HYDROLOGY OF THE WIBAUX-BEACH LIGNITE DEPOSIT AREA, EASTERN MONTANA AND WESTERN NORTH DAKOTA

By W. F. Horak

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4157

Prepared in cooperation with the

U.S. BUREAU OF LAND MANAGEMENT

Bismarck, North Dakota

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONTENTS

CONTENTS, Continued

ILLUSTRATIONS

ILLUSTRATIONS, Continued

TABLES

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM OF UNITS (SI)

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

Multiply inch-pound unit	By	To obtain SI unit
Acre	0.4047	hectare
Cubic foot per second (ft^3/s)	0.02832	cubic meter per second
Foot (ft)	0.3048	meter
Foot per day (ft/d)	0.3048	meter per day
Foot per foot (ft/ft)	1	meter per meter
Foot per mile (ft/mi)	0.1894	meter per kilometer
Foot squared per day (ft^2/d)	0.0929	meter squared per day
Gallon (gal)	3.785	liter
	0.003785	cubic meter
Gallon per minute (gal/min)	0.00006309	cubic meter per second
Gallon per minute per foot [(gal/min)/ft]	0.000207	cubic meter per second per meter
Inch (in.)	25.40	millimeter
Micromho per centimeter (μmho/cm) (at 25°C)	1	microSiemen
Mile (mi)	1.609	kilometer
Square mile (mi^2)	2.590	square kilometer

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula °C = (°F-32)x5/9.

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

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ABSTRACT

The Paleocene Harmon lignite, the principal commercial bed of the Wibaux-Beach deposit, underlies at least 150 square miles along the Montana-North Dakota border. An estimated 1 billion tons of strippable reserves underlies about 50 square miles. The Harmon lignite bed also is the most consistently occurring shallow aquifer in the area. This study was conducted to determine possible impacts of surface mining on the area's water resources.

Two aquifer systems, the lower Tongue River and the upper Ludlow, were identified within about 300 feet below the Harmon lignite aquifer, but none were identified within the overlying 350 feet. The aquifers (systems) are separated by varying thicknesses of interbedded clay and silt. The Harmon lignite aquifer extends uninterrupted for several miles eastward (down dip) from the outcrop. It is from 3 to 34 feet thick and from zero to 350 feet deep. The top of the lower Tongue River aquifer system is from 0 to 115 feet below the Harmon lignite and the system is 13 to 98 feet thick. The upper Ludlow aquifer system is 128 to 214 feet below the Harmon lignite and is 5 to 84 feet thick.

Both the lower Tongue River and upper Ludlow aquifer systems consist of discontinuous, vertically stacked, sinuous sand bodies deposited as channel fill in meandering and braided streams. The probability of encountering a sand bed within the aquifer systems at any one location in the study area is about 60 percent for the lower Tongue River aquifer system and 80 percent for the upper Ludlow aquifer system.

Water in each aquifer flows toward the northeast and occurs under confined conditions, except in the Harmon lignite aquifer near its outcrop. Recharge occurs directly by precipitation at the outcrops and by downward leakage elsewhere. The major discharge from each aquifer is by downward leakage, although the Harmon lignite aquifer discharges less than 0.20 cubic foot per second to surface drainages within the study area.

Differences in chemical quality of water among the three aquifers are subtle, but significant. The mean dissolved-solids concentrations are: Harmon lignite aquifer, 1,930 milligrams per liter; lower Tongue River aquifer system, 1,810 milligrams per liter; and upper Ludlow aquifer system, 1,550 milligrams per liter. Alkalinity, calcium, and magnesium concentrations decrease with aquifer depth. The majority of the samples were a sodium sulfate-bicarbonate type. The median pH values, from the uppermost to the lowermost aquifer, were 8.1, 8.3, and 8.5.

The chemical quality of water in the Harmon lignite aquifer near the outcrop is affected by reactions in the aerated soil zone and unsaturated parts of the aquifer. Where the outcrop is heavily clinkered, recharge waters reach the aquifer rapidly and have little opportunity for solute uptake in the unsaturated zone. In nonclinkered areas, recharge waters slowly percolate through chemically active soil and unsaturated parts of the aquifer. The resulting water commonly contains 2,500 to 5,000 milligrams per liter of dissolved solids, is a calcium-magnesium sulfate type, and has a pH of less than 7.0.

The impacts of mining on streamflow and stream water quality should be manageable through the effective use of earth structures for routing and impoundment of runoff water. Mining-induced potentiometric declines in the Harmon lignite aquifer probably will be several feet up to 2 or 3 miles from the mine. Mining impacts on other aquifers will be minor.

INTRODUCTION

The pace of development of the coal reserves in the northern Great Plains has quickened in the years since the world energy-resource situtation was brought to public attention in the early 1970's. Exploration activities heightened and plans for the development of lignite reserves were promulgated by energy-related industries. One such reserve, commonly known as the "Wibaux-Beach" deposit due to its geographical setting near the communities of Wibaux, Montana, and Beach, North Dakota (fig. 1), has been the subject of a proposal for mining and conversion to synthetic natural gas. About 1 billion tons of lignite-grade coal is recoverable by surface-mining methods within the Wibaux-Beach deposit. Obstacles heretofore inhibiting the development of the coal reserve include natural resource, economic, and political considerations. Remedies to these obstacles are being engineered and negotiated, however, and development of the Wibaux-Beach deposit may occur within this decade.

The lignite of the Wibaux-Beach deposit, the Harmon bed, lies in the lower part of the Tongue River Member of the Fort Union Formation. The lignite occurs without interruption over an area of at least 150 mi^2, and is recoverable by strip-mining methods over about 50 mi^2. Because it occurs so consistently and is a reliable source of water for low-yield domestic and stock wells, the Harmon lignite is also the major shallow aquifer throughout its minable area.

Sand beds deposited in fluvial environments during Tertiary and latest Cretaceous time occur inconsistently within the 200 to 300 ft of stratigraphic section beneath the Harmon lignite. These sand beds constitute aquifers which may be affected by the mining process. They are utilized by wells in the area and also could be considered as the most probable source of ground water to replace those water supplies lost due to destruction of the lignite aquifer and associated wells.

The study area boundaries (fig. 1) were drawn to include all of the strip-minable area of the Wibaux-Beach lignite deposit and all of the Beaver Creek water course that would receive runoff from the potential mine area.

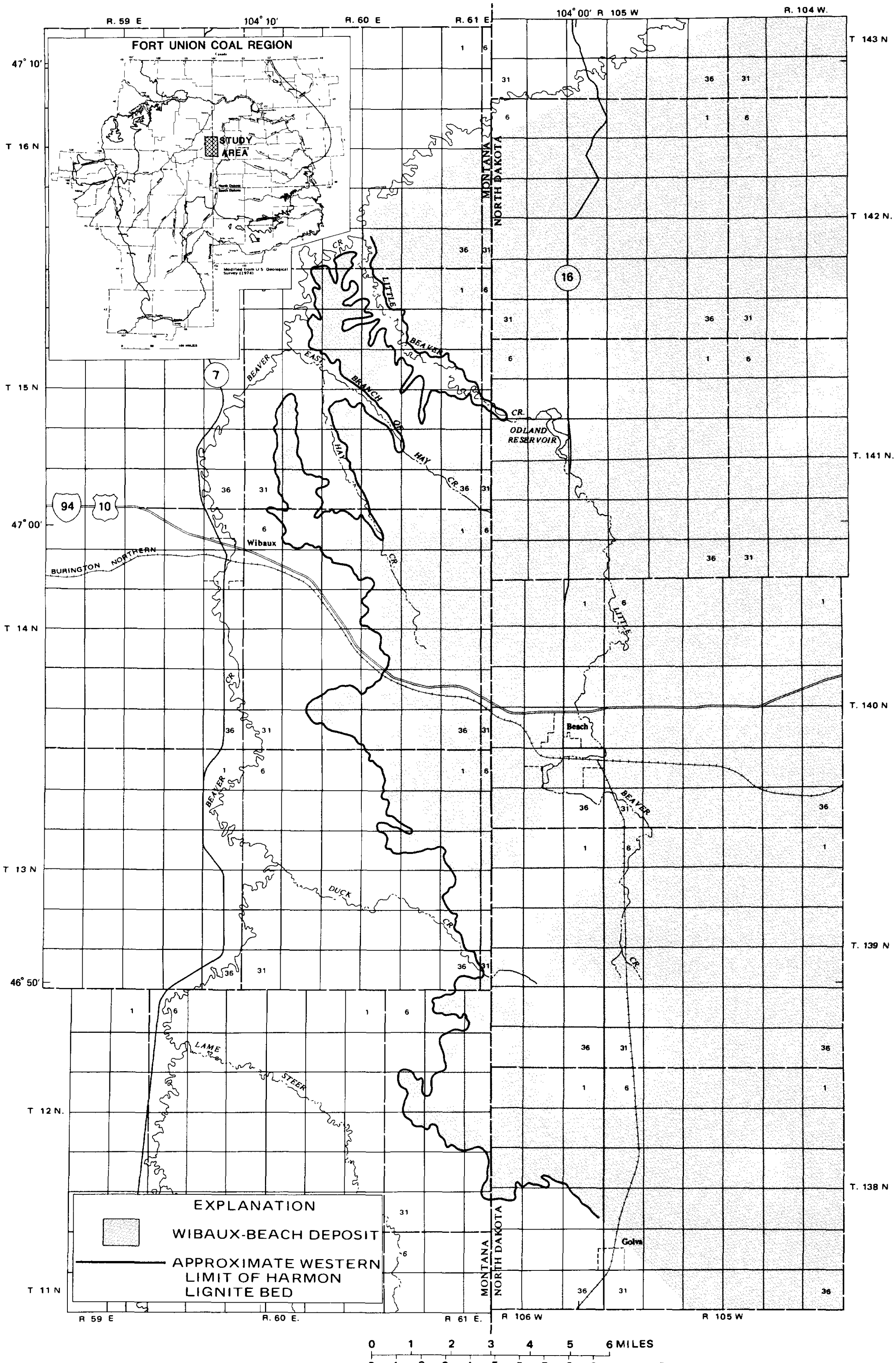


FIGURE 1.—Location of study area.

The strippable area is from 2 to 5 mi wide and parallels the outcrop of the Harmon lignite bed as shown in figure 1. Although the lignite dips northeastward and is too deep to economically strip mine beyond the 2- to 5-mi zone, it underlies all of the study area eastward of the outcrop. That area is referred to as the Wibaux-Beach deposit area in this report.

Objectives and Scope

This study was undertaken in response to U.S. Bureau of Land Management concerns for the water resources of the Wibaux-Beach area in the event of lignite mining. The objectives of the study were to: (1) Define the stratigraphic sequence within a few hundred feet above and below the minable lignite; (2) define the premining hydrologic and geochemical regime of the Wibaux-Beach deposit area; and (3) describe some of the hydrologic implications of the strip-mining process. A fourth objective, the establishment of a historical data base with which to access any modifications to the system attributable to future mining, was accomplished as a byproduct of the other three.

This report describes the geologic framework of the study area in terms of dominant lithologies and bed associations, cites the flow characteristics of the major streams in the area, identifies the major aquifers and interprets the ground-water flow regime of each aquifer, hypothesizes the mode and degree of interaction between the aquifers, describes the water-quality characteristics of the streams and aquifers and identifies possible mechanisms for the genesis of those characteristics, and qualitatively describes the probable hydrologic consequences of strip mining.

At the beginning of this project, it was intended that watershed modeling be a part of the overall report. In 1979, however, the watershed-modeling efforts were separated from this project and given project status under independent management. A final report on that work is scheduled for 1983. Interim or data reports were published by Emerson (1981) and Emerson and others (1983).

Acknowledgments

The cooperation of the landowners who allowed well-site easements and access to their land for data acquisition by project personnel is gratefully acknowledged. Many U.S. Geological Survey personnel contributed in a variety of ways to the completion of this project, but one individual, Kelvin Boespflug, performed many of the field duties throughout the project and is due special recognition.

Previous Investigations

Several reports concerning the coal resources of the Wibaux-Beach and adjacent areas have been published. Leonard and Smith (1909) made a reconnaissance map of the outcropping lignite beds in the northern part of the Wibaux-Beach deposit. Leonard and others (1925) described the thickness and areal extent of exposed lignite in Golden Valley County, North Dakota. Hares (1928) mapped the lignite exposures in southwestern North Dakota, including beds in the southernmost part of the Wibaux-Beach deposit. May (1954) used test-hole data in addition to surficial information to map and describe in considerable detail the commercial lignite bed (and overlying strata) of the Wibaux-Beach deposit. An open-file report issued by the Conservation Division of the U.S. Geological Survey presents the geophysical and lithologic logs for some 100 test holes drilled in the Wibaux-Beach deposit (Harksen, 1978). That report and the report by May (1954) were drawn upon freely in the course of the current study.

As part of a long-standing cooperative program involving the U.S. Geological Survey, North Dakota Geological Survey, North Dakota State Water Commission, and County Water Management Districts, C. G. Carlson (written commun., 1981) studied the geology and Anna (1981) the geohydrology of Billings, Golden Valley, and Slope Counties. Data obtained from these studies formed, in part, the basis for the regional geohydrologic interpretations of the current study.

Reports of U. S. Geological Survey studies in North Dakota that have some objectives similar to the current study include studies in the Gascoyne area by M. G. Croft (written commun., 1981), and in the Beulah-Zap area by Crawley and Emerson (1981). Other reports dealing with hydrologic effects of mining in North Dakota include Moran and others (1976), Moran, Groenewold, and Cherry (1978), and Groenewold and others (1979).

Location-Numbering System

The wells and test holes referred to in this report are numbered according to a system of land survey modified from one in use by the U.S. Bureau of Land Management. The system for North Dakota is illustrated in figure 2. The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 139-106-15ADC in North Dakota, would be in the SW1/4SE1/4NE1/4 sec. 15, T. 139 N., R. 106 W. Consecutive terminal numerals are added if more than one well or test hole is recorded within a 10-acre tract. The well-numbering system is similar in Montana, except that township and range designations are relative to different index latitudes and longitudes.

The surface-water stations have been assigned a station number in downstream order. A station on a tributary that enters between two main-stream stations is listed between them. Gaps are left in the series of numbers to allow for new stations that may be established. The complete eight-digit number for each station, such as 06336500, includes the two-digit part number "06", which identifies the major drainage, plus the six-digit downstream order number "336500."

METHODS OF INVESTIGATION

Geophysical logs from about 200 test holes were used to interpret the geologic framework within the study area. Most of these holes penetrated

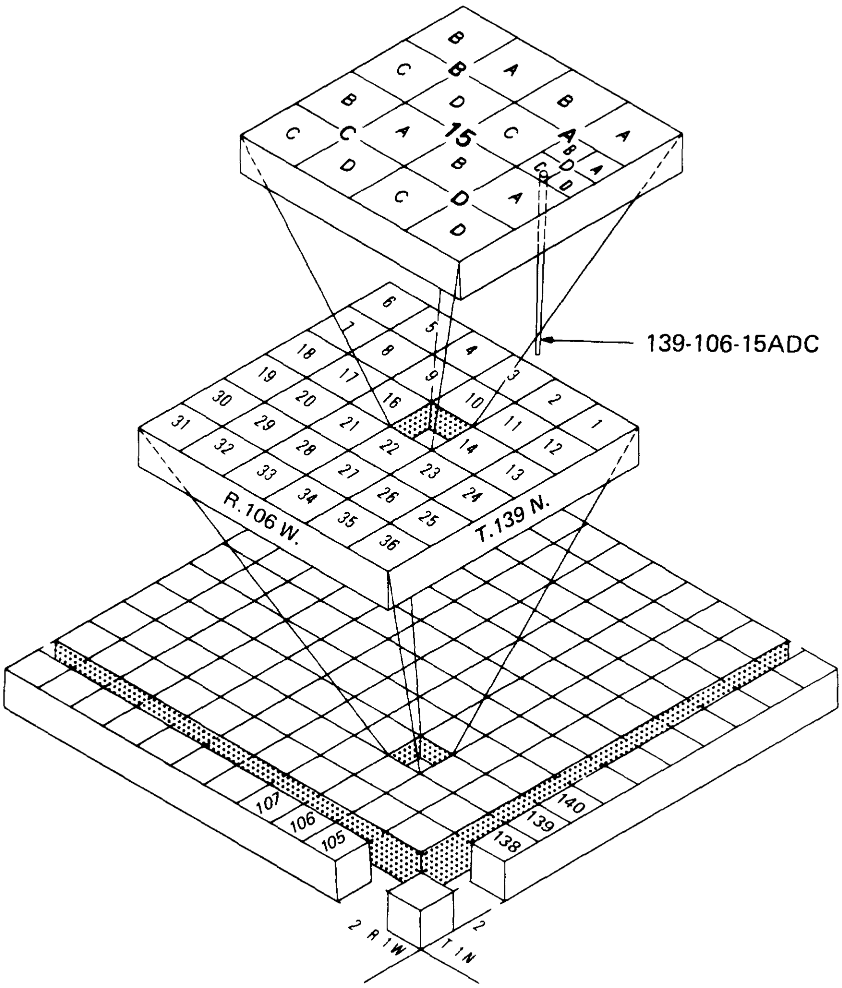


FIGURE 2.—Location-numbering system.

the Harmon lignite bed and provide data for a structure-contour map of the bed. Somewhat fewer penetrated to the base of the Tongue River Member to aid in the mapping of the basal Tongue River sand, and only about 25 penetrated enough of the section to contribute to the mapping of sand beds in the upper Ludlow Member. Water-level data from 102 observation wells at 74 sites were the basis for the geohydrologic interpretations in this report. Ninety-five of the observation wells were sampled for chemical analysis to enable the water quality interpretations in this report. Six continuous-record streamflow-gaging stations monitored the discharge of streams in the study area.

Drilling, Logging, and Well Construction

All the test holes completed during this project were drilled by forward hydraulic rotary method. The nominal 5-in. holes were drilled with air injection whenever possible in order to detect zones of saturation. When wetness of the drill cuttings made air drilling ineffective, water injection was used along with air to circulate the cuttings. The deeper test holes were drilled with water circulation from the point where air and water injection failed to flush the cuttings.

The test holes were geophysically logged upon completion of the drilling. The suite of logs for each hole usually included a natural gamma and gamma-gamma density combination. Several of the test holes were logged for either single-point resistance or 16- and 64-in. resistivity. Neutron logs were run on a few holes.

Most observation wells were constructed with 2-in. diameter PVC casing and 2-in., factory slotted, PVC screens with 0.008- or 0.012-in. slot openings. One, two, or three 6-ft long screens or one 10-ft long screen was emplaced in each well. Most wells less than 250 ft deep were sand packed with a commercially graded, rounded silica sand. Cement grout was pumped to the top of the sand pack by means of a 1¼-in. treme pipe and a centrifugal pump. This process provided a cement plug in the well anulus about 20 ft thick that isolated the screened aquifer from any overlying aquifers. In the wells that were not sand packed and grouted, commercial rubber packers were used to isolate the aquifer intervals. All well annuluses were backfilled with clayey cuttings. For observation wells deeper than about 350 ft, 2-in. diameter steel casing was used. One, two, or three 6-ft long, 1¼-in. diameter, galvanized steel screens of wire-wrapped construction were coupled to the end of the casing string in these wells. Aquifer isolation was accomplished with commercial rubber packers and backfill of clayey cuttings.

Most of the wells were developed by airlifting water from the well with an air compressor and rubber hose. The wells were pumped in this manner until several thousands of gallons of water were recovered and the specific conductance of the pumped water had stabilized.

Sampling

Sampling of water from wells for chemical analysis was accomplished with a rubber-bladdered pump, in which the bladder is squeezed with compressed nitrogen around a porous core which is connected to a polyurethane discharge line. Water samples collected by this method are totally unaerated.

Chemical analyses of both ground-water and surface-water samples were done in the U.S. Geological Survey Central Laboratory in Denver, Colorado. All analytical techniques conformed to U.S. Geological Survey standard methods (Skougstad and others, 1979).

Monitoring

Two wells were equipped with hourly recording, automatic water-level monitors. Water-level measurements were made in all other observation wells with a weighted steel tape on approximately a monthly schedule.

Determination of Hydraulic Conductivity

Hydraulic-conductivity measurements were made on 35 wells by the slug-test method; however, a variation of the traditional technique was used. Each well was fitted with a valve device that accommodated a transducer cable, a pressurizing line, and a large diameter ball valve. The transducer was lowered to an appropriate depth below the water surface and the well casing was pressurized to a selected head equivalent. After complete equilibration of the water level to the introduced gas pressure in the overlying casing, the gas was released to simulate an instantaneous removal of a "slug" of water. The transducer then signaled the head recovery to a recorder at the surface.

Two different methods of analysis were used to determine hydraulic conductivities from recovery data. Cooper and others (1967) presented a solution of the equation for nonsteady radial flow of confined ground water, with boundary conditions appropriate for the slug-test procedure. The Cooper method entails a curve-matching technique similar to the Theis nonquilibrium solution. The assumptions of the radial-flow equation--homogeneity, isotropy, uniform thickness, artesian conditions, and fully penetrating well--apply to Cooper's solution for flow to (from) a finite-diameter well following an instantaneous removal (addition) of a slug of water. The aquifer transmissivity is determined by a curve-fitting process (fig. 3) and the hydraulic conductivity is estimated as the transmissivity divided by the length of the intake contributing flow to the well.

In theory, the storage coefficient can be calculated using the α value of the "best fit" type curve and the diameters of the casing and screen. As noted by Cooper and others (1967), however, storage values so determined may not be valid because the α value is defined by the very subjective process of curve fitting, and may vary by orders of magnitude within the range of reasonable fits.

The other method used for the analysis of slug-test data is based on theory developed by Hvorslev (1951). Assumptions inherent in the derivation of Hvorslev's formulas are those of homogeneity, isotropy, infinite aquifer thickness, incompressibility of water and aquifer material, and adherence to Darcian flow. It also is assumed that the aquifer potentiometric level is

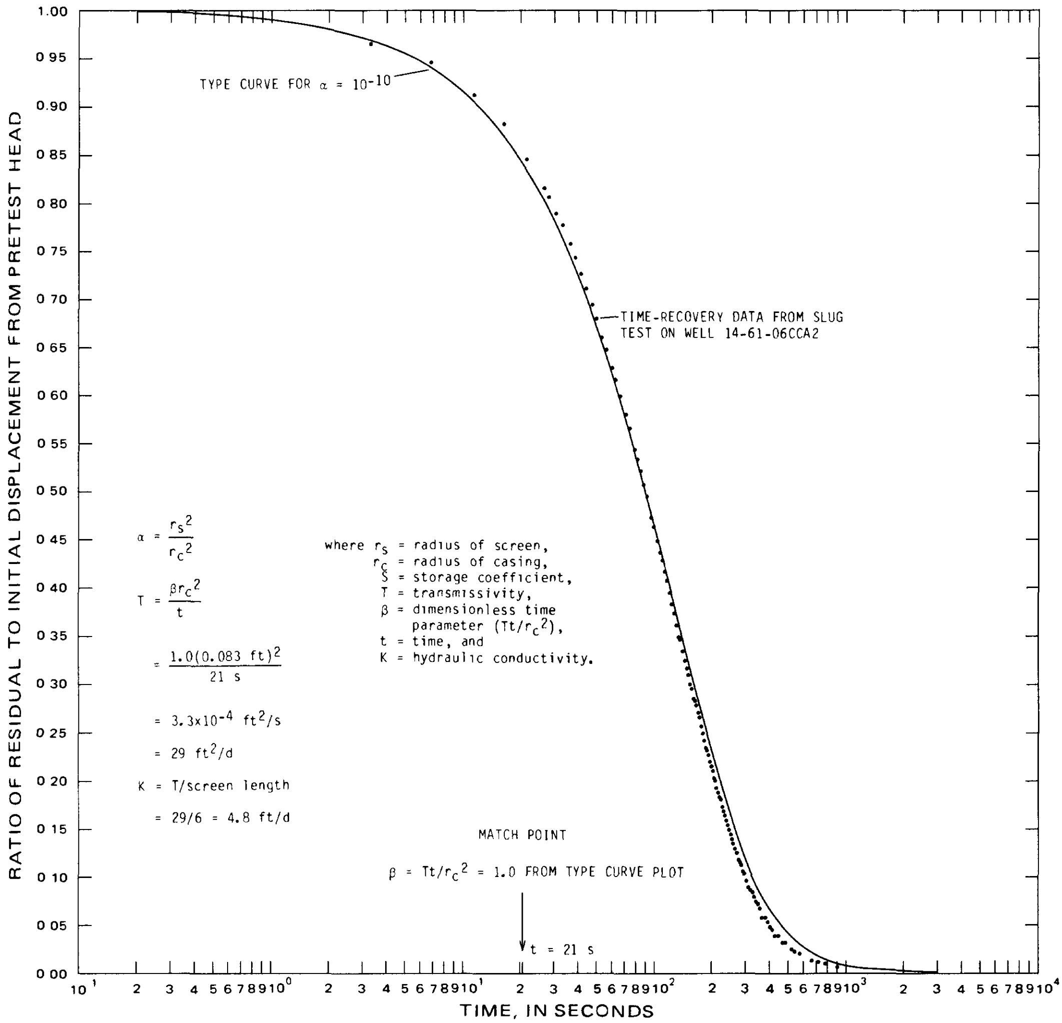


FIGURE 3.—Example of method of Cooper and others (1967) for determination of aquifer transmissivity.

unaffected by the flow required to equalize the pressure differential induced between the well screen and the aquifer by the slug. Hvorslev's formula for the typical aquifer settings and well installations of this project assumes spherical flow (or semispherical if the screen is set at the aquifer top or bottom), but is explicitly solved for the horizontal component of hydraulic conductivity. A coefficient,

$$m = \frac{K_h}{K_v}$$

where K_h = horizontal hydraulic conductivity and K_v = vertical hydraulic conductivity, is included that compensates for known conditions of anisotropy. A value of $m = 1.0$ was assumed in all calculations for values presented in this report.

A convenient application of the Hvorslev theory involves a semilogarithmic plot of the ratio residual (a decreasing function of time: $H(t)$) to initial displacement (a constant head value: H_o) from pretest head versus time (fig. 4). The data points, according to theory, plot along a straight line passing through the origin. The slope of this line determines a parameter, called the basic time lag (τ), that is used in an equation for the determination of the horizontal component of hydraulic conductivity.

Results of the slug-test analyses are compiled by aquifer in table 1. Most of the hydraulic-conductivity values calculated by the Cooper method are higher than those of the Hvorslev method. The mean ratio of the two values for all the pairs listed is 2.0, although 24 of the 34 values are in the range from 2.2 to 2.4. The relationship between the two sets of values, represented graphically in figure 5, indicates that the methods yield highly correlative results (coefficient of determination (R^2) = 0.95), but that one is about twice the magnitude of the other.

The discrepancy probably is attributable to the differing assumptions inherent to the two methods. If the aquifer is essentially isotropic, flow will deviate from the assumed radial condition of the Cooper method due to the effects of the partially penetrating wells typical of this project. The Cooper method will, therefore, overestimate the horizontal hydraulic conductivity because some of the water entering the well does so with a vertical component of velocity. If, on the other hand, the aquifer is highly anisotropic with a horizontal to vertical hydraulic-conductivity ratio in the 100 to 1,000 range, values determined by the Hvorslev method should be 1.4 to 1.7 times greater than the values, all based on the assumption of isotropy, shown in table 1 and in figure 5. This reasoning is essentially that suggested by Prudic (1982) in a study of the hydraulic conductivity of fine-grained till.

Without knowledge of the degree of anisotropy prevalent in the aquifers studied, there is no basis for selecting one method of analysis over the other. Therefore, a simple mean of the two values, as shown in table 1, is used in subsequent discussions.

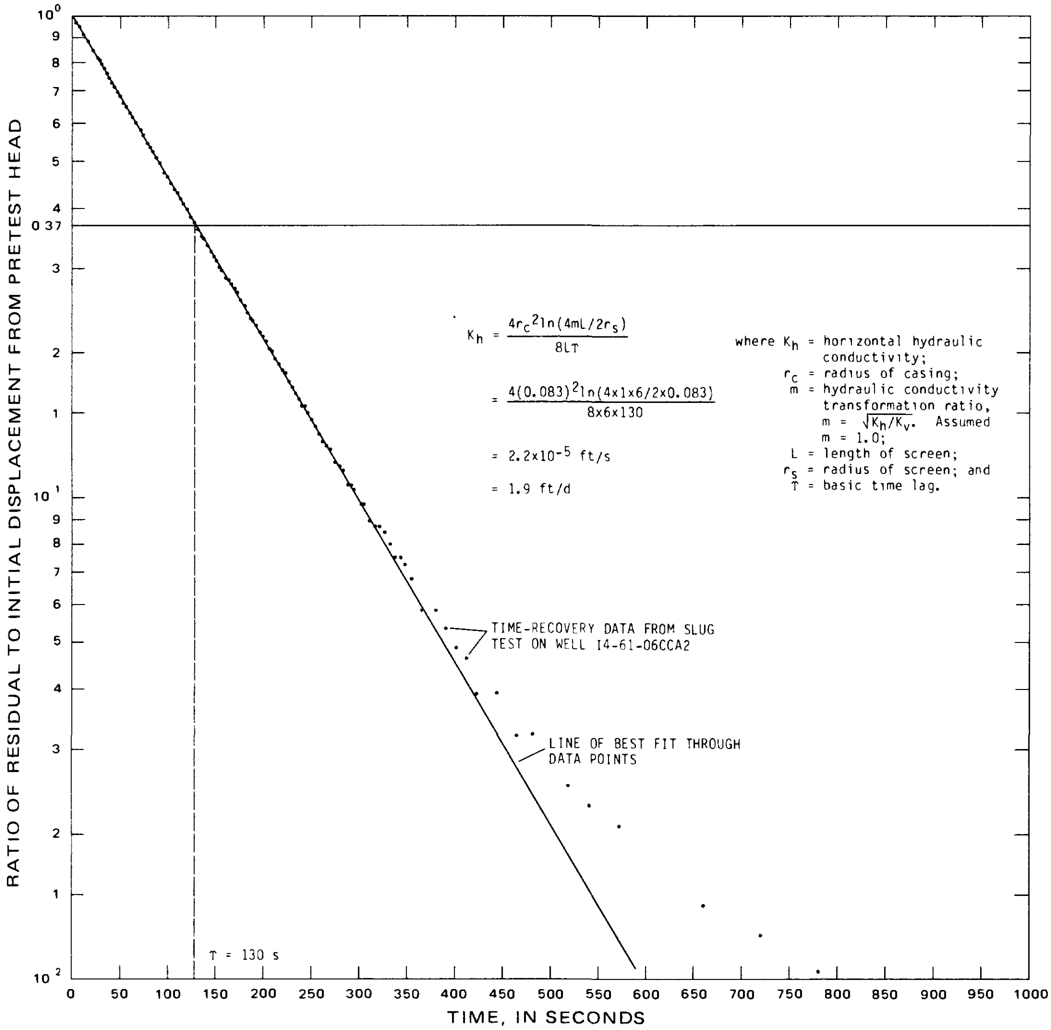


FIGURE 4.—Example of method of Hvorslev (1951) for determination of aquifer hydraulic conductivity.

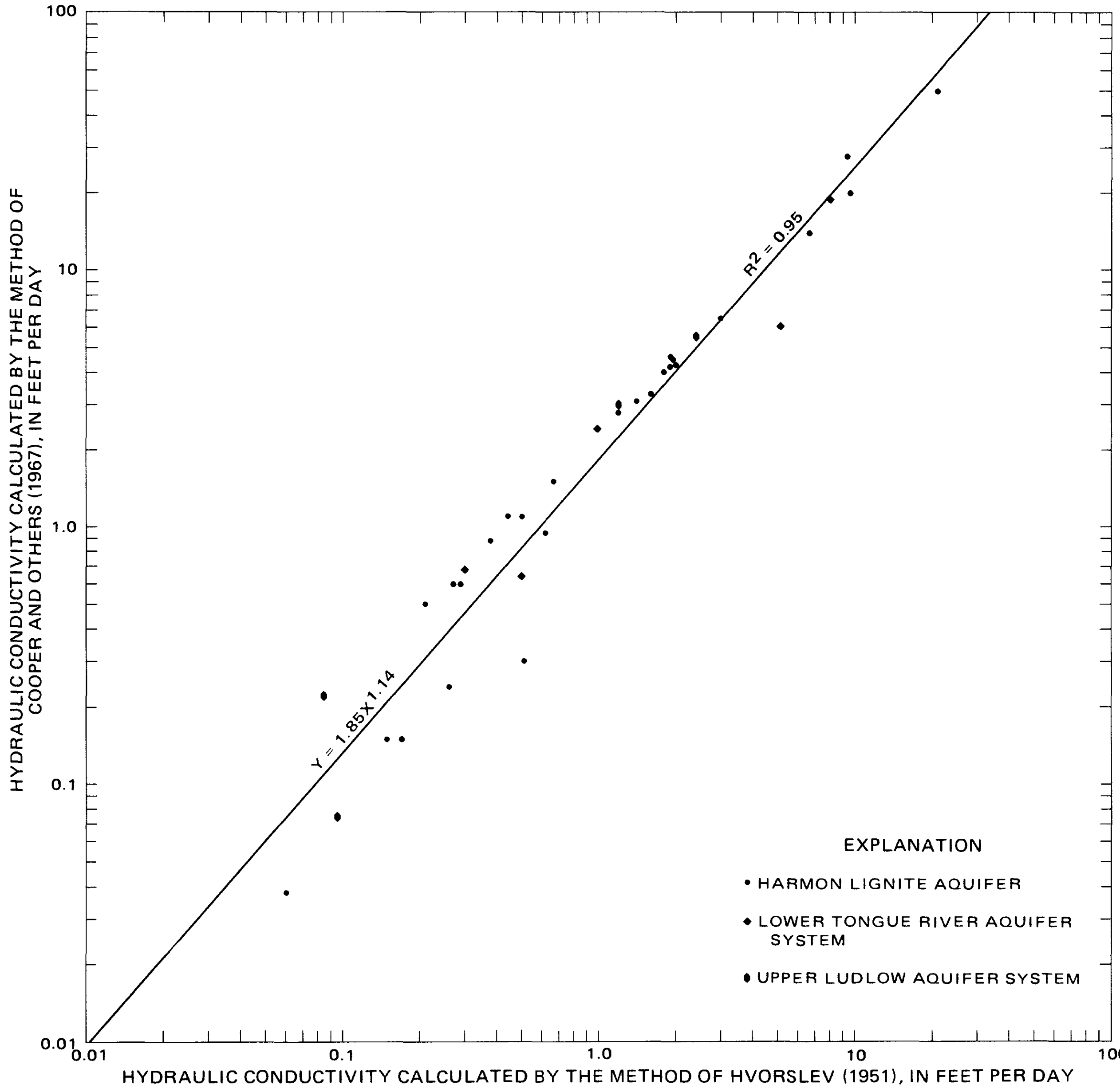


FIGURE 5.—Comparative results of two methods of determination of hydraulic conductivity from slug-test data.

