RECHARGE OF SHALLOW AQUIFERS THROUGH TWO EPHEMERAL-STREAM CHANNELS IN NORTHEASTERN WYOMING, 1982-83

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CONVERSION FACTORS

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

Multiply	By	To obtain
acre	0.4047	hectare
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot squared per hour (ft^2/h)	0.09290	meter squared per hour
foot per day (ft/d)	0.3048	meter per day
square mile	2.590	square kilometer
acre-foot per mile	0.000766	cubic hectometer per kilometer
cubic foot	0.02832	cubic meter
foot squared per day	0.09290	meter squared per day

Temperatures in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9(°F-32)$$

RECHARGE OF SHALLOW AQUIFERS THROUGH TWO EPHEMERAL-STREAM CHANNELS IN NORTHEASTERN WYOMING, 1982-83

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ABSTRACT

Quantifying the recharge from ephemeral streams to alluvial and bedrock aquifers will help evaluate the effects of surface mining on alluvial-valley floors in Wyoming. Two stream reaches were chosen for study in the Powder River basin. One reach was located along the North Fork Dry Fork Cheyenne River near Glenrock, Wyoming, and the other reach was located along Black Thunder Creek near Hampshire, Wyoming.

The reach along the North Fork Dry Fork Cheyenne River was instrumented with 3 gaging stations to measure streamflow and with 6 observation wells to measure ground-water-level fluctuations in alluvial and bedrock aquifers in response to streamflow. The 3 streamflow-gaging stations were located within the 2.5-mile study reach to measure the approximate gain or loss of discharge along the reach. Computed streamflow losses ranged from 0.43 acre-feet per mile on July 9, 1982, to 1.44 acre-feet per mile on August 9, 1982. The observation wells completed only in the alluvial aquifer were dry during flow in the North Fork Dry Fork Cheyenne River, whereas water levels in half of the observation wells completed in the bedrock aquifer or the alluvial and bedrock aquifers rose in response to flow in the North Fork Dry Fork Cheyenne River. Ground-water recharge on August 9, 1982, was calculated using a convolution technique using ground-water levels at the upstream site and was estimated to be 26.5 acre-feet per mile.

The reach along Black Thunder Creek was instrumented with one gaging station to measure streamflow and with 4 observation wells to measure water-level response in alluvial and bedrock aquifers to streamflow. Recharge to the alluvial aquifer from flow in Black Thunder Creek ranged from 3.56 to 12.4 acre-feet per mile. The recharge was estimated using the convolution technique using water-level measurements in the observation wells completed in the alluvial aquifer. Water-level measurements in the observation wells indicated water-level rises in the alluvial and bedrock aquifers in response to flow in Black Thunder Creek.

INTRODUCTION

An alluvial-valley floor is an important element of the geohydrologic system of the plains area of Wyoming. Because of the importance of alluvial-valley floors, regulations have been established to protect these floors in areas of current or potential surface mining. The Federal Surface Mining Control and Reclamation Act (1977) requires the protection of "...the essential hydrologic function of alluvial valley floors..." either by preservation or reclamation. According to Guideline No. 9 of the Wyoming Department of Environmental Quality (1981) and criteria of the Office of Surface Mining (U.S. Department of the Interior, 1983), the concern is principally for protection of subirrigation from shallow aquifers and flood irrigation from surface-water flow in ephemeral- and perennial-stream channels that occur in the valleys.

Recharge of shallow aquifers is part of the essential hydrologic function of alluvial-valley floors. Shallow aquifers are defined in this report as the alluvial aquifer along a stream and bedrock aquifer immediately below the alluvial aquifer in alluvial valleys. Ephemeral streams flowing on alluvial-valley floors can be an important source of recharge to shallow aquifers because the streams provide an intermittent, but potentially large source of water and because alluvium generally is more permeable and can store and transmit more water than upland soils. This is significant because precipitation and overland runoff usually are of such short duration that infiltrated water in the upland areas may be discharged by evapotranspiration before recharge can occur.

Identifying and quantifying the recharge from ephemeral streams are useful in order to evaluate the effects of surface mining on ground-water recharge. The significance of recharge from ephemeral streams to shallow aquifers within alluvial-valley floors may be demonstrated by computing the quantity of ground-water recharge contributed by ephemeral streams. Establishing a method for determining the quantity of ground-water recharge is important because it could provide data needed for future studies.

Two ephemeral-stream reaches in northeastern Wyoming were chosen for study using two methods of estimating ground-water recharge from ephemeral streams. A reach along the North Fork Dry Fork Cheyenne River was selected because it is typical of many ephemeral streams in the plains areas of Wyoming and because suitable sites for streamflow-gaging stations were available. The 2.5-mile study reach is a sand channel located about 25 miles north of Glenrock, Wyo. (fig. 1). The reach is instrumented with a streamflow-gaging station and ground-water observation wells at each end of the reach, and with a streamflow-gaging station on a major tributary along the study reach. The second study reach is located along Black Thunder Creek near Hampshire, Wyo. (fig. 1). The alluvial channel material consists of gravel and sand; it also is typical of many ephemeral streams in the plains areas of Wyoming. This channel was selected because it is geologically different than the first study reach and because there has been a streamflow-gaging station along the reach since 1972. Ground-water observation wells also were drilled along this reach.

Purpose and Scope

There were two primary objectives of this study. The first objective was to determine the relation between streamflow in ephemeral streams and water levels in wells completed in bedrock and alluvial aquifers. The second objective was to estimate ground-water recharge from flow in ephemeral streams.

Two methods of calculating ground-water recharge were used. One method estimates recharge by calculating surface-water losses along an ephemeral-stream reach; the method required streamflow-gaging stations along the reach to measure surface-water inflow and outflow. The other method calculates recharge using water-level data obtained from two observation wells located near an ephemeral stream.

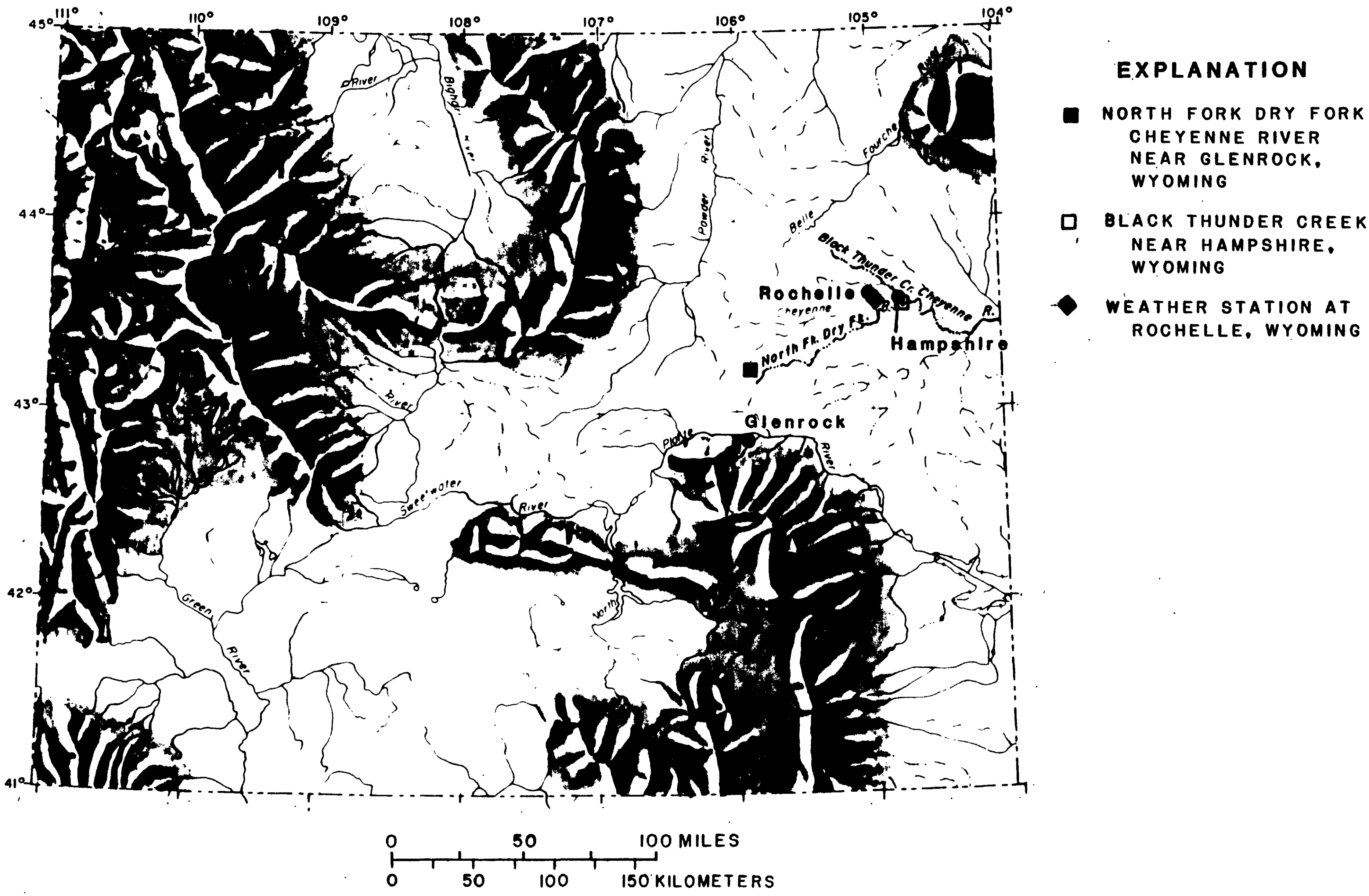

Figure 1.--Location of study sites and weather station.

The report is limited to the examination of two particular stream reaches located in northeastern Wyoming, which were instrumented for the purpose of this study. Results of the study may have application to other instrumented sites.

Acknowledgments

The author acknowledges the cooperation of Willis Bruce, William Henry, Michael Henry, and the Peabody Coal Co. who permitted the drilling of ground-water observation wells and the construction of streamflow-gaging stations on their property. This study was conducted in cooperation with the U.S. Bureau of Land Management.

Well-Numbering System

The numbering system used to identify wells in this report is based on the Federal system of land subdivision (fig. 2). The first number indicates the township, the second number the range, and the third number the section in which the well is located. The lowercase letters following the section number locate the well in the section. The first letter denotes the quarter section, the second letter the quarter-quarter section, and the third letter the quarter-quarter-quarter section; a quarter-quarter-quarter section is the equivalent of 10 acres. The subdivisions of a section are lettered a, b, c, d in a counterclockwise direction starting in the northeast quarter. When more than one well is located within a 10-acre tract, consecutive two-digit numbers starting with 01 follow the last lowercase letter of the well number. Each of the three instrumented sites with ground-water observation wells was located within a 10-acre tract; the two-digit numbers in the text and illustrations are abbreviations of the entire well number.

