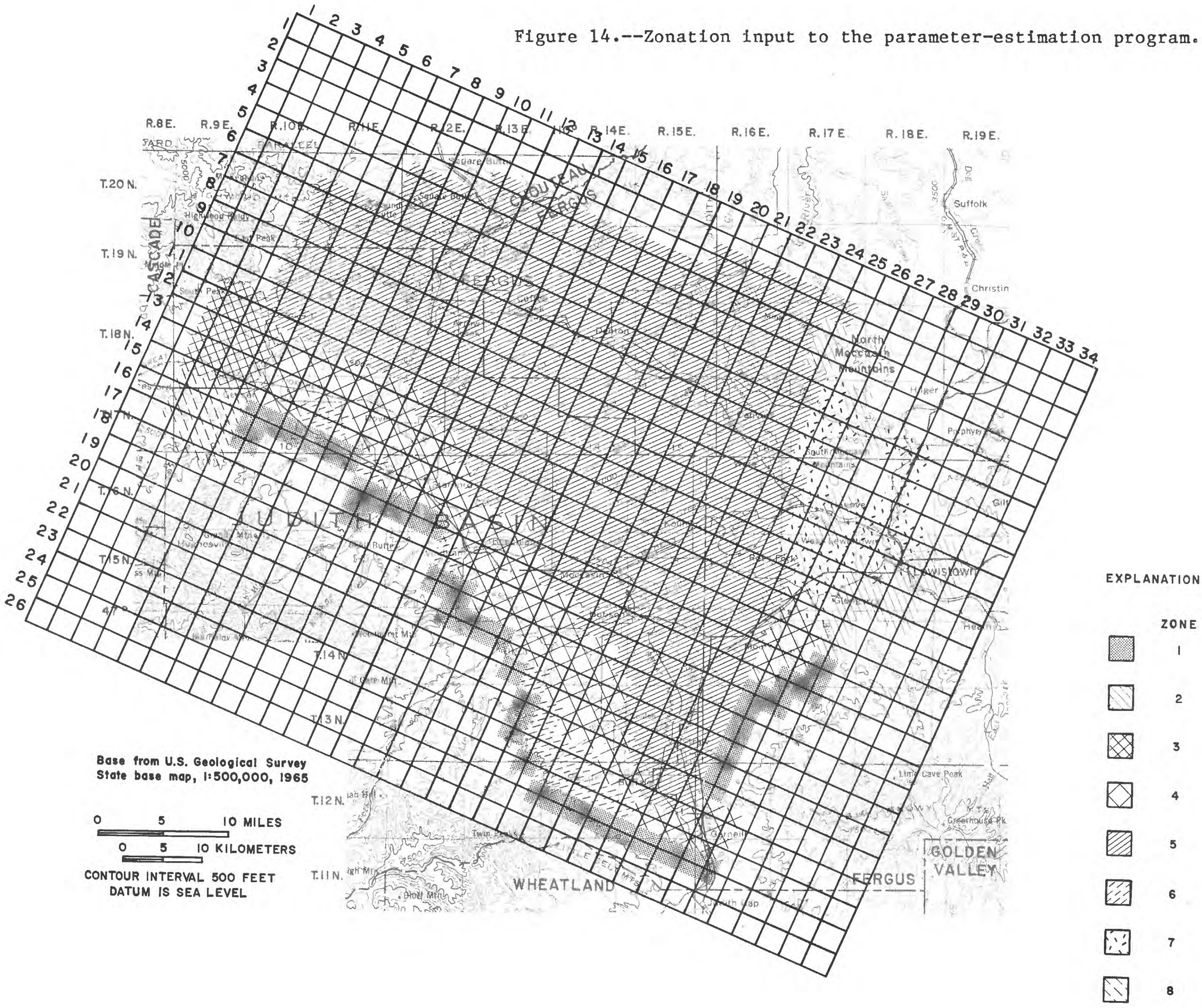
Figure 13.--Diagrammatic representation of the lattice grid. Head data are input at the nodes indicated by solid circles, and flow data are input at the open circles.

Establishing zones

The grid is separated into zones or areas that represent variability in the geology, hydraulic properties, or recharge and discharge characteristics of the aquifer. Values of transmissivity, vertical hydraulic conductivity for the confining layers, and recharge are input for every zone. At any particular node, then, an aquifer property is the product of the corresponding zonal value times the nodal value. In this program, these zonal properties are the basic element of the regression analysis, whereas the relative variation of nodes within a zone remains constant throughout the procedure.

