HYDROLOGIC CONDITIONS IN THE WHEATLAND FLATS AREA,

PLATTE COUNTY, WYOMING

by Marvin A. Crist

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

For those readers interested in using the International System of Units (SI), the following table may be used to convert the inch-pound units of measurement used in this report to metric units:

Multiply	By	To obtain
acre	4.047×10^{3}	square meter
acre-foot (acre-ft)	1.233×10^{3}	cubic meter
cubic foot per day per foot [$(ft^3/d)/ft$]	9.290×10^{-2}	cubic meter per day per meter
cubic foot per day per square foot [$(ft^3/d)/ft^2$]	3.048×10^{-1}	cubic meter per day per square meter
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
foot (ft)	3.048×10^{-1}	meter
gallon per day per per foot [(gal/d)/ft]	1.437×10^{-7}	cubic meter per second per meter
gallon per day per square foot [$(gal/d)/ft^2$]	4.130×10^{-6}	cubic meter per second per square meter
inch (in.)	2.540×10^{1}	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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

HYDROLOGIC CONDITIONS IN THE WHEATLAND FLATS AREA, PLATTE COUNTY, WYOMING

By Marvin A. Crist

ABSTRACT

The area described in this report includes about 260 square miles in central Platte County that consists of Wheatland Flats and a border region, ranging in width from about 2 to about 5 miles beyond the flats. Principal interest of this investigation is Wheatland Flats, an area of about 100 square miles, bounded by Chugwater Creek on the east, the Laramie River on the north, and Sybille Creek on the west. The southern boundary is approximately the southernmost limit of the terrace deposits.

A combination of surface water diverted from the Laramie River and ground water from two aquifers is used to irrigate 55,284 acres of land within the Wheatland Irrigation District, most of which is on Wheatland Flats. In addition, approximately 2,000 acres on and adjacent to the flats are irrigated by ground water. More than 200 wells are used for irrigation, industry, and municipal supplies. Irrigation wells are completed in an upper aquifer consisting of shallow alluvial deposits of Quaternary age and the upper part of the Arikaree Formation of early Miocene age where the Arikaree is exposed; and a lower aquifer that consists of the saturated Arikaree Formation below a depth of 100 feet.

Net water-level decline in each of the two aquifers after approximately 20 years (1958-60 to 1979) generally is less than 10 feet. Water-level declines of as much as 13 feet in the lower aquifer and as much as 8 feet in the upper aquifer have been noted at specific locations.

Almost all the recharge is from precipitation and seepage from surface-water irrigation. Recharge to Wheatland Flats by underflow and from streams is considered to be negligible. Annual recharge to the flats estimated for 1971-80 ranges from 15,700 to 36,600 acre-feet per year.

Pumpage by irrigation and municipal wells and natural drainage to streams are the principal means by which ground water is discharged. Annual pumpage was estimated to range from 4,410 to 15,150 acre-feet per year for 1971-80. Seepage measurements on Sybille Creek, the Laramie River, and Chugwater Creek, January 5, 1981, showed there was a gain of 37.9 cubic feet per second in stream discharge. This gain represents ground-water discharge.

A digital model was used to simulate hydrologic conditions in the Wheatland Flats area. Accuracy of the model was tested by a transient simulation of hydrologic conditions during 1971-78. Hydraulic-head distribution calculated at the end of the simulation was compared with the hydraulic-head distribution interpreted from water-level measurements made prior to start of irrigation in 1979. The root-mean-square deviation between the calculated and interpreted hydraulic head was 4.2 feet with a maximum difference of 22.0 feet for the upper aquifer and a root-mean-square deviation of 6.3 feet with a maximum difference of 43.4 feet for the lower aquifer. The model indicated that ground-water discharge to the streams decreased by 10 percent during this period. Although stream-discharge measurements are not available to verify the loss, it is reasonable to assume, on the basis of hydraulic-head decline in the aquifers, that there has been some loss of ground-water contribution to the streams. Continuous stream-discharge gages would have to be installed on the streams to verify streamflow change.

INTRODUCTION

The area described in this report includes about 260 mi^2 in central Platte County (fig. 1) that consists of Wheatland Flats and a border region ranging in width from about 2 to about 5 mi along the west, north, and east sides of the flats. Principal interest of this investigation is Wheatland Flats, an area of about 100 mi^2 bounded on the east by Chugwater Creek, on the north by the Laramie River, and on the west by Sybille Creek. The southern boundary is approximately the southernmost limit of the terrace deposits (Weeks, 1964, p. 3).

A combination of surface water diverted from the Laramie River and ground water is used to irrigate 55,284 acres of land within the Wheatland Irrigation District, most of which is on Wheatland Flats. In addition, approximately 2,000 acres, on and adjacent to the flats, are irrigated by ground water. Adequate supplies of surface water for irrigation are available only during years when stream runoff is greater than normal. Additional water is provided by wells drilled into shallow alluvial deposits of Quaternary age and a deeper underlying aquifer, the Arikaree Formation of early Miocene age.

In this report, the following terminology is used. The upper aquifer consists of saturated terrace deposits and the upper part of the Arikaree where the Arikaree is exposed in Wheatland Flats. The alluvium along Rock Creek-Wheatland Creek, Sybille Creek, Laramie River, and Chugwater Creek is also considered to be part of the upper aquifer. All wells 100 ft deep or less are considered to be completed in the upper aquifer. The lower aquifer consists of the saturated Arikaree Formation below a depth of 100 ft, and all wells deeper than 100 ft are considered to be completed in the lower aquifer.

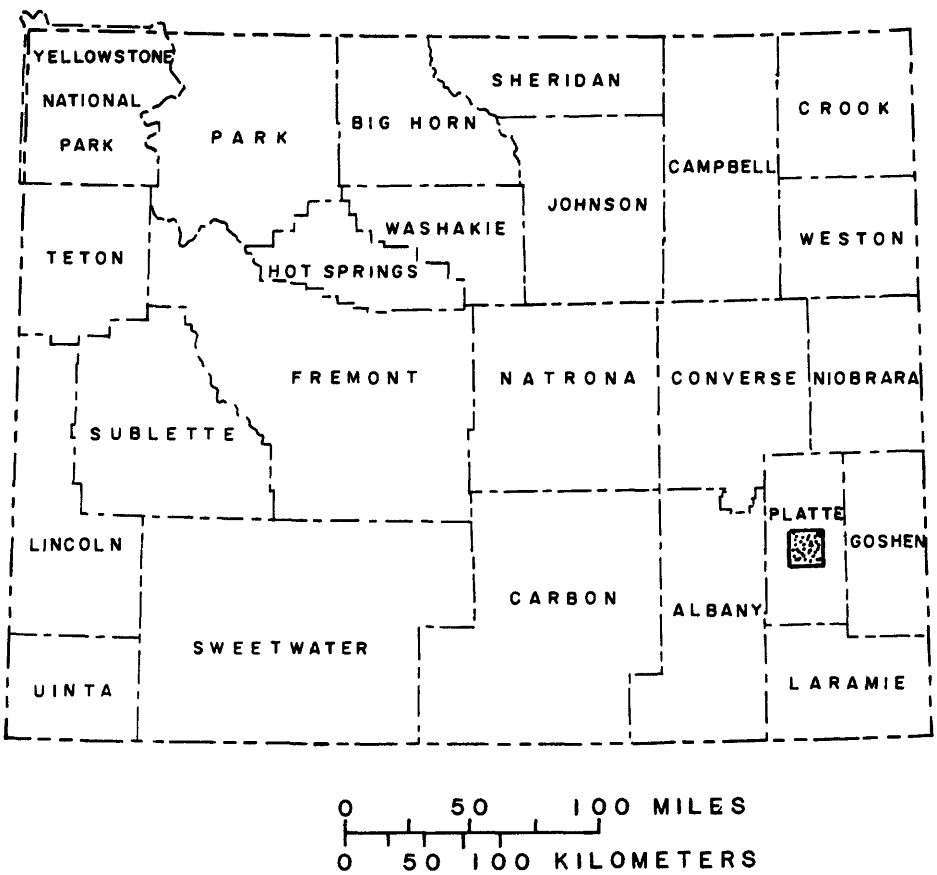


Figure 1.--Location of the study area (shaded).

The number of irrigation wells pumping in the area has increased from approximately 85 in 1960 to about 205 in 1980 (fig. 2). Yield from some of the irrigation wells completed in the upper aquifer has decreased, so most of the recent wells are drilled to the lower aquifer. The increased number of irrigation wells has resulted in substantially more pumpage of ground water especially from the lower aquifer. Thus from 1958-60 to 1980, water-level declines have occurred in both aquifers.

The water-level decline in the upper aquifer may be attributed to other factors besides increased pumpage. Lining of irrigation canals and laterals plus more efficient irrigation practices may have decreased the quantity of recharge from imported surface water. Another factor that could decrease the quantity of water in the upper aquifer on Wheatland Flats is the method of well completion in the deeper aquifer. The general practice is to drill a large hole, about 24-30 in. in diameter, to a total depth of 400-600 ft. Casing is set through the upper aquifer into the lower aquifer and the annular space between the hole and the casing is backfilled with gravel. This allows water from the upper aquifer to readily flow down to the deeper aquifer.

State water administrators need more information about the present ground-water development and its effect upon water levels and streamflow. At present (1982), the water administrators have no way of estimating or predicting the result of any management decisions to regulate future development. A digital model of the hydrologic system in the Wheatland Flats area would help test the present (1982) concepts of the hydrologic flow system.

Purpose and Scope

The purpose of this investigation was to: (1) Determine the extent of present ground-water development for irrigation, industrial, and municipal use and describe the effect of this development on water levels in the separate aquifers; and (2) determine the net result of imported surface water and pumpage on water levels and stream discharge in the area. A digital model was developed to simulate three-dimensional flow in the hydrologic system. The model was used to examine the present (1982) concepts of the stream-aquifer relationship.

Methods of Investigation

The water level in both aquifers was mapped from water-level measurements made during the spring of 1979. Previous water-level maps were published by Weeks (1964) and Morris and Babcock (1960). A map of the geology was prepared that is a compilation of the geologic maps available for the area. Geologic sections are given for the major stream valleys at six locations using information from test holes augered through the alluvium.

