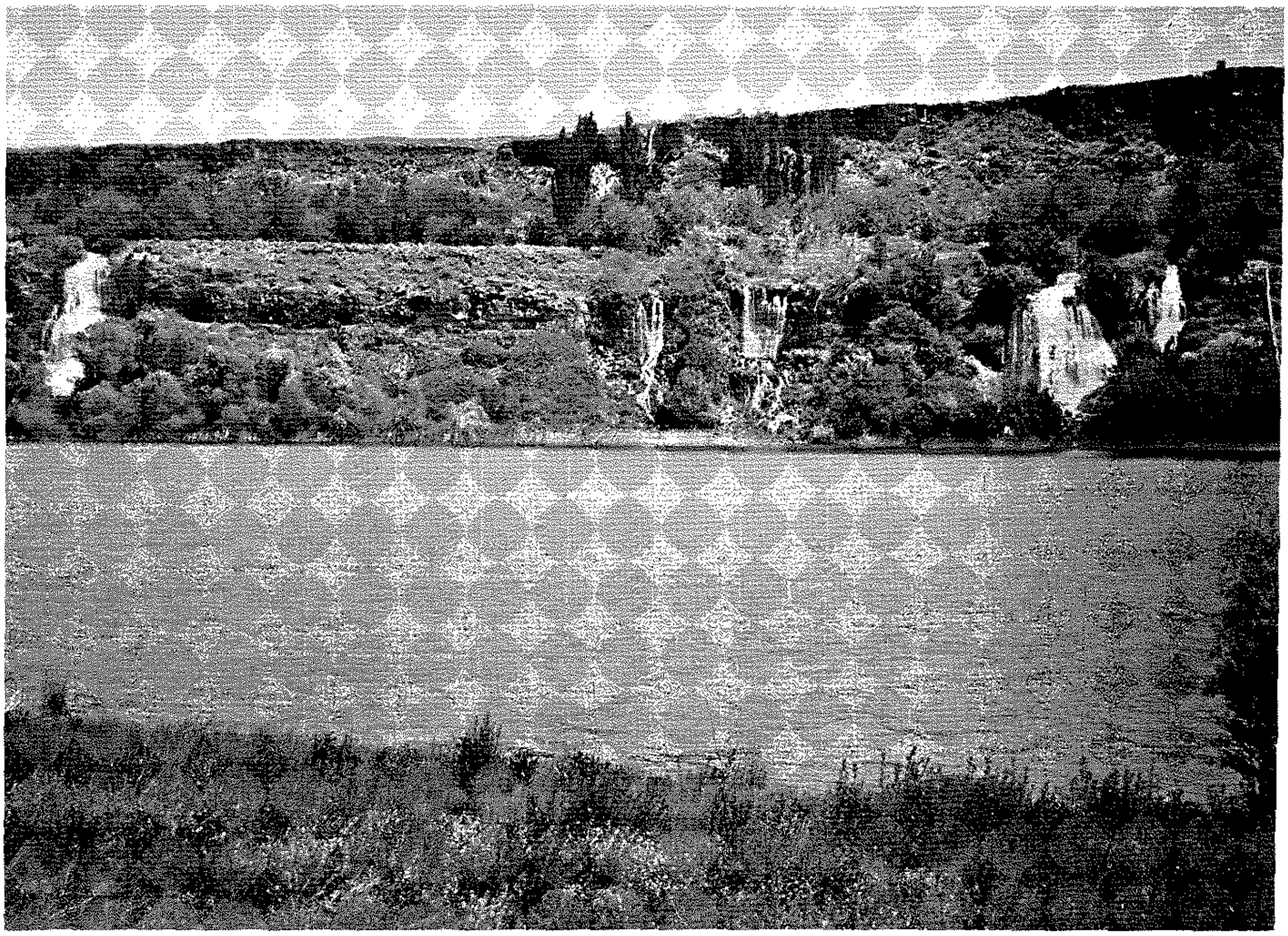
Digital-model analysis of the

EFFECTS of WATER-USE ALTERNATIVES ON SPRING DISCHARGES

Gooding and Jerome Counties, Idaho

Quartet Falls of Thousand Springs, Snake River, Hagerman Valley, Idaho



Idaho Department of Water Resources
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DIGITAL-MODEL ANALYSIS OF THE EFFECTS OF WATER-USE ALTERNATIVES ON SPRING DISCHARGES, GOODING AND JEROME COUNTIES, IDAHO

by

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Prepared by the U.S. Geological Survey
in cooperation with
the Idaho Department of Water Resources
Statehouse
Boise, Idaho

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ACKNOWLEDGMENTS

Before this study was begun, an analysis of the hydrologic system underlying the entire Snake River Plain was initiated by the WRRI (Idaho Water Resources Research Institute). Much of that study was done by Jos de Sonneville under the immediate direction of C.E. Brockway. The study was primarily aimed at demonstrating the utility of a digital hydrologic model developed by WRRI. Much of the data assembled and processed for the WRRI model was directly usable in this investigation. The kind assistance of Messrs. de Sonneville and Brockway in supplying the applicable information, even before their work was completed, made completion of this study possible.

The pumpage computations made in this study would have been virtually impossible without the complete cooperation of several employees of the Idaho Power Company. Not only did they supply considerable data on power consumption for irrigation use, but they kindly assisted in correlating the power records to pumping sites.

Local residents, too numerous to acknowledge individually, were helpful in granting permission to measure their wells and in supplying useful information concerning ground-water pumpage and historic water-level changes.

This study was begun by E.G. Crosthwaite, who completed much of the work of correlating power records to pumping sites. He also assisted in selection of wells for depth-to-water measurements and supplied information from previous investigations and personal knowledge.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

Springs discharging from the Snake Plain aquifer contribute approximately 6,000 cubic feet per second (170 cubic metres per second) to flow in the Snake River between Milner and King Hill. Before irrigation began on the Snake River Plain north and east of the springs, total spring discharge was about 4,200 cubic feet per second (120 cubic metres per second). Increasing amounts of irrigated acreage from the early 1900's to the mid-1940's contributed more irrigation-return water to the aquifer resulting in increased discharge at the springs. Maximum discharge of about 6,800 cubic feet per second (190 cubic metres per second) occurred during the late 1940's and early 1950's. Increased use of pumped ground water for irrigation and changing irrigation practices have since resulted in a decline in spring discharge.

Individual springs respond seasonally to stresses applied by irrigation-return water. Spring flow declines during the nonirrigation season (November through March) reaching a minimum late in April, and then increases during the irrigation season (April through October) reaching a maximum late in October.

Ground-water withdrawals for irrigation have increased significantly in recent years. Electrical power consumed for irrigation uses (including booster pumps) has increased from about 45 million kilowatt hours in 1966 to over 70 million kilowatt hours in 1973. Using electrical power consumed by irrigation pumps, ground-water extractions in southern Gooding and western Jerome counties during the 1973 irrigation season were computed to be over 84,000 acre-feet (1×10^8 cubic metres).

A digital model utilizing the iterative alternating-direction implicit procedure was used to simulate the aquifer system. The model simulates two-dimensional flow through an unconfined aquifer and generates spring discharges from the aquifer. Inputs for 1966 supplied by Idaho Water Resources Research Institute were used to calibrate the model. Water-table contours were simulated with aquifer transmissivities ranging from less than 1 million gallons per day per foot (1.2×10^4 square metres per day) to 30 million gallons per day per foot (3.7×10^5 square metres per day).

Using nonirrigation (January through March) and irrigation (April through October) periods as stresses, the model was calibrated for transient conditions. Although precise duplication of water-level change was not achieved, the general pattern and magnitude of change was simulated. Aquifer-storage coefficients used in final transient calibration ranged from 0.07 to 0.15.

The calibrated model was used to generate spring discharges and water-level declines resulting from six alternative plans supplied by the Idaho Department of Water Resources. Plan A (reduced surface diversions to major irrigation canals throughout the study area) resulted in the most significant decline in model-generated spring discharge (155 cubic feet per second, or 4.4 cubic metres per second after 5 years). Plan B (reduced surface diversion in the Big Wood River system) resulted in the least decline in model-generated spring discharge (about 30 cubic feet per second, or 0.85 cubic metres per second after 5 years). Plans C, D, E, and F (increased ground-water withdrawals of up to 138 cubic feet per second, or 3.9 cubic metres per second) resulted in varying amounts of decline in model-generated spring discharge. The most significant decline in model-generated spring discharge from increased ground-water withdrawal resulted from Plan E (about 105 cubic feet per second, or 3.0 cubic metres per second decline after 5 years).

FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text, the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	Multiply by	Metric (SI)
acre-feet (acre-ft)	1.233×10^{-3}	cubic metres (m^3)
feet (ft)	3.048×10^{-1}	metres (m)
feet per mile (ft/mi)	1.894×10^{-1}	metres per kilometre (m/km)
cubic feet per second (ft^3/s)	2.832×10^{-2}	cubic metres per second (m^3/s)
kilowatt hours per acre-foot per foot of lift (KWH/acre-ft)/ft of lift	2.472×10^{-3}	kilowatt hours per cubic metre per metre of lift (KWH/m^3)/m of lift
million gallons per day per foot (Mgal/d)/ft	1.242×10^{4}	square meters per day (m^2/d)
miles (mi)	1.609	kilometres (km)
square miles (mi^2)	2.590	square kilometres (km^2)
pounds per square inch (psi)	7.031×10^{-2}	kilograms per square centimetre (kg/cm^2)

INTRODUCTION

Flow in the Snake River increases an average of 7,400 ft^3/s (210 m^3/s) (Thomas, 1969) between Milner and King Hill (fig. 1). Approximately 6,000 ft^3/s (170 m^3/s) of this increase is contributed by a series of springs, some of the world's largest, which discharge from the vast Snake Plain aquifer. The springs, cascading down the talus-covered slopes of the canyon wall or gushing up in sparkling pools in reentrant alcoves along the river, are an impressive sight in both magnitude and beauty.

The springs have been utilized since the earliest days of Idaho's development. Farmers have taken advantage of the no-lift source of water for irrigation of bottom lands along the river. Power companies have used the abundant supply of high-elevation water to drive hydroelectric plants. Fish hatcheries and trout farms rely on the springs for a relatively stable source of the good-quality, well-aerated, constant-temperature water needed to maintain their highly successful industries. In recent years, the picturesque springs have drawn an increasing number of tourists who enjoy the many recreational aspects of the area.

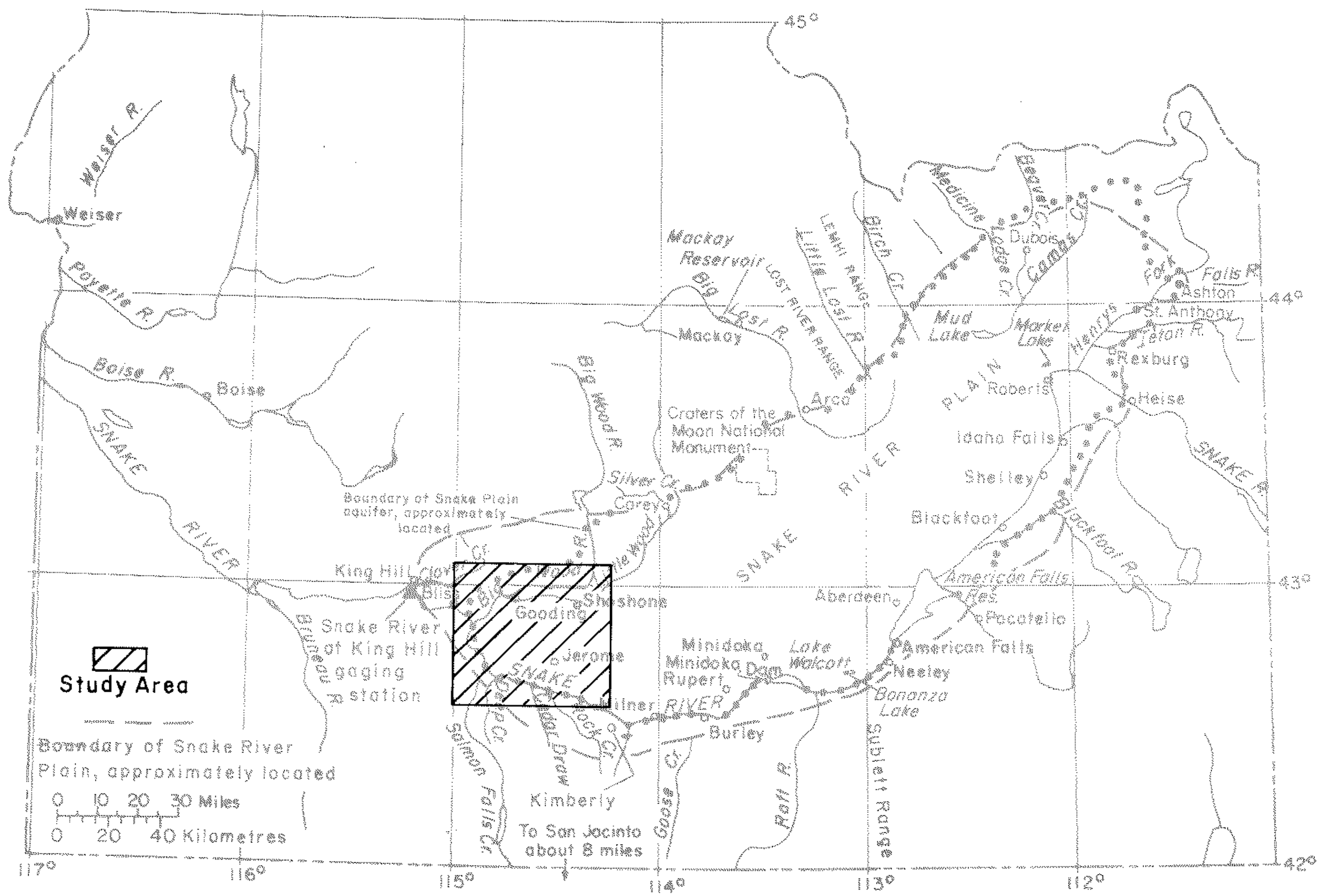
Because of the importance of the springs to the local economy, any decline in the quality or quantity of flow would cause concern. Previous investigations have established that changes in the ground-water regimen of the Snake Plain aquifer cause a corresponding change in spring discharge. A significant increase in spring flows from 1902-17, for example, has been attributed to irrigation return from flood irrigation on large tracts of land north and east of the springs (Stearns and others, 1938). Realizing the direct relation, users of the spring flow are concerned that recent changes in irrigation practices upstream from the springs and increased withdrawals of ground water from the Snake Plain aquifer may affect spring discharge. If the springs respond positively to increased amounts of water in the aquifer, it is reasonable to assume that the converse will be true.

Purpose and Scope

In response to the concerns raised by users of the spring flow, the IDWR (Idaho Department of Water Resources) requested that the U.S. Geological Survey investigate the potential effects of increased pumpage and other water-use alternatives on spring discharge in the southern part of Gooding and the western part of Jerome counties. This report contains the results of the investigation.

To evaluate the potential effects of future pumpage, the existing conditions must first be established. Of specific concern are (1) quantity and distribution of ungaged spring

Figure 1. Index map of southern Idaho.



discharge; (2) occurrence and movement of ground water; (3) quantity and distribution of current ground-water pumpage; and (4) response of springs to changes in hydrologic inputs. The scope of this investigation included (1) analysis of records from streamflow gages on the Snake River between Kimberly and King Hill; (2) field collection of depth-to-water data at approximately 200 wells in April 1974 and 30 wells in October 1974 and analysis of several hundred depth-to-water measurements obtained from drillers' logs and previous studies; (3) field inspection of irrigation wells and computation of pumpage from power-consumption records; and (4) analysis of ground-water-level and spring-discharge fluctuations.

Because of the complex nature of the Snake Plain aquifer and its dynamic hydrologic relation to spring discharge, simple mathematical equations relating stresses to changes in discharge are meaningless. Successful fulfillment of the project objectives, therefore, necessitated the use of a hydrologic model to simulate the dynamics of the system. A hydrologic model capable of predicting water-level changes resulting from various stresses is a valuable tool in analyzing the areal and temporal changes in ground-water levels and spring discharges resulting from various management schemes.

GEOHYDROLOGY

The geology and hydrology of the Snake Plain aquifer have been described in detail by numerous investigators. Some of the more complete studies include reports by Russell (1902), Stearns and others (1938), Mundorff and others (1964), and Norvitch and others (1969). Detailed descriptions of geography, structure, stratigraphy, and sources of recharge and discharge can be obtained from these and other more specific reports. For this reason, only a brief description of the geohydrology of the study area is presented here.

Snake Plain Aquifer

The Snake River Plain (fig. 1) is an area of about 13,000 mi^2 (34,000 km^2) in southeastern Idaho. The broad, undulating plain is underlain by a sequence of successive basaltic lava flows interlain with layers of pyroclastic and sedimentary material. The aggregate thickness of the lava and sedimentary deposits is unknown, but probably exceeds 5,000 ft (1,500 m). This vast reservoir of rocks known as the Snake Plain aquifer contains interconnected pore spaces that transmit phenomenal quantities of ground water. The porous zones occur at contacts between successive lava flows; in coarse-grained alluvial deposits and layers of ash and cinders interlain between lava beds; and in fractures, lava tubes, and vesicles within individual lava flows. Water enters the aquifer as seepage from tributary streams, underflow through alluvial- and basalt-filled tributary canyons, seepage from the Snake River, percolation of excess irrigation water, and infiltration of precipitation on the plain. After entering the aquifer, the water moves generally south and west to points of discharge. Part discharges along the Snake River between Blackfoot and Neeley. The remainder, save that intercepted by pumpage, discharges through the springs in the study area.

Within the study area (fig. 1), the aquifer is composed almost entirely of basalt flows of Quaternary age. These flows (basalt of the Snake River Group) overlie a thick sequence of older basalt flows, consolidated sedimentary rocks, and rhyolitic volcanic rocks of Tertiary age (Malde and Powers, 1972). Although the older flows (Banbury Basalt of the Idaho Group) and sedimentary rocks (Idaho Group) may contain water, they are generally much less permeable than the overlying Quaternary basalts and are not considered to be part of the Snake Plain aquifer. Many of the major springs in the area issue from the canyon wall at the contact between the Tertiary and Quaternary rocks.