DESCRIPTION OF STUDY SITES

North Fork Dry Fork Cheyenne River

The North Fork Dry Fork Cheyenne River study reach is a 2.5-mile long sand channel. The drainage area above the downstream end of the study reach is approximately 30 square miles. Several tributaries enter the channel along the reach. One of the tributaries, referred to in this report as the "unnamed tributary", has a larger drainage area than the others and enters the reach from the left bank about 1,500 feet downstream from the upstream end of the reach.

Streamflow-gaging stations are located at each end of the North Fork Dry Fork Cheyenne River study reach (fig. 3), and one along the unnamed tributary. The gage along the unnamed tributary was located about 300 feet upstream from the North Fork Dry Fork Cheyenne River.

The lithology of the rocks underlying the gaged sites at the ends of the reach was defined by data obtained from 13 observation wells drilled at the two sites. A general description of the geology in the Powder River basin was obtained from Hodson and others (1973).

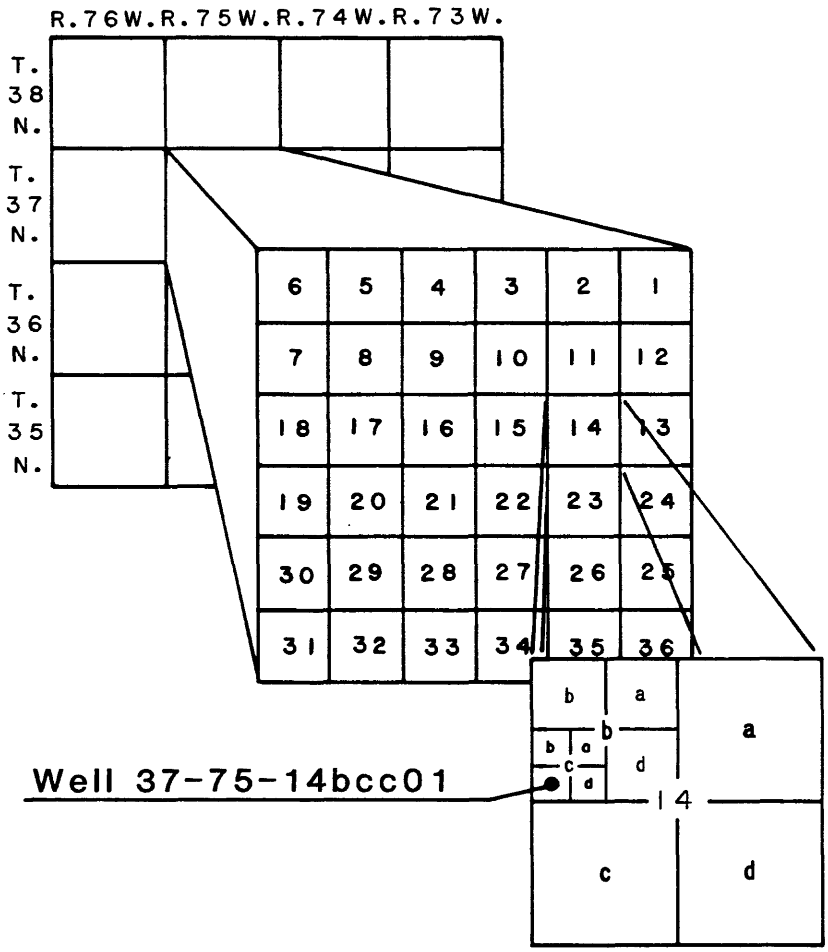

Figure 2.--Well-numbering system.

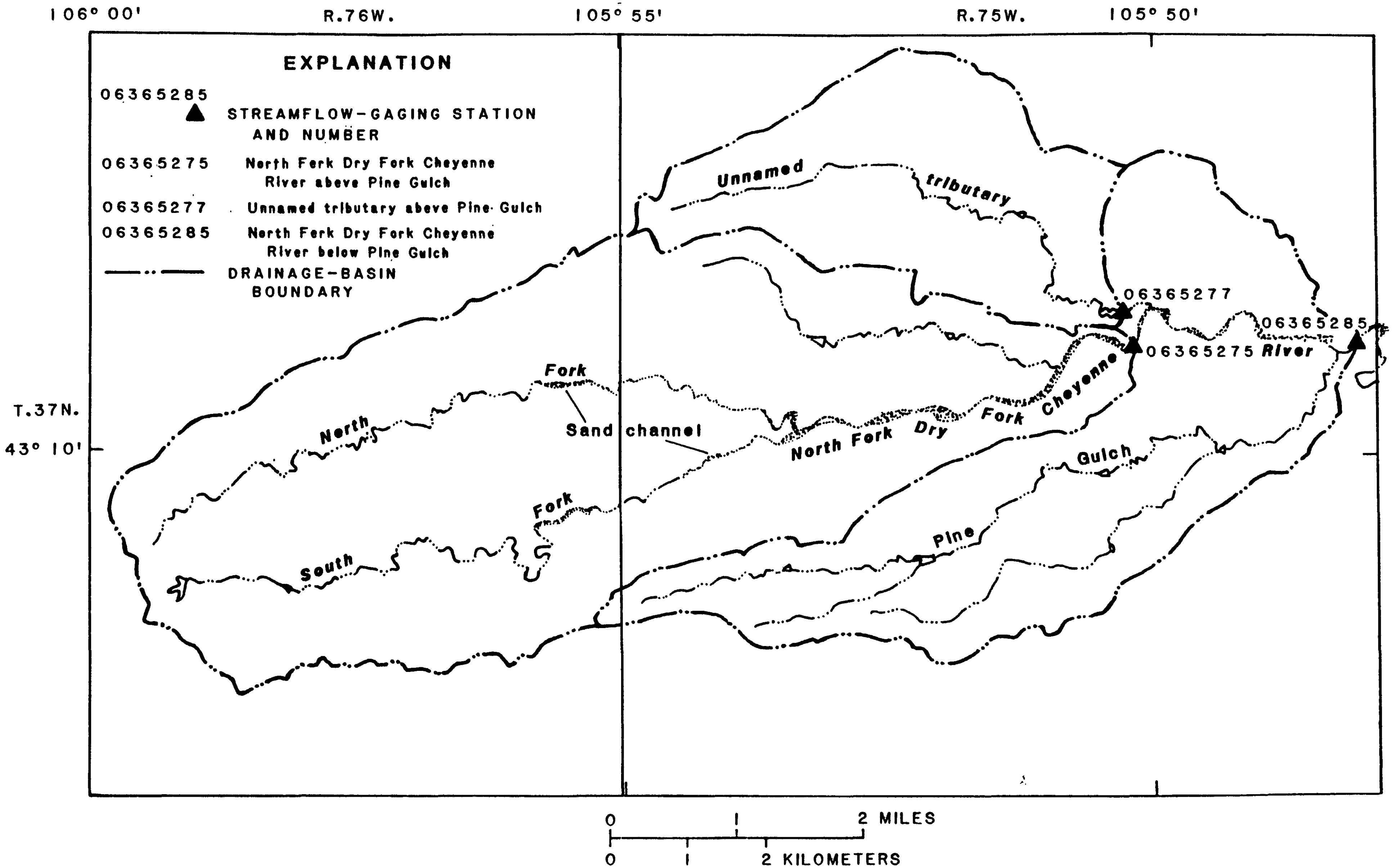

Figure 3.--Location of streamflow-gaging stations and drainage areas above gaging stations along North Fork Dry Fork Cheyenne River and unnamed tributary above Pine Gulch.

The alluvial aquifer at the observation wells along the North Fork Dry Fork Cheyenne River is 24 to 83 feet thick and consists of silt and fine- to coarse-grained sand. The characteristics of the alluvial aquifer along the study reach were assumed to be similar to the characteristics at the ends of the study reach.

The Wasatch Formation of Eocene age constitutes the bedrock aquifer along the study reach (Hodson and others, 1973, sheet 3), and consists of fine- to coarse-grained sandstone with interbedded shale and coal. Because the drill cuttings of the alluvial and bedrock aquifers were similar, the location of the top of the Wasatch Formation at the two drilling sites was approximate. Shale and coal were found in the drill cuttings from the wells near the stream channel and on the right (southeast) bank at the upstream site indicating the top of the bedrock. Coal was not found in the drill cuttings from the wells on the left (northwest) bank or from the wells at the downstream site.

Seven observation wells, 37N 075W 14bcc01-07, were drilled at the upstream site along a line approximately perpendicular to the North Fork Dry Fork Cheyenne River. Wells 03 and 07 were completed in the alluvial aquifer; wells 01 and 06 were completed in the bedrock aquifer; and well 05 was drilled as deep as the thin coal layer near the top of the bedrock aquifer and was completed in both the alluvial and bedrock aquifers. These wells were equipped with continuous water-level recorders. Wells 02 and 04 were drilled to determine the lithology of the alluvial and bedrock aquifers. Both wells were completed in the bedrock aquifer and used for periodic measurement of water levels. A hydrogeologic section at the upstream site shows the approximate location and depth of the wells, depth of casing perforations, and lithology from driller's logs (fig. 4).

Six observation wells, 37N 075W 13adb01-06, were drilled at the downstream site along a line approximately perpendicular to the North Fork Dry Fork Cheyenne River. Wells 01, 02, and 03 were completed primarily in the bedrock aquifer, and wells 04, 05, and 06 were completed primarily in the alluvium. All wells were instrumented with continuous water-level recorders. A hydrogeologic section at the downstream site shows the approximate location and depth of the wells, depth of casing perforations, and lithology from driller's logs (fig. 5).

Water was perched on top of the shale and coal layers in the alluvial aquifer near the North Fork Dry Fork Cheyenne River at the upstream site. Well 05 was drilled to the top of the coal layer and was completed in both the alluvial and bedrock aquifers. Water levels in well 05 were at least 8 feet above the coal layer; well 04, drilled into and completed in the aquifer below the coal layer, was dry during the period of record. Shale and coal were not found in the drill cuttings above 110 feet (gage datum) indicating that the extent of the shallow layers of shale and coal near the streambed is limited to a small area; water levels measured in well 05 represent water levels in a local area.

