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WATER-SUPPLY BULLETIN 48

Computer Simulation and Geohydrology Of a Basalt Aquifer System In the Pullman-Moscow Basin, Washington and Idaho

By
R. A. BARKER

Prepared Cooperatively by the
UNITED STATES GEOLOGICAL SURVEY
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[Plate in pocket]

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Multiply	By	To obtain
Inches	25.40	millimeters (mm)
Feet (ft)	0.3048	meters (m)
Miles (mi)	1.609	kilometers (km)
Square feet (ft^2)	0.09290	square meters (m^2)
Acres	4047.	square meters (m^2)
Square miles (mi^2)	2.590	square kilometers (km^2)
Acre-feet (acre-ft)	1233.	cubic meters (m^3)
Feet per second (ft/s)	0.3048	meters per second (m/s)
Feet per mile (ft/mi)	0.1894	meters per kilometer (m/km)
Feet squared per second (ft^2/s)	0.09290	meters squared per second (m^2/s)
Cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
Horsepower (hp)	0.7457	kilowatts (kw)

COMPUTER SIMULATION AND GEOHYDROLOGY OF A
BASALT AQUIFER SYSTEM
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WASHINGTON AND IDAHO

By R. A. Barker

ABSTRACT

A digital-computer model, using a finite-difference technique, was developed to simulate hydrologic characteristics of the primary (deep) basalt aquifer system in the Pullman-Moscow basin. The State of Washington Department of Ecology and the local water agencies expect to use the model to help evaluate water-management alternatives involving the distribution of well pumping and artificial recharge.

Ground water in the Pullman-Moscow basin occurs primarily in the basalt and interbedded sediments of the Columbia River Basalt Group. These rocks underlie about 88,000 acres (138 square miles) in the basin and are thickest near Pullman, Wash., where the estimated depth to an impermeable basement complex is about 2,600 feet.

The primary aquifer system is distinguishable from the overlying upper aquifer zone on the basis of measurable differences in the hydraulic properties of each and in the long-term response to pumping activity. Water-level decline in the primary aquifer system began in the 1890's and is the result of year-to-year increases in ground-water development, coupled with the relatively slow rate of natural ground-water replenishment. Pumpage during 1971-75 averaged about 6,600 acre-feet per year, and by 1975 water levels had declined nearly 80 feet below those of pre-development conditions. The calibrated model simulates the historical water-level decline in the Pullman area to within 5 feet of measured levels for any year.

Model simulation supports the belief that vertical leakage from the upper aquifers is the most important source of recharge to the primary aquifer system within the basin; this simulated flux for 1975 is about 4,900 acre-feet. Model analysis indicates that lateral recharge to these aquifers from the southwest increased from zero under pre-development conditions to about 1,450 acre-feet in 1975. Lateral discharge from the basin, according to the model analysis, was about 2,850 acre-feet per year under pre-development conditions; it is simulated to now occur at less than half that rate (1,250 acre-ft in 1975), as a result of ground-water withdrawals.

Model simulation, which projects a doubling of present-day pumping rates by 2000, indicates a water-level decline in the Pullman-Moscow area of 30 to 35 feet below 1975 levels. When simulated pumping rates are nearly tripled by 2000, the projected decline is, in places, as much as 55 feet. However, a projection with pumping stabilized at 6,600 acre-feet per year indicates a decline of less than 10 feet below 1975 levels and an annual decline rate of about 0.2 foot per by 2000.

INTRODUCTION

Significant development of the ground-water supply in the Pullman-Moscow basin (fig. 1) began in the 1890's. By 1896 more than a dozen wells in each locality tapped separate artesian zones beneath Pullman, Wash., and Moscow, Idaho. Nearly 75 percent of these wells were flowing upon completion, generally at depths of 100 feet or less. Much of the water from these early wells was apparently wasted to surface drains as artesian fountains were commonly allowed to flow freely. With uncommon foresight for that era, I. C. Russell (1897, p. 81) warned:

> "Several of the wells at Pullman are allowed to flow, thus wasting a large volume of water and decreasing the [artesian] pressure. If the blessings accompanying the discovery of an excellent water supply are to be maintained, all wells should be closed when not in use."

Unfortunately Russell's warnings went unheeded and the days of a seemingly inexhaustible supply of ground water were shortlived. Since 1896 water levels in the deeper aquifers have declined progressively to nearly 80 feet below pre-development levels. By 1960 water levels in the shallowest artesian aquifers in the Moscow area had declined by as much as 100 feet.

Additional water-level decline may be expected. Although present (1975) and anticipated demands for irrigation water are small, future population increases (owing to the continual growth of educational facilities, business, and industry) will undoubtably sustain an increasing need for ground water. Whereas ground-water pumpage from the basin in 1975 totalled less than 7,500 acre-ft, the estimated total water requirement by year 2000 for only the immediate Pullman-Moscow area is as much as 18,630 acre-ft/yr (Stevens and others, 1970).

Despite several water-resource studies in the area during the past 15 years, local concern over the possibility of ground-water depletion has remained largely unsettled. Because water levels have continued to decline, and because virtually all human activity in the area is dependent to some extent on the ground-water resource, questions raised by the local populace such as "How long will the water last?" (Jones and Ross, 1969), are certainly not without reason.

Future demands for water may be difficult to satisfy, especially without the support of artificial recharge to the ground-water reservoir or surface-water importation (Foxworthy and Washburn, 1963; Stevens, 1960). However, finding excess water that is chemically suitable for artificial recharge is a major problem, and the importation of water involves complexities in conveyance design and high costs. It has become critically important, then, to understand the local ground-water system, to properly assess its limitations as a future source of water, and to judiciously manage the available water resources.

State and local water planners have acknowledged the need for decisive management of the ground-water resources. Such action requires that the probable effects of different water-management alternatives be evaluated before guidelines for future ground-water development are implemented. The digital-computer model is believed to provide one of the most reliable and efficient means by which to evaluate the effects of various management alternatives regarding pumping and artificially recharging the local ground-water system.

Purpose and Scope

The purpose of the study was to (1) define the basic geohydrology of the Pullman-Moscow basin, (2) compile a historical record of ground-water development and the hydrologic effects of that development, (3) calibrate a digital model of the most productive and extensive aquifer system, and (4) use the model to project the effects of anticipated future ground-water development on water levels in the basin. This report (1) documents geohydrologic data pertinent to the study, (2) presents an explanation of the area's ground-water-flow system, and (3) describes the model in terms of its uses, limitations, and data requirements.

The study was made in cooperation with the State of Washington Department of Ecology (DOE). DOE intends to use the model to help formulate policies regarding the future management of the area's ground-water resources.

This study was built upon the results of previous investigations (discussed below), some of which provided conflicting interpretations of the geohydrology of the basin. In formulating a hydrologic rationale for the model, it was necessary to carefully consider and choose between some of the previous interpretations, as well as to expand upon those chosen. Accordingly, brief discussions of previous interpretations and their relation to the model study are included herein (p. 21-25).

Location and Extent of Study Area

The Pullman-Moscow basin lies across the Washington-Idaho state line (fig. 1), and covers approximately 256 mi^2 (164,000 acres), of which about 173 mi^2 (111,000 acres) is within Whitman County, Wash.; the remaining 83 mi^2 is in Latah County, Idaho. The areas west and east of the State line have been defined arbitrarily in previous reports as the Pullman and Moscow subbasins, respectively.

The digital model was developed to simulate hydraulic conditions in the area's major aquifer system, which is enclosed laterally in all directions--except on the west--by crystalline rocks (fig. 2). The westward extension of the modeled area spans the gap in the crystalline rock boundary between Albion and Chambers and crosses the drainage divide to Union Flat Creek, another natural boundary of the aquifer system. The modeled area encompasses nearly 112,000 acres, of which 88,000 acres lie within the Pullman-Moscow basin.

Geographic Setting

Pullman and Moscow, with 1976 populations (including college students) of 23,552 and 16,693, respectively, are communities of similar size, interests, and livelihoods. Separated by less than 10 miles, both are commercial centers founded upon the need to serve the surrounding areas of dryland wheat farming. Both cities support state universities whose faculties and students comprise over 50 percent of the city populations. Washington State University (WSU) at Pullman and University of Idaho (UI) at Moscow had enrollments in the fall of 1976 of 16,736 and 7,600, respectively.[1]

The Pullman-Moscow basin, roughly circular in shape and about 20 miles across, is bounded on the north, east, and south by mountains and low hills (fig. 1). These highlands are erosional remnants of an ancient, more rugged mountain range. Altitudes in this shallow basin range from about 2,225 feet near Albion, Wash., to nearly 5,000 feet at the summit of Moscow Mountain, Idaho, in the easternmost part of the basin (pl. 1). The interior lowland of the basin, underlain by the Columbia River Basalt Group, consists of a moderately dissected lava plain forming low rolling hills which are generally mantled by thick accumulations of windblown silt (loess). These irregularly shaped, rounded hills generally rise less than 200 feet above the intervening depressions and are known locally as the Palouse Hills.

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[1]City and student population data obtained from the city business offices and university registrars, respectively, by Diane Weber (Washington State University Department of Civil and Environmental Engineering, oral commun., December 1976).

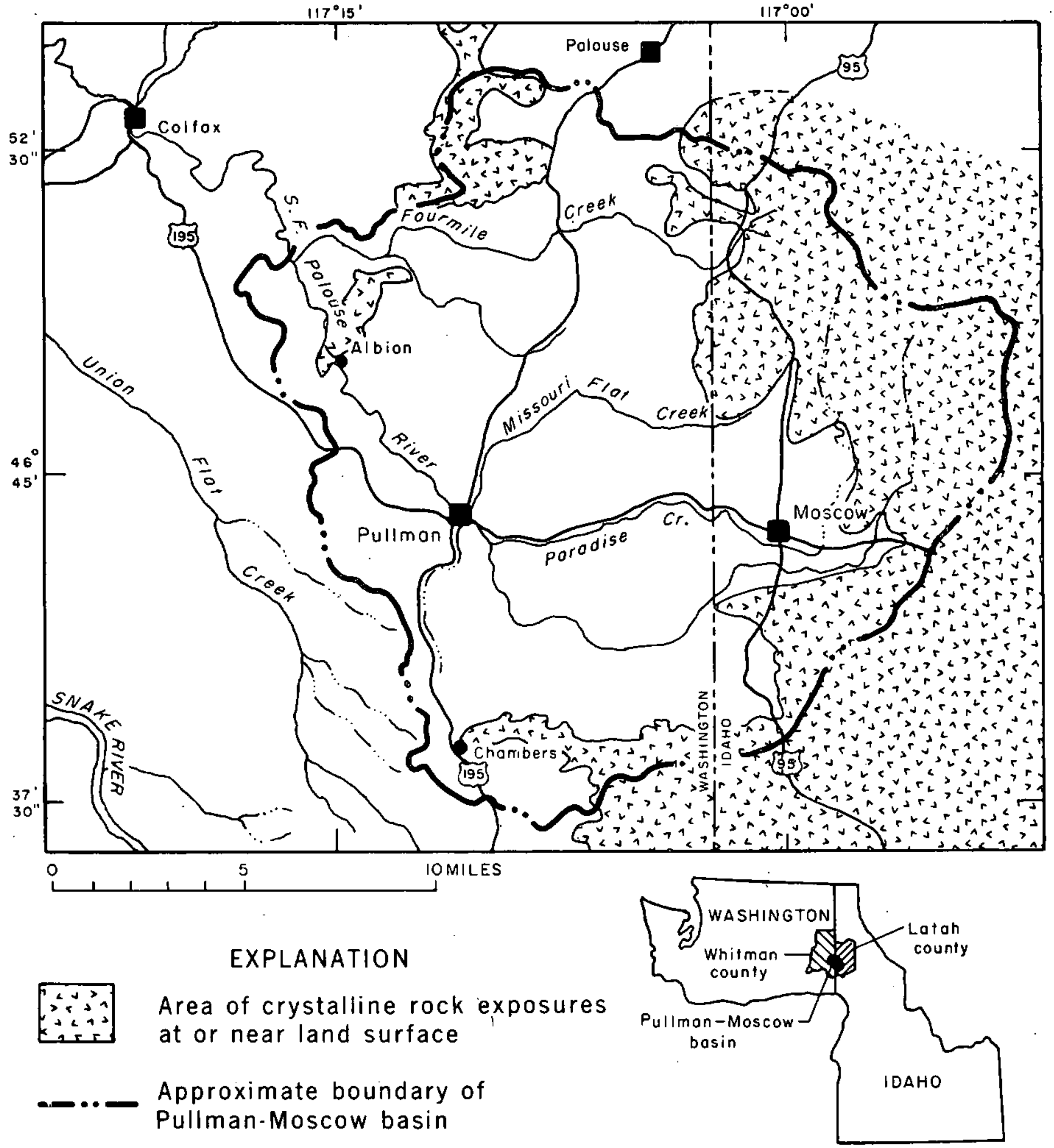


FIGURE 1.--Location map of study area, showing streams and crystalline rock exposures.

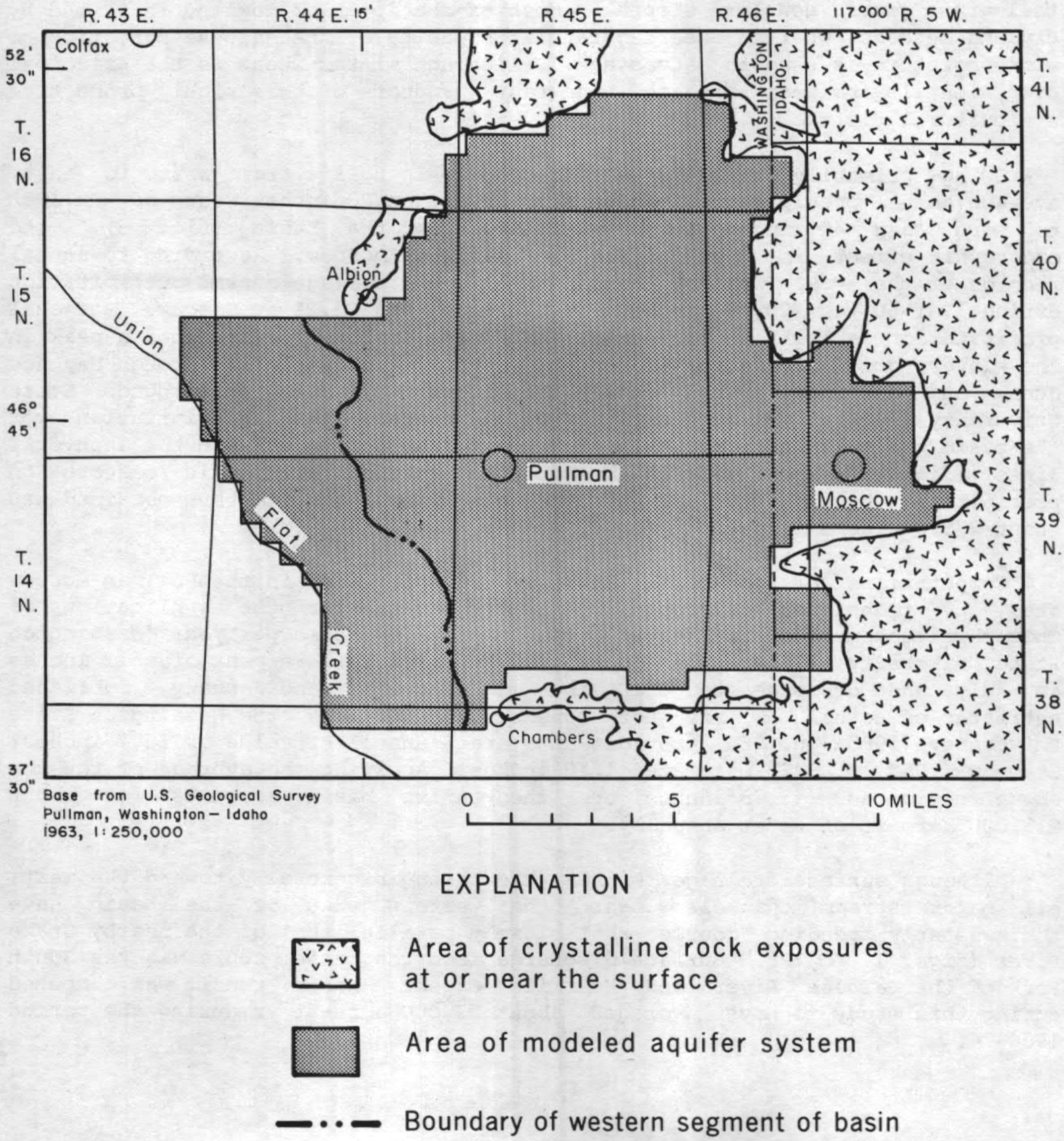


FIGURE 2.--Location of modeled area.

A thick coniferous forest covers much of the steep topography of the higher mountains to the east, thus protecting the generally thin soils of that area from erosion; at lower elevations, scattered stands of ponderosa pine and tall grass cover gentler slopes. Much of the interior lowland is farmed by dryland methods, wherein the substantial capacity of the Palouse Formation to store moisture is used to advantage. Although winter wheat is the principal crop, lentils and peas also are important products of this richly productive agricultural district.

Owing primarily to the effect of orographic uplift from west to east, average annual precipitation ranges from less than 20 inches west of Pullman to more than 40 inches in the eastern part of the basin (fig. 3). The orographic effect is most noticeable east of Moscow. According to annual records of the U.S. Weather Bureau (NOAA), the average annual precipitation during 1931-60 was 20.49 inches at Pullman and 22.21 at Moscow. Seasonal precipitation is light in the summer, increases in the fall, reaches a peak in the winter, gradually decreases in the spring, levels off through May and June, and declines sharply near the first of July (Washington State University, 1965). A rough estimate of the average annual precipitation over the basin was obtained for this study by planimetering between the isohyetal lines (fig. 3) and correcting for the assumed orographic effects on precipitation between the isohyets; the basinwide estimate thus obtained was about 275,000 acre-ft/yr.

Computations of potential ET (evapotranspiration) in the Pullman-Moscow area, by techniques developed by Palmer-Havens for the application of Thornthwaite's method provides an estimate of 24.6 inches per year (Washington State University, 1965). These potential ET rates reach a peak of 5.2 inches in July and decrease to 0.10 inch in December and January. Published estimates of actual ET are not consistent. Whereas the Washington State University (1965, p. 64) provides an average annual ET value of 14.7 inches; Stevens (1960, p. 342) estimated 16.8 inches. Applying the average of the two above estimates (15.75 inches) over the entire basin accounts for about 215,000 acre-ft of water annually.

Although surface drainage within the basin is generally toward the west, all major stream channels near the western edge of the basin have northwesterly trending courses that closely parallel that of the nearby Snake River (figs. 1 & 12). Surface discharge from the basin occurs via the South Fork of the Palouse River and Fourmile Creek. Basin runoff was computed during this study to have averaged about 53,000 acre-ft/yr during the period 1960-74.

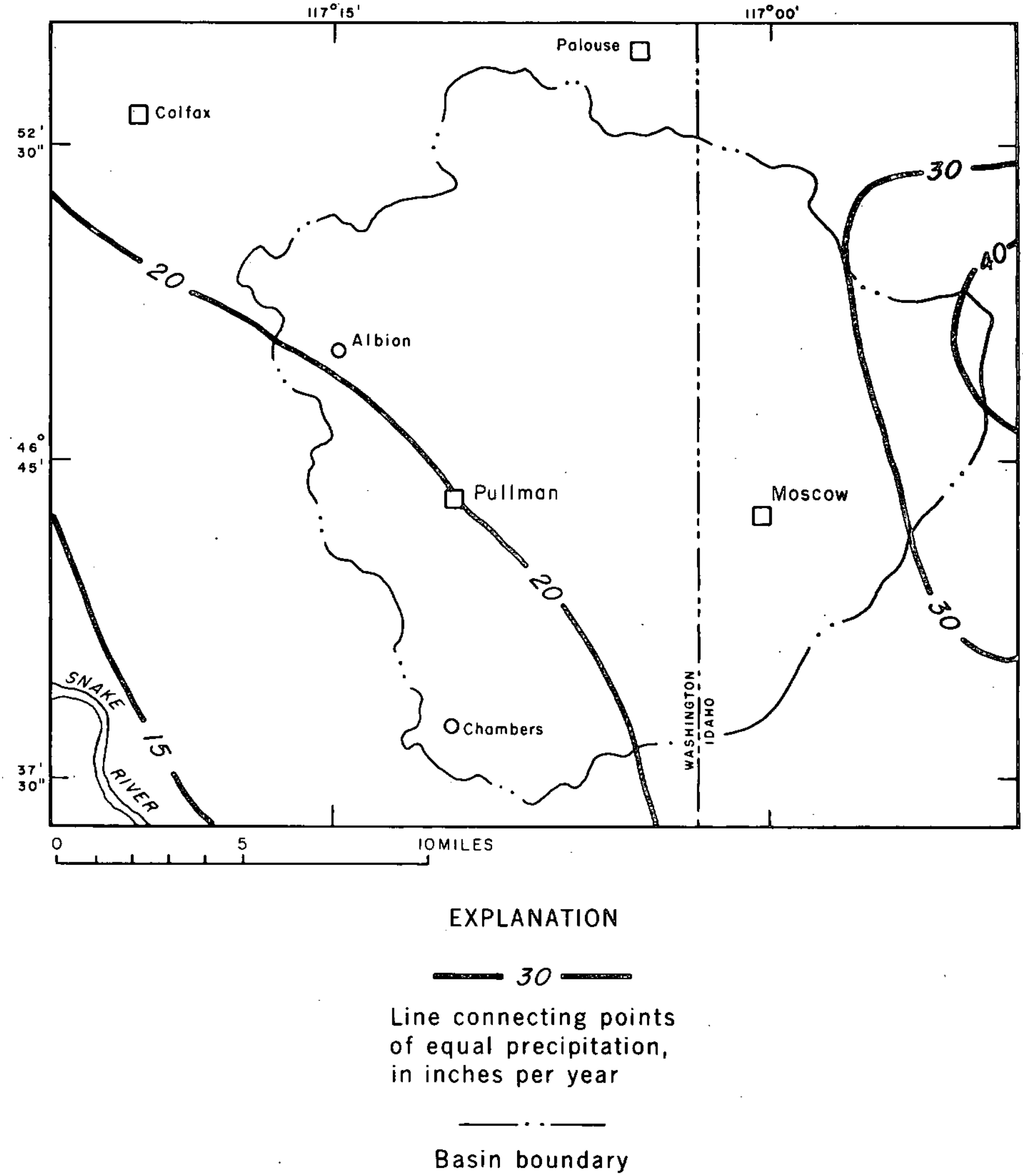


FIGURE 3.--Areal distribution of average annual precipitation in Pullman-Moscow basin and vicinity. From Pacific Northwest River Basins Commission (1969).

Previous Investigations

The study and documentation of the geology and water resources of the Pullman-Moscow basin began with a reconnaissance of the area and report by Russell (1897). The report provides indispensable information about the locations and depths of, and the original water levels in, the first wells drilled in Pullman and Moscow. Since Russell's report, more than two dozen publications have been produced about the geology and hydrology of the basin, parts of the basin, and areas adjacent to the basin. Only those reports most important to the development of the digital model are summarized below.

A report by Stevens (1960) discusses the geology, hydrology, and development of ground-water resources in the vicinity of Moscow, and also provides estimates of future demands on the ground-water supply. The report includes an assessment of the ability of the ground-water system to satisfy these demands with the support of supplemental sources, such as provided by artificial recharge or by surface water.

A report by Foxworthy and Washburn (1963) provides similar information, mainly for the Pullman area, in addition to providing evidence that the Pullman and Moscow areas are two hydraulically distinct subbasins, having a common ground-water boundary near the Idaho-Washington state line. Those writers suggested that artificial recharge might provide the best solution to offset the effects of the continuing water-level decline, and they discussed use of local stream water to accomplish this recharge. Although they recognized that discharge from the artesian aquifers had exceeded local recharge during at least 22 years (1937-59), they presented evidence that natural discharge had decreased during this time while recharge had increased in response to the declining potentiometric surface.

Crosby and Chatters (1965) applied carbon-14 dating techniques to ground-water samples taken from different depths in the basin. From this, the writers concluded that recharge to the deep aquifers in the Pullman area was extremely limited and was perhaps nonexistent in the Moscow area.

Sokol (1966) made an investigation of short-term water-level fluctuations in shallow and deep wells in the Moscow area. He attempted to correlate water-level fluctuations with changes in barometric pressure, pumping, rainfall, surface runoff, wind, and earthquake activity, and he thus provided valuable insight into the hydraulic connection among different artesian zones in the Moscow area.

Tables included in a report by Walters and Glancy (1969) provide an indispensable record of ownership, depth, water levels, and drillers' logs for specific wells in the modeled area. In addition, the report presents a general description of the availability and degree of development of ground water throughout Whitman County.

A comprehensive evaluation of the geology and hydrology of the Moscow subbasin was provided by Jones and Ross (1972). Their work produced valuable data and interpretation related to the geochemistry of the area's waters as well as generalized mathematical models of pumping and associated effects in the Moscow subbasin. These models were based on the theory of image wells (Ferris and others, 1962) and were designed with the assumptions that (1) water-level declines observed in the Moscow area aquifers were solely the result of pumping in the Moscow subbasin (east of the Washington-Idaho state line), and (2) there was no recharge to these aquifers. Experimentation with their models led them to conclude that recharge actually had to be in excess of pumpage and that the ground-water supply in the Moscow subbasin was sufficient to meet the expected demands of that area through at least the year 2000.

A report by Luzier and Burt (1974), although primarily concerned with the regional aspects of ground-water development and depletion in east-central Washington, summarizes the pertinent factors contributing to the water-level declines in the Pullman-Moscow basin. It provides substantial evidence that the deepest aquifers in Moscow are correlative with and in hydraulic connection with the aquifers from which the city of Pullman and Washington State University pump their ground water. In many ways, the explanation of the Pullman-Moscow ground-water situation offered by Luzier and Burt has proven to be the most satifactory to date; much of their interpretation has been incorporated into the design of the ground-water model for the Pullman-Moscow area.

A basic-data report by Crosthwaite (1975) contains well logs, historic water levels, and water-use data for the Moscow subbasin. The interpretation of hydrologic characteristics for that area of the model was aided considerably by data in this report.

In addition to the published reports, a number of unpublished records and reports have likewise contributed to the understanding of the hydrology of the Pullman-Moscow basin. The most important of these include (1) a WSU masters degree thesis on ground-water recharge in the Moscow subbasin by Lin (1967); (2) a collection of pertinent information on the ground-water supply in the Pullman-Moscow area by Packer (1955); (3) an estimate and discussion of the population growth and future water demands for Pullman and Moscow by the engineering consultants, Stevens, Thompson, and Runyan (1970); and (4) a report by Warnick (1971) to the Moscow City Council concerning the advisability of relying on ground water from the aquifers identified at that time in the Moscow area.

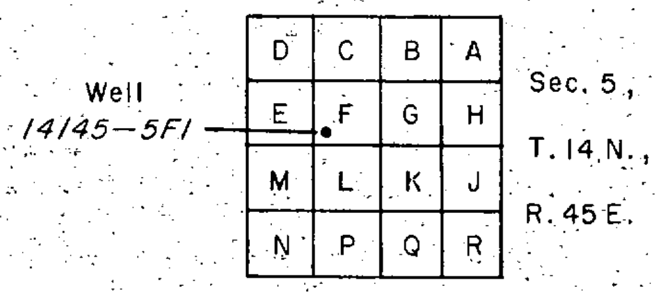
Acknowledgments

The cooperation, services, and advice of many have helped to make this digital model possible. The study was begun by H. H. Tanaka, now with the State of Washington Department of Ecology. His efforts in the spring of 1973 to locate recently drilled wells, measure water levels, analyze historical well data, and construct water-level maps helped to provide a solid data base for the study. Special thanks are due the many land owners and tenants in the study area who allowed use of their wells and property for the measurement of water levels and observation of other geohydrologic conditions. The efforts of Fred Cooper (City of Pullman), Bruce Rutherford (Director, WSU Physical Plant), Roy Reynolds and Bob Schlott (Moscow Water Department), and George Gagon (Engineer-in-Charge, UI Physical Plant) to provide the kind of detailed pumpage data required for reliable calibration of the model are greatly appreciated. Also deserving credit are the city engineering and water departments and their staffs at Moscow and Pullman for assistance throughout the study period. Ideas and suggestions regarding the influence of the basin's geology on the hydrology by J. C. Brown and J. W. Crosby II of WSU, D. R. Ralston of the Idaho Bureau of Mines and Geology, and B. L. Foxworthy of the U.S. Geological Survey helped the author formulate the conceptual model of the area's ground-water-flow regime. The quality of field data collected for this study by Geological Survey colleagues D. R. Cline, B. W. Drost, W. E. Lum II, H. E. Pearson, and C. F. Schneider proved to be invaluable during the model development and calibration.

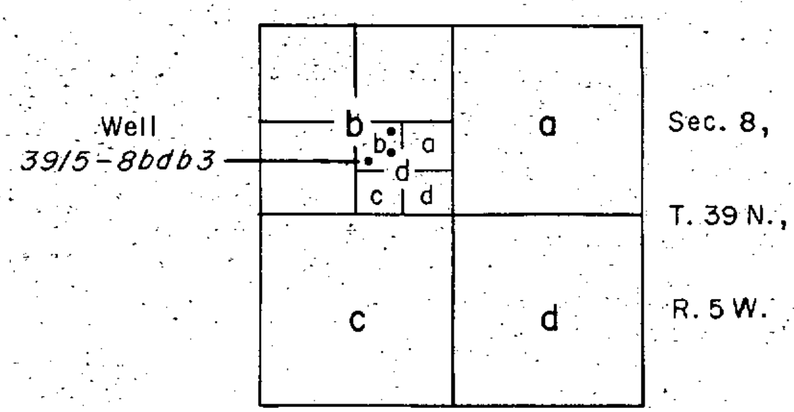
Well-Numbering Systems of Washington and Idaho

Wells providing data for this study have been assigned numbers identifying them by location within a section and township. The numbering systems vary slightly between Washington and Idaho, as described below.

In Washington, in the symbol 14/45-5F1, the part preceding the hyphen indicates successively the township and range (T. 14 N., R. 45 E.) north and east of the Willamette base line and meridian. Because the study area in Washington lies entirely north and east of the Willamette base line and meridian, the letters indicating the directions north and east are omitted. The first number following the hyphen indicates the section (sec. 5), and the letter "F" gives the 40-acre subdivision of the section, as shown in the figure below. The number "1" indicates that this well is the first one recorded within the subdivision.



The well-numbering system used in Idaho indicates the location of wells with reference to the Boise base line and meridian. As in Washington, the first three segments of the number designate the township and range and section number, with the "N" and "W" for north and west of the Boise base line and meridian being deleted. In Idaho the section number is followed by three letters and a numeral, which indicate the quarter section, the 40-acre tract, the 10-acre tract, and the serial number of the well within the tract, respectively. Quarter sections are lettered a, b, c, and d in counterclockwise order from the northeast quarter of each section. Within the quarter sections and 40-acre tracts, quarters are lettered in the same manner. As shown below, well 39/5-8bdb3 is in the NW¼SE¼NW¼ sec. 8, T. 39 N., R. 5 W., and was the third well recorded in that tract.



BASIC DATA

Table 1 contains data on well construction, pumping tests, and pumpage for the most productive wells in the modeled aquifer system. Table 1 also provides a convenient cross reference between the Geological Survey's method of numbering wells (explained in the preceding section) and the sequential well-numbering system used by the local municipalities and universities. Table 4 (at end of report) contains detailed water-level and well data from all known wells in the modeled aquifer system. Plate 1, located in the jacket pocket, shows the locations of all wells that provided data for this study, and the distribution of and average annual pumpage from the modeled aquifer system during the period 1971-75. The finite-difference grid, required for model development, is superimposed on plate 1 to index the sources of well data used to formulate model input. Readers seeking information on wells tapping aquifers other than those in the modeled (primary) aquifer system should consult the reports by Walters and Glancy (1969) and Crosthwaite (1975).

The records of post-1935 pumpage are probably the most complete and reliable of the various kinds of data available to the study. Since the mid-1930's, most pumpage by the local municipalities and universities (which accounts for about 95 percent of the basin's pumpage) has been metered. Annual pumpage from the primary aquifers in the Pullman area was tabulated for years 1936-44 and 1949-59 by Foxworthy and Washburn (1963). Although no year-to-year pumpage totals have been published since 1963, Luzier and Burt (1974) brought the basin's pumpage trends up to date through 1969 in the form of a bar graph, including a breakdown on pumpage from the deep aquifers in Moscow. Requests made of well owners during the period 1973-75 for pumpage totals through 1975 and for specific locations of pumping sites, have provided essentially all the pumpage data required for the calibration of the model.

Original water levels in the Pullman area are available in the report by Russell (1897). More recent water-level data from primarily the same area, dating from the 1930's to the present, are available in the reports by Foxworthy and Washburn (1963) and Walters and Glancy (1969) and from unpublished observation-well records stored at the Geological Survey office in Tacoma, Wash. The reports by Stevens (1960), Jones and Ross (1972), and Crosthwaite (1975) provided this kind of data for the Moscow area. Although historical water-level data from areas other than Pullman and Moscow are generally scarce, water-level measurements since 1972 in outlying areas have provided much useful information.

Surface-water data from gaging sites on Union Flat Creek near Colfax, Wash., Fourmile Creek at Shawnee, Wash., and Missouri Flat Creek at Pullman, Wash., were provided by publications of the Geological Survey (1956, 1962-65, and 1966-75). Although discharge data are generally available for years since 1960, serious gaps in these data for streams inside the basin exist between 1940 and 1959. In September 1974, three miscellaneous discharge measurements were made along Paradise Creek, between the Moscow sewage-treatment plant and a point about 3 miles downstream, in an attempt to detect seepage loss to the underground basalt formations. (See p. 95.)

TABLE 1.--Records of municipal- and university-supply wells tapping the primary aquifer system at Pullman and Moscow

Well owner and owner's number	Model cell location	USGS well number	Well depth (ft)	Altitudes between which the well is open to aquifer (ft)	Average annual pumpage, 1971-75 (acre-ft)	Pump-test data		Computed transmissivity (see p. 62 of text)	
						Yield (gal/min)	Drawdown (ft)	(ft^2/s)	(gpd/ft)
City of Pullman wells:									
1	(21,17)	14N/45E-5D1	155	2187-2207	75	1200	6	0.62	400,000
2	(20,18)	15N/45E-32N1	231	2119-2326	50	800	43	.06	37,000
3	(21,17)	14N/45E-5D3	167	2175-2302	525	1350	106	.04	26,000
4	(20,18)	15N/45E-32N2	954	1396-1951	525	1000	18.5	.17	108,000
5	(23,17)	14N/45E-8E1	712	1730-1770	425	1799	175	.03	20,500
6	(18,18)	15N/45E-32C2	518	1912-2195	550	1500	15	.31	200,000
Washington State University wells:									
1	(21,18)	14N/45E-5F2	237	2127-2324	175	500	--	--	--
2	(21,18)	14N/45E-5F5	213	--	125	--	--	--	--
3	(21,18)	14N/45E-5F3	223	--	650	1500	23	1.55	1,000,000
4	(21,18)	14N/45E-5F4	275	2089-2101 2103-2158 2262-2299	900	1690	1.5	3.49	2,000,000
5	(20,22)	15N/45E-34L2	396	2119-2215	175	503	2.67	.58	377,000
6	(20,20)	14N/45E-4D1	702	1834-2144	(new well in 1975)	1865	53	.11	70,000
City of Moscow wells:									
6	(19,39)	39N/5W-8bdb1	600	1292-1695	600	900	26	.11	69,000 *(100,000)
8	(19,33)	39N/5W-7bda2	1458	1159-1570	1000	1200	43	.08	56,000 *(80,000)
University of Idaho well:									
3	(20,33)	39N/5W-7cbb1	1336	1222-1357 1422-1666 1782-1897	825	2400	7	1.06	686,000 *(1,000,000)

*From Jones and Ross (1972, p. 30).

Monthly records of average daily treated sewage discharge into Paradise Creek by the Moscow sewage-treatment plant are available for the years 1960-75. Records of effluent into the South Fork Palouse River from the Pullman plant are available for all years since 1949. These data were important to the study for evaluating recent increases in basin runoff.

Climatological data published by the U.S. Weather Bureau (through 1969) and [U.S.] National Weather Service (since 1969) were used in conjunction with precipitation maps developed by the Pacific Northwest River Basins Commission (1969) to estimate the amount and distribution of annual precipitation over the basin. Crop-growth data provided by the U.S. Department of Agriculture (1967), as well as information provided by Stevens (1960, p. 342), were used to estimate rates of ET in the basin. These kind of data were used to help define recharge and discharge relationships within the study area.