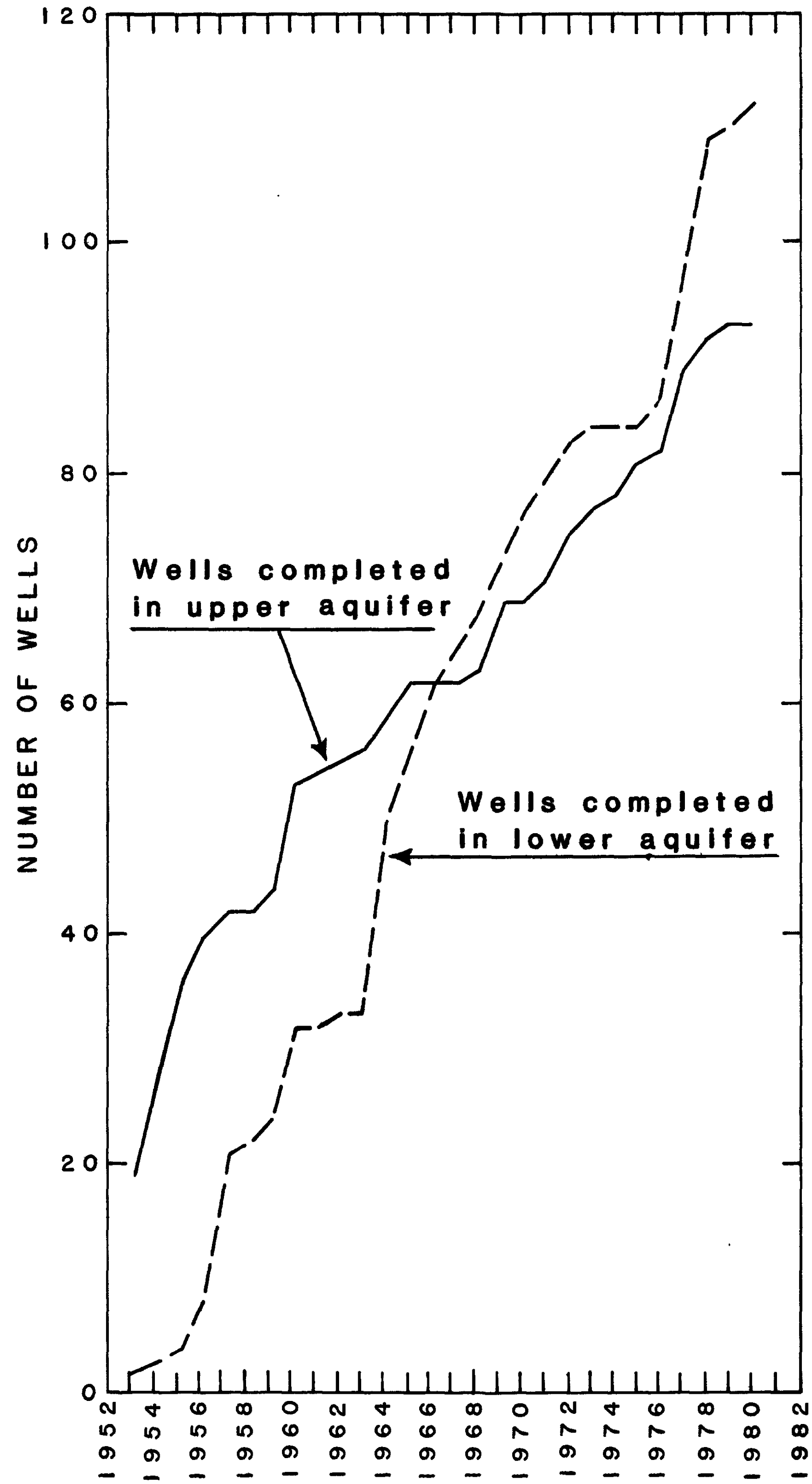


Figure 2.--Estimated cumulative annual well completions for irrigation, industrial, and municipal use.

A network of observation wells was established, and the water level was measured monthly in these wells. Several observation wells that had been used in previous studies were incorporated in the network. Digital water-level recorders were installed in two observation wells drilled in 1979. A third digital water-level recorder was installed in an existing well completed in the alluvium along Chugwater Creek. In 1980, the Wyoming State Engineer's office drilled two additional observation wells and installed digital water-level recorders to monitor water-level fluctuations in the lower aquifer.

The inventory of irrigation, industrial, and municipal wells was updated in 1980 from data published by Weeks (1964). Estimates of pumpage from these wells are based on electric-power records. Seepage measurements were made on the streams to estimate the stream-aquifer relationship. The streams were measured in March 1980 and January 1981 to estimate ground-water discharge.

Acknowledgments

The author thanks the many residents in the area who permitted U.S. Geological Survey personnel to measure water levels in wells and especially thanks those landowners who permitted observation wells to be drilled on their property. Wheatland Irrigation District provided data on the volume of surface water imported, and the Wheatland Rural Electric Association office provided power records of irrigation wells.

Previous Investigations

Weeks (1964) compiled detailed quantitative hydrologic data for Wheatland Flats. These data are used extensively in this report. Other ground-water resources studies have been made by Edwards (1941), Littleton (1950), and Morris and Babcock (1960).

Digital models have been developed for the Arikaree Formation in two adjacent areas; the Muleshoe Flat area (Hoxie, 1983) on the west and the Dwyer area (Lines, 1976; Hoxie, 1977) on the north. Using the model, Hoxie (1979a, 1979b) predicted results of water use in the Dwyer area.

Well-Numbering System

Wells cited in this report are numbered by a method based on the U.S. Bureau of Land Management system of land subdivision in Wyoming (fig. 3). The first number indicates the township, the second the range, and the third the section in which the well is located. Lowercase letters following the section number indicate the position of 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 (10-acre tract). The subdivisions of a section are lettered a, b, c, and d in a counterclockwise direction, starting in the northeast quarter. If more than one well is listed in a 10-acre tract, consecutive numbers starting with 1 follow the lowercase letters of the well number. If a section does not measure 1 mi square, it is treated as a full section with the southeast section corner serving as the reference point for the subdivision of the section.

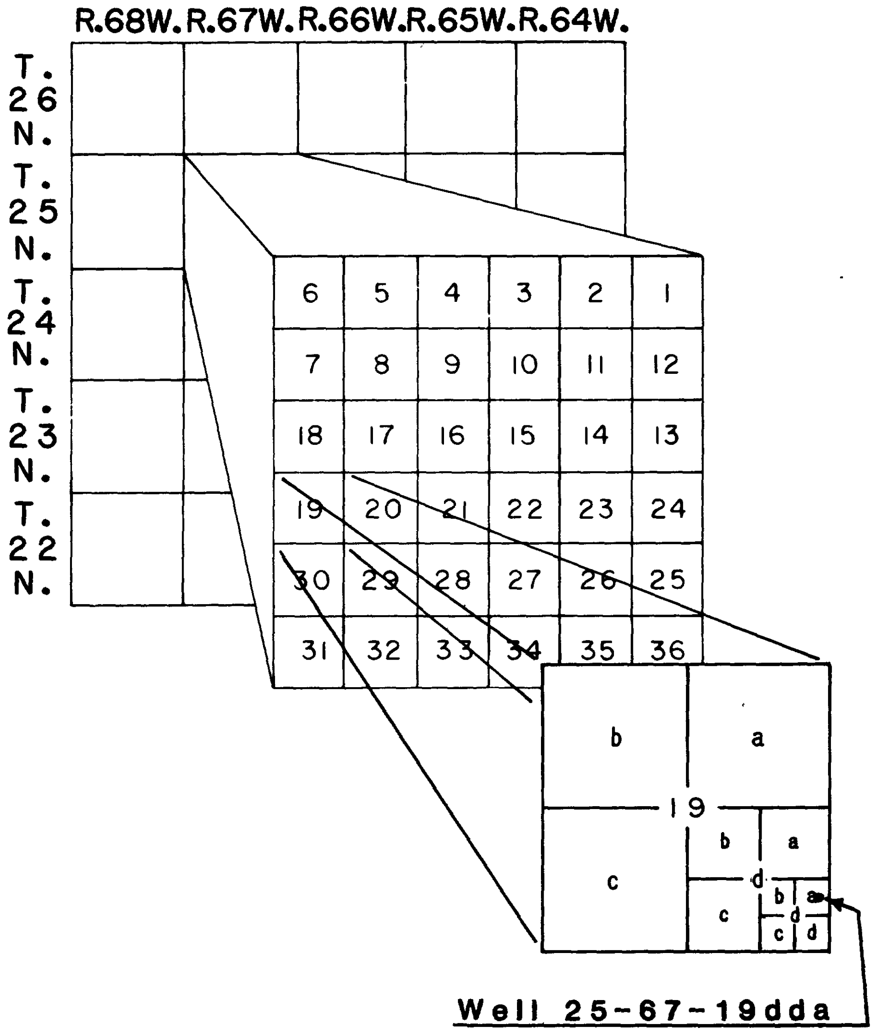


Figure 3.--Well-numbering system.

HYDROLOGIC SYSTEM

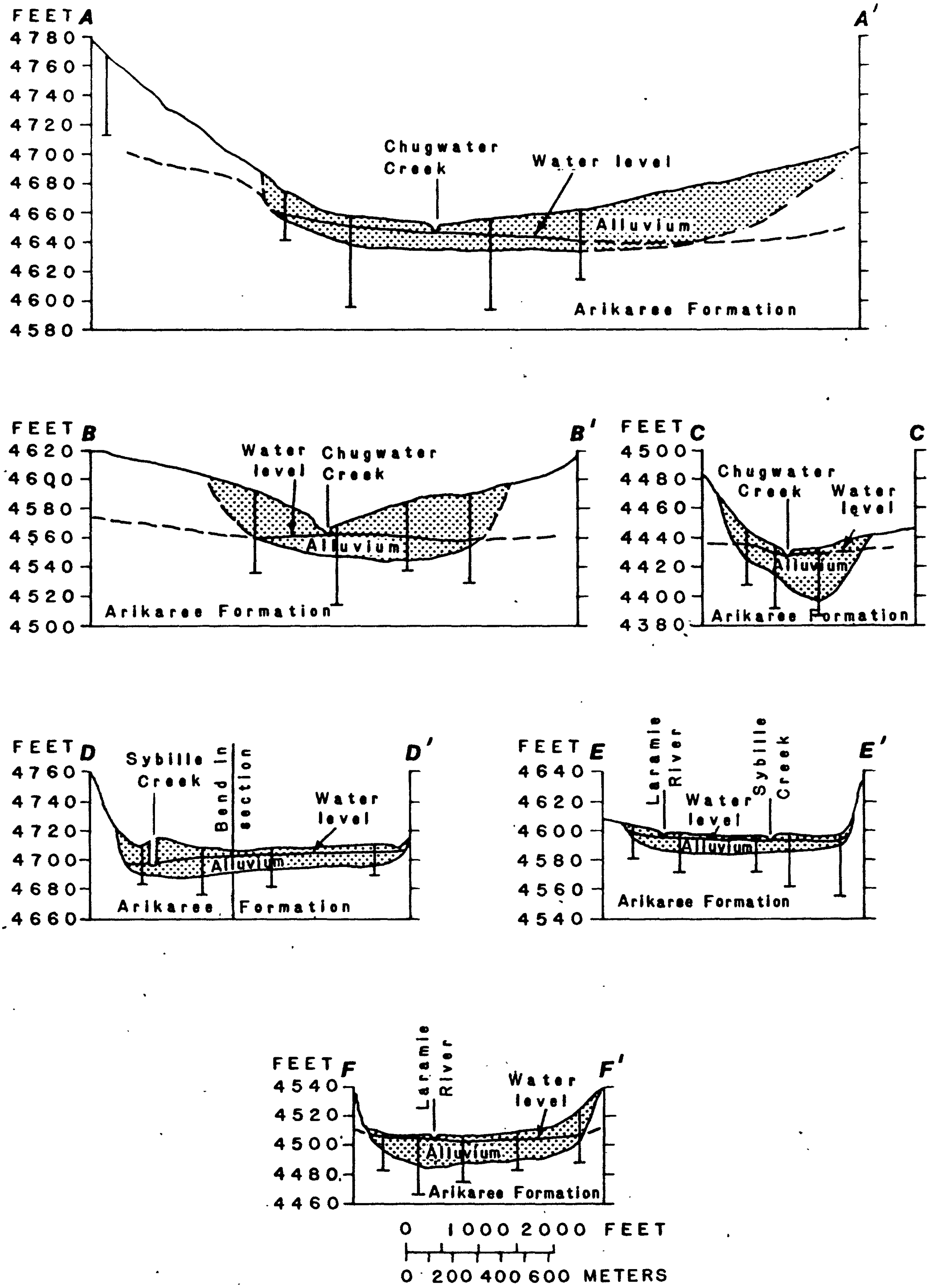
The principal water-bearing formations are the Arikaree Formation and the overlying alluvial deposits which consist of alluvium and terrace deposits (pl. 1). Alluvium in the valleys along the three major streams is partly saturated (fig. 4) and is in hydraulic connection with the Arikaree Formation. The terrace deposits are very permeable and water that is applied to the land infiltrates readily so surface water used for irrigation provides most of the recharge to ground water.