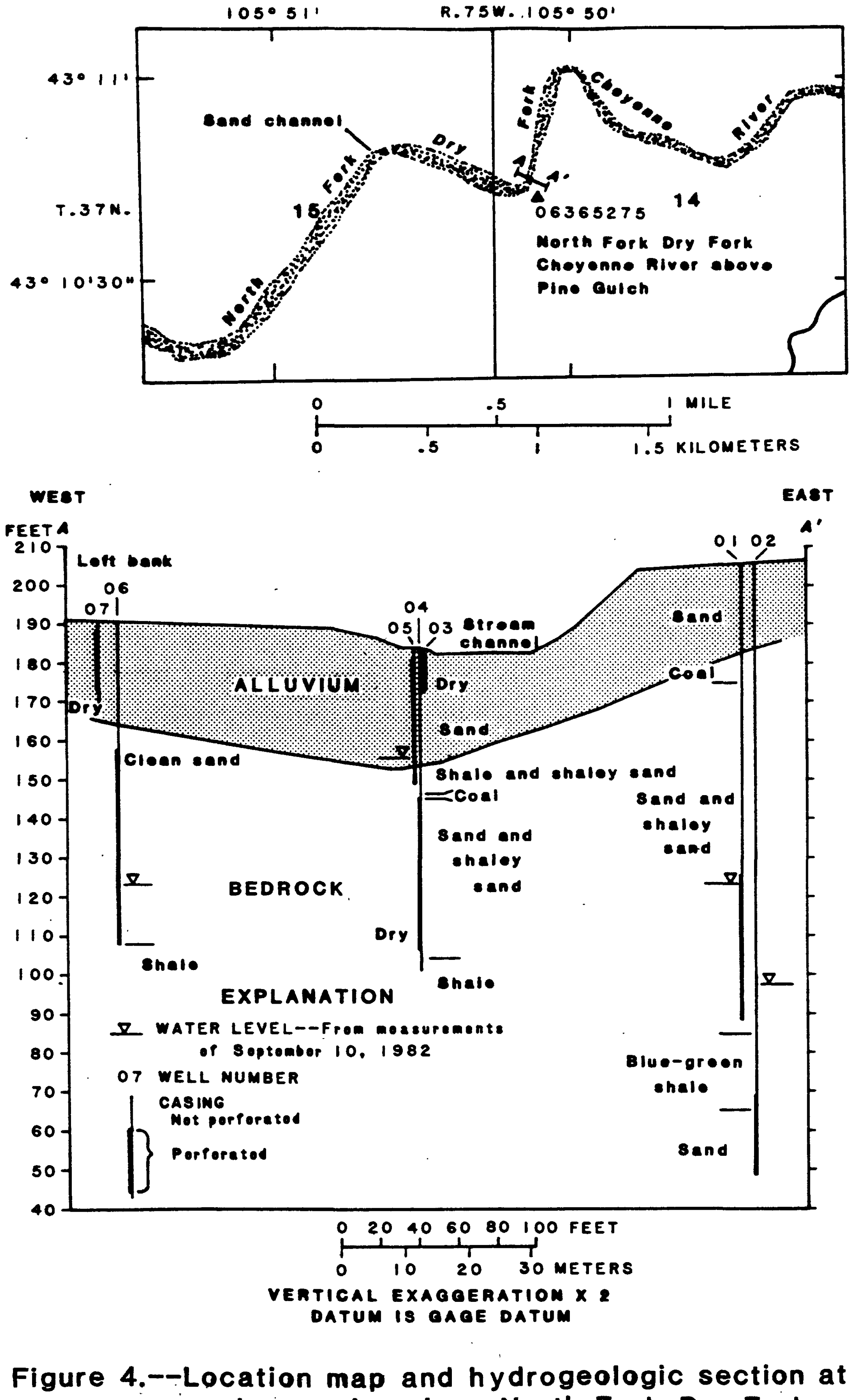

Figure 4.--Location map and hydrogeologic section at upstream site along North Fork Dry Fork Cheyenne River (lithology from driller's logs).

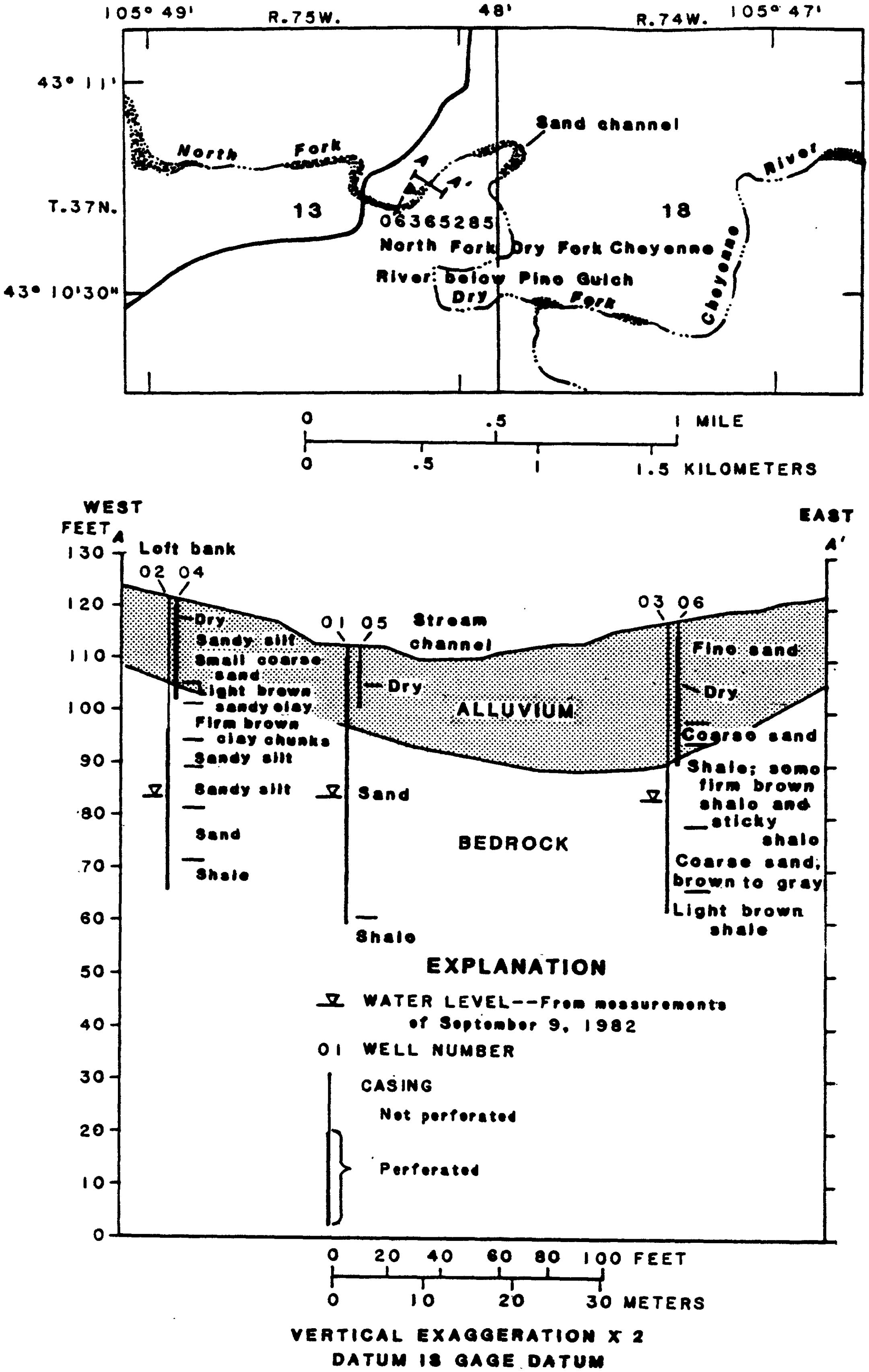

Figure 5.--Hydrogeologic section at downstream site along North Fork Dry Fork Cheyenne River (lithology from driller's logs).

Black Thunder Creek

The Black Thunder Creek channel consists of sand and gravel. The drainage area above the Black Thunder Creek streamflow-gaging station at the study site is 535 square miles. The streamflow-gaging station equipped with a manometer is located approximately 100 feet downstream from the observation wells. The gaging station has been in operation since October 1972.

The lithology of the gaged site was defined by data obtained from four observation wells drilled at the site. A general description of the geology in the Powder River basin was obtained from Hodson and others (1973).

The alluvium at the wells is approximately 20 feet thick. It consists of silt, fine sand, and gravel. The alluvium at Black Thunder Creek is coarser grained than the alluvium found along the North Fork Dry Fork Cheyenne River.

The bedrock aquifer consists of sandy shale, shale, silt and a thin bed of coal. The bedrock in this area is identified as the Lance Formation of Late Cretaceous age by Hodson and others (1973, sheet 1).

Four observation wells, 42N 066W 25ddd01-04, were drilled on the right (south) bank, in a line approximately perpendicular to Black Thunder Creek. Wells 01 and 03 were drilled to the bottom of the alluvial aquifer and into the confining shale layer; both wells were completed in the alluvial and bedrock aquifers. Wells 02 and 04 were drilled into and completed in the bedrock aquifer. All of the observation wells were equipped with recorders. A hydrogeologic section at the observation wells shows the approximate depth and location of the wells, depth of casing perforations, and lithology from driller's logs (fig. 6).

DATA COLLECTION

The two study reaches were instrumented to collect both streamflow data and water-level data in alluvial and bedrock aquifers. Streamflow data were collected to determine dates of occurrence and magnitude of surface-water flow. Water-level data were collected to show ground-water responses to streamflow, to indicate water-level changes with time, and to determine the gradient of the water-level surface perpendicular to the stream.

North Fork Dry Fork Cheyenne River Sites

Data were collected at the streamflow-gaging stations and the observation wells at each end of the reach from January 1982 through October 1983; water-level measurements were continued in some of the wells through December 1983. Periodic, usually monthly, measurements of stream stage and water levels were made prior to the installation of digital recorders in May 1982. After May 1982, stream stage was recorded at 5-minute intervals and water levels were recorded at 30-minute intervals. Water levels were measured periodically in the wells that were not equipped with continuous water-level recorders.

