THE GROUND-WATER SYSTEM IN THE LaGRANGE AQUIFER NEAR LaGRANGE, SOUTHEASTERN WYOMING

By William B. Borchert

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CONVERSION FACTORS

For those readers interested in using the metric system, the following table may be used to convert the inch-pound units of measurement used in this report to metric units.

Multiply inch-pound unit	By	To obtain metric unit
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
foot (ft)	0.3048	meter
foot per foot (ft/ft)	0.3048	meter per meter
foot per second	0.3048	meter per second
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per day (ft/d)	0.3048	meter per day
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

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ABSTRACT

Ground water is being developed from the LaGrange aquifer, which consists of saturated permeable alluvium that is hydraulically connected with most of the underlying White River Group. In the area of principal interest east of Horse Creek, Hawk Springs Reservoir and 14 adjacent wells used to supplement surface-water supply in the reservoir are in a natural discharge area. Upgradient of the reservoir there are 28 irrigation wells in about a 6-square-mile area. In this area, water levels declined between 3 and 12 feet from 1973 to 1978 causing concern about the effects of well pumpage on the hydrologic system.

A digital model was developed and used to simulate the two-dimensional ground-water flow system in the unconfined LaGrange aquifer. Transient simulations were made for 1973-78 using 12 time periods and for 1978-80 using 25 time periods. The perimeter location and altitude of Hawk Springs Reservoir, discharge from ground-water pumpage, and recharge from surface-water and precipitation varied for each time period. Hydrographs showed good agreement between calculated and measured water levels for both transient simulations. Comparison of the measured and calculated hydraulic heads for 1978 and 1980 showed agreement with a root-mean-square deviation of 2.6 feet for 1978 and 2.8 feet for 1980 in the area of principal interest east of Horse Creek, and ranging from 3.3 to 5.6 feet for the other parts of the LaGrange area. For the area of principal interest, the sensitivity analysis of the model, using the 1973-78 transient simulation, indicates the model to be more sensitive to recharge from Horse Creek No. 1 irrigation ditch than to pumpage from wells.

The calibrated digital model was used to simulate four 6-month pumping alternatives including three hypothetical alternatives for the area of principal interest east of Horse Creek. The reservoir altitude was held constant, approximating a reservoir volume of 7,000 acre-feet. Pumping alternative 1 simulated historic conditions for 1973-78 including monthly recharge from precipitation which was included in the next three pumping alternatives. These three alternatives each simulated pumpage from either the wells adjacent to Hawk Springs Reservoir, the 28 irrigation wells upgradient from the reservoir, or the total 42 wells. At the end of the first 6-month simulation, the average calculated drawdown for 17 water-level nodes east of Horse Creek was 3.2 feet with the 14 wells pumping, 4.8 feet with the 28 irrigation wells pumping, and 8.2 feet with the 42 wells pumping. For pumping alternative 1, the calculated rate of discharge at the end of the 6-month simulation was 5.2 cubic feet per second from the aquifer to the reservoir. At the end of the 6-month simulations for pumping alternatives 2 and 3, the calculated rate of discharge to the reservoir was decreased to 0.4 cubic feet per second by pumpage from the 14 wells and to 3.8 cubic feet per second by pumpage from the 28 irrigation wells. For pumping alternative 4, pumpage from the total 42 wells resulted in a 1.0 cubic feet per second loss from the reservoir to the aquifer.

INTRODUCTION

The study area, referred to as the LaGrange area in this report, consists of about 130 mi^2 of which most is in southeastern Goshen County, Wyo. (fig. 1). Small parts of the area extend into Laramie County, Wyo. and into Nebraska in order to maintain continuity of the boundaries used in the model developed for the LaGrange area.

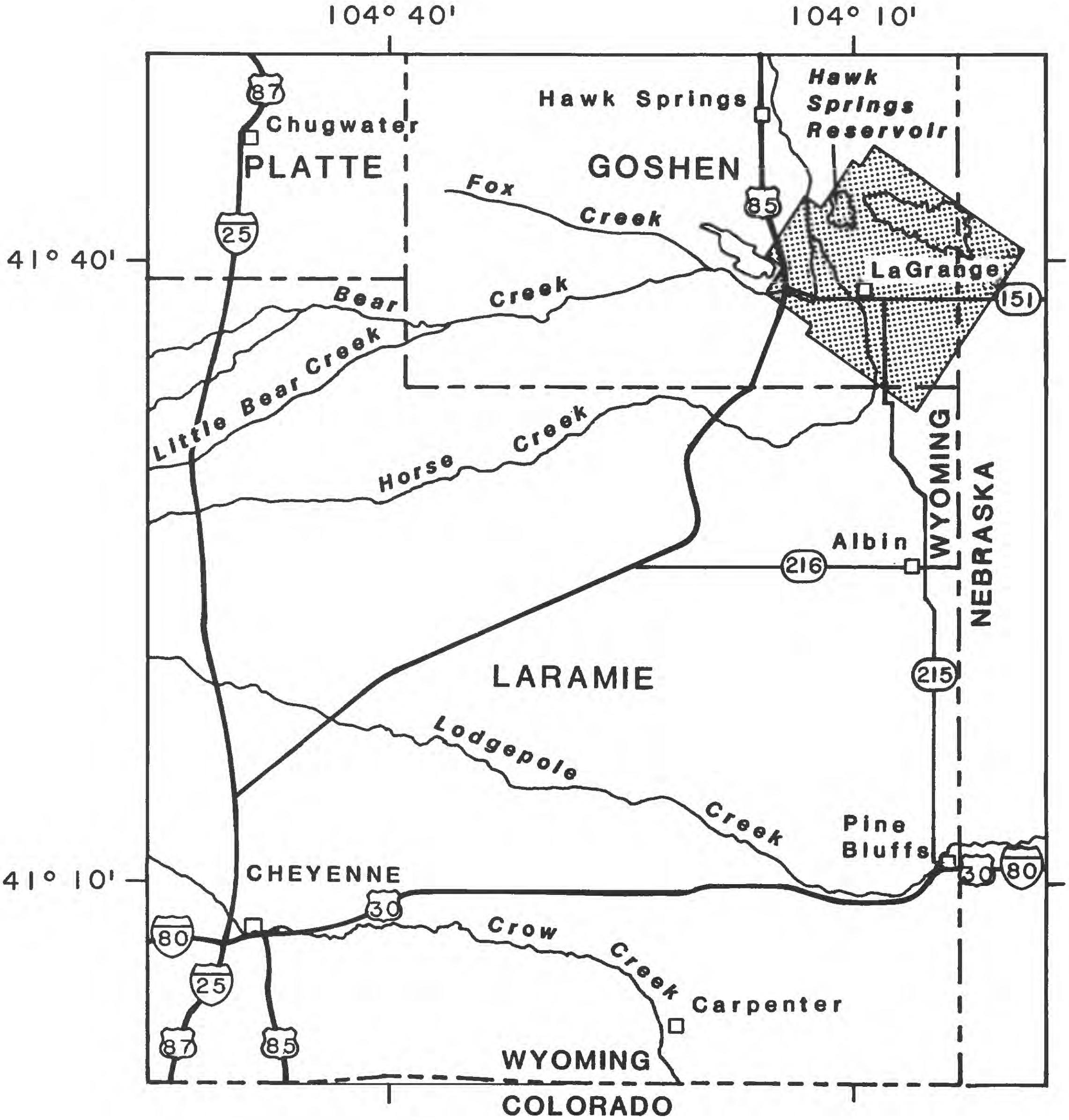
In the LaGrange area during 1978, about 9,500 acres were irrigated using surface water and ground water. All surface-water and most ground-water irrigation occurs in the areas east and west of Horse Creek as outlined in figure 2. Ground-water pumpage from all wells in the area east of Horse Creek, the area of principal interest, more than doubled from 1973 to 1978. During this time, precipitation was less than the normal of 15.47 in. (fig. 3). From April 1973 to April 1978, water levels in observation wells in the area east of Horse Creek declined between 3 and 12 ft and in the area west of Horse Creek between 0 and 3 ft. However, in the area east of Horse Creek, pumping water levels in many irrigation wells were 17 to 38 ft lower in August 1978 compared with August 1973 pumping water levels. Decreased well yields resulted for some wells, and at times, yields from some wells were not great enough to operate water-driven, center-pivot sprinkler systems. The annual water-level declines and consequent smaller well yields have resulted in concern by landowners in the LaGrange area and by water administrators about the effects of ground-water development on water levels. A digital model was developed to improve the understanding of the ground-water system in the LaGrange area and to provide a means of predicting the effects of future ground-water development on water levels.

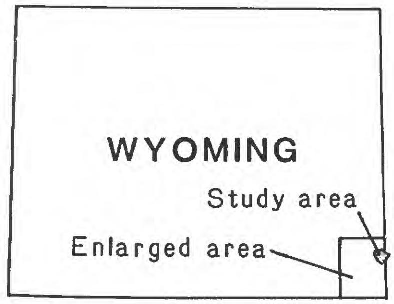
Purpose and Scope

The purpose of this study was to define the effects of surface-water and ground-water development on ground-water levels and to provide a means of predicting the effects of possible stresses. A digital model was developed to simulate the ground-water system, recharge from surface-water irrigation, ground-water pumpage, and to predict the effects of these stresses on ground-water levels, streamflow, and discharge from the aquifer to Hawk Springs Reservoir.

Previous Investigations

Several investigations that include part or all of the LaGrange area have been made. A description of the geology, streams, and springs of the area shown on the Patrick and Goshen Hole quadrangles was made by Adams (1902). Part of the LaGrange area was described in the reports on the stratigraphy and paleontology of the Goshen Hole area by Schlaikjer (1935 a, b, and c). The ground-water resources of the Horse Creek and Bear Creek valleys were described by Dockery (1940) and Babcock and Rapp (1952). Most of the LaGrange area was described by Rapp and others (1957) in their report on the geology and ground-water resources of Goshen County and by Borchert (1976) in a report on the geohydrology of the Albin and LaGrange areas.





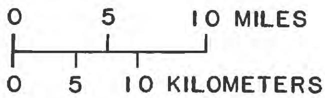


Figure 1.--Location of the study area.

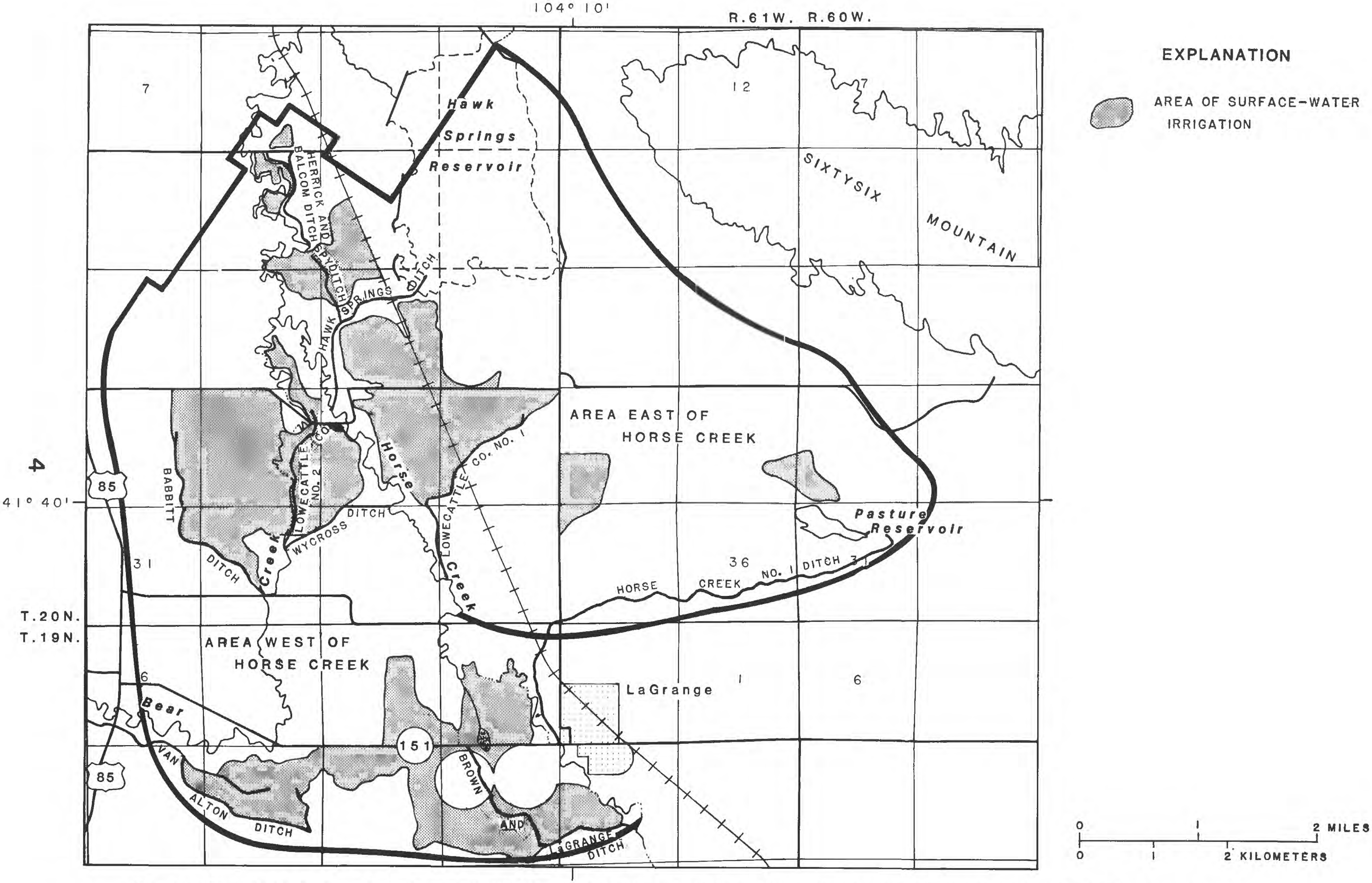


Figure 2.--Areas east and west of Horse Creek showing the approximate locations of surface-water irrigation in the LaGrange area, 1973-80.

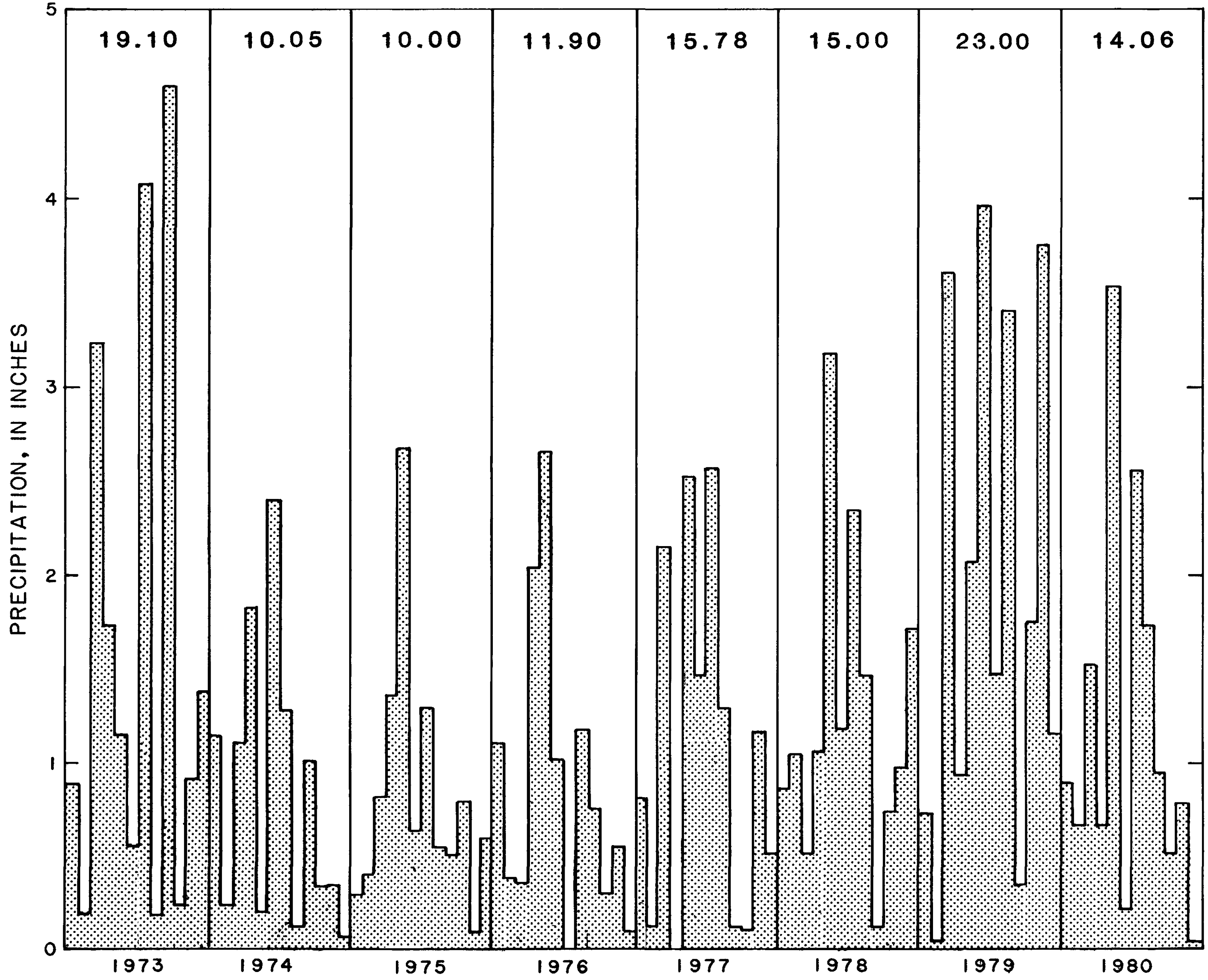


Figure 3.--Monthly precipitation at LaGrange, 1973-80. Numbers above bar graphs are annual total precipitation.

Well-Numbering System

Wells or test holes cited in this report are identified by a number based on the U.S. Bureau of Land Management system of land subdivision in Wyoming (fig. 4). The first number indicates the township, the second the range, and the third the section in which the well or test hole is located. The lowercase letters following the section number locate the well or test hole 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. The reference point for the subdivision of a complete section is the southeast section corner; a section that is not 1-mi square is treated as a complete section using the same reference point. When more than one well is located in a 10-acre tract, consecutive numbers starting with 1 follow the last lowercase letter of the well number.

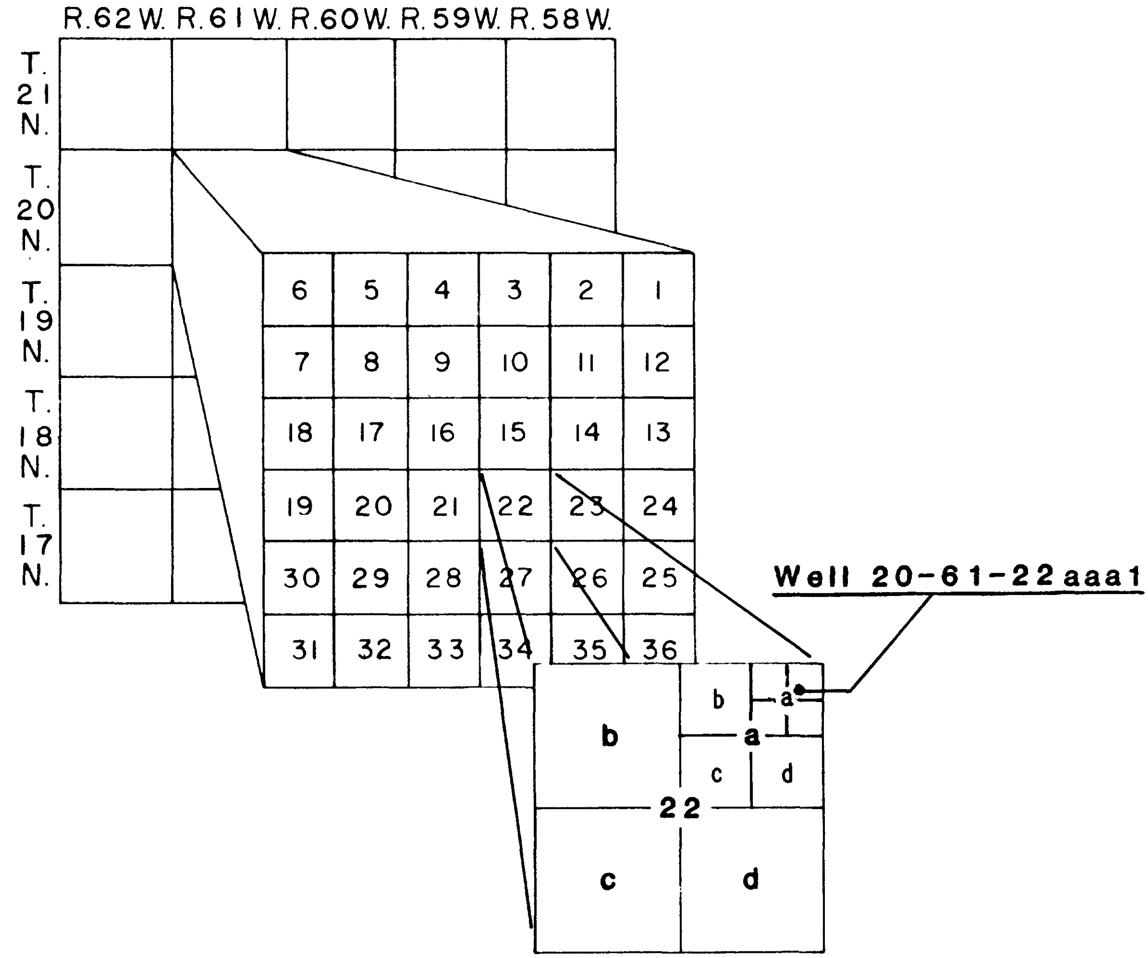


Figure 4.--Well-numbering system.

