ADEQUACY OF AVAILABLE HYDROGEOLOGIC DATA FOR EVALUATION OF DECLINING GROUND-WATER LEVELS IN THE FORT ROCK BASIN, SOUTH-CENTRAL OREGON

By W.D. McFarland and G.N. Ryals

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4047.	square meter (m^2)
	Volume	
acre-feet (acre-ft)	1233.	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.0631	liter per second (L/s)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°C = 0.555\ (°F-32)$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

In the Fort Rock Basin of south-central Oregon, development of ground-water resources for irrigation has caused water levels to decline at an average rate of as much as 0.5 feet per year since the mid-1970's. Pumpage from about 400 irrigation wells in the basin reached 92,000 acre-feet per year in 1984. The adequacy of available information to understand and quantify the ground-water resources in the basin was evaluated by constructing a mathematical model that simulated three-dimensional ground-water movement. Model sensitivity experiments indicated the relative importance of hydrogeologic parameters and defined data deficiencies.

As a result of the model analysis, it was determined that available hydrogeologic information was inadequate to allow accurate quantification of the flow system. To refine the conceptualization of ground-water movement in the basin, and to further identify the boundaries to the ground-water system, additional mapping of the potentiometric surfaces and extent and thickness of aquifers in the basin is needed. Additional information also is needed on aquifer storage and hydraulic conductivity, and the rate and magnitude of ground water lost by evapotranspiration under present and declining water levels. Specifically, data needs include: (1) determining the water table configuration over a much larger area; (2) refining estimates for the rate of spring discharge; (3) refining estimates of distribution and rates of recharge; (4) continuing efforts to monitor the distribution and rates of ground-water pumpage; and (5) determining the depth to water in areas of phreatophyte growth, rates of water usage of these plants, and the maximum depth of root penetration.

Model experiments indicate that a small reduction in spring discharge probably has occurred from the beginning of pumping until the present (1983); however, most of the water withdrawn by pumpage has been derived from aquifer storage. The rate at which water is lost by evapotranspiration has been reduced as a result of lowered water levels, but the magnitude of the reduction is unknown.

INTRODUCTION

Development of ground-water resources for irrigation has increased substantially in the Fort Rock Basin of south-central Oregon since the mid-1970's. Irrigation in the basin was negligible until 1956, when electricity was introduced. Ground-water pumpage gradually increased from 2,000 acre-feet in 1956 to 17,000 acre-feet in 1971. Pumpage increased rapidly from 1971 to 1984, when withdrawal of ground water reached 92,000 acre-feet and approximately 400 irrigation wells were in use. By 1984, ground-water withdrawal permits had been issued for more than 75,000 acres of land (Miller, 1984). Several tens of thousands of additional acres could be irrigated in the future if ground-water continues to be available.

As a result of pumpage, water levels have declined at an average rate of as much as 0.5 feet per year since 1976 (Miller, 1984, p. 44). Although these rates are not as alarming as the 5 or more feet per year of decline elsewhere in Oregon (such as in the Umatilla Basin), they are sufficiently high to cause concern. The degree to which the resource is regulated is dependent largely on the magnitude of water-level declines and on decreases in natural discharge that result from ground-water withdrawals. To properly manage ground water, the Oregon Water Resources Department (OWRD) needs to know if water levels eventually will stabilize or if they will continue to decline at the same rate. The effects of any additional pumpage on the rate of water-level decline or decrease in natural discharge also needs to be understood.

In 1979, the OWRD began their most recent study of the Fort Rock Basin to assess ground-water conditions, and in March 1984 the Director of OWRD signed a proclamation that began proceedings to determine whether the basin should be declared a "critical ground-water area." The Director of OWRD has the authority to make such a declaration when ground-water levels are declining or have declined and when the available ground-water supply is being, or is about to be, overdrawn. This declaration allows the State of Oregon to limit the use of ground water in designated areas. The initiation of proceedings to declare the Fort Rock Basin a critical area halted issuance of new permits for ground-water use until a critical area determination was reached. In August 1986, the Oregon Water Resources Commission directed the OWRD to proceed with authorization through a withdrawal or classification process for unappropriated ground water, instead of declaring the Fort Rock Basin a critical ground-water area. This process could close the area to new appropriations for certain uses, but would not restrict existing uses as could a critical-area determination.

Purpose and Scope

This report describes the results of a cooperative study by the U.S. Geological Survey and the Oregon Water Resources Department that was begun in 1984. The purpose of this report is to evaluate the adequacy of available information to understand and quantify the ground-water resources in the Fort Rock Basin. An additional objective is to identify additional data that would improve this understanding. A knowledge of the adequacy of the data is needed by agencies charged with managing the ground-water resources in the basin.

To accomplish the objectives of the study, available information concerning the hydrogeology of the Fort Rock Basin was used to construct a three-dimensional ground-water flow model. This model was used as a tool to better understand the hydrogeology of the basin, but was not calibrated for predictive modeling. A sensitivity analysis of the model aided in evaluating the adequacy of the available information and in identifying data deficiencies. Aquifer transmissivity, recharge distribution and rates, and storage coefficient were adjusted in the sensitivity analysis. The sensitivity of the model was tested under both predevelopment and pumping conditions; and water levels, drawdowns, and spring discharge were compared to observed values to assess the reasonableness of the model results.

The scope of the study did not allow collection of new data; components of the hydrogeologic system were evaluated in the following manner. Aquifer-system geometry and boundaries were defined using results from previous studies and also by reviewing the 1,400 well logs for the basin. Hydraulic conductivities were estimated from specific capacities of 177 irrigation wells with pump or bailer tests. A range of recharge rates and distributions was estimated using available data on temperature, precipitation, crop-growth coefficients, soil moisture-holding capacities, and vegetation-root depths. Ground-water movement and discharge were evaluated by using data from previous studies and historic water-level and spring-discharge data.

Description of The Area

The Fort Rock Basin is part of the high desert of south-central Oregon and lies largely in Lake County, but also includes parts of Klamath and Deschutes Counties (fig. 1). The boundary between two distinct physiographic provinces, the High Lava Plains and the Basin and Range, lies within the basin. Included in the Fort Rock Basin are the Fort Rock, Christmas Lake, and Silver Lake-Thorn Lake Valleys. The total area of the basin is approximately 3,000 mi^2 (square miles). The basin floor has an average altitude of about 4,300 feet and the surrounding uplands reach altitudes of 8,000 feet. Average annual precipitation at Fremont, Oregon at the western edge of the basin floor is approximately 10 inches and the growing season is about 100 days.

The basin is a closed basin in that all surface-water drainage is internal. There are only three perennial streams in the basin: Buck, Silver, and Bridge Creeks. These streams carry water from the upland slopes in the southwest to Paulina Marsh, which covers about 30-square miles just northwest of Silver Lake. Many ephemeral streams flow during the spring, carrying runoff from the uplands to the basin floor; however, in some areas little runoff occurs and snow either melts and directly infiltrates the ground or it sublimates.

Although the Fort Rock Basin is topographically closed, ground water is believed to discharge both within and beyond its boundaries. Two basins adjacent to the Fort Rock Basin, the Deschutes and Summer Lake Basins, have been noted as potential ground-water discharge areas (Hampton, 1964). The Deschutes River drains northward and eventually flows into the Columbia River. The Summer Lake basin lies to the south and is also a closed basin. The Deschutes River and Summer Lake are 100 and 150 feet, respectively, below the altitude of the Fort Rock Basin floor. Limited evidence supports the concept of ground-water discharge from the Fort Rock Basin to the Deschutes River drainage. However, the northern part of the Summer Lake basin is a large ground-water discharge area with many springs, seeps, and flowing wells. The largest spring in this area is Ana Spring, a primary source of water for Summer Lake. Average discharge at Ana Springs is approximately 90 ft^3/s [cubic feet per second] (65,000 acre-ft/yr), for the period 1931 to present (Hubbard and others, 1983). These springs are located approximately 5 miles south of the Fort Rock Basin, and their discharge cannot be explained solely by their surface drainage areas; therefore, a source of water outside the local drainage basin is likely.

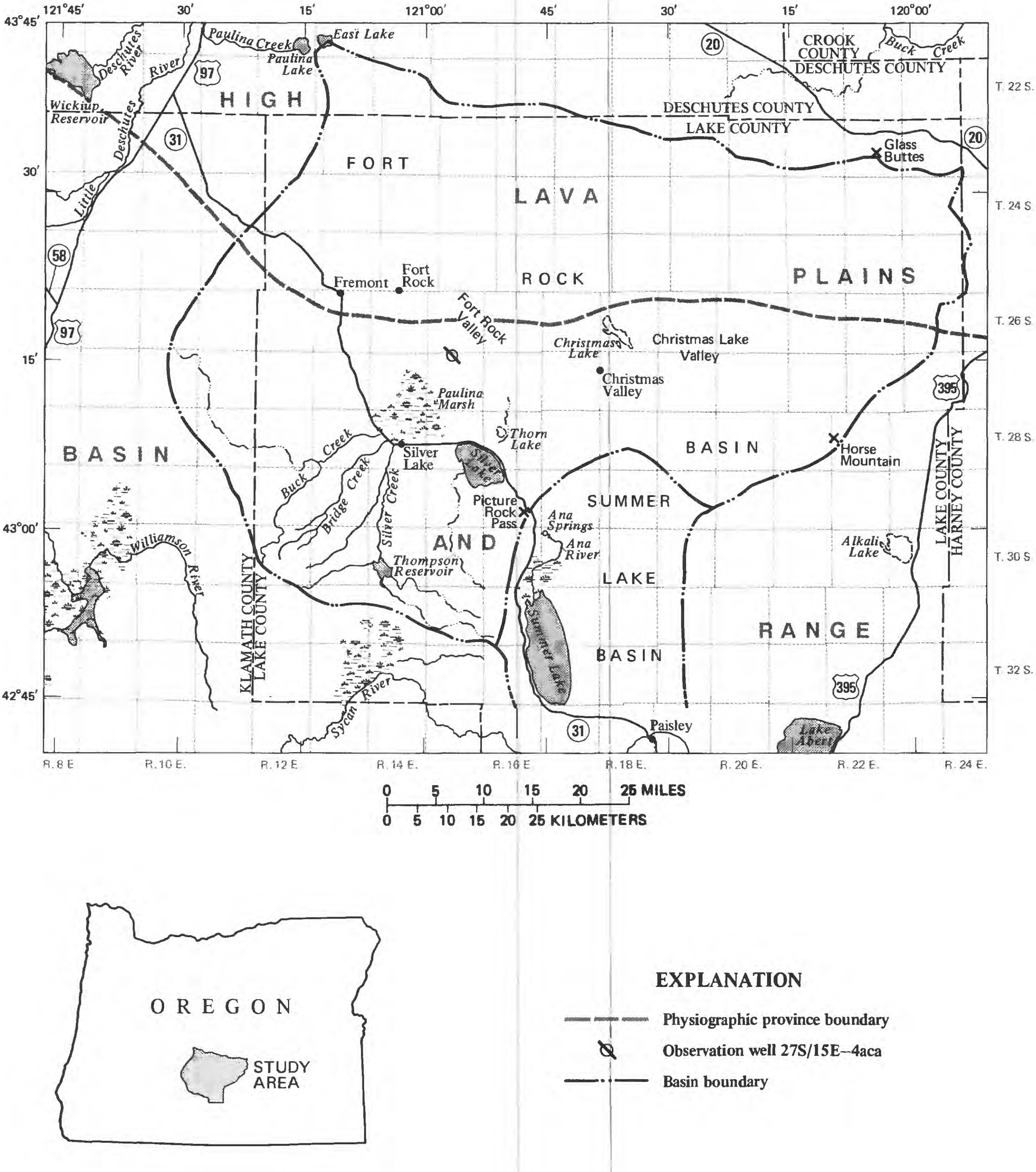


Figure 1.--Location of the the Fort Rock Basin and physiographic provinces.

Previous Studies

The geology and ground-water resources of the Fort Rock Basin and adjacent areas have been studied by several workers. Much of the background material for this report was derived from the two most recent reports concerning the ground-water hydrology of the basin: Hampton (1964) and Miller (1984). Hampton studied the geologic factors that control occurrence and availability of ground water in the basin and Miller did an appraisal of ground-water conditions in the basin. In Miller's report several statistical models are discussed in relation to ground-water appropriation assessment. Miller's 1984 report was later formally published as an Oregon Water Resources Department ground-water report (Miller, 1986).

Early studies in the area include a geologic reconnaissance of southern Oregon by Russell (1884, p. 431-464) and a study of the geology and water resources of south-central Oregon by Waring (1908). A comprehensive study of the ground-water resources of Lake County was done by Trauger (1950). Trauger's work included collection and compilation of information on wells, springs, and chemical quality of ground water and the compilation of a reconnaissance geologic map of Lake County. An estimate of ground water available for irrigation in the Fort Rock Basin was made by Newcomb (1953), and Brown (1957) conducted a detailed hydraulic analysis of Ana Springs.

More recent geologic compilations which include portions of the Fort Rock Basin include work by Walker and others (1967) and Peterson and McIntyre (1970). Walker and others compiled a reconnaissance geologic map of the western half of the Fort Rock Basin, and Peterson and McIntyre made a reconnaissance of the geology and mineral resources of eastern Klamath County and western Lake County; this reconnaissance included just the western margin of the Fort Rock Basin.

The hydrogeology and geochemistry of the lakes in south-central Oregon were studied by Phillips and Van Denburgh (1971).

Acknowledgments

The authors would like to thank Fred Lissner and Donn Miller of OWRD for supplying information on current conditions and general hydrology of the Fort Rock Basin. Especially helpful were unpublished maps of permitted acreage for estimating pumpage distribution and rates.

Well-numbering System

The well- and spring-numbering system used in Oregon is based on the rectangular system for subdivision of public land, and each number indicates the location of the well with respect to township, range, and section. Well number 27S/15E-4aca indicates a well in T. 27 S., R. 15 E., sec. 4. The letters show the location within the section, as shown in figure 2. The first letter (a) represents the quarter section, the second (c) the quarter-quarter section, and the third (a) the quarter-quarter-quarter section.

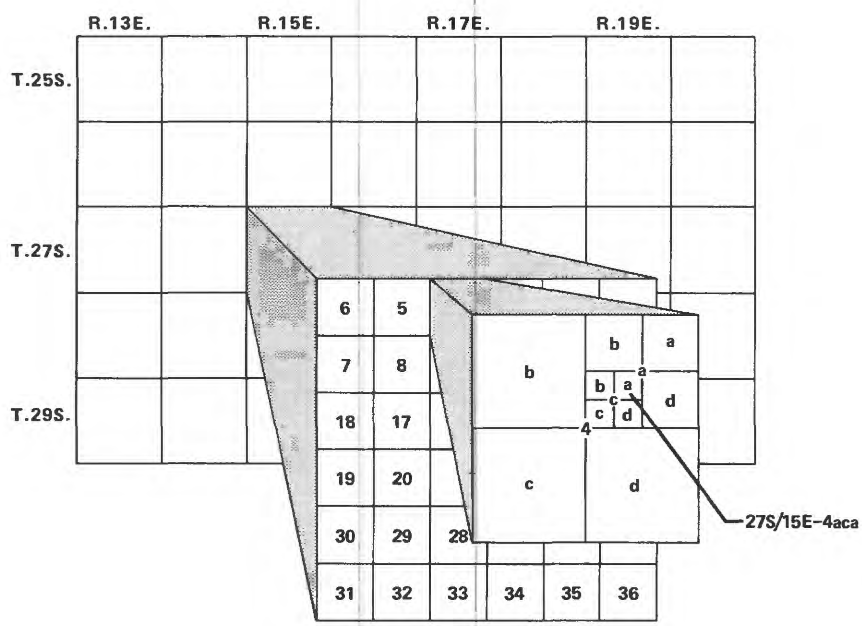


Figure 2.--Well-numbering system.

HYDROGEOLOGIC CHARACTERISTICS

Geologic Formations and Their Water-bearing Characteristics

The geologic units in the Fort Rock Basin range in age from Pliocene to Holocene and include the following from oldest to youngest: Picture Rock Basalt, volcanic rocks of intermediate composition, Fort Rock Formation, Hayes Butte Basalt, Peyerl Tuff, Paulina Basalt, unconsolidated lacustrine and alluvial deposits, and younger basalts (pl. 1). The most important water-bearing formations are the Picture Rock Basalt and the Fort Rock Formation. Most of the geologic units adjacent to the basin are mapped as undifferentiated volcanic rocks.

In general, thicknesses of geologic formations in the basin are poorly known. Exposures provide limited information on thickness and well data are concentrated in the center of the basin. Many wells do not fully penetrate the geologic formations. Estimated thicknesses in this report are from Hampton (1964).

The Picture Rock Basalt was named after Picture Rock Pass, which is on the southern boundary of the basin and forms the divide with the Summer Lake basin. The formation is a thick sequence of basaltic lava flows and interbedded pyroclastic materials. Individual flows of basalt generally are 10 to 50 feet thick, and the thickness of pyroclastic material between flows may reach 250 feet. The formation has not been fully penetrated by wells; its total thickness may be more than 1,000 feet. At Picture Rock Pass the basalts crop out and form the St. Patrick anticline, which trends west-east and is somewhat arcuate to the south (pl. 1). Superimposed on the folding of the basalts is extensive block faulting characteristic of the Basin and Range Province. The northern limb of the anticline dips gently (2 to 5 degrees) north and lies beneath the Fort Rock Basin. The southern limb dips more steeply (7 to 10 degrees) and lies beneath the northern part of Summer Lake basin.

Zones of greatest permeability in the Picture Rock Basalt are generally along tops and bottoms of flows. In some places cinder and scoria zones make up most of the unit's thickness. The center of basalt flows in the unit are generally massive with very few vesicles or open cracks and joints, indicating that vertical permeabilities are probably less than horizontal permeabilities (Hampton, 1964). The formation generally yields adequate quantities of water for irrigation.

Unconformably overlying the Picture Rock Basalt are the volcanic rocks of intermediate composition and the Fort Rock Formation. The volcanic rocks of intermediate composition form two large lava cones in the basin. No wells have been drilled in these rocks, and therefore little is known about their water-bearing characteristics.

The Fort Rock Formation underlies much of the basin floor and is composed largely of interlayered tuff, diatomite, basaltic agglomerate, and basaltic lava (Hampton, 1964). These materials were erupted from volcanic centers within and bordering the area and deposited in basins formed by the Picture Rock Basalt. The eruptions occurred preferentially where the Picture Rock Basalt was faulted. The Fort Rock Formation generally is thickest at the eruptive centers. This formation thickens to more than 1,500 feet to the north (fig. 3) and pinches out to the south against the Picture Rock Basalt. Because of block faulting in the Picture Rock Basalt, the thickness overlying the Fort Rock Formation varies considerably over short distances.

Most of the wells in the Fort Rock Basin are completed in the Fort Rock Formation. The different materials in the formation have different water-bearing characteristics. Furthermore, because approximately 50 drilling companies have drilled in the basin and individual drillers describe materials differently, tracing an individual water-bearing zone from one well to another using drillers' logs is difficult.

