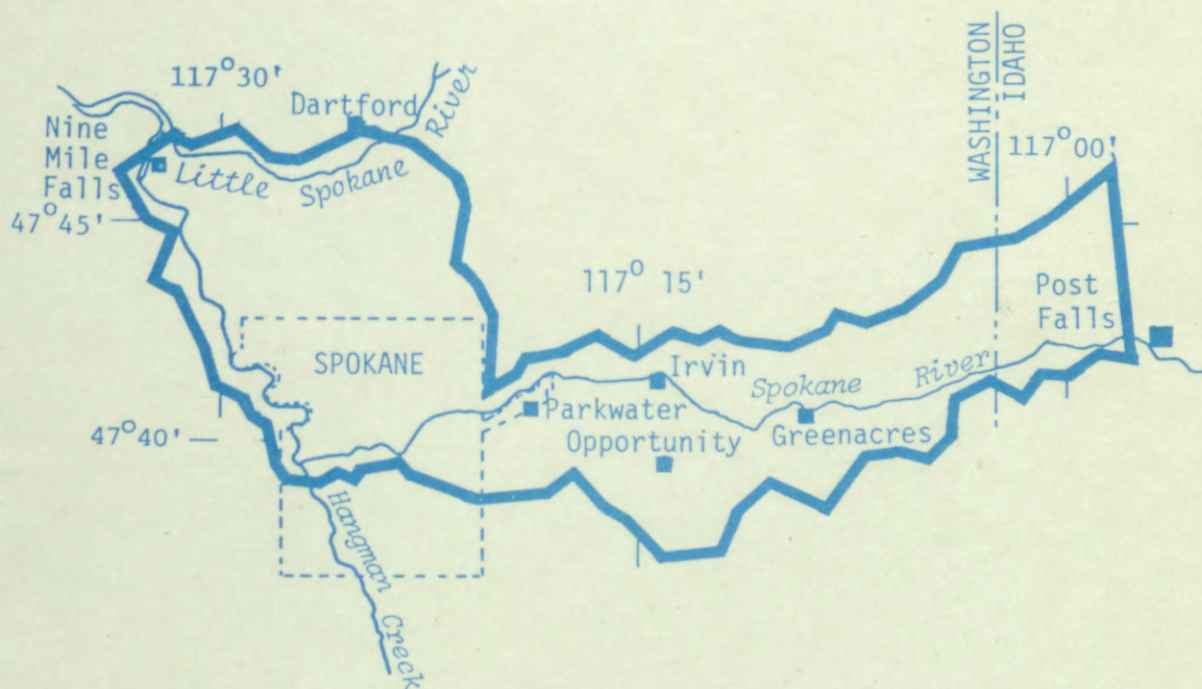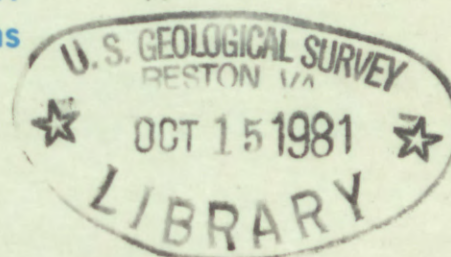# DIGITAL-MODEL SIMULATION OF THE HYDROLOGIC FLOW SYSTEM, WITH EMPHASIS ON GROUND WATER, IN THE SPOKANE VALLEY, WASHINGTON AND IDAHO

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Open-File Report 80-1300

Prepared in Cooperation With
State of Washington Department of Ecology
and Spokane County Engineers Office

DIGITAL-MODEL SIMULATION OF THE HYDROLOGIC

FLOW SYSTEM, WITH EMPHASIS ON GROUND WATER,

IN THE SPOKANE VALLEY, WASHINGTON AND IDAHO

By E. L. Bolke and J. J. Vaccaro

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Tacoma, Washington
1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas Peck, Director

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ILLUSTRATIONS

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot squared per second (ft^2/s)	0.0929	meter squared per second (m^2/s)

DIGITAL-MODEL SIMULATION OF THE HYDROLOGIC FLOW SYSTEM, WITH EMPHASIS ON GROUND WATER, IN THE SPOKANE VALLEY, WASHINGTON AND IDAHO

By E. L. Bolke and J.J. Vaccaro

ABSTRACT

A digital-computer model of the hydrologic flow system, with emphasis on ground water, was developed for Spokane Valley, Washington and Idaho. The current rate of ground-water pumping in Spokane Valley has little effect on water levels in the Spokane aquifer, although short-term water-level declines occur locally. The model was used to show the effects of increased ground-water pumpage on aquifer heads and streamflow. A simulated pumping rate twice that of actual 1977 pumping rates of 227 cubic feet per second lowered water levels in the Spokane aquifer less than 3 feet during a 1-year simulation period. This doubling of the ground-water pumpage caused a decrease in discharge of the Spokane River, as measured at Spokane, of about 150 cubic feet per second during the summer months and about 50 cubic feet per second during the rest of the year. Leakage from the aquifer to the Little Spokane River was decreased by less than 10 cubic feet per second.

INTRODUCTION

Purpose and Scope

The water supply for the City of Spokane, Washington, and the surrounding area is obtained principally from a highly permeable water-table aquifer that underlies the area. The importance of this aquifer as the major source of drinking water for the area was officially recognized in 1978 when it was designated as a sole- or principal-source aquifer by the U.S. Environmental Protection Agency (EPA) under the provisions set forth in the Safe Drinking Water Act of 1974. Prior to this designation, the Washington State Department of Ecology required information on the water quality of the Spokane aquifer as part of their responsibilities under Public Law 92-500. The Spokane County Engineer's Office was designated by the Washington State Department of Ecology as the lead agency for this effort.

In December 1976, the U.S. Geological Survey, in cooperation with the Spokane County Engineer's Office, undertook a study that would (1) evaluate the ground-water quality of the Spokane aquifer, (2) determine the nature and relative amounts of selected chemical constituents entering the aquifer under various land-use categories, and (3) develop a water-quality model of the aquifer to simulate the movement of selected chemical constituents. Construction of a water-quality model required, first, the construction of a ground-water model upon which a transport model could subsequently be superposed. This report is the second of these reports to be published on the study. The first report was a basic data report (Bolke and Vaccaro, 1979) that presented the data collected during the study.

The purpose of this report is to describe the construction and calibration of the ground-water flow model. This model simulates movement of water in the Spokane aquifer, as well as between the aquifer and the Spokane and Little Spokane Rivers. The report includes a description of the hydrologic setting of the Spokane Valley, along with the hydraulic characteristics of the Spokane aquifer. The final report will describe construction and calibration of the transport model.

Data used for this study consisted partly of data collected by the U.S. Geological Survey during the period from March 1977 to May 1978. These data include (1) water-levels measured in 142 wells during seven field trips during this period, (2) records of pumpage from 135 wells that are used for irrigation, industrial, and public supplies, and (3) records of streamflow for the Spokane and Little Spokane Rivers and Hangman Creek. The report was also based upon data and results from earlier studies and partly upon data available in the files of the U.S. Geological Survey, Tacoma, Wash. The study period on which this report is based extended from February 1977 to May 1979.

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Description of the Study Area

The study area is located in the Spokane River basin in eastern Washington and northwestern Idaho (fig. 1) and includes the Spokane River valley from near Post Falls, Idaho, on the east to near Nine Mile Falls, Wash., on the west, a distance of about 27 mi. The valley ranges in width from about 3 to 8 mi and covers an area of about 135 mi^2. The boundaries north and south of the Spokane River coincide with the contact between the unconsolidated materials that make up the Spokane aquifer and the consolidated rock of the valley sides (fig. 2). A mesa known as Fivemile Prairie, northwest of the city of Spokane, is composed of Tertiary rocks and separates the aquifer into the Hillyard Trough on the east and the lower Spokane River valley on the southwest. The aquifer is split at a second location by exposed Precambrian rock, just north of Opportunity, Wash.

Major tributaries to the Spokane River in the study area are the Little Spokane River and Hangman Creek. Numerous other small tributaries, most of which are ephemeral, also enter the valley. Precipitation averages about 17 in. annually.

Land uses include urban in the City of Spokane, with a population of approximately 177,000, suburban, industrial, and agricultural. Some land is undeveloped.

Acknowledgments

The cooperation and assistance of Washington Water Power Co., who provided flow and reservoir data for the Spokane River and information on water wells, is gratefully acknowledged. Many local land owners and water purveyors were especially helpful by permitting access to their property and providing ground-water data and general information about the area.

Previous Investigations

Previous work in the study area that applies to the current study includes geologic mapping by Griggs (1966) and Weis (1968), interpretation of seismic cross sections in two parts of Spokane Valley by Newcomb (1953), and analysis of streamflow records of the Spokane and Little Spokane River, in relation to the movement of water between the rivers and the ground-water system, by Broom (1951) and McDonald and Broom, (1951). Also, Drost and Seitz (1978) compiled ground-water inflow from work by Thomas (1963) for the small drainage basins that surround the study area. Giles (1943) compiled topographic maps and longitudinal profiles of the Spokane River between Post Falls, Idaho, and Spokane, Wash. A more complete summary of previous work in this area by other investigators has been presented by Drost and Seitz (1978, pp. 2-4). Data collected during 1977-78, upon which part of this report is based, were presented by Bolke and Vaccaro (1979).
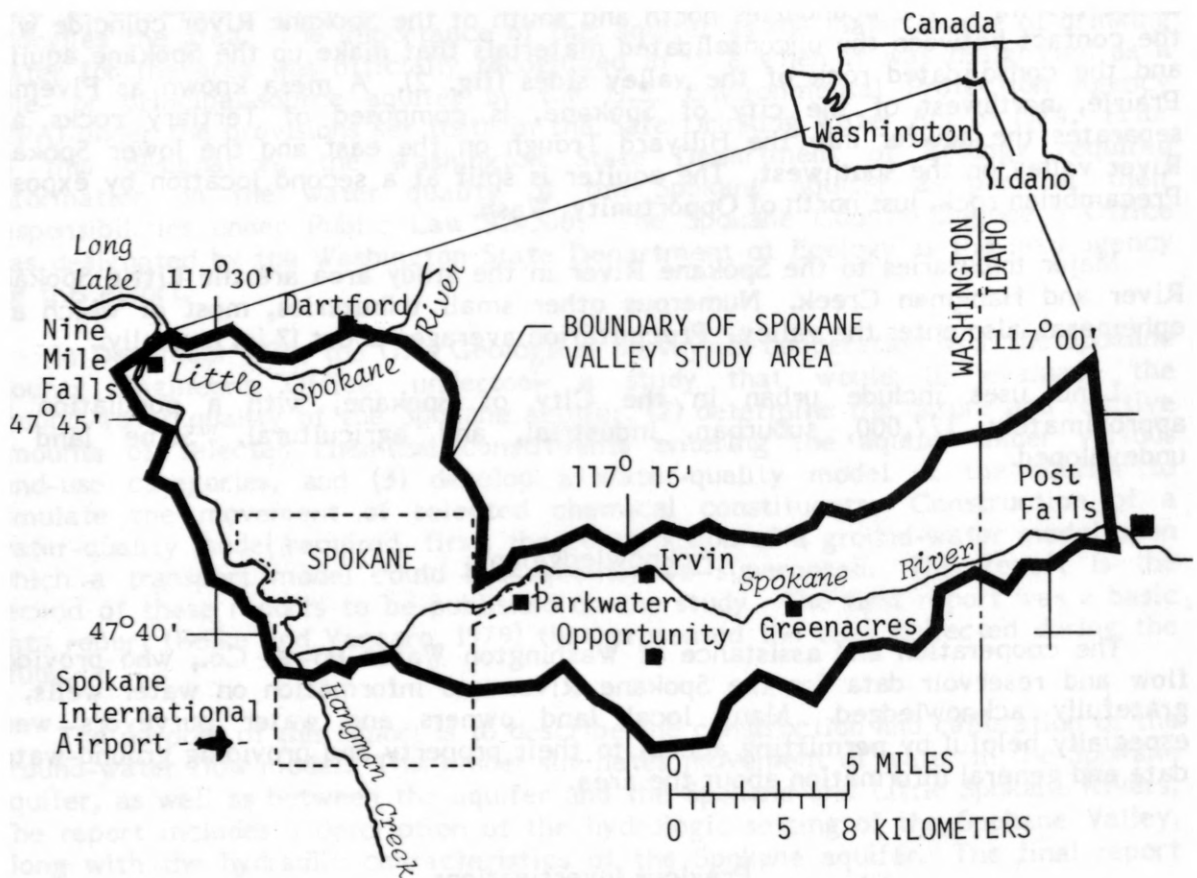
FIGURE 1.--Location of the study area.
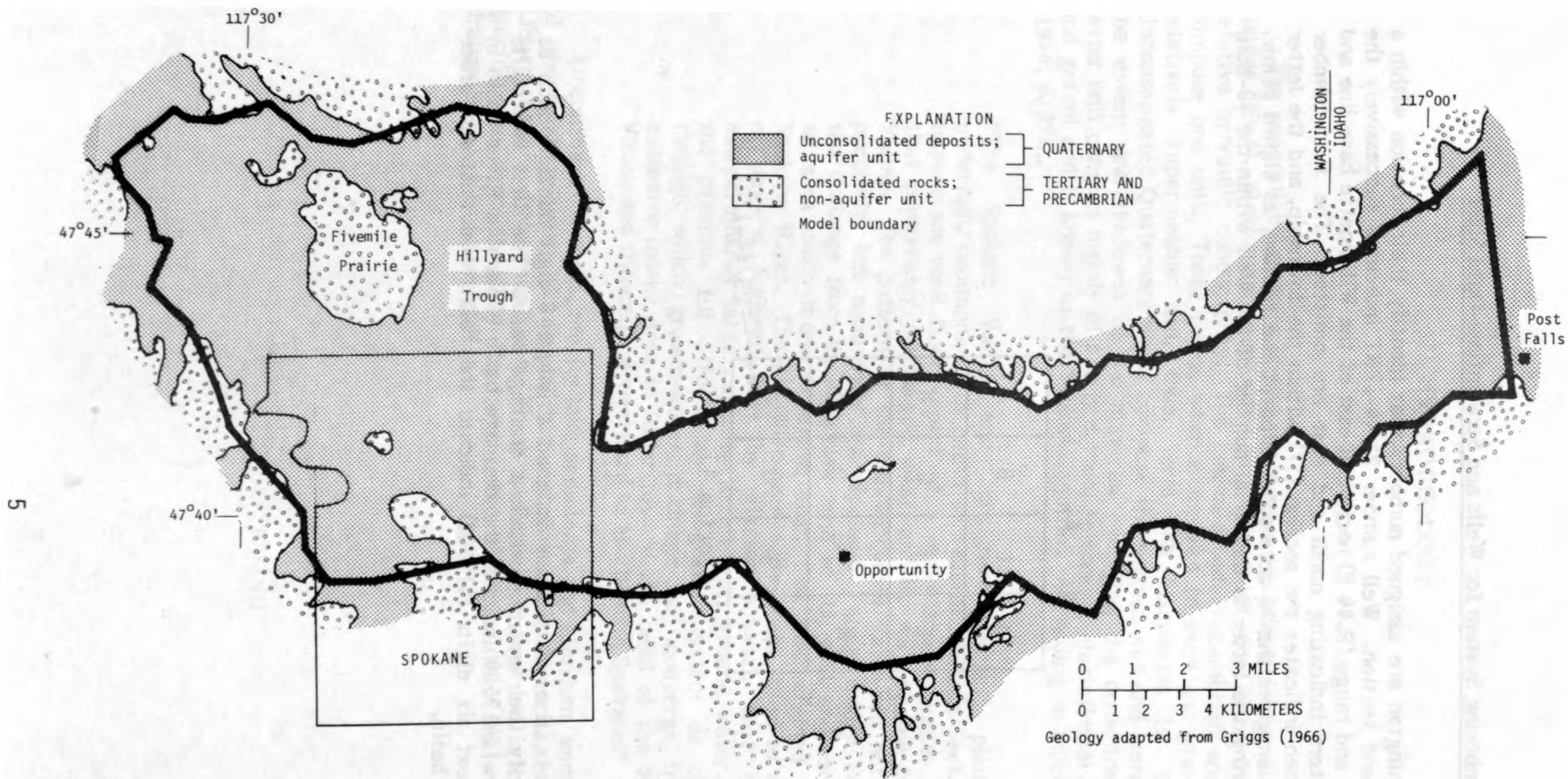
FIGURE 2.--Generalized geology of the study area.