Acknowledgments

This study was done by the U.S. Geological Survey in cooperation with the Wyoming State Engineer. The author appreciates the cooperation of the many residents in the LaGrange area who allowed the drilling of test holes and observation wells on their land and permitted water-level measurements in their wells. The Horse Creek Conservation District also permitted observation wells to be drilled on their land, water-level measurements to be made in their wells, and an aquifer test to be made in one of their wells. The Wyrulec Company, Lingle, Wyo. provided information from power records for irrigation wells. The assistance of personnel from the Wyoming State Engineer's Office in measuring water-levels and providing surface-water-diversion records is greatly appreciated.

GENERAL GEOLOGY

The rocks exposed in and adjacent to the LaGrange area, in ascending order, are as follows: The Lance Formation of Late Cretaceous age, the White River Group of Oligocene age, the Arikaree Formation of early Miocene age, the terrace deposits of Pleistocene age, and the alluvium of Pleistocene and Holocene age (pl. 1).

The Lance Formation, Arikaree Formation, and the terrace deposits are not modeled as part of the ground-water system in the LaGrange area. The Lance is outside the model area, and the Arikaree yields water only to stock and domestic wells on top of Sixtysix Mountain and to springs along the perimeter of Sixtysix Mountain. The terrace deposits east and southeast of LaGrange are above the water table and therefore are not an aquifer.

Lance Formation

The Lance Formation is not exposed in the LaGrange area and is not a significant aquifer. The upper unit of the Lance Formation consists of a variegated sequence of beds of clay, sandy clay, sandstone, and shale. Because of the lithologic character of the Lance, it is assumed to be impermeable where it is exposed outside and adjacent to the northwestern boundary of the model.

The top of the Lance Formation can be identified on electric logs at the base of a low-resistivity zone. Lithologic samples from test holes drilled for this study indicated a zone of pale-yellowish-brown to grayish-orange-pink, hard, silty clay just above the top of the Lance Formation. According to N. M. Denson (U.S. Geological Survey, oral commun., 1978), this clay zone is a paleosol that may be post-Lance and pre-White River Group. This paleosol is apparently in the lower part of the low-resistivity zone as shown by the upper part of the electric log for test hole 20-61-22aaa1 in figure 5.

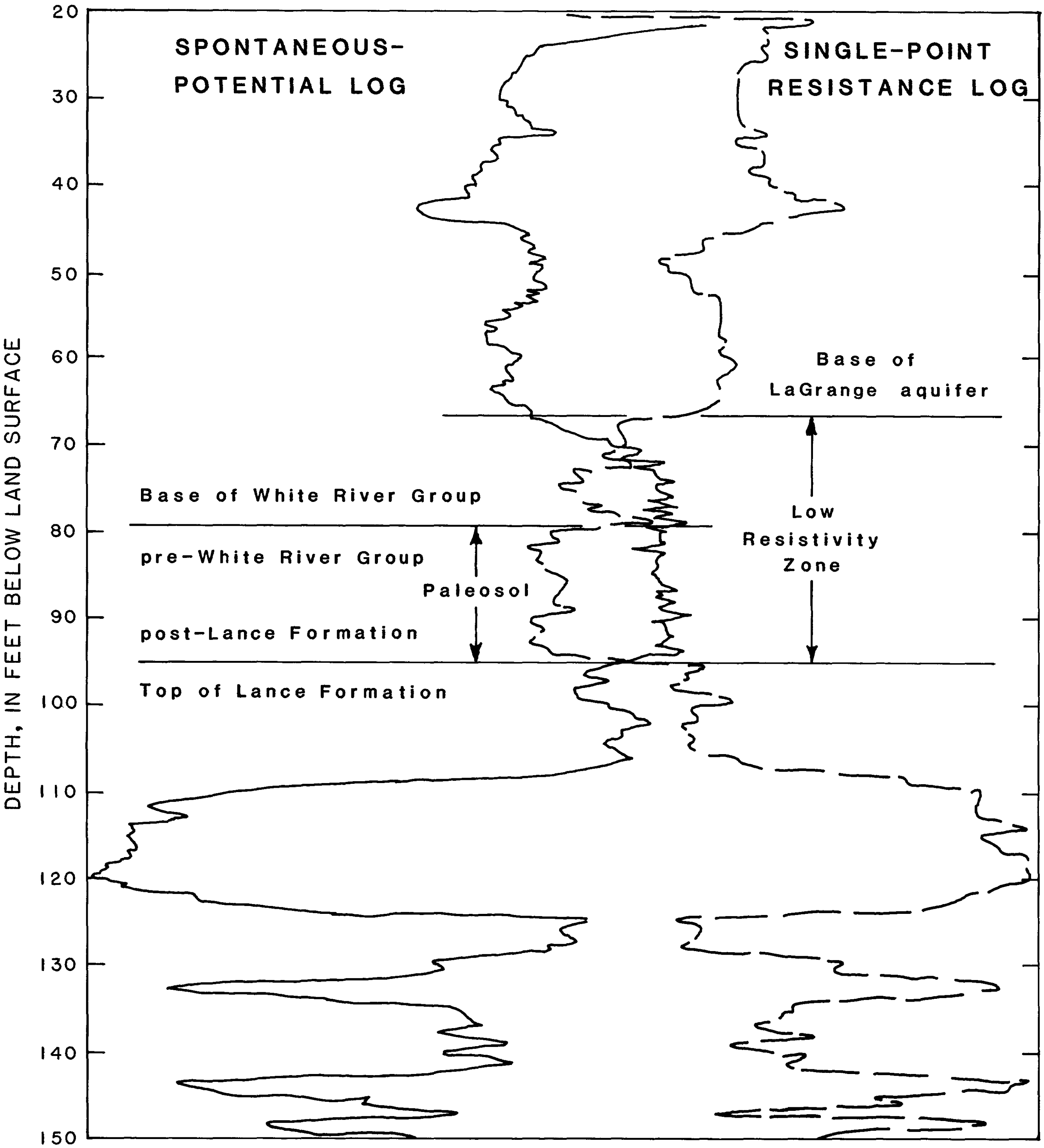


Figure 5.--Upper part of the electric log of test hole 20-61-22aaa1.

A lithologic log for the upper part of well 20-61-22aaa1 using color descriptions from a rock-color chart (Geological Society of America, 1963) is as follows:

Depth (feet)	Lithology
0-1	Silty topsoil, tan
1-5	Silty clay, yellowish-gray
5-18	Sand and gravel, medium-to coarse-grained
18-65	Sandy siltstone, very pale orange
65-72	Clayey siltstone, yellowish-gray
72-78	Clayey siltstone, light-greenish-gray
78-95	Silty clay, grayish-orange-pink, hard
95-102	Sandy clay, grayish-blue-green
102-108	Sandy clay, pale-yellow-brown
108-124	Clayey sandstone, pale-yellow-brown and pale-red, very fine-grained
124-130	Clay, pale-blue-green
130-134	Sandy clay, pale-red, with calcareous, hard, fine-grained sandstone
134-150	Sandstone, variegated yellow-orange, pale-red, greenish-gray, clayey and silty, very fine-grained

White River Group

The White River Group has been divided into a lower unit, the Chadron Formation, and an upper unit, the Brule Formation (Rapp and others, 1957, p. 21). The geology shown on plate 1 was modified from Rapp and others (1957, pl. 1) and shows the exposed areas of the Chadron and Brule Formations.

According to Rapp and others (1957, p. 29-31) the Chadron Formation of the White River Group is divided into a lower and an upper part. The lower part consists of a series of lenses and beds that range from brick-red, dark-red, or green to blue-green clay and silt to brick-red, maroon, purple, and green sandstone and conglomerate. The upper part consists predominately of green, brown, red or buff, bentonitic, loosely to moderately cemented clay and silt. In places, fine- to coarse-grained sandstone is formed in channel deposits usually concentrated near the top of the Chadron. In the LaGrange area, the Chadron is exposed only in one area northeast of Hawk Springs Reservoir, where it consists of a very light greenish-gray, clayey silt intermixed with light-pinkish-brown silty clay. It has weathered to gently undulating, well-rounded hills.

The Brule Formation of the White River Group consists of a massive, very pale orange or light-grayish-orange-pink, moderately hard, brittle, argillaceous siltstone. Generally the Brule is composed mainly of silt but locally may be sandy or clayey. The Brule is exposed throughout much of the LaGrange area and underlies the terrace deposits and most of the alluvium.

In this study, the Chadron and the Brule Formations are considered to be one geohydrologic unit and referred to as the White River Group. Sufficient data are not available to separate the Chadron and Brule hydrologically.

Alluvium

The alluvium in the LaGrange area is predominately valley-fill deposits that consist mostly of sand and gravel with siltstone pebbles and abundant fragments of pink feldspar. Lenses of silt and clay are common. The alluvium was deposited mostly on the Brule Formation except in secs. 8 and 9, and the northern parts of secs. 10, 16, and 17, T. 20 N., R. 61 W., where it overlies the Lance Formation.

HYDROGEOLOGY

The LaGrange aquifer referred to in this report consists of the saturated part of the alluvium where present and most of the White River Group. The alluvium and the White River Group are assumed to be hydraulically connected and to respond as one aquifer. In order to test this assumption, seven paired observation wells, such as wells 20-61-15dcd1 and 20-61-15dcd2, were drilled 10 ft apart, with one well completed in the alluvium and one in the White River Group. The hydrographs for these wells (fig. 6) and for the other six paired observation wells indicate similar water-level changes in each paired well. The ground-water system in the LaGrange aquifer is unconfined, which means that water does not rise above the top of the aquifer in wells.

The base of the LaGrange aquifer is the top of the low-resistivity zone identified in electric logs (see fig. 5). The thickness of this low-resistivity zone in the area ranges from 20 to 72 ft. The configuration of the base of the aquifer is shown by the contours on plate 1.

Potentiometric Surface

A potentiometric surface can be defined as an imaginary plane that coincides with the hydraulic head in the aquifer. The hydraulic head in an unconfined aquifer is the altitude of the water level above sea level. The potentiometric surface is contoured using the altitudes of the water levels measured in wells. In the LaGrange area, most of the wells in which water levels are measured are open to the full saturated thickness penetrated by the well. Usually the irrigation wells are constructed with perforated casing through the alluvium and completed without casing (open hole) in the White River Group.

In order to adequately contour the potentiometric surface, 52 observation wells were drilled and completed during March, April, and May 1978 and during November 1979. This was accomplished with the assistance of personnel from the Wyoming State Engineer's Office. Land-surface altitudes were determined by differential leveling for 84 wells. The observation wells on the western and southern flanks of Sixtysix Mountain were completed so that the wells would be open to the LaGrange aquifer in the same interval as the irrigation wells just south of the mountain. Cement was placed in the annular space between the casing and the hole above the completion interval. Therefore, the altitudes of the water levels measured in the observation wells and the irrigation wells are both representative of the average hydraulic head for a similar saturated thickness of aquifer penetrated by the wells.

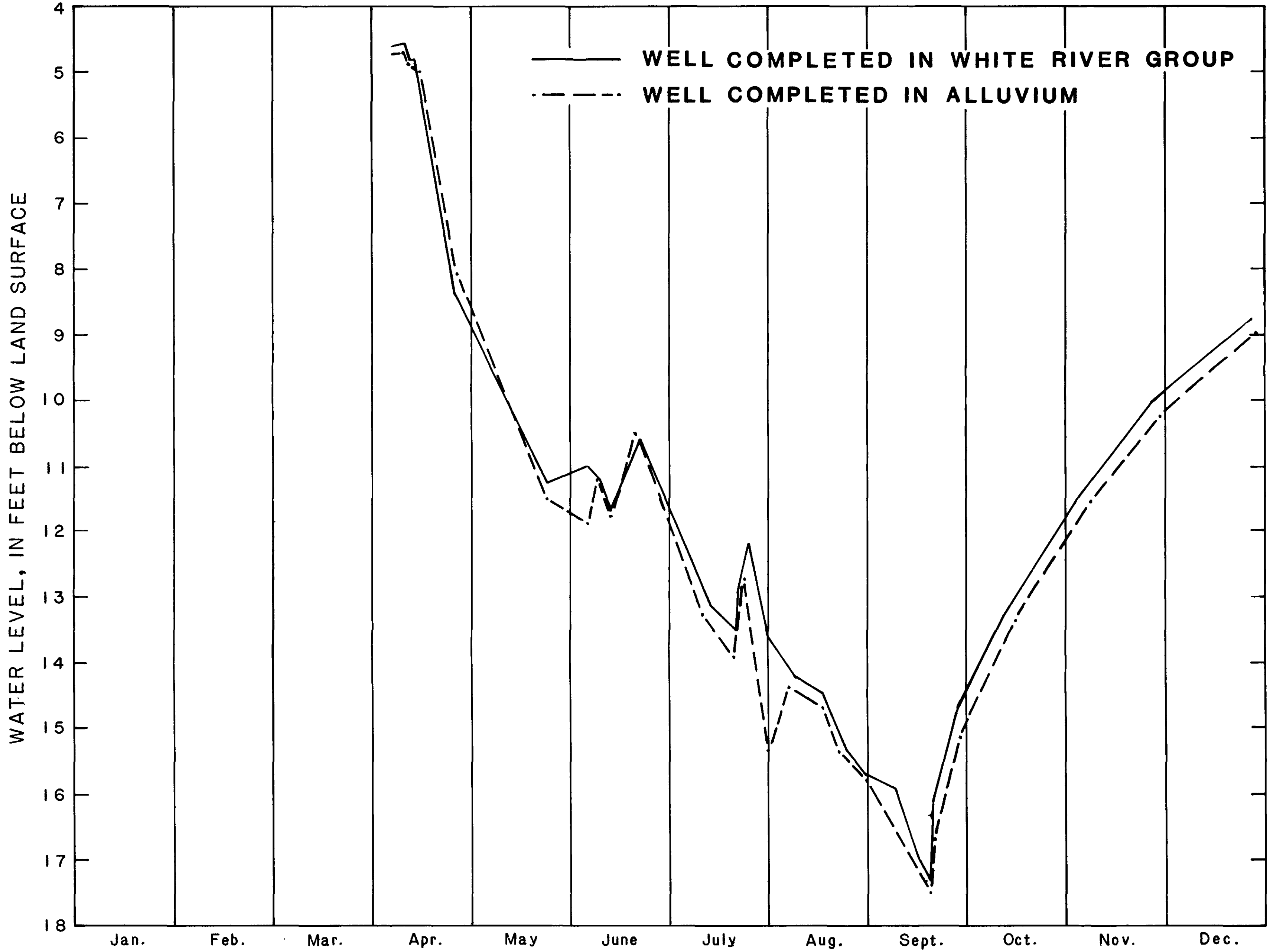


Figure 6.--Water-level fluctuations in well 20-61-15dcd1, completed in the alluvium, and well 20-61-15dcd2, completed in the White River Group.

The potentiometric surface for the LaGrange aquifer was obtained by contouring the water-level altitudes either measured during or estimated for April 1973 (pl. 2) and April 30, 1980 (pl. 3). At both times the reservoir altitude was about 4,480 ft; its approximate area and perimeter is shown on plate 2. Along the western and southern flanks of Sixtysix Mountain, water-level altitudes for April 1973 in wells 20-60-29daa, 29dcc, 29ddd, 30ada, 30bbb, and wells 20-61-11ccd, 14cda, and 23aaa were estimated using water levels measured in nearby wells in April 1973 and water-level gradients in April 1980. Water-level altitudes for April 1973 in wells 20-60-19aca, 19caa, 19cac, and 20-61-11cdd and 11dcd were assumed to be the same as those measured in April 1980, because water levels do not significantly fluctuate in those wells. Because of a lack of data, the potentiometric-surface contours along the northern and eastern flanks and beneath Sixtysix Mountain are conceptualized and thus approximately located. The potentiometric-surface contours for April 30, 1980, in the NW¼ T. 19 N., R. 60 W. indicate anomalies probably due to local differences in hydraulic conductivity. Therefore the approximate potentiometric-surface contours for April 1973 in that area were smoothed and generalized for use with the model.

Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of the rock to transmit water under a potential gradient. It can be expressed as the rate of flow, in cubic feet per day, through a cross-sectional area of 1 ft^2 under a hydraulic gradient of 1 ft/ft. In the two-dimensional aquifer approximation of the LaGrange aquifer, hydraulic conductivity represents a mean value averaged for the saturated thickness of the aquifer.

The hydraulic conductivity of the White River Group in the LaGrange area varies considerably. Successful irrigation wells drilled in the White River Group must penetrate zones of secondary permeability as the matrix is composed primarily of silt-sized particles and yields little water to wells. The hydraulic conductivity of the White River Group without secondary permeability is about 0.01 ft/d (units reduced from $(ft^3/d)/ft^2$). This is the smallest value reported by Rapp and others (1957, p. 42) as determined by hydrologic-laboratory analysis. Hydraulic conductivities determined from aquifer tests in the area (Borchert, 1976, p. 37 and 38) ranged from 480 to 1,730 ft/d for the alluvium and from 640 to 810 ft/d for the White River Group. Using the closed-contour method described by Lohman (1972, p. 46-49), the hydraulic conductivity of the LaGrange aquifer was estimated at about 770 ft/d in the vicinity of the 14 wells adjacent to Hawk Springs Reservoir.

The values of hydraulic conductivity used in this model range from 0.01 to 950 ft/d. The smallest values were used where the steep gradients in the potentiometric surface exist adjacent to Sixtysix Mountain. The largest values were used in the area east of Horse Creek where the flat gradients in the potentiometric surface exist and where specific capacities (yield per foot of drawdown) of irrigation wells range from 45 to 230 (gal/min)/ft.

The greatest change in hydraulic conductivity is modeled along the flanks of Sixtysix Mountain. This change is indicated by a change in the hydraulic gradient of the potentiometric surface. A generalized geohydrologic section showing the potentiometric surface on the western flank of Sixtysix Mountain is shown in figure 7. The line of section A-A′ is shown on plate 2. The diagram illustrates the change from a fairly flat hydraulic gradient between wells 20-61-10ddd and 11ccd to a very steep hydraulic gradient beginning between wells 20-61-11ccd and 11cdd2. A qualitative indication of a difference in hydraulic conductivity along the western and southern flanks of Sixtysix Mountain was obtained during drilling of observation wells. When well 20-61-11ccd was drilled using air, it was obvious when the water table was reached. However when wells 20-61-11cdd2 and 11dcd were drilled farther up the slope also using air, the holes were initially dry; the water levels did not stabilize for approximately 24 hours. Similar conditions were encountered while drilling wells 20-61-19aca, 19caa, and 23aaa along the southern flanks.

Specific Yield

Specific yield is a property of an unconfined aquifer that relates to the storage capacity of the aquifer and to the volume of water that an unconfined aquifer will either gain or lose with a change of the potentiometric surface. It can be expressed as the ratio of the volume of water drained by gravity to the total volume of the aquifer drained.

A specific yield of 0.13 was computed by dividing the volume of water pumped by the volume of aquifer dewatered during April 10-17, 1978, when only the 14 Horse Creek Conservation District wells adjacent to Hawk Springs Reservoir were pumping. The volume of water was determined from readings of in-line, totalizing flow meters on each well. Using water-level measurements obtained on April 10 prior to any pumping and again on April 17, an estimated drawdown pattern was contoured. The volume of aquifer dewatered was then computed by summing the products of the area between each drawdown interval and the average drawdown.

A specific yield of 0.10 was used in the model for the transient (time-dependent) simulations. The value of this specific yield is considered a reasonable average value for the area. It is supported by the results of sensitivity analyses of the model to specific yield (discussed later in the report) along with the estimated specific yield of 0.13 determined from field data.

Hydrologic Balance

The rates and distribution of recharge and discharge along with the hydrologic properties of an aquifer determine the configuration of the potentiometric surface. In a two-dimensional model the gradient or change in hydraulic head with distance along this potentiometric surface controls the flow of water within the ground-water system. Water enters the system in areas of recharge, flows downgradient from areas of higher hydraulic heads to areas of lower hydraulic heads, and leaves the ground-water system in areas of discharge.