Ground-Water Movement

Depth-to-water measurements were made in nearly 200 wells during April 1974 to define patterns of ground-water movement through the aquifer. These measurements, supplemented with several hundred obtained from previous investigations and drillers' logs, were used to construct a water-table-contour map of the study area (fig. 2). Postulated directions of ground-water flow are shown on the map.

Direction of flow is generally south and west through the study area. The flow lines are, at best, only diagrammatic because of the complex nature of the aquifer. However, they do indicate the general paths of ground-water flow to the major springs.

Recharge to the Aquifer

Of the approximate 6,000 ft^3/s (170 m^3/s) of water that discharges from the Snake Plain aquifer within the study area, about 4,850 ft^3/s (137 m^3/s) enters upstream from the study area. Thus, only about 1,150 ft^3/s (33 m^3/s) originates as local recharge.

Total recharge to the study area from irrigation return (including leakage from canals), precipitation, and seepage from tributary streams was calculated by de Sonneville (1974). For reasons to be explained later in this report, his calculations for recharge, as listed below, are accepted as correct with only slight modification in distribution.

Source	Approximate amount in ft^3/s	m^3/s
Irrigation-return flow	950	27
Percolation of precipitation	95	3
Seepage from tributary streams and canals	105	3
Total	1,150	33

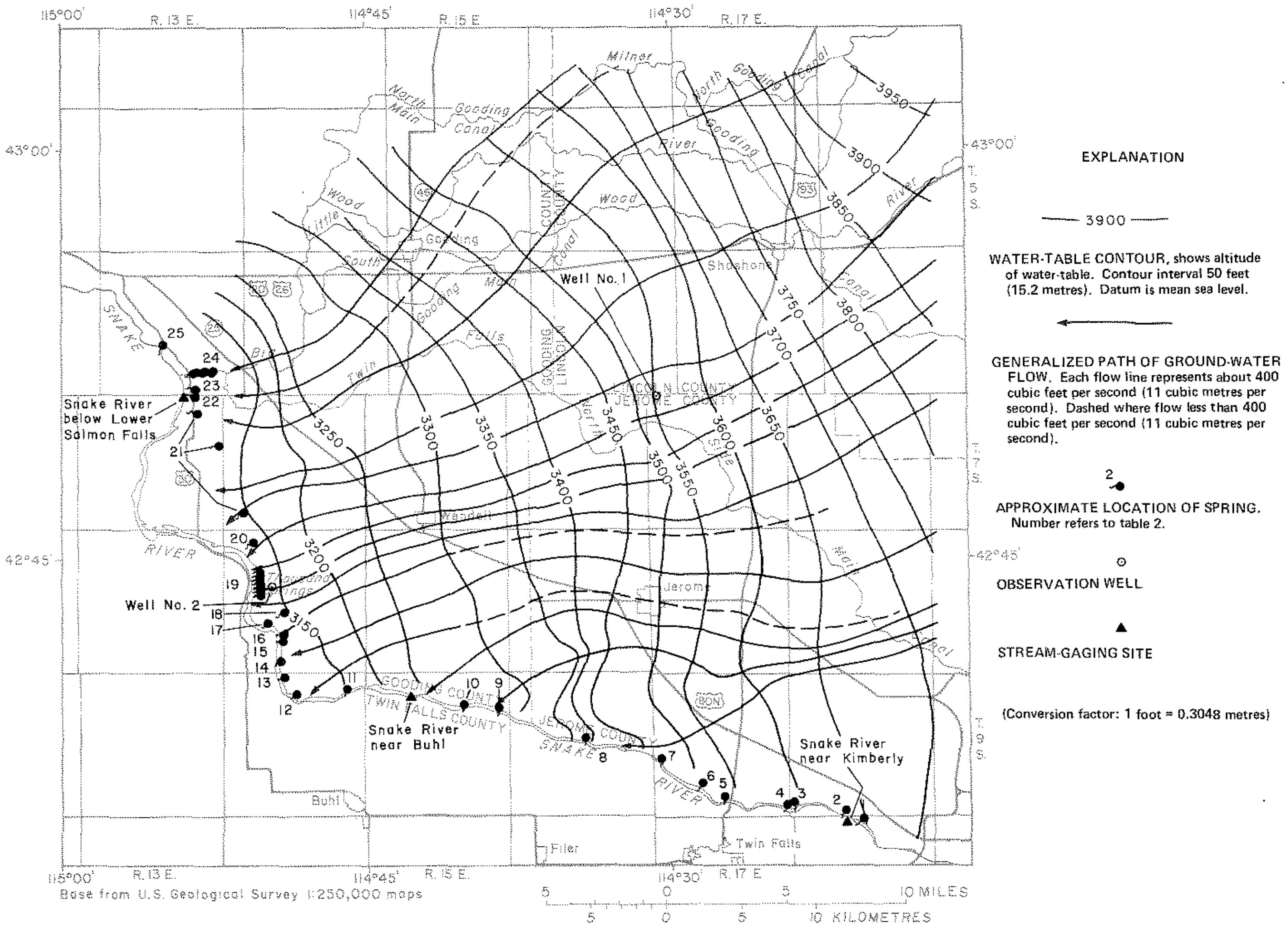


Figure 2. Water-table contours and generalized paths of flow, April 1974, and locations of springs, gaging stations, and observation wells.

THE SPRINGS

Springs issuing from the Snake Plain aquifer occur singly, in clusters, and in continuous zones along the Snake River Canyon (fig. 2). The larger springs or groups of springs are named, but innumerable small springs and seeps are either unnamed or known only to local residents. Nace and others (1958) and Thomas (1968) compiled records of discharges from the springs from the earliest known measurements through the 1967 water year. Descriptions of the springs, including altitude of points of discharge, locations of measuring sections, and evaluation of measurement accuracy are included in those reports. Table 1 summarizes the flow characteristics of the major springs.

Accuracy of Spring-Flow Measurements

Although discharge measurements made at specific sites range from poor to excellent, several factors make accurate total discharge measurements from specific springs impossible. Seepage losses in talus- or boulder-covered channel bottoms, diversions at numerous points, and irrigation waste-water returns affect the total amount of flow at measuring sites. Aquatic vegetation, rocky cross sections, turbulent flow, and backwater conditions generally make measuring difficult. Also, most springs issue from several widely spaced points, and flow is rarely in single channels. Furthermore, attempts to compare early (prior to 1950) measurements with recent measurements are frustrating because the earlier measurements often were made at different or unspecified sites. Thus, total discharge of specific springs is not only difficult to measure but is of questionable accuracy. Since 1950, considerable effort has been made to measure at the same sites so that changes in discharge from year to year can be compared.

Distribution of Spring Flow

Thomas (1969) investigated the sources of inflow to the Snake River between Milner and King Hill (fig. 1). He compared discharge records between gaging sites on the main stem of the Snake River and estimated the distribution of contributions from south-side and north-side inflows for reaches between sites.

South-side inflows generally consist of irrigation-return water from irrigated lands south of the river, whereas north-side inflows are mainly spring discharges from the Snake Plain aquifer.

Using Thomas's estimates for south-side inflow, the total estimated contributions from north-side springs were computed for the 1966 water year for each reach. The total north-side inflow for each reach was then distributed between known springs within the reach by subjectively analyzing discharge measurements for the springs.

Table 2 summarizes the estimated distribution of spring flow between Kimberly and King Hill for the 1966 water year. Although flows for individual springs may be in error, the total of all flows in each reach is reasonably accurate. Approximate locations of the springs are shown in figure 2 and keyed to table 2.

TABLE 1
MAJOR SPRINGS IN STUDY AREA

Spring	Approximate range of discharge at measuring site ft³/s	Discharge spring of 1966 ft³/s	Discharge spring of 1973 ft³/s	Remarks
Blue Lakes Spring	180- 260	191	205	Continuous recorder
Crystal Springs	430- 580[1]	475	479	Includes flow in many channels, partly estimated
Niagara Springs	200- 360	283	295	Continuous recorder
Clear Lakes	470- 540[1]	535	474	Includes flow in diversions
Briggs Creek	105- 115[1]	110	108	Includes flow in diversions
Banbury Springs	95- 140[1]	111	114	Adjusted for diversions and irrigation waste
Box Canyon Springs	350- 480	383	384	Continuous recorder upstream from mouth—does not measure total discharge; discharge at mouth measured 4/6/56 was 852 ft^3/s
Sand Springs	85- 115[1]	94	92	Includes flow in diversions
Thousand Springs	750-1,430[1]	1,260	1,100	Discharge calculated from difference in flow in Snake River above and below springs
Riley Creek	-	181[2]	-	Only measurement available for flow at mouth—includes all spring flow from Riley to Lewis Springs
Billingsley Creek	150- 230[1]	153	206	Not adjusted for numerous diversions
Malad Springs	1,220-1,360[1]	1,230	-	Measurements adjusted for diversions

[1] All measurements made in spring only—no data on seasonal fluctuation.
[2] Measurement of total flow at mouth, spring of 1967.

TABLE 2

DISTRIBUTION OF SPRING DISCHARGE BETWEEN KIMBERLY AND KING HILL

Point of measurement or estimate	Discharge, in ft^3/s				
	Measured flow in springs[1]	Total estimated flow in springs	Estimated inflow from south side[2]	Total computed inflow[3]	Flow in Snake River[4]
Snake River near Kimberly					3,270
Estimated inflow from south side			470		
1 Devils Washbowl Springs	16	16			
2 Devils Corral Springs	46	45			
3 Unnamed Spring No. 1	2	2			
4 Unnamed Spring No. 2	4	4			
5 Unnamed Spring No. 3	1	1			
6 Blue Lakes Springs	191	230			
7 Warm Creek	17	50			
8 Ellison Springs	2	2			
9 Crystal Springs	475	500			
10 Niagara Springs	283	310			
Unspecified locations		100			
Total inflow	1,037	1,260	470	1,730	
Snake River near Buhl					5,000
Estimated inflow from south side			391		
11 Clear Lakes outlet	535	535			
12 Briggs Creek	110	140			
13 Banbury Springs	111	125			
14 Unnamed Spring	4	5			
15 Blind Canyon Spring	11	15			
16 Box Canyon Springs	383	850[5]			
17 Blue Springs		50			
18 Sand Springs	94	100			
19 Thousand Springs	1,260	1,450			
20 Riley Creek	181[6]	200			
21 Billingsley Creek	153	230			
22 Lower White Springs		20			
Total inflow	2,842	3,720	391	4,111	

Table 2. Distribution of Spring Discharge between Kimberly and King Hill *(Continued)*

Point of measurement or estimate	Discharge, in ft³/s				
	Measured flow in springs[1]	Total estimated flow in springs	*Estimated* inflow from south side[2]	Total computed inflow[3]	Flow in Snake River[4]
Snake River below lower Salmon Falls					9,111
Estimated inflow from south side			6		
23 Birch Creek	9	20			
24 Malad Springs	1,230	1,350			
25 Springs below Big Wood River	—	30	—		
Total inflow	1,239	1,400	6	1,406	
Snake River at King Hill, minus flow of Big Wood River near Gooding, plus 75 percent of flow of King Hill Canal					10,517
Total Kimberly to King Hill	5,118	6,380	867	7,247	

[1] Measured or estimated in 1966 (Thomas, 1968).
[2] From estimates by Thomas (1969).
[3] Computed as difference between adjacent main-stem gages.
[4] Average for 1966 water year.
[5] Estimated from measurement at mouth, April 1956.
[6] Measured in 1967.

Long-Term Fluctuations

Before man applied stresses to the Snake Plain aquifer, the total flow from the springs was about 4,200 ft^3/s (120 m^3/s) (Thomas, 1969). Flow fluctuated little between 1902 and 1911. In 1912, spring flow began to increase as a result of irrigation-return water from large tracts of newly developed land north and east of the springs. Although total irrigation diversions were relatively constant from about 1920 through the early 1940's, flow continued to increase through the mid-1940's—presumably because of time required for recharge "waves" to travel to the springs. From the mid-1940's until 1959, the annual average flow remained fairly constant at about 6,800 ft^3/s (190 m^3/s) indicating that the springs were in equilibrium with recharge to the aquifer. Increased ground-water pumpage and a concurrent decline in recharge to the aquifer after 1959 resulted in a decline of spring flows to less than 6,000 ft^3/s (170 m^3/s) as estimated for the 1962 water year. Since 1962, spring flows have remained relatively constant, averaging about 6,200 ft^3/s (175 m^3/s) and fluctuating less than 500 ft^3/s (14 m^3/s) from year to year, in response to changes in annual precipitation and pumpage. Figure 3 illustrates the long-term fluctuation from 1902-73.

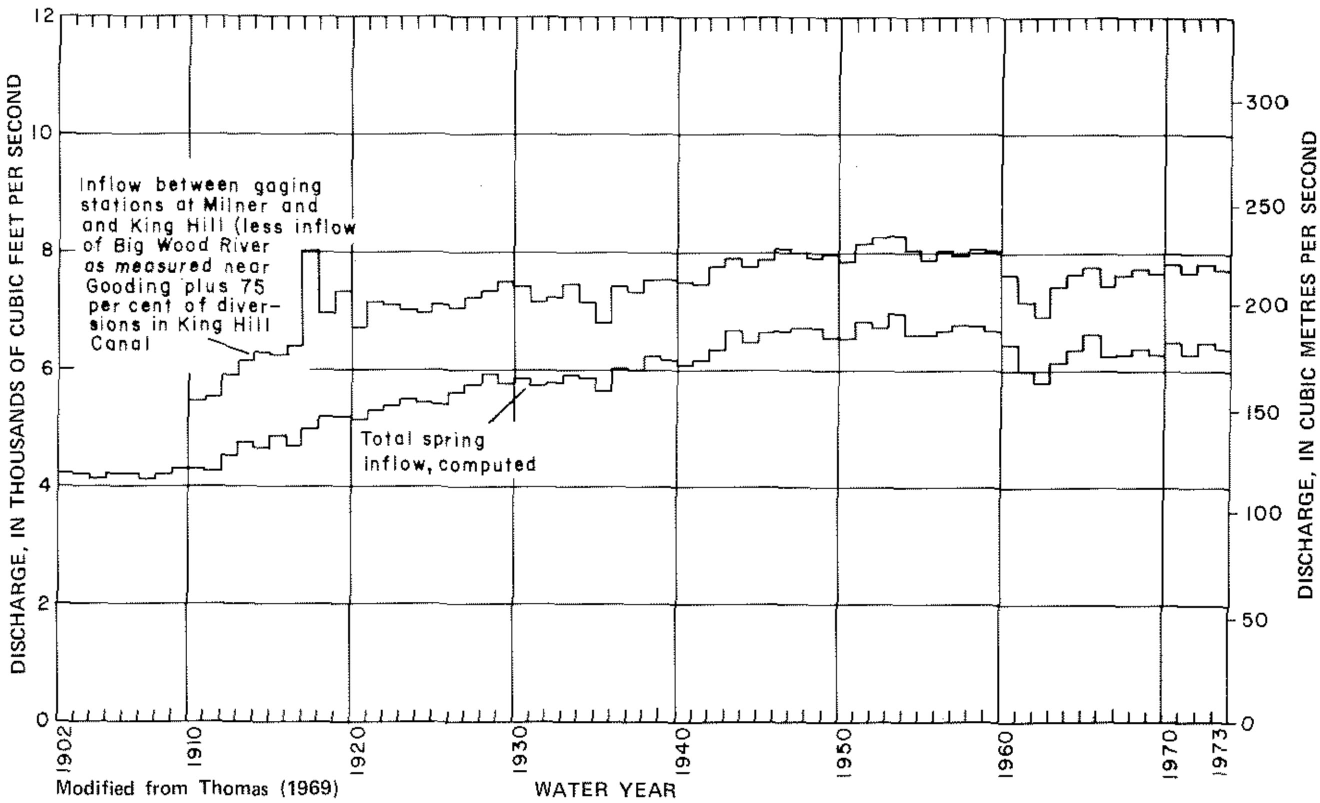


FIGURE 3. Inflow to Snake River between Milner and King Hill and computed total spring inflow.

Seasonal Fluctuations

A comparison of records from gaging sites on the Snake River indicates that cyclic fluctuations in spring discharge began in the early 1920's (Thomas, 1969). The regular rise and fall in discharge approximately coincides with the irrigation record. Discharge increases after irrigation begins, reaches a maximum about 3 or 4 weeks after irrigation ceases, declines during the winter and early spring, and again rises after the next irrigation period begins. The springs for which continuous records are available clearly display this pattern of seasonal fluctuation. Assumably, this pattern is common to all the springs, but records are not available to document the magnitude or time of maximum and minimum discharge for most of them.

The hydrograph of Niagara Springs (fig. 4) for 1966 is typical of these seasonal fluctuations. To compare irrigation diversions and spring discharge, diversions for the same year to the North Side Twin Falls Canal are also plotted on figure 4.

A time lag between the start of irrigation diversion and the resulting change in spring discharge is clearly shown. Several factors contribute to this lag, including (1) travel time in the canal system from the point of diversion to the areas of use; (2) travel time through the unsaturated zone from land surface to the underlying ground-water body; and (3) travel time within the aquifer from areas of recharge to points of discharge.

Another major factor contributing to lag time is use of water. Early in the irrigation season, much of the applied water is required to fulfill soil-moisture deficiencies and crop needs. As soil-moisture requirements are satisfied and irrigation-application rates increase, more of the applied water is available to recharge the aquifer.