TABLE 1.--Hydraulic conductivity values as determined by two methods of analysis for slug-test data

Well location	Screened interval (feet)	Hydraulic conductivity by method of Cooper and others (1967) (foot per day)	Hydraulic conductivity by method of Hvorslev (1951) (foot per day)	Mean value (foot per day)
		Harmon lignite aquifer		
13-60-11DDD2	60-70	4.5	2.0	3.3
13-61-07DDD	80-90	4.3	2.0	3.2
14-60-24BAA	124-134	3.3	1.6	2.5
14-61-06CCA2	118-124	4.6	1.9	3.3
14-61-30AAA2	260-270	.50	.21	.36
15-60-35DCC2	126-138	.24	.26	.25
15-61-30AAA2	56-66	50	21	36
138-106-01AAA	112-122	.60	.27	.44
138-106-02AAA	51-61	2.8	1.2	2.0
138-106-11AAA	38-50	28	9.4	19
139-105-21AAA2	340-350	.60	.29	.45
139-106-23BBB	82-92	3.1	1.4	2.3
139-106-25CCC	85-95	6.5	3.0	4.8
140-105-06BBB2	125-135	20	9.6	15
140-106-02DDC	177-189	.15	.17	.16
140-106-12ADD	216-226	.15	.15	.15
140-106-36BCC	140-150	1.1	.50	.80
141-105-03BBB	269-279	.95	.62	.79
141-105-09BBB	236-246	.30	.51	.41
141-105-17ADC	55-65	14	6.6	10
141-105-20BBB	95-107	4.2	1.9	3.1
141-105-20CCC2	142-152	1.1	.44	.77
141-105-28AAB	130-142	4.0	1.8	2.9
141-105-29ADD	123-133	.88	.38	.63
141-105-36AAA2	360-370	1.5	.66	1.1
		Lower Tongue River aquifer system		
13-60-11DDD	208-218	6.1	5.0	5.6
14-61-06CCA1	143-155	.68	.30	.49
140-105-06BBB1	190-201	19	8.0	14
141-105-05BBB1	196-206	2.4	1.0	1.7
141-105-07DDD2	197-207	.64	.50	.57
		Upper Ludlow aquifer system		
14-61-30AAA1	453-459	5.5	2.4	4.0
15-61-30AAA1	289-299	3.0	1.2	2.1
139-105-21AAA1	580-586	.073	.095	.084
141-105-36AAA1	593-599	.22	.085	.15

GEOGRAPHY

Topography and Drainage

The study area lies within the unglaciated Missouri Plateau section of the Great Plains physiographic province (Fenneman, 1946). South of latitude 47°00' N., the landscape is relatively level and local relief generally is very gradual. The northern part of the area, however, is markedly dissected by Beaver Creek, Little Beaver Creek, and Hay Creek. Local relief in the near-stream areas can be several tens of feet. Regionally the land surface slopes to the north at about 15 ft/mi. Altitudes at the top of a few of the buttes scattered around the area exceed 3,000 ft, while the altitude at Beaver Creek where it flows across the Montana-North Dakota border is about 2,420 ft.

The study area lies within the drainage basin of the Little Missouri River. Most of the minable part of the study area is drained by Beaver Creek and its tributaries--Duck, Hay, East Branch Hay, and Little Beaver Creeks. Beaver Creek flows into the Little Missouri River about 35 mi northeast of Beach in the northwestern corner of Billings County (northeast of the mapped area). The southeastern and eastern parts of the study area are drained by Bullion, South Branch Garner, Andrews, and Elk Creeks (fig. 6), all tributaries of the Little Missouri River.

Climate

Long, cold winters and short, hot summers are typical of the semiarid climate of the study area. The area has a mean annual temperature of 41.5°F, as recorded at Wibaux, Mont. by the U.S. Environmental Data Service (1973). The daily high temperature is greater than or equal to 90°F on an average of 23 days per year. The daily low temperature is less than or equal to 0°F on an average of 43 days per year (Jensen, 1977). About 80 percent of the mean annual precipitation of 14.19 in. occurs during the months of April through September. The mean annual pan evaporation potential for the study area is about 52 in.

The length of the growing season, defined as the number of days between the average date of the last spring frost and the first fall frost, is about 125 days and extends from May 20 to September 18 (Jensen, 1977).

Commerce

The Wibaux-Beach area is served by U.S. Interstate 94, Montana State Highway 7, and North Dakota State Highway 16. Also, a main line of the Burlington Northern Railroad traverses the study area (fig. 1).

Nearly all of the land in the southern two-thirds of the study area is farmed for the production of small grain crops. Wheat, oats, and barley are the most common grains. Alfalfa production also is common in this area. Pastureland used for grazing of cattle and sheep is more prevalent in rougher topography along the lower reaches of Little Beaver and Hay Creeks in the northern third of the area.

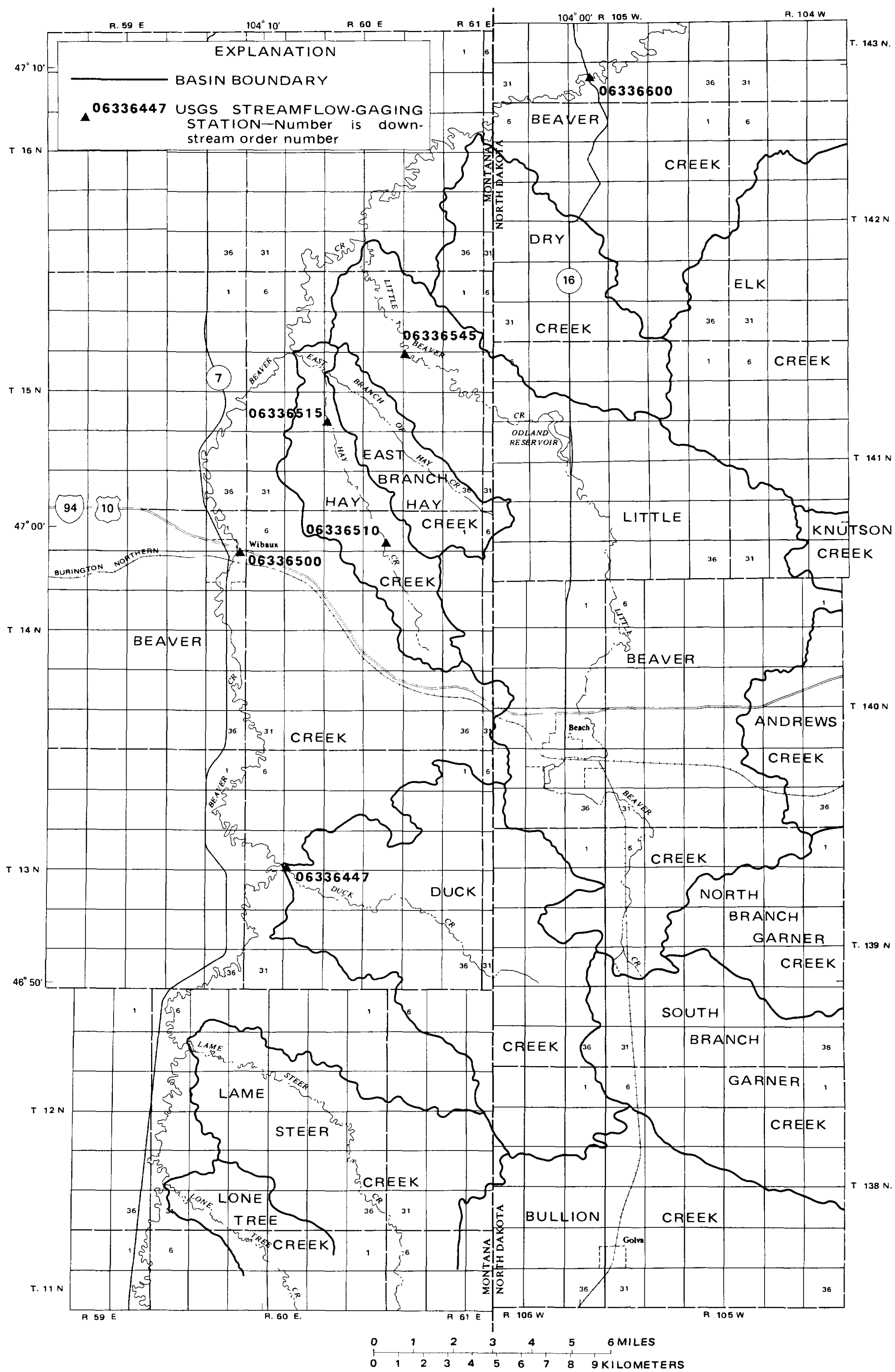


FIGURE 6.—Streams, basin boundaries, and streamflow-gaging stations in the study area.

The economy of the area is based almost entirely on agriculture and related small businesses. There is no commercial production of lignite at this time (1982).

GEOLOGY

The Wibaux-Beach study area lies on the western flank of the Williston basin, one of the largest structural basins in North America. The basin underlies about 200,000 mi^2 in parts of North and South Dakota, Montana, Saskatchewan, and Manitoba. The total thickness of sedimentary deposits at the deepest part of the basin in western North Dakota is at least 15,000 ft. From the basin center, all beds ascend in altitude and thin toward the basin fringes, where each feathers to extinction due either to erosion or non-deposition. The Fort Union coal region of North Dakota and easternmost Montana corresponds with the area bounded by the crop of the Tertiary-Cretaceous contact.

A generalized stratigraphic column for the study area, ascending from the base of the Upper Cretaceous, is shown in table 2. Tongue River strata form the land surface of the study area except where scattered remnants of the Sentinel Butte Member, Fort Union Formation, occur at the top of a few of the highest buttes. Alluvial deposits a few feet thick lie along some of the streams in the area. A north-south hydrogeologic section of the study area is shown on plate 1 (in pocket).

Pre-Cenozoic Rocks

The Upper Cretaceous Fox Hills Sandstone generally is considered the lowest stratigraphic unit that yields potable water in the study area. The rocks beneath the Fox Hills consist of shale, limestone, dolomite, sandstone, and evaporites. As much as 13,000 ft of these deposits overlies the Precambrian crystalline rocks beneath the study area, and for the most part these deposits contain brackish water. The Upper Cretaceous Pierre Shale underlies the Fox Hills Sandstone and consists of some 2,000 to 3,000 ft of dark-gray marine shale.

Fox Hills Sandstone (Upper Cretaceous)

The Fox Hills Sandstone is of marine and brackish origin and consists of interbedded sandstone, siltstone, and shale. The sandstone generally is poorly consolidated but in places is well cemented. Lignitic shale laminae are present in the upper part. The Fox Hills underlies the entire study area as well as the western two-thirds of North Dakota and a large part of eastern Montana.

Depth to the top of the Fox Hills in test hole 140-105-30CCC at Beach was 1,032 ft (altitude 1,738 ft; Anna, 1980). A structure-contour map by Anna (1981) indicates that the base of the Fox Hills lies at an altitude of about 1,600 ft at the southern end of the study area and at about 1,000 ft at the northern end.

In western North Dakota the Fox Hills ranges in thickness from about 60 ft (Hares, 1928) to nearly 400 ft (Cvancara, 1976). The Fox Hills is 258 ft thick (pl. 1) in the test hole at Beach (Anna, 1980).

TABLE 2.--Generalized Tertiary-Upper Cretaceous section for the Wibaux-Beach study area

Erathem	System	Series	Formation or member: Eastern Montana		Formation or member: Western North Dakota		Lithologic characteristics
Cenozoic	Tertiary	Paleocene	Fort Union Formation	Tongue River Member	Fort Union Formation	Sentinel Butte Member	Interbedded sand, silt, clay, and lignite.
						Tongue River Member	Interbedded yellow to gray sand and sandstone, silt, clay, lignite, and limestone lenses. (Includes the Harmon and Hanson lignite beds.)
				Lebo Shale Member		Cannonball Member	Lebo Shale Member: Gray clay, silt, shale, and lignite.
				Tullock Member		Ludlow Member	Tullock Member: Gray interbedded sand, silt, clay, and lignite. Cannonball Member: Greenish-gray marine clay and silt; minor sand. Ludlow Member: Gray clay, silt, sand, and lignite.
Mesozoic	Cretaceous	Upper Cretaceous	Hell Creek Formation				Interbedded gray claystone, siltstone, and sandstone.
			Fox Hills Sandstone				Grayish-white sandstone and interbedded gray siltstone and shale.
			Pierre Shale				Dark-gray fissile marine shale with thin limestone concretions.
			Niobrara Formation				Interbedded gray calcareous shale and marl.
			Carlile Shale				Interbedded gray marl, shale, and siltstone.
			Greenhorn Formation				Gray calcareous shale and marl.
			Belle Fourche Shale				Gray shale with scattered limestone concretions.

Hell Creek Formation (Upper Cretaceous)

Continental deposits of the Hell Creek Formation in North Dakota resulted from the eastward progradation of detrital sediments behind the retreating Fox Hills sea at the close of Cretaceous time. The Hell Creek primarily consists of lignitic and bentonitic claystone, siltstone, and sandstone. Concretions and siderite nodules are common, as are localized, thin lignite beds.

The Hell Creek Formation underlies the western half of North Dakota and eastern Montana, including all of the study area. The top of the Hell Creek was penetrated at a depth of 760 ft in test hole 140-105-30CCC at Beach. Anna (1980) recognized 272 ft of Hell Creek strata in this test hole.

Cenozoic Rocks

Fort Union Formation (Tertiary)

Ludlow-Cannonball (Tullock-Lebo Shale) Members

Tertiary deposition in North Dakota began with the fluvial sedimentation of the Ludlow Member of the Fort Union Formation (Paleocene). Nearly contemporaneously, a final westward transgression of the waning inland sea into western North Dakota resulted in the deposition of the marine and marginal marine Cannonball Member of the Fort Union Formation. The two members are lateral time equivalents and may be loosely described as opposite-facing, intertonguing clastic wedges. The Cannonball Member pinches to extinction near the North Dakota-Montana border, however, and probably is absent beneath the study area. The Lebo Shale Member, a nonmarine, apparently lacustrine unit, is recognized in Montana as a probable time equivalent to the Cannonball.

The time and rock sequence recognized as the Ludlow Member in western North Dakota is designated the Tullock Member in Montana. Although the Tullock deposits are somewhat coarser grained than the Ludlow because of proximity to the sediment source area, there is no distinction near the Montana-North Dakota border--the difference is only in nomenclature between the two states. The term Ludlow will be used in this report.

The Ludlow Member is composed of alternating beds of gray clay, silt, and sand. The clays and silts generally are unconsolidated, but the sand sometimes is moderately cemented. Thin lignite beds are common throughout the member and Hares (1928) described a lignite bed of commercial thickness near Rhame, in north-central Bowman County, N. Dak.

Ludlow strata underlie most of the western half of North Dakota, including all of the study area. The member crops out in an arcuate band along the southern tier of counties in the western part of the State. It crops out in the study area only along the extreme western edge. In general, from west to east, the fully preserved Ludlow section thins, intertongues with the Cannonball, and nearly pinches out near the eastern crop area.

Anna (1980) picked the top of the Ludlow Member at a depth of 288 ft and identified a total of 330 ft of Ludlow strata, split by a tongue of material equivalent to the Lebo, in test hole 140-105-30CCC (pl. 1). Sand beds of the Ludlow Member were deposited mainly as channel fill in a near-terminal fluvial and upper deltaic environment. Individual sand beds generally are a few tens of feet thick, but a bed 84 ft thick was penetrated in test hole 140-106-1AAA (Anna, 1980).

The Lebo Shale Member and equivalent, which consist of bluish to dark-gray clay and silt, brown to black carbonaceous shale, and localized thin lignite beds, probably underlie the entire study area. Anna (1980) identified 142 ft of strata equivalent to the Lebo in test hole 140-105-30CCC. No attempt was made to discriminate the Lebo Shale Member from the Ludlow Member on the geophysical and lithologic logs obtained during this project.

Tongue River and Sentinel Butte Members

Background.--The name "Tongue River" became part of the stratigraphic nomenclature of the northern Great Plains in 1909 when Taff (1909, p. 129) referred to a "Tongue River coal group" while describing coal-bearing Tertiary beds exposed along the Tongue River near Sheridan, Wyo. Meanwhile, Leonard and Smith (1909) cited a "very noticeable difference," mainly in color, between the buff and light-gray beds in the lower part of the Fort Union strata exposed in the bluffs of the Little Missouri River, and the darker gray beds in the upper part of the Fort Union. Because a nearly full section of the somber gray sequence was exposed on Sentinel Butte, Leonard and Smith (1909) called it the "Sentinel Butte lignite group." The U.S. Geological Survey now recognizes a Tongue River Member and a Sentinel Butte Member, which, in North Dakota, are the uppermost units in the Paleocene Fort Union Formation.

The North Dakota Geological Survey recently assigned much of the stratigraphic sequence that it had recognized as the Tongue River Formation (Fort Union Group) to a new unit, Bullion Creek Formation, for the expressed purpose of avoiding "***the confusion of using different criteria for defining the Tongue River in different areas***" (Clayton and others, 1977). This report will use the U.S. Geological Survey naming convention.

Whether or not strata equivalent to the Sentinel Butte occur in Montana, all Fort Union deposits above the Lebo Shale Member in that State are relegated to the Tongue River Member. Although some of the highest buttes within the Wibaux-Beach study area in North Dakota are capped with Sentinel Butte remnants, the occurrences are too isolated to be of significance to the hydrologic study of the area.

Depositional Environment.--The Tongue River Member was deposited on the lower part of an aggradational detrital plain stretching from an eroding highland in north-central Wyoming and central Montana to the retreating Cannonball sea in central North Dakota. The sand, silt, and clay beds originated as channel, levee, and overbank deposits, respectively, and the lignite was derived from peat accumulations in swamps adjacent to either braided or meandering streams (Jacob, 1973; Rehbein, 1977). The occurrence of thick channel sands and areally extensive lignite beds indicates a relatively stable channel configuration during much of the depositional period.

Lithology.--The Tongue River Member consists of very fine to (rarely) medium-grained sand, sandstone, silt, clay, lignite, and thin limestone lenses. The Tongue River clastic deposits are shades of brown, yellow, and rust within the oxidized zone near the surface. All of the clastics are shades of gray and green where reduced, or grayish-brown to nearly black if abundant organic material is included. The sands, especially those in the lower part of the Tongue River, often have a "salt and pepper" appearance. White and black mineral grains predominate in this material, and there usually is a generous scattering of green minerals.

The clastics generally are in varying states of admixture, but occasionally are well sorted. The silts and clays are markedly layered and individual bed thicknesses range from less than an inch to a few feet. Uniform beds more than 5 ft thick are unusual. Fissility of the clay beds (thereby distinguishing them as soft shales) was observed very infrequently. With the exception of some cemented sandstone "ledges" normally less than 1 ft thick, the clastic sediments in the subsurface are unconsolidated and yield very readily to a drag-type drill bit. Some of the limestone lenses are very firm, but generally are only inches thick and exist at few places.

Occurrence and thickness.--The Tongue River Member lies at the land surface over nearly the entire study area and is everywhere an erosional surface except on a few scattered buttes where the Sentinel Butte Member overlies a full section of Tongue River. The preserved thickness of the Tongue River increases from west to east across the study area. From the Harmon lignite outcrop where some 90 to 190 ft of Tongue River section is present, the member thickens down dip toward the northeast where as much as 450 ft of Tongue River strata may be present.

Lignite beds exist throughout the Tongue River section and are the most areally persistent lithology within the member. The commercial bed of the Wibaux-Beach deposit is the Harmon bed (bed "C" of May, 1954). The Harmon probably is the most widespread and one of the most commercially important lignite beds in North Dakota. Rehbein (1977), using borehole geophysical logs, mapped the Harmon bed throughout a 6,600 mi^2 study area in west-central North Dakota.

The top of the Harmon bed lies 108 to 206 ft above the base of the Tongue River Member and from virtually zero to about 350 ft below the land surface in the study area. The Hanson lignite bed underlies the Harmon by some 20 to 100 ft and was the only lignite bed recognized by the author as part of the Tongue River section below the Harmon bed.

The maximum thickness observed for the Harmon lignite was 34 ft in a test hole at 14-60-34CBB. Thicknesses of 30 ft or more are identified over several square miles on the thickness map (fig. 7). The lignite thickness is greater than 25 ft in a broad, east-west trending belt encompassing the town of Beach. It progressively thins with distance to the north and south. Structure contours drawn of the top of the Harmon lignite bed are shown in

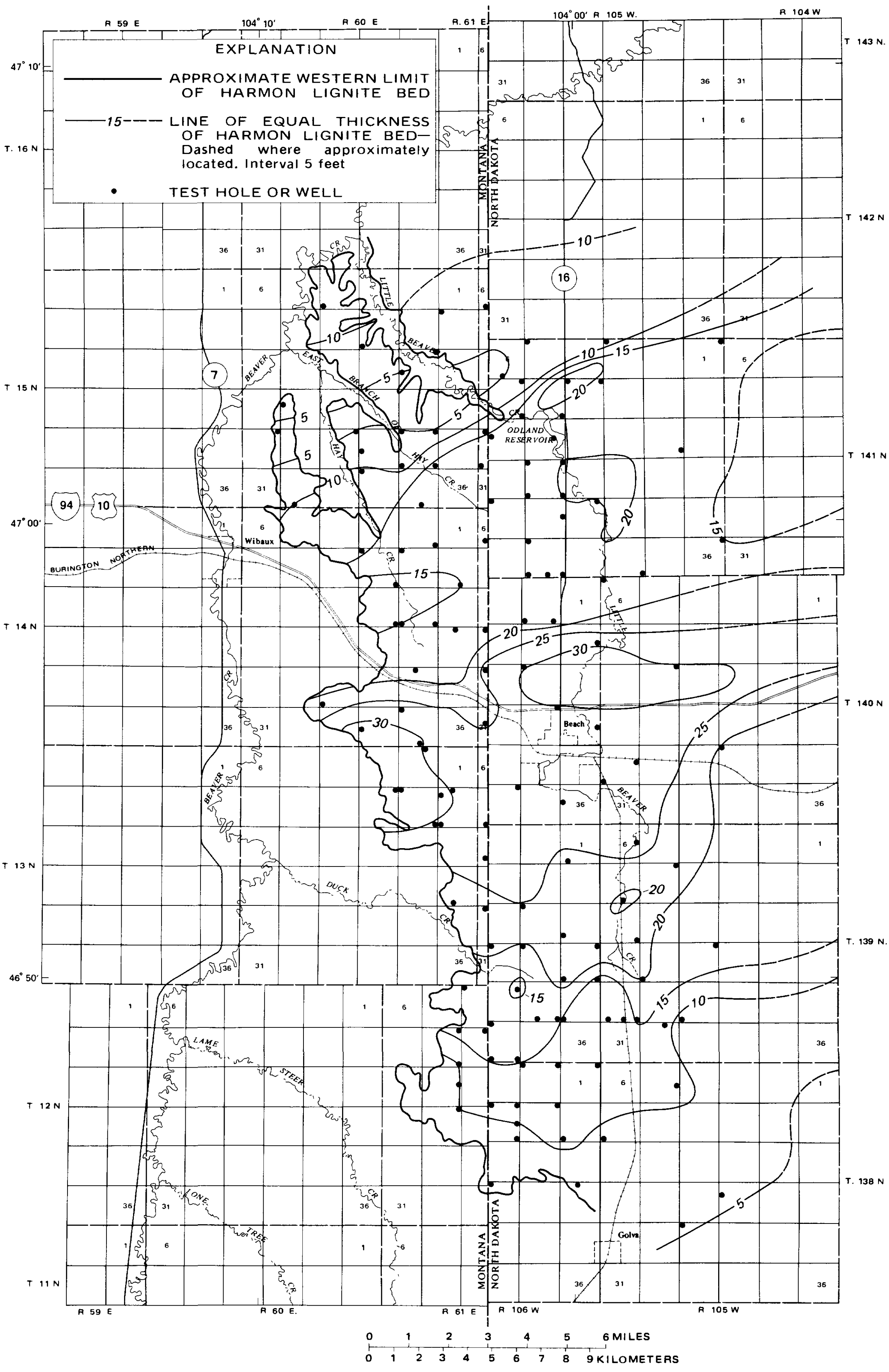


FIGURE 7.—Thickness of the Harmon lignite bed.

figure 8. The Harmon dips to the east-northeast throughout the study area at a gradient that ranges from 15 to 80 ft/mi. Except in the synclinal and anticlinal areas near the top of T. 140 N., R. 106 W., the gradient generally is from 40 to 60 ft/mi.

Although many lignite beds occur within the 300 ft of section overlying the Harmon, most are less than 4 ft thick. No attempt was made by the author to correlate or map these beds. Due to the general lack of sand and of lignite beds more than 4 ft thick above the Harmon bed, the Harmon lignite bed was considered the shallowest aquifer throughout the study area.

The sands in the Tongue River Member in western North Dakota and easternmost Montana were deposited as channel and mouth bar sediments in meandering and braided stream systems. The sands occur in long, sinuous bodies that may or may not coalesce to form broader tabloid bodies. The density of test holes in the study area that penetrate to the base of the Tongue River Member is not sufficient to define the width of the meander "belts" or of the individual channels. The aggregate thickness of sand in the lower Tongue River Member--defined here as that part of the member between the Harmon lignite bed and the base of the Tongue River Member--is shown in figure 9. Many of the test holes throughout the study area encountered no sand in the lower Tongue River Member. If the assumption is made that the observed sand beds were deposited in generally eastward flowing streams, the zero thickness sites may be associated with areas of interstream nondeposition, also trending generally eastward. A possible configuration is shown in figure 9. It is very likely that additional sand belts or channels would be found if the test-hole density were greater.

The lower Tongue River section was completely penetrated at 27 test-hole sites during this or earlier hydrology projects. No sand was encountered at 10 (37 percent) of the test-hole sites. The aggregate sand thickness at the other 17 (63 percent) sites ranged from 18 to 118 ft and the sand generally occurred in a single bed. The proportion of sand to the total lower Tongue River interval ranged from 0 to 0.69. The mean value at all 27 sites was 0.28.

At least 140 ft of Tongue River section overlying the Harmon lignite was penetrated at 27 sites. No sand was encountered at 10 of the sites. The sand proportion values ranged from 0.06 to 0.38 at the other sites. The mean value at all 27 sites was 0.11.

Basal contact.--The criteria for picking the contacts of the Tongue River Member evolved largely from studies of surface exposures where color development accompanies the weathering processes and can impart a distinct signature to the outcropping beds. In surface exposures, the basal Tongue River contact has conventionally been placed where the gray beds of the Ludlow give way to the yellow beds of the Tongue River. The color distinction, however, does not occur in the unweathered subsurface deposits where all the sediments are shades of gray, green, and blue green. Rather, the member boundary is drawn at the bottom of the lower Tongue River sands. In the absence of a lower sand, this author drew the contact at the top of the first lignite bed below the Hanson bed. For the infrequent condition where

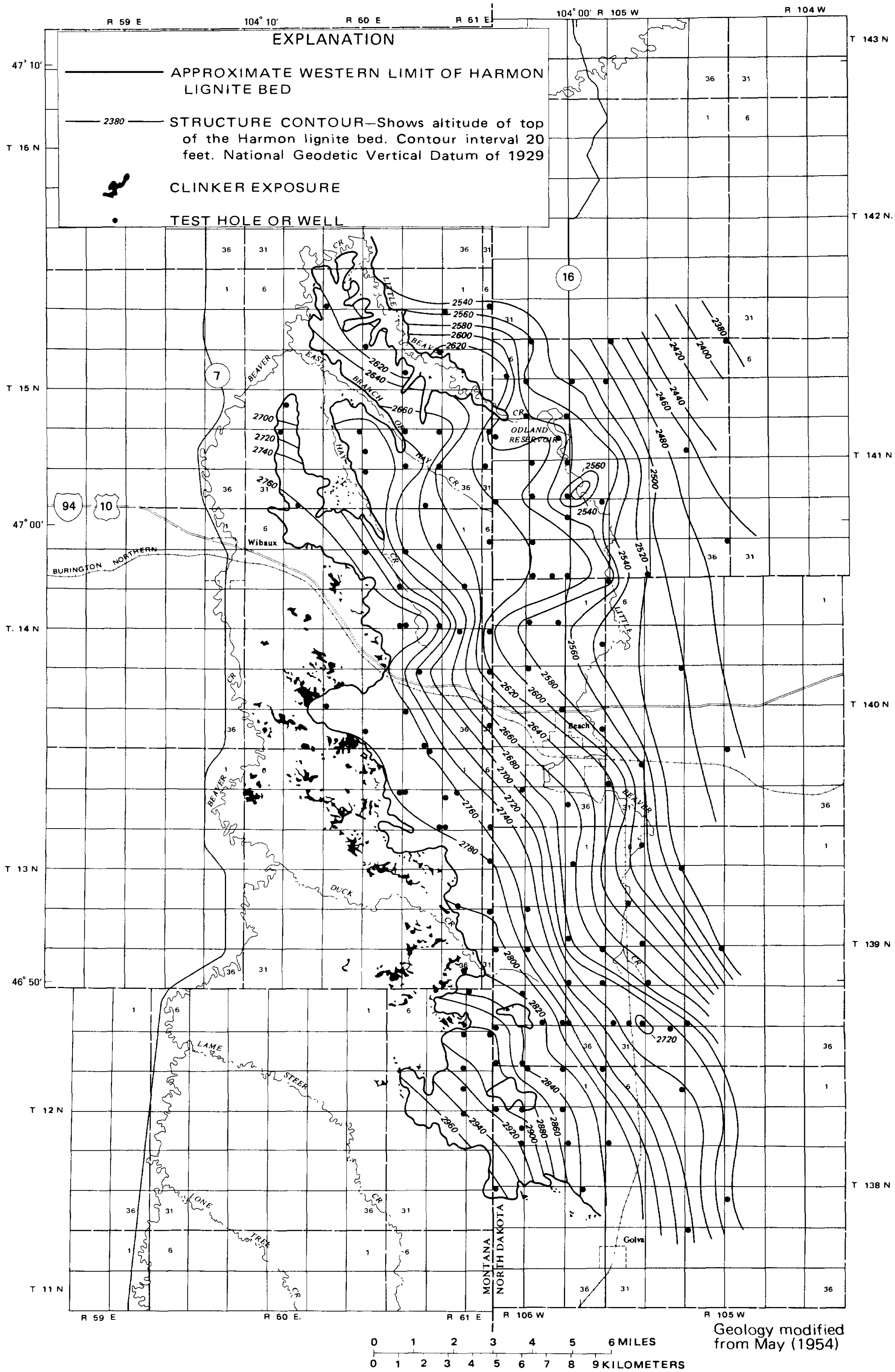


FIGURE 8.—Structure contours of the top of the Harmon lignite bed.

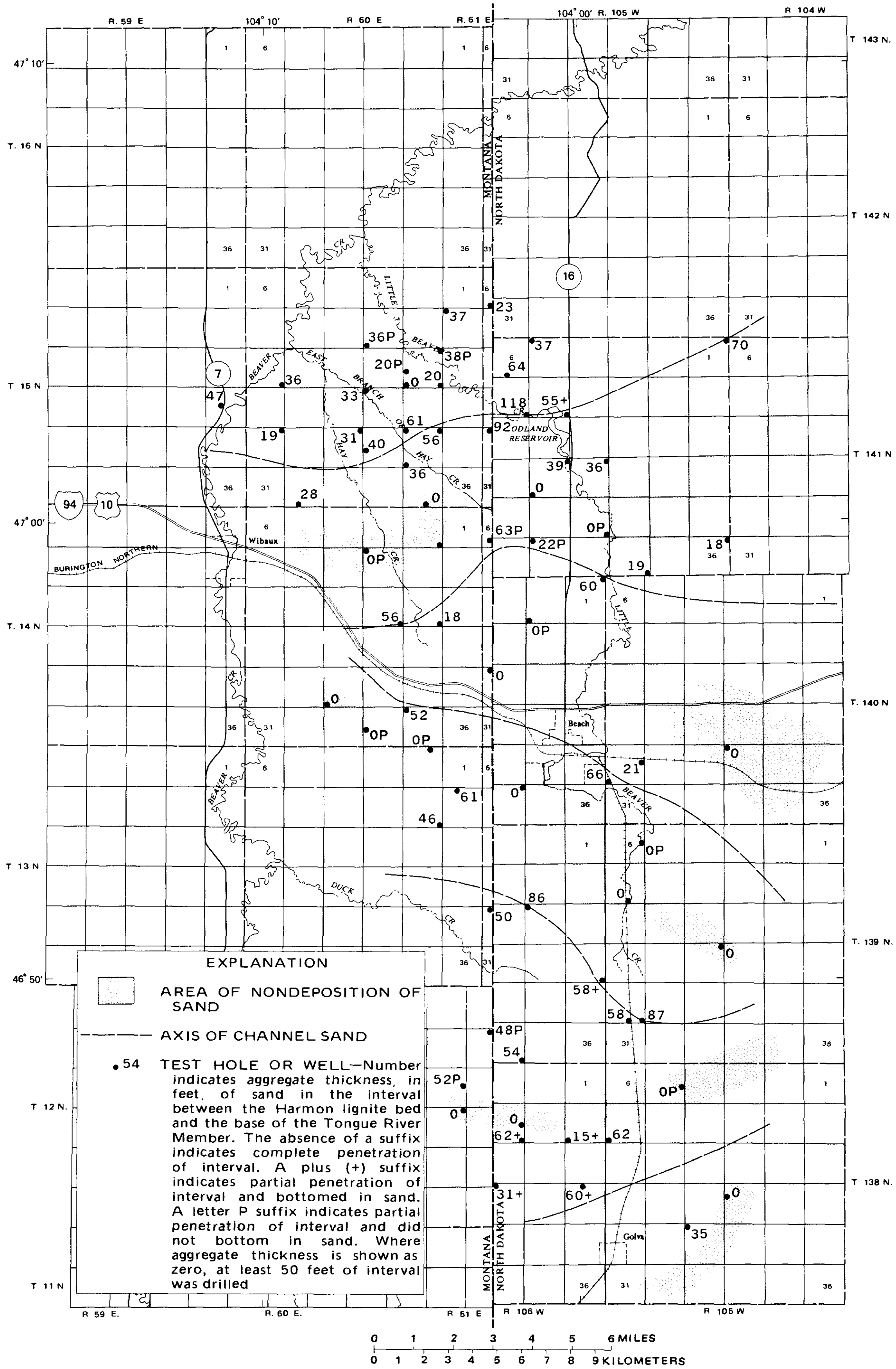


FIGURE 9.—Aggregate thickness of sand between the Harmon lignite bed and the base of the Tongue River Member.

both the lower Tongue River sand and an uppermost Ludlow lignite were absent, the contact was placed at the base of the coarsest clastic bed occurring within an appropriate interval (100 to 150 ft) beneath the Harmon lignite.

Structure contours drawn of the base of the Tongue River Member are shown in figure 10. The contours indicate an east-northeasterly dip ranging from about 15 to nearly 100 ft/mi. The general appearance of this structure map is similar to that of the Harmon lignite bed.

Quaternary Deposits

The Wibaux-Beach study area was not glaciated during the Pleistocene advances. Quaternary deposition, therefore, is represented only by thin alluvial deposits along some of the streams in the area. Alluvial materials were encountered at two test-hole sites. Test hole 141-105-07DDD was drilled about 200 ft from Little Beaver Creek on what appeared to be a broad terrace a few feet above the present level of the stream. About 26 ft of silt and clay with pebble-size clinker and carbonate rock inclusions was penetrated above the bedrock. Test hole 15-60-27ADD, at East Branch Hay Creek, was drilled through about 20 ft of silt, sand, and gravel before the hole was abandoned due to caving. Alluvial deposits undoubtedly underlie Beaver Creek and may be a few tens of feet thick, although data are not available to confirm this.

HYDROLOGY

Surface-Water Resources

The streams of the Wibaux-Beach area, their respective basin boundaries, and streamflow-gaging stations are shown in figure 6. Those streams that drain the minable area include Beaver, Little Beaver, Hay, East Branch Hay, Duck, Bullion, and North and South Branch Garner Creeks. Continuous-record streamflow-gaging stations were established in October 1977 on Beaver Creek at North Dakota Highway 16, and in March 1978 on Little Beaver Creek, at two locations on Hay Creek, and on Duck Creek. A station on Beaver Creek at Wibaux that had been operated from 1938 to 1969 was reinstated in October 1978. The discharge data and station descriptions for each of these stations are published in the annual U.S. Geological Survey report "Water Resources Data for North Dakota."

Discharge data in terms of mean monthly flows, mean annual flows, and instantaneous maximum and minimum flows for each of the streams over the period of available record are summarized in table 3. Duration curves of daily flow for Duck Creek, Hay Creek, Little Beaver Creek, and for two sites on Beaver Creek are shown in figure 11. It is important to note that all of the discharge statistics for each stream are based on only 2 to 3 years of record. However, these years had a large range in runoff conditions. Great snow accumulations were recorded during the 1977-78 winter and somewhat less, but still much more than average snowfall, occurred during the 1978-79 winter. From mid-1979 through September 1980, severe drought conditions prevailed. The streams will be discussed in the U.S. Geological Survey's "downstream order" as they appear in the annual data reports.