The zoning scheme input to the parameter-estimation program is shown in figure 14. Zones 1, 2, and 8 are areas that receive recharge from precipitation on the outcrop. Zone 6 consists of the remaining area of steeply dipping beds along the mountain fronts. Zone 5 corresponds approximately to where the Kootenai Formation is overlain by more than 850 feet of Colorado Shale--the level above which the shale sequence ceases to contain sporadic sandstone beds. Zones 3, 4, and 7 are the transition zones between zone 5 and the mountain front zones. Zones 2 and 7 represent the structurally complex area near Lewistown, and zones 3 and 8 repre-

Figure 14.--Zonation input to the parameter-estimation program.



sent the area near the Highwood Mountains where numerous dikes and sills exist in the subsurface.

Zonal aquifer properties in the regression analysis were treated as either individual regression parameters or combined into groups represented by a single parameter. Adjustments to a group parameter were applied to all zonal properties in the group. Constant-head boundaries were also considered as regression parameters. In this instance, each parameter is composed of a linear sequence of nodes. Adjustments to these parameters are apportioned over all nodes in the sequence. Prior estimates of the regression parameters that are available from other sources (for example aquifer tests) can be considered by introducing a finite limit on the variability of the parameter in the form of a normalized standard error of estimate.

Regression parameters

The final version of the regression analysis for Judith basin contained 12 regression parameters. Five linear constant-head parameters were needed to constrain the solution at the constant-head boundary to the north. Otherwise, the lack of observation wells in the vicinity of this outflow boundary resulted in a best-fit solution exhibiting a head gradient in reverse to that shown in figure 6 for which no basis in fact exists. These parameters were each assigned a normalized standard error of estimate of 0.1.

The remaining seven parameters and the zones they represent are given in table 2. Recharge to the Kootenai from precipitation (parameter 4) was assigned a standard error of estimate of 0.35 and an initial value of 2 percent of precipitation. The transmissivity of the Kootenai aquifer for zone 5 (parameter 3) was assigned a standard error of estimate of 0.25 and an initial value of 158 ft^2/d. (This number corresponds to a transmissivity of 150 ft^2/d at the node containing well 2 in table 1.) The transmissivity of the Kootenai for the remaining zones (parameters 1 and 5) was assigned a standard error of estimate of 0.35 and an initial value of 350 ft^2/d. When multiplied in the model by the values of kinematic viscosity at model-node values near Lewistown and those near well 3 in table 1, the resulting values of transmissivity are about 250 ft^2/d. Because no prior information was known for vertical hydraulic conductivities of the confining layers (parameters 2, 6, and 7), they were not assigned initial standard errors of estimate.

The maximum number of zonal aquifer properties that could be successfully determined by this regression analysis was limited by the lack of any prior information on vertical hydraulic conductivities of the confining beds. When a combination of any more than three vertical-leakage parameters were attempted in addition to recharge and transmissivity, one of three conditions developed: the program failed to converge, the solution was physically impossible, or at least two of the regression parameters were too highly correlated with respect to each other to produce a unique solution for either one.

The three parameters (2, 6, and 7 in table 2) that were finally used in the regression analysis were located in areas where estimates of vertical hydraulic conductivity were likely to have the greatest meaning and use (fig. 14). The scarcity of head data for the Swift aquifer, except at the margins of the basin, would make estimates of vertical hydraulic conductivities anywhere else in the Morrison Formation unreliable. Because it is not clear whether the water levels representing the Kootenai aquifer and those representing the water-bearing sandstone beds in the Colorado Shale are hydraulically connected in the region where the relatively impermeable upper part of the Colorado Shale crops out and thickens downdip (zone 5), and because water levels in the Colorado in this region represent several aquifers, estimates of vertical hydraulic conductivity for the Colorado Shale are of questionable significance in zone 5.