The most permeable materials in the formation are "black sands" and "pumice gravels" as defined by drillers. Wells completed in these deposits generally yield quantities of water adequate for irrigation. Less-permeable materials, such as fine-grained tuffs and diatomite, generally yield quantities of water sufficient only for stock or domestic use. Fine and coarse pyroclastic materials are interlayered in the Fort Rock Formation; therefore, vertical permeabilities are assumed to be less than horizontal permeabilities.

The Hayes Butte Basalt unconformably overlies the Fort Rock Formation and crops out principally in upland areas on the west and east of the basin. The basalt flows of the unit generally are from 10 to 30 feet thick. The total thickness generally is less than 100 feet, but near eruptive centers it probably exceeds 1,300 feet. The basalts are faulted, but fault displacement generally is less than 50 feet.

Only a few wells have been drilled in the Hayes Butte Basalt because the basalts are above the water table in much of the area, because soils generally are not favorable for irrigation where the basalts occur, and because surface water is available for irrigation in some areas where the basalts occur. Wells completed in this formation generally yield adequate quantities of water for irrigation.

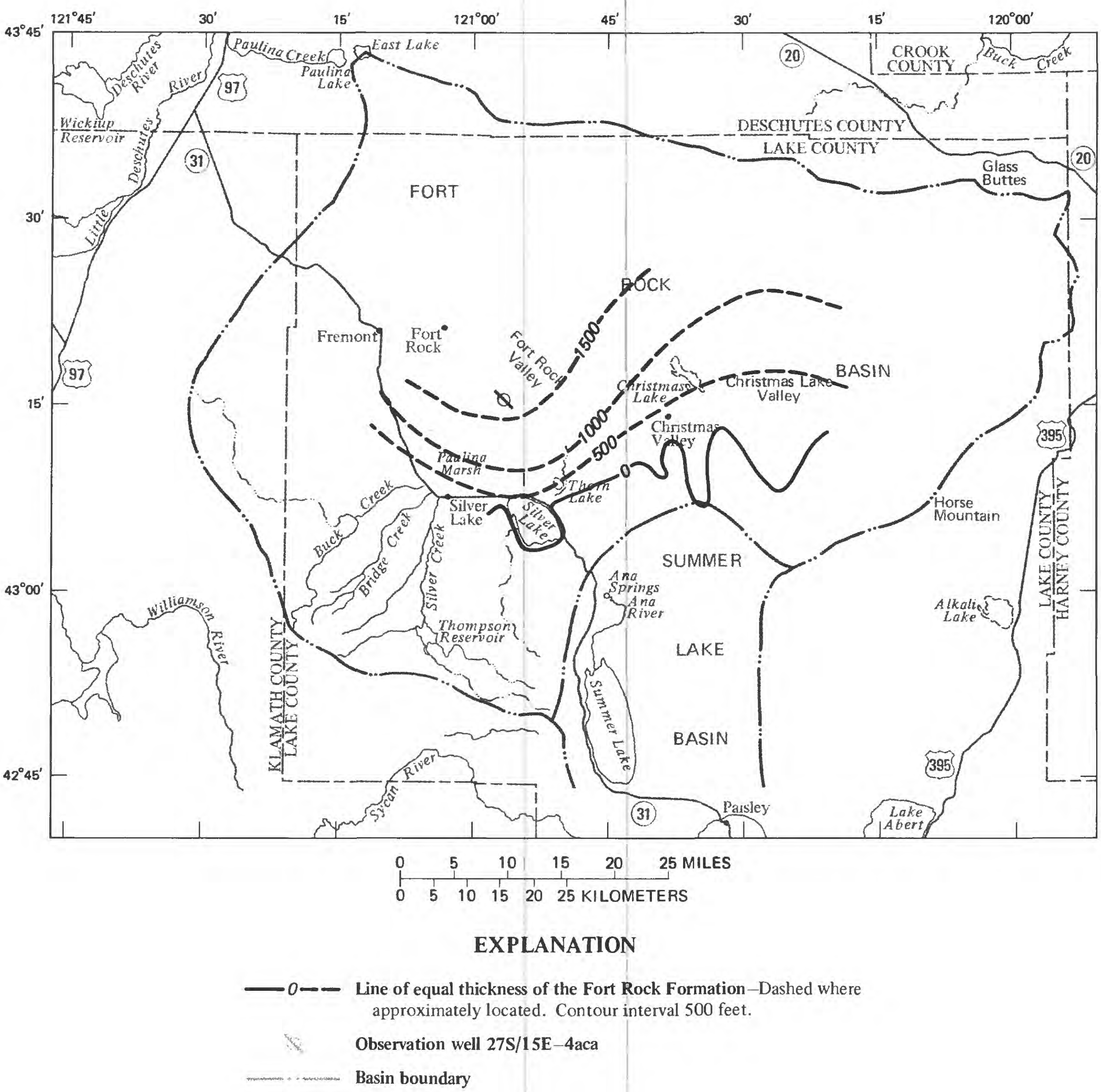


Figure 3.--Thickness of the Fort Rock Formation.

The Peyerl Tuff unconformably overlies the Hayes Butte Basalt and is found in a relatively small area (10 mi^2) on the western edge of the basin floor. It is composed of largely tuffaceous, pumiceous volcanic materials of intermediate composition with a total thickness of approximately 400 feet. These deposits have not been found below the water table, and therefore their water-bearing characteristics are not known.

Unconformably overlying the Peyerl Tuff is the Paulina Basalt, which underlies much of the upland area to the north, within and adjacent to the basin. These basalt flows usually are brecciated slightly on the bottom, dense in the middle, and scoriaceous on the top. Individual flows range in thickness from 5 to 20 feet; and the total thickness of the basalts probably exceeds 1,000 feet near eruptive centers. Minor faulting in the Paulina Basalt has caused displacements of about 5 to 10 feet. Horizontal and vertical permeability of the basalts is good; and where they occur below the water table, they yield adequate quantities of water for irrigation.

Unconsolidated sedimentary deposits form a thin layer over the older volcanic rocks in the basin and include lakebed deposits and associated terrace, spit, bar, and deltaic deposits of Pleistocene age and stream-valley alluvium, playa deposits, and wind-blown sand and silt of Holocene age. These deposits generally occur on the basin floor, are above the water table, and generally are not important water-bearing units.

Basalts of Holocene age, termed "Younger Basalts" by Hampton (1964), occur along the northern border of the basin. These basalts occur as lava flows and cinder cones; they are virtually unweathered and possess almost all of their original flow structures. They are above the water table and therefore are not considered aquifers.

The Ground-water Flow System

Recharge to aquifers in the Fort Rock Basin is derived from local precipitation. Available information suggests that ground-water movement generally is in a southerly direction, with most of the natural discharge occurring either as springs and seeps along the northern edge of, or as underflow to, the Summer Lake basin. Some water also discharges into Paulina Marsh, Silver Lake, and the perennial streams that flow into them. Where water levels are close to the land surface and where phreatophytes exist, water also is discharged by evapotranspiration. Except along its common boundary with the Summer Lake basin, the ground-water divide in the Fort Rock Basin is assumed to correspond to the topographic divide.

The amount of ground water that can be developed in the Fort Rock Basin is limited by the maximum acceptable drawdown in wells and by the maximum acceptable diversion of water from discharge components of the hydrologic system. The "basin yield" is dependent on the geometry of the ground-water system, the permeability distribution within the Fort Rock Basin aquifer system, the hydraulic connection of the ground-water system with discharge areas, and by the distribution of wells and their rates of pumpage.

Before development, the ground-water system in the Fort Rock Basin was in equilibrium; recharge equalled discharge, and average water levels remained stable over the long term. Removal of ground water by pumped wells upset this equilibrium. Pumpage initially was derived from aquifer storage, causing water levels to decline. Water levels will continue to decline until a new equilibrium is reached. This can occur only if pumpage is balanced by a new source of recharge and (or) a reduction in discharge from the ground-water system (Theis, 1940). The only potential source of additional recharge for the basin is the deep percolation of irrigation waters, which is probably small compared to pumpage. Discharge from the basin, in addition to pumpage, occurs by evapotranspiration at and near Paulina Marsh and Silver Lake, from springs and seeps along the southern slopes of the St. Patrick anticline, and as underflow into the Summer Lake basin. Ground-water pumpage from the basin in 1984 is estimated at 92,000 acre-ft/yr (acre-feet per year). If this rate continues, water levels in the basin will continue to decline unless an equal amount of water can be diverted from one or more of the above discharges. The fact that water levels are continuing to decline indicates that this has yet to occur.

The possibility of a new equilibrium being established under present ground-water pumpage, the configuration of water levels if a new equilibrium is reached, and the amount of water diverted from each of the discharge areas represent some of the major information needs at the present time.

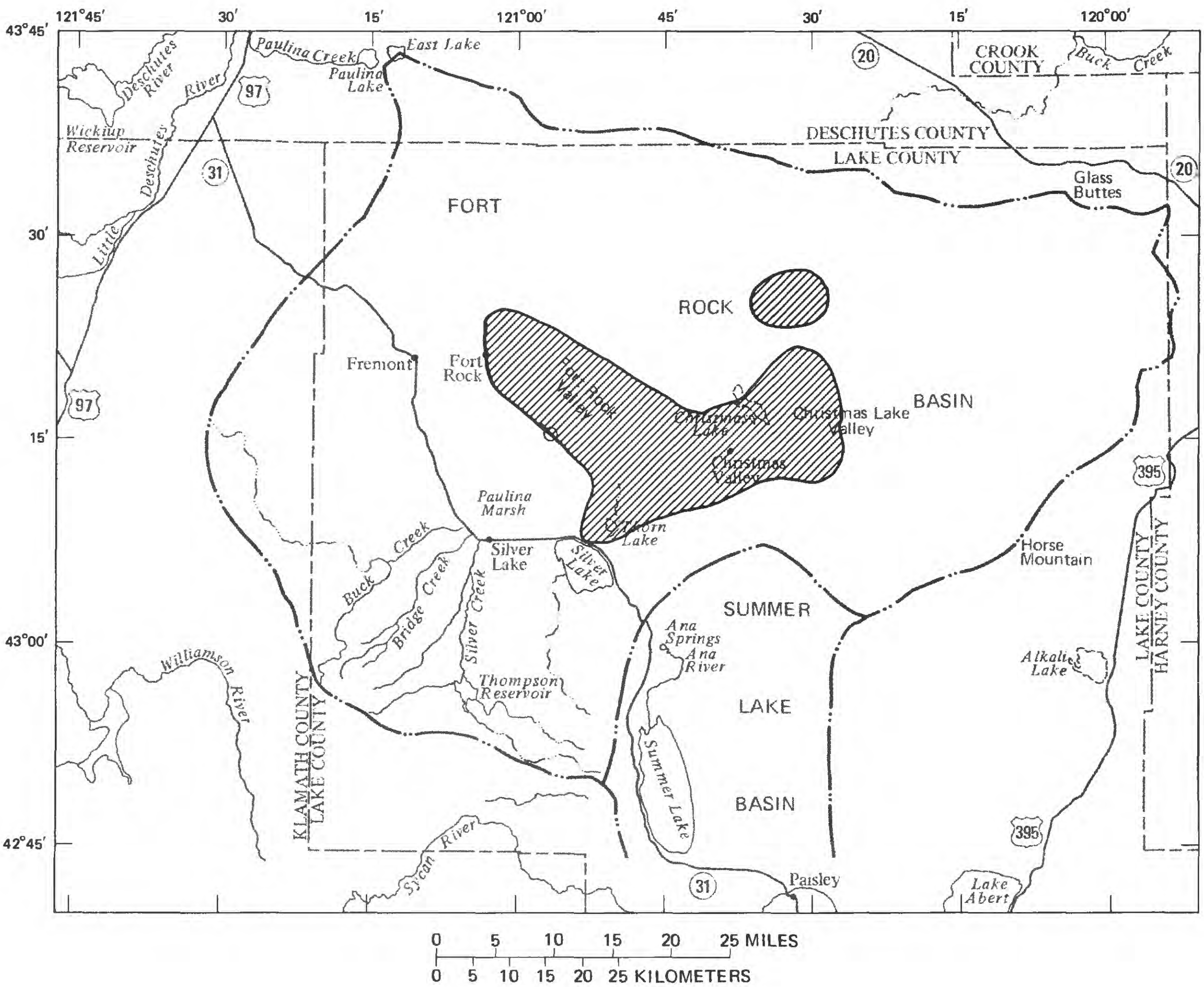
Hydraulic Characteristics

The rocks in the Fort Rock Basin have a wide range of permeabilities because of the nature of their deposition. Materials of the Fort Rock Formation have been described by Hampton (1964) as most permeable several miles from their eruptive centers. Permeability is believed to decrease toward these eruptive centers, where sedimentary materials apparently are poorly sorted and more tightly cemented. The Picture Rock Formation is most permeable along flow tops and bottoms and may have higher permeability caused by faulting.

Estimates of hydraulic conductivity were made for the major water-bearing formations, using specific capacity data from driller's reports. Data from 177 irrigation wells were used to calculate hydraulic conductivity. These wells were selected because they were tested by pumping or bailing rather than by air injection, which is of limited accuracy, and also because irrigation well tests generally are longer in duration and at a greater pumping rate than tests of domestic wells. The selected wells are completed primarily in the Picture Rock Basalt and (or) the Fort Rock Formation; however, a few wells in the Paulina Basalt and the Hayes Butte Basalt may be included in the group. In general, wells in the basin are completed in multiple formations; therefore, it is difficult to evaluate hydraulic conductivity of separate formations. For this analysis, well data from different formations were grouped together. Most of the 177 wells are in the center of the basin (fig. 4); values determined from them are assumed to be representative of the entire basin.

Estimates of horizontal hydraulic conductivity were made by first converting specific-capacity values into values of transmissivity, using a method by Vorhis (1979). Transmissivities then were divided by the uncased or perforated interval to obtain an estimate of hydraulic conductivity for the open interval of each well. More than 50 percent of the wells for which hydraulic conductivities were estimated are from 100 to 399 feet deep (fig. 5a). The frequency distribution of hydraulic conductivities (fig. 5b) shows that nearly 40 percent of the values fall into the 10 to 49 ft/d (feet per day) class. The median value is approximately 40 ft/d. Hydraulic conductivity values were plotted on maps to evaluate the areal variation in the data. In general, estimated values are distributed randomly. The median value of 40 ft/d is considered representative of horizontal hydraulic conductivity for the Picture Rock Basalt and the Fort Rock Formation.

The presence of the permeable flow tops and bottoms and the low-permeability flow centers in the Picture Rock Basalt suggest that vertical hydraulic conductivities are less than horizontal hydraulic conductivities. Interlayering of pyroclastic materials in the Fort Rock Formation also indicates such a relation.



EXPLANATION

Distribution of irrigation wells for which hydraulic conductivity was estimated

Observation well 27S/15E–4aca

Basin boundary

Figure 4.--Areal distribution of wells with specific capacity and construction data for hydraulic conductivity calculations.

Storage coefficients for the aquifers in the basin were based largely on estimates by Miller (1984) and observations reported by drillers. A specific yield of 10 percent, estimated by Miller (1984) based on the "limited decline response of long-term water levels to pumping," is used as an initial estimate for the aquifers in the present study. Drillers have reported drilling through the Fort Rock Formation in some parts of the basin with little water production and, upon reaching the Picture Rock Basalt, finding water levels that rise close to land surface.

Recharge

A knowledge of recharge is needed to help understand and describe the ground-water flow system in the Fort Rock Basin. Estimates of recharge are used to determine ranges of transmissivity and specific yield of aquifer material in the basin. These hydraulic properties, along with a knowledge of the boundaries, must be known reasonably well in order to assess the effect of ground-water development in the basin.

The magnitude of development in the basin depends on the magnitude of hydrologic effects that can be tolerated from pumping. Pumping results in a decrease in the water discharging from the basin, a loss of water from storage, or a combination of both. Pumping does not cause a change in the natural recharge of the area, because there is ample space in the unsaturated aquifer material for any increase in natural recharge that may occur.

The amount of "surplus" precipitation available for recharge to the aquifers is dependent on a number of factors, including the amount of precipitation, temperature, crop growth coefficients, soil moisture holding capacities, vegetation root depths, latitude, and altitude. "Surplus" precipitation is the precipitation that eventually percolates into the ground-water reservoir; the remainder of the precipitation is intercepted by plants, added to soil moisture, evaporated directly, or runs off the land surface.

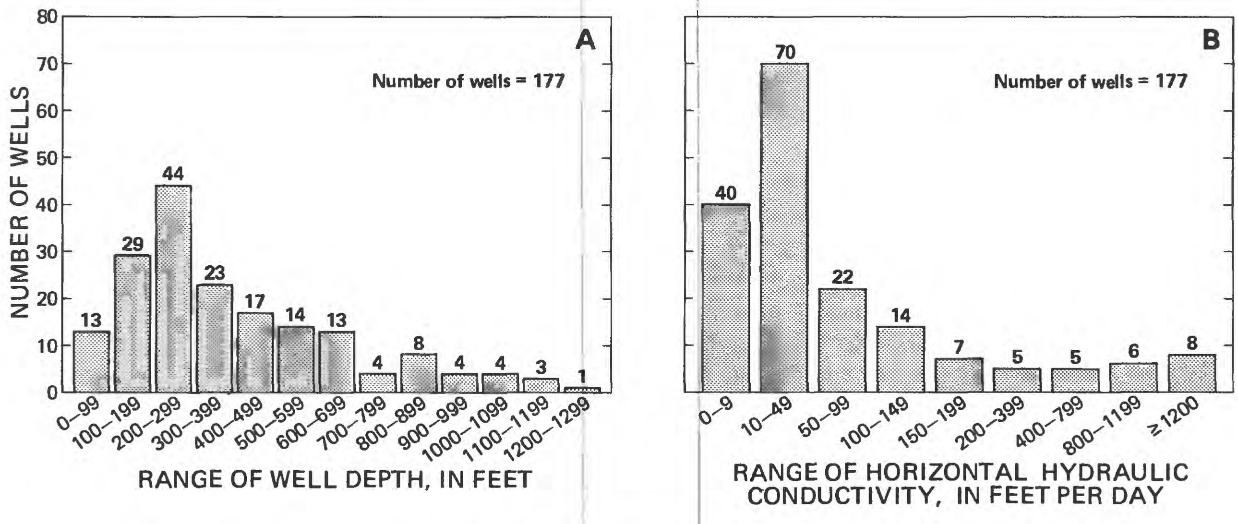


Figure 5.--Frequency distribution of well depths (a) and horizontal hydraulic conductivities (b) for irrigation wells with specific capacity and construction data.

In the Fort Rock Basin, two types of natural vegetation are important in estimating surplus precipitation: open forest (uplands to the west) and shrub-grassland-barrenland (valley floor and eastern parts of the basin). These two vegetation types require different quantities of water for growth and have different root depths. The distribution of surplus precipitation may be dependent largely on the distribution of these natural vegetations; therefore, several different recharge scenarios, both dependent and independent of natural vegetation types, were evaluated in this study.

A reasonable hypothesis is that recharge in the basin is greatest in the upland areas to the west, where precipitation is greatest (20 to 30 inches/year) and where the Paulina and younger basalts are relatively permeable; and recharge is less in the lowlands to the east where precipitation generally is less (10 to 15 inches/year) and permeabilities probably are lower. Although this hypothesis seems plausible, it does not account for temperature, crop growth coefficients, soil-moisture holding capacities, vegetation root depths, or other factors upon which recharge is dependent. To account for these factors a detailed analysis was required.