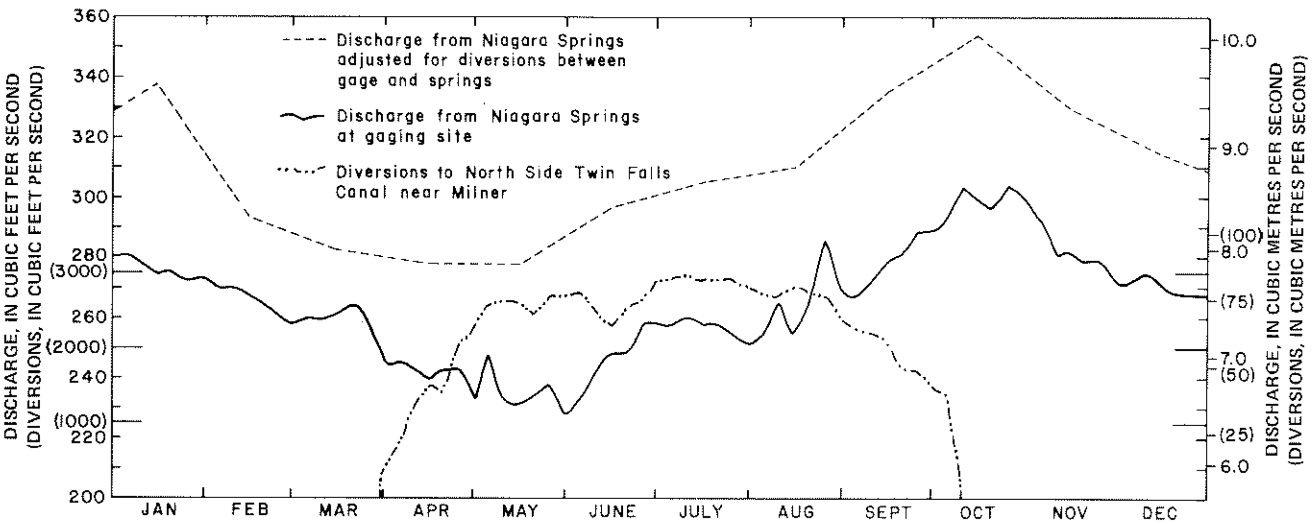


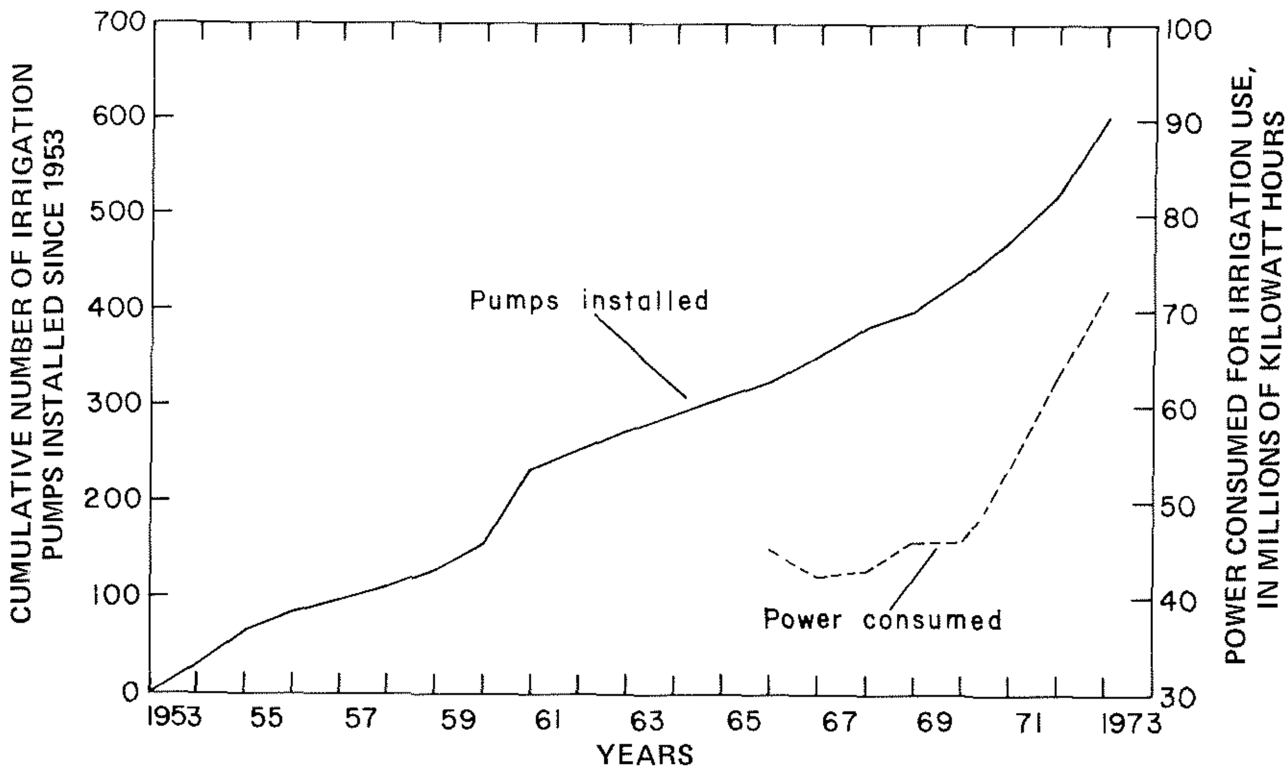
FIGURE 4. Discharge from Niagara Springs and diversions to North Side Twin Falls Canal, 1966.

GROUND-WATER WITHDRAWALS

Since about 1946, ground water has become increasingly more important as a source of irrigation water for the Snake River Plain (Thomas, 1968). An indication of the increased reliance on ground water is illustrated in figure 5. Information from Idaho Power Company shows that an average of 25 new irrigation pumps per year were installed in the Wendell, Gooding, and Jerome power districts (about the same area as the study area) from 1953-69. Since 1969, the rate of installation of new pumping units has increased yearly.

Although the new irrigation pumps include booster pumps and surface-water relift pumps, as well as ground-water pumps, the curve is indicative of the recent changes in irrigation practices.

Also shown in figure 5 is the total annual power consumed for irrigation in the three power districts from 1966-73. Because power consumption can be directly related to the amount of water pumped, this curve illustrates the increased use of pumped water. From 1966-70, power consumption remained fairly constant, but since 1970, it has increased rapidly.



(DATA SUPPLIED BY THE IDAHO POWER COMPANY)

FIGURE 5. **Cumulative number of irrigation pumps installed and annual electrical power consumed for irrigation in Wendell, Gooding, and Jerome power districts.**

Method Used to Calculate Withdrawals

Many methods are available for computing ground-water withdrawals. One method relates power consumed for lifting and delivering water for irrigation to total withdrawal. Because most irrigation wells within the study area are equipped with electrical pumps, and because Idaho Power Company maintains separate accounts for irrigation uses, the following method was used.

Power consumption at a pumping site is directly related to the pumping efficiency of the pump, the total lift of water, and the amount of water pumped. Expressed mathematically:

$$KWH = E \times [(H_o - H_p) + P_h] \times Q, \quad \text{or} \quad Q = \frac{KWH}{E \times [(H_o - H_p) + P_h]} \quad \text{where,}$$

KWH = power consumed, in kilowatt hours;
E = pump efficiency, in kilowatt hours per foot of lift per acre-foot of water pumped;
$(H_o - H_p)$ = lift from the pumping level, H_p, to land surface, H_o, in feet;
P_h = pressure head at land surface, in feet of water; and
Q = total amount of water pumped, in acre-feet.

Calculation of pumpage for each well thus requires a knowledge of lift, pressure head, pumping efficiency, and power consumed. Visits to each well site supplied information on depth to water and method of irrigation. Additional information, including owner's name, horsepower of the motor, and meter numbers were also obtained where possible. Power records for 1973, obtained from Idaho Power Company, were correlated with the field data to determine the total power used at each well.

Because drawdown owing to pumping is generally negligible in this area, lift was assumed to be equal to the static depth to water. If possible, water-level measurements were made at each site. If no measurement could be made, depth to water was estimated from the water-table contour map (fig. 2) and topographic maps.

Pressure head can be estimated if the method of irrigation is known. For flood irrigation, discharge is at or near land surface, and pressure head can be assumed to be zero. Young and Harenberg (1971) measured pressure heads at 124 wells equipped with conventional sprinkler systems on the Snake River Plain. These systems had an average pressure of about 55 psi (3.9 kg/cm^2), or 126 ft (38 m) of water, which is assumed to apply to all conventional sprinkler systems in the area. Center-pivot sprinkler systems, increasingly more popular among local irrigators, operate under much higher pressure heads. According to local irrigation system installers, average operating pressure for these systems is about 90 psi (6.3 kg/cm^2), or 210 ft (64 m) of water.

Pumping efficiency varies from pump to pump depending upon the age, condition, and type of pump and motor. Efficiency data collected by Young and Harenberg (1971) were used. They obtained an average value for 155 wells on the Snake River Plain. The values ranged from about 1.2 to 3.9 (KWH/acre-ft)/ft of lift [0.3 x 10^{-2} to 1.0 x 10^{-2} (KWH/m^3)/m of lift] and averaged 2.06 (KWH/acre-ft)/ft of lift [0.5 x 10^{-3} (KWH/m^3)/m of lift].

Idaho Power Company supplied a summary of power used for irrigation during 1973. Because customer confidentiality precludes reporting information for individual accounts, no attempt was made to list pumpage or power consumed by wells. However, because computation of pumpage from power-consumption data requires knowledge of total lift at each pumping site, account numbers had to be cross indexed to specific wells or groups of wells. Such information as meter numbers, owner's name, and horsepower of pump motors was helpful in determining account numbers for specific wells.

Using the information outlined above, ground-water withdrawal was computed for each irrigation well equipped with electric power within the study area. A fictitious well and irrigation account are used in the example below to illustrate the computations involved in calculating ground-water withdrawals.

AN EXAMPLE IN CALCULATING GROUND-WATER WITHDRAWALS

Physical Data Collected at Well Site

1. Location of well—section 25, T. 7S, R. 14E.
2. Method of irrigation—sprinkler.
3. Horsepower of pump motor—50.
4. Owner's name—J. Smith.
5. Depth to water—86 ft (26 m).

Fictitious Account No.	Customer	Horse-power	KWH Consumed in 1973
2257-345-12	J. Smith	20	120,000
2257-346-12	T. Williams	50	20,000
2257-347-12	J. Smith	50	210,000

From the data collected at the well site and information supplied by the power company, account No. 2257-347-12 is assumed to be the correct account for the well in question. Using the formula:

$$KWH = E \times [(H_o - H_p) + P_h]\ Q,$$

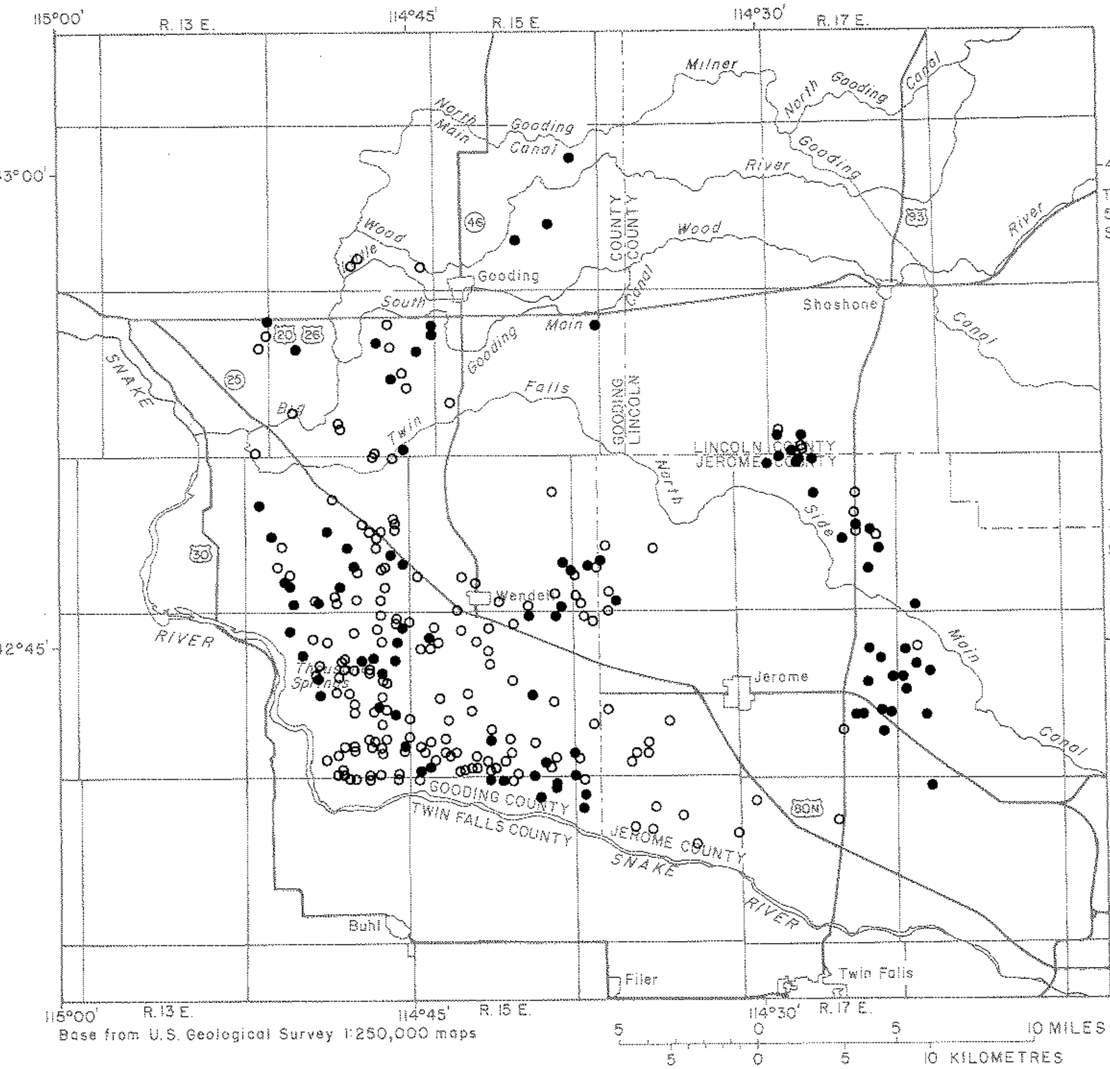
$$210{,}000 = E \times (86 + P_h) \times Q.$$

From Young and Harenberg (1971), average pumping efficiency, E, is 2.06 (KWH/acre-ft)/ft of lift, [0.5 x 10^{-3} (KWH/m^3)/M of lift], and average P_h for sprinkler systems is 55 psi (3.9 kg/cm^2), or 126 ft (38 m). Thus,

$$Q = \frac{210{,}000 \text{ KWH}}{2.06 \text{ (KWH/acre-ft)/ft} \times (86 \text{ ft} + 126 \text{ ft})} = 486 \text{ acre-ft } (590 \times 10^3 \text{ m}^3) \text{ of water pumped during 1973.}$$

Irrigation Withdrawals, 1973

The distribution of irrigation wells within the study area is shown in figure 6. To insure confidentiality, no wells numbers are shown and well locations are only approximate. Total irrigation pumpage for 1973 is calculated by township in table 3.



EXPLANATION

● IRRIGATION WELL with average discharge more than 0.5 cubic feet per second (0.01 cubic metres per second).

○ IRRIGATION WELL with average discharge less than 0.5 cubic feet per second (0.01 cubic metres per second).

FIGURE 6. Irrigation wells.

TABLE 3
PUMPAGE FOR IRRIGATION
IN SOUTHERN GOODING AND WESTERN JEROME COUNTIES

Township	1973 Irrigation pumpage (acre-ft)	Township	1973 Irrigation pumpage (acre-ft)
5S-14E	480	7S-18E	440
5S-15E	2,020	8S-14E	19,230
6S-13E	700	8S-15E	10,090
6S-14E	4,570	8S-16E	2,250
6S-15E	850	8S-17E	6,000
6S-17E	1,840	8S-18E	3,280
7S-13E	160	9S-14E	610
7S-14E	11,490	9S-15E	3,500
7S-15E	2,880	9S-16E	2,940
7S-16E	2,280	9S-17E	590
7S-17E	7,880	9S-18E	570
		Total	**84,650**

HYDROLOGIC MODEL

A hydrologic model of the ground-water system was constructed to evaluate the effects of pumpage on spring discharge. The model used in this study was developed by Pinder and Bredehoeft (1968). The model uses the iterative alternating-direction implicit procedure to solve the simultaneous equations that describe ground-water flow between adjacent, discrete points in the ground-water system.

The discrete points were established by superimposing a rectangular grid over the study area (fig. 7). The discrete points, or nodes, are defined as the center points of the compartmented areas bounded by the grid lines. The grid system has a spacing of 1 mi (1.6 km) over most of the area, with a finer spacing of 0.5 mi (0.8 km) near the springs.

The model simulates two-dimensional flow through a confined or unconfined aquifer with an irregular boundary. Various boundary conditions including no-flow, constant-flow, and constant-head boundaries can be simulated. The model can simulate head-dependent leakage through a confining layer — a feature that proved helpful in modeling variable spring discharge.