Table 2.--*Summary of parameter-estimation procedure and regression analysis*

Regression parameter No.	Variable being regressed[1]	Zone (fig. 14) included in the parameter	Factor estimated from analysis	Normalized standard error of factor	
				Initial estimate	Final estimate
1	T_{xx}, T_{yy}	1,2,4,6,7	350	0.35	0.14
2	K_{vm}	1,2,6,8	.0215	--	.86
3	T_{xx}, T_{yy}	5	154	.25	.11
4	Q_k	1,2,8	1.99	.35	.15
5	T_{xx}, T_{yy}	3,8	350	.35	.14
6	K_{vc}	7	.000133	--	.75
7	K_{vc}	3,4,6	.00316	--	.29

[1] T_{xx} = transmissivity of Kootenai in x horizontal direction, in feet squared per day;
T_{yy} = transmissivity of Kootenai in y horizontal direction, in feet squared per day;
K_{vm} = vertical hydraulic conductivity of Morrison Formation, in feet per day;
K_{vc} = vertical hydraulic conductivity of Colorado and upper part of the Kootenai, in feet per day; and
Q_k = recharge to Kootenai as percentage of rainfall

Parameter sensitivities

Scaled sensitivities for each parameter at every active node were calculated by the parameter-estimation program. By studying them, it was possible to determine which parameters in what parts of the study area could have the greatest effect on the final solution with the least amount of change in their current values. More information and better definition of the reasonable limits of a parameter where it is very sensitive will make the most improvement to the solution of the model as currently formulated.

An examination of the computed sensitivities for the final solution indicates that the specified hydraulic heads at the northern boundary of the model are the most sensitive parameters. This condition is probably due to the paucity of nearby observation-well data and to the function of this boundary as the only means of discharge for water flowing into or already present in zone 5. The next most sensitive parameters were transmissivity and vertical leakage through the upper confining layer where zones 4 and 5 are adjacent to each other (parameters 1 and 7 in table 2; fig. 14). This location coincides with the place where vertical leakage ceases in the model and where transmissivities change between zones. The least sensitive of all the parameters was recharge from precipitation (parameter 4).

Additional hydraulic-head data near the constant-head boundary would improve the model fit significantly. However, the sensitive area for parameters 1 and 7 is more likely to be a function of the general lack of information on the rate and extent of vertical leakage through the confining layers coupled with the current choice of zonal boundaries. If the vertical hydraulic conductivity were known for both confining layers in zone 5, it is possible that the sensitivity of the constant-head boundary would also diminish.

Statistical validity

The results of the regression analysis and the normalized standard errors for each parameter estimate are listed in table 2. By incorporating the factor estimated from the analysis, transmissivities in the Kootenai ranged from 137 to 364 ft^2/d and had small standard errors of estimate. The standard errors are largest for the vertical-leakage parameters (2, 6, and 7) for which no prior information was available. However, without these vertical-leakage parameters, an acceptably large correlation coefficient between observed and computed heads could not have been obtained.

A correlation coefficient of 0.9936, which was calculated for the model, indicates a good fit to the actual data. The error variance is 1,719 and the standard deviation, s, of the solution is 41.5 feet. Despite the impreciseness of the estimates of parameters 2 and 6 in table 2, the value of $s/\Delta h$ (where Δh is the difference between the highest and lowest value of observed head) is only about 0.028 (41.5 divided by 1,463), implying that errors in the model appear to be only a small fraction of the total model response.