Numbering System for Wells and Streamflow-Data Sites

Wells in Washington are assigned numbers that identify their location within a township, range, and section. Well number 25/44-17R1 indicates successively the township (T.25 N) and range (R.44 E) north and east of the Willamette base line and meridian; the letters indicating north and east are omitted. The first number following the hyphen indicates the section (17) within the township, and the letter following the section gives the 40-acre subdivision of the section, as shown below. The number following the letter is the serial number of the well within the 40-acre subdivision.

R.   44   E.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R● ——— 25/44-17R1

T.

25

N.

Section 17

Streamflow data sites have been assigned a unique 8-digit number, such as 12419500, to identify their position within a drainage basin. The first two digits (12) in the number 12419500 indicate the drainage basin (Columbia River Basin in this case). The next six digits (419500) indicate the relative downstream-order position within the basin.

HYDROGEOLOGY

Setting

The generalized geology of the study area was adapted from a geologic map by Griggs (1966). Rocks were separated into two units (fig. 2) on the basis of their relative hydraulic conductivity. The consolidated Precambrian and Tertiary rocks compose one unit. These rocks, when compared to sand and gravel deposits, are relatively impermeable and, thus, form the boundaries for the study area. Unconsolidated Quaternary rocks compose the second unit and were used to define the extent and thickness of the material overlying the consolidated rocks. The latter unit consists mainly of poorly sorted, reworked, glaciofluvial deposits of sand and gravel and is known as the Spokane aquifer. According to Piper and LaRocque, (1944, p. 87)...

"The Spokane Valley and contiguous lowland plains are underlain, commonly at a depth of several hundred feet, by an impervious rock floor - part of a pre-Wisconsin valley system that presumably discharged westward by way of the Spokane Valley. The pattern of the pre-Wisconsin Valleys is not known precisely, but apparently the Spokane Valley trough received the drainage from an extensive area to the east and northeast, an area much more extensive than that now drained by the Spokane River. The pre-Wisconsin valleys are filled to a depth of several hundred feet by glacial outwash that has an extraordinarily large capacity to transmit ground water. Thus, the previous fill affords an integrated system of conduits through which ground-water drainage can converge from an extensive intake area in Idaho toward the head of the Spokane Valley and thence pass westward to and beyond Spokane."

Unconsolidated rocks, mostly lake sediments and alluvium, underlie the valleys of the small tributary drainages that surround the study area, such as those of Liberty Lake and Newman Lake. These rocks, where they are in contact with the glaciofluvial deposits, allow for conveyance of water from the small surrounding drainages to the Spokane aquifer.

Extent and Thickness of the Aquifer

Unconsolidated sands and gravels of glaciofluvial origin that compose the Spokane aquifer extend throughout the study area except for an outcrop of Precambrian rock north of Opportunity, Wash., outcrops of Tertiary basalt near Spokane, and Tertiary rocks that compose the mesa at Fivemile Prairie (fig. 2). The saturated thickness of the unconsolidated rocks was determined from the contoured altitude of the average water table for 1977-78 and the estimated altitude of the bottom of the deposits. Water levels were measured at about 2-month intervals at 142 wells and were averaged at each well during the period of study. Bottom altitudes were estimated mainly on the basis of two seismic profiles by Newcomb (1953) and from interpretation of drillers' logs. One seismic profile was run near the Idaho-Washington State line and the other in Hillyard Trough north of Spokane. A geologic section by Weis (1968) across Spokane Valley near Greenacres and a gravity map complied by Purves (1969) were used to help identify the bottom of the unconsolidated rocks. The above-mentioned contour maps (not shown in report) were then overlayed with the grid network shown in figure 13, and altitude values for the water table and the bottom were determined at each node of the grid. The difference between the values at each node is the saturated thickness, and this difference was used to construct the map of the saturated thickness of the deposits shown in figure 3. Fivemile Prairie and the other areas of consolidated rock that were mentioned earlier were included in the map of saturated thickness for simplifying the use of the model. These areas were delineated by assigning a relatively small value of hydraulic conductivity to them.

Precipitation

Precipitation was estimated to be uniformly distributed within the Spokane Valley study area and was based partly on similarity of data at Spokane International Airport and at Spokane and partly on the low relief (about 900 ft) within the study area.

The 1941-70 average annual precipitation in the study area was 17 in., as compared with 16 in. during 1977 and 19 in. during 1978. Precipitation for the 1-year period May 1977-April 1978 was 21 in. The long-term average annual and monthly precipitation, along with the precipitation for the May 1977-April 1978 period, are shown in figure 4. The volume rate of precipitation for the study area was 209 ft^3/s during this period.

EXPLANATION

Model boundary

Saturated thickness, in feet

1-50   51-100   101-200

201-300   301-400   401-500
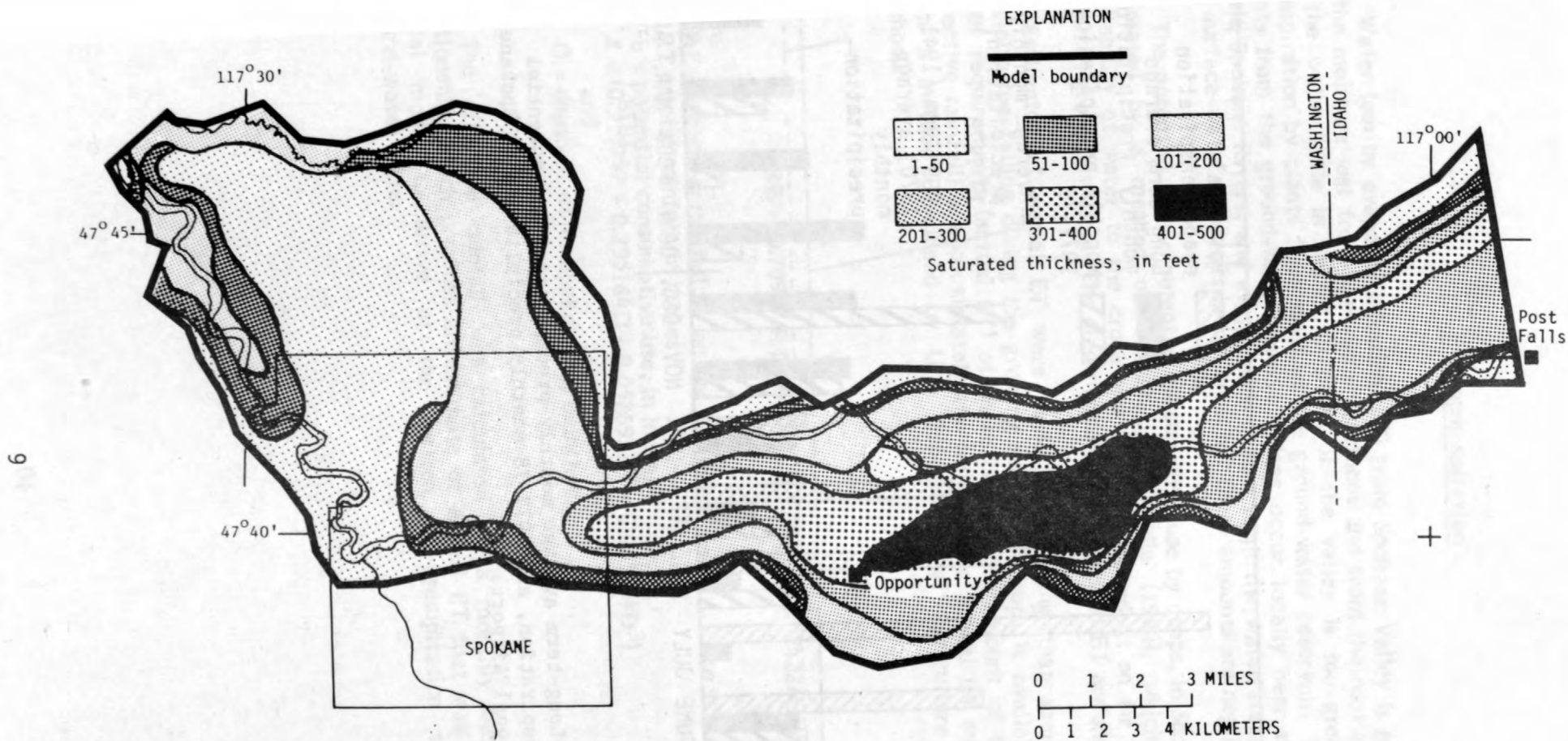
FIGURE 3.--Saturated thickness used in the model of the Spokane aquifer.
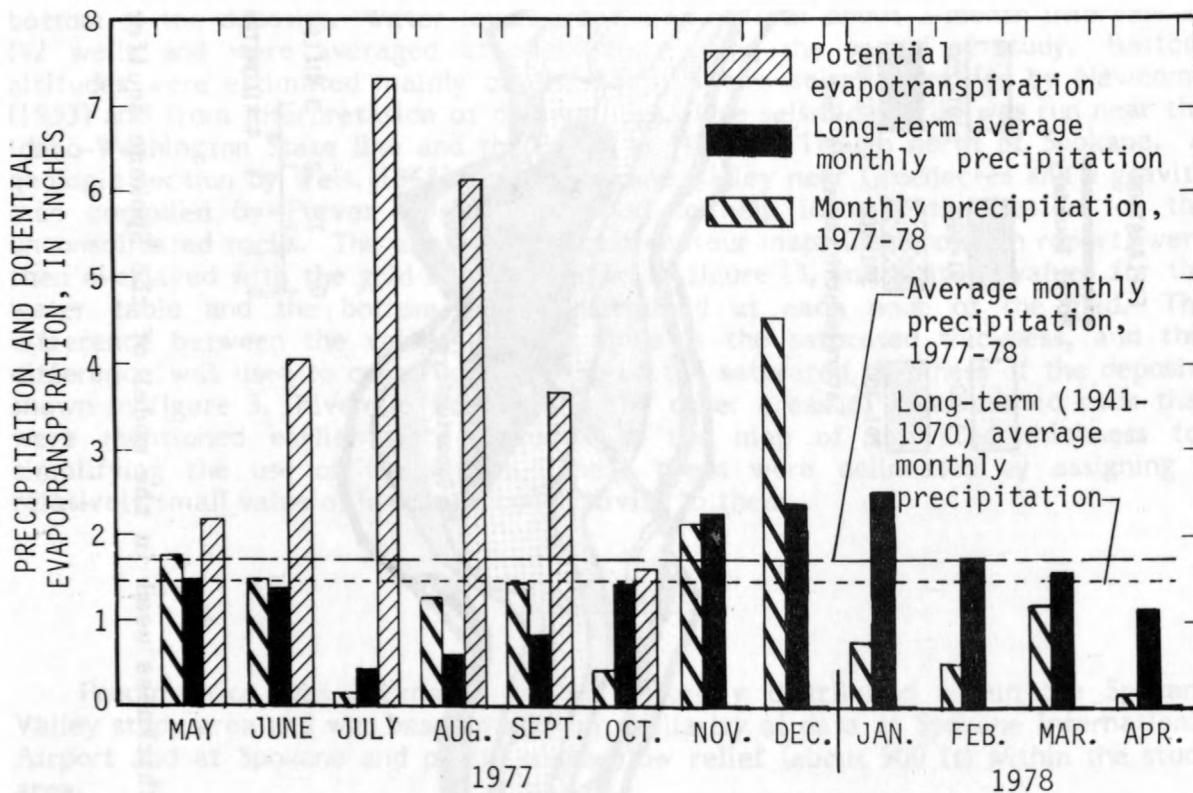
FIGURE 4.--Long-term average monthly precipitation and potential
evapotranspiration, and 1977-78 monthly precipitation at Spokane
International Airport.