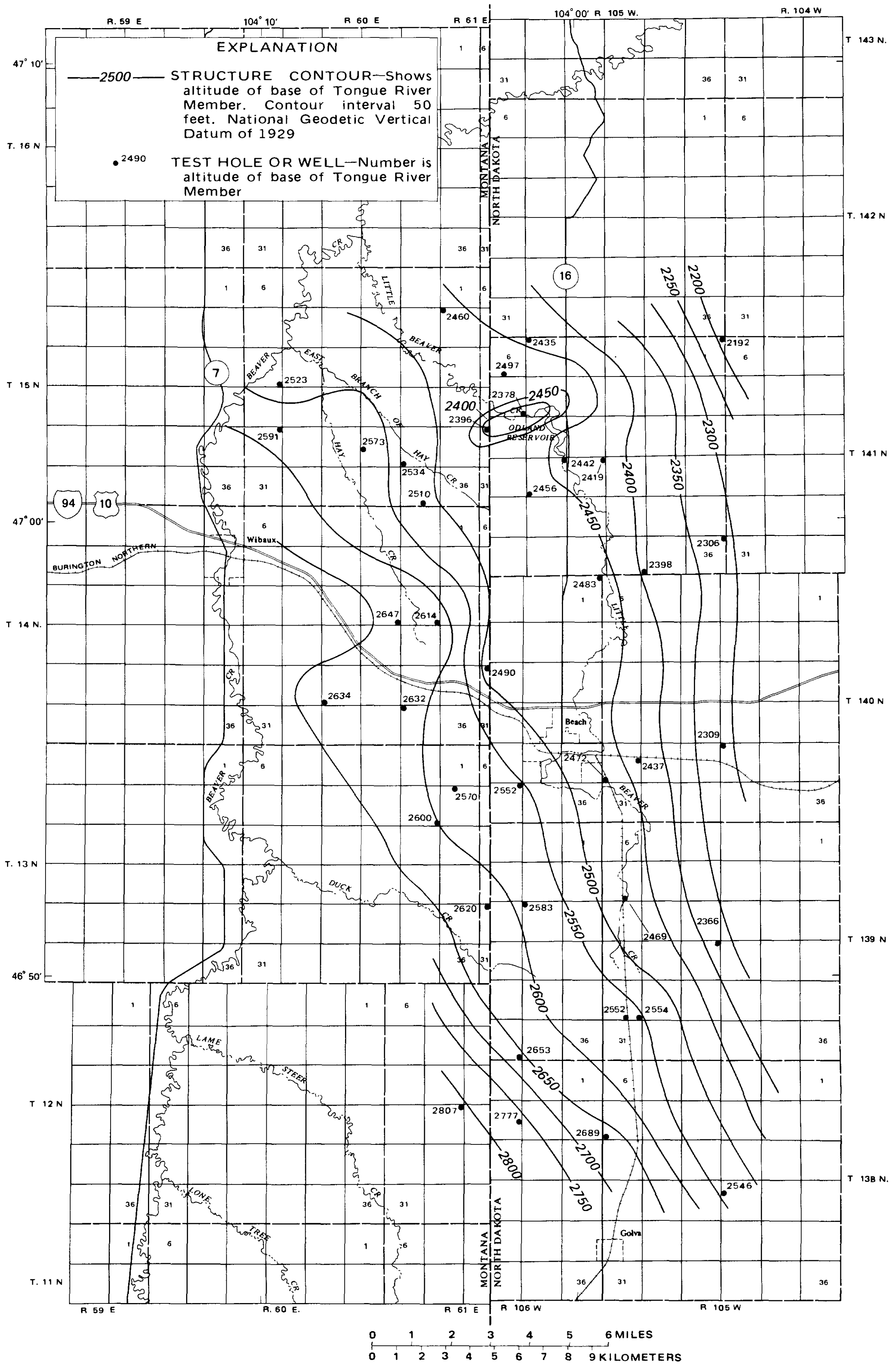


FIGURE 10.—Structure contours of the base of the Tongue River Member.

TABLE 3.--Streamflow statistics for gaged streams in the study area

Drainage area (square miles)	Period of record	Instantaneous extremes for period of record (cubic feet per second) Maximum	Minimum	Mean annual flow (cubic feet per second)	Year	Monthly mean flows (cubic feet per second) Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					06336447 Duck Creek near Wibaux, Montana												
46.5	March 1978 to September 1980	580	0	34.32	1978	--	--	59.0	1.85	0.38	1.10	2.82	0.000	0.000	0.000	0.000	0.000
					1979	0.000	0.000	4.87	18.2	.58	.031	.010	.001	.000	.000	.000	.000
					1980	.000	.000	.003	.000	.000	.000	.000	.000	.000	--	--	--
					06336500 Beaver Creek at Wibaux, Montana												
351	April 1938 to June 1969	3,780	0	22.6													
351	Oct. 1978 to September 1980	1,280	0	16.8	1978	--	--	--	--	--	--	--	--	--	2.86	4.77	2.82
					1979	1.30	2.75	32.7	281	24.8	8.18	6.70	1.62	.80	1.63	4.26	2.83
					1980	1.96	4.52	11.6	6.81	1.87	.18	.16	.018	.18	--	--	--
					06336510 Hay Creek No. 2 near Wibaux, Montana												
4.1	March 1978 to September 1980	85	0	.287	1978	--	--	4.57	0.002	0.000	0.006	0.12	0.000	0.000	0.000	0.000	0.000
					1979	.000	.000	.50	.64	.000	.000	.000	.000	.000	.000	.000	.000
					1980	.000	.000	.061	.000	.000	.000	.000	.000	.000	--	--	--
					06336515 Hay Creek near Wibaux, Montana												
11.4	March 1978 to September 1980	58	0	1.09	1978	--	--	10.1	0.60	0.54	0.98	0.55	0.035	0.038	0.014	0.006	0.000
					1979	.000	.000	2.69	5.16	.59	.16	.11	.031	.010	.010	.010	.010
					1980	.000	.000	.14	.066	.025	.009	.000	.003	.009	--	--	
					06336545 Little Beaver Creek near Wibaux, Montana												
96.2	March 1978 to September 1980	1,850	0	10.41	1978	--	--	154	9.71	4.08	22.2	8.55	0.035	0.039	0.075	0.20	0.17
					1979	.077	.022	24.0	80.3	3.69	.28	5.51	.14	.13	.19	.20	.16
					1980	.15	.21	4.48	1.17	.19	.12	.013	.12	.075	--	--	--
					06336600 Beaver Creek near Trotters, North Dakota												
485	March 1978 to September 1980	2,720	0.04	50.0	1978	1.53	1.60	609	175	41.9	55.3	48.5	8.00	1.61	2.45	5.46	5.13
					1979	4.04	5.11	55.4	406	45.7	14.0	15.5	2.85	.38	.37	2.39	4.70
					1980	3.37	3.07	24.0	10.6	2.38	1.03	.094	.051	.049	--	--	--

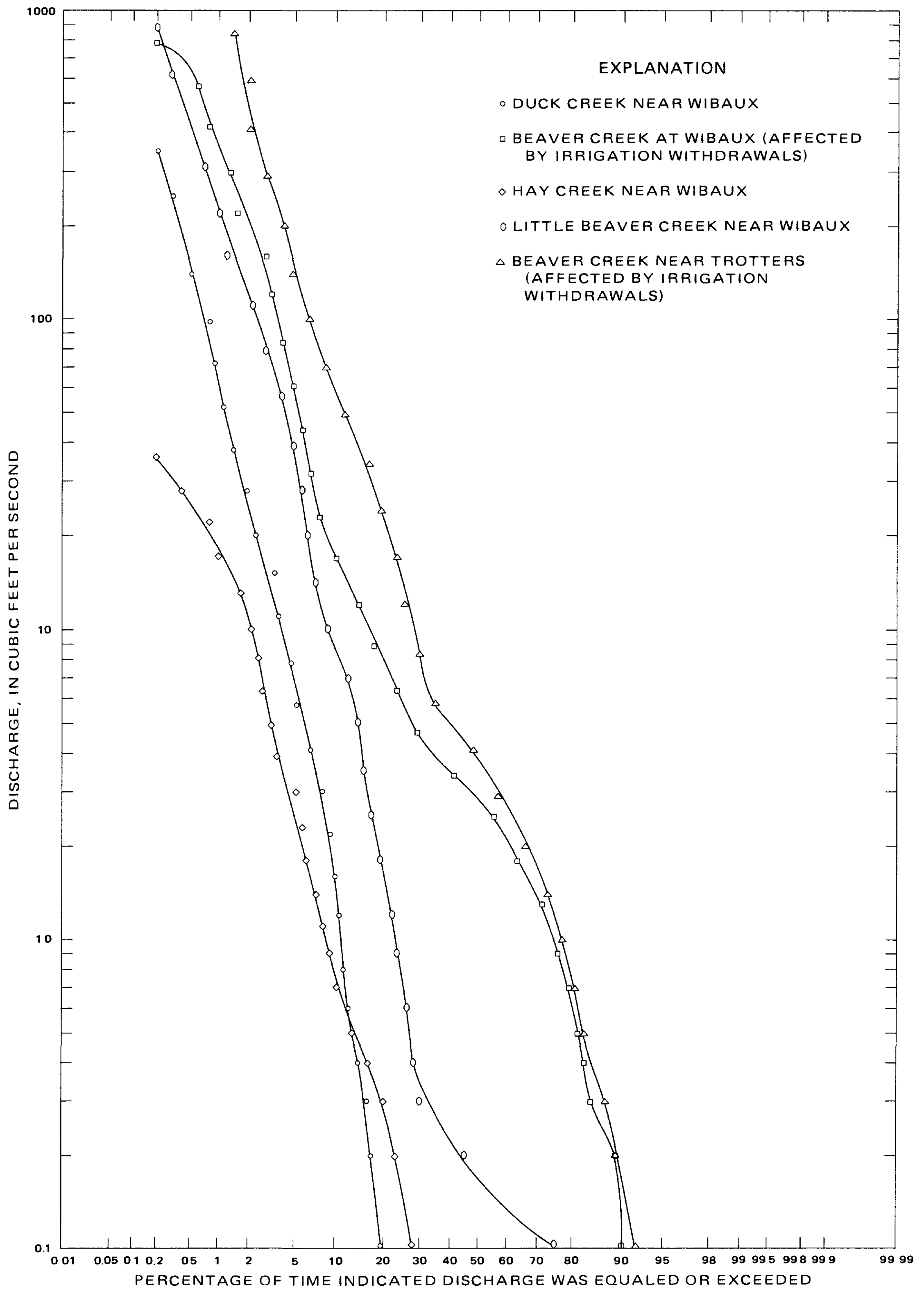


FIGURE 11.—Duration curves of daily flow for streams draining the study area, March 1978 through September 1980.

Duck Creek drains an area of about 47 mi^2 in the southern part of the minable area. The stream flows for only a brief time each year during the snowmelt period and occasionally for a few days immediately following heavy rainstorms. Very flat slopes prevail throughout the drainage basin and nearly all of the area is tilled for crop production. The resulting high infiltration potential limits the amount of precipitation water available for runoff. Inasmuch as no aquifers are incised by the poorly defined stream channel, Duck Creek receives no ground-water inflow.

Of the 351 mi^2 of drainage area above the gaging station on Beaver Creek at Wibaux, roughly 30 mi^2 is within the lignite-deposit area. Flow duration is significantly influenced by upstream withdrawals from the stream for irrigation. The stream occasionally ceases to flow for short periods during the summer, but always flows later in the season after irrigation withdrawals and consumption by riparian vegetation have stopped.

The upstream gaging station on Hay Creek (Hay Creek No. 2) was established as part of the intensive data-collection network for the U.S. Geological Survey Wibaux-Beach watershed project. The station monitors runoff from only 4.1 mi^2 of drainage area. The stream flows at this site only during the spring snowmelt period and immediately following heavy rainstorms. Periods of flow are so brief that the duration curve was not plotted in figure 11.

The lower station on Hay Creek monitors runoff from 11.4 mi^2 of the basin. The stream ceases to flow only during the coldest part of the winter when all water is stored in the channel as ice. The base flow of a few hundredths of a cubic foot per second probably is derived from storage in minor thicknesses of alluvial deposits along the stream channel.

Little Beaver Creek has a poorly defined channel in the upper two-thirds of the basin. The land surface has very gentle slopes and is intensively farmed. Flow occurs only during the spring and immediately following intensive rainstorms. The channel in the lower third of the basin is better defined and, in many places, deeply incised. Seepage runs indicate, however, that the stream flows perennially only in that reach beginning just downstream from the dam on Odland Reservoir (fig. 1). Discharge from the outcropping Harmon lignite aquifer probably is the source of base flow, which ranges from nearly zero to 0.2 ft^3/s, at the gaging station.

Runoff from most of the minable part of the Wibaux-Beach deposit drains, through several tributaries, to Beaver Creek. The station on Beaver Creek near Trotters monitors all of that runoff as well as the runoff from a few hundred square miles of the basin outside the deposit area. Beaver Creek flowed continuously at the Trotters site during the period of record. Much of the channel downstream from Wibaux is deeply incised and, in places, a broad alluvial valley has been established. Discharge from adjacent bedrock aquifers and probably from the alluvial deposits provide a base flow of a few cubic feet per second. Diversions for irrigation greatly deplete this flow during the summer months, however.

Ground-Water Resources

Rocks beneath the base of the Fox Hills Sandstone (Upper Cretaceous) in western North Dakota and easternmost Montana generally are not considered as economically feasible sources of potable water due to excessive depth and the high salinity of the water. The expense associated with drilling through the 2,000 to 3,000 ft of Pierre Shale is prohibitive to most prospective water uses.

Based on prior knowledge of the geology and hydrology of the Wibaux-Beach study area, it was determined that aquifers in the part of the geologic section from the middle of the Ludlow Member to the land surface would be evaluated as part of this study. Potential effects of mining on the lower aquifers would be dampened sufficiently to make their study of less immediate need. Inasmuch as the deeper aquifers are potential sources of water to replace those which may be lost due to disruption of shallow aquifers, they will be discussed briefly here. Well-construction and water-level data for all observation wells utilized during this study are listed in Attachment A near the end of the report.

Aquifers of the Fox Hills Sandstone

The aquifer associated with the Fox Hills Sandstone has been defined both as entirely within the Fox Hills and as an aquifer system occurring in parts of both the Fox Hills Sandstone and the Hell Creek Formation (Croft, 1978; Anna, 1981). Extensive sandstone beds in the upper part of the Fox Hills constitute an important aquifer throughout western North Dakota. In test hole 140-105-30CCC at Beach, the upper Fox Hills sandstone is 122 ft thick and another sandstone section in the lower part of the formation is 60 ft thick. Anna (1980) picked the top of the Fox Hills aquifer at a depth of 1,032 ft in test hole 140-105-30CCC. There was no significant thickness of aquifer material in the lower Hell Creek at this test-hole site.

Reported transmissivities and specific capacities for the Fox Hills-Hell Creek aquifer system vary widely but may be as much as 1,200 ft^2/d and 6.6 (gal/min)/ft, respectively (Klausing, 1979). Potential yields from the aquifer or aquifer system reportedly are as much as 300 gal/min (Anna, 1981), but more generally would be about 50 gal/min. Flow gradients vary widely, but most commonly are between 5 and 20 ft/mi. The water level in the observation well at Beach is about 330 ft below land surface (May 1981).

Many cities in southwestern North Dakota obtain part or all of their municipal water supply from the Fox Hills aquifer or Fox Hills-Hell Creek aquifer system. One of Beach's municipal wells, located one-half mile west of test hole 140-105-30CCC is completed in the Fox Hills at about the horizon of the lower sandstone.

Aquifers of the Hell Creek Formation

Sandstone beds at various horizons within the Hell Creek Formation constitute aquifers, but some are quite localized and no consistent sequence of sandstone beds is recognized throughout the region. Hydrologists have described aquifer systems consisting of the association of sandstone beds in the basal Hell Creek with those in the upper Fox Hills and of sandstone beds in the upper Hell Creek with those in the lower Ludlow Member (Croft, 1973, 1978; Anna, 1981). In one area, three aquifer zones were recognized in the Hell Creek (Randich, 1979). In other areas, aquifers were indicated as randomly occurring in the Hell Creek section with little or no hydraulic interconnection (Klausing, 1979; Ackerman, 1980).

Anna (1980) picked the Hell Creek Formation from 760 to 1,032 ft below land surface in test hole 140-105-30CCC at Beach (pl. 1). The logs show that only one sandstone bed, 20 ft thick, occurred in the Hell Creek in this test hole. In other areas of North Dakota individual sandstone beds within the Hell Creek may be as much as 60 ft thick and aquifer systems involving parts of the Hell Creek reportedly are hundreds of feet thick (Croft, 1973, 1978; Anna, 1980).

Reported hydraulic conductivities for aquifers of the Hell Creek Formation range from 0.5 to 2.0 ft/d and specific capacities generally range from 0.1 to 1.0 (gal/min)/ft. Potential yields are as much as 150 gal/min. Hydraulic flow gradients range from 5 to 20 ft/mi. Water-level data are not available for aquifers within the Hell Creek Formation in the study area.

The Hell Creek aquifers commonly are tapped for water supplies along the fringes of the Williston basin where the formation lies at a shallow depth. Elsewhere, including the study area, wells drilled to depths greater than the Ludlow Member (Fort Union Formation) usually are completed in the Fox Hills aquifer.

Aquifers of the Ludlow Member, Fort Union Formation

The Ludlow Member, for geohydrologic consideration, commonly has been divided into three units; upper and lower aquifer sections separated by a confining layer (Croft, 1978; Anna, 1981). None of the test holes drilled for this project fully penetrated the Ludlow Member, but Anna (1980) reported thicknesses of sand beds in the lower part of the Ludlow of 49 feet in test hole 139-105-30DDD and 46 ft in test hole 140-105-30CCC1. Reported depths to the top of the beds were 687 and 642 ft. The water level in the lower Ludlow sand in test hole 140-105-30CCC2 was about 168 ft below land surface in May 1981.

Sand usually was encountered within the top 100 ft of the Ludlow section in the study area. Any one sand bed in the upper Ludlow and lower Tongue River Members is quite limited in scope as a discrete permeable unit. However, the lateral proximity of one sand bed to another and the vertical stacking or tongueing of the beds produces a 3-dimensional association of beds that may be considered, at the scale of this project, a somewhat homogeneous hydraulic unit or "aquifer system." Thus, as indicated by the respective potentiometric-surface maps, it is assumed that ground-water flow is not disrupted near areas of zero sand thickness in the upper Ludlow and lower Tongue River aquifer systems.

Sand beds of the upper Ludlow and lower Tongue River Members have been collectively termed the upper Ludlow-lower Tongue River aquifer by other investigators (Croft, 1978; Anna, 1981). Because the contact between the Tongue River and Ludlow Members was readily identifiable in most test holes drilled during this project, the aquifer systems were differentiated for stratigraphic clarity. It is doubtful, however, that an abrupt hydraulic discontinuity exists between the two systems considering the similarities in the mode of deposition of the two members and the fact that intermittent sand deposits occur throughout the stratigraphic sequence associated with the aquifer systems. Because the prevailing vertical hydraulic gradient is strongly downward throughout the study area, distinction between the aquifer systems is desirable when making interpretations of areally distributed water-level data.

For purposes of this report, the upper Ludlow aquifer system consists of any sand beds occurring within the upper 200 ft of the Ludlow Member (although the potentiometric level for well 139-105-07DCC1, completed in an upper Ludlow sandy silt, is included on the potentiometric map for the upper Ludlow aquifer system). The following discussion of the upper Ludlow aquifer system is based on data obtained from 24 test holes that penetrated at least 94 ft of the Ludlow section; 11 of the test holes penetrated at least 200 ft of Ludlow section.

The upper Ludlow aquifer system underlies the entire study area and is virtually everywhere a confined aquifer. Depth to the top of the aquifer within the area of occurrence of the Harmon lignite ranges from a minimum of about 150 ft in the west to a maximum of about 600 ft along the eastern border of the study area. The average interval between the base of the Harmon lignite and the top of the first sand of the upper Ludlow aquifer system in the 19 test holes (80 percent of the total of 24) that encountered the aquifer was about 190 ft.

Individual sand beds in the upper Ludlow aquifer system ranged in thickness from 5 to 84 ft. The mean and median bed thicknesses in the 19 test holes were both about 44 ft. More than one sand bed was penetrated in the upper 200 ft of Ludlow section in only two of the test holes. The areal distribution of aggregate sand thickness in the upper 200 ft of the Ludlow Member is shown in figure 12.

Hydraulic conductivity values from slug tests on four wells were 0.08, 0.15, 2.1, and 4.0 ft/d. These values, when multiplied by the respective bed thicknesses, are well within the range of values for transmissivity reported for Ludlow aquifers at various places in western North Dakota (Croft, 1978; Anna, 1981; Randich, 1979).

Values for specific storage calculated by the slug-test method of Cooper and others (1967) are not valid. Because the upper Ludlow aquifer system is a confined aquifer of moderate depth, it is probable that specific storage values are in the range 10^{-4} to 10^{-6} per ft.

The potentiometric surface of the upper Ludlow aquifer system is shown in figure 13. The contours indicate that ground water flows toward the northeast under a gradient that ranges from about 10 to 35 ft/mi and averages about 20 ft/mi. The wide interval between the 2,550- and 2,600-ft

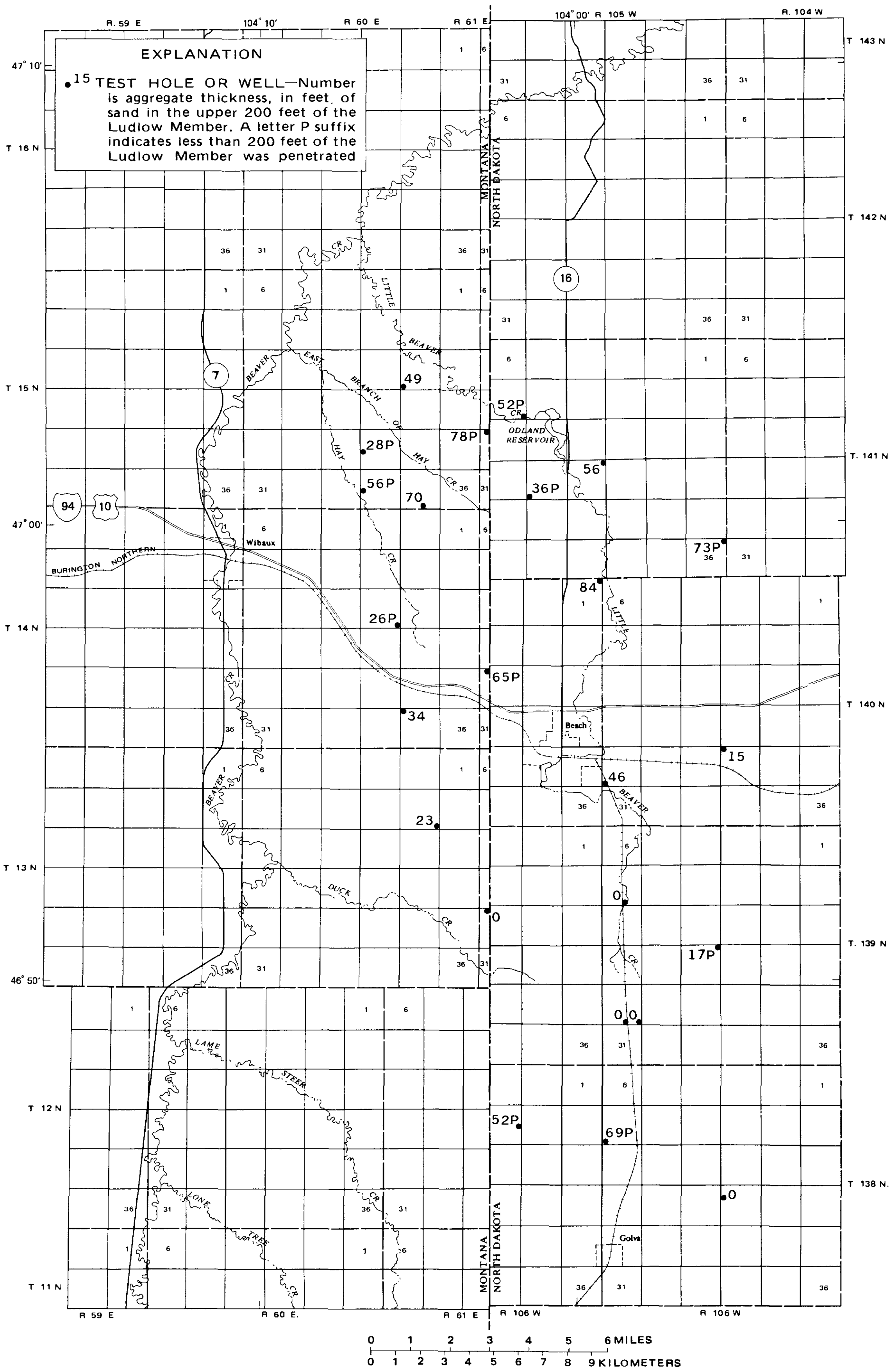


FIGURE 12.—Aggregate thickness of sand in the upper 200 feet of the Ludlow Member.

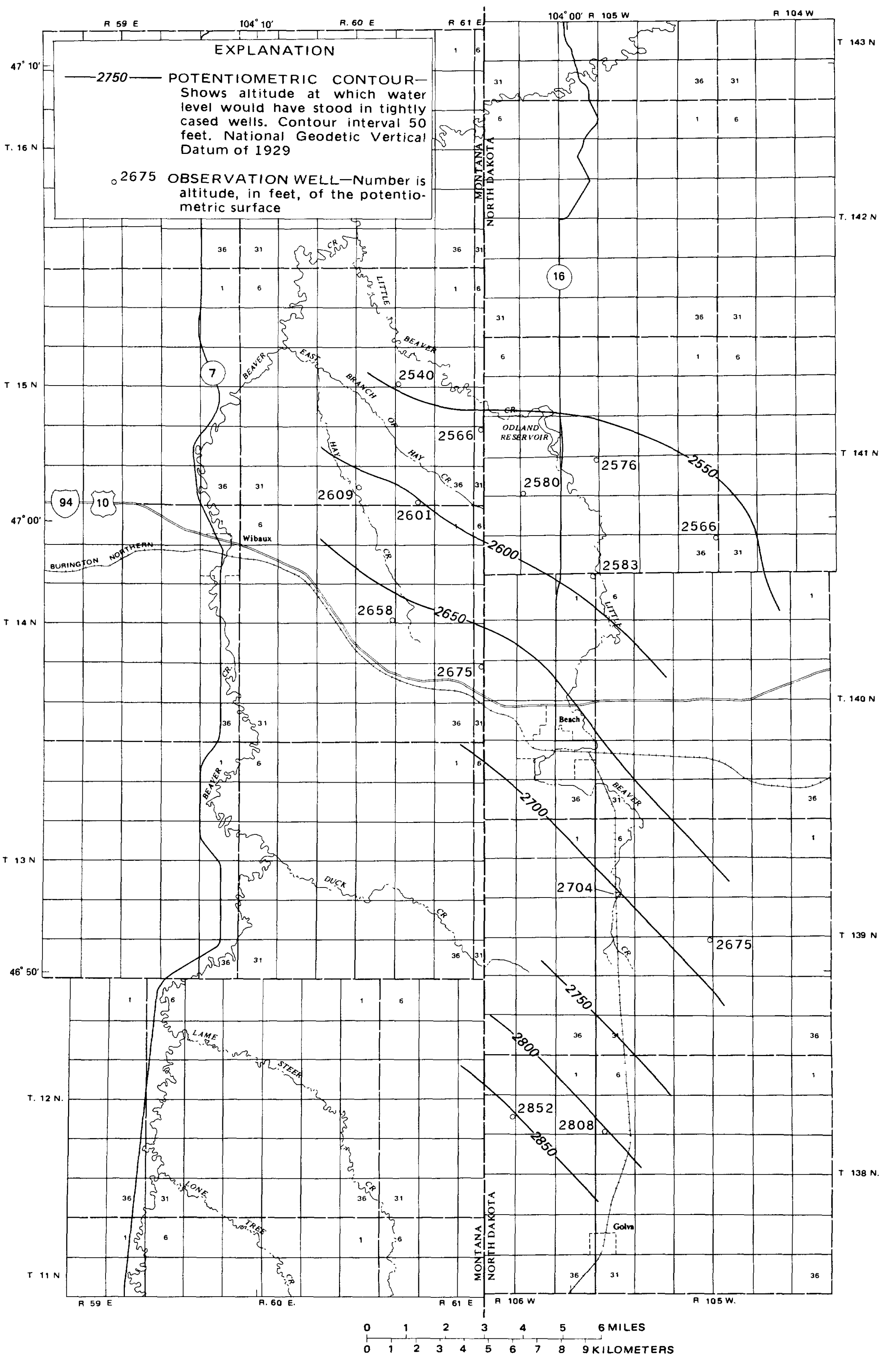


FIGURE 13.—Potentiometric surface of the upper Ludlow aquifer system, September 1980.

contour may reflect a high aquifer transmissivity in the area. Most of the aggregate sand thicknesses penetrated in test holes in the area between the contours were somewhat greater than the average thickness.

Recharge to the upper Ludlow aquifer system primarily is by downward leakage from the overlying lower Tongue River aquifer system. The aquifer system also is recharged directly by precipitation in its outcrop area to the west of the Wibaux-Beach study area, but in terms of the total water budget for the aquifer system in the study area, the direct contribution from precipitation is minor.

Discharge from the aquifer system mainly is by downward leakage and to a much lesser extent, by underflow toward the northeast out of the study area. The aquifer system is too deep to discharge at the land surface within the study area.

Hydrographs of wells completed in the upper Ludlow aquifer system show little to no water-level response to individual precipitation events. Water levels over the 3 years of available record are very stable, indicating a long-term balance in the aquifer recharge-discharge fluxes and negligible storage changes. Most of the short-term fluctuations observed on the otherwise steady hydrographs were due to barometric effects.

Few existing wells obtain water from the upper Ludlow aquifer system in the study area.

Aquifers of the Tongue River Member, Fort Union Formation

Channel sand deposits and lignite beds constitute aquifers in the Tongue River Member. Although sand beds tens of feet thick and lignite beds several feet thick occur sporadically throughout the Tongue River section in the Williston basin, the thickest and most consistent sand and lignite beds lie in the lower part of the member. Reports of ground-water studies in several western North Dakota counties have noted this sand distribution pattern biased toward the lower part of the member, and some have defined a basal sand aquifer as the only one of more than localized importance (Croft, 1973; Anna, 1981; Randich, 1979). In the Wibaux-Beach study area the sands in the lower Tongue River and the Harmon lignite are the only two aquifers in the Tongue River section that are of area-wide importance.

Lower Tongue River Aquifer System

Individual sand beds in the Tongue River Member are narrow, elongate, sinuous bodies that originated as channel-fill deposits in meandering or braided streams. Abrupt lateral facies changes are typical of this stratigraphic sequence as the aggregate sand thickness map (fig. 9) indicates. As described in the previous section (aquifers of the Ludlow Member), sand beds in the lower Tongue River Member are considered as a more or less homogeneous hydraulic unit or aquifer system.

The lower Tongue River aquifer system underlies the eastern three-fourths of the study area. From its outcrop area in the vicinity of Beaver

Creek, the aquifer system dips to the northeast and can be as much as 500 ft deep along the eastern edge of the study area. It consists of sand beds that exist anywhere between the base of the Harmon lignite and the base of the Tongue River Member. The thickness of confining materials between the base of the Harmon lignite and the top of the shallowest sand of the lower Tongue River aquifer system is shown in figure 14. Several test holes, those marked with a "c" on figure 14, encountered no sand in the entire lower Tongue River interval. Trend lines could be drawn on this map as with figure 9, but the possible positions and orientation of such lines are limitless. The significance of the figure is in showing that the vertical distribution of sand beds within the lower Tongue River section virtually is random at this scale and level of control.

The thickness of the confining materials between the base of the Harmon lignite and the first Tongue River sand in the test holes drilled for this or earlier hydrology projects ranged from zero (sand in contact with the lignite) to 115 ft. The median thickness was 75 ft. Thicknesses of individual sand beds within the lower Tongue River aquifer system ranged from 13 to 98 ft and the median thickness was 45 ft. Only 2 of 22 observed beds were less than 20 ft thick. The number of distinct sand beds found at each of the 27 sites where the lower Tongue River interval was completely penetrated was: 10 sites, none; 13 sites, 1 bed; 3 sites, 2 beds; 1 site, 3 beds. The total thickness of the lower Tongue River interval ranged from 91 to 188 ft and median thickness was 134 ft.

The hydraulic characteristics of sand beds in the lower Tongue River aquifer system were evaluated at five sites by the slug-test method. Hydraulic conductivity values ranged from 0.57 to 14 ft/d, and had a mean of 4.5 ft/d. These values are in the upper range of those reported by Groenewold and others (1979, p. 64) for Tongue River and Sentinel Butte confined sand aquifers in the Knife River basin.

The storage coefficient values determined from the five slug tests, as with the other tests, are considered invalid. Values of specific storage for Paleocene sand aquifers reported by Rehm and others (1980) range from 10^{-3} to 10^{-5} per ft.

Potentiometric contours for the lower Tongue River aquifer system are shown in figure 15. Ground-water flow in the aquifer is to the northeast under an average gradient of about 20 ft/mi, although the gradient varies from about 10 ft/mi in the vicinity of Beach to about 30 ft/mi in parts of T. 141 N.

The lower Tongue River aquifer system is recharged by infiltration and downward percolation of precipitation in the area to the west of the Harmon lignite outcrop where the permeable sand units lie near the land surface. This area, in general, is along Beaver Creek. East (down dip) of the outcrop zone the aquifer is recharged by downward leakage.

The lower Tongue River aquifer system does not discharge to surface drainages anywhere within the study area. Rather, all water either leaks to underlying aquifers or flows to the northeast out of the study area as underflow.