An additional streamflow-gaging station was constructed along the unnamed tributary after significant flow was observed in June 1982. It was

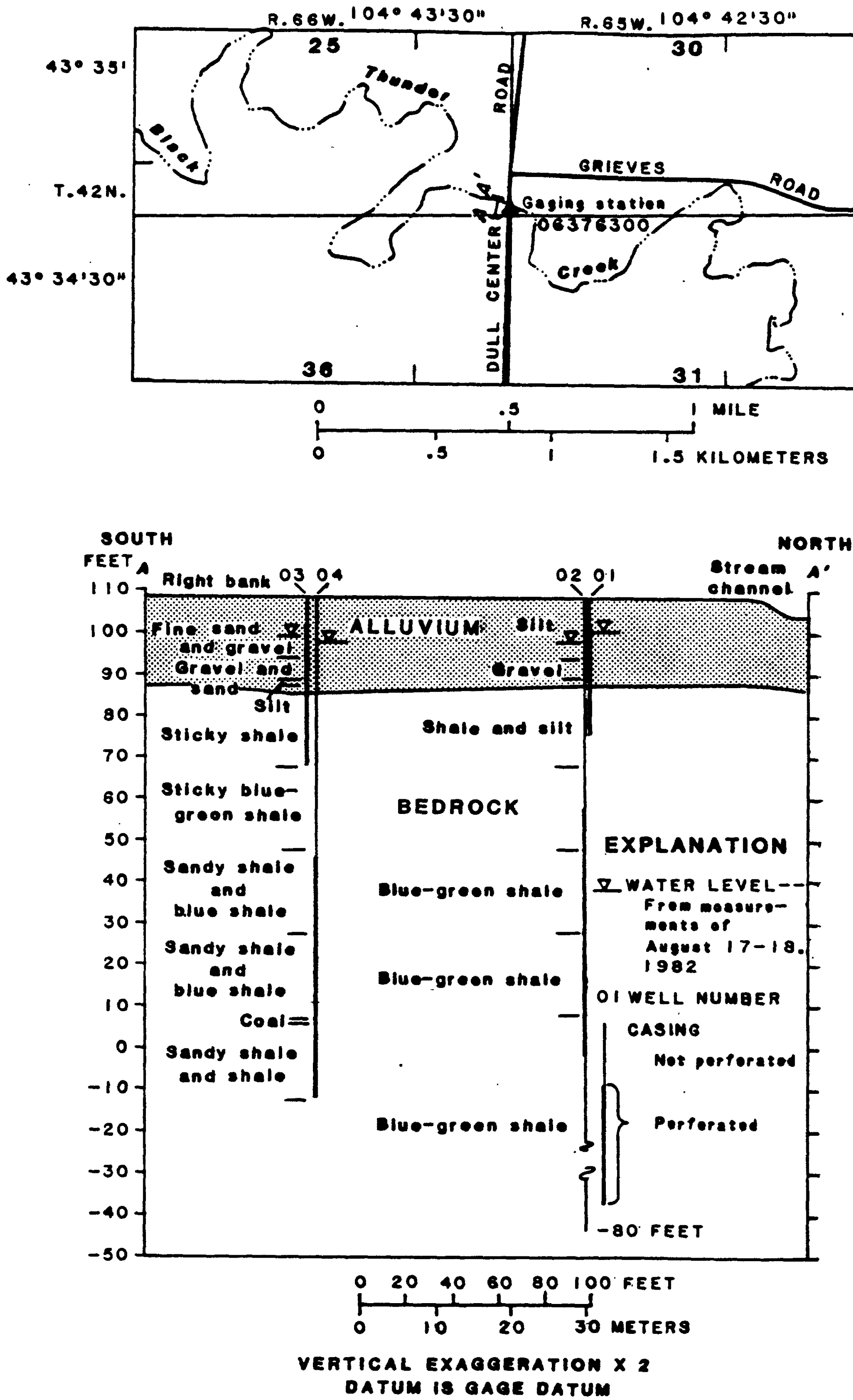

Figure 6.--Hydrogeologic section at Black Thunder Creek site (lithology from driller's logs).

instrumented to record stream stage at 5-minute intervals using a digital recorder. Data were collected from late June 1982 through October 1983, except for July 9-30, 1982 when the recorder failed to operate. Several significant floodflows were not recorded because of the recorder failure.

Wells 03 and 07 completed in the alluvial aquifer and well 04 completed in the bedrock aquifer at the upstream site and alluvial wells 04-06 at the downstream site were dry from January through September 1982 even though there was significant streamflow during this period. Data collection in these wells was discontinued in September 1982.

Black Thunder Creek Site

Streamflow and ground-water-level data were collected from April 1982 through January 1984; streamflow data were available only through October 1983. Stream stage and ground-water levels were recorded at 30-minute intervals by digital recorders.

Air-temperature data were collected and were used in the analysis of the hydrographs for the alluvial-aquifer wells. Maximum and minimum daily temperatures at Rochelle, Wyo., located about 12 miles northwest of the study reach, were provided by the U.S. Department of Commerce (1982-83).

METHODS FOR CALCULATING GROUND-WATER RECHARGE

Two methods of calculating ground-water recharge were used. One method estimates recharge by calculating surface-water losses along an ephemeral stream reach; this method was used for the North Fork Dry Fork Cheyenne River reach. The other method calculates recharge using ground-water level data; this method was used for both the North Fork Dry Fork Cheyenne River and Black Thunder Creek reaches. Ground-water recharge was calculated in units of acre-feet per mile of stream reach for both methods.

Surface-Water Method

Surface-water losses along an ephemeral-stream reach are an indication of the amount of water available for ground-water recharge. Losses are determined by calculating the difference between surface-water inflow and outflow measured within the study reach. Simply stated, loss can be computed from:

$$\text{Streamflow loss} = \text{Inflow} - \text{Outflow}$$

Because surface-water inflow and outflow were measured at three discrete points within the North Fork Dry Fork Cheyenne River reach, inflow from overland runoff and outflow from evapotranspiration between the points were not accounted for in the calculation of surface-water losses.

Ground-Water Method

Ground-water levels may be used to estimate recharge to shallow aquifers using a method of Moench and Kisiel (1970). Their method is a linear model that computes recharge to the water table using aquifer properties. The method computes the input (recharge) to the system given the output (changes in ground-water levels in time) of the system using a convolution technique.

The data required to run the model consist of water levels measured in an observation well, estimated aquifer constants, and land-surface geometry. The estimated aquifer constants include the storage coefficient and the diffusivity, which is the transmissivity of the aquifer divided by the storage coefficient. Land-surface geometry includes the stream width and the distance from the stream to the observation well; any reasonable estimate of stream width can be used and the distance from the stream to the observation well is easily measured. Storage coefficients in an unconfined aquifer generally range from about 0.1 to 0.3 and average about 0.2 (Lohman, 1972, p. 8). The remaining parameter, the diffusivity of the aquifer, can be estimated by many accepted methods.

Several assumptions were made in the derivation and implementation of the model. The system was assumed to be linear and time-invariant. This means aquifer coefficients are not a function of water-level fluctuations and do not change with time. Prior to recharge, the water table is assumed horizontal. It was assumed that the only source of recharge to the aquifer was the ephemeral stream; significant vertical infiltration due to snowmelt or rainfall can cause an overestimation of recharge from the ephemeral stream. Similarly, if there is significant leakage from the water-table aquifer to underlying formations it would cause an underestimation of recharge from the stream; it was assumed that there was insignificant leakage to underlying formations.

Aquifer diffusivity can be calculated by using a method of Grubb and Zehner (1973). The method uses the flood-wave response technique. The method requires water-level hydrographs for two observation wells situated in a line approximately perpendicular to a stream, estimates of the diffusivity of the aquifer, and the horizontal distances from the observation wells to the contact between the alluvial and bedrock aquifers. Hydrographs are computed for the observation well farthest from the stream using the actual hydrograph for the observation well nearest the stream and a range of diffusivity estimates for the aquifer. Hydrographs computed from the estimated diffusivity values are compared with the actual hydrograph in the observation well farthest from the stream. The estimated diffusivity value is selected as a result of the best fit of the actual and computed hydrographs.

Rorabaugh (1960) discusses a graphical solution for diffusivity. He stated that after recharge in an aquifer, water levels decline exponentially with time and that the slope of the water-level recession, after time has been allowed for water levels to stabilize, can be used to compute diffusivity. The equation for diffusivity (T/S) is:

$$\frac{T}{S} = \frac{0.933a^2 \log h_1/h_2}{(t_2 - t_1)}$$

where

a = 0.5 width of the aquifer,

h_1 = ground-water level at time t_1,

h_2 = ground-water level at time t_2, and

$\frac{\log h_1/h_2}{(t_2 - t_1)}$ = the slope of the recession.

The slope of the water-level recession is determined graphically by plotting the logarithm of the difference in elevation between observed ground-water levels and the static ground-water level for the well versus time. Diffusivity is then computed by solving the equation.

The diffusivity and storage coefficient of the aquifer also may be determined from an aquifer test that uses two wells. This method was not used in this study.

DATA ANALYSIS

North Fork Dry Fork Cheyenne River

Hydrographs for wells 01, 05, and 06 at the upstream site and wells 01-03 at the downstream site and streamflow-gaging stations at both sites were used to show the correspondence of ground-water levels to flow in the North Fork Dry Fork Cheyenne River. Hydrographs of ground- and surface-water levels at the upstream site are shown in figure 7 and hydrographs of ground- and surface-water levels at the downstream site are shown in figure 8. All elevations shown are measured from an arbitrary datum common to both sites.

Observation wells 03 and 07 completed in the alluvial aquifer at the upstream site were dry from January to September 1982 because they were completed above the water table. The unsaturated thickness of the aquifer above the coal layer near the North Fork Dry Fork Cheyenne River, as indicated by the water level in well 05, was as least 30 feet prior to September 1982. The bottom of well 03, complete in the alluvial aquifer and about 10 feet from well 05, was only 12 feet below the land surface and was at least 18 feet above the water table. The bottom of well 07, completed in the alluvial aquifer on the left bank, was at least 50 feet above the ground-water levels measured in well 06.

The observation wells completed in the alluvial aquifer, 04-06, at the downstream site also were dry from January to September 1982 because they were completed above the water table. Water levels in well 01, completed in the alluvial and bedrock aquifer and wells 02-03 completed in the bedrock aquifer indicated the unsaturated thickness of the aquifer was 30 feet or more. The depths of the wells completed in the alluvial aquifer were no greater than 22 feet.