An inventory of wells drilled since about 1965 and an update of information on older wells were conducted during this study in the spring of 1973. At that time, water levels in more than 100 wells were measured to help delineate the distribution of the potentiometric levels in known aquifer zones. Water levels were measured again in March and October of 1974 and June 1975 to help define the current patterns of water-level declines in the various aquifer zones.

Boundaries and aquifer properties of the modeled flow system were interpreted mostly from well logs, well records, and geologic maps and cross sections provided by the following reports: Crosby and Cavin (1960), Foxworthy and Washburn (1963), Lin (1967), Walters and Glancy (1969), and Crosthwaite (1975). In general, surficial contacts between the basalt and the crystalline rocks shown in these reports were mapped originally by Treasher (1925).

Serious obstacles to an adequate understanding of the ground-water-flow regime in the Pullman-Moscow basin have long resulted from extremely limited information on the subsurface distribution of the crystalline basement complex--expecially in the area of ground-water outflow between Albion and Chambers (fig. 2). To alleviate difficulties of this kind facing the modeling effort, a geophysical survey using gravity and electrical-resistivity methods was made in October 1974. The results of this survey are summarized on pages 48-50 of this report.

GEOHYDROLOGIC SETTING

The oldest rocks in the Pullman-Moscow basin are quartzite and gneiss of Precambrian age and granitic rocks of Cretaceous age (Tullis, 1944). These crystalline rocks form the outlying ridges and buttes encircling the basin (figs. 1 & 12) and constitute the basement complex underlying the modeled aquifer system. Before Miocene time, the ancestral mountains (of which the ridges and buttes are remnants) had been eroded to a mature land surface of considerable relief by westerly and southwesterly flowing streams.

During Miocene time, the lower parts of the basin were buried by a sequence of nearly horizontal basaltic lava flows and less extensive layers of sediment eroded from the surrounding crystalline highlands. The sediments (primarily clay, silt, and sand) were deposited along streams and in lakes created by the damming of streams by lava flows around the margins of the basin. These sedimentary interbeds within the basalt sequence are as much as 400 feet thick in the Moscow area, near the base of the crystalline highlands, but thin sharply toward Pullman, where they are generally less than 10 to 15 feet thick.

After the filling of the basin lowland by basalt and sedimentary deposits during middle Miocene through early Pliocene time, the upper surface of these materials were dissected by erosion. Then windblown silt (loess), originating primarily from glacial lakebed deposits, settled over the area in thicknesses exceeding 100 feet in places. Most of the loess is included in the Palouse Formation, named by Treasher (1925), which is of Pleistocene age. Subsequent and continuing erosion have reduced the crystalline highlands to their present heights and sculptured the lowlands into the rolling topography characteristic of the area today (fig. 12).

The basalt and minor interbedded sedimentary rocks (fig. 4) are all considered to belong to the Columbia River Basalt Group (Griggs, 1976). The basalt was mapped by Walters and Glancy (1969) as the Yakima Basalt, which was originally defined by Waters (1961). However, the nomenclature of the lacustrine and alluvial deposits which interfinger with the Columbia River Basalt Group in the Pullman-Moscow basin differs among some investigators. Stevens (1960) considered these as part of the Latah Formation, the name given by Pardee and Bryan (1926) for sedimentary exposures along Latah Creek south of Spokane (north and outside the present study area). Siems, Bush, and Crosby (1974, p. 1061) considered these sedimentary interbeds to be part of the Ellensburg Formation.

The Basalt and Regional Hydrology

The Columbia River Basalt Group underlies about 55,000 mi^2 in Washington, Oregon, and Idaho--the area known as the Columbia Plateau (Fenneman, 1931). Because the most important aquifers in the Pullman-Moscow basin are in rocks of this group, certain aspects of the regional geohydrology are pertinent to an understanding of the ground-water occurrence and availability in the basin, and are therefore discussed below.

A typical sequence of the Columbia River Basalt Group is composed of extensive lava flows, from 10 to 150 feet thick, which thin toward the margins and overlap laterally. The sequence in eastern Washington ranges from more than 10,000 feet in thickness to a few feet where it abuts the crystalline basement rocks around the margins of the Columbia Plateau province (Newcomb, 1959, p. 2-3). Originally, the basalt flows were horizontal, or nearly so, but deformation of the earth's crust has altered the original altitudes in places. Deformation of the basalt in eastern Washington is usually observed as a gentle warping of the rock layers. However, in some places crustal disturbances have been of greater magnitude, resulting in large-scale folds or vertical displacements of individual flows along fracture surfaces (faults).

Ground water beneath the Columbia Plateau occurs most commonly in (1) the upper, characteristically broken parts of basalt flows; (2) the unconsolidated sedimentary material between flows; and (3) the basal parts of the basalt flows, particularly in pillow structures formed where the lava flowed into water and cooled very rapidly. These permeable flow-contact zones are most often found to be from 1 to 10 feet thick. The cracks and crevices characteristic of the flow-contact zones and the interflow sedimentary materials cause a basalt sequence to transmit water through a series of stacked, roughly horizontal layers which are virtually isolated from each other by the massive, nearly impermeable strata--the basalt flow centers. These massive interior parts of basalt flows are typically dense and do not generally transmit or store significant quantities of water. However, these dense layers are generally crossed vertically to some extent by narrow cracks which developed as the molten lava shrank upon cooling, and these cracks may provide avenues for vertical seepage between aquifers. However, ground-water seepage through such cracks occurs very slowly compared to the lateral seepage in the flow-contact zones.

Because sedimentary interbeds between basalt flows--where they exist--are generally fine grained, they generally do not yield water at appreciable rates. In general, interbeds restrict the passage of ground water and they are often observed to confine water under artesian pressure within underlying more permeable layers. However, coarse interbeds of sand or gravel are productive aquifers in some areas beneath the Columbia Plateau.

Water in the basalt aquifers is typically confined under pressure and the resulting hydrostatic heads--when defined over large areas--comprise what is known as a potentiometric surface. Vertically separated aquifers beneath the Columbia Plateau generally exhibit different potentiometric surfaces. In general, the magnitude of head difference between two or more aquifers is a measure of the degree of hydraulic isolation provided by the intervening interbeds or dense basalt. Hydrostatic heads are typically highest in the shallowest aquifers and are progressively lower in the deeper zones.

Wells tapping the basalt sequence typically penetrate more than one water-bearing zone, with each zone displaying a different pressure head. Because hydraulic isolation does not exist inside a well bore, water levels measured in wells which are not completely cased may represent composite heads from all aquifers open to the well. The more productive aquifers have more influence on composite water levels than do the less productive aquifers. In deep, multi-aquifer wells that are uncased, or partially so, water may move up or down within the well bore between the deeper and shallower aquifers. Because heads are commonly lower in the deeper aquifers, cascading water is characteristic of most wells in the region (Luzier and Burt, 1974, p. 8-10).

Faults, folds, and dikes in the basalt sequence are known to substantially affect the lateral movement of ground water in many areas of eastern Washington. Such features can control water levels and impede, or even effectively block, ground-water movement. In addition, spring locations are generally structurally controlled--as may be the temperature and chemical quality of ground water.

Newcomb (1965, p. 29) described other effects of basalt geology on the hydrology:

> "The permeability and transmissive qualities of even the thickest aquifers differ from place to place. Tight, nonporous places are present at intervals along most aquifers. Stratigraphic discontinuities--the pinching out, overlapping, and fusion of flows and interflow zones--are present. Stratigraphic traps, in which the permeable zones taper out between less permeable strata, in places cause ground water to be impounded back to a point of overflow or leakage around the structure."

Because there are many physical and structural variables affecting the occurrence and transmission of ground water in basalt of the Columbia River Basalt Group, local circulation patterns can be extremely complex. The relief in the potentiometric surface of even an individual aquifer can vary substantially, depending on local recharge and discharge relationships, and on lateral and vertical changes in rock porosity and hydraulic conductivity. As described by Jones and Ross (1972, p. 12):

> "The lateral extent of the different aquifers is variable; therefore, hydraulic connection between nearby wells of similar depths is variable. In some places, water levels in a well will show considerable effect of pumping from a nearby well of similar depth; in other places, nearby wells will have little effect and more distant wells may have noticeable effect."

In spite of the complexities of basalt hydrology, the water-bearing zones can usually be divided into at least two general aquifer groups: an upper, shallow aquifer unit and a lower, deeper unit. This subdivision has been used in modeling the basalt aquifers in the Columbia Plateau (Luzier and Skrivan, 1973, Mac Nish and Barker, 1976). The subdivision has been based on the somewhat different aquifer characteristics and contrasting water-level patterns displayed by the two different depth intervals. The shallower aquifers are cut locally by canyons or other surface depressions so that their areal extent is limited and they are not generally connected to significant sources of lateral recharge. The deeper aquifers are generally continuous areally over greater distances than are the shallower aquifers and are usually the more productive. These deeper aquifers typically comprise the regional flow system and are often referred to collectively (as in this report) as the primary aquifer system (fig. 4).

Previous Interpretations of the Local Ground-Water System

Previous hydrologic studies in the Pullman-Moscow basin have yielded useful information regarding ground-water conditions in the immediate vicinity of the cities of Moscow and Pullman, including the University of Idaho and Washington State University. However, because of a scarcity of wells elsewhere, an understanding of other parts of the ground-water system had to be largely extrapolated from those two centers of information. In the following discussions of previous studies and how they contributed to the present understanding of the ground-water system, only the major basalt aquifers and associated sedimentary materials are emphasized.

Moscow Subbasin

Jones and Ross (1972) and Crosthwaite (1975) subdivided the aquifers in the Moscow subbasin into so-called upper, middle, and lower artesian zones on the basis of water levels, chemical quality, and stratigraphic position. The distribution of these zones and their relationship to rock types in the area can be seen in figure 4. This illustration combines the geologic contacts that were defined by Lin (1967, fig. 12) with the nomenclature on the stratigraphy and artesian zones defined by Jones and Ross (1972, fig. 4). The most productive aquifers within each of the three zones are in basalt, although some wells penetrating the upper artesian zone near the eastern part of the area may produce entirely from the upper interbeds (fig. 4).

Jones and Ross (1972, p. 12), described the upper artesian zone as extending "from the surface--or the base of the surficial aquifers--to depths of about 700 feet." Until 1964 all significant quantities of ground water pumped in the Moscow subbasin came from this zone. Probably 95 percent of the pumping was done by the city of Moscow and the University of Idaho; together, this withdrawal averaged about 1,700 acre-ft/yr between 1948 and 1960 (Jones and Ross, 1972, p. 37).

Although the first wells drilled into the upper artesian zone (in the 1890's) were flowing at the time of completion, by 1960 static water levels in this zone had declined to nearly 100 feet below land surface at some places. Because of this decline and the fact that excessive amounts of dissolved iron and moderate hardness were characteristic of water in the shallow zone, new public-supply and university wells were drilled in the early 1960's to pump from deeper strata.

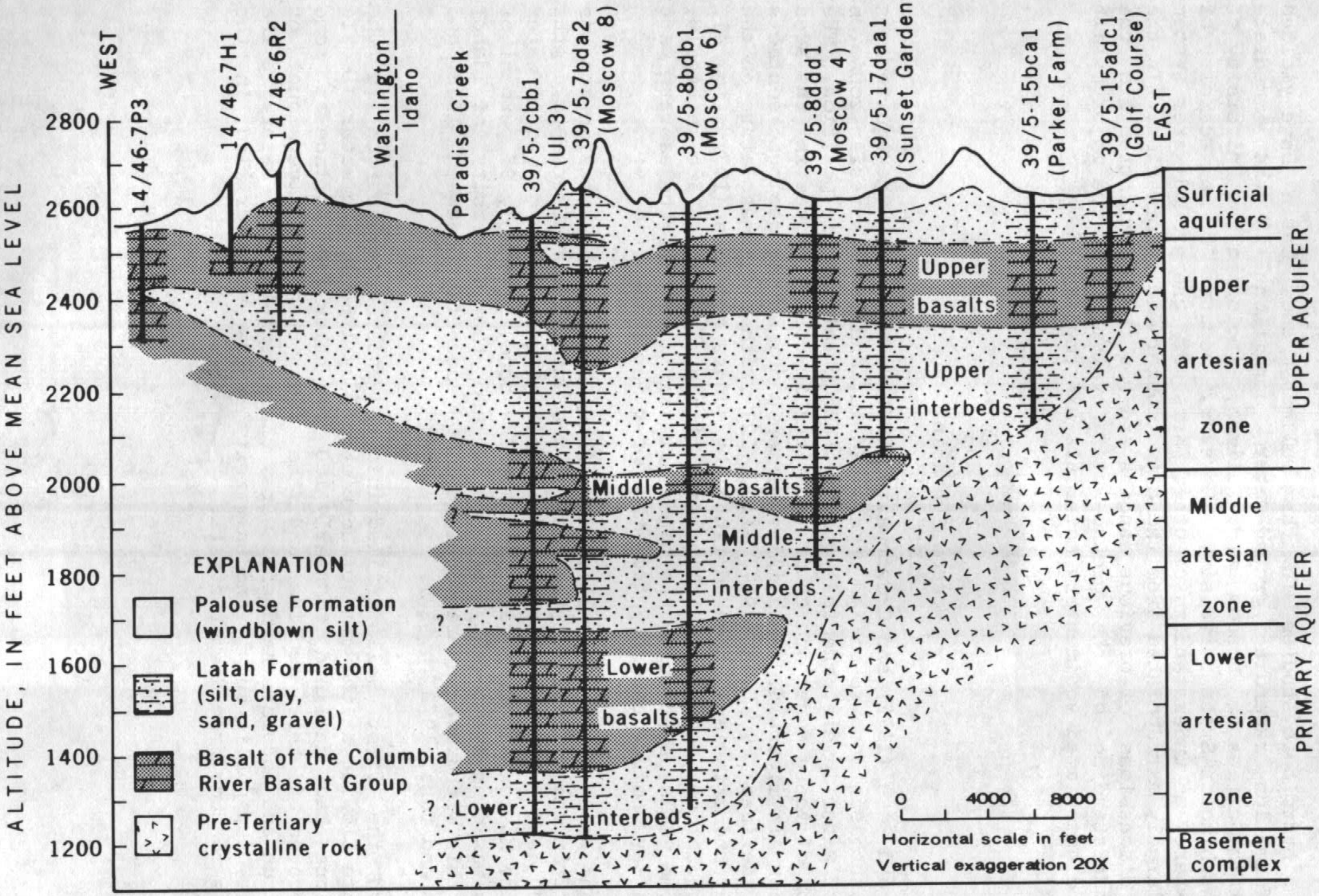


FIGURE 4.--West-to-east schematic geologic section through Moscow subbasin, showing nomenclature of aquifer units and correlation of units between wells. From Lin (1967) and Jones and Ross (1972).

As described by Jones and Ross (1972, p. 13):

> "By the mid-1960's, heavy pumping from the upper artesian zone ceased except during peak demand periods or during emergencies when the deeper wells could not be pumped because of difficulties with the pumps. Although the number of domestic wells drilled into the upper artesian zone has increased every year, the combined total pumpage of the domestic wells in the late 1960's probably was no more than 100 gpm [gal/min]."

From the time pumping from the upper artesian zone abated, water levels in the zone have been rising--having recovered as of March 1974 to an altitude of approximately 2,505 feet (fig. 5), or to within about 50-60 feet of the land surface in most areas.

Jones and Ross (1972, fig. 4) defined the middle artesian zone as lying between altitudes of about 1,700 and 2,000 feet and the lower artesian zone as lying between altitudes of about 1,200 and 1,700 feet. As of 1975, these zones were penetrated by only three producing wells. According to Jones and Ross (1972, p. 13):

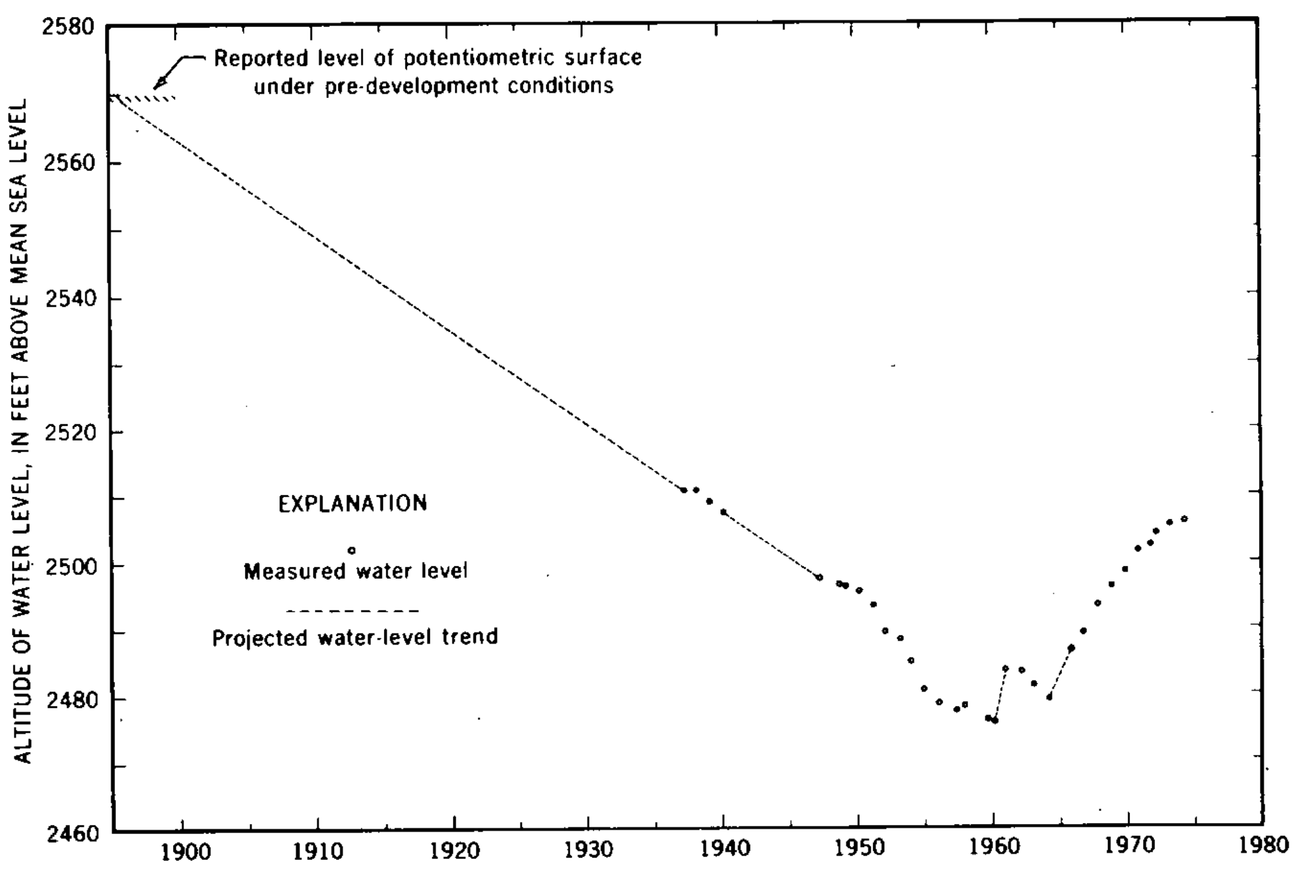


FIGURE 5.--Hydrograph of well 39/5-7ddc1, showing typical pattern of water-level change in "upper artesian zone" in Moscow area.

> "The only well that obtains large amounts of water from the middle artesian zone is University of Idaho Well 3. Although the well was drilled through the lower artesian zone and into the crystalline basement, the lower artesian zone was not productive at University 3 and the casing was perforated between depths of 660 and 775 feet, (elevation 1,905-1,790) in the middle artesian zone***.

Those authors continue to say:

> "City 6 and City 8 Moscow wells 6 and 8 derive water from the lower artesian zone--City 6, from both basalt and a sedimentary interbed, and City 8, from basalt. The productive zones are in the lower part of the lower artesian zone, at about depths of 1,000 to 1,400 feet (elevations 1,600-1,200 feet)."

During 1971-75 pumpage from the University of Idaho well 3 averaged about 800 acre-ft/yr and pumpage from Moscow wells 6 and 8 together averaged about 1,600 acre-ft/yr. During the recent 5 years, combined pumpage from the middle and lower artesian zones has averaged about 2,400 acre-ft/yr.

Although water levels in the two deeper artesian zones in Moscow were not measured before 1960, the potentiometric surface of each of the deeper zones is believed to have been always lower than that of the upper zones. In 1965 the static (non-pumping) water levels in Moscow wells 6 and 8 and in UI well 3 were all within 5 feet of the 2,310-foot altitude and presently (1975) stand at about the 2,280-foot level. Therefore, the average annual rate of decline during the last 10 years has been about 3 feet per year in each of the three wells.

Pullman Subbasin

Although in the past the characteristics of ground-water occurrence and availability in the Pullman subbasin appeared in some ways similar to that in the Moscow subbasin, in other ways it appeared to be very dissimilar. As a result, controversies developed regarding the degree of hydraulic interconnection between the two subbasins.

Foxworthy and Washburn (1963) provided evidence supporting the existence of a ground-water barrier between Moscow and Pullman "on the basis of significant differences in altitudes and fluctuations of water levels in the two areas and differences in chemical character of the ground water." At that time, however, the only pertinent data available for the Moscow area was from the so-called upper artesian zone (fig. 4); these data came from wells tapping aquifers primarily in the upper basalts, at altitudes above 2,300 feet. Most data for the Pullman area were collected from the most productive WSU and city wells, which tapped aquifers below the 2,300-foot level. To conclude that aquifers in each of the two areas were hydraulically distinct, therefore, Foxworthy and Washburn (1963) had compared data for aquifers below the 2,300-foot altitude in the Pullman area to data representative of aquifers above that altitude in the Moscow area.

Data that became available after Foxworthy and Washburn's fieldwork allowed Luzier and Burt (1974) to compare hydraulic characteristics of the deeper aquifers at Moscow to the same at Pullman. In doing so, they discovered similarities not only between static water levels but in long-term water-level declines in both areas. Luzier and Burt (1974, p. 33) suggested that the reason for the apparent mismatch between hydraulic and water-quality data for Pullman and for Moscow--which had been documented earlier by Foxworthy and Washburn (1963)--might be explained by differences in the altitudes of the aquifers from which the data were collected. Because the static water level and the rate of water-level decline in UI well 3 (drilled near Moscow in 1963) seemed to correspond to the static water levels and the rates of decline in the city and university wells at Pullman, Luzier and Burt (1974, p. 33) suggested that hydraulic continuity in the "deep" aquifers does indeed exist between Moscow and Pullman. As they stated:

> "***evidence strongly suggests that (1) prior to 1960, pumpage and water-level declines at Pullman and Moscow were occurring in aquifers vertically and hydraulically separated from one another, those at Moscow being at a higher level; and (2) the newly tapped deeper aquifers at Moscow are probably correlative with and hydraulically connected with aquifers used for public supply at Pullman. Therefore, accelerated rates of decline at Pullman may be due in part to pumpage in the Moscow area as well as increased pumping at Pullman."

Foxworthy and Washburn (1963) had earlier acknowledged the difference in the hydraulic characteristics between wells in the vicinity of Pullman which penetrate strata above about 2,300 feet and those wells which penetrate below this level. They recognized that the upper parts of the basalt sequence in Pullman (above an altitude of about 2,300 ft) contained aquifers of relatively small yields and high, variable water levels, whereas at greater depths the water levels were somewhat lower and more consistent, and the yields much greater.

Geohydrologic Interpretation and Rationale for Model Study

Because any aquifer system is too complex to model exactly, all that is known and hypothesized about the system must be first condensed into a conceptual model (a mental "blueprint") retaining only those characteristics essential to the goals of the project. It is from this conceptual model that the working model is later developed. The conceptual model is based on the construction and study of various kinds of geohydrologic maps and quantitative descriptions of the aquifer system in time and space. This section of the report describes such data and much of the reasoning used in formulating the conceptual model--and eventually the digital model--of the major aquifer system in the Pullman-Moscow basin.

Much of the local controversy and concern over whether or not the Pullman and Moscow subbasins are hydraulically isolated continued into the recent (1973-75) study, in spite of the well-founded conclusions by Luzier and Burt (1974). However, data collected during the recent study indicate that a legitimate argument <u>against</u> interconnection might exist only for the upper aquifers of both areas and that aquifers below altitudes of approximately 2,300 ft in the Pullman area are part of the same aquifer system as are those aquifers within the so-called middle and lower artesian zones in Moscow.

The deep, relatively productive aquifer system--common to all explored areas within the horseshoe-shaped enclosure of crystalline rocks (fig. 2)--is herein referred to as the primary aquifer system. Also, for convenience, all aquifers of the Columbia River Basalt Group overlying the primary aquifer system are collectively referred to as the upper aquifer zone. As will be shown in following discussions, static-water levels and the pattern of water-level decline in all aquifers of the primary system are remarkably consistent, thus permitting these aquifers to be modeled as a single hydrologic unit; the upper aquifer zone is treated in the model as being the source of vertical recharge to the primary aquifer system.

The separation of the aquifers in the Pullman-Moscow basin into two units was based largely on the relationship seen in figure 6, where water-level altitudes measured in rocks of the Columbia River Basalt Group inside the basin are plotted against the altitudes at the bottoms of the wells from which the measurements were obtained. The contrast between static water levels in the primary aquifer system and those in the upper aquifer zone becomes readily apparent in this comparison.

With the one exception noted below for Moscow well 7, all water levels shown in figure 6 were measured during the period 1973-74. All water levels in the Pullman subbasin were measured in March 1974. Water levels in the Moscow subbasin in all but the four deepest wells (Moscow wells 6, 7, and 8, and UI well 3), were measured in March 1973 by E. G. Crosthwaite (written commun., 1973).

Unfortunately, Moscow well 7 (well 39/5-7bda1 in table 4 and fig. 6) had no access for water-level measurement during the recent study. This well is unused, having been abandoned at a depth of 632 feet because of caving problems during drilling (Sokol, 1966, p. 11). The water level in the well was most recently measured (December 31, 1966) to be 217.13 feet below land surface (Crosthwaite, 1975, p. 58). Because Moscow well 7 penetrates strata for which water-level data are extremely scarce, this water level is shown in figure 6.

Water levels used in figure 6 for the three deepest wells in the Pullman-Moscow basin (Moscow wells 6 and 8, and UI well 3) were measured on August 21 and 22, 1974. This was during a time of prolonged pumping and it was not possible to shut off the pumps long enough to allow full recovery of the water levels. Nevertheless, the nonpumping water levels, which ranged from 2,259 to 2,280 feet in altitude, seem to correlate reasonably well with those measured elsewhere in the primary aquifer system during March of the same year. When water levels in these wells were measured during a period of less intensive pumping on June 4, 1975, the altitudes were 2,281 feet in Moscow well 6 (unpumped for 4 months), 2,271 feet in Moscow well 8 (unpumped for 30 minutes and water level still recovering), and 2,282 feet in UI well 3 (unpumped for 30 minutes).

Although the bottoms of most wells tapping the primary aquifer system in the Pullman subbasin are between altitudes of 2,000 and 2,300 feet, three wells penetrate deeper, to altitudes of 1,396 feet in Pullman well 4, 1,730 feet in Pullman well 5, and 1,912 feet in Pullman well 6. Measured water-level altitudes in these wells on March 28, 1974, were 2,291.2, 2,281.6, and 2,291.7, respectively.

One of the shallowest wells in the primary aquifer system (bottom-hole altitude of 2,219 ft) is the WSU observation well (14/45-5F1). The measured water-level altitude in this well was 2,286.7 feet on March 28, 1974. It is noteworthy that, although the WSU well taps only strata that are completely sealed off in Pullman wells 4, 5, and 6 (table 1), static water levels in all four wells are remarkably similar.

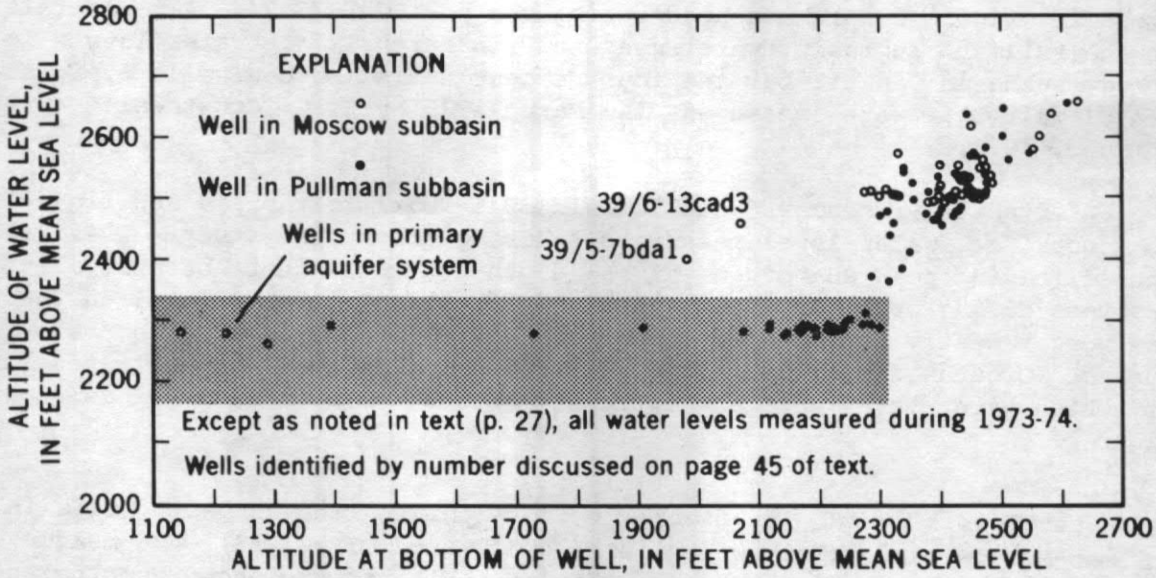


FIGURE 6.--Relationship between altitudes of well bottoms and of water levels within the Pullman-Moscow basin.

Upper Aquifer Zone

Hydraulic conditions observed in wells above the primary aquifer system vary greatly from place to place, depending mainly on each well's finished depth and on the number and nature of the water-bearing zones penetrated. The most important characteristics of these upper aquifers are discussed below.

Many of the shallowest wells penetrate aquifers which are apparently perched above impervious lenses of clay or dense basalt. These surficial aquifers are generally limited in extent, contain water under water-table (unconfined) conditions, and are not everywhere dependable as year-around sources of water.

Although deeper wells in the upper aquifer zone penetrate confined aquifers that are generally more dependable, well yields in the Pullman subbasin are substantially less than those in the Moscow subbasin. Typically yielding less than 20 gal/min, upper-aquifer wells in the Pullman subbasin will not support heavy pumping. In contrast, upper-zone wells in Moscow have yielded sufficient water to satisfy the demand for university and public supply in that area until the early 1960's (p. 21).

At present, conditions in the upper aquifer zone make this zone important primarily as a source of domestic and stock water. Such conditions can be generalized as (1) limited productivity of the upper aquifers in the Pullman subbasin and (2) generally poor quality of water in these aquifers in the Moscow subbasin. In addition the upper aquifer zone serves as the source layer for downward leakage to the primary aquifer system, as explained in detail, beginning on page 72.

Water levels in the upper aquifer zone in the Pullman subbasin have characteristically declined less than 10 feet since first observed in the 1940's or 1950's. Although continuous, long-term water-level data from the relatively shallow basalt wells in the Pullman subbasin are not available, comparisons made between earliest available water levels and those measured during 1973-75 indicate that the upper aquifers in most places have undergone little, if any, historical water-level decline. Water levels at some places in the shallow aquifers appear to have actually risen in recent years. These water-level trends in the Pullman area are, of course, in sharp contrast to those in the Moscow area (shown in fig. 5), owing primarily to the different conditions of pumping stress in each of the two areas.

Because most of the wells in the upper aquifer zone were drilled only to a depth of the first reasonably productive aquifer, the bottom-hole altitudes of these wells are generally good indicators of aquifer altitudes. The general relationship displayed by most aquifers in the upper zone is that of decreasing head with decreasing altitude of aquifer (fig. 6). Because heads in the upper aquifers are typically graded to the level of the nearest major surface drainage, there is generally a strong similarity between the shape of the potentiometric surface and the overlying land surface.

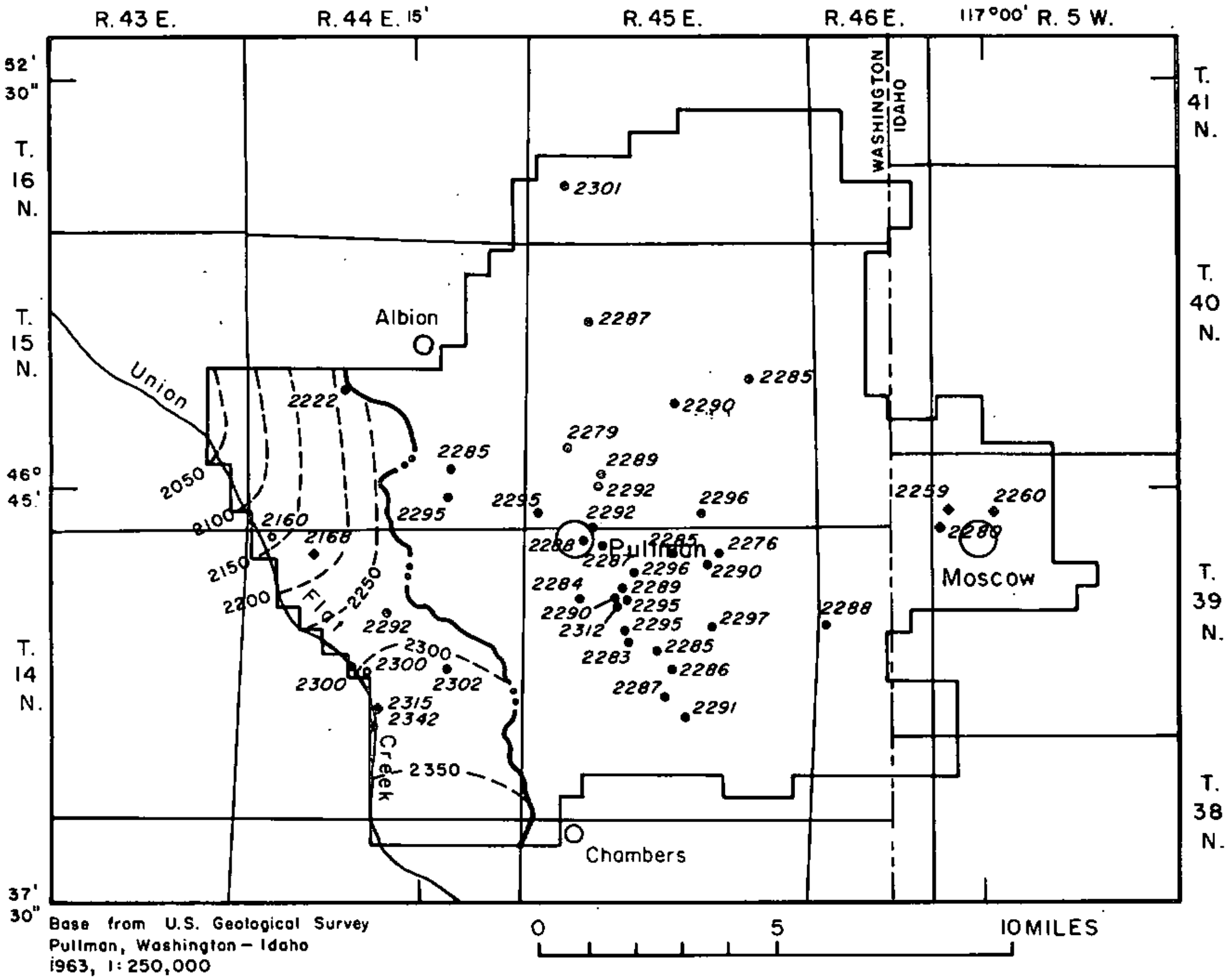
A potentiometric map for the upper aquifer zone, depicting pre-development ground-water conditions, was constructed (fig. 23, p. 76) using water-level data presumed to be most representative. Although the potentiometric surface is highly generalized, the overall gradient pattern is similar to that mapped for basalt aquifers elsewhere in eastern Washington (Luzier and Burt, 1974, figs. 4 and 5; and Mac Nish and Barker, 1976, fig. 2). Data extrapolated from figure 22 were used in the model to represent head conditions in the upper layer. These data for the Moscow subbasin were adjusted throughout transient simulation to account for the historical water-level fluctuation in that area, as explained further on page 75.

The Primary Aquifer System

In contrast to the varied nature of the hydraulic conditions observed in the upper aquifer zone, conditions within most of the underlying, primary aquifer system appear to be remarkably consistent, both areally and with depth. The most important differences are observed, not within the basin, but in the area west of the basin, between the surface-water divide and Union Flat Creek. These similarities and contrasts are discussed below, in relation to explanations of how the local ground-water system is believed to function.