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Evapotranspiration

Water lost by evapotranspiration (ET) from Spokane Valley is generally limited to the moisture lost from open-water surfaces and from the root zone. The depth to the water table in nearly all parts of the valley is too great to allow for transpiration by plants from most of the ground-water reservoir. Transpiration by plants from the ground-water reservoir does occur locally near the Spokane and Little Spokane Rivers, and evaporation occurs from the water surface of the rivers and surface-water reservoirs in the area, but these amounts are negligible.

The potential ET, or potential consumptive use by crops, in Spokane Valley was estimated by a method of Blaney and Criddle (1962), which assumes total availability of water to the crops and which is dependent on air temperature and length of growing season. The monthly values of potential ET are shown in figure 4.

Estimates of actual ET were made by assuming that some or all of the precipitation falling during the growing season of crops is available to meet the water requirements (actual ET) of those crops. The amount of this precipitation (effective rainfall) is approximately the same as the actual ET and was estimated from a method developed by U.S. Department of Agriculture (1967). In this method,

$$RE = (0.70917 \, RT^{0.82416} - 0.11556)(10^{0.024226u})(f)$$

where

RE = effective rainfall, or actual ET, in inches
RT = total rainfall, in inches
u = potential consumptive use, in inches
$f = (0.513747 + 0.295164D - 0.057697D^2 + 0.003804D^3)$
    and
D = depth of water application, in inches.

The effective rainfall was calculated on a monthly basis by using this relationship, which provides an estimate of actual ET that was used later in the digital model to arrive at the portion of precipitation that reaches the ground-water table.

Ground-Water Pumpage

The total amount of ground water pumped from the study area by wells during 1977 was about 164,000 acre-ft, which is an average rate of 227 cubic feet per second (ft^3/s) during the year. The estimated pumping rate ranged from 119 ft^3/s during March to 465 ft^3/s during July. These estimates were based on a 1978 water-use inventory of all the major water purveyors in the study area. For comparison, the U.S. Army Corps of Engineers (1976) estimated pumpage from the Washington part of the Spokane aquifer as 129,000 acre-ft for 1972, or an average pumping rate of 178 ft^3/s. Previous to this, Piper and LaRocque (1944) estimated ground-water withdrawals to be 75,000 acre-feet for 1938, or an average rate of 100 ft^3/s for the year. The principal sources of pumpage in 1977, along with the estimated average pumping rate for 1977, are shown in figure 5. The rates of pumping range from 0.01 ft^3/s at several wells to 36.24 ft^3/s from a group of Spokane City wells near Parkwater.

The principal uses of ground water in Spokane Valley are municipal, irrigation, and industrial. In 1977, water used for municipal purposes was about 70 percent of the total pumpage, or 116,000 acre-ft. Uses of water for irrigation and industry were each about 15 percent of the total, or 24,000 acre-ft.

A percentage of the water pumped from the aquifer is applied to the land surface as part of municipal or irrigation practices. The percentages applied are related to the purpose for which the water is used. The estimated percentages are based on information from the various water purveyors and are as follows. Of the water pumped from Spokane city wells that are used only seasonally, 50 percent is applied to the land surface and 50 percent is discharged to the sewer. Of the water pumped from Spokane city wells that are used continuously, 10 percent is applied to the land surface and 90 percent is discharged to sewers. Seventy percent of the water pumped for municipal use by cities other than Spokane is applied to the land surface and 30 percent is estimated to directly recharge the aquifer through septic tank systems. If pumping is used for irrigation, 100 percent of the pumped water is applied to the land surface. If pumping is used for industry, none of the water is applied to the land surface.
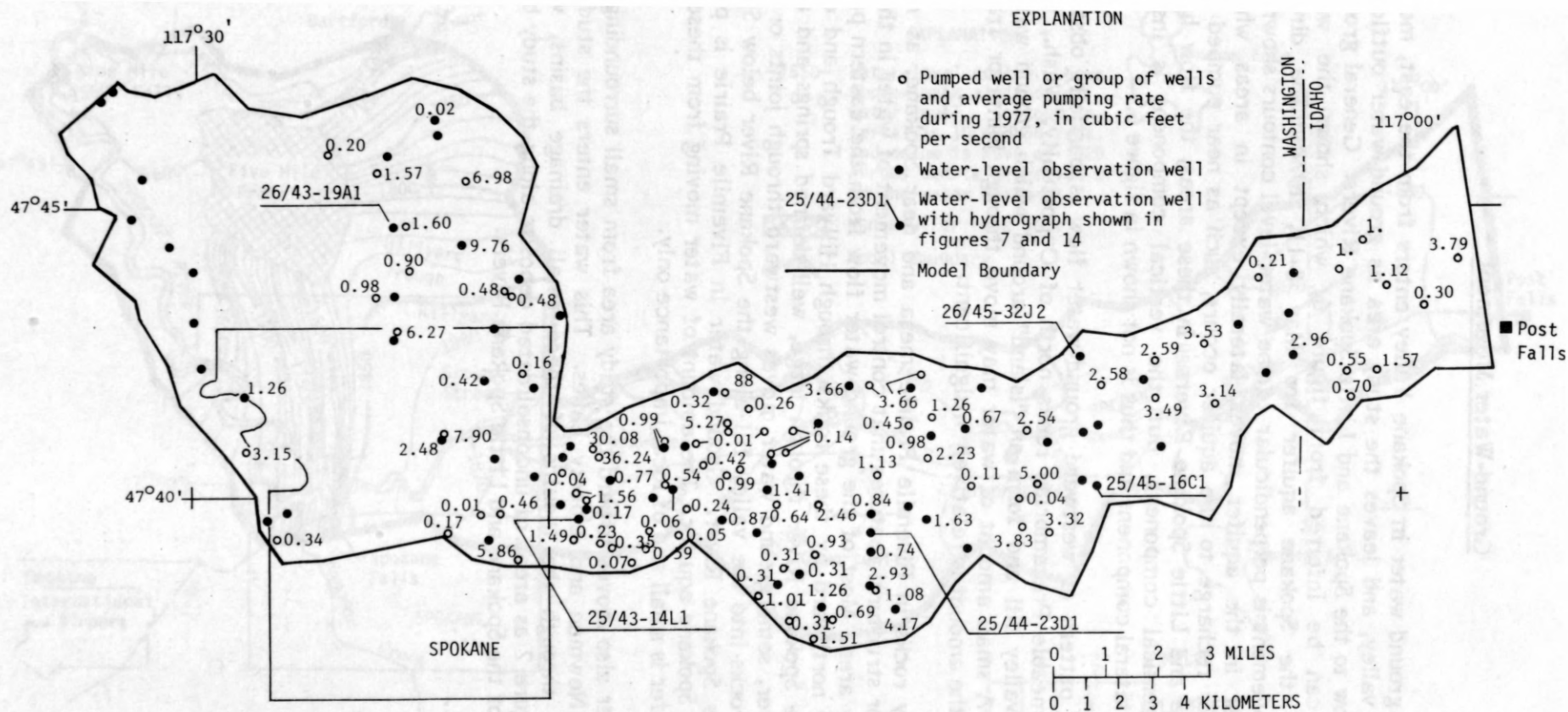
FIGURE 5.--Sources and rates of major ground-water pumping and water-level observation
wells used for calibration of the model.

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Ground-Water Movement

Most of the ground water in Spokane Valley enters from the east, moves along the axis of the valley, and leaves the study area as ground-water outflow and as surface-water flow to the Spokane and Little Spokane Rivers. General ground-water flow direction can be inferred from figure 6, which shows the water-table configuration of the Spokane aquifer for May 8-11, 1978. The direction of ground-water movement is perpendicular to the water-level contours shown in figure 6. Ground water in the aquifer moves laterally except in areas where local discharge from or recharge to the aquifer occurs, such as near pumped wells and near the Spokane and Little Spokane Rivers. In these areas, the flow has both a lateral and a vertical component, but the vertical component is insignificant compared to the lateral component and thus is not shown in figure 6.

The general pattern of westward ground-water flow is partially obstructed by relatively impermeable Precambrian rocks north of Opportunity, Wash., which are exposed in the valley fill and form an "island" around which ground water moves (figs. 2 and 6). A small amount of water may move through joints or fractures in these rocks, but the amount is relatively insignificant.

The Tertiary rocks in Fivemile Prairie mesa and near Spokane, as mentioned earlier, are major structural features that control movement of water in the western part of the study area. Most of the ground-water flow from the eastern part of the area is diverted northward by these rocks through Hillyard Trough and eventually enters the Little Spokane River through large, well-defined springs and as diffuse seepage. However, some ground water moves westward through joints or fractures in the Tertiary rocks into the valley fill along the Spokane River below Spokane or directly into the Spokane River. Ground water in Fivemile Prairie is perched in zones above the Spokane aquifer. The amount of water moving from these zones to the Spokane aquifer is small and of local importance only.

Ground water also moves toward the study area from small surrounding drainage basins, such as Newman and Liberty Lakes. This water enters the study area as subsurface flow through the mouths of these small drainage basins, which are delineated in figure 2 as areas of unconsolidated deposits along the study boundaries north and south of the Spokane and Little Spokane Rivers.
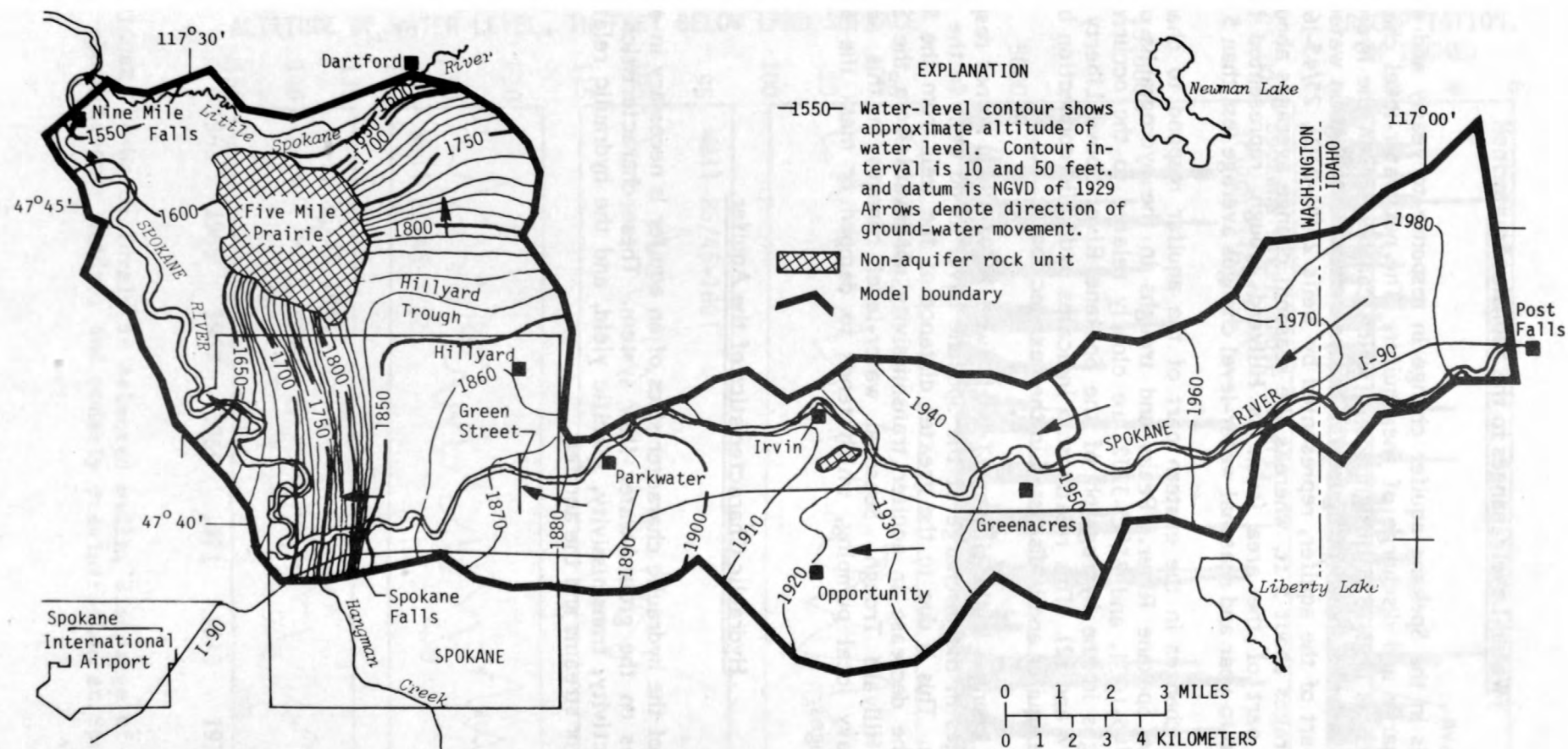
FIGURE 6.--Water-table configuration of the Spokane aquifer, May 1978.