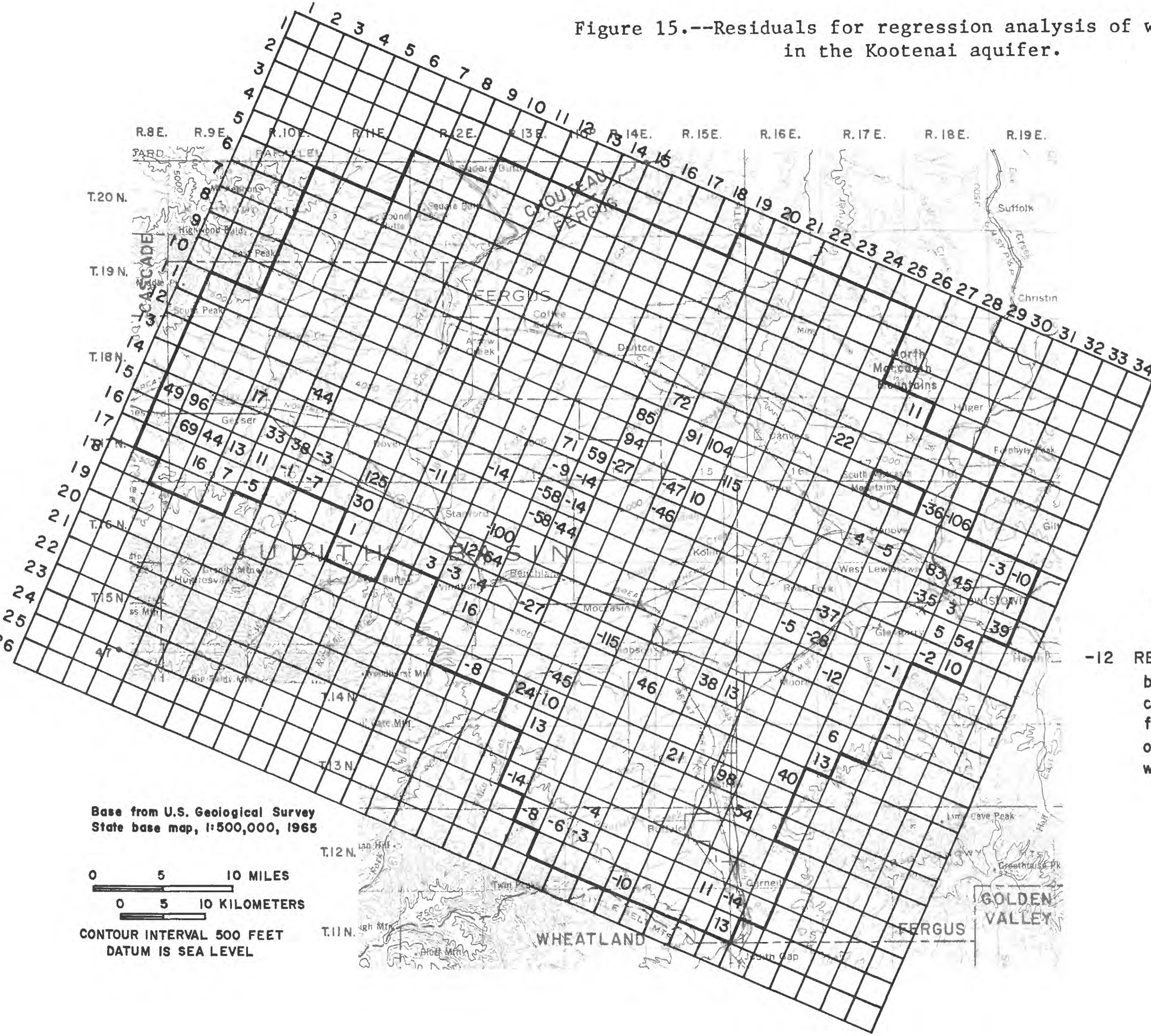
The pertinence of statistical parameters to an interpretation of the overall fit of the calibrated model depends on whether the solution fits a normal distribution, a requirement that can be tested by checking a map plot of the residuals (the difference between observed and computed heads) for randomness. A visual inspection of figure 15 shows what appears to be a fairly random variation in sign and magnitude of the residuals in any direction for this model. Based on these statistical criteria, the model was determined to be successfully calibrated.

RESULTS

The steady-state potentiometric surface computed by the calibrated model superimposed on the observed potentiometric surface is shown on plate 1. The steep hydraulic gradient near the Little Belt Mountains and the cone of depression near Lewistown agree fairly well between observed and computed. The fit is not as good in the center of the basin where vertical leakage was not estimated. At the southeastern end of the basin, the simulated ground-water divide is offset by about 4 miles.

The difference between the computed and observed heads is less than 20 feet in 28 percent of the modeled area; 20 to 50 feet in 30 percent; and 50 to 100 feet

Figure 15.--Residuals for regression analysis of water flow in the Kootenai aquifer.



EXPLANATION

-12 RESIDUAL--Difference between steady-state and computed head values, in feet above or below (-) observed steady-state water level

Base from U.S. Geological Survey State base map, 1:500,000, 1965

0 5 10 MILES

0 5 10 KILOMETERS

CONTOUR INTERVAL 500 FEET
DATUM IS SEA LEVEL

in 34 percent. All but one node in the model was calibrated to within 200 feet of the observed water level. Some of the error in calibration is undoubtedly due to the misinterpretation of sparse observed data and to the lack of knowledge about variations of the aquifer's hydrologic properties. Collection of additional onsite data may enable these errors to be further resolved.