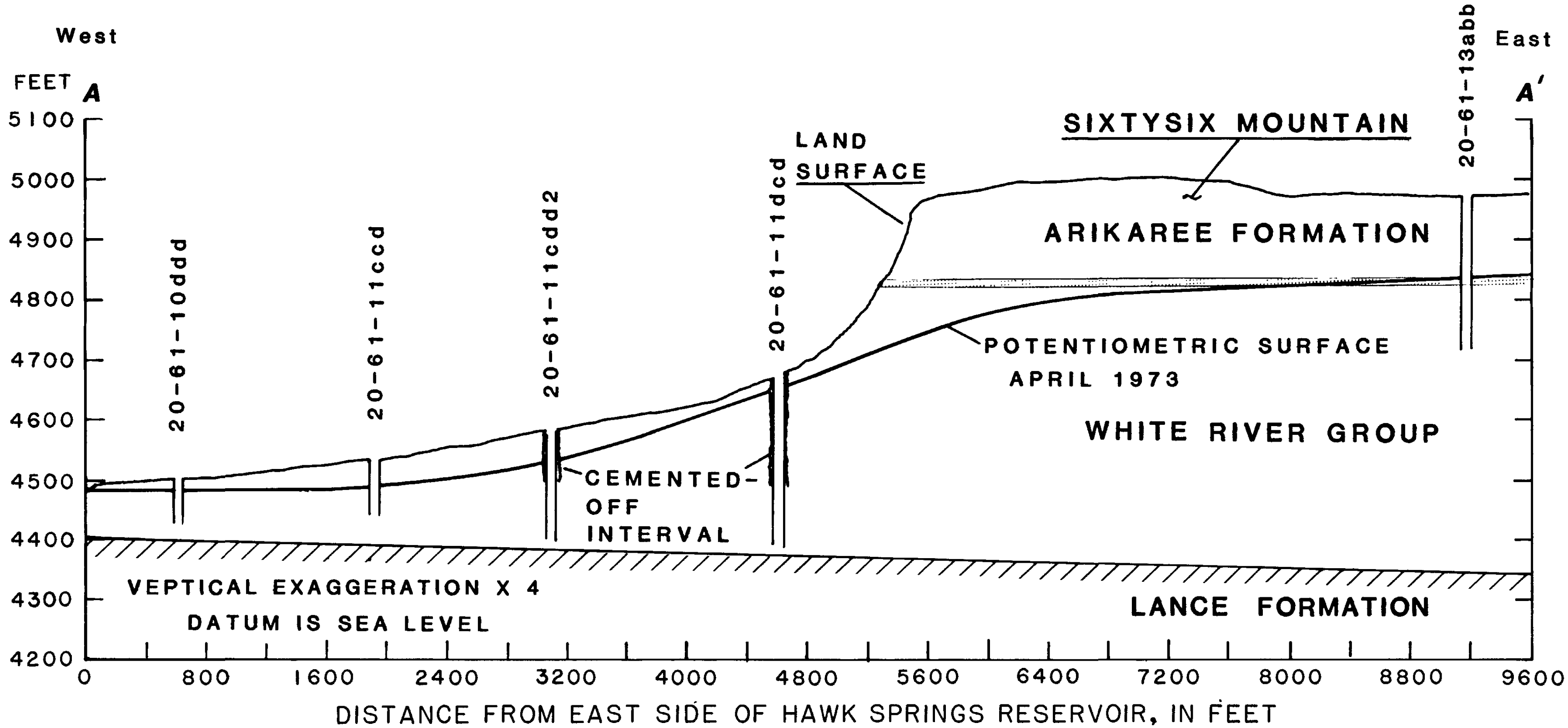


Figure 7.--Potentiometric surface at the west end of Sixtysix Mountain. Location of section A-A′ shown on plate 2.

Whenever the rates of recharge and discharge remain fairly constant for a sufficient time, the potentiometric surface will adjust to a configuration that will allow the long-term average rates of recharge and discharge to be equal. Under these conditions the ground-water-flow system approaches steady-state flow in which there is not significant change in hydraulic heads with time. An approximate steady-state potentiometric surface will be established to maintain the rates of recharge and discharge. Its configuration can fluctuate in response to short-term and seasonal changes in the rates and distribution of recharge and discharge.

Recharge

Precipitation, surface-water irrigation, and underflow are the sources of recharge to the LaGrange aquifer. Normal annual precipitation at LaGrange is 15.47 in. The departure graphs in figure 8 show the variation of precipitation from 1949 through 1979 (U.S. Department of Commerce, 1949-79). The annual-departure graph commonly can be used for correlation of water-level hydrographs with precipitation, whereas the 3-year, moving-average-departure graph is useful for showing long-term trends. Comparison of the hydrographs for the three wells shown in figure 8 with the precipitation-departure graphs shows correlation between water-level changes and precipitation departures, which indicates some recharge from precipitation to the ground water.

Recharge to the LaGrange aquifer from surface-water irrigation has occurred probably since before 1900. Diversions from Horse Creek and Bear Creek are the only sources of surface water applied to lands in the LaGrange area (fig. 2). Information on the quantity and distribution of surface-water diversions prior to 1971 generally is not available. Most of the time, diversions through Horse Creek No. 1 Ditch were transported to Pasture Reservoir, where at times, water was released to land north of the reservoir. During the early spring of 1979 and 1980, some water from Horse Creek No. 1 Ditch was applied to the land north of the ditch in sections 26 and 35.

During each month, James Ward, the hydrographer-commissioner working in the LaGrange area, makes periodic measurements or estimates of the discharge for each diversion ditch. Using these discharges provided by the Wyoming State Engineer's Office, the surface water diverted annually from 1973 to May 1980 to each ditch has been estimated and is listed in table 1. Annual surface-water diversions from Horse Creek to Hawk Springs Reservoir through Hawk Springs Ditch are not listed in table 1 because the reservoir water is used by members of the Horse Creek Conservation District for irrigation of lands north of the LaGrange area.

Most of the ditches have flumes or pend vanes to measure the rate of flow at the point of diversion. There is no measuring device at the point of diversion to Horse Creek No. 1 Ditch; therefore, most of the diversions made during 1973-78 were estimated by the hydrographer-commissioner. During 1979 some diversion volumes were based on current-meter measurements.

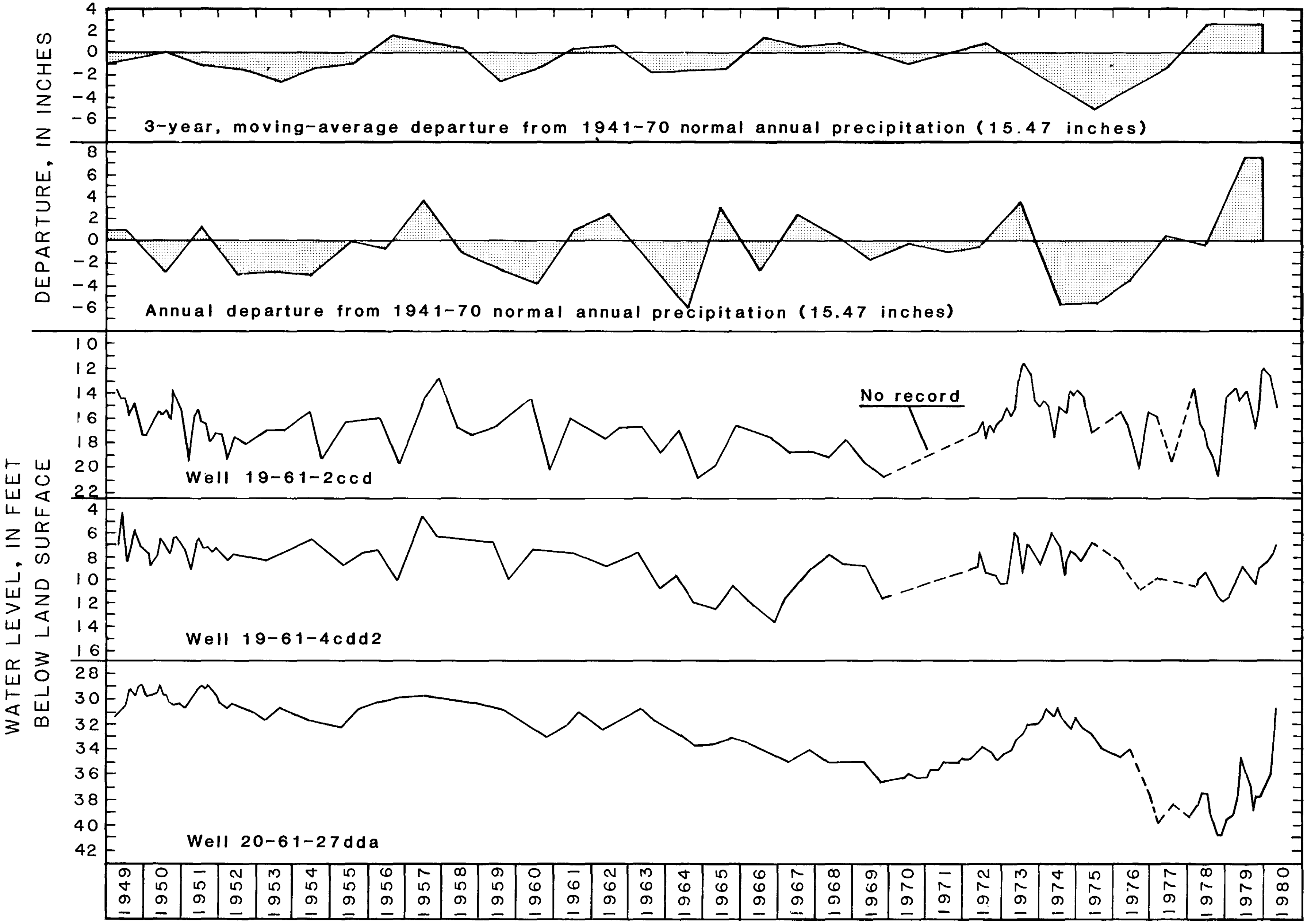


Figure 8.--Average and annual departure from normal annual precipitation at LaGrange and water-level fluctuations in three wells, 1949-80

Table 1.--Estimated volume of annual surface-water diversions, in acre-feet.

Ditch	1973	1974	1975	1976	1977	1978	1979	1980*
Brown and LaGrange	5,460	7,760	6,163	3,219	6,847	5,581	7,036	--
Horse Creek No. 1	1,921	1,451	1,726	1,483	2,237	1,233	4,209	2,601
Lowe Cattle Co. No. 1	3,460	3,828	1,110	1,174	2,142	1,619	2,314	704
Spy	251	503	432	362	660	638	137	--
Herrick and Balcom	--	325	808	739	748	--	--	--
Van Alton	1,702	1,774	1,030	871	1,295	264	452	849
Babbitt	2,139	1,499	2,028	2,695	2,124	1,086	2,359	760
Lowe Cattle Co. No. 2	2,125	3,486	3,527	3,193	4,134	4,155	2,408	--

* Only January through April

Recharge to the LaGrange aquifer from underflow is considered fairly constant year to year. Water enters the LaGrange area as underflow generally from the south. Configuration of the potentiometric surface has not significantly changed in the southern part of the study area as indicated by annual water-level measurements. Thus the volume of underflow into the LaGrange area has been fairly constant for a long time.

Discharge

Discharge from the LaGrange aquifer occurs as ground-water pumpage, leakage to Horse Creek, underflow, and evapotranspiration. Most of the ground-water withdrawals from the aquifer have been from 70 irrigation wells and 14 wells adjacent to Hawk Springs Reservoir. These 14 wells, referred to as the Conservation District wells in the remainder of this report, are used by the Horse Creek Conservation District to supplement surface-water supply in the reservoir. Because water pumped from the Conservation District wells is not used for irrigation in the LaGrange area, they are not included in the references to irrigation wells in this report. During 1978-79, only 11 of the Conservation District wells had been pumped as the 3 northernmost wells have not been used since 1977. Prior to 1980, the Conservation District wells were pumped in the spring whenever insufficient surface water was available to fill Hawk Springs Reservoir to peak capacity of 16,735 acre-ft and generally from June through September when peak irrigation demands occurred. Beginning in 1980, the Wyoming State Engineer, upon the recommendation of the State Board of Control, required that the Conservation District wells not be pumped before April 15. If the reservoir has 7,000 acre-ft or more in storage on or after April 15, the rate of pumpage by the Conservation District wells cannot exceed the rate of water being released from the reservoir.

Ground-water pumpage from wells in the LaGrange area increased significantly after 1968 (fig. 9). Of the 70 irrigation wells in the LaGrange area, 29 were drilled after 1968. Of the total 28 irrigation wells and 14 Conservation District wells in the area east of Horse Creek, 20 irrigation and 7 Conservation District wells were drilled after 1968. In this same area, annual ground-water pumpage from the irrigation wells during 1969-79 averaged about 2,500 acre-ft and has shown little annual change, particularly from 1970-79.

Annual ground-water pumpage from the Conservation District wells during 1969-79 ranged from about 500 to 5,200 acre-ft and averaged about 3,200 acre-ft. Although ground-water pumpage from the Conservation District wells during 1973-78 also averaged about 3,200 acre-ft, pumpage during 1976-78 was greater than 4,000 acre-ft each year. The greater annual pumpage during 1976-78 correlates with probably decreased surface-water availability because the years 1974-78 were very dry. Conservation District wells are used to supplement surface water diverted into Hawk Springs Reservoir; therefore, annual discharge from the wells fluctuates according to the quantity of surface water available.

Annual ground-water pumpage from irrigation wells in the area west of Horse Creek and the remaining area during 1969-79 ranged from about 3,000 to 6,200 acre-ft and averaged about 4,000 acre-ft.

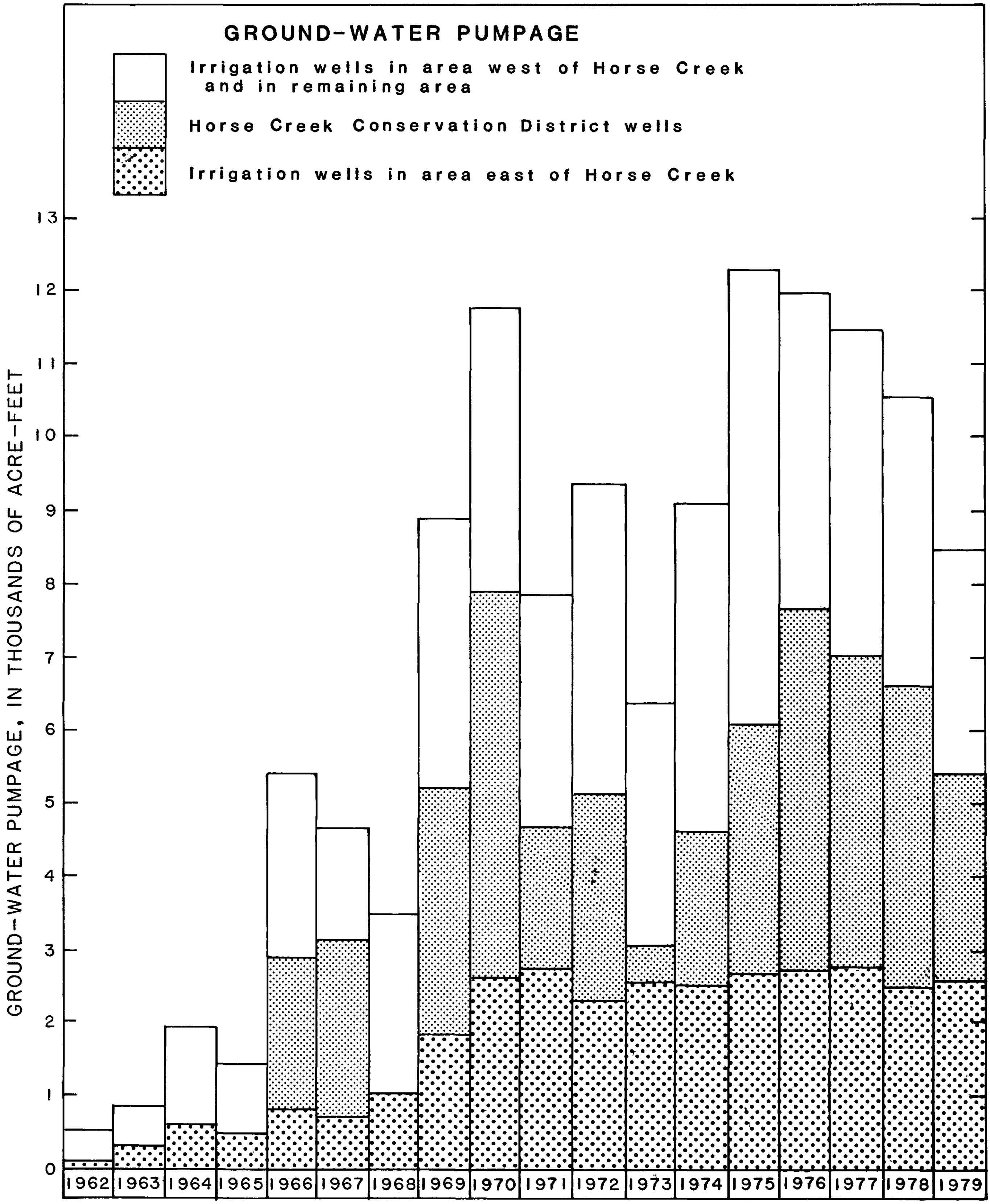


Figure 9.--Estimated annual ground-water pumpage in the LaGrange area, 1962-79.

Leakage from the LaGrange aquifer is primarily to Horse Creek north of LaGrange. Discharge measurements made in September 1978, April 1979, and November 1979 indicated a net gain of streamflow in Horse Creek in the reach from about the SE¼NW¼ sec. 3, T. 19 N., R. 61 W., to the SE¼SW¼ sec. 8, T. 20 N., R. 61 W. Streamflow measurements made along Horse Creek from the southern model boundary to the SE¼NW¼ sec. 3, T. 19 N., R. 61 W. and along Bear Creek within the model area indicated no streamflow gains or losses greater than the accuracy of streamflow measurements.

Underflow results in discharge from the model area in the northeast corner and along the northwestern and northeastern boundaries (pl. 1). Some discharge from the LaGrange aquifer occurs through the alluvium west of Hawk Springs Reservoir. Discharge from the area east of Horse Creek occurs as underflow primarily to Hawk Springs Reservoir. Before Hawk Springs Reservoir was built in 1908, ground water discharged from Hawk Springs located by Adams (1902, pl. 8) at about the NW¼SE¼ sec. 9, T. 20 N., R. 61 W., and referred to as "***perhaps the largest so-called spring in Goshen Hole Country" (Adams, 1902, p. 27). There is no record of any measured discharge of the spring. The boundary of the model area crosses the reservoir at about the edge of the LaGrange aquifer. It is also near where Adams located Hawk Springs and where early maps show the apparent beginning of two creeks called Hawk Springs and Indian Springs.

Evapotranspiration includes all the water lost to the atmosphere by evaporation and by transpiration from plants. Evaporation from Hawk Springs Reservoir is not considered in this study because water in the reservoir is not used in the LaGrange area. Evapotranspiration losses from plants are included as part of the water consumptively used. However, evapotranspiration from ground water is considered as a separate discharge from the ground-water system in areas where the water table is less than 10 ft below land surface.

DIGITAL MODEL

The ground-water system in the LaGrange aquifer including boundaries, hydrologic properties, and stresses are represented mathematically by use of a digital-simulation model. The model was used to improve the conceptualization of the aquifer system and the imposed stresses and to predict the effects of hypothetical stresses on the aquifer system. With this model, the effects of ground-water pumpage from April 1973 to April 1978 and from April 1978 to May 1980 were simulated using a digital computer. These two periods will hereafter be referred to in this report as 1973-78 and 1978-80.

The flow of water in an aquifer generally is three dimensional with both horizontal and vertical components of flow present. The vertical-flow velocity within the LaGrange aquifer is assumed to be negligible in comparison to the horizontal-flow velocity. Jacob (1963) indicated that in an unconfined aquifer, the two-dimensional approximation is adequate if the gradient of the water table is small. This requirement is met in most of the model area and particularly in the area east of Horse Creek where water-table gradients average 5 ft/mi. In this area, larger water-table gradients can occur in the immediate vicinity of pumping wells;

however, in unconfined aquifers the two-dimensional approximation is considered valid by Hantush (1964) at distances greater than 1.5 times the prepumping saturated thickness. Also in this area, saturated thicknesses at irrigation wells before pumping range from about 70 to 180 ft. Thus the two-dimensional approximation of the LaGrange aquifer is assumed to be valid in this digital model in which the minimum finite-difference grid spacing is 1,000 ft.

Theoretical Basis

Using the two-dimensional aquifer approximation, the basis for the digital simulation model of the LaGrange aquifer is the following two-dimensional ground-water flow equation for an unconfined aquifer.

$$\frac{\partial}{\partial x}\left(Kb\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kb\,\frac{\partial h}{\partial y}\right) = S_y\,\frac{\partial h}{\partial t} + W \qquad (1)$$

where

K is K (x,y), hydraulic conductivity, in feet per second;
b is b (x,y,t), saturated thickness, in feet;
h is h (x,y,t), hydraulic head, in feet;
S_y is the specific yield, dimensionless;
t is time, in seconds;
W is W (x,y,t), the source-sink term, in feet per second; and
x,y are spatial variables, in feet.

The equation yields the two-dimensional distribution of hydraulic head within the aquifer as a function of location and time. This flow equation is derived from Darcy's law and the equation of continuity using the assumption that vertical-flow velocities throughout the aquifer are negligibe. In this equation, the variables K and h represent averages throughout the saturated thickness of the aquifer. The specific yield is assumed to be constant in time and space. Although specific yield may vary temporally and spatially in nature, the variations usually are sufficiently small to neglect without seriously affecting the accuracy of the solution to the flow equation. The source-sink term W includes recharge from precipitation and surface water, discharge to streams, and discharge from wells.