Basically, the model computes the water levels at each node, which uniquely satisfy the modeled physical parameters of the ground-water system and the stresses applied to it. The investigator first defines the physical parameters at each node — transmissivity, storage coefficient, and initial water level — and specifies a set of inflow and outflow conditions. The model then generates a set of water levels, node by node, which mathematically satisfies

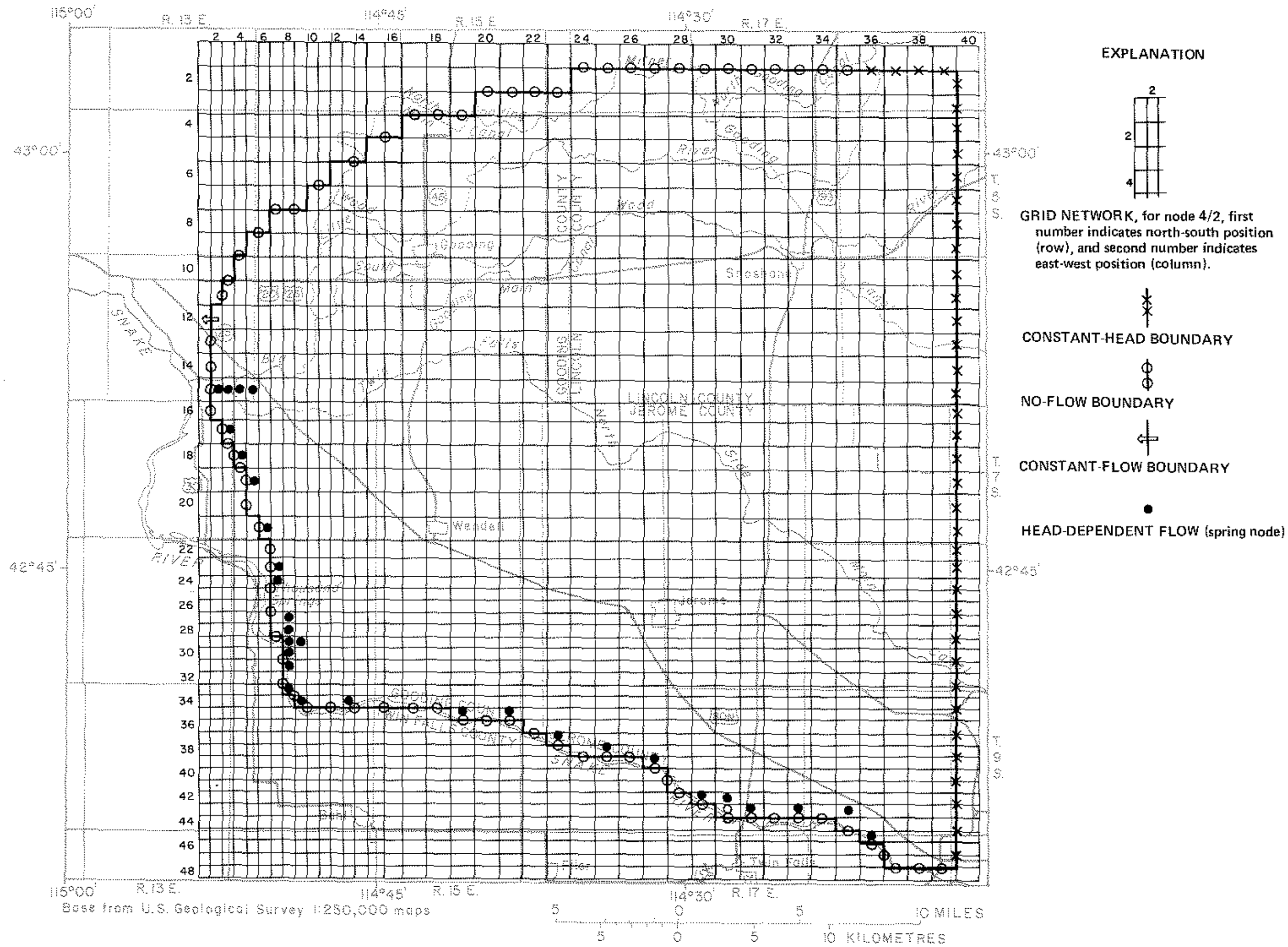


FIGURE 7. Model grid and boundary conditions.

the specified conditions. By comparing model-generated water levels to known water levels, the investigator can evaluate the accuracy of the model. The model is calibrated by adjusting (within reasonable limits) the physical parameters and inflow and outflow until satisfactory agreement is obtained between model-generated and known water levels.

Assumptions Required for Modeling

Modeling of a ground-water system is accomplished by substituting an artificial system for the real system. To do this, the real system must be simplified, the degree of simplification depending upon the complexity of the model. The simplifying assumptions made in this study include:

1. Within each node, ground-water flow obeys Darcy's law and moves through an isotropic, homogeneous aquifer,

2. Flow is two dimensional; vertical flow is ignored,

3. The thickness of the aquifer is sufficient that, for the range of water-level fluctuations anticipated, transmissivity does not change with changes in water levels,

4. Recharge to the ground-water system is instantaneous; transit time through the unsaturated zone is ignored,

5. Changes in ground-water storage occur instantaneously with change in water level; no provisions are made for slow release from storage,

6. Discharge from or recharge to a node occurs at a constant rate of flux over the entire nodal compartment; a pumping well or grouping of wells has a much larger effective radius than actual. Drawdown generated by the model reflects this large effective radius and, therefore, does not accurately indicate true drawdown from a pumping well or grouping of wells.

The validity of these assumptions varies considerably for different conditions. An understanding of how the assumptions affect the reliability of the model is essential in evaluating the usefulness of the model for simulating various conditions.

The assumption that ground-water flow obeys Darcy's law and moves through an isotropic, homogeneous aquifer, for example, is invalid for the Snake Plain aquifer when considered on a small scale of tens or hundreds of feet. The nature of the aquifer (lava tubes, fracture zones, complex joint systems, and permeable zones between basalt flows) is not isotropic and homogeneous. However, if viewed on a scale of thousands of feet, the aquifer system more closely resembles a classical porous medium. The assumption that flow obeys Darcy's law is difficult to assess. In local parts of the aquifer having large openings, the inertial forces of the flow may approach the magnitude of the resistive forces. However, for most of the aquifer system, resistive forces are probably dominant, and thus application of Darcy's law is justifiable.

The significance of the assumption of two-dimensional flow is difficult to assess. Most wells within the study area are uncased holes drilled only a few feet into the saturated zones. Because of this, little data are available to document head differences with depth. However, as with the previous assumption, vertical flow is probably negligible when viewed on a large scale.

The assumption that transmissivity is not significantly affected by water-level changes is valid for this aquifer system. Although total thickness of the aquifer is unknown, previous estimates and available information suggest that it greatly exceeds the few tens of feet that water levels are known to fluctuate.

The assumption that recharge to the aquifer is instantaneous is invalid if short-term conditions are considered. Transit time through the unsaturated zone, particularly in areas where the unsaturated zone is several hundred feet thick, may be several days or weeks. However, when considered over longer time periods (year-to-year conditions, for example,) transit time can be ignored.

The assumption that changes in ground-water storage occur instantaneously is comparable to the previous assumption. For short time periods, the assumption can cause significant error in simulation of pumping stresses. However, over long periods, the error becomes small.

The assumption that discharge from or recharge to a node occurs at a constant rate of flux over the entire nodal compartment is a more important factor for aquifers with much lower transmissivities than the Snake Plain aquifer. In this system, however, the high transmissivity of the aquifer precludes development of significant local cones of depression because the effects of pumped wells or point sources of recharge are spread rapidly over large areas.

Compatibility with WRRI Model

Before this study was begun, considerable effort and money were expended by WRRI to develop a model of the Snake Plain aquifer (de Sonneville, 1974). That model will be used by the IDWR to evaluate the hydrologic effects of regional-scale management plans on the aquifer. Although the WRRI model can provide meaningful answers to broad, regional-type questions, it is not sufficiently detailed near the springs to evaluate the effects of localized stresses on individual spring discharges.

In constructing the detailed model of this study area, future interface with the WRRI model was considered. To be of maximum benefit, the detail model should be compatible with the WRRI model. Therefore, such factors as base period for calibration, computed inputs to the model, and assumptions made in simulating the aquifer had to be in general agreement.

An important factor in achieving compatibility was the use of the same base period for calibration. WRRI selected 1966 as a period of dynamic equilibrium (inflows and outflows to the aquifer were approximately equal and ground-water levels were relatively stable). They assumed that 1966 inputs were comparable to the average annual inputs that resulted in the state of dynamic equilibrium. Analysis of inflow data indicates that, although precipitation was less than average for this period, other factors (irrigation return, pumpage, spring discharge) were about equal to the average of several preceding years.

The future interface of the two models was considered to be more important than possible errors introduced by using a period of below-average precipitation. Therefore, the inputs computed by WRRI were accepted without modification. Distribution of the input was modified slightly to fit the detailed model grid network, but this modification did not affect the hydrologic budget developed by WRRI.

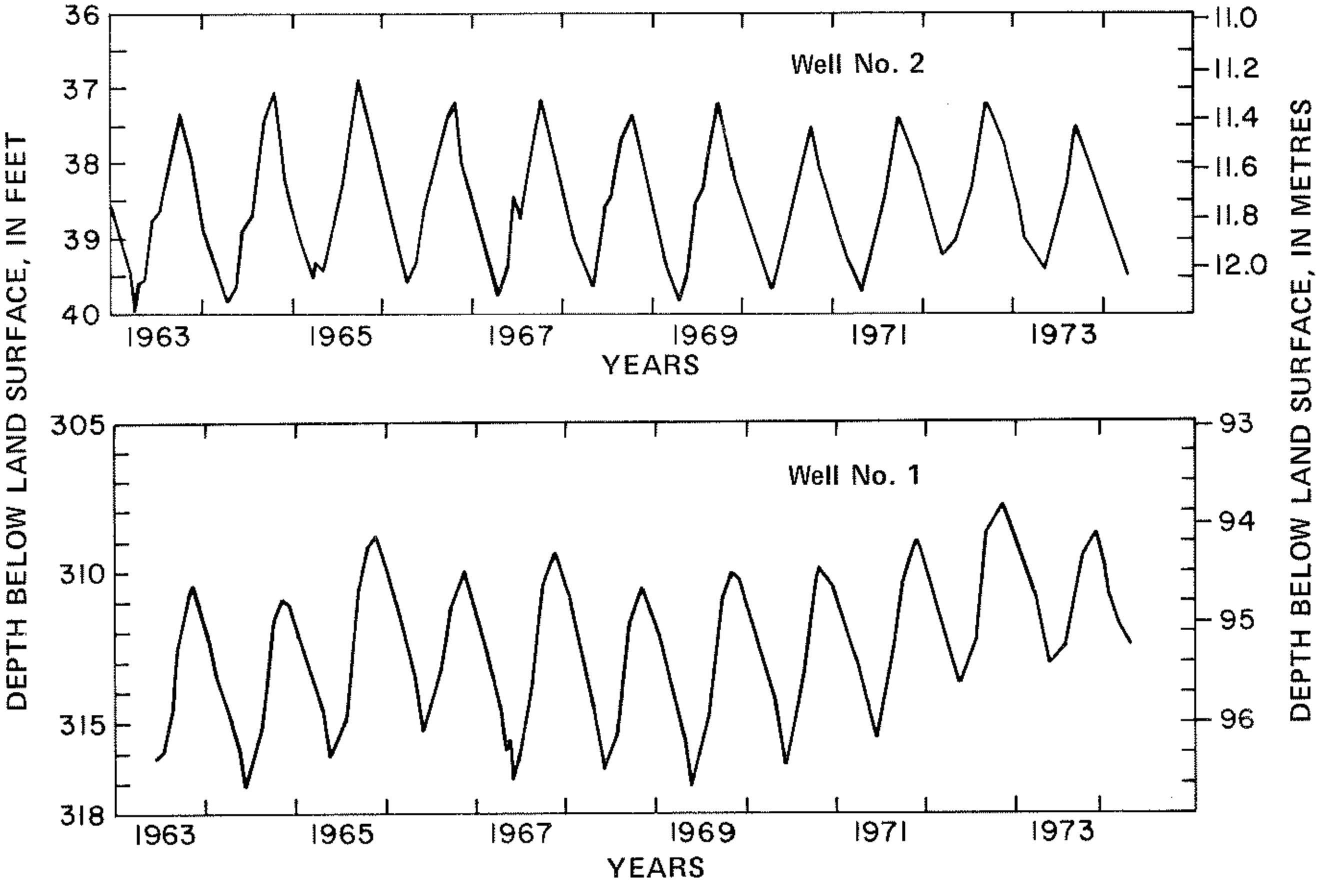


FIGURE 8. Hydrographs of observation wells.

Using the 1966 inputs but calibrating the model for 1974 water-level conditions can be justified by analyzing water-level records from observation wells (fig. 8). Actual water-level differences between 1966 and 1974 are, in general, less than 2 ft (0.6 m). Water-level contours drawn on 1966 data would be indistinguishable from contours drawn on 1974 data. In fact, errors in land-surface elevations at individual well sites are probably much more significant than water-level differences between the two periods.

Model runs using the 1966 inputs were compared with similar runs in which precipitation was changed to average values. Water-level differences were less than 1 ft (0.3 m) everywhere in the study area. Thus, the use of WRRI data appears justified within the range of accuracy available.

Boundary Conditions

Only the part of the Snake Plain aquifer within the area of study was modeled (fig. 1). The southern and western boundaries coincide with the Snake River Canyon and, ostensibly, with the boundary of the Snake Plain aquifer. The northwestern and northern boundaries generally coincide with the limits of the highly permeable basalt aquifer. The eastern boundary was arbitrarily selected as a convenient limit and has no hydrologic significance.

The model affords three methods of simulating a boundary: no flow, constant flow, and constant head. A no-flow boundary is self-explanatory; no water enters or leaves the model along the boundary. A constant-flow boundary supplies or removes a constant, predetermined rate of water from the model. A constant-head boundary automatically holds the water levels at a specified value, supplying or removing water at a rate sufficient to maintain the water level.

Those boundaries that coincide with the Snake River Canyon (the southern and western boundaries) were modeled as no-flow boundaries. Where springs occur, nodes were initially specified as constant-flow boundaries. A small part of the northwest boundary, along which the permeable Snake Plain aquifer merges with less permeable sedimentary material, was modeled as a constant-flow boundary. Because total flow is small, the total amount of underflow was assigned to one node. The northern boundary, with the exception of the easternmost section, was modeled as a no-flow boundary.

Because the eastern and extreme northeastern limits of the model arbitrarily transect the Snake River aquifer, a meaningful method of simulating boundary conditions along this line had to be selected. A no-flow boundary obviously would be inappropriate because most of the ground water flowing through the study area enters as underflow across the eastern boundary. Both the constant-flow and constant-head methods allow for underflow and, therefore, could be used.

A constant-flow boundary more correctly represents true hydrologic conditions. However, this type of boundary condition requires computation or estimation of the underflow at each boundary node. If hydrologic conditions change, either by a change in ground-water levels or a change in gradient at the boundary, the resulting change in underflow must be calculated. This factor would severely limit the use of the model in conjunction with the large-scale model of the entire aquifer. For example, if the large-scale model predicts that changes in irrigation practices upstream from the study area result in a 10-ft (3-m) water-level decline at the model boundary, considerable effort would be required to compute the resulting change in underflow for input to the detailed model.

A constant-head boundary has the distinct advantage of being compatible with the large-scale model. Any predicted change in water levels at the boundary can be easily used as input for the detailed model by simply adjusting the head values along the constant-head boundary. The most serious limitation of this type of boundary is that the boundary, by definition, cannot respond to stresses placed on the model. When the zone of influence of any stress placed on the model extends to the constant-head boundary, the boundary becomes an infinite source of recharge or discharge and prevents the zone of influence from spreading beyond the boundary. This factor must be considered when evaluating the usefulness of the model. Stresses near the model boundary cannot be accurately simulated.

Also, simulation of long-term stresses that result in large zones of influence must be evaluated to insure that boundary effects do not unduly affect the predicted water-level changes.

The problems associated with the selection of an appropriate boundary condition were analyzed during construction and use of the model. The constant-head boundary was replaced with a constant-flow boundary, and duplicate runs were made to determine the boundary effects. Only the results of runs made with the constant-head boundary are included in this report. In general, the results of model runs made with the constant-head boundary were similar to results of model runs made with the constant-flow boundary for equivalent time periods or length of simulation. The primary difference between the constant-head and constant-flow boundaries was the length of time required to attain equilibrium. For the constant-flow boundary simulations, equilibrium is not attained until changes in spring discharge equal changes in input — usually much longer than with the constant-head boundary.

Spring Discharge

As with boundary conditions, the model offers several methods for modeling spring discharge. These include constant flow, constant head, and head-dependent flow.

By modeling the spring discharge as constant flow during initial calibration, adjustments in physical parameters can be made without affecting the modeled spring discharges. This method, while helpful in calibrating the model, is not acceptable for modeling the effects of stresses on spring discharge. If modeled as constant flow, no changes within the model could cause changes in discharge.

The constant-head method permits spring discharge to vary as a function of the ground-water gradient. However, no control over the amount of discharge from the springs is afforded. The model simply removes water at a rate sufficient to maintain the specified head. Spring discharge can only be controlled with this method by adjusting transmissivity values at adjacent nodes until the rate of removal is in agreement with the known rate of discharge — a time-consuming chore. Even then, no relation between ground-water fluctuations and rate of discharge can be specified.

The third alternative, modeling spring discharge as head-dependent flow, does offer a method of relating ground-water fluctuations to spring discharge. With this method, the nodes in which spring discharge occur are simulated as being overlain by a confining layer. A single hydraulic conductivity value for the confining layer is specified for all nodes, but the thickness of the layer can be varied from node to node. The hydraulic head (a constant) above the confining layer can also be specified. The amount of water leaking through the node (total spring discharge) is determined from the equation:

$$Q = \frac{K\,(H\text{-}W)\,A}{L}$$ where,

Q = spring discharge in cubic feet per second,
K = hydraulic conductivity of simulated confining layer in feet per second,
L = thickness of simulated confining layer in feet,
H = hydraulic head in aquifer in feet,
W = simulated head above confining layer in feet, and
A = area of node in square feet.

By adjusting the spring-discharge parameters (K and L), the spring discharge can be simulated. If the water level at the node changes, the spring discharge also changes. By properly choosing the spring-discharge parameter, W, the relation between changes in ground-water levels and spring discharge can be modeled. The relation between water levels and spring discharges can be obtained for some springs by plotting discharge against water levels in nearby wells. Because data are insufficient to define relations for all the springs, transfer of relations between nearby springs was required.

MODEL CALIBRATION

Model calibration was done in two steps – simulation of an assumed equilibrium state using average annual inputs, and simulation of transient annual fluctuations using inputs for a nonirrigation period and an irrigation period. The simulation of equilibrium conditions was used to adjust transmissivity values and spring discharges, whereas the simulation of annual fluctuations was used to adjust storage coefficients and evaluate the validity of the model in simulating stresses.

Equilibrium Conditions

The WRRI model used annual averages of recharge and discharge computed for 1966 as representative of equilibrium conditions. These same values for recharge (irrigation return, percolation of precipitation, and leakage from tributary streams) and discharge (ground-water withdrawals for irrigation) were used as input to the model of this study. Ground-water underflow entering the study area was simulated by the constant-head boundary technique. Under equilibrium conditions, the underflow generated by the model was, by definition, equal to underflow in the WRRI model. Ground-water underflow leaving the area was simulated by the constant-flow technique. Spring discharges, as listed in table 2, were also simulated as constant flow.