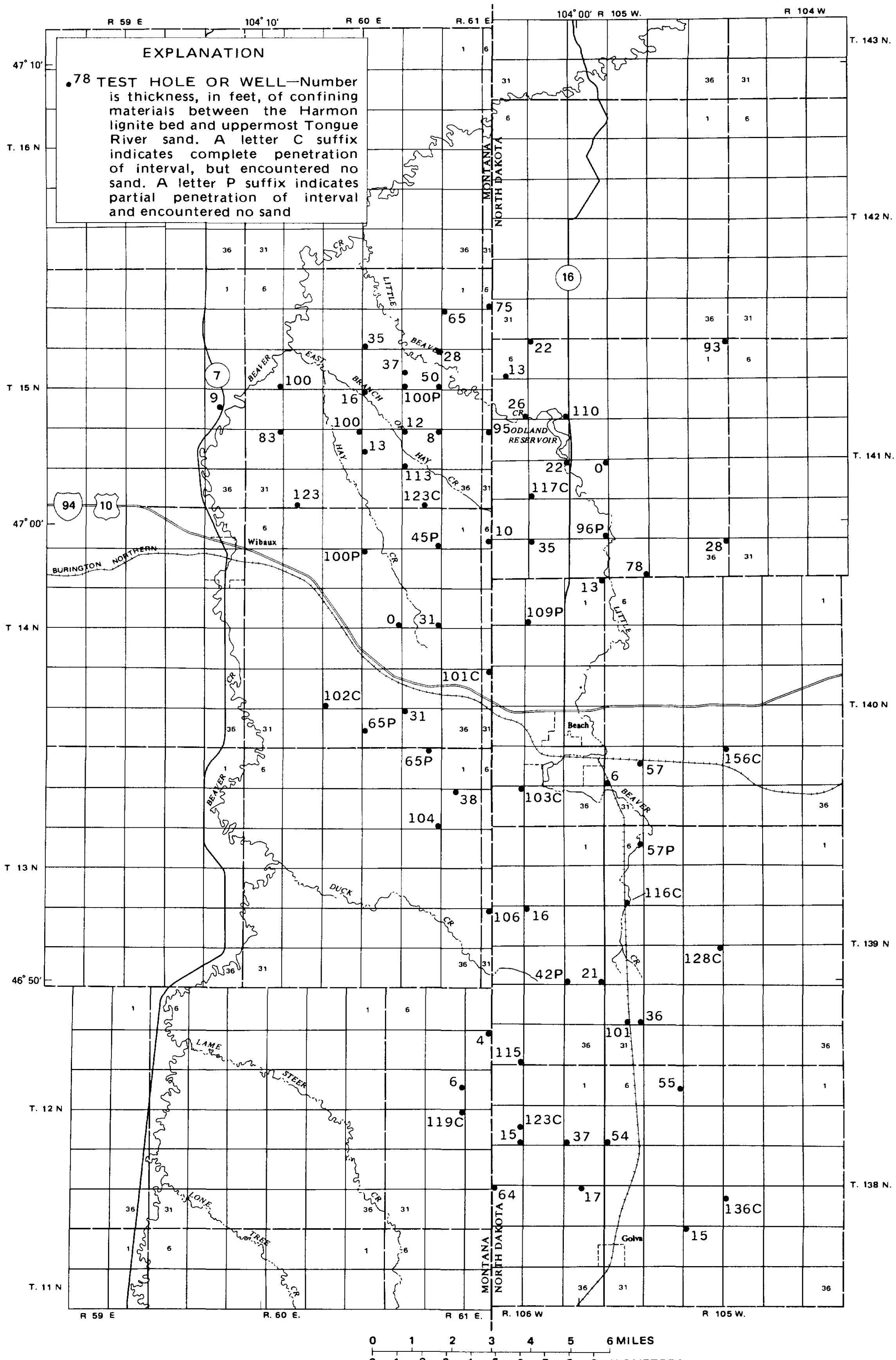


FIGURE 14.—Thickness of confining materials between the Harmon lignite and the uppermost sand of the lower Tongue River aquifer system.

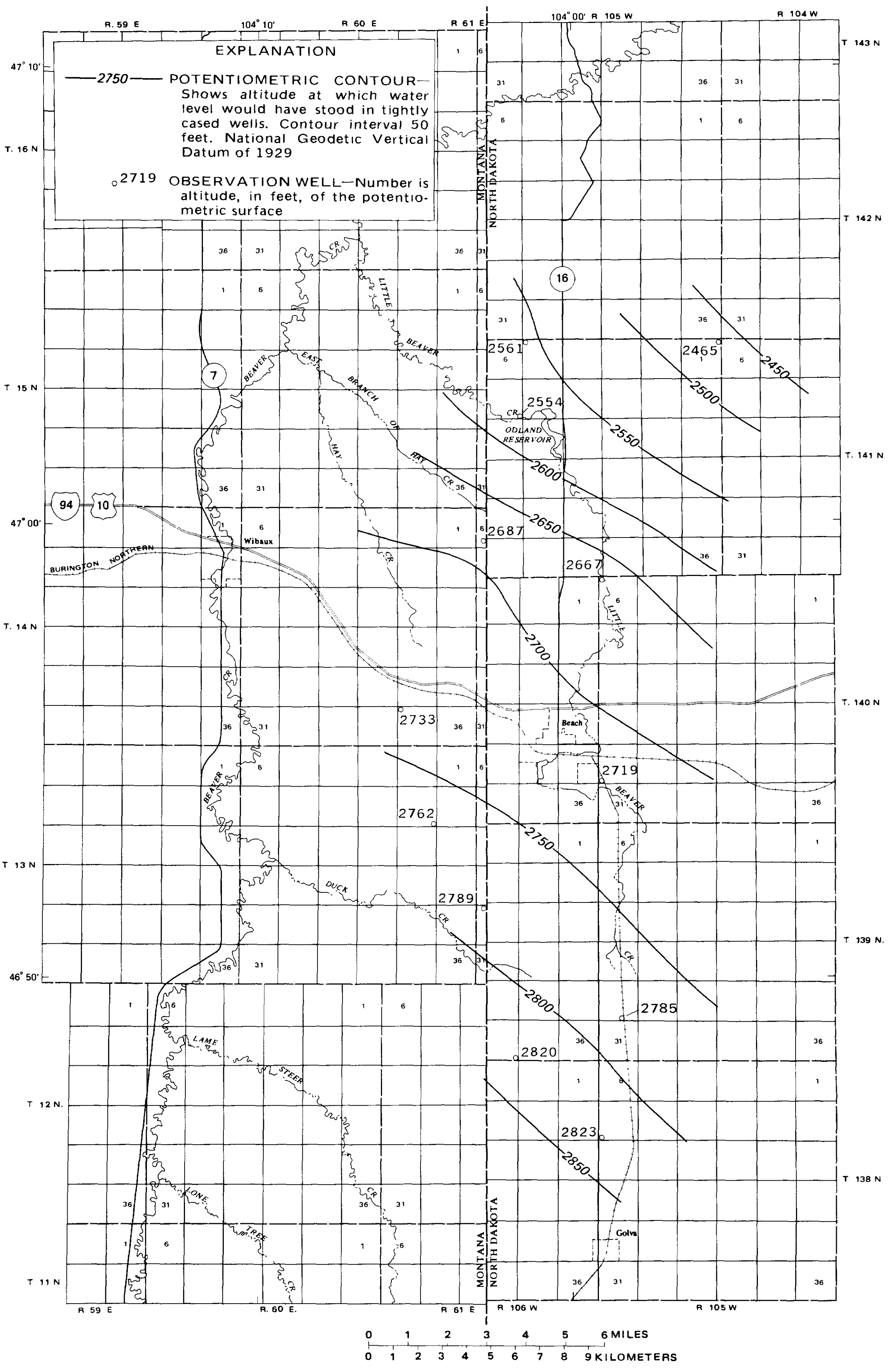


FIGURE 15.—Potentiometric surface of the lower Tongue River aquifer system, September 1980.

Hydrographs of most of the wells completed in the lower Tongue River aquifer system show a very slight rise (1 ft or less) in potentiometric levels over the 3 years of available record. The hydrographs, for the most part, are very smooth, suggestive of an aquifer well buffered from direct recharge by precipitation. The aquifer apparently is adjusting to contributions from storage in overlying confining beds.

Pumpage from wells is of little significance to the water budget of the aquifer system in the study area.

Harmon lignite aquifer

Occurrence.--Test-drilling results indicate, without exception, that the Harmon lignite aquifer underlies all of the study area east of the Harmon bed outcrop (fig. 8). The aquifer, therefore, is a reliable source of water, particularly where its thickness is greater than 10 ft.

Depth to the top of the Harmon lignite aquifer ranges from virtually zero at the outcrop to about 350 ft at the eastern limit of the study area. The lignite does not actually lie at the land surface along the crop line. Through geologic time as the land surface was eroded to expose the lignite, the lignite was ignited by prairie fires and burned for some distance down dip (beneath the surface) until the oxygen supply was insufficient to maintain combustion. The silt and clay deposits overlying the burning lignite were baked and fused to form clinker. Today the clinker, rather than the lignite, lies at the land surface and marks the approximate western limit of the Harmon lignite (see fig. 8). It is assumed that the easternmost clinker deposits are in hydraulic connection with the lignite.

Within some short, but unknown, distance to the east of the outcrop, the Harmon lignite aquifer changes from an unsaturated state to an unconfined aquifer and finally to a confined aquifer. A few test holes drilled within a mile of the outcrop encountered unsaturated lignite, but no test holes were drilled where the aquifer was under unconfined conditions. The transition from an unsaturated state to a confined aquifer, therefore, occurs within a narrow zone.

Hydraulic properties.--The hydraulic properties of coal aquifers, including those of the lignite aquifers in North Dakota, are still rather poorly defined. Because hydraulic conductivity and storage capacity of coal aquifers are derived entirely from secondary (fracture) porosity, conventional methods of determination developed for granular aquifers do not, in the strictest sense, apply. However, it generally is believed that the fracture planes in shallow coals of the northern Great Plains are spaced sufficiently close that the coals may be treated as a macroscopically homogeneous medium in which Darcian flow prevails. Any determination of hydraulic conductivity for a coal aquifer is, nontheless, biased by the fracture density prevailing around the borehole(s) used for the determination.

Experience at Wibaux-Beach and at other study sites in North Dakota has shown that, within the area of saturation, lignite wells nearly always yield some quantity of water. That is, fracture spacings evidently are close enough that nearly any well completion will intercept sufficient fractures to yield water. Yields and hydraulic conductivities, though, vary widely as a function of communicative fractures intercepted at or near the well bore.

The range in values of coal aquifer hydraulic conductivities reported in the literature is far too broad to enable a confident selection of one value to represent any given aquifer. A recent compilation of published data for coal and related materials in the northern Great Plains showed a range in hydraulic conductivity of six orders of magnitude, from about 0.0009 to 900 ft/d. The mean of 193 reported values was about 0.9 ft/d (Rehm and others, 1980).

The extreme range in reported coal hydraulic conductivities implies either gross inconsistencies in the methods of well construction, data collection, and data interpretation or some site-dependent mechanism of control on the degree and spacing of fractures in the coal. It is probable that both factors contribute to the observed range in conductivity values. The problem of inconsistent methods is particularly troublesome in testing thin coal aquifers with small permeabilities. Miscues in well construction (including placement of screen, gravel pack, and isolation packers) that might otherwise be of minor importance can result in missing most of the permeable aquifer zone or may include a more permeable zone that could mask or overwhelm the lignite permeability.

The mechanisms responsible for the fracture and permeability characteristics of a given coal bed are not well known. McCulloch and others (1974) and Leach (1975) studied the occurrence of cleat, fractures in coal formed near-orthogonally to bedding planes, in Pennsylvania and southern Wyoming. They concluded that cleat in bituminous and subbituminous coal beds resulted from tectonic forces. Stone and Snoeberger (1976) related cleat orientation to regional structural features of the Powder River basin in Wyoming. It has not been determined if high-density fracture trends in Tertiary coals in the Williston basin correlate with regional structural lineaments.

A frequent observation that does seem to lend itself to defensible theory on coal permeability is the relationship of depth of burial to coal hydraulic conductivity. Rehm and others (1980) presented data that indicate that North Dakota lignites commonly have a higher hydraulic conductivity along outcrop and subcrop areas than in areas of deeper burial. Moran and others (1976, p. 164) implied a correlative relationship between depth and hydraulic conductivity in a plot of the two parameters. Calculations of hydraulic conductivity from 25 slug tests in the Harmon lignite in the Wibaux-Beach study area indicate a possible relationship between overburden thickness and hydraulic conductivity (fig. 16). The correlation coefficient (R^2) is about 0.48. Presumably the greater burial depths result in greater pressures that restrict the size of the fracture openings. With lessening overburden pressures the fractures are allowed to widen and new fractures are formed due to the unloading effect or abatement of the compressive stress. Both of these mechanisms could result in an increase in hydraulic conductivity with decreasing depth of burial.

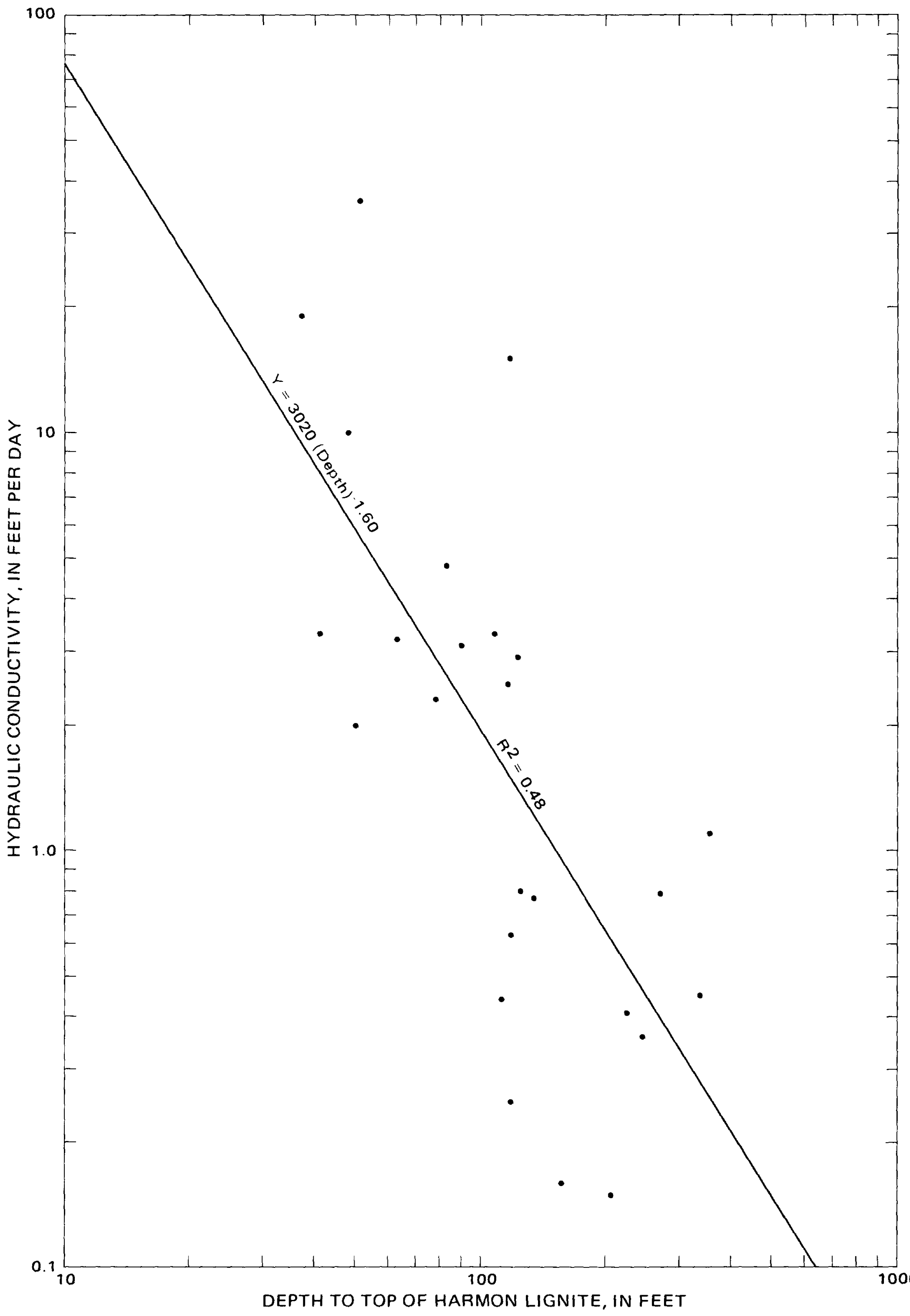


FIGURE 16.—Relationship of hydraulic conductivity of Harmon lignite aquifer to depth of overburden.

There is a distinct break in the hydraulic conductivity data for the Harmon lignite aquifer in the 110- to 125-ft depth range. The overburden depths for the 13 conductivity values of 2.0 ft/d or greater are all less than 125 ft. Conversely, the overburden depths for the 12 conductivity values less than 2.0 ft/d were all greater than 110 ft. This depth versus hydraulic conductivity relationship should be of some practical value in mapping aquifer permeabilities for simulation purposes.

Hydraulic conductivities determined for the Harmon lignite aquifer at Wibaux Beach ranged from 0.15 to 36 ft/d, a little less than 2.5 orders of magnitude. The mean of the 25 values is 4.5 and the median is 2.0. Eleven of the 25 values ranged from 0.15 to 0.80 (inclusive) and 10 ranged from 1 to 5.

Two 4-in. diameter wells were installed with the intention of conducting aquifer tests on the Harmon lignite aquifer and the lower Tongue River aquifer system. Unfortunately, development of the wells to a satisfactory hydraulic efficiency was not possible due to problems encountered in construction. The important objective of making correlative determinations of hydraulic conductivity by pumping, as well as slug-testing methods was, therefore, precluded. Other investigators (Moran and others, 1976; Stone and Snoeberger, 1976) have found that multiple-well aquifer tests yielded hydraulic conductivities for coal aquifers of as much as an order of magnitude greater than slug-test methods. The discrepancy typically is attributed to the smaller radius of investigation and lesser degree of fracture interception inherent to the slug-test method.

The storage capacity of coal aquifers is not well documented. Due apparently to the fracture-controlled porosity, specific storage values derived from pumping-test data have been found to vary widely within a given aquifer (Rehm and others, 1980). The few values for specific storage reported in the literature range from about 10^{-3} to 10^{-7} per ft and have a mean of about 10^{-4} per ft.

Specific storage for the Harmon lignite aquifer was not determined for this study due to the lack of an aquifer test. A value for storage coefficient (S) can, in theory, be calculated from the method of slug-test analysis of Cooper and others (1967). The applicable equation dictated that S be identical to the "alpha" parameter of the best-fit type curve. The best fit was nearly always on the alpha = 10^{-10} type curve. Stone and Snoeberger (1976), in their study of a subbituminous coal aquifer in Wyoming, also found a best fit on the alpha = 10^{-10} type curve of Cooper and others (1967) and were "unwilling to speculate on the value of S on the basis of this slug test." A storage coefficient of 10^{-10} is not reasonable, but the designation of a representative value or range for the Harmon bed in this study area would only be conjecture.

Flow system.--The potentiometric surface of the Harmon lignite aquifer shown in figure 17 indicates that ground water flows in a general northeastward direction. The flow system originates along the Harmon bed outcrop and extends eastward to and beyond the study area boundary. The hydraulic gradient varies from 3 or 4 ft/mi near the highly permeable outcrop area south

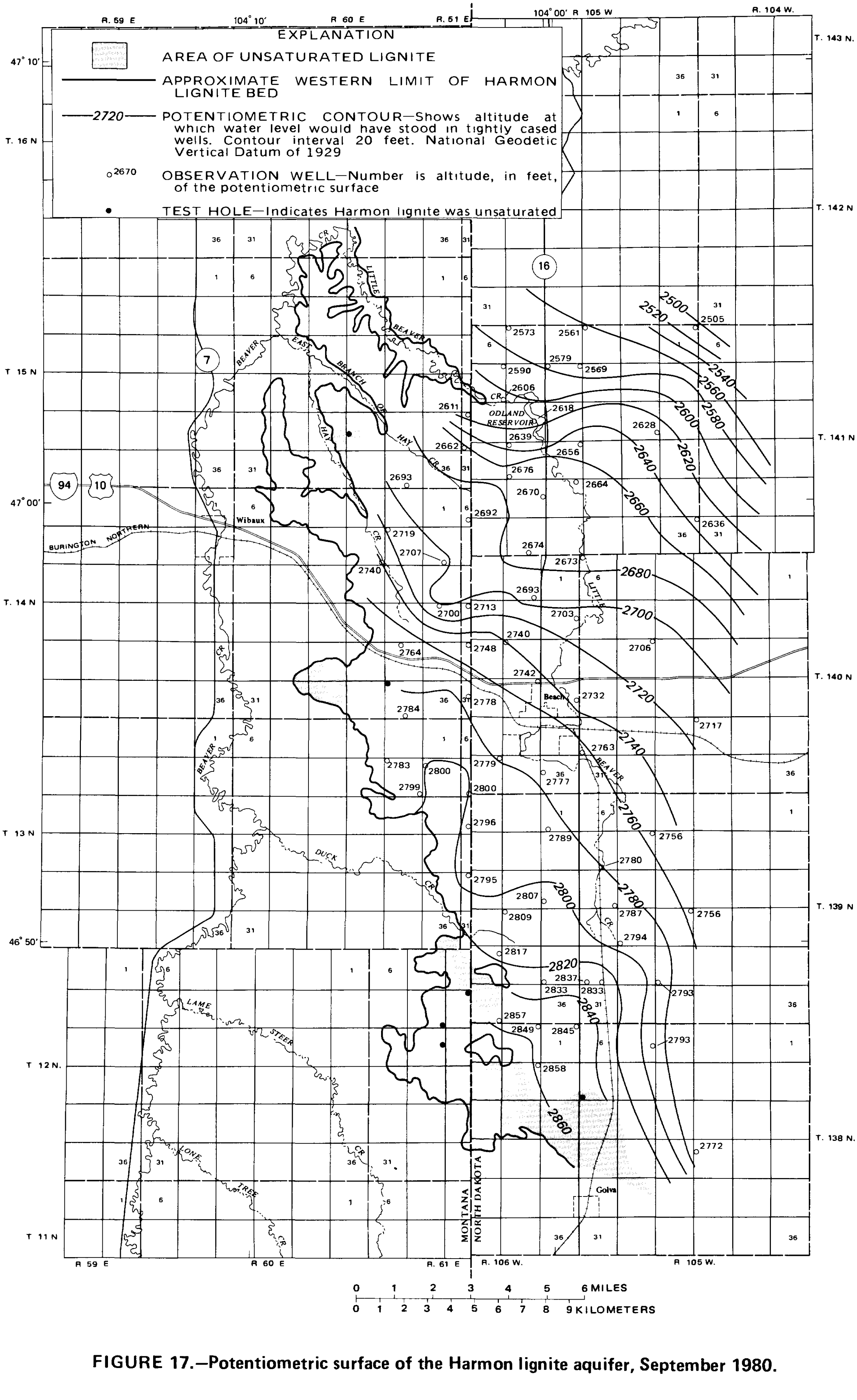


FIGURE 17.—Potentiometric surface of the Harmon lignite aquifer, September 1980.

and west of Beach to a more general 10 to 15 ft/mi in the rest of the study area.

Recharge to the aquifer is by infiltration of precipitation along the outcrop and by leakage through overlying silt and clay where the aquifer is confined. The Harmon lignite aquifer receives the greatest volume of recharge per unit area of land surface along its heavily clinkered outcrop. The hydraulic conductivity of the clinker was not determined during this study, but it probably is orders of magnitude higher than that of the lignite. The clinker serves as an extremely transmissive medium that very rapidly conveys rainfall and snowmelt to depths beyond the effective reach of evapotranspiration. Similar observations were made by Van Voast and Hedges (1975) in Montana and by Davis and Rechard (1977) in Wyoming. Davis and Rechard (1977) stated "***scoria outcrops are probably the single most important zones of aquifer recharge."

The aquifer receives much less recharge per unit area over the rest of the study area as leakage through overlying confining beds. Because no wells were installed in the material overlying the lignite, data are not available on the position of the water table. Experience in other parts of western North Dakota, however, indicates that the water table probably would be at least a few tens of feet below the land surface. Because the potentiometric surface of the Harmon lignite aquifer lies within 50 ft of the land surface over much of the study area, there can be little head differential available between the water table in the overlying material and the Harmon lignite aquifer to induce flow through the silts and clays overlying the lignite.

One of two sites with anomalously high potentiometric levels is in the vicinity of a perennial wetland that occupies an area of 50 to 100 acres in the north-central part of sec. 31, T. 139 N., R. 105 W. The potentiometric high in the Harmon lignite aquifer probably is a response to recharge received from the wetland.

The other anomalous area is in the north-central part of T. 141 N., R. 105 W. The reason for this anomaly is not clear, although it may be related to geologic factors. The Harmon bed structure-contour map (fig. 8) shows a local depression at this location and the Harmon bed thickness map (fig. 7) shows this as an area of somewhat thicker lignite.

The Harmon lignite aquifer is discharged primarily by leakage to the underlying lower Tongue River or upper Ludlow aquifer systems. A very minor part of the water that is introduced into the aquifer within the study area actually flows across the eastern boundary of the study area still within the aquifer. A sample calculation illustrates the relative importance of leakage versus throughflow in the debit side of the water budget for the Harmon lignite aquifer. If it is assumed that flow occurs across the 32-mi-long eastern boundary of the study area within an aquifer having an average thickness of 15 ft and an average hydraulic conductivity of 0.5 ft/d (the mean of the seven values for depths greater than 150 ft), under an average gradient of 10 ft/mi, the Darcy equation

$$Q = KA \frac{dh}{dl}$$

indicates a total flow of 2,400 ft^3/d as throughflow.

The quantity of ground water discharged as downward leakage from the aquifer can be estimated with the Darcy equation in the following form and with the listed values for the indicated parameters.

$$Q = K'A \frac{dh}{dl}$$

K' = vertical hydraulic conductivity of 10^{-5} ft/d,
A = area over which leakage occurs, 200 mi^2, and
$\frac{dh}{dl}$ = vertical hydraulic gradient, 0.4 ft/ft.

The result is 22,000 ft^3/d.

The values assumed for the throughflow equation should be reasonably accurate, although the actual hydraulic conductivity values could deviate somewhat from the one assumed. The vertical hydraulic conductivity assumed for the leakage calculation is at the low end of the range of reasonable values. It is possible, therefore, that the leakage discharge could be somewhat greater than the given estimate. The two discharge values thus determined are rough estimates that are important only as a ratio. The numbers indicate that the quantity of ground water that flows across the eastern boundary of the study area within the Harmon lignite aquifer as throughflow is very minor in comparison to the quantity that discharges from the aquifer as downward leakage across the study area.

The Harmon lignite aquifer probably is the source of base flow observed in Little Beaver Creek at gaging station 06336545 (15-60-14BBB). Late fall and winter streamflow there generally ranges from nearly 0.0 to 0.20 ft^3/s. This flow occurs when there is no discharge over the spillway at Odland Reservoir. It is attributable, in part, to seepage from the Harmon bed which outcrops along that reach of the stream. It also is possible that some of the water is discharged from minor thicknesses of alluvium along the stream.

Water-level fluctuations in response to recharge.--Hydrographs for nine observation wells that were completed in the Harmon lignite aquifer in mid-1976 are shown in figure 18. Monthly precipitation at Wibaux, Mont., also is shown. The well hydrographs are arranged sequentially from top to bottom in the order that the well sites occur from north to south.

The figure shows the relationship between the magnitude and timing of precipitation events and aquifer response. The hydrographs for the recorded part of 1976 and much of 1977 for the four southern wells indicate the water levels were declining after what must have been a large water-level rise in response to the very heavy precipitation in the spring and early summer of

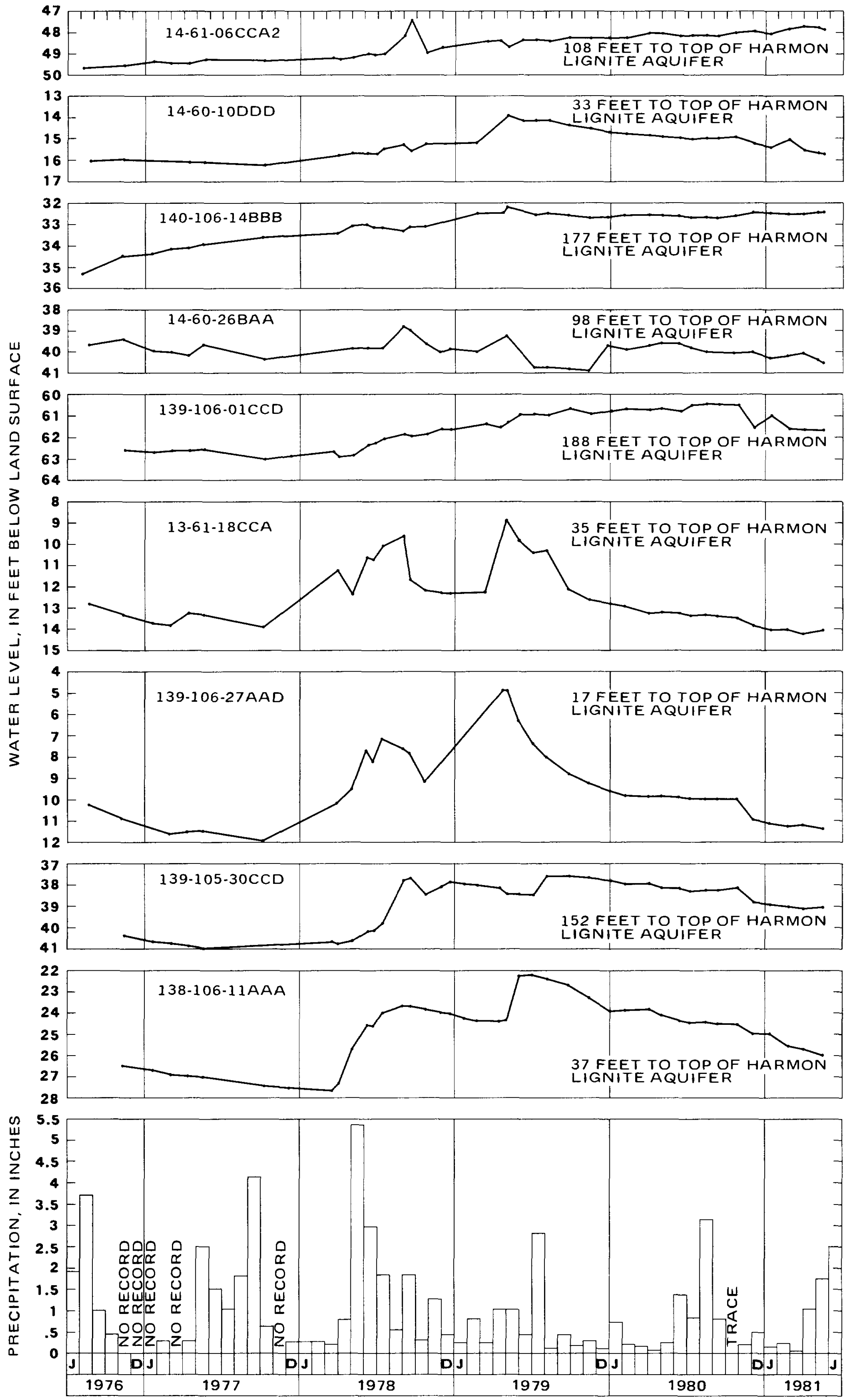


FIGURE 18.—Water-level fluctuations in selected wells completed in the Harmon lignite aquifer and precipitation at Wibaux, Mont.

1975. During the 4 months March through June of 1975, 11.66 in. of precipitation was recorded at Wibaux, nearly 4.6 in. above normal for the period. The rapidly declining water levels in wells 13-61-18CCA and 139-106-27AAD beginning in August 1976 indicate no significant recharge occurred during 1976, even though 9.68 in. of precipitation was recorded during June, July, and August at Wibaux. The decline in storage continued through the summer of 1977 at the four southern sites. The effect of the 4.13 in. of rain in September is not evident at three of the four sites due to the lack of data during the fall of 1977. The fact that the rain produced no measurable effect on the water level in well 138-106-11AAA, however, is an indication that significant recharge did not occur in the area.

The rise in water levels observed in the four southern wells beginning in March or April of 1978 was initiated by recharge from snowmelt. The 1977-78 winter was one of very heavy snow accumulations and extensive flooding accompanied the spring breakup. The high antecedent soil moisture condition caused by the heavy rainfall of the preceding September further complimented the snowmelt to produce the recharge event. The 5.35 in. of rain in May and the 2.97 in. in June fell on an already very wetted soil profile and culminated a series of climatic events that produced the greatest slug of recharge during the 5 years of record.

Over a period of a few months, water levels rose 2.5 to 4 ft in the four southern wells in response to the recharge. Water levels then declined until the following spring (1979) when the melt of another very heavy accumulation of snow resulted in another sizeable recharge slug that was reflected in the hydrographs for the three shallowest wells. The subsequent recession began very quickly, however, and continued virtually uninterrupted into May 1981. Single-month rainfall magnitudes of about 3 in. that occurred once during each of the summers of 1979 and 1980 had no effect on the water levels.

Wells 13-61-18CCA and 139-106-27AAD are both very shallow and are within a mile of an extensively clinkered part of the Harmon bed outcrop. Appropriately, the hydrographs show that the water levels in these wells respond quickly to recharging precipitation or snowmelt events. Well 138-106-11AAA, although it is not in an area of visibly extensive clinker deposits, penetrated the top of the Harmon at only 37 ft and lies within a mile of an isolated Harmon bed outcrop area. The top of the Harmon lignite is 152 ft deep in well 139-105-30CCD, 3 mi from the nearest Harmon outcrop. Therefore, the water-level response in well 139-105-30CCD is somewhat dampened and time-lagged from that of the other three wells.

The water levels in the other five wells in figure 18 were not nearly as sensitive to precipitation as the water levels in the southern four wells. Water levels in wells 14-60-10DDD and 14-60-26BAA show only slight responsiveness to the recharge-drought cycles discussed previously, even though they are near the Harmon bed outcrop. A reason for this could be that the aquifer receives little recharge in that area due to the lack of extensive clinkering along the outcrop. Another possible reason, one that is indicated by the close spacing of the potentiometric contours in figure 17, might be that the hydraulic conductivity of the lignite is anomalously low in the vicinity--resulting in a poor hydraulic connection between the outcrop and the well site.

The hydrographs of wells 14-61-6CCA2, 140-106-14BBB, and 139-106-1CCD show almost no correlation with seasonal precipitation trends. Rather, the water levels have increased at a fairly uniform rate through nearly the entire 5-year period of record. These wells, for the most part, are deeper and further from the outcrop than the others. Water-level changes in the down-dip, deeper part of the aquifer are the product of a time-integrated sum of recharge and discharge influences, where leakage into and out of the aquifer becomes increasingly more important with distance from the outcrop. The deeper part of the aquifer apparently is still adjusting to the higher than average recharge of 1979, 1978, and perhaps even 1975. It hasn't as yet, or perhaps has just begun to adjust to the drought conditions prevalent since early 1979. Examination of the hydrographs for all the observation wells completed in the Harmon lignite aquifer in the study area reinforces this observation.

The net change in water levels in observation wells completed in the Harmon lignite aquifer from September 1979 to May 1981 are shown in figure 19. This period of time was one of severe drought in western North Dakota. The response of the aquifer to the drought is manifest by declining water levels that generally occur within about 3 to 5 mi of the outcrop. The eastward-extending lobes of declining water levels are probably areas of either relatively high transmissivity or high leakage loss to underlying beds.

Water-level fluctuations associated with changes in barometric pressure.--Water levels in observation wells penetrating confined aquifers fluctuate in response to changes in atmospheric pressure. The pressure change is conveyed, unattenuated, to the water column in the observation well. Some part of the pressure change acting on the land surface is transmitted vertically downward through the beds overlying the aquifer and results in an increase in both the compactive force on the aquifer material and in the pore-water pressure. The increased pore-water pressure tends to expel water from the aquifer to the well, thereby partly compensating for the downward force acting on the water surface in the well casing. The net effect is that increases in atmospheric pressure cause declines in water levels in wells. The ratio of atmospheric pressure change, expressed in feet of water, to water-level change is referred to as barometric efficiency. The value of the ratio ranges between 0 and 1 and varies according to the proportion of the pressure change at the land surface that is: (1) Neutralized by the bridging effect of the overburden; (2) absorbed through changes in compactive stress on the aquifer medium; and (3) conveyed to the aquifer fluid as changes in pore-water pressure. Predominance of the first two mechanisms results in a high ratio value, while prevalence of the third results in a low value.