In an attempt to estimate recharge distribution and rates for the basin, a method developed for a similar study of the Horse Heaven Hills area in Washington (Packard, F. A., U.S. Geological Survey, oral commun., 1985) was used. This method involves the use of a computer program to calculate the amount of surplus precipitation available for recharge after losses to evapotranspiration and runoff are accounted for. The Blaney-Criddle equation (Blaney and Criddle, 1962) is used in the program to estimate losses to evapotranspiration. A modified version of this method has been recently published by Bauer and Vaccaro (1988). Zero runoff was inferred because the Fort Rock Basin is a closed basin.

Data requirements for the analysis include daily temperature and precipitation, crop growth coefficients, soil moisture holding capacities, vegetation root depth, and latitude and altitude of site. Data sources include Franklin and Dyrness, 1969; U.S. Department of Agriculture, 1973 and 1977; Oregon State Water Resources Board, 1969; Pacific Northwest River Basin Commission, 1970; Western Land Grant Universities and Colleges, 1964; and National Weather Service, 1983. Daily temperature and precipitation data were available only for one long-term weather station in the basin at Fremont, Oregon (fig. 1), for the period 1964-77.

The scope of this study precluded a rigorous analysis of recharge for the basin. Therefore a series of calculated surplus precipitation values were developed for a range of soil-moisture capacities, root depths, and soil profiles for two general areas: (1) the open forest uplands and (2) the valley floor shrub-grassland-barrenland (fig. 6; U.S. Department of Agriculture, 1977). The amount of surplus precipitation estimated for the two general areas is summarized below:

> Open Forest--Soil-moisture holding capacities of 0 to 6 inches per foot, maximum root depths of 20 to 60 inches, and a combination of grassland and conifer crop-growth curves resulted in a calculated range of surplus precipitation of 0 to 3 inches, averaging about 1 inch.

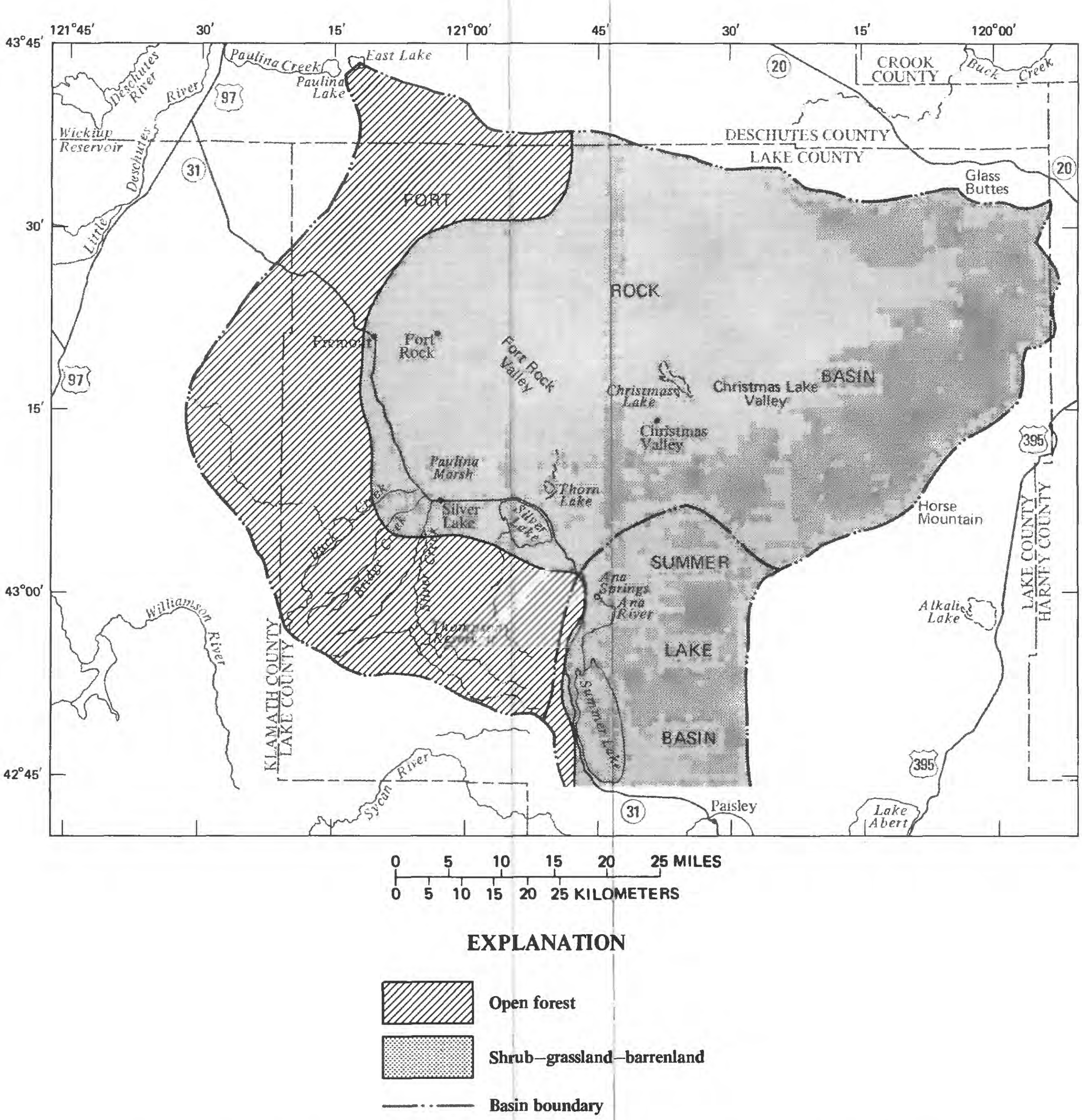


Figure 6.--Open forest and shrub-grassland-barrenland areas. (U.S. Department of Agriculture, 1977)

Shrub-Grassland-Barrenland--Soil-moisture holding capacities of 0 to 3 inches per foot, maximum root depths of 12 to 36 inches, and a combination of grassland and barrenland crop-growth curves resulted in a range of surplus precipitation of 0.5 to 6 inches, averaging about 3 inches.

This generalized analysis provided estimates of recharge for the basin ranging from 53,000 to 799,500 acre-ft/yr; the most plausible estimate is 370,000 acre-ft/yr, based on average surplus precipitation.

The use of only one daily-precipitation and temperature station to represent the entire study area may limit the accuracy of calculated surplus precipitation. The station is located in the extreme western part of the Fort Rock Basin and receives more precipitation than the eastern part of the basin. The open forest area is in the uplands and receives more precipitation than the Fremont area. By using only the Fremont data, recharge calculated for the open forest area probably is underestimated and recharge calculated for the eastern part of the basin probably is overestimated.

Precipitation for the 14-year period averaged about 10.8 inches per year. Reported information (U.S. Weather Bureau, 1964) suggests that the precipitation for the open forest area may be 2 to 3 times greater than that observed for Fremont. Conversely, the eastern part of the basin has reported precipitation of less than half the observed Fremont precipitation. Recharge estimates could not be weighted according to the areal distribution of soil and vegetation types within the open-forest and shrub-grassland-barrenland areas because the information was not available. Areally distributed precipitation, soil, temperature, and vegetation data for discrete areas would provide more accurate calculations of magnitude and distribution of recharge.

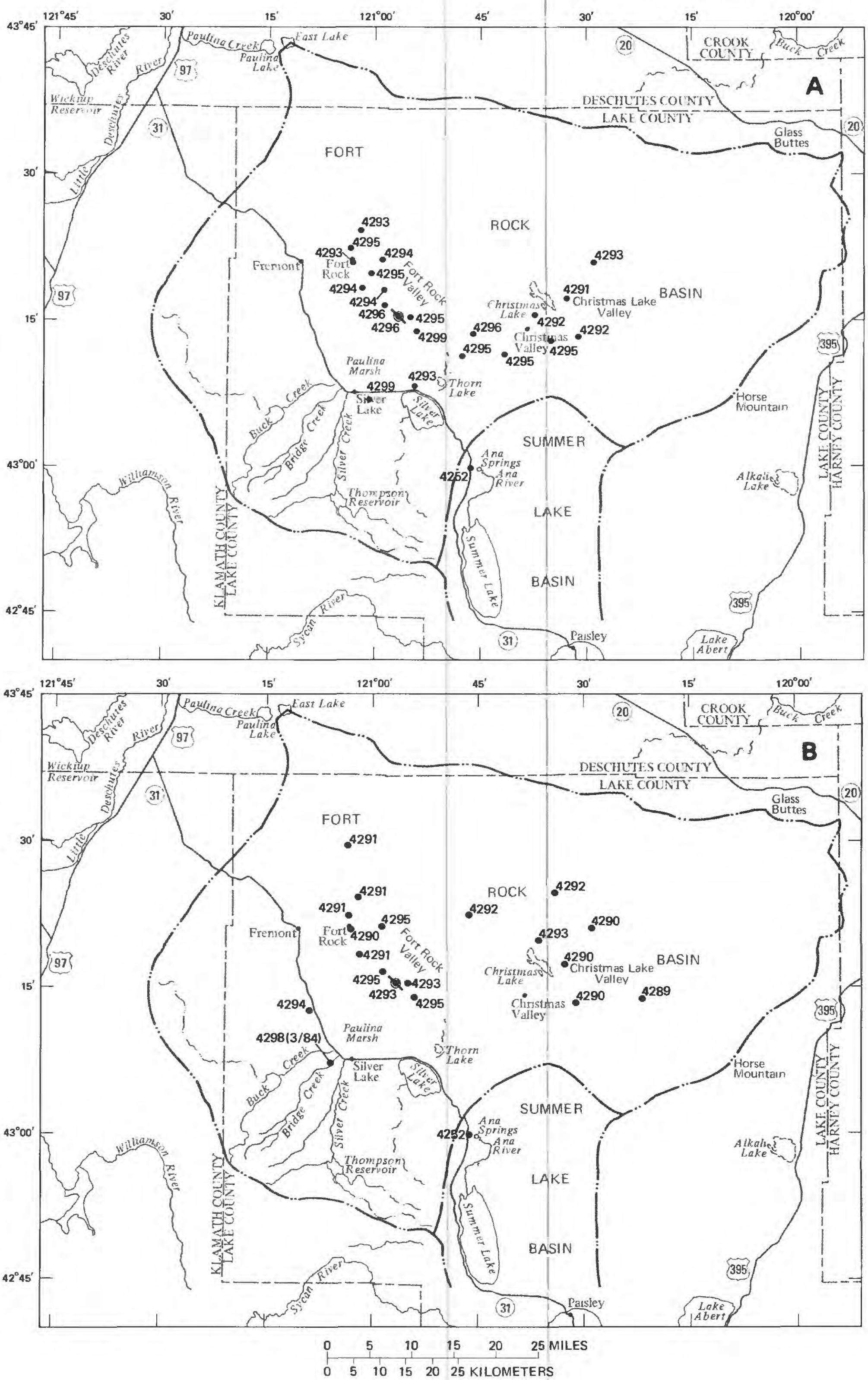
The estimates for recharge, based on the computer program, indicate a higher average annual amount of recharge for the shrub-grassland-barrenland (3 inches) and less for the open forest in the upland areas to the west (1 inch). The distribution of these rates is the reverse of the simple hypothesis presented earlier in this section. Therefore, several recharge scenarios are considered in this study.

Ground-water Movement

Water levels in the Fort Rock Basin indicate that the potentiometric surface in the basin has little relief. Throughout much of the area, water-level altitudes are between 4,290 and 4,295 feet above sea level (fig. 7) and gradients generally are on the order of a few feet over several miles. Near the town of Silver Lake, water-level altitudes are slightly higher (4,298 feet), indicating ground-water flows from uplands in the southwestern part of the basin toward the Paulina Marsh area. In the Summer Lake basin, the altitude of the reservoir at Ana Springs is approximately 4,220 feet and the lake level at Summer Lake is approximately 4,150 feet. Summer Lake, the lowest point within a 70-mile radius, may be the ultimate discharge area for the Fort Rock ground-water flow system.

Ground-water flow is inferred to be from the north, west, and eastern basin divides toward the central part of the Fort Rock Basin and then to the south through the St. Patrick anticline to the Summer Lake basin. Just north of Summer Lake, ground water discharges to the land surface as springs (including Ana Springs), seeps, and flowing wells. Some ground water probably moves as underflow from the Fort Rock Basin into the Summer Lake basin. Ground water also discharges within the Fort Rock Basin by evapotranspiration at and near Paulina Marsh and Silver lake, as well as into perennial streams flowing into the marsh and the lake.

Similar concepts of ground-water flow have been suggested by previous investigations (Waring, 1908; Hampton, 1964; and Phillips and Van Denburgh, 1971; Miller, 1984), for the southwestern part of the basin. They have proposed that surface and ground water flows from the uplands in the



EXPLANATION

- 4293 — Water-level altitude
- Observation well 27S/15E–4aca
- Basin boundary

Figure 7.--Water-level altitudes for observation wells in and adjacent to the Fort Rock Basin: (a) March/April 1965 and (b) March 1983. (From Miller (1984) and U.S. Geological Survey unpublished observation well records.)

southwestern part of the basin into Paulina Marsh, which drains into Silver Lake. Water then leaks through the bottom of Silver Lake because of extensive faulting in the Picture Rock Basalt, flows down-gradient, and contributes to the discharge at Ana Springs.

The St. Patrick anticline forms the topographic divide between the Fort Rock Basin and the Summer Lake basin. This structure, composed of Picture Rock Basalt, has been extensively block faulted by northwest trending faults; its fold axis is perpendicular to the probable north-to-south direction of ground-water flow.

Discharge

In addition to water discharging by evapotranspiration within the Fort Rock Basin and as springs and underflow into the Summer Lake basin, ground-water pumpage for irrigation has become an important component of discharge in the basin.

Discharge of ground water from the Fort Rock Basin to the northern Summer Lake basin and Ana Springs is supported by several factors (Miller, 1984). The most obvious is that the head at Ana Springs is about 70 feet lower than heads in the ground-water reservoir in the Fort Rock Basin, indicating a significant gradient between the two basins. Ground-water quality of the springs is similar to that found in wells in the Fort Rock Basin. Discharge from the springs is nearly constant, suggesting a distant source. Hydrographs and precipitation records presented by Miller (1984) indicate that water levels in the Summer Lake basin have been affected by pumpage in the Fort Rock Basin. Miller also states that flow from Ana Springs has been slightly less in recent years. And finally, the discharge from the springs cannot be explained solely by the extent of their surface drainage areas.

Discharge from the ground-water flow system at Ana Springs is gaged; however, the flows of many other springs, seeps, and flowing wells in the northern Summer Lake basin are not measured. U.S. Geological Survey records indicate that a significant amount of water discharges from these other areas. Average discharge at Ana Springs is approximately 90 ft^3/s (65,000 acre-ft/yr), and an additional 50 ft^3/s (36,000 acre-ft/yr) probably discharges from other springs, seeps, and flowing wells. Total discharge from the northern Summer Lake basin is estimated to be about 140 ft^3/s (101,000 acre-ft/yr).

Evapotranspiration is an important mechanism for ground-water discharge in many of the closed-lake basins of south central Oregon; however, it appears that evapotranspiration is not the most significant component of ground-water discharge in the Fort Rock Basin. The Fort Rock Basin differs from other closed-lake basins in that it does not contain a playa where large amounts of evaporation could occur and the depth to water in much of the basin is 10 feet or more, which generally is too deep to be affected by direct solar evaporation. The area of greatest evaporation in the basin is the Paulina Marsh-Silver Lake area, where the water table is at or above the land surface. Miller (1984) estimated that approximately 50,000 acre-ft/yr of water is discharged from the ground-water system by phreatophytes and assumes a rate of transpiration equal to 0.2 ft/yr in those areas of the basin where depth to water is 50 feet or less. This apparent limited discharge of ground water by evapotranspiration reinforces the concept that most ground water discharges from the basin as subsurface outflow.

Ground-water pumpage for irrigation in the Fort Rock Basin essentially began in 1956 when electricity was introduced into the basin. Prior to that time, ground-water pumpage was an insignificant component of discharge. For the period 1956-71, pumpage increased at a steady rate from 2,000 acre-ft/yr to 17,000 acre-ft/yr. Pumpage increased significantly between 1971 and 1984, when the total for the basin reached 92,000 acre-ft/yr.

Estimates made by Miller (1984) of total ground-water pumpage in the basin for the period 1956 through 1984 are based on a relation between power consumption and volume of ground water pumped; however Miller did not estimate vertical and areal pumpage distribution and rates.

Although pumpage distribution and rates were required for the present study, estimating pumpage distribution and rates from power records was not within the scope of the study. Permit applications were used to make a timely estimate of the vertical and areal distribution of pumpage for the period 1965-83. This period was selected because permit applications could be separated easily by year after 1964. In 1965, total pumpage for the basin was approximately 11,000 acre-ft; and well hydrographs indicate that the aquifer system was not significantly affected by this pumping rate. Pumpage was defined using permit application numbers and priority dates, maps of permitted land, and an assumed average application rate of 2 acre-ft/yr (Miller, 1984). The maximum allowed water application rate is 3 acre-ft/yr. OWRD supplied maps of land for which permits had been issued. The application dates then were used to break down the acreages by year, so that pumpage for each year could be estimated. These were assigned to the appropriate areas of the basin. Then drillers' logs for irrigation wells were used to ascribe pumpage to different vertical zones. Most of the pumpage in the basin is from the uppermost zones (less than 350 feet below land surface). The assumptions required for this procedure included the following:

- o irrigation of an individual acreage started the year of the application date;
- o irrigation of that acreage continued for every year thereafter; and
- o the application rate of water was 2 acre-ft/yr.

These assumptions could result in slight overestimations of pumpages because irrigation of land does not necessarily begin the year that a permit is issued and not all the land is irrigated every year. Also, the application rate varies depending on the amount of precipitation in a given year.

A comparison of total pumpage based on power records (Miller, 1984) and permitted acreage is shown in figure 8. Part of the discrepancy for the period 1980-83 may have occurred because of economic conditions. Although new permits were issued, farmers did not use their additional water rights. For this period, power-record totals probably are more accurate.

