STATE OF WASHINGTON
Daniel J. Evans, Governor

DEPARTMENT OF ECOLOGY
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WATER-SUPPLY BULLETIN 45

Digital Model of The Gravel Aquifer, Walla Walla River Basin, Washington and Oregon

By
R. A. BARKER AND R. D. MAC NISH

Prepared in Cooperation With
UNITED STATES GEOLOGICAL SURVEY
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The following factors are provided for conversion of English values used in this report to metric values:

Multiply	By	To obtain
Inches-----------------	25.40	millimetres (mm)
Feet (ft)--------------	0.3048	metres (m)
Miles (mi)-------------	1.609	kilometres (km)
Square feet (ft^2)------	0.0929	square metres (m^2)
Acres------------------	4047.	square metres (mi^2)
Square miles (mi^2)-----	2.590	square kilometres (km^2)
Acre-feet (acre-ft)----	1233.5	cubic metres (m^3)
Feet per second (ft/s)-	0.3048	metres per second (m/s)
Feet per mile (ft/mi)--	0.1894	metres per kilometre (m/km)
Feet squared per second. (ft^2/s)	0.0929	metres squared per second (m^2/s)
Cubic feet per second-- (ft^3/s)	0.02832	cubic metres per second (m^3/s)
Horsepower (hp)--------	0.7457	kilowatts (kW)
Gallons per minute----- (gal/min)	0.06308	litres per second (1/s)

DIGITAL MODEL OF THE GRAVEL AQUIFER, WALLA WALLA RIVER BASIN, WASHINGTON AND OREGON

By R. A. Barker and R. D. Mac Nish

ABSTRACT

A digital model using a finite-difference technique simulates hydrologic characteristics of a gravel aquifer which underlies about 120,000 acres of the Walla Walla River basin's interior lowland. The gravel aquifer is underlain by a basalt aquifer system and is coupled to an extensive surface network of streams, canals, and springs. The model permits testing of various water-management alternatives involving the spatial and temporal distribution of well pumpage, irrigation application, and surface-water diversion.

Trial-and-error simulation of hydrologic phenomena characteristic of the aquifer during typical, recent years (and believed to be applicable for 5-10 years in the future) was used to calibrate the model. Time-dependent fluxes were programmed for each month of the model year on the basis of recently observed local irrigation practices and pumping withdrawals, average crop requirements, and long-term precipitation. The calibrated aquifer hydraulic conductivities range from slightly less than 1.55×10^{-4} to 2.50×10^{-3} foot per second. Storage coefficients range from 0.1 to 0.25. After beginning the simulation with water levels contoured for January and continuing for 1 year, the calibrated model computed levels to within 10 feet of those originally contoured over about 95 percent of the modeled area--the match was within 5 feet over about 50 percent of the area.

A test of the method of calibration is provided by comparing results of a simulation run using 1970 precipitation data to streamflow data and water-level measurements for the same year. Model simulation of 1970 conditions indicate that the annual recharge and discharge to the aquifer--resulting from its interaction with canals, streams, and springs--totaled about 117,000 and 132,000 acre-feet, respectively. Infiltration of 34,000 acre-feet of water, resulting from irrigation and precipitation, exceeded current annual pumpage withdrawals by nearly 10,000 acre-feet. The 10,000 acre-feet of net annual recharge to the gravel aquifer by steady leakage from the underlying basalt bedrock system was closely balanced by annual losses from ground-water evapotranspiration. Inflow across the model boundaries totaled about 15,000 acre-feet a year, while subsurface outflow was only about 2,000 acre-feet a year. Computed hydrographs generally reflect the seasonal trends of water-level change during 1970 for most areas.

INTRODUCTION

Purpose and Scope

In 1969 a comprehensive study of the water resources of the Walla Walla River basin of southeastern Washington and northeastern Oregon was begun as a cooperative effort between the State of Washington Department of Ecology and the U.S. Geological Survey. The study was prompted by an increasing public awareness during recent years of water demands and shortages, particularly in the more heavily pumped agricultural areas in eastern Washington. The principal objective of the study was to develop digital-computer models of the basin's shallow gravel aquifer and underlying basalt aquifers that could simulate hydrologic characteristics of these aquifers under various stress conditions. Such simulation models would enable State and local water managers to evaluate different management schemes that might be implemented to better satisfy the increasing requirements for water in the Walla Walla River basin.

This report discusses the gravel-aquifer model and a concurrent report being prepared by Mac Nish and Barker (1975) discusses the basalt-aquifer model; together the reports cover the final phase of the investigation. This report introduces the basic concepts of the gravel-aquifer model to the State and county water managers, city engineers, and other concerned citizens who must manage and conserve the water resources in the Walla Walla area. A general description of data requirements, simulation procedures, and capabilities and limitations of the model is also provided.

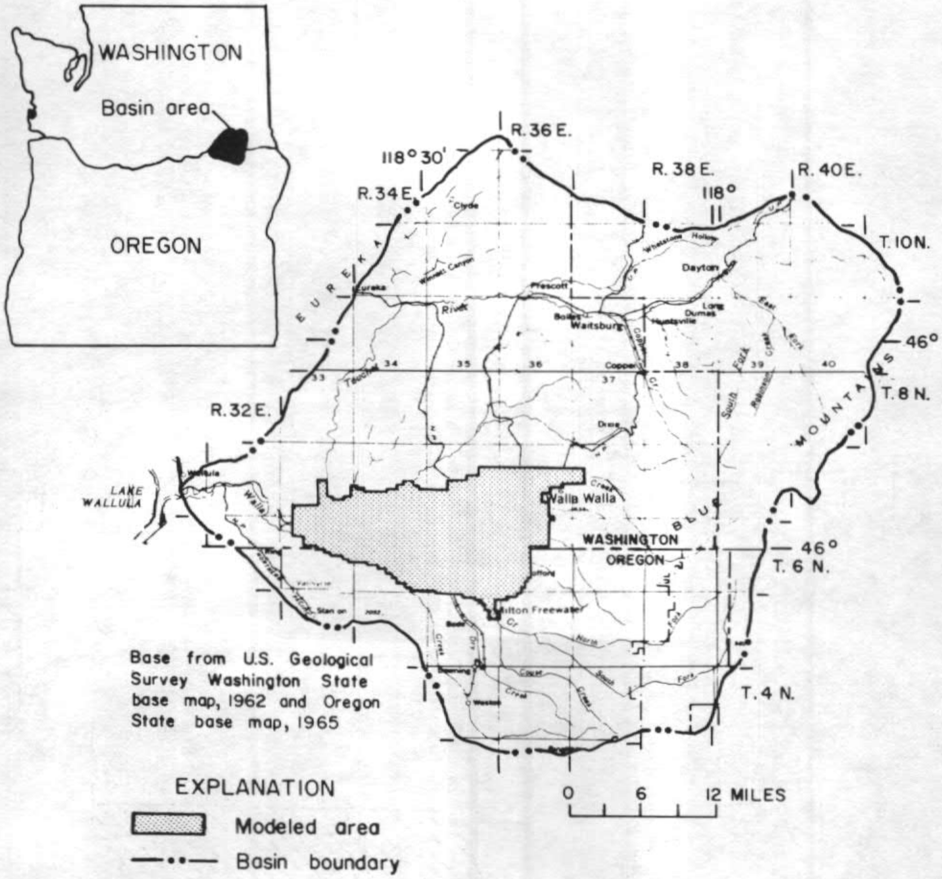


FIGURE 1.--Location of the Walla Walla River basin and the modeled area.

Location and Description of Area

The Walla Walla River basin is situated in southeastern Washington and northeastern Oregon (fig. 1). The basin's gravel aquifer, as defined by Mac Nish, Myers, and Barker (1973), consists of the unconsolidated sediments lying above a clay unit approximately 200 feet thick that separates the gravel aquifer from an underlying basalt aquifer system in the central lowland part of the basin. The gravel aquifer consists primarily of gravel and sand, but varying amounts of silt and clay occur from place to place. The aquifer probably averages about 200 feet in thickness but is as much as 500 feet thick in places. The area for which the model was constructed (fig. 2), includes all potentially productive areas of the gravel aquifer and encompasses nearly 120,000 acres, of which about 42,000 were irrigated in 1970.

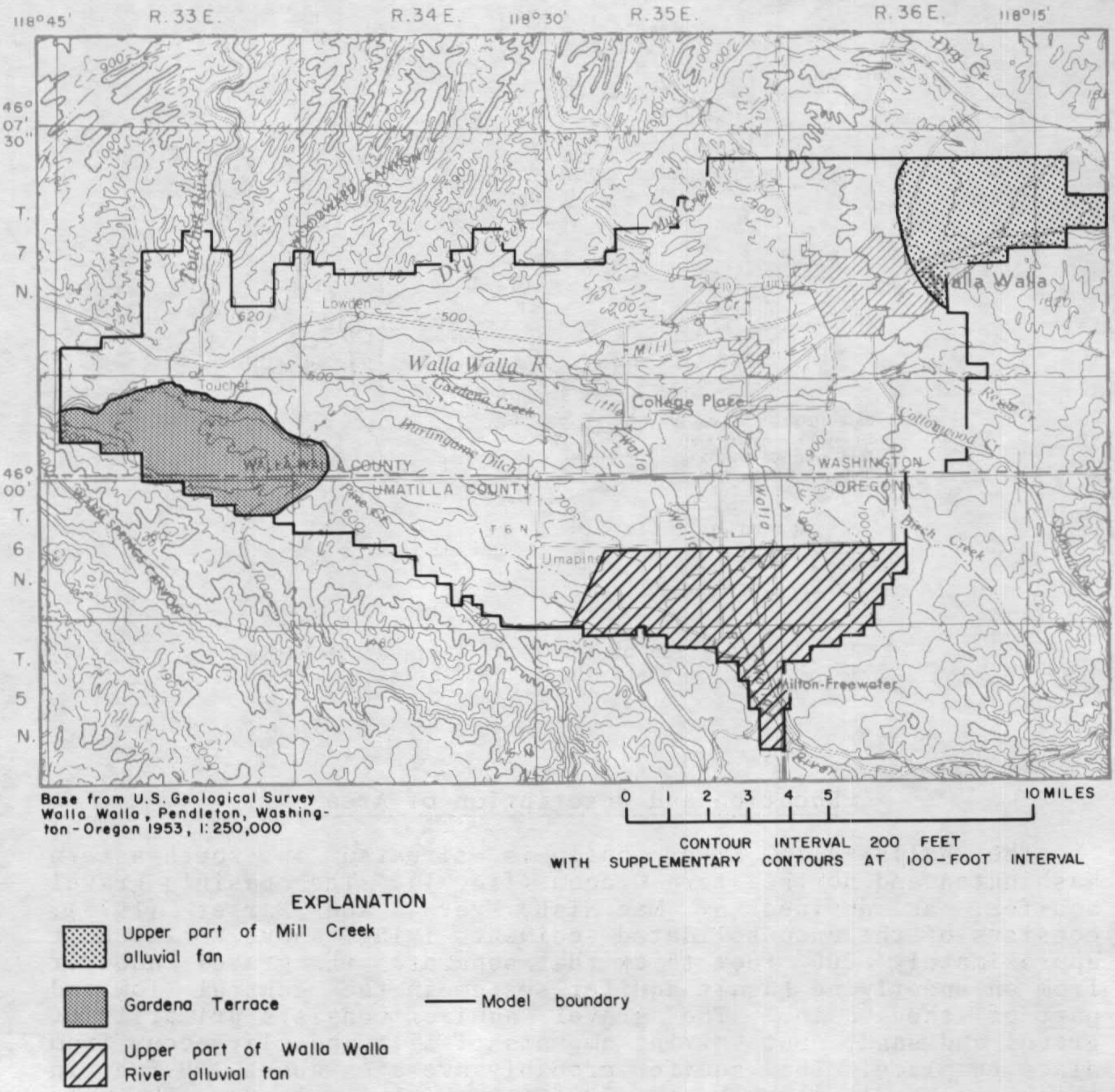


FIGURE 2.--The lower Walla Walla River basin, showing the modeled area and selected topographic features.