Water levels in the Spokane aquifer change in response to yearly and seasonal changes of recharge and discharge of the aquifer. The net water-level change for long periods, such as 1963-78, is insignificant, which can be seen in the hydrographs of water levels in wells shown in figure 7. The year-to-year change in water levels in the eastern part of the aquifer, represented by wells 25/44-23D1, 25/45-16C1, and 25/45-32J2, averages about 5 ft, whereas the seasonal change averages about 10 ft. In the western part of the area (such as Hillyard Trough, represented by well 26/43-19A1), year-to-year and seasonal water-level changes average less than 5 ft.

Water-level changes in the eastern part of the aquifer respond to changes in discharge of the Spokane River. Peaks and troughs in the hydrographs of wells 25/44-23D1, 25/45-16C1, and 25/45-32J2 are closely related to the occurrence of peaks and troughs in the hydrograph of the Spokane River above Liberty Bridge (12419500) (figs. 7 and 12). This relationship indicates hydraulic connection between the river and the aquifer and is discussed in the next section.

Water-level changes in the Hillyard Trough, (well 26/43-19A1) do not respond as readily to changes in the discharge of the Spokane River as do wells in the eastern part of the area. This is due to the greater distance of the well from the Spokane River and to the decrease in aquifer transmissivity northward from the Spokane River through Hillyard Trough. Seasonal water-level changes in this area are affected by heavy local pumping, which tends to dampen or mask the seasonal water-level changes.

Hydraulic Characteristics of the Aquifer

Knowledge of the hydraulic characteristics of an aquifer is necessary in order to evaluate stresses on the ground-water flow system. These characteristics include hydraulic conductivity, transmissivity, specific yield, and the hydraulic relationship between the major streams and the aquifer.

PRECIPITATION, IN INCHES

6
4
2
0

Monthly precipitation at Spokane WSO Airport

Average

DISCHARGE, IN CUBIC FEET PER SECOND

25,000
15,000
5000
0

Spokane River above Liberty Bridge (12419500)

Average

ALTITUDE OF WATER LEVEL, IN FEET BELOW LAND SURFACE

Well 25/44-23D1

80
90
100

Well 25/45-16C1

95
105
115

Well 26/45-32J2

120
130
140

Well 26/43-19A1

130
140
150

1963   1965   1967   1969   1971   1973   1975   1977

FIGURE 7.--Water levels in selected wells, discharge of the Spokane River above Liberty Bridge, and monthly precipitation at Spokane WSO Airport.

Values of lateral hydraulic conductivity were estimated for the aquifer from specific-capacity data. Because nearly all wells in the study area are partially penetrating, values of specific capacity could not be converted directly to those of hydraulic conductivity. Instead, apparent values for transmissivity were computed on the basis of specific-capacity data, as used in the method of Theis (in Bentall, 1963). This method requires the use of an assumed value of storage coefficient. Also, well-entrance losses are assumed to be negligible, and the flow into the well is assumed to be horizo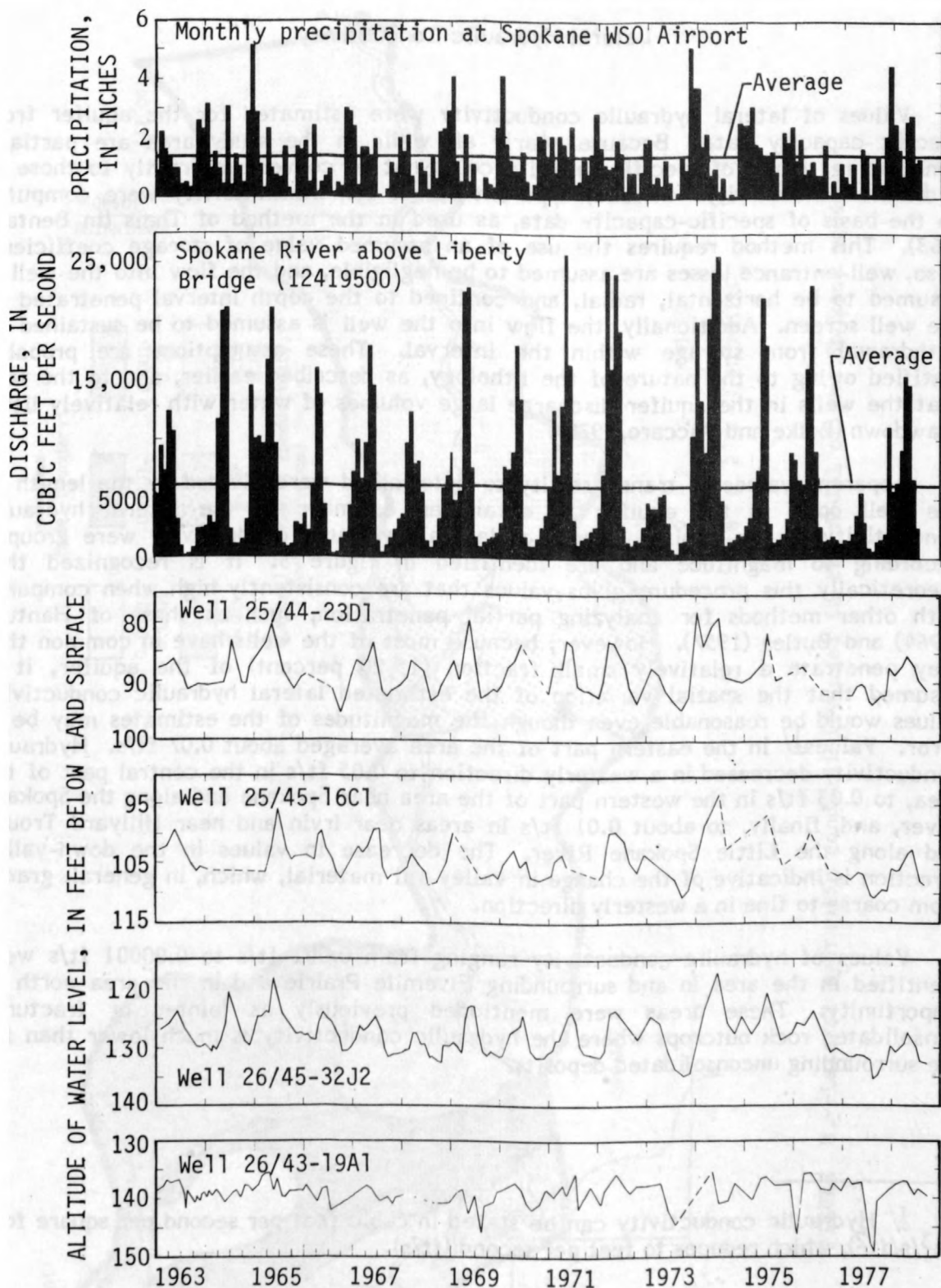ntal, radial, and confined to the depth interval penetrated by the well screen. Additionally, the flow into the well is assumed to be sustained by withdrawal from storage within the interval. These assumptions are probably justified owing to the nature of the lithology, as described earlier, and to the fact that the wells in the aquifer discharge large volumes of water with relatively little drawdown (Bolke and Vaccaro, 1979).

Apparent values of transmissivity so determined were divided by the length of the well open to the aquifer to obtain an estimate of the lateral hydraulic conductivity of the aquifer. Zones of lateral hydraulic conductivity were grouped according to magnitude and are identified in figure 8. It is recognized that theoretically this procedure gives values that are consistently high when compared with other methods for analyzing partial penetration, such as those of Hantush (1964) and Butler (1957). However, because most of the wells have in common that they penetrate a relatively small fraction (15-20 percent) of the aquifer, it is assumed that the spatial variation of the estimated lateral hydraulic conductivity values would be reasonable even though the magnitudes of the estimates may be in error. Values[1] in the eastern part of the area averaged about 0.07 ft/s. Hydraulic conductivity decreased in a westerly direction to 0.05 ft/s in the central part of the area, to 0.03 ft/s in the western part of the area near Spokane and along the Spokane River, and, finally, to about 0.01 ft/s in areas near Irvin and near Hillyard Trough and along the Little Spokane River. The decrease in values in the down-valley direction is indicative of the change in valley-fill material, which, in general, grades from coarse to fine in a westerly direction.

Values of hydraulic conductivity ranging from 0.001 ft/s to 0.00001 ft/s were identified in the area in and surrounding Fivemile Prairie and in the area north of Opportunity. These areas were mentioned previously as jointed or fractured consolidated rock outcrops where the hydraulic conductivity is much lower than for the surrounding unconsolidated deposits.

---

[1] Hydraulic conductivity can be stated in cubic feet per second per square foot $(ft^3/s/ft^2)$, which reduces to feet per second (ft/s).

EXPLANATION

Model boundary

| 0.00001-0.0001 | 0.0001-0.001 | 0.001-0.02 |
| 0.02-0.04 | 0.04-0.06 | 0.06-0.08 |

Lateral hydraulic conductivity,
in feet per second
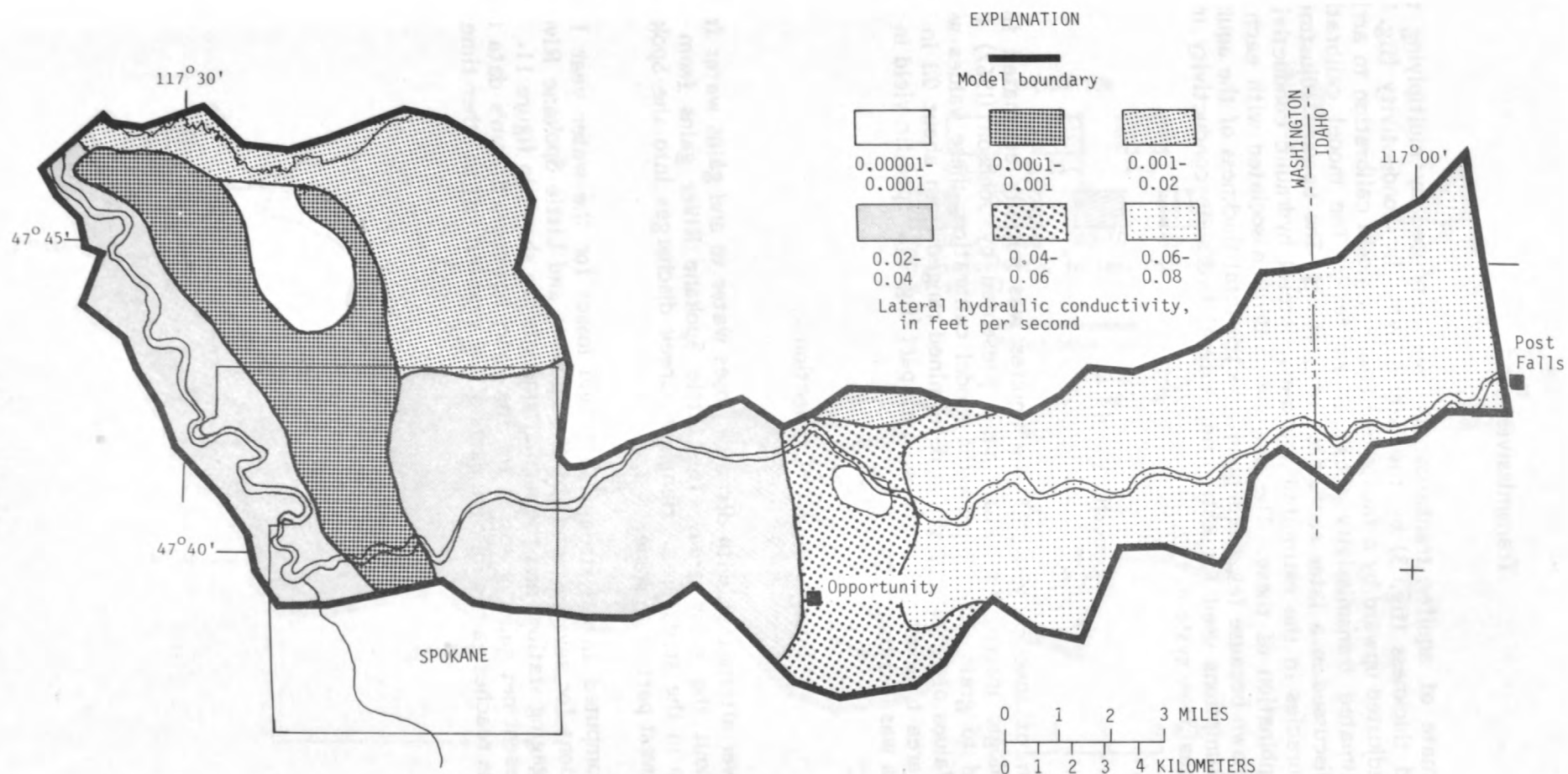
FIGURE 8.--Lateral hydraulic conductivity used in the model of the Spokane aquifer.

Transmissivity

An initial estimate of aquifer transmissivity was computed by multiplying the estimated saturated thickness (fig. 3) by the lateral hydraulic conductivity (fig. 8). These values were adjusted upward by a factor of 1.9 during model calibration to arrive at the map of estimated transmissivity shown in figure 9. The model calibration procedure will be discussed in a later section of this report. The upward adjustment could reflect inaccuracies in the estimated thickness, lateral hydraulic conductivity, model, or some combination of these. The amount of error associated with each of these factors is unknown because few wells penetrate the total thickness of the aquifer and because the assumptions used for estimating lateral hydraulic conductivity may deviate from the actual flow system.

Specific Yield

The distribution of specific yield of the aquifer was initially estimated from comparison of lithologic information with tables presented by Johnson (1967) that relate specific yield to grain size. During the model calibration, these values were uniformly halved. Values of specific yield so determined ranged from about 0.1 in the eastern part of the area to about 0.2 in the western part (fig. 10). Specific yield in the Fivemile Prairie area was less than 0.05.

Stream-Aquifer Connection

The Spokane River alternately, with distance, loses water to and gains water from the aquifer throughout the study area. The Little Spokane River gains from the ground-water system in the study area. Hangman Creek discharges into the Spokane River near the southwest part of Spokane.