The solution of the flow equation for a particular aquifer requires specifying boundary conditions and initial conditions such as the distribution of hydraulic head at a particular instant of time, hydraulic conductivity, saturated thickness, and quantities of water produced by sources and sinks. In order to solve the flow equation for the hydraulic-head distribution as a function of the spatial variables and time, it is necessary to use numerical procedures which are an integral part of the ground-water flow model.

The theoretical development, documentation, and general computer program for this model used to simulate ground-water flow is explained by Trescott and others (1976). There is no general solution to the flow equation, so their model obtains a numerical solution to the equation through a finite-difference approach. A rectangular grid, referred to as a finite-difference grid, is superimposed over a map of the LaGrange aquifer as shown in plate 4. The intersection of the grid lines are called nodes. Each node is referenced to a block or cell whose boundaries are equidistant between nodes. This grid is referred to as a face-centered grid in contrast with block-centered grid where nodes are located at the center of each block. The general computer program was originally written for a block-centered grid but changes for the program to use the face-centered method were written by S. P. Larson (U.S. Geological Survey, written commun., 1978). At each of the nodes, the flow equations are replaced by finite-difference approximations from which a set of algebraic equations are produced that are solved iteratively on a digital computer using the strongly implicit procedure (Stone, 1968). The aquifer properties are assumed to be uniform within each cell although they may vary from cell to cell.

The general computer program by Trescott and others (1976) also has been modified to include a streamflow-accounting procedure described by Hoxie (1977, p. 21-24). This procedure allows designated stream cells of the finite-difference grid to either gain or lose water or to disconnect from and reconnect to the aquifer depending on the computed hydraulic heads. The rate of leakage to or from the stream cells depends on the vertical hydraulic conductivity of the streambed and the hydraulic-head difference between the stream and the aquifer. A cumulative total of the net flow in the stream is maintained, and leakage from a given stream cell is not permitted to exceed the calculated net flow in the stream at that cell.

Development

The development of the digital model of the ground-water system of the LaGrange aquifer begins with a finite-difference grid, the definition of boundary conditions, and compilation of hydrologic data for use in the model. Required at each of nearly 2,500 nodes of the finite-difference grid within the model area are altitudes of the potentiometric surface, the base of the aquifer, and the land surface; a value for hydraulic conductivity; a value for specific yield (for transient conditions); and a rate for recharge from precipitation. Required at specified nodes where leakage is simulated are an altitude of the stream or reservoir, thickness of the streambed or reservoir bed, a value for streambed or reservoir bed hydraulic conductivity, and an initial leakage rate for streams. Values for the rate of recharge from surface water or discharge from pumping wells are required at specified nodes.

Finite-Difference Grid

The finite-difference grid (pl. 4) used in the calibration and the transient simulations of the ground-water system in the LaGrange aquifer consists of 51 rows (i) and 55 columns (j). Reference in this report to a node or cell location is by row and column; for example, the location of the northernmost reservoir cell would be referred to as 14,10. Variable grid spacing was used with 1,000-ft as the minimum spacing. To minimize computer-core storage requirements, the spacing was increased toward the boundaries where there was less hydrologic control. The grid was oriented so that the direction of maximum changes in hydraulic conductivity and potentiometric-surface gradient were as perpendicular to the cell boundaries as possible, particularly in the area east of Horse Creek. This orientation also resulted in the northwest model boundary approximately paralleling the northwestern edge of the LaGrange aquifer. The finite-difference grid was aligned over the model area so that node locations would correspond as closely as possible to the location of observation and irrigation wells, particularly in the area east of Horse Creek.

Boundary Conditions

The location and type of boundary conditions used for this model are shown on the finite-difference grid (pl. 4). The no-flow boundary around the border of the model is automatically assigned and used by the computer program (Trescott and others, 1976, p. 30). Consequently, if no other boundary condition is specified, a no-flow boundary will automatically be assigned. This is the case for small parts of the northwestern boundary west of Horse Creek and also just west of Hawk Springs Reservoir where the Lance Formation crops out and a no-flow condition is assumed.

A constant-head boundary was used for most of the model because it was believed that either underflow into or out of the modeled area or recharge was sufficient to maintain nearly constant water-level altitudes at those points. Along the constant-head boundary, the values of the hydraulic heads at the nodes are maintained at their initial values throughout the simulation.

Reservoir cells along the eastern and southern edges of Hawk Springs Reservoir comprise a small part of the northwestern boundary of the model where leakage to or from the reservoir is simulated. The program was modified by D. T. Hoxie (U.S. Geological Survey, written commun., 1980) to allow the perimeter location and altitudes of the reservoir to change each pumping period during a computer simulation.

Data Requirements and Assumptions

After the finite-difference grid for the model area and the boundary conditions are defined, hydrologic data are required for the calibration and transient simulation of the model. The required hydrologic data and assumptions are discussed in this section.

Hydrologic data are determined for each node in the finite-difference grid for the model area. The value of the hydrologic data is assumed to be the average value for the cell area assigned to each node. For example, a value of 4,500 ft for the water-table altitude at a particular node is assumed to represent the average hydraulic head for that same area of aquifer in the real system. The area of each cell is calculated by the computer using the spacing in the i and j directions in the finite-difference grid. The spacing between nodes is uniformly 1,000 ft in most of the area except toward the boundaries where the spacing is increased geometrically by a factor of 1.5.

The potentiometric surface for April 1973 was assumed to approximate the potentiometric surface during steady-state conditions for the purpose of model calibration. The values for the altitudes of the potentiometric surface were obtained from plate 2. Comparison of water levels measured during 1949-51 with those measured during April 1973 show about a 1- to 3-ft difference. During 1949-51 ground-water pumpage was a negligible stress on the ground-water system. There was only one irrigation well in the area east of Horse Creek and eight irrigation wells in the total area.

The altitudes of the base of the LaGrange aquifer were obtained directly from plate 1. Control for the structure contours of the base of the LaGrange aquifer (pl. 1) consisted mostly of electric logs of wells or test holes drilled in 1978 or of test holes drilled by oil companies.

The LaGrange aquifer is assumed to be isotropic and nonhomogeneous with respect to hydraulic conductivity. An isotropic aquifer is one in which the hydrologic properties of the aquifer, such as hydraulic conductivity, do not vary with direction. A nonhomogeneous aquifer is one in which the hydrologic properties of the aquifer, such as hydraulic conductivity, may vary from location to location in the aquifer. Initial estimates of hydraulic conductivity for the steady-state calibration were obtained by the methods described previously. As a result of steady-state calibration, hydraulic conductivity during transient simulations ranged from 0.01 to 950 ft/d.

For the streamflow-accounting procedure, stream cells for Bear Creek and Horse Creek are designated as shown on plate 4, and the values of stream discharge at the upstream model boundaries are specified. Based on streamflow measurements of Horse Creek made in April 1979, the net streamflow gain in the reach from about the SE¼SW¼ sec. 3, T. 19 N., R. 61 W. to about the SW¼NW¼ sec. 28, T. 20 N., R. 61 W. was 6.5 ft^3/s. The net streamflow gain in the reach from about the SW¼NW¼ sec. 28, T. 20 N., R. 61 W. to about the SE¼SW¼ sec. 8, T. 20 N., R. 61 W. was estimated as 5.0 ft^3/s based on discharge measurements made in September 1978 and November 1979. These net streamflow gains are assumed to approximate the gain in streamflow during steady-state conditions assumed for April 1973. The average difference between water levels measured in the same wells in April 1973 and in April 1979 west of Horse Creek and near the east side of Horse Creek was less than 1 ft.

Recharge from precipitation is assumed to be 5 percent of the normal annual precipitation of 15.47 in. for steady-state calibration and 5 percent of the actual precipitation for the transient simulations. This recharge percentage is considered reasonable for use in model simulations based on a study in Laramie County by Morgan (1946, p. 19) and on estimates in Platte County studies by Morris and Babcock (1960, p. 64-65) and by Weeks (1964, p. 28).

The perimeter location of and leakage to or from Hawk Springs Reservoir is approximated in the model by the use of reservoir cells around the southern and eastern boundaries of the reservoir. The altitudes of the reservoir, estimated from the volume of water in storage, control the location and hydraulic heads of the reservoir leakage cells. The hydraulic head of the reservoir is the altitude of the water surface above sea level. The rate of leakage to or from the reservoir cells is dependent on the vertical hydraulic conductivity and thickness of the reservoir bed, and the hydraulic-head difference between the reservoir and the aquifer. For steady-state calibration, the reservoir altitude was 4,480.0 ft (pl. 2) and the location of the reservoir cells were as shown on the finite-difference grid (pl. 4). This was the approximate altitude and perimeter location of the reservoir in April 1973. For transient simulations, the reservoir altitude and the location of the reservoir cells are changed each time period to approximate the fluctuations of the reservoir. The 4,475-ft and 4,480-ft topographic contours on the LaGrange 7.5-minute quadrangle and shown on plate 2 were used as a basis for estimation of the reservoir perimeter location at different water-surface altitudes.

The specific yield is set at zero in the steady-state calibration. In the transient simulation a value of 0.10 was used.

Ground-water pumpage data for the 1973-78 and 1978-80 transient simulations were estimated by dividing the power consumption into the total kilowatt hours used during a specified time. Electric-power information was obtained from the Rural Electric Association in Lingle, Wyo. The power consumption (kilowatt hours of power used to pump 1 acre-ft of water) was calculated using well discharge and the electric-power use. Well discharges and electric-power use measured during 1972-73 and 1978 were used to calculate power consumption for 1973-79. During 1978, most well discharges and electric-power uses were measured for many of the irrigation wells and all the Conservation District wells. In-line, total-flow meters were used on the Conservation District wells during 1978 and 1979. For the Conservation District wells, ground-water pumpage estimated from power consumption and total ground-water pumpage recorded by the flow meters were within 7 percent during 1978 and within 0.5 percent during 1979. Therefore, it is reasonable to assume that ground-water pumpage estimated from well discharge and electric-power use is adequate for the purposes of this model. Most of the ground water pumped in the LaGrange area is applied to the land using center-pivot sprinkler systems. The quantity of ground-water pumped from irrigation wells that returns to the aquifer is assumed to be negligible. The quantity applied generally was less than the consumptive irrigation requirements estimated for the most common crops (Trelease and others, 1970, p. 52).

Pumpage for wells is simulated at the nodes identified on the finite-difference grid (pl. 4) as pumpage nodes or water-level and pumpage nodes. The pumpage simulated at each of these nodes is the total pumpage from one or more Conservation District or irrigation wells that are within the area of the cell assigned to the particular node. In order to simplify the finite-difference grid, pumpage nodes are shown rather than pumpage cells. In the model, pumpage is simulated at the node for the total area of the cell just as recharge from surface-water irrigation is simulated for the total area of a surface-water recharge cell.

The cells identified on the finite-difference grid (pl. 4) as surface-water recharge cells approximate the area irrigated by surface water (see fig. 2). Under transient conditions, 40 percent of the water diverted onto these areas is assumed to recharge the aquifer. This percentage of recharge is comparable to the apparent percentage in the

North Platte River Valley, which was estimated to be 36 percent of the total surface water diverted by canals (Crist, 1975, p. 25). Because of the possibility of error in the estimate of surface water diverted by Horse Creek No. 1 Ditch, evaporation losses are ignored, and the total estimated surface water diverted is assumed to recharge the LaGrange aquifer. A seepage run on the Horse Creek No. 1 Ditch in April 1979 indicated that 25 percent of the flow in the ditch is lost between the southwest corner of sec. 35, T. 20 N., R. 61 W. and Pasture Reservoir. The remaining 75 percent of the flow enters Pasture Reservoir, where it is either released from the reservoir onto lands to the north or percolates downward beneath the reservoir. Relatively rapid infiltration properties of the reservoir bottom were indicated by a test hole in the northwestern part of Pasture Reservoir (pl. 1) that penetrated generally very fine to fine sand and silty sand from 0 to 14 ft overlying the White River Group.

In the general program of Trescott and others (1976, p. 7-9), evapotranspiration from the ground-water reservoir is treated as a linear function of the depth to water below land surface. It is assumed that the maximum rate of evapotranspiration is equal to the potential evapotranspiration rate and occurs when the water table is at land surface. The evapotranspiration rate is assumed to decrease linearly to zero where the water table is 10 ft below land surface. For LaGrange, the potential evapotranspiration rate estimated by the U.S. Department of Commerce and U.S. Department of Agriculture (written commun., 1978) is about 0.01 ft/d. Any losses from ground water due to phreatophytes are assumed to be included in the losses attributed to evapotranspiration where the water table is less than 10 ft below land surface. Evapotranspiration is included in the steady-state approximation because in April 1973 water levels were within 10 ft of land surface in several areas, and the potential for evapotranspiration exists at that time of the year.

Steady-State Procedures

Steady-state procedures are part of model calibration in order to demonstrate that the model realistically simulates the ground-water system. In this study, calibration refers to the processes in which the hydrologic data used in the model are adjusted, generally by trial and error, to minimize the difference between the measured data and the calculated values using either steady-state or transient simulations. This is an evolutionary process in which successive adjustments and modifications to the model are based on the results of previous simulations.

The steady-state calibration is useful to eliminate erroneous data, demonstrate the numerical accuracy of the model, and, most importantly, to refine the data used in the model. All parameters in the model, except for the hydraulic conductivity of the aquifer, are assumed to be correct for steady-state conditions. The hydraulic-conductivity distribution is repeatedly adjusted by trial and error until hydraulic heads calculated by the model are similar to interpolated hydraulic heads at water-level nodes near to or at wells. When this occurs, the hydraulic-conductivity distribution produces an internally consistent steady-state simulation and steady-state calibration is complete.

One method of judging the agreement between calculated and interpolated hydraulic heads is the use of the rms (root-mean-square) deviation, r, defined as:

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

where

n is number of water-level nodes;
i is an index by which nodes are numbered from 1 to n;
h_i is the calculated value of hydraulic head, in feet, at node i; and
h_i^o is the interpolated value of hydraulic head, in feet, at node i.

For steady-state simulation, the rms deviation is a measure of the mean departure of the calculated hydraulic heads from the interpolated hydraulic heads at only water-level nodes. In the finite-difference grid, these nodes are near to or at the location of each well where water-level data were collected. If the rms deviation is calculated using hydraulic heads at all the nodes in the model, it may have a variability or error introduced from water-level-contouring interpretations, especially where wells are widely spaced.

The steady-state calibration of the model for the LaGrange aquifer resulted in calculated steady-state hydraulic heads that depart from the interpolated hydraulic heads at water-level nodes in the specified areas with rms deviations as follows:

		Interpolated hydraulic heads versus calculated hydraulic heads		Measured hydraulic heads versus calculated hydraulic heads	
Area	No. of wells	Root-mean-square deviation (feet)	Maximum departure (feet)	Root-mean-square deviation (feet)	Maximum departure (feet)
East of Horse Creek	20	1.7	4.4	1.6	3.5
West of Horse Creek	13	1.5	4.5	3.8	7.5
Remaining area	22	3.5	8.1	5.8	9.9
Total area	55	2.5	8.1	4.2	9.9

To simplify the discussion of the model results and hydrology in this report, the following terminology is used for the specified areas: Total area refers to all of the model area except north of and including Sixtysix Mountain and the part of the model in Nebraska; area east of Horse Creek or area of principal interest and area west of Horse Creek are shown in figure 2; remaining area refers to all the rest of the total area.

The interpolated hydraulic heads at water-level nodes were obtained from plate 2 and were used for initial conditions in the model. The measured hydraulic heads were determined directly from water levels measured at the wells at or near water-level nodes. The rms deviation was calculated using both types of hydraulic heads to illustrate the possible effects on the rms deviation of hydraulic-head differences between nodes and wells whenever the two did not coincide. The similarity between the rms deviation calculated using interpolated and measured hydraulic heads in the area east of Horse Creek reflects the attempt to align the finite-difference grid over that area with well locations coinciding with nodes where possible.

The calculation of the rms deviation does not include any wells around the edge of Sixtysix Mountain or in the south corner of the model where steep potentiometric-surface gradients exist. The absolute difference between the calculated hydraulic-head distribution and the interpolated hydraulic-head distribution around the edge of Sixtysix Mountain generally was less than 10 ft. This difference proved to be of no significance to the model calibration because the smaller values of hydraulic conductivity used around Sixtysix Mountain resulted in nearly a zero-flow boundary. Thus no attempt was made during calibration to improve the model simulation adjacent, beneath, and north of Sixtysix Mountain.

Based on the rms deviation calculated at water-level nodes throughout the model area, the model simulation of the steady-state hydraulic-head distribution was considered to be satisfactory. The calculated steady-state streamflow gain for Horse Creek was 9.5 ft^3/s. For the gaining reach of Horse Creek from about the SE¼NW¼ sec. 3, T. 19 N., R. 61 W. to about the SW¼NW¼ sec. 28, T. 20 N., R. 61 W., the streamflow gain calculated by the model was 5.8 ft^3/s. This is within about 10 percent of the measured gain. The calculated discharge to the reservoir was 4.3 ft^3/s.

Under steady-state conditions, the following water budget is estimated for the ground-water system in the LaGrange aquifer:

Recharge	
Sources	Rates (cubic feet per second)
1. Precipitation	5.2
2. Underflow	34.8
Total	40.0

Discharge	
Sources	Rates (cubic feet per second)
1. Discharge to streams	
Horse Creek	9.5
Bear Creek	.6
2. Leakage to reservoir	4.3
3. Underflow	19.7
4. Evapotranspiration	5.9
Total	40.0

Part of the calibration procedure involves sensitivity analysis of the model in order to indicate the effect of variation in parameters on the calculated solution. The sensitivity analysis is performed by changing only one parameter and maintaining all other model parameters at their calibrated values. The results of the steady-state sensitivity analysis are presented in table 2. The sensitivity analysis indicates that calculated hydraulic heads east of Horse Creek are most sensitive to a change in the reservoir hydraulic head. However, calculated aquifer discharge is sensitive to changes in any of the three parameters.

Table 2.--Results of sensitivity analysis of the model using steady-state simulations.

Evapotranspiration: Percent of steady-state value 100	Evapotranspiration: Percent of steady-state value 0	Hydraulic conductivity: Percent of steady-state value 125	Hydraulic conductivity: 100	Hydraulic conductivity: 75	Reservoir altitude (feet) 4480.0	Reservoir altitude (feet) 4472.5	Root-mean-square deviation (feet): East of Horse Creek	West of Horse Creek	Remaining area	Total area	Aquifer discharge (cubic feet per second): Horse Creek	Reservoir
X	--	--	X	--	X	--	1.7	1.5	3.5	2.5	9.5	4.3
--	X	--	X	--	X	--	1.8	1.8	3.4	2.6	13.3	5.7
X	--	X	--	--	X	--	1.7	1.4	3.6	2.6	12.1	5.5
X	--	--	--	X	X	--	1.7	1.6	3.4	2.5	6.8	3.1
X	--	--	X	--	--	X	2.1	1.5	3.5	2.6	9.1	5.2

Transient Procedures

The digital model of the ground-water system was further calibrated using transient simulations. The hydraulic-conductivity distribution resulting from the steady-state calibration is used in the transient simulations. In transient simulations, the various discharge and recharge parameters in the model can vary with time. Storage properties of the aquifer, indicated by specific yield, also are included. Thus, in transient simulations, the model attempts to reproduce aquifer response to time-dependent stresses.

Transient Simulation, 1973-78

The ground-water system was simulated under transient conditions from April 1973 to April 1978. In order to approximate the changing altitude and perimeter location of Hawk Springs Reservoir, the 5 years were divided into 12 time periods each simulating from 3 to 7 months of changes in the physical system. The altitude of the reservoir was used as the primary criterion for selecting time periods to be simulated. Altitudes of the reservoir higher than 4,475 ft were considered high and less than 4,475 ft were considered low. The area of Hawk Springs Reservoir at an altitude of 4,475 ft is shown on plate 2. The available data for estimating pumpage also were criteria for selecting the time periods. Generally, the first reading of the electric-power meters was not made until late June. The estimate of pumpage from the Conservation District wells prior to July was made using a value of kilowatt hours, possibly representing one or several months of pumping.

Periodic measurements of reservoir altitude were made and reservoir storage volumes were determined by James Ward (written commun., 1980). Using these reservoir-storage volumes, monthly average storage and altitudes were estimated (fig. 10). The monthly average reservoir altitude was estimated using the Hawk Springs Reservoir capacity table and a silt-volume correction and decreasing this altitude by 5 ft. This decrease resulted from a 5-ft difference between reservoir altitudes measured at the reservoir dam and reservoir altitudes measured at observation wells in the southeastern part of the reservoir in 1980. Therefore, reservoir altitudes determined from reservoir volume were decreased by 5 ft so that the altitude of the reservoir used in the model would be related to the same reference point as the hydraulic heads for wells in and near the reservoir. For each simulation period, the average monthly reservoir altitude was used at reservoir cells approximating the estimated perimeter of the reservoir. In addition, values for recharge from precipitation and surface water, and values for ground-water pumpage were determined as described in the section on data requirements and assumptions and are summarized in table 3.