The areal distribution of the water levels measured in the primary aquifer system in 1974 is shown in figure 7. The uniformity among water levels inside the basin is, again, strongly evident here. Water-level differences in wells at various locations in the central part of the basin are relatively insignificant; considering the possible errors in land-surface altitude and the effects of composite heads in wells tapping several water-bearing zones, it becomes futile to attempt to delineate flow gradient in detail or contour a potentiometric surface. Only when consideration is given to water levels measured outside and west of the basin does the pattern of a nearly flat potentiometric surface break down. Water levels observed in the deepest explored aquifers west of the basin indicate a potentiometric surface that, for the most part, slopes toward Union Flat Creek--although limited data suggest that this surface slopes toward the basin in the southwestern part of the modeled area. Possible causes and implications of this apparent change in the slope of the ground-water gradient west of the basin are discussed beyond, beginning on page 37.

Year-to-year water-level data for the primary aquifer system exist only for wells in the vicinity of Pullman and Moscow. Figure 8 shows hydrographs of static water levels for four wells in the Pullman area and one well--the UI well 3 (39/5-7cbbl)--in Moscow. These hydrographs indicate a long history of similar water levels in all explored deep aquifers in the area surrounding Moscow and Pullman.



EXPLANATION

Water level measured March 1974

Water level measured August 1974

Water level reported (by owner) August 1974

Boundary of western segment of basin

---2200---
Inferred location of equi-potential lines, based on water-level measurements and elevation of stream stage in Union Flat Creek. Indicated altitudes are in feet above mean sea level.

FIGURE 7.--Areal distribution of 1974 water-level altitudes in primary aquifer system.

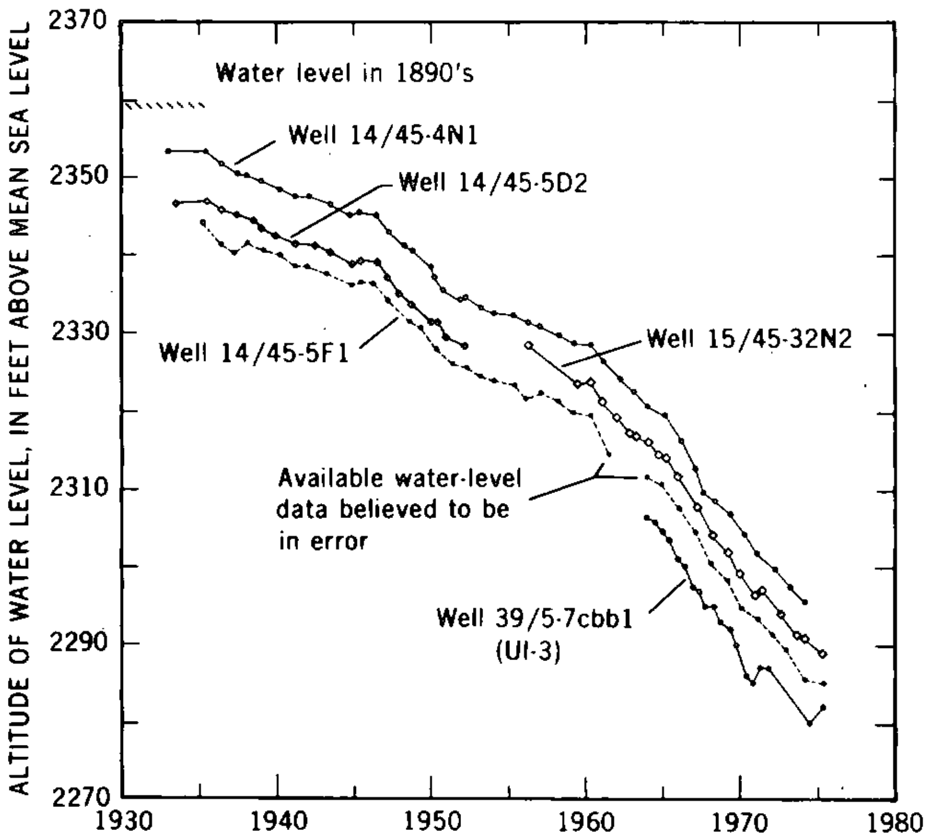


FIGURE 8.--Hydrographs showing water-level declines in wells tapping the primary aquifer system.

Historical water-level data for areas other than Pullman and Moscow are relatively sparse. However, static water levels reported by drillers upon the completion of new wells are generally available for outlying areas. In addition, water levels were measured in numerous outlying wells for the first time during the 1950's by Foxworthy and Washburn (1963). Water levels in almost all of these outlying wells were again measured in June 1975. In figure 9, earliest recorded water levels (prior to 1960) are paired with water levels measured in the same wells in June 1975. Although each hydrograph in figure 9 is based on only two data points--and is therefore a straight line--the consistent pattern of water-level decline in the primary aquifers throughout the Pullman-Moscow basin can be recognized from these data.

Many of the earliest recorded water levels shown in figure 9 were reported by well owners and drillers, and most of these levels compare favorably with those measured by Geological Survey personnel at a comparable time. However, because of the questionable accuracy of the earliest reported water levels in wells 15/45-8M2, 15/45-9C1, and 15/45-14Q1 (table 4), hydrographs for these wells are not included in figure 9.

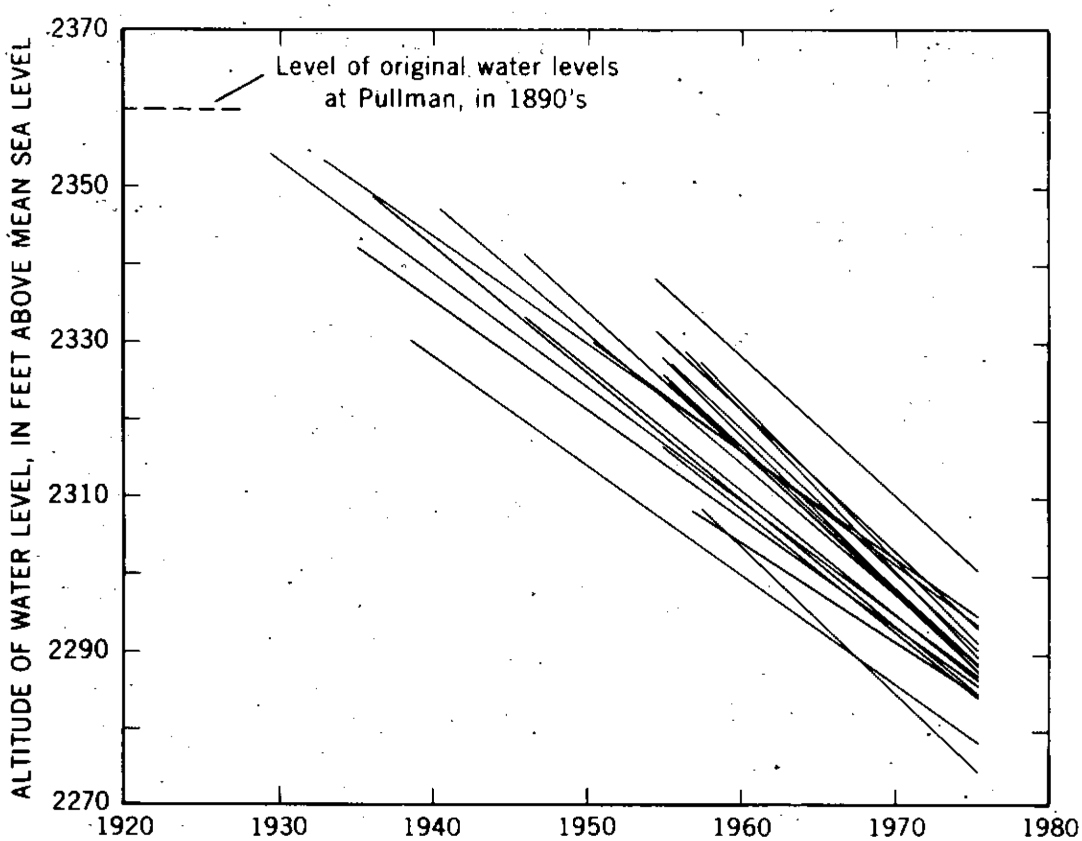


FIGURE 9.--Comparison of earliest recorded water levels (left end of lines) in wells tapping primary aquifer system with water levels measured in same wells in June 1975 (right end of lines).

Year-to-year water-level data have been recorded since the mid-1960's for each of the three deepest wells in the Moscow area; however, only the records for UI well 3 (fig. 8) appear to be dependable through the entire period of record. Although the long-term pattern of water-level decline in Moscow wells 6 and 8 generally conforms with that in UI well 3, the shorter-term fluctuations in both Moscow wells are comparatively erratic (fig. 10), which is related partly to the fact that these two city wells penetrate rocks of lower transmissity (table 1) and therefore recover from pumping at a slower rate than does the university well. In addition, these Moscow wells must be pumped almost continuously during most of the year to maintain a public supply, whereas the university well is pumped less frequently. Therefore, non-pumping water-level measurements made in the different wells at the same time do not necessarily represent comparable hydraulic conditions. Contributing also to the apparent water-level differences between the two Moscow wells and UI well 3 are differences in the methods used to obtain the data and the different agencies and personnel involved with the data collection. Yet another reason for the observed water-level irregularities is the fact that water levels in either city well are affected by pumping in the other, whereas water levels in the UI well do not appear to be immediately affected by pumping in either of the city wells.

This short-term immunity of UI well 3 from the effects of pumping in Moscow wells 6 and 8 led Sokol (1966, p. 25) to suggest that the apparent producing zone in the university well (middle basalts in fig. 4), has poor hydraulic connection with the producing zone in the two city wells (lower basalts). However, data gathered for the model study indicate that all three wells are producing from aquifers which are, in the long term, mutually interconnected and, thus, for modeling purposes, they are considered part of the same (primary) aquifer system.

Although the apparent producing zones are separated locally in the vertical direction by more than 100 feet of sedimentary material (the middle interbeds in fig. 4), the intervening layer probably thins sharply to the west, perhaps disappearing altogether, thus allowing crossbed hydraulic continuity through thinner sedimentary beds or more permeable basalt. The circuitous route to hydraulic continuity may account for the apparent delay in water-level response to pumping in wells on opposite sides of the middle interbeds in the Moscow area.

Similar delay of water-level response in unpumped wells to pumping in other wells in the primary aquifer system is noted in the Pullman area. The WSU observation well (14/45-5F1, 145 ft deep) is abcut 2,500 feet southeast of Pullman well 4 (15/45-32N2, 954 ft deep). The principal aquifer in the WSU well lies between altitudes of 2,260 and 2,300 feet (Crosby and Anderson, 1971); the city well is open only to strata below an altitude of 1,951 feet. In other words, the aquifers open to the WSU observation well are physically separated from those pumped in Pullman well 4 by more than 300 feet. When their respective water levels are observed only over short periods of time, the aquifers may also seem to be hydraulically isolated. For example, on March 28, 1974, the static water-level altitude in the WSU well was 2,287.1 feet, while that in Pullman well 4 was 2,291.2 feet. The water level in the city well was drawn down to an altitude of 2,238.9 feet after the pump was started. However, the water level in the WSU observation well did not change measurably--even after 6 hours of pumping from the city well (during which time all other pumping in the area remained relatively constant).

Yet, if the productive zones in each of the above wells are not interconnected by some means, how can the static water-level hydrographs for both wells (fig. 8) be so similar? The answer is, of course, that in the long term the deeper aquifers in the Pullman-Moscow basin must be interconnected to a significant degree. Probable reasons for the unusually strong hydraulic interconnection among these basalt aquifers are discussed below.

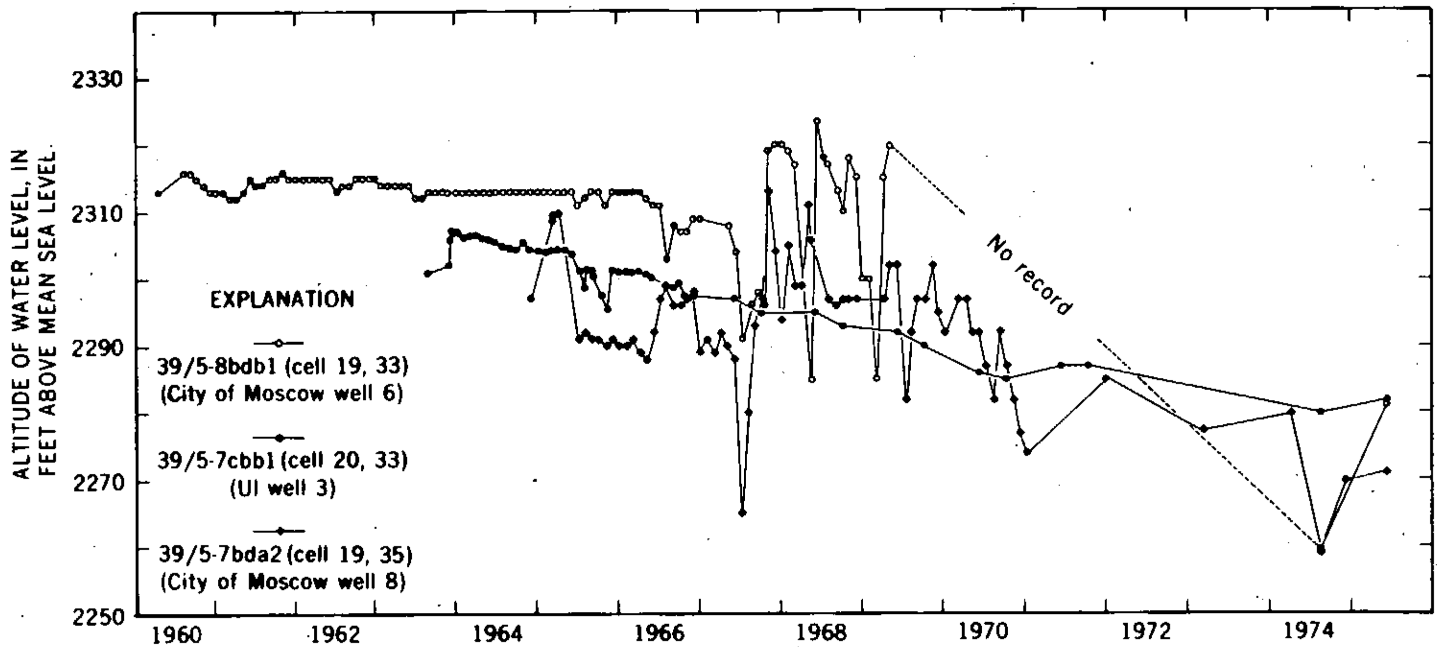


FIGURE 10.--Hydrographs showing water-level decline in wells tapping primary aquifer system in Moscow area during period 1960-75.

Barrier Zone to Ground-Water Flow

During the early stages of the recent study, emphasis was placed on defining and understanding the hydrology inside the basin. However, as the study progressed, and it became necessary to formulate a conceptual description of the entire flow system to be modeled, concern shifted to the area between the basin boundary on the west and Union Flat Creek. Owing to insufficient data, very little was known about the hydraulic relationship between the aquifers in that area and those inside the basin. Although information provided in prior reports was sketchy, it was generally believed that the area to the west received ground-water "overflow" from the basin.

Water-level data collected from the deepest explored aquifers west of the basin defined a potentiometric surface that sloped, in general, toward Union Flat Creek and, in places, toward the basin (fig. 7). The gradients there were in contrast to the nearly-flat head surface observed for the primary aquifer system within the basin. Owing to the configuration of the obvious geologic boundaries which enclose the basin's aquifers on the north, east, and south, and which underlie the basin, it seemed appropriate that ground water would discharge laterally from the basin and flow toward Union Flat Creek through the open end of the crystalline "horseshoe" (fig. 2). However, questions arose regarding the change in the slope of the deep ground-water gradient near the basin boundary on the west (fig. 7).

Hydrologic irregularities in other areas in the Columbia Plateau that are similar to those observed in the Pullman-Moscow area, have been attributed to the effects of subsurface geologic structures. Luzier and Burt (1974, p. 11) documented the existence of such a ground-water barrier in the Odessa-Lind area in Washington. Although the exact nature of the obstruction near Odessa and Lind is unknown, abrupt changes in the regional ground-water gradient and differences in long-term decline rates (on opposite sides of the feature) were interpreted as resulting from a band of rock having relatively low hydraulic conductivity in the lateral direction. Additional examples of buried ground-water dams in basalt terrain--and discussions of their causes and effects--are provided by Newcomb (1961 and 1969).

To explain the abrupt steepening of the deep potentiometric gradient just west of the basin, in contrast to its uniformly flat character inside the basin, it is postulated that there is an obstruction to deep, lateral ground-water flow somewhere between the basin boundary on the west and Union Flat Creek. Without the damming effect provided by such an obstruction to the west, head differences among the deeper aquifers within the basin should be more discernible and the resulting potentiometric surfaces should be expected to grade at a generally even slope all the way from the eastern margin of the aquifer system to Union Flat Creek. As noted above and in figure 7, such is not the case.

At the present time, the origin and exact nature of the apparent ground-water barrier west of Pullman is open to speculation. As Foxworthy and Washburn (1963, p. 11) pointed out, the nearly parallel alignment of the major surface features in the region (fig. 12) suggests linear structural control, such as that resulting from volcanic dikes, or perhaps from folded or faulted rock layers. The possibilities for, and implications of, the existence of such features are discussed below.

Swanson, Wright, and Helz (1975, p. 896) have recently mapped exposures of relatively young basalt flows paralleling the trend of Union Flat Creek in the area west of the basin boundary. They describe these flows as occurring "in narrow belts elongate in a northwest to north-northwest direction." On the basis of field mapping, they believe that each "belt is best explained as an accumulation of flows erupted along a linear vent system" in the near vicinity. Vertical or high-angle volcanic dikes in the area of the suspected ground-water barrier could have resulted from such a vent system.

The possibility that a ridge of crystalline rock lies buried below the basin boundary on the west, linking the exposed ridges between Albion and Chambers (fig. 2), has been speculated for years. During the recent study, an attempt was made to define the subsurface geology in the area by geophysical methods (p. 48). The resulting interpretations suggest that the basin floor is indeed "lipped" on the west by a basement "high" trending in a northwesterly direction (fig. 15). Because depths to basement rock are also interpreted to be much greater west of the high and a depression on the basin floor is indicated north and a little west of Pullman, there is the additional suggestion that the basin's aquifers lie within a bowl-like alcove, perched above the general level of the regional basement (fig. 12).

Brown (1976) has correlated chemically similar basalts within the basin, as determined by analyses of basalt drilling samples. Although a key stratigraphic contact (see p. 45) was mapped to be nearly horizontal within the basin, Brown found the same contact to exist 700 feet lower near Almota, 15 miles west of the basin (fig. 12). This and other evidence led Brown to conclude that areas west of the basin subsided while the basin remained relatively stable. (The concept of regional subsidence in the central parts of the Columbia Plateau during volcanic episodes, while the marginal basalt areas remained relatively high, has been discussed and is generally supported by many, including Bingham and Walters (1965), Bush and others (1972), Siems and others (1974), and Swanson and others (1975).

The evidence provided by Brown (1976, p. ii) for "the presence of a tectonic transition area, possibly basement controlled, west of Pullman"--coupled with the apparent existence of basement irregularities in the same area, as interpreted from geophysical data--suggest that subsidence to the west may have hinged along the western edge of the basin. Certainly, folds and (or) faults could be expected to have resulted in the basalt sequence near such a "hinge line", in association with the type of differential subsidence described by Brown and other recent authors.

Any one of the above-mentioned structures (dikes, basement high, folds, and faults), or a combination of these, in the area west of the basin would almost certainly retard lateral exchange of ground water between the basin area and the area of Union Flat Creek. Water movement to and from the basin across this area could be restricted to the extent that a common hydrostatic potential would exist inside the basin for all aquifers among which hydraulic circulation in the vertical direction was reasonably good and within which lateral flow was equally retarded west of the basin.

Because the effects of the (presumed) obstruction to ground-water flow on the west, so clearly evident in the deeper aquifers, are not obvious in the upper aquifers, it appears that the upper aquifers are unaffected by the obstruction. In fact, the very reason why the aquifers in the basin can be readily separated into two groups seems to result from the existence of the obstruction; the primary system has been defined on the basis of somewhat atypical conditions, probably caused by the obstruction, that are not characteristic of the upper aquifers. The upper aquifers apparently lie above the feature(s) responsible for the restricted ground-water flow at depth and, therefore, exhibit hydraulic characteristics that are more typical of the Columbia River Basalt Group elsewhere in eastern Washington (p. 18; Luzier and Burt, 1974, p. 6-10).

Explanations for the upper aquifers being unaffected by the ground-water obstruction are only speculative at this time. However, if the obstruction is the result of tectonic activity, one explanation may be that suggested by Brown (1976, p. ii), that little tectonic activity has occurred in the basin since the extrusion of the older (deeper) basalts.

Although the postulated obstruction to ground-water flow west of the basin might result from a single, narrow geologic structure coincident with--or just west of--the basin boundary, the barrier effect also could be the result of a complicated network of structure(s) spanning the entire area between the boundary and Union Flat Creek. Because available data do not warrant an attempt in this report to define the exact location, origin, and nature of the obstruction, the general area of its probable existence is regarded as an obstruction and is henceforth referred to as the "barrier zone" (figs. 11 and 12).

Although differences between the shallow and deeper aquifers in the barrier zone are not as discernible as they are within the basin, sufficient data exist to separate the aquifers over most of the barrier zone into upper and lower groups, each resembling their counterparts within the basin more than they do each other. As within the basin, water levels in the shallower aquifers in the barrier zone have apparently not changed much with time. As within the basin, water levels in the deeper aquifers there have declined--although apparently at rates much less than within the basin. Because pumpage from the barrier zone (and adjacent area to the north, west, and south) has been insignificant, the decline there must have been a result of the pumpage within the basin. Because the deeper potentiometric surface in the barrier zone seems to merge with that of the primary system within the basin, and this surface seems to have declined in response to pumping within the basin, the deeper aquifers in the barrier zone must have some hydraulic link with those in the basin. In other words, while deep ground-water exchange between the basin and Union Flat Creek appears to be severely restricted, flow does not appear to be completely blocked in an east-west direction across the barrier zone.

Because hydrologic data for the barrier zone are extremely sparse, it is impossible at this time to draw conclusions regarding hydraulic relationships for the area that could not be disputed or perhaps disproved with additional data. However, presently available data suggest that significant water-level differences do not exist among the different aquifers immediately adjacent to Union Flat Creek. It appears that the two distinguishable potentiometric surfaces existing to the east merge somewhere near the stream channel and that the resulting, singular water-level surface coincides with the level of stream stage in the channel. It follows intuitively, then, that the stream must be hydraulically linked to the adjacent aquifers.

The aquifers are believed to be mutually interconnected adjacent to the channel to a greater degree than to the east because of an increase in the vertical permeability of the basalt sequence near the channel. Similar increases in the hydraulic interconnection among basalt aquifers have been noted along canyons in the Columbia Plateau elsewhere in eastern Washington. Such interconnection has possibly been caused by the release of internal rock pressure and resulting expansion of the basalt as overburden was eroded from its surface (J. D. Luzier and R. D. Mac Nish, U.S. Geological Survey, oral commun., 1972).

In order to expedite the modeling effort, it was assumed that (1) the deeper aquifers in the barrier zone function as a westward extension of the primary aquifer system, (2) the potentiometric surface of this system is graded to and is hydraulically continuous with Union Flat Creek, and (3) the upper aquifers and the primary aquifer system merge near the channel of Union Flat Creek. As explained later, on page 59, Union Flat Creek is treated as a constant-head boundary during model simulation; in other words, the aquifer heads in the area of the stream channel are fixed at stream stage in the model.

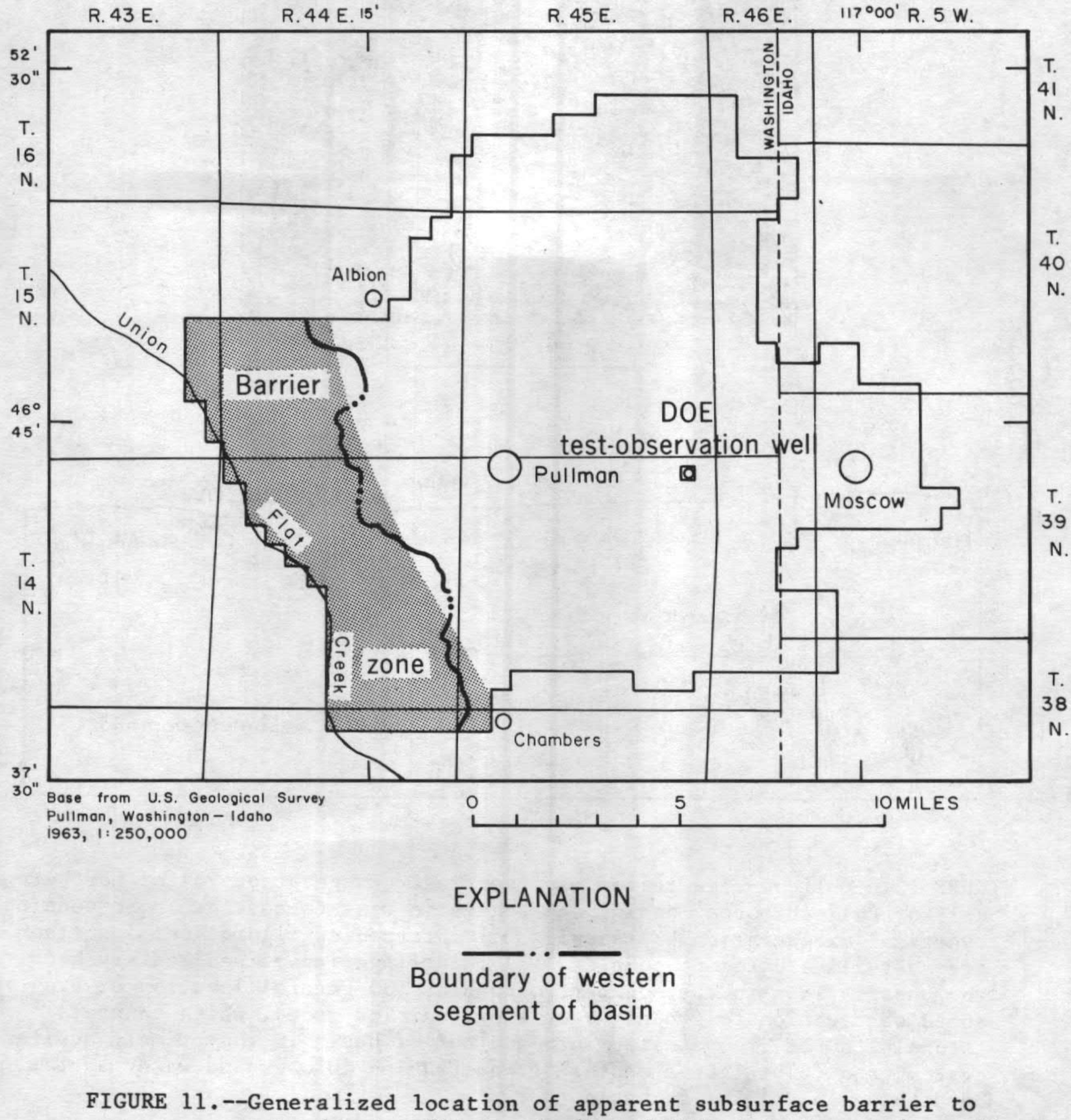
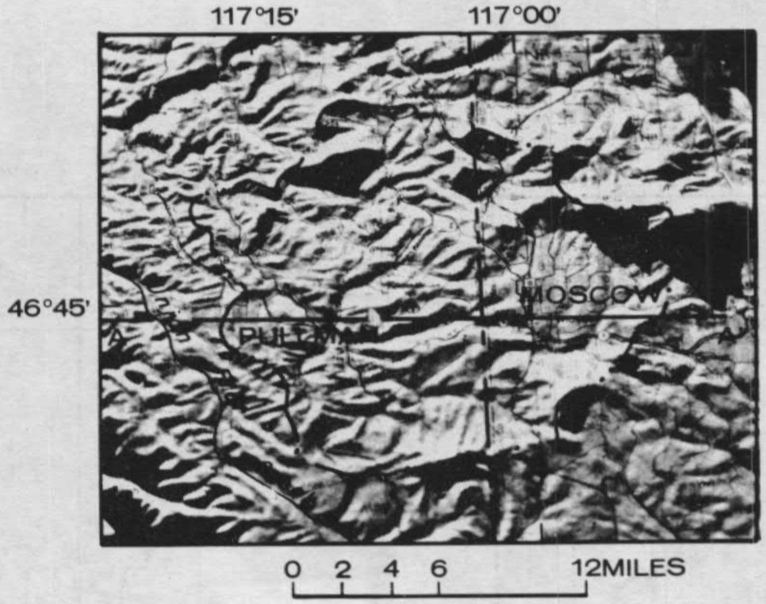


FIGURE 11.--Generalized location of apparent subsurface barrier to ground-water flow, and site of DOE test-observation well.



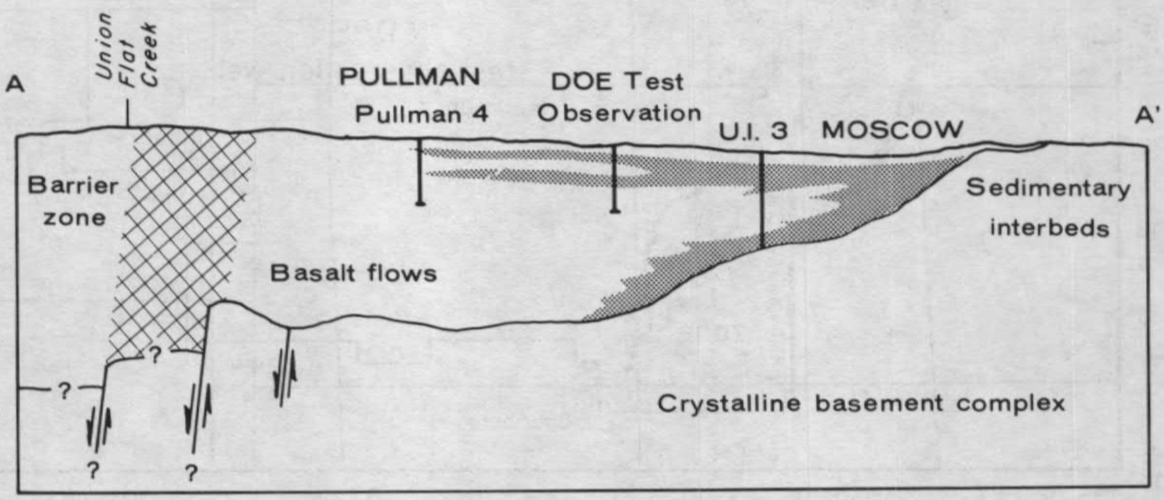


FIGURE 12.--Oblique-view relief map (vertical exaggeration 2X) of northern half of Pullman-Moscow basin, and schematic west-to-east geologic section (vertical exaggeration 8X) showing (1) inferred configuration of surface of crystalline basement complex, (2) interfingering of sedimentary beds and basalt flows in eastern part of basin, (3) general location of presumed obstruction to ground-water flow (barrier zone), which controls lateral flow of ground water into and out of basin in the primary aquifer system, and (4) relative depths of penetration into ground-water system by deep wells drilled in basin.

Upper map shows entire basin, locations of nearby towns, Union Flat Creek, and the Snake River Canyon. Depths to basement complex are inferred from results of geophysical exploration (p. 48). Base from U.S. Geological Survey 1:250,000 Pullman, Wash. quadrangle (1953), with raised relief by Army Map Service.

Relationship Between Hydrologic and Stratigraphic Subdivisions

Although the causes for the sharp hydraulic transition between the primary aquifer system and the upper aquifer zone can not at this time be completely defined, it is necessary to define where this transition occurs over as much of the study area as possible because the areal distribution of this boundary represents the top of the modeled aquifer system. Perhaps the shape of this boundary surface offers a clue as to why there are significant hydraulic contrasts on opposite sides. The boundary is not at the same altitude everywhere in the modeled area. However, judging from the water-level relationship shown in figure 6, the boundary would appear to be nearly horizontal at an altitude of about 2,300 feet over most of the Pullman subbasin. Because of the apparent consistency in relief over much of the basin, the boundary may correlate with some aspect of the nearly flat-lying geologic units within the basin.

At places in the Pullman subbasin, the top of the primary aquifer system appears to be associated with the top of an interbed of sand and clay. Russell (1897, p. 79) and Foxworthy and Washburn (1963, p. 15) made reference to this sedimentary layer as being the aquifer that was earliest tapped and pumped at Pullman (where it lies 50-75 ft below the surface). The interbed appears to be fairly widespread over the Pullman subbasin, generally lying between altitudes of 2,270-2,310 feet above sea level. Where penetrated by wells in the Pullman area, the interbed generally responds as the uppermost aquifer of the primary aquifer system.

According to J. W. Crosby III and J. C. Brown (oral commun., 1975), both of WSU, this interbed is the geologic-time equivalent of the Vantage Sandstone Member of the Yakima Basalt (Waters, 1961, p. 607) of the Columbia River Basalt Group (fig. 13). Recent investigators of regional stratigraphy in the Columbia Plateau have used this rather characteristic sedimentary horizon to separate the middle Yakima Basalt from the underlying lower Yakima Basalt (Ledgerwood and others, 1973; Wright and others, 1973, p. 374; and Siems and others, 1974, p. 1061). Where traced in the Pullman area, the interbed is generally overlain by a layer of massive basalt, believed to be the Lolo Flow (Siems and others, 1974, p. 1064; and Brown, 1976, p. 14).

In south-central Washington, the basal part of the middle Yakima Basalt sequence is generally comprised of the Roza and Frenchman Springs Members (Bingham and Grolier, 1966). However, Siems and others (1974, p. 1064) report that neither of these units, which commonly overlie the Vantage Sandstone Member of the Yakima Basalt over most of the Columbia Plateau, is present in the Pullman area. According to Brown (1976, p. 14):

> "The Roza thins rapidly to the east and has been found within the Moscow-Pullman basin only in a thin exposure northwest of Pullman, near the town of Albion. Indications are that the Roza pinches out just to the west of Pullman, perhaps along a line roughly corresponding to the western basin boundary."

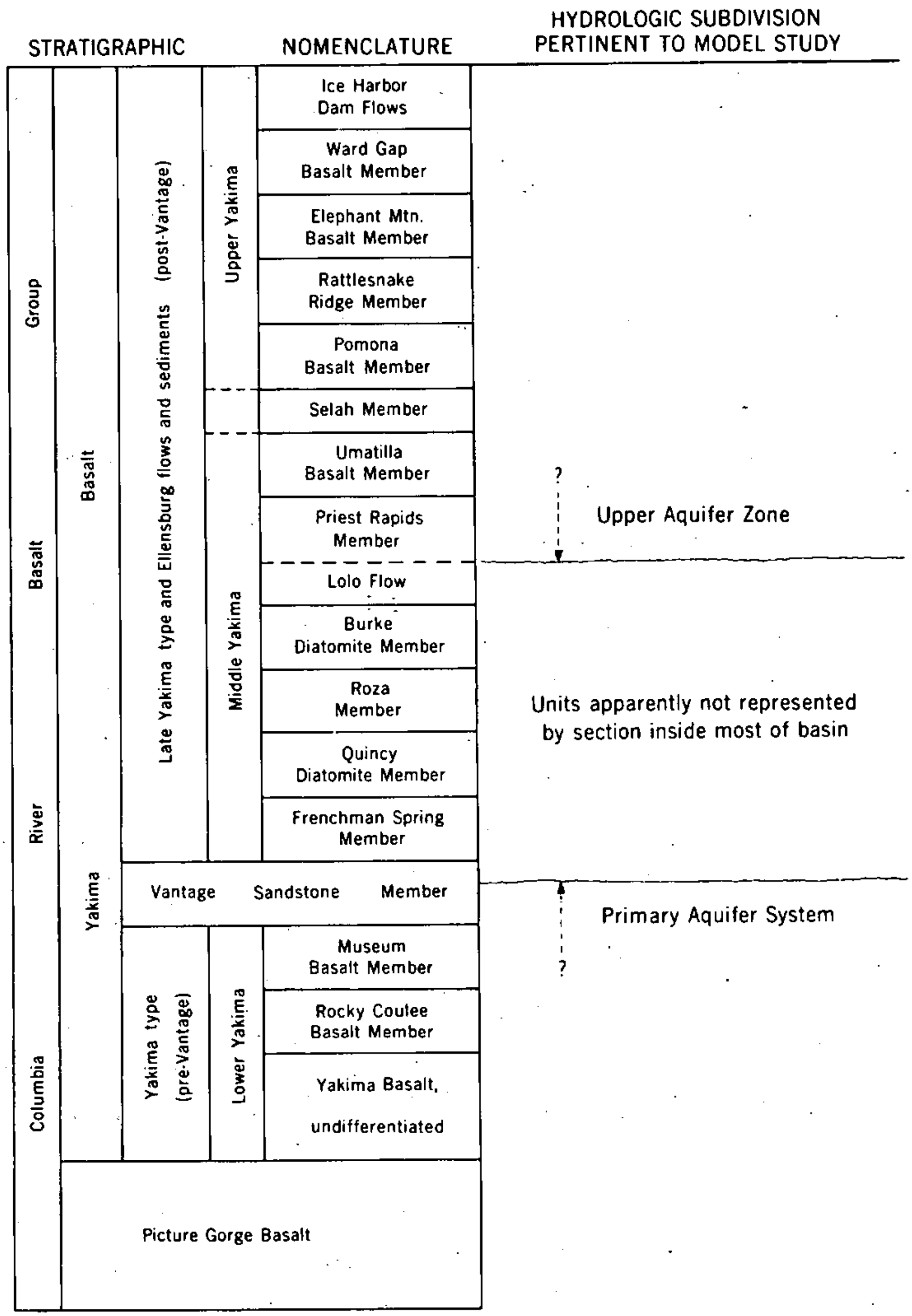


FIGURE 13.--Stratigraphic nomenclature of Columbia River Basalt Group with relation to hydrologic subdivision made for ground-water model study of Pullman-Moscow basin. Stratigraphic nomenclature is modified from Siems, Bush, and Crosby (1974, p. 1061) and is a compilation from several sources that do not necessarily follow the usage of the U.S. Geological Survey.