The three-dimensional digital flow model calculates a mass balance at the end of every steady-state simulation. It contains the computed net flow contributed by each hydrologic component. In this way, the relative importance of the components can be compared to one another. The hydrologic budget for the calibrated steady-state model is summarized in table 3. Net recharge includes 5.44 ft^3/s from precipitation and 32.48 ft^3/s of vertical leakage from the Swift aquifer. Net discharge includes 0.84 ft^3/s by wells, 1.83 ft^3/s by underflow across the northern boundary, and 35.25 ft^3/s of vertical leakage to the water-bearing sandstone beds in the Colorado Shale. The flow contributed by vertical leakage into and out of the Kootenai aquifer can be considered only as approximate, because the estimated vertical hydraulic conductivity values have not been verified. The relative magnitude of this flow component (85.7 and 93.0 percent) within the context of the current conceptual model would seem to dictate a high priority for any additional data collection.

Table 3.--*Components of the hydrologic budget for the calibrated model of the Kootenai aquifer*

Component	Computed flow (cubic feet per second)	Percent of total recharge or discharge
Net recharge to aquifer		
Precipitation	5.44	14.3
Vertical leakage from Swift aquifer	32.48	85.7
Total recharge	37.92	100.0
Net discharge from aquifer		
Well pumpage	0.84	2.2
Underflow	1.83	4.8
Vertical leakage to sandstone beds in Colorado Shale	35.25	93.0
Total discharge	37.92	100.0

ADDITIONAL STUDIES

The current conceptual model of ground-water flow in the Judith basin could be improved by the collection of several kinds of additional data. Currently available hydraulic-head data for the composite potentiometric-surface map of the Colorado Shale could be carefully re-examined. If complete test-hole data were obtained at a few selected locations, re-examination could result in the separation of water-level data representing a single water-bearing sandstone bed such as the First Cat Creek sandstone from other individual sandstone beds in the Colorado Shale. Then hydraulic-head data for this layer and for the Swift could be supplemented with additional water-level data collected from existing wells completed in the layers to give better definition to their potentiometric surfaces in the deeper parts of the basin. Values of vertical hydraulic conductivity in the confining layers bounding the Kootenai aquifer could also be determined analytically from multiple-zone aquifer tests conducted in properly designed and constructed wells. Prior estimates of vertical-leakage coefficients could then be included in the parameter-estimation program.

By collecting and analyzing additional data on the transmissivity and storage characteristics of the Swift and Kootenai aquifers and the First Cat Creek sandstone from aquifer tests, flow in the model's top and bottom constant-head layers could be explicitly modeled, and the current transmissivity distributions could be re-evaluated. Annual and long-term water-level fluctuations could be monitored in the tested wells to aid in the analysis and modeling of transient characteristics of the aquifers.

Finally, the hydrologic system would be better understood if the extent, location, and magnitude of subsurface faulting and fracturing could be investigated by surface geophysical methods or by test drilling. The information obtained would improve the knowledge of the relationship between faulting, fracturing, and ground-water flow in the Judith basin. Specifically, the current assumption that the fault along Warm Spring Creek is a barrier to flow could be investigated. If the existence of the postulated zones of faulting along Beaver Creek and Big Spring Creek were verified, their effect on the flow system could also be explored and quantified. For example, the final version of the calibrated model does not simulate sufficient drawdown along Big Spring Creek despite withdrawals from numerous wells in the area and vertical leakage upward to the creek where it crosses the Colorado Shale. One possible explanation is that the movement of ground water in the vertical direction is enhanced along a fault trace. If faulting and fracturing prove to affect ground-water flow and the simulation of ground-water levels in the Judith basin, a finite-element model would be better suited to the precise placement of these linear features than the finite-difference model.

SUMMARY

The hydrogeology of five Jurassic and Cretaceous geologic formations in the Judith basin was investigated to improve the understanding of water flow in the Kootenai aquifer. For this purpose, a three-dimensional digital model of water flow in the aquifers was constructed from existing data. Calibration and evaluation of a steady-state model were performed using a parameter-estimation procedure.