Beginning with the best estimates available for aquifer transmissivities (maps from previous studies), the model was used to generate water-level contours that satisfied the assumed equilibrium values of inflow and outflow. Generated and known water-table contours were compared, and adjustments were made in the original transmissivity map where discrepancies were noted. This process was continued until reasonable agreement was achieved between the model-generated and known water-table contours (fig. 9).

Although the water-table contour map (fig. 2) used as a basis of comparison was constructed from data collected in April 1974, it is reasonable to assume that this comparison is valid. For example, figure 8 shows that water levels changed little in observation wells 1 and 2 from 1966 to 1974. Data for other observation wells also indicate that long-term water levels throughout the study area changed little between 1966 and 1974. Changes that have occurred are less than the annual fluctuations in ground-water levels and are generally less than the accuracy of estimating the altitude of land surface at the wells.

After reasonable agreement was achieved between model-generated and known water-table contours, constant spring discharge was changed to head-dependent leakage.

Several additional runs were made to refine aquifer transmissivities and spring-discharge parameters.

Model-generated and known water-table contours after final calibration of equilibrium conditions are shown in figure 9. Except for the area north of the Big Wood River and a small area south of Jerome, the model-generated water-table contours closely agree with those constructed from 1974 data.

The final transmissivity map (one that produced the best agreement between model-generated and known water-table contours) is shown in figure 10. In general, the southern part of the aquifer has higher transmissivities [as much as 30 (Mgal/d)/ft, or $3.7 \times 10^5 m^2/d$] than the northern part [less than 10 (Mgal/d)/ft, or $1.2 \times 10^5 m^2/d$]. This general pattern is similar to transmissivity maps constructed by previous investigators (Norvitch and others, 1969) but is considerably more detailed.

The transmissivity map indicates several places of comparatively low transmissivity [less than 1 (Mgal/d)/ft or $1.2 \times 10^4 m^2/d$]. These occur in relatively long, narrow zones trending north and northwest. Although their origin is unknown, possible explanations include dikes and fault zones filled with low-permeability material.

Transient Conditions

Simulating long-term changes in hydrologic conditions is the generally accepted method of modeling transient conditions to evaluate accuracy of the model. However, in this study, long-term, area-wide hydrologic conditions within the aquifer are poorly documented. Sufficient data are available to document changes in spring discharge since the early 1900's, and long-term records are available to document stresses due to irrigation and precipitation. However, accurate water-level data for parts of the aquifer are available only since the mid-1940's. Figure 3 indicates that hydrologic conditions have been relatively stable since the mid-1940's, except for a short period in the early 1960's. Even then, data were insufficient to document water-level distributions or change over the entire study area.

Well-defined annual fluctuations occur in spring discharge and ground-water levels in response to seasonal irrigation practices (figs. 4 and 8). Jos de Sonneville (1974) used these cyclic fluctuations to calibrate the WRRI model. In the absence of long-term records of ground-water levels (prior to 1910 and area-wide in recent years), this study also used the seasonal fluctuations to calibrate the model.

A note of caution is appropriate on the overuse of this technique of calibrating models using only short-term seasonal fluctuations. By modeling only short-term fluctuations, no analysis is made of how long-term changes in one part of the aquifer affect conditions in other, distant parts of the aquifer.

Seasonal fluctuations primarily result from local stresses and, as such, do not reflect interrelations between different parts of the aquifer. By simulating only the short-term effects of local stresses, no verification is made of how well the model simulates long-term stresses. Because water-level fluctuations at any point in the aquifer are a result of superposition of effects from all stresses imposed at all places and at all previous times, calibration based on only one seasonal fluctuation could introduce serious errors.

However, for this study, data restrictions necessitate the use of short-term analysis. This should be considered in evaluating model simulation of various stresses.

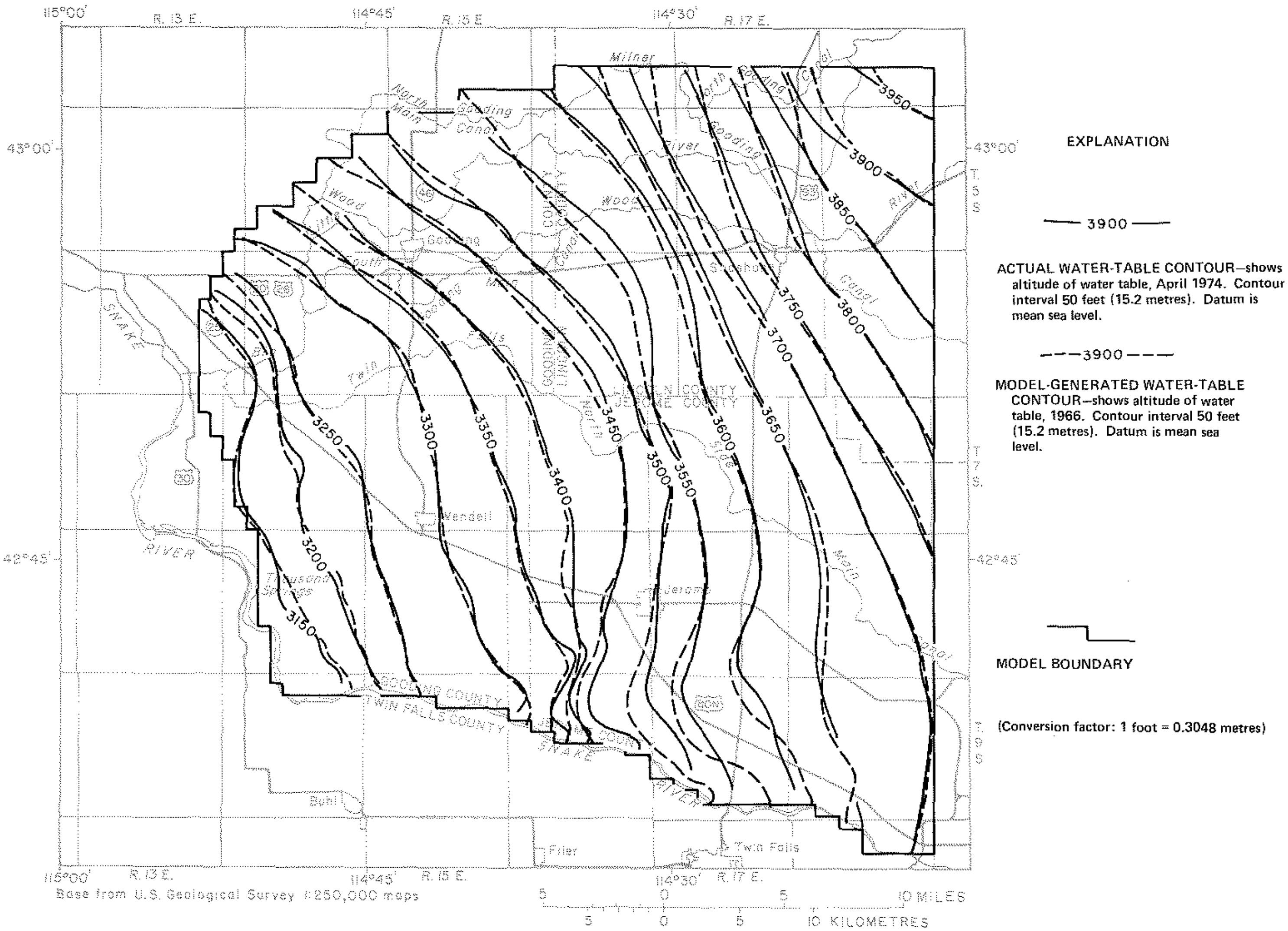


FIGURE 9. Model-generated and actual water-table contours.

In modeling transient conditions, two periods were simulated: a nonirrigation period when input to the aquifer was minimal, and an irrigation period when recharge from irrigation return and ground-water withdrawals for irrigation were maximum. Because the equilibrium calibration assumed average conditions, it was not possible to begin the transient simulation at the beginning of either the nonirrigation or the irrigation period. To do so would require beginning the transient simulation with ground-water levels and spring discharges at below or above average values. January is a convenient starting point for transient simulation because ground-water levels and spring discharges are at or near the average annual values (figs. 4 and 8). The water levels and spring discharges in January have declined somewhat from the fall highs and are reasonably near average annual values.

Using WRRI's 1966 inputs, average rates for irrigation return, percolation of precipitation, seepage in tributary streams, and ground-water withdrawals were computed for January through March (nonirrigation period) and April through October (irrigation period).

Beginning with the equilibrium state, the model was stressed with January through March inputs to generate conditions at the end of the nonirrigation period. Ground-water levels resulting from this simulation were then used as the starting point for the second modeled period. The model was stressed with April through October inputs to generate conditions resulting from the irrigation period. Water-level differences between the two modeled periods were then compared to a water-level-difference map made from data collected in April and October 1974. Adjustments were made in aquifer-storage coefficients and spring-discharge parameters, and the process was repeated.

The model-generated water-level change proved to be relatively insensitive to changes in storage coefficient. Changes in storage coefficients of as much as 50 percent resulted in water-level differences of less than 2 ft (0.6 m). The storage-coefficient map used in the simulation of transient conditions is shown in figure 11. Because the model-generated water levels and spring discharges were relatively insensitive to the range of storage coefficients tried in the model calibration, the reliability of the S distribution is uncertain. However, the general pattern of distribution and range of storage coefficients agrees with previous studies (de Sonneville, 1974). Error in the storage-coefficient distribution will not significantly affect the ultimate response of aquifer to stresses. However, the length of time required to attain new equilibrium after a stress is applied may be in error.

Actual and model-generated water-level rises between April and October are illustrated in figure 12. In general, the gross pattern of water-level rises was simulated by the model. Water-level rises in excess of 10 ft (3 m) were observed north of Gooding and between Wendell and Jerome. The model-generated rises also exceed 10 ft (3 m) north of Gooding, but the area of maximum rise between Wendell and Jerome was displaced eastward compared to actual changes. The area north of Wendell had between 6 and 8 ft (1.8 and 2.4 m) of rise in both the actual and model-generated maps.

Agreement between actual and model-generated conditions is poor in the area north and east of Jerome (near the constant-head boundary), because no change is generated along the constant-head boundary (fig. 7). This boundary not only precludes change along the eastern edge of the model but attenuates changes for some distance from it. Using a constant-flow boundary instead of a constant-head boundary resulted in almost identical water-level rises (not shown) throughout the area, except near the boundary, as expected.

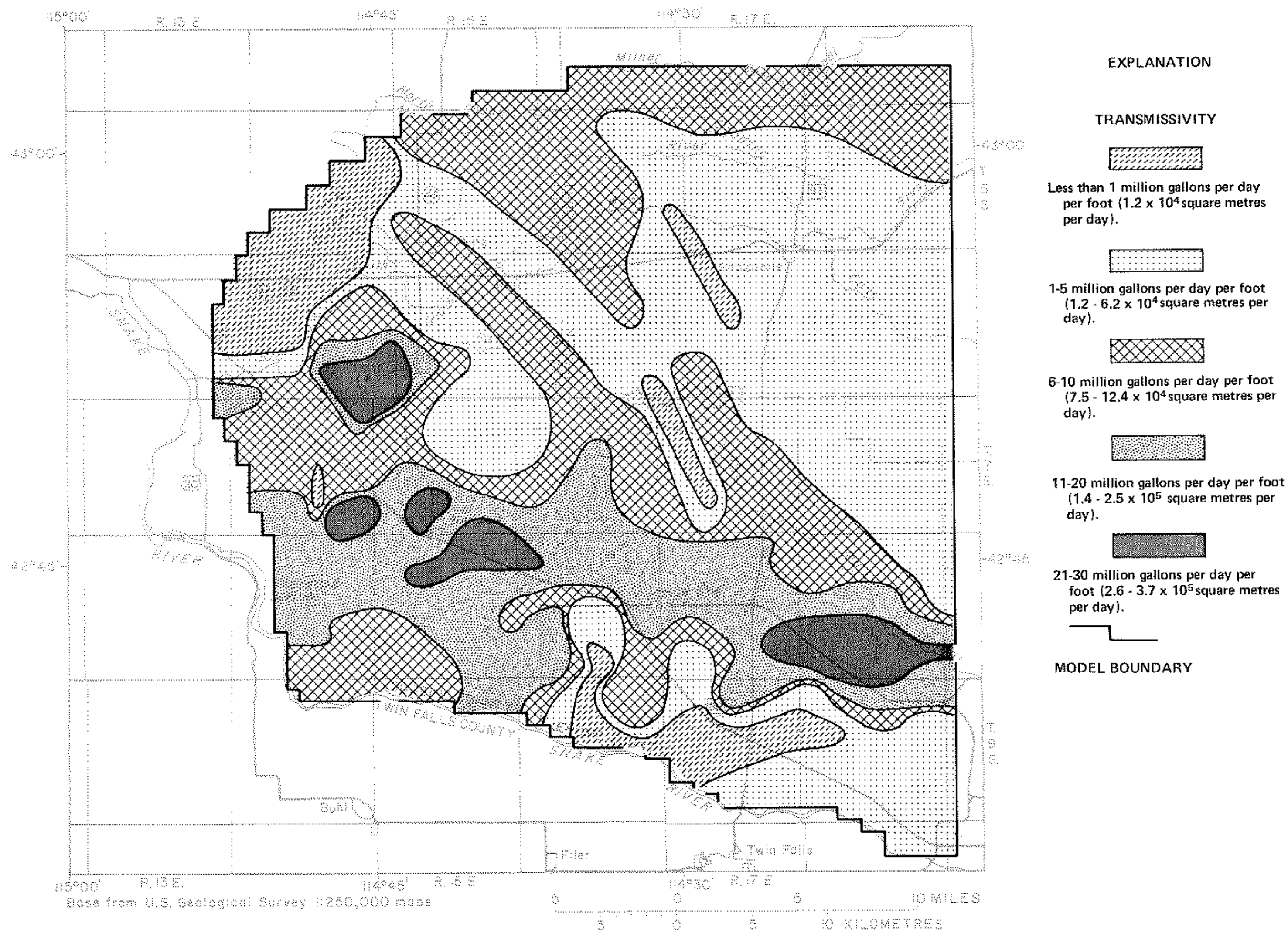
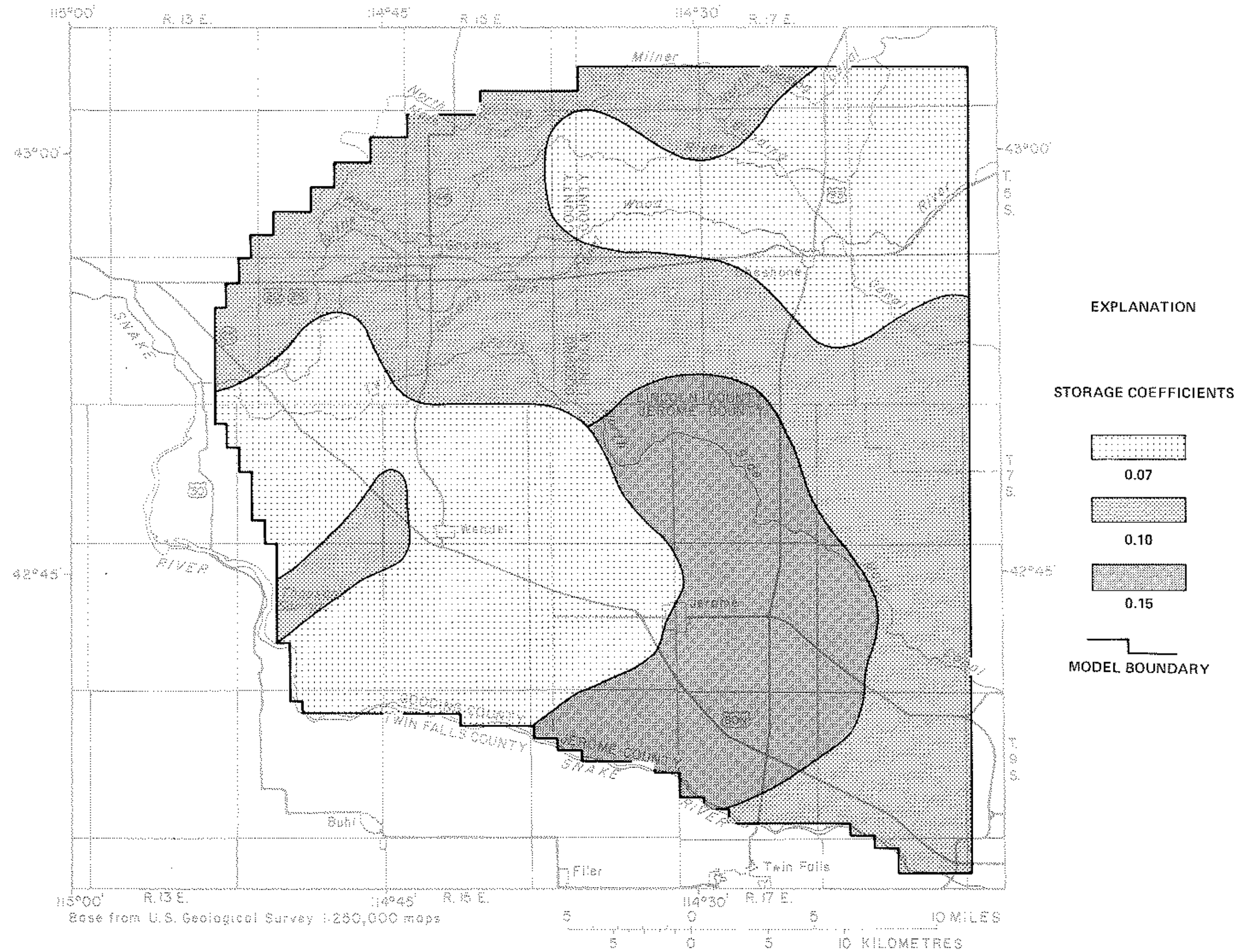
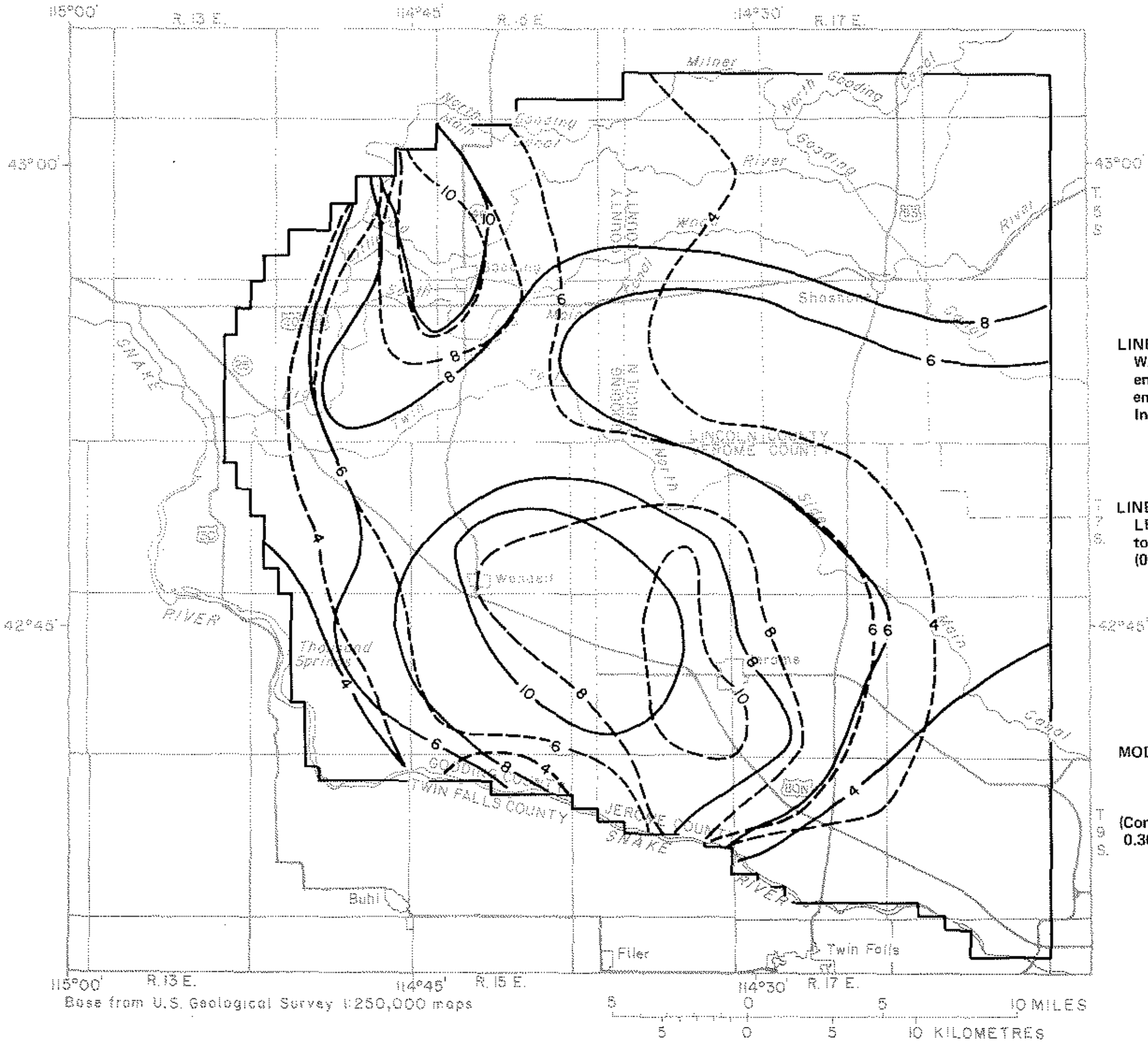