Hydrographs of stream stage and of water levels in well 05 at the upstream site (fig. 7) indicate water-level fluctuations in the shallow aquifer above the coal layer correspond to streamflow in the North Fork Dry Fork Cheyenne River. With few exceptions, ground-water levels increased or the

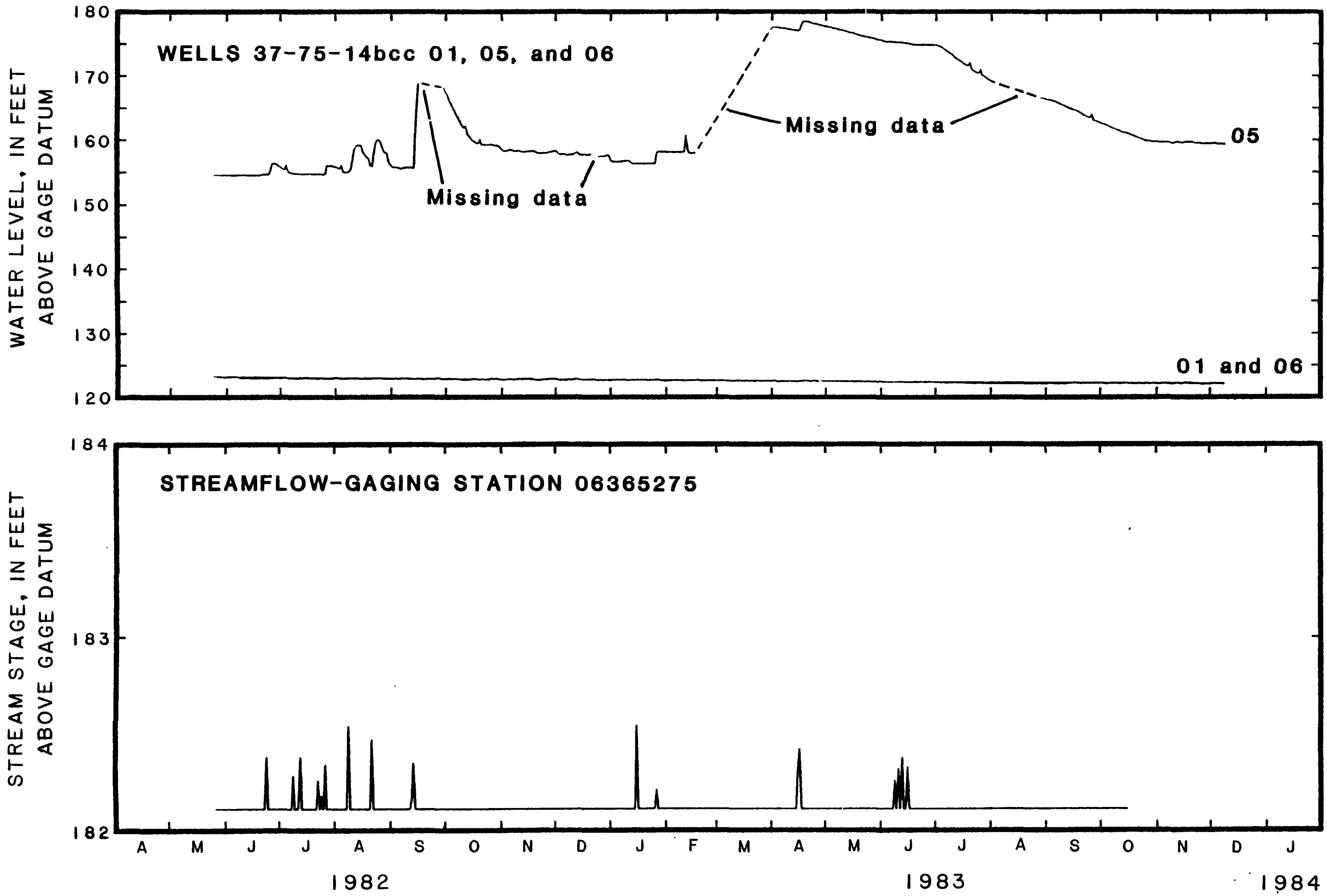

Figure 7.--Hydrographs for wells completed in alluvium and bedrock, and stream at the upstream site along North Fork Dry Fork Cheyenne River.

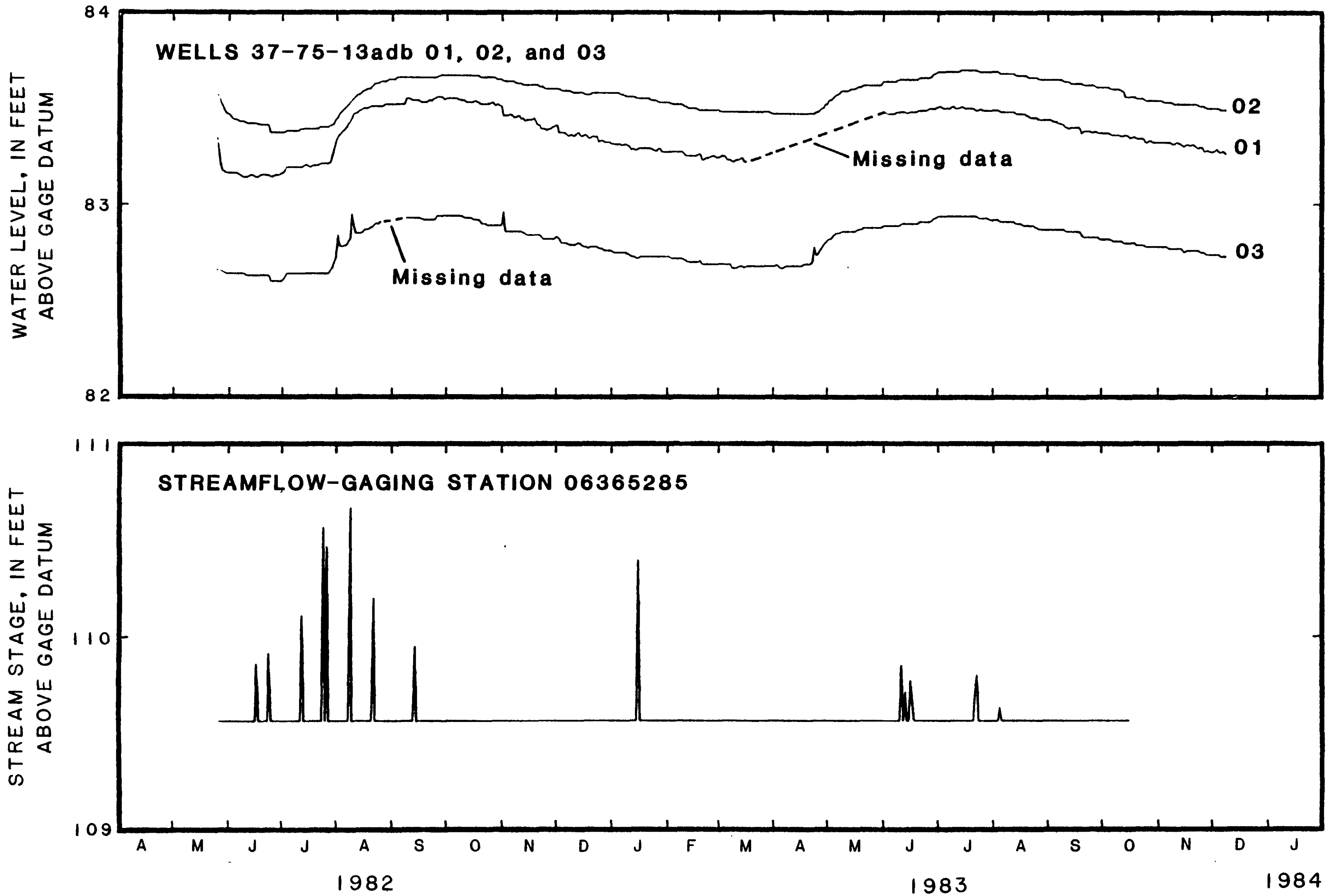

Figure 8.--Hydrographs for wells completed in alluvium and bedrock at the downstream site along North Fork Dry Fork Cheyenne River.

recession rate of ground-water levels decreased in response to streamflow. It was assumed that the increase in ground-water levels from February through March 1983 was caused by vertical infiltration of water from snowmelt. Water levels in well 05 increased about 5 feet after January 1982 and about 3 feet from January to September 1983 as a result of ground-water recharge.

Hydrographs for wells 01 and 06 completed in the bedrock aquifer at the upstream site (fig. 7) indicate no correspondence between water-level changes in the bedrock aquifer and streamflow. No water-level fluctuations occurred because little, if any, of the surface water that infiltrated into the alluvial aquifer reached the bedrock aquifer. This water probably was lost either to evapotranspiration, to horizontal flow down valley, or to soil moisture above the zone of saturation. Water levels in wells 01 and 06 were about 123 feet above gage datum and were influenced by regional rather than local conditions within the aquifer.

Measurements of the depth of well 04 indicated that the bottom 15 feet had filled with sand and that the bottom of the well during the study period was at an elevation of approximately 124 feet above gage datum. Well 04 was dry during the study period because the bottom of the well was approximately 1 foot above water level in the bedrock aquifer.

Hydrographs for well 01, completed in the alluvial and bedrock aquifer, and wells 02 and 03, completed in the bedrock aquifer, and for the stream stage at the downstream site (fig. 8) indicate a correspondence between water-level fluctuations in the bedrock aquifer and streamflow. Water-level fluctuations occurred because surface water infiltrated through the alluvial aquifer and recharged the bedrock aquifer. Water levels in the observation wells were between 30 and 39 feet below land surface during the period of record and rose in response to streamflow. Recharge of the bedrock aquifer from streamflow is evident from July through September 1982 and June through July 1983, and from snowmelt beginning in April 1983.

Streamflow was computed at each of the gaged sites using stream-stage records and stage-discharge ratings developed for each of the streamflow-gaging stations and was used to estimate streamflow losses along the North Fork Dry Fork Cheyenne River. Ratings were developed from a stage-discharge relation computed using a step-backwater analysis and from a known elevation of zero flow. Although the ratings are not as accurate as those developed using current-meter measurements, they were assumed to be sufficiently accurate for calculating estimates of streamflow losses.

Two basic assumptions in computing streamflow losses and in equating losses with recharge in this study were made: (1) Insignificant streamflow was lost to evapotranspiration and (2) insignificant streamflow was gained from tributary and overland runoff. Streamflow loss due to evapotranspiration was assumed insignificant because of the sparse vegetation along the study reach. It was assumed that all of the significant tributary inflow and overland runoff between the upstream and downstream sites was recorded by the streamflow-gaging station on the unnamed tributary.

Streamflow losses were determined by estimating the volume of flow at each streamflow-gaging station within the study reach for eight periods of flow. Losses were computed by subtracting the volume of flow at the downstream site (outflow) from the sum of the volume of flow at the upstream and tributary sites (inflow). The volume of streamflow loss, in cubic feet, is listed in table 1. Streamflow losses were then calculated in terms of acre-feet of water lost per mile of reach (table 1) and ranged from 0.43 to 1.44 acre-feet per mile.