Therefore, the horizon inside the Pullman-Moscow basin between the top of the interbed of Vantage age and the overlying Lolo Flow appears to represent a significant time gap. This apparent time gap in the rock record within the basin may have resulted because areas to the west were subsiding during the extrusion of the Roza and Frenchman Springs Basalt Members, while the basin area remained relatively high. This explanation is consistent with the concept of a tectonic transition zone--or hinge line--near the basin divide on the west (p. 38) and is compatible with the belief of Brown (1976, p. 18) that there was "tectonic independence of the Pullman-Moscow basin" during periods of volcanic activity and regional subsidence farther to the west.

Brown (1976) used chemical analyses of cuttings from basalt wells to map the contact between the middle and lower Yakima Basalt units over much of the Pullman-Moscow basin. Although this stratigraphic contact, as defined by Brown, does not coincide exactly with the boundary between the upper aquifer zone and the primary aquifer system, some significant similarities are evident. For example, available data suggest that most, if not all, identified aquifers of the upper aquifer zone are within middle Yakima strata, whereas the lower Yakima strata contain only aquifers classified herein as part of the primary aquifer system. This apparent relationship between the stratigraphy of the Columbia River Basalt Group inside the basin and the local ground-water regime would seem to deserve intensive study and consideration during future geologic and hydrologic investigations in the basin.

The main difference between Brown's stratigraphic subdivision and the hydrologic subdivision made for the model study exists in the Moscow subbasin. Brown (1976, p. 15) has placed the contact between the middle and lower Yakima Basalt units immediately above a thick clay sequence there (the upper interbeds shown in fig. 4), whereas the criteria (see below) used to separate the upper aquifer zone from the primary aquifer system indicate that the hydrologic distinction be made immediately above the so-called middle artesian zone--at the base of this clay sequence.

The hydrologic subdivision made for the model study was based primarily on the fact that wells bottoming in the interbed sequence apparently have static water levels ranging from 100 to 175 feet higher than those in wells penetrating the primary aquifer system. Water-level data from two wells (39/6-13cad3 and 39/5-7bda1) bottoming in the interbed sequence are provided by Crosthwaite (1975, p. 10 and 11), and the relationship between static water levels in these wells and others in the basin are shown in figure 6.

Because water levels in wells penetrating the upper interbeds (fig. 4) appear to be most characteristic of those in the upper aquifer zone, and the sequence is assumed to function as a confining layer to the underlying, modeled system (see p. 72), the upper interbeds--for the purposes of the model study--were categorized as part of the upper aquifer zone. The distribution of the bottom of this sediment sequence is not well understood, especially in areas north and south of Moscow. However, the bottom is believed to lie near an altitude of about 2,000 feet beneath most of the Moscow subbasin.

As defined for the model study, therefore, the top of the primary aquifer system slopes quite steeply from an altitude of about 2,300 feet beneath most of the Pullman subbasin to an altitude of 2,000 feet beneath Moscow (fig. 14). Limited data from the barrier zone suggest that the aquifers there below an altitude of about 2,175 feet function as a westward extension of the primary aquifer system. Owing to insufficient data indicating otherwise, the top of the modeled (primary) system is therefore assumed to be at an altitude of 2,175 feet everywhere in the barrier zone. Although this surface (fig. 14) is not presently clearly defined in places, being based on sparse or incomplete information, it's definition can (and should) be improved for future refinement of the model as more data become available.

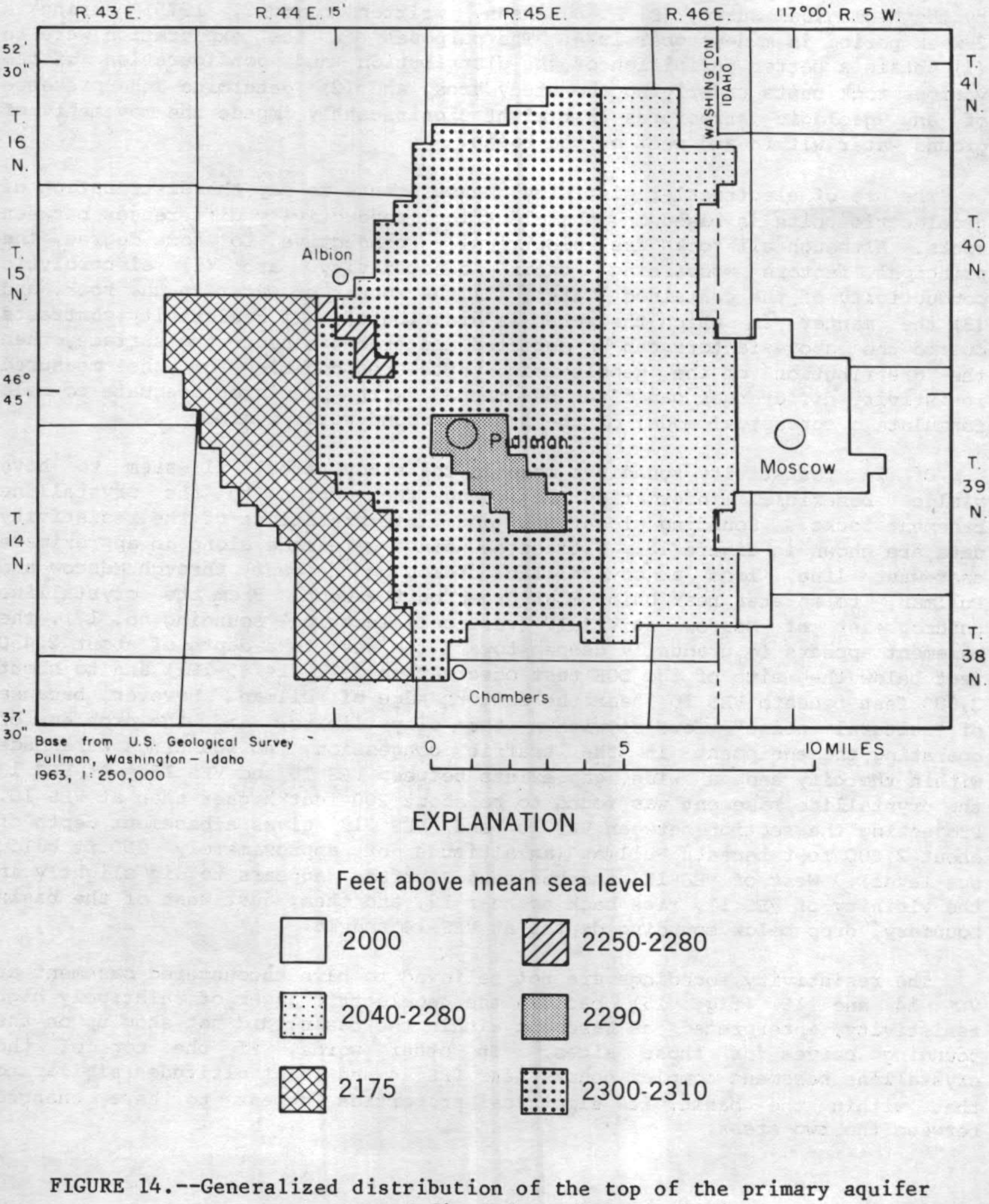


FIGURE 14.--Generalized distribution of the top of the primary aquifer system, as defined for model simulation.

Geophysical Exploration

To obtain a clearer understanding of the area's subsurface geohydrology, a geophysical survey--using electrical-resistivity and gravity methods--was made by the Geological Survey (D. B. Jackson, written commun., 1975) during a 2-week period in mid-October 1974. The purposes of the exploration were to (1) obtain a better definition of the distribution and configuration of the various rock units underlying the study area, and (2) determine the presence of any geologic structures that might significantly impede the movement of ground water within and west of the basin.

The use of electrical-resistivity measurements to map the distribution of geoelectric units is based on the electrical conductivity differences between rocks. Although all rocks are electrically conductive to some degree, the principal factors governing their conductivity are (1) electrolytic conductivity of the contained water, (2) the amount of water in the rock, and (3) the manner in which the water is distributed. If resistivity contrasts due to the above factors can be detected and traced beneath the surface, then the distribution of the geoelectric units responsible for the measured resistivity differences can often be mapped with precision adequate to help formulate a conceptual model of the area's ground-water regime.

Of 24 resistivity soundings made in the study area, 21 seem to have yielded beneficial information regarding the depths to the crystalline basement rocks. Sounding locations and interpretations of the resistivity data are shown in figure 15. Fifteen soundings were made along an approximate east-west line, from a crystalline outcrop on the east, through Moscow and Pullman, to an area near Union Flat Creek on the west. From the crystalline outcrop east of Moscow at VES 17 (vertical electrical sounding no. 17), the basement appears to gradually deepen toward the west to a depth of about 2,450 feet below the site of the DOE test observation well (14/45-1F1) and to about 2,800 feet beneath VES 10 near the eastern edge of Pullman. However, because of "cultural noise" levels within the city limits, and the problems of operating the equipment in the traffic congestion, no soundings were made within the city and a wide gap exists between VES 10 and VES 13. At VES 13 the crystalline basement was found to be about 200 feet higher than at VES 10. Projecting the section between VES 10 and VES 13 gives a basement depth of about 2,600 feet beneath Pullman (an altitude of approximately 250 ft below sea level). West of VES 13, the basement surface appears to dip slightly in the vicinity of VES 11, rise back up near 12, and then, just west of the basin boundary, drop below sounding depths at VES 14 and 15.

The resistivity soundings are not believed to have encountered basement at VES 14 and 15 (fig. 15) because the geoelectric layer of relatively high resistivity, interpreted as basement within the basin, did not show up on the sounding curves for those sites. In other words, if the top of the crystalline basement complex occurs near VES 14 and 15 at altitudes similar to that within the basin, its electrical properties appear to have changed between the two areas.

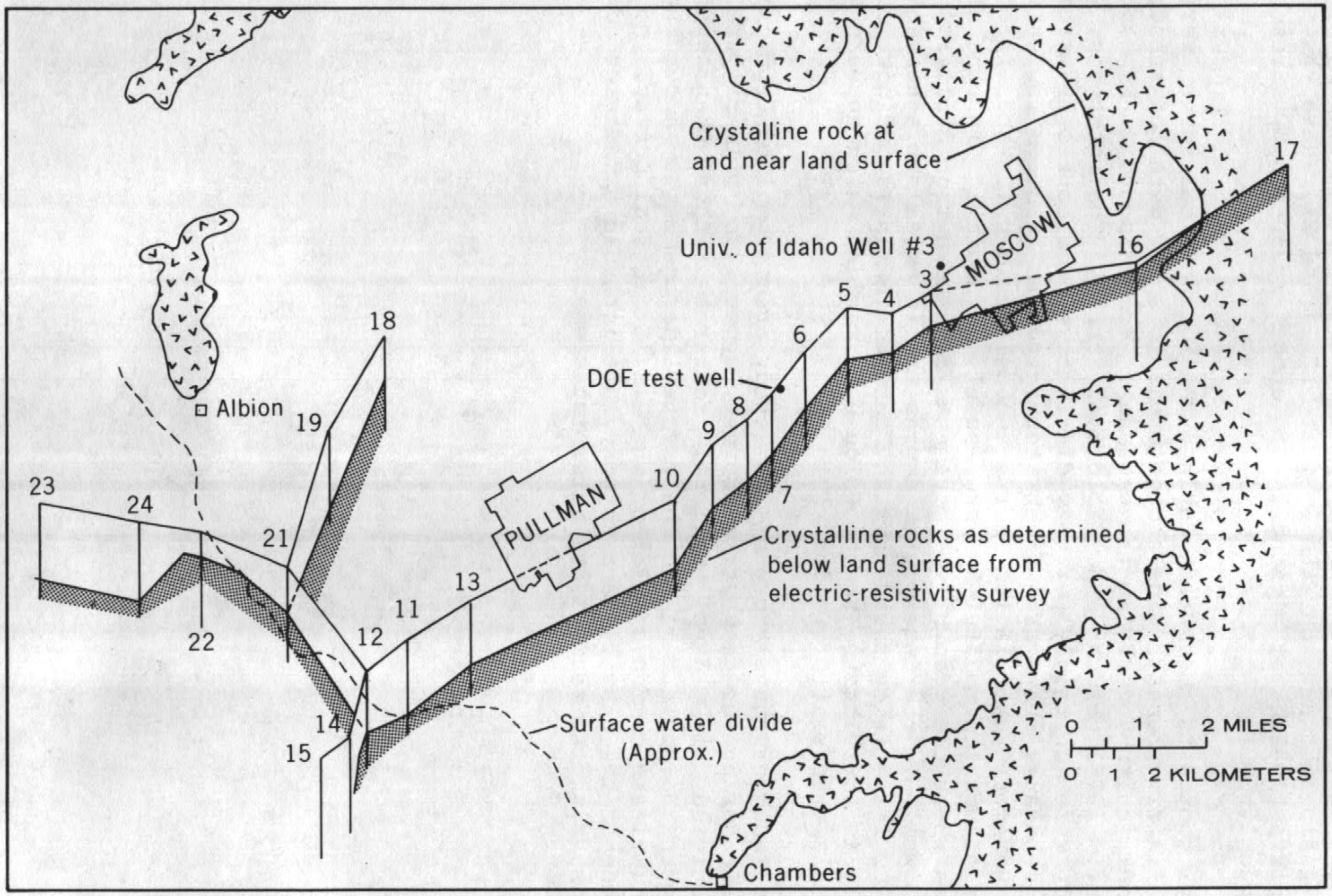


FIGURE 15.--Fence diagram showing sites of resistivity soundings during geophysical survey, and indicated profile on top of the buried crystalline rocks beneath the basalt. Tops of sounding locations represent land surface for each site. From D. B. Jackson (written commun., 1975).

To the north, at VES 23 and 24, resistivities characteristic of the basement did show up--at altitudes of about 800 and 1,000 feet below sea level. These basement depths are in sharp contrast to those interpreted for areas near the basin boundary on the west at VES 22 and 21, where the top of the basement apparently lies at altitudes of about 1,350 and 500 feet above sea level, respectively.

Resistivity contrasts measured during the geophysical survey were not sufficiently definitive beneath wide enough areas to allow detailed subsurface mapping of rock units overlying the basement. According to D. B. Jackson (written commun., 1975) of the U.S. Geological Survey, "The interbeds, where we have control, are certainly not very distinctive geoelectrically from the basalts, perhaps because they are freshwater deposits from a low salinity environment." However, correlation between geoelectric units and lithologic data in drillers' logs was moderately successful, especially in the Moscow area. At places where the depth to basement is known from drillers' logs (such as at UI well 3), the interpreted depths are in excellent agreement. A layer of very low resistivity found near the surface in many soundings west of Pullman probably is correlative to the Palouse Formation, which appears to be much thicker there than east of Pullman.

The complete Bouguer gravity map of the study area, compiled from gravity measurements made during the geophysical survey, appears to primarily reflect gradients associated with deep, regional features rather than hoped-for contrasts between the basin fill and the crystalline basement. According to D. B. Jackson (written commun., 1975) of the U.S. Geological Survey, no use has yet been made of the gravity data to postulate interbasin features or to make correlations with the resistivity interpretations.

DIGITAL MODEL SIMULATION

The Digital Model

Reliance upon digital models to aid in the analyses and management of ground-water resources in the State of Washington has increased substantially during the 1970's. A vital function of the State of Washington Department of Ecology is the formulation of regionalized guidelines for ground-water development which are in the best overall interests of satisfying the need for the water resource, while at the same time providing for its conservation. In addition to requiring an evaluation of ground-water occurrence and availability, this responsibility involves accessing the advantages and predicting the consequences of utilizing the ground-water supply. The digital model can help to test the effects of alternate ground-water-development plans before they are actually enacted. Benefits resulting from such model analysis are being realized in areas of the State for which ground-water-flow models have been developed in the last several years. Such models are now available for the Odessa-Lind area (Luzier and Skrivan, 1973), the Columbia Basin Irrigation Project area (Tanaka and others, 1974), and the Walla Walla River basin (Mac Nish and Barker, 1976; Barker and Mac Nish, 1976).

Use of a ground-water-flow model as a predictive tool is based on the theory that, if historical hydrologic phenomena can be satisfactorily approximated by the model, future conditions also can be approximated. For this presumption to hold, the historical cause-and-effect relationship between stresses on the real flow system and the system's response to those stresses must be simulated accurately. It is further required that this cause-and-effect relationship does not change significantly in the real system during the period for which responses are predicted.

The model was developed over a period of about 8 months, during which time important geohydrologic characteristics of the real flow system were incorporated into a FORTRAN computer program that can be run on any large-capacity digital computer, such as the IBM 360. Most of the developmental time was spent calibrating the model to reproduce the cause-and-effect relationship between historic pumping and the decline of water levels. During calibration, input parameters such as aquifer transmissivities, storage coefficients, and rates of vertical leakage were adjusted--within the limits of sound hydrologic intuition and principles--until a satisfactory approximation of the response to historical hydraulic stresses was achieved.

Calibration of the Pullman-Moscow model involved simulation of both steady-state conditions and transient conditions. The steady-state model is a numerical representation of ground-water conditions in the Pullman-Moscow basin before significant ground-water withdrawal by man. Before the mid-1890's the system was in a state of approximate equilibrium; recharge was essentially equal to discharge. Because the volume of ground water in storage was nearly constant, water levels were virtually stable. Owing to the constant nature of hydrologic processes during that era, the steady-state model was designed to depict conditions independently of time. The transient model provides a reproduction of historic ground-water conditions since 1896, when pumping of ground water at significant rates is assumed to have begun.

Because conditions since 1896 have obviously not remained constant, transient simulation includes the dimension of time.

The steady-state model was formulated first and served as a basis for the transient-model design. The transient model is nothing more than the steady-state model upon which the historical pumping stresses are superimposed and in which the dimension of time and the effects of changes in ground-water storage are considered. Although each model includes much of the same program logic and input data, each represents a different set of conditions, thus requiring adjustment of different data in each of the models to achieve calibration. Because the success of transient simulation proved to be so dependent on the rates of vertical leakage (which were manipulated during experimentation with the steady-state model), calibration became, basically, a process of alternating steady-state runs with transient runs and attempting to make corrections between each simulation which were mutually agreeable to both models. Details of data input to the model and the results of adjustments made to achieve calibration are provided later in the report.

Mathematical Description

The digital model of the Pullman-Moscow primary aquifer system was developed from a computer program written by Pinder (1971) and shares many characteristics with ground-water-flow models developed for other areas. The Pinder model, based on mathematical techniques described by Pinder and Bredehoeft (1968), uses an iterative, alternating-direction implicit procedure (ADIP) to solve finite-difference approximations of the nonlinear, partial differential equations describing nonsteady two-dimensional ground-water flow. ADIP is a numerical technique used to solve sets of simultaneous equations which result from the finite-difference approximations (Peaceman and Rachford, 1955).

The general equation which describes the two-dimensional flow of ground water under confined conditions is:

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

where

- S = storage coefficient;
- h = potentiometric head or water level;
- t = time;
- T = transmissivity;
- x and y = horizontal dimensions of rectangular segment of aquifer; and
- W = rate at which water moves vertically to or from the aquifer segment.

Expressed literally, equation 1 reads:

Rate of net lateral flow to and from some segment of the aquifer system	=	Rate of change of the volume of water stored in that segment	+	Rate at which water is being added to or removed from that aquifer segment vertically (e.g. as from wells).

Use of the finite-difference approximations for the numerical solution of the flow equation requires subdividing the modeled area into a grid of intersecting rows and columns (pl. 1). The rectangles thus formed are called cells. Cell dimensions of 1/2 mile per side are used in the Pullman-Moscow model. All model cells are numerically indexed and can thus be addressed individually; within parenthesis the row number is listed first, followed by a comma, and then the column. For example, as shown in plate 1, the town of Chambers, Wash., is within cell (33,17). Hydraulic parameters required by the model (such as transmissivity, storage, and water levels) were either measured, calculated, or estimated for the center (node) of each cell.

In addition to the requirements of space subdivision, the method of finite-difference approximation requires that transient simulation proceed through a series of discrete time elements, called time steps. In order to minimize truncation and other related errors, a progression of five time steps per year was used in the Pullman-Moscow model. The chronology and lengths of the time steps are as follows: 1 day, 5 days, 25 days, 125 days, and 209 days. The incremental approximation of the continuous time functions introduce some error into the simulation. However, the error is generally inconsequential so long as the time steps are not allowed to become too long.

Because space and time are broken into discrete segments, the model's numerical approximation to equation 1 differs from the analytical solution in that it is not continuous in time and space. However, because high-speed digital computers with large storage capacity can calculate the numerical approximations so rapidly, it is possible to solve equation 1 for small segments of the aquifer over short time steps--and thereby approximate continuity. In general, the smaller the size of the cell, and the shorter the time steps, the more closely the numerical solution approaches the analytical solution.

As used in the model, the finite-difference approximation of equation 1 for a single point in time and point in space (node (i, j)) can be expressed as:

$$\left(\frac{2T_{(i,j)}T_{(i+1,j)}}{T_{(i,j)}Y_{(i+1)} + T_{(i+1,j)}Y_{(i)}}\right)\left(\frac{h_{(i+1,j,t)} - h_{(i,j,t)}}{Y_{(i)}}\right)$$

$$+ \left(\frac{2T_{(i,j)}T_{(i-1,j)}}{T_{(i,j)}Y_{(i-1)} + T_{(i-1,j)}Y_{(i)}}\right)\left(\frac{h_{(i-1,j,t)} - h_{(i,j,t)}}{Y_{(i)}}\right)$$

$$+ \left(\frac{2T_{(i,j)}T_{(i,j+1)}}{T_{(i,j)}\,x_{(j+1)} + T_{(i,j+1)}x_{(j)}}\right)\left(\frac{h_{(i,j+1,j,t)} - h_{(i,j,t)}}{x_{(j)}}\right)$$

$$+ \left(\frac{2T_{(i,j)}T_{(i,j-1)}}{T_{(i,j)}\,x_{(j-1)} + T_{(i,j-1)}x_{(j)}}\right)\left(\frac{h_{(i,j-1,t)} - h_{(i,j,t)}}{x_{(j)}}\right)$$

--------------lateral flow expression----------------

$$= S_{(i,j)}\left(\frac{h_{(i,j,t)} - h_{(i,j,t-1)}}{\Delta t}\right) + W_{(i,j,t-1)} \qquad (2)$$

-------storage term---------   ---vertical flow term---

where the i and j subscripts correspond to the numerical addresses of the particular cells from which the indicated data are extracted to solve the equation. The t subscripts denote the time levels to which the heads apply, and the Δt in the storage term refers to the length of the time step for which the equation is being solved.

Other elements of equation 2 are:

h = potentiometric head in cell, in feet;
T = transmissivity, in feet squared per second;
x and y = length and breadth of the cell, in feet;
S = storage coefficient (dimensionless); and
W = vertical flux of water to or from cell, in feet per second.

To describe the hydraulics of the entire aquifer system, equation 2 must be compiled for every node where head values are desired. The result is a system of simultaneous linear equations from which the unknown heads are calculated using the iterative ADIP.

Basically, use of the iterative ADIP involves sweeping the finite-difference grid (pl. 1) with a sequence of head solutions which alternate between rows and columns of the grid. First, head values are computed for each model node with respect to rows while all terms related to the columns are held constant. After all the head computations have been processed row by row, the direction of solution is then alined with the columns and the heads are again computed, column by column. Two such alternate-direction sweeps, first by rows, then by columns, completes what is known as an iteration. After each iteration, the differences between head calculations in successive iterations are analyzed. Iterations are repeated until the difference becomes insignificant, and convergence is considered to have been achieved.

The vertical-flow term ($W_{(i,j,t-1)}$) in equation 2 includes all components of vertical flow into and out of a cell. These components include the discharge of water through wells tapping the modeled (primary) aquifer system and leakage to and from the upper aquifer zone overlying the primary aquifer system. An expansion of the "W term" is shown by equation 3 below:

$$W_{(i,j,t)} = P_{(i,j)} + \frac{K}{M\,(i,j)} \left[h_{u(i,j,t_o)} - h_{(i,j,t-1)} \right] \qquad (3)$$

where

P = rate of pumping at a particular cell during the time interval of the solution, in feet per second;
K = vertical hydraulic conductivity of the confining layer, in feet per second;
M = thickness of the confining layer, in feet;
h_u = head of the upper aquifer zone, in feet;
t_o = initial time;
t = current time; and
t-1 = time at the end previous time step.

Rigorous mathematical explanations of the procedures used for the finite-difference approximations are provided by Bredehoeft and Pinder (1970).

Hydraulic Characteristics of the Modeled Aquifer System

In hydraulic-modeling terminology, the flow of water through a given cross-sectional area in a given time is called flux. In the real world, flux may occur in any direction. However, when designing a ground-water flow model, it is usually most expedient to consider flux as occurring either vertically or laterally. If a difference is affected between total flux into an aquifer system (recharge) and total flux from the system (discharge), a change of water in storage results, and thus water levels rise or decline. Phenomena affecting flux conditions--and therefore water levels--are termed hydraulic stresses.

How a ground-water system reacts to hydraulic stress, such as well pumping, depends upon (1) the proximity and nature of the hydrologic and geologic boundaries of the system, (2) the effective aquifer properties (transmissivity and storage) of the system, and (3) the distribution of recharge to and discharge from the system. In order for a model to accurately simulate water-level change resulting from stress imposed on a real aquifer system, all the above items listed must be defined and incorporated into the simulation model with reasonable accuracy.

Data input to the model must, therefore, include the following:

1. Specified boundary conditions,
2. Transmissivity of the primary aquifer system,
3. Storage coefficients of the primary aquifer system,
4. Pumping rates in wells tapping the primary aquifer system,
5. Thickness and hydraulic conductivity of the assumed confining layer between the upper aquifer zone and the primary aquifer system, and
6. Head distributions in both the upper aquifer zone and the primary aquifer system.

Due to limitations in the availability and accuracy of basic data, some compromises and assumptions are inherent in the data input to the Pullman-Moscow basin ground-water model. The following pages describe the interpretations of basic data and the formulation of input data--and also point out some of the most important compromises involved in the translation of "real-world" data to the model.

Boundary Conditions

Boundary conditions are specified in the Pullman-Moscow model to control lateral flow at the edges of the modeled aquifer system. The boundaries used are the no-flow and the constant-head boundaries (fig. 16).

A no-flow boundary is used to depict the effects of the lateral termination of the primary aquifer system against the impervious crystalline basement complex. This condition is also assumed where depths to basement are believed to be within a few tens of feet from land surface, such as between the gap in the crystalline outcrops south of Palouse, Wash. (fig. 1). The effect of having no lateral flow across the modeled system's edge is accomplished in the model by assigning zero transmissivity values to cells where this condition exists--either because of geologic phenomena or hydraulic coincidences, as explained below.

From the crystalline ridge, which tapers out just north of Albion, the no-flow boundary is continued west to abut the constant-head boundary along Union Flat Creek. The no-flow designation in this direction is believed to be justified, because water-level contours drawn from available water-level data indicate that the direction of virtually all lateral flow in the area is from east to west enroute to the area of Union Flat Creek (fig. 7). This condition probably will not change in the near future, as long as anticipated rates of ground-water pumping continue within the basin and as long as the area west of the basin remains essentially unstressed by ground-water withdrawals. Because contours of the potentiometric surface run approximately north-south across this area, the compromise of using a no-flow boundary (which runs perpendicular to these contour lines) appears to pose no serious difficulty concerning model validity at this time (1975).

Constant-head boundaries are used to maintain given water levels at specific model cells, regardless of water-level changes simulated for all other cells. Because water levels for the constant-head cells are not re-computed for each time step, they do not deviate from those assigned originally to represent steady-state conditions. The effect is to allow lateral rates and direction of flow across the constant-head cells to fluctuate, depending on simulated water-level changes in cells adjacent to the constant-head cells.

Union Flat Creek was treated as a constant-head boundary to the modeled aquifer system because (1) the potentiometric surfaces of all explored aquifers immediately adjacent to the stream are apparently graded to and are hydraulically continuous with the stream, (2) the stream stage has apparently not changed, and is not expected to change, significantly with time, and (3) Union Flat Creek is hydraulically remote from the basin proper to a sufficient degree that reasonably small errors in the simulation for the stream area are not likely to significantly limit the accuracy or usefulness of simulated data for the basin area. Item (1) above was discussed on page 40 and item (3) is discussed on page 98; item (2) is discussed below.

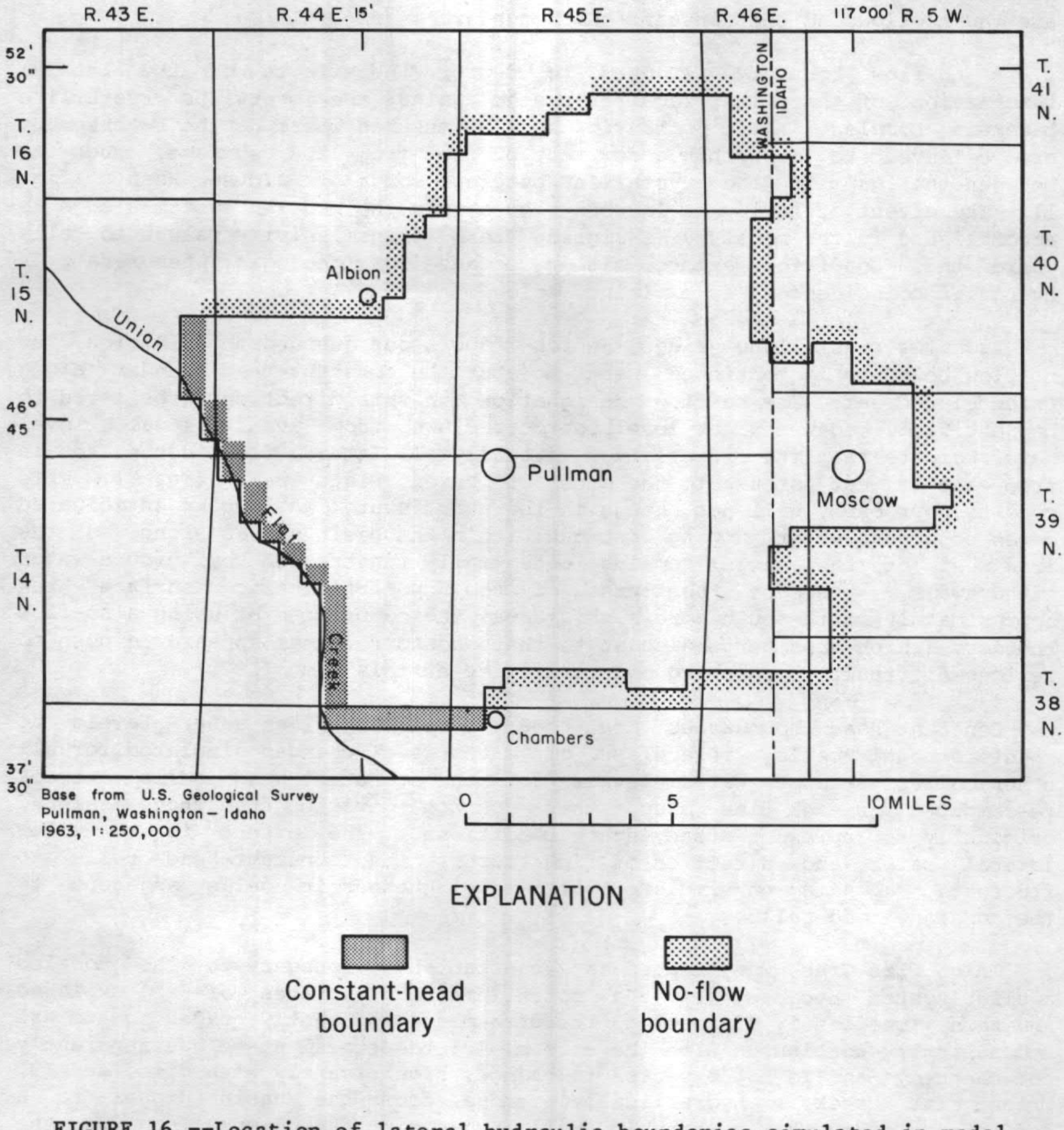


FIGURE 16.--Location of lateral hydraulic boundaries simulated in model of primary aquifer system.

Although no ground-water levels adjacent to Union Flat Creek were found during the present study to be measurably lower or significantly higher than the stream level, the local aquifers are believed to discharge to and receive recharge from the stream; the rate and direction of such exchange depends on the head relationship between the stream and the aquifers at the time and place in question. Judging from the shape of the generalized potentiometric contours for the area (fig. 7), it appears that, at the present time, the aquifers are primarily discharging to the stream channel. However, the stream-aquifer head relationship near the southwestern part of the modeled area probably is such that some local recharge to the aquifers occurs via seepage from the stream.

Aquifer discharge to Union Flat Creek from the barrier zone has probably diminished somewhat in recent years, because of pumping in the basin and some flattening of the deep ground-water gradient across the barrier zone. However, stream gains from the shallower aquifers on the opposite (southwest) side of Union Flat Creek have probably helped to offset any detectable stream depletion and lowering of average stream stage. The stream is perennial, and, during a recent 18-year period (1953-71), the average annual discharge of the stream, as measured at the gaging station near Colfax, Wash., was 27,000 acre-feet (37 ft^3/s). Analysis of cumulative precipitation at Pullman versus cumulative runoff in Union Flat Creek fails to indicate any significant deviation in the long-term relationship between the two. It is believed, therefore, that stream-stage elevations have not been significantly affected; Union Flat Creek is, and apparently always has been, only 1 or 2 feet deep during most of the year. Thus, the use of a constant-head boundary for this area of the model, with the aquifer head specified as at the approximate adjacent stream level appears to be justified.

As ground-water development continues in the basin, ground-water discharge to Union Flat Creek can be expected to continue to decrease, while recharge to the primary aquifer system (at the expense of the stream) increases. However, as long as the pumping rates are no greater than anticipated, changes in stage and flow as a result of the pumping will probably remain difficult to detect along this stream. Likewise, as long as the model is used to project only the effects of pumping within the basin at rates no greater than two or three times the present rates, the simulated exchange of water between the primary aquifer system and Union Flat Creek is not expected to depart seriously from actual conditions. If, however, the effect of simulated pumping is great enough to cause water levels adjacent to the stream to decline significantly--thereby causing computed rates of recharge to approach or exceed the average annual streamflow--the projected effects of pumping could be overly optimistic.

The southern edge of the modeled area, between Union Flat Creek and the town of Chambers, was also treated as a constant-head boundary during model calibration. The rationale for this condition being used here is that the area south of the modeled area is virtually free of man-influenced changes in the natural environment, and the water levels are expected to remain essentially undisturbed by development in that area for at least 25 years. Because water levels in this area to the south are believed to be higher than anywhere within the modeled area, flow across the boundary could be expected to increase in response to ground-water development within the modeled area to the north. Of course, as development continues to increase within the basin, the area of head decline could encroach into areas south of the constant-head boundary and might limit the actual amount of induced recharge from the south. However, as long as simulated water levels immediately north of the constant-head boundary do not decline excessively, so as to produce unreasonable amounts of north-flowing recharge across the boundary, there should be no adverse effects on the accuracy of simulated water levels for areas within the basin.

As a safeguard against overly optimistic water-level projections during future use of the model for management purposes, the southern constant-head boundary can be converted--if desired--to a "steady-flux" boundary. The steady-flux boundary would allow north-flowing recharge to occur, but at a rate that neither increases nor decreases with time. Such a rate can be effected during simulation at some specified time or when the computed rate reaches a specified magnitude.