The semiarid climate of the region provides an average annual precipitation of about 12 inches, ranging from about 8 inches in the lower, western part of the basin to more than 15 inches in the eastern part. The area has a growing season of more than 200 days. A more detailed discussion of the area's geology, physiography, and climate is available in reports by Newcomb (1965) and Mac Nish, Myers, and Barker (1973).

Acknowledgments

Previous investigations in the Walla Walla River basin by Piper, Robinson, and Thomas (1933), and Newcomb (1965) provided geohydrologic data and insight of considerable value to the development of the gravel-aquifer model.

For their cooperation in the collection of basic data, special acknowledgment is due the many land and property owners, tenants, and well drillers in the study area. The suppliers of electrical energy in the basin--the Columbia Rural Electric Association, Pacific Power and Light Co. and City Power and Light Co.--are commended for their generous help in locating pumping sites and providing records of electrical-energy consumption. The local watermasters, Harry Hanson of Walla Walla County, Wash., and Steve Isitt of Milton-Freewater, Oreg., deserve special thanks for their help. Our appreciation also is expressed to the various city engineers, and their staffs, all of whom contributed to a better understanding of local water-use practices.

The Digital-Computer Model

The importance of high-speed digital computers for the evaluation of water resources has increased substantially in recent years. The computer's ability to solve, very rapidly and relatively inexpensively, repetitive sets of mathematical equations accounting for all the important hydrologic phenomena in an area, has encouraged a widespread and growing use of digital-computer models for ground-water studies. Because computer simulation can be extended far into the future, it can provide a practical means of assessing future ground-water responses to proposed changes in the system.

The computer model of the Walla Walla gravel aquifer was developed under the premise that, if a history of observed hydrologic phenomena could be approximated by the model, then response of the aquifer to anticipated stresses might be projected with reasonable accuracy. Because no long-term trends of changing water levels and rates of spring discharge in the aquifer were definable from available data, it was assumed for purposes of calibration that hydrologic conditions are virtually equal at the same point in time from one year to the next--that is, seasonal variations are duplicated approximately year after year. This assumption permitted the model calibration to be based on a 1-year period only. It is a reasonable assumption in terms of stresses imposed on the aquifer, because since 1968, conditions of pumpage and diversion rates have remained relatively uniform from year to year.

The initial water-level surface for calibration runs was represented by what was determined as the average position of the water table in the month of January. A single map of January water levels was drawn from plots of all water-level measurements made during January 1969-72. Patterns of water-level differences between years in this period could not be defined sufficiently over large enough areas to warrant the construction of separate maps in an attempt to distinguish conditions in one January from those in another.

During model calibration, repetitive trial-and-error simulations were made, beginning with calculations in January and running through December. The attempt was made to duplicate water levels, spring discharges, and stream-aquifer relationships throughout the year as accurately as possible within reasonable limits of time and cost. Various parameters, such as aquifer hydraulic conductivity, storage coefficient, infiltration potential, and time incrementation were adjusted (within the constraints of sound hydrologic reasoning) until a satisfactory approximation of the seasonal variations in hydrologic conditions during the typical year was achieved.

Finally, to provide documentation of the model's validity in this report, a simulation run was made with 1970 precipitation input, and the results are compared with water levels and surface-ground water relationships measured during 1970.

BASIC DATA

Of vital importance to the design and calibration of the computer model was having accurate input data which would properly describe the modeled system in time and space. Much geohydrologic background material was available from previous work. Any geology not already defined by Newcomb (1965) or others could usually be interpreted from aerial photgraphs; little field mapping of geology was done during this study. Aquifer boundaries and characteristics were defined on the basis of drillers' well logs as well as well records, geologic sections, and maps included in the report by Newcomb (1965).

Surface-water basic data were provided primarily by publications of the U.S. Geological Survey and of the State of Oregon. The locations of major canal diversion points and rates of diversion were also obtained from records retained by the local watermasters. Much information on spring locations and discharge rates was provided by Newcomb (1965) and Piper, Robinson, and

Thomas (1933). Climatological data published by the [U.S.] National Oceanic and Atmospheric Administration (1971; formerly U.S. Weather Bureau) were used to define the distribution of precipitation over the modeled area. These data were also used in conjunction with crop-growth data provided by the U.S. Department of Agriculture, to determine the rates of consumptive use applicable in the model.

Ground- and surface-water data-collection sites used during the study are shown on plate 1 (in pocket). Where required, the streamflow data from continuously operated gaging stations and published spring-flow records were supplemented by flow measurements at miscellaneous sites. The miscellaneous measurement sites for stream discharge (pl. 1 and table 1) were maintained for observations between April 1970 and October 1971.

An inventory of wells and ditch-pump installations was conducted between January 1969 and October 1970. On nine separate occasions between January 1969 and January 1973, measurements of water levels in more than 200 observation wells were conducted to define seasonal fluctuations of the water table and to provide data for water-level maps used to calibrate the model. In addition, records of electric-power consumption for irrigation wells were compiled for the years 1969-70 in order to compute annual pumpage totals and the seasonal distribution of pumpage.

The basin's complex ditch and canal system was mapped in the field during the fall of 1972, to provide a detailed and accurate map of water diversions in the area. The types of irrigation (rill, sprinkler, or both), the areas receiving irrigation, and the types of crops being irrigated were also recorded for all areas during this time.

Seepage tests to determine the rates of leakage to and from the gravel aquifer were conducted on three stream reaches and a canal. The seepage rates computed from these tests helped to establish values applicable to various parts of the modeled area.

WATER BUDGET

Sufficient data were available before the development of the model to determine only a generalized water budget for the area to be modeled. For interested readers, generalized budget elements are provided in previous reports by Newcomb (1965) and Mac Nish, Myers, and Barker (1973). Because the model was to simulate various quantities of water flowing into and out of the aquifer--or fluxes--the budget served as a framework within which the model could be developed and calibrated. The generalized budget was useful for understanding the relative accuracy of each computed element of recharge and discharge and thus a check was maintained between real and simulated fluxes.

By simulating the real system, the calibrated model provides additions to and refinements in the original analysis of water inflow and outflow for the area. Using the added and refined values a comprehensive water budget representing 1970 hydrologic conditions is presented in table 1, where the computed aquifer fluxes and various routings of surface flow are tabulated. It should be recognized that the budget in table 1 lists elements derived mostly from use of the calibrated model. The elements are those required to allow simulation of the historic or measured fluxes and hydrologic changes within reasonable limits, and they are in reasonable accord with generalized water budget items presented in prior reports.

DATA ANALYSIS AND INPUT TO THE MODEL

Pumpage

Annual ground-water pumpage from all irrigation wells tapping the gravel aquifer was computed by converting electric-power consumption into pumpage volumes. The areal distribution of this pumpage is illustrated in the report by Mac Nish, Myers, and Barker (1973, p. 22). The technique of converting electric-power consumption has been used successfully in various areas of the country and is described in numerous reports, including those by Olgilbee and Mitten (1970), Sandberg (1966), and McClelland (1963). The formula for the conversion as used in this study is

$$P = \frac{K}{HF} \quad ,$$

where

- P = pumpage, in acre-feet;
- K = electric power consumption, in kilowatthours;
- H = total pumping head, in feet; and
- F = a variable related to the efficiency of the pumping plant; it is equal to the kilowatthours required to lift 1 acre-foot of water a height of 1 foot. Values of 1.73 were used for pumps of 100 horsepower or more and 2.28 for pumps of less than 100 horsepower.

A range of pump-efficiency factors (F) based on pump horsepower was recently developed by Luzier and Burt (1974) for areas in eastern Washington. For comparison, F factors were computed for six municipal-supply wells having metered pumpage in the Walla Walla River basin. The average F factor for five of the six wells was 1.74. The value used by Luzier and Burt for wells in the same horsepower range was 1.73 (J.E. Luzier, written commun., 1974), although the value was rounded to 1.7 in the report (Luzier and Burt, 1974). A significant difference in results for the sixth well was attributed to poor well construction. Because poor well construction is not characteristic of

TABLE 1.--1970 water budget for the gravel-model area in the Walla Walla River basin, Washington and Oregon

Water incident to the land surface: Method of movement	Acre-ft	Water from the land surface: Method of movement	Acre-ft
Precipitation[1]	136,000	Consumptive use[1]	218,000
Irrigation, provided by:		Runoff (includes diversion and irrigation waste)[1]	86,000
Pumpage from basalt aquifer system[2]	18,000	Infiltration[3]	34,000
Pumpage from gravel aquifer[2]	25,000		
Pumpage from stream channels[2]	9,000		
Gravity diversions from stream channels[4]	150,000		
Total	338,000	Total	338,000

Water entering the gravel aquifer: Method of movement	Acre-ft	Water leaving the gravel aquifer: Method of movement	Acre-ft
Leakage from stream channels[3]	112,000	Ground-water evapotranspiration[3]	11,000
Infiltration of incident water[3]	34,000	Leakage to basalt aquifer system[3 5]	1,000
Subsurface inflow across model boundary[3]	15,000	Subsurface outflow across model boundary[3]	2,000
Leakage from basalt aquifer system[3 5]	11,000	Leakage to stream channels[3]	76,000
Leakage from ditches and canals[3]	5,000	Spring discharge[3]	56,000
		Pumpage[2 3]	25,000
		Storage change[3]	5,000
		Mass balance residual*	1,000
Total	177,000	Total	177,000

*Required to balance budget resulting from round-off errors inherent in simulation procedure.

Stream channel gains and losses

Gain	Acre-ft	Loss
Surface-water inflow to modeled area:		
Gaged[6]	468,000	
Correction in Touchet River discharge for difference between Bolles and Touchet**	15,000	
Estimated[7]	96,000	
Leakage from gravel aquifer[3]	76,000	
Spring discharge[3]	56,000	
Runoff of incident water[1]	86,000	
	-150,000	Gravity diversions for ditch and canal distribution.[4]
	-9,000	Pumpage from stream channels[2]
	-112,000	Leakage to gravel aquifer[3]
Net computed outflow	526,000	(Gaged outflow from area = 521,000 acre-ft[8])

**Average annual gain between surface-water gage at Bolles, Wash., and discontinued gage (sta. 14017175) near Touchet (U.S. Geological Survey, 1963).

[1]Compiled by simulation model, independent of the computation of aquifer fluxes affected by calibration.

[2]Computed from electric-power consumption.

[3]Computed by simulation model of gravel aquifer.

[4]Compiled from records of local watermasters and gaged diversion rates.

[5]Computed by simulation model of basalt aquifer system (Mac Nish and Barker, 1975).

[6]Compiled from U.S. Geological Survey surface-water data collected from the following stations:
14010000. South Fork of the Walla Walla River near Milton, Oreg.
14011000. North Fork of the Walla Walla River near Milton, Oreg.
14013000. Mill Creek near Walla Walla, Wash.
14013500. Blue Creek near Walla Walla, Wash.
14017000. Touchet River at Bolles, Wash.

[7]Compiled from U.S. Geological Survey surface-water data collected at the following miscellaneous sites, discontinued stations, and ungaged streams: Couse Creek, Oreg. (ungaged); Birch Creek near Spofford, Oreg., Dry Creek near Barrett, Oreg., Pine Creek near Umapine, Oreg., Cottonwood Creek near Spofford, Oreg., and Russel Creek near Walla Walla, Wash. (published discharges in U.S. Geol. Survey, 1972); Dry Creek near Walla Walla, Wash. (station 1401600, discontinued).