Table 3.--Summary of data used in 12 simulation periods, 1973-78.

Simulation period number	Time period simulated	Reservoir altitude (feet)	Recharge from precipitation (inches)	Recharge from surface water (acre-feet)	Ground-water pumpage (acre-feet)
1	4/73 - 7/73	4,480.0	0.4	3,650	3,610
2	8/73 - 10/73	4,472.7	.2	2,120	2,560
3	11/73 - 3/74	4,481.1	.2	690	0
4	4/74 - 7/74	4,479.1	.3	3,010	4,050
5	8/74 - 2/75	4,466.4	.1	4,250	4,930
6	3/75 - 7/75	4,478.8	.3	3,020	4,190
7	8/75 - 2/76	4,464.0	.2	2,870	8,010
8	3/76 - 6/76	4,476.4	.3	2,560	1,450
9	7/76 - 10/76	4,463.4	.2	2,410	10,280
10	11/76 - 3/77	4,465.0	.2	1,600	0
11	4/77 - 10/77	4,465.3	.6	5,220	10,560
12	11/77 - 3/78	4,458.7	.2	1,480	0

Transient calibration of the model using the 1973-78 data included several computer simulations in which only specific yield was varied. These simulations provided a sensitivity analysis of the model to specific yield and indicated an approximate value of specific yield to use in subsequent simulations.

For transient simulations, the rms deviation was computed from the calculated and measured 1978 hydraulic heads assigned to the water-level nodes shown on plate 4. A graph of the rms deviations for the specific yield values in figure 11 indicates that a specific yield between 0.05 and 0.15 gives the best model results. A value of 0.10 was judged to be appropriate for this model based on the transient-calibration results. This value compares favorably with 0.13 determined for specific yield previously. The data in the graph also indicate that the model is relatively insensitive to specific yield. However, the small differences among the rms deviations for the various specific yields for the area west of Horse Creek and for the remaining area are, to some degree, indicative of small changes in storage in the aquifer from 1973-78.

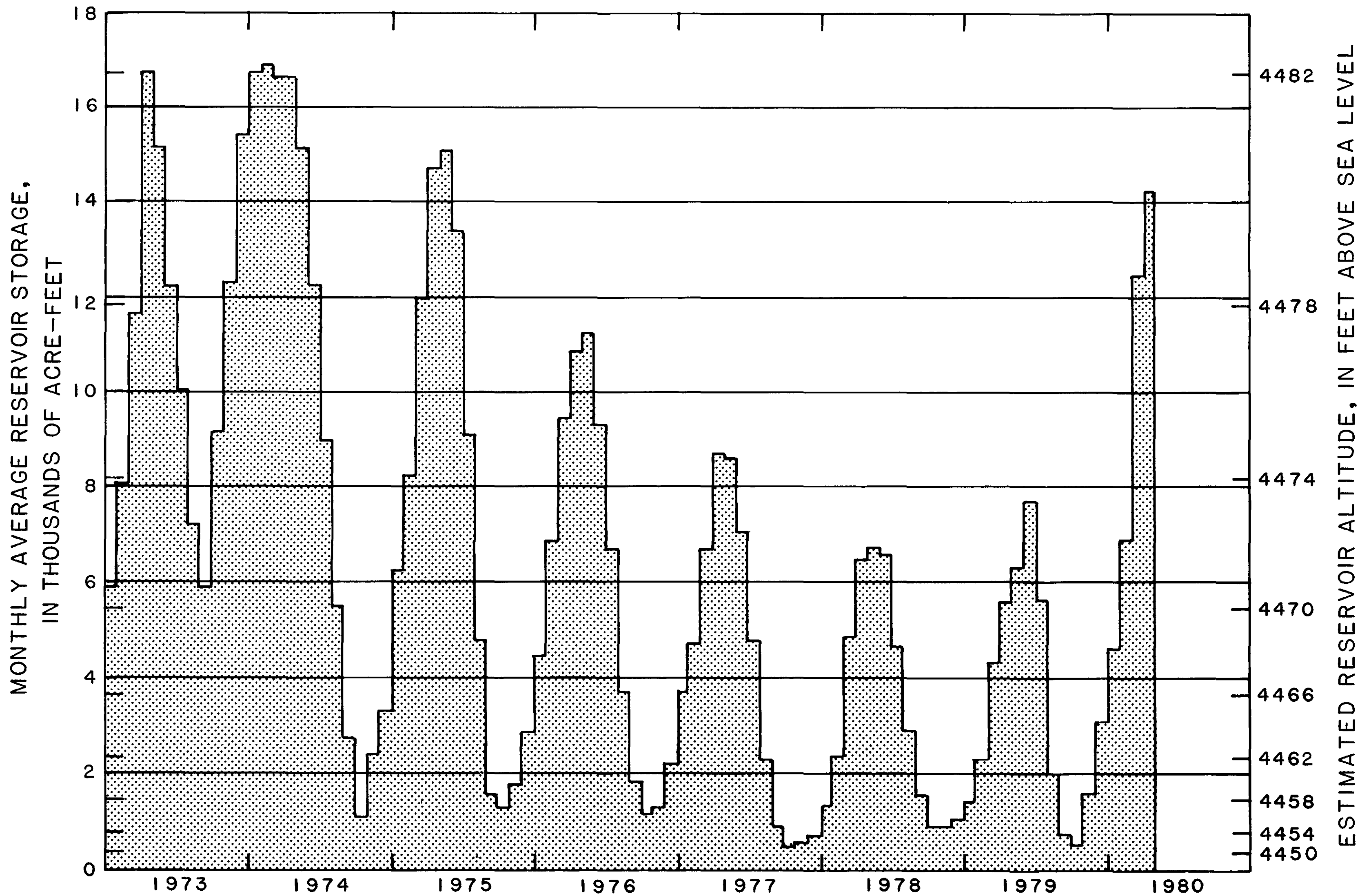


Figure 10.--Estimated monthly average storage and altitude of Hawk Springs Reservoir, 1973-80.

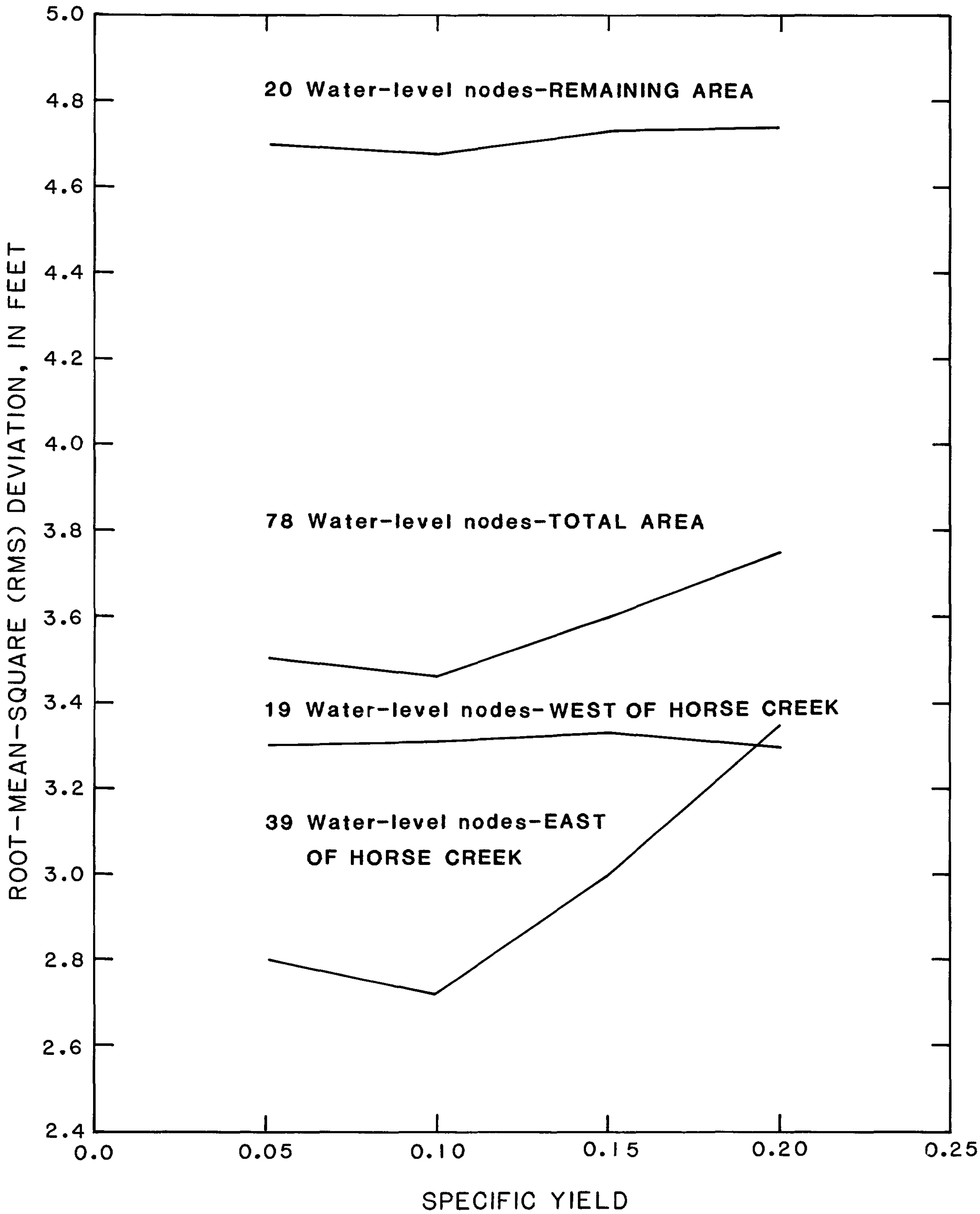


Figure 11.--Root-mean-square deviations computed from calculated versus measured hydraulic heads at water-level nodes in selected areas of the model for different values of specific yield used in 1973-78 transient simulations.

Using a value of 0.10 for specific yield, and the transient data summarized in table 3, the model calculated the hydraulic heads for 1973-78. The calculated and measured water-level fluctuations between 1973 and 1978 at six sites are shown in figures 12-14. The calculated water-level fluctuations are for water-level nodes assigned to coinciding observation wells. The match between the calculated and measured fluctuations is satisfactory considering that the extreme water-level changes are averaged out by the model. For example, ground water pumped from a well is withdrawn from virtually a small point with the cone of depression radiating outward from that point. In the model, pumpage results in water removed from the total area of the pumping cell instantaneously and the calculated water-levels represent the average water level for the whole area of the pumping and non-pumping cells. A slight variation between calculated and measured water levels may result from the manner in which the data for each of the simulation periods reflect the actual conditions in the aquifer system. In addition, the actual location of the observation wells and pumping wells may differ slightly from their location with respect to each other in the model.

The measured 1978 water levels provide a good basis for comparison with the model results because, as spring measurements, they are fairly stable and represent the net effects of recharge to and discharge from the ground-water system. The calculated 1978 water levels also are representative of the net effects of all the recharge and discharge simulated for 1973-78. The calculated 1978 hydraulic heads depart from the measured 1978 hydraulic heads at the water-level nodes in the specified areas with rms deviations as follows:

Area	No. of wells	Root-mean-square deviation (feet)	Maximum departure (feet)
East of Horse Creek	42	2.6	6.9
West of Horse Creek	19	3.3	10.3
Remaining area	22	5.6	10.9
Total area	83	3.8	10.9

Potentiometric-surface contours based on measured and calculated 1978 water levels are in good agreement (figs. 15 and 16) for the areas east and west of Horse Creek where ground-water development is extensive. In the area east of Horse Creek at 17 water-level nodes, the average calculated 1973-78 drawdown (6.0 ft) and the average measured 1973-78 drawdown (6.2 ft) showed agreement within 0.2 ft.

For April 1978, the calculated discharge from the aquifer to Horse Creek was 10.8 ft^3/s and to the reservoir 4.2 ft^3/s. For the gaining reach of Horse Creek from about the SE¼NW¼ sec. 3, T. 19 N., R. 61 W. to about the SW¼NW¼ sec. 28, T. 20 N., R. 61 W., the streamflow gain calculated by the model was 6.2 ft^3/s.

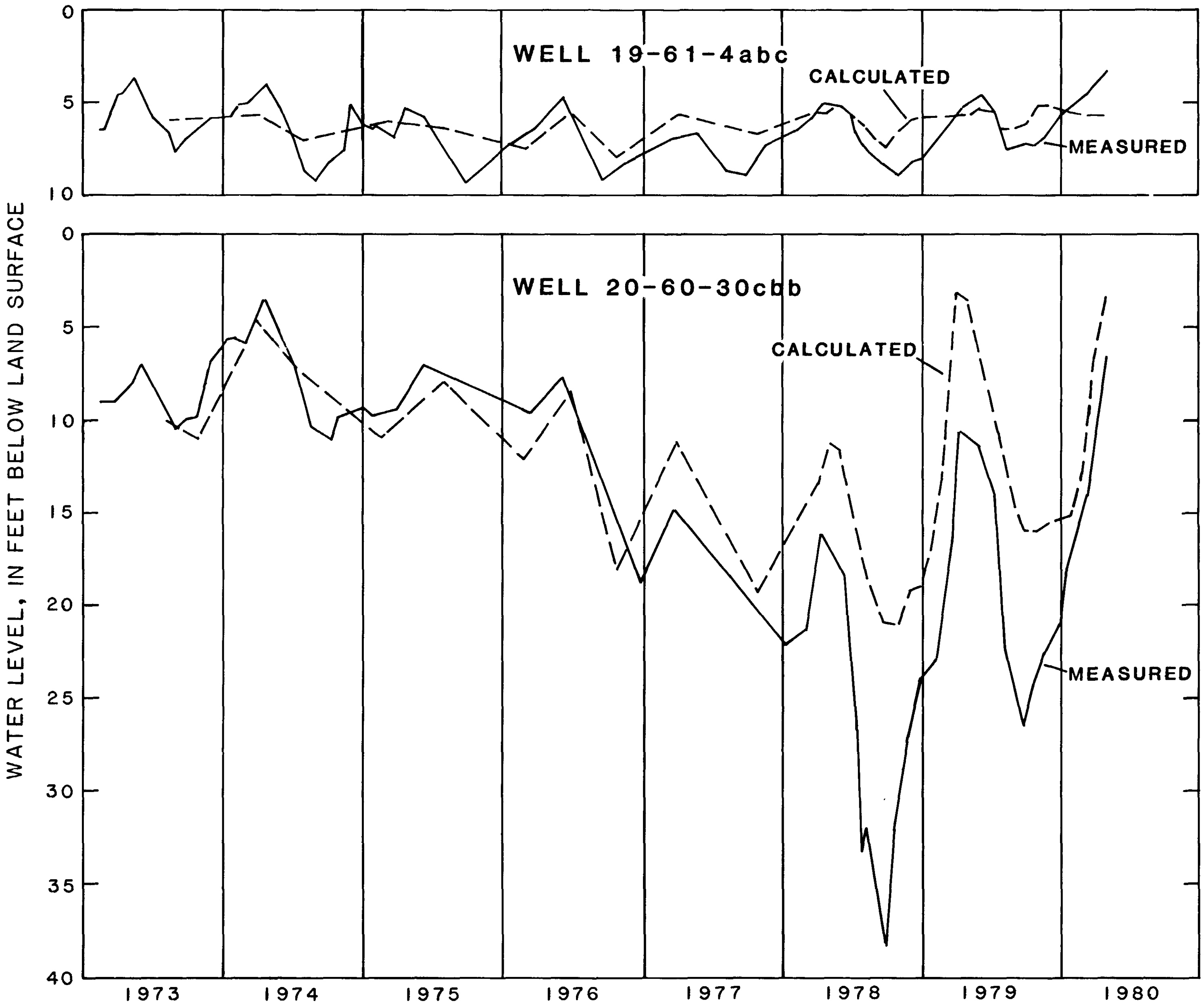


Figure 12.--Calculated and measured water-level fluctuations at wells 19-61-4abc and 20-60-30cbb, 1973-80.

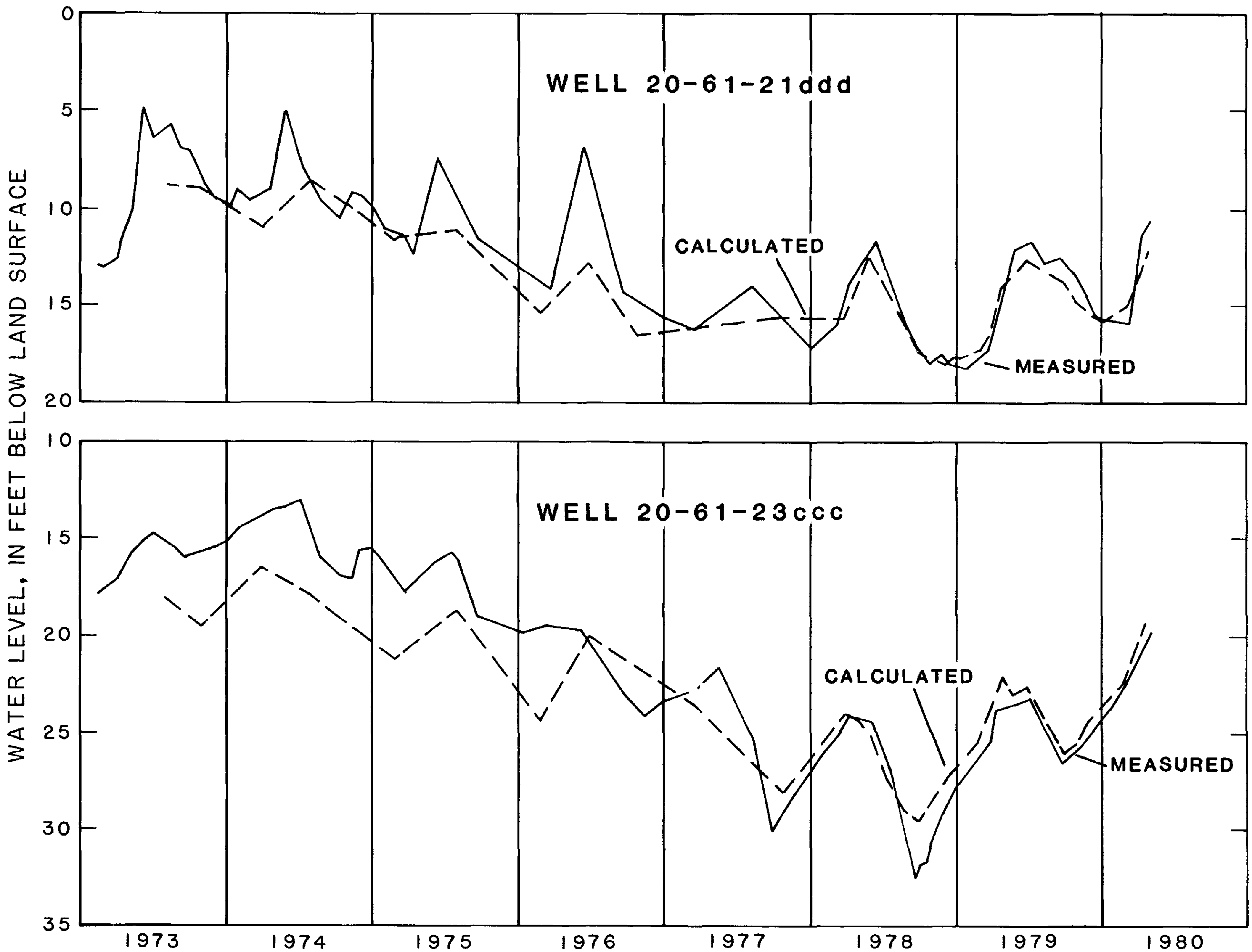


Figure 13.--Calculated and measured water-level fluctuations at wells 20-61-21ddd and 20-61-23ccc, 1973-80.