Water levels in two Harmon lignite wells equipped with hourly water-level recorders are compared with barometric pressure, continuously recorded at 15-60-34CBB, in figure 20. All data plotted on the figure are daily mean values. Barometric efficiencies were calculated for the two wells during

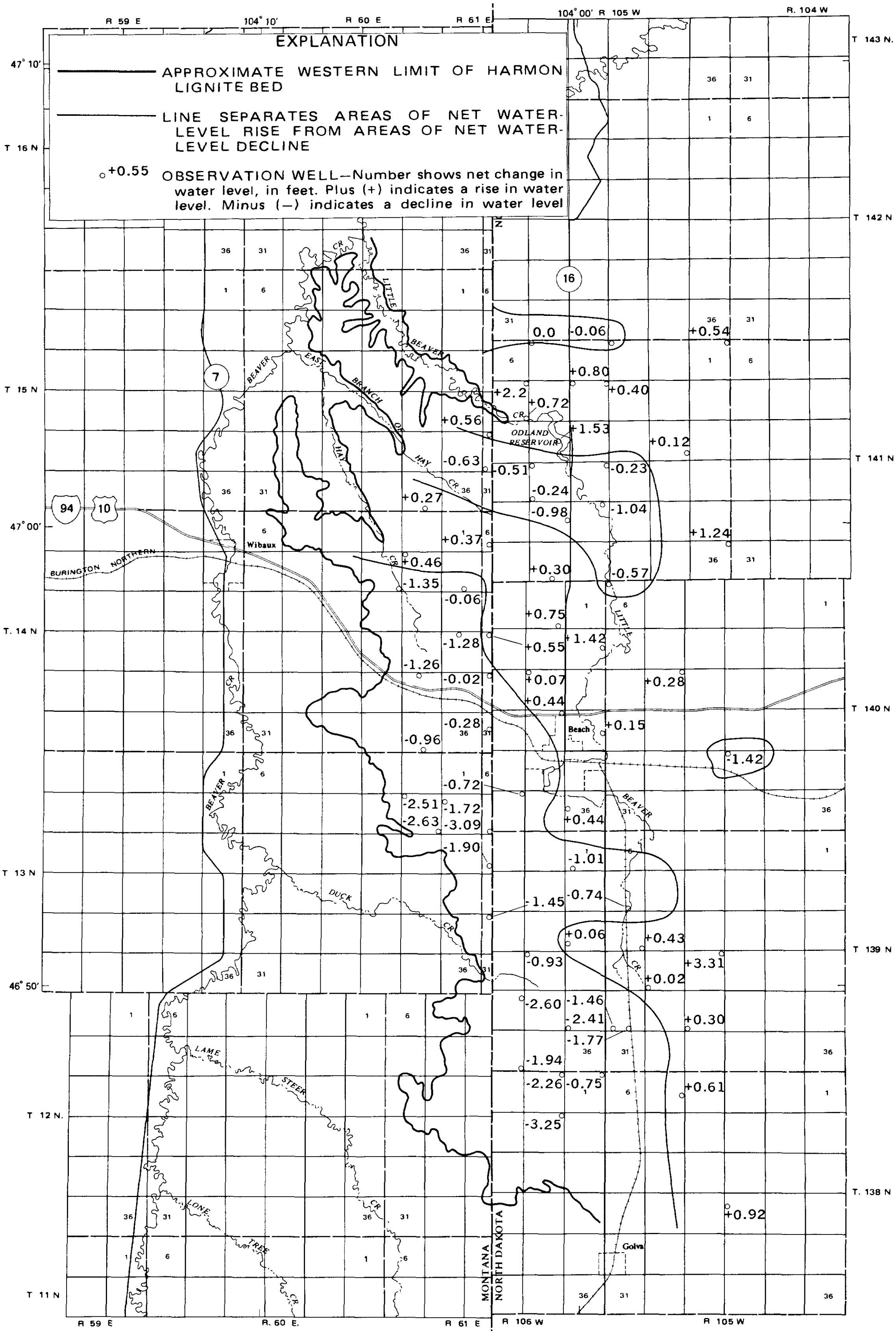


FIGURE 19.—Net change in water levels in the Harmon lignite aquifer from September 1979 to May 1981.

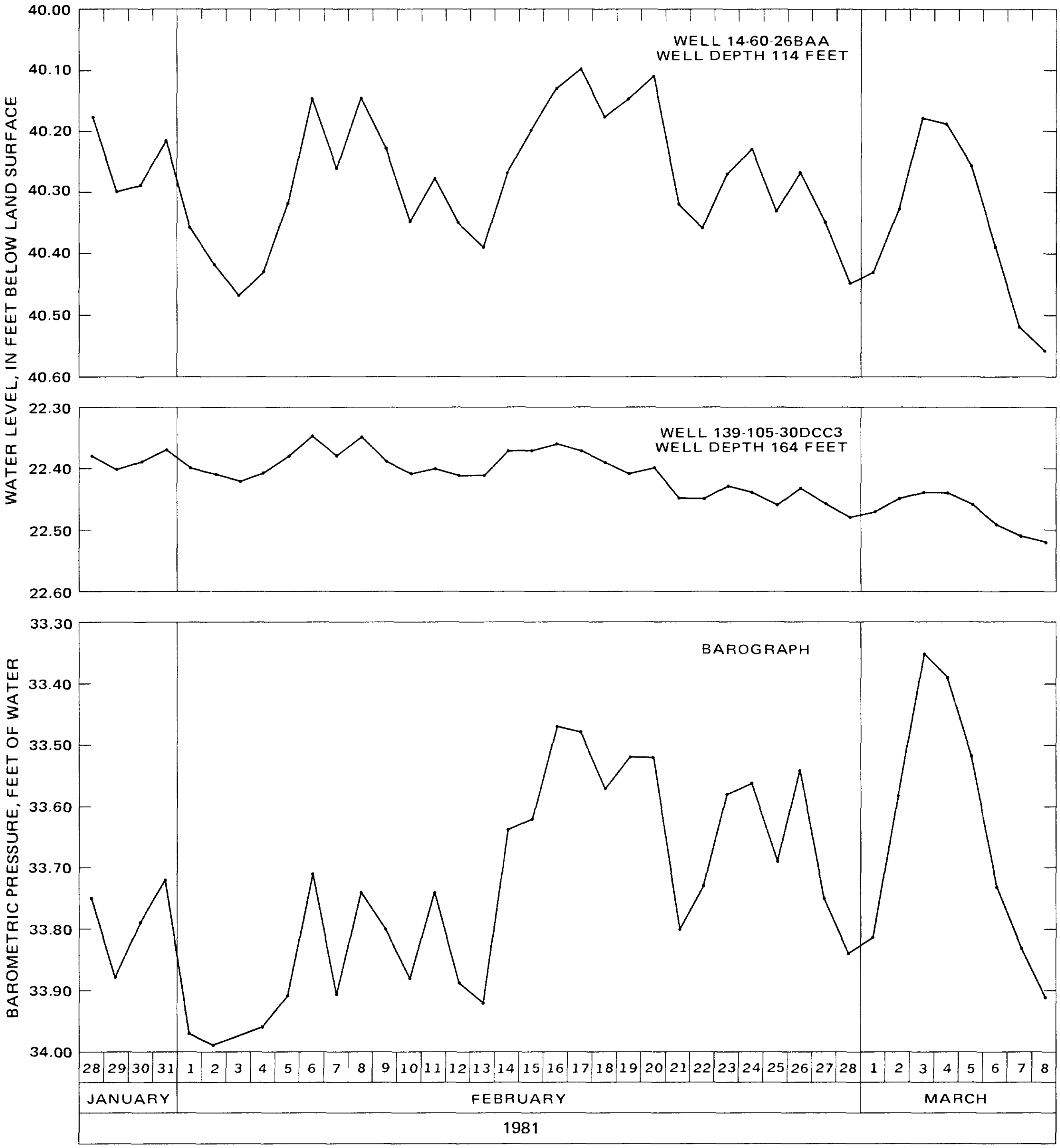


FIGURE 20.—Relationship of water-level fluctuations in two observation wells completed in the Harmon lignite aquifer to barometric pressure fluctuations.

eight different time periods having relatively great barographic excursions. The mean value for well 14-60-26BAA was 0.67 and that for 139-105-30DCC3 was 0.15.

From the definition of barometric efficiency (*BE*) stated previously, McWhorter and Sunada (1977) derived an equivalent expression in terms of physical characteristics of the aquifer, overburden, and aquifer fluid;

$$BE = f - 1 - f\left(\frac{\beta}{\alpha p + \beta}\right)$$

Where: f $(0<f<1)$ is a coefficient expressing the tendency of the overburden material to transmit atmospheric pressure changes to the top of the aquifer,
β is the compressibility of water, and
αp is the pore volume compressibility.

The compressibility of water should be uniform throughout the Harmon lignite aquifer and probably is not a factor in contributing to the difference in barometric efficiencies of the two wells. Because the depth to the top of the aquifer differs by only 50 ft at the two sites and the overburden material is very similar, the f coefficient should be approximately equivalent for the two wells. The contrast in barometric efficiency between the wells, therefore, probably is due to a disparity in pore volume compressibility related to the compressive resistance of the lignite.

The data illustrated in figure 20 show that water-level fluctuations of as much as several tenths of a foot occurring within a brief time span may be attributable to nothing more than barometric effects and have nothing to do with actual changes in storage in the aquifer.

Water Quality

The quality of water in the streams and aquifers of the study area was documented by either spring and fall or monthly sampling of the surface waters and generally one-time sampling of the observation wells. Repeated sampling of a few selected observation wells showed that no significant changes in water quality occurred between 1976 and 1980.

Water-quality analyses of the surface waters are reported in the annual data reports of the U.S. Geological Survey. Regional interpretations of the chemical quality of water from the deeper aquifers underlying the study area may be drawn from reports on the ground-water resources of various counties in western North Dakota. The water-quality interpretations in this report for the three uppermost aquifers underlying the study area are based on data collected specifically for this project. All water-quality data acquired from the sampling of observation wells are listed in Attachment B near the end of the report.

Surface Water

Spring and fall sampling for chemical analyses of common ions was carried out for Duck, Hay, and Little Beaver Creeks. Common-ion analyses were done monthly and trace-constituent and nutrient analyses were done twice annually for Beaver Creek at Wibaux and Beaver Creek near Trotters. All these data are published in annual data reports of the U.S. Geological Survey. The following are statistical summaries (table 4 and fig. 21) of the data that indicate seasonal variations of water quality within a given stream and differences in quality among the various streams. Means and standard deviations of chemical concentrations by range of discharge for each station are shown in table 4. The data in the discharge range of less than 1 ft^3/s are intended to represent the base-flow condition for each station. Duck Creek, however, has no base flow. The highest discharge range for each station represents conditions during the spring snowmelt period.

As with most surface waters, the concentration of nearly every constituent for each station decreased with increasing discharge. Standard deviations from the mean generally increased with increasing discharge. This increase is particularly evident in the data for Beaver Creek at Wibaux. The trend evident in the standard deviations is indicative of the consistent quality of base-flow water, in contrast with the diverse quality of water that is generated during different overland-flow events.

The relative ionic composition of all the stream samples is illustrated in figure 21. Sodium constituted 42 to 58 percent of the cations in the samples from Little Beaver Creek and Beaver Creek, but only constituted 22 to 35 percent of the cations in the samples from Duck and Hay Creeks. The deviation in composition in the samples from Duck and Hay Creeks probably is due to differences in dominant soil types in the respective basins. Sulfate constituted 65 to 78 percent of the anions in the samples from all the streams at all flow rates, except one. The high sulfate composition probably indicates that the runoff was generated over soils rich in evaporative salts.

Ground Water

Aquifers in the Fox Hills Sandstone, Hell Creek Formation, and lower part of Ludlow Member, Fort Union Formation

Each of these three stratigraphic units is penetrated by only one observation well in the Wibaux-Beach study area. Other hydrologic studies in southwestern North Dakota (Croft, 1978; Anna, 1981), however, provide a substantial water-quality data base for the aquifers. All aquifers in the sequence yielded a sodium bicarbonate type water. Dissolved-solids concentrations ranged from about 870 to 2,500 mg/L and the reported means of dissolved solids for all of the aquifers ranged from 1,060 to 1,400 mg/L. In general, the dissolved-solids concentration decreased from the shallower to the deeper aquifers. Sodium constituted over 90 percent of the cations in the aquifer waters and bicarbonate generally more than 60 percent of the anions. The water usually was soft and often contained detectable levels of

TABLE 4.--Statistical summary of water-quality analyses by range of discharge for streams in the study area

[All units are in milligrams per liter unless otherwise specified; ft^3/s, cubic feet per second; µg/L, micrograms per liter; µmho/cm at 25°C, micromhos per centimeter at 25 degrees Celsius; > indicates greater than; < indicates less than]

Discharge range (ft^3/s)	Number of samples		Sodium	Potassium	Calcium	Magnesium	Alkalinity	Sulfate	Chloride	Fluoride	Dissolved solids	Hardness (as $CaCO_3$)	Silica	Boron (µg/L)	Iron (µg/L)	pH (units)	Specific conductance (µmho/cm at 25°C)	Sodium-adsorption ratio	Percent sodium
06336447 Duck Creek near Wibaux, Montana																			
1.0-10	2	Mean	130	18	76	69	160	590	5.8	0.10	990	480	13	570	150	7.7	1,240	2.3	31
>100	1	Mean	5.5	9.3	17	5.8	57	25	1.9	.10	110	66	7.3	80	90	7.9	175	.3	13
06336500 Beaver Creek at Wibaux, Montana																			
<1.0	10	Mean	340	9.6	120	98	400	970	13	0.26	1,790	700	8.9	760	31	8.1	2,520	5.6	51
		Standard deviation	13	3.2	14	6.3	40	39	3.3	.05	53	56	2.0	62	20	.1	82	.4	2
1.0-10	21	Mean	360	9.7	120	95	390	1,020	9.5	.26	1,850	680	8.2	690	30	8.1	2,580	6.0	55
		Standard deviation	72	1.2	18	19	82	180	3.5	.06	320	110	2.1	280	19	.3	440	.8	5
>10	5	Mean	180	10	75	54	220	550	5.4	.16	1,020	410	7.9	370	110	8.0	1,460	3.6	46
		Standard deviation	94	1.7	28	23	110	250	2.1	.09	460	170	.9	170	65	.3	560	1.3	6
06336515 Hay Creek near Wibaux, Montana																			
<1.0	7	Mean	150	11	150	160	340	1,060	18	0.20	1,750	1,060	7.1	410	150	7.4	2,090	2.1	26
		Standard deviation	74	2.3	56	85	82	550	7.6	.14	800	490	3.0	230	94	.6	970	.5	6
>1.0	6	Mean	65	12	88	79	170	510	6.9	.11	870	550	8.5	330	240	7.8	1,140	1.1	19
		Standard deviation	69	2.4	71	82	96	550	4.1	.04	830	530	2.1	280	140	.4	880	.6	3
06336545 Little Beaver Creek near Wibaux, Montana																			
<1.0	5	Mean	600	14	110	170	500	1,620	17	0.26	2,830	970	2.2	790	40	8.0	3,130	8.5	63
		Standard deviation	58	3.5	39	36	130	68	6	.05	430	250	1.7	450	23	.4	1,160	.5	13
>1.0	4	Mean	240	14	92	120	230	940	15	.18	1,570	730	7.3	560	210	7.9	1,710	3.9	41
		Standard deviation	140	5.0	23	71	50	460	12	.05	720	340	1.2	290	170	.3	410	1.3	4
06336600 Beaver Creek near Trotters, North Dakota																			
<1.0	13	Mean	430	11	102	100	470	1,110	12	0.32	2,020	680	5.0	790	30	8.3	2,740	7.3	57
		Standard deviation	64	1.7	20	14	44	92	4.6	.08	160	95	2.2	150	18	.2	210	1.4	6
1.0-10	20	Mean	410	11	120	100	470	1,080	11	.24	2,020	720	8.3	650	31	8.1	2,690	6.7	57
		Standard deviation	73	1.4	23	19	76	190	3.1	.06	360	130	3.0	76	28	.2	470	.8	6
10-100	12	Mean	260	10	92	68	320	690	6.9	.22	1,320	510	6.9	500	32	8.3	1,850	5.1	54
		Standard deviation	71	1.4	26	23	71	180	1.4	.08	310	150	1.9	160	30	.1	400	1.2	8
>100	2	Mean	82	7.8	51	30	160	280	3.1	.15	560	250	7.3	210	85	8.0	800	2.2	40

PLOTTING SYMBOL	STATION	DISCHARGE RANGE (CUBIC FEET PER SECOND)	NUMBER OF SAMPLES IN RANGE	MINIMUM AND MAXIMUM DISCHARGE IN RANGE (CUBIC FEET PER SECOND)	MEAN DISSOLVED SOLIDS (MILLIGRAMS PER LITER)
D1	DUCK CREEK NEAR WIBAUX	1 TO 10	2	4 3/4 9	990
D2	DUCK CREEK NEAR WIBAUX	> 100	1	369	107
BW1	BEAVER CREEK AT WIBAUX	< 1	10	0 01/0 78	1 790
BW2	BEAVER CREEK AT WIBAUX	1 TO 10	21	1 2/9 0	1 850
BW3	BEAVER CREEK AT WIBAUX	> 10	5	16/653	1 020
H1	HAY CREEK NEAR WIBAUX	< 1	7	0 01/0 49	1 750
H2	HAY CREEK NEAR WIBAUX	> 1	6	1 57/16	870
LB1	LITTLE BEAVER CREEK NEAR WIBAUX	< 1	5	0 11/0 16	2 830
LB2	LITTLE BEAVER CREEK NEAR WIBAUX	> 1	4	8 8/309	1 570
BT1	BEAVER CREEK NEAR TROTTERS	< 1	13	0 02/0 94	2 020
BT2	BEAVER CREEK NEAR TROTTERS	1 TO 10	20	1 2/6 5	2 020
BT3	BEAVER CREEK NEAR TROTTERS	10 TO 100	12	11/56	1 320
BT4	BEAVER CREEK NEAR TROTTERS	> 100	2	293/965	560

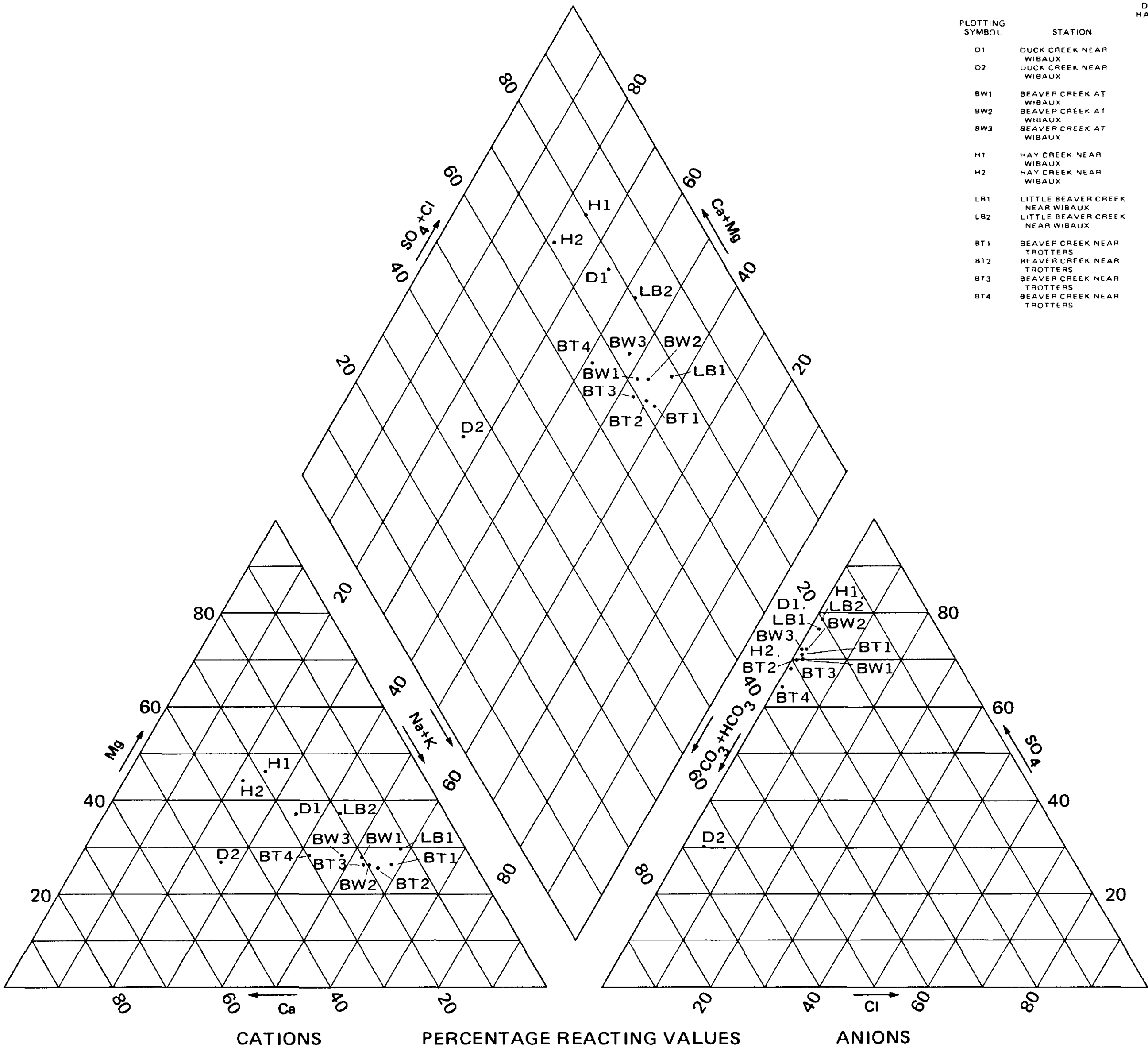
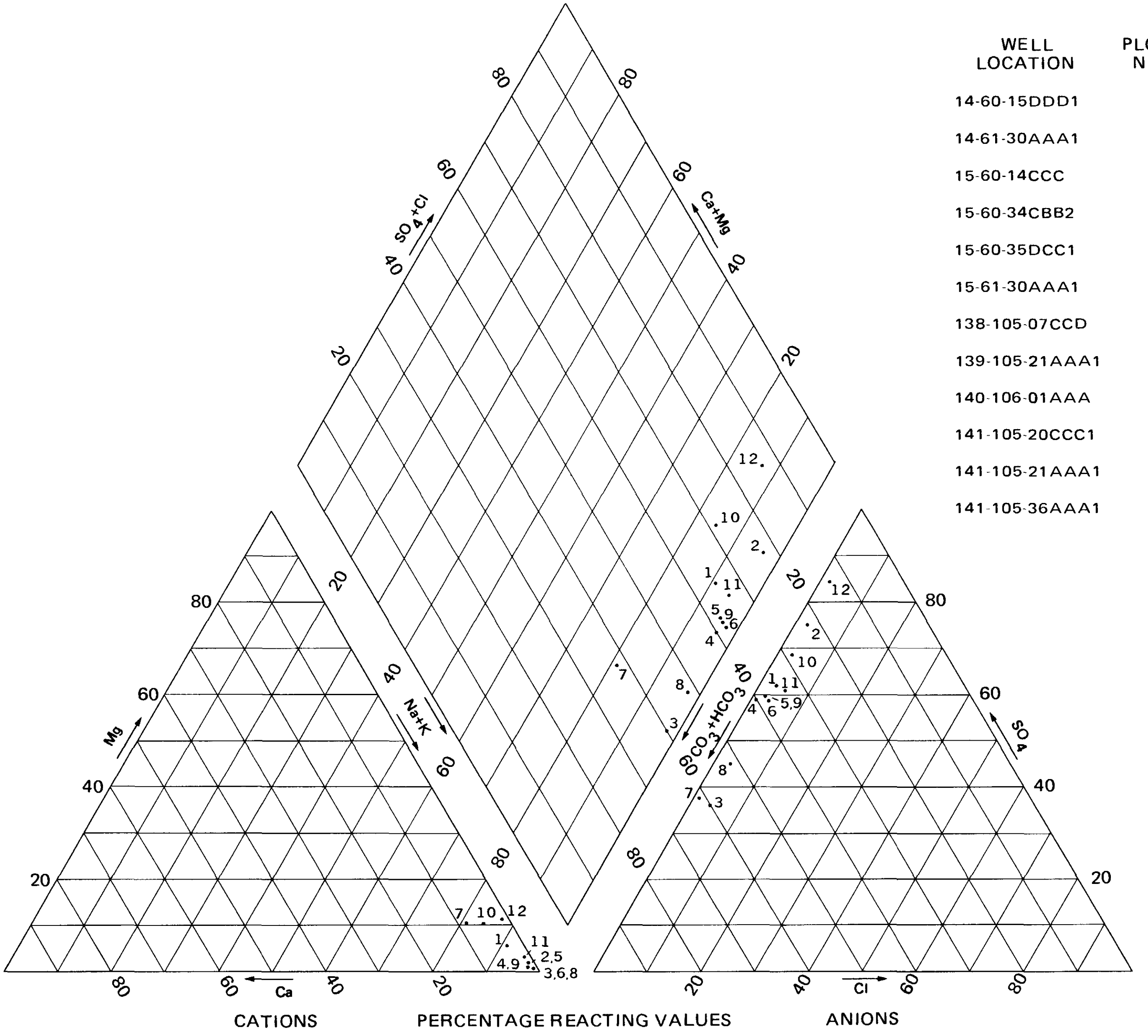
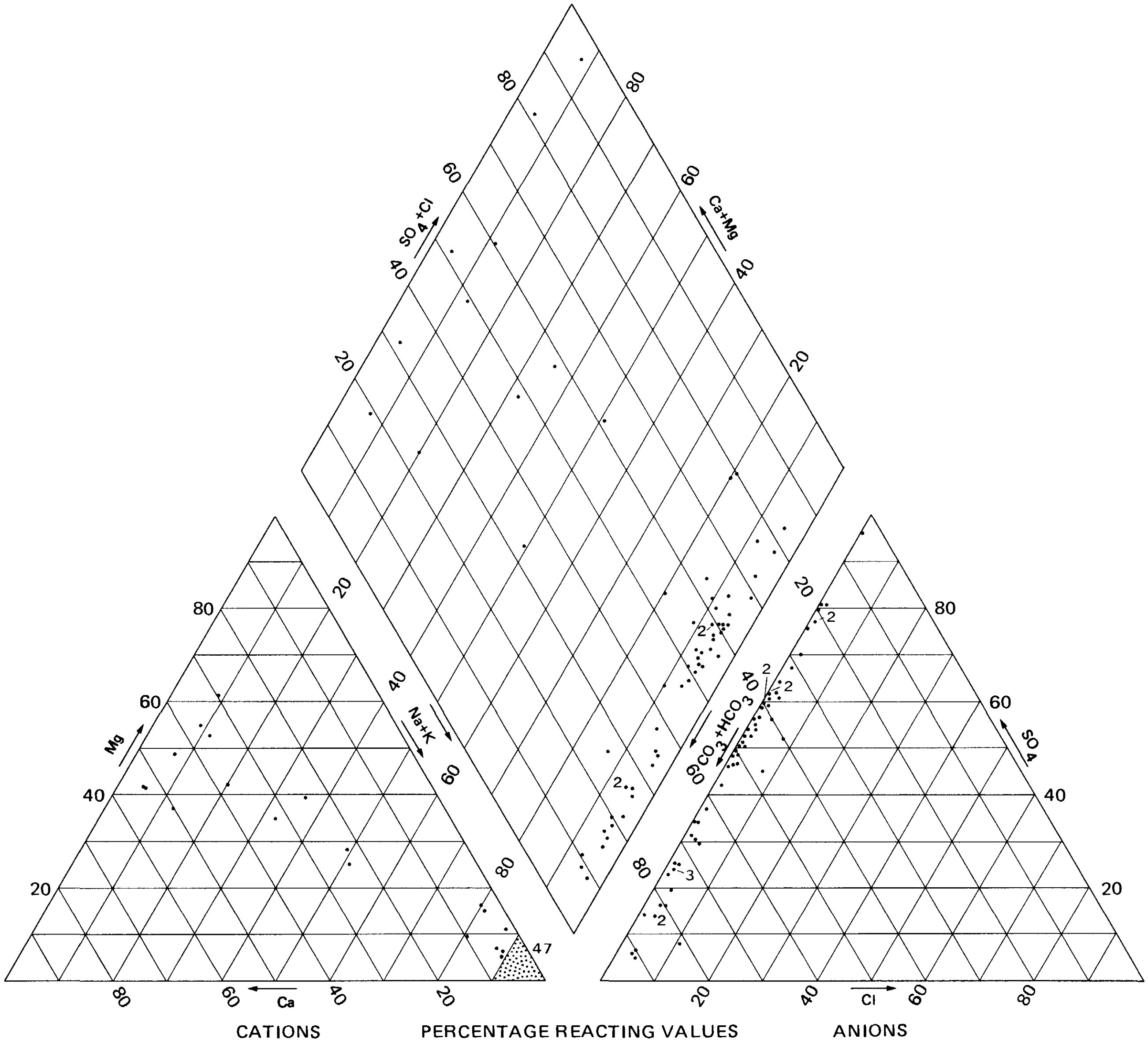


FIGURE 21.—Relative concentrations of common ions in water samples from streams in the study area.



WELL LOCATION	PLOTTING NUMBER	DISSOLVED SOLIDS (MILLIGRAMS PER LITER)	WELL DEPTH (FEET)
14-60-15DDD1	1	1,820	216
14-61-30AAA1	2	1,490	459
15-60-14CCC	3	1,150	182
15-60-34CBB2	4	1,780	200
15-60-35DCC1	5	1,370	354
15-61-30AAA1	6	1,430	299
138-105-07CCD	7	1,220	306
139-105-21AAA1	8	1,220	586
140-106-01AAA	9	1,410	354
141-105-20CCC1	10	1,900	360
141-105-21AAA1	11	1,500	371
141-105-36AAA1	12	2,290	599

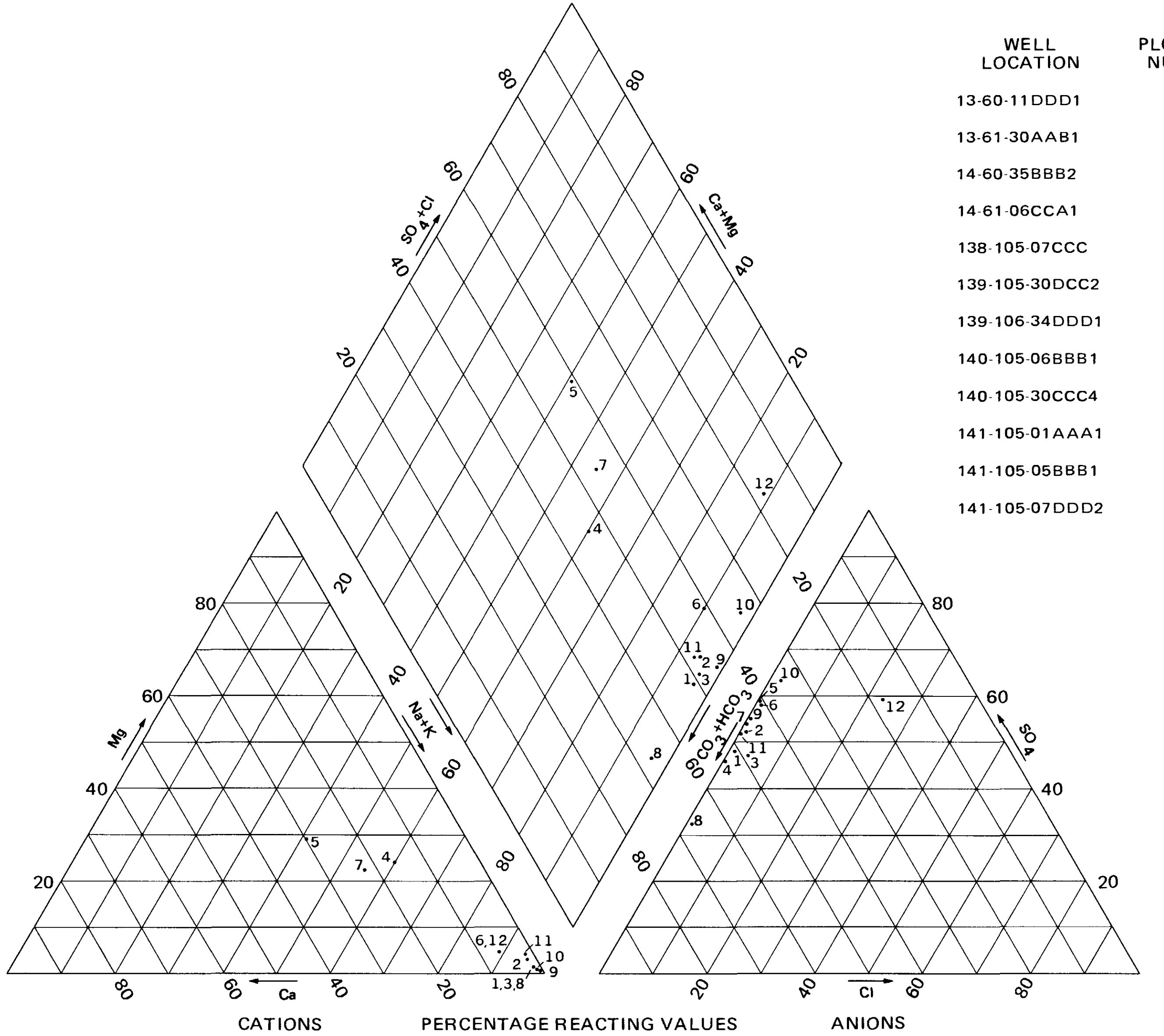
FIGURE 22.—Relative concentrations of common ions in water samples from the upper Ludlow aquifer system.



EXPLANATION

2
• PLOTTING POINT—Number indicates the number of samples plotting at the same location

FIGURE 24.—Relative concentrations of common ions in water samples from the Harmon lignite aquifer.



WELL LOCATION	PLOTTING NUMBER	DISSOLVED SOLIDS (MILLIGRAMS PER LITER)	WELL DEPTH (FEET)
13-60-11DDD1	1	1,600	218
13-61-30AAB1	2	2,220	240
14-60-35BBB2	3	1,180	170
14-61-06CCA1	4	1,060	155
138-105-07CCC	5	2,350	228
139-105-30DCC2	6	2,000	303
139-106-34DDD1	7	1,540	198
140-105-06BBB1	8	1,600	201
140-105-30CCC4	9	1,720	288
141-105-01AAA1	10	1,430	514
141-105-05BBB1	11	2,310	206
141-105-07DDD2	12	2,660	207

FIGURE 23.—Relative concentrations of common ions in water samples from the lower Tongue River aquifer system.

Water-Quality Differences Among Aquifers

Differences in chemical quality among the three aquifers are detectable, although, for the most part, fairly subtle. Tables 5, 6, and 7 present a statistical summary of each of the measured chemical constituents for each of the aquifers. The data indicate that, for many constituents, concentrations decrease with increasing aquifer depth. The median, rather than the mean, is the preferred statistic for this comparison because the mean was unduly biased by a few extreme values. Extreme values occurred most commonly in the Harmon lignite aquifer. The statistical data also show that the standard concentration value for a given constituent generally decreases with increasing aquifer depth.

Median and mean sodium and potassium concentrations are lowest in the upper Ludlow aquifer system although the differences are minor. Percent sodium and SAR are highest in the Ludlow and lowest in the Harmon lignite aquifer. The calcium and magnesium concentrations in the Ludlow are only one-third to one-half as great as those in the lower Tongue River aquifer system and the Harmon lignite aquifer (upper two aquifers). Alkalinity also is markedly lower in the Ludlow, but the median sulfate concentrations for the three aquifers are virtually equal. Chloride and fluoride median concentrations for the Ludlow are twice those in the Harmon and three times those in the Tongue River. Standard deviations for sodium, percent sodium, calcium, magnesium, alkalinity, and chloride were lowest in the Ludlow and, except for chloride, decreased with aquifer depth.

Median and mean dissolved-solids concentrations and specific conductance, and the corresponding standard deviations, are highest in the Harmon and decrease with aquifer depth. Mean and median values for hardness, nitrogen, silica, and strontium concentrations are all significantly lowest for the Ludlow, but are of very similar magnitude for the Tongue River and Harmon. Median pH values are lowest in the Harmon and highest in the Ludlow.

Statistics for the trace elements boron, iron, manganese, and molybdenum show that iron and manganese concentrations are highest in the Harmon and that the iron concentration in the Harmon has a large standard deviation. Median boron levels are virtually the same in the three aquifers. Detectable molybdenum concentrations were found in a majority of samples only in the Ludlow.

Water-Quality Variations Within the Harmon Lignite Aquifer

Areal variations in the water quality of the Harmon lignite aquifer are the result of a complex combination of organic and inorganic reactions, some microbially mediated, taking place within the lignite aquifer. Superposed on the reactions are the chemical effects of the mixing of leakage waters from overlying confining beds. The following section will present simple mechanisms that probably are instrumental in generating the geochemical regime of the Harmon lignite aquifer.