FIGURE 10. Modeled aquifer transmissivity.

FIGURE 11. Modeled aquifer storage coefficients.





EXPLANATION

— — 4 — — LINE OF EQUAL MODEL-GENERATED WATER-LEVEL RISE—shows rise from end of nonirrigation season (April) to end of irrigation season (October). Interval 2 feet (0.6 metres).

——— 4 ——— LINE OF EQUAL ACTUAL WATER-LEVEL RISE—shows rise from April to October, 1974. Interval 2 feet (0.6 metres).

MODEL BOUNDARY

(Conversion factor: 1 foot = 0.3048 metres)

FIGURE 12. Model-generated and actual water-level change between spring and fall.

Head-dependent leakage at the springs apparently also causes some attenuation of water-level rise. Actual water-level rises are somewhat higher near the springs than model-generated rises.

Figure 13 illustrates how model-generated changes in discharges of specific springs and water levels at specific wells compare to actual changes. As shown, the model does not simulate sufficient change in Blue Lakes Springs but reasonably approximates change in Niagara Springs. The lack of response in Blue Lakes Springs is primarily due to the nearness of the constant-head boundary.

Comparison of water-level changes at the two observation wells indicates violation of the assumption of instantaneous response. Depth to water in observation well 1 is over 300 ft (90 m), whereas depth to water in observation well 2 is only about 37 ft (11 m). Figure 13 shows that the water level in well 1 responded to irrigation months after irrigation began in April. In well 2, the response occurred within 15 days after irrigation began. This indicates a lag time between irrigation application and water-level response. The great thickness of unsaturated material at well 1 greatly impedes the response. Because response to recharge or discharge is instantaneous in the model, the model-generated hydrographs for both wells reverse direction with no lag at the end of the nonirrigation period.

Table 4 lists discharges generated by the model for 12 major springs at the end of each modeled period. As shown by the totals, model-generated spring discharges for these springs differ by about 400 ft^3/s (11 m^3/s) between the spring (season) lows and the fall highs. This difference is somewhat lower than expected from analysis of continuous records for Niagara and Box Canyon springs. Three major factors contribute to the difference:

1. Effects of constant-head boundary,
2. Effects of ignoring lag time, and
3. Use of average values for inputs for the total length of each model period.

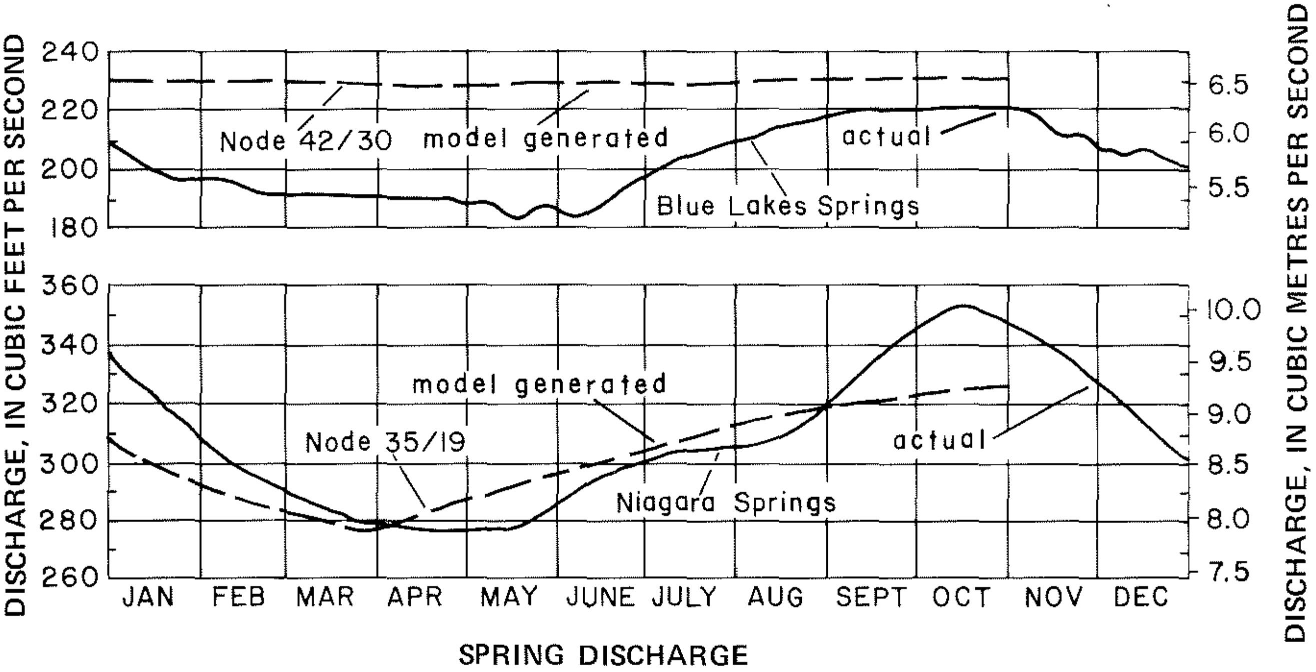
Effects of 1973 Ground-Water Withdrawals

As discussed, both equilibrium and transient conditions were simulated using WRRI inputs computed for 1966. Because more accurate determinations of ground-water withdrawals were made for the 1973 irrigation period, an attempt was made to evaluate the effects of recent increases in pumpage on spring discharges.

All water applied in excess of consumptive use requirements returns to the aquifer as irrigation return. Therefore, total 1973 extractions were reduced by a factor obtained from data collected by Young and Harenberg (oral commun., 1974). They computed irrigation efficiency for flood irrigation and sprinkler irrigation at 27 sites during a study of pumpage on the Snake Plain. Data indicate that 50 percent of water applied by flood irrigation and 80 percent of water applied by sprinkler irrigation is consumptively used.

The modified inputs were applied for a 9-year period 1966-74. The increased ground-water withdrawals produced no declines in ground-water levels and only minimal declines in spring discharges. Declines for the 12 major springs totaled only 33 ft^3/s (1 m^3/s).

The relatively insignificant effects of the increased 1973 pumpage is not surprising, for 1966 values were based on rough estimates of areas irrigated by ground water. The 1966 estimated extractions seem to be higher than actual.



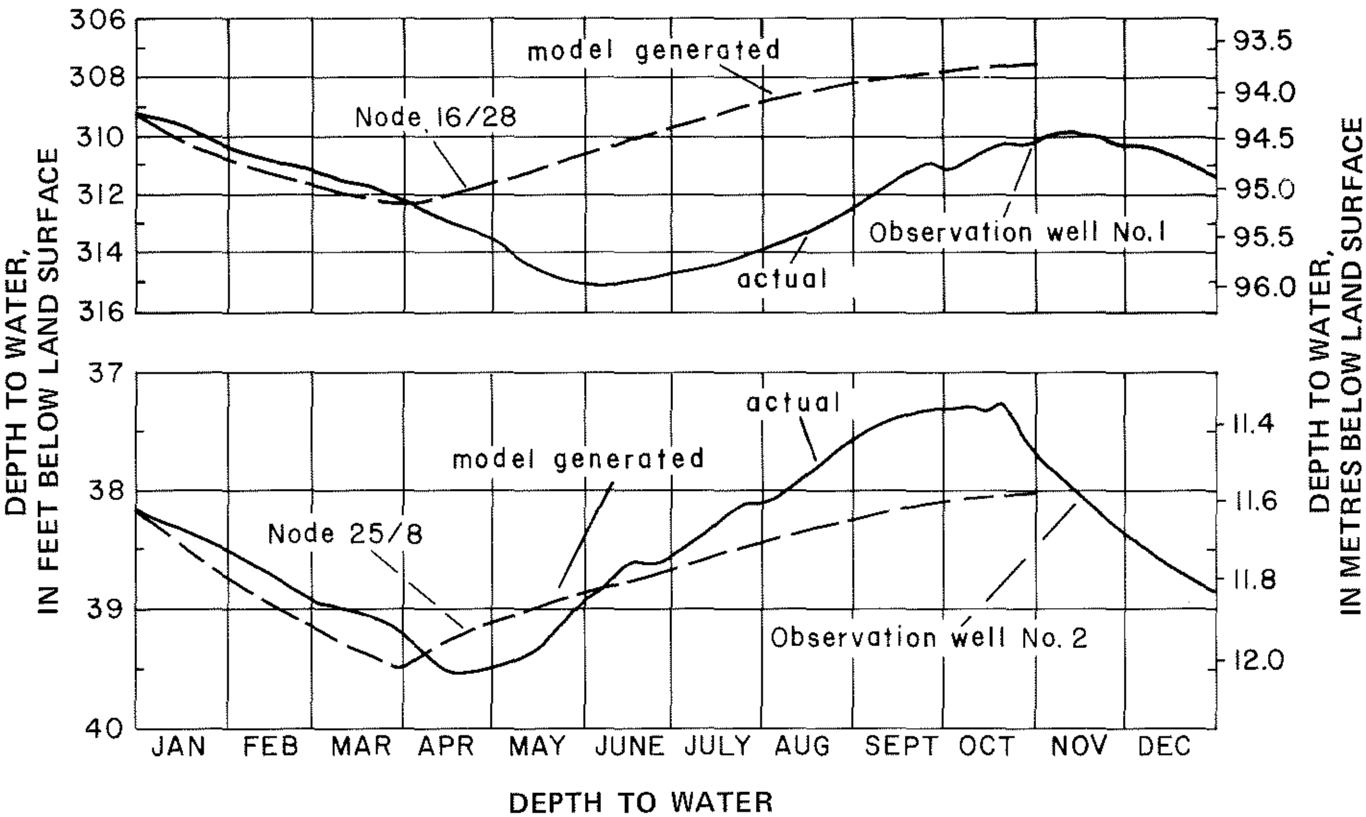


FIGURE 13. Model-generated and actual spring discharge and depth to water, 1966.

TABLE 4
MODEL-GENERATED SPRING DISCHARGES
FOR TRANSIENT CONDITIONS

Spring	Spring discharge, in ft^3/s		
	At end of equilibrium period (1966)	At end of nonirrigation period, Jan-Mar	At end of irrigation period, Apr-Oct
Malad Springs	1,379	1,338	1,405
Billingsley Creek	236	214	250
Riley Creek	202	187	212
Thousand Springs	1,303	1,267	1,327
Sand Springs	99	91	105
Box Canyon Springs	848	828	861
Banbury Springs	123	118	126
Briggs Creek	141	134	146
Clear Lakes	538	520	551
Niagara Springs	307	276	327
Crystal Springs	501	455	530
Blue Lakes Springs	230	228	231
Total	5,907	5,656	6,071

ALTERNATIVE PLANS OF WATER USE AND THEIR EFFECTS ON SPRING FLOWS

The IDWR provided six alternatives for simulation on the calibrated model to test effects on spring discharges. These plans included two schemes of reduced surface-water diversion in various irrigation canals and four schemes of increased ground-water withdrawals for irrigation:

Plan A—Reduced surface-water diversion to the Twin Falls North Side, North Gooding Main, South Gooding Main, and Milner-Gooding canals. Total surface-water irrigated acreage was assumed to be unchanged. The proposed schedule of reduction was:

Canal	Diversions, in Acre-Ft Per Year 1966	Plan A
Twin Falls North Side	1,317,900	1,017,400
North Gooding Main	151,800	143,700
South Gooding Main	125,300	118,600
Milner-Gooding	133,490	126,400
Total of four canals	1,728,490	1,406,100

This plan would reduce total inflow to the Snake Plain aquifer from irrigation return by about 445 ft^3/s (13 m^3/s). However, much of the land irrigated by the Twin Falls North Side and Milner-Gooding canals lies outside the study area. Within the study area, this plan would reduce total inflow by about 315 ft^3/s (9 m^3/s).

Plan B—Reduced surface-water diversions to the North Gooding Main, South Gooding Main, and North Gooding canals. Total surface-water irrigated acreage was assumed to be unchanged. The proposed schedule of reduction was:

Canal	Diversions, in Acre-Ft Per Year 1966	Plan B
North Gooding Main	151,800	128,000
South Gooding Main	125,300	110,000
North Gooding	54,600	45,000
Total of three canals	331,700	283,000

In this plan, all canals lie within the study area, and the total reduction in inflow to the study area would be about 70 ft^3/s (2 m^3/s).

Plan C—Increased ground-water withdrawals in townships 5S-15E, 5S-16E, 7S-14E, and 7S-15E. Schedule of increased withdrawals over 1966 values was:

Township	Increased Withdrawals in ft^3/s
5S-15E and 5S-16E	40
7S-14E	9.2
7S-15E	60
Total increase	109.2

In this plan, as in the other plans for increased ground-water withdrawals, the assumption was made that all increased pumpage was consumptively used.

Plan D—Increased annual ground-water withdrawals of 100,000 acre-ft ($1.2 \times 10^8 m^3$), or 138 ft^3/s (3.9 m^3/s) south of Jerome.

Plan E—Increased annual ground-water withdrawals of 100,000 acre-ft ($1.2 \times 10^8 m^3$), or 138 ft^3/s (3.9 m^3/s) southwest of Wendell.

Plan F—Increased annual ground-water withdrawals of 100,000 acre-ft ($1.2 \times 10^8 m^3$), or 138 ft^3/s (3.9 m^3/s) west of Shoshone.

In evaluating the effects of these proposed alternatives, it is important to consider how the magnitude of the proposed changes compares to other items of inflow and outflow. For example, total spring discharge was about 6,000 ft^3/s (170 m^3/s) for the 1966 model period; recharge from precipitation (calculated by WRRI for the 1966 model period) was about 90 ft^3/s (2.5 m^3/s); surface water diverted to irrigate 223,000 acres ($9 \times 10^8 m^2$) of land was about 1,840 ft^3/s (52 m^3/s); irrigation-return from irrigated lands was about 950 ft^3/s (27 m^3/s); and total ground-water withdrawals were about 75 ft^3/s (2.1 m^3/s).

Possible fluctuations in the various items of inflow and outflow should also be compared to the proposed alternatives. For example, if the rate of recharge from precipitation is increased by 0.1 ft (0.03 m) per year over the 840 mi^2 (2,200 km^2) of the study area, an additional 75 ft^3/s (2.1 m^3/s) would be added. If consumptive use by crops was increased by 0.1 ft (0.03 m) per year over the total irrigated acreage, irrigation-return flow would be 35 ft^3/s (1 m^3/s) less. If the ground-water gradient at the eastern boundary of the study area increased 1 ft/mi (0.2 m/km) along the entire boundary, an additional 240 ft^3/s (6.8 m^3/s) would enter the study area as underflow. Thomas (1969, fig. 11) shows that total spring discharge varies as much as 350 ft^3/s (9.9 m^3/s) from year to year.