Broom (1951) computed annual stream gains and losses for the water year 1950 between gaging stations for seven reaches of the Spokane and Little Spokane Rivers. The location of the gaging stations and the annual amounts are shown in figure 11. The amounts shown represent net gains or losses for the year; however, Broom's data also show that some of the reaches gained in some parts of the year but lost at other times.

EXPLANATION

Transmissivity, in feet squared per second.

Model boundry
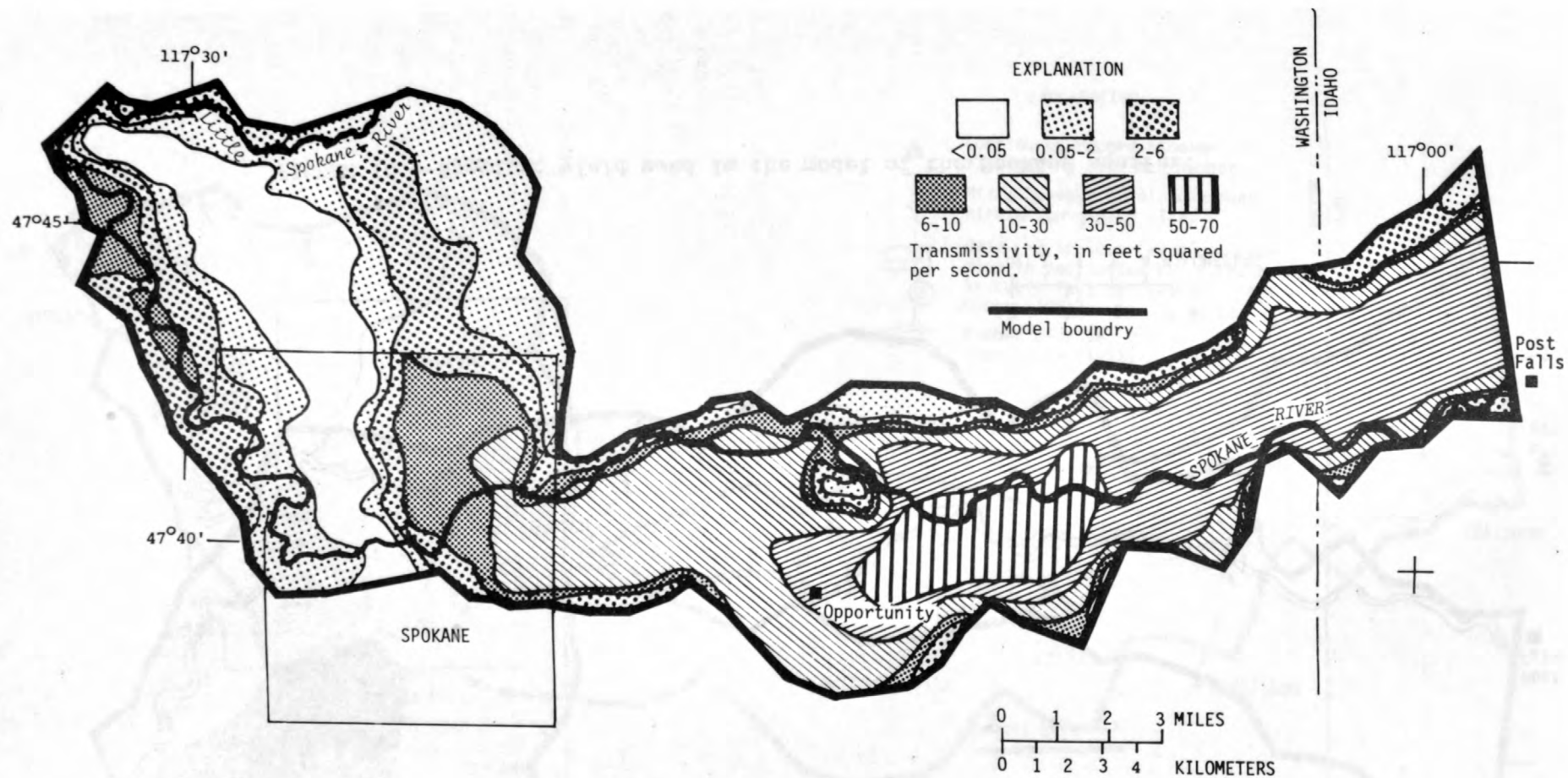
FIGURE 9.--Transmissivity used in the model of the Spokane aquifer.
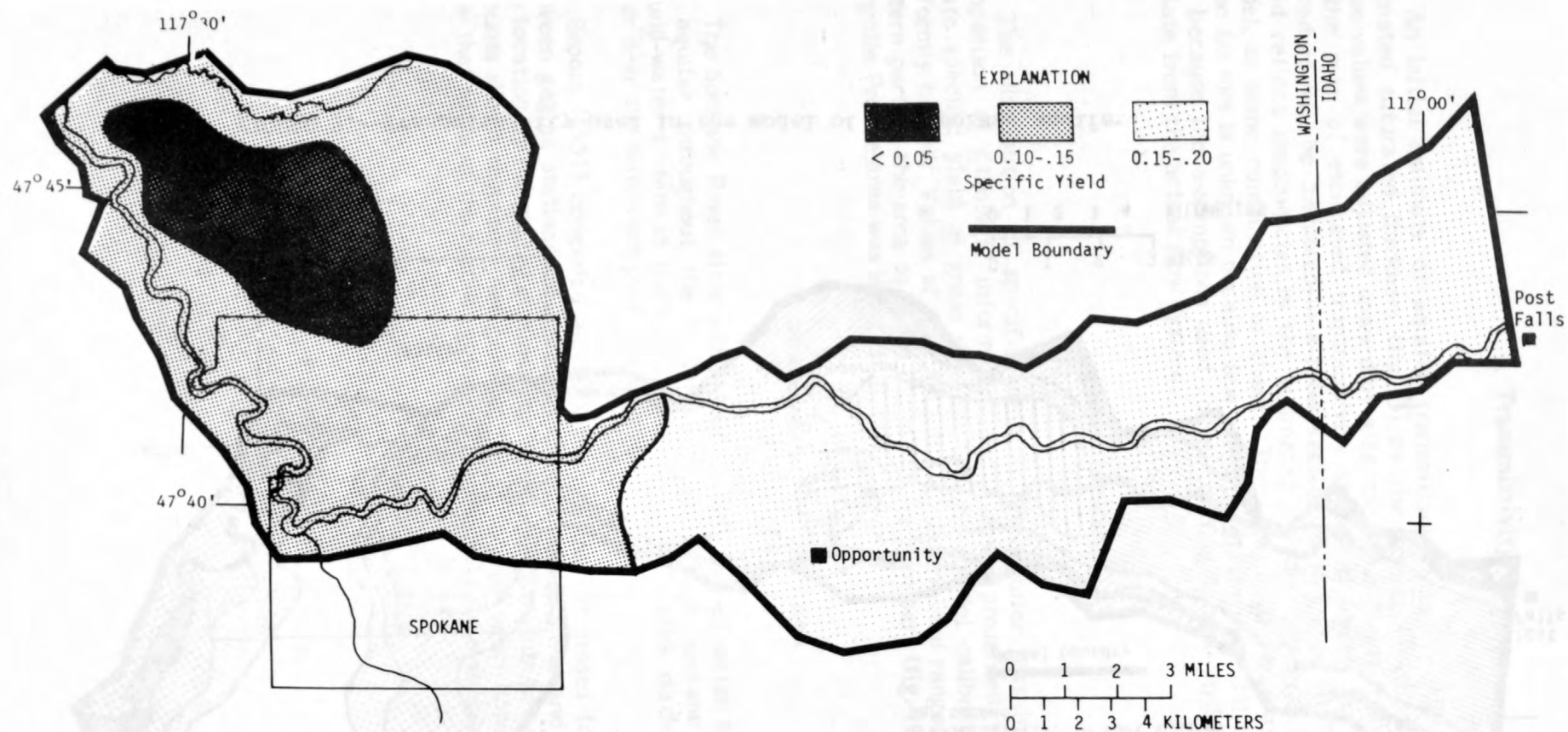
FIGURE 10.--Specific yield used in the model of the Spokane aquifer.

EXPLANATION

< 0.05   0.10-.15   0.15-.20

Specific Yield

Model Boundary

117°30'

47°45'

47°40'

SPOKANE

■ Opportunity

WASHINGTON
IDAHO

117°00'

Post
Falls

22

0   1   2   3 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

▲ Continuous-record stream-
flow gaging site and number.

△ Miscellaneous or discontinued
streamflow gaging site.

□-78 Gain (+) or loss (-) of stream-
⑦   flow in designated river reach,
      in cubic feet per second, from
      Broom (1951).

⑦ Number of river reach,
   from Broom (1951)

117°30'

12431000

Little
Spokane
River

⑥ ⑦
+21 +218

47°45'

+126

⑥ ⑤

+566

△

④ ③

-39

⑤ ④

12422500
12424000

Hangman Creek

SPOKANE

③ ②

+370

② ①

-78

■ Opportunity

WASHINGTON
IDAHO

117°00'

Post
Falls
■

SPOKANE   RIVER

①

△

12419000

▲

124195000

47°40'

+

0   1   2   3 MILES
├──┼──┼──┼──┤
0 1 2 3 4 KILOMETERS

FIGURE 11.--Location of streamflow gaging stations, designation of river reaches, and
gains and losses, in the reaches of the Spokane and Little Spokane Rivers.

For saturated flow, the movement of water between the river and aquifer can be approximated by a form of Darcy's law such that:

$$Q = \frac{k_S}{m} (h_S - h_a) A \qquad\qquad (1)$$

where
Q = flow rate from stream to aquifer, L^3/T
k_S = vertical hydraulic conductivity of the streambed, L/T
m = thickness of the stream bed, L
h_S = elevation of stream surface, L
h_a = elevation of aquifer head, L; or, if h_a is below the streambed, then the elevation of the streambed is used.
A = area of streambed, L^2

The ratio k_S/m is often called a leakage coefficient and is denoted as C. A leakage coefficient for each reach in figure 11 was calculated from the above equation by using Broom's annual gain-or-loss data and stream-stage data from the gaging station. Ground-water heads were not measured during Broom's study, but were estimated from a contour map of ground-water levels constructed at a later time from many years of historic data. The area of the streambed was calculated for each reach from U.S. Geological Survey maps (Giles, 1943).