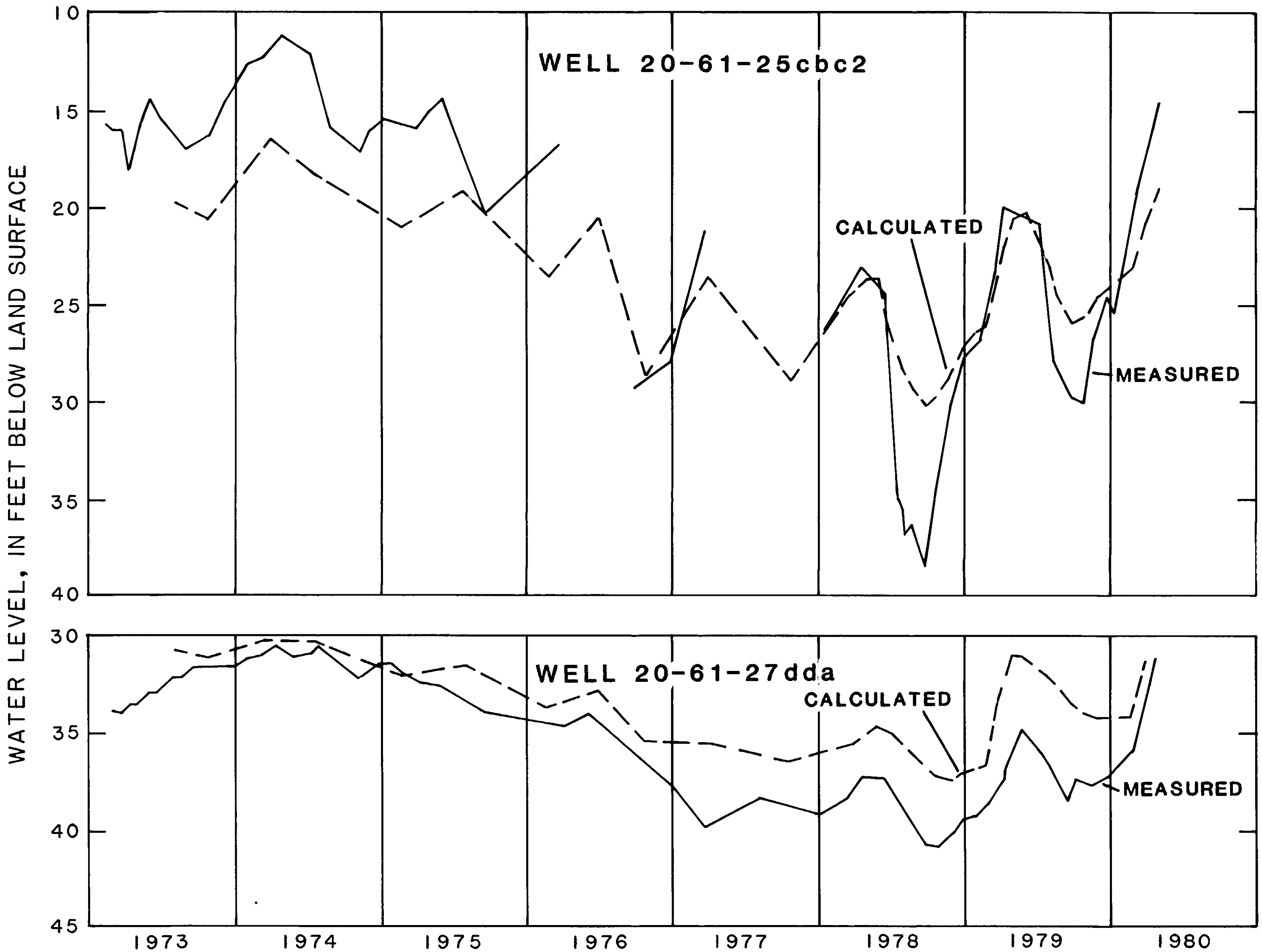
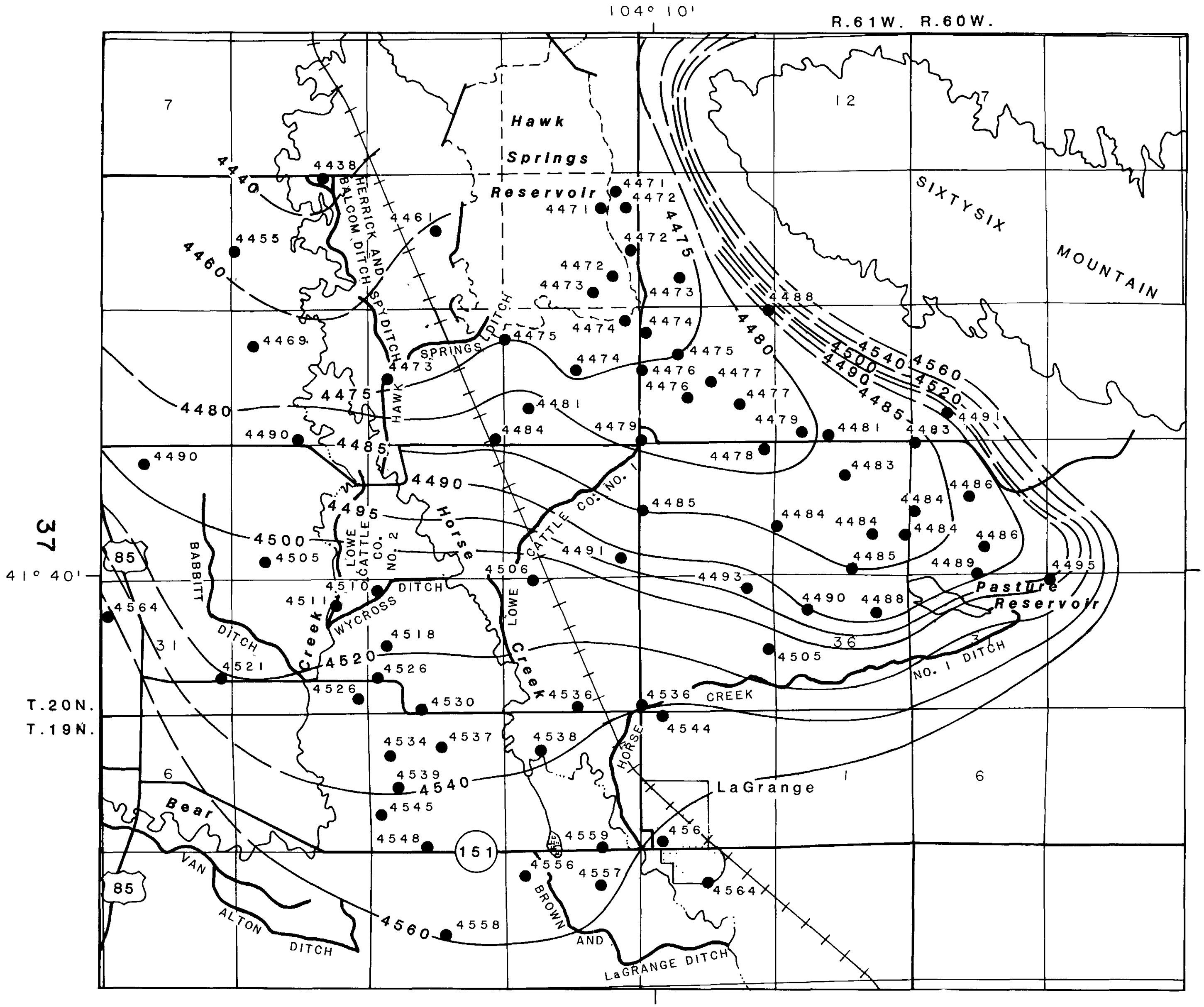


Figure 14.--Calculated and measured water-level fluctuations at wells 20-61-25cbc2 and 20-61-27dda, 1973-80.



EXPLANATION

—— 4560 — — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, April 1978. Dashed where approximately located. Contour interval 20 feet; 5 feet in most of the area east of Horse Creek. Datum is sea level

● 4495 WATER-LEVEL CONTROL POINT--Number is altitude of water level, in feet above sea level

Figure 15.--Potentiometric-surface contours based on measured water levels for the LaGrange aquifer in the areas east and west of Horse Creek, April 1978.

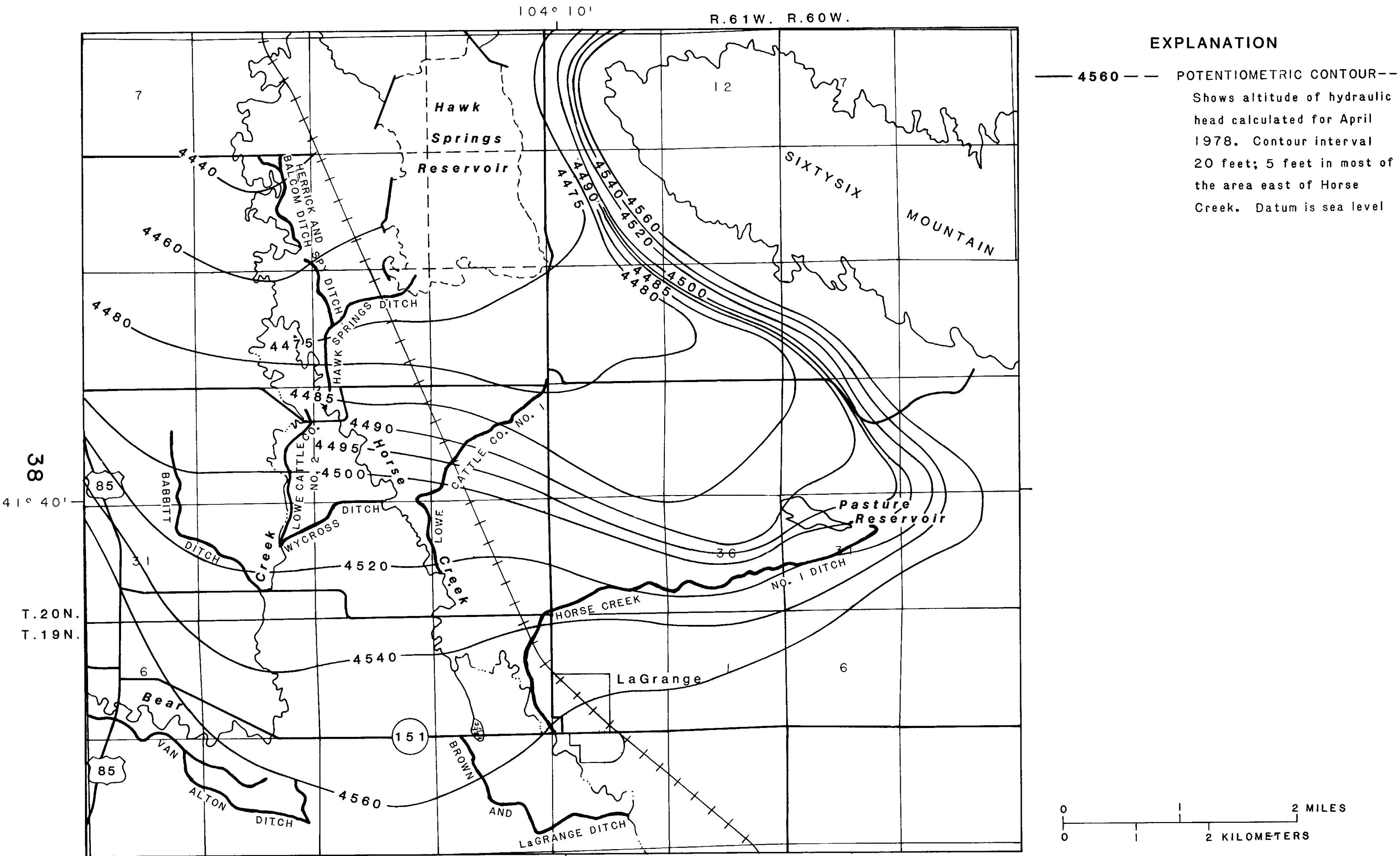


Figure 16.--Potentiometric-surface contours based on calculated water levels for the LaGrange aquifer in the areas east and west of Horse Creek, April 1978.

The reasonably good agreement between the calculated 1978 hydraulic heads and the measured 1978 hydraulic heads indicates that the model adequately simulates the ground-water system in the vicinity of the observation wells. In addition to the rms deviation, the favorable comparison between the average calculated 1978 drawdown and the average measured 1978 drawdown also indicates the model adequately simulates the area of principal interest.

Further sensitivity analysis was made in addition to those tests in which different values of specific yield were used with the 1973-78 transient simulations. The results of the additional sensitivity analysis of the model using the 1973-78 transient simulation with a specific yield of 0.10 are shown in table 4. For the area east of Horse Creek, a greater average difference between the calculated and measured hydraulic heads at the 42 water-level nodes is indicated by larger rms deviations for simulations 2-4 than for simulation 1. The rms deviation indicates how closely the calculated results compare to the measured results. However, the average calculated drawdown east of Horse Creek is the difference between the 1973 calculated steady-state hydraulic head and the 1978 calculated hydraulic head. This drawdown indicates the hydraulic-head change resulting from the model response to the parameter change. The difference between 1973 and 1978 water levels measured in the same 17 wells assigned to the 17 water-level nodes was used to determine an average drawdown of 6.2 ft east of Horse Creek.

Table 4.--Results of sensitivity analysis of the model using 1973-78 transient simulations with a specific yield of 0.10.

Run No.	Recharge from precipitation, Percent of 12.80 inches per year: 6	5	Ground-water pumpage, Percent of value used in 1973-78 transient simulation: 120	100	Horse Creek No. 1 diversion ditch, Percent of value used in 1973-78 transient simulation: 100	40	Root-mean-square deviation (feet): East of Horse Creek	West of Horse Creek	Remaining area	Total area	Aquifer discharge (cubic feet per second): Horse Creek	Reservoir	Average calculated drawdown east of Horse Creek using 17 water-level nodes (feet)
1	--	X	--	X	X	--	2.6	3.3	5.6	3.8	10.8	4.2	6.0
2	--	X	--	X	--	X	3.7	3.3	5.6	4.2	10.4	3.7	9.4
3	X	--	--	X	--	X	3.7	3.3	5.6	4.2	10.7	3.8	9.2
4	--	X	X	--	X	--	3.0	3.3	5.6	3.9	10.1	3.6	8.2

Simulation 1 represents the previously discussed calibrated transient simulation in which precipitation varied as actual precipitation varied 1973-78 and averaged 12.80 in. per year. In this simulation, the recharge from precipitation was equivalent to 5 percent of 12.80 in. per year, 40 percent of the surface water was recharge, 100 percent of the ground-water pumpage was discharge, and 100 percent of the water diverted by Horse Creek No. 1 Ditch was recharge. In simulation 2, the recharge from Horse Creek No. 1 Ditch was decreased to 40 percent to test the transient response of the model to decreased recharge east of Horse Creek. This change resulted in a decrease of recharge to the area east of Horse Creek by about 5,600 acre-ft. The decrease to 40 percent was selected to illustrate the model response assuming water diverted by

Horse Creek No. 1 Ditch would be either decreased significantly by a lack of streamflow in Horse Creek or used to irrigate crops, in which case 40 percent of the volume diverted was assumed to recharge the aquifer. In simulation 3, recharge from Horse Creek No. 1 Ditch was decreased to 40 percent, and recharge from precipitation was increased to 6 percent of the 12.80 in. per year which is equivalent to 5 percent of the annual normal precipitation of 15.47 in. per year. In simulation 4, recharge and discharge were the same as in simulation 1 except that ground-water pumpage was increased by 20 percent or approximately an additional 10,000 acre-ft from April 1973 to April 1978. Because 56 percent of the total pumpage from the LaGrange area during 1973-78 was from wells in the area east of Horse Creek, the additional discharge from the aquifer east of Horse Creek used in simulation 4 was about 5,600 acre-ft during 1973-78. A ground-water pumpage increase was used because the pumpage estimate in simulation 1 was based on measurements made in August 1978, and it is assumed that pumpage may be underestimated. The 20-percent pumpage increase also resulted in a discharge stress nearly equal to the recharge stress caused by the 40-percent decrease of recharge from Horse Creek No. 1 Ditch in simulation 2. The change in the total volume of recharge to or discharge from this area was about 5,600 acre-ft.

For the area east of Horse Creek, the sensitivity analysis indicates that in the model the increased pumpage from wells and the decreased recharge from Horse Creek No. 1 Ditch each separately cause the calculated aquifer discharge to the reservoir to decrease nearly the same. However, greater calculated drawdowns were caused by the decreased recharge than by the increased pumpage. The decreased recharge is a stress in the model that is more concentrated than the more evenly distributed stress resulting from the increased pumpage.

This sensitivity analysis indicates the model responds to different input parameters, each with a degree of uncertainty attached to their estimate. It is not known to what degree possible errors in the estimate of each parameter may balance out the error in another parameter, such as with pumpage and surface-water recharge. However, the result of the combination of parameters is illustrated by the similarity between calculated and measured hydraulic heads in the 1973-78 simulation.

Transient Simulation, 1978-80

In order to further assess the predictive capability of the model, a short-term, 25-month transient simulation was made with the model. The ground-water system was simulated from April 1978 to May 1980. Water-levels in most of the wells in the areas east and west of Horse Creek were measured on April 30, 1980. For this date, the potentiometric surface and the area of Hawk Springs Reservoir at an altitude of about 4,480 ft is shown in plate 3. The 25 months were simulated in the model by 25 periods, each simulating 1 month of change in the physical system. The calculated hydraulic-head distribution for April 1978 was used for the initial conditions. For each month, the monthly average altitude of Hawk Springs Reservoir was estimated and used at reservoir cells approximating the perimeter of the reservoir. Ground-water pumpage during each month was estimated so that the corresponding simulation period in the model would have pumpage stress similar to that in the physical system.

For the Conservation District wells, monthly values of ground-water pumpage during 1978 were determined from weekly readings of in-line flow meters. Most of the readings were made by Pete Gibbs with the Horse Creek Conservation District. Monthly pumpage during 1979 was estimated from the electric-power records. The total pumpage estimated from the electric-power records for 1979 was within 0.5 percent of the total pumpage determined from the total-flow meters and reported by the Horse Creek Conservation District (Wyoming State Engineer, written commun., 1980). The 1978-80 estimated monthly ground-water pumpage, diversions from Horse Creek No. 1 Ditch, and average reservoir altitudes used in the model are shown in figure 17. The annual volume of surface-water diversions is included in table 1.

The results of the simulated monthly changes in precipitation, surface-water application, ground-water pumpage, and reservoir altitude and perimeter location are shown in figures 12-14 and figure 18. These figures show the calculated and measured monthly water-level fluctuations at observation wells. Because of the greater water-level changes occurring east of Horse Creek, most of the hydrograph comparisons are made for wells in that area.

Generally, the calculated monthly water-level fluctuations satisfactorily represent measured fluctuations. This is particularly true for wells 20-61-21ddd and 20-61-23ccc in figure 13. Water-level fluctuations are not as large at both wells as at other locations. Water-level fluctuations at well 20-61-21ddd are affected more by surface-water recharge than by ground-water pumpage. Land in the vicinity and upgradient of the well are irrigated by surface water diverted by Lowe Cattle Co. No. 1 Ditch (fig. 2). Water-level fluctuations in well 20-61-23ccc are predominately affected by ground-water pumpage. This well is downgradient from many of the irrigation wells east of Horse Creek, therefore, the water-level fluctuations seem to be representative of the average changes throughout the area. The water-level decline from 1973-78 in well 20-61-23ccc was within 1 ft of the average decline for 17 wells in the area east of Horse Creek.

Water-level fluctuations in well 20-60-30cbb reflect both surface-water recharge and ground-water pumpage. This observation well is located downgradient from Pasture Reservoir where most of the diversion by Horse Creek No. 1 Ditch is collected and at times released to the north (see fig. 2), inundating land near the well. This also is in the area where the largest seasonal water-level declines occur (fig. 19).

The hydrographs in figure 18 are for wells located in the area east of Horse Creek where water-level declines from April to October 1978 exceeded 15 ft. Wells 20-61-15dcd2 and 20-61-23bdb2 are on opposite sides of and about 2,000 ft from the north-trending axis through the Conservation District wells. The hydrographs of measured water levels show a water-level decline of 7.2 ft from April to June in well 20-61-15dcd2 and a decline of 3.5 ft in well 20-61-23bdb2.

The cone of depression around the Conservation District wells from April 10 to June 12, 1978, was elliptically shaped with the long axis of the elliptical cone trending north and the shorter axis trending east. Observation well 20-61-15dcd2 is located near the east-west axis of the

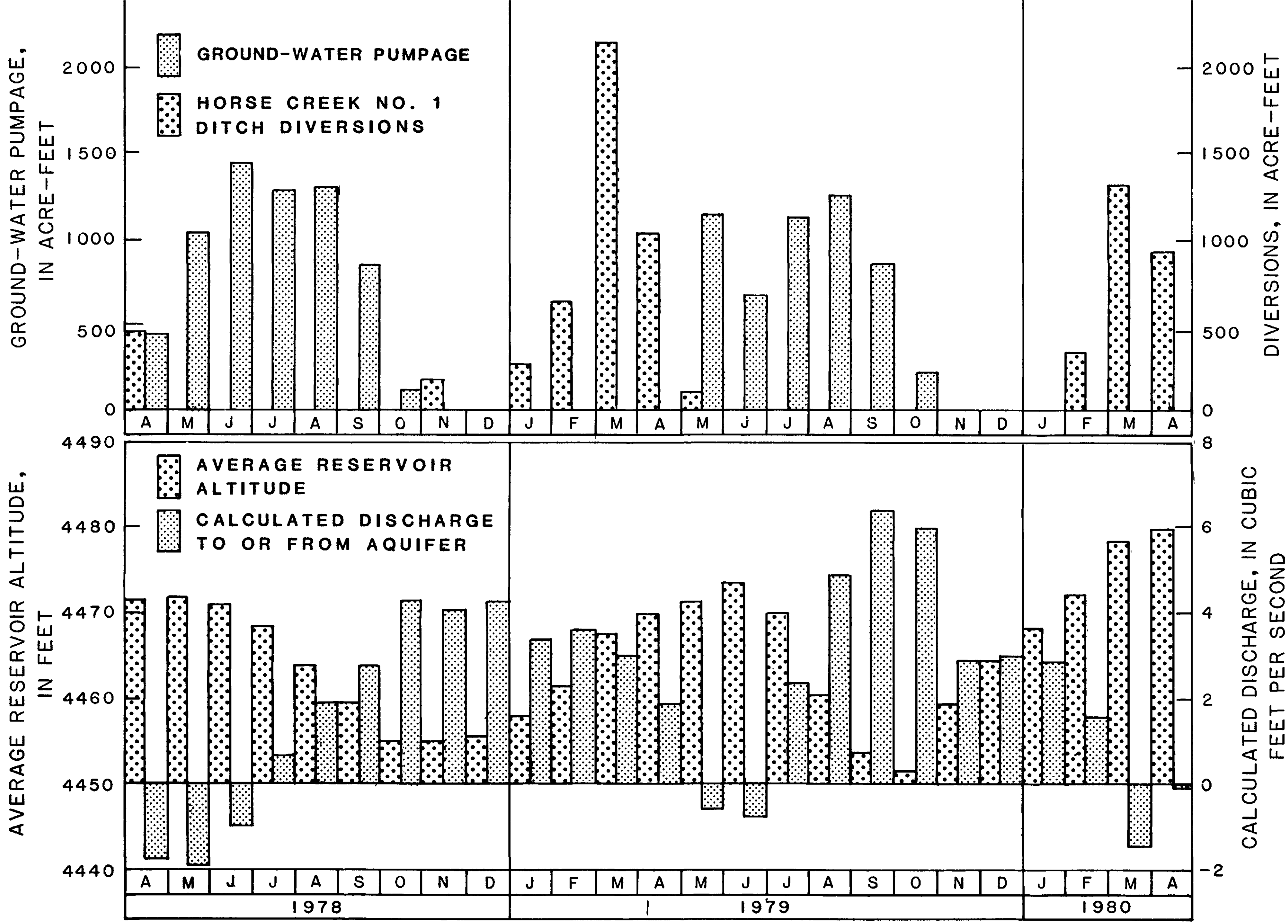


Figure 17.--Estimated monthly ground-water pumpage, Horse Creek No. 1 Ditch diversions, average reservoir altitude, and calculated discharge in the area east of Horse Creek (+, from aquifer to reservoir; -, from reservoir to aquifer), 1978-80.