The actual streamflow losses along the North Fork Dry Fork Cheyenne River reach probably were significantly greater than the computed streamflow losses. Ungaged overland runoff was observed during several occasions when the stream was flowing and greatly increased streamflow. Because streamflow loss is equal to the inflow minus the outflow of the reach and because unmeasured outflow is considered insignificant, an increase in the inflow from unmeasured runoff without a significant increase in outflow would result in an increase in streamflow loss. Calculations of streamflow for July 13-14, July 25, July 27, and August 22, 1982, indicate a gain in streamflow along the channel (table 1). This gain in streamflow was caused by ungaged inflow along the study reach that produced more streamflow than was lost to the alluvial aquifer as recharge.

Recharge of the shallow aquifer at the upstream site was computed using water levels in well 05 and the method of Moench and Kisiel (1970) for a comparison with the results of the streamflow loss method. Diffusivity was estimated as 547 feet squared per hour using a graphical technique described by Rorabaugh (1960) and a water-level recession on the hydrograph for well 05 (fig. 9). A storage coefficient of 0.10 was assumed a reasonable approximation for the shallow aquifer which is composed of fine-grained sand. Well 05 was about 5 feet from the left bank of the North Fork Dry Fork Cheyenne River, and the stream width was about 30 feet. Using a diffusivity of 547 feet squared per hour, the recharge computed using the method of Moench and Kisiel (1970) on August 9, 1982, was 26.5 acre-feet per mile. The results of this analysis are questionable because the water levels in well 05 represent a local ground-water condition and because the value for diffusivity is questionable. In computing diffusivity, most of the assumptions pertaining to the method were not met and the aquifer width was approximated from an aerial photograph.

Computed streamflow loss along a stream reach cannot be equated to ground-water recharge unless <u>all</u> inflow and outflow of the system can be determined. The computed streamflow loss on August 9, 1982 (1.44 acre-feet per mile) is considerably less than the recharge computed using the Moench and Kisiel (1970) method (26.5 acre-feet per mile) for the same date. Computed streamflow loss usually is significantly underestimated along this reach because of unmeasured inflow within the reach, therefore, computed streamflow loss should be less than the actual ground-water recharge.

Black Thunder Creek

Data collected at one gaged site helped determine recharge from Black Thunder Creek. Hydrographs of stream stage and ground-water levels indicated the response of ground-water levels to streamflow. Ground-water recharge was computed from water levels in the alluvial aquifer using the method of Moench and Kisiel (1970).

Table 1.--Streamflow and streamflow losses of the North Fork Dry Fork Cheyenne River, 1982.

[min, minutes; ft^3, cubic feet; --, no data]

	North Fork Dry Fork Cheyenne River above Pine Gulch			Unnamed tributary above Pine Gulch			North Fork Dry Fork Cheyenne River below Pine Gulch				
Date	Begin time	Duration (min)	Volume (ft^3)	Begin time	Duration (min)	Volume (ft^3)	Begin time	Duration (min)	Volume (ft^3)	Loss[1] (ft^3)	Loss[1] (acre-feet per mile)
June 24-25	2155	240	122,500	--	--	--	2235	225	68,330	54,170	0.49
July 9	1700	185	47,500	--	--	([2])	--	--	0	47,500	.43
July 13-14	2200	160	75,100	--	--	([2])	2200	185	111,600	--	--
July 23-24	2205	225	49,600	--	--	([2])	--	--	0	49,600	.45
July 25	1630	80	7,800	--	--	([2])	1640	310	292,100	--	--
July 27	1450	130	40,115	--	--	([2])	1515	215	204,900	--	--
August 9	1820	180	166,500	1855	270	312,000	1935	270	318,000	160,500	1.44
August 22	0455	240	210,600	--	--	0	0550	345	310,000	--	--

[1] Inflow from tributaries and overland runoff between the upstream and downstream gages along the North Fork Dry Fork Cheyenne River could have occurred during any of the measurement periods, so the computed loss represents the minimum quantity lost because it does not account for additional inflow between the sites. When a gain in discharge is indicated, it probably was the result of more inflow from tributaries and overland runoff than losses to ground-water recharge; gains in discharges were not calculated.

[2] Data collection began on June 28. The record of stage from July 9-30 was lost due to a recorder malfunction.

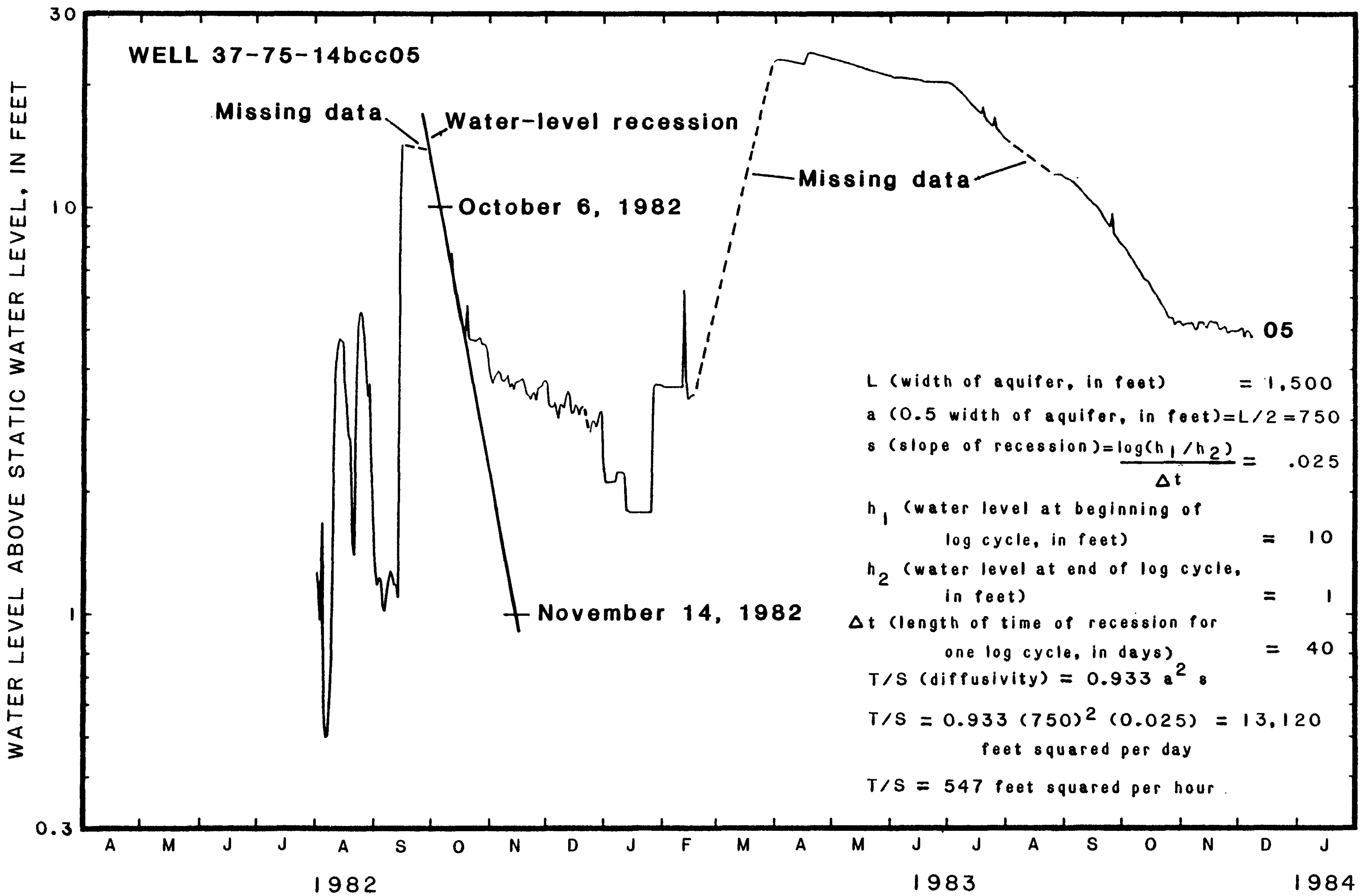

Figure 9.--Hydrograph for ground-water-level recession used in graphical solution for diffusivity.

A comparison of the hydrographs for the observation wells completed in the alluvial and bedrock aquifers and the hydrograph of stream stage (fig. 10) indicates the relation between water-level fluctuations in the alluvial and bedrock aquifers and flow in Black Thunder Creek. Surface water infiltrates into the alluvial aquifer at a relatively rapid rate when streamflow occurs because of the larger hydraulic conductivity of alluvium and is transmitted through the bedrock aquifer at a slower rate because of the smaller hydraulic conductivity of the bedrock.

Hydrographs for the wells completed in the alluvial aquifer and for stream stage indicate an excellent correspondence determined during the study between streamflow and water-level fluctuations in the alluvial aquifer; water levels increased in response to streamflow as the alluvial aquifer was recharged. Water levels in well 01 responded within an hour, and water levels in well 03 responded within 3 hours after flow in Black Thunder Creek for each recorded flow occurrence.

Water levels in the alluvial aquifer slope away from Black Thunder Creek, indicating movement of ground water away from Black Thunder Creek after recharge. Water-level recessions with time indicate water movement out of the alluvial aquifer after recharge. Downward movement of ground water into the bedrock aquifer is indicated by water level rises in wells 02 and 04 after recharge of the alluvial aquifer (fig. 10).

Hydrographs of water levels in the bedrock aquifer indicate that water levels in the bedrock aquifer are affected by flow in Black Thunder Creek. Hydraulic head in the alluvial aquifer increased during recharge; the increased hydraulic head in the alluvial aquifer caused increases in hydraulic heads in the bedrock aquifer. Water levels in the observation wells completed in the bedrock aquifer were about 8 feet above the base of the alluvial aquifer indicating that artesian conditions exist in the bedrock aquifer.

A distinctive decline of water levels occurred in the alluvial aquifer from November 1982 through early January 1983 and in November 1983 (fig. 10). This decline did not occur in the bedrock aquifer as indicated by the relatively constant water levels in wells 02 and 04. The reason for the water-level decline is not known but may be a combination of many factors including: (1) A lack of streamflow, (2) decreased hydraulic conductivity of the aquifer, and (3) ground water migrating to the frost zone. A lack of ground-water recharge from surface water may cause ground-water levels to decline. Varying air temperatures can affect ground-water levels by changing the hydraulic conductivity of the aquifer. Colder weather can cause the hydraulic conductivity to decrease because the viscosity of water increases with a decrease in temperature; this can cause a decrease of the rate that water is transmitted through the aquifer.