Transmissivity

Transmissivity data are a quantitative indication of an aquifer system's ability to transmit water throughout its entire thickness. Because the magnitude and distribution of transmissivity values for the primary aquifer system was subject to conjecture, the transmissivity data for the model had to be calibrated by trial-and-error simulation with the steady-state model.

Initial transmissivity estimates were based on a relationship believed to exist between this parameter and the specific capacities of the deeper municipal and university wells tapping the primary aquifer system. (Specific capacity is the ratio of well discharge rate to drawdown.) The method of estimating transmissivities from specific-capacity data has been used successfully in other model studies of basalt aquifer systems in eastern Washington (Luzier and Skrivan, 1973; Mac Nish and Barker, 1976). By using yield and drawdown data from drillers' short-term[1] pumping tests in combination with the relationship suggested by Theis, Brown, and Meyer (1963), transmissivity estimates were computed by the formula:

$$T = 3.1 \times 10^{-3} \frac{Q}{s}$$

where T = transmissivity of the aquifer system in vicinity of well, in feet squared per second;
Q = yield of well, in gallons per minute, and
s = water-level drawdown of pumped well, in feet.

---

[1] Most pumping tests by local drillers to determine approximate well production are run for periods of from 2 to 6 hours.

Transmissivities computed in this manner, for productive wells in the primary aquifer system, are shown in table 1.

Because the computed transmissivity values in table 1 are so variable, even for wells of similar depths in the same area, average values were believed to be most applicable for use in the model. Computations using only data from the area's eight deepest production wells--which are believed to best represent overall conditions over most of the basin--provided an average transmissivity of 0.30 ft^2/s; this average was used for the entire basin area during early stages of model development. Ultimately, however, the initial values had to be adjusted, as part of the calibration process, in order to simulate the appropriate potentiometric gradients.

The final, calibrated distribution of transmissivity values is shown in figure 17. Because transmissivity is a function of aquifer thickness, the values decrease near the margins of the basin to account for the thinning of the aquifer system along the edges of the crystalline outcrops. Also, to duplicate the effects of the apparent barrier to ground-water flow west of the basin (p. 37), the calibrated transmissivities decrease to minimum values of 0.001-0.09 ft^2/s just west of the basin boundary, in a band roughly paralleling the major topographic features in the area.

The potentiometric surface for the primary aquifer system has been declining below the top of the system (as defined in fig. 14) in most parts of the basin during the past 5-10 years, resulting in gravity drainage and conversion to water-table conditions. As a result, transmissivities are decreasing as the water levels decline. Model transmissivities were not adjusted to duplicate such an effect, for the following reasons:

1. The saturated thickness of the primary aquifer system has not been established well enough over broad enough areas to make the operation feasible.

2. The actual effects of the transmissivity decreases are thought to be insignificant. Assuming, conservatively, that the average saturated thickness of the primary aquifer system over most of the area affected is 1,000 feet, water levels must decline an additional 100 feet before a 10-percent change in the average transmissivity would be realized. Until adequate saturated-thickness data become available--at which time the model can be easily modified by changing transmissivity values in accordance with the computed water-level changes--the accuracy of water-level projections into the future should be affected only slightly as a result of using time-constant transmissivity values.

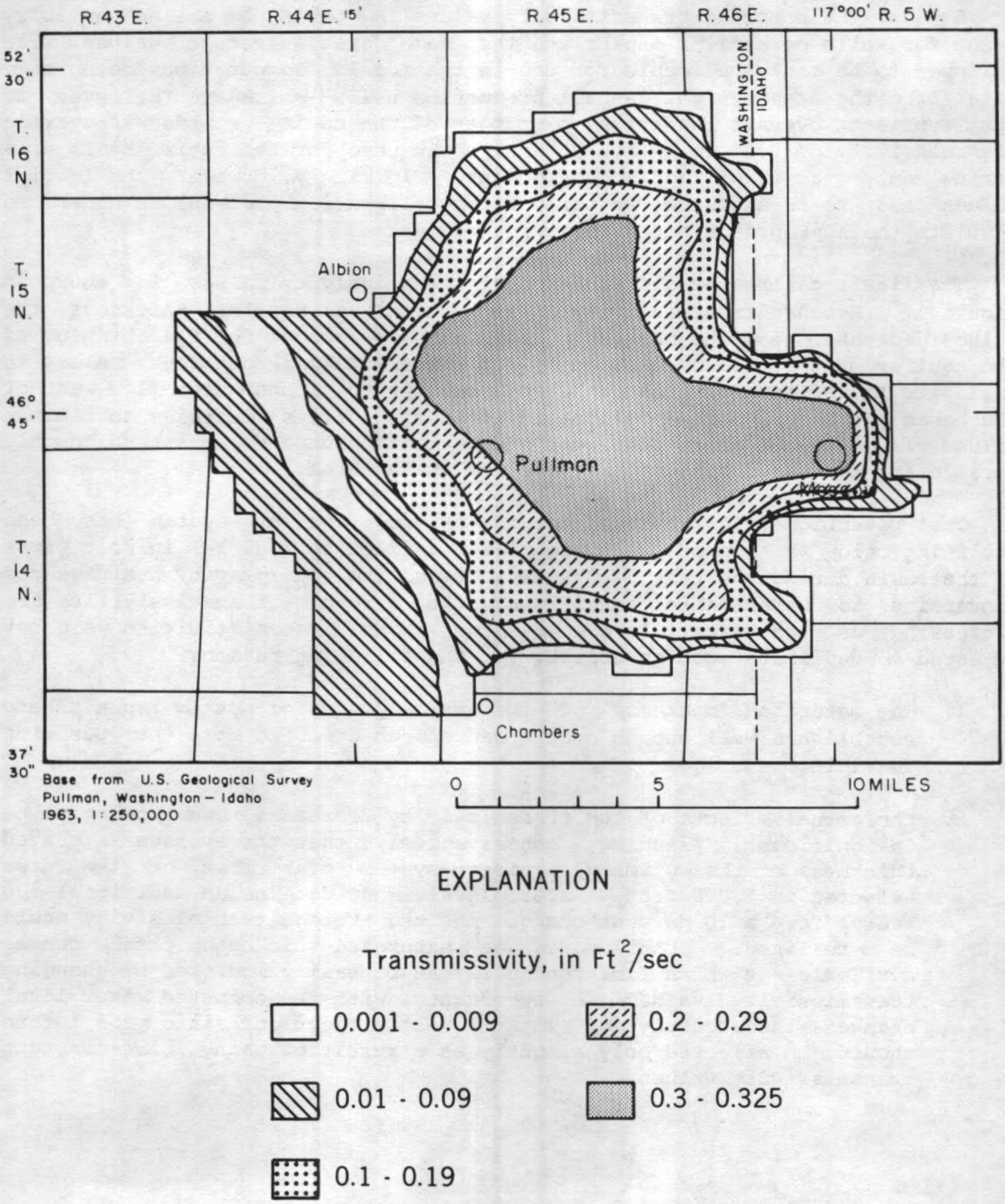


FIGURE 17.--Areal distribution of calibrated transmissivities used in model of primary aquifer system.

Storage Coefficient

The magnitude of the water-level change that occurs in an aquifer system in response to changes in recharge and discharge depends partly on the storage coefficient. Storage coefficient--the measure of an aquifer's capacity to store and yield water--may be defined as the volume of water that an aquifer system releases from or takes into storage per unit horizontal surface area of aquifer per unit change in head.

For an aquifer under confined conditions, the storage coefficient is mainly a quantitative expression of the elasticity of the aquifer and its water. Although rigid limits cannot be practically established, the storage coefficients of most confined aquifers range from about 0.001 to 0.00001 (Lohman, 1972, p. 8).

Previous studies of confined basalt aquifer systems in the Columbia Plateau have used the following storage-coefficient values for model simulation:

1. Between 0.0015 and 0.006 in the Odessa-Lind area (Luzier and Skrivan, 1973).

2. 0.0025 in the Columbia Basin Irrigation Project Area (Tanaka and others, 1974).

3. Between 0.00047 and 0.00475 in the Walla Walla River basin (Mac Nish and Barker, 1976).

Storage coefficients computed from results of aquifer tests in the Columbia Plateau area are, in general, smaller values than those used in the models. La Sala and Doty (1971, p. 35) reported that storage coefficients in confined basalt aquifers in the area of Hanford, Wash., were found to range from 0.0006 to an extremely low value of 0.000014. Also, Price (1960, p. 29) reported a storage coefficient of "about 0.0002" from a pumping test in the city of Walla Walla, Wash.

The calibrated storage-coefficient values used for confined conditions in the model of the primary aquifer system in the Pullman-Moscow basin ranged from 0.005 to 0.006 (fig. 18). These values are the result of much deliberation and trial-and-error transient simulation in which the attempt was made to match the magnitude and slope of the long-term water-level declines in the area (fig. 8). Use of coefficients as little as even 10 percent smaller than those illustrated caused unacceptable differences between simulated and measured water levels.

Although the range of calibrated storage coefficients in the Pullman-Moscow model is within the upper part of the range in values used in the other modeling studies of the basalt aquifers, the values are somewhat larger than those indicated by aquifer-test data for basalt aquifers in the same region. Storage coefficients somewhat larger than those generally computed from aquifer tests probably are required in the models, because the effects of delayed yield from storage must be incorporated into the simulation, whereas the effects of such phenomena are less likely to show up during short-term pumping tests.

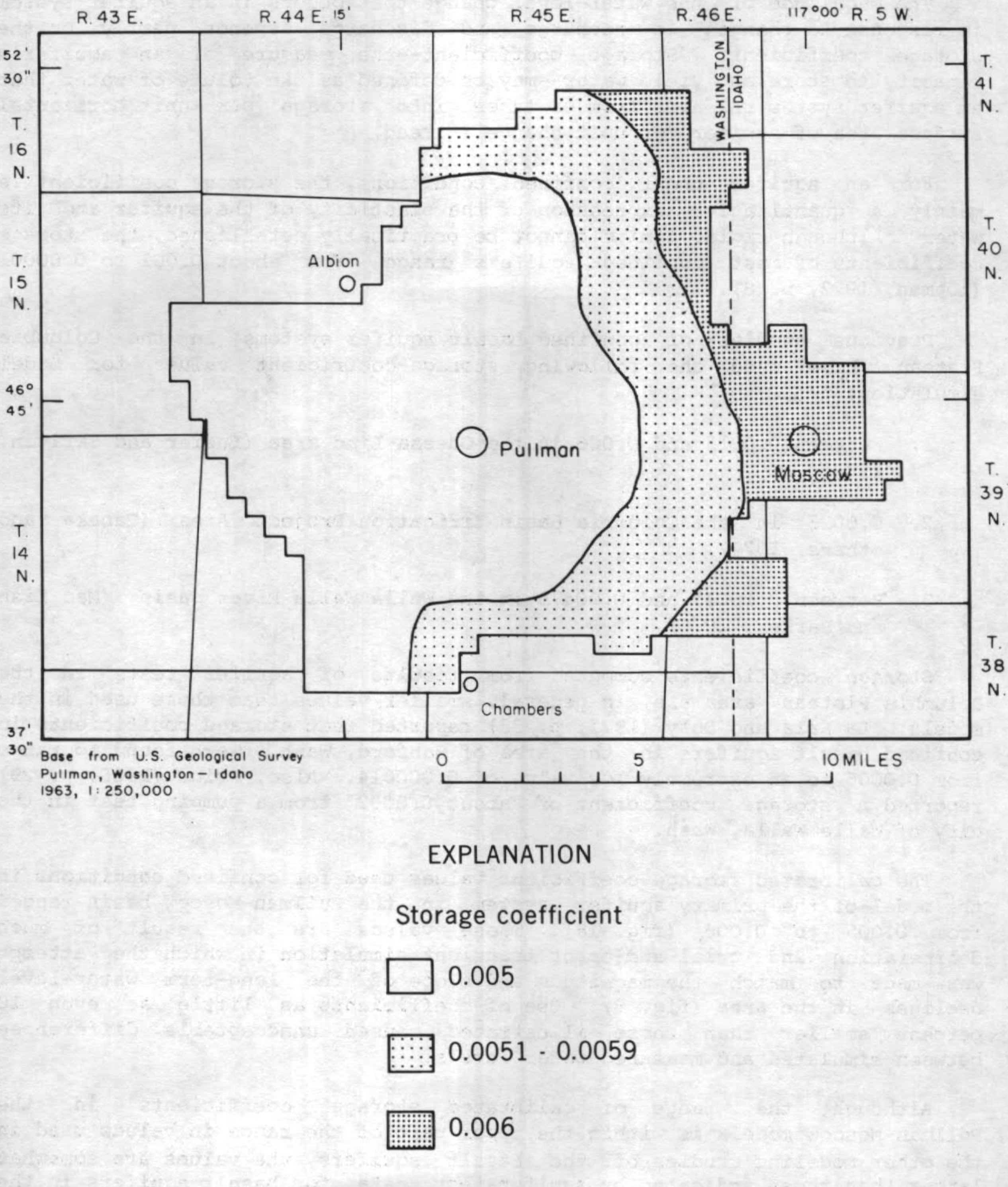


FIGURE 18.--Areal distribution of storage coefficients, under confined conditions, as calibrated in model of primary aquifer system.

Delayed yield of water from storage (Boulton, 1954, p. 472) can occur from a compressible bed of fine-grained sediment--such as a lens of the Latah Formation--within an artesian aquifer sandwiched between relatively impermeable layers--such as dense basalt flows. As Boulton (1954) explained:

> "If an artesian aquifer contains beds of fine-grained compressible material, these beds do not compress immediately when the pore-water pressures at their boundaries are reduced by pumping. Thus, water is squeezed out of them rather slowly, causing a delayed yield from storage similar to that produced by the slow draining of fine-grained beds under water-table conditions."

The widespread occurrence of clays and silts within the basin are believed to be primarily responsible for the relatively large storage-coefficient values required to match the slope changes in the long-term hydrographs for wells in the primary aquifer system.

Although the storage coefficients shown in figure 18 worked well for simulation of periods before about 1968, the water-level-decline curves (fig. 8) could not be matched into the 1970's unless these values were adjusted, where applicable, to account for the transition from confined to water-table conditions (first discussed on page 63). Experimentation during transient simulation with the model indicated that the effective storage coefficients in the primary aquifer system increased from the values shown in figure 18 to about 0.075, where and when the potentiometric surface declined below the top of the system (defined in fig. 14). Figure 19 illustrates the consequences of <u>not</u> simulating the effects of this apparent increase in the storage coefficient for model cell (21,18).

The storage coefficient of a typical sedimentary aquifer under water-table conditions is a function almost entirely of gravity drainage, as only a small part of the yield from such an aquifer comes from compression of the aquifer and expansion of the water. However, when water is released from or taken into storage in a basalt aquifer system under water-table conditions, the process becomes more complicated because of the heterogeneous nature of the joint and cavity structures within a basalt sequence. As a result, the storage coefficients of unconfined basalt aquifers are generally somewhat lower than the values commonly quoted for other nonartesian aquifers, such as the 0.1-0.3 values of Lohman (1972).

To date (1975), the transition from artesian to water-table conditions has not yet occurred everywhere in the primary aquifer system, and the present definition of the top of this aquifer system is somewhat generalized. As a result, the effects of the changing conditions may not yet be fully recognized and incorporated into the simulation model with as much accuracy as would be possible following another decade or so of observation. Although the change to an unconfined storage coefficient of 0.075 seems to be justified based on available data, additional data could suggest a somewhat different interpretation.

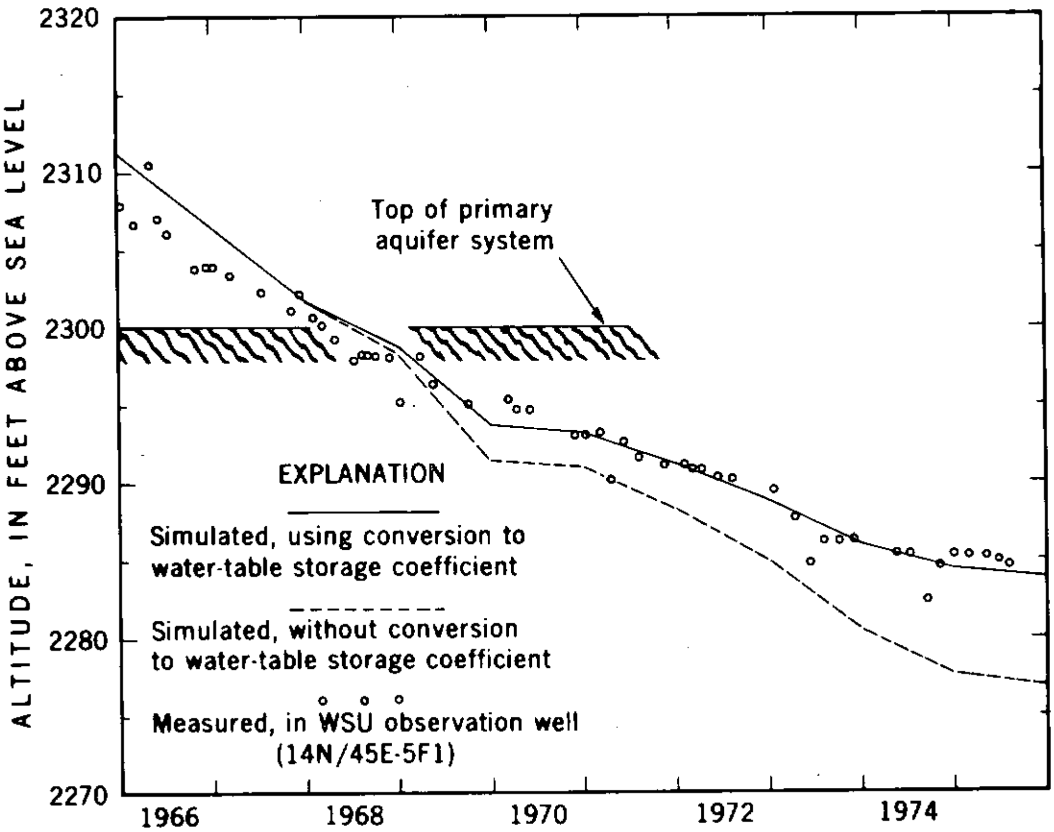


FIGURE 19.--Comparison of simulated and observed water levels for cell (21,18), which show the effect of the rise in storage coefficient accompanying the conversion to water-table conditions in the primary aquifer system.

Pumpage

The time distribution of pumping (the "P" component of equation 3, p. 56) from the primary aquifer system is illustrated in figure 20. These data for years prior to 1936 represent a straight-line projection from an estimated annual pumpage of 300 acre-feet for 1896. The 1896 pumpage was derived by assuming an average daily discharge of about 18,000 gallons (about 12 gal/min) from each of the 15 wells reported by Russell (1897) to exist in Pullman at that time.

A reliable basis for model calibration was insured by the cooperation of the local municipalities and universities in providing records of metered pumpage during generally all years since 1935. Except for the gap in the records between 1944-49, the data are generally excellent. Estimates of unmetered private and industrial pumpage for years prior to 1960 were made and used during transient simulation. However, no attempt was made to account for such pumpage since 1959, because it is believed to have amounted to less than 5 percent of the total (Luzier and Burt, 1974, p. 28), and the major effort required to compile such data did not appear justified.

As the rate of pumping has changed with time, so has the areal distribution. Until 1937 significant pumping from the primary aquifer system occurred only near Pullman--in areas represented in the model by cells (21,17) and (21,18). (As mentioned earlier, pumping from the primary aquifer system in the Moscow area did not begin until the mid-1960's.) However, by 1974 pumping had spread to areas represented by nine cells, three of which are in Moscow. The average annual rate of pumping from the primary aquifer system between years 1971 and 1975 was about 6,600 acre-ft/yr; the areal distribution of the pumpage is shown in plate 1.

Annual pumping rates have been used in the simulation instead of attempting to duplicate seasonal fluctuations in the pumping rate because (1) only annual totals were consistently available for most pumping sites, (2) the additional cost required to simulate seasonal pumping variations was prohibitive, and (3) static water levels do not show significant effects of seasonal fluctuations in pumping stress (Foxworthy and Washburn, 1963, figs. 5 and 7).

Owing primarily to the absence of seasonally oriented irrigation and the fact that water for public and university supplies is pumped essentially year around, seasonal variations in pumping are not as pronounced in the Pullman-Moscow basin as they are in most rural areas in eastern Washington. Figure 21 illustrates the month-to-month distribution of all significant pumpage during a recent year (1974) for the Pullman area. This graph shows that, although there is moderate seasonal fluctuation in the total pumpage, the variation during most of the year does not deviate severely from the steady rate used for simulation.

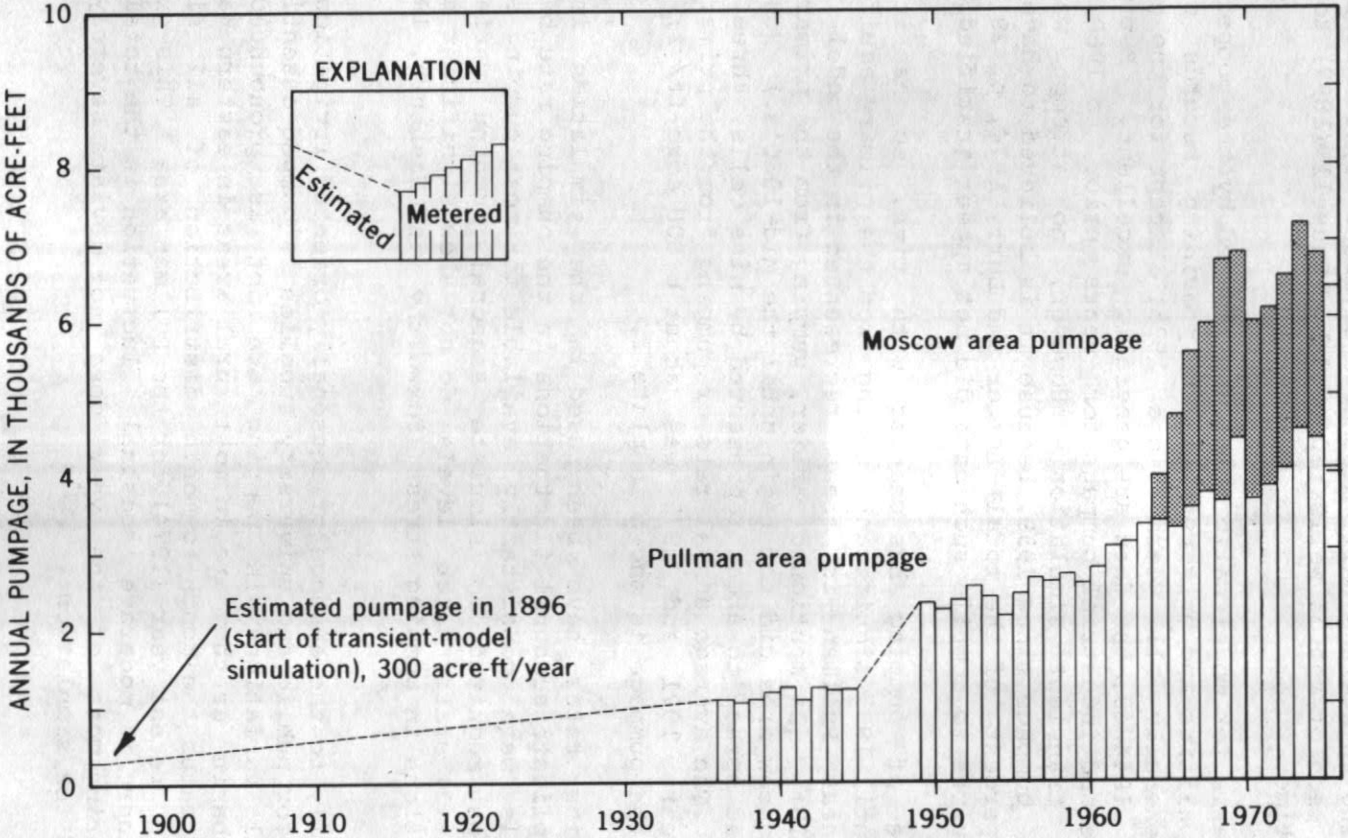


FIGURE 20.--Long-term distribution of pumpage from primary aquifer system.

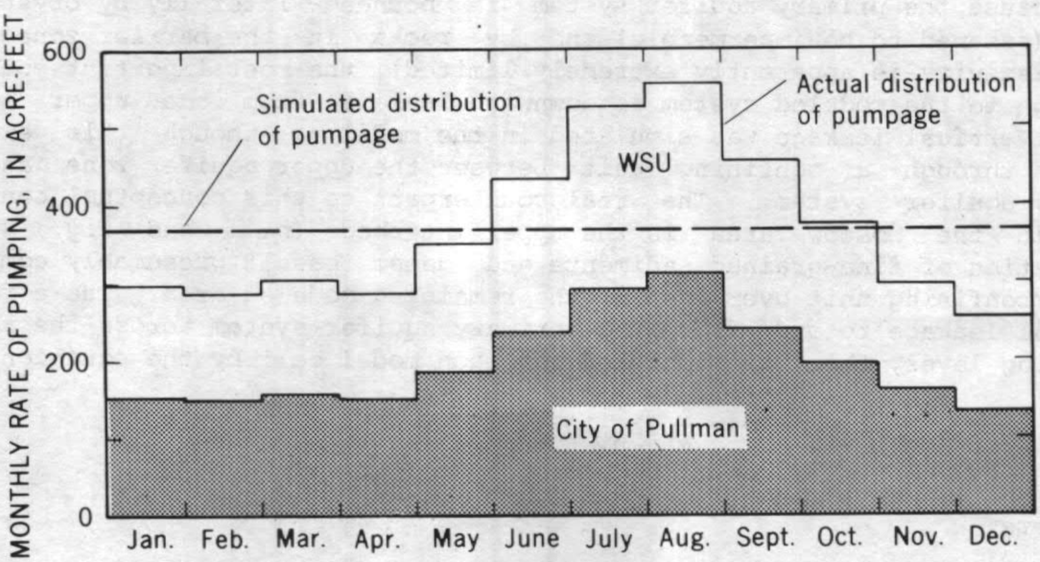


FIGURE 21.--Month-to-month distribution of actual and simulated pumpage during 1974 from WSU and city wells in Pullman area.

The use of a constant annual rate of pumping, which was updated at the beginning of every year, is not considered to have limited the ability of the model to simulate the long-term effects of pumping from the primary aquifer system. However, if desired, and if the additional cost required were deemed justifiable, seasonal variations in pumping could be accounted for during future simulations for water-management purposes.

Vertical Leakage

Because the primary aquifer system is bounded laterally by crystalline rocks (assumed to be impermeable) and by rocks in the barrier zone (whose transmissivity is apparently extremely limited), the most important source of recharge to the modeled system is downward leakage from the upper aquifer zone. Vertical leakage was simulated in the model as though this exchange occurs through a confining unit between the upper aquifer zone and the primary aquifer system. The real counterpart to this conceptual confining unit in the Moscow area is the upper interbeds (p. 45 and fig. 4). A combination of fine-grained sediments and dense basalt presumably comprises such a confining unit over most of the remaining modeled area. The effect of vertical leakage to and from the primary aquifer system across the assumed confining layer, then, is simulated for each model cell by the equation:

$$Q = \frac{K}{M} (h_u - h) A,$$

where

Q = vertical flux across the confining layer, in cubic feet per second;
K = vertical hydraulic conductivity of the confining layer, in feet per second;
M = thickness of the confining layer, in feet;
h_u = head in the upper aquifer zone above the confining layer, in feet;
h = head in the modeled (primary) aquifer system, in feet; and
A = surface area of model cell, in feet squared.

Although values of A are known absolutely and data for both the space and time distribution of the head variables (h_u and h) are generally very good, values of K and M had to be estimated or derived empirically. A "reasonable" hydraulic conductivity (K) value of 2.0×10^{-9} ft/s--chosen from a wide range of possibilities suggested by Bredehoeft and Hanshaw (1968, table 4, p. 1101)--was used for all areas of the aquifer system. A calibrated distribution of M values was developed by trial-and-error simulation with the transient model while attempts were made to duplicate the magnitude and slope of the historic water-level decline in the modeled area (fig. 8).

In theory, the M values represent the thickness of the upper interbeds (fig. 4) in the Moscow area and the effective thickness of the basalt and sedimentary layers that act as the confining unit elsewhere. The calibrated M values (fig. 22), however, probably account for more than these dimensions. Because K is a constant in the model, the M values resulting from the calibration will, of course, compensate somewhat for any errors resulting from differences between actual values of K and the assumed value. In addition, they probably help account for other differences between the real system and the model such as those involving storage in the confining layer (see below). Although the calibrated M values may not be directly comparable to a specific, measurable parameter in the real system, it should be recognized that they do appear to allow a reasonably accurate simulation of the effects of vertical leakage to and from the modeled system.

In response to adjustments in the pressure gradient across a confining layer (which result from fluctuating water levels above and below the layer), changes may occur in the volume of water in the confining layer. The associated exchange of water (known as transient leakage) between the confining layer and the aquifers above and below is related to the elastic properties of the water and the confining medium in addition to the porosity of the confining material. Effects of storage in a confining layer are described mathematically by Bredehoeft and Hanshaw (1968). Numerical techniques have been developed to approximate the effects of storage in a confining layer (Bredehoeft and Pinder, 1970, and Trescott and others, 1976). However, such procedures were not believed necessary in the simulation of vertical leakage in the Pullman-Moscow model for the following reasons: (1) real data for the geometry and storage characteristics of the confining layer were nonexistent and could only be generalized from well logs and the available literature (remembering that the value already being used for the hydraulic conductivity (K) of the confining bed was, in itself, a generalized value from the literature), and (2) the actual volume of water associated with any transient leakage to the primary aquifer system is believed to have been relatively small and, therefore, to have had negligible affects on the potentiometric surface in the primary aquifer system. Such reasoning is consistent with conclusions resulting from a recent model study of a similar basalt aquifer system in the Walla Walla basin (Mac Nish and Barker, 1976).

Under actual conditions that existed prior to about 1968, downward leakage increased over most the basin as the potentiometric surface in the primary system declined. Since about 1968, however, heads in certain places started declining below the top of the primary aquifer system, resulting in unsaturated flow conditions between the upper aquifers and the deeper system. In consideration of these unsaturated conditions--when and where the upper zone becomes perched above the deeper system--the rate of vertical leakage is at a maximum when the potentiometric surface for the primary aquifer system is at the base of the confining unit through which leakage occurs (Walton, 1970, p. 362). In accordance with this phenomenon, an algorithm is used in the model to prevent the rate of vertical leakage at any model cell from increasing above that computed when the head in the modeled system is at the base of the overlying confining layer.

An important effect of the vertical-leakage limitation--in both the real and modeled system--is that vertical recharge to the primary aquifer system beneath much of the basin will not increase above present (1975) rates as a result of continued pumping development and increased head decline in the system. As the potentiometric surface beneath most of the Pullman subbasin is presently below the top of the aquifer system, it would appear that this area is already receiving vertical recharge at about the maximum rate possible.

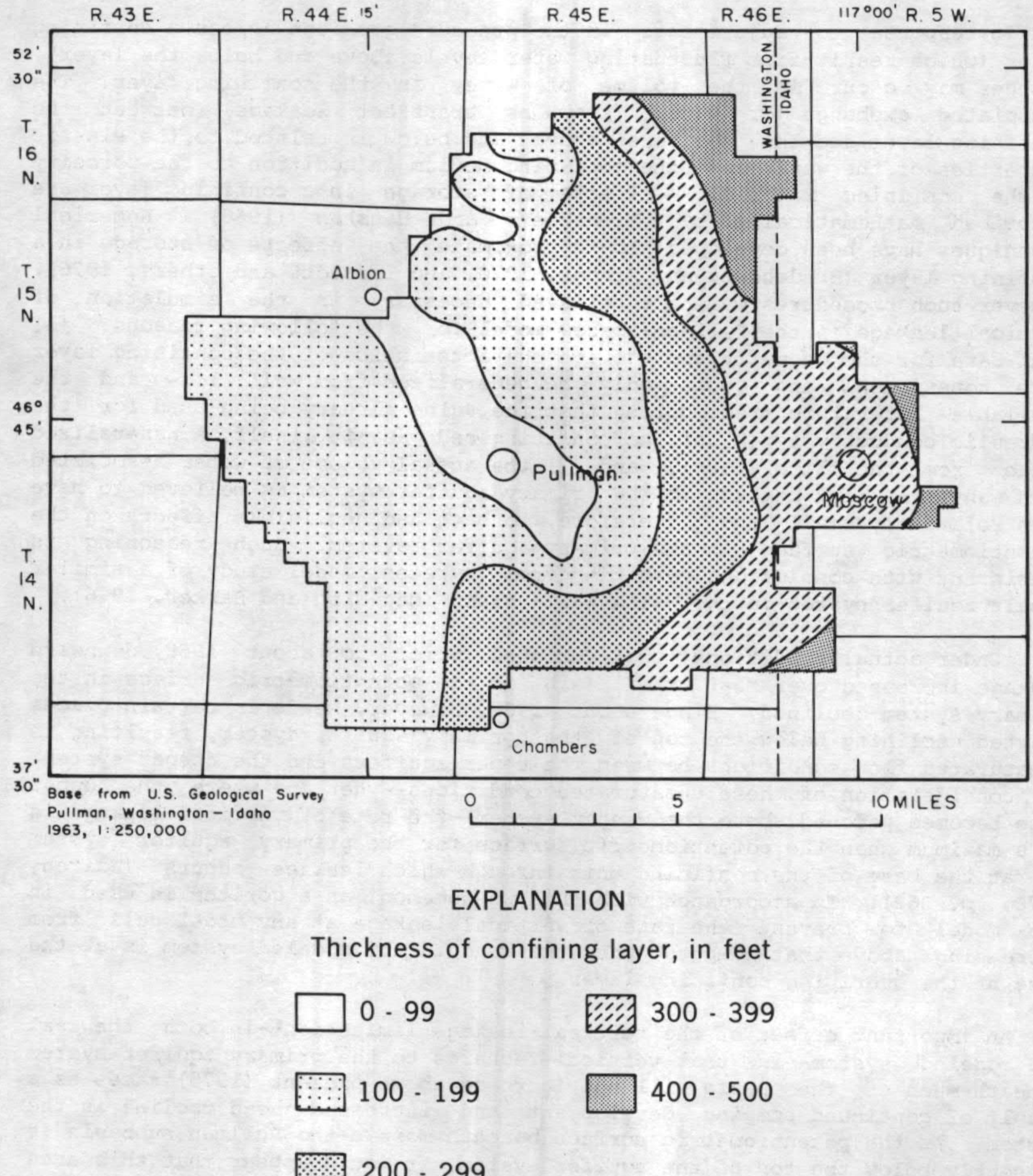


FIGURE 22.--Areal distribution of thickness of confining layer overlying primary aquifer system, as simulated in the model.

As explained earlier, water levels in the upper aquifer zone (fig. 23) have not changed substantially from their steady-state positions over most of the Pullman subbasin. In the Moscow area, however, the upper potentiometric surface declined nearly 100 feet by 1960 and has since gained back about one-half of that decline (fig. 5). In an attempt to account for the basic effects that this historical fluctuation is believed to have had on the time distribution of vertical leakage to the primary system, the head values in the upper aquifer zone were corrected where applicable during transient simulation by use of an algorithm which takes into account the shape of the hydrograph in figure 5.