For purposes of this report the hydrologic system has been simplified, as discussed previously, by dividing the system into an upper aquifer and a lower aquifer that are hydraulically connected. Only water levels measured in wells drilled deeper than 100 ft are used to represent the potentiometric surface (a surface which represents the hydraulic head in the aquifer) in the lower aquifer. Most of these wells are constructed so that water from the entire saturated interval can enter the well bore. Therefore, the water levels measured in the deeper wells are probably a composite hydraulic-head of the saturated interval penetrated by the well. A considerable hydraulic-head decline with depth (on the order of tens of feet), associated with the downward movement of water, exists in the area. The potentiometric surface has been interpreted from water-level measurements made in wells drilled (fig. 5) into the lower aquifer. Generally, except in the major stream valleys, the altitude of the hydraulic head in the lower aquifer is below the altitude of the water level in the upper aquifer.

Underflow (in this report underflow refers to ground water that moves through the subsurface) to and from Wheatland Flats is limited by deeply entrenched streams on three sides and by a relatively impermeable zone in the Arikaree Formation on the south (Weeks, 1964, p. 17). Some of the water in the upper aquifer (terrace deposits) moves downward into the less permeable lower aquifer and from there to the major streams, which are at a much lower altitude than the terrace deposits in Wheatland Flats. Some water in the terrace deposits does not reach the lower aquifer and is discharged to streams, seeps, and constructed drains (Weeks, 1964, p. 31).

Arikaree Formation

The Arikaree Formation has been described (Morris and Babcock, 1960, p. 33) as consisting primarily of loosely to moderately cemented very fine to fine white to gray sand and silt. Because of different lithology in the upper and lower part of the formation, Morris and Babcock (1960, p. 34) considered the Arikaree as composed of two units. The lower unit consists of loosely to well-cemented coarse to very coarse sandstone interbedded with lenses of well-cemented conglomerate and the upper unit is principally very fine-grained moderately hard, generally massive, sandstone and silt.



VERTICAL EXAGGERATION X 20

NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 4.--Geologic sections of stream valleys interpreted from augered test holes.

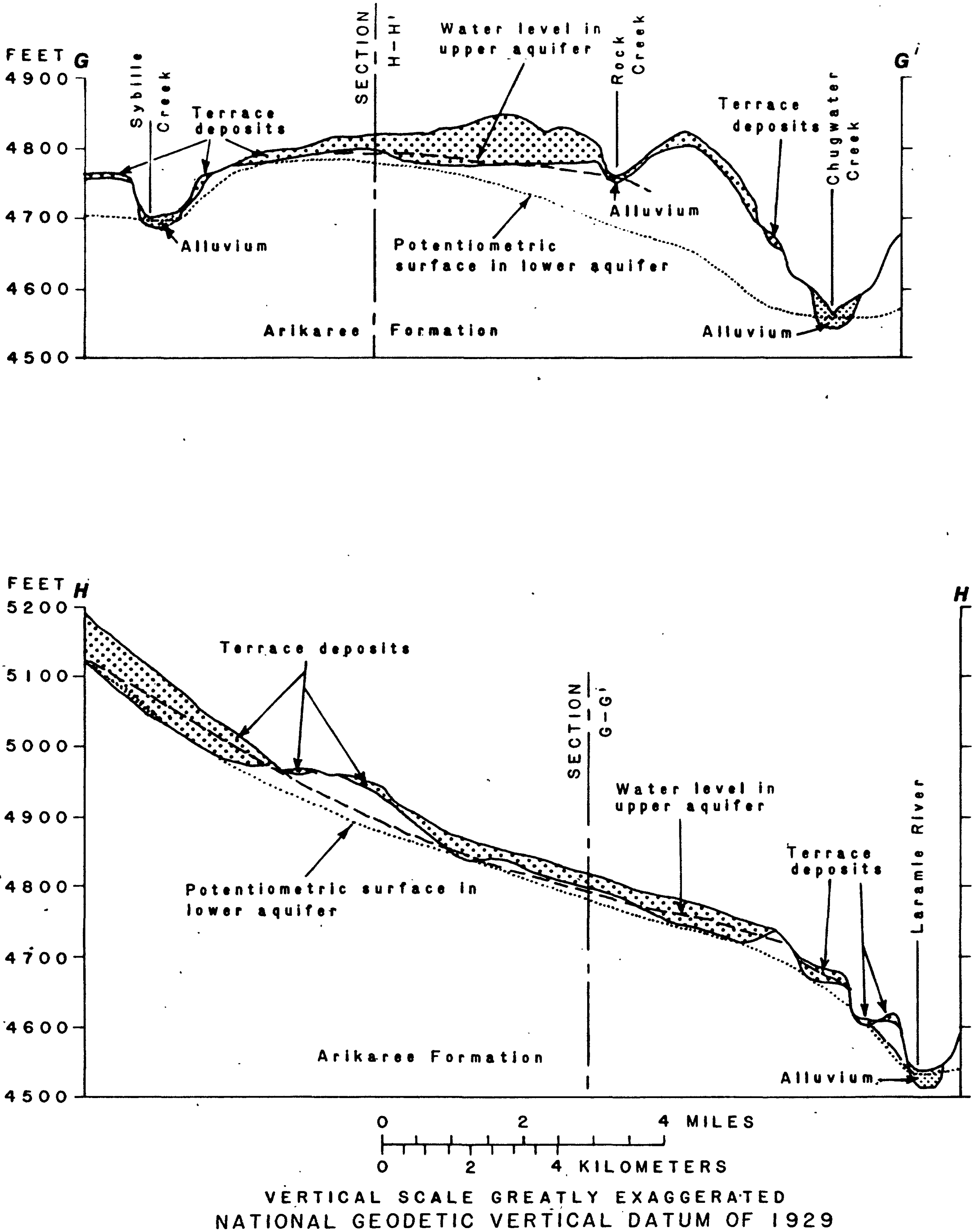


Figure 5.--Relationship of the geologic formations, the water level in the upper aquifer, and the potentiometric surface interpreted from water-level measurements in wells drilled into the lower aquifer.

Weeks (1964, p. 9) described the uppermost part of the upper sandy unit as being very poorly cemented and locally referred to as quicksand. There is not a well-defined boundary between the two units; most of the irrigation wells drilled to the lower aquifer produce water from the entire saturated interval penetrated. The Arikaree Formation thickness ranges from 0 to about 1,100 ft, (Weeks, 1964, p. 11).

Several faults of the Wheatland and Whalen fault systems exist in the Arikaree Formation within the study area. However, there has been insufficient drilling and testing in these fault areas to determine the hydrologic significance of the fault systems.

Hydraulic Characteristics

Weeks (1964, p. 37-46) described several methods used to determine the transmissivity of the Arikaree Formation. Transmissivity is defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman, 1979, p. 6). Transmissivity replaces the term "coefficient of transmissibility" used in Weeks' report. From nine aquifer tests made by Weeks, the transmissivity ranged from about 350 to about 1,340 $(ft^3/d)/ft$ and averaged about 760 $(ft^3/d)/ft$ [published as coefficients of transmissibility ranging from 2,600 to about 10,000 (gal/d)/ft and averaging about 5,700 (gal/d)/ft]. Larger values were determined from two aquifer tests but were not considered to be typical for the Arikaree Formation. Weeks used two ideal geometric figures to estimate transmissivities of about 1,470 and 1,340 $(ft^3/d)/ft$ [published as coefficients of transmissibility of 11,000 and 10,000 (gal/d)/ft] which are probably representative for the entire aquifer.

Weeks (1964, p. 40 and 48) reported that the vertical hydraulic conductivity of the Arikaree ranged from about 8×10^{-3} to about 9×10^{-2} $(ft^3/d)/ft^2$ published as vertical coefficient of permeability ranging from 0.06 to about 0.7 $(gal/d)/ft^2$ The term "coefficient of permeability" has been replaced by "hydraulic conductivity", which is a measure of the ability of a porous medium to transmit a volume of water through a cross section of unit area of aquifer in a specified time. The hydraulic conductivity is dependent on the nature of the pore spaces and their interconnection. The vertical hydraulic conductivity controls the quantity of water that moves down through the formation.

Horizontal hydraulic conductivity in a formation usually is much greater than vertical hydraulic conductivity because of the manner in which the sediments were deposited. The average horizontal hydraulic conductivity can be determined by dividing transmissivity by saturated thickness.

Specific yield (the volume percentage of water that will drain by gravity from saturated sediments) was determined by Weeks (1964, p. 25) to be 12 percent. Weeks used 12 percent to represent an average for all the different materials in the terrace deposits and the Arikaree Formation. Accuracy of the specific yield is estimated to be about ±5 percent; specific yields ranging from 7 to 17 percent would be reasonable for the deposits underlying Wheatland Flats.

Potentiometric Surface

The potentiometric-surface contours on plate 2 represents the position of the hydraulic head of water moving through the lower aquifer in April 1979. Generally, the direction of ground-water movement is perpendicular to the contours. A major part of the water that leaves the lower aquifer is discharged to the three principal streams through the flood-plain alluvium. Weeks (1964, p. 17) stated that water in the Arikaree (lower aquifer) is under artesian pressure in the areas underlying the major stream valleys. This concept is supported in this study. Seepage measurements showed the streams to be gaining, and a piezometer tube installed through Chugwater Creek streambed showed that the water level in the piezometer fluctuated but was consistantly about 1 ft above the water level in the stream.