An explanation for rapidly declining ground-water levels due to ground-water migration to the frost zone during winter months is discussed by Benz and others (1968):

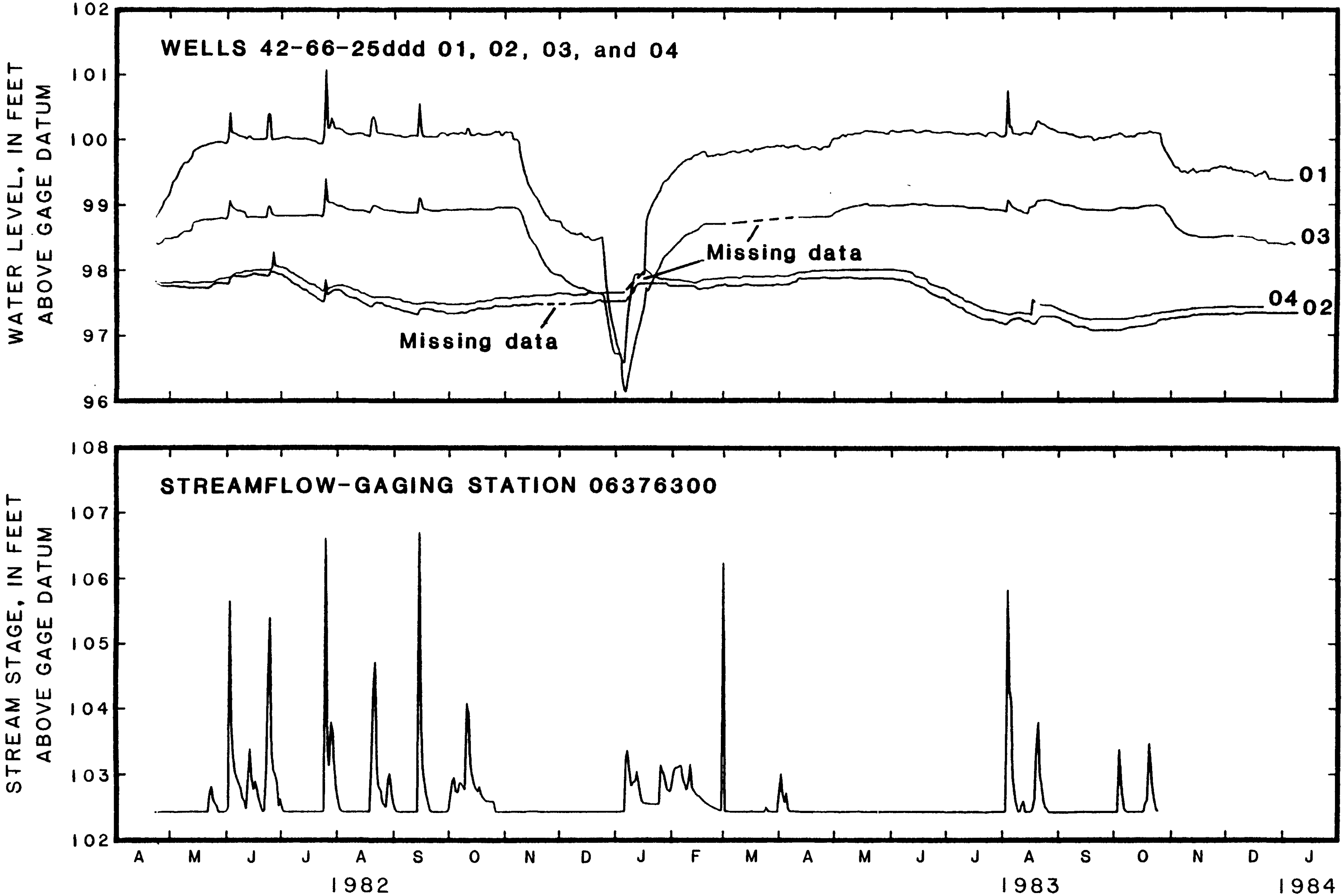

Figure 10.--Hydrographs for wells completed in alluvium and bedrock, and stream at the Black Thunder Creek site.

"The mechanics involved in transport of soil water due to temperature, plus their interactions, have not been entirely resolved. It is generally agreed, however, that soil water migration occurs by the two principal mechanisms of liquid or film flow and of vapor movement where the vapor condenses upon reaching the colder soil."

They cite several examples where ground water migrated upward from the water table towards the colder surface soil. This phenomenon occurred in areas having a high water table and where temperature gradients exist in the soil. The rapid decline of ground-water levels in wells 01 and 03 completed in the alluvial aquifer began when sustained subfreezing minimum daily temperatures occurred in late October 1982 (fig. 11); ground-water migration during periods of cold weather could explain the rapid ground-water-level decline at Black Thunder Creek.

Ground-water recharge along Black Thunder Creek was computed using the method of Moench and Kisiel (1970). Data required by this method consist of water levels in an observation well, the distance from the stream to the observation well, stream width, and estimates of the storage coefficient and diffusivity of the aquifer. Observation-well data used by the method were obtained from well 01 which is located 100 feet from Black Thunder Creek. Stream width is about 10 feet. A storage coefficient of 0.15 was assumed for the alluvial aquifer. The diffusivity of the aquifer was computed using the method of Grubb and Zehner (1973).

The diffusivity of the aquifer was computed for five recharge occurrences using the method of Grubb and Zehner (1973) (table 2). Several ground-water hydrographs were computed at well 03 for each recharge occurrence using a range of diffusivity estimates and the actual hydrograph for well 01. The actual hydrograph for well 03 was compared with the computed hydrographs. The diffusivity value for each recharge occurrence was selected as a result of the best fit between the actual hydrograph for well 03 and the hydrograph computed using the diffusivity value at well 03. The actual and computed hydrographs for the June 24-25, 1982, and September 15-16, 1982, recharge occurrences are compared in figure 12. Calculations of diffusivity for the 5 recharge occurrences ranged from 900 to 4,100 feet squared per hour. The average value for diffusivity was 2,500 feet squared per hour and was used in the calculation of ground-water recharge. Although the range of diffusivity values calculated by the Grubb and Zehner (1973) method is considerable, all of the estimates are within an order of magnitude. It will be shown that the calculation of recharge using the Moench and Kisiel (1970) method is relatively insensitive to changes within the estimated range of diffusivities.

An independent estimate of diffusivity was made to substantiate the computed estimate of diffusivity. If the diffusivity of the alluvial aquifer is 2,500 feet squared per hour and the storage coefficient is 0.15, then the transmissivity of the aquifer is 375 feet squared per hour. The saturated thickness of the aquifer is about 15 feet. The computed hydraulic conductivity is 600 feet per day. This is the hydraulic conductivity of very coarse sand (Lohman, 1972, p. 53), which is similar to the alluvial material found at the Black Thunder Creek site.

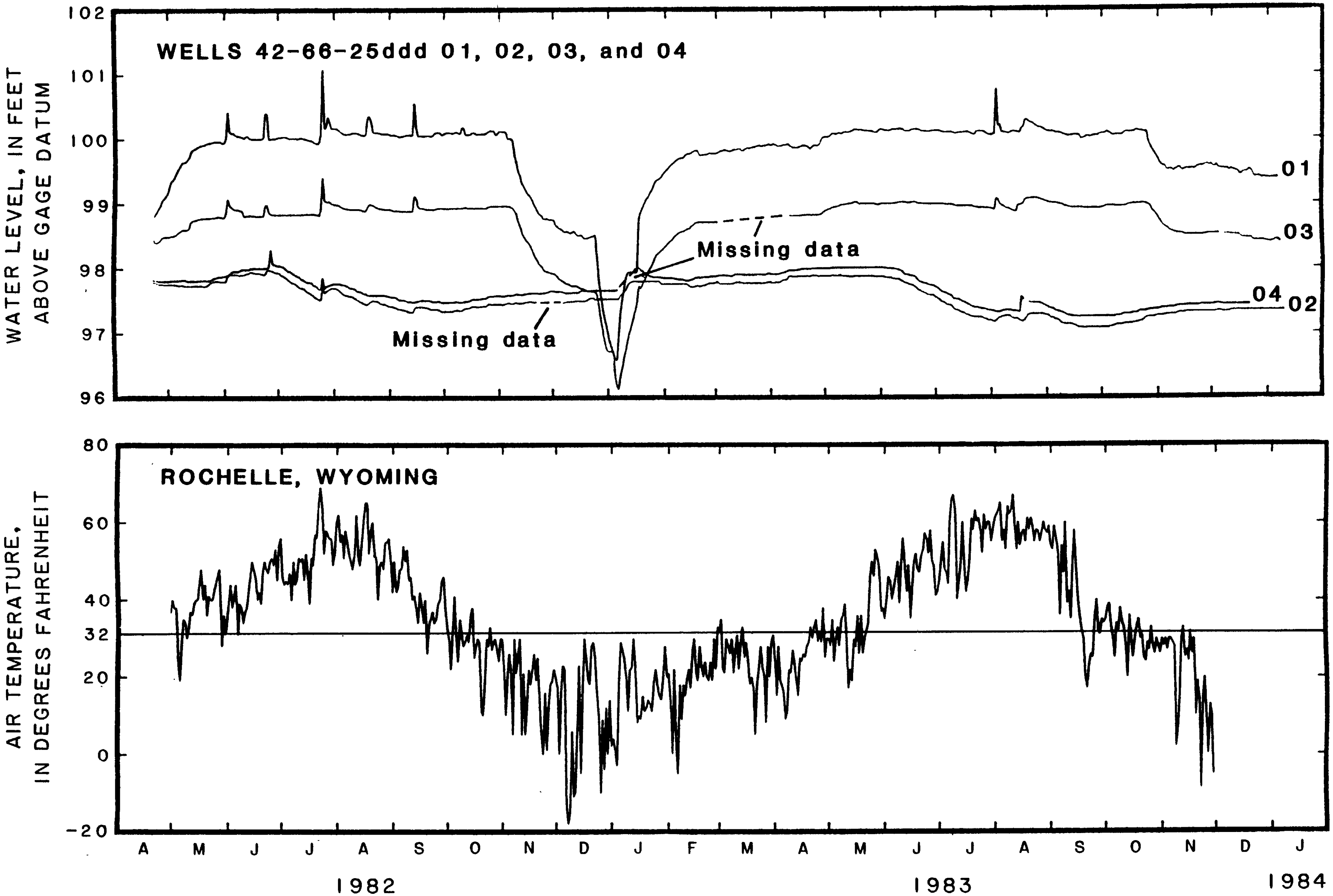

Figure 11.--Hydrograph for wells completed in alluvium and bedrock at the Black Thunder Creek site and minimum air temperature at Rochelle, Wyoming.