[8]Compiled from U.S. Geological Survey surface-water data collected from station 14018500 on the Walla Walla River near Touchet, Wash.

other wells in the basin, the use of the F factors developed by Luzier and Burt (1974) was considered justified for the present study.

Total pumping heads (H) were compiled from measured pumping lifts and gaged line pressures for all wells where possible. Where such data were not available, average values from similar nearby installations were used. Kilowatthour consumption (K) was provided for all pumping sites by local power companies.

Monthly pumpage totals were computed for about 25 percent of the installations; only annual totals could be computed for the remainder. The ratios of monthly totals to the annual sum for the 25 percent were used as a basis for estimating the time distribution of pumping for other parts of the modeled area. Figure 3 (graph E) illustrates the programmed annual variation of irrigation water withdrawal from the gravel aquifer.

Consumptive Use

Consumptive use is defined by the U.S. Department of Agriculture (1967) as "the amount of water used by the vegetative growth of a given area in transpiration and building of plant tissue and that evaporated from adjacent soil or intercepted precipitation on the plant foliage in a specified time." A modification of the Blaney-Criddle method, as presented by the U.S. Department of Agriculture (1967), was used to compute rates of consumptive-use demand for application in the model.

Consumptive use, which is dependent on local climatological phenomena and crop type, was estimated for each month using the following formula:

$$U = (K_t)(K_c)\frac{(tp)}{100} \quad ,$$

where

U = consumptive use of crop, in inches per month;
K_t = a climatic coefficient related to mean monthly air temperature;
K_c = a coefficient reflecting the crop's monthly growth stage;
t = mean monthly air temperature, in degrees Fahrenheit; and
p = monthly percentage of daylight hours in the year.

After the monthly K_t, t, and p values were determined (using formulas and tables from the U.S. Department of Agriculture, 1967) for the Walla Walla River basin, crop type remained the only variable. Curves computed from the above formula and shown

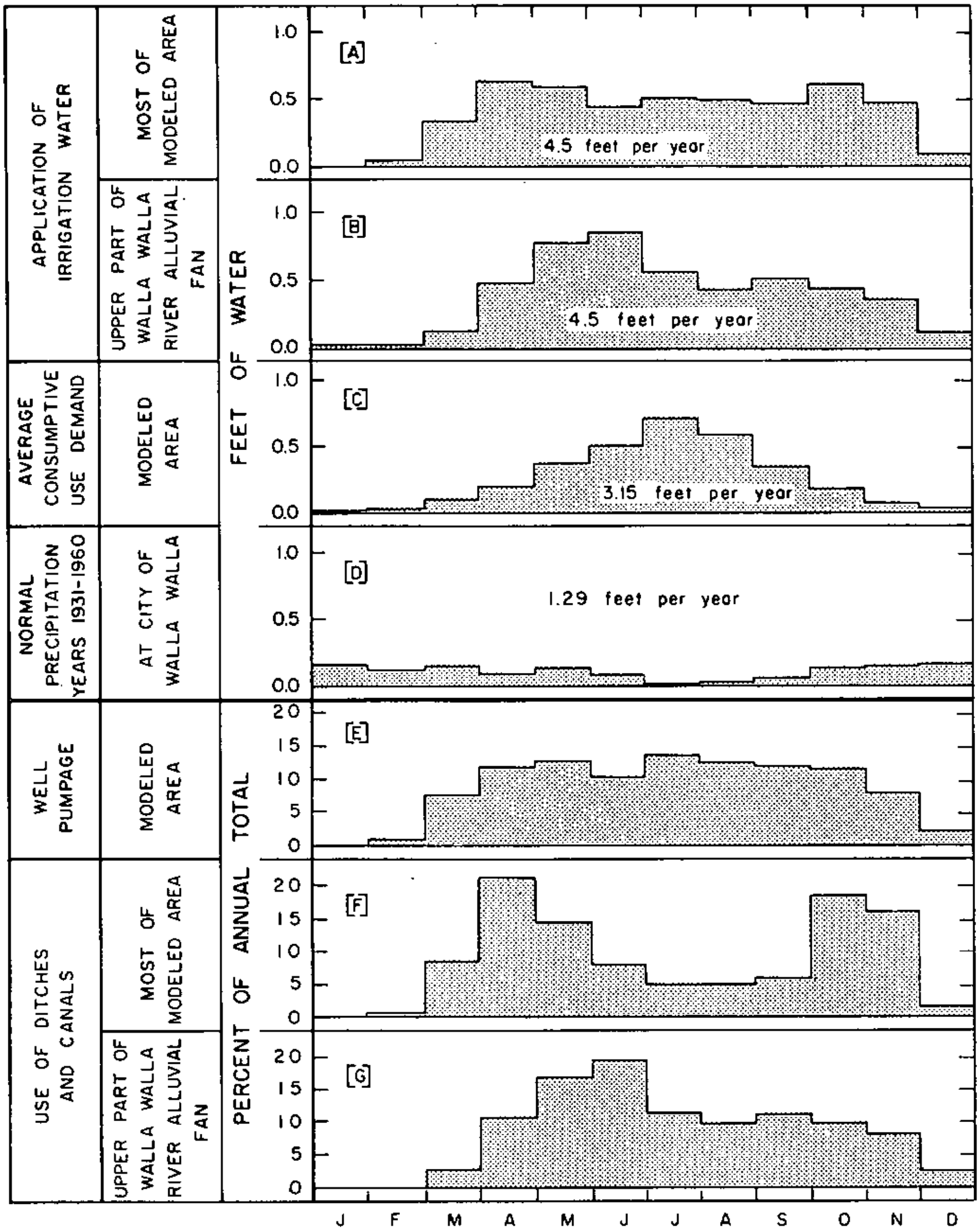


FIGURE 3.--Time distribution of selected hydrologic parameters used to calibrate the model.

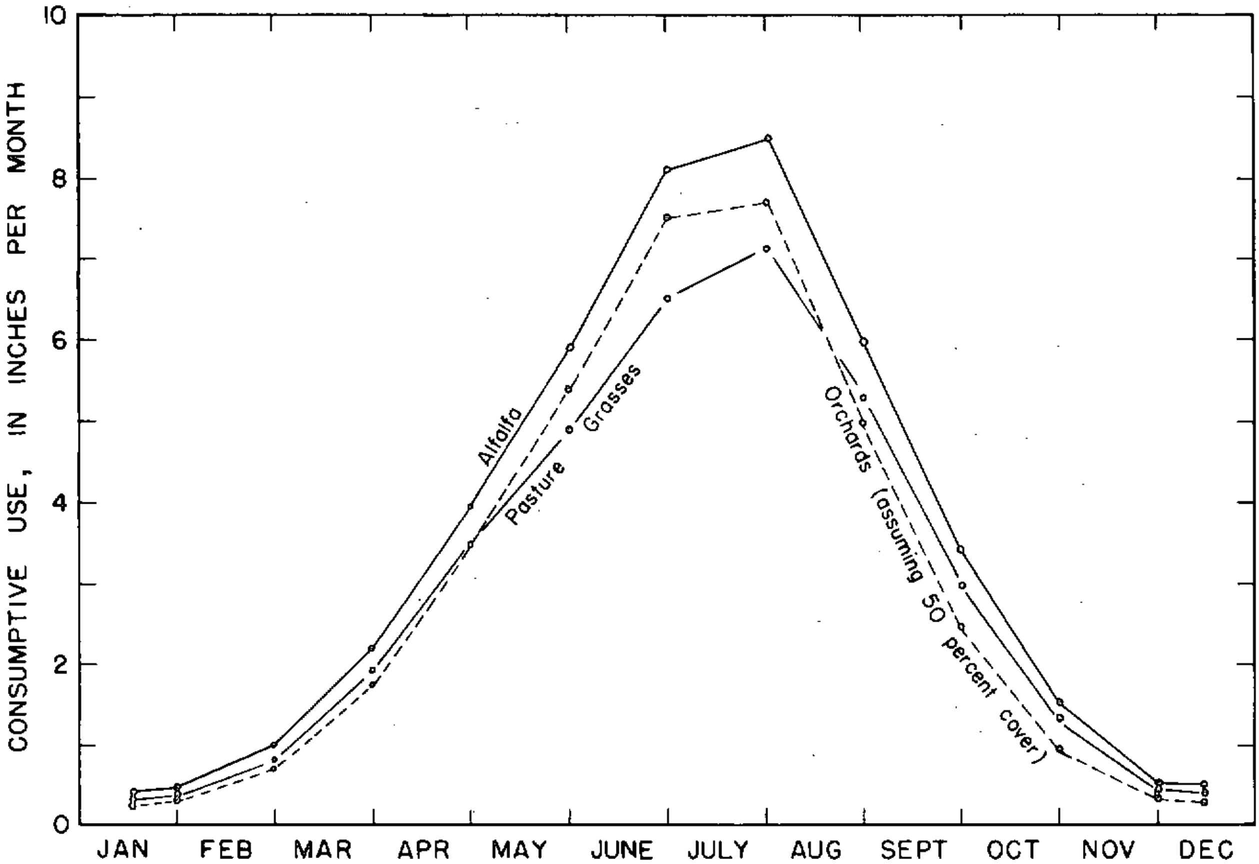


FIGURE 4.--Comparison of consumptive-use rates of the three principal perennial crops in the Walla Walla River basin.

in figure 4 depict the consumptive-use demands by pasture grasses, orchards, and alfalfa (the principal perennial crops in the basin). Deviation from the average of all three curves by any single curve was judged small enough to allow the use of the average curve to distribute seasonal water demands for consumptive use during simulation (fig. 3, graph C).

Ground-Water Evapotranspiration

If ground-water levels are sufficiently shallow or if capillary movement of ground water reaches plant roots, significant discharge from an aquifer may occur as a result of ground-water evapotranspiration.

In conjunction with the simulation of evapotranspiration effects in the model, ground-water evapotranspiration (where applicable) is computed according to the relationship shown in figure 5. Ground-water evapotranspiration is calculated and removed from the aquifer in the model only when the demands of consumptive use cannot be met by available applied water and (or)

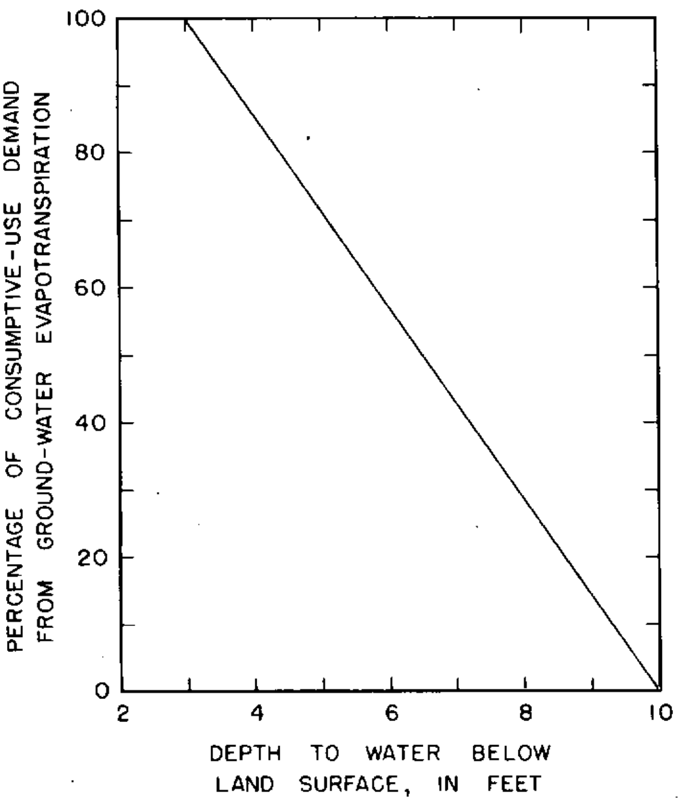


FIGURE 5.--Relationship between ground-water evapotranspiration and depth to water table in the Walla Walla gravel-aquifer model.

precipitation. As is evident from figure 5 ground-water evapotranspiration will completely satisfy consumptive-use demands until the water table is more than 3 feet below land surface. Below 3 feet, that part of consumptive-use demand that can be satisfied by water from the aquifer reduces about 14 percent per foot and is zero at depths of 10 feet and greater. A similar relation was used successfully in a model study of the Columbia Basin Irrigation Project area (Tanaka, Hansen, and Skrivan, 1974).