The most chemically active part of the Harmon lignite aquifer is along the western boundary. The aquifer is unsaturated for some variable, unknown hydrogen sulfide. Water from the Fox Hills aquifer in west-central and southwest North Dakota has been described as having a "rotten egg" odor--a result of hydrogen sulfide.

Upper Ludlow aquifer system

Water samples were taken from 12 wells in the upper Ludlow aquifer system in the study area (Attachment B). Analyses of the samples show that the water is a sodium bicarbonate or sodium sulfate type. Sodium constituted over 90 percent of the cations in nine of the samples and over 80 percent of the cations in the other three (fig. 22). Sulfate constituted over 50 percent of the anions in nine of the samples and bicarbonate constituted over 50 percent of the anions in the other three.

Dissolved-solids concentrations in the 12 samples ranged from 1,150 to 2,290 mg/L and the mean value was 1,550 mg/L. Most of the water samples were soft and contained little dissolved iron. The median pH value was 8.5.

Lower Tongue River aquifer system

Water samples were collected from 12 wells in the lower Tongue River aquifer system in the study area (Attachment B). Analyses of the samples show the water is a sodium bicarbonate-sulfate type. Sodium constituted over 89 percent of the cations in 9 of the 12 samples and from 40 to 60 percent in the other 3 samples (fig. 23). The anionic composition in most of the samples was evenly distributed between bicarbonate and sulfate. Each constituted between 40 and 60 percent of the total anions.

Dissolved-solids concentrations in the 12 samples ranged from 1,060 to 2,660 mg/L and the mean value was 1,810 mg/L. The water varied from soft to very hard, and most samples contained little dissolved iron. The median pH value was 8.3.

Harmon lignite aquifer

Water samples were collected from 66 observation wells completed in the Harmon lignite aquifer (Attachment B). The wide variety of ionic composition represented in the water from the 66 wells is illustrated in figure 24. Sodium constituted over 90 percent of the cations in 71 percent of the samples. However, calcium and magnesium comprised over 50 and 60 percent of the cations in the water from some wells. The percentages of calcium and magnesium were nearly equal in most of the samples.

The anionic compositions in the 66 samples represented nearly the entire range of possible combinations of sulfate versus bicarbonate (fig. 24). However, sulfate constituted between 45 and 65 percent of the anions in about half of the samples. Chloride constituted less than 5 percent of the anions in all but three of the samples.

Dissolved-solids concentrations in the 66 samples ranged from 412 to 8,560 mg/L and the mean value was 1,930 mg/L. The water varied from soft to very hard and most samples contained little dissolved iron. The median pH value was 8.1.

TABLE 5.--Statistical summary of water-quality analyses for samples from the upper Ludlow aquifer system

[All units are in milligrams per liter unless otherwise specified; µg/L, micrograms per liter; µmho/cm at 25°C, micromhos per centimeter at 25 degrees Celsius; °C, degrees Celsius; where more than one analysis was available for a given well, the analyses were averaged]

Constituent or physical property	Number of samples	Mean	Standard deviation	Median	Minimum value	Maximum value	Quartiles (percent) 25	Quartiles (percent) 75
Sodium	12	490	87	490	330	650	440	580
Potassium	12	4.3	1.7	3.4	2.7	8.1	3	5
Calcium	12	12	9.5	6.5	4.1	31	4.8	16
Magnesium	12	13	14	5.5	1.7	46	2.8	21
Alkalinity	12	450	110	430	250	590	410	550
Sulfate	12	710	290	700	330	1,400	540	850
Chloride	12	17	9.3	15	2.9	40	13	22
Fluoride	12	1.5	1.2	1.4	.3	4.9	.6	1.8
Dissolved solids	12	1,550	330	1,490	1,150	2,290	1,300	1,800
Hardness (as $CaCO_3$)	12	82	77	37	21	220	22	150
Boron	11	.58	.20	.58	.26	1.1	.47	.62
Iron	12	.16	.35	.06	.0	1.3	0	.10
Manganese	12	.027	.02	.02	.007	.065	.010	.04
Molybdenum (µg/L)	12	6.7	7	5	0	24	0	10
Nitrogen (ammonia plus dissolved organic)	12	1.0	.50	.84	.32	2.1	.67	1.1
Silica	12	5.8	3.9	6.3	.40	13	1.0	8.2
Strontium	12	.19	.15	.16	.0	.56	.13	.31
pH (units)	12	--	--	8.5	8.0	9.5	8.3	9.0
Specific conductance (µmho/cm at 25°C)	12	2,340	477	2,300	1,860	3,400	1,940	2,680
Sodium-adsorption ratio	12	31	15	38	11	47	21	41
Percent sodium	12	95	6	97	80	98	95	98
Temperature (°C)	12	11.0	2.0	11.0	9.0	17	10.0	11.5

TABLE 6.--Statistical summary of water-quality analyses for samples from the lower Tongue River aquifer system

[All units are in milligrams per liter unless otherwise specified; µg/L, micrograms per liter; µmho/cm at 25°C, micromhos per centimeter at 25 degrees Celsius; °C, degrees Celsius; where more than one analysis was available for a given well, the analyses were averaged]

Constituent or physical property	Number of samples	Mean	Standard deviation	Median	Minimum value	Maximum value	Quartiles (percent)	
							25	75
Sodium	12	540	180	580	240	800	370	680
Potassium	12	6.4	5.4	3.6	2.4	18	2.7	11
Calcium	12	46	67	18	2.5	230	6.3	57
Magnesium	11	31	43	16	1.5	140	2.7	52
Alkalinity	12	630	180	640	380	910	480	780
Sulfate	12	730	260	700	390	1,200	480	910
Chloride	12	35	96	5.2	3.2	340	3.4	12.4
Fluoride	12	.7	.7	.4	.0	2.3	.2	1.0
Dissolved solids	12	1,810	500	1,660	1,060	2,660	1,460	2,290
Hardness (as $CaCO_3$)	12	320	420	140	12	1,200	27	540
Boron	12	.69	.29	.65	.18	1.20	.50	.92
Iron	12	.32	.71	.03	.0	2.3	.01	.12
Manganese	12	.057	.098	.029	.0	.36	.013	.055
Molybdenum (µg/L)	12	8	18	.0	.0	63	.0	6.3
Nitrogen (ammonia plus dissolved organic)	12	1.23	.44	1.15	.70	2.3	1.03	1.3
Silica	12	8.9	3.5	8.6	.4	14	7.6	11.8
Strontium	12	1.2	1.7	.43	.0	6.0	.19	1.6
pH (units)	12	--	--	8.3	7.1	9.2	7.5	8.4
Specific conductance (µmho/cm at 25°C)	12	2,490	730	2,330	1,600	4,080	1,890	2,790
Sodium-adsorption ratio	11	30	21	32	5	74	6	44
Percent sodium	12	84	21	95	40	99	66	98
Temperature (°C)	12	11.0	1.5	11.0	10.0	14.0	10.0	12.0

TABLE 7.--Statistical summary of water-quality analyses for samples from the Harmon lignite aquifer

[All units are in milligrams per liter unless otherwise specified; µg/L, micrograms per liter; µmho/cm at 25°C, micromhos per centimeter at 25 degrees Celsius; °C, degrees Celsius; where more than one analysis was available for a given well, the analyses were averaged]

Constituent or physical property	Number of samples	Mean	Standard deviation	Median	Minimum value	Maximum value	Quartiles (percent)	
							25	75
Sodium	66	560	350	550	5.6	2,400	390	750
Potassium	66	6.1	4.6	4.7	1.6	26	3.9	6.2
Calcium	66	52	100	19	4.6	530	11	37
Magnesium	66	44	110	12	.4	660	6.9	27
Alkalinity	66	690	260	680	170	1,310	530	890
Sulfate	66	810	840	680	18	5,000	250	1,100
Chloride	66	12	11	7.5	2.6	63	5.3	15
Fluoride	66	.8	.6	.7	.1	3.8	.3	1.1
Dissolved solids	66	1,930	1,210	1,740	410	8,560	1,250	2,420
Hardness (as $CaCO_3$)	66	320	700	95	21	4,300	59	200
Boron	66	.74	.70	.56	.08	5.3	.49	.73
Iron	66	1.1	6.8	.07	.01	55	.03	.20
Manganese	66	.19	.58	.04	.0	40	.03	.08
Molybdenum (µg/L)	66	2	4	.0	.0	13	.0	2
Nitrogen (ammonia plus dissolved organic)	65	1.53	1.84	.99	.06	10	.80	1.35
Silica	66	9.4	5.2	8.3	.5	39	7.6	10
Strontium	66	1.1	2.0	.50	.12	12	.34	.96
pH (units)	66	--	--	8.1	5.6	10.6	7.7	8.3
Specific conductance (µmho/cm at 25°C)	66	2,780	1,440	2,580	770	10,600	1,890	3,480
Sodium-adsorption ratio	66	26	13	31	.1	51	18	35
Percent sodium	66	81	30	94	3	98	88	96
Temperature (°C)	66	11.0	1.5	11.0	9.0	18.0	10.0	12.0

distance from the outcrop, except possibly where the outcrop abuts saturated scoria. Sufficient quantities of atmospheric oxygen can reach the aquifer at depths of up to several tens of feet (M. G. Croft, written commun., 1980) to oxidize otherwise insoluble minerals such as pyrite and marcasite. Minerals such as calcium and magnesium carbonates, gypsum, limonite, and many other iron oxyhydroxide minerals are abundant in the overburden near the surface and are readily soluble in percolating waters. Atmospheric CO_2 or CO_2 produced as a byproduct of microbial activity in the soil zone reacts with water in the shallow environment to form carbonic acid, which aids in the dissolution of carbonate minerals. Collectively the processes of oxidation, hydrolysis, and dissolution tend to produce a low pH water enriched in dissolved solids. Water of such composition may be generated within the oxygenated part of the aquifer or within the overlying unsaturated zone to subsequently percolate to the aquifer.

An exception to the generalizations of the previous paragraph occurs in some of the clinkered areas. Where the clinker is in contact with the lignite, it serves effectively as a conduit to transmit atmospheric water to the aquifer, and allows little opportunity for chemical reaction and solute uptake in the soil zone or other unsaturated detrital material. A dissolved-solids contour map (fig. 25) shows that dissolved-solids concentrations are consistently less in the central part of the study area downgradient from the heavily clinkered areas than they are at the north and south ends where the clinker is much less evident or is absent (fig. 8 shows clinker exposures).

The high dissolved-solids concentrations in the north and south parts of the area are assumed to arise in part from reactions in the unsaturated lignite. A large lobe of the Harmon bed in the southern part of the area is unsaturated (five test holes penetrated unsaturated lignite) and a substantial part in the uplands near Hay Creek apparently is unsaturated (three test holes were drilled through unsaturated lignite).

The uniformity of the dissolved-solids concentrations in the central and northeastern parts of the area suggests that 1,200 mg/L$\pm$200 mg/L may be some sort of "buffered" end point for solids concentration. This is an empirical observation for which no causative mechanisms are put forth.

Dissolution of gypsum ($CaSO_4 \cdot H_2O$) and of calcium-magnesium carbonate minerals by CO_2-charged water in the near-surface unsaturated zone and the shallow (a few tens of feet) saturated areas results in high calcium and magnesium concentrations relative to sodium. The prevalence of divalent cations does not persist long in the flow system, however. The percentage of total cationic equivalents contributed by sodium is shown in figure 26. Three lobes of low percent sodium, indicating relatively high calcium and magnesium concentration, are evident near the outcrop area, but persist for only a short distance downgradient. The most probable mechanism responsible for the loss of calcium and magnesium and concurrent increase in sodium is cation exchange, a process whereby cations are attracted in a specific order of affinity to negatively charged microsurfaces on the aquifer material. The divalent cations are adsorbed on the exchange sites in preference to sodium, which is released to the pore water.

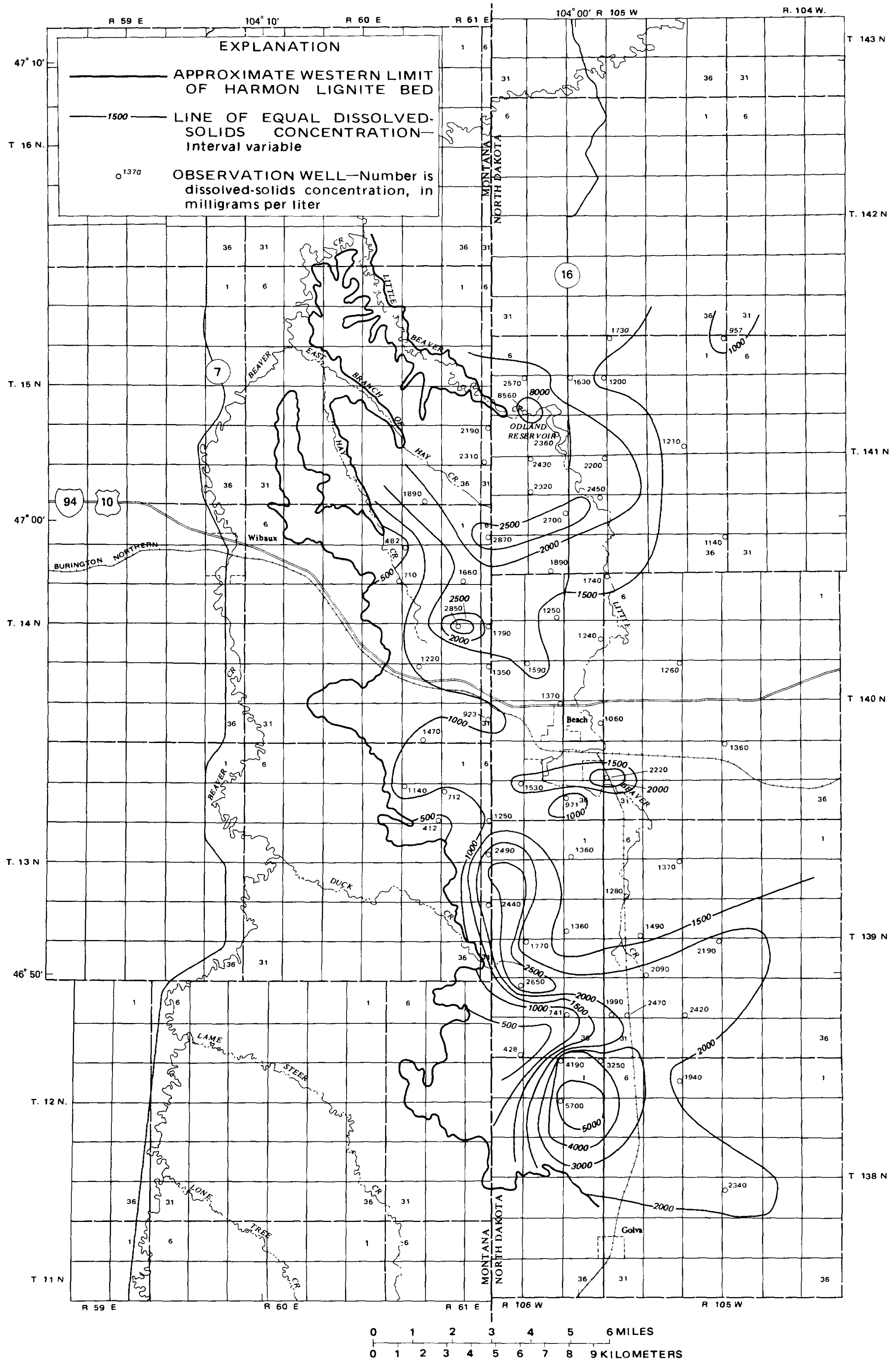


FIGURE 25.—Concentration of dissolved solids in the Harmon lignite aquifer.

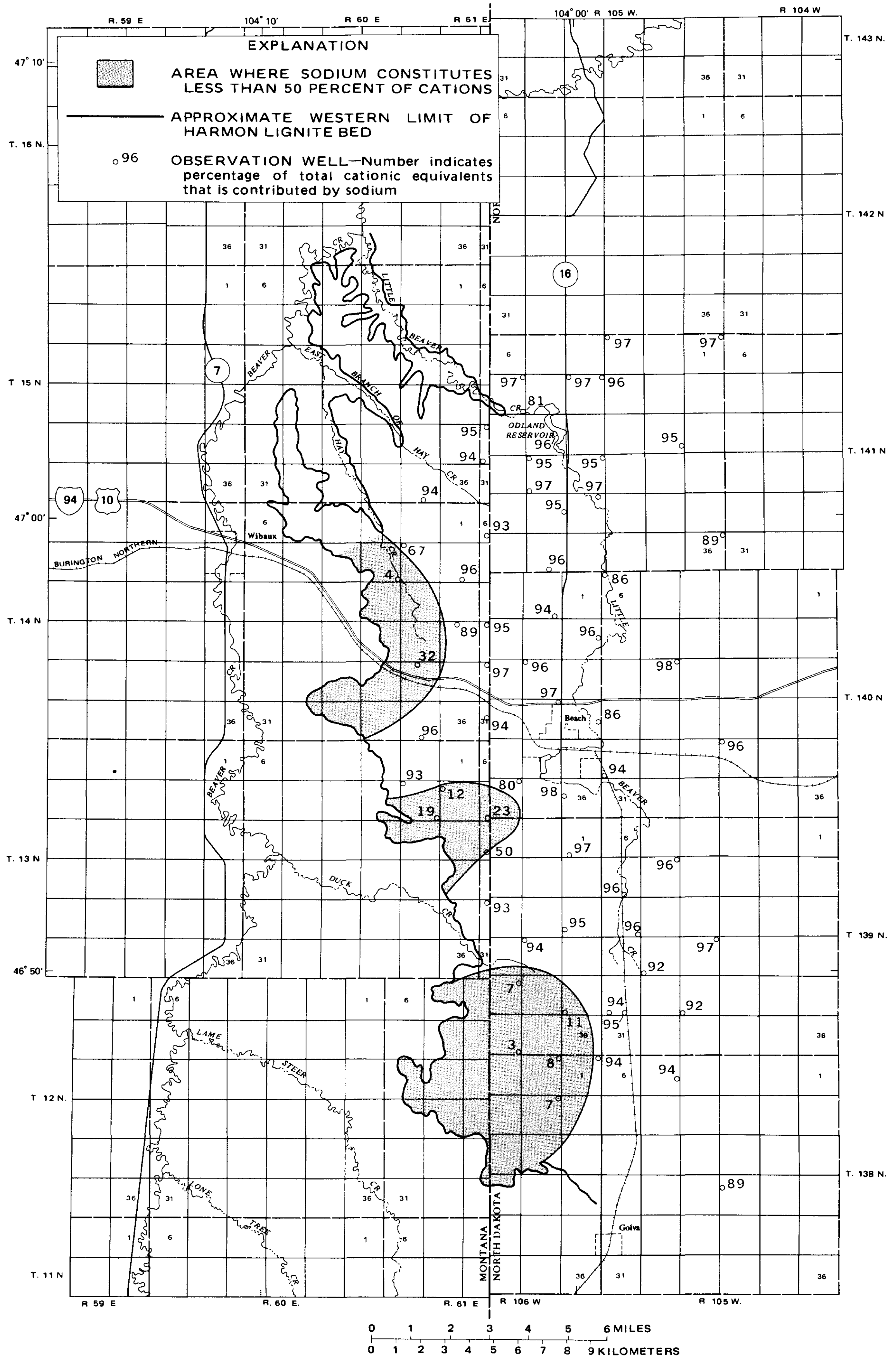


FIGURE 26.—Distribution of percent sodium in the Harmon lignite aquifer.

The cation-exchange concept is reinforced by the findings of M. G. Croft (written commun., 1980), who stated that lignite cation-exchange capacity is extremely high. Croft also found that sodium was in abundance as an exchangeable cation. The cation exchange quickly converts the calcium-magnesium type water to water with a cationic composition of about 95 percent sodium.

Based on the preceding observations, it may be hypothesized that a functional relationship should exist between sodium, calcium, and magnesium concentrations and depth of the sampled well or between the cationic concentrations and the length of flow path from the aquifer outcrop to the sampled well--if it is assumed that depth and length of flow path are indices of the residence time of a "particle" of water in the aquifer. The effects of mixing or exchange of water by vertical leakage will not be considered for purposes of this discussion.

Plots were made of each cationic concentration versus well depth and of each cationic concentration versus length of flow path. The flow path was approximated by drawing streamlines, orthogonally intersecting the potential contours, from each well to the outcrop.

Linear regressions were made of each ionic concentration (dependent variable) versus well depth (independent variable) and of each ionic concentration (dependent variable) versus flow distance (independent variable). Four models were evaluated for each combination of ionic concentration (y) versus well depth or flow distance (x): $y = a+bx$, $y = a+b\log x$, $y = ae^{bx}$, and $y = ax^b$. Although the point scatter is great on nearly all the plots, most of the regressions proved statistically significant at the 1 percent level. With some exceptions, the greatest R^2 (coefficient of determination) value among the four models relating ion concentration to well depth and the greatest R^2 value among the four models relating ion concentration to flow distance were fairly close. Due to the lack of prominence of one class of models over the other, only the concentration versus depth relationship will be examined here. The well-depth parameter is much easier to obtain and is more precise than the flow-distance parameter.

Two of the most significant regressions related the logarithms of calcium and magnesium concentrations to the log of well depth at the sampling sites. Figures 27 and 28 show that calcium and magnesium concentrations decrease about 1.5 and 1.7 log cycles, respectively, per log cycle of increasing depth. The R^2 values are 0.59 for calcium and 0.58 for magnesium.

The correlation of sodium with well depth is not very good, especially at shallow depths. Figure 29 shows that the range in sodium concentrations was great at well depths of less than 100 ft, but below 100 ft the values were all (except one) between about 350 and 950 mg/L. At shallow depths, the variety of prevailing geochemical environments and the relatively broad spectrum of available minerals cause the wide range of concentrations observed for sodium as well as for calcium and magnesium. The three plots and the percent sodium map (fig. 26) indicate the downgradient influence of cationic exchange in stabilizing what may be a highly variable cationic composition to one that invariably consists of greater than 90 percent sodium.

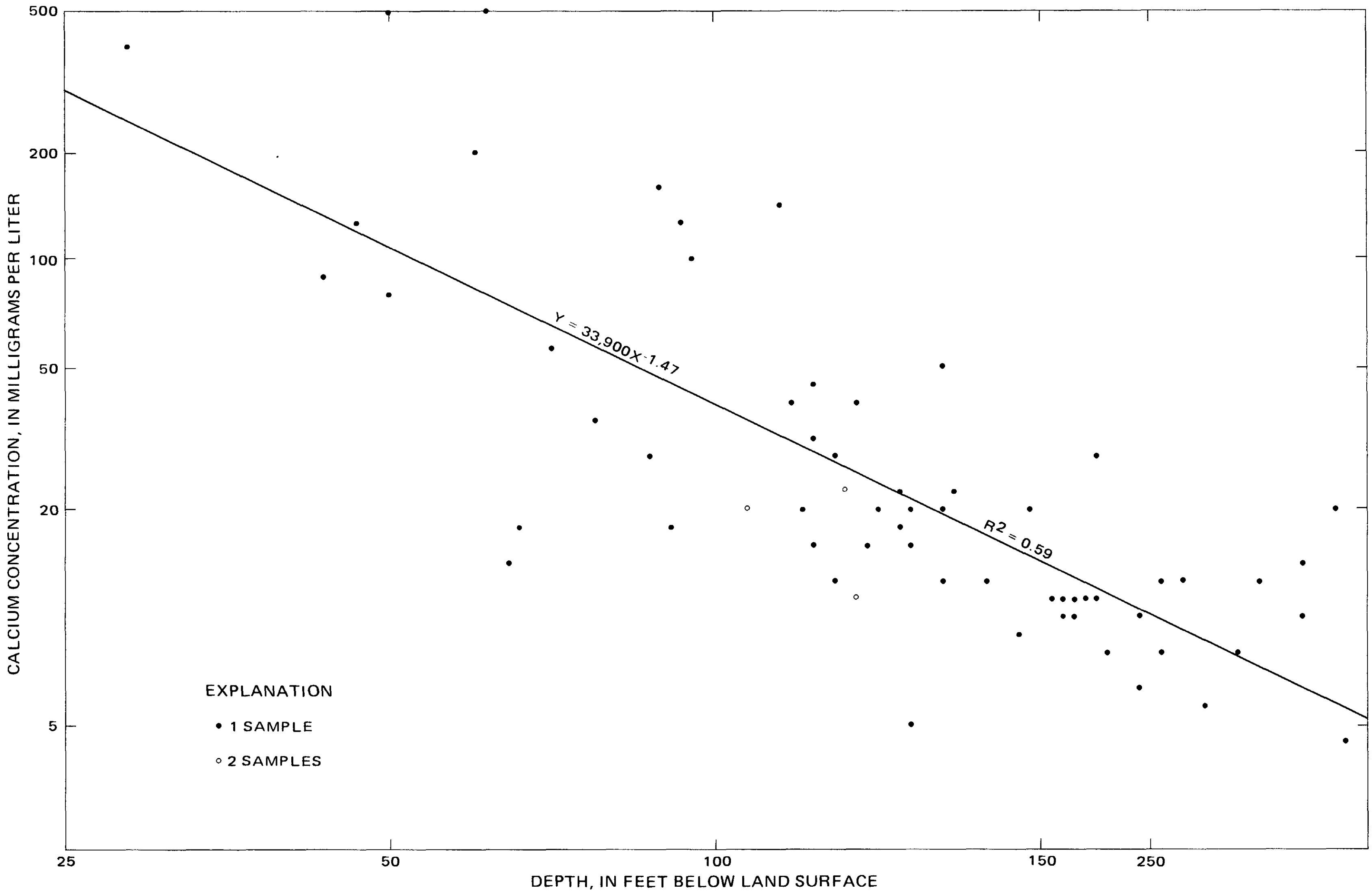


FIGURE 27.—Calcium concentration versus depth of well for samples from the Harmon lignite aquifer.

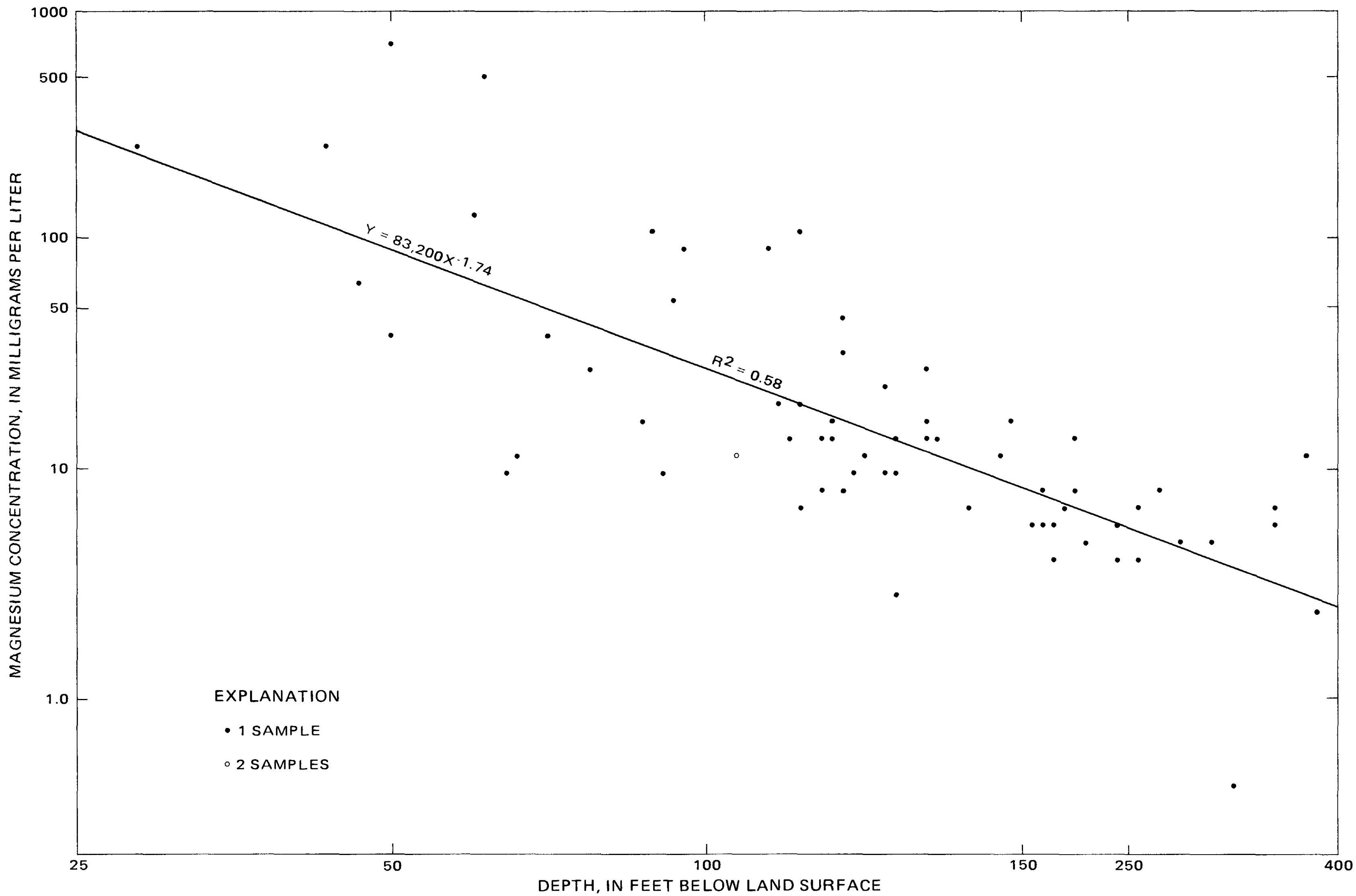


FIGURE 28.--Magnesium concentration versus depth of well for samples from the Harmon lignite aquifer.

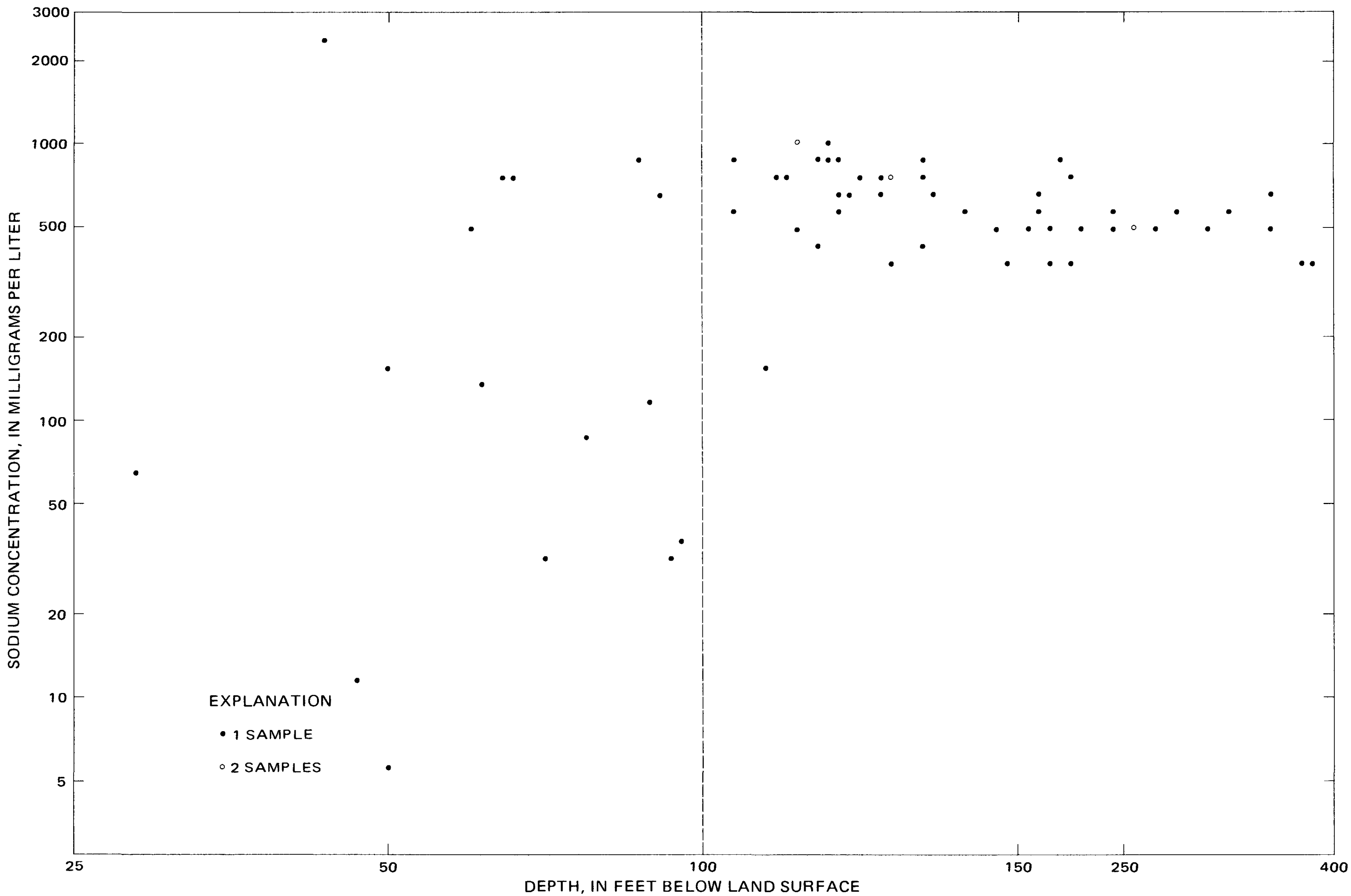


FIGURE 29.—Sodium concentration versus depth of well for samples from the Harmon lignite aquifer.

The areal variation in major anionic composition of water in the Harmon lignite aquifer is depicted on maps showing the sulfate (fig. 30) and alkalinity (fig. 31) concentrations. The sulfate concentrations vary greatly and often abruptly over the study area, whereas the alkalinity concentrations are quite uniform. Two major lobes of high sulfate water are evident in figure 30 at about the same locations as the occurrence of high dissolved-solids water. The high sulfate values associated with the southern lobe persist to the east as far as data are available. There are wells to the east of the northern lobe, however, that yielded water with quite low sulfate concentrations. A few wells in the interior part of the study area also yielded water with greater than 750 mg/L sulfate.

Although there are exceptions, most of the alkalinity values less than 500 mg/L occur near the outcrop. The values for the rest of the study area typically range from 500 to 1,000 mg/L. No other significant trends are evident on the alkalinity map.

Although the statistical correlation is weak, there is a tendency for sulfate concentration to decrease and alkalinity concentration to increase with depth. This trend is consistent with observations by Thorstenson and others (1979) of decreases in sulfate concentration with flow distance downgradient in the Fox Hills aquifer in southwestern North Dakota. The mechanism they proposed called for reduction of sulfate to pyrite (or marcasite) with oxidation of lignitic carbon serving as the energy source. The bacterially catalyzed reaction that was assumed responsible for this phenomenon was represented as:

$$15CH_2O + 2Fe_2O_3 + 8SO_4^{-2} + H_2CO_3 \rightleftarrows 4FeS_2 + 16HCO_3^- + 8H_2O;$$

where CH_2O, representing organic carbon, is derived from lignite. Iron, introduced in the form of an oxide or hydroxide, acts as a sulfur sink with the formation of pyrite or marcasite, FeS_2. The reaction generates one equivalent of alkalinity in the form of bicarbonate for each equivalent of sulfate reduced.

Inasmuch as iron sulfide concretions were often observed in the drill cuttings at or near the horizon of the lignite, the predicted sulfide reaction product is compatible with field observations. Increases in alkalinity along the flow path are not uniform or consistent across the study area and do not seem to proceed on a one-for-one equivalent basis with the reduction in sulfate concentration. If the preceding equation is indeed responsible for the sulfate reduction, then some mechanism must be eliminating the bicarbonate from the system. This mechanism has not been identified by geochemical researchers.