Table 2.--Estimated diffusivity and recharge of alluvial aquifer at the Black Thunder Creek site, with sensitivity analysis.

[ft^2/h, feet squared per hour; acre-ft/mi, acre-feet per mile; ft, feet; RMS difference, Root Mean Square difference]

Date	Estimated diffusivity[1] (ft^2/h)	RMS difference[2] (ft)	Sensitivity Analysis[3] Diffusivity (ft^2/h)	Recharge (acre-ft/mi)	Percent difference from estimated recharge	Estimated recharge[4] (acre-ft/mi)
June 3-4, 1982	3,900	0.015	900	3.13	-13	3.59
			4,100	4.30	+20	
June 24-25, 1982	2,200	.010	900	3.17	-11	3.56
			4,100	4.27	+20	
July 25-30, 1982	4,100	.028	900	10.1	-18	12.4
			4,100	14.7	+19	
Sept. 15-16, 1982	1,500	.024	900	4.70	-19	4.95
			4,100	5.86	+18	
Aug. 4-6, 1983	900	.035	900	5.93	-12	6.76
			4,100	7.88	+17	

[1] Diffusivity value selected as a result of the best fit between the actual hydrograph for well 03 and the hydrograph computed using this diffusivity value.

[2] The RMS difference indicates the closeness of fit between the actual and computed observation-well hydrographs, and is, therefore, a measure of confidence in the computed diffusivity; the smaller the RMS difference, the better the fit, and the greater the confidence in the diffusivity value.

[3] The calculated recharge values represent the range of recharge values calculated from the range of diffusivity values computed by the Grubb and Zehner (1973) method.

[4] The estimated value of recharge for the particular flow is calculated using the Moench and Kisiel method (1970) and the average value of diffusivity of 2,500 feet squared per hour.

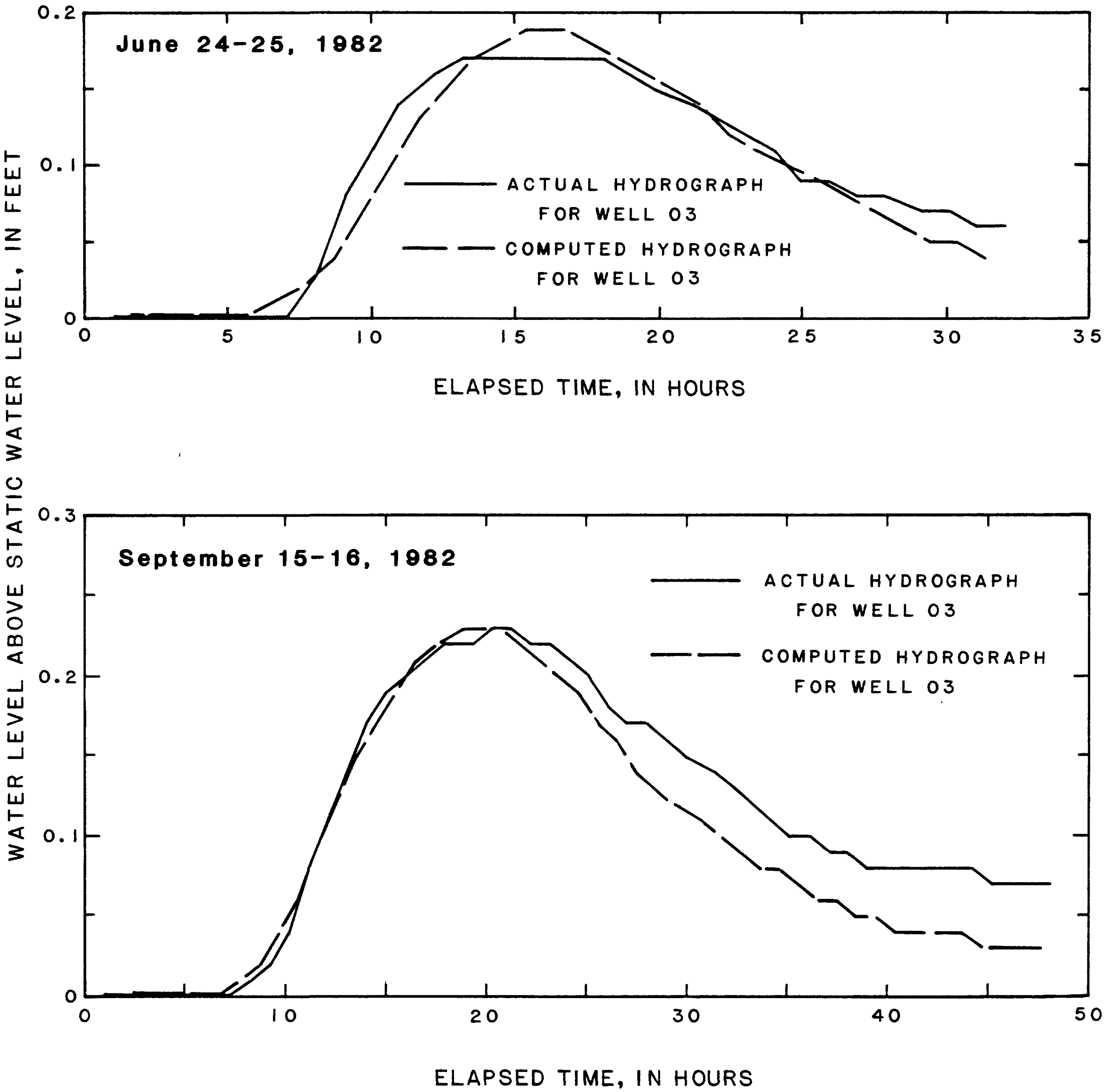

Figure 12.--Actual and computed water levels above static water level in well 03 at the Black Thunder Creek site for June 24-25, 1982, and September 15-16, 1982.

Recharge to the alluvial aquifer was calculated using the method of Moench and Kisiel (1970) for five periods of streamflow at the Black Thunder Creek site. Duration and magnitude of the streamflows varied and recharge varied accordingly. The computed recharge from the five streamflows ranged from 3.56 acre-feet per mile for June 24-25, 1982 to 12.4 acre-feet per mile for July 25-30, 1982 (table 2).

The system was not linear and time invariant because aquifer coefficients varied with water-level fluctuations and time; this contradicts the first assumption made in using the Moench and Kisiel (1970) model. However, the model was relatively insensitive to variations in the diffusivity of the aquifer. To illustrate the insensitivity of the method to changes in diffusivity, recharge values were calculated using diffusivity values of 900 and 4,100 feet squared per hour for each of the five discharge periods and are shown in table 2. Recharges calculated for diffusivities of 900 and 4,100 feet squared per hour are all within ± 20 percent of the estimated recharge for the five streamflows.

The water table was not horizontal prior to recharge. The water-table gradient was approximately 0.9 percent. It was assumed that this gradient did not affect the response of the system because recharge was computed using water levels from well 03 in addition to those from well 01 with similar results.

Vertical infiltration of water from precipitation is a possibility at the Black Thunder Creek site and may affect measured water levels in the observation wells. But it was assumed that the time of water-level response to infiltration from precipitation was significantly longer than the 1-hour response of water levels to streamflow. Therefore, it was assumed that the effect of precipitation on recharge calculations using the Moench and Kisiel (1970) method was negligible.

SUMMARY AND CONCLUSIONS

A comparison of surface-water and ground-water hydrographs at the gaged sites along the two study reaches indicates the occurrence of ground-water recharge from streamflow in ephemeral streams. Surface water infiltrates the alluvium and generally causes water levels in the alluvial aquifer to rise in response to streamflow. Some of the infiltrated water reaches the bedrock aquifer causing water-level rises. The remaining water probably is lost either to evapotranspiration, to horizontal flow down valley, or to soil moisture in the unsaturated zone.

Hydrographs at the upstream site along the North Fork Dry Fork Cheyenne River indicated ground-water recharge to the perched water table above the coal layer and no apparent recharge to the bedrock aquifer. Water levels in the alluvial aquifer responded to streamflow in the North Fork Dry Fork Cheyenne River either with an increase in water levels or with a decrease in the rate of recession of water levels. The hydrographs of water levels in the bedrock aquifer virtually were flat during the period of the study. It was assumed that little, if any, of the surface water that infiltrated into the alluvial aquifer reached the bedrock aquifer.

Hydrographs at the downstream site along the North Fork Dry Fork Cheyenne River indicated ground-water recharge to the bedrock aquifer. Water in the bedrock aquifer responded to streamflow in the North Fork Dry Fork Cheyenne River either with an increase in water levels or with a decrease in the rate of recession of water levels.

Hydrographs for wells completed in the alluvial and bedrock aquifers indicated recharge to the aquifers from streamflow in Black Thunder Creek. Water levels in the alluvial aquifer increased within 3 hours of streamflow in Black Thunder Creek. Some water from the alluvial aquifer leaked into the bedrock aquifer causing water level rises in the observation wells completed in the bedrock aquifer.

Seasonal changes in air temperatures can affect ground-water levels in shallow aquifers. Air temperatures can affect the hydraulic conductivity of aquifers by changing the viscosity of water. As air temperatures decrease, water on or near the land surface becomes more viscous causing the hydraulic conductivity of an aquifer to decrease. Cold weather may cause temperature gradients in the soil. Temperature gradients may cause ground water to migrate upward to the frost zone, lowering the water table. A combination of these factors may have caused the distinctive drop of water levels in the alluvial aquifer during the winter months along the Black Thunder Creek study reach.

Computed streamflow loss along a stream reach could not be equated to ground-water recharge because all inflow and outflow of the system could not be determined. The computed streamflow losses and ground-water recharge along the North Fork Dry Fork Cheyenne River ranged from 0.43 acre-feet per mile on July 9, 1982, to 1.44 acre-feet per mile on August 9, 1982. The computed streamflow loss may be significantly underestimated because of unmeasured inflow and outflow along the reach. An estimate for recharge of 26.5 acre-feet per mile on August 9, 1982, was made using a convolution method.

Ground-water recharge was estimated from water levels in one well at the Black Thunder Creek site. The estimates of recharge were calculated directly from changes in water levels using the convolution method. Computed recharge to the alluvial aquifer ranged from 3.56 to 12.4 acre-feet per mile.

Future studies of ground-water recharge can be conducted using the convolution method. All of the data needed to estimate ground-water recharge at a specific point can be obtained from two carefully located observation wells. Water levels can be measured continuously with a water-level recorder on one well. The needed aquifer properties can be obtained using an established method or by conducting an aquifer test.

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