During subsequent model analysis, the Spokane and Little Spokane Rivers were divided into 13 new reaches. Within each reach, the leakage coefficient was assigned a uniform value based on streambed lithology and whether or not the stream was gaining or losing within each reach. This division and the resulting leakage coefficients were based on successive model interactions designed to match a percentage (57) of the gains and losses established by Broom, which was necessary d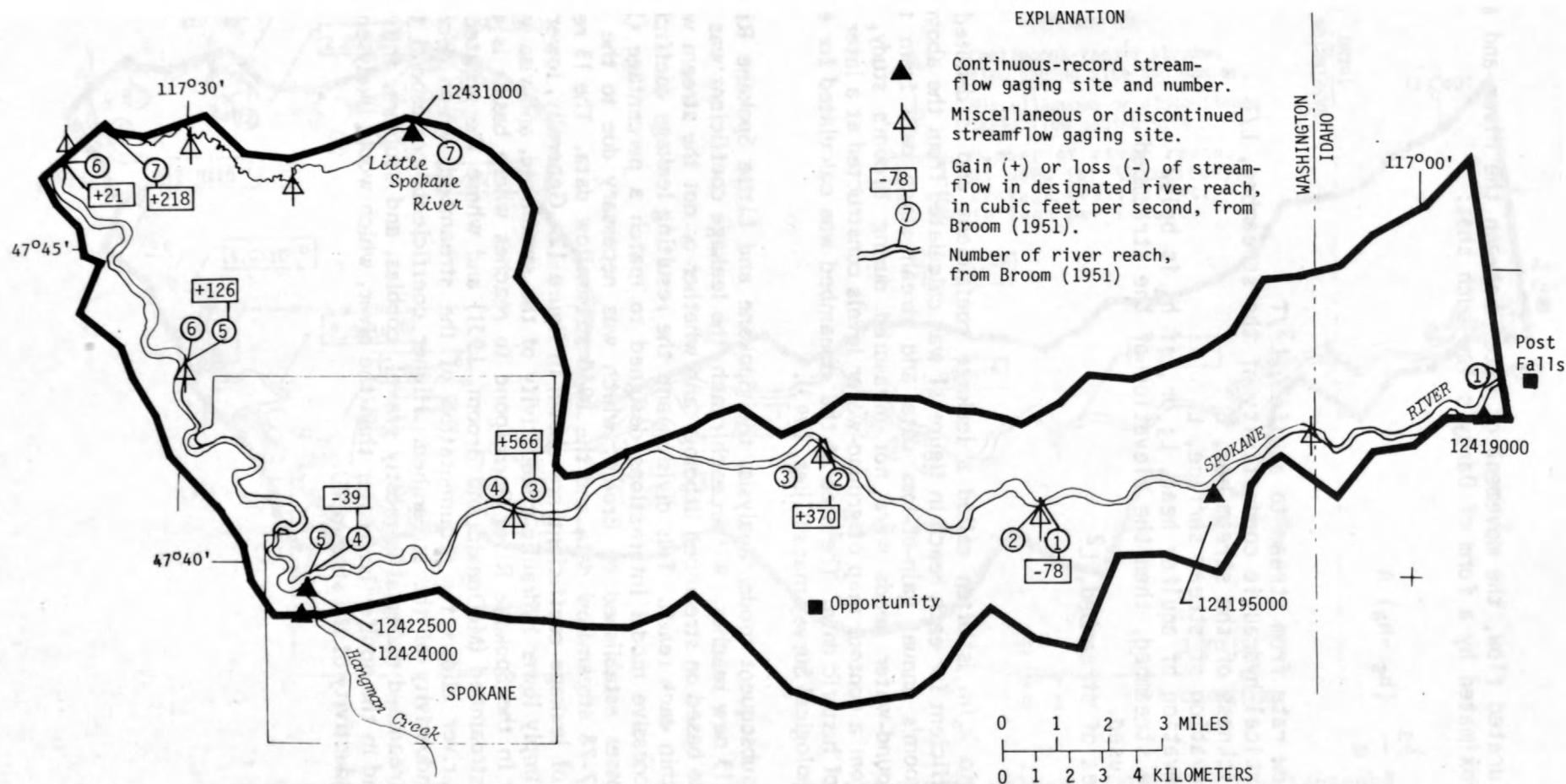ue to the difference between 1977-78 streamflow data and the 1950 streamflow data. The 13 reaches and final values of leakage coefficient are shown in figure 12. Generally, lower values of coefficients imply lower hydraulic conductivity of the streambed, and visa versa. The lower values in the Spokane River correspond to reaches where basalt is exposed in part of the streambed (McDonald and Broom, 1951) and where the greater hydraulic head in the river allows for sedimentation of the streambed, which decreases the hydraulic conductivity of the streambed. Higher coefficients correspond to reaches where the streambed material is mostly gravel, cobbles, and boulders, and where the hydraulic head in the aquifer is greater than the river, which would likely enhance the hydraulic conductivity of the streambed.
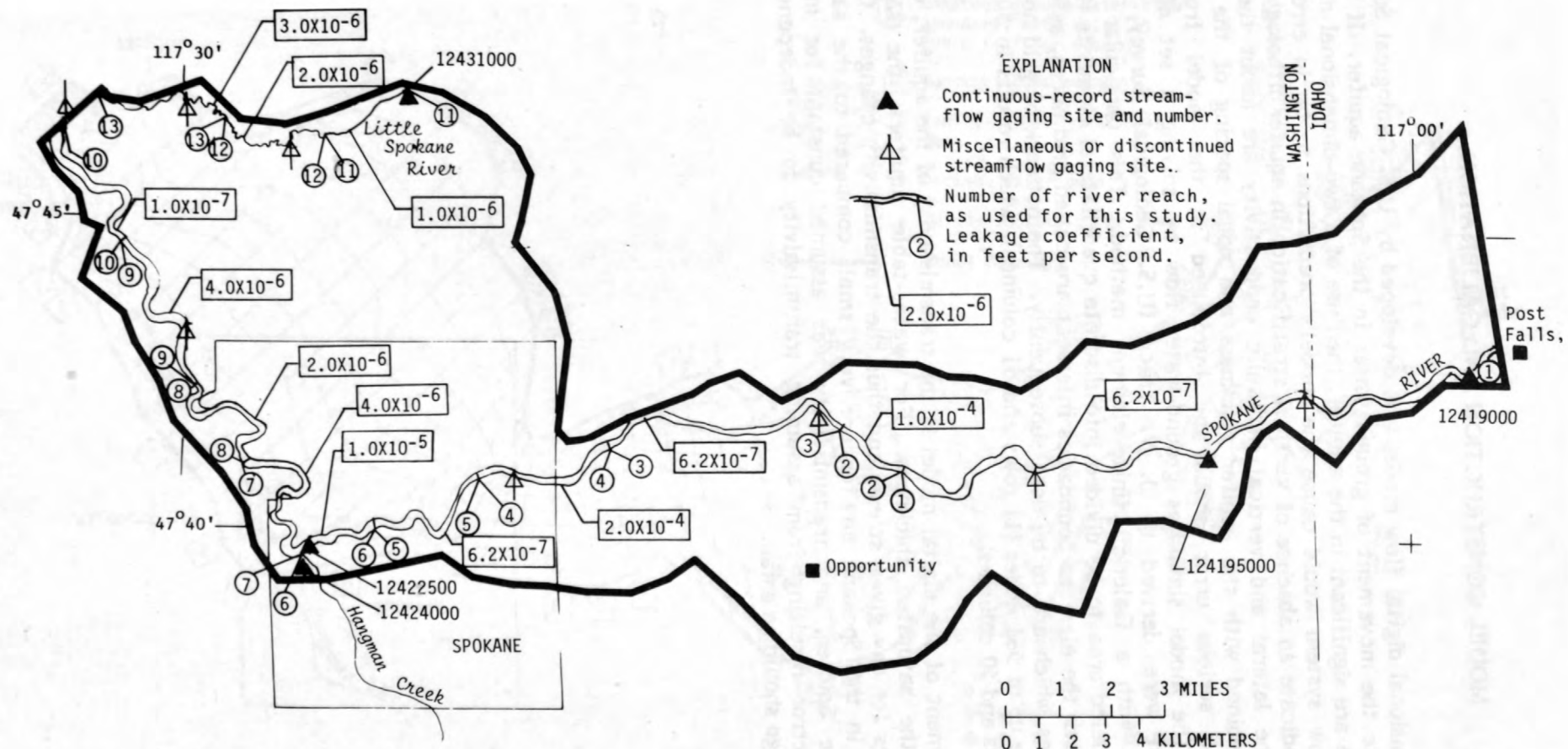
FIGURE 12.--Designation of river reaches and associated values of leakage coefficients obtained from model analysis.

A two-dimensional digital flow model was developed by U.S. Geological Survey in order to simulate the movement of ground water in the Spokane aquifer. If vertical flow or gradients are significant in the aquifer, then use of a two-dimensional model to simulate the flow system would cause the model's predictions to be in error. The available data indicate an absence of vertical stratification in aquifer lithology, which suggests that the lateral and vertical hydraulic conductivity are about the same. These data, combined with the aquifer thickness and nodal spacing of the model, suggest that no serious error should be introduced in the model from this simplification. The model simulates ground-water flow by solving a set of linear equations, which were derived by J. V. Tracy (U.S. Geological Survey, written commun., 1977), with a Galerkin finite-element method. This particular method requires the modeled area to be divided into discrete quadrilateral elements (fig. 13). The points at which the element boundaries intersect are called grid nodes, as opposed to the river nodes which are to be used subsequently. The network of grid nodes and elements is made up of 561 nodes (11 rows and 51 columns), which results in 500 finite elements (10 rows and 50 columns).

One requirement of the digital model is the transmissivity of the aquifer, which is a function of the saturated thickness. For water-table aquifers, the saturated thickness changes for any given stress, and thus the transmissivity changes. Changes in water levels in the Spokane aquifer are very small compared to the saturated thickness of the aquifer, and transmissivity was assumed constant for modeling purposes. The error resulting from assuming transmissivity to be independent of water-level change should be small.

FIGURE 13.--Model grid network, boundary conditions used in the model, and river nodes for the Spokane and Little Spokane Rivers.

Model Boundaries

The boundaries of the model (fig. 13) coincide with the boundaries of the study area, which were previously described. Each node on the eastern bou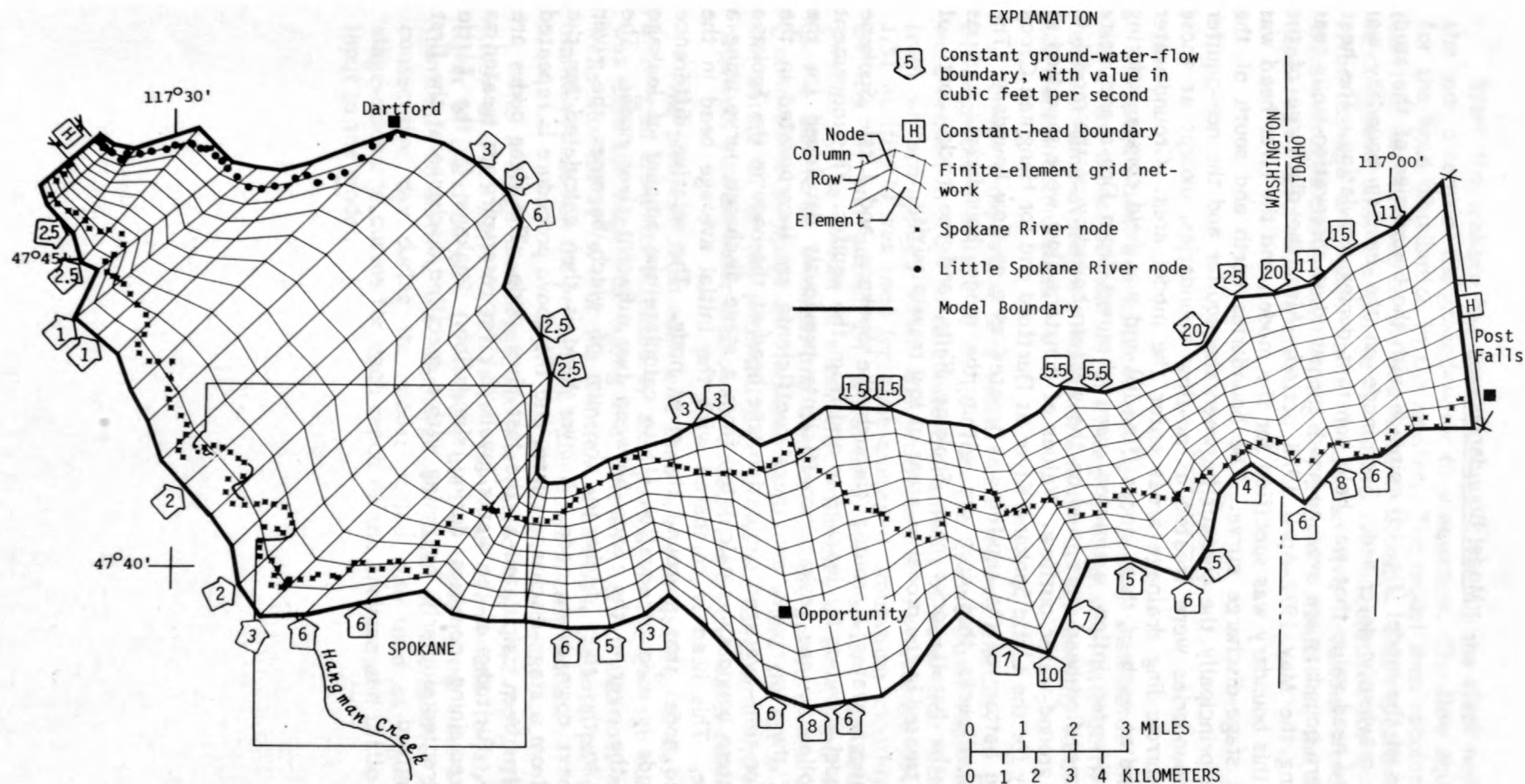ndary was assigned a specified head value that was held constant during simulation. The head values at the eastern boundary are average heads measured at observation wells near the boundary during the May 1977-April 1978 period. Also, the discharge of the Spokane River at this boundary was specified for the model, and the river head was calculated from a stage-discharge curve. The boundaries north and south of the Spokane River are principally the contact between the aquifer and the non-aquifer material. These boundaries were treated as no-flow boundaries, except at those nodes where the surrounding drainage areas enter the model area. Ground-water inflow was specified at each of these nodes (fig. 13) and was held constant during simulation. Ground-water inflow estimates were obtained from Drost and Seitz (1978). Values of specified head were used on the western boundary of the model to simulate constant ground-water outflow. Values of constant flow were specified at the model boundary for the Little Spokane River at Dartford and for Hangman Creek near Spokane. The bottom of the aquifer was treated as a no-flow boundary. The areas of consolidated rocks that crop out within the model boundaries, such as Fivemile Prairie, the basalt rocks near Spokane Falls, and the rocks north of Opportunity, were treated in the model as areas of low transmissivity.

Within the model, water is routed through the Spokane and Little Spokane Rivers, and the model accounts for leakage to and from the aquifer. This movement is partially controlled by the leakage coefficients previously developed for the various reaches of the two rivers, and these coefficients are incorporated in the model. Initially, for time-averaged simulation, the head at the node in the Spokane River near the eastern boundary is calculated from a stage-discharge curve using a specified discharge. This head is compared with the initial average head in the aquifer at the grid nodes that surround the river node. The relative difference between these heads is used in equation (1) to calculate the amount of leakage gained or lost by the river in the reach between two adjacent river nodes. The leakage is added to the river discharge, the sum of which becomes the river discharge at the next downstream node. A river head is then calculated for the downstream node from a stage-discharge curve, and the above procedure is repeated until this leakage has been calculated at the last river node. The river nodes are shown in figure 13. Altitudes of the water levels in river reservoirs are treated as specified heads, remaining constant during simulation. Leakage to the Little Spokane River is treated similarly, beginning with a specified discharge at the first river node near Dartford.

After the leakage has been calculated for all the river nodes, it is added into the source term of the ground-water flow equation. The flow equation is then solved for the head distribution in the aquifer. The model then recomputes the leakage at all river nodes, based on the new head distibution. This repetition process (iteration) is continued until the changes in successive calculations for both aquifer head and river leakage are insignificant. Less than five iterations were necessary for the time-averaged simulation. During the transient simulation, the above procedure was repeated for each time interval.

Model Input

Precipitation was assumed to be uniformly distributed through all elements within the model boundary. An average precipitation rate of 1.72 in. per month was used for time-averaged simulation, and the actual monthly values (fig. 4) were used for transient simulation.