The potentiometric surface prepared by Weeks (1964, pl. 5) and the potentiometric surface on plate 2 do not correspond everywhere, because identical control points were not used to construct the two maps. Comparison of the water levels measured during Weeks' study and in 1979 can be made from the water-level measurements in the same wells during each investigation. Water levels measured in wells in 1958-60 and again in 1979 (table 1) indicate the net changes that have occurred in the lower aquifer in Wheatland Flats between the two periods. The measurements indicate a decline has occurred at the majority of locations.

Most of the wells listed in table 1 are open to the entire saturated interval penetrated by the well. The observation wells that are referred to in figures 6 and 7 are sealed off from the upper aquifer; therefore, the water levels in these wells are representative of the hydraulic-head changes that have occurred only in the lower aquifer. Water levels in the other wells in table 1 probably represent changes in the composite hydraulic head of the saturated interval in the well.

Long-term hydrographs (figs. 6 and 7) show a general decline in water levels from 1958 to about 1966. From about 1968 through about 1974 water levels generally rose to near the 1958 level. The upward trend changed to a downward trend from about 1975 to about 1978. Since 1978, the water level in well 24-68-3dad in the northern part of Wheatland Flats has risen to about the 1958 level. Water levels in wells 24-68-33abb and 23-68-15ddd have had minor seasonal fluctuations since 1978. The water level in well 23-68-18dad has had only a general decline from 1958 to about 1966; thereafter, only minor water-level fluctuations have been observed at this location. The large fluctuations, shown by the hydrographs at the other three locations, appear to be dampened out at well 23-68-18dad. The probable reason is that little pumpage occurs near this well and the seasonal effects of pumpage are of much less magnitude.

Comparison of the long-term hydrographs with the annual precipitation (U.S. Department of Commerce, 1958-81, for example see U.S. Department of Commerce, 1980) and annual diversions for irrigation (Wheatland Irrigation District, written commun., 1981), (fig. 8) does not show conclusive correlation of the water-level trends with either the annual surface-water diversions or the annual precipitation.

Table 1.--Water-levels in wells completed in the lower aquifer.
[Measurements made in 1958-60 and in 1979]

Well	Depth to water below land surface (feet)	Date
23-68-4abc	67	June 30, 1960
	69.18	April 23, 1979
23-68-10cdd	13.34	June 26, 1958
	14.05	April 24, 1979
23-68-15ddd	57.73	Dec. 11, 1958
	70.71	April 24, 1979 (see fig. 6)
23-68-18dad	52.34	Dec. 11, 1958
	63.00	April 24, 1979 (see fig. 6)
24-67-7add	114.58	June 24, 1958
	114.03	May 24, 1979
24-68-3dad	12.84	Oct. 15, 1958
	15.36	April 19, 1979 (see fig. 7)
24-68-6adc	17.22	May 14, 1958
	13.00	April 19, 1979
24-68-9ccc4	51.17	Feb. 6, 1959
	44.40	April 19, 1979
24-68-27bdd	70.00	Jan. 11, 1960
	83.45	April 23, 1979
24-68-33abb	72.24	Sept. 24, 1958
	76.78	April 23, 1979 (see fig. 7)
25-67-31cdc2	37.00	Feb. 6, 1959
	44.07	May 24, 1979
25-67-33cdd1	84.92	June 18, 1958
	86.70	April 16, 1979
25-68-31cbd	32.22	May 20, 1958
	34.02	April 16, 1979

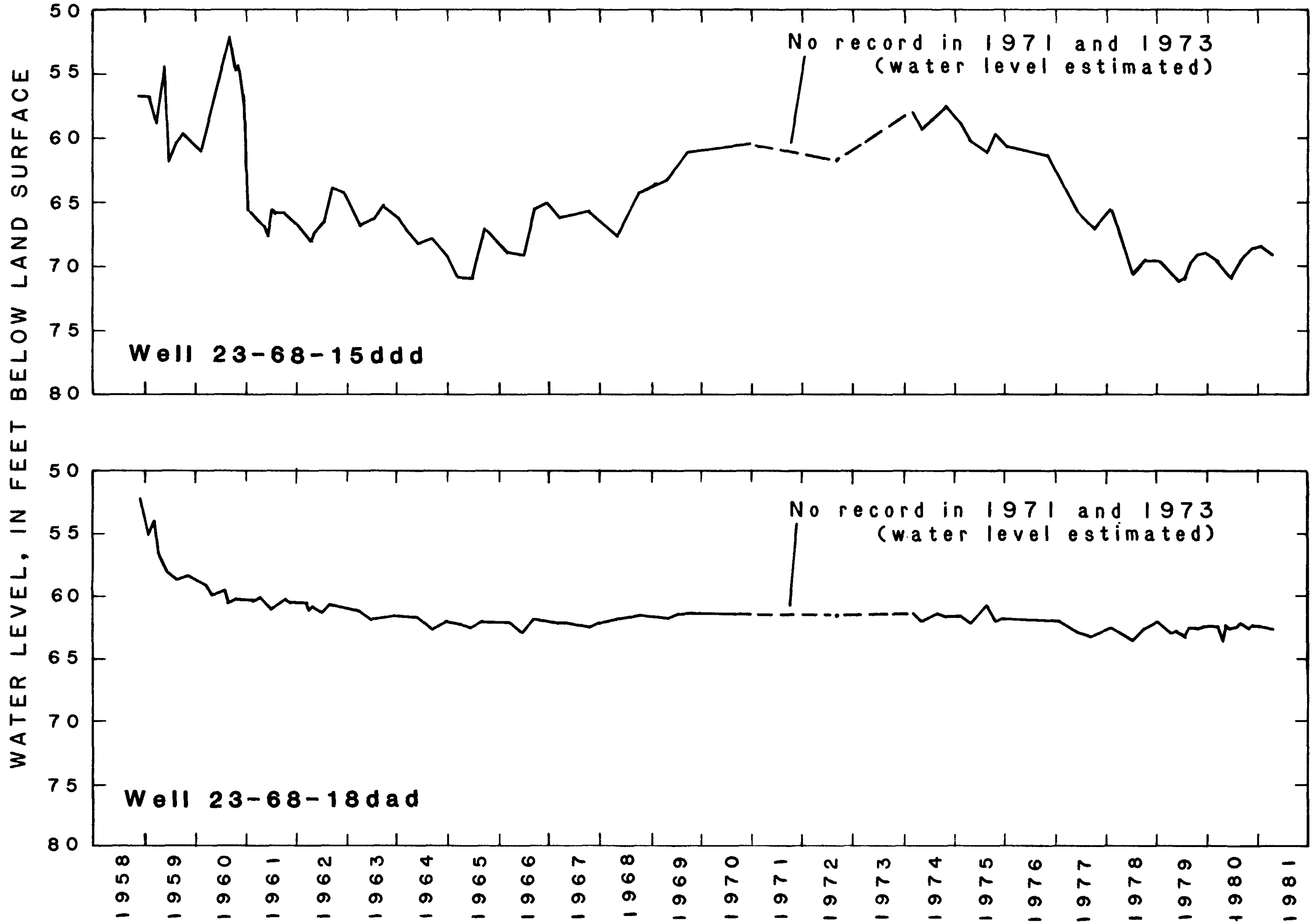


Figure 6.--Water-level fluctuations in two wells completed in the lower aquifer in the southern part of Wheatland Flats.

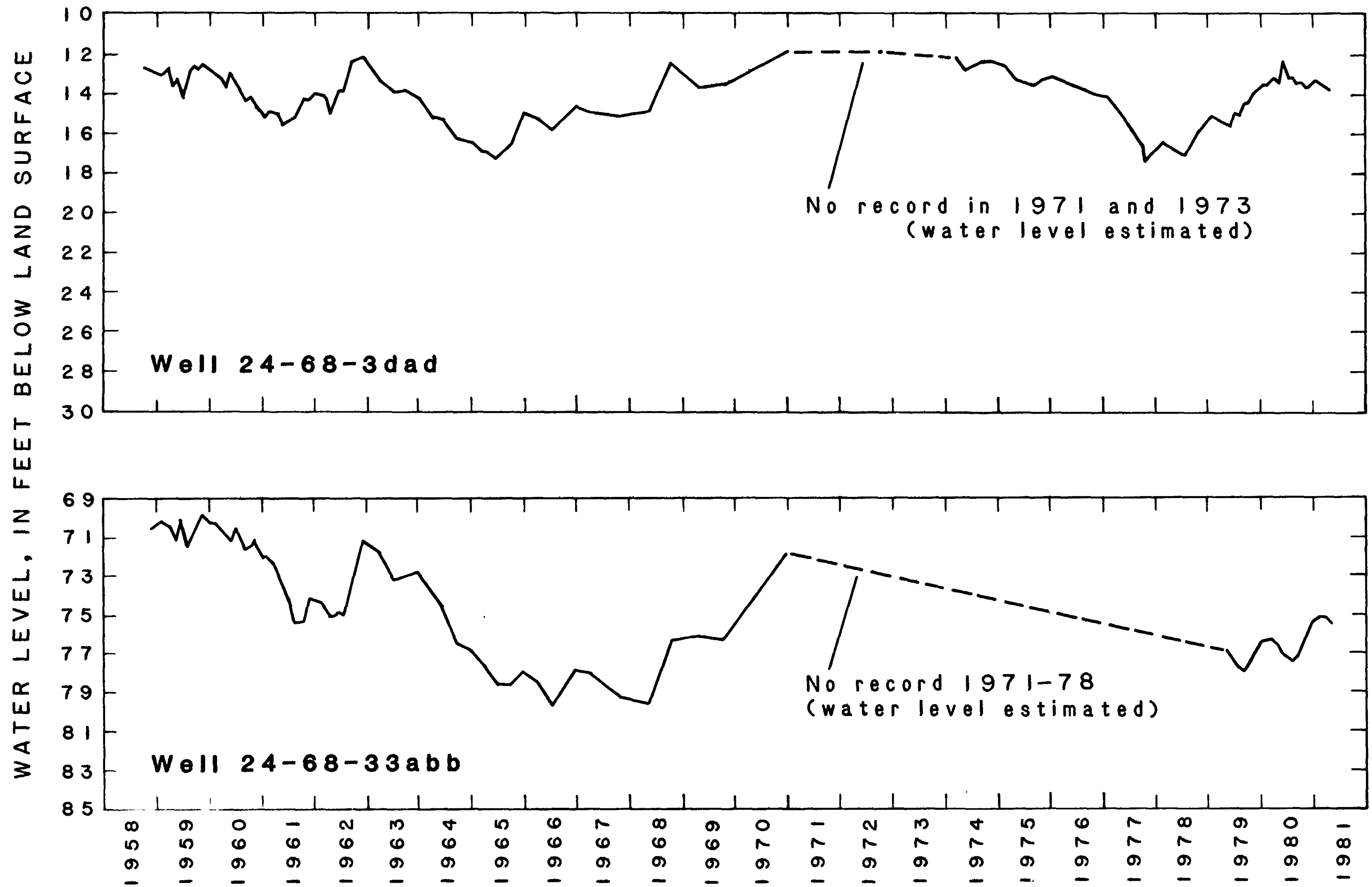


Figure 7.--Water-level fluctuations in two wells completed in the lower aquifer in the northern and central parts of Wheatland Flats.