The maximum rate of ground-water evapotranspiration used by Tanaka, Hansen, and Skrivan (1974) was constant between land surface and depths of 2 feet. The maximum rate was maintained to depths of 3 feet in the model for the Walla Walla River basin to reflect better the conditions of finer grain sizes in the Umapine Series soils of the lowlands. In these areas, capillarity is probably greater than in the generally sandier soils of the Columbia Basin Irrigation Project area (Strahorn and others, 1929, p. 31-35; 1964, p. 42-43).

Stream Leakage

Perennial streams in the modeled area include Mill Creek, the Walla Walla River, the Little Walla Walla River, and others of lesser extent, such as Birch and Yellowhawk Creeks (pl. 1). The Walla Walla River enters the modeled area from the southeast at an altitude of about 1,100 feet and leaves the area across the western boundary at an altitude of nearly 400 feet. Mill Creek enters from the northeast at an altitude of about 1,400 feet and joins the main stem of the Walla Walla River near the center of the modeled area at an altitude of about 600 feet. The gradients of these streams have an average drop of about 40 ft/mi over the modeled area.

The pattern of water exchange between the gravel aquifer and the stream channels may be generalized as follows: (1) perennial stream channels above a land-surface altitude of about 850 feet characteristically lose water to the aquifer during the entire year; (2) channels with altitudes below about 750 feet generally gain water from the aquifer during the entire year; and (3) reaches with altitudes between about 750 and 850 feet may gain or lose water, depending upon the seasonal fluctuation in the gravel-aquifer water table adjacent to the stream channels.

The average effects of recharge and discharge via stream channels during the year are simulated in the model. Assuming continuous flow throughout the year in the perennial stream channels, the instantaneous rate of leakage occurring in any given stream reach (model cell) is provided by the equation

$$Q = \frac{(h_s - h_a)(kA)}{m},$$

where

Q = rate of infiltration through the streambed, in cubic feet per second;

h_s = altitude of stream channel, in feet;

h_a = altitude of water level in aquifer, in feet;

m = thickness of streambed (assumed = 1), in feet; and

kA = the product of the streambed hydraulic conductivity (k) and area of stream channel (A) through which leakage occurs, in cubic feet per second.

Ideally, h_s should be the altitude of the water surface in the stream channels. However, the altitude of the stream channel is used in the simulation model because available vertical control (topographic maps with a 10-ft contour intervals) did not permit separation of the two. Differences between the water-surface altitudes and channel altitudes are generally less than 1 foot in about 90 percent of the pernnial stream reaches during most of the year.

From the equation, a positive Q value represents an aquifer gain of water and, consequently, a stream loss. Walton, Hills, and Grundeen (1967) stated that "leakage of water through a streambed is directly proportional to the drawdown beneath the streambed until the water table declines below the streambed. Thereafter, induced infiltration remains constant provided the stream stage and temperature remain stationary." Because in this study the authors' use of the stream channel's altitude for h_s in the model maintains a constant stream stage, the gradient $(h_s - h_a)$ is limited so that it may never exceed the streambed thickness (m) when the water table (h_a) is below the streambed. This is an approximation of the phenomena described for losing stream reaches by Walton, Hills, and Grundeen (1967).

The streambed thickness (m) was assigned a value of 1 foot for all reaches, owing to the absence of real data. The error introduced by this assumption is considered small.

The combined effect of k and A is considered here because the estimated value of either for any given model cell is not necessarily accurate. As a product, however, the two parameters provide a relatively good match between observed and computed water levels in areas adjacent to streams.

Streambed conductivities (k) measured on streams ranged from 6.7×10^{-6} ft/s for a silt-and-clay bottomed stream to 6.0×10^{-5} ft/s for the coarse gravel channel of the Walla Walla River at the head of the alluvial fan. A typical value of conductivity for most stream channels would lie between these two values. For the model, a k value of 1.55×10^{-5} was assumed for all stream reaches modeled. This is within the range of streambed conductivities published by other investigators for similar streambeds, as follows:

> 2.17×10^{-5} ft/s and 2.63×10^{-5} ft/s, for the Arkansas River in Colorado (Moore and Jenkins, 1966); 1.55×10^{-5} ft/s and 6.2×10^{-5} ft/s, for the Little Plover River in Wisconsin (Weeks, Erickson, and Holt, 1965); and an average of 6.38×10^{-6} ft/s for three reaches on the Miami River near Venice, Ohio (Walton, Hills, and Grundeen, 1967).

The values for the area of stream channels (A) were originally estimated from topographic maps and aerial photographs to represent the average area occupied by perennial streams within each model cell during the course of a year. During model development, however, values of A were altered for some model cells to compensate for computed versus observed water-level descrepancies, probably caused by using a single streambed-conductivity rate. For example, some values of A as used in the model are larger or smaller than those originally estimated because simulation indicated either more or less leakage was required to match observed water levels than could be provided by the constant k of 1.55×10^{-5} ft/s.

Canal and Ditch Leakage

About 750 linear miles of mostly unlined ditches and canals traverse the land surface above the gravel aquifer. The total bottom area of these conveyances is calculated to be about 170 acres. Before leakage from the ditch and canal network could be simulated, the space-and-time distribution of flow in the major canal and ditch systems had to be approximated. The area of each cell occupied by ditches or canals was estimated from maps of the diversion system. Lengths of ditches were multiplied by average ditch widths noted during the ditch mapping.

The theoretical controls on where and when water flows in the ditches and canals are the adjudicated and appropriated water rights for the basin. However, separate and equally complex water-right systems are in effect on both sides of the Washington-Oregon State line and the many exceptions and compromises within the actual functioning of each system precluded attempts to relate ditch and canal flow directly to the existing water-right structures. As a result, some generalizations were used as a basis for approximating characteristics of ditch usage, for the purpose of simulating ditch leakage in the model. These generalizations are as follows:

1. Gravity irrigation is practiced in many parts of the study area, but is concentrated primarily in the upper parts of the Walla Walla River alluvial fan (fig. 2).

2. The trunk canals contain water during the entire diversion periods, whereas the laterals and rills do not; these smaller ditches comprise the largest part of the total area of canals and ditches.

3. Throughout the modeled area the ditch bottoms are almost everywhere above the water table.

4. The Little Walla Walla River diversion provides the bulk of the water used by the gravity-irrigated upper part of the Walla Walla River alluvial fan (fig. 2), thus, the amount

of ditch use in any one month for that area may be expressed as a ratio of that month's diversion to the maximum monthly diversion.

5. Similarly, in areas where the diverted surface water is pumped to sprinklers for irrigation, the amount of ditches in use in any one month is reflected by the ratio of the amount of electric-power consumption by ditch pumps in that month to the maximum monthly power consumption by ditch pumps.

Although these generalizations are not precise, the low hydraulic conductivities of the ditch bottoms and their relatively small areal extent minimize the significance of any associated error. Thus, the infiltration from ditches and canals to the aquifer can be approximated by the equation

$$Q_m = kAC_m \quad ,$$

where

Q_m = average rate of recharge received by the gravel aquifer during a month (m), in cubic feet per second;
k = ditch leakage rate, in feet per second;
A = area occupied by ditches and canals, in square feet; and
C_m = monthly proportionality constant for ditch usage (for month of maximum use $C_m = 1$).

The time distribution of ditch use in the modeled area is shown in figure 3. Graph F shows this variation for most of the irrigated areas as it was developed from ditch-pump power consumption. Graph G shows the distribution as developed from the diversion records of the Little Walla Walla River, the principal source of water for the Walla Walla River alluvial fan.

As indicated by observations by local watermasters, most ditches and canals probably leak at maximum rates of about 1.55×10^{-5} ft/s (the year-around average assumed for all streambeds) during the first few days of use in the spring until their bottoms become sealed. A seepage measurement on a ditch near Umapine that typifies the silt-floored ditches in the lower part of the basin (and the sealed ditch bottoms in most other areas) indicated a seepage loss of 0.03 ft^3/s over an area of 15,00 ft^2. These data yield a leakage rate of 2.0×10^{-6} ft/s, which was used for all modeled areas except the upper parts of the Walla Walla River alluvial fan, where coarser bed materials led to an increase in the estimate of k to 3.0×10^{-6} ft/s.

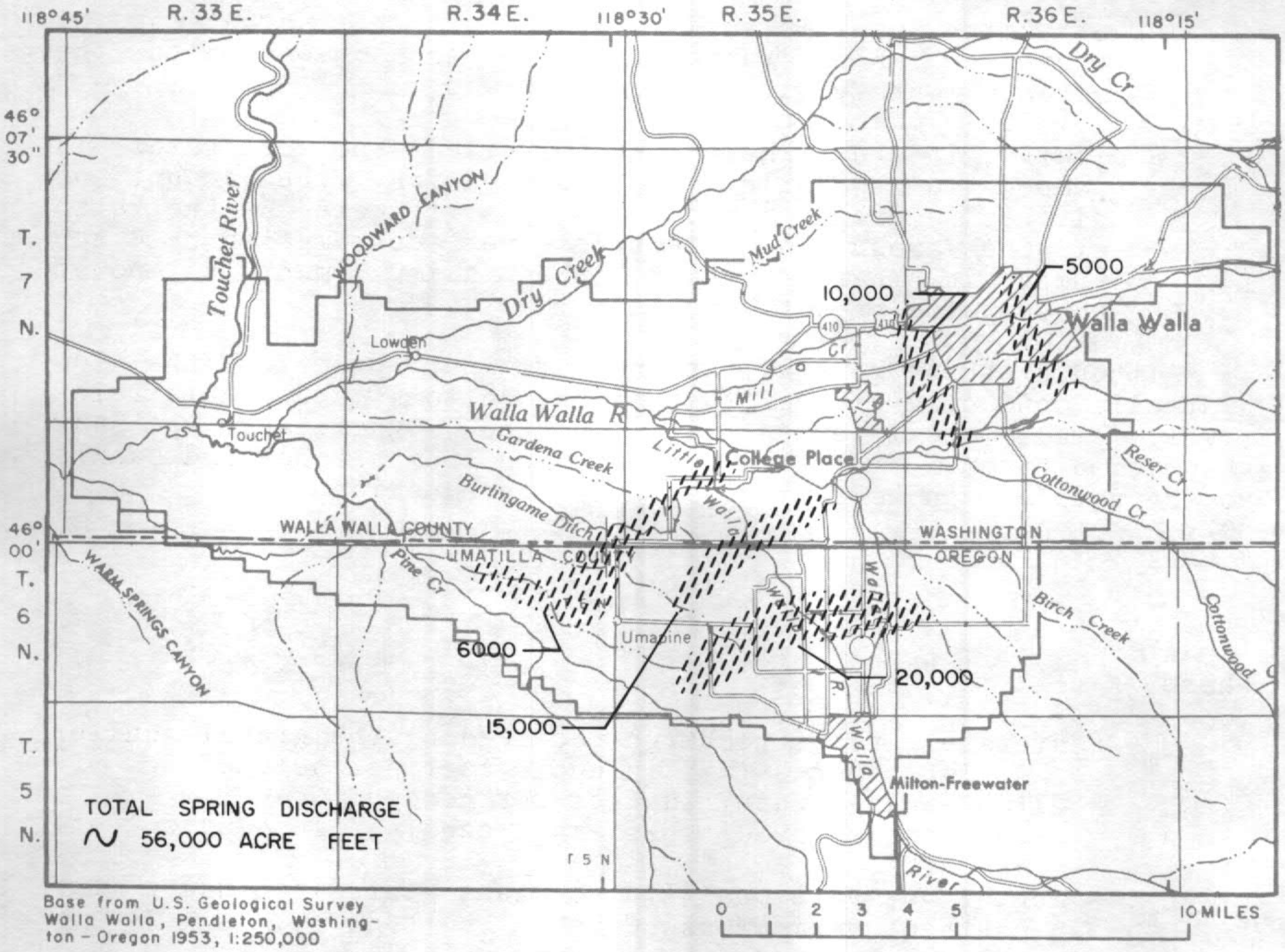


FIGURE 6.--Spring zones in the modeled area, with approximate annual discharge from each, in acre-feet.