Evapotranspiration (ET) values were treated similarly to precipitation values. Although there is little or no ET from the ground-water reservoir, estimates of ET were needed in order to calculate the amount of water that recharges the reservoir from surface-applied water and precipitation. An average potential ET value of 1.31 in. (fig. 4) was used for time-averaged simulation; monthly values of potential ET (fig. 4) and actual ET were used for transient simulation. During either simulation, the amount of water that infiltrates to the ground water was calculated as the difference between the sum of the precipitation and applied water from ground-water pumpage and the amount of ET, where the ET is the lesser of either the actual ET or the potential ET. If the resulting infiltration is either zero or negative, then no water is allowed to reach the ground-water reservoir.

The pumpage from each well used in the model (fig. 5) was applied over one or more grid elements affected by that pumpage. The average pumping rate for 1977 was used for each well during the time-averaged simulation, and the total of all wells was 227 ft^3/s. For the transient simulation, the total pumpage was distributed monthly, based on the percent of water pumped each month.

The average discharges, for the period May 1977-April 1978, of the Spokane River at Post Falls (5,383 ft^3/s), Hangman Creek (268 ft^3/s), and Little Spokane River at Dartford (229 ft^3/s) were used as input to the time-averaged model. For transient simulation, the discharge at each of the above sites on each fifth consecutive day during the model period was used as input. Additionally, the stage-discharge curves for each reach of the Spokane and Little Spokane Rivers are input to the model.

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The values of specified head along the east boundary ranged from 1,980 to 1,985 ft above the National Geodetic Vertical Datum of 1929 (NGVD) for both simulations, and the specified heads along the west boundary ranged from 1,536 to 1,543 ft above NGVD. The total flow at specified-flow boundaries was 269 ft^3/s, and the flow at individual nodes is shown on figure 12. These values remained unchanged during time-averaged and transient simulation.

Time-Averaged Simulation

There are no long-term changes in water levels for the 1963-78 period (fig. 7), which indicates that the ground-water system is in dynamic equilibrium, where discharge from the system is equal to recharge to the system and the change in head with time is insignificant. This allowed for calibration of the ground-water model using average values of input parameters for the May 1977 to April 1978 period. This period was used because of the reliability of the aquifer data obtained during the study. The procedure to calibrate the time-averaged model was to adjust uniformly the initial values of transmissivity at each node in the model until the least differences were obtained between observed and calculated heads at 73 control wells. This calibration procedure assumes that all specified flows, such as the inflow to the north and south boundaries, precipitation, applied water, and the stream-aquifer leakage coefficients, are known and "fixed" in the model to pre-determined values.

Values of saturated thickness and hydraulic conductivity, from which initial values of transmissivity were calculated, were obtained by overlaying distribution maps of these parameters (figs. 3 and 8) with the grid network (fig. 13). The values at the nodes were used as input to the model in order to calculate initial transmissivity at each node. These transmissivities were repeatedly adjusted until the average difference between the observed heads and the heads calculated by the model at 73 control wells (fig. 5) were apparently close to a minimum value. The minimum average head difference for this procedure was about 6 ft, and the initial transmissivities were increased by a factor of 1.9 during the calibration procedure. The final transmissivity distribution is shown in figure 9. The upward adjustment shows that either the initial values of hydraulic conductivity are too low, perhaps due to estimating the initial values using specific-capacity data, or the estimates of saturated thickness are too low.

The calibration procedure also included using the discharge from the aquifer to the Little Spokane River as a limiting value for adjusting the transmissivity. The water that is gained by the Little Spokane as it flows through the project area was measured by the U.S. Geological Survey during September of each year from 1955 to 1970, in 1973, and in 1977. The average gain in the river for these years was 267 ft^3/s, with a variation from 223 to 336 ft^3/s. Since the measurements during September are probably representative of the low-streamflow period, the average value of 267 ft^3/s is assumed to be the average value of ground-water discharge to the Little Spokane River from the Spokane aquifer. Also, during the period December 1976 to September 1977, 13 miscellaneous discharge measurements were made near the mouth of the Little Spokane. Comparing these discharges with mean daily values at Dartford shows an average gain in the river of 266 ft^3/s, with a range of 236 to 318 ft^3/s. Thus, for time-averaged conditions, an average value of 267 ft^3/s ($\pm$ 5 percent measurement error) was used to limit the amount of water allowed to discharge to the Little Spokane River while using the various configurations for transmissivity as discussed above.

The reliability of the calibration was checked in two ways. First, the discharge of the Spokane River as measured during May 1977 to April 1978 at three sites within the model boundaries was compared to the discharge calculated by the model. These data appear in the following table.

Streamflow site number (fig 11)	(1) Average measured discharge (May 77-Apr. 78) (ft^3/s)	(2) Calculated discharge from model (ft^3/s)	Difference (2)-(1) (ft^3/s)
12419000	5,383	5,380	-3
12419500	5,236	5,351	115
12422500	5,640	5,722	82

The differences between the average measured discharges and the calculated discharges are less than the error inherent in the discharge measurement (5 percent), so that the discharges calculated by the model are reasonable.

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Second, the reliability was tested by calculating a water balance of the river area above the streamflow gaging site on the Spokane River below Long Lake (fig. 1) and then comparing that with the water budget calculated by the model. The streamflow site below Long Lake was used because the discharge at this site includes all the streamflow that affects ground water in the project area and because a negligible amount of ground water moves past this site. The amount of ground water (GW) contributed to the river system within the project boundaries was estimated using the following relationship.

$$GW = LL - PF - HC - DT - S \pm DSLL,$$

where,
LL = discharge of Spokane River below Long Lake,
PF = discharge of Spokane River near Post Falls, Idaho,
HC = discharge of Hangman Creek near Spokane,
DT = discharge of Little Spokane River at Dartford,
S = sewer effluent,
DSLL = change in storage of Long Lake,
and where all units are in cubic feet per second.

By substituting average values for the May 1977-April 1978 period into the equation, the ground-water contribution to the river was estimated as follows:

$$GW = 6449 - 5383 - 268 - 229 - 54 + 38 = 553 \ ft^3/s.$$

The ground-water flow across the eastern boundary of the project area, as calculated by the model for the May 1977-April 1978 period, was about 400 ft^3/s, and the ground-water flow leaving the project area at the western boundary was calculated as 110 ft^3/s. The net gain of the Spokane River for all the reaches of the river within the project boundaries as calculated by the model was 280 ft^3/s, and the calculated net gain for the Little Spokane River was 250 ft^3/s. The sum of the gains in the Spokane (280 ft^3/s) and Little Spokane River (250 ft^3/s), and the ground-water flow from the project area (110 ft^3/s), which eventually flows into Long Lake, is the ground-water contribution to the river system. This sum equals 640 ft^3/s, and is 87 ft^3/s more than the amount calculated from the measured discharges. The accuracy of the discharge of the Spokane River measured at the gage below Long Lake is probably +5 percent, so that the measured discharge is 6,449 ft^3/s, plus or minus about 320 ft^3/s. Comparing this accuracy with the difference from above (87 ft^3/s) shows that accuracy of the amount of ground-water flow calculated by the model is within the limits of accuracy of the discharge measurement.

The water budget of the ground-water system for the modeled area, as calculated from the time-averaged simulation, is shown in the following table.

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	Cubic feet per second
Recharge	
Ground-water inflow (east, north, and south boundaries)	668
Precipitation	209
Water applied to land surface from ground-water pumpage (infiltration)	99
Direct infiltration from septic tanks	35
Total (rounded)	1,010
Discharge	
Ground-water outflow (west boundary)	105
Ground-water pumpage	227
Evapotranspiration	143
Leakage to Spokane River	282
Leakage to Little Spokane River	254
Total (rounded)	1,010

The gains and losses of streamflow calculated by the time-averaged model for various reaches of the Spokane and Little Spokane Rivers are shown in figure 14. The values shown are average values for the May 1977-April 1978 period. Each reach either consistently gains or consistently loses streamflow within that reach. For instance, the reach from Post Falls, Idaho, to Greenacres, Wash., loses streamflow along the entire reach, and the next downstream reach gains water along its entire length, and so forth. In terms of quantity, the largest gains are in the reach near Irvin (240 ft^3/s), the reach near the eastern part of Spokane (270 ft^3/s), and the Little Spokane River (250 ft^3/s). The reach showing the largest loss (200 ft^3/s) is the reach in Spokane above Spokane Falls.

Transient Simulation

The response of the Spokane aquifer to time-varying stresses was simulated by the transient model for the period May 1977-April 1978. The time-varying stresses are precipitation, evapotranspiration, ground-water pumpage, and streamflow. A 1-year period is sufficient to define the effect of stress, such as ground-water pumpage, on streamflow depletion in the Spokane stream-aquifer system because the system reaches near equilibrium in about 1 year in response to imposed stress. The 1-year period was estimated by using a method by Jenkins (1970). A hypothetical well located 2 mi from the Spokane River was pumped for 90 days at 29 ft^3/s. With the assumption of $T = 4,320,000$ ft^2/day (50 ft^2/s) and S=0.2 in the method of Jenkins, the calculated ratio of stream depletion to well discharge ranged from 0.9 at the end of the 90-day pumping period to 0.02 at the end of 1 year, or 275 days after pumping stopped. Likewise, letting $T = 864,000$ ft^2/day (10 ft^2/s), the ratio ranged from 0.7 at the end of the 90-day pumping period to 0.02 at the end of 1 year. This indicates that stream depletion due to well discharge was only about 2 percent after pumping a well for 90 days and allowing 275 days for recovery. The T values in the above analysis are typical values of T in the Spokane aquifer (fig. 9). The 1-year period from May 1977 to April 1978 was used for simulation because of the reliability of observed aquifer heads during this period.
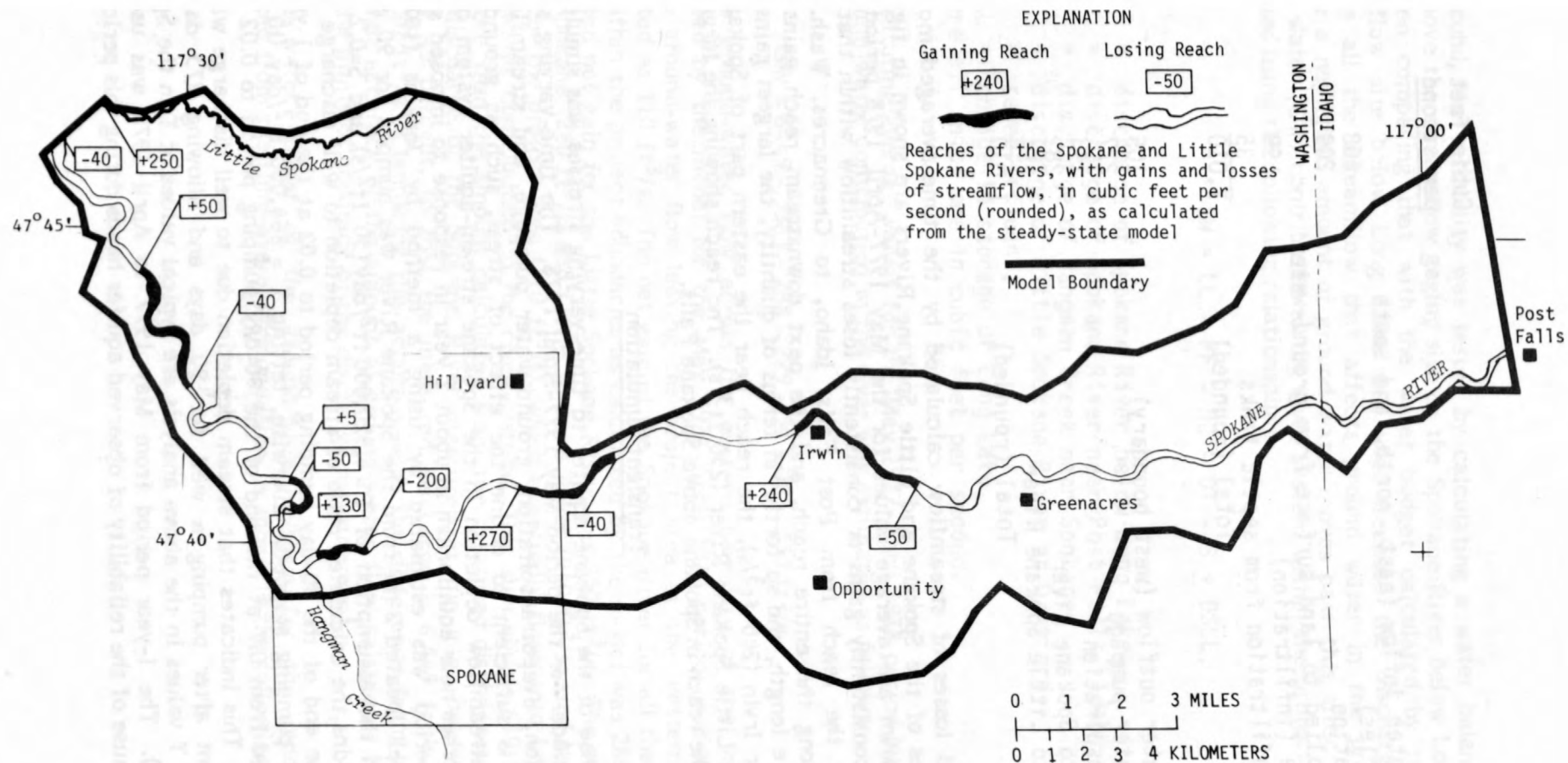
FIGURE 14.--Gains and losses in streamflow in the Spokane and Little Spokane Rivers, May 1977-April 1978 period, as calculated from time-averaged simulation.

The boundary flows for transient simulation were specified with the same values as those used in the time-averaged model. Monthly values of precipitation, evapotranspiration, and pumpage from major wells, along with streamflow data for the Spokane and Little Spokane Rivers and Hangman Creek, are input to the model. Output consists of head distribution in the aquifer and the gains and losses to the Spokane and Little Spokane Rivers. The model period was divided into 73 five-day time increments for the simulation.