In general, total pumpages derived from power records are more accurate than those derived from permitted acreage. Consequently, the distributed pumpage values derived from permitted acreage were adjusted on a yearly basis, based on a ratio between Miller's estimates and permitted acreage totals. With this adjustment to the permitted-acreage estimates, the total pumpage estimates for the basin agree with the power-record derived total pumpages;

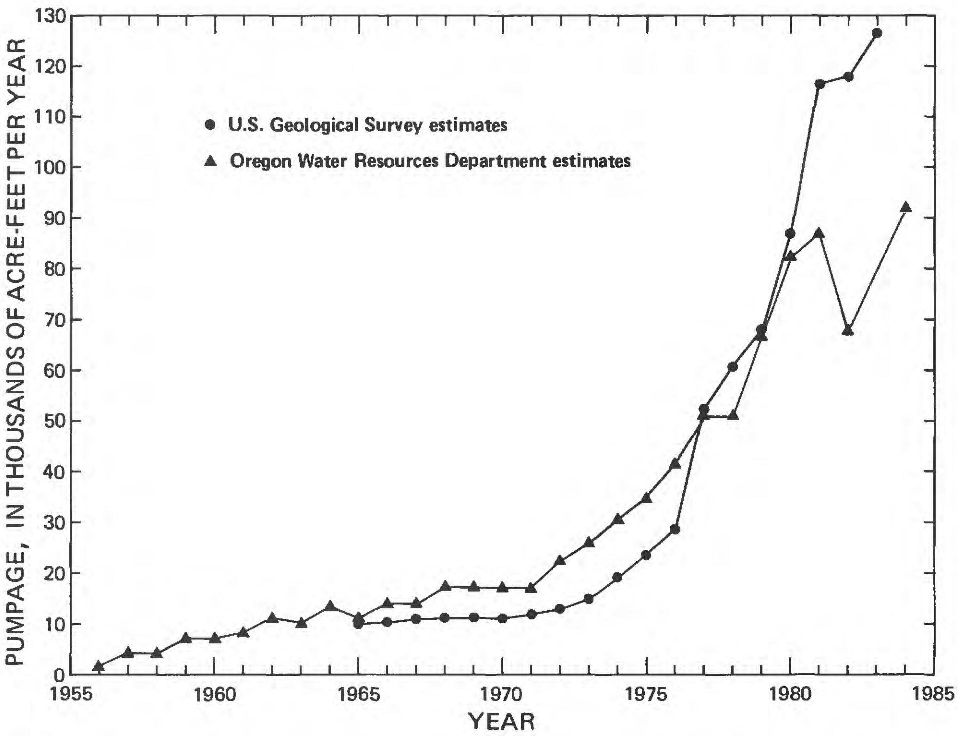


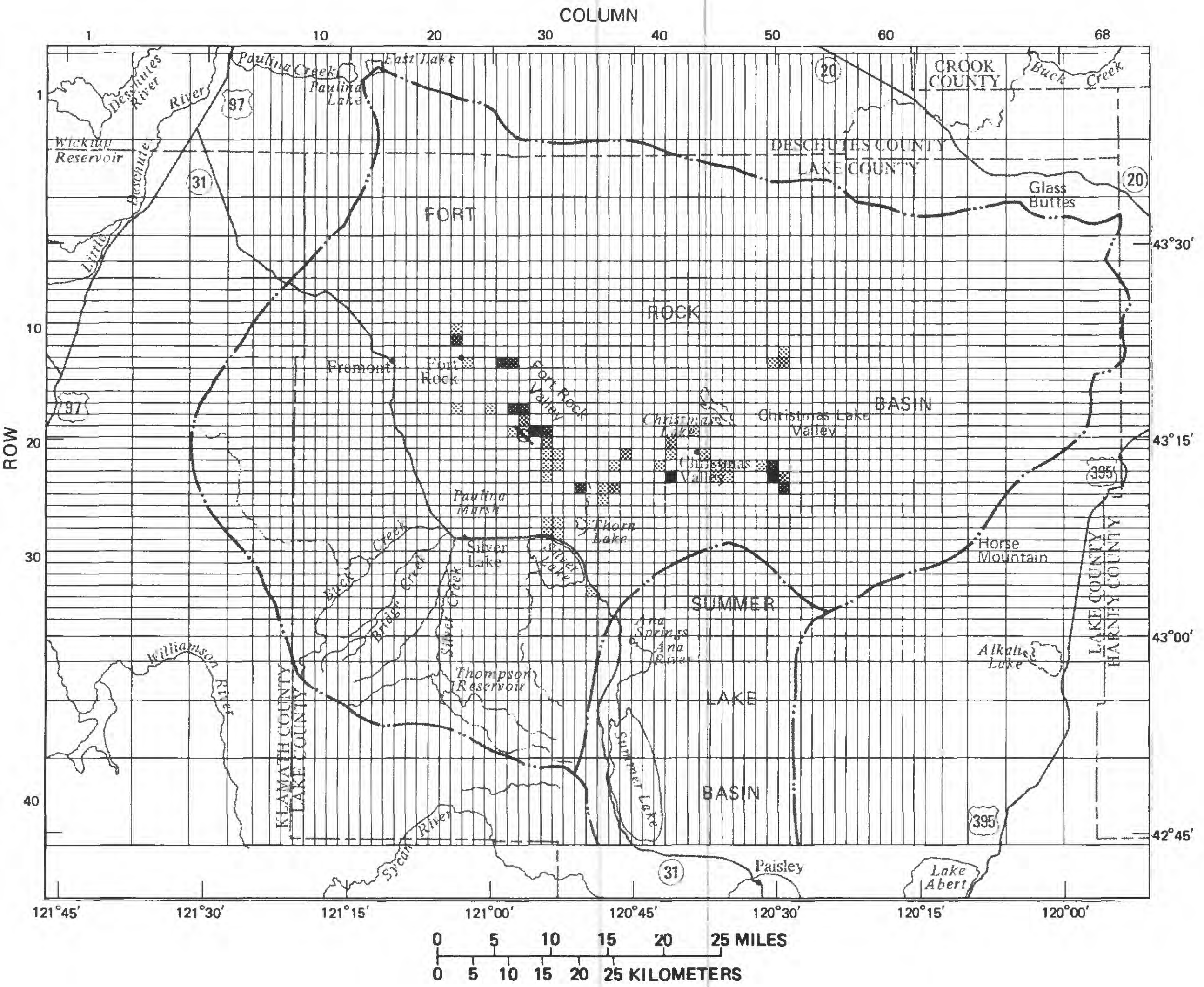
Figure 8.--Comparison of total annual ground-water pumpage estimates for the Fort Rock Basin based on power records (Miller, 1984; D.W., Miller, Oregon Water Resources Department, oral commun., 1985) and permitted acreage.

and the distributed rates fluctuate in proportion to the power records. Pumpage distribution for 1966 and 1983 are shown in figures 9 and 10, respectively, based on corrected permitted-acreage estimates.

Long-term Water-level Changes

Prior to ground-water withdrawals in the Fort Rock Basin, discharge from the basin equalled recharge on a long-term annual basis, and water levels were stable except for seasonal fluctuations. Pumping caused discharge to exceed recharge; and, because natural recharge is assumed to be relatively constant on a long-term basis, water-level declines induced by pumpage for the most part are independent of natural recharge. Natural recharge does not represent a new source of water to offset the additional discharge. Water-level declines induced by pumpage will continue unless a reduction in natural discharge or a new source of recharge occurs that equals the pumpage.

Although ground-water pumpage in the basin began in 1956 and began to increase significantly in 1971, hydrographs of observation wells do not show significant declines until 1976. Before 1976, water levels fluctuated in response to natural conditions. Since 1976, water levels have declined at an average rate up to 0.5 ft/yr (Miller, 1984, p. 44). The "Parks well" (27S/15E-4aca; fig. 7) is a typical well in the Fort Rock Basin. The well is 257 feet deep, is in the Fort Rock Valley, and is completed in cinder beds and lava of the Fort Rock Formation. The water level in this well has been



EXPLANATION

Ground-water pumpage in acre-feet per year

- 0
- 1–230
- 231–460
- 461–690
- 691–920
- Model grid cell
- Basin boundary
- Observation well 27S/15E–4aca

Figure 9.--Areal distribution of ground-water pumpage in the Fort Rock Basin, 1966, estimated from permitted acreage and an average application rate of 2 acre-feet per year.

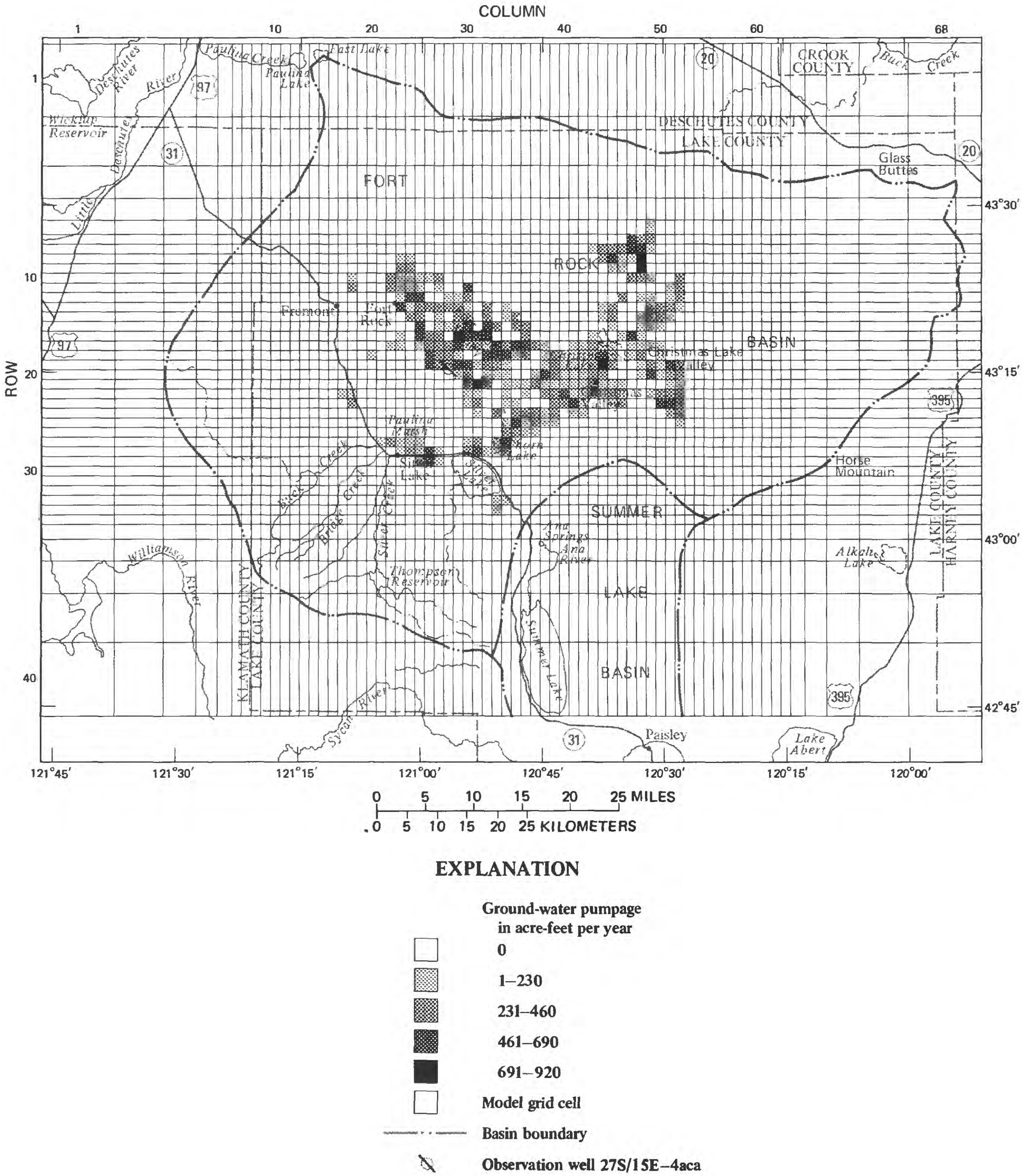


Figure 10.--Areal distribution of ground-water pumpage in the Fort Rock Basin, 1983, estimated from permitted acreage and an average application rate of 2 acre-feet per year.

measured on a regular basis for the past 50 years (fig. 11). From 1976 to the present (1984), water levels in the well have declined approximately 2.4 feet, at a rate of approximately 0.3 ft/yr. The Parks well was used as a reference well for transient (post-development) model simulations in this study.

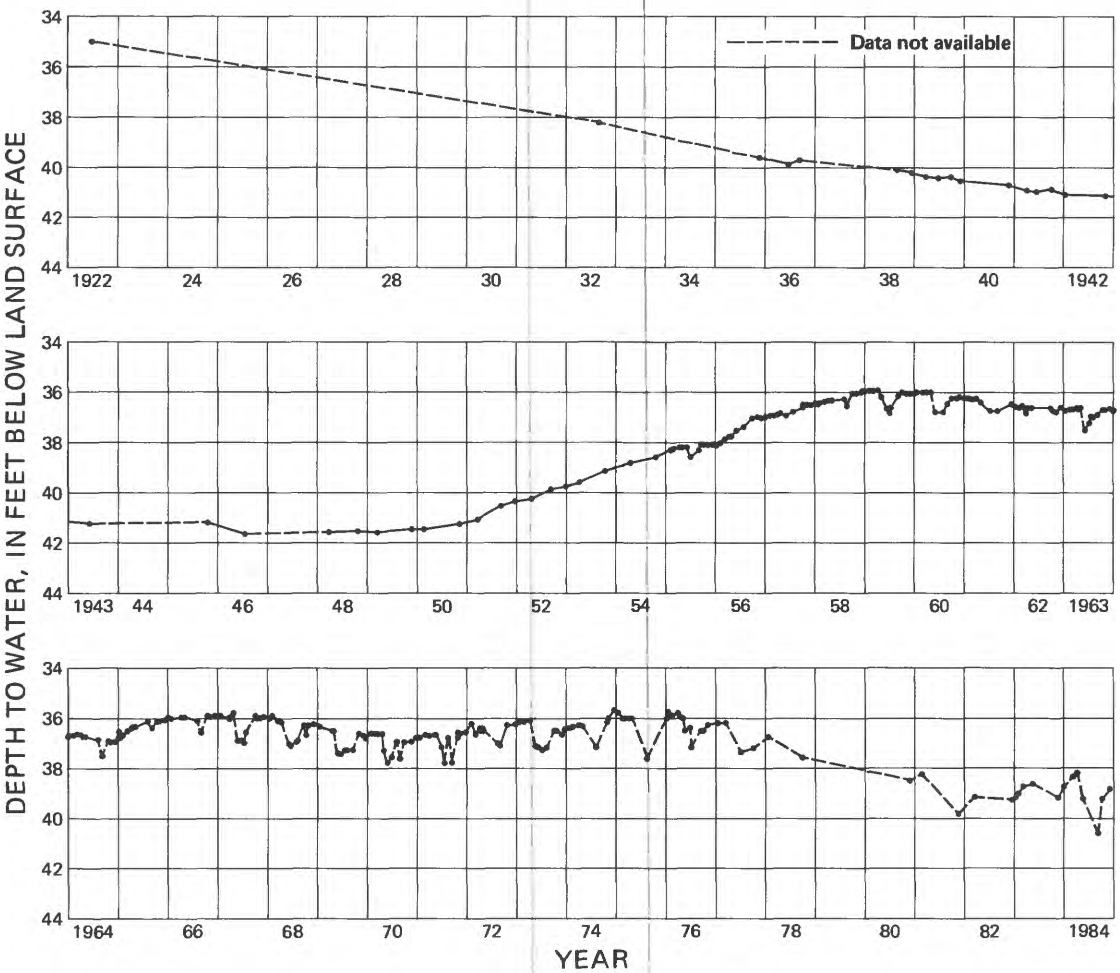


Figure 11.--Water levels at the Parks well (27S/15E-4aca) 1922-84. (From Miller, 1986.)

Precipitation records indicate that for the period 1920 to present, the cumulative departure of annual precipitation from mean annual precipitation generally has increased since 1940 (Miller, 1984, p. 46). A period of above-average precipitation probably would cause recharge to the aquifers to increase. Consequently, the water-levels may have declined even more than reported if precipitation had not been increasing. In this study, an average recharge rate for the period 1964-77 was used. In a few areas of the basin, water levels in shallow wells have risen due to irrigation-return flow and possibly to trends in precipitation.

Water-level declines and a decrease in spring flow would occur in the Summer Lake basin if there were a direct hydraulic connection between it and the Fort Rock Basin. As mentioned earlier, the water level in an observation well in the northern Summer Lake basin has declined and spring flow at Ana Springs has decreased slightly (Miller, 1984). The effect on water availability in an adjacent basin may be the most important consideration in limiting development in the Fort Rock Basin.

ADEQUACY OF DATA AND NUMERICAL SIMULATION

A numerical simulation is an appropriate method of evaluating the adequacy of available data for defining additional data needs. This approach allows the simulation of the complex interaction between ground-water pumpage, water-level declines, and decreases in ground-water discharge. The hydrogeologic information needed to determine the response of the ground-water system to pumpage, and thus needed for model construction, includes thickness and extent of hydrogeologic units, spatial distribution of hydraulic conductivity and storage coefficient, the hydraulic connection between the Fort Rock Basin and adjacent areas, the temporal-spatial distribution of water levels, the locations and rates of ground-water pumpage, and distribution and rates of recharge. The only factors known with any certainty are the distribution and rates of pumpage and the temporal-spatial distribution of water levels. Model analysis was designed to gain a greater understanding of the flow system and to determine which parameter(s) need to be further refined.

Model Construction and Analysis

A three-dimensional flow model was constructed to simulate ground-water movement in the basin and ground-water discharge from the basin under predevelopment conditions. The computer program used is discussed in detail by McDonald and Harbaugh (1984). The model was constructed by using the best initial estimates for all of the input parameters. Water levels and discharge simulated by the model were compared to observed values to evaluate the reasonableness of the initial estimates of recharge, vertical and horizontal hydraulic conductivity, and storage.

The Fort Rock Basin model grid, composed of 40 rows by 68 columns, encompasses over 6,800 mi^2 (fig. 12). The axes of the model grid were aligned in a north-south, east-west direction parallel to the predominant axes of the basin. The principal area of pumping was discretized into 1-square-mile grid cells. The area of the grid cells was expanded with distance from the principal area of pumping. The model area includes part of the Summer Lake basin to account for discharge from the Fort Rock Basin into the Summer Lake basin as springs and as underflow.

The model consists of four layers, representing a total thickness of about 2,500 feet. In the upper layer of the model, layer 1, the aquifer system is unconfined and the average layer thickness is 350 feet. Layers 2, 3, and 4 are confined and represent thicknesses of 350, 800, and 1,000 feet, respectively. The flow system is discretized vertically to provide a better representation of the three-dimensional movement of water in the basin. Thickness of the four layers is based on the open intervals of irrigation wells. The bottom boundary is assumed to be impermeable. Spring discharge from layer 1 was simulated in the model by drains at locations corresponding to major springs and flowing wells.