In general, pH values in the Harmon lignite aquifer are between 7.8 and 8.7 at distances of more than 2 or 3 mi from the outcrop. All values of less than 7.0 occur very near the outcrop. The distribution of pH values observed in the aquifer fits the theory proposed by Thorstenson and others (1979) for pH buffering in the Fox Hills aquifer. They cited an equation presumed responsible for the maintenance of Fox Hills aquifer pH's between

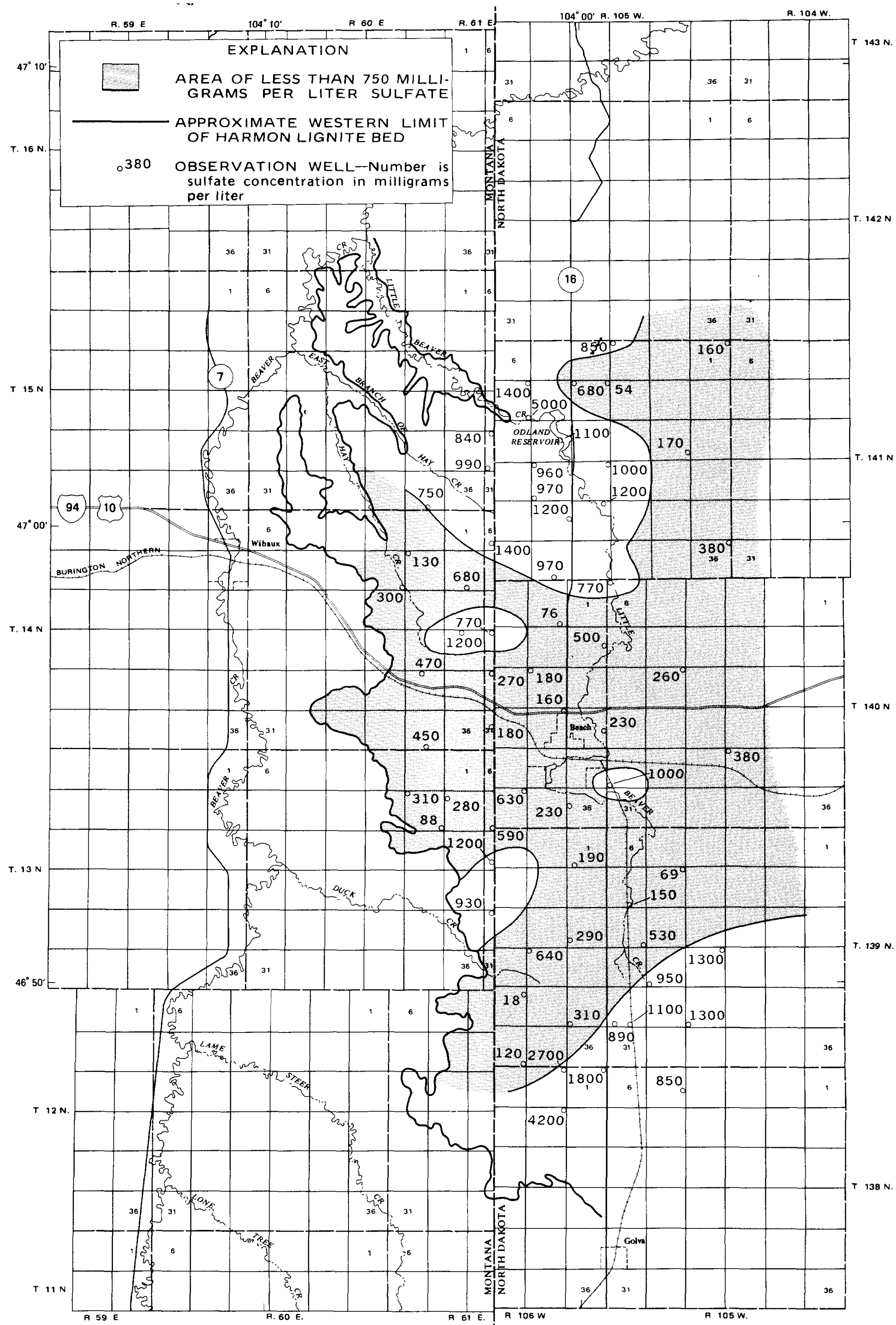


FIGURE 30.—Concentration of sulfate in the Harmon lignite aquifer.

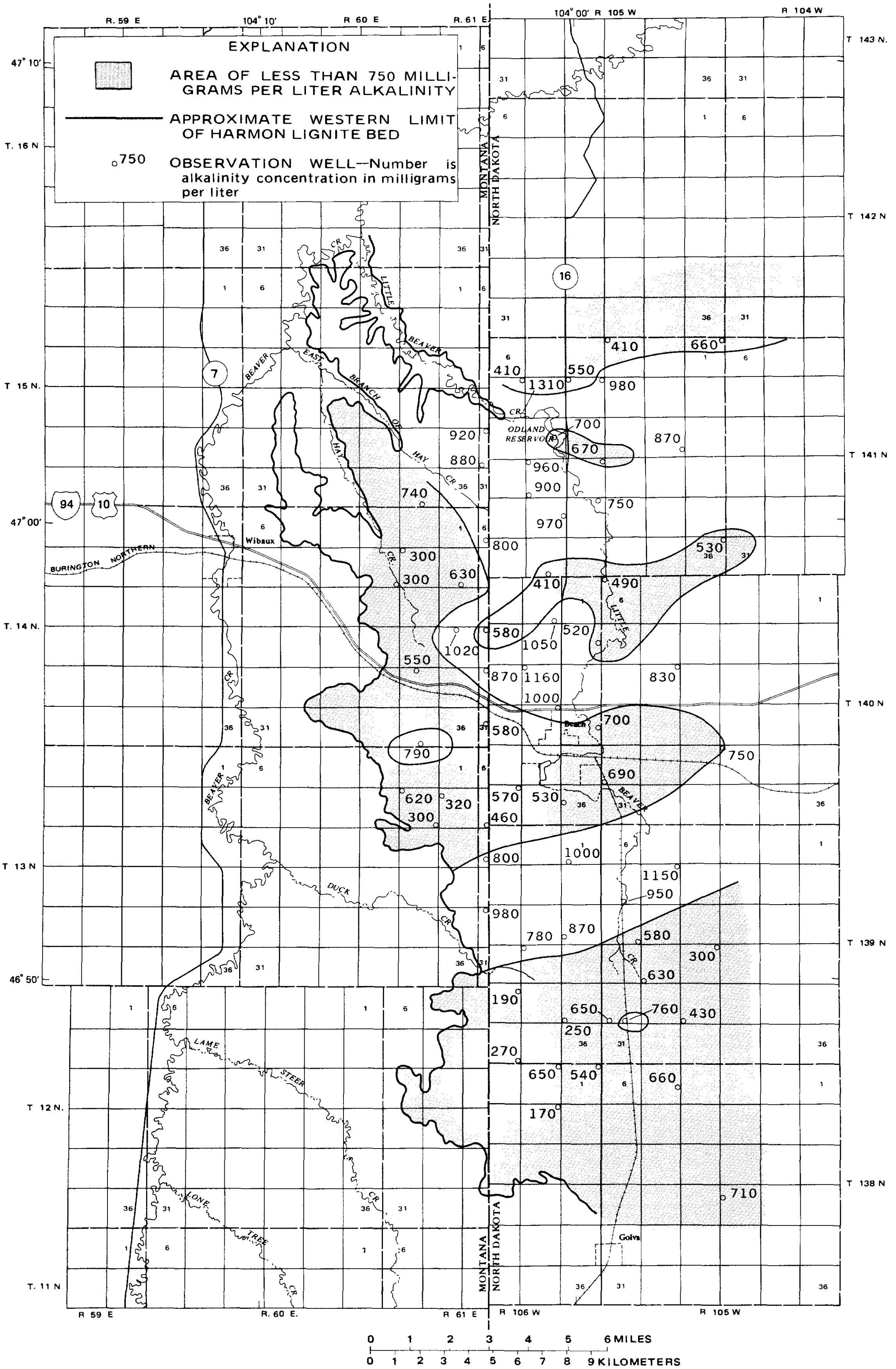


FIGURE 31.—Concentration of alkalinity in the Harmon lignite aquifer.

8.3 and 8.8. The equation specifies the reaction of calcium carbonate with carbonic acid in the presence of exchangeable sodium to produce sodium bicarbonate and calcium bonded on cation-exchange sites. Without the removal of calcium through cation exchange for sodium the reaction would come to equilibrium far short of achieving the 8.3 pH. The lowest pH's in the Harmon lignite aquifer occur in waters containing 20 percent or less sodium (of total cationic makeup), far from the apparent equilibrium level of about 95 percent sodium. As the calcium (magnesium)-sodium exchange process is driven toward equilibrium, the pH rises to 7.9 and above.

No areal trends are apparent in the iron-concentration data. Rather, it seems that the dissolved iron levels are generally low and quite randomly distributed. Extremely high iron concentrations (the mean of four values was 55 mg/L) were observed in samples from one well, 138-106-11AAA. Samples from the well also had a median pH of 6.0, a mean sulfate concentration of 4,200 mg/L, and a mean calcium concentration of 530 mg/L, the highest observed. The top of the Harmon bed at this site is at a depth of 37 ft. The high iron concentration probably is generated by the oxidation of iron sulfides (such as pyrite) either within the aquifer or in the sediments just above it.

Spacial variations in concentration of other ions do not seem to follow any particular trend. Concentrations, for the most part, are low and fluctuate somewhat about a mean background level in response to localized geochemical variations.

HYDROLOGIC IMPLICATIONS OF STRIP MINING

The potential hydrologic effects of strip mining entail impacts to surface water and ground water, both in quantity and quality. Impacts to the surface-water flow system are more readily measurable and manageable than are those to the ground-water system. Streamflow and stream water-quality impacts can be mitigated by applying appropriate mining practices. Overland flow can be routed by earth shaping techniques to minimize interaction with active mine areas. That water which unavoidably flows into or falls directly into the mine area as precipitation can be pumped or otherwise routed to impoundments where excessive sediment loads and objectionable chemical concentrations may be ameliorated. Mining impacts on stream systems in arid areas having subdued topography such as the Wibaux-Beach area, therefore, can be managed largely through careful design of earth structures for beneficial routing and impoundment of runoff water.

Impacts of mining on shallow ground-water systems, however, are not nearly so manageable through design features. Removal of the lignite will disturb enormous volumes of earth, some of which may have served as a local aquifer. In some instances, effects of mining excavations will extend into a regional flow system. In any event, all disturbed earth, whether it is saturated or unsaturated, serves as a medium for the movement of subsurface water and removal of the material must disturb the natural flow regime. Any aquifers within or above the lignite will be destroyed at the mine site and will undergo depletions in head for some distance from the mine. The distance to which the drawdown extends and the rate at which it spreads depend on the magnitude of recharge and discharge fluxes, the proximity of the mine to the ground-water recharge and discharge areas, and the hydraulic characteristics of the aquifers and adjacent materials.

The following qualitative considerations of the impact of strip mining on the shallow ground-water flow system describe the processes for the Wibaux-Beach area, but would apply to any similar setting where the minable lignite constitutes a confined aquifer and is the shallowest aquifer in the area.

For some brief time immediately following the initial opening of a mine cut, all water discharged into the pit from the lignite at the highwall will come from storage within the lignite aquifer. The decline in water level will convert the aquifer to water-table conditions for several hundred feet from the mine cut. Aquifer discharge initially may be great but will soon begin to abate due to a reduction in the height of the seepage face and the time-dependent decay of the hydraulic gradient near the cut. Water derived from storage per unit volume of aquifer material per unit decline in head probably will be two or three orders of magnitude greater within the unconfined part of the aquifer than it is in the confined part.

The propagation of the head decline in the aquifer quickly will radiate away from the mine face, affecting a large area of the aquifer. Concurrent with the head decline in the Harmon lignite aquifer, leakage from the silty clayey overburden will increase due to an increase in the hydraulic gradient, and leakage of water from the lignite aquifer to the underlying lower Tongue River aquifer system will decrease. In fact, for some small distance (less than 1 mile) down dip from the mine, the potentiometric level in the lignite will be drawn down below that of the lower Tongue River aquifer system, thereby inducing flow upward toward the lignite. Because all available recharge currently is being accepted by the Harmon lignite aquifer and no boundries representing a potential source of additional recharge are within reach of a mining-induced stress on the aquifer, the only sources of water for diversion to the mine cut are storage within the lignite aquifer and the leakage flux modifications.

Discharge from the lignite at the mine cut gradually will decrease while the net contribution to the aquifer from the leakage components gradually will increase. At some point in time the two fluxes will balance, thereby establishing a steady-state condition in the Harmon lignite aquifer.

If it is assumed that a 5 to 1 overburden to lignite stripping ratio is economically feasible at the time the Wibaux-Beach deposit is mined, overburden may be stripped to depths as great as 150 ft to expose the broad expanse of lignite in the 25- to 30-ft thickness class. Potentiometric levels in the Harmon lignite aquifer commonly are 100 ft or more above the top of the lignite where the lignite lies at 150 ft below the surface. Drawdowns relative to the present potentiometric levels at such sites, therefore, would be close to 130 ft at the mine face, or 100 ft at the point where the aquifer converts from water-table to artesian conditions.

To gain an appreciation for the effect this drawdown would have on an idealized artesian aquifer that received no augmenting recharge of any kind, the line-sink method for one-dimensional aquifer analysis presented by Stallman (1962) may be applied. For the conservative case where a transmissivity of 25 ft^2/d and a storage coefficient of $5x10^{-4}$ are assumed, a drawdown of about 40 ft would be observed after 1 year at a distance of 1 mi from the mine cut. If a transmissivity of 100 ft^2/d and a storage coefficient of $1x10^{-5}$ are assumed, a drawdown of over 90 ft would occur after 1 year at a distance of 1 mi. The fact that drawdowns of these magnitudes are not observed in the active mine areas of North Dakota indicates that the typical lignite aquifer is subject to recharge from leakage and abatement of natural discharge by leakage during mining-imposed stress. However, in spite of the moderating influence of the leakage effects, potentiometric declines in the Harmon lignite aquifer in response to mine cuts over 100 ft deep will extend for several miles and probably will be several feet in magnitude up to a distance of 2 or 3 mi.

The impact of mining on the Harmon lignite aquifer will be compounded somewhat by the nature of the geohydrologic setting particular to the Wibaux-Beach deposit. The Harmon bed outcrop is the origin of the flow system within the lignite aquifer and a major flux of recharge is received there. Placement of the mine cuts parallel to the outcrop and the down dip pit progression will isolate the aquifer from this major recharge area. As a result, the potentiometric decline will be somewhat more pronounced than declines that would occur in settings receiving normal recharge.

Potentiometric effects on the lower Tongue River aquifer system will develop as a function of the diminishment of the downward hydraulic gradient driving water through the confining beds between the Harmon lignite aquifer and the lower Tongue River aquifer system. In some areas the vertical gradient could be reversed, thereby inducing an upward flux. Head declines will be measurable in the lower Tongue River aquifer system beginning some time after the nearby encroachment of mining, but generally should not be in excess of several feet. Due to the storage attributes of the confining materials underlying the Harmon lignite, head declines in the lower Tongue River aquifer system will develop slowly and probably never will reach a steady-state condition prior to surface reclamation and an approximate reestablishment of the premining potentiometric profile. Wells completed in the aquifer system that are not physically destroyed by mining should remain serviceable, although some pump intakes may need to be set deeper.

Potentiometric effects on the upper Ludlow aquifer system would be very minor, if at all perceivable. The upper Ludlow and the lower Tongue River aquifer systems, therefore, are the shallowest, consistently occurring sources of ground water that could be used to replace water supplies lost due to the destruction of the lignite aquifer. Other potential sources of ground water include aquifers in the lower Ludlow Member, the Hell Creek Formation, and the Fox Hills Sandstone. Details concerning these deeper aquifers are given in a previous section of this report.

Efforts to quantify the potentiometric effects of mining with a two-dimensional computer model were frustrated by uncertainties in the hydraulic characterization of the flow system. The problem is compounded by the "leaky" nature of the Harmon lignite aquifer. Data deficiencies, which apparently have hindered the predictive capabilities of lignite and subbituminous coal hydrology studies throughout the northern Great Plains region, include: (1) The vertical hydraulic conductivity of shallow confining beds--these data probably should be determined as a function of overburden depth; (2) hydraulic conductivities of lignite aquifers at relatively great depth; (3) specific storage of confining beds; (4) specific storage and specific yield of lignite aquifers; (5) recharge magnitudes typical of the arid prairie of this region and the mechanisms by which this recharge occurs; and (6) water-table profiles in the clayey silty near-surface overburden materials through which percolating waters must pass to recharge the lignite aquifer.

SUMMARY

The Harmon lignite bed (lower part of the Tongue River Member, Fort Union Formation), the principal commercial bed of the Wibaux-Beach deposit, underlies at least 150 mi^2 along the Montana-North Dakota border. Strippable reserves are estimated to be about 1 billion tons and underlie about 50 mi^2. The great available tonnage and low overall stripping ratio have targeted the deposit for development. The Harmon lignite bed, however, also is the most consistently occurring shallow aquifer in the area.

A study was conducted in response to concern for possible impacts of surface mining on the area's water resources. The study objectives were to define the stratigraphic sequence associated with the lignite deposit, determine the premining hydrologic and geochemical regime of the deposit area, and, to whatever extent possible, specify in type and quantity the probable effects of surface mining on the water resources.

The minable part of the study area is drained by Beaver Creek and several tributaries, including Duck, Hay, East Branch Hay, and Little Beaver Creeks. Base flow in Little Beaver Creek generally ranges from nearly zero to 0.2 ft^3/s and in Beaver Creek (at the station near Trotters) base flow generally is a few cubic feet per second. The other streams flow only during the snowmelt period and following heavy rainstorms.

Sedimentary deposits extend about 13,000 ft in depth beneath the study area. The Fox Hills Sandstone (Upper Cretaceous) conventionally is considered the base of fresh-water-bearing formations in western North Dakota. In ascending order, the Hell Creek Formation (Upper Cretaceous), and the Ludlow, Lebo Shale equivalent, Tongue River, and Sentinel Butte Members of the Fort Union Formation (Paleocene) constitute the upper part of the section in the Wibaux-Beach area.

The Fox Hills Sandstone underlies the entire study area and consists of interbedded sandstone, siltstone, and shale. Its top is 1,032 ft below the surface and it is 258 ft thick in test hole 140-105-30CCC at Beach.

The Hell Creek Formation underlies all of the study area and consists of lignitic and bentonitic claystone, siltstone, and sandstone. Its top is 760 ft deep and it is 272 ft thick in the test hole at Beach.

The Ludlow Member of the Fort Union Formation underlies the entire study area and outcrops along the extreme western edge. The Ludlow is composed of alternating beds of clay, silt, sand, and lignite. The top of the member lies at a depth of 288 ft and the member is 330 ft thick in the test hole at Beach. The Lebo Shale Member equivalent intertongues with the Ludlow and is 142 feet thick in the same test hole.

The Tongue River Member forms the land surface over most of the study area. It consists of clay, silt, very fine to medium-grained sand, sandstone, lignite, and thin limestone lenses. Tongue River strata may be as much as 450 ft thick where fully preserved from erosion.

The Sentinel Butte Member is represented only as erosional remnants on isolated buttes in the area and is not of significance to the hydrologic regime of the study area.

Pleistocene deposition is represented only by thin alluvial deposits along some of the streams in the study area. The maximum thickness of alluvium actually penetrated was 26 ft at a site on Little Beaver Creek.

Extensive sandstone beds in the upper part of the Fox Hills, in some places hydraulically associated with sandstones in the lower Hell Creek, constitute an important aquifer in western North Dakota. The aggregate thickness of sandstone in the Fox Hills is 182 ft in test hole 140-105-30CCC at Beach. A total of only 20 ft of sandstone was penetrated in the Hell Creek Formation at this test-hole site. Potential yields for the Fox Hills aquifer or the Fox Hills-Hell Creek aquifer system may be as much as 300 gal/min. The water level in the Fox Hills observation well (140-105-30CCC1) at Beach is about 330 ft below land surface. Sand beds 46 and 49 ft thick were penetrated in the lower Ludlow Member at two sites in the study area. The water level in the lower Ludlow aquifer in observation well 140-105-30CCC2 is about 168 ft.

Laterally discontinuous, sinuous beds of sand that were deposited as channel fill in meandering or braided streams constitute aquifers in the upper 200 ft of the Ludlow Member and about the lower 90 to 190 ft (that part of the member below the Harmon lignite bed) of the Tongue River Member. Although the sand beds are discrete bodies, they apparently are sufficiently interlaced within the three-dimensional sedimentary matrix to function as coherent hydraulic units. Thus, the terms upper Ludlow aquifer system and lower Tongue River aquifer system were used to describe the loosely integrated system of sand beds within the two stratigraphic intervals. The probability of encountering a sand bed at any one location in the study area is about 80 percent for the Ludlow aquifer system and about 60 percent for the lower Tongue River aquifer system.

The uppermost sand of the upper Ludlow aquifer system lies an average of about 190 ft below the Harmon lignite. Aggregate sand thickness of the aquifer system, where it occurs, ranges from 15 to 84 ft. The uppermost sand of the lower Tongue River aquifer system lies from 0 to 115 ft below the Harmon lignite. Aggregate sand thickness of the lower Tongue River aquifer system, where it occurs, ranges from 18 to 118 ft. The Harmon lignite aquifer extends without interruption for several miles eastward (down dip) from the outcrop. Depth to the aquifer ranges from virtually 0 to 350 ft, and its thickness ranges from 3 to 34 ft. The three aquifers are separated by varying thicknesses of layered silts and clays.

Hydraulic conductivity values for each of the three aquifers were determined by slug-test measurements analyzed by methods introduced by Cooper and others (1967) and Hvorslev (1951). The ranges and mean values were: upper Ludlow aquifer system, 0.08 to 4.0, 1.6 (ft/d); lower Tongue River aquifer system, 0.49 to 14, 4.5 (ft/d); Harmon lignite aquifer, 0.15 to 36, 4.5 (ft/d). Values for storage coefficient derived from the curve-matching technique of Cooper and others (1967) were not valid. Values reported in the literature for these or similar aquifers in other areas vary over several orders of magnitude.

Water in each aquifer occurs under confined conditions, except very near the outcrop. The structural dip, as well as the direction of ground-water flow, generally is toward the northeast for all three aquifers. The aquifers are recharged directly by precipitation at the outcrop and by downward leakage everywhere else. Only the Harmon lignite aquifer discharges water to surface drainages within the study area, and that discharge is minor. The major discharge from each aquifer is downward leakage.

Two-year hydrographs for wells completed in the upper Ludlow and lower Tongue River aquifer systems indicate a virtual equilibrium condition. Potentiometric levels in the Harmon lignite aquifer within a few miles of the outcrop receded as much as 3 ft in response to the drought conditions of 1979-81. Potentiometric levels in areas far removed from the outcrop did not respond to the drought during the period of this study.

No areally extensive aquifers overlying the Harmon bed were identified.

The water quality of the streams in the study area varies inversely with the discharge. Dissolved-solids concentrations ranged mostly from 1,900 to 2,100 mg/L. Although the cationic makeup varied somewhat from stream to stream, most samples consisted of 40 to 60 percent sodium. The anionic composition of almost every sample was greater than 60 percent sulfate.

Differences in chemical quality of water among the three aquifers are subtle, but significant. The mean dissolved-solids concentrations are: upper Ludlow aquifer system, 1,550 mg/L; lower Tongue River aquifer system, 1,810 mg/L; and Harmon lignite aquifer, 1,930 mg/L. Sodium and sulfate concentrations vary little among the aquifers and average about 550 and 750 mg/L, respectively. Alkalinity, calcium, and magnesium concentrations decrease with aquifer depth. Water in the upper Ludlow aquifer system generally is a sodium sulfate type, with sodium always greater than 80 percent. Although the ionic makeup of water in the Harmon lignite aquifer does vary greatly, the majority of samples were a sodium sulfate-bicarbonate type. Water in the lower Tongue River aquifer system is intermediate in ionic composition relative to the other two aquifers. Water in the upper Ludlow aquifer system generally is soft, but varies from soft to very hard in the other two aquifers. Iron concentration is very rarely a problem in any of the three aquifers. The median pH values, from the lowermost to the uppermost aquifer, were 8.5, 8.3, and 8.1.

The chemical quality of water in the shallowest parts of the Harmon lignite aquifer is affected by reactions in the aerated soil zone and unsaturated parts of the aquifer nearest the outcrop. Where the outcrop is heavily clinkered, recharge waters reach the aquifer rapidly and have little opportunity for solute uptake in the unsaturated zone. In the nonclinkered areas, recharge waters slowly percolate through chemically active soil profiles and unsaturated aerated parts of the aquifer. Abundant soluble minerals such as calcium and magnesium carbonates, gypsum, and limonite are dissolved in the CO_2-charged percolating waters. Water from the aquifer near the outcrop in these nonclinkered areas commonly contains 2,500 to 5,000 mg/L of dissolved solids, is a calcium-magnesium sulfate type, and has a pH of less than 7.0. Cation-exchange reactions in the lignite aquifer, however, generate a cationic composition of over 90 percent sodium generally within several thousand feet of the outcrop. The very high sulfate and low pH values are moderated to more normal levels by redox and exchange reactions within a like distance down the flow gradient.

Mining-induced impacts on streamflow and stream water quality should be manageable through sound engineering practices. The arid climate and subdued topography of the Wibaux-Beach area are conductive to effective management through the use of earth structures for beneficial routing and impoundment of runoff water. Mining-induced potentiometric declines in the Harmon lignite aquifer probably will be several feet in magnitude up to a distance of 2 or 3 mi. Potentiometric effects of mining on aquifers underlying the Harmon lignite aquifer are expected to be minor.

Efforts to quantitatively assess the extent of drawdown with a two-dimensional computer model were frustrated by uncertainties in the hydraulic characterization of the flow system. The problem is compounded by the "leaky" nature of the Harmon lignite aquifer.

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ATTACHMENT A.--Drilling, well-completion, and water-level data for test holes and observation wells.

EXPLANATION

Aquifer

125 - Paleocene
211 - Upper Cretaceous

HCFH - Hell Creek-Fox Hills aquifer
HRMN - Harmon lignite aquifer
LDLW - Upper Ludlow aquifer system
LHCK - Lower Ludlow-upper Hell Creek aquifer system
TGRVL - Lower Tongue River aquifer system
TRVL - Tongue River-Ludlow aquifer

Water level (feet)

D - Dry
F - flowing

Types of logs available

C - Caliper
D - Drillers
E - Electric
G - Geologists
J - Natural gamma
N - Neutron
T - Temperature
U - Gamma-gamma density

LOCAL NUMBER	ALTITUDE OF LAND SURFACE (FEET)	DATE COMPLETED	DEPTH DRILLED (FEET)	DEPTH OF WELL (FEET)	DEPTH TO FIRST OPENING (FEET)	CASING DIAM-ETER (INCHES)	DEPTH TO AQUIFER (FEET)	PRINCIPAL AQUIFER	LITHOLOGY OF AQUIFER	WATER LEVEL (FEET)	DATE WATER LEVEL MEASURED	TYPES OF LOGS AVAILABLE
MONTANA												
12-61-08DDD	2920	07/16/1976	120	--	--	--	--	--	--	--	--	G,N,D
12-61-09AAA	2925	08/26/1978	122	--	--	--	--	--	--	--	--	D,G
12-61-17ADD	2945	08/26/1978	100	--	--	--	--	--	--	--	--	D,G
13-60-11BBB	2865	05/24/1979	140	129	119	2	99	125HRMN	LIGNITE	85.45	09/11/1980	D,G,J
13-60-11DDD1	2820	05/30/1979	600	218	208	2	174	125TGRVL	SAND	58.07	09/11/1980	D,E,G,J,U
13-60-11DDD2	2820	05/30/1979	74	70	60	2	41	125HRMN	LIGNITE	22.31	09/11/1980	D,E,G,J,U
13-60-12BBC	2830	08/25/1978	106	94	88	2	62	125HRMN	LIGNITE	26.00	09/11/1980	D,E,G,J
13-61-07DDD	2825	05/24/1979	95	90	80	2	63	125HRMN	LIGNITE	25.18	09/11/1980	D,G,J
13-61-18CCA	2815	07/15/1976	67	60	54	2	35	125HRMN	LIGNITE	13.34	09/11/1980	J,N,D,G
13-61-30AAB1	2870	08/03/1978	455	240	234	2	200	125TGRVL	SAND	81.30	09/11/1980	D,E,G,J,N
13-61-30ABB2	2870	08/04/1978	91	87	75	2	72	125HRMN	LIGNITE	70.42	09/11/1980	D,E,G,J,N
14-60-10DDD	2755	07/15/1976	60	47	41	2	33	125HRMN	LIGNITE	14.99	09/10/1980	J,N,D,G
14-60-11BBB	2740	09/11/1978	79	78	72	2	57	125HRMN	LIGNITE	25.53	09/10/1980	D,G,J
14-60-12DCC	2755	09/10/1978	114	108	102	2	94	125HRMN	LIGNITE	48.08	09/10/1980	D,G,J
14-60-15DDD1	2815	05/25/1979	262	216	204	2	200	125LDLW	SAND	157.14	09/10/1980	D,E,G,J
14-60-15DDD2	2815	05/25/1979	50	50	40	2	42	125HRMN	LIGNITE	D	--	D,E,G,J
14-60-24BAA	2800	05/24/1979	160	134	124	2	117	125HRMN	LIGNITE	101.84	09/10/1980	D,G,J
14-60-26BAA	2804	07/15/1976	120	114	108	2	98	125HRMN	LIGNITE	40.05	08/13/1980	J,N,D,G
14-60-35BBB1	2830	08/01/1978	474	466	460	2	460	125LDLW	SAND	149.14	09/11/1980	C,D,E,G,J,N
14-60-35BBB2	2830	08/02/1978	170	170	158	2	120	125TGRVL	SAND	97.25	09/11/1980	C,D,E,G,J,N
14-60-35DCC	2855	05/24/1979	132	123	113	2	93	125HRMN	LIGNITE	66.76	09/11/1980	D,G,J
14-61-06CCA1	2739	07/14/1976	200	155	143	2	137	125TGRVL	SAND	51.83	09/10/1980	D,E,G,J,N
14-61-06CCA2	2739	07/14/1976	125	124	118	2	108	125HRMN	LIGNITE	48.12	09/10/1980	D,E,G,J,N
14-61-19AAA	2765	09/10/1978	198	178	166	2	163	125HRMN	LIGNITE	46.50	09/10/1980	D,E,G,J
14-61-30AAA1	2865	05/29/1979	500	459	453	2	446	125LDLW	SAND	190.26	09/10/1980	D,E,J,L,G
14-61-30AAA2	2865	05/29/1979	270	270	260	2	245	125HRMN	LIGNITE	114.31	09/10/1980	D,E,G,J
14-61-31ADD	2860	08/03/1978	228	212	200	2	184	125HRMN	LIGNITE	80.11	09/11/1980	D,E,G,J
15-60-14CCC	2640	09/11/1978	207	182	170	2	158	125LDLW	SAND	100.38	09/10/1980	D,G,J,U
15-60-27ADD	2685	09/11/1978	20	--	--	--	--	--	--	--	--	D,G
15-60-27CBB	2770	06/13/1979	320	98	88	2	75	125TGRVL	SAND	D	--	D,E,G,J,U
15-60-34CBB1	2720	06/14/1979	220	180	170	4	146	125LDLW	SAND	113.02	09/10/1980	D,E,G,J,N,U
15-60-34CBB2	2720	06/14/1979	200	200	190	2	146	125LDLW	SAND	111.36	09/10/1980	D,E,G,J,N,U
15-60-35DCC1	2770	09/21/1978	372	354	342	2	303	125LDLW	SAND	169.09	09/10/1980	C,D,E,G,J,N
15-60-35DCC2	2770	09/22/1978	205	138	126	2	119	125HRMN	LIGNITE	67.00	09/10/1980	C,D,G,J,N,U
15-61-30AAA1	2650	06/12/1979	360	299	289	2	262	125LDLW	SAND	84.17	09/10/1980	D,E,G,J
15-61-30AAA2	2650	06/13/1979	66	66	56	2	51	125HRMN	LIGNITE	35.92	09/10/1980	D,E,G,J
15-61-30CCC	2705	09/11/1978	120	120	108	2	98	125HRMN	LIGNITE	33.95	09/10/1980	D,G,J,N

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NORTH DAKOTA												
138-105-05DAA	2865	08/28/1978	205	148	142	2	139	125HRMN	LIGNITE	71.87	09/11/1980	D,E,G,J
138-105-07CCC	2930	08/27/1978	266	228	222	2	174	125TGRVL	SAND	107.22	09/11/1980	D,E,G,J
138-105-07CCD	2926	07/28/1976	380	306	288	2	283	125LDLW	SAND	117.89	09/11/1980	C,E,G,J,N,U
138-105-22BCB	2800	05/21/1979	460	118	112	2	112	125HRMN	LIGNITE	27.66	09/11/1980	D,E,G,J
138-106-01AAA	2875	05/22/1979	130	122	112	2	112	125HRMN	LIGNITE	23.39	09/11/1980	D,G,J
138-106-02AAA	2870	05/22/1979	68	61	51	2	50	125HRMN	LIGNITE	19.92	09/11/1980	D,G,J
138-106-10DAA	2925	08/27/1978	266	238	232	2	200	125LDLW	SAND	72.72	09/11/1980	D,E,G,J,U
138-106-11AAA	2887	07/16/1976	60	50	38	2	37	125HRMN	LIGNITE	24.44	09/11/1980	J,D,G
139-105-07DCC1	2815	05/31/1979	700	490	484	2	404	125LDLW	SAND	110.79	09/11/1980	D,E,G,J,U
139-105-07DCC2	2815	06/01/1979	260	230	220	2	212	125HRMN	LIGNITE	33.73	09/11/1980	D,E,G,J
139-105-08AAA	2810	09/08/1978	324	316	304	2	292	125HRMN	LIGNITE	54.42	09/11/1980	D,E,G,J
139-105-18DDD	2860	08/31/1978	285	247	235	2	230	125HRMN	LIGNITE	75.16	09/11/1980	C,D,E,G,J
139-105-20CCC	2870	05/23/1979	240	222	212	2	212	125HRMN	LIGNITE	75.50	09/11/1980	D,E,G,J
139-105-21AAA1	2855	06/01/1979	640	586	580	2	581	125LDLW	SAND	180.38	09/11/1980	D,E,G,J,U
139-105-21AAA2	2855	06/04/1979	350	350	340	2	338	125HRMN	LIGNITE	99.31	09/11/1980	D,E,G,J,U
139-105-28CCC	2830	05/23/1979	160	148	138	2	140	125HRMN	LIGNITE	36.73	09/11/1980	D,G,J
139-105-30CCD	2879	07/16/1976	200	166	154	2	152	125HRMN	LIGNITE	38.30	09/11/1980	E,J,N,D,G
139-105-30DCC1	2860	08/28/1978	594	574	562	2	532	125LDLW	SAND	129.58	09/11/1980	D,E,G,J
139-105-30DCC2	2860	08/30/1978	304	303	291	2	263	125TGRVL	SAND	75.38	09/11/1980	D,E,G,J
139-105-30DCC3	2860	08/30/1978	164	164	158	2	148	125HRMN	LIGNITE	22.57	09/11/1980	D,E,G,J
139-105-30DDD	2870	07/27/1976	780	728	716	2	684	125LHCK	SAND	126.82	09/11/1980	C,E,G,J,N,U
139-106-01CCD	2852	07/15/1976	220	205	198	2	188	125HRMN	LIGNITE	60.49	09/11/1980	E,J,N,D,G
139-106-13CCB	2880	08/26/1978	226	214	202	2	192	125HRMN	LIGNITE	71.34	09/11/1980	D,E,G,J,U
139-106-23BBB	2845	06/18/1979	102	92	82	2	78	125HRMN	LIGNITE	35.15	09/11/1980	D,G,J
139-106-25CCC	2865	05/23/1979	100	95	85	2	83	125HRMN	LIGNITE	28.60	09/11/1980	D,G,J
139-106-27AAD	2833	07/16/1976	32	30	24	2	17	125HRMN	LIGNITE	9.98	09/11/1980	D,G,J,N
139-106-34DDD1	2875	05/22/1979	280	198	192	2	168	125TGRVL	SAND	54.82	09/11/1980	D,E,G,J,U
139-106-34DDD2	2875	05/22/1979	50	50	40	2	38	125HRMN	LIGNITE	10.83	09/11/1980	D,E,G,J,U
140-105-06BBB1	2710	09/20/1978	201	201	190	2	144	125TGRVL	SAND	43.39	09/10/1980	D,G,J,U
140-105-06BBB2	2710	09/20/1978	135	135	125	2	118	125HRMN	LIGNITE	36.36	09/10/1980	D,G,J,U
140-105-17AAA	2745	09/09/1978	300	260	248	2	246	125HRMN	LIGNITE	38.70	09/10/1980	D,E,G,J
140-105-27BBB	2775	06/18/1979	702	305	295	2	290	125HRMN	LIGNITE	57.78	09/10/1980	D,E,G,J,U
140-105-30CCC1	2770	07/22/1977	1400	1251	1239	2	1192	211HCFH	SANDSTONE	322.07	09/10/1980	E,G,J,N,D
140-105-30CCC2	2770	07/22/1977	700	684	672	2	642	125LHCK	SAND	166.60	09/10/1980	D,E,G,J,N
140-105-30CCC3	2770	07/22/1977	114	114	108	1.25	106	125TRVL	SAND	2.50	06/13/1980	D,E,G,J,N
140-105-30CCC4	2760	07/28/1978	310	288	282	2	265	125TGRVL	SAND	40.96	09/10/1980	D,E,G,J,N
140-105-30CCC5	2760	07/30/1978	165	163	151	2	134	125HRMN	LIGNITE	F	--	D,E,G,J,N
140-106-01AAA	2710	07/20/1976	440	354	336	2	310	125LDLW	SAND	126.79	09/10/1980	E,G,J,N
140-106-02DDC	2730	09/10/1978	193	189	177	2	156	125HRMN	LIGNITE	35.52	09/10/1980	D,E,G,J
140-106-12ADD	2730	06/15/1979	242	226	216	2	207	125HRMN	LIGNITE	31.23	09/10/1980	D,G,J