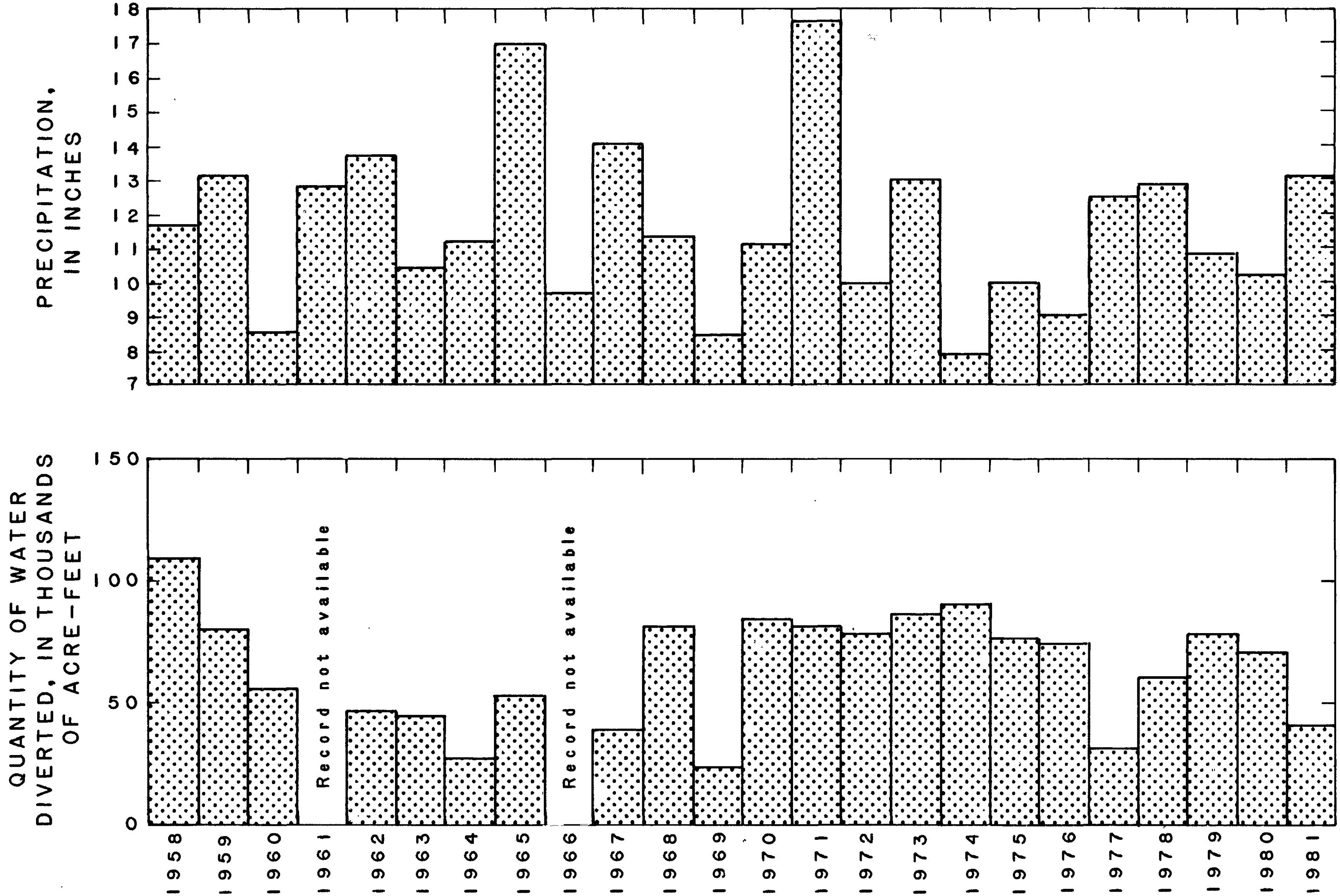


Figure 8.--Estimated annual precipitation in the Wheatland Flats area and annual surface-water diversions to the Wheatland Irrigation District.

Alluvial Deposits

Aquifers of Quaternary age in the Wheatland Flats area include terrace deposits and alluvium. Morris and Babcock (1960, p. 39) mapped seven terraces that range in thickness from 5 to 85 ft. The terrace deposits consist of subangular to rounded unsorted unconsolidated sand, gravel, cobbles, and boulders, interbedded with lenses of clay and silt (Weeks, 1964, p. 12). An observation well (24-68-22aaa) drilled by the Wyoming State Engineer's office penetrated terrace deposits as much as 90 ft thick.

Test holes augered in the three major stream valleys show that the alluvium consists of lenses of silt, sand, and gravel, and total thickness ranges from 0 to about 40 ft (fig. 4). The thickest saturated alluvium (see fig. 4 and pl. 1) is in the lower reach of Chugwater Creek valley, although no irrigation wells exist in this area. Nearly all the irrigation wells in the stream valleys are completed through the alluvium into the Arikaree Formation and withdraw water from both formations. All the irrigation wells in Chugwater Creek valley are assumed to pump water from only the Arikaree Formation because of the relatively thin saturated alluvium. Hydraulic interconnection is assumed to exist between the alluvium and the Arikaree.

Hydraulic Characteristics

Morris and Babcock (1960, p. 54) determined that transmissivity of the terrace deposits ranged from about 8,960 to about 16,040 $(ft^3/d)/ft$ published as the coefficient of transmissibility ranging from 67,000 to 120,000 (gal/d)/ft. Weeks (1964, p. 61) determined from aquifer tests that the hydraulic conductivity ranged from about 67 to about 535 $(ft^3/d)/ft^2$ published as the coefficient of permeability ranging from 500 to 4,000 $(gal/d)/ft^2$. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness. Hydraulic characteristics of the alluvium are assumed to be similar to those in the terrace deposits because of similar lithology. Water in the terrace deposits and in the alluvium is considered to be under water-table conditions because the water level in a well generally does not rise above the level at which it was encountered while drilling the well.

Water-Level Surface

The configuration of the water-level surface (referred to as the water table by Weeks, 1964) in the upper aquifer (pl. 3) is similar in shape to the potentiometric surface (pl. 2) within Wheatland Flats. Saturation is continuous between the upper and the lower aquifers in much of the area (Weeks, 1964, p. 14). The contours (pl. 3) represent the water-level surface April 1979 in the upper aquifer, which includes the terrace deposits, the upper part of the Arikaree Formation, and the alluvium in Sybille Creek and Laramie River valleys.

Water-level fluctuation in the upper aquifer is related to the irrigation season: rising during the growing season and declining after surface-water application stops.

Water-levels measured in the upper aquifer in 1958-60 and again in 1979 in the same wells (table 2) indicate that the water level has declined in all the wells. The decline could be caused by pumpage, decreased recharge from surface-water irrigation resulting from more efficient irrigation practices, and by wells drilled to deeper zones that are left open to the shallow aquifer, allowing more water to move to the deeper Arikaree Formation. Fluctuation of the water level is the resultant effect of all these stresses that probably occur simultaneously. The reader needs to be aware that the water levels listed in table 2 may indicate only the difference in the water levels between the dates specified. The trend of water-level changes in the upper aquifer is better shown by plotting the water levels for several years (fig. 9).

Recharge

Almost all recharge to the ground-water reservoir in Wheatland Flats is from precipitation and from seepage of imported surface water used for irrigation (Weeks, 1964, p. 26). It is assumed that all pumpage is consumed and none is available to return to the aquifer as recharge. Recharge to the flats by underflow and from streams is considered to be negligible.

Weeks (1964, p. 28) did not estimate recharge to each aquifer but estimated total recharge to be about 55,000 acre-ft during 1959 and about 25,000 acre-ft during 1960. Annual recharge to the flats from precipitation and surface-water irrigation was estimated for 1971-80 (table 3). Precipitation data were obtained from the U.S. Department of Commerce, and data on surface-water irrigation deliveries (1971-80) were provided by the Wheatland Irrigation District (written commun., 1981).

Discharge

Pumpage by irrigation and municipal wells and underflow to streams are the principal means by which ground water is discharged. Annual pumpage for irrigation, industrial, and municipal use in the Wheatland Flats area south of the Laramie River was estimated for 1971-80 (table 4). Power use, together with drawdown and yield data obtained during aquifer tests run by the Agricultural Extension Service, University of Wyoming (written commun., 1979) and the Wyoming Department of Economic Planning and Development (written commun., 1980), provided the basis for estimates of irrigation pumpage. It was estimated that total pumpage increased more than three times from 1971 to 1977. Pumpage decreased each year from 1978 through 1980. These trends in pumpage probably are related to the quantity and time of precipitation and the availability of surface water for irrigation, because the acreage irrigated remained constant.

Table 2.--Water-levels in wells open to the upper aquifer
[Measurements made in 1958-60 and in 1979]

Well	Depth to water below land surface (feet)	Date
23-68-10cdd	12.18	Feb. 6, 1959
	14.05	April 24, 1979
23-68-18acc	8.90	Dec. 8, 1959
	10.45	April 24, 1979
23-68-22bcc	7.0	1959
	7.84	April 24, 1979
24-68-3bcb	12.27	May 22, 1959
	17.18	April 19, 1979
24-68-5add	12.77	May 20, 1958
	15.24	April 19, 1979
24-68-9ccc2	17.67	May 20, 1958
	22.91	April 19, 1979
24-68-10dcc1	16.30	June 15, 1960
	17.31	April 19, 1979
24-68-16cdd	18.33	May 22, 1959
	26.65	April 20, 1979
24-68-20ccd	11.34	Feb. 6, 1959
	18.75	April 20, 1979
25-67-31cdc1	12.12	June 16, 1960
	22.10	April 16, 1979
25-68-36ccc2	4.56	June 7, 1958
	7.59	April 16, 1979