The northern Fort Rock, east and west Fort Rock and Summer Lake, and southern Summer Lake drainage basin divides were simulated as no-flow boundaries. The model area does not include the southern discharge point for

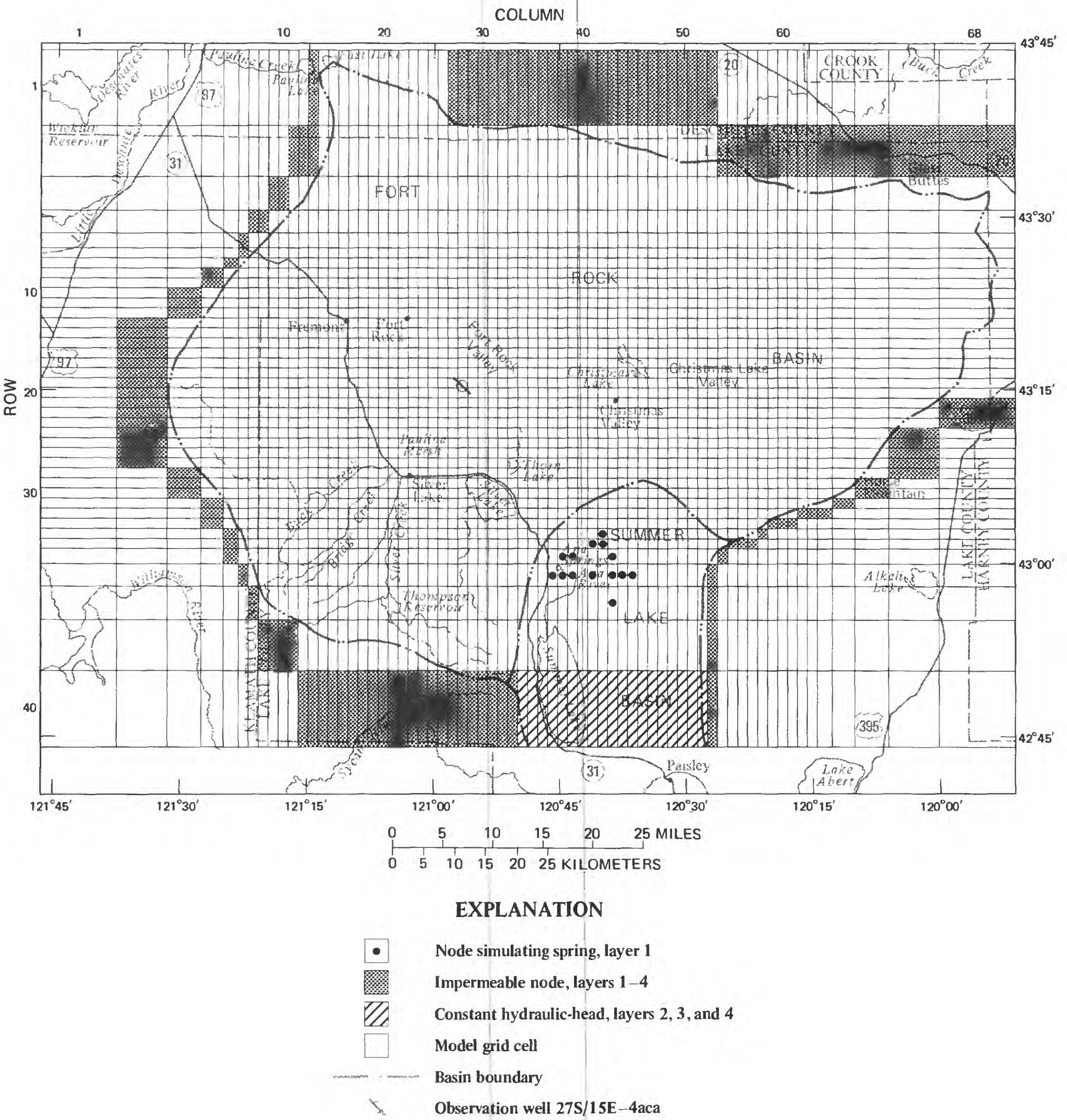
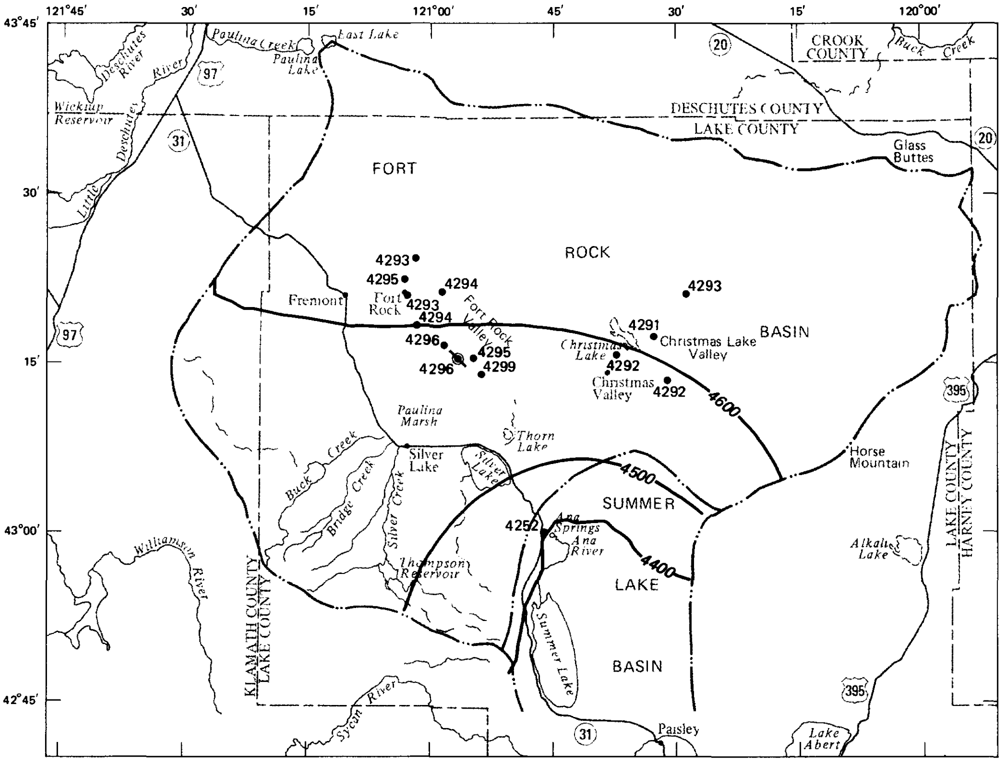


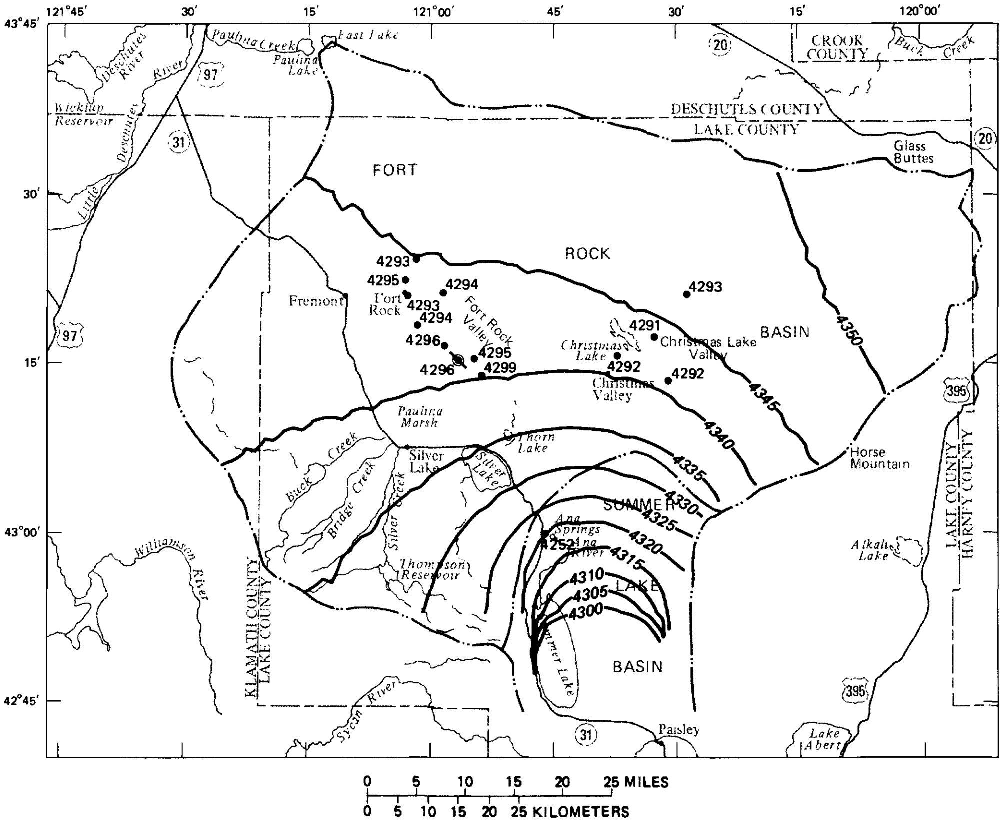
Figure 12.--Finite-difference grid of model area including boundary conditions.

the regional flow system. Constant hydraulic heads, based on water levels reported by drillers, were incorporated into layers 2, 3, and 4 on the southern edge of the model to simulate underflow or the subsurface discharge of water.

Measured heads and drawdowns were compared with simulated heads and drawdowns under a range of hydraulic conductivity, specific yield, and recharge values in steady-state and transient sensitivity analyses. Only layer 1 contained sufficient measured data for meaningful comparisons. Thirteen observation wells in the basin have open intervals at depths corresponding to layer 1 and provided long-term (1965-83) measured head (fig. 13) and drawdown data. For illustrative and discussion purposes, the following sections focus on layer 1.

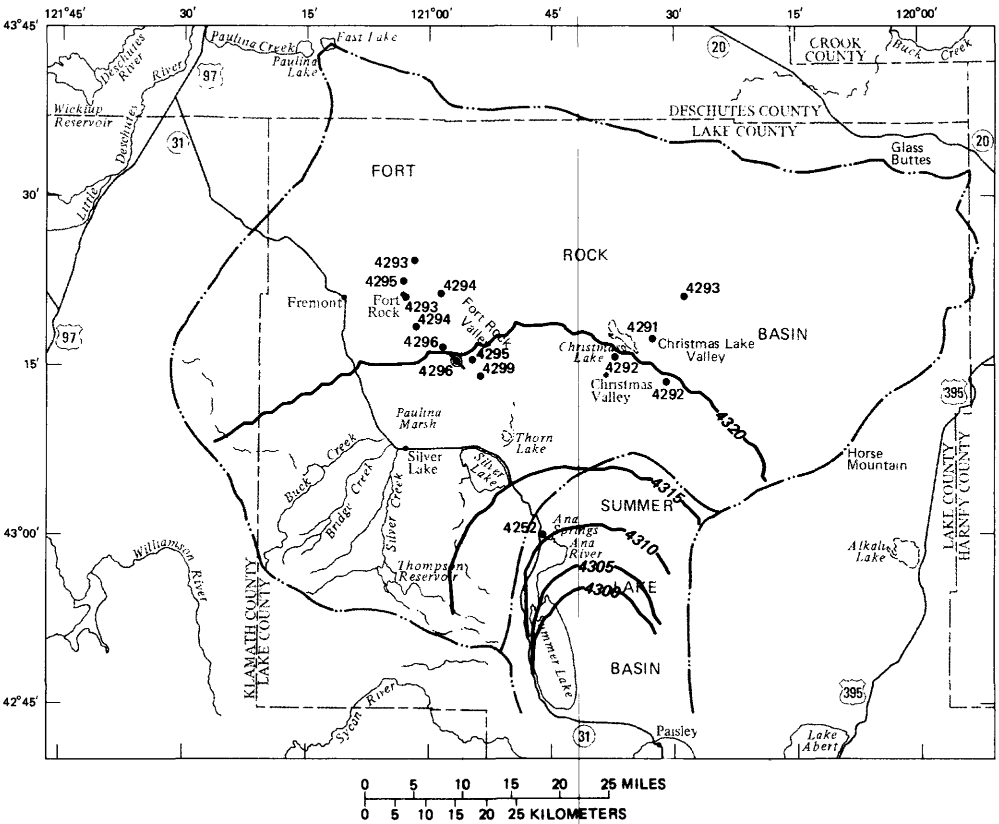


A. Baseline parameter values



B. Baseline values of hydraulic conductivity times 10

Figure 13.--Computed and observed heads for predevelopment conditions (layer 1), relative to adjustments in hydraulic conductivity.



C. **Baseline values of hydraulic conductivity times 100**

EXPLANATION

—*4325*— **Potentiometric contour**–Shows altitude of computed steady-state head, layer 1. Contour interval 5 and 100 feet. Datum is sea level.

•4295 **Data point**–Number is altitude of measured head in selected observation wells (March/April 1965). Heads shown only for wells with data for March/April 1965 and March/April 1983. Datum is sea level.

Observation well 27S/15E–4aca

—··— **Basin boundary**

Figure 13.--Computed and observed heads for predevelopment conditions (layer 1), relative to adjustments in hydraulic conductivity--Continued.

An initial average horizontal hydraulic conductivity of 40 ft/d was used for each layer in the model. This is a median value based on specific capacity data. No information was available concerning the magnitude of vertical hydraulic conductivity; but given the lithology and depositional nature of the deposits, the ratio of vertical to horizontal hydraulic conductivity probably is 1 to 10 or less. Although some local variation in this ratio could be expected, it probably is fairly uniform on a regional basis. A vertical hydraulic conductivity of 4 ft/d was used in the initial model. Finally, a value for recharge of 370,000 acre-ft/yr was used assuming the distribution from the deep percolation model results of 1 inch per year recharge in the conifer-shrub areas and 3 inches per year in shrub-grassland-barrenland areas.

Predevelopment Conditions

Water levels and spring discharge as simulated by the model for predevelopment conditions were considerably higher and greater, respectively, than those observed. Computed and observed heads for the initial parameter estimates are shown in figure 13a. In addition to contour plots, computed and observed heads were compared using root-mean-squared-error (RMS):

$$\text{RMS} = \left[\Sigma(\text{observed-computed heads})^2/(\text{number of observations})\right]^{1/2}.$$

The RMS between observed and computed heads for the initial parameter estimates is 308 feet and the computed spring discharge is 356 ft^3/s, as compared to total estimated spring discharge of 140 ft^3/s (table 1).

The lack of a good fit between simulated and observed water levels and discharge indicates that estimates of one or more of the model parameters are in error or that the conceptualization of the ground-water system needs refinement. Simulated water levels are several hundred feet above land surface. These water levels can be lowered by either increasing hydraulic conductivity or reducing recharge or adjusting both simultaneously. It also is possible that the boundaries to the ground-water flow system are not as restrictive as those simulated in the model. Less restrictive boundaries would allow greater discharge from the basin and possibly lower water levels.

To evaluate the sensitivity of the model to parameter adjustments, the value of each parameter was increased or decreased separately in order to observe which values improved the model's fit with observed data and by how much. Values for parameters used to construct the initial model are referred to as "baseline values" and the initial model will be referred to hereafter as the "baseline model".

Decreasing vertical and horizontal hydraulic conductivity from the baseline value while maintaining a ratio of vertical to horizontal hydraulic conductivity of 1:10 results in an RMS and spring discharge even greater than the baseline value. Therefore, the lower limit established for vertical and horizontal hydraulic conductivity was considered to be the initial estimate of 4 and 40 feet per day, respectively. Six model simulations were made, increasing hydraulic conductivity values while maintaining the ratio of 1:10 between vertical and horizontal hydraulic conductivity values. The maximum increase in conductivity was two orders of magnitude greater than the baseline value. Values ranging from 16 to 400 feet per day for vertical hydraulic conductivity and from 160 to 4,000 feet per day for horizontal conductivity were simulated. Sensitivity of the model to these changes is shown in figure 14a and table 1. The model was very sensitive to changes in hydraulic conductivity up to one order of magnitude; through a one-order magnitude increase, the RMS and spring discharge were reduced by 259 feet and 161 ft^3/s to 49 feet and 195 ft^3/s, compared to the baseline values of 308 feet and 356 ft^3/s. These changes allowed the model to match initial or natural conditions far more closely (fig. 13b). From the one-order magnitude increase through the second order increase the fit between simulated and observed values improved, but by much less than before. The RMS was reduced below the first order

Table 1.--Variations in root-mean squared error between observed and computed predevelopment heads, transient computed water-level declines and drawdown, and spring discharge

["--" = values are omitted where a heading is not applicable or where a predevelopment or transient simulation was not made; ft = feet; ft^3/s = cubic feet per second; acre-ft/yr = acre-feet per year. Transient simulations were made only for recharge rates between approximately 140,000 and 370,000 acre-ft/yr]

Model simulations	RMS[1/] for predevelopment versus observed head, in ft	Water-level decline, in ft/yr 1966-1983	Computed Drawdown[2/], in ft 1966	Computed Drawdown[2/], in ft 1983	Spring discharge, in ft^3/s Steady state	Spring discharge, in ft^3/s 1966	Spring discharge, in ft^3/s 1983	Reduction in, spring discharge in ft^3/s Steady state to 1983	Recharge (acre-ft /yr)
Baseline model	308	0.46	0.98	8.87	356	356	353	3	370,000
Specific yield, layer 1:									
0.2	--	.37	.65	6.89	--	356	355	1	370,000
0.01	--	1.11	2.06	20.90	--	356	338	18	370,000
Vertical and horizontal hydraulic conductivity:									
Baseline values x 4.00	87	--	--	--	225	--	--	--	370,000
Baseline values x 6.25	64	.16	.32	2.99	207	207	206	1	370,000
Baseline values x 10.00	49	.10	.31	2.05	195	195	194	1	370,000
Baseline values x 15.00	41	--	--	--	188	--	--	--	370,000
Baseline values x 25.00	34	.08	.31	1.72	182	182	180	2	370,000
Baseline values x 100.00	27	.08	.31	1.62	175	174	172	3	370,000
Vertical hydraulic conductivity:									
Baseline value x 0.1	327	.44	1.10	8.61	339	339	336	3	370,000
Baseline value x 10.0	299	.54	1.10	10.35	355	355	352	3	370,000
Baseline recharge:									
Baseline values x 0.5	137	.48	1.02	9.16	201	202	199	2	186,000
Baseline values x .25	60	--	--	--	134	--	--	--	93,000
Baseline values x .125	28	--	--	--	106	--	--	--	47,000
Inverted baseline recharge:									
Inverted baseline values	214	.48	1.01	9.11	263	262	260	3	269,000
Inverted baseline values x 0.5	89	.49	1.18	9.56	156	156	152	4	134,000
Inverted baseline values x .25	42	--	--	--	117	--	--	--	67,000
Inverted baseline values x .125	18	--	--	--	97	--	--	--	34,000
Uniform recharge:									
6 inches	795	--	--	--	825	--	--	--	962,000
4 inches	537	--	--	--	568	--	--	--	641,000
2 inches	262	.47	1.00	8.97	310	310	307	3	321,000
1 inch	114	.49	1.02	9.28	180	180	177	3	160,000
0.5 inches	51	--	--	--	126	--	--	--	80,000
Vertical and horizontal hydraulic conductivity St. Patrick anticline, layers 1-4:									
Baseline values x 0.1	538	.46	.98	8.72	355	355	353	2	370,000
Baseline values x 10.0	262	.43	.93	8.31	348	348	346	2	370,000
Vertical and horizontal hydraulic conductivity (K) and storage coefficient (S):									
K x 100 and S = 0.2	--	.08	.32	1.66	--	174	172	3	370,000
K x 100 and S = 0.01	--	.08	.31	1.59	--	174	172	3	370,000

1/ RMS = Root-mean squared error = $(\Sigma(\text{observed} - \text{computed heads})^2 / (\text{number of observations}))^{1/2}$