Spring Discharge

The rate and direction of ground-water flow through the gravel aquifer is influenced by the relative amounts of coarse and fine material encountered during the water's downgradient movement. As the percentage of clay and silt increases, the aquifer's ability to transmit water decreases and ground water is forced upward toward the surface, where it may emerge as spring flow.

Spring discharge from the gravel aquifer occurs mainly from five spring zones (fig. 6), three of which are associated with the Walla Walla River alluvial fan, and two with the Mill Creek alluvial fan. Piper, Robinson, and Thomas (1933) estimated an average annual spring discharge of about 50,000 acre-feet and measurements in 1942-43 by Newcomb (1965) substantiated this total. A comparison of present spring-discharge rates with those published for the 1940's and 1950's, yields little evidence to confirm Newcomb's hypothesis that "the total amount of discharge from springs on the alluvial fan of the Walla Walla River has decreased progressively since the 1940's." Measurements and observations made between 1969 and 1973 indicate that spring discharge in the modeled area still averages between 50,000 and 60,000 acre-feet annually, and that the present-day areal and seasonal distribution of flow differs little from that of the past.

Spring locations and rates of flow provided by Newcomb (1965) and updated by recent observations and measurements were used during model development to calibrate the simulation of spring flow. Spring discharge is simulated with an equation similar to that for stream leakage,

$$Q = (h_o - h_a)\left(\frac{kA}{m}\right) ,$$

where

Q = rate of discharge from the aquifer from a spring, in cubic feet per second (computed only when h_a exceeds h_o);

h_o = altitude of spring outlet, in feet;

h_a = altitude of water level in aquifer, in feet; and

$\frac{kA}{m}$ = a quantity equal to the product of the vertical hydraulic conductivity (k) of the aquifer in the vicinity of spring and the area (A) of spring outlet(s) divided by the thickness of aquifer material (m) through which spring flow emerges. Units of this term are feet squared per second.

The constant $\frac{kA}{m}$ quantity for each spring locality was derived by trial-and-error simulation. Because determination of the individual components from literature or field measurements was very difficult, if not impossible, a suitable combination of those values for each spring discharge site was derived empirically so as to provide a reasonable duplication by the model of observed water levels and gaged or estimated spring flow.

Irrigation Application

It is estimated that an average 4.5 feet of irrigation water is applied annually to the 42,000 irrigated acres within the modeled area. The 4.5-foot-per-year value is derived by summing annual volumes of irrigation water from all sources, and dividing by the number of irrigated acres. The sources, listed in table 1, include: (1) ground water pumped from both the gravel and basalt aquifers (43,000 acre-ft), (2) water pumped directly from streams (9,000 acre-ft), and (3) water diverted by gravity methods for ditch and canal distribution systems (150,000 acre-ft). Assuming that about 95 percent of all water originally diverted or pumped for irrigation reaches the fields, about 190,000 acre-feet of irrigation water is annually applied to the land surface above the gravel aquifer. Thus, 190,000 acre-feet per year divided by 42,000 acres equals 4.5 feet per year.

Estimates of the seasonal variations in the use of irrigation water were developed similarly to the estimation of ditch usage. The resultant estimates are shown in figure 3, graphs A and B.

Graph A, employed for most of the modeled area, was compiled using the ratios of monthly to annual totals of electric-power usage by ditch and well pumps during 1969. Data for the curve were supplied by an electrical-power company serving irrigation installations located primarily in the northern and western parts of the modeled area. The data generally apply to all areas of the basin except the predominantly rill-irrigated orchard areas on the upper parts of the Walla Walla River alluvial fan. Because the source of most orchard irrigation water is the Little Walla Walla River, graph B was compiled from ratios of 1969 monthly flow to the annual total at this river's origin (point of diversion), to estimate the seasonal fluctuation in irrigation water application for the orchard areas.

The two curves are applicable to the same areas as are the curves F and G (fig. 3) and both represent a total annual application of 4.5 feet of irrigation water--only the seasonal distribution of this application differs between curves. The difference is a result, primarily of differences in water source and availability between the two areas--surface water for the alluvial fan versus ground water for the remainder of the modeled area.

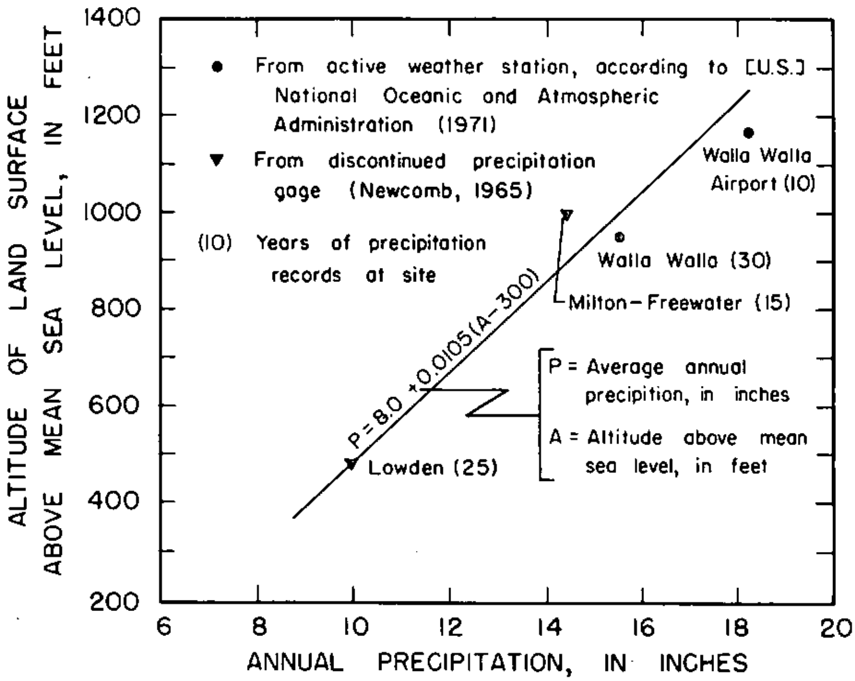


FIGURE 7.--Relationship between altitude of land surface and long-term average precipitation in the Walla Walla basin.

Precipitation

Graph D in figure 3 illustrates the monthly variation in precipitation that was used in the model calibration. The curve is based on the monthly normal precipitation for the period 1931-60 compiled at the weather station at Walla Walla ([U.S.] National Oceanic and Atmospheric Administration, 1971). To account for the orographic effect of basin topography on long-term average precipitation (Mac Nish, Myers, and Barker, 1973, fig. 2), the relationship shown in figure 7 was developed. Using this relationship in conjunction with graph D of figure 3, the spatial and temporal distribution of long-term average precipitation was approximated during calibration runs.

The relationships illustrated in figure 8 were used in the model to obtain computed water-budget values (table 1) and water levels (fig. 17) representative of conditions in 1970. A striking difference between the 1970 precipitation and the long-term average was that over three times the normal January precipitation was received in 1970. There was a 33 percent overall increase in 1970 precipitation compared to the annual average of 15.5 inches.

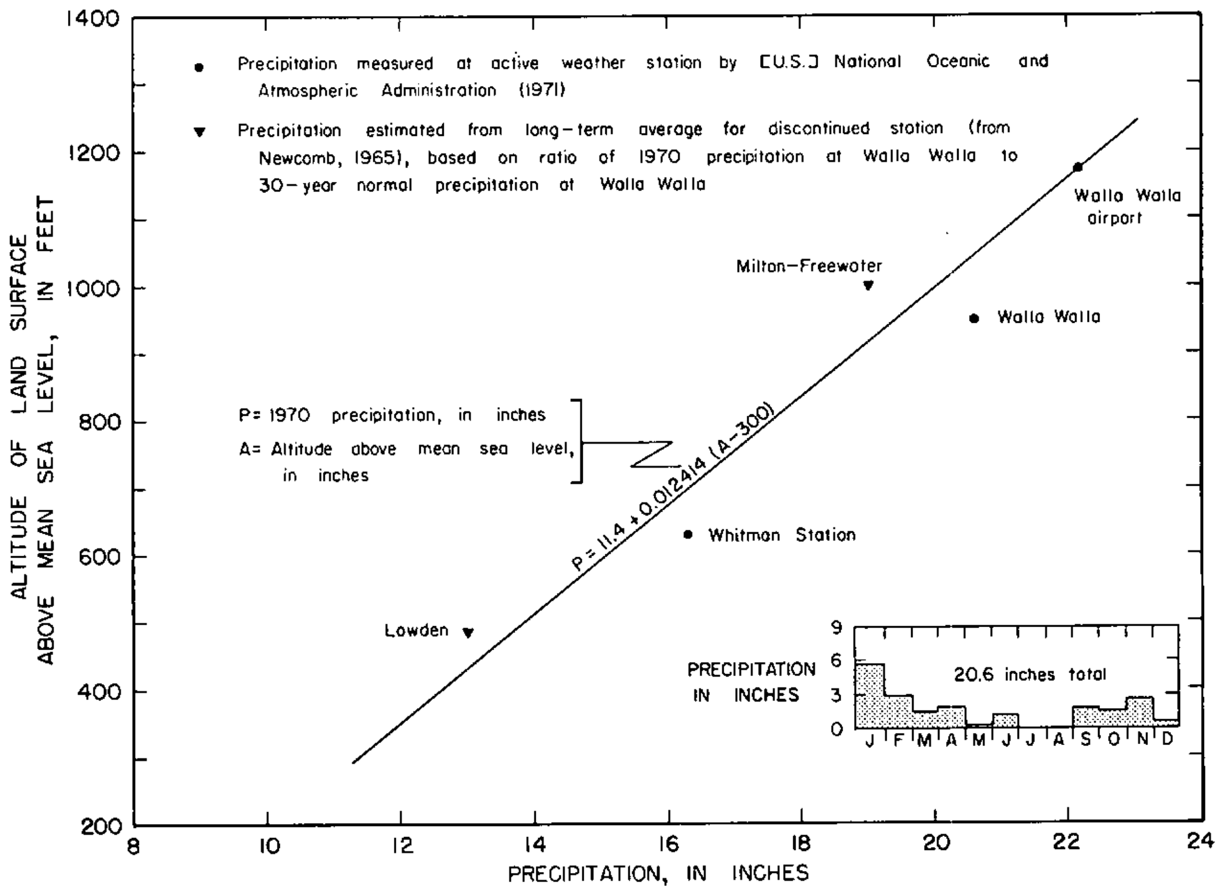


FIGURE 8.--Relationship between land-surface altitude and 1970 precipitation and 1970 monthly distribution of precipitation at Walla Walla.