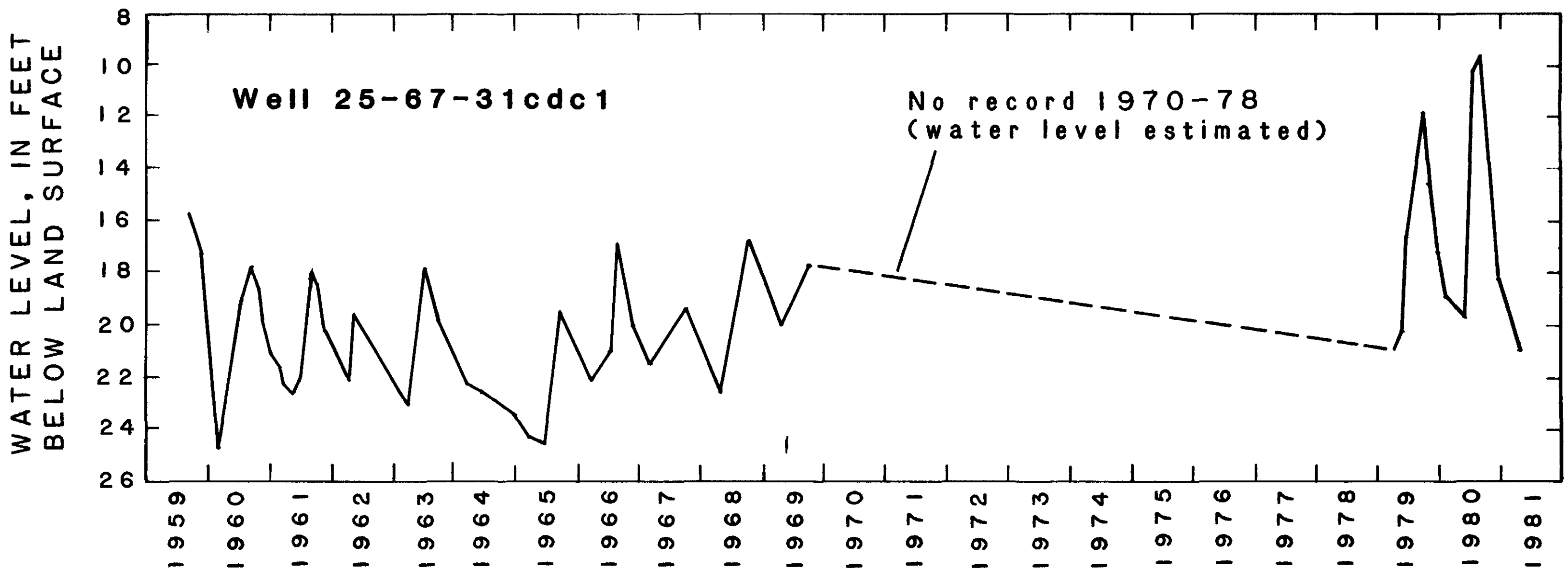


Figure 9.--Water-level fluctuation in a well completed in the upper aquifer in the northern part of Wheatland Flats.

Table 3.--Estimated annual recharge 1971-80 to Wheatland Flats from surface-water irrigation and precipitation

Year	Recharge from surface-water irrigation (37.5 percent of application) [1] (acre-feet)	Annual precipitation Wheatland 4N [2] (inches)	Recharge from precipitation (6.5 percent of annual) [3] (acre-feet)	Total (acre-feet)
1971	30,400	17.74	6,200	36,600
1972	29,200	9.77	3,400	32,600
1973	31,100	13.00	4,500	35,600
1974	33,700	7.72	2,700	36,400
1975	28,300	9.89	3,400	31,700
1976	27,300	8.91	3,100	30,400
1977	11,400	12.37	4,300	15,700
1978	22,200	12.84	4,500	26,700
1979	29,000	10.75	3,700	32,700
1980	26,000	10.66	3,700	29,700

[1] From Weeks (1964, p. 60)

[2] From U.S. Department of Commerce 1958-81 (for example see U.S. Department of Commerce, 1980)

[3] From Lines (1976, p. 8)

Table 4.--Estimated annual pumpage 1971-80 for irrigation, industrial, and municipal use in Wheatland Flats area south of Laramie River

Year	Upper aquifer (acre-feet)	Lower aquifer (acre-feet)	Total (acre-feet)
1971	1,030	3,380	4,410
1972	2,170	5,050	7,220
1973	3,410	4,870	8,280
1974	3,890	6,190	10,080
1975	4,140	6,790	10,930
1976	3,400	6,700	10,100
1977	4,840	10,310	15,150
1978	4,450	9,320	13,770
1979	4,320	8,800	13,120
1980	3,970	7,880	11,850
Average	3,560	6,930	10,490

The gain in stream discharge was estimated from two seepage runs on Sybille Creek, Laramie River, and Chugwater Creek (table 5). North Laramie River discharge also was measured, so that this water could be accounted for in calculating the net gain in stream discharge. Evapotranspiration losses were considered minimal at the time of the seepage runs and were neglected. Surface-water gain in the three streams bordering Wheatland Flats was 81.8 ft^3/s on March 6, 1980 and 37.9 ft^3/s on January 5, 1981. Total flow leaving the area was about 72 ft^3/s more on March 6, 1980, than on January 5, 1981, reflecting increased flow entering in addition to ground-water seepage from Wheatland Flats area. A large amount of snow had accumulated on the ground during the winter of 1979-80 and much water had ponded in the area at the time of the 1980 seepage run. In contrast, there was little snowfall and no accumulation of snow during the winter of 1980-81. Because temperatures were mild during the latter winter, farmers were able to work in the fields throughout the winter months. This probably accounts for the difference in surface-water gain measured during the two seepage runs. The gain in the stream discharge of 37.9 ft^3/s more nearly represents ground-water discharge and is nearly the same value (41.9 ft^3/s) determined by Weeks (1964, p. 24) in February 1959. It is assumed that the differences in stream-discharge-measurement points between Weeks' study and this investigation is not a major factor in comparing the seepage runs in 1959 and 1981.

Recharge-Discharge Relationship

Recharge from precipitation and surface-water irrigation estimated for 1971-80 (table 3) ranged from 15,700 to 36,600 acre-ft per year. Pumpage estimated for the same period ranged from 4,410 to 15,150 acre-ft per year. Although annual ground-water discharge to the streams during this period cannot be estimated because of lack of stream-discharge measurements, seepage measurements (1959 and 1981) were used to estimate that ground-water discharge is about 38-42 ft^3/s. It is not possible to determine if ground-water discharge to the streams has changed since irrigation began in Wheatland Flats but on the basis of two series of stream-discharge measurements, it is estimated that ground-water discharge in January 1981 was nearly the same as it was in February 1959. With recharge (from precipitation and surface water) and discharge (by pumpage) varying from year to year, changes can be expected in ground-water storage and ground-water discharge to the streams. Changes in ground-water storage were estimated (table 6) by using the Theissen mean method (Theissen, 1911, p. 1082) as described by Weeks (1964, p. 22). Although different observation wells were used and the area expanded to the three streams, the method is valid to estimate changes of ground water in storage. Two years of record of water-level fluctuations without continuous stream-discharge records are not sufficient data to determine correlation of recharge, discharge, and change in ground-water storage.

Table 5.--Results of seepage measurements made on the major streams

Stream	Measurement location	Discharge (cubic feet per second) Inflow	Outflow	Gain in reach
		March 6, 1980		
Chugwater Creek	23-67-25bdd	37.9		
Sybille Creek	23-69-4bdb	13.2		
------Do------	25-69-26ddc		18.2	5.0
North Laramie River	25-67-20bbc	14.4	14.4	0.0
Laramie River	25-69-26dcc	24.7		
------Do------	25-66-19dd		[1] 172.0	[2] 76.8
Total		90.2		81.8
		January 5, 1981		
Chugwater Creek	23-67-5bdc	17.2		
------Do------	25-67-23ddb		44.9	27.7
Sybille Creek	23-69-4bdb	9.1		
------Do------	25-69-26ddc		17.0	7.9
North Laramie River	25-67-20bbc	14.1	14.1	0.0
Laramie River	25-69-26dcc	21.4		
------Do------	25-66-19dd		[1] 99.7	2.3
Total		61.8		37.9

1 Discharge from records of the Wyoming State Engineer.

2 Includes Chugwater Creek gain.

Table 6.--Recharge from precipitation and surface-water irrigation, discharge by pumpage, and change in ground-water storage estimated for April 1979 to March 1980 and April 1980 to March 1981

	Total volume (acre-feet) April 1979 to March 1980	Total volume (acre-feet) April 1980 to March 1981	Average rate gain (+), loss (-) April 1980 to March 1981 (cubic feet per second)
Recharge from precipitation and surface-water irrigation	33,460	28,960	+40.0
Discharge by pumpage	13,120	11,850	-16.4
Increase (+) or decrease (-) of ground water in storage	+14,330	-1,100	+ 1.5
Net stream-discharge gain			25.1

Estimates of recharge, pumpage, and change in ground-water storage, for April 1980 to March 1981 (table 6), indicates that the gain in stream discharge averaged 25.1 ft^3/s. It is recognized that this gain differs from the 37.9 ft^3/s estimated from seepage measurements. Several factors may account for the difference such as: (1) Different time periods are used, (2) response of the aquifer as indicated from observation wells may not occur in the same time interval that recharge and discharge occur, and (3) there could be error in the estimates. Observation wells are most useful to determine long-term trends of the water level (see figs. 6, 7, and 9). Gaging stations to measure stream discharge continuously would be required if changes in stream discharge are to be estimated accurately.

DIGITAL MODEL

The digital model described in this report is a computer program to simulate hydrologic conditions in the alluvial deposits and the Arikaree Formation. Hydrologic data used to model the system include hydraulic-head distribution, recharge from surface-water irrigation and from precipitation, ground-water discharge to streams and by pumpage, and hydraulic characteristics of the aquifers.

The general computer program for the model was written by Trescott (1975). A supplemental report by Trescott and Larson (1976) is part of the general computer program of the three-dimensional model used in this study. The area modeled is subdivided into variable-size cells forming a grid (fig. 10). The differential equation that describes ground-water flow in a porous medium (Jacob, 1950; Cooper, 1966) is replaced by finite-difference approximations of the derivatives at the center (referred to as a node) of each block or cell. A digital computer was used to solve the finite-difference equation for each cell using the strongly implicit procedure (SIP) (Stone, 1968, and Weinstein and others, 1969).

The hydrologic system is modeled as two layers; one aquifer overlays the other, and there is vertical flow between the aquifers. Alluvial deposits and the upper part of the Arikaree Formation comprise the top layer (upper aquifer). The bottom layer (lower aquifer) consists of the deeper Arikaree Formation. The model boundary for the bottom layer (lower aquifer) is placed beyond the anticipated effect of pumping in Wheatland Flats. Water is permitted to move between the streams and the upper aquifer. The upper aquifer exists at all stream nodes so that water moving to or from a stream passes through the upper aquifer (alluvium). Areal extent of the top layer, as modeled, is about 75 mi^2 bounded by Sybille Creek, Laramie River, Rock Creek-Wheatland Creek, and by the approximate southern limit of the terrace deposits (pl. 3). The upper aquifer is also modeled at the stream nodes that are outside this boundary. These streams and Chugwater Creek serve as line sinks for ground-water discharge.