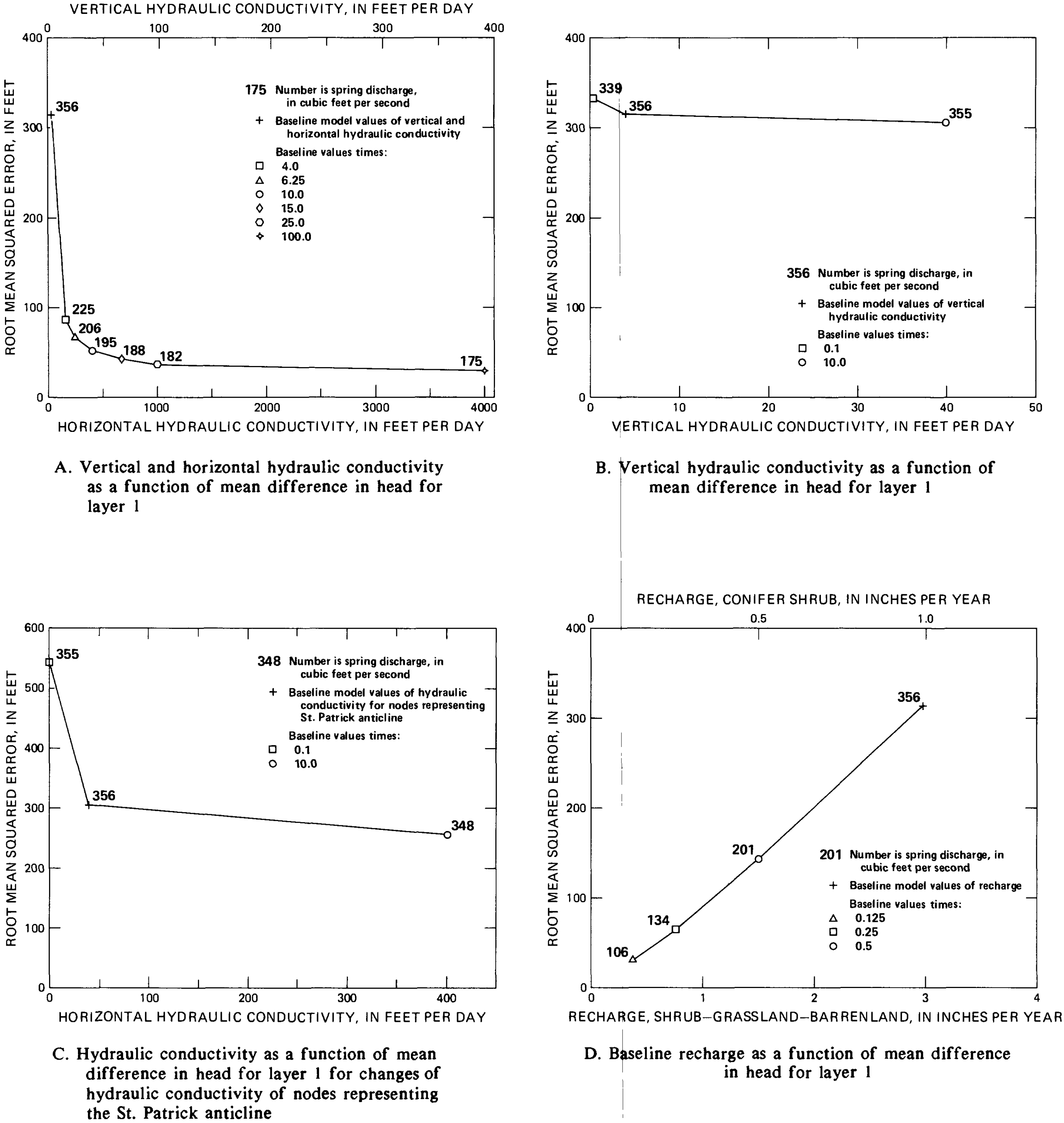
2/ Based on node exhibiting maximum drawdown.

increase by only 22 feet and the spring discharge was reduced by only an additional 20 ft^3/s. RMS and spring discharge were 27 ft and 175 ft^3/s (table 1) with hydraulic conductivities 100 times the baseline value (fig. 13c.)

Given the lack of knowledge concerning thickness and the possible variation in permeability indicated by the results of the specific capacity tests, it is possible that baseline values of horizontal hydraulic conductivity could be in error by as much as two orders of magnitude. The reasonableness of the initial estimate of vertical hydraulic conductivity was less certain because of a lack of supporting data. The sensitivity of the simulated heads and spring discharge to changes in vertical hydraulic conductivity therefore was evaluated using two simulations in which the ratio of vertical to horizontal hydraulic conductivity was varied. The vertical hydraulic conductivity was increased one order of magnitude from the baseline value for one simulation, resulting in a ratio of 1:1, and was decreased an order of magnitude, resulting in a ratio of 1:100, for the other simulation. These simulations showed that the computed heads and spring discharge are relatively insensitive to changes in the ratio or in the vertical hydraulic conductivity (table 1 and fig. 14b).

The sensitivity of the model to horizontal hydraulic conductivity or simultaneous changes in vertical and horizontal hydraulic conductivity may be related to the geometry of the flow system and (or) the hydraulic parameters. The vertical and horizontal hydraulic conductivity are used with thickness data to compute transmissivity and vertical leakage coefficient, which influence the ability of aquifers to transmit water from recharge areas to discharge areas. Increased vertical and horizontal hydraulic conductivity results in lower computed heads in the model as the resistance to flow is decreased. Increasing the hydraulic conductivity decreases the hydraulic head, which controls the spring discharge, and the outflow of water from the springs decreases in the model.

The effects of St. Patrick anticline on the ground-water flow system were uncertain. Faulting and structural deformation associated with the anticline may or may not affect ground-water movement through the anticline. The initial treatment of the anticline for the baseline model was to uniformly distribute hydraulic conductivity across the modeled area, not explicitly modeling the anticline. The other possible effects were evaluated using two sensitivity simulations. The ratio of vertical to horizontal hydraulic conductivity of 1:10 for the nodes representing the anticline was retained in both simulations. First, vertical and horizontal conductivities were increased an order of magnitude in all layers to 40 and 400 feet per day, respectively. Second, they were decreased an order of magnitude to 0.4 and 4 feet per day, respectively. The simulations showed that the computed heads are very sensitive to decreases in the vertical and horizontal hydraulic conductivity (RMS of 538 feet) of the nodes representing St. Patrick anticline, and relatively insensitive to increases in these parameters (RMS of 262 feet) as shown in table 1 and figure 14c. This relation suggests that faulting and structural deformation associated with the St. Patrick anticline does not inhibit ground-water movement through the anticline. The effects of the anticline could not be precisely established with the available data; however, the limits set for the sensitivity analysis probably encompass the actual values.



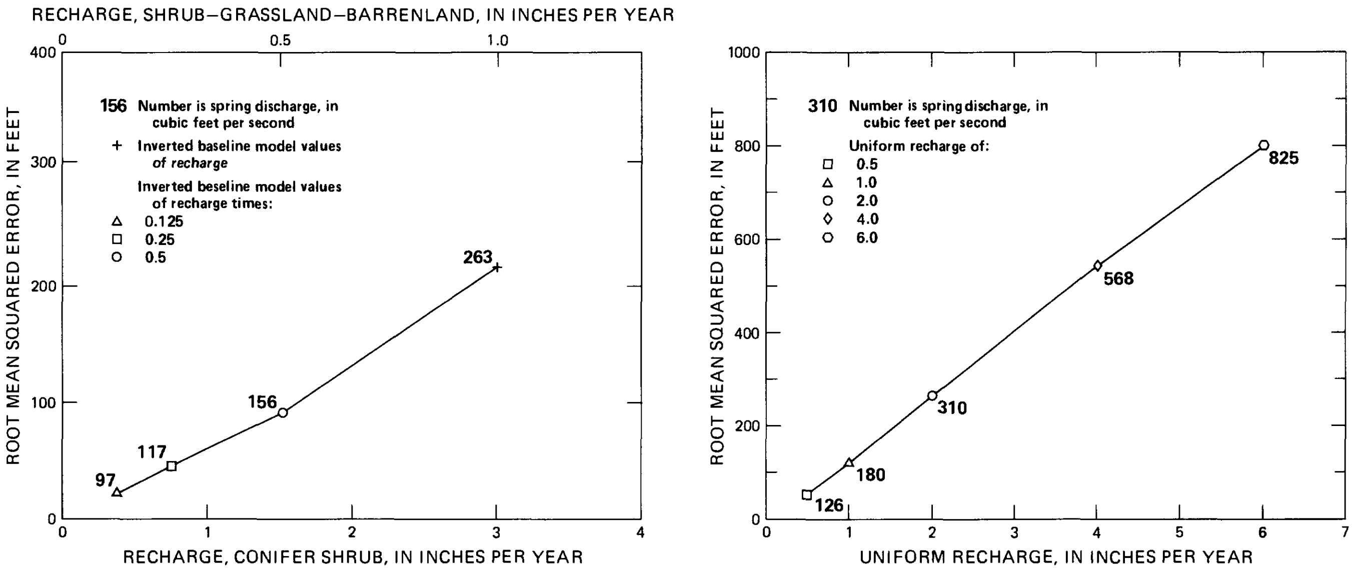
A. Vertical and horizontal hydraulic conductivity as a function of mean difference in head for layer 1

B. Vertical hydraulic conductivity as a function of mean difference in head for layer 1

C. Hydraulic conductivity as a function of mean difference in head for layer 1 for changes of hydraulic conductivity of nodes representing the St. Patrick anticline

D. Baseline recharge as a function of mean difference in head for layer 1

Figure 14.--Sensitivity of simulated predevelopment heads to changes in modeled parameters.



E. Inverted model recharge as a function of mean difference in head for layer 1

F. Uniform recharge as a function of mean difference in head for layer 1

Figure 14.--Sensitivity of simulated predevelopment heads to changes in modeled parameters--Continued.

Although acceptable changes in baseline vertical and horizontal hydraulic conductivity substantially improved the fit between simulated and observed water levels and spring discharge, simulated values were still higher than observed for both. Assuming a two-order magnitude increase in hydraulic conductivities as an upper limit for these parameters and noting that substantial increases beyond this limit will still not lower simulated water levels substantially (fig. 14a), it is reasonable to assume that natural recharge is less than the baseline estimate of 370,000 acre-ft/yr.

Reducing the rate of recharge used in the model will, of course, lower simulated water levels and spring discharge, everything else being equal. Given the uncertainty in recharge, the following three groups of recharge experiments were conducted to test the model's response:

Group 1--By using the initial estimate of recharge distribution and initial rates, total recharge was reduced from 370,000 to 47,000 acre-ft/yr in three successive simulations.

Group 2--To simulate the possibility that more recharge enters the system from the conifer-shrub areas than from the shrub-grassland-barrenland areas, the initial distribution of recharge was inverted (1 inch per year in shrub-grassland-barrenland areas and 3 inches per year in the open-forest areas). The resulting recharge rate to the basin of 269,000 acre-ft/yr was reduced in three successive simulations similarly to group 1.

Group 3--The initial estimate of recharge was based on a variety of parameters that provided surplus precipitation available for recharge for a variety of conditions. The values ranged from about 0.5 to 6 inches per year. To represent alternate extremes in the uncertainty of the initial recharge estimates, the sensitivity of computed heads and spring discharge was evaluated on the basis of uniformly distributed recharge. A uniform recharge rate ranging from 0.5 to 6 inches per year (80,000 to 962,000 acre-ft/yr) distributed uniformly through the basin, was simulated in five successive model experiments.

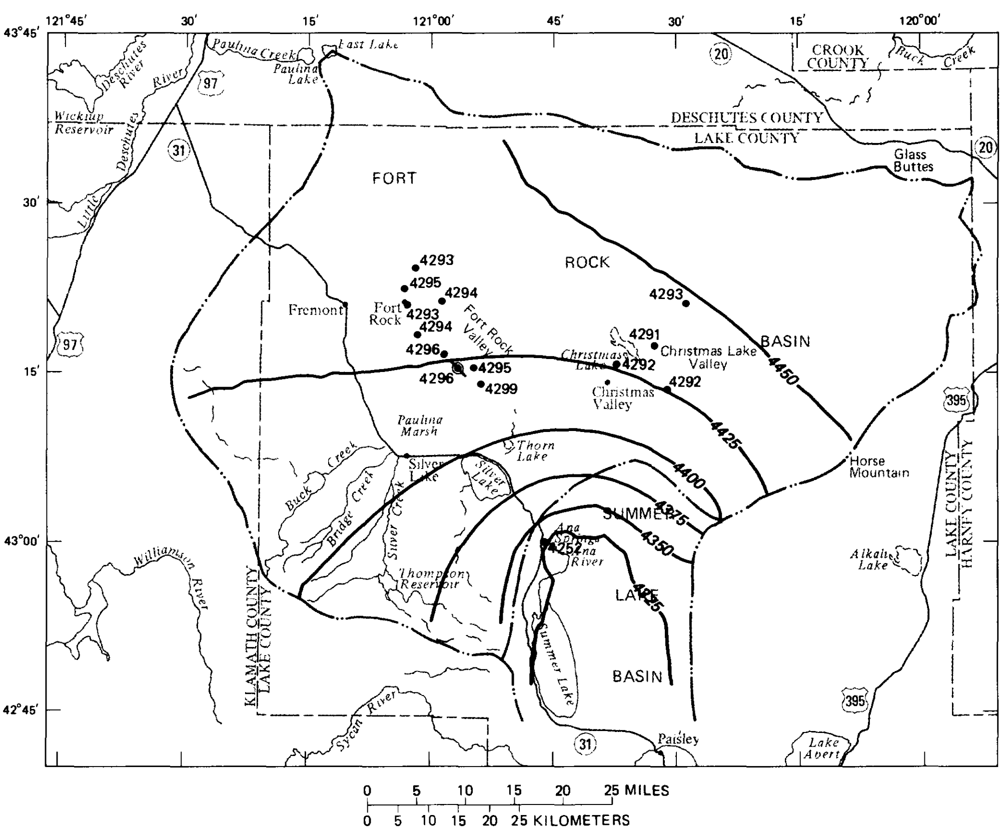
Computed heads and spring discharge were sensitive to changes in recharge (table 1 and figs. 14d, 14e, and 14f). The RMS between computed and measured heads and spring discharge decreased as recharge was decreased in all three groupings of sensitivity simulations. A reduction in recharge reduces the amount of water discharged and lowers the computed heads.

In each group of sensitivity analyses in which the lower limits of recharge were virtually simulating observed conditions, the RMS ranged from about 18 to 51 feet for the lowest values of recharge. The computed spring discharge, which ranged from 97 to 126 ft^3/s for the lowest values of recharge, was similar to the estimate of observed total spring discharge (140 ft^3/s). A comparison of RMS and computed spring discharge for the uniformly distributed recharge (group 3) simulations versus the areally distributed recharge (groups 1 and 2) shows that the group 3 values were much greater. This fact supports the concept that the definition of areally distributed recharge is important. Further examination, comparing groups 1 and 2, indicates that the group 2 RMS and spring discharge values are less than the group 1 values. The RMS for the baseline model, for instance, was 308 feet and the RMS for the inverted baseline simulation was 214 feet. The above results strongly indicate the sensitivity of the model to both the distribution and rate of recharge, but do not allow further refinement of recharge.

Although sensitivity analysis indicates that a reduction in recharge and various recharge distributions can vastly improve the comparison of calculated to observed heads, a lower limit of recharge can be established for the Fort Rock Basin. As mentioned earlier in this report, the spring discharge to the northern Summer Lake basin cannot be explained solely by the local surface drainage area, indicating a source of water outside the area. The maximum amount of discharge which could be contributed by the local drainage area was calculated for each model experiment. These calculations were made using the drainage area behind the springs and the recharge rates for the corresponding experiment. This number was compared to simulated discharge, and this comparison suggests that only 8 percent or less of total spring discharge is derived from the Summer Lake basin. Thus, approximately 92 percent (93,000 acre-ft/yr) or more of the water being discharged from the springs is derived from the Fort Rock Basin. If this amount of water is added to the estimated 50,000 acre-ft/yr discharged by evapotranspiration, the minimum recharge rate to the basin must equal approximately 140,000 acre-ft/yr. This quantity is a minimum because water also appears to move from the Fort Rock Basin into the

Summer Lake basin as underflow. As stated previously, the baseline estimate of recharge is 370,000 acre-ft/yr, so that long-term annual recharge to the Fort Rock Basin appears to be between 140,000 and 370,000 acre-ft/yr.

Within these limits of recharge, sensitivity analysis indicates that recharge values closest to 140,000 acre-ft/yr provide the best fit to observed conditions. For the three scenarios of recharge distribution (Groups 1-3), the baseline recharge times 0.5, the inverted recharge times 0.5, and the uniformly distributed recharge of 1.0 inch were closest to the 140,000 acre-ft/yr value. For those model simulations the RMS ranged from 89 to 137 feet, and spring discharge ranged from 156 to 201 ft^3/s. Head distribution for these simulations is shown in figures 15a, 15b, and 15c.



A. Baseline values of recharge times 0.5

EXPLANATION

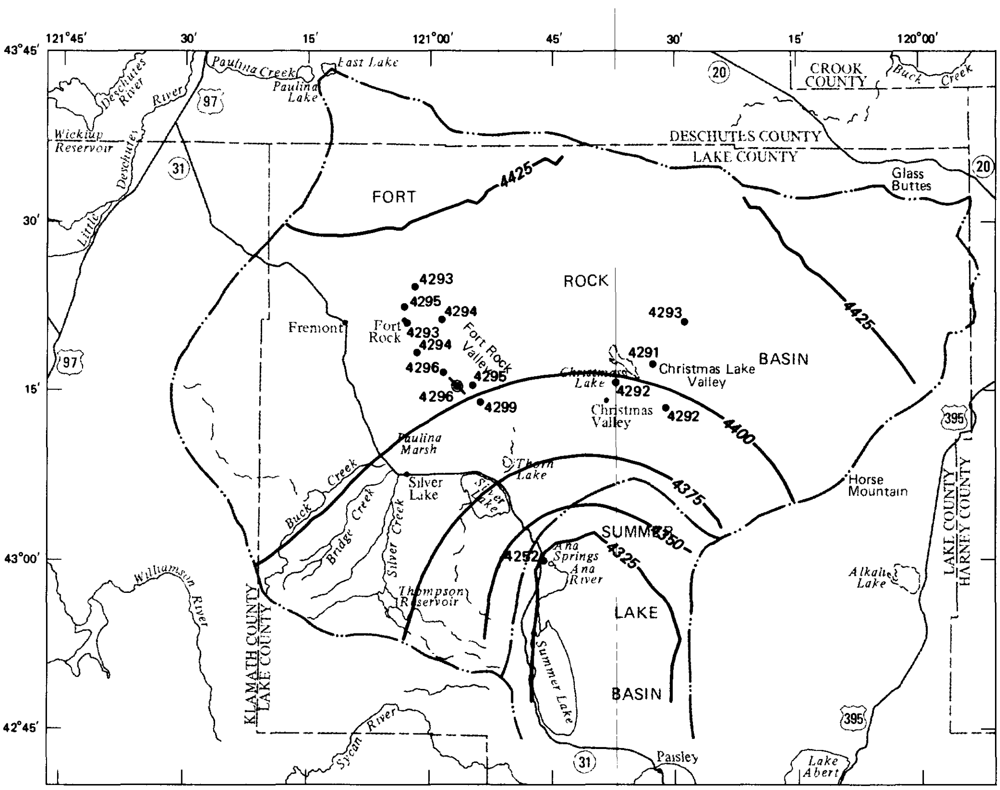
—4350— **Potentiometric contour**–Shows altitude of computed steady-state head, layer 1. Contour interval 25 feet. Datum is sea level.