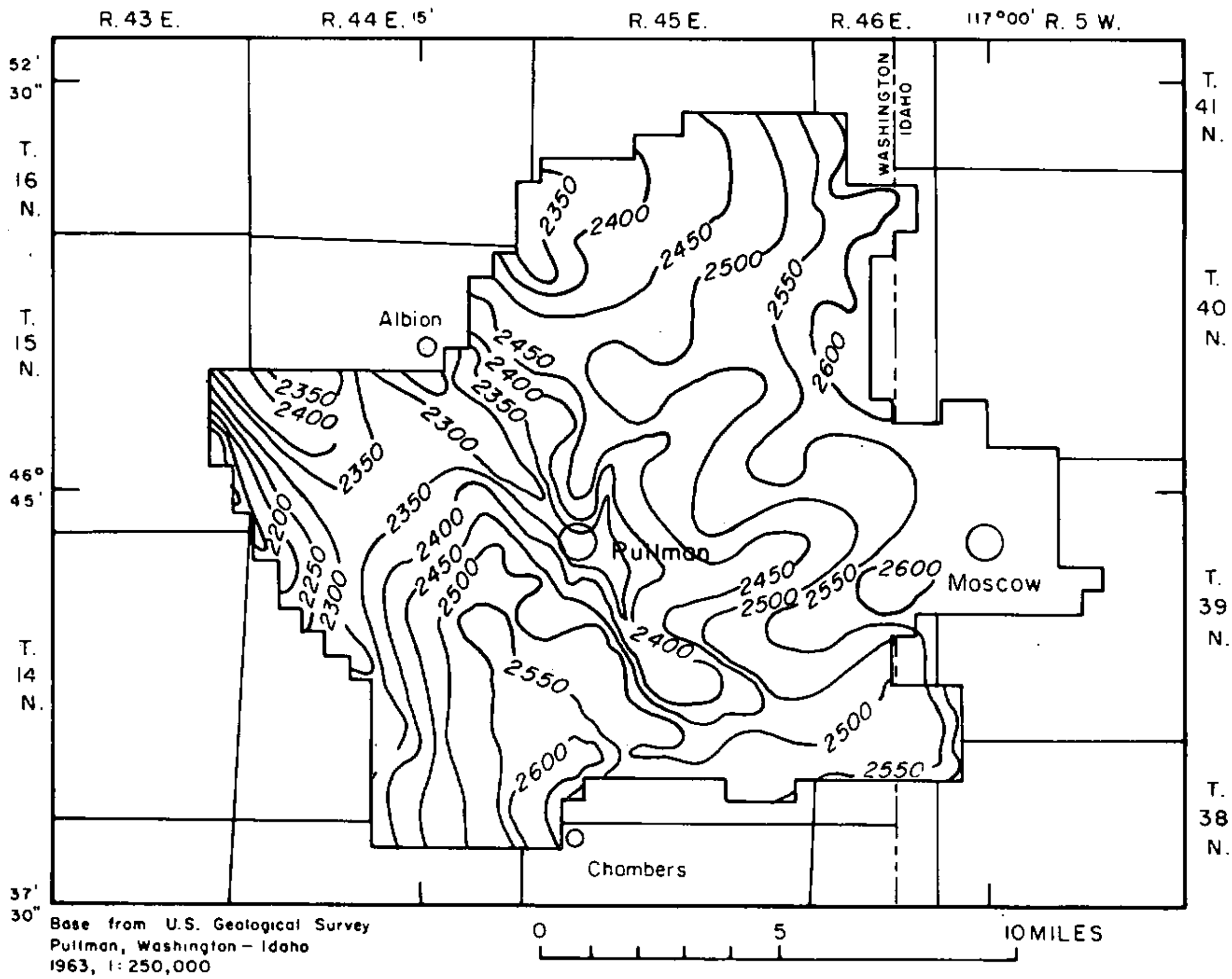
The only water levels adjusted during the correction procedure were the upper-zone levels east of column 26 of the finite-difference grid (pl. 1); upper-zone water levels over the remaining 80 percent of the modeled area were fixed at their steady-state position throughout the transient simulation. Maximum correction was applied to water levels east of column 30, in accordance with the full displacement dictated by the hydrograph in figure 5. Water levels were adjusted to 75 percent of that maximum in column 29, to 50 percent in column 28, and to 25 percent in column 27.

By adjusting the upper-zone heads during calibration of the transient model, the resulting simulated leakage to the primary aquifer system in the Moscow area is less than it would be without the adjustments. This provides a more accurate approximation of the historical water-level conditions in the Moscow area. The maximum improvement gained by the adjustment is about 5 feet for the period 1955-65.

Historical changes in the upper-zone water levels in the Moscow area have apparently influenced conditions in the primary aquifer system. It would be advantageous, therefore, to account for changes in the upper-zone water levels during model simulations into the future. Unfortunately, it is difficult to anticipate the future trend of water levels in the upper aquifer zone beneath Moscow. If the zone were to remain relatively unstressed (unpumped), as during the past 12-15 years, the water levels would almost certainly continue to recover for a time, as they have since about 1960 (fig. 5). However, a new (1975) filter plant is under construction in Moscow to treat upper-zone water and make it more suitable for use; if pumping from the upper zone here increases again as expected (Bill Smith, Moscow city engineer, oral commun., 1975), the upper potentiometric surface in the Moscow area may decline once more.

Although any set of upper-zone head values can be used in the model, the more accurate these data, the more reliable the simulated results will be for the functioning of the primary aquifer system. However, in the absence of better estimates for future water levels in the upper aquifer zone, it is probably reasonable to expect adequate results for most water-management purposes by assuming that the heads in the upper zone will remain unchanged from their 1975 positions.

The interaction between the upper aquifer zone and the primary aquifer system could be simulated with more accuracy if a multi-layer model were used such as that developed by Trescott (1975). The advantages of such a model for the Moscow subbasin are discussed further on page 106.



EXPLANATION

——— 2400 ———

Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 50 feet.

FIGURE 23.--Assumed potentiometric surface of upper aquifer zone under steady-state (prepumping) conditions of ground-water flow.

Steady-State Analysis

The steady-state model is a numerical representation of the hydraulic state of the primary aquifer system prior to approximately the mid-1890's, before man introduced stresses which altered the initial, or pre-development, conditions. Except for the original water levels measured in Pullman by Russell (1897), real data defining initial hydrologic conditions in the study area do not exist. As a result of this severe data limitation, control for the steady-state model was largely extrapolated from patterns of head and flux observed in the area since the 1930's.

Basically, the steady-state analysis involved simulating a set of hydraulic conditions upon which 80 years of historic pumping stress could be superimposed in a transient model that would, then, reproduce the historical water-level decline through 1975. Because of the lack of data to define the actual steady-state conditions, there was not a unique solution to the steady-state analysis; different combinations of vertical flux and transmissivity distributions would allow a reasonable depiction of the potentiometric surface to be generated by simulation. Presumably, however, only a reasonably correct combination would allow adequate simulation of the transient events through 1975 to follow--using the generated steady-state head surface as initial water-level conditions.

Without evidence to the contrary, the potentiometric surface in the mid-1890's was conceived as resembling the surface as it is observed over much of the area today--nearly flat within the basin and sloping toward Union Flat Creek in the barrier zone (fig. 7). The water-level altitudes within the basin were assumed to be at about 2,360 feet, as reported by Russell (1897) for wells at Pullman. Water levels in the barrier zone near the southern boundary of the modeled area, between Chambers and Union Flat Creek, were also assumed to be at an altitude of about 2,360 feet.

Because the steady-state potentiometric surface was virtually constant with time, so must have been all elements of recharge and discharge. Owing to the confining nature of the lateral boundaries to the primary aquifer system, all lateral discharge from the basin to the barrier zone must have been equal to the net vertical leakage (recharge) to the system within the basin. Initially, all lateral flow beneath the western basin boundary was presumably toward the west--out of the basin. In turn, the lateral discharge to the western model boundary (Union Flat Creek) was necessarily equal to the sum of all fluxes to the system in the barrier zone, including (1) the lateral flow from the basin, (2) lateral inflow across the southern boundary (between Chambers and Union Flat Creek), and (3) the net vertical leakage (recharge) inside the barrier zone.

The final steady-state potentiometric surface simulated with the calibrated model is shown in figure 24. Figure 25 illustrates the general distribution of simulated lateral flow under pre-development conditions in the primary aquifer system. Figure 26 shows the distribution of the simulated rates of vertical flux in the area at this time.

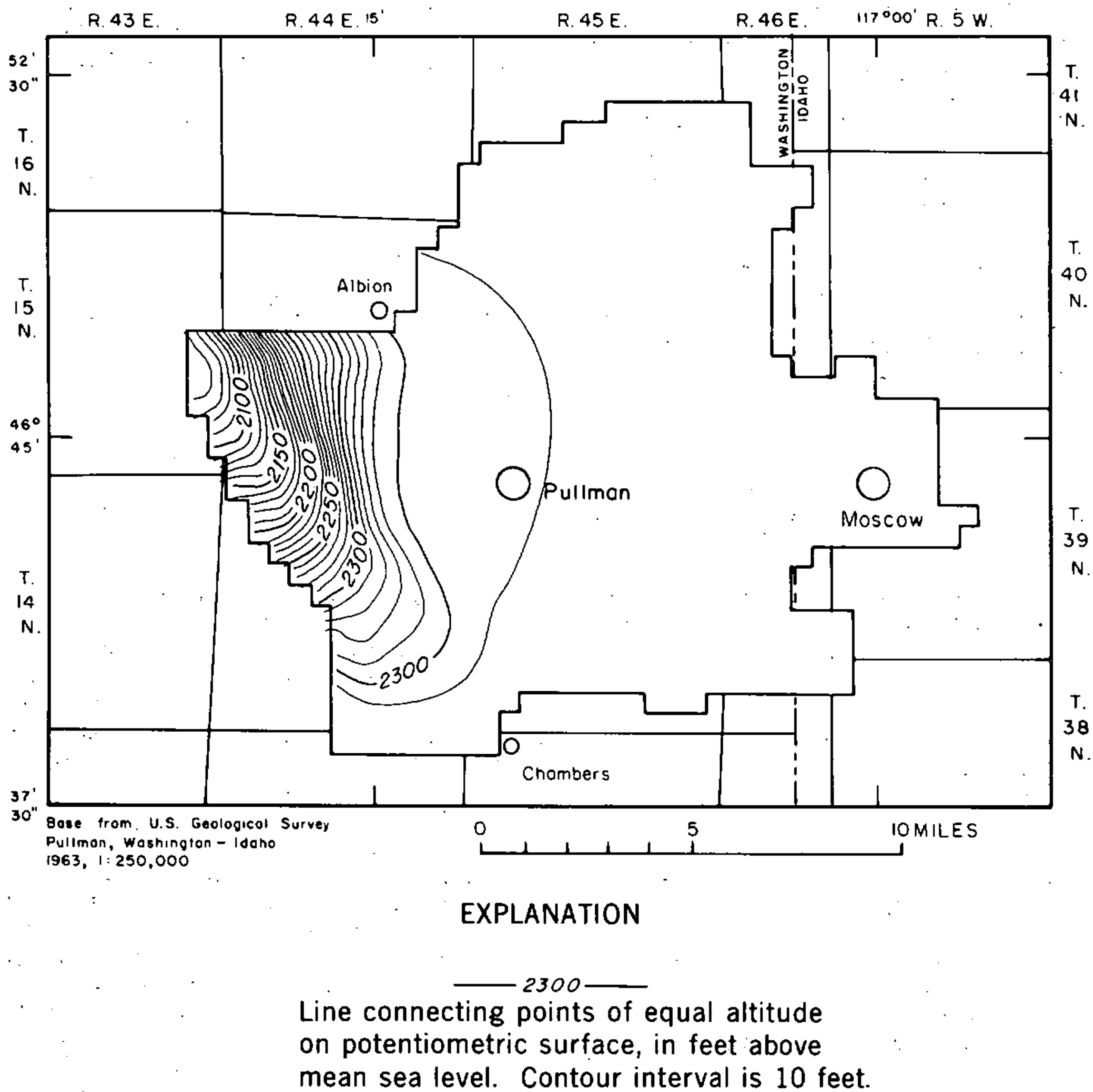
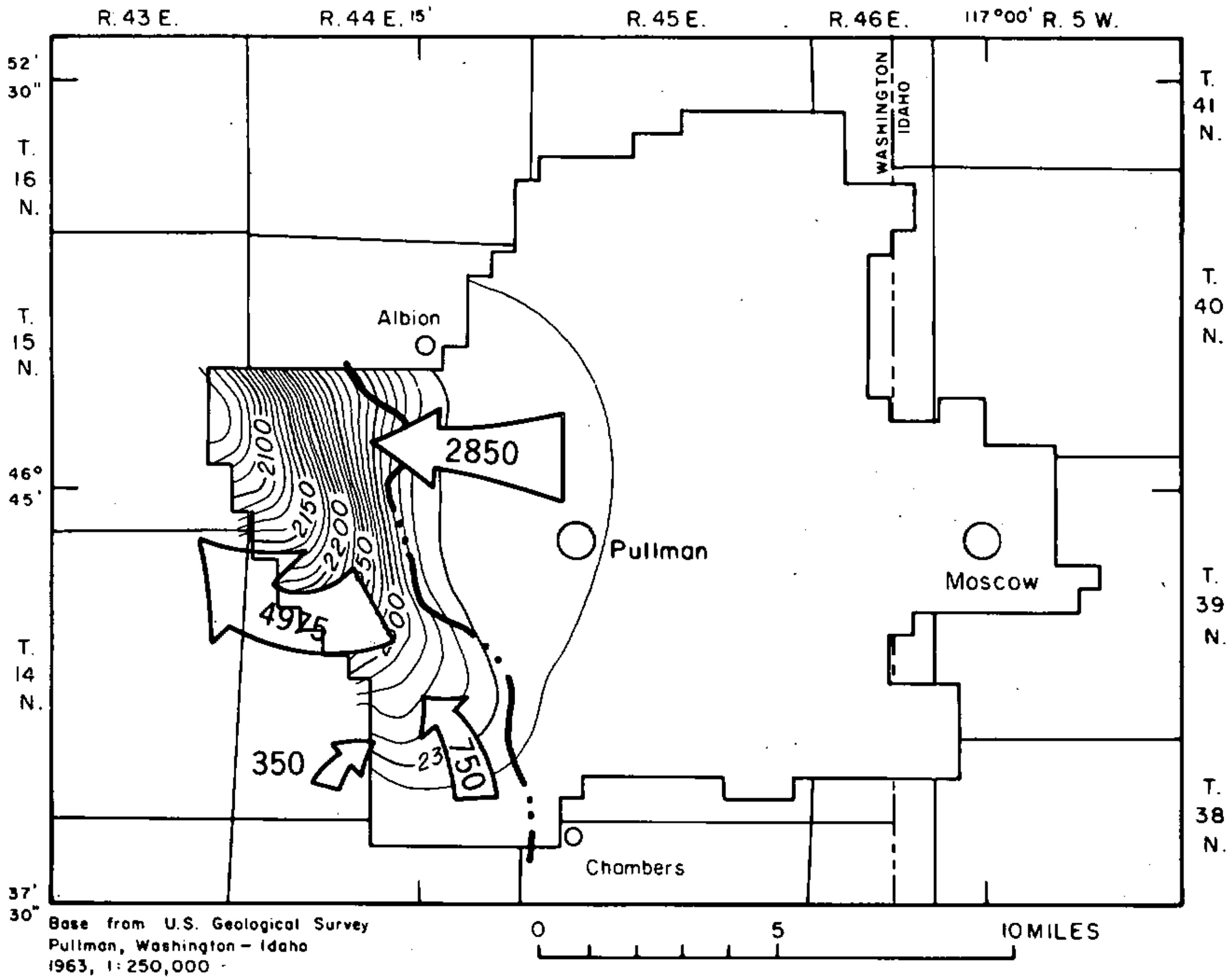


FIGURE 24.--Simulated potentiometric surface representing steady-state conditions in the primary aquifer system.



EXPLANATION

—— 2300 ——
Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 10 feet.

—— • • ——
Boundary of western segment of basin

FIGURE 25.--Generalized dirctions of lateral ground-water flow in the primary aquifer system under steady-state conditions. Rates of flow relate to simulated quantities in table 2 in acre-feet/yr; arrows indicate general flow directions. Potentiometric contours are same as in figure 24.

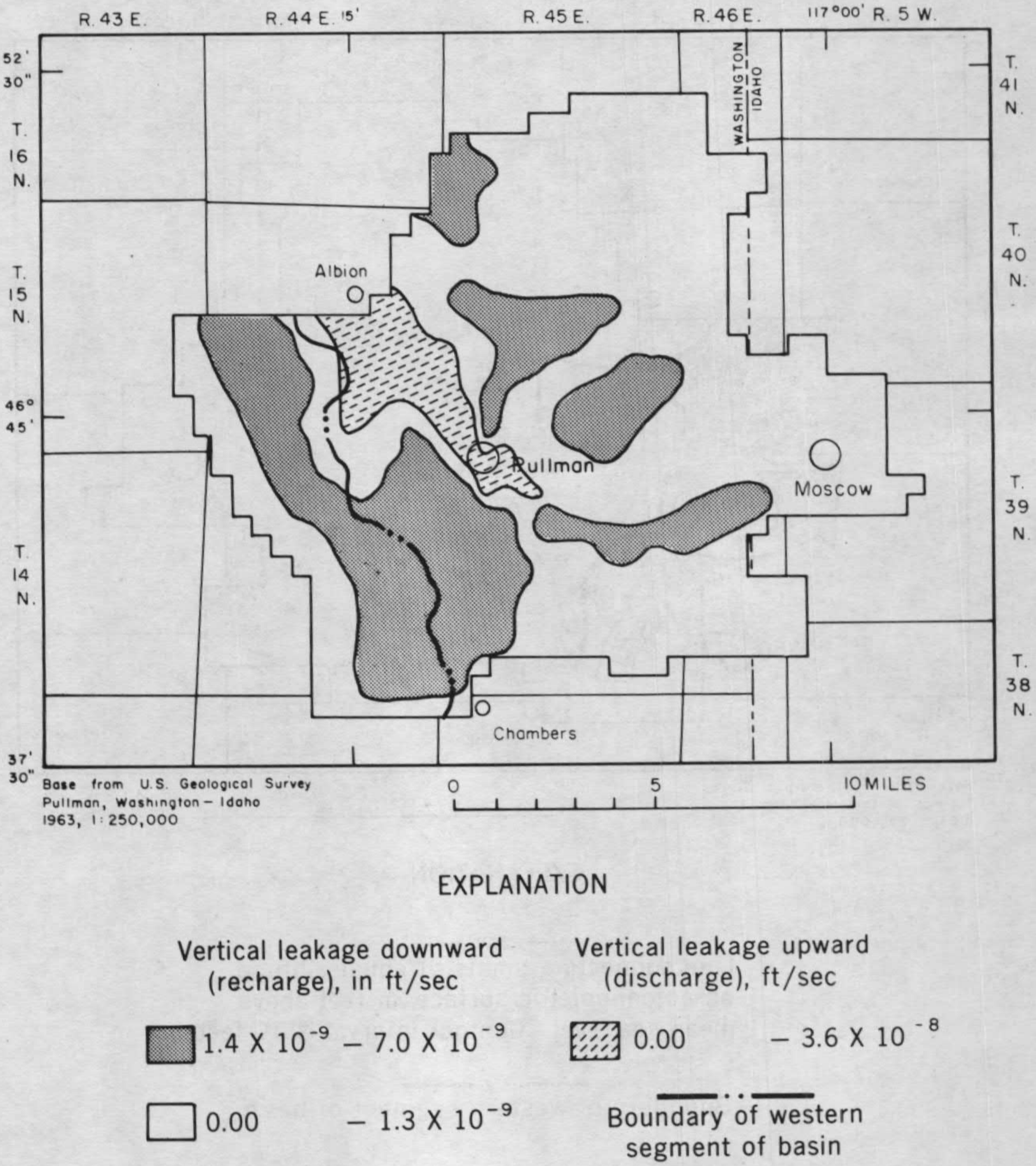


FIGURE 26.--Areal distribution of simulated rates of vertical leakage into and out of primary aquifer system under steady-state conditions.

Transient Simulation

The transient model, which uses the solution of the steady-state analysis for initial conditions, provides a simulation of hydrologic conditions in the primary aquifer system, beginning in 1896. Calibration of the transient model was achieved primarily by adjusting storage coefficient values. Whereas storage coefficients were fixed at zero everywhere in the steady-state model (no change of the amount of water in storage with time), the effect of changes in storage on water levels was the prime consideration during transient model calibration.

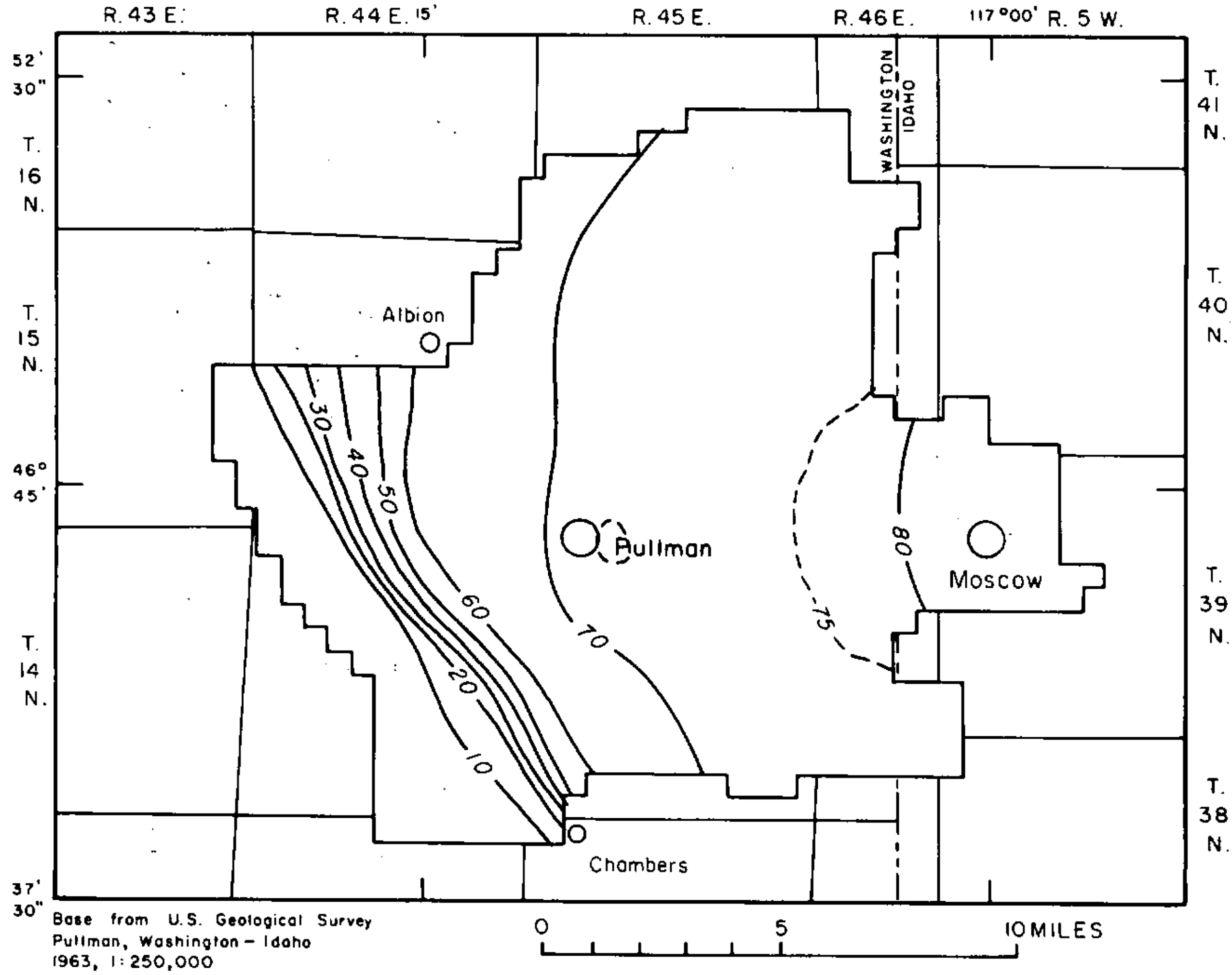
When the 80 years of historical pumping stress (fig. 20) is simulated in the calibrated transient model, the resulting distribution of total water-level decline as of June 1975 is as shown in figure 27. The simulated potentiometric surface for this point in time is as depicted in figure 28. Figure 29 illustrates the time distribution of simulated fluxes in the primary aquifer system pertaining to only the basin area. Figure 30 shows the general distribution of lateral flow in the modeled area, as simulated for June 1975; figure 31 shows the distribution of simulated rates of vertical flux in the area at this time.

Observed Versus Simulated Conditions

Before the model could be used to indicate the response of the primary aquifer system to anticipated stresses, it was necessary that it demonstrate a reasonable ability to duplicate the observed response to appropriate historical stresses. Such an evaluation of the model's reliability was continually maintained during the calibration period by comparing simulated water level and water-budget items to those supported by field measurements or deduced from hydrologic observation.

As discussed earlier, data pertaining to the era represented by the steady-state simulation are virtually nonexistent. Except for the original water levels reported by Russell (1897) for the Pullman area, and the general characteristics of a conceptual model formulated from present-day observations, there was no information upon which to base calibration--and evaluation of the validity--of the steady-state model. Because there was no unique steady-state solution, it was established during model development that the validity of any steady-state analysis could be accepted only if a suitably accurate transient model resulted when the steady-state solution was used as initial conditions for transient simulation.

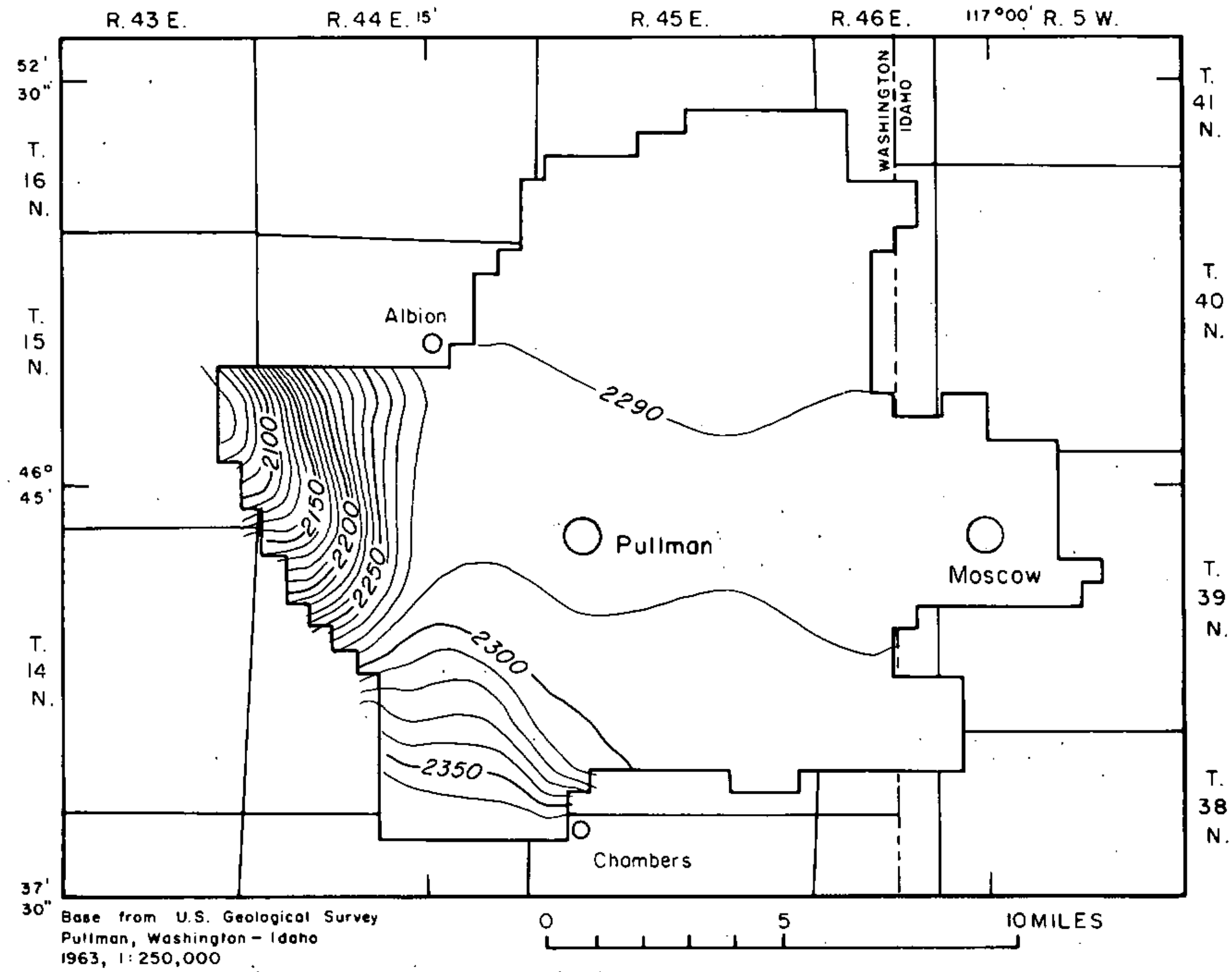
Figure 32 shows deviations of the final simulated steady-state water levels from those conceived to exist in the real system under those conditions. Theoretically, these deviations are a measure of the error in the steady-state solution. However, because of the extremely limited data with which the pre-develoment conditions were defined, any further attempt to improve the model regarding this kind of error was deemed impractical and unjustified.



EXPLANATION

—— 60 ——
Line connecting points of equal decline of potentiometric surface, in feet. Contour interval is 10 feet.

FIGURE 27.--Simulated decline in potentiometric surface of primary aquifer system during January 1896-June 1975.



EXPLANATION

—— 2300 ——
Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 10 feet.

FIGURE 28.--Simulated potentiometric surface of primary aquifer system, June 1975.

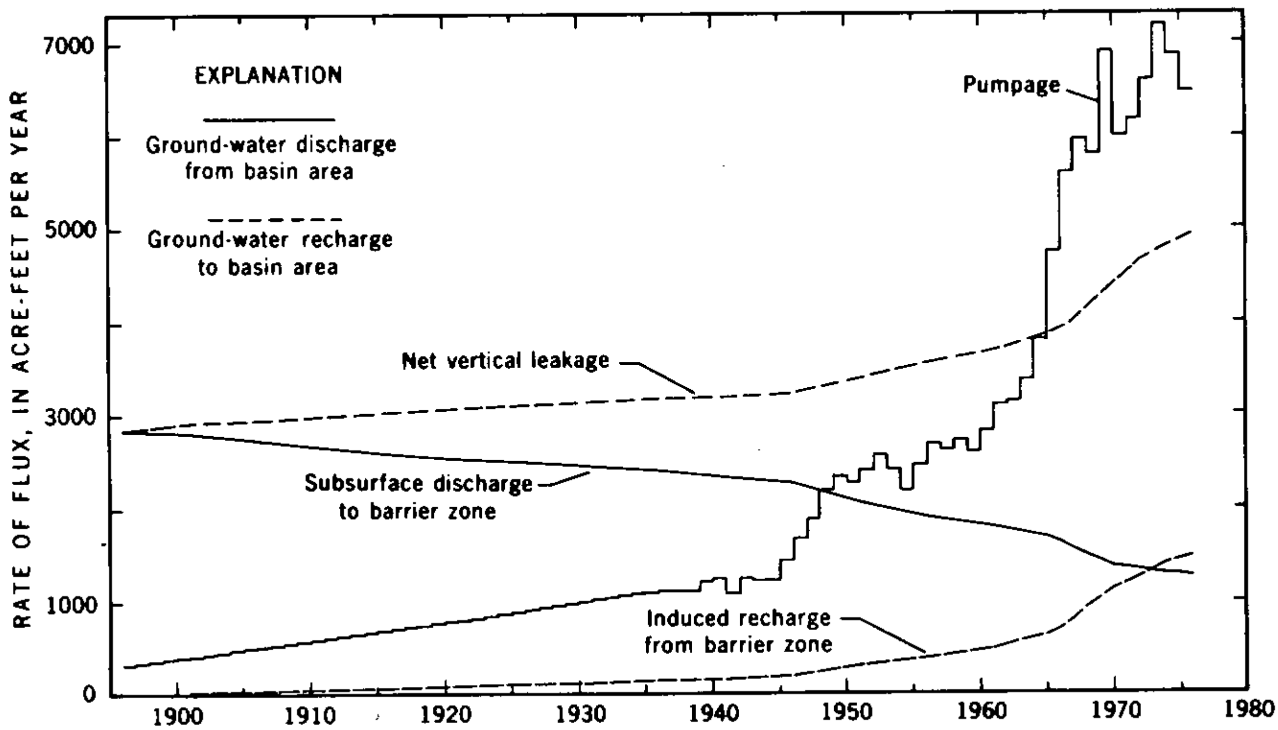
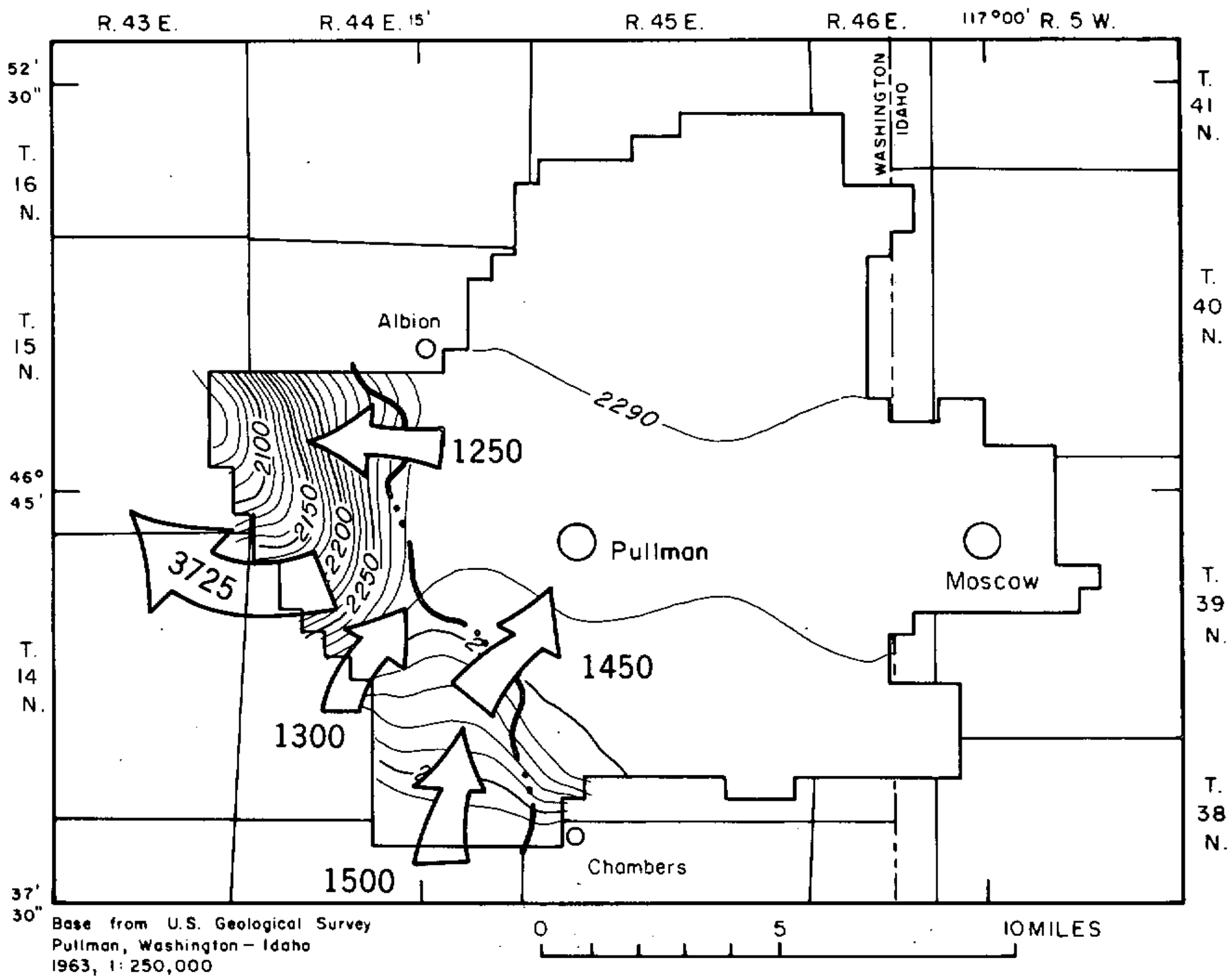


FIGURE 29.--Simulated rate of recharge to and discharge from that part of the primary aquifer system underlying the Pullman-Moscow basin. Left and right extremes of curves correspond to values in table 2.



EXPLANATION

2300
Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 10 feet.

Boundary of western segment of basin

FIGURE 30.--Generalized directions and quantities of lateral ground-water flow in the primary aquifer system under conditions of June 1975.

Rates of flow relate to simulated quantities in table 2 and are in acre-ft/yr; arrows indicate general flow directions. Potentiometric contours are same as in figure 28.