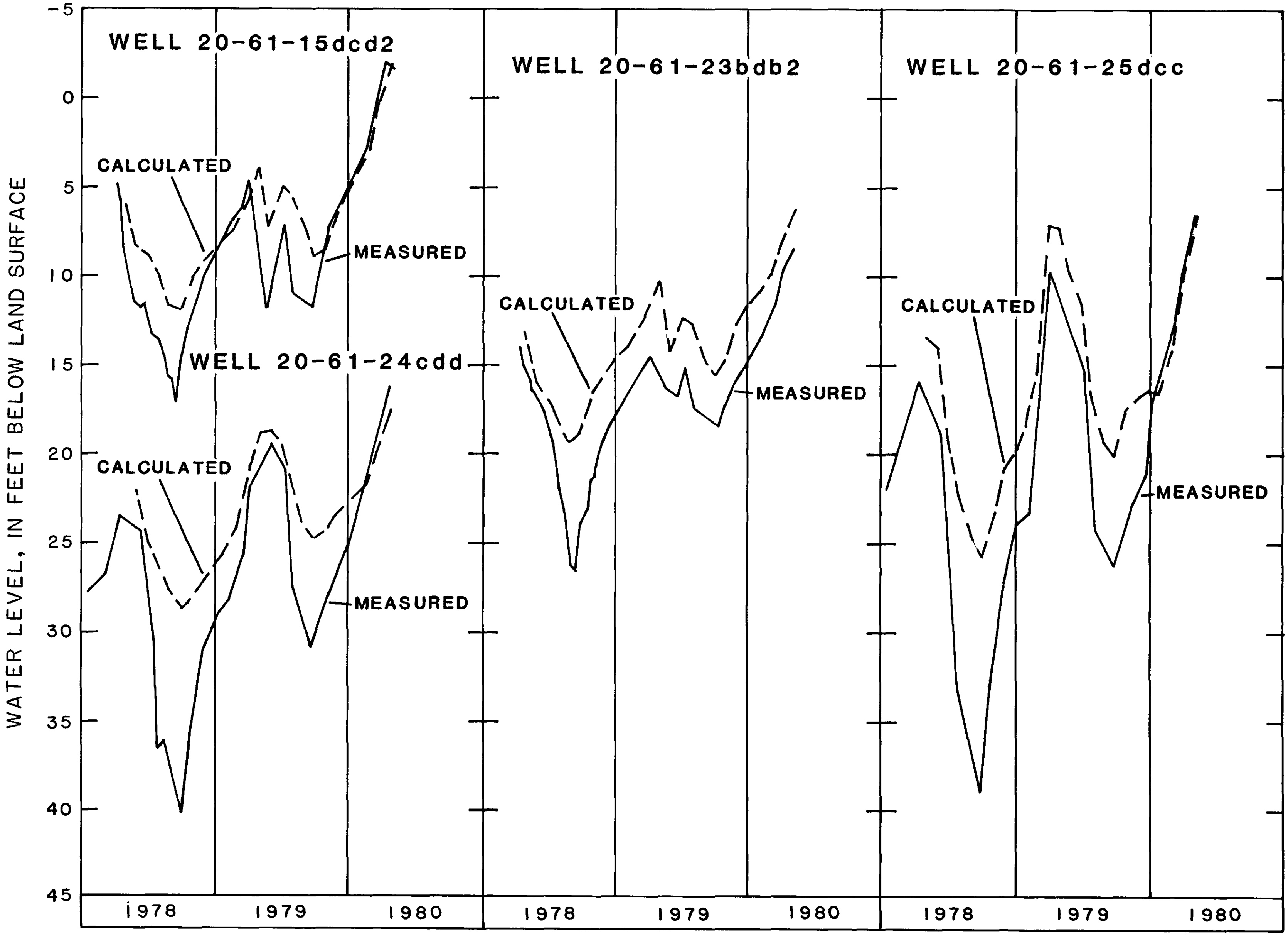


Figure 18.--Calculated and measured water-level fluctuations in wells 20-61-15dcd2, 20-61-23bdb2, 20-61-24cdd, and 20-61-25dcc, 1978-80.

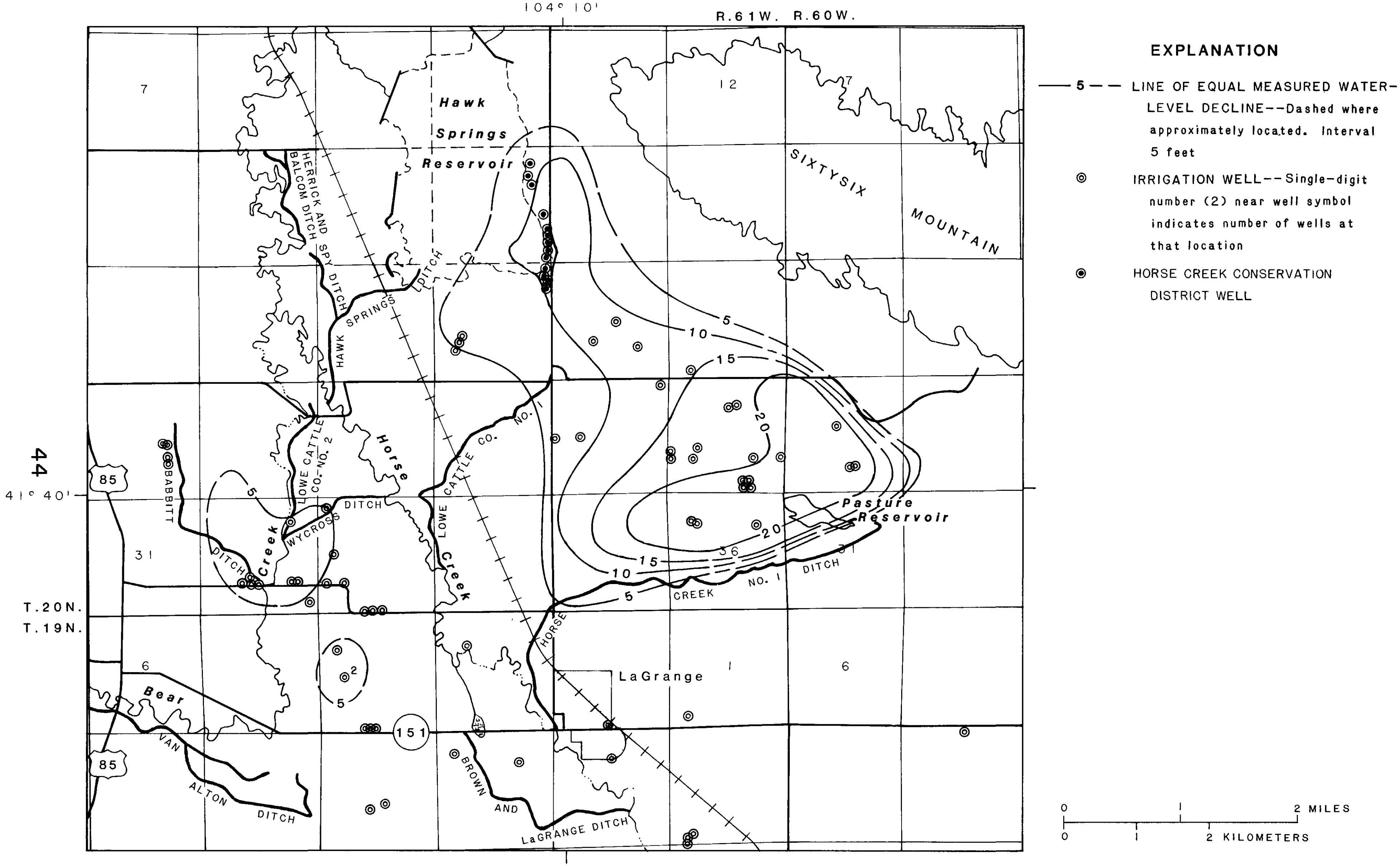


Figure 19.--Measured water-level declines in the LaGrange aquifer for the areas east and west of Horse Creek, April to October, 1978.

elliptical cone of depression resulting in larger water-level declines at this well. The transmissivity decreases east and west of the Conservation District wells but increases south and southeast of the wells. The April 1978 potentiometric surface (fig. 15) indicates that ground-water movement towards the Conservation District wells primarily is from the southeast. Therefore, because of the different hydraulic properties encountered by the cone of depression, pumpage from the Conservation District wells during spring 1978 did not cause ground-water gradients to change as much in the vicinity of well 20-61-23bdb2 as they did in the vicinity of well 20-61-15dcd2.

The difference between the calculated and measured water levels during the pumping season, at the wells shown in figure 18, at well 20-60-30cbb in figure 12 and at well 20-61-25cbc2 in figure 14 is due primarily to the difference between the way pumpage and water-level changes occur in nature and how the model simulates each change. In the model, water is removed from the entire area of the pumping cells, from surrounding cells, and beyond. Water can move toward those pumping cells within the limits of the values and distribution of transmissivity and specific yield. The resultant water-levels calculated by the model are also are representative of the water level in the entire area of the cell. The model averaged the effects and results of pumpage throughout an area possibly larger than actually affected in nature, creating a discrepancy between the calculated and measured water levels during the pumping season. However, all the hydrographs do indicate that the combination of parameters in the model are adequate to sufficiently average the effects of seasonal discharge and recharge in time and space to produce calculated water-level trends that approximate the measured water-level trends.

After 1974, water levels in the area declined annually until reaching their lowest level of record during the summer of 1978. During the spring of 1980, water levels rose to nearly the 1973 levels. The calculated 1980 water levels are the net result of simulated changes in recharge and discharge during 1978-80. Hydraulic heads calculated for the end of April 1980 depart from the hydraulic heads determined from water levels measured in observation wells April 30, 1980, with rms deviations as follows:

Area	No. of wells	Root-mean-square deviation (feet)	Maximum departure (feet)
East of Horse Creek	38	2.8	8.6
West of Horse Creek	19	3.6	8.8
Remaining area	32	4.1	10.1
Total area	89	3.5	10.1

For the area east of Horse Creek, the comparison between the average calculated and average measured 1980 water levels at 18 water-level nodes show an agreement within 0.6 ft. The average calculated rise was 6.2 ft and represents the difference between the 1978 calculated hydraulic head and the 1980 hydraulic head calculated at the end of simulation period 25. The average measured rise of 6.8 ft represents the difference between the measured 1978 and 1980 water levels at the 18 observation wells. For May 1980, the calculated discharge from the aquifer to Horse Creek was 10.6 ft^3/s and from the reservoir to the aquifer it was 0.3 ft^3/s.

The reservoir overlies the natural discharge area for most of the area east of Horse Creek, thus the altitude and perimeter location of the reservoir affects the hydraulic heads in the aquifer upgradient of the reservoir. During the spring of 1980, the reservoir was at its highest level since 1975 (fig. 10). The calculated water-level profiles shown in figure 20 give a representative idea of the water-level gradients towards the reservoir. The profiles are plotted using water levels calculated at the end of February, March, and April, 1980 at each node along row 20 in the finite-difference grid (pl. 4) from column 8 through column 36. The water profiles also illustrate that the increase of the reservoir altitude in the model has a damming effect on the calculated hydraulic heads in the aquifer upgradient of the reservoir. The nodes along the relatively flat parts of the profile from node 20,11 to 20,34 have hydraulic conductivities in the model ranging from 100 to 950 ft/d.

As illustrated in figure 20, an increase of the reservoir altitude in the model from March to April results in a similar increase of the calculated hydraulic head in the aquifer upgradient of the reservoir. A confirmation of the calculated results of the change in reservoir altitude on the hydraulic heads in the aquifer was obtained from water-level measurements in April and May 1980. The water-level at well 20-61-23bdb2 rose 1.7 ft from April 30 to May 29, whereas the reservoir altitude had increased about 2 ft. At the end of March A, the total calculated discharge for all the reservoir cells was 1.5 ft^3/s from the reservoir to the aquifer, but at reservoir cell 20,15, the calculated discharge was 0.53 ft^3/s from the aquifer to the reservoir. The calculated hydraulic head in the aquifer was 0.1 ft higher than the hydraulic head of the reservoir. At the end of April, the total calculated discharge was 0.3 ft^3/s from the reservoir to the aquifer, but at reservoir cell 20,15 the calculated discharge was 0.65 ft^3/s from the aquifer to the reservoir. The calculated hydraulic head in the aquifer at cell 20,15 was about 0.2 ft higher than the hydraulic head of the reservoir.

The calculated water-level profile for February (fig. 20) depicts no recharge from Horse Creek No. 1 Ditch. The total calculated discharge for all the reservoir cells was 1.6 ft^3/s from the aquifer to the reservoir, and at reservoir cell 20,11 the calculated discharge was 0.16 ft^3/s from the aquifer to the reservoir. The calculated hydraulic head in the aquifer was less than 0.05 ft higher than the hydraulic head in the reservoir. For March A and April profiles, the calculated water-level rise along row 20 from column 26 to 34 was due to nodes located upgradient that simulated Pasture Reservoir, which received about 660 acre-ft of recharge from Horse Creek No. 1 Ditch in March 1980 and about 700 acre-ft in April 1980. In simulation March B, conditions are identical to simu-

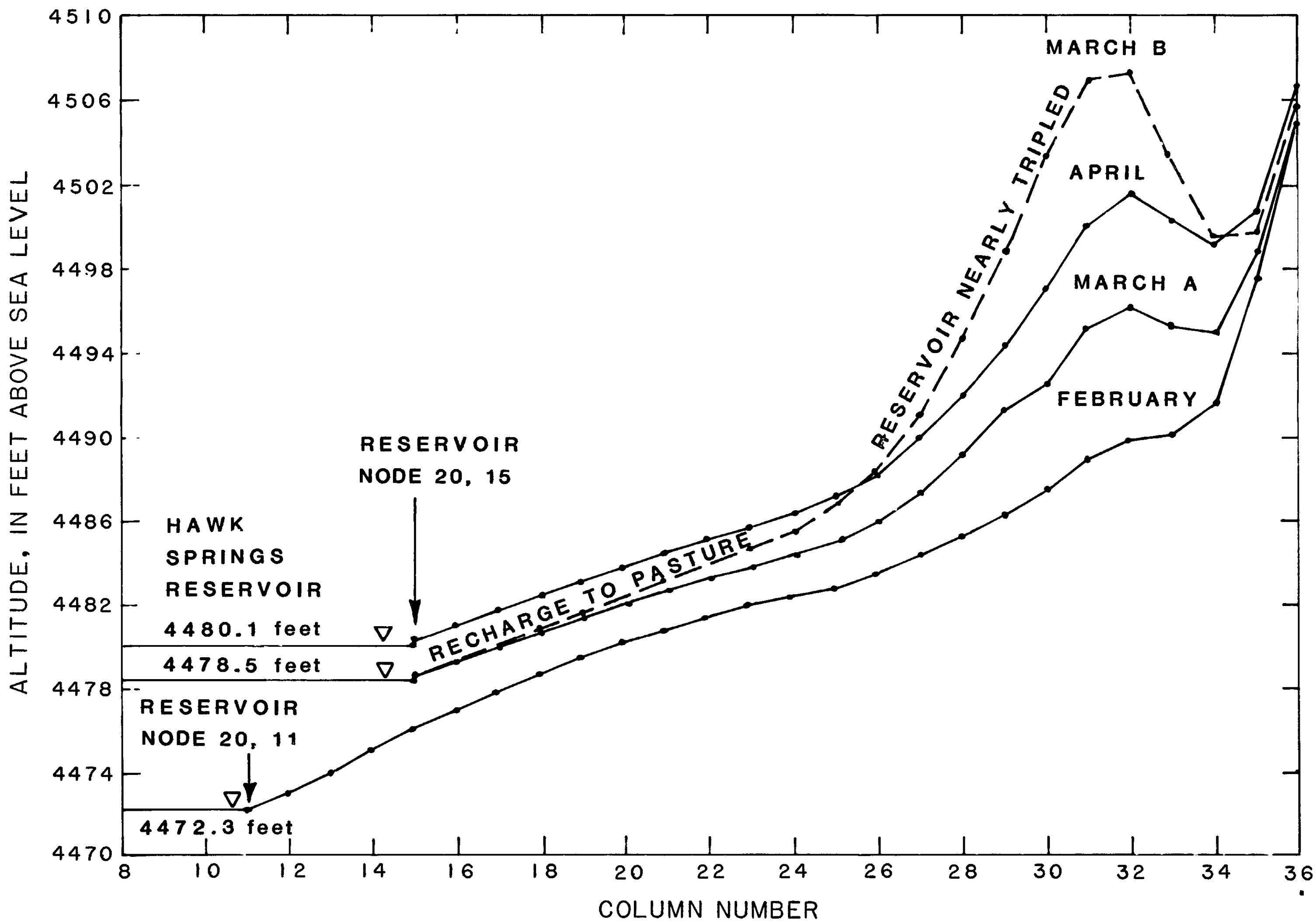


Figure 20.--Water-level profiles along row 20 in the finite-difference grid using water levels calculated at the end of February, March A and B, and April, 1980 simulations.

lation March A except that simulated recharge to Pasture Reservoir was nearly tripled to about 1,750 acre-ft. The calculated water-level profile March B in figure 20 illustrates the extreme calculated water-level rise. However, even with this additional simulated recharge to the aquifer, the calculated hydraulic head in the aquifer at the reservoir cell 20,15 was not changed by more than 0.1 ft and the calculated discharge from the aquifer only increased 0.06 ft^3/s from the calculated discharge for simulation March A.

These model results indicate that the reservoir altitude and perimeter location in addition to ground-water pumpage and surface-water recharge also affect the calculated discharge to and from the reservoir (fig. 17). This effect has not been calibrated and thus needs to be considered only a qualitative guide as what may be occurring in nature.

The perimeter of the reservoir is approximated in the model by leakage cells dimensioned 1,000 by 1,000 ft, so the reservoir altitude and perimeter location only can be grossly approximated especially during months when the reservoir volume is changing rapidly. For some simulated months, the reservoir altitude changed without the reservoir perimeter location changing; in other months the reservoir altitude and perimeter location both changed but resulted in small discharge changes. For example, the rise of the reservoir altitude as shown in figure 17 for February 1979 may result in a smaller discharge in February than in January 1979. However, in the model, the reservoir perimeter was enlarged in February 1979 by one cell (1,000 ft), and the net effect was little difference in the calculated discharge for February and January 1979 (fig. 17). Thus calculated discharges to and from the aquifer at the reservoir cells need to be used only as guides for indicating relative changes in most of the discharge to and from the aquifer east of Horse Creek.

Hypothetical Model Application

The calibrated digital model was used to simulate hypothetical pumping alternatives for the area east of Horse Creek. In order to make the pumping alternatives realistic and to facilitate data entry into the model, 1978 monthly values of precipitation and ground-water pumpage east of Horse Creek were used. Model simulation of each pumping alternative comprised six time periods representing April through September. The initial hydraulic-head distribution used was in equilibrium with the constant reservoir altitude of 4472.5 ft, evapotranspiration, and the 6-month average recharge from precipitation. These latter two stresses are operative throughout the area of the model. For each pumping alternative, the monthly pumpage is listed in table 5, and the calculated discharge from or to the aquifer is listed in table 6. The reservoir altitude of 4472.5 ft corresponds to a reservoir volume of about 7,000 acre-ft. For these pumping alternatives, it was assumed that releases from the reservoir equal pumpage from the Conservation District wells plus diversions from Horse Creek resulting in no change in reservoir altitude during each simulation. The calculated discharges are the net recharge and discharge calculated for months prior to and including the month for which the discharges are listed. For example, the calculated discharges listed for September are the net fluxes for the 6 months from April through September.