These examples of inflow and probable fluctuations in inflow and outflow illustrate that any evaluation of alternatives should be made with the understanding that natural fluctations in other items of inflow or outflow could completely mask the effect due to the alternatives. Thus, to obtain any reasonable estimate of effects due to the proposed plans, all other factors must be held constant.

In addition, the model must be in a state of equilibrium with all the inputs before stresses can be applied. If an equilibrium state is not used as a starting point for projection, the changes due to imbalance in the system could easily mask the effects of the stresses.

For these reasons, a technique to isolate the effects due to the stresses was used. Basically, the model was run for a period of time sufficient to attain equilibrium with a given set of inflows. After equilibrium was achieved, the proposed stresses were applied, leaving all other factors constant. Thus, model-generated changes in water levels and spring discharges were due only to applied stresses.

Because the model was initially calibrated using WRRI 1966 inputs, that year was selected as the base for projection. Any other year for which inputs were near average would have been equally valid, but inputs had already been computed for the 1966 period.

The projections made in this fashion can only be used to evaluate the effects of the proposed alternatives. Because natural fluctuations are not included, the model-generated spring discharges cannot be considered as predicted values. They serve only to illustrate the alternatives' contributions to future changes in spring discharge.

No attempt was made to simulate annual fluctuations. Annual average values for all inputs were used to generate the effects of the various plans on annual average ground-water levels and spring discharges.

Each plan was run for approximately 15 years with model-generated conditions computed for the end of 1-, 5-, and 15-year periods. In all plans, the effects of the alternatives had nearly stabilized by the end of 5 years (changes in water levels or spring discharge after 5 years were very small), so the 15-year projections are not shown in figures 14-19.

Although some plans were simulated using both constant-head and constant-flow boundaries, only the constant-head boundary simulations are included in this report. Because the model was designed to be compatible with the WRRI model, the constant-head boundary was selected as the most useful. However, in all cases, the results obtained from the constant-flow boundary simulations were quite similar (for the same time periods) to those obtained from the constant-head technique. Significant differences did occur for longer periods of simulation. While the constant-head technique resulted in nearly stabilized conditions after 5 years, the constant-flow technique produced further changes for several more years. As would be expected, spring discharges in the constant-flow simulation stabilized at values reduced by the same amount as the change in input from each plan.

Plan A

In this alternative, surface-water diversions to the Twin Falls North Side, North Gooding Main, South Gooding Main, and Milner-Gooding canals were reduced by about 315 ft^3/s (8.9 m^3/s) within the study area. As shown in figure 14, water-level declines in excess of 2 ft (0.6 m) occurred over most of the southern part of the area after 1 year. After 5 years, water levels had declined in excess of 2 ft (0.6 m) over most of the entire study area. Maximum declines in excess of 5 ft (1.5 m) occurred south of Jerome.

Table 5 shows that declines in model-generated spring discharge totaled 125 ft^3/s (3.5 m^3/s) after 1 year and 155 ft^3/s (4.4 m^3/s) after 5 years. This plan affected discharges in all the springs with most significant declines occurring in Crystal, Thousand, and Malad Springs.

The effects of the constant-head (eastern) boundary (fig. 7) are readily apparent in figure 14. Water-level declines were asymmetrical toward the boundary, illustrating that much of the total effects were masked by the boundary. The same alternative simulated with a constant-flow boundary resulted in larger declines near the boundary for the same period of simulation, but spring discharges were only slightly less. However, with this method, spring discharges continued to decline for several years until reductions in spring flow equaled reductions in input.

Plan B

In this alternative, surface-water diversions were reduced in the Wood River system, including the North Gooding Main, South Gooding Main, and North Gooding canals. Total reduction was about 70 ft^3/s (2.0 m^3/s). Water-level declines were more localized in this alternative than for Plan A and were limited to the northern half of the study area. Figure 15 shows maximum declines of about 4 ft (1.2 m) north of Gooding after 5 years.

TABLE 5

MODEL-GENERATED SPRING DISCHARGES FOR ALTERNATIVE PLANS

Spring	Model equilibrium with WRRI inputs (ft^3/s)	Spring discharge, ft^3/s (lower number is decline in discharge, ft^3/s) Plan A After 1 year	Plan A After 5 years	Plan B After 1 year	Plan B After 5 years	Plan C After 1 year	Plan C After 5 years	Plan D After 1 year	Plan D After 5 years	Plan E After 1 year	Plan E After 5 years	Plan F After 1 year	Plan F After 5 years
		1,361	1,355	1,374	1,371	1,370	1,367	1,377	1,376	1,371	1,369	1,375	1,370
Malad Springs	1,379	18	24	5	8	9	12	2	3	8	10	4	9
		226	223	234	233	231	229	235	234	229	228	234	232
Billingsley Creek	236	10	13	2	3	5	7	1	2	7	8	2	4
		194	192	201	200	197	196	201	200	193	193	200	199
Riley Creek	202	8	10	1	2	5	6	1	2	9	9	2	3
		1,284	1,280	1,301	1,299	1,294	1,291	1,300	1,298	1,280	1,279	1,300	1,296
Thousand Springs	1,303	19	23	2	4	9	12	3	5	23	24	3	7
		95	94	99	98	97	97	98	98	94	94	98	98
Sand Springs	99	4	5	0	1	2	2	1	1	5	5	1	1
		838	836	847	846	844	843	846	845	837	837	846	845
Box Canyon Springs	848	10	12	1	2	4	5	2	3	11	11	2	3
		120	120	122	122	122	122	122	122	121	121	122	122
Banbury Springs	123	3	3	1	1	1	1	1	1	2	2	1	1
		138	138	141	141	140	140	141	141	139	139	141	141
Briggs Creek	141	3	3	0	0	1	1	0	0	2	2	0	0
		530	528	538	537	536	535	537	537	531	531	537	536
Clear Lakes	538	8	10	0	1	2	3	1	1	7	7	1	2
		291	288	306	305	302	301	303	301	296	295	305	302
Niagara Springs	307	16	19	1	2	5	6	4	6	11	12	2	5
		477	471	499	498	494	492	494	491	486	485	497	492
Crystal Springs	501	24	30	2	3	7	9	7	10	15	16	4	9
		228	227	230	230	230	230	227	226	230	230	229	229
Blue Lakes Springs	230	2	3	0	0	0	0	3	4	0	0	1	1
		5,782	5,752	5,892	5,880	5,857	5,843	5,881	5,869	5,807	5,801	5,884	5,862
Total of 12 springs	5,907	125	155	15	27	50	64	26	38	100	106	23	45

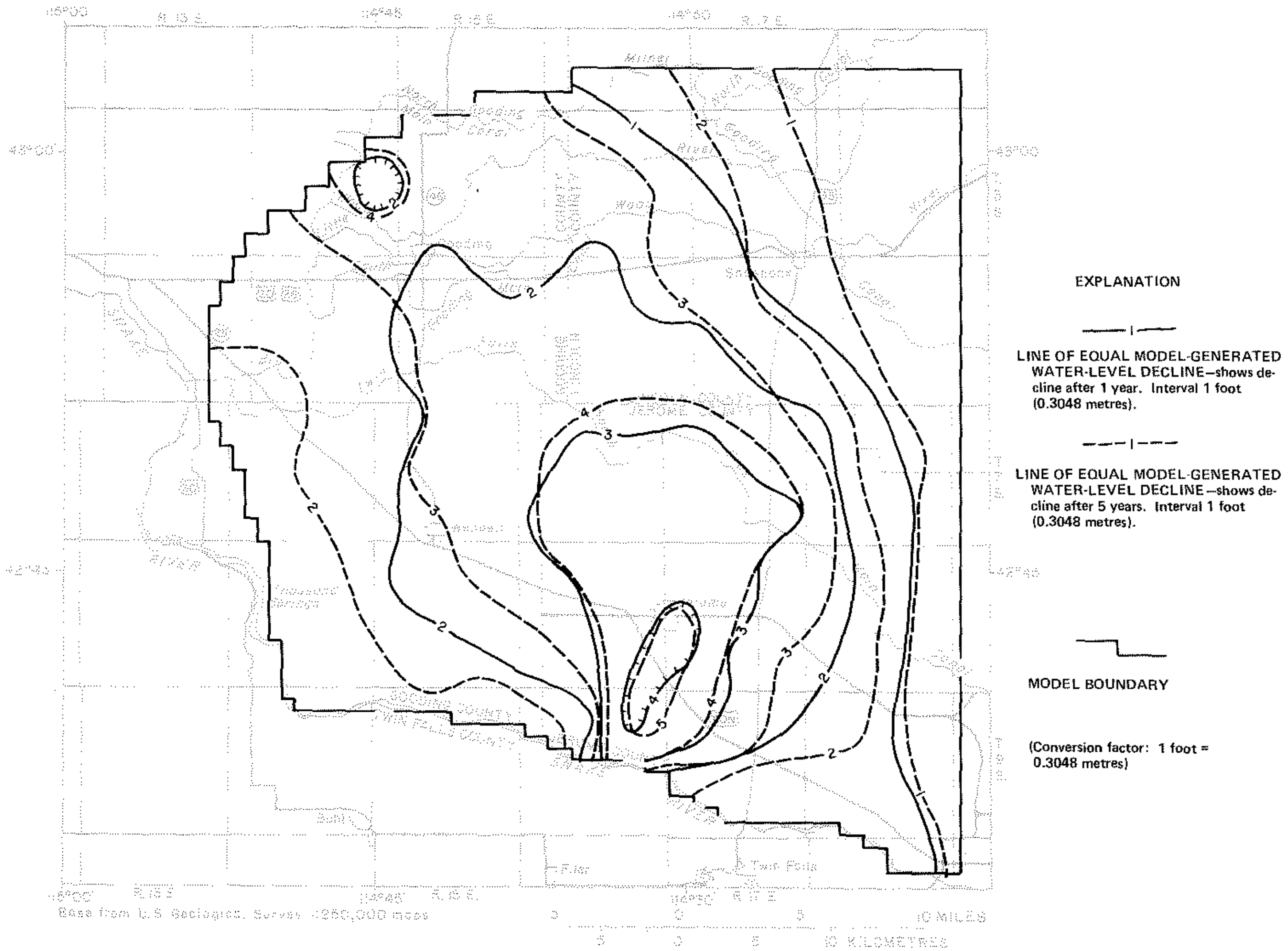
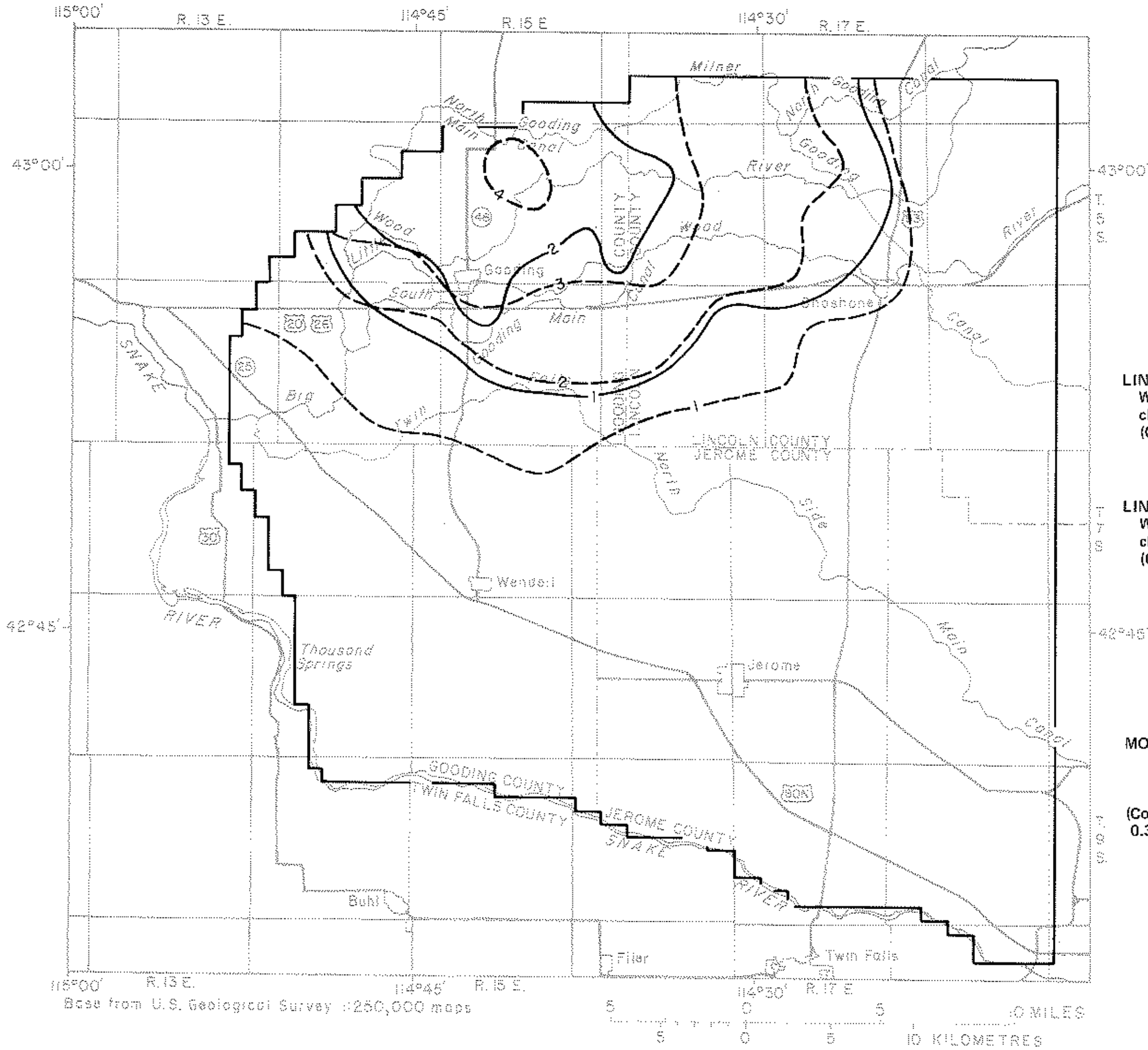


FIGURE 14. Model-generated water-level declines resulting from Plan A.

FIGURE 15. Model-generated water-level declines resulting from Plan B.



EXPLANATION

LINE OF EQUAL MODEL-GENERATED WATER-LEVEL DECLINE—shows decline after 1 year. Interval 1 foot (0.3048 metres).

LINE OF EQUAL MODEL-GENERATED WATER-LEVEL DECLINE—shows decline after 5 years. Interval 1 foot (0.3048 metres).

MODEL BOUNDARY

(Conversion factor: 1 foot = 0.3048 metres)

Table 5 shows only 27 ft^3/s (0.8 m^3/s) of decline in model-generated spring discharge with this alternative. Most of the decline was in Malad Springs. This alternative was also significantly affected by the constant-head boundary. Effects of reduced diversions north of Shoshone were completely masked by the boundary effects. Comparable runs made with a constant-flow boundary resulted in more water-level decline near the boundary for equivalent time periods but had little effect on spring discharge.

Plan C

In Plan C, increased ground-water withdrawals were imposed in townships 5S-15E, 5S-16, 7S-14E, and 7S-15E. Total extraction was about 110 ft^3/s (3.1 m^3/s). Figure 16 shows widespread water-level declines over the northern and western parts of the study area with maximum declines of 4 ft (1.2 m) north of Gooding after 5 years.

Total decline in spring discharge was about 65 ft^3/s (1.8 m^3/s) after 5 years with over half of the decline in Malad Springs, Billingsley Creek, Riley Creek, and Thousand Springs.

Plan D

In Plan D, 138 ft^3/s (3.9 m^3/s) of increased ground-water withdrawals were imposed south of Jerome. Figure 17 shows localized water-level declines with maximum declines of about 8 ft (2.4 m) after 5 years.

Table 5 shows that much of the effects of this plan were masked by the constant-head boundary. Spring discharge declined only 38 ft^3/s (1.1 m^3/s) after 5 years. Most of the decline occurred in Niagara, Crystal, and Blue Lakes Springs.

Plan E

In Plan E, 138 ft^3/s (3.9 m^3/s) of ground-water withdrawals were imposed southwest of Wendell. Figure 18 illustrates the localized effects of this alternative. Maximum water-level decline was about 3 ft (1 m) after 5 years.