•4295 **Data point**–Number is altitude of measured head in selected observation wells (March/April 1965). Heads shown only for wells with data for March/April 1965 and March/April 1983. Datum is sea level.

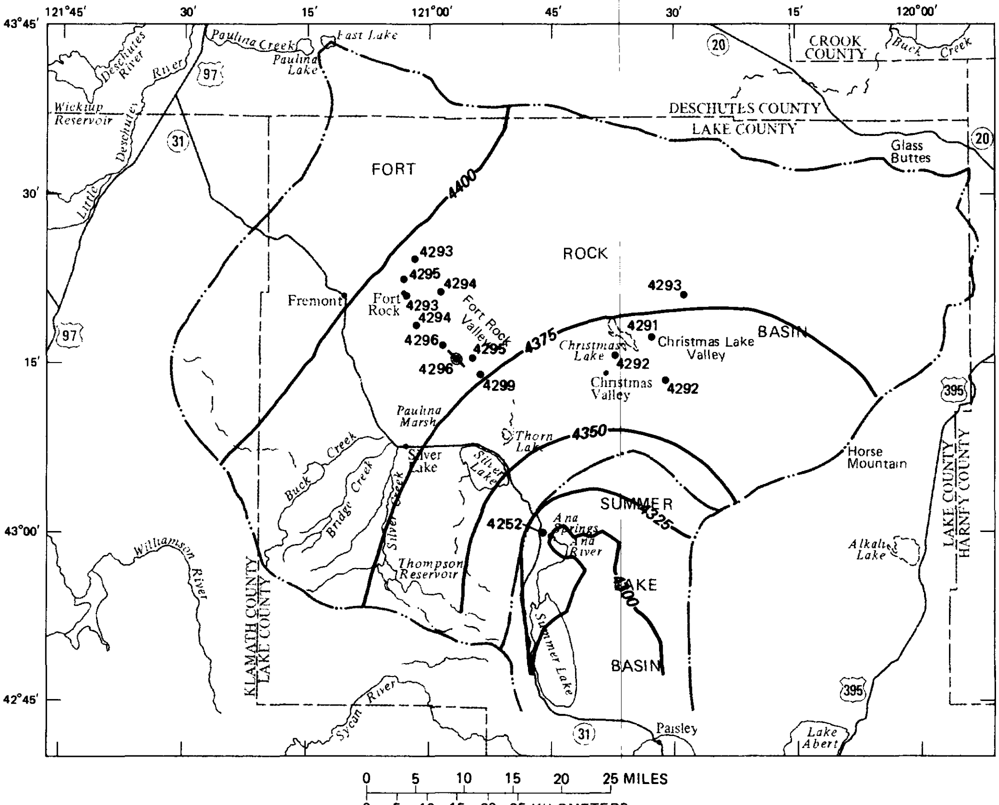
Observation well 27S/15E–4aca

Basin boundary

Figure 15.--Computed and observed heads for predevelopment conditions (layer 1), relative to adjustments to recharge.



B. Baseline parameter values with inverted recharge times 0.5



C. Baseline parameter values with uniform recharge of 1 inch

Figure 15.--Computed and observed heads for predevelopment conditions (layer 1), relative to adjustments to recharge--Continued.

The lack of a good fit between the baseline model-computed heads and the observed heads also may result from a limited understanding of the boundaries to the aquifer system. Refinement of the understanding of these boundaries would improve simulation of the ground-water system.

As indicated previously, the lateral boundaries to the ground-water flow system in the Fort Rock Basin are not well known; however, the modeled conceptualization of those boundaries was based on all available information. The surface-water divide bounding the basin was assumed to correspond to the ground-water divide; this boundary to the ground-water system was simulated in the model as a no-flow boundary, except to the south where Ana Springs discharges to the northern Summer Lake basin.

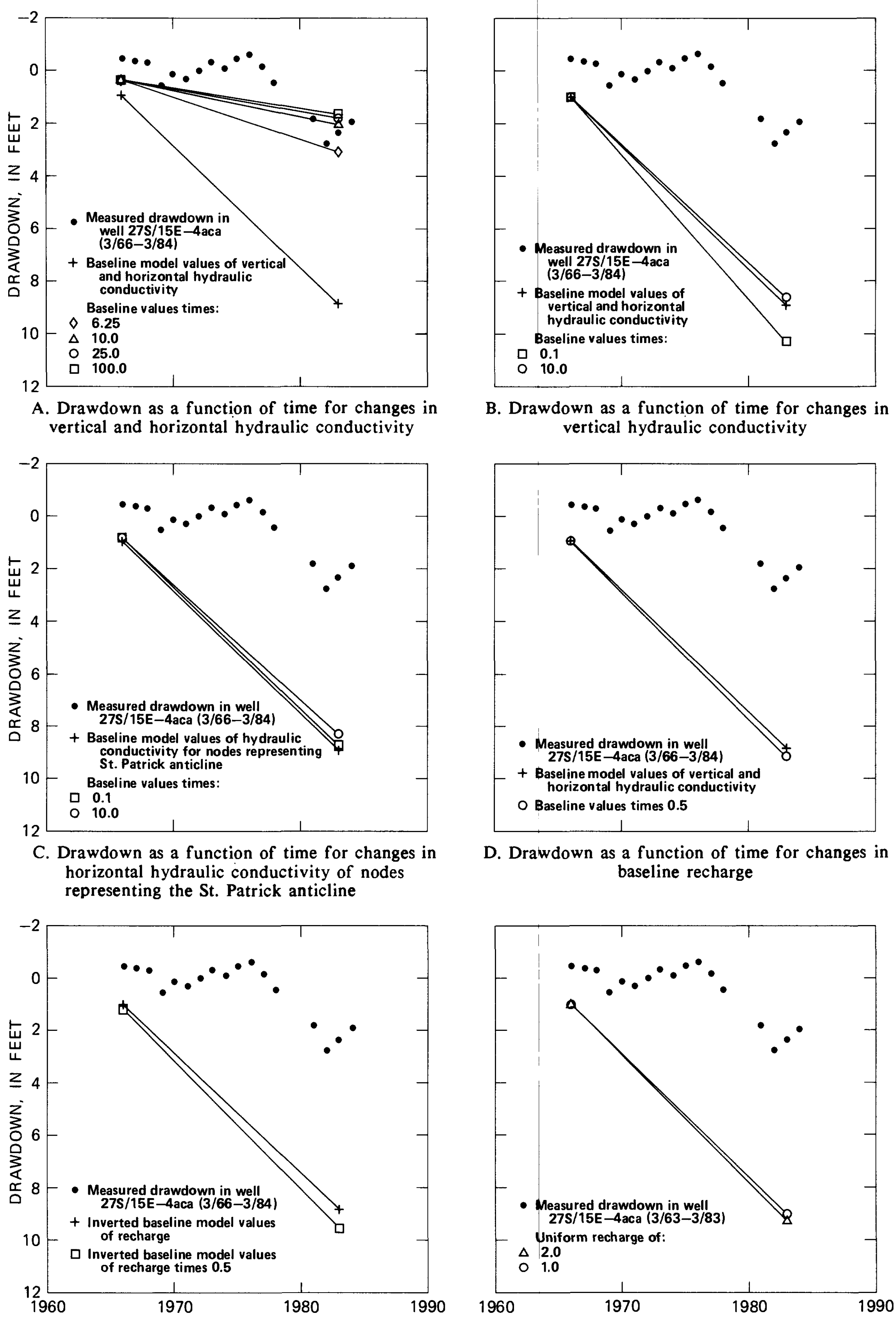
With the exception of permeability adjustments to the St. Patrick anticline, adjustments to the lateral boundary conditions of the model were not made. Previous workers have suggested that ground-water discharge from the Fort Rock Basin also may occur toward the Deschutes Basin; however, there is little evidence to support this theory.

The combination of these somewhat restrictive lateral boundary conditions and an impermeable lower boundary in the model could cause the excessively high heads computed by the baseline model. However, additional data collection and analysis of the extent, thickness, and boundaries of the aquifer will be required to improve this conceptualization. Additional work is needed before the possible error associated with boundary conditions can be properly evaluated.

Transient Simulation

The model of predevelopment conditions allowed estimates to be made of the possible range in values for horizontal hydraulic conductivity and, to some extent, vertical hydraulic conductivity of the aquifer system. In addition, the annual recharge rate to the aquifer was determined to be between 140,000 and 370,000 acre-ft/yr. Because steady-state conditions were modeled, no water was withdrawn from aquifer storage. Therefore, the predevelopment model could not be used to refine estimates of aquifer storage.

To evaluate transient model sensitivity to adjustment of specific yield and other parameters adjusted in the predevelopment model, a series of model experiments were conducted. The historical rates and distribution of ground-water pumpage were imposed for the years 1965 through 1983. As with the predevelopment model, the values simulated for horizontal hydraulic conductivity, vertical hydraulic conductivity, and recharge were changed one at a time and model results recorded (table 1 and fig. 16). In addition, the specific yield was changed while holding all other parameters to their baseline values. Two additional simulations were made for the transient model, which involved adjusting specific yield and hydraulic conductivities simultaneously.



A. Drawdown as a function of time for changes in vertical and horizontal hydraulic conductivity

B. Drawdown as a function of time for changes in vertical hydraulic conductivity

C. Drawdown as a function of time for changes in horizontal hydraulic conductivity of nodes representing the St. Patrick anticline

D. Drawdown as a function of time for changes in baseline recharge

E. Drawdown as a function of time for changes in inverted model recharge

F. Drawdown as a function of time for changes in uniform recharge

Figure 16.--Sensitivity of simulated transient drawdowns to changes in modeled parameters within limits established in predevelopment sensitivity analysis for the node representing observation well 27S/15E-4aca, layer 1.

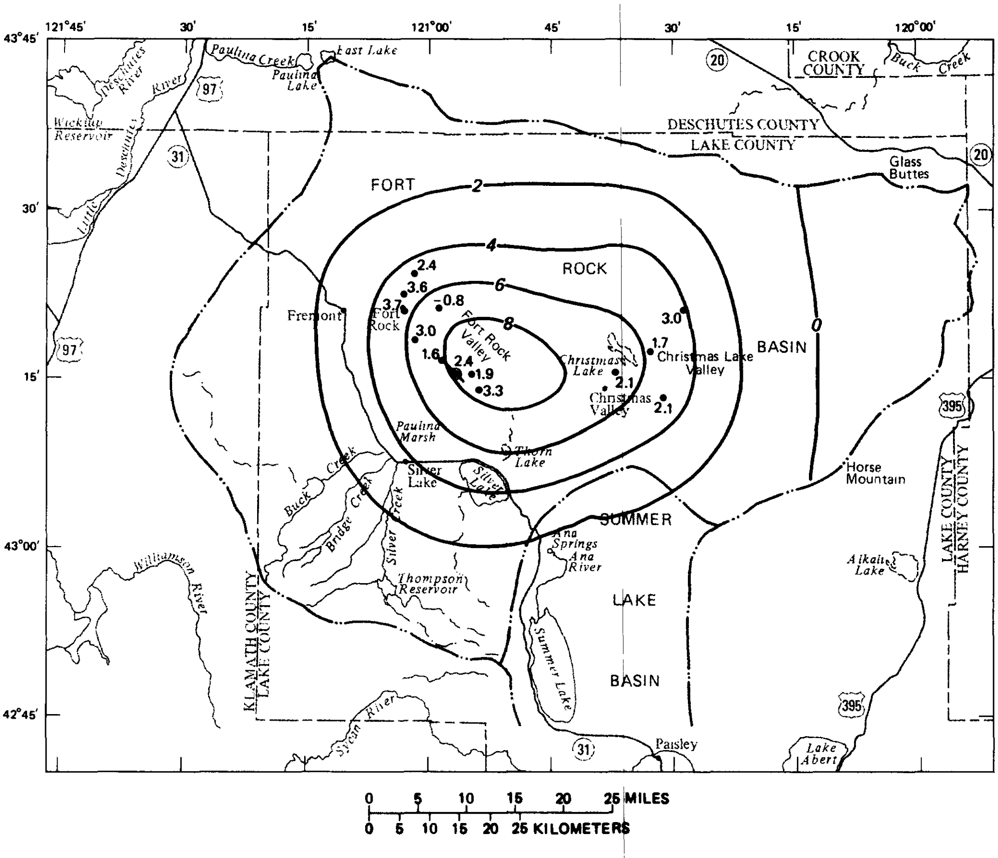
An important relation not simulated during the transient analysis is the relation between evapotranspiration losses from the aquifer system and the depth to water. The rate of ground water discharged by evaporation is primarily a function of depth to water. Evaporation is negligible about 10 feet below the land surface, but the depth at which transpiration ceases is not well known. Transpiration would cease when the water table is lowered (for example, by pumping) below the root depth of the phreatophytes. Information on this relation would be required for any transient model used to match or predict the response of the ground-water system to pumpage. Because reduction in evapotranspiration losses was not accounted for in the transient-model sensitivity analysis in this study, reduction in water levels and in spring discharge can be considered maximum values for any given experiment.

The combined results of the individual parameter sensitivity analysis cannot identify the possible range in total error associated with predicting declines in water levels and spring discharge because only one variable was changed at a time. Available data are insufficient for delineating the possible range in values for all of the parameters, and therefore the total error cannot be determined. The approach taken does allow the sensitivity of the model to potential errors in any parameter to be recorded, thereby indicating what additional information is needed for predictive modeling.

The sensitivity of the baseline model to estimated values for specific yield was tested in the first series of model experiments conducted. Three values of specific yield were simulated for layer 1; the baseline estimate of 0.1, and 0.2 and 0.01. The remaining three layers were assigned a constant value of storage coefficient equal to 0.0001 for all model experiments, because dewatering would only occur in the upper layer and the other layers would respond more as confined aquifers. Results of these and subsequent model experiments are shown in table 1.

Areal distribution and magnitude of simulated and observed drawdowns for 1965-83 are shown in figure 17. Model results are from the baseline model with the aquifer specific yield equal to 0.1. The maximum simulated drawdown is about 9 feet, which is more than twice the observed maximum water-level decline for the Fort Rock Basin. Simulated rates of water-level decline for 1966-83 are shown in table 1. These rates would vary spatially; the values given in the table are for the area of greatest computed decline, which is near observation well 27S/15E-4aca (fig. 7).

The maximum simulated rate of water-level decline for 1966-83 is 0.46 feet per year, as compared to observed average rates of water-level decline of up to 0.5 feet per year. An analysis of the model-computed water budget showed that 93 percent of pumpage, during 1965-83, was derived from storage, 2 percent was derived from water diverted from the springs, and the remaining water came from diverted underflow to the Summer Lake basin.



EXPLANATION

——2—— **Line of equal computed drawdown**—Number represents feet of drawdown. Contour interval 2 feet.

•1.7 **Point of measured drawdown in an observation well**—Number represents feet of drawdown.

Observation well 27S/15E–4aca

—— · · —— **Basin boundary**

Figure 17.--Computed and observed drawdowns for the baseline model, layer 1, 1965-83.

Increasing the value for specific yield from 0.1 to 0.2 resulted in relatively small changes in model-computed drawdowns and rate of drawdown. Maximum drawdown decreased from approximately 9 feet to about 7 feet and the rate of decline decreased by about 0.1 ft/yr. The computed decline in spring discharge was only about one-third that obtained when a value of 0.1 was used for specific yield.

The model proved to be very sensitive to a decrease in specific yield. Decreasing the value from 0.1 to 0.01 increased total calculated drawdown for 1983 by approximately 2 times. Maximum model-calculated drawdown for 1983 was 20.9 and feet (fig. 18 and table 1), and is nearly 10 times the observed value. The reduced value for specific yield caused the cone of depression to spread further and deeper for the time period simulated. This resulted in a greater amount of water being diverted from springs. The model computed a diversion of 18 ft^3/s by 1983, which represents 13 percent of the total spring discharge.

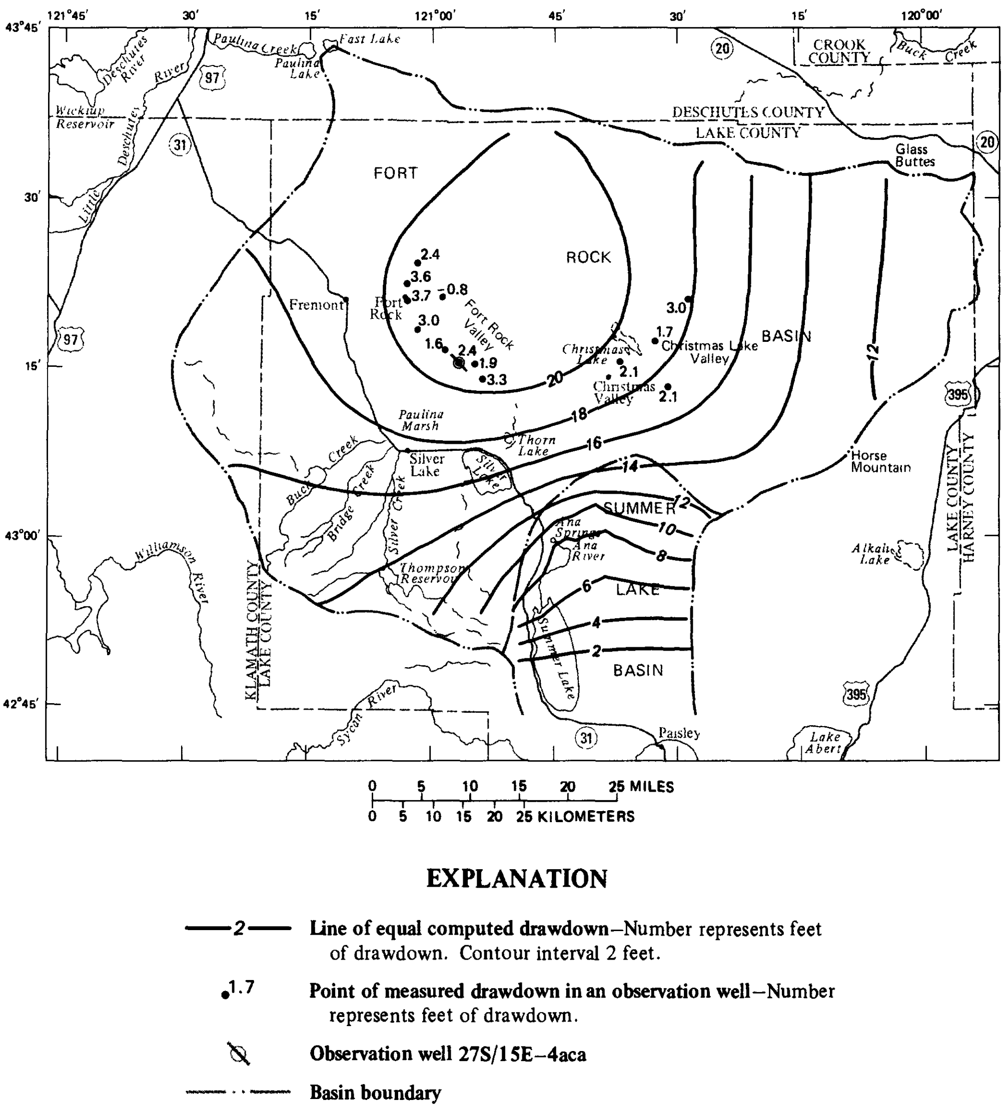
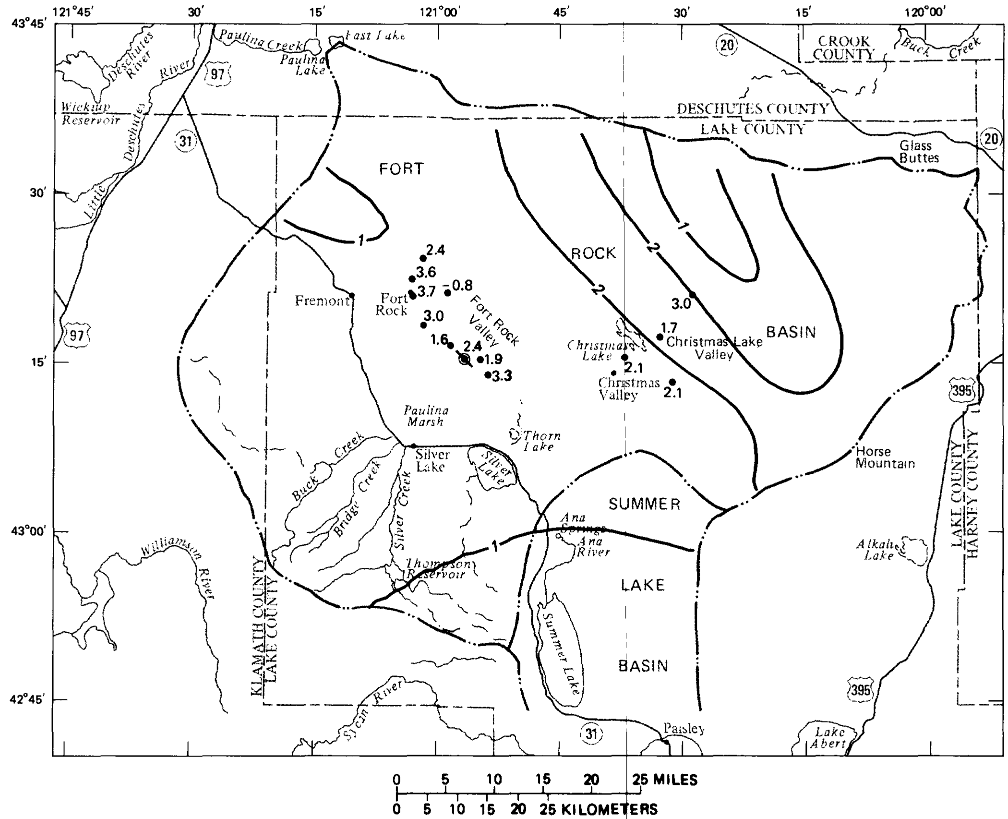


Figure 18.--Computed and observed drawdowns for baseline parameter values and storage coefficient of 0.01, layer 1, 1965-83.