The formations studied were, in ascending order: Swift, Morrison, and Kootenai Formations, Colorado Shale, and Telegraph Creek Formation. The Swift Formation is

a 45- to 280-foot thick, medium- to coarse-grained marine sandstone with interbeds of shale. The Morrison Formation consists mainly of 50 to 300 feet of nonmarine shale and siltstone. The basal part of the Kootenai Formation (Third Cat Creek sandstone) is a fluvial sandstone and conglomerate typically 20 to 120 feet thick; the middle part (Second Cat Creek sandstone) contains fine- to coarse-grained sandstone lenses ranging from 0.5 to about 20 feet in thickness interspersed with siltstone and shale; and the upper part consists of about 200 feet of predominantly varicolored shale and siltstone. The Colorado Shale primarily consists of 1,500 to 2,000 feet of dark-gray to black marine shale with several isolated very fine grained sandstone interbeds in the lower 850 feet. The Telegraph Creek Formation is a 160-foot-thick shale and sandy shale unit that was mapped with the Colorado Shale.

The Swift, the lower two-thirds of the Kootenai, and several sandstone beds in the Colorado are confined aquifers, whereas the intervening Morrison and upper one-third of the Kootenai in combination with parts of the Colorado are effectively confining layers. The Kootenai aquifer, the most widely used aquifer in the Judith basin, produces a reliable supply of water for domestic and stock needs from both the Second Cat Creek and the Third Cat Creek sandstones.

Potentiometric maps of the three aquifers all show the same general flow pattern -- recharge from precipitation in the mountains around the southern perimeter of the basin and discharge as underflow along the northern boundary of the basin. Anomalies in this pattern may be due to subsurface faulting and fracturing.

The major identifiable sources of recharge to the Kootenai aquifer are infiltration of precipitation and upward leakage of water from the Swift aquifer. The major sources of discharge are upward leakage of water into the Colorado Shale, outflow along the northern basin boundary, and withdrawal of water from wells.

A three-dimensional digital model (Trescott, 1975) was used to simulate horizontal flow in the Kootenai aquifer and vertical leakage through the adjacent confining layers. The model consisted of three layers corresponding to the Swift, Kootenai, and Colorado aquifers. The top and bottom aquifers consisted only of constant-head nodes and were used to aid in simulating vertical leakage through the confining layers.

The model was calibrated to 1980 water levels, which represent essentially steady-state conditions. The calibration process was completed in stages, with each additional stage adding complexity to the model and contributing to a better overall match of simulated and observed water levels. The first stage was a two-dimensional model of the Kootenai with a uniform transmissivity of 150 ft^2/d. Improvements to this stage of the model included adjusting transmissivities for the effects of viscosity and for partial sections of the aquifer along the outcrop. The next stage included a major adjustment to incorporate into the model known water withdrawals from wells completed in the Kootenai aquifer. The final stage was simulated for vertical leakage through adjacent confining layers. A parameter-estimation program was used to estimate vertical hydraulic conductivities for which no prior information existed and to obtain better estimates for all the hydrologic parameters involved in the calibration.

Values of transmissivity for the Kootenai aquifer obtained from the calibrated model range from 137 to 364 ft^2/d. Recharge in the form of precipitation on the outcrop is about 2 percent of total precipitation or 5.44 ft^3/s. The other component of net recharge to the aquifer is 32.48 ft^3/s of vertical leakage from the Swift aquifer (85.7 percent of total recharge). The cumulative rate of discharge from all known wells completed in the aquifer is about 0.84 ft^3/s, or 2.2 percent of total discharge from the aquifer. Other components of net discharge from the aquifer are 1.83 ft^3/s of underflow (4.8 percent of total discharge) and 35.25 ft^3/s of vertical leakage to the water-bearing sandstone beds in the Colorado Shale (93.0 percent of total discharge). Estimates of vertical hydraulic conductivity are 2.15×10^{-2} ft/d for the lower confining layer, and 3.16×10^{-3} and 1.33×10^{-4} ft/d for the upper confining layer. These conductivity values on which the flow components of vertical leakage are based were derived solely from the application of the parameter-estimation procedure during model calibration, and require onsite verification.

The difference between the computed and observed hydraulic heads is less than 20 feet in 28 percent of the modeled area; 20 to 50 feet in 30 percent; and 50 to 100 feet in 34 percent. All but one node in the model were calibrated to within 200 feet of the observed water level.

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