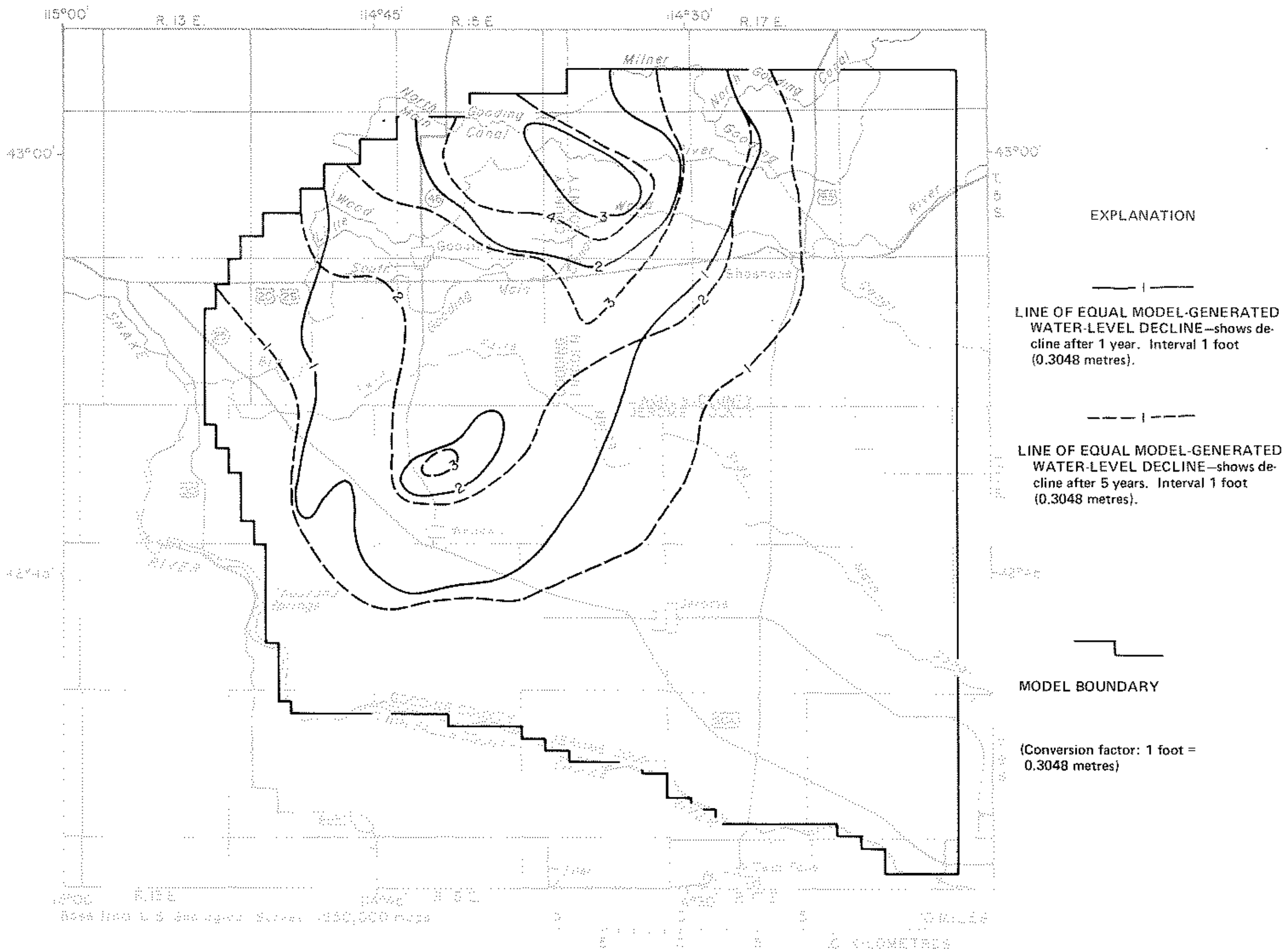
Table 5 shows that spring discharges declined 106 ft^3/s (3.0 m^3/s) as a result of this alternative. Springs that were most significantly affected included Crystal, Niagara, Box Canyon, and Thousand Springs. The constant-head boundary had little effect on projected water-level declines or spring discharges for this plan.

Plan F

In this alternative, 138 ft^3/s (3.9 m^3/s) of ground-water withdrawals were imposed near Shoshone. Water-level declines (fig. 19) were more widespread in this alternative than in the previous two plans (D and E), and maximum declines were greater. More than 20 ft (6 m) of decline were generated after 5 years.

Table 5 shows that this plan resulted in 45 ft^3/s (1.3 m^3/s) of decline in spring discharge, with most of the decline in Malad Springs and Crystal Springs. Because the center

FIGURE 16. Model-generated water-level declines resulting from Plan C.



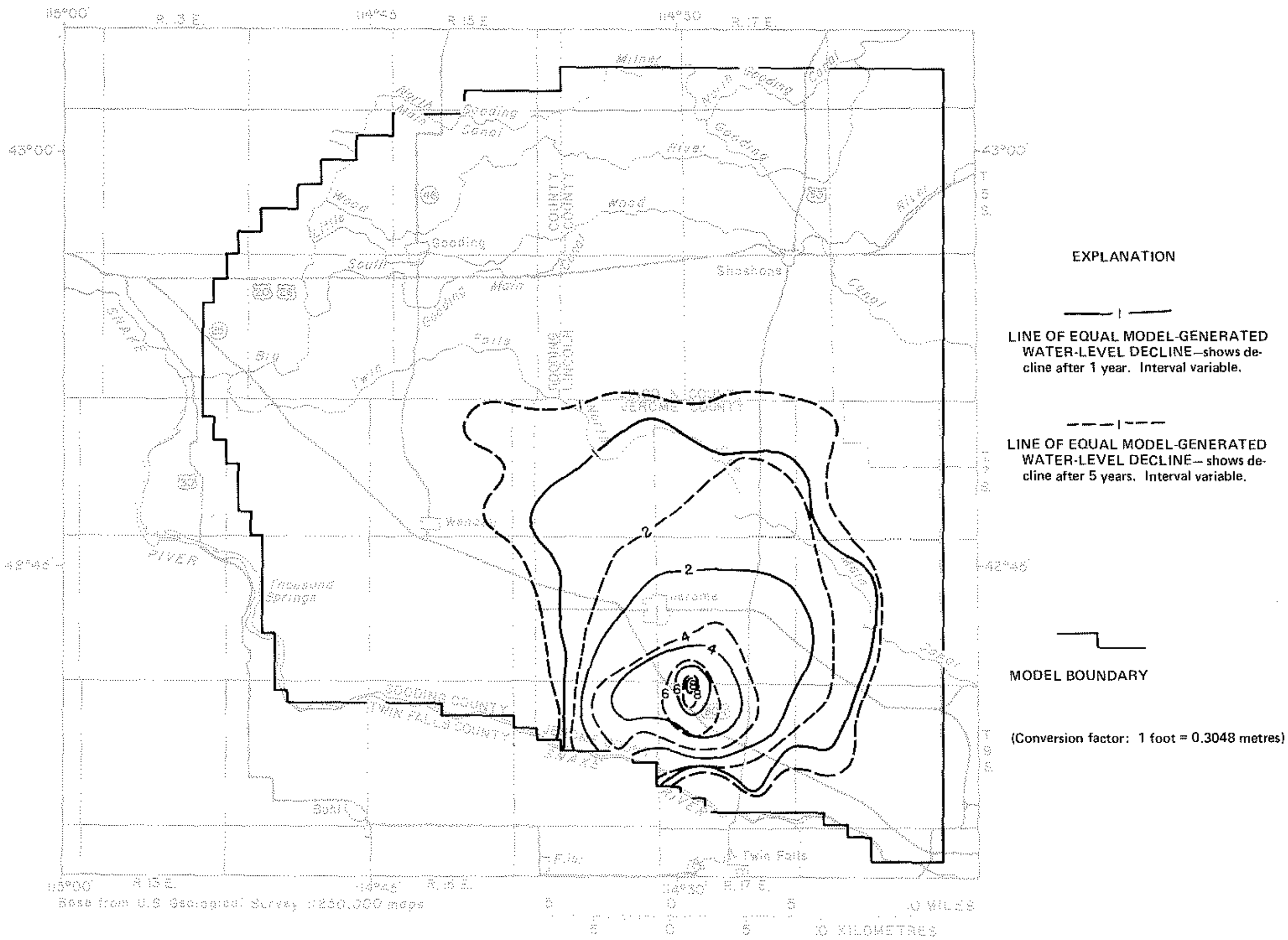
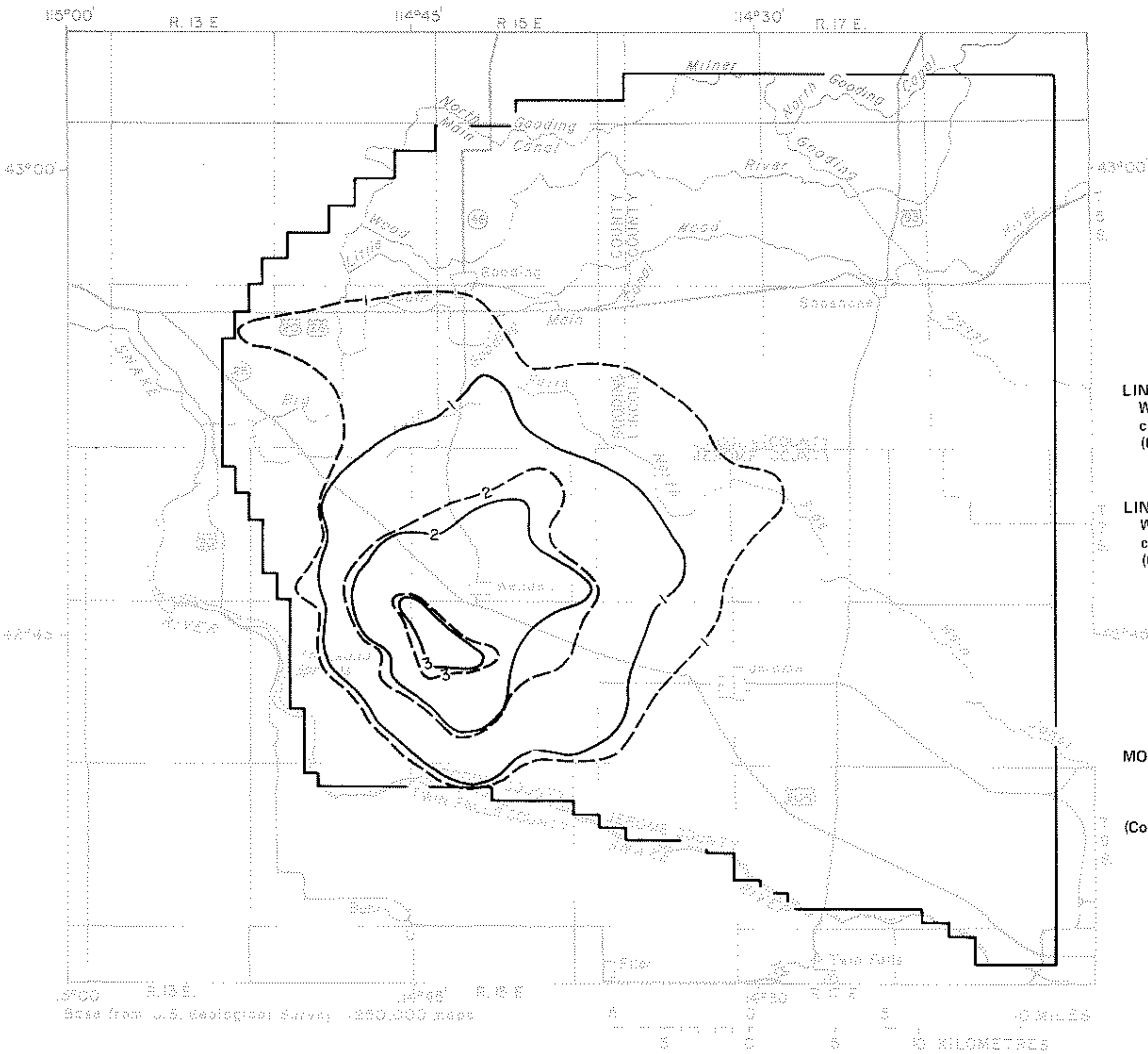


FIGURE 17. Model-generated water-level declines resulting from Plan D

FIGURE 18. Model-generated water-level declines resulting from Plan E.



EXPLANATION

LINE OF EQUAL MODEL-GENERATED WATER-LEVEL DECLINE—shows decline after 1 year. Interval 1 foot (0.3048 metres.)

LINE OF EQUAL MODEL-GENERATED WATER-LEVEL DECLINE—shows decline after 5 years. Interval 1 foot (0.3048 metres).

MODEL BOUNDARY

(Conversion factor: 1 foot = 0.3048 metres)

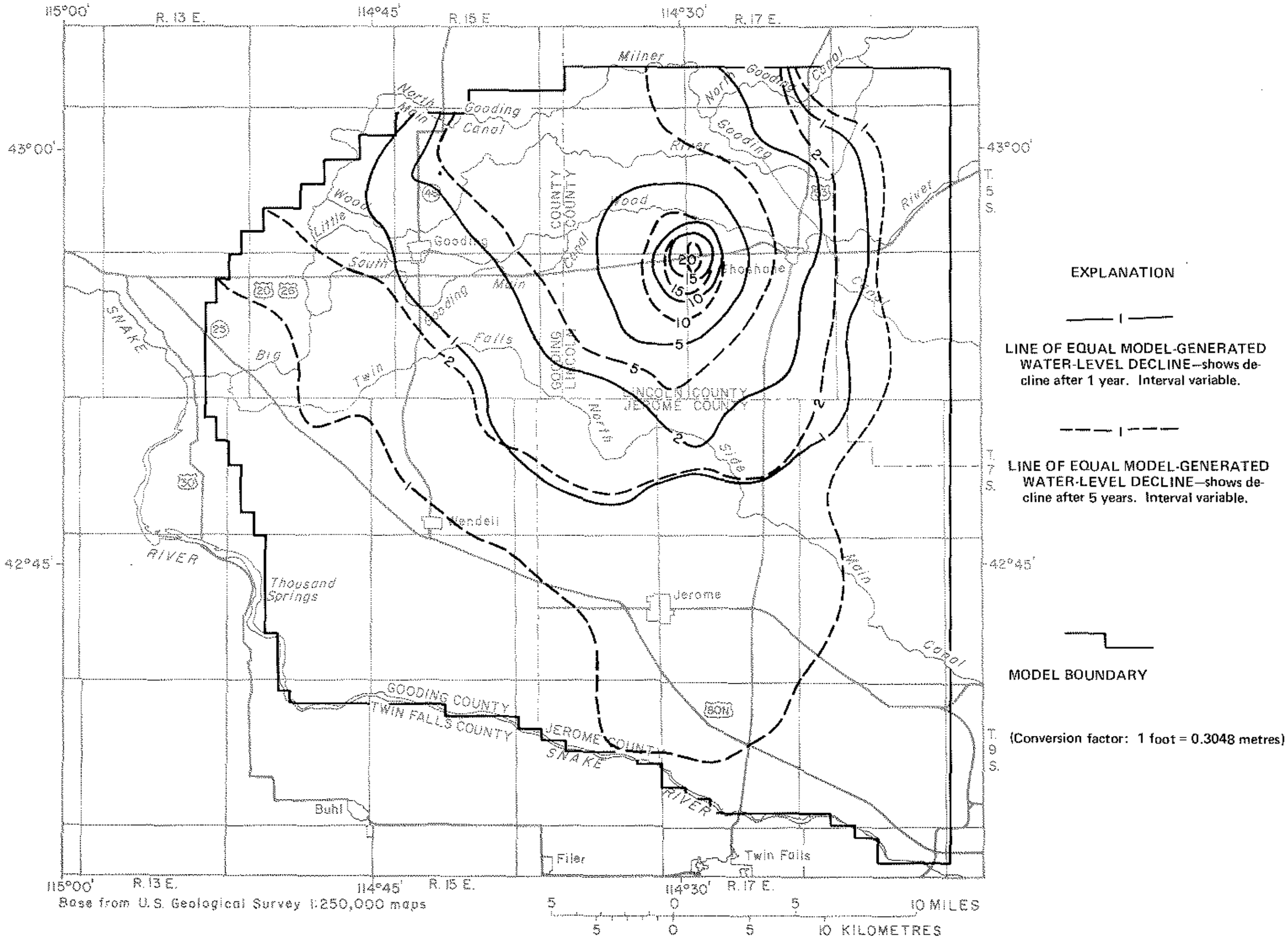


FIGURE 19. Model-generated water-level declines resulting from Plan F.

of extraction was relatively near the constant-head boundary, the total effects of the plan were partly masked. Using a constant-flow boundary, projected declines were slightly more than with a constant-head boundary, particularly east of the center of extraction. However, spring discharges were the same with both boundary conditions for the time periods shown in table 5. After 15 years, spring discharges were still declining at a significant rate in the constant-flow boundary simulation, but total reduction was still considerably less than the 138 ft^3/s (3.9 m^3/s) increase in withdrawals.

SUMMARY AND CONCLUSIONS

Between 1902 and the mid-1940's, springs discharging from the Snake Plain aquifer between Kimberly and King Hill increased in flow from about 4,200 ft^3/s (120 m^3/s) to about 6,800 ft^3/s (190 m^3/s). The increase has been attributed to increased irrigation return from irrigated lands north and east of the springs. The combined discharge of the springs remained relatively constant from the mid-1940's until 1959. Increased use of ground-water for irrigation and a concurrent decline in recharge caused a reduction in spring discharge between 1959 and 1962. Since 1962, spring discharge has remained fairly constant at about 6,200 ft^3/s (175 m^3/s).

Total ground-water withdrawals for irrigation within the study area during the 1973 irrigation season totaled over 84,000 acre-ft ($1 \times 10^8 m^3$). This pumpage has not significantly affected discharge from the springs.

A digital model was constructed to evaluate the effects of various alternatives of diversion regulation or ground-water withdrawals on ground-water levels and spring discharges. Aquifer transmissivities range from less than 1 to about 30 (Mgal/d)/ft (1.2×10^4 to $3.7 \times 10^5 m^2/d$) and storage coefficients range from 0.07 to 0.15. Satisfactory agreement was achieved between water-table contours constructed from data collected in April 1974 and contours generated by the model under equilibrium conditions. Transient conditions were modeled using one annual cycle with nonirrigation and irrigation periods used as imposed stresses. In general, water-level declines were reasonably simulated, but simulation of discharges in some springs and water-level fluctuations at specific wells were affected by assumptions required in modeling.

Of six alternatives simulated on the calibrated model, Plan A, which specified 315 ft^3/s (8.9 m^3/s) of reduced surface diversions to major canals resulted in the largest declines in model-generated spring discharge. Plan B (reduced surface diversion to the Big Wood River system) had the least effect on spring discharges. Of the plans proposing increased ground-water withdrawals, Plan E (increased withdrawals southwest of Wendell) had the most effect on spring discharges.

The constant-head boundary used to model ground-water underflow across the eastern boundary of the study area affected the simulation of all plans to some degree. The effects of this boundary should be considered when comparing the model-generated water-level declines and changes in spring discharges for the various alternatives.

All hydrologic analyses of the Snake Plain aquifer have concluded with a plea for additional data. This study is no exception. Some of the more important data needs in this part of the aquifer include:

1. Definition of the vertical extent of the aquifer,

2. More precise measurement of distribution of spring discharge between gaging stations on the Snake River,

3. Definition of annual fluctuations in major springs not currently or recently monitored by continuous recorders,

4. More data on ground-water levels near the major springs,

5. Periodic estimates of ground-water withdrawals for irrigation.

Many of the analyses made during this study were based on assumption because of the severe lack of data, most of which are outlined above. Hopefully, the results of this study emphasize the need for more accurate base information before other studies of this type are attempted. Making meaningful analyses of effects of future stresses without an adequate data base is difficult at best.

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