Infiltration Potential

An important source of recharge to the gravel aquifer is the infiltration of incident water from the land surface. Throughout much of the Walla Walla gravel aquifer the relatively high water levels are sustained during most of the year by recharge from irrigation and precipitation. Newcomb (1965) estimated that, on the average, nearly one-half of all irrigation water diverted from Mill Creek above Walla Walla and from the Walla Walla River at and just below Milton-Freewater percolates to the ground-water body. The potential for infiltration is considerably less, however, in the central and western parts of the modeled area, due to the finer grained soils in areas away from the higher altitudes on the alluvial fans. Thick accumulations of loess probably result in little or no infiltration of incident water in some areas, such as in the low hills between Walla Walla and Touchet just north of State Highway 12.

The actual rate of infiltration occurring in any given area at any given time depends on several physical and climatic factors, including the permeability and moisture content of the soil, the type and density of crop cover, and the rates and type of irrigation application, or the intensity of rainfall. Although the independent effects of each of these factors on infiltration rates cannot be readily simulated, the integrated effects are approximated in the model by use of a single parameter which limits infiltration as a percentage of the incident irrigation and (or) precipitation water. Although the percentages vary with location, variation with time does not occur unless the demands of consumptive use exceed the available precipitatation and applied water. In that case, the percentage used is decreased according to the ratio of available water to demand as explained in detail on page 39.

Originally, percentages ranging from 0 to 50 were assigned in a relative manner that attempted to account for the assumed effects of (1) soil type, (2) type of irrigation, and (3) ground slope. However, in order to provide the best agreement between simulated and observed water levels, some of the percentages were adjusted during the latter stages of model development. In general, however, the "calibrated" percentages, as shown in figure 9, still agree with the concept that infiltration potential decreases as soils become finer.

Steady Leakage to and From the Basalt Aquifer System

Differences in water levels between the gravel aquifer in the Walla Walla River basin and the underlying basalt aquifer system result in an exchange of water between the two systems. The 200-foot thick clay unit (Newcomb, 1965, pl. 3A and 3B) separating the base of the gravel aquifer from the underlying basalt system acts as a confining layer between the two. Although pumping stress applied to the basalt aquifer system--starting in the early 1900's--has caused declines in the original water-level surface in the basalt, the thickness of this confining layer has apparently prevented the declines in the basalt system from significantly affecting the original flow conditions between the confining clay and the overlying gravel aquifer.

The amount and distribution of the steady-state (original) vertical leakage between the gravel and basalt aquifer systems have been simulated by the digital-computer model of the basalt aquifer system (Mac Nish and Barker, 1975). According to this simulation, the gravel aquifer annually receives a net 10,000 acre-feet from the basalt aquifer system. Because the simulation model of the gravel aquifer can provide no additional refinement in the calculation, output from the model of the basalt aquifer system is used as input to the model of the gravel aquifer to account for the exchange of water between the two aquifers.

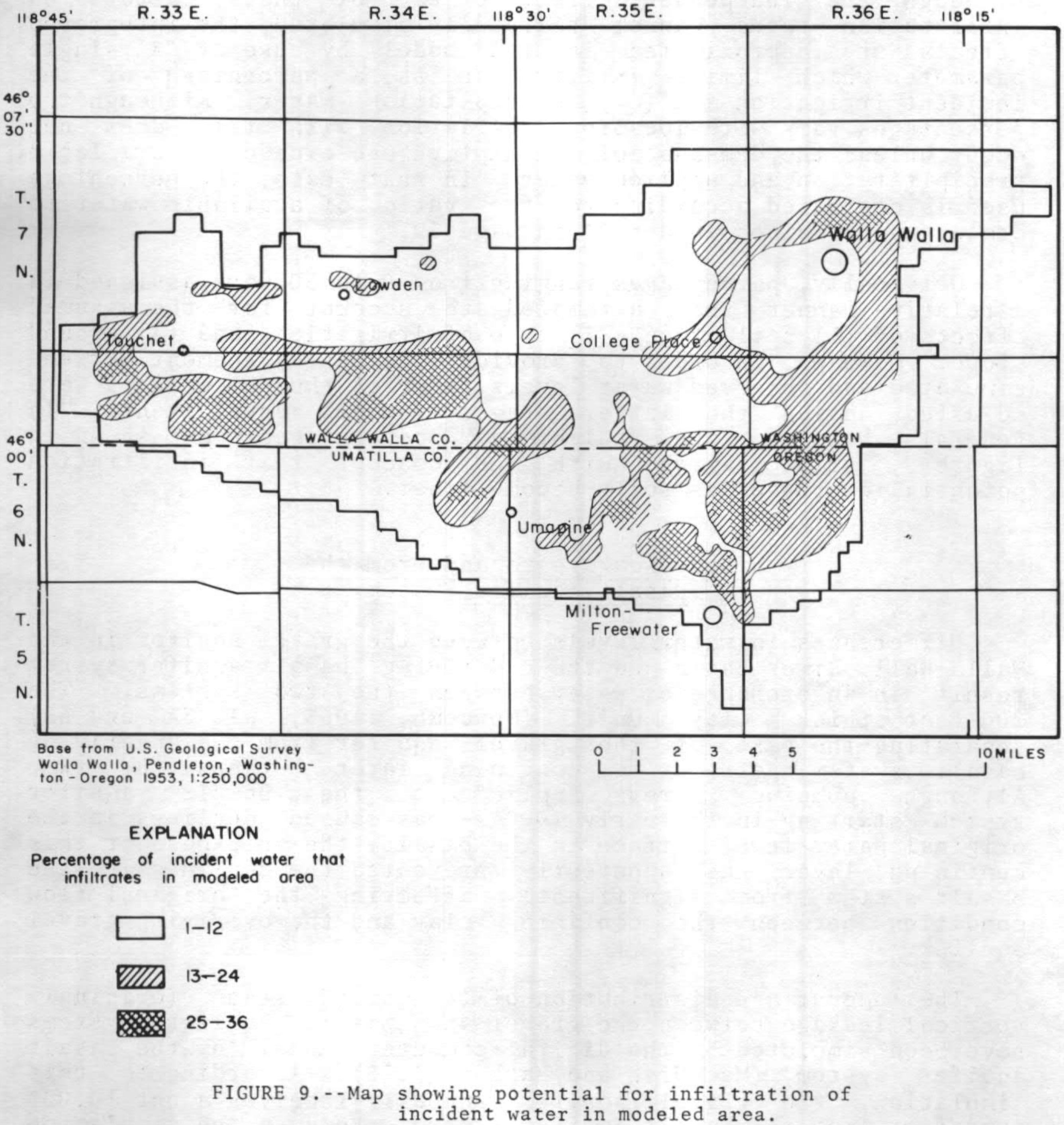


FIGURE 9.--Map showing potential for infiltration of incident water in modeled area.

Water Levels

The configuration of the water table in the gravel aquifer at various times of the year was defined primarily by water-level measurements made during January, April, June, July, August, and October of 1970. Supplemental measurements were made between January 1969 and January 1973. Water-level contour maps were constructed for each of the months above. The water-level contour map shown in figure 10 depicts the average position (as determined by the 1969-73 measurements in January) of the water table in January--the time of the year when the aquifer is least stressed. These January water levels were used in the model as part of the initial conditions under which calibration runs began.

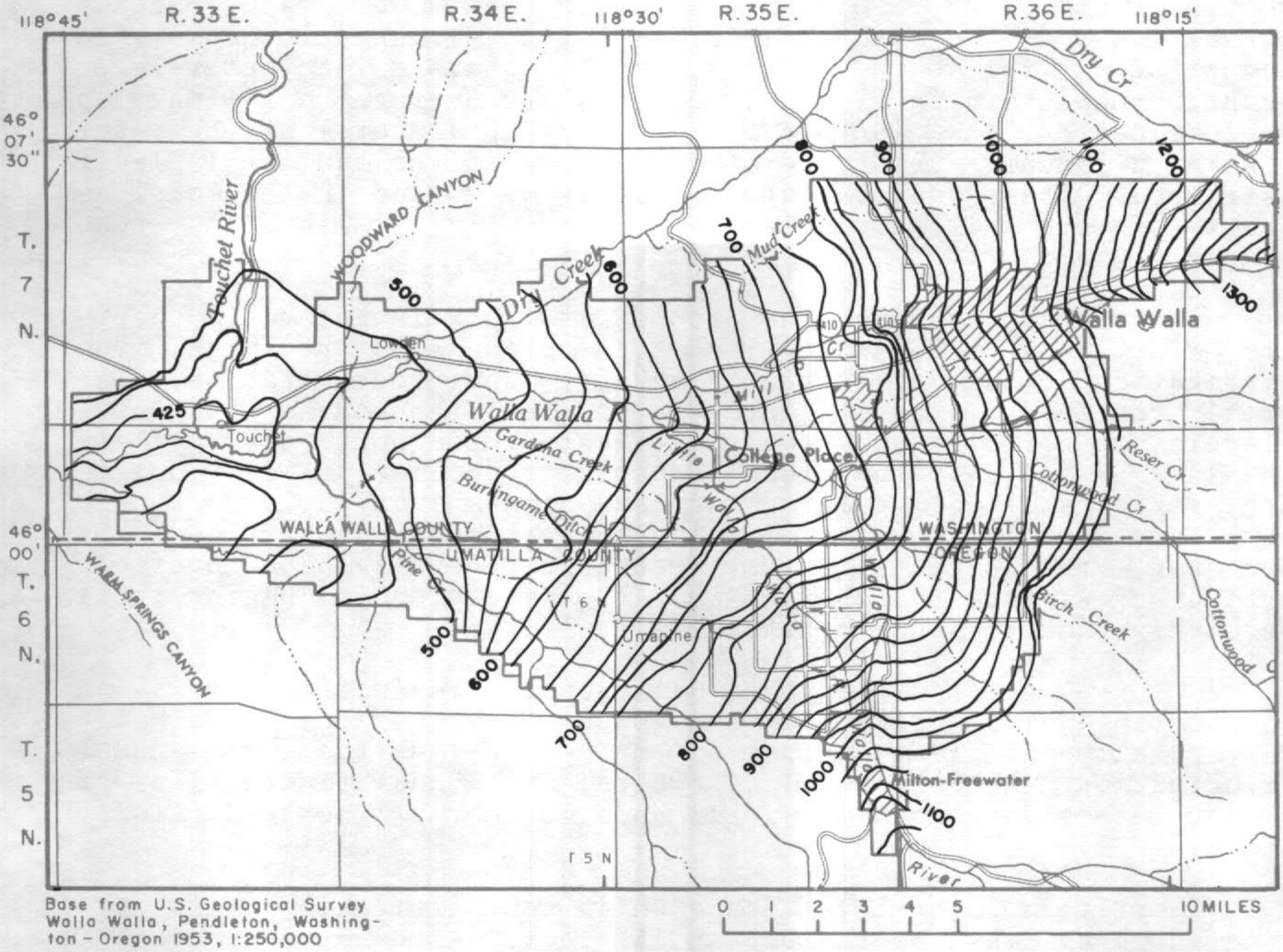
In February or March the ground-water levels generally begin to rise above the January levels in response to recharge from irrigation, canal and stream leakage, and precipitation. The rise continues steadily into May or June, the months when water levels are normally at their highest throughout most of the basin. By July, water levels begin to decline steadily due to the stresses of well pumping and evapotranspiration, and usually by late September water levels reach their annual low. By October, the effects of fall recharge generally have overcome those of summer discharge and the water levels begin their recovery back to January levels (fig. 10).