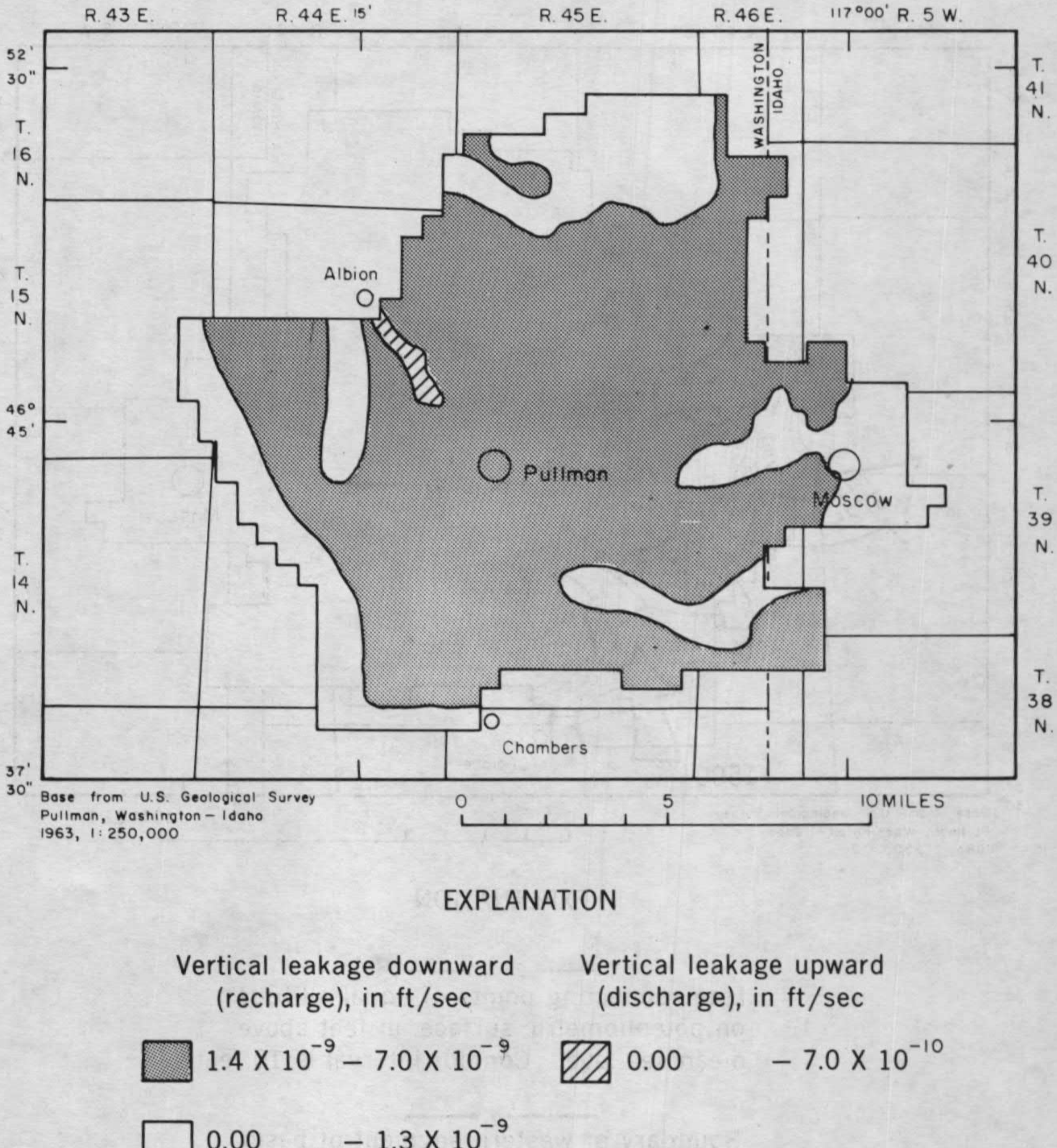


FIGURE 31.--Areal distribution of simulated rates of vertical leakage into and out of primary aquifer system under June 1975 conditions.

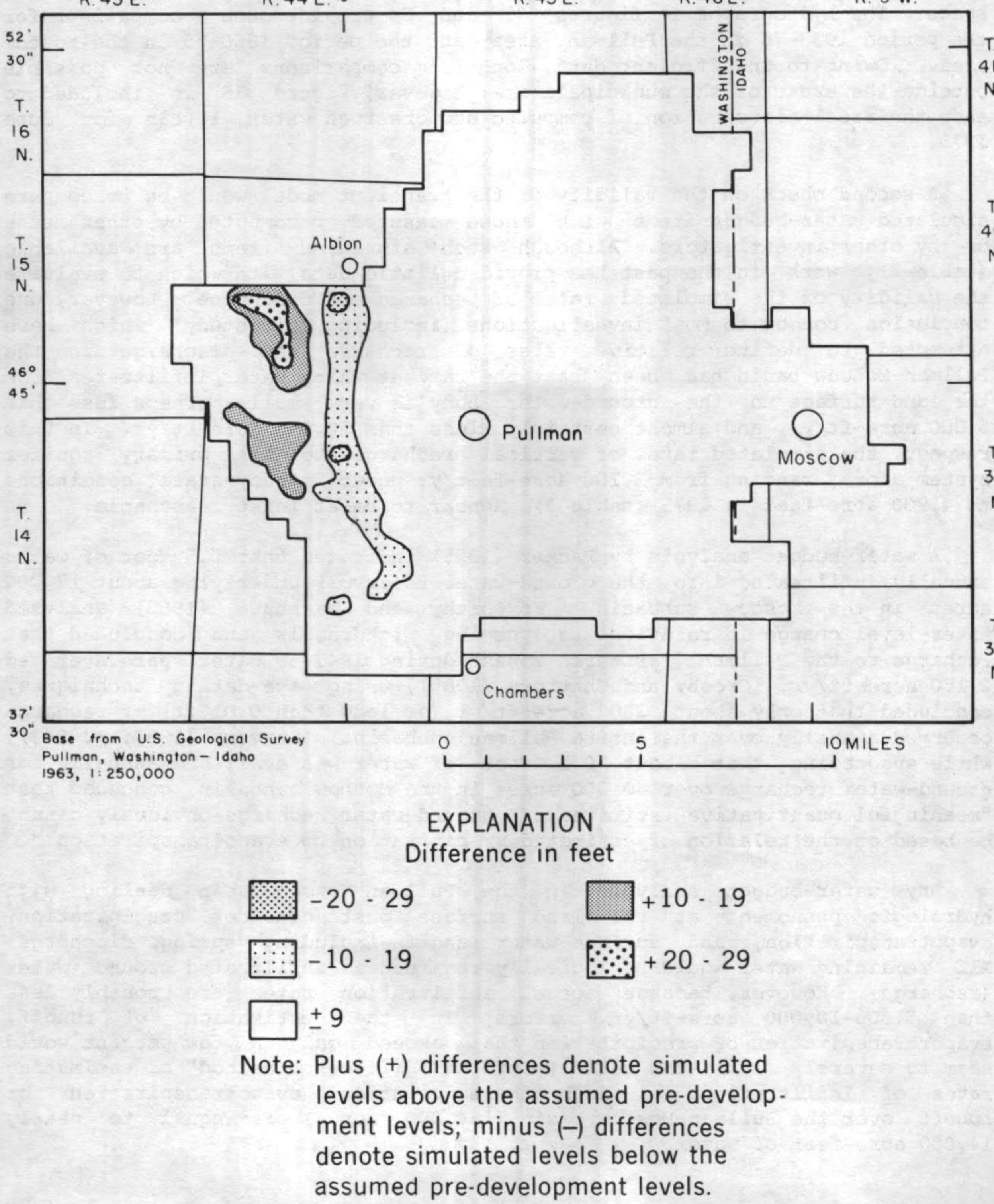


FIGURE 32.--Differences between simulated steady-state and assumed predevelopment potentiometric surface.

The accuracy of the transient simulation can be checked by comparing the simulated water levels with those measured at the same points in time and space. The hydrographs in figures 33 and 34 provide such a comparison for the period 1933-75 in the Pullman area and the period 1960-75 in the Moscow area. Owing to insufficient data, long-term comparisons are not possible outside the areas of the municipalities; however, figure 35 is included to show the areal distribution of computed and observed water levels for June 1975.

A second check on the validity of the transient model would be to compare simulated water-budget items with those measured or computed by other means or by other investigators. Although such simulated items are available (table 2), work in the past has provided little data with which to evaluate the validity of the simulated rates of recharge and discharge. However, one conclusion common to most investigations (including this study) which have attempted to define relative rates of recharge and discharge in the Pullman-Moscow basin has been that the rate at which water infiltrates from the land surface to the ground-water body is very small--perhaps less than 5,000 acre-ft/yr, and almost certainly less than 10,000 acre-ft/yr. In this respect, the simulated rates of vertical recharge to the primary aquifer system alone, ranging from 3,100 acre-feet/yr under steady-state conditions to 4,900 acre-feet in 1975 (table 2), appear to be at least reasonable.

A water-budget analysis by Packer (1955) indicated that 0.5 foot of water annually infiltrated into the ground-water reservoir underlying about 17,000 acres in the Moscow subbasin. Foxworthy and Washburn (1963) analyzed water-level change in relation to pumping withdrawals and concluded that recharge to the Pullman "artesian zones" during 1949-59 water years averaged 2,150 acre-ft/yr. Crosby and Chatters (1965), using age-dating techniques, concluded that only about 330 acre-ft/yr (or less than 0.01 ft) of recharge occurred annually over the entire Pullman subbasin. Stevens (1960, p. 343), while suggesting that about 0.1 foot of water was available annually for ground-water recharge over 40,000 acres in the Moscow subbasin, conceded that "meaningful quantitative estimates of ground-water recharge obviously cannot be based on the relation of estimated precipitation to evapotranspiration."

Any water-budget analysis in the Pullman-Moscow basin dealing with hydrologic phenomena at the land surface must consider precipitation, evapotranspiration, and surface-water runoff--including spring discharge. All remaining water would be logically regarded as infiltrated ground water (recharge). However, because actual infiltration rates are probably less than 5,000-10,000 acre-ft/yr, errors in the estimation of runoff, evaportranspiration or precipitation that exceed only a few percent would seem to severely limit the validity of the "difference method" of estimating rates of infiltration: 1 inch of precipitation, evapotranspiration, or runoff over the Pullman-Moscow basin (164,000 acres) is equal to nearly 14,000 acre-feet of water.

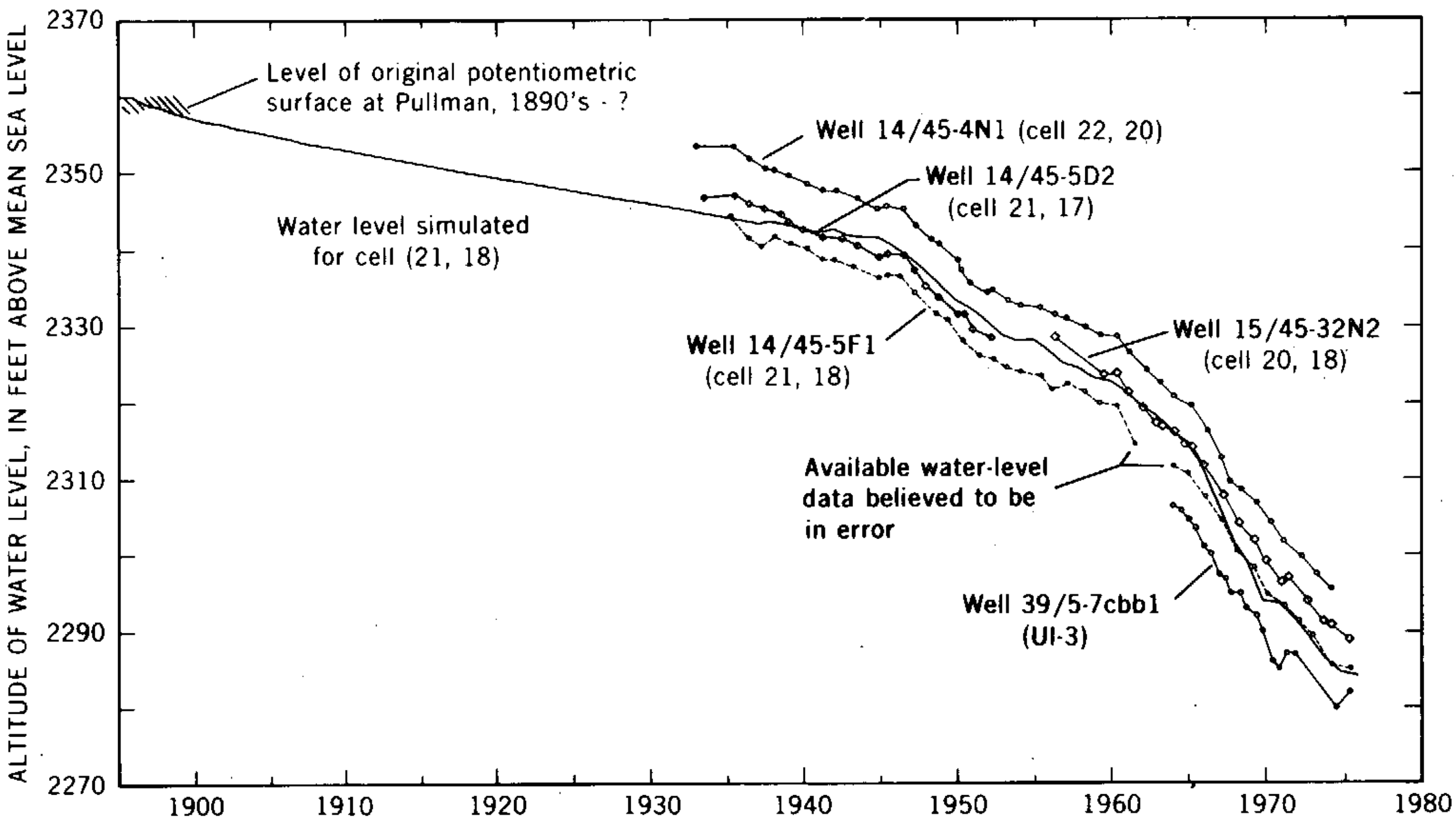


FIGURE 33.--Comparison of observed and simulated water levels in wells in the Pullman area.

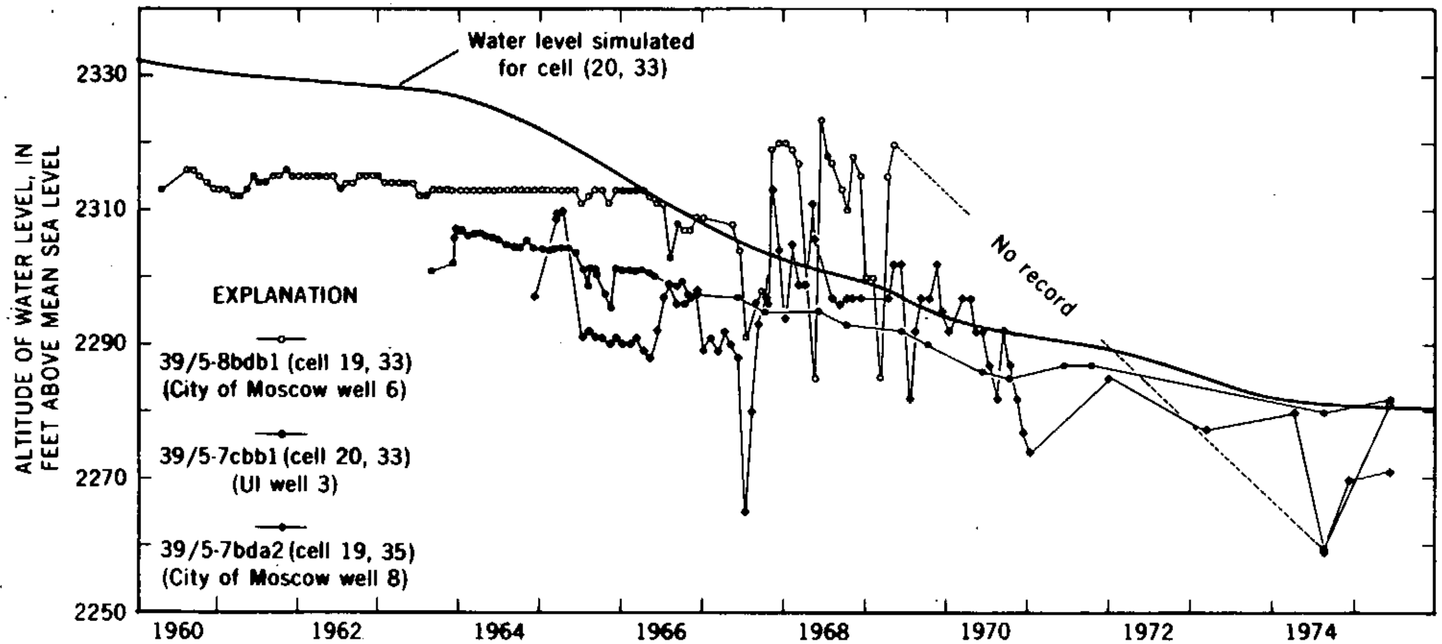
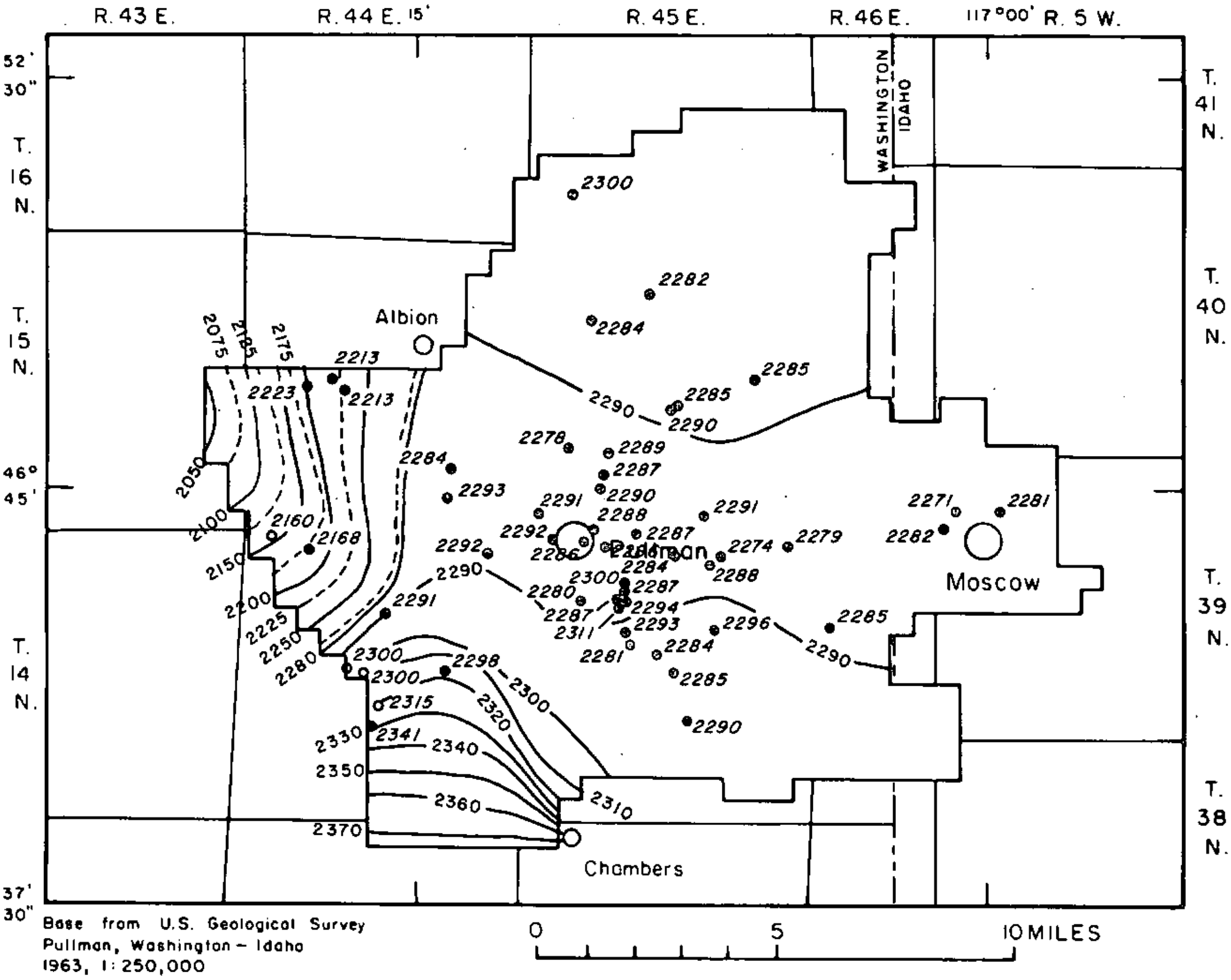


FIGURE 34.--Comparison of observed and simulated water levels in wells in the Moscow area.



EXPLANATION

2260

Well location and altitude of water level measured in June 1975, in feet above mean sea level

2300

Well location and altitude of water level measured or reported in August 1974, in feet above mean sea level

2300

Line connecting points of equal water-level altitude, in feet above mean sea level, simulated for June 1975

FIGURE 35.--Comparison between water levels simulated for June 1975 and those measured in June 1975 and measured or reported in August 1974.

TABLE 2.--Comparison of simulated rates of recharge to and discharge from the primary aquifer system, under pre-development and 1975 conditions

(All values in acre-feet/yr)

	Pre-development conditions		1975 conditions	
FLOW ACROSS MODEL BOUNDARIES	Recharge	Discharge	Recharge	Discharge
Vertical leakage within basin area	3,100	250	4,900	25
Vertical leakage within barrier zone	1,025	0	1,075	0
Lateral flow across southern constant-head boundary (between Chambers and Union Flat Creek)	750	0	1,500	0
Lateral flow across western constant-head boundary (along Union Flat Creek)	350	4,975	1,300	3,725
Pumpage	0	0	0	6,400
Change in storage	0	0	1,375	0
Totals	5,225	5,225	10,150	10,150
FLOW BETWEEN BASIN AND BARRIER ZONE, BENEATH WESTERN BASIN BOUNDARY				
Subsurface discharge from basin area into barrier zone	2,850		1,250	
Induced flow from barrier zone into basin area	0		1,450	

Probably the most reliable data upon which to base estimates of annual precipitation in the basin is provided by the isohyetal map shown in figure 3, from the Pacific Northwest River Basins Commission (1969). However, different planimetering techniques used on the map (in attempts to account for the wide range in land-surface altitude and associated orographic effects on precipitation) could easily cause differences in computed annual precipitation amounting to 10,000 acre-feet--which is less than 1 inch of water when averaged over the entire basin.

A literature search for applicable rates of evapotranspiration in the Pullman-Moscow basin provides differences, for the crop of wheat alone, that exceed 50 percent between rates computed by different methods. In addition to difficulties regarding the estimation of precipitation and evapotranspiration, any computation of a basinwide water budget must include an analysis of basin runoff requiring an estimate of discharge through Fourmile Creek, which has not been measured on an annual basis since 1939.

Because of the lack of reliable data for defining elements for recharge and discharge, the modeled quantities can only be assessed for their "reasonableness" in light of observed water-level conditions in the area. Table 2 compares the annual rates of recharge and discharge to and from the modeled aquifer system as simulated for the pre-pumping era and for 1975. This table and figures 25 and 30 show that, as pumping within the basin increased and water levels declined, the rate of lateral flow from the basin to the west decreased while the flow into the basin from the southwest increased. Although there is no simulated lateral inflow to the basin for 1896, by 1973 such recharge exceeded the amount discharging laterally from the basin (fig. 29). Model analysis indicates that this combination of salvaged discharge and captured recharge is presently providing about 3,000 acre-feet more water per year to the basin than was provided under pre-pumping conditions. Apparently, however, this additional water--plus the additional water resulting from increased vertical leakage from the upper aquifer zone--has not been sufficient to prevent changes in ground-water storage presently (1975) amounting to nearly 1,400 acre-ft/yr over the modeled area. At the present-day rates of pumping, water is simply leaving the system faster than it is being replaced, thus, causing the reduction of ground water in storage and the continuing water-level decline.

A question may seem to exist regarding the source of water made available to the primary aquifer system via vertical leakage from the upper aquifer zone which, according to model analysis, amounted to nearly 2,000 acre-feet more per year in 1975 than under pre-development conditions. Unless this leakage were continually replenished to the upper zone, head loss would be expected to occur in the upper aquifers. However, except for places in the Moscow subbasin, water levels in the upper aquifers apparently have not declined significantly.

The heads in the upper aquifer zone are believed to have remained relatively stable beneath most of the Pullman subbasin because of the increased percolation of surface water in recent years. Water that may have been rejected by the soils and streambed materials in the past is probably now accepted and helps to maintain equilibrium within the shallower aquifers of the area. Although this hypothesis cannot be proven because of a serious lack of reliable data on precipitation and streamflow, evidence supporting the idea is discussed below.

A computation of basin runoff during 1935-39 was made using published Geological Survey records of gaged discharges of Fourmile Creek, Missouri Flat Creek, and the South Fork of the Palouse River. This computation, which included an estimate of unmetered (and ungaged) sewage effluent, indicates that the average annual discharge from the basin during 1935-39 was about 38,000 acre-feet. Another computation of runoff was made for the period 1960-74; this computation included metered (but ungaged) sewage effluent, and reconstructed stream discharge in Fourmile Creek, which was ungaged during the latter period. These results show that the average annual runoff during 1960-74 was about 53,000 acre-feet--which represents an apparent increase of about 39 percent since the 1930's.

At first glance, the runoff data may seem to indicate a historic decrease in subsurface infiltration rather than an increase, as suggested herein. However, there are other important factors to consider.

Although the meagerness of the available data precludes an infallible means to relate the historical increase in runoff to basinwide precipitation, records of precipitation at Pullman for the period 1954-75--published by the U.S. Weather Bureau (1954-69) and the [U.S.] National Weather Service (1970-75)--show a 30-percent increase in the average annual precipitation during the same periods of record used for the runoff analysis. Precipitation during 1960-74, which averaged 21.6 inches/yr, exceeded the 1935-39 average (16.6 inches/yr) during 13 of the 15 years, and exceeded the former average by at least 25 percent during 8 of those years. Seemingly, then, most of the increase in basin runoff since the 1930's could be attributed to the concurrent increase in precipitation.

The increased runoff has also been a result of more water being diverted into the surface-drainage system in recent years because of man-induced changes. Farmers in the northern and eastern parts of the basin have increased their attempts to drain excess water from their fields by installing culverts and tile-lined trenches. Population growth and increased water use have also resulted in greater runoff from wastewater, such as that from car washes, laundromats, swimming pools, industrial activities, and sewage disposals.

Records of treated sewage contributions to Paradise Creek below Moscow and the South Fork of the Palouse River below Pullman were not maintained before 1950, but total effluent during the 1930's is estimated to have been no more than 1,000 acre-ft/yr. More recently, however, metered sewage effluent from the Pullman treatment plant increased from about 1,150 acre-feet in 1950 to more than 4,000 acre-feet in 1974, and records from the Moscow plant show an increase from about 1,100 acre-feet in 1960 to more than 2,000 acre-feet in 1974. The present rate of total effluent discharging to the surface drains (6,000 acre-ft/yr) represents a 600-percent gain over the estimated 1,000 acre-feet/yr during the 1930's--which indicates an average increase of almost 150 acre-feet/yr since the thirties.

The historical increases in surface wastage resulting from field drains, car washes, swimming pools, and laundromats cannot be computed accurately. However, such increases probably are safely assumed to be proportional to the estimated increases in sewage effluent during the same period (the 600-percent increase since the 1930's, as described in the previous paragraph).

What has happened to the increasing amounts of water on the surface of the basin owing to the historical increases in precipitation, sewage effluent, and other wastewater? It was stated earlier that most of the increase in basin runoff could probably be accounted for by the corresponding increase in precipitation alone. Because the concurrent increase in sewage effluent draining to basin streams was apparently about 150 acre-ft/yr, it seems highly likely that enough of the additional water at the surface in recent years has percolated into the upper aquifers to offset the effects of the increasing leakage losses to the primary aquifers. The water loss from the upper aquifer zone within the basin via vertical leakage to the primary aquifer system is simulated to have increased at a rate averaging only 44 acre-ft/yr (0.06 ft^3/s) since the 1930's. Increasing losses of this small magnitude would be extremely difficult to detect--even if the additional loss each year was directly from the stream channels--considering that the increasing wastewater contributions to streamflow can not be precisely defined. Additional examples and discussion of ground-water recharge in areas of basalt terrain as a result of direct infiltration from stream channels and soil surfaces are provided by Luzier and Burt (1974, p. 5-6), and Sokol (1966, p. 7-8).

During the recent study stream-discharge measurements were made on September 11, 1974, at three sites (pl. 1) between Moscow and Pullman in an attempt to determine whether or not seepage to shallow basalt strata was occurring through the streambed. An attempt was made to make the measurements during a period of constant sewage discharge from the Moscow treatment plant, but it is suspected that effects of fluctuating rates of effluent discharge were not entirely eliminated. Although a gain of 0.51 ft^3/s was recorded in the streamflow between sites 1 and 2, a loss of 1.01 ft^3/s was measured between sites 1 and 3. Between sites 2 and 3 the measured loss was 1.52 ft^3/s. Although these measurements suggest that streambed leakage is occurring, additional measurements are needed that are not affected by fluctuating rates of sewage effluent to help establish the premise for streambed leakage as fact.

Projections of Water-Level Trends to 2000

Three model runs were made to 2000, projecting different patterns of pumping from 1976. In two instances, the simulated pumping was increased annually as a percentage of the previous year's rate, and in the other case the pumping was held at the estimated 1976 rate of 6,600 acre-ft/yr during the entire period of projection.

The pumping rate was estimated for 1976 by averaging the annual pumpage for the previous 5 years (1971-75). Likewise the areal distribution of pumpage during each of the 24-year projections was based on sites of 1971-75 pumpage (pl. 1).

To help guard against projecting unreasonable rates of lateral recharge across the southern constant-head boundary between Chambers and Union Flat Creek, the rate of influx here was fixed through the entire projection period at the rate simulated for 1975 with the calibrated model. (The concept of this steady-flux boundary is explained on page 62.) Because of the inability to anticipate upper-zone water-level fluctuations, all upper-zone heads in the model were also assumed to be fixed at their 1975 levels.

When the simulated pumping rate is held at a constant 6,600 acre-ft/yr, water levels in the primary aquifer system continue to decline through 1999. However, the total decline by 2000 is less than 10 feet below 1975 levels and the rate of decline decreases to about 0.2 ft/yr, as seen in figure 36. The resulting water-budget items are shown in table 3.

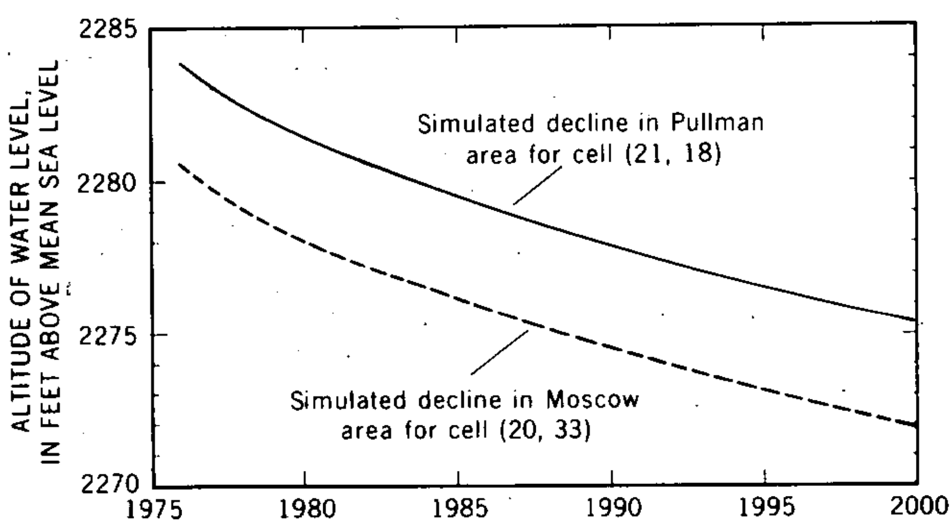


FIGURE 36.--Projected water-level declines in Pullman and Moscow areas, if average annual pumping rate of period 1971-75 (6,600 acre-ft/yr) is continued to 2000. Projection based on digital simulation of primary aquifer system.

TABLE 3.--Comparison of simulated rates of recharge to and discharge from the primary aquifer system by 2000, under three conditions of pumping projected from 1976 rate of pumping (average of 1971-75 rates)

FLOW ACROSS MODEL BOUNDARIES	RATES OF FLUX BY 2000 AS RESULT OF PROJECTING 1976 RATE OF PUMPING TO INDICATED MULTIPLES OF THAT RATE [All values in acre-feet/yr]					
	(1976 pumping rate x 1)[1]		(1976 pumping rate x 2)[2]		(1976 pumping rate x 2.8)[3]	
	Recharge	Discharge	Recharge	Discharge	Recharge	Discharge
Vertical leakage within basin area	5,000	0	5,100	0	5,175	0
Vertical leakage within barrier zone	1,100	0	1,125	0	1,150	0
Lateral flow across southern constant-head boundary (between Chambers and Union Flat Creek)	1,500	0	1,500	0	1,500	0
Lateral flow across western constant-head boundary (along Union Flat Creek)	1,450	3,550	1,850	3,400	2,125	3,350
Pumpage	0	6,600	0	13,200	0	18,600
Change in storage	1,100	0	7,025	0	12,000	0
Totals	10,150	10,150	16,600	16,600	21,950	21,950
FLOW BETWEEN BASIN AND BARRIER ZONE, BENEATH WESTERN BASIN BOUNDARY						
Subsurface discharge from basin area into barrier zone	1,150		1,000		875	
Induced flow from barrier zone into basin area	1,675		2,100		2,425	

1/ Constant pumping rate through all 24 years of projection (at 6,600 acre-feet/yr)

2/ 3-percent increase in pumping rate each year, beginning in 1977

3/ 4.6-percent increase in pumping rate each year, beginning in 1977

By increasing the simulated rate of pumping each year by about 3 percent, the 1976 rate of 6,600 acre-ft/yr is doubled by year 2000. Results of this projection indicate that water-level decline in both the immediate Pullman and Moscow areas by year 2000 would be slightly more than 30 feet below 1975 levels (fig. 37), and that the potentiometric surface would be approximately as shown in figure 38. The simulation indicates that such decline would cause increased flow to the basin from the southwest which, in turn, would result in greater decline in the barrier zone than has previously occurred.

Stevens, Thompson, and Runyan (1970) estimated that by 2000 the total annual water requirement in the Pullman-Moscow area will be 18,600 acre-feet--or about 2.8 times the estimated 1976 pumpage. To pump the indicated requirement by the year 2000 requires an annual increase of about 4.6 percent from the 1976 pumping rate of 6,600 acre-ft/yr. When such a projection is made with the model, the results shown in figures 39 and 40 and table 3 are obtained. The maximum projected water-level decline below 1975 levels is about 55 feet in the Moscow area. Aside from the rather large change in the volume of water annually lost from storage by year 2000 (12,000 acre-ft/yr; table 3), the most striking adjustment in the rates of recharge shown by this model projection is that of water coming into the modeled area from the western model boundary along Union Flat Creek.

Pumping in the basin at rates which are double or nearly triple the 1976 rates would certainly be expected to affect the western part of the modeled area in ways that have not yet been noticed. Although the results of such pumping can be simulated with the model, it is difficult to judge the validity of the simulated effects for areas near Union Flat Creek. Simulated rates of recharge and discharge to and from the constant-head boundary representing Union Flat Creek are, of course, dependent on head relationships that are based on sparse data (p. 59). However, experience with the model has shown that moderate changes in the rates of flow to and from this boundary have relatively little impact on simulated water levels inside the basin. Apparently, the productive areas of the primary aquifer system inside the basin are somewhat buffered from hydrologic events near the western boundary of the modeled area, owing to the wide band of extremely low transmissivities that presumably span the barrier zone between Union Flat Creek and the basin. So, although the presently (1975) available data is insufficient to confirm the projected fluxes along Union Flat Creek, the simulated fluxes appear to be reasonable in light of available information, and the effects of any reasonably small errors in the simulation for this area should not significantly limit the usefulness of simulated results for the manageable parts of the primary aquifer system within the basin.