By combining the vertical and horizontal hydraulic conductivities of the baseline model with a specific yield in layer 1 of 0.01, the resulting drawdowns and water-level declines could be considered maximum or worst case values. As mentioned earlier, the hydraulic conductivities in the baseline model are probably minimum values considering the results of the predevelopment model.

The sensitivity of the model to hydraulic conductivity was examined in a series of model experiments wherein the simulated value for horizontal hydraulic conductivity was increased with the same set of values used in the predevelopment model experiments. In these experiments, the ratio of vertical to horizontal hydraulic conductivity was 1 to 10. Substantial changes occurred in model-computed total drawdown for 1983, the rate of drawdown, and the quantity of water diverted from springs, compared to the baseline model. The greatest change from the baseline model occurred for an increase in hydraulic conductivity equal to 6.25 times the baseline value (table 1 and fig. 16a). Total computed drawdown decreased from approximately 9 to 3 for 1983. For the time period 1966-83, the rate of water-level decline decreased from 0.46 to 0.16 ft/yr. Also, the amount of water diverted from the springs was significantly reduced from 3 to 1 ft^3/s. Further changes in total drawdown, rate of water-level decline, and the amount of water diverted from the springs were small as a result of increasing the estimated value for hydraulic conductivity beyond 6.25 times the baseline value. Increasing the estimated values of hydraulic conductivity substantially decreased maximum drawdown (fig. 19).



EXPLANATION

—2— **Line of equal computed drawdown**—Number represents feet of drawdown. Contour interval 1 foot.

•1.7 **Point of measured drawdown in an observation well**—Number represents feet of drawdown.

Observation well 27S/15E–4aca

—·· — **Basin boundary**

Figure 19.--Computed and observed drawdowns for baseline values of vertical and horizontal hydraulic conductivity times 100, layer 1, 1965-83.

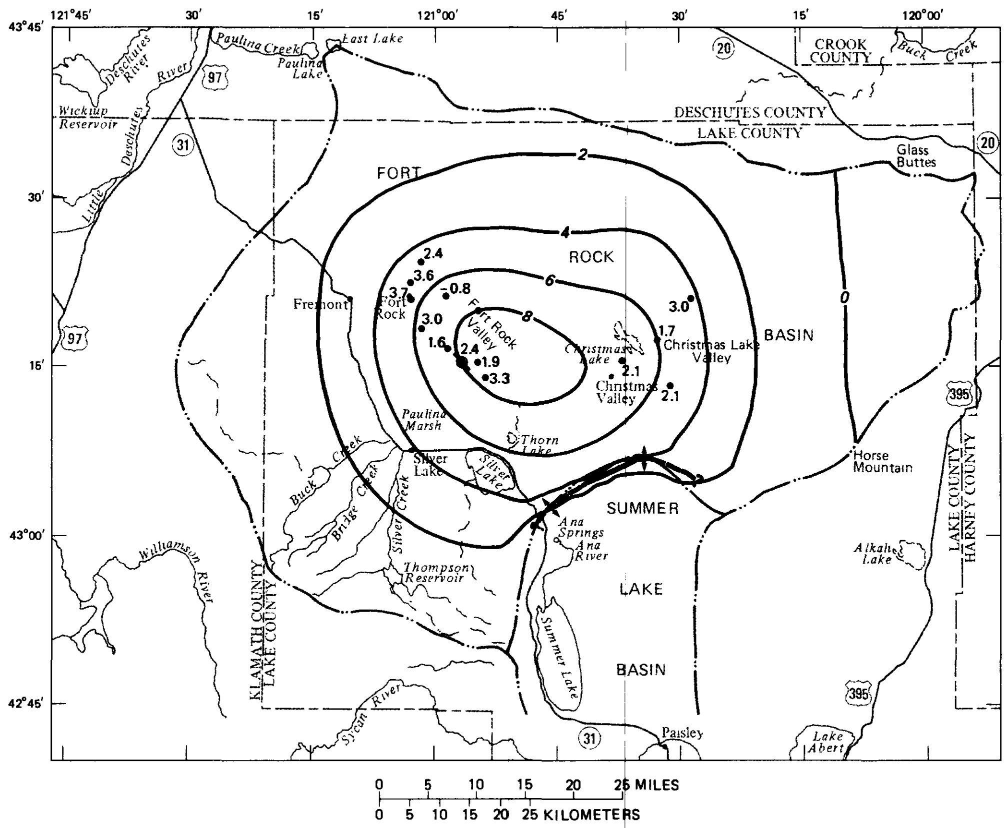
The sensitivity of the computed rate of water-level decline to changes in vertical hydraulic conductivity was evaluated with two model experiments. In one experiment, the ratio of vertical to horizontal hydraulic conductivity was reduced to 1:100 and in the other it was increased to 1:1. The simulations indicate that the rates of water-level decline and reductions in spring discharge are relatively insensitive to changes in vertical hydraulic conductivity (table 1 and fig. 16b).

Possible alternative effects of the St. Patrick anticline on computed declines in water level and spring discharge were examined by two model experiments. The horizontal hydraulic conductivity of the anticline was first reduced by one order of magnitude from its baseline value and next increased one order of magnitude above the baseline value. Results of these model experiments indicate that computed water-level declines are relatively insensitive to changes in the hydraulic conductivity of the nodes representing the anticline (table 1 and fig. 16c). Configuration of the computed drawdown was essentially the same as the baseline configuration (figs. 17 and 20) except in the vicinity of the anticline. The adjustments to horizontal hydraulic conductivity resulted in small changes in spring discharge and the rate of reduction in spring discharge (table 1).

As indicated previously in this section, the combination of the baseline hydraulic conductivity values and a specific yield of 0.01 result in maximum or worst case drawdown values. The results from the predevelopment and transient models indicate that the baseline horizontal hydraulic conductivity can be considered a minimum value.

To evaluate a minimum drawdown situation and the effect of adjusting hydraulic conductivities and specific yield, two model simulations were made with baseline hydraulic conductivities times 100 and specific yields of 0.2 and 0.01 (figs. 21 and 22). The results for these runs indicate drawdowns similar to those for the simulation of hydraulic conductivities times 100 and baseline specific yield of 0.1. This suggests that for hydraulic conductivity values 100 times the baseline value the model is relatively insensitive to specific yield adjustments. These simulations indicate that if hydraulic conductivities are close to the baseline value, specific yield is important for calculating drawdown. However, if hydraulic conductivities are close to 100 times the baseline value, specific yield may be relatively unimportant.

Results of the predevelopment model experiments indicate that long-term annual recharge to the basin is probably between 140,000 to 370,000 acre-ft/yr. The results also indicate that some reduction in recharge from the initial estimate of 370,000 acre-ft/yr is necessary to improve the fit between simulated and observed heads and discharges. Reducing estimated recharge values from the baseline value of 370,000 acre-ft/yr in the transient model would lower the simulated water levels. Because the aquifer is unconfined, lower water levels result in lower model-computed transmissivity.



EXPLANATION

—2— **Line of equal computed drawdown**–Number represents feet of drawdown. Contour interval 2 feet.

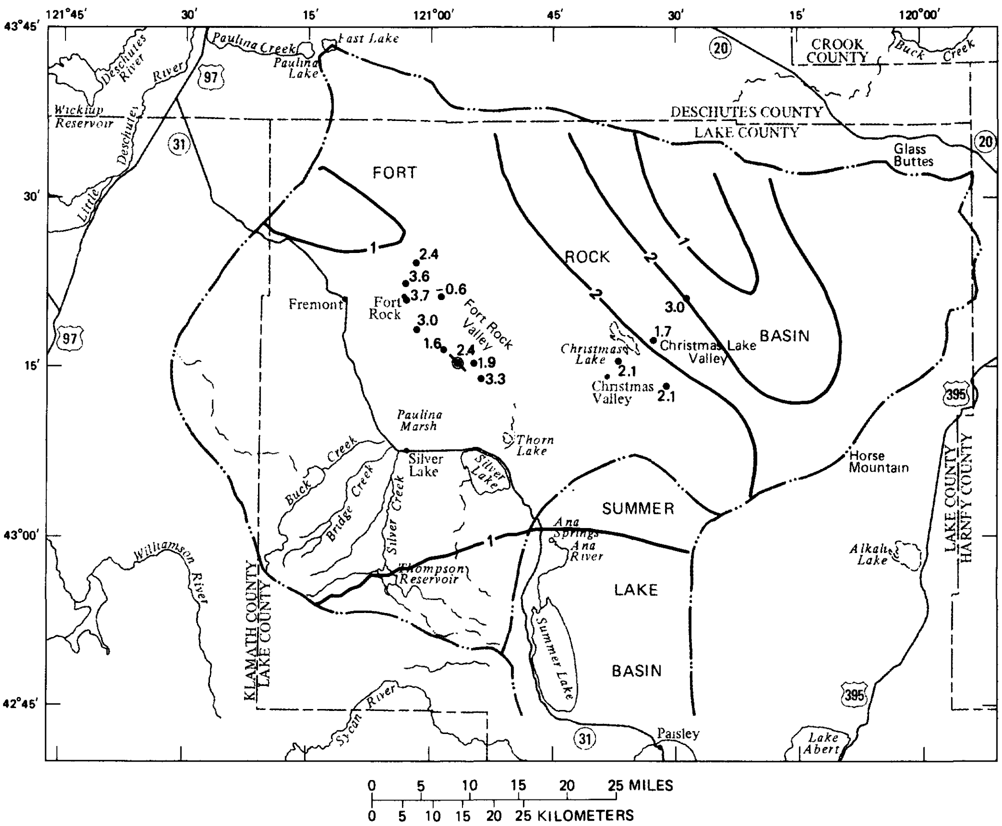
St. Patrick anticline–showing trace of crestal plane. Dashed where approximately located; queried where uncertain.

•1.7 **Point of measured drawdown in an observation well**–Number represents feet of drawdown.

Observation well 27S/15E–4aca

Basin boundary

Figure 20.--Computed and observed drawdowns for baseline values of hydraulic conductivity of nodes representing St. Patrick anticline times 0.1, layer 1, 1965-83.



EXPLANATION

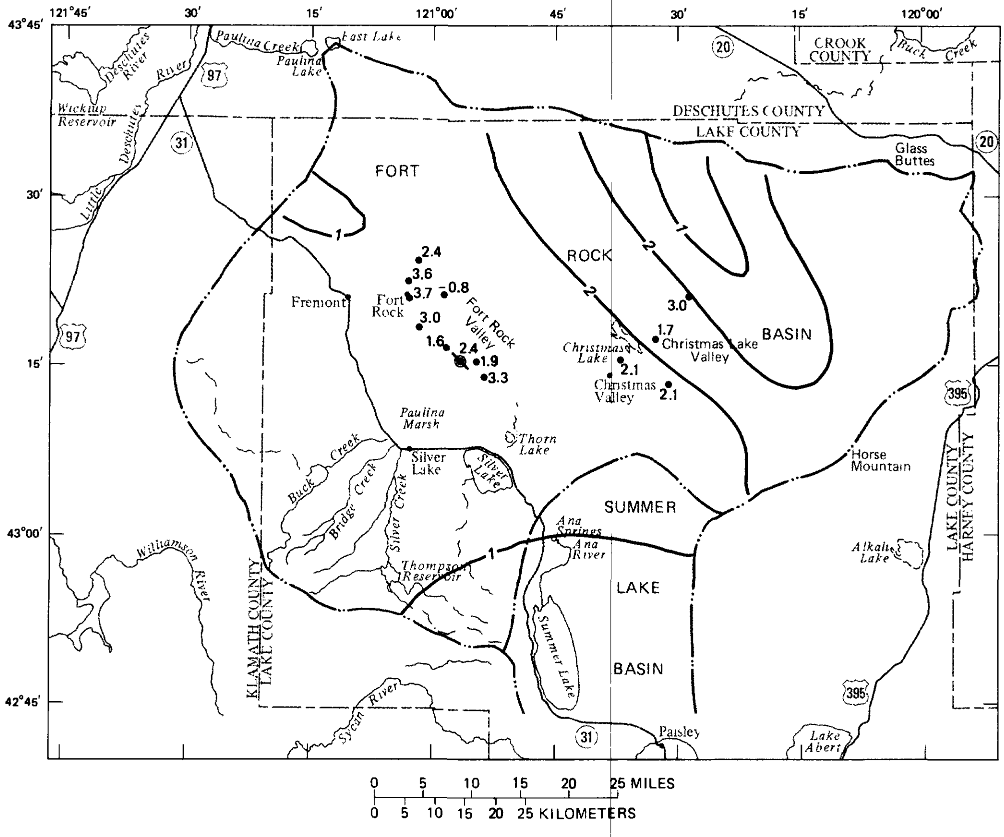
—2— **Line of equal computed drawdown**—Number represents feet of drawdown. Contour interval 1 foot.

•1.7 **Point of measured drawdown in an observation well**—Number represents feet of drawdown.

Observation well 27S/15E–4aca

—··— **Basin boundary**

Figure 21.--Computed and observed drawdowns for baseline values of hydraulic conductivity times 100 and storage coefficient of 0.2, layer 1, 1965-83.



EXPLANATION

—2— **Line of equal computed drawdown**—Number represents feet of drawdown. Contour interval 1 foot.

•1.7 **Point of measured drawdown in an observation well**—Number represents feet of drawdown.

Observation well 27S/15E–4aca

Basin boundary

Figure 22.--Computed and observed drawdowns for baseline values of hydraulic conductivity times 100 and storage coefficient of 0.01, layer 1, 1965-83.

To observe the effects of lower water levels on the transient model simulations, estimated recharge for each spatial configuration of recharge used in the predevelopment model was reduced within the range of recharge approximately between 370,000 and 140,000 acre-ft/yr. A total of 5 model experiments with reduced estimated recharge were conducted (table 1). The results of all the experiments are nearly identical to the baseline prediction, indicating that the reduction of transmissivity associated with the reduced recharge is not a significant factor in predicting the effects of pumpage (figs. 16d, 16e, 16f).

NEEDS FOR ADDITIONAL STUDY

To refine the conceptualization of ground-water movement in the Fort Rock Basin, and to improve definition of the boundaries to the ground-water system, additional mapping of the potentiometric surfaces and the extent and thickness of the aquifers is needed. This can be accomplished with continued surveying of well-head altitudes to accurately determine water-level altitudes and by using bore-hole geophysical logging methods in conjunction with drillers' lithologic descriptions to map the geometry of the aquifers. Land-surface geophysical techniques also could be helpful in mapping the aquifers in the basin. Additional supporting evidence on ground-water flow within and outside the basin could be obtained by analysis of ground-water and precipitation samples for stable isotopes.

The results of this study also indicate that, of all the aquifer parameters needed to determine the effects of pumpage on the ground-water system, additional information is needed most on specific yield and horizontal hydraulic conductivity. Data also are needed on the rate and magnitude of ground water discharged by evapotranspiration under present and falling water levels. Information that would allow refinement of horizontal hydraulic conductivity includes: (1) determination of the configuration of the water table over a much larger area of the Fort Rock Basin than is presently possible, (2) better definition of the rate of spring discharge in the St. Patrick anticline area, and (3) more knowledge concerning the distribution and rates of recharge. Information required to improve definition of specific yield includes all of the above, plus continued efforts to monitor the distribution and rates of ground-water pumpage and the temporal-spatial changes in water levels. Finally, to refine estimates of evapotranspiration from the ground-water system, it would be necessary to determine the depth to water in areas of phreatophyte growth, rates of water usage of these plants, and the maximum depth of root penetration.

SUMMARY AND CONCLUSIONS

Several studies have addressed aspects of the hydrogeologic setting of the Fork Rock Basin, but the detailed information needed to allow accurate predictions of the effect of existing and future pumpage on water levels and spring discharge is not available.

This study utilized existing ground-water-resource information for the Fort Rock Basin to develop a conceptualization of the ground-water flow system and to develop a preliminary ground-water flow model. The model was used as an investigative tool to improve the understanding of ground-water movement in the basin and to identify additional data needs.

The results of this study indicate that to accurately predict the effect of existing and future pumping on the aquifer system, additional information is needed on the extent, thickness, and boundaries of the aquifers. Also, additional data are needed on specific yield, hydraulic conductivity, and the rate and magnitude of ground water lost to evapotranspiration in the basin.

Results of the model experiments suggest that a small reduction in spring discharge probably has occurred since the beginning of pumping; however, most of the water withdrawn by pumping has been derived from aquifer storage. Evapotranspiration has been reduced also, but the amount is unknown.

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