The greatest seasonal differences in water levels in nonpumping wells occurs near the upper part of the Walla Walla River alluvial fan, where as much as 30 feet of annual fluctuation is observed. Elsewhere, the annual fluctuation of water levels in nonpumping wells does not normally exceed 5 to 10 feet.

Short-term water-level drawdown in some irrigation wells during pumping may be as much as 150 feet. After pumping ceases, however, recovery to prepumping levels is usually reached within 24-36 hours.

Saturated Thickness of the Modeled Aquifer

The location of the bottom of the gravel aquifer was a necessary input to the model. Drillers' logs were used to define the distribution of this surface within the model boundaries. Except for near the edges of the aquifer, where wells are scarce, the log data were generally sufficient. Logs from over 100 deep wells drilled through the sediments into the underlying basalt aquifer system were available to provide most of the information. In addition, some logs available for gravel aquifer wells were helpful because many of these wells penetrate to the thick, distinctive clay formation which is almost everywhere at the base of the gravel aquifer.



EXPLANATION

—300— WATER-TABLE CONTOUR-Shows altitude of water table. Contour interval 25 feet. Datum is mean sea level

FIGURE 10.--Water-table map, typifying average conditions in January.

The map in figure 11 was derived by subtracting the altitude of the gravel aquifer base from the altitude of the water table, shown in figure 10. The map shows the areal distribution of saturated thickness in the aquifer.

Aquifer Hydraulic Conductivity and Storage Coefficient

An important aquifer characteristic required by the simulation model is hydraulic conductivity, a measure of an aquifer's ability to transmit water. A calibrated distribution of hydraulic-conductivity values for the model was obtained using trial-and-error simulation.

Initial hydraulic-conductivity values were estimated using data on specific capacity (the ratio of well yield to water-level drawdown). From a method suggested by Theis, Brown, and Meyer (1963),

$$P \sim 0.003 \frac{Q}{s} \left(\frac{1}{h}\right) ,$$

where

P = hydraulic conductivity of the aquifer, in feet per second;

Q = yield of well, in gallons per minute;

s = water-level drawdown of pumped well, in feet; and

h = saturated thickness of the aquifer, in feet.

Hydraulic conductivities were calculated using this formula with data from drillers' well records and were extended to all areas of the aquifer by use of a moving-average computer program. The resulting hydraulic-conductivity distribution was characterized by a gradation of generally higher values near the upper alluvial-fan altitudes to lesser values where the fans broaden and coalesce near the lower, central area of the basin. This configuration was analogous to the expected grain-size distribution of typical alluvial-fan deposits, and proved accurate enough to be used without modification until the latter stages of model development. The final (calibrated) distribution of model hydraulic conductivity is shown in figure 12.

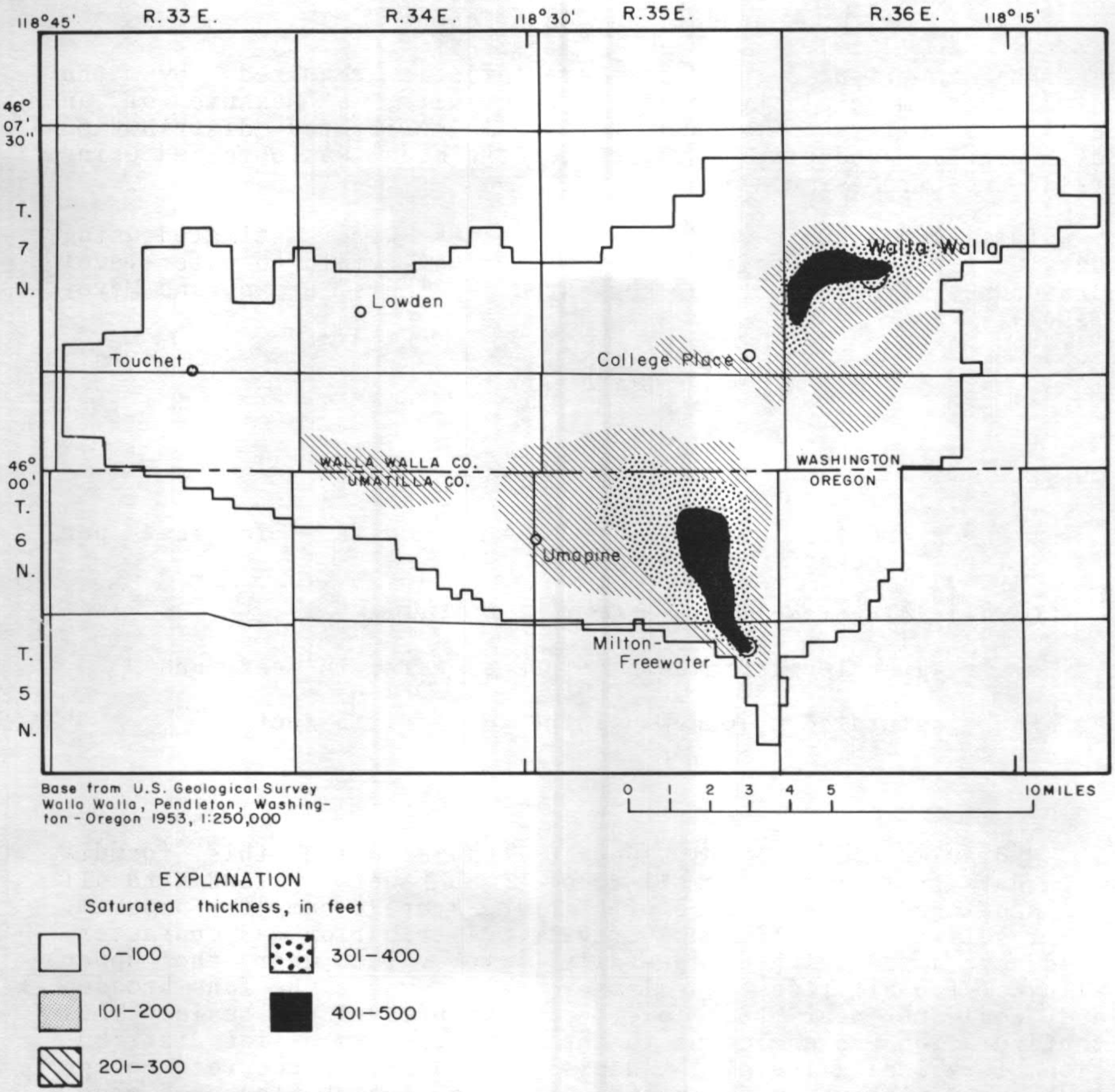


FIGURE 11.--Saturated thickness of gravel aquifer.

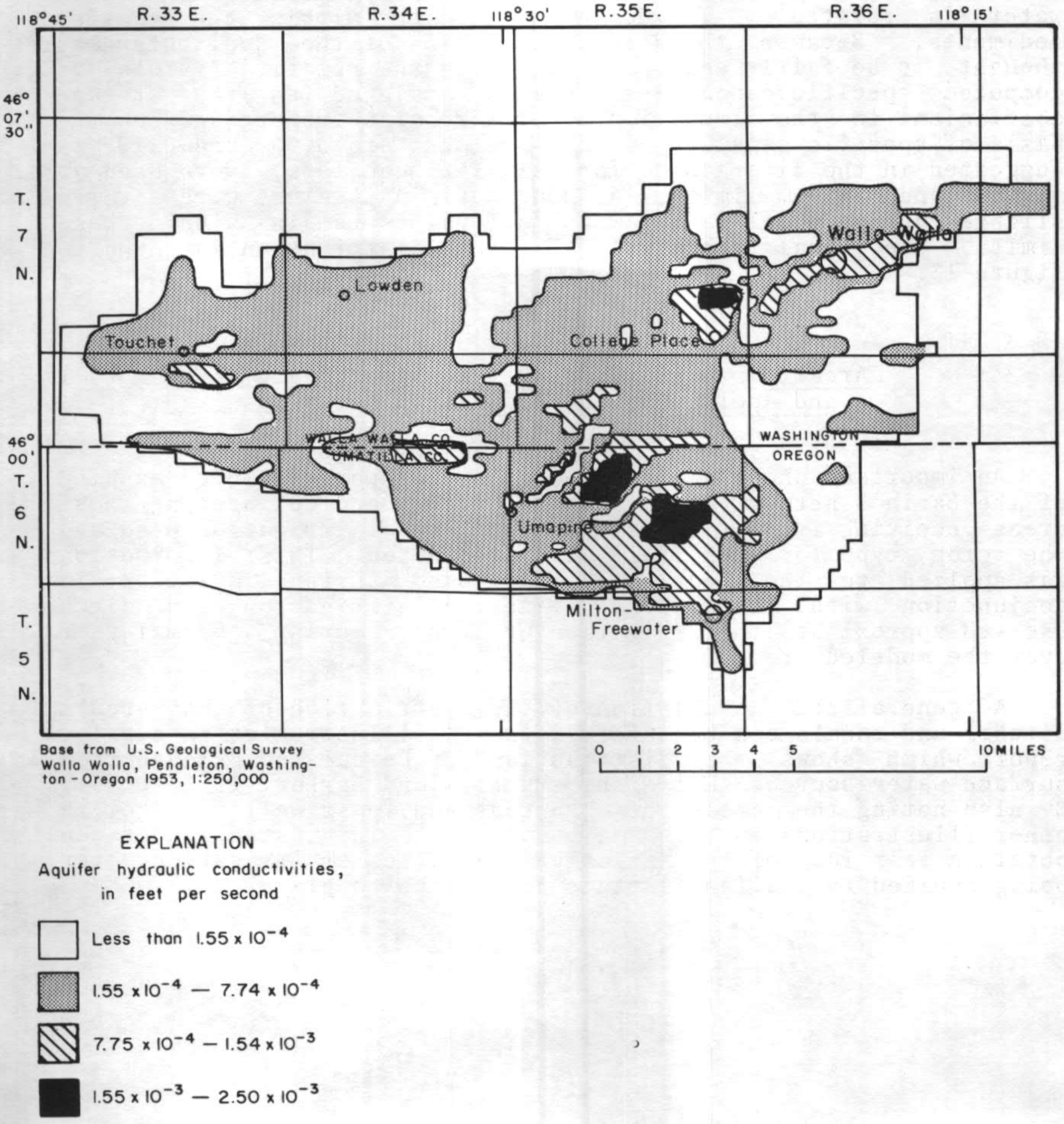


FIGURE 12.--Distribution of calibrated hydraulic conductivities in the gravel-aquifer model.

The magnitude of water-level change that occurs in an aquifer in response to recharge or discharge of ground water depends upon the storage coefficient of the aquifer. The storage coefficient--a measure of an aquifer's ability to store and yield water--is related to the degree of sorting within the aquifer sediments. Because the degree of sorting of the sediments was thought to be fairly well represented by the relative values of computed specific capacities, values assigned as the storage coefficient in the simulation model were also proportioned on the basis of specific-capacity data. Values of 0.25 and 0.10, as suggested in the literature for similar aquifers, were used as maximum and minimum limits. Although original values were altered slightly during model calibration, all values remain within these limits. The final storage-coefficient distribution is shown in figure 13.

Areal Distribution of Ditches and Canals and Application of Irrigation Water

An important phase of the project's fieldwork included mapping of the basin's network of canals and ditches and delineating those areas receiving irrigation water. The kind of irrigation used and the crop type for each field were also noted. This information was applied to the model and was used during simulation--in conjunction with the seasonal rates of irrigation and ditch use--to approximate the irrigation practices during a normal year over the modeled area.