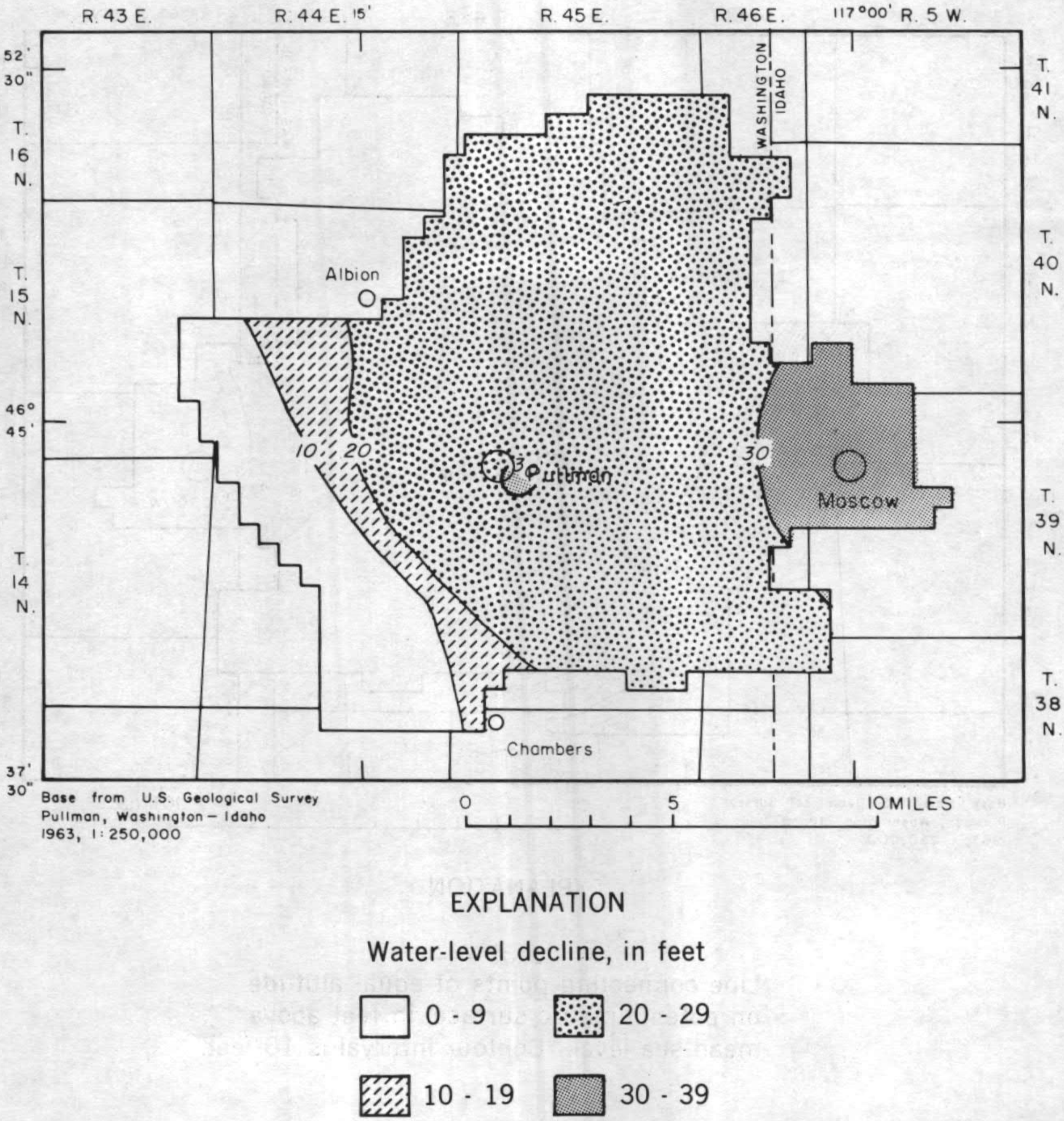
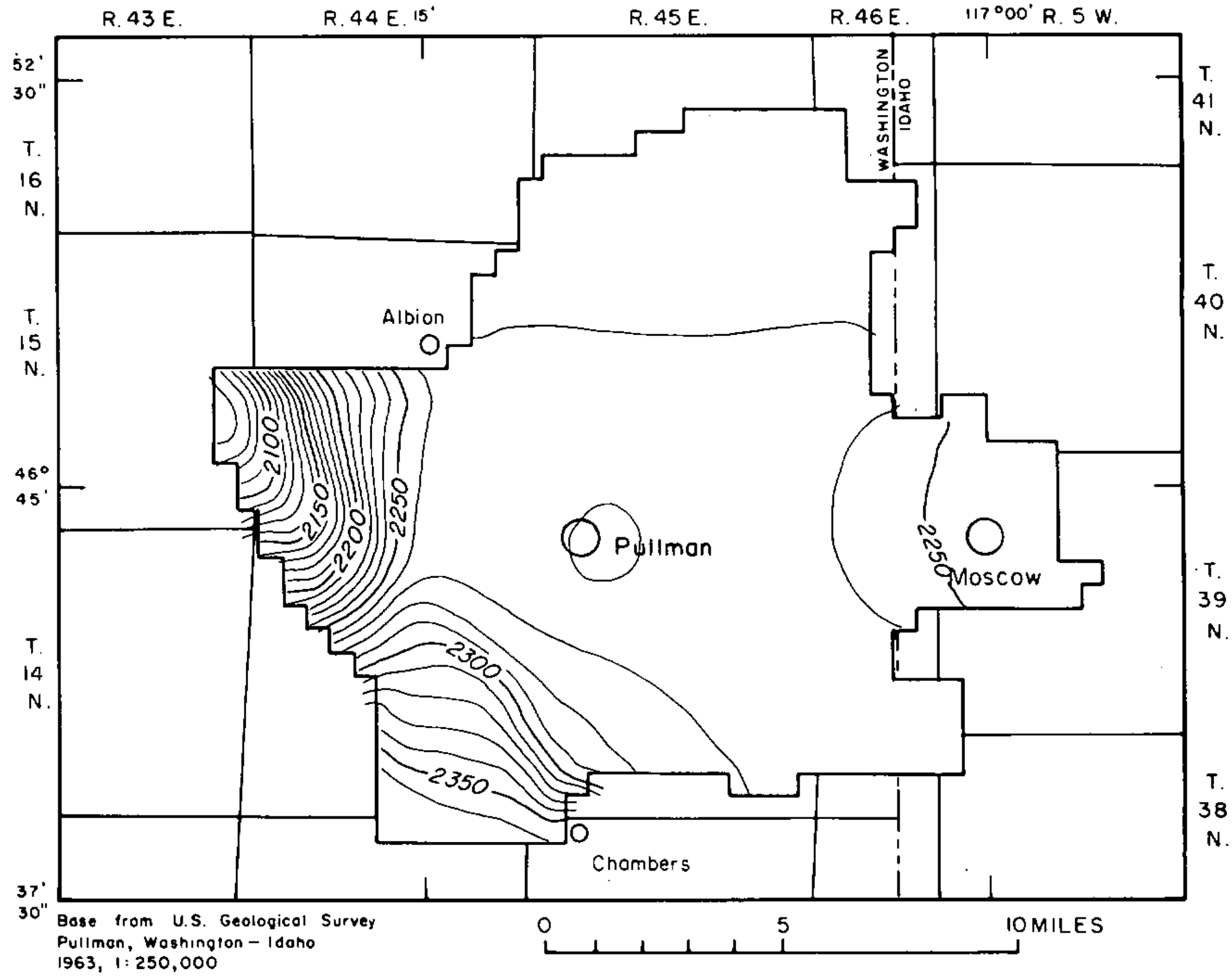


FIGURE 37.--Projected water-level decline below 1975 levels, by year 2000, if average annual pumping rate of period 1971-75 is doubled between 1976-99. Projection based on digital simulation of primary aquifer system.



EXPLANATION

2300

Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 10 feet.

FIGURE 38.--Simulated potentiometric surface for year 2000, assuming average annual pumping rate of period 1971-75 is doubled between 1976-99.

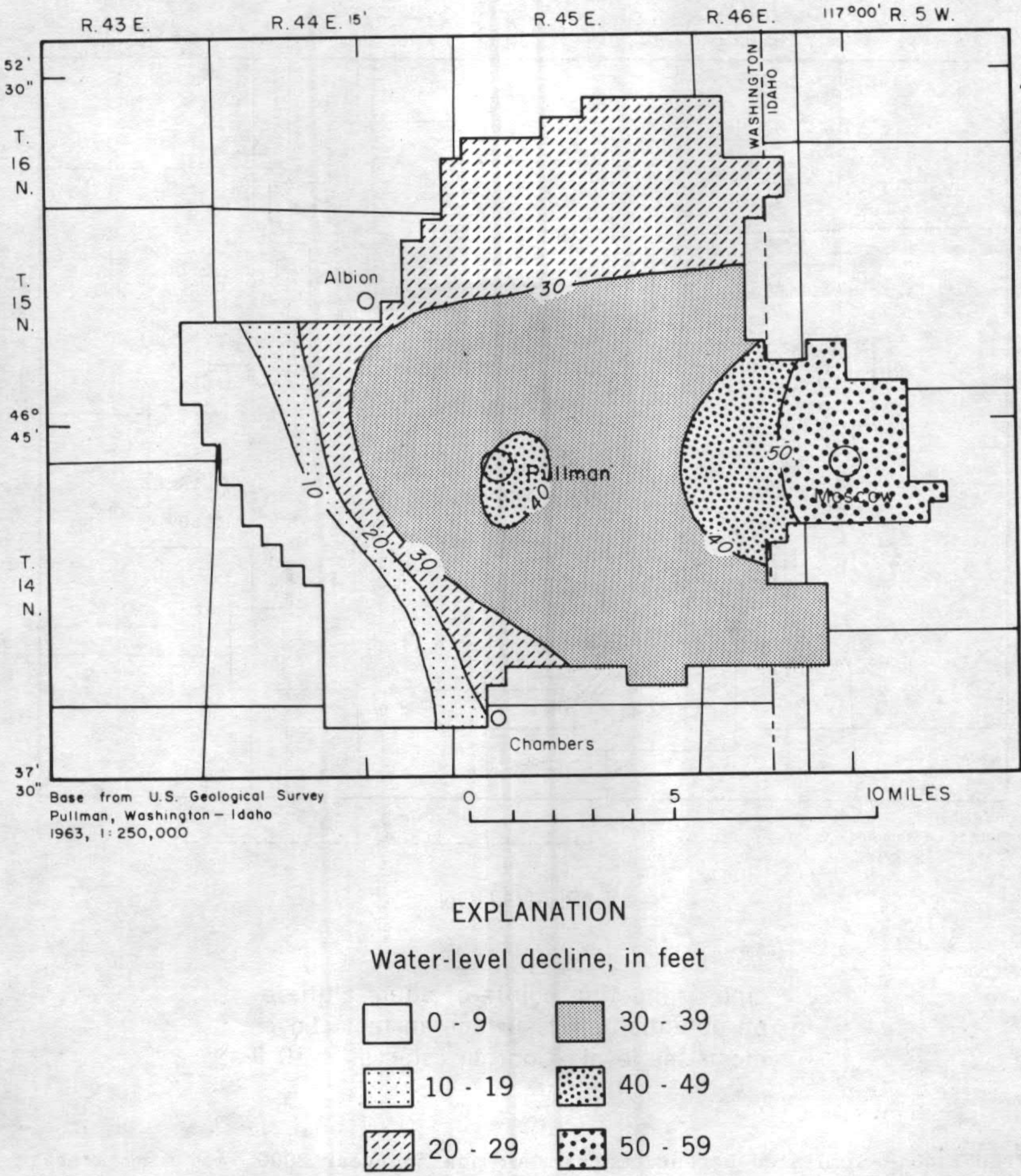
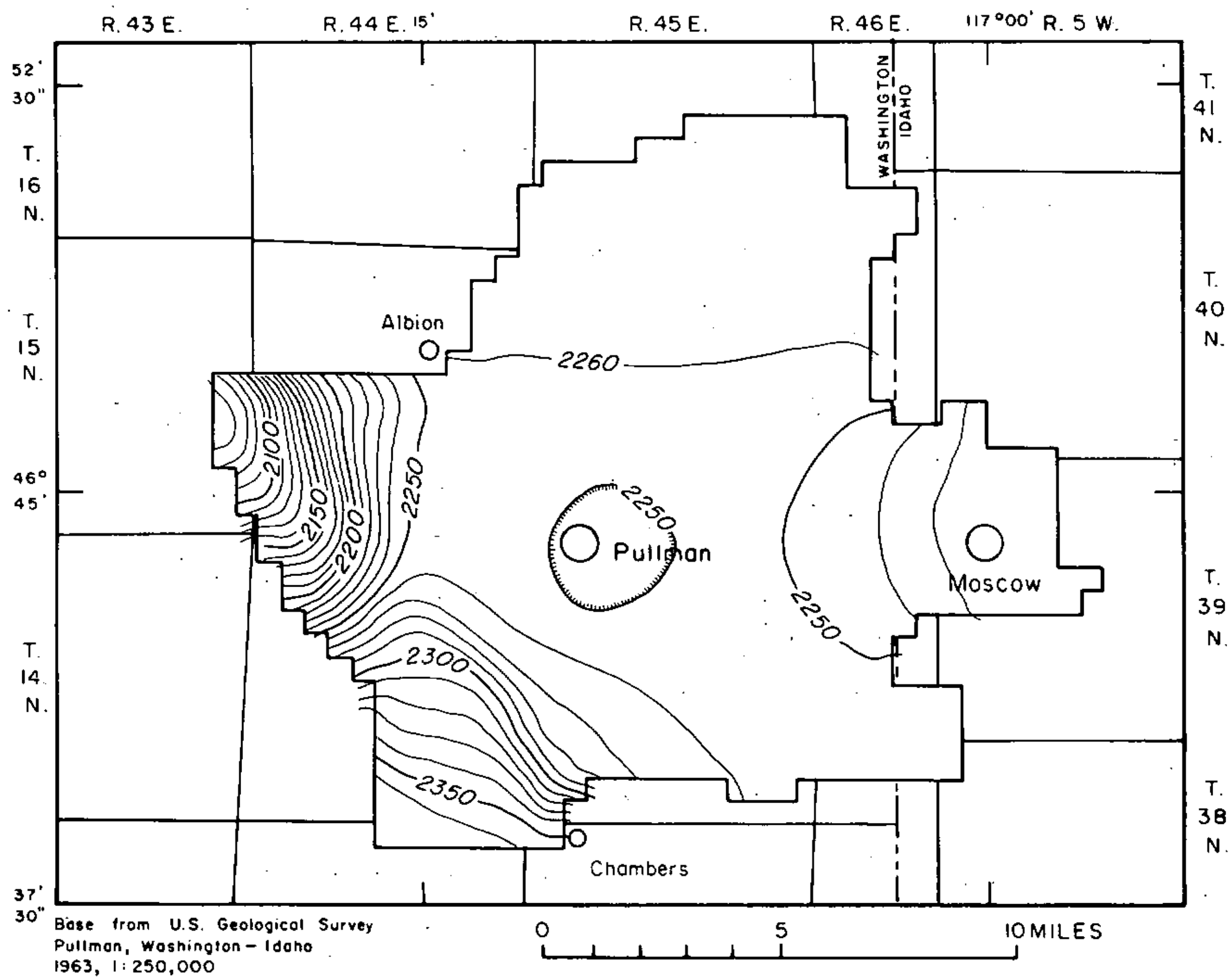


FIGURE 39.--Projected water-level decline below 1975 levels, by year 2000, if average annual pumping rate of period 1971-75 is nearly tripled between 1976-99. Projection based on digital simulation of primary aquifer system.



EXPLANATION

——2300——
Line connecting points of equal altitude on potentiometric surface, in feet above mean sea level. Contour interval is 10 feet.

FIGURE 40.--Simulated potentiometric surface for year 2000, assuming average annual pumping rate of period 1971-75 is nearly tripled between 1976-99.

SUMMARY

Ground water in the Pullman-Moscow basin (164,000 acres) occurs primarily in basalt and in interbeds of gravel, sand, and clay beneath the 88,000 acres of the basin lowland. Dense crystalline rocks underlie the basalt flows and unconsolidated sedimentary materials and form the hills surrounding the basin on the north, east, and south; the crystalline rocks neither store nor transmit significant quantities of water. Although largely unmapped at depth, the basalt-sediment sequence increases in thickness toward the center of the basin. Recent geophysical data suggest that the bottom of the basalt is deepest near Pullman, where it is estimated to be about 2,600 feet below the land surface, or about 250 feet below sea level. To expedite the modeling procedure, the basalt-sediment sequence was subdivided into two units on the basis of measurable differences in water levels in the shallow and deeper aquifers.

All explored aquifers below altitudes of about 2,300 feet above sea level in the Pullman subbasin and about 2,000 feet near Moscow belong to the deeper unit. These deeper aquifers function collectively as a hydrologic system, because the hydraulic properties, water levels, and long-term response to pumping are remarkedly consistent among the various aquifers which comprise this unit. This relatively productive group of aquifers was designated in this study as the primary aquifer system.

All aquifers above the primary aquifer system were for convenience combined into what is called the upper aquifer zone. This group of aquifers, however, does not comprise a true hydrologic system because the aquifers do not display hydraulic properties that are consistently compatible from place to place. In addition, historically the unit has responded to stress in ways that differ markedly from the response observed in the primary aquifer system.

The differences between the primary aquifer system and the upper aquifer zone are believed to be largely controlled by geologic variations in the area between the basin boundary on the west and Union Flat Creek. Lateral flow of ground water in this area appears to be restricted by some kind of subsurface barrier, possibly related to a buried ridge of crystalline rock or fault offset(s). More information is required to sufficiently define the relationship between the geologic controls and the movement of ground water in this area, which is referred to as the barrier zone.

Ground-water recharge to and discharge from the basin occurs by (1) lateral flow across the basin boundary on the west and (2) vertical leakage to and from the land surface. The prevailing direction of ground-water flow is from east to west, out of the basin. Although the rate of this lateral discharge from the primary aquifer system is decreasing annually, the rate of vertical recharge to the system is increasing. Both phenomena result from declining water levels in the system, owing to a progressive, almost year-to-year increase in water pumped for public and university supplies. Pumping rates from the primary aquifer system during the 1971-75 period averaged about 6,600 acre-ft/yr.

The primary aquifer system was modeled by means of a digital-computer program using the technique of finite-difference approximation. The effects of the vertical movement of water between the upper aquifer zone and the primary aquifer system were accounted for by assuming this exchange occurs through an intervening confining layer that thins from east to west. The model's ability to reproduce with reasonable accuracy the historical relationship between ground-water pumpage and water-level decline, and to simulate elements of recharge and discharge which do not violate the small amount of information on the various elements of the water budget, is a positive indication that it can be used successfully to predict for some time period the response of the primary aquifer system to different conditions of hydraulic stress.

The digital model should be of value in helping State and local water planners establish a comprehensive and practical water-management policy regarding future ground-water development. Experience with the model to date (1975) suggests that it will adequately meet the needs for information required for most ground-water-management decisions, provided that (1) the projected pumping is confined to the interior lowland of the basin, (2) the total pumping stress does not exceed about 20,000 acre-ft/yr, and (3) the period of projection does not exceed about 25 years.

Results of model analysis, in which different conditions of pumping were projected to 2000, indicate that water-level declines will continue if the present-day pumping rates are maintained or increased. A maximum additional decline of about 55 feet is indicated if pumping rates were nearly tripled during 1976-99. However, because of the strong correlation between the pumping stress and water-level decline, simulation indicates that the rate of decline would be reduced to less than 0.2 ft per year if pumping rates were to stabilize near the present-day average of 6,600 acre-ft/yr.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

A program of water-level monitoring in wells representative of both the upper aquifer zone and the primary aquifer system should be continued. Water levels in the upper aquifers should be monitored to document any changes occurring in response to the heavier pumping anticipated from all aquifers during the next few years. Water levels in the primary aquifer system should be monitored to provide a continuing data base upon which to judge the reliability of the model.

Because the water-level decline is so closely controlled by the pumping rates, it is critically important that accurate and comprehensive pumpage data be compiled on a continuing basis. Such data incorporated each year into the model would keep the simulation up to date and would provide the base from which pumping projections into the future can be made. Unless the pumpage input is reasonably accurate, there would be no justification for making revisions to the calibrated model to achieve a better fit with observed water levels.

If the pumpage input is thought to be reasonably accurate and the model still fails to simulate water levels that adequately resemble observed conditions, the storage coefficient is the model-input parameter that should first be considered for re-adjustment. Owing to the ongoing conversion from confined- to water-table conditions, storage coefficients in the primary aquifer system are undergoing change at the present time (1975). Because of this, the full nature and extent of this change may not yet be realized and accounted for in the model.

Another way to improve the model formulation would be to obtain a better definition of the top of the primary aquifer system (fig. 14), especially for areas west of the basin and east of the DOE test-observation well (14/45-1F1). Because the transition to water-table conditions and larger storage coefficients is a function of the positioning of this upper boundary surface, the ability of the model to simulate future water levels might depend greatly on the accuracy with which this feature is defined. To help define this boundary, well drillers should be encouraged to report all water-level changes that occur during the drilling of wells, the depth at which each change occurs, and the final water level.

To contribute significantly toward a better understanding of the basin's geohydrology and to establish additional control for model simulation, the barrier zone--the area between the basin boundary on the west and Union Flat Creek--should receive intensive consideration during all future geologic and hydrologic investigations. This zone is the least understood part of the modeled area, and more subsurface exploration in the area is required to make an appropriate assessment of its future effect on the basin's ground-water supply.

Deepening and testing of the DOE test-observation well (Brown, 1976) should be continued to help provide a better explanation of the basin's hydrology and to establish additional control for further stratigraphic correlation in the area. If extended to the crystalline basement rocks, the well could provide information that would either substantiate or disprove estimates of the depths of the aquifer system as suggested by geophysical profiles. Also, if fitted with multiple piezometer tubes tapping the principal aquifers, the well would allow observations of water-level fluctuations in each aquifer, thereby providing valuable insight into hydraulic relationships between aquifers at various depths in the area.

An alternative to the importation of water into the basin might be to make more efficient use of the surface-water supply; the possibilities would seem to warrant serious consideration. A careful study should be made of the feasibility of using some of the surface water that presently discharges from the basin (at rates averaging about 53,000 acre-ft/yr) to artificially recharge the aquifers. A minimum discharge of about 1.5 ft^3/s (about 675 gal/min) in Paradise Creek, between Moscow and Pullman, is presently sustained by sewage effluent from the Moscow treatment plant. The quality of the treated effluent is sufficient to allow its use for irrigating the local parks and golf course, according to the late Orrin Crooks (oral commun., 1974), former head of the plant.

Both the upper aquifer zone and the primary aquifer system are being pumped at the present time (1975) in the Moscow area, and both are proven sources of water supply. The productivity of the upper aquifers in the Moscow subbasin is substantially superior to that in the Pullman subbasin. If the problem of the local occurrence of high iron concentrations and high hardness in the upper aquifer zone can be resolved or adequately reduced by treatment, Moscow's dependence upon water from this zone would probably increase in the future, perhaps to the extent that water-level declines in this zone will again become a serious consideration.

To allow a more accurate simulation of water levels in the primary aquifer system and to provide the means by which the effects of future development of the total ground-water system--including the upper aquifer zone--can be evaluated, development of a two-layer digital model is suggested for the Moscow subbasin. For each aquifer unit, such a model would simulate water levels and provide water-budget analyses. Although the present model can provide information upon which to base most water-management decisions on future ground-water development in the deeper aquifers (assuming a limited change of conditions in the upper aquifers), only a two-layer model would have the capability to aid in water-use planning and decisions on development of, and artificial recharge to, the upper aquifer zone.

Future investigations of the occurrence, availability, and chemical quality of ground water in the area should not be limited to only one side of the State line, as were many previous studies. To restrict hydrologic analyses to either Washington or Idaho because of political boundaries could only hinder an adequate understanding of the total ground-water system.

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TABLE 4

RECORDS OF WELLS

TABLE 4.--Records of wells tapping the primary aquifer system in and immediately west of Pullman-Moscow basin

EXPLANATION: *, well west of basin boundary; a, well being pumped when measurement made; b, well recently pumped prior to measurement; R, reported water level, not measured by Geological Survey personnel

N.A. - Not available

USGS Well number	Lat and Long location	Model cell location	Owner or Tenant	Altitude of land surface (ft)	Well depth (ft)
T.14 N, R.44 E.					
1E1	46°43'43"N117°13'17" (1)	(21,13)	R. Harlow	2555	375
* 5F1	46°43'47"N117°17'51" (1)	(21,6)	F. Brands	2360	242
* 6B1	46°44'02"N117°18'58" (1)	(20,4)	F. Lyle	2180	60
* 9J2	46°42'36"N117°16'00" (1)	(24,9)	J. Olson	2485	286
* 14P1	46°41'33"N117°14'27" (1)	(26,12)	WSU Dairy	2475	600
* 16P1	46°41'36"N117°16'59" (1)	(26,8)	K. Hinderer	2318	140
* 16Q1	46°41'31"N117°16'29" (1)	(26,8)	L. Slusser	2325	65
* 21J1	46°40'56"N117°16'13" (1)	(27,9)	V. Henson	2335	58
* 28A1	46°40'31"N117°16'23" (1)	(28,8)	V. Rumley	2385	111
T.14 N, R.45 E.					
1F1	46°43'51"N117°05'17" (1)	(21,26)	Wash. State Dept. of Ecology Test-obs well	2478	982
3H3	46°43'39"N117°07'09" (1)	(21,23)	Washington Water Power	2460	259
3K1	46°43'33"N117°07'26" (1)	(22,23)	Rolling Hills Development Co.	2455	230
4D1	46°44'04"N117°09'23" (1)	(20,20)	WSU Well 6	2536	702
4H1	46°43'37"N117°08'23" (1)	(21,21)	WSU Experimental Farm	2440	265
4N1	46°43'20"N117°09'24" (1)	(22,20)	WSU	2390	100
5D1	46°43'55"N117°10'47" (1)	(21,17)	City of Pullman Well 1	2342	155
5D2	46°43'55"N117°10'47" (2)	(21,17)	Standard Lumber	2340	162
5D3	46°43'55"N117°10'47" (3)	(21,17)	City of Pullman Well 3	2342	167
5F1	46°43'48"N117°10'12" (1)	(21,18)	WSU Observation well	2364	145
5F2	46°43'48"N117°10'12" (2)	(21,18)	WSU Well 1	2364	237
5F3	46°43'48"N117°10'12" (3)	(21,18)	WSU Well 3	2364	223
5F4	46°43'48"N117°10'12" (4)	(21,18)	WSU Well 4	2364	275
5F5	46°43'47"N117°10'11" (1)	(21,18)	WSU Well 2	2365	213

Altitude of bottom of well (ft)	Date of first water-level observation (before 1973)	Altitude of first available water level (before 1973) (ft)	Altitude of Mar 1973 measured water-level (ft)	Altitude of Mar 1974 measured water level (ft)	Altitude of June 1975 measured water level (ft)	Remarks
2180	--	--	--	--	2292.1	Well has continuous water-level recorder
2118	--	--	--	--	--	8/22/74 water-level altitude = 2168
2120	?	2165(R)	--	--	--	8/22/74 water-level altitude = 2160 (R)
2199	--	--	2292.8	2291.8(b)	2290.9	
1975	2/25/59	2339(R)	--	2302.5	2298. (b)	Airline length = 320 feet
2178	--	--	--	--	--	8/-/74 water-level altitude = 2300 (R)
2260	1949	2300(R)	--	--	--	8/22/74 water-level altitude = 2300 (R)
2277	--	--	--	--	--	8/23/74 water-level altitude = 2314.8
2274	--	--	--	2342.4	2341.2(b)	
1496	--	--	--	--	2279.1	
2201	8/-- /57	2308(R)	2280	2275.9	2274.3	First available reported water-level (8- -57) not considered reliable
2225	1940	2347(R)	--	2289.6	2287.7(b)	
1834	--	--	--	--	2286.8	Well drilled in Spring 1975
2175	6/11/36	2348.54	2286	2285	2284.2	3/--/69 water-level altitude = 2292
2290	12/15/32	2353.2	2298	2295.6	--	Well went dry in 1974
2187	1929	2354(R)	2291.34	2288.9	2286.73(b)	Well flowed when drilled in 1913
2178	4/--/33	2346.95	--	--	--	Well sealed at 17 feet
2175	3/--/46	2333(R)	2289.91	2287.5	2285.7	
2219	3/15/35	2341.98	2289.6	2286.7	2285.6	
2127	4/--/33	2343(R)	--	--	--	10/14/53 water-level altitude = 2322.76
2141	10/--/46	2333(R)	--	--	--	7/15/57 water-level altitude = 2319.31
2089	4/8/63	2313.12	--	2287	--	
2152	12/4/37	2340.25	--	--	--	3/18/69 water-level altitude = 2303

TABLE 4.--Records of wells tapping the primary aquifer system in and immediately west of Pullman-Moscow basin--Continued

USGS Well number	Lat and Long location	Model cell location	Owner or tenant	Altitude of land surface (ft)	Well depth (ft)
T.14 N. R.45 E. cont.					
7F2	46°42'48"N117°11'38" (1)	(23,16)	Evergreen Builders No. 1	2510	273.8
7F4	46°42'55"N117°11'34" (1)	(23,16)	Evergreen Builders No. 2	2560	438
8A2	46°43'05"N117°09'45" (1)	(23,19)	M. Wise	2385	105
8A3	46°43'00"N117°09'43" (1)	(23,19)	M. Gormsen	2445	200
8E1	46°42'48"N117°10'52" (1)	(23,17)	City of Pullman Well 5	2442	712
8G2	46°42'51"N117°09'55" (1)	(23,19)	D. Brown	2400	200
8J2	46°42'39"N117°09'54" (1)	(24,19)	J. Askins	2445	164
8L1	46°42'36"N117°10'16" (1)	(24,18)	City of Pullman	2582	365
9E2	46°42'49"N117°09'36" (1)	(23,19)	H. Neil	2420	240
10M1	46°42'39"N117°07'59" (1)	(24,22)	G. Bloomfield	2530	250
15B2	46°42'16"N117°07'24" (1)	(24,23)	G. Leonard	2605	330
16E1	46°42'03"N117°09'29" (1)	(25,19)	W. Stratton	2395	110
16E2	46°42'01"N117°09'34" (1)	(25,19)	W. Stratton	2455	230
16G1	46°41'50"N117°08'52" (1)	(25,20)	WSU Agronomy Farm	2480	400
16R1	46°41'30"N117°08'24" (1)	(26,21)	G. Wise	2418	195
17A1	46°42'15"N117°09'44" (1)	(24,19)	H. Jacobson	2420	175
21D1	46°41'19"N117°09'32" (1)	(27,19)	W. Boyd	2480	265
21H2	46°41'02"N117°08'37" (1)	(27,21)	A. Barnes	2440	N.A.
22P2	46°40'42"N117°08'00" (1)	(28,22)	A. Fairbanks	2464	250
T.14 N. R.46 E.					
7N3	46°42'24"N117°04'17" (1)	(24,28)	J. Braden	2575	353
T.15 N. R.44 E.					
15G2	46°47'10"N117°15'06" (1)	(13,11)	City of Albion	2390	290
* 17R1	46°46'54"N117°17'26" (1)	(14,7)	J. Reeves	2340	180
* 20D1	46°46'43"N117°18'06" (1)	(14,6)	L. Cay	2342	280
* 21D1	46°46'40"N117°17'07" (1)	(14,7)	O. McCroskey	2355	177
26L1	46°45'18"N117°14'16" (1)	(17,12)	M. Harlow	2390	160
35E1	46°44'44"N117°14'25" (1)	(19,12)	V. Michaelson	2420	300
T.15 N. R.45 E.					
8M2	46°47'55"N117°10'30" (1)	(11,18)	R. Howell	2505	290
9C1	46°48'26"N117°09'04" (1)	(10,20)	P. Vernier	2522	260

Altitude of bottom of well (ft)	Date of first water-level observation (before 1973)	Altitude of first available water level (before 1973) (ft)	Altitude of Mar 1973 measured water level (ft)	Altitude of Mar 1974 measured water level (ft)	Altitude of June 1975 measured water level (ft)	Remarks
2236.2	10/18/54	2360.6(R)	--	--	--	Original water level (on 10/18/54) thought to be influenced by upper zone aquifers
2122	--	--	--	--	2291.6	
2280	5/19/54	2338.47	2303.7	--	2300.1	
2245	10/15/54	2325.60	2290.6	2288.7	2287	
1730	5/ /69	2294(R)	2283.69	2281.6	2279.57(b)	
2200	10/04/54	2327.04	2292.84	2290	2287.33	
2281	--	--	2314.5	2312.4	2310.8	
2217	1931	2346(R)	--	--	--	"Old" well used to irrigate cemetary grounds
2180	--	--	--	2295.3	2293.7	
2280	6/14/72	2302(R)	--	--	--	
2275	--	--	2300.3	2297.3	2296.20	
2285	5/21/54	2329.31	--	--	--	Well was dry on 3/31/73
2225	--	--	2284.4	2282.7(b)	2281.2(b)	
2080	12/28/56	2308(R)	2289	2284.5	2284	
2223	--	--	--	2286.2	2285.5	
2245	1950	2330(R)	2296.4	2294.7	2293.3(b)	
2215	--	--	2299.5	--	--	
N.A.	--	--	2289.8	2287.4(b)	--	
2214	--	--	2293.5	2291.4	2289.5	
2222	--	--	2290.3	2287.7	2285.3	
2100	3/19/69	2244	--	2229.8(a)	2231.9(a)	This well may reflect hydraulic characteristics of granite bedrock
2160	--	--	--	--	2212.9	
2062	--	--	--	--	2212.9	
2178	7/--/54	2255(R)	2223.03	2222.1	2222.97	
2230	7/08/55	2316.45	2287.2	2284.6	2283.6	
2120	6/8/54	2331.13	2297	2294.7	2293.1	
2215	After 1933	2445(R)	2286.4	2287.20	2283.5	Original water level-- if reported correctly--is thought to have been influenced by upper zone aquifers
2262	1938 or 1939	2360-2370(R)	2285.6	--	2282.1	Original water level--if reported correctly --is thought to have been influenced by upper zone aquifers

TABLE 4.--Records of wells tapping the primary aquifer system in and immediately west of Pullman-Moscow basin--Continued

USGS Well number	Lat and Long location	Model cell location	Owner or tenant	Altitude of land surface (ft)	Well depth (ft)
T.15 N, R.45 E. cont.					
10E1	46°48'05"N117°08'00" (1)	(11,22)	E. Steever	2554	263
14Q1	46°46'50"N117°06'11" (1)	(14,25)	J. McConaghy	2518	285
21H1	46°46'19"N117°08'20" (1)	(15,21)	C. Boyd	2520	326
21H2	46°46'20"N117°08'18" (1)	(15,21)	C. Boyd	2485	324
26K1	46°45'22"N117°06'14" (1)	(17,25)	O. Boyd	2608	302
29G1	46°45'32"N117°09'58" (1)	(17,19)	McGregor Co.	2430	220
29G2	46°45'33"N117°10'04" (1)	(17,19)	Davenport Chemical	2458	247
29P1	46°45'05"N117°10'14" (1)	(18,18)	Pierce Ranch	2445	140
30G4	46°45'37"N117°11'10" (1)	(17,17)	USDA Research Station	2520	371
31M1	46°44'24"N117°11'55" (1)	(20,16)	WSU	2350	172
32C2	46°44'52"N117°10'19" (1)	(18,18)	City of Pullman Well 6	2430	518
32N1	46°44'09"N117°10'32" (1)	(20,18)	City of Pullman Well 2	2350	231
32N2	46°44'09"N117°10'32" (2)	(20,18)	City of Pullman Well 4	2350	954
32N3	46°44'09"N117°10'32" (3)	(20,18)	City of Pullman	2350	238
33J1	46°44'31"N117°08'18" (1)	(19,21)	WSU	2615	438
34L2	46°44'24"N117°07'37" (1)	(20,22)	WSU Well 5	2515	396
T.16 N. R.45 E.					
30Q1	46°50'16"N117°11'08" (1)	(6,17)	J. Kinzer	2370	120
30Q2	46°50'24"N117°11'22" (1)	(6.17)	J. Kinzer	2342	99
Idaho wells					
T.39N., R.5W.					
7bda2	46°44'28"N117°00'43" (1)	(19,33)	City of Moscow Well 8	2617	1458
7cbb1	46°44'14"N117°01'14" (1)	(20,33)	U. of Idaho Well 3	2558	1336
8bdb1	46°44'27"N116°59'40" (1)	(19,35)	City of Moscow Well 6	2600	1308

Altitude of bottom of well (ft)	Date of first water-level observation (before 1973)	Altitude of first available water level (before 1973) (ft)	Altitude of Mar 1973 measured water level (ft)	Altitude of Mar 1974 measured water level (ft)	Altitude of June 1975 measured water level (ft)	Remarks
2291	10/6/53	2324.3	--	--	--	Well has been destroyed
2233	1949	2372(R)	2287.2	2285.0	2284.7	Original water level -- if reported correctly -- is thought to have been influenced by upper zone aquifers
2194	8/03/55	2326.7	2292.7	2290.5	2289.9	
2161	--	--	--	--	2285.2	
2306	10/27/53	2326.95	--	--	--	Well reported dry on 3/15/73
2210	9/--/63	2313(R)	2290	--	--	Airline length estimated 200 feet long
2211	9/--/63	2303(R)	--	--	2287.8	
2305	4/29/55	2324.62	--	2288.7	2287.1	
2149	1938	2330(R)	2281.2	2278.7	2278.2(b)	10/18/54 water-level altitude = 2315.60
2178	5/--/57	2327(R)	2296	2295	2291	Airline length reported to be 84 feet
1912	6/12/68	2298(R)	2294.38	2291.7	2290.2	3/18/69 water-level altitude = 2303.50
2119	3/12/46	2341(R)	2293	2292	2288	Airline length reported to be 62 feet
1396	6/5/56	2328.52	2293.55	2291.2(b)	2289.16	
2112	--	--	--	--	2289.1	Well is concentric to and outside 15N/45E-32N2
2177	1933	2344(R)	--	--	--	Well is apparantly buried
2119	1/29/64	2318.42	--	2295.9	2291	
2250	--	--	2303.06	2301.42	2300.0	
2243	11/--/55	2320(R)	--	--	--	
1159	12/11/64	2297(R)	2277.5	2280 (R)	2271(b)	8/22/74 water-level altitude at 2259.35 (unpumped for 15 min)
1222	12/14/63	2305.90	--	--	2282	8/21/74 water-level altitude = 2280 (airline measurement - unpumped for 15 min)
1292	4/27/60	2313(R)	--	--	2281.2	8/22/74 water-level altitude at 2259.6 (unpumped for 30 min)