The procedure used to calibrate the model was to uniformly adjust initial estimates of specific yield in the model until the least average difference between the observed and calculated water levels was obtained for the 1-year period. In addition to the assumptions used for calibrating the time-averaged model, the values of transmissivity calculated from the time-averaged model were used as input to the transient model. Nodal values of specific yield (S) were obtained by overlaying a distribution map of S, discussed earlier, with the grid network shown in figure 13. Values of S were taken at the nodes of the grid and used as input to the model. During simulation these values were uniformly adjusted by factors ranging from 0.25 to 1.5 to obtain, by trial and error, the least average difference between observed and calculated heads. The least average difference was found by using a factor of 0.5, and the results are shown in figure 10. Hydrographs of water levels from four wells were used to show the difference between observed and calculated heads in various parts of the aquifer (fig. 15). The average differences were generally less than 2 ft for well 25/43-14L1, which is near the east city limits of Spokane, and for well 25/44-23D1, which is east of Opportunity. The hydrograph for well 22/45-16C1, which is east of Greenacres near Liberty Lake, shows differences averaging about 6 ft. Calculated water levels in the Hillyard Trough (well 26/43-19A1) are about 25 ft below the observed levels. The average difference between observed and calculated water levels for 73 control wells at the end of the simulation period, April 1978, was about 6 ft.

Reliability of the transient model was tested by comparing the observed 5-day gains or losses of the Spokane River, as measured in the reach from the Post Falls, Idaho, gage (12419000) to the Spokane gage (12422500), with the calculated 5-day gains and losses for the same reach (fig. 16). The smallest differences between observed and calculated gains and losses were during periods when the river discharge was relatively constant, such as the September-November period. The largest differences were during periods of rapidly changing discharge in the river, such as December and March, and were due partly to inaccuracies in the model parameters and partly to inaccuracies in the observed gains and losses.

Well 25/45-16C1

EXPLANATION
⊙ Observed water level
△ Calculated water level using 1977 pumpage
● Calculated water level, using doubled 1977 pumpage

Well 25/44-23D1

Well 25/43-14L1

Well 26/43-19A1

ALTITUDE OF WATER LEVEL, IN FEET ABOVE NGVD OF 1929

1954
1952
1950
1948
1946
1944
1942
1940
1938
1936

1930
1928
1926
1924
1922

1886
1884
1882
1880
1878
1876

1810
1800
1790
1780
1770
1760

MAY   JUNE   JULY   AUG.   SEPT.   OCT.   NOV.   DEC.   JAN.   FEB.   MAR.   APR.

1977   1978

FIGURE 15.--Observed and calculated water levels in selected wells.

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GAIN (+) OR LOSS (-), IN CUBIC FEET PER SECOND

+800

+400

0

-400

-800

Calculated gain or loss in streamflow, based on 1977 ground-water pumpage.

Observed gain or loss in streamflow.

Calculated gain or loss in streamflow, based on doubled 1977 ground-water pumpage.

Calculated gain or loss in streamflow, based on quadrupled 1977 ground-water pumpage

MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC. | JAN. FEB. MAR. APR.
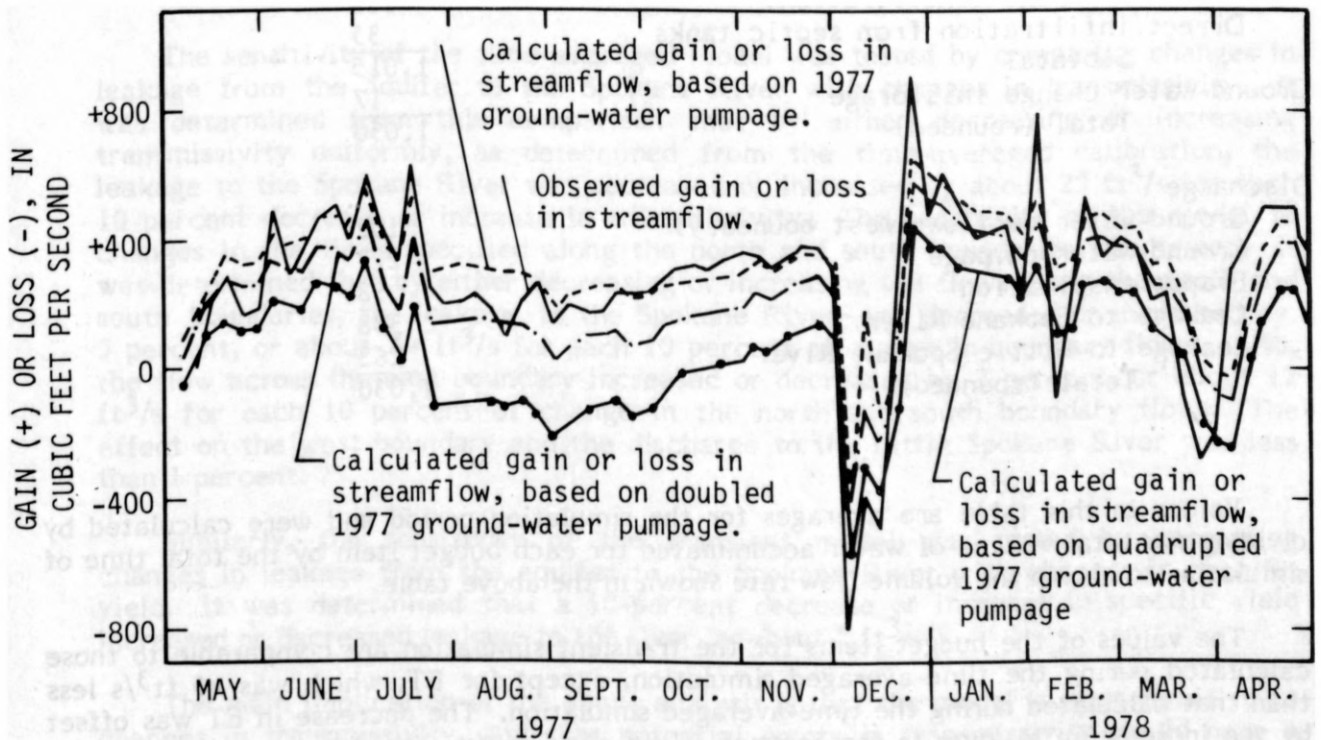
1977   1978

FIGURE 16.--Observed and calculated gains and losses of the Spokane River as determined at the Spokane gaging station (12422500).

The water budget calculated during transient simulation is shown in the following table.

	Cubic feet per second
Recharge	
Ground-water inflow (east, north and south boundaries)	656
Precipitation	216
Water applied to land surface from ground-water pumpage (infiltration)	108
Direct infiltration from septic tanks	35
Subtotal	1,015
Ground-water change in storage	17
Total (rounded)	1,030
Discharge	
Ground-water outflow (west boundary)	102
Ground-water pumpage	227
Evapotranspiration	98
Leakage to Spokane River	338
Leakage to Little Spokane River	263
Total (rounded)	1,030

Values in this table are averages for the simulation period and were calculated by dividing the total volume of water accumulated for each budget item by the total time of simulation to obtain the volume flow rate shown in the above table.

The values of the budget items for the transient simulation are comparable to those calculated during the time-averaged simulation, except for ET, which was 45 ft^3/s less than that calculated during the time-averaged simulation. The decrease in ET was offset by the increase in leakage to the Spokane River of 56 ft^3/s. The difference between the calculated ET values is due to the use of monthly values of ET (zero for November through April) in the transient model, rather than an average annual ET rate.

Ground-water inflow to the study area, as calculated during transient simulation, averaged 656 ft^3/s, which included all the inflow to the area along the north, east, and south boundaries. Ground-water inflow ranged in value from 740 ft^3/s during the 5-day period August 29-September 2, 1977, to 500 ft^3/s during the 5-day period May 1-5, 1977.

The average accumulated leakage to the Spokane River, calculated at the last river node at the downstream boundary, was 338 ft^3/s. Interchange ranged from a gain of about 700 ft^3/s during the 5-day period December 22-26, 1977, to a loss of about 470 ft^3/s during the 5-day period December 2-6, 1977. Leakage to the Little Spokane River averaged 263 ft^3/s and varied from about 280 ft^3/s during the period May 31-June 4, 1977, to about 250 ft^3/s during the period December 12-16, 1977.

Ground-water outflow from the study area averaged 102 ft^3/s, which includes the subsurface flow across the west boundary. The outflow ranged from about 80 ft^3/s during May 1-5, 1977, to about 110 ft^3/s during December 27-31, 1977. The average amount of total outflow at the western boundary, which was derived from the study area, is the sum of (1) gain in the Spokane River (338 ft^3/s), (2) gain in the Little Spokane River (263 ft^3/s), and (3) ground-water outflow (102 ft^3/s), for a total of about 700 ft^3/s.

Sensitivity of the Model

The sensitivity of the time-averaged model was tested by comparing changes in leakage from the aquifer to the Spokane River with changes in transmissivity. It was determined from this comparison that by either decreasing or increasing transmissivity uniformly, as determined from the time-averaged calibration, the leakage to the Spokane River was decreased or increased by about 25 ft^3/s for each 10 percent decrease or increase in transmissivity. The sensitivity of the model to changes in the flows specified along the north and south boundaries was tested. It was determined that by either decreasing or increasing the flows along the north and south boundaries, the leakage to the Spokane River was decreased or increased by 5 percent, or about 14 ft^3/s for each 10 percent of change in boundary flows. Also, the flow across the east boundary increased or decreased by 3 percent, or about 12 ft^3/s for each 10 percent of change in the north and south boundary flows. The effect on the west boundary and the discharge to the Little Spokane River was less than 1 percent.

Similarly, the sensitivity of the transient model was tested by comparing changes in leakage from the aquifer to the Spokane River with changes in specific yield. It was determined that a 10-percent decrease or increase in specific yield increased or decreased leakage to the river by about 5 ft^3/s.

The main implication of the above analysis is that the model is most sensitive to changes in transmissivity, and that potential errors in transmissivity would have a greater effect on the model-predicted heads and discharges than would errors in boundary flows or specific yields.

The transient model, developed as part of this project, was used to show the effect of increased ground-water withdrawals on the water levels in the Spokane aquifer and on the discharge of the Spokane and Little Spokane Rivers. In order to show this effect, the 1977 ground-water pumping rates were doubled and used as input to the model. Values of the doubled pumping rate ranged from 230 ft^3/s during March to 930 ft^3/s during July, and averaged 454 ft^3/s for the simulation period. For this analysis the rates for individual wells were doubled; however, greater or lesser pumping stresses could be applied over the modeled area or the stresses could be applied locally within the area to fit any desired management scheme. All other input parameters were unchanged.

The effect of doubling the 1977 ground-water pumping rate on water levels in the eastern part of the area was a predicted water-level lowering of 0.5 ft below the 1977 levels during the summer months (June-September) and 0.2 ft during the rest of the year. This lowering is shown in hydrographs of water levels for wells 25/44-23D1 and 25/45-16C1 in figure 15. In the central part of the area (well 25/43-14L1), water levels were lowered 1 ft during the summer months and 0.5 ft during the rest of the year in response to the doubled pumping rates. The largest water-level changes were in the Hillyard Trough (well 26/43-19A1), where they were lowered 2-3 ft during the entire year. The relatively small declines in water levels were due to stream depletion owing to the high transmissivity of the aquifer.

The effect on the discharge of the Spokane River as measured at Spokane (station 12422500) of doubling the 1977 ground-water pumping rates can be seen in figure 16. A comparison of the calculated gains and losses in the river, using the doubled 1977 pumping rate, shows a decrease in river discharge of 150 ft^3/s from the middle of July to the middle of November. For the rest of the modeled period, except for the high-flow period during December, doubling the 1977 pumping rate caused a decrease in river discharge of 50 ft^3/s.

The leakage of ground water to the Little Spokane River was decreased by less than 10 ft^3/s as a result of doubling the 1977 ground-water pumping rates.

The effect of doubling the pumping rate on constant-head nodes at the east boundary was to increase the flow by about 2 percent. The effect at the west boundary was nil. Thus, it appears that the assumptions for constant head at these boundaries are reasonable.

The only source of water for additional pumpage is either stream-depletion or ground-water storage. Because of the nature of the aquifer, depletion from ground-water storage is only temporary, and practically all additional pumpage will soon come from the surface-water system. For instance, increasing the ground-water pumpage by a factor of 4 times the 1977 pumpage changes the Spokane River from a gaining stream to a losing stream from mid-July to about the end of October (fig. 16).

SUMMARY AND CONCLUSIONS

1. The digital model described in this report simulates the ground-water flow system in Spokane Valley within the accuracy of the input data.

2. The model was used for calculation of aquifer heads and streamflow variations based on changes in ground-water pumpage. The model can also be used to show the effects of changes in other parameters, such as precipitation, streamflow, and flow across the project boundary.

3. The current rate of ground-water pumping has little effect on water levels in the Spokane aquifer, although short-term water-level declines occur locally.

4. Increasing pumping rates by a factor of 2 over the 1977 rates has a more significant effect on the discharge of the Spokane River than on the change in water levels in the aquifer.

RECOMMENDATIONS FOR FUTURE STUDIES

Future studies in the area covered by this report should include:

1. Test drilling combined with seismic surveying in order to further define the thickness and extent of the Spokane aquifer.

2. Aquifer-head measurements near the rivers in conjunction with stage and discharge measurements of the river in order to better define the river-aquifer interchange.

3. A combination of test drilling and tests for hydraulic properties near the model boundaries to determine the ground-water inflow to and ground-water outflow from the project area.

4. Linking of this model with the model being developed concurrently for the Idaho part of the aquifer in order to allow for better prediction of aquifer heads and streamflow variations. By combining the two models, a better understanding of the river-aquifer connection would be possible.

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