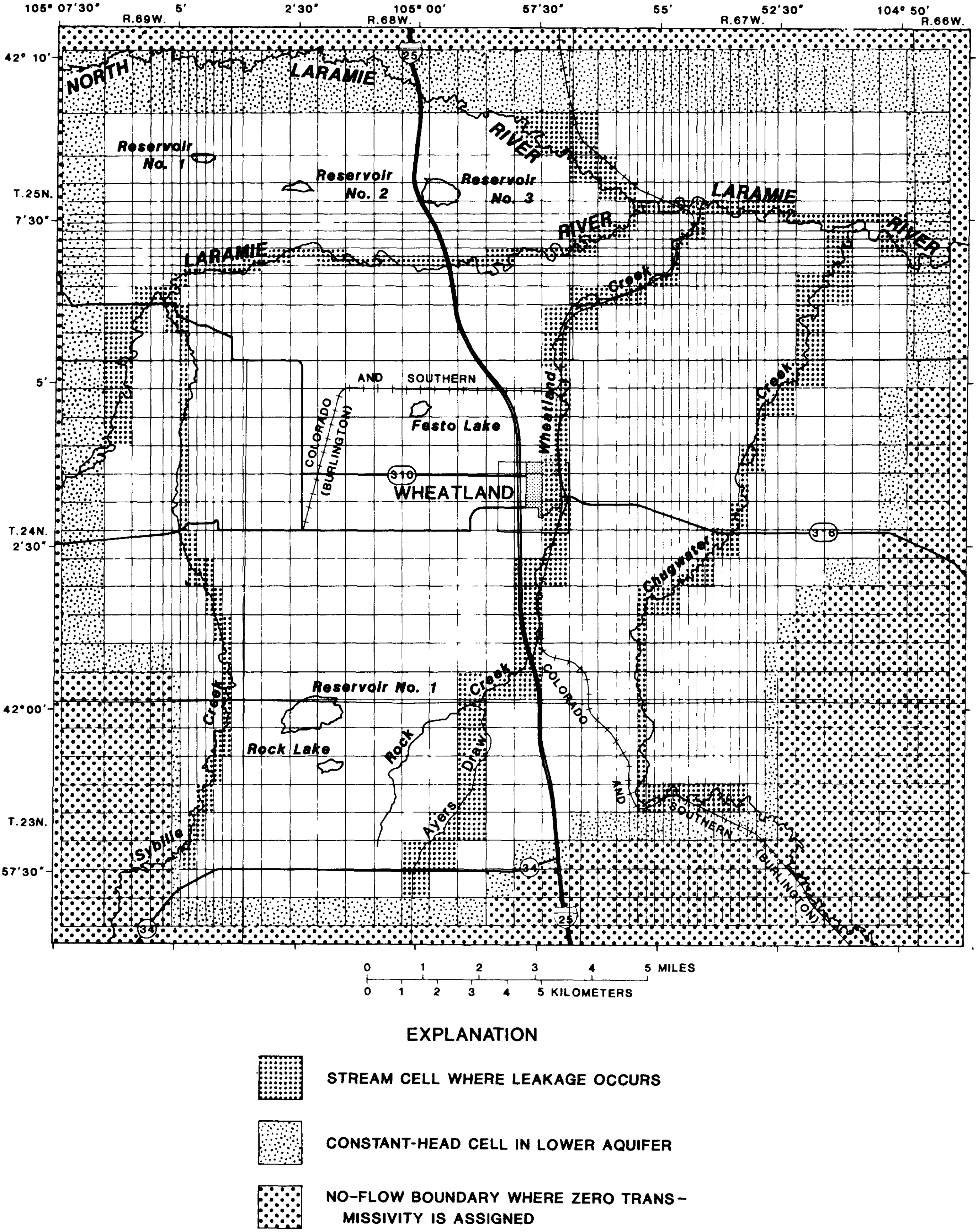


Figure 10.--Rectangular grid used to model hydrologic conditions in the Wheatland Flats area.

D. T. Hoxie (U.S. Geological Survey, written commun., 1980) modified the general computer program (Trescott, 1975; Trescott and Larson, 1976) to include a streamflow-accounting procedure by which the interaction between the streams and the aquifers is approximated. A stream cell can gain all the water that is commensurate with the hydraulic gradient in the aquifer, the hydraulic-head difference between the stream and the aquifer, the transmissivity of the aquifer, the thickness and hydraulic conductivity of the streambed, and the gradient of the stream between stream cells. A stream cell cannot lose more water than the cumulative volume in that cell. Streambed thickness was assumed to be 1 ft, and its hydraulic conductivity was assumed to be 2.7 ft/d. Hydraulic conditions of the streambed were assumed to be enough similar to those in the Arkansas River in Colorado that the same hydraulic conductivity (Moore and Jenkins, 1966, p. 696) could be used. Hoxie (1977) used the streamflow-accounting procedure in his study of the Arikaree near Wheatland.

Actual hydraulic conditions are complex and are simplified for the purpose of modeling. Several other assumptions were made and are as follows:

1. Specific yield was assumed to be 0.12 for both aquifers.

2. The hydraulic-head distribution in the upper aquifer may be interpreted from the altitudes of water levels measured in wells that are 100 ft deep or less.

3. The hydraulic-head distribution in the lower aquifer may be interpreted from the altitudes of water levels measured in wells that are deeper than 100 ft.

4. Recharge is evenly distributed and is 6.5 percent of the annual precipitation and 37.5 percent of the applied surface-water irrigation.

5. During steady-state conditions, net leakage to the streams from the ground-water reservoir occurs at the rate estimated from seepage runs (38 ft^3/s) made January 5, 1981.

6. The contour maps prepared for each aquifer (pls. 2 and 3) can be used to represent the hydraulic-head distribution in the aquifers during steady-state conditions.

Steady-State Procedures

Steady-state procedures involve the entering of aquifer properties and recharge-discharge data that are estimated to occur in the physical system into the computer. From these input data, the computer calculates a mass balance, hydraulic-head distribution in both aquifers, and the stream discharge.

Areal distribution of hydraulic conductivity in the upper aquifer, transmissivity in the lower aquifer, and vertical hydraulic conductivity between the aquifers were estimated by trial and error. The trial-and-error procedure was continued until the values of hydraulic head in each aquifer and the stream discharge calculated by the model agree, within acceptable limits, with the values estimated for the real system.

The rate of recharge calculated by the model (table 7) for the Wheatland Flats part of the model area is nearly the same as the rate of recharge estimated for April 1980 through March 1981 (table 6). Comparison of the measured gain in stream discharge for January 5, 1981 (table 5) and the calculated gain in stream discharge (table 7) shows good agreement for two streams. The substantial difference between the measured and calculated gain for the Laramie River shows that, for the Wheatland Flats part of the model too much water moves from the ground-water reservoir to the stream. Examination of the model printout data showed that this difference occurs primarily in the lower reach of the Laramie River. Because this part of the Laramie River is outside the Wheatland Flats area, the discharge may represent flow from parts of the model outside the Wheatland Flats area. The recharge and discharge shown in table 7 therefore do not balance, even though the model as a whole is in equilibrium. Hydraulic conductivity for the upper aquifer ranged from about 9 to about 690 $(ft^3/d)/ft^2$. Transmissivity for the deeper aquifer ranged from about 35 to about 2,600 $(ft^3/d)/ft$. Vertical flow between the aquifers was regulated by vertical hydraulic conductivity that ranged from about 5.2×10^{-5} to about 3.5×10^{-2} $(ft^3/d)/ft^2$. Weeks (1964, p. 48) estimated the vertical hydraulic conductivity to be about 8×10^{-3} $(ft^3/d)/ft^2$.

Transient Procedures

Accuracy of the model was tested by making transient simulations. Examination of the long-term hydrographs (figs. 6 and 7) indicates that the interval from 1971 to 1978 was a period when water levels changed from a high to a low level. Because the hydrographs indicate relatively small fluctuations for several years after 1971, it was assumed that steady-state conditions existed in 1971. The calculated hydraulic-head distribution for steady-state conditions was then assumed to be the hydraulic-head distribution in 1971. Annual pumpage and recharge from precipitation and irrigation for 1971-78 were applied as stress to the model. Evapotranspiration was not used in the model, as the streams were measured during a period when the evapotranspiration rate was low and could be neglected. A variable time step was used for transient simulation. The initial time step was 6 hours, and each subsequent time step was 1.5 times greater than the previous one.

Table 7.--Water budget calculated by the model during steady-state conditions for Wheatland Flats

	Rate (cubic feet per second)
Recharge from precipitation and surface-water irrigation	43.1
Gain in stream discharge:	
Chugwater Creek	29.6
Sybille Creek	7.4
Laramie River	36.0

The calculated hydraulic-head distribution at the end of 1978 was compared to the hydraulic-head distribution interpreted from the water-level measurements obtained prior to start of irrigation pumping in 1979. A measure of the difference between the two hydraulic heads at all nodes was obtained with the use of the rms (root-mean-square) deviation r, defined as:

$$r = \left[\frac{1}{N} \sum_{i=1}^{N} (h_i - h_i^o)^2 \right]^{\frac{1}{2}} , \qquad (1)$$

where

N = total number of nodes,

i = an index numbering nodes sequentially from 1 to N,

h_i = calculated hydraulic head, in feet at node; and

h_i^o = hydraulic head from water-level contours, in feet at node.

The difference is referred to as the rms deviation which is a measure of the departure of the calculated hydraulic heads from the contoured hydraulic heads for the entire modeled area. For the upper aquifer, comparison of the two hydraulic heads showed an agreement with an rms deviation of 4.2 ft and a maximum difference of 22.0 ft. Comparison of the calculated and interpreted hydraulic heads in the lower aquifer showed an agreement with an rms deviation of 6.3 ft and a maximum difference of 43.4 ft.

The largest difference appears in areas (fig. 11) where the model calculated the hydraulic head in the lower aquifer below the interpreted hydraulic head (pl. 2). In these areas the model is least accurate in duplicating the hydrologic conditions in the lower aquifer. Water-level measurements in Wheatland Flats from 1958-60 to 1979 have not shown declines as large as calculated by the model. Water-level measurements were not made in Chugwater Creek valley in 1958, but it is doubtful that the hydraulic head in the lower aquifer has declined 10 ft since 1958 in any part of the valley.

There are several possible reasons for the discrepancy between hydraulic heads calculated by the model and the hydraulic heads indicated by the potentiometric-surface contours (pl. 2): (1) More recharge, from surface-water irrigation, occurs in these areas than is put into the model; (2) the transmissivity used in the model could be less than the transmissivity that exists in the physical system; and (3) water levels measured in the wells represents a composite hydraulic head of all the zones open in the well. If drainage of the upper aquifer is occurring through the well bore (well construction discussed previously), the water level in the lower aquifer may be higher than if the upper aquifer was sealed off from the lower zones. It is impossible to gage or estimate the rate of water movement from the shallow zones to the deeper zones through the well bore of the many wells that are open throughout the saturated interval (capable of producing water from the entire saturated interval).