A generalized description of the distribution of the area's ditches and canals can be inferred from an illustration in a prior report which shows the distribution of calculated pumpage from surface-water sources (Mac Nish, Myers, and Barker, 1973, p.15). By also noting the areas of greatest and least well pumpage, in other illustrations in the same report, the interested reader can obtain a fair idea of the relative quantities of irrigation water being applied to the land surface from place to place.

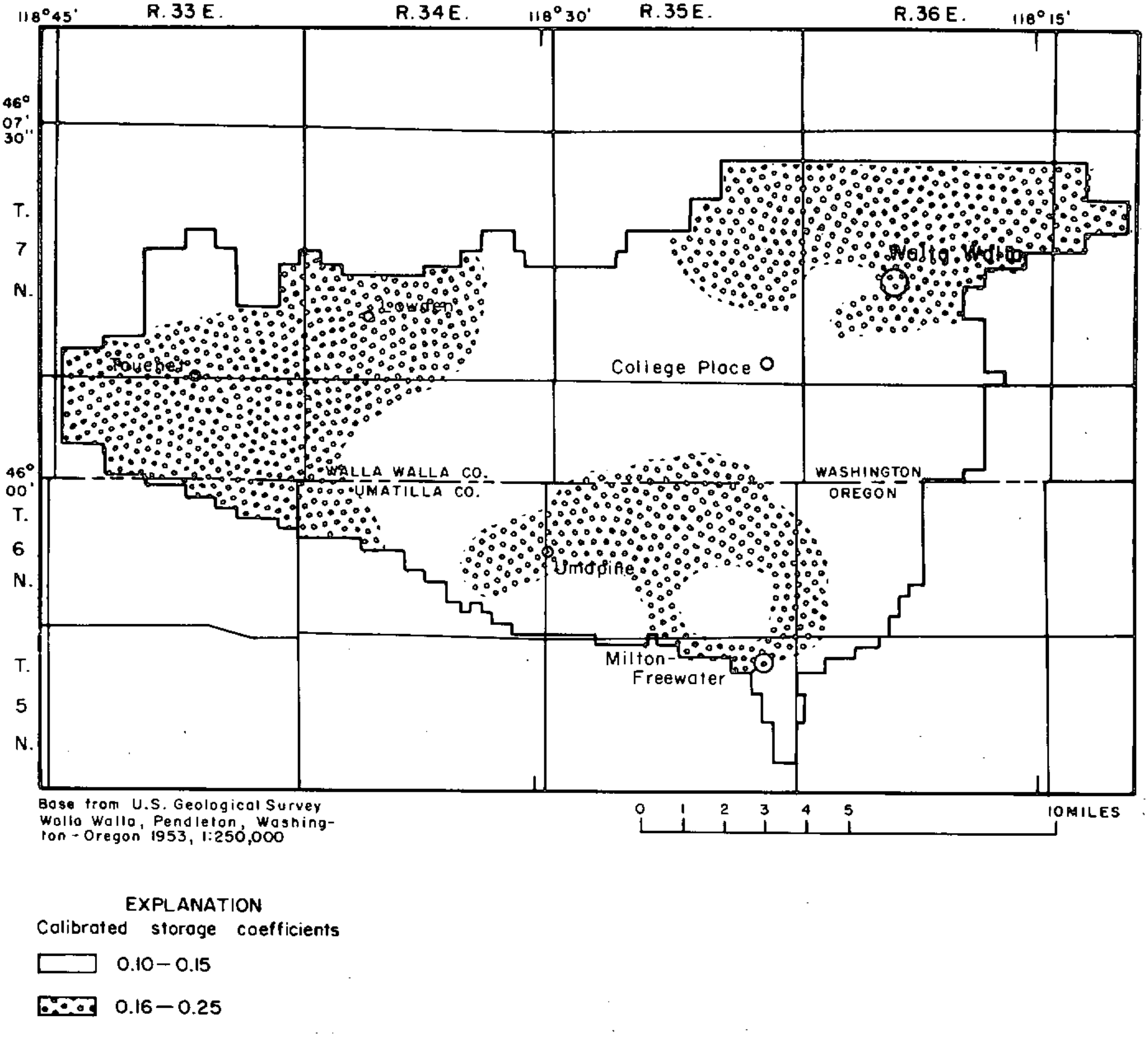


FIGURE 13.--Distribution of calibrated storage coefficients in gravel-aquifer model.

DIGITAL-MODEL SIMULATION

Computer Program

A computer program originally written by Pinder (1971) was used, with minor modifications, for the Walla Walla gravel aquifer model. The program uses an alternating-direction-implicit procedure to solve the finite-difference approximations of nonlinear, partial differential equations describing transient two-dimensional flow in a saturated, porous medium. The mechanics of the basic program were described previously by Pinder (1971) and in a concurrent study by Mac Nish and Barker (1975), thus, only those parts of the model unique to the Walla Walla gravel aquifer are described in this report.

Grid and Time-Step Dimensions

Use of the finite-difference approximations for a numerical solution of the flow equations requires subdividing the modeled area into a grid of intersecting horizontal rows and vertical columns (fig. 14). Areas within each intersection are called cells. Model cells are addressed individually with the row number listed first, followed by the column. For example, as shown in figure 14, the town of Umapine, Oreg., is within cell (15,46).

To minimize the cost of computer storage and execution time, a grid having variable cell dimensions was selected for the model. Near the center of the modeled area, where significant hydrologic stress (well pumpage, spring discharge, and stream-aquifer leakage) occur, square cells having one-quarter mile dimensions were used to provide a finer definition of this area's relatively rapid- changing flux rates and hydraulic gradients. Toward the periphery of the modeled area, grid spacing becomes progressively coarser, where cell dimensions are as much as a mile square.

In the model, water-level changes in the gravel aquifer are simulated through a series of discrete time increments, or time steps. The rate at which water enters and leaves the aquifer vertically (rate of vertical flux) is simulated using water levels computed at the previous time step. Thus, changes in water levels between two time steps affect the rate of vertical flux. If the change in water levels between two successive time steps is too great, errors are introduced in the computed rates of vertical flux. In order to minimize these errors, 2-day time steps were used for the period May-September when aquifer stresses are the greatest and water levels are therefore changing most rapidly. Maximum time increments of 5 days were used during the fall and winter months.

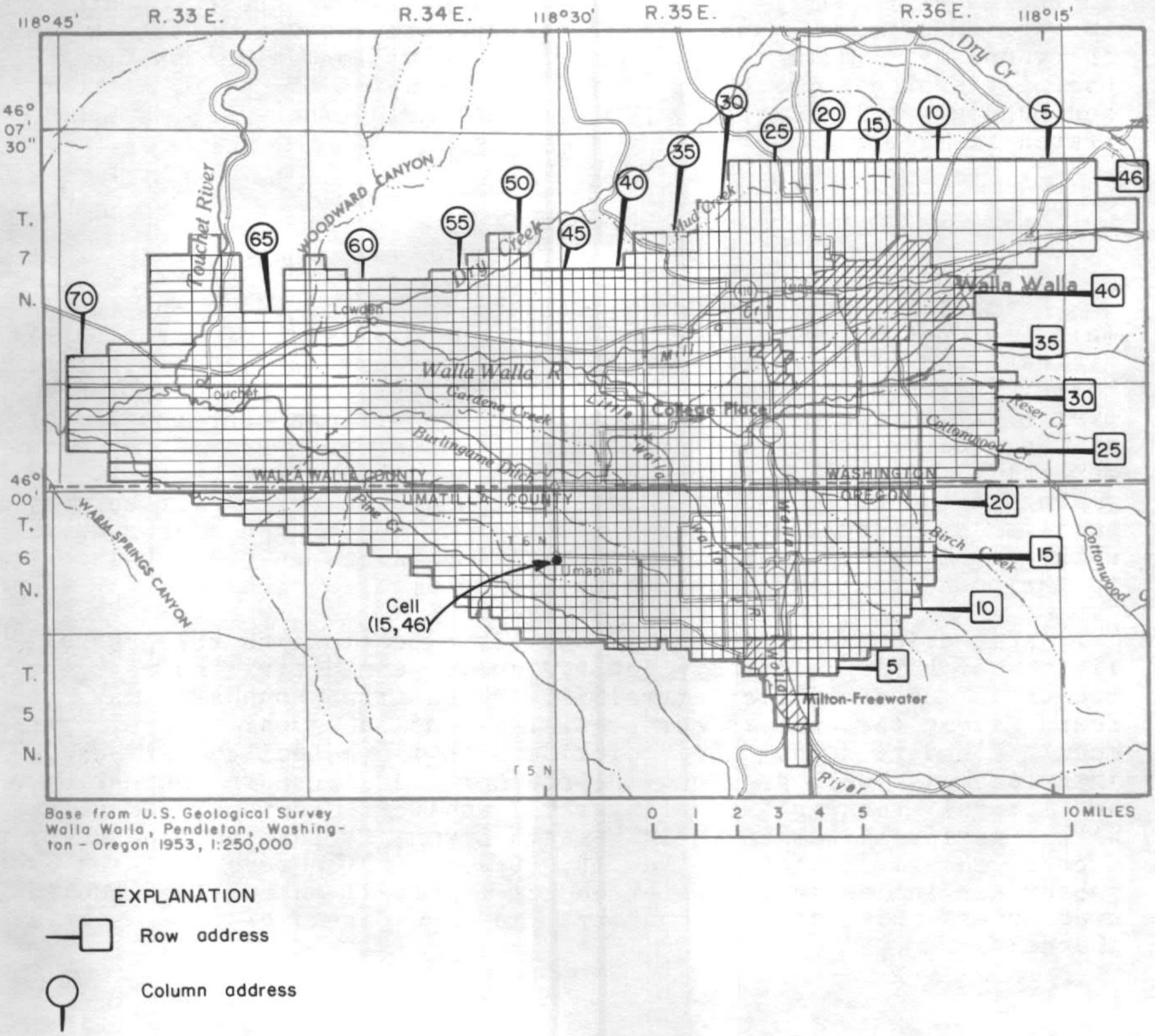


FIGURE 14.--Variable-grid subdivision of modeled area.

Hydrologic Subareas

Groups of cells in the model were categorized into "hydrologic subareas" within each of which the prevalent hydrologic processes are similar. This subdivision facilitates addressing those cells in the model requiring unique treatment (such as those containing springs or streams), and is used to expedite water budgeting within groups of similar cells. Such a subdivision also provides a useful visual display of the areal distribution of spring, stream, and boundary cells relative to the entire modeled area, as illustrated in figure 15.

Boundary Conditions

A constant-head boundary convention is used in the model. This is not a completely realistic approximation of actual conditions and it is recognized that the boundary condition might be better represented by a no-flow or constant-flux boundary. However, little information on hydrologic conditions near the limits of the aquifer system is available. Because the gravel deposits generally thin to a "feather edge" against the basalt bedrock, the amounts of water transmitted laterally near the edges must be very small. As a result, the assumptions of a constant-head boundary, with extremely low hydraulic-conductivity values in cells adjacent to the boundaries, does not seriously depart from reality.

As is evident in figures 10 and 12, exceptions to the generalization of having extremely low hydraulic conductivities near the boundaries and little lateral flow across the boundary may be found along the eastern border of the modeled area. Here, the model boundaries do not coincide with the actual gravel-basalt interface as well as along the southern and northern boundaries, and lateral recharge to the gravel aquifers occurs as underflow within buried stream channels beneath Birch, Cottonwood, and Reser Creeks. Nearly half of the 15,000 acre-feet per year listed as subsurface inflow in the water budget (table 1) enters the modeled area across this eastern boundary, in the areas of these stream channels.