LOCAL NUMBER	ALTITUDE OF LAND SURFACE (FEET)	DATE COMPLETED	DEPTH DRILLED (FEET)	DEPTH OF WELL (FEET)	DEPTH TO FIRST OPENING (FEET)	CASING DIAM-ETER (INCHES)	DEPTH TO AQUIFER (FEET)	PRINCIPAL AQUIFER	LITHOLOGY OF AQUIFER	WATER LEVEL (FEET)	DATE WATER LEVEL MEASURED	TYPES OF LOGS AVAILABLE
140-106-14BBB	2774	07/14/1976	260	207	195	2	177	125HRMN	LIGNITE	32.72	09/10/1980	E,J,N,D,G
140-106-23AAA	2770	06/15/1979	227	209	199	2	185	125HRMN	LIGNITE	19.83	09/10/1980	D,G,J
140-106-24DAA	2745	09/08/1978	215	197	185	2	172	125HRMN	LIGNITE	12.63	09/10/1980	D,E,G,J
140-106-34AAA	2820	07/31/1978	209	164	158	2	139	125HRMN	LIGNITE	34.98	09/10/1980	C,D,E,G,J
140-106-36BCC	2795	05/24/1979	160	150	140	2	125	125HRMN	LIGNITE	14.63	09/11/1980	D,G,J
141-105-01AAA1	2730	06/07/1979	572	514	508	2	468	125TGRVL	SAND	265.09	06/12/1980	D,E,G,J,U
141-105-01AAA2	2730	06/11/1979	380	377	367	2	350	125HRMN	LIGNITE	224.74	09/10/1980	D,E,G,J,U
141-105-03BBB	2710	06/11/1979	288	279	269	2	270	125HRMN	LIGNITE	150.07	09/10/1980	D,G,J
141-105-05BBB1	2715	06/11/1979	380	206	196	2	185	125TGRVL	SAND	154.08	09/10/1980	D,G,J,U
141-105-05BBB2	2715	06/12/1979	162	162	152	2	152	125HRMN	LIGNITE	139.82	09/10/1980	D,G,J,U
141-105-07AAA	2760	09/14/1978	220	217	211	2	211	125HRMN	LIGNITE	175.96	09/10/1980	D,G,J
141-105-07DDD1	2610	09/14/1978	393	--	--	--	--	--	--	--	--	D,E,G,J,T,U
141-105-07DDD2	2610	09/16/1978	207	207	197	2	134	125TGRVL	SAND	56.43	09/10/1980	D,E,G,J,T,U
141-105-07DDD3	2610	09/16/1978	44	44	34	2	26	125HRMN	LIGNITE	12.60	09/10/1980	D,E,G,J,T,U
141-105-09AAA	2740	09/16/1978	263	255	245	2	236	125HRMN	LIGNITE	168.52	09/10/1980	D,E,G,J
141-105-09BBB	2760	06/07/1979	262	246	236	2	224	125HRMN	LIGNITE	175.62	09/10/1980	D,G,J,U
141-105-14DDA	2795	09/17/1978	370	345	333	2	328	125HRMN	LIGNITE	166.58	09/10/1980	D,E,G,J
141-105-17ADC	2645	06/06/1979	68	65	55	2	48	125HRMN	LIGNITE	24.30	09/10/1980	D,G,J
141-105-20BBB	2700	09/20/1978	114	107	95	2	90	125HRMN	LIGNITE	52.39	09/10/1980	D,G,J
141-105-20CCC1	2725	06/05/1979	420	360	354	2	340	125LDLW	SAND	144.61	09/10/1980	D,E,G,J,U
141-105-20CCC2	2725	06/06/1979	152	152	142	2	134	125HRMN	LIGNITE	49.63	09/10/1980	D,E,G,J,U
141-105-21AAA1	2695	06/07/1979	420	371	365	2	340	125LDLW	SAND	118.58	09/10/1980	D,E,G,J,U
141-105-21AAA2	2695	06/07/1979	150	150	140	2	128	125HRMN	LIGNITE	34.02	09/10/1980	D,E,G,J,U
141-105-28AAB	2685	09/17/1978	186	142	130	2	123	125HRMN	LIGNITE	17.75	09/10/1980	D,G,J
141-105-29ADD1	2695	06/06/1979	140	129	119	4	117	125HRMN	LIGNITE	21.58	09/10/1980	D,G,J
141-105-29ADD2	2695	06/06/1979	140	133	125	2	119	125HRMN	LIGNITE	22.44	09/10/1980	D,G,J,U
141-105-29ADD3	2695	06/15/1979	142	131	121	2	117	125HRMN	LIGNITE	21.57	09/10/1980	D,G,J
141-105-32DCC	2720	09/20/1978	145	136	124	2	116	125HRMN	LIGNITE	48.09	09/10/1980	D,G,J,U
141-105-36AAA1	2825	06/04/1979	660	599	593	2	547	125LDLW	SAND	258.89	09/08/1980	D,E,G,J,U
141-105-36AAA2	2825	06/05/1979	373	370	360	2	353	125HRMN	LIGNITE	188.88	09/08/1980	D,E,G,J,U

ATTACHMENT B.--Water-quality data for sampled observation wells.

[MG/L = milligrams per liter, UMHOS = micromhos per centimeter at 25° Celsius, DEG C = degrees Celsius, E = estimated. UG/L = micrograms per liter, < = less than]

EXPLANATION

125 = Paleocene
211 = Upper Cretaceous
HCFH = Hell Creek-Fox Hills aquifer
HRMN = Harmon lignite aquifer

LHCK = Lower Ludlow-upper Hell Creek aquifer system
LDLW = Upper Ludlow aquifer system
TGRVL = Lower Tongue River aquifer system
TRVL = Tongue River-Ludlow aquifer

LOCAL IDENT-I-FIER	PRINCIPAL AQUIFER	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	ALKA-LINITY FIELD (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	PH (UNITS)
MONTANA												
13-60-11BBB	125HRMN	129	80-05-22	420	4.3	12	7.3	620	310	4.3	.8	7.0
13-60-11DDD1	125TGRVL	218	79-08-21	560	2.4	8.4	3.7	670	610	4.0	.4	8.3
13-60-11DDD2	125HRMN	70	79-07-10	31	3.1	56	37	300	88	2.6	.2	6.9
13-60-12BBC	125HRMN	94	79-07-19	32	7.6	120	55	320	280	9.9	.2	7.1
13-61-07DDD	125HRMN	90	79-08-06	110	12	150	98	460	590	7.1	.1	7.2
13-61-18CCA	125HRMN	60	76-08-18	480	13	210	130	814	1200	8.0	.2	7.0
	125HRMN	60	79-07-19	490	12	200	130	820	1100	8.3	.2	7.2
	125HRMN	60	80-07-30	450	12	200	120	780	1200	6.0	.3	8.3
	125HRMN	60	80-07-30	460	11	190	120	800	1200	5.8	.3	8.2
13-61-30AAB1	125TGRVL	240	79-08-01	700	2.8	15	--	740	790	4.2	.3	8.3
13-61-30ABB2	125HRMN	87	79-08-14	850	4.6	28	17	980	930	7.0	.7	8.4
14-60-10DDD	125HRMN	47	76-07-28	11	4.1	130	58	293	270	5.7	.1	6.5
	125HRMN	47	79-07-17	14	4.5	130	62	300	320	4.7	.1	7.2
	125HRMN	47	80-07-29	11	3.6	130	62	290	310	4.6	.1	7.9
	125HRMN	47	80-07-29	12	3.8	130	63	300	300	4.5	.2	8.1
14-60-11BBB	125HRMN	78	79-07-17	86	5.0	35	27	300	130	6.2	.2	7.4
14-60-12DCC	125HRMN	108	79-07-16	550	4.7	20	12	630	680	6.6	.8	8.3
14-60-15DDD1	125LDLW	216	79-09-17	550	4.9	20	18	520	880	22	.5	8.1
14-60-24BAA	125HRMN	134	79-09-04	900	6.7	42	33	1020	1200	43	.2	7.8
14-60-26BAA	125HRMN	114	76-08-17	150	8.2	140	95	556	460	7.6	.2	7.1
	125HRMN	114	79-05-17	160	2.1	130	93	550	480	8.1	.1	7.4
14-60-35BBB2	125TGRVL	170	79-07-10	410	2.5	5.6	2.5	480	440	22	1.0	8.5
14-60-35DCC	125HRMN	123	79-09-13	500	4.1	15	7.2	790	450	9.4	1.1	8.0
14-61-06CCA1	125TGRVL	155	76-07-29	250	10	82	65	555	440	4.6	.1	7.6
	125TGRVL	155	79-07-17	230	21	40	35	400	360	2.9	.1	8.9
	125TGRVL	155	80-07-29	240	12	58	55	480	380	2.2	.3	8.2
14-61-06CCA2	125HRMN	124	76-07-29	920	6.7	27	21	810	1300	5.5	.6	8.2
	125HRMN	124	79-07-17	960	5.3	35	20	800	1400	6.2	.6	8.3
	125HRMN	124	80-07-29	950	5.3	32	19	760	1400	5.0	.8	8.7
	125HRMN	124	80-07-29	950	5.5	32	20	810	1400	1.8	.7	8.6
14-61-19AAA	125HRMN	178	79-07-16	600	3.8	12	6.8	580	770	34	1.3	8.4
14-61-30AAA1	125LDLW	459	79-10-08	500	2.7	7.2	2.9	260	800	14	1.3	8.5
14-61-30AAA2	125HRMN	270	79-10-18	510	6.0	12	8.6	870	270	10	1.1	8.0
14-61-31ADD	125HRMN	212	79-07-19	360	3.3	11	3.9	580	180	5.2	1.1	8.1
15-60-14CCC	125LDLW	182	79-07-18	420	3.4	4.5	2.5	590	340	20	2.5	8.8
15-60-34CBB1	125LDLW	180	79-10-19	950	6.9	130	73	390	1900	280	.6	--
15-60-34CBB2	125LDLW	200	79-10-19	600	3.1	8.9	5.5	570	800	6.1	.6	8.5
15-60-35DCC1	125LDLW	354	79-10-16	450	4.6	5.7	5.5	410	630	12	1.7	8.6
15-60-35DCC2	125HRMN	138	79-06-25	650	4.9	16	10	740	750	5.2	.7	8.5
15-61-30AAA1	125LDLW	299	79-10-04	490	3.7	4.1	2.6	430	640	15	1.8	8.7
15-61-30AAA2	125HRMN	66	79-10-04	750	5.3	17	11	920	840	4.4	.6	8.2
15-61-30CCC	125HRMN	120	79-07-17	740	3.9	21	13	880	990	5.1	.6	8.2

LOCAL IDENT-I-FIER	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	SODIUM AD-SORP-TION RATIO	PERCENT SODIUM	TEMPER-ATURE (DEG C)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	HARD-NESS (MG/L AS CACO3)	BORON, DIS-SOLVED (UG/L AS B)	IRON, DIS-SOLVED (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NITRO-GEN, AM-MONIA + ORGANIC DIS. (MG/L AS N)	SILICA, DIS-SOLVED (MG/L AS SIO2)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)
MONTANA														
13-60-11BBB	1140	1725	24	93	10.5	0	60	640	140	20	13	1.1	8.3	340
13-60-11DDD1	1600	2450	41	98	11.5	0	37	510	<10	<10	<1	1.1	8.3	280
13-60-11DDD2	412	770	.8	19	9.0	0	290	290	40	110	<10	.38	12	1500
13-60-12BBC	712	1125	.6	12	11.0	210	530	350	150	140	<1	1.4	12	2000
13-61-07DDD	1250	1790	1.7	23	12.0	320	780	670	140	260	<10	1.2	.6	830
13-61-18CCA	2550	3000	6.4	49	10.0	250	1100	1200	270	500	<1	1.1	14	6500
	2450	3650	6.6	50	11.0	220	1000	1300	60	350	<1	1.1	12	5800
	2470	3400	6.2	49	9.0	220	1000	1300	50	330	0	1.5	7.4	4500
	2480	3350	6.4	50	11.0	170	970	500	50	180	0	1.6	7.4	1400
13-61-30AAB1	2220	2775	--	97	12.0	330	1100	650	<10	<10	<1	.71	8.7	340
13-61-30ABB2	2440	3600	31	93	9.0	0	140	550	70	50	<1	.98	13	770
14-60-10DDD	670	1000	.2	4	11.0	270	570	290	30	200	<1	--	13	1300
	735	1160	.3	5	9.0	280	580	390	90	180	>10	.42	17	1500
	713	1000	.2	4	8.5	290	580	520	30	180	<10	1.1	15	1500
	712	1000	.2	4	13.0	290	590	1300	40	310	<10	1.3	11	5300
14-60-11BBB	482	825	2.7	67	10.5	0	200	510	40	60	<10	.47	11	1100
14-60-12DCC	1660	2600	24	96	11.0	0	100	470	70	50	<1	.97	6.9	500
14-60-15DDD1	1820	2800	22	96	10.0	0	120	600	20	30	3	.84	7.3	420
14-60-24BAA	2850	4000	25	89	10.5	0	240	980	130	40	<1	.06	9.5	1200
14-60-26BAA	1220	1550	2.4	30	12.0	190	740	500	20	210	<1	.53	16	2800
	1220	1750	2.6	33	9.0	160	710	610	<10	200	<1	.86	13	750
14-60-35BBB2	1180	1850	36	97	14.0	0	24	180	20	30	12	.70	7.3	150
14-60-35DCC	1470	2300	27	96	10.0	0	67	610	30	40	<1	.67	8.3	280
14-61-06CCA1	1200	1650	5.0	53	10.0	0	470	360	20	40	4	--	11	2000
	944	1575	6.4	80	10.5	0	250	660	<10	<10	<10	1.1	12	1400
	1050	1580	5.4	57	10.0	0	370	940	<10	30	<10	1.5	12	2000
14-61-06CCA2	2780	4000	32	93	11.0	0	160	490	20	50	2	.96	8.0	970
	2920	4400	32	92	10.5	0	170	530	40	50	<1	.99	8.0	1000
	2880	4100	33	93	9.5	0	160	540	30	30	4	1.3	5.7	1000
	2900	4200	32	92	13.0	0	160	540	40	40	2	1.2	5.8	820
14-61-19AAA	1790	2550	34	95	11.0	0	58	530	240	30	<1	.77	7.9	410
14-61-30AAA1	1490	2400	40	97	9.5	0	30	260	10	10	6	.73	1.1	150
14-61-30AAA2	1350	1950	27	97	10.0	0	66	980	10	50	0	1.8	10	290
14-61-31ADD	923	1510	24	94	12.0	0	44	590	200	20	<1	.67	8.8	250
15-60-14CCC	1150	1875	39	97	17.0	0	22	650	60	7	18	.71	6.3	140
15-60-34CBB1	3590	4500	17	86	9.0	240	630	760	40	460	0	.51	11	890
15-60-34CBB2	1780	2550	39	98	10.0	0	45	450	60	8	0	.50	7.6	210
15-60-35DCC1	1370	1980	32	96	12.0	0	37	540	70	20	1	.32	9.2	120
15-60-35DCC2	1890	2800	31	94	10.0	0	82	210	2400	70	<1	.84	8.1	470
15-61-30AAA1	1430	2000	47	98	11.5	0	21	510	10	10	0	.94	8.7	140
15-61-30AAA2	2190	3200	35	95	13.0	0	88	500	140	30	0	.92	8.7	520
15-61-30CCC	2310	3740	31	94	11.0	0	110	80	70	40	<1	.95	9.3	670

LOCAL IDENT-I-FIER	PRINCIPAL AQUIFER	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	ALKA-LINITY FIELD (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	PH (UNITS)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	SODIUM AD-SORP-TION RATIO	PERCENT SODIUM	TEMPER-ATURE (DEG C)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	HARD-NESS (MG/L AS CACO3)	BORON, DIS-SOLVED (UG/L AS B)	IRON, DIS-SOLVED (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NITRO-GEN, AM-MONIA + ORGANIC DIS. (MG/L AS N)	SILICA, DIS-SOLVED (MG/L AS SIO2)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)
NORTH DAKOTA																										
138-105-05DAA	125HRMN	148	79-10-02	650	4.9	17	8.8	660	850	3.7	.5	8.5	1940	2550	32	94	10.0	0	79	500	30	40	0	.83	8.3	450
138-105-07CCC	125TGRVL	228	79-10-02	360	18	230	140	790	1100	3.2	.1	7.3	2350	2160	4.6	40	11.0	370	1200	1200	10	60	0	1.8	12	6000
138-105-07CCD	125LDLW	306	76-09-10	370	5.8	32	24	589	370	3.4	.4	8.7	1180	1900	12	81	12.0	0	180	640	<10	<10	--	--	13	--
	125LDLW	306	79-10-02	290	7.3	30	22	540	280	2.4	.1	7.6	1250	1320	9.8	78	11.0	0	<170	530	2600	120	10	.99	290	<10
138-105-22BCB	125HRMN	118	79-08-23	730	8.4	41	19	710	1100	4.2	.2	8.0	2340	3250	24	89	12.0	0	180	480	300	70	<1	.83	8.0	1100
138-106-01AAA	125HRMN	122	79-07-27	950	22	43	100	540	1800	4.9	.4	8.2	3250	4250	18	94	11.5	0	520	530	<10	80	1	1.1	8.1	1200
138-106-02AAA	125HRMN	61	79-07-27	130	21	480	450	650	2500	10	.1	6.6	4010	3200	1.0	8	11.0	2400	3100	3200	130	2000	<1	4.7	22	3700
	125HRMN	61	80-06-30	120	21	510	490	650	2800	8.5	.1	E7.6	4370	5500	.9	7	18.5	2700	3300	2300	100	2200	0	6.7	13	15000
138-106-11AAA	125HRMN	52	76-08-18	160	28	590	600	153	3900	14	.1	6.1	5500	5500	1.1	8	10.0	3800	4000	6800	38000	4600	<1	7.8	44	14000
	125HRMN	52	79-07-31	170	26	440	54	130	4200	17	.1	5.9	5110	6000	2.0	21	13.0	1200	1300	320	64000	4000	<1	14	48	12000
	125HRMN	52	80-07-30	160	23	540	720	160	4300	24	.1	7.0	5980	5800	1.1	7	9.0	4200	4300	11000	59000	3800	0	9.5	29	10000
	125HRMN	52	80-07-30	160	23	560	720	220	4400	19	.2	5.9	6120	5800	1.1	7	12.5	4100	4400	12000	58000	3700	0	9.2	35	1100
139-105-07DCC2	125HRMN	230	79-08-16	510	2.5	8.0	4.7	950	150	22	1.3	8.1	1280	1760	35	96	14.5	0	40	1000	200	20	<10	1.7	8.0	240
139-105-08AAA	125HRMN	316	79-07-31	540	16	12	.4	1150	69	26	2.1	8.6	1370	1960	42	96	13.0	0	32	1600	340	100	<1	3.3	9.6	300
139-105-18DDD	125HRMN	247	79-07-31	520	5.3	10	5.2	580	530	63	.7	8.5	1490	2200	33	96	14.5	0	47	620	80	40	3	.25	8.4	380
139-105-20CCC	125HRMN	222	79-08-23	700	5.4	29	14	630	950	7.6	.4	7.9	2090	3200	27	92	10.5	0	130	620	20	30	<1	.86	7.8	750
139-105-21AAA1	125LDLW	586	79-10-11	430	2.9	5.0	1.7	530	440	16	4.9	9.5	1220	1860	42	98	11.0	0	20	--	<10	20	24	.86	.7	160
139-105-21AAA2	125HRMN	350	79-08-23	660	3.0	14	5.7	300	1300	15	1.1	8.0	2190	3010	38	97	11.0	0	59	640	150	<10	<1	.48	7.5	350
139-105-28CCC	125HRMN	148	79-07-30	800	7.2	23	21	430	1300	6.2	.3	8.3	2420	3500	29	92	10.0	0	150	540	<10	70	6	.50	5.5	1000
139-105-30CCD	125HRMN	166	76-08-19	600	5.7	20	13	658	770	7.0	.9	8.4	1820	2650	26	92	10.0	0	100	590	30	30	4	.29	6.8	530
	125HRMN	166	79-10-10	660	7.8	23	14	630	950	6.4	.6	8.7	2050	2850	27	96	9.5	0	120	530	10	20	0	.61	8.1	480
	125HRMN	166	80-07-31	730	4.9	24	12	650	940	4.0	.7	8.9	2110	3300	30	93	12.5	0	110	600	30	30	2	1.3	5.1	690
139-105-30DCC2	125TGRVL	303	79-08-06	630	8.5	31	20	660	890	5.8	<.1	8.4	2000	2800	22	89	13.0	0	160	990	30	40	<1	2.3	11	920
139-105-30DCC3	125HRMN	164	79-05-17	850	1.6	12	16	760	1100	25	.2	8.1	2470	3300	38	95	9.5	0	97	790	30	150	<1	1.2	8.1	710
139-105-30DDD	125LHCK	728	79-10-03	600	2.7	.0	3.6	500	810	13	1.7	9.4	1730	2500	68	99	11.0	0	15	620	10	10	11	.74	.9	400
139-106-01CCD	125HRMN	205	79-08-06	500	4.5	11	5.4	1000	190	23	.3	8.3	1360	2000	31	97	12.5	0	50	910	390	40	<1	.89	18	380
139-106-13CCB	125HRMN	214	79-08-02	500	9.3	9.6	5.5	870	290	10	.8	8.3	1360	2100	32	95	11.5	0	47	620	60	30	<1	10	7.4	330
139-106-23BBB	125HRMN	92	79-08-07	610	5.5	18	9.8	780	640	7.2	.5	8.0	1770	2600	29	94	10.5	0	86	510	<10	40	<1	.67	9.3	500
139-106-25CCC	125HRMN	95	79-07-27	34	6.9	97	89	250	310	34	.1	6.9	741	1275	.6	11	13 0	360	610	970	330	290	12	.98	15	3300
139-106-27AAD	125HRMN	30	76-08-17	58	11	380	270	188	1500	20	.1	6.0	2380	3000	.6	6	10.0	1900	2100	990	1300	1600	<1	1.3	12	7100
	125HRMN	30	79-08-01	77	10	390	260	190	1800	16	.1	6.4	2690	3100	.7	8	13.0	1900	2100	1100	1000	1700	<1	1.1	12	6300
	125HRMN	30	80-07-30	65	11	370	250	200	1900	17	.3	8.0	2750	3000	.6	7	9.0	1800	2000	1100	800	1400	0	1.3	8.7	6600
	125HRMN	30	80-07-30	64	11	380	260	200	1900	16	.5	8.0	2770	3000	.6	6	12.0	1800	2000	1100	1000	1400	0	1.2	8.8	6300
139-106-34DDD1	125TGRVL	198	79-07-30	330	12	120	71	570	640	3.2	.2	7.1	1540	2000	5.9	54	11.0	25	600	1100	2300	80	<1	1.2	9.7	3000
139-106-34DDD2	125HRMN	50	79-07-30	5.6	4.4	83	39	270	120	2.7	.1	7.3	428	770	.1	3	12.0	99	370	220	190	130	<10	.30	9.5	740
140-105-06BBB1	125TGRVL	201	79-07-12	600	2.8	8.2	3.6	910	420	4.9	.4	8.4	1600	2600	44	97	10.0	0	36	470	<10	20	<1	1.3	8.4	290
140-105-06BBB2	125HRMN	135	79-07-12	590	4.2	11	41	490	770	15	1.1	8.4	1740	2720	18	86	10.0	0	200	530	40	20	<1	1.0	7.4	420
140-105-17AAA	125HRMN	260	79-08-14	460	3.1	7.8	4.0	830	260	15	1.9	7.9	1260	2250	33	98	9.0	0	36	930	150	40	<1	1.1	9.0	230
140-105-27BBB	125HRMN	305	79-08-23	110	3.5	--	--	810	500	4.8	.9	8.3	1130	2380	6.1	79	13.5	0	61	610	90	20	<1	1.2	7.8	340
	125HRMN	305	80-09-09	500	3.0	7.9	4.7	750	380	5.3	.7	8.0	1360	2300	35	96	12.0	0	39	560	810	40	0	1.1	5.2	220
140-105-30CCC1	211HCFH	1251	77-10-13	570	3.3	13	19	662	640	31	.7	8.8	1680	2060	24	92	10.0	0	110	810	40	20	--	--	7.3	--
140-105-30CCC2	125LHCK	684	79-10-18	700	5.7	5.1	20	620	1000	20	1.5	9.5	2130	3100	31	99	14.0	0	95	910	40	10	8	.87	1.0	90
140-105-30CCC3	125TRVL	114	77-09-28	420	3.5	14	11	521	460	8.5	.4	8.1	1240	1850	20	92	8.0	0	80	520	140	20	--	--	6.7	--
	125TRVL	114	79-08-15	600	2.9	10	6.4	1250	33	22	1.6	8.2	1440	2060	36	96	9.5	0	52	1400	150	50	<1	1.7	9.7	360
140-105-30CCC4	125TGRVL	288	79-08-24	130	2.8	--	--	600	790	6.6	.4	9.1	1300	2700	11	90	10.5	0	27	430	30	30	11	1.1	1.9	250
	125TGRVL	288	80-09-09	600	3.7	2.5	1.5	620	730	7.5	.4	9.2	1720	2200	74	99	10.0	0	12	490	30	20	63	1.2	.4	0
140-105-30CCC5	125HRMN	163	79-08-24	750	4.7	21	13	690	1000	6.5	.8	8.1	2220	3250	32	94	11.5	0	110	490	1100	60	<1	.46	9.9	600
140-106-01AAA	125LDLW	354	76-10-13	510	1.8	5.8	5.0	476	630	13	1.1	8.9	1460	2190	37	97	11.0	0	35	450	130	60	--	--	7.8	--
	125LDLW	354	79-10-17	480	3.1	6.5	3.5	430	640	13	1.4	8.4	1410	2075	38	98	9.5	0	31	450	70	20	5	.63	6.5	120
140-106-02DDC	125HRMN	189	79-05-17	490	.5	10	4.6	1020	76	28	2.2	8.4	1230	1810	32	96	9.0	0	44	640	500	50	3	3.7	7.8	30
	125HRMN	189	79-07-11	470	4.8	7.0	19	1070	76	25	2.1	8.3	1260	2000	21	91	11.0	0	96	790	280	30	<1	2.5	7.5	290
140-106-12ADD	125HRMN	226	79-08-14	390	4.1	11	8.1	520	500	4.3	.4	8.0	1240	2280	22	96	10.0	0	61	640	<10	20	<10	.73	7.3	360
140-106-14BBB	125HRMN	207	76-07-28	600	4.1	10	5.5	1210	240	46	1.3	8.1	1650	2400	38	96	11.0	0	48	770	320	30	<1	.92	8.8	230
	125HRMN	207	79-07-16	600	3.2	11	5.8	1180	170	9.5	1.2	8.3	1520	2450	36	96	11.5	0	52	610	40	<10	<1	.95	8.9	380
	125HRMN	207	80-07-29	610	3.8	9.0	5.3	1160	240	5.7	1.3	8.9	1590	2400	40	96	11.0	0	45	9000	50	10	0	1.3	5.1	300
	125HRMN	207	80-07-29	610	3.8	9.0	5.6	1070	290	6.9	1.3	8.9	1560	2450	39	96	13.5	0	46	5100	150	10	0	1.6	5.3	320
140-106-23AAA	125HRMN	209	79-08-15	550	4.4	11	8.0	1000	160	20	1.2	7.9	1370	2250	31	97	12.0	0	61	880	510	40	<1	2.2	9.4	340
140-106-24DAA	125HRMN	197	79-06-27	350	6.5	21	15	700	230	8.4	.3	8.2	1060	1600	14	86	13.5	0	110	160	30	130	>10	.99	11	600

LOCAL IDENT-I-FIER	PRINCIPAL AQUIFER	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	ALKA-LINITY FIELD (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	PH (UNITS)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	SODIUM AD-SORP-TION RATIO	PERCENT SODIUM	TEMPER-ATURE (DEG C)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	HARD-NESS (MG/L AS CACO3)	BORON, DIS-SOLVED (UG/L AS B)	IRON, DIS-SOLVED (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NITRO-GEN, AM-MONIA + ORGANIC DIS. (MG/L AS N)	SILICA, DIS-SOLVED (MG/L AS SIO2)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)
140-106-34AAA	125HRMN	164	79-07-19	450	4.6	50	28	570	630	4.6	.6	7.9	1530	2500	13	80	10.5	0	240	560	30	60	<1	.71	14	1200
140-106-36BCC	125HRMN	150	79-07-27	390	2.9	5.0	2.7	530	230	11	1.4	8.3	971	1450	35	98	11.0	0	24	170	20	<10	<1	1.3	9.4	130
141-105-01AAA1	125TGRVL	514	80-08-28	490	2.6	4.1	2.7	390	670	14	1.9	8.3	1430	1800	46	98	12.0	0	22	720	40	30	4	1.1	6.3	160
141-105-01AAA2	125HRMN	377	80-06-17	370	1.6	4.6	2.3	660	160	14	.3	E8.2	957	1500	35	97	12.5	0	21	5300	240	30	2	2.2	1.7	210
141-105-03BBB	125HRMN	279	79-10-04	600	4.0	5.4	4.6	410	850	13	1.6	8.7	1730	2200	46	97	9.5	0	33	520	10	20	3	.84	8.1	250
141-105-05BBB1	125TGRVL	206	80-05-13	800	3.8	21	16	880	920	5.5	.8	7.8	2310	3500	32	93	10.0	0	120	660	140	10	0	1.1	8.5	750
141-105-07AAA	125HRMN	217	79-10-22	880	5.8	11	6.9	410	1400	11	1.0	10.6	2570	4000	51	97	9.0	0	56	480	30	0	2	1.6	2.2	240
141-105-07DDD2	125TGRVL	207	79-09-13	800	3.4	48	22	380	1200	340	2.3	7.4	2660	4080	24	93	10.5	0	210	630	1200	360	7	1.0	14	520
141-105-07DDD3	125HRMN	44	79-07-18	2400	15	87	240	1310	5000	8.4	.4	7.4	8560	10620	30	81	18.0	0	1200	670	150	1000	5	2.0	20	2500
141-105-09AAA	125HRMN	255	79-09-18	490	5.0	13	7.2	980	54	21	3.8	8.3	1200	1930	27	96	14.0	0	63	2100	300	80	<1	6.1	13	350
141-105-09BBB	125HRMN	246	80-04-24	59.	2.4	6..	4.2	55.	680	10	1.6	7.8	1630	2600	45	97	11.0	0	33	600	70	10	0	1.2	8.2	250
141-105-14DDA	125HRMN	345	79-11-06	460	4.7	10	6.4	870	170	27	1.9	8.2	1210	1850	28	95	10.0	0	51	610	2500	60	0	--	1.6	120
141-105-17ADC	125HRMN	65	79-10-04	800	3.9	14	9.1	700	1100	6.3	.9	5.6	2360	3475	41	96	11.0	0	73	470	40	20	0	1.2	8.1	480
141-105-20BBB	125HRMN	107	79-07-18	840	3.7	20	11	960	960	4.8	.7	S.1	2430	3750	37	95	10.5	0	96	530	40	20	<1	'94	11	640
141-105-20CCC1	125LDLW	360	79-09-20	550	5.1	27	36	430	1000	22	1.4	8.0	1900	2950	16	94	11.0	0	220	600	120	60	5	1.2	2.8	560
141-105-20CCC2	125HRMN	152	79-09-20	750	5.6	19	13	900	970	4.6	.4	7.5	2320	3600	32	97	10.0	0	100	660	40	60	<1	.99	10	520
141-105-21AAA1	125LDLW	371	79-09-20	490	3.1	5.8	10	410	700	40	1.2	8.3	1500	2300	29	98	11.0	0	56	560	<10	30	<1	1.8	6.1	180
141-105-21AAA2	125HRMN	150	79-09-20	750	3.1	16	9.2	670	1000	8.0	1.1	7.8	2200	3300	37	95	10.0	0	78	560	30	40	<1	1.1	7.9	380
141-105-28AAB	125HRMN	142	79-09-13	750	3.7	19	11	750	1200	5.3	.7	8.1	2450	3750	34	97	10.0	0	93	460	70	30	<1	.89	7.5	480
141-105-29ADD1	125HRMN	129	79-09-13	900	4.2	27	13	900	1200	5.9	1.0	8.2	2700	3750	36	94	11.0	0	120	490	150	30	<1	.89	7.6	600
141-105-29ADD2	125HRMN	136	79-08-15	950	4.1	23	15	970	1200	5.9	.7	8.1	2790	4000	38	94	11.5	0	120	470	30	30	<1	1.1	7.8	730
141-105-29ADD3	125HRMN	131	79-09-13	920	4.5	23	13	980	1200	5.0	.8	8.1	2760	3800	38	95	10.0	0	110	480	30	30	<1	1.4	8.0	600
141-105-32DCC	125HRMN	136	79-08-01	--	3.2	14	63	400	990	14	1.2	8.3	1330	2700	--	--	12.0	0	290	250	110	30	<1	2.9	7.3	410
	125HRMN	136	80-06-30	630	3.9	11	7.7	410	970	16	1.5	8.6	1890	2900	36	96	13.5	0	60	440	70	20	0	2.4	.5	360
141-105-36AAA1	125LDLW	599	79-09-17	650	8.1	12	46	250	1400	25	.6	9.1	2290	3400	19	86	9.1	0	220	1100	190	50	6	2.1	.4	180
141-105-36AAA2	125HRMN	370	79-09-17	600	16	180	250	440	2400	31	.2	7.5	3750	4900	6.8	74	12.0	1000	1500	2300	30	230	4	1.2	5.6	3700
	125HRMN	370	80-09-08	390	6.4	19	11	530	380	7.1	.4	7.7	1140	1600	18	89	10.0	0	93	750	140	40	<10	1.7	9.5	420