Table 5.--Pumpage used for hypothetical pumping alternatives for the area east of Horse Creek.

Pumping alternative	Pumping source	Pumpage (acre-feet / cubic feet per second) April	May	June	July	August	September	Total pumpage (acre-feet)
1	None	--	--	--	--	--	--	--
2	Horse Creek Conservation District wells	454 / 7.6	1007 / 16.4	758 / 12.7	704 / 11.4	740 / 12.0	406 / 6.8	4069
3	Irrigation wells	--	--	691 / 11.6	619 / 10.1	559 / 9.1	451 / 7.6	2321
4	Horse Creek Conservation District and irrigation wells	454 / 7.6	1007 / 16.4	1449 / 24.3	1323 / 21.5	1299 / 21.1	857 / 14.4	6390

Table 6.--Calculated discharge for hypothetical pumping alternatives for the area east of Horse Creek.

Pumping alternative	Pumping source	Calculated discharge +, from aquifer; -, to aquifer (cubic feet per second) April Horse Creek	April Reser-voir	May Horse Creek	May Reser-voir	June Horse Creek	June Reser-voir	July Horse Creek	July Reser-voir	August Horse Creek	August Reser-voir	September Horse Creek	September Reser-voir
1	None	9.5	5.3	10.1	5.4	9.7	5.3	10.0	5.4	9.8	5.3	9.3	5.2
2	Horse Creek Conservation District wells	9.5	3.3	10.1	.5	9.6	.0	9.8	.1	9.5	-.2	9.0	.4
3	Irrigation wells	9.5	5.3	10.1	5.4	9.7	5.0	9.9	4.6	9.7	4.1	9.2	3.8
4	Horse Creek Conservation District and irrigation wells	9.5	3.3	10.1	.5	9.6	-.3	9.8	-.7	9.5	-1.4	8.8	-1.0

Under the conditions set forth in these hypothetical pumping alternatives, the simulated results give an indication of how the physical system might respond under similar conditions in nature. Pumping alternative 1 represents the transient simulation with no stresses other than recharge of 5 percent of the monthly precipitation. Results of pumping alternatives 2 and 3 indicate that pumpage from the Conservation District wells would affect the calculated discharge from the aquifer to the reservoir and to Horse Creek more than would pumpage from the irrigation wells in the area east of Horse Creek. This would be a result of the greater concentration of withdrawal by the Conservation District wells nearer the reservoir than the more distributed areal withdrawal by the irrigation wells upgradient of the reservoir. The discharge value of zero, calculated for June in pumping alternative 2, indicates that the ground-water discharge normally reaching the reservoir would be intercepted by the Conservation District wells. At the end of the 6-month simulation of the pumping alternatives, the calculated rate of discharge to the reservoir was decreased to 0.4 ft^3/s by pumpage from the 14 Conservation District wells and to 3.8 ft^3/s by pumpage from the 28 irrigation wells. Pumpage from the total 42 wells resulted in a 1.0-ft^3/s loss from the reservoir to the aquifer. The calculated discharge to Horse Creek was decreased to 9.0 ft^3/s by pumpage from the Conservation District wells, to 9.2 ft^3/s by pumpage from the irrigation wells, and to 8.8 ft^3/s by pumpage from the 42 wells.

The areal distribution of drawdown calculated by the model for pumping alternatives 2 and 3 is shown in figure 21. In pumping alternative 2 where only the Conservation District wells were pumped, the shape of the area of calculated drawdown from 5 to less than 10 ft probably is a result of different hydrologic conditions encountered by the cone of depression as it enlarged. As discussed previously, the cone of depression around the Conservation District wells was initially elliptically shaped with the long axis parallel to the wells in a northerly direction. As the model simulation progressed and the cone of depression enlarged, it encountered decreasing saturated thickness to the west and north and decreasing hydraulic conductivity to the east. Each condition caused decreased transmissivity resulting in larger drawdowns with less water available from those areas for withdrawal by the wells. Initially, the cone of depression did not greatly enlarge to the south and the southeast because the transmissivity increases in these directions, allowing more water to be available to wells resulting in less drawdown in these areas. With continued pumpage, the elliptical cone of depression necessarily became distorted to the south and southeast as shown by the model simulation of pumpage by the Conservation District wells in pumping alternative 2. The calculated drawdowns in the immediate vicinity of the Conservation District wells were from 7 to 8 ft. The simulation of pumpage by the irrigation wells in pumping alternative 3 resulted in calculated drawdown in the vicinity of the Conservation District wells from 2 to 3 ft. Thus, when pumpage from both the Conservation District and irrigation wells was simulated in pumping alternative 4 (fig. 22), greater drawdown developed in the immediate vicinity of the Conservation District wells than that shown for pumping alternative 2. Using the 17 water-level nodes, the average calculated drawdown in the area east of Horse Creek was 3.2 ft for pumping alternative 2, 4.8 ft for pumping alternative 3, and 8.2 ft for pumping alternative 4.

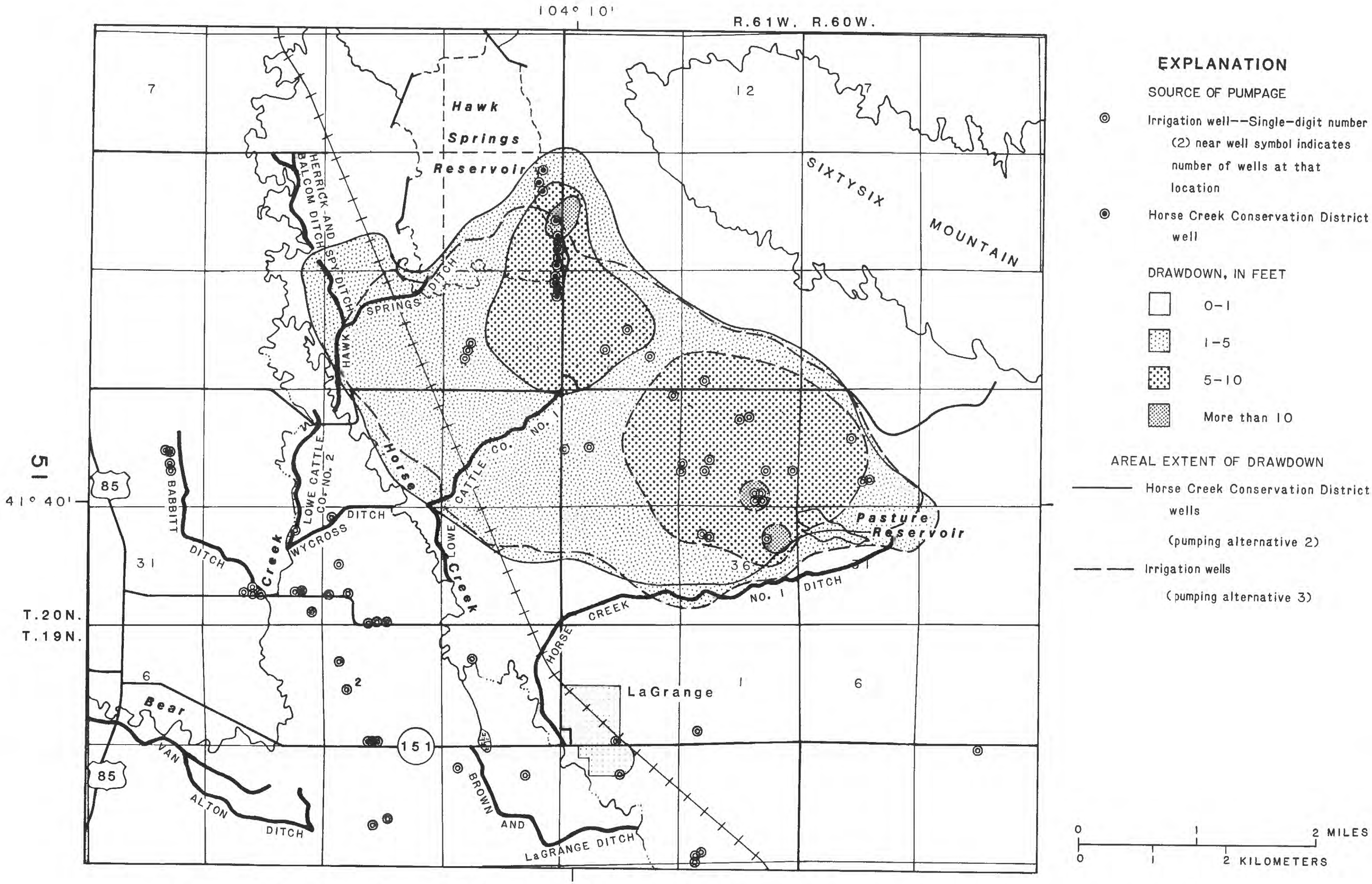


Figure 21.--Drawdown distribution calculated by the model at the end of 6-month simulations for pumping alternatives 2 and 3.

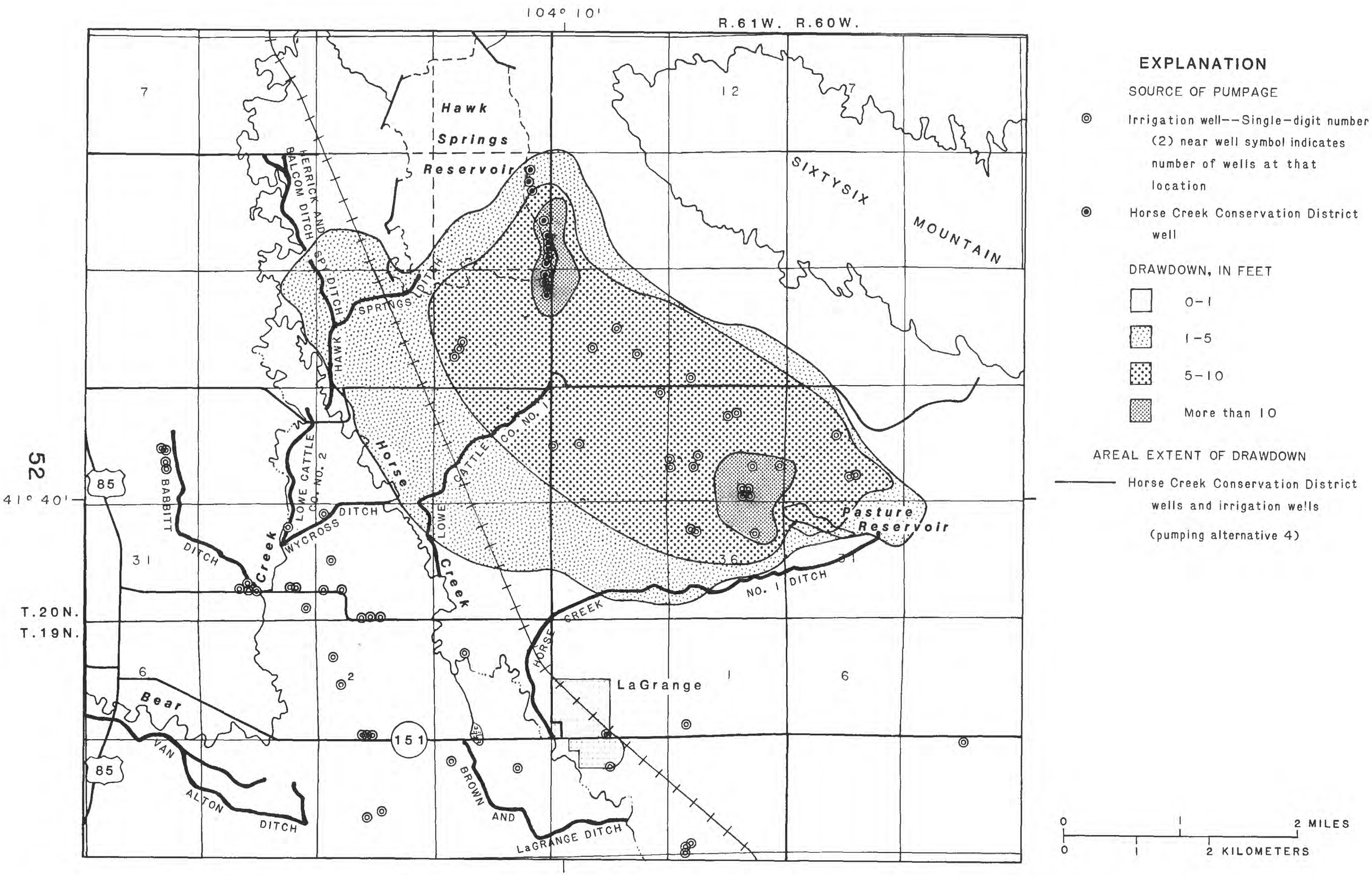


Figure 22.--Drawdown distribution calculated by the model at the end of 6-month simulation for pumping alternative 4.

SUMMARY AND CONCLUSIONS

A digital model of the ground-water system in the unconfined LaGrange aquifer was developed. The model uses finite-difference techniques to numerically solve the ground-water flow equation which approximates the flow system in the LaGrange aquifer as two-dimensional. The LaGrange aquifer for this report consists of the saturated permeable materials of the alluvium where present and most of the White River Group which are hydraulically connected.

Steady-state calibration of the model, with respect to the hydraulic-conductivity distribution, was based on the potentiometric surface for April 1973, which is assumed to approximate steady-state conditions. The steady-state calibration of the model resulted in calculated hydraulic heads departing from interpolated hydraulic heads at water-level nodes in the specified areas with rms deviations as follows: East of Horse Creek, 1.7 ft; west of Horse Creek, 1.5 ft; and the remaining area, 3.5 ft. The steady-state calculated discharge from the aquifer to Horse Creek was 9.5 ft^3/s and from the aquifer to Hawk Springs Reservoir it was 4.3 ft^3/s.

The ground-water system was simulated under transient conditions from April 1973 to April 1978 using 12 time periods. During each time period, the perimeter location and altitude of the reservoir, recharge by precipitation and surface water, and discharge by ground-water pumpage were simulated. The initial conditions for the transient simulations were provided by the steady-state model. Hydrographs and rms deviations showed good agreement between calculated and measured water levels. The calculated hydraulic heads for 1978 departed from measured hydraulic heads at water-level nodes in the specified areas with rms deviations as follows: East of Horse Creek, 2.6 ft; west of Horse Creek, 3.3 ft; and the remaining area, 5.6 ft. The average drawdown at 17 observation wells east of Horse Creek during 1973-78 was 6.2 ft, and the average calculated drawdown at 17 corresponding water-level nodes was 6.0 ft. The April 1978 calculated discharge from the aquifer to Horse Creek was 10.8 ft^3/s and to the reservoir it was 4.2 ft^3/s. Based on the agreement between the measured and the calculated responses for the 1973-78 transient simulation, the model is judged to adequately simulate the effects of surface-water use and ground-water pumpage on water levels in the LaGrange area.

For the area east of Horse Creek, the sensitivity analysis of the model using the 1973-78 transient simulation indicates that the increased pumpage from wells and the decreased recharge from Horse Creek No. 1 Ditch each separately cause the calculated aquifer discharge to the reservoir to decrease nearly the same. However, greater calculated drawdowns were caused by the decreased recharge than by the increased pumpage. Thus the model is more sensitive to recharge from Horse Creek No. 1 Ditch than to pumpage from wells.

In order to further assess the predictive capability of the calibrated transient model, the ground-water system was simulated under transient conditions from April 1978 to May 1980 using 25 time periods. One month of changes in the physical system was simulated for each time period. The trends of the calculated and measured monthly water-level changes showed good agreement. The hydraulic heads calculated for the end of April 1980 departed from the hydraulic heads determined from water levels measured April 30, 1980, at wells assigned to water-level nodes in the specified areas with rms deviations as follows: East of Horse Creek, 2.8 ft; west of Horse Creek, 3.6 ft; and the remaining area, 4.1 ft. The average water-level rise during 1978-80 at 18 observation wells east of Horse Creek was 6.8 ft, and the average calculated water-level rise at 18 corresponding water-level nodes was 6.2 ft. The May 1980 calculated discharge from the aquifer to Horse Creek was 10.6 ft^3/s and from the reservoir to the aquifer it was 0.3 ft^3/s.

The calibrated digital model was used to simulate four hypothetical pumping alternatives for the area east of Horse Creek. The initial hydraulic-head distribution used for the pumping alternatives was in equilibrium with evapotranspiration, the 6-month average recharge from precipitation for 1978, and a constant reservoir altitude of 4472.5 ft, which approximates a reservoir volume of 7,000 acre-ft. Each pumping alternative used 6 time periods representing April through September. The only changing stress in pumping alternative 1 was a different monthly value for recharge from precipitation which was included in the next three pumping alternatives that also simulated pumpage from only the Conservation District wells, only the irrigation wells in the area east of Horse Creek, and both. For alternative 1, the calculated discharge from the aquifer to Horse Creek was 9.3 ft^3/s and to the reservoir it was 5.2 ft^3/s at the end of the 6-month simulation. These discharge results were used as the basis for comparison with the other three alternatives. At the end of the 6-month simulation of these pumping alternatives, the calculated rate of discharge to the reservoir was decreased to 0.4 ft^3/s by pumpage from the 14 Conservation District wells and to 3.8 ft^3/s by pumpage from the 28 irrigation wells. Pumpage from the total 42 wells resulted in a 1.0-ft^3/s loss from the reservoir to the aquifer. At the end of 6-months simulation, the average calculated drawdown for 17 water-level nodes east of Horse Creek was 3.2 ft with the Conservation District wells pumping, 4.8 ft with the irrigation wells pumping, and 8.2 ft with both pumping.

Results of the various transient simulations indicate that the perimeter location and altitude of the reservoir can affect the hydraulic heads in the aquifer upgradient of the reservoir. Ground-water pumpage and surface-water recharge, also can affect discharge to and from the reservoir. However, the calculated values of discharge and recharge at reservoir cells need to be considered only as a guide for indicating relative changes in most of the discharge to or from the aquifer east of Horse Creek.

REFERENCES CITED

Adams, G. I., 1902, Geology and water resources of the Patrick and Goshen Hole quadrangles, in eastern Wyoming and western Nebraska: U.S. Geological Survey Water-Supply Paper 70, 50 p.

Babcock, H. M., and Rapp, J. R., 1952, Reconnaissance of the geology and ground-water resources of the Horse Creek-Bear Creek area, Laramie and Goshen Counties, Wyoming: U.S. Geological Survey Circular 162, 28 p.

Borchert, W. B., 1976, Geohydrology of the Albin and La Grange areas, southeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 76-118, 72 p.

Crist, M. A., 1975, Hydrologic analysis of the valley-fill aquifer, North Platte River valley, Goshen County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 3-75, 60 p.

Dockery, W. L., 1940, Underground water resources of Horse Creek and Bear Creek valleys, southeastern Wyoming: Wyoming Geological Survey Bulletin 30, 32 p.

Geological Society of America, 1963, Rock-color chart [prepared by the Rock-Color Chart Committee]: Boulder, Colorado, 11 p.

Hantush, M. S., 1964, Hydraulics of wells, in Chow, V. T., ed., Advances in Hydroscience, volume 1: New York, Academic Press, p. 281-442.

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.

Jacob, C. E., 1963, Determining the permeability of water-table aquifers, in Bentall, Ray, compiler, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 245-271.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Morgan, A. M., 1946, Progress report on geology and ground-water resources of the Cheyenne area, Wyoming: U.S. Geological Survey Open-File report, 55 p.

Morris, D. A., and Babcock, H. M., 1960, Geology and ground-water resources of Platte County, Wyoming, with a section on Chemical quality of the water, by R. H. Langford: U.S. Geological Survey Water-Supply Paper 1490, 195 p.

Rapp, J. R., Visher, F. M., and Littleton, R. T., 1957, Geology and ground-water resources of Goshen County, Wyoming: U.S. Geological Survey Water-Supply Paper 1377, 145 p.

Schlaikjer, E. M., 1935a, The Torrington member of the Lance formation and a study of a new _Triceratops_, Part 2 _of_ Contributions to the stratigraphy and paleontology of the Goshen Hole area, Wyoming: Bulletin of the Museum of Comparative Zoology at Harvard College, v. 76, no. 2, p. 31-68.

____ 1935b, A new basal Oligocene formation, Part 3 _of_ Contributions to the statigraphy and paleontology of the Goshen Hole area, Wyoming: Bulletin of the Museum of Comparative Zoology at Harvard College, v. 76, no. 3, p. 69-97.

____ 1935c, New vertebrates and the stratigraphy of the Oligocene and early Miocene, Part 4 _of_ Contributions to the stratigraphy and paleontology of the Goshen Hole area, Wyoming: Bulletin of the Museum of Comparative Zoology at Harvard College, v. 76, no. 4, p. 97-189.

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

Trelease, F. J., Swartz, T. J., Rechard, P. A., and Burman, R. D., 1970, Consumptive use of irrigation water in Wyoming: Wyoming State Engineer's Office, Wyoming Water Planning Report 5, 83 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

U.S. Department of Commerce, 1949-79, Climatological Data; National Oceanic and Atmospheric Administration: Washington, U.S. Government Printing Office.

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

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