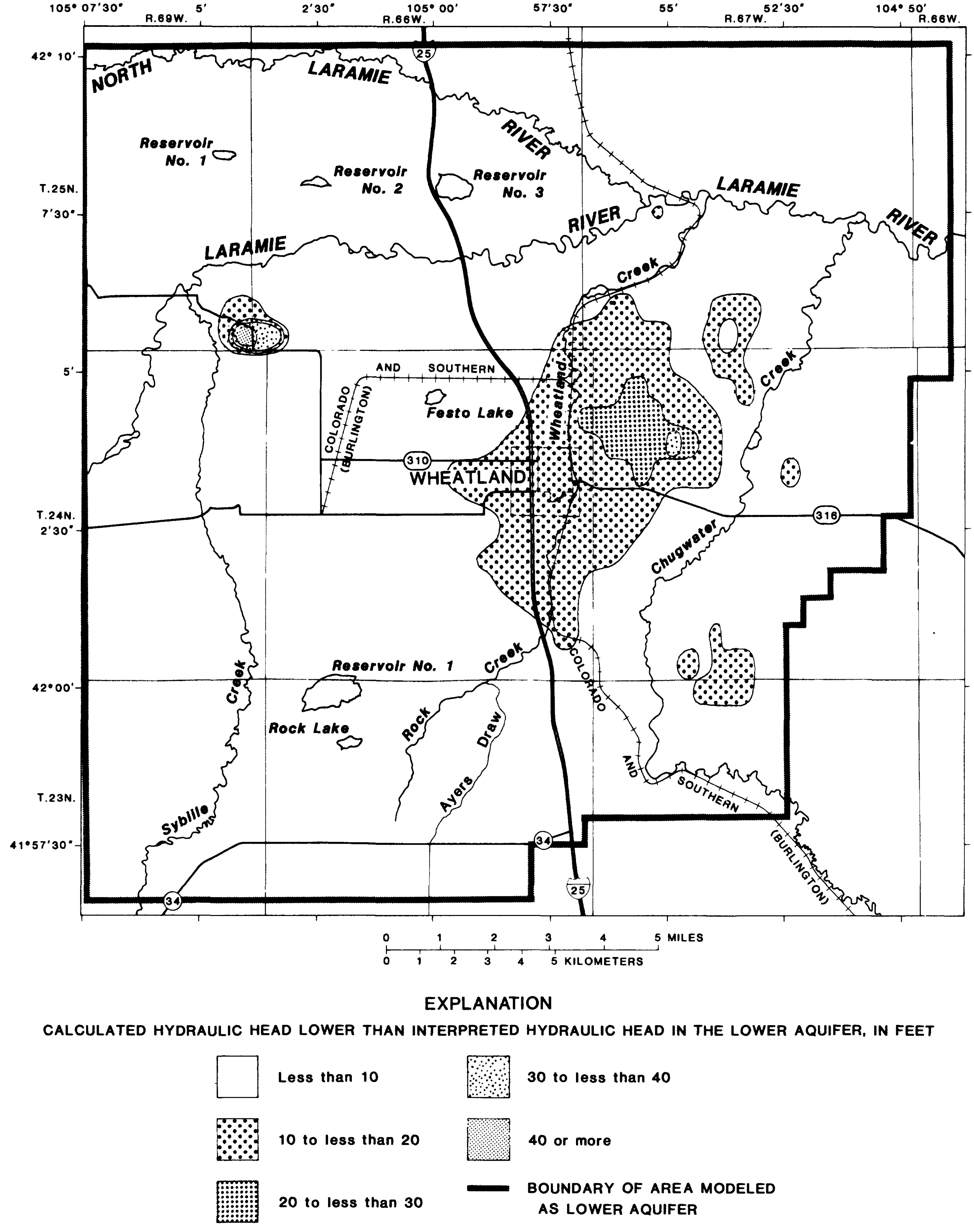


Figure 11.--Difference between the hydraulic head interpreted from contours shown on plate 2 and the hydraulic head calculated by the model for the lower aquifer at the end of 1978.

Changing any one of the parameters (recharge from surface-water irrigation, transmissivity, or vertical permeability to increase ground-water movement downward) would require recalibration of the model by the process of trial and error outlined in the steady-state procedures. Changing the parameter values would not improve the model accuracy without onsite measurements to verify the changes. The model, however, is useful to indicate areas where more information is needed. The model also is useful to test the concept of ground-water discharge to the streams as indicated during steady-state procedures. Estimated gain of stream discharge in Sybille Creek, Chugwater Creek, and part of the Laramie River was duplicated in the model. Even though the gain calculated in the model for the Laramie River was larger than the gain estimated from seepage runs, examination of the calculated data indicates the reaches of the Laramie River that agree and disagree with estimated ground-water discharge.

The model simulation of transient conditions for 1971-78 indicates that ground-water discharge to the major streams was decreased by about 10 percent. Stream-discharge measurements are not available to verify the loss calculated by the model. However, it is reasonable to assume that there has been some loss of ground-water contribution to the streams on the basis that the hydraulic head in the aquifers has declined. The actual quantity of loss in stream discharge would have to be verified by stream-discharge gages operated throughout the year.

SUMMARY AND CONCLUSIONS

Surface water diverted from the Laramie River and ground water from wells is used to irrigate 55,284 acres of land within the Wheatland Irrigation District. In addition, approximately 2,000 acres on and adjacent to Wheatland Flats are irrigated with ground water. More than 200 wells are used to supply ground water for irrigation, industrial, and municipal uses. These wells are completed in shallow alluvial deposits (upper aquifer) and the deeper Arikaree Formation (lower aquifer).

The net water-level decline in both aquifers generally is less than 10 ft after approximately 20 years. Water-level measurements in 1958-60 and 1979 indicate that declines of as much as 13 ft in the lower aquifer and as much as 8 ft in the upper aquifer have occured at specific locations. Pumpage probably is the principal cause of the water-level declines. Well yields from some of the wells in the upper aquifer have decreased. Some water-level decline in the upper aquifer may be attributed to: (1) More efficient irrigation practices that decrease recharge from surface-water irrigation, and (2) well construction that allows water to move downward from the upper aquifer to the lower aquifer through the well bore.

Almost all recharge to Wheatland Flats is from precipitation and seepage from surface-water irrigation. Recharge by underflow and from streams is considered to be negligible. Annual recharge to the flats estimated for 1971-80 ranges from 15,700 to 36,600 acre-ft per year.

Pumpage by irrigation and municipal wells and natural drainage to streams are the principal means by which ground water is discharged. Annual pumpage was estimated to range from 4,410 to 15,150 acre-ft per year for 1971-80. A seepage run on Sybille Creek, Laramie River, and Chugwater Creek, January 5, 1981, showed there was a gain of 37.9 ft^3/s in stream discharge. This gain represents ground-water discharge and is nearly the same value (41.9 ft^3/s) determined from a seepage run in February 1959.

A digital model was used to simulate hydrologic conditions in the Wheatland Flats area. Accuracy of the model was tested by transient simulation of hydrologic conditions during 1971-78. Comparison of the hydraulic-head contoured from water-level measurements in 1979 and the calculated hydraulic heads at the end of 1978 showed an agreement with a root-mean-square deviation of 4.2 ft with a maximum difference of 22.0 ft in the upper aquifer (terrace deposits and upper part of the Arikaree Formation). The same comparison of hydraulic heads in the lower aquifer (deeper Arikaree Formation) showed an agreement with a root-mean-square deviation of 6.3 ft with a maximum difference of 43.4 ft. The largest difference occurs in areas where the model calculated the hydraulic head in the lower aquifer below the hydraulic head interpreted from water-level measurements. Possible reasons for the discrepancy are: (1) Recharge from surface-water irrigation is more in those areas than was used in the model; (2) the transmissivity used in the model is less than in the physical system; and (3) the measured water levels may be higher if water from a shallow zone enters the well bore and recharges the lower aquifer as a result of well construction that allows free movement of water between zones that have different hydraulic heads.

Model simulation of transient conditions for 1971-78 implied that ground-water discharge to the streams decreased by 10 percent during this period. Although stream-discharge measurements are not available to verify the loss, it is reasonable to assume that there has been some loss of ground-water contribution to the streams as hydraulic head in the aquifers has declined. Continuous stream-discharge gages would have to be installed on the streams to verify streamflow changes.

REFERENCES CITED

Cooper, H. H., Jr., 1966, The equation of ground-water flow in fixed and deforming coordinates: Journal of Geophysical Research, v. 71, no. 20, p. 4785-4790.

Edwards, A. R., 1941, Underground water resources of Chugwater Creek, Laramie River, and North Laramie River valleys, Wyoming: Wyoming Geological Survey Bulletin 32, 32 p.

Hoxie, D. T., 1977, Digital model of the Arikaree aquifer near Wheatland, Southeastern Wyoming: U.S. Geological Survey Open-File Report 77-676, 54 p.

—— 1979a, Results of transient simulations of a digital model of the Arikaree aquifer near Wheatland, southeastern Wyoming: U.S. Geological Survey Open-File Report 79-1280, 17 p.

—— 1979b, Projected effects of intermittent changes in withdrawal of water from the Arikaree aquifer near Wheatland, southeastern Wyoming: U.S.Geological Survey Open-File Report 80-15, 38 p.

____ 1983, Hydrologic evaluation of proposed ground-water withdrawals in Muleshoe Flat near Wheatland, Southeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 78-143, 16 p.

Jacob, C. E., 1950, Flow of ground water, chapter V in Rouse, Hunter, ed, Engineering Hydraulics: New York, John Wiley and Sons, p. 321-386.

Lines, G. C., 1976, Digital model to predict effects of pumping from the Arikaree aquifer in the Dwyer area, southeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 8-76, 24 p.

Littleton, R. T., 1950, Reconnaissance of the ground-water resources of the Wheatland Flats area, Wyoming: U.S. Geological Survey Circular 70, 31 p.

Lohman, S. W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McGrew, L. W., 1967a, Geologic map of the Wheatland NE Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-628, scale 1:24,000.

—— 1967b, Geologic map of the Wheatland Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-627, scale 1:24,000.

—— 1967c, Geologic map of the Antelope Gap Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-619, scale 1:24,000.

—— 1967d, Geologic map of the Natwick Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-624, scale 1:24,000.

—— 1967e, Geologic map of the Ferguson Corner Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-622, scale 1:24,000.

—— 1967f, Geologic map of the Bordeaux Quadrangle Platte County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-620, scale 1:24,000.

Moore, J. E., and Jenkins, C. T., 1966, An evaluation of the effect of ground-water pumpage on the infiltration rate of a semipervious streambed: Water Resources Research, v. 2, no. 4, p. 691-696.

Morris, D. A. and Babcock, H. M., 1960, Geology and ground-water resources of Platte County, Wyoming: U.S. Geological Survey Water-Supply Paper 1490, 195 p.

Stone, H.K., 1968, Iterative solution of implicit approximations of multi-dimensional partial differential equations: Journal of Numerical Analysis, v. 5, no. 3, p. 530-558.

Theissen, A. H., 1911, Precipitation averages for large areas: Monthly Weather Review, July, p. 1082. (Theissen mean method).

Trescott, P. C., 1975, Documentation of finite difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 32p.

Trescott, P. C., and Larson, S. P., 1976, Supplement to Open-File Report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.

U.S. Department of Commerce, 1980, Climatological Data, Annual Summary: National Oceanic and Atmospheric Administration, v. 89, no. 13, 18 p.

Weeks, E. P., 1964, Hydrologic conditions in the Wheatland Flats area, Platte County, Wyoming: U.S. Geological Survey Water-Supply Paper 1783, 79 p.

Weinstein, H. C., Stone, H. L., and Kwan, T. V., 1969, Iterative procedure for solution of systems of parabolic and elliptic equations in three dimensions: Industry Engineering Chemistry Fundamentals, v. 8, no. 2, p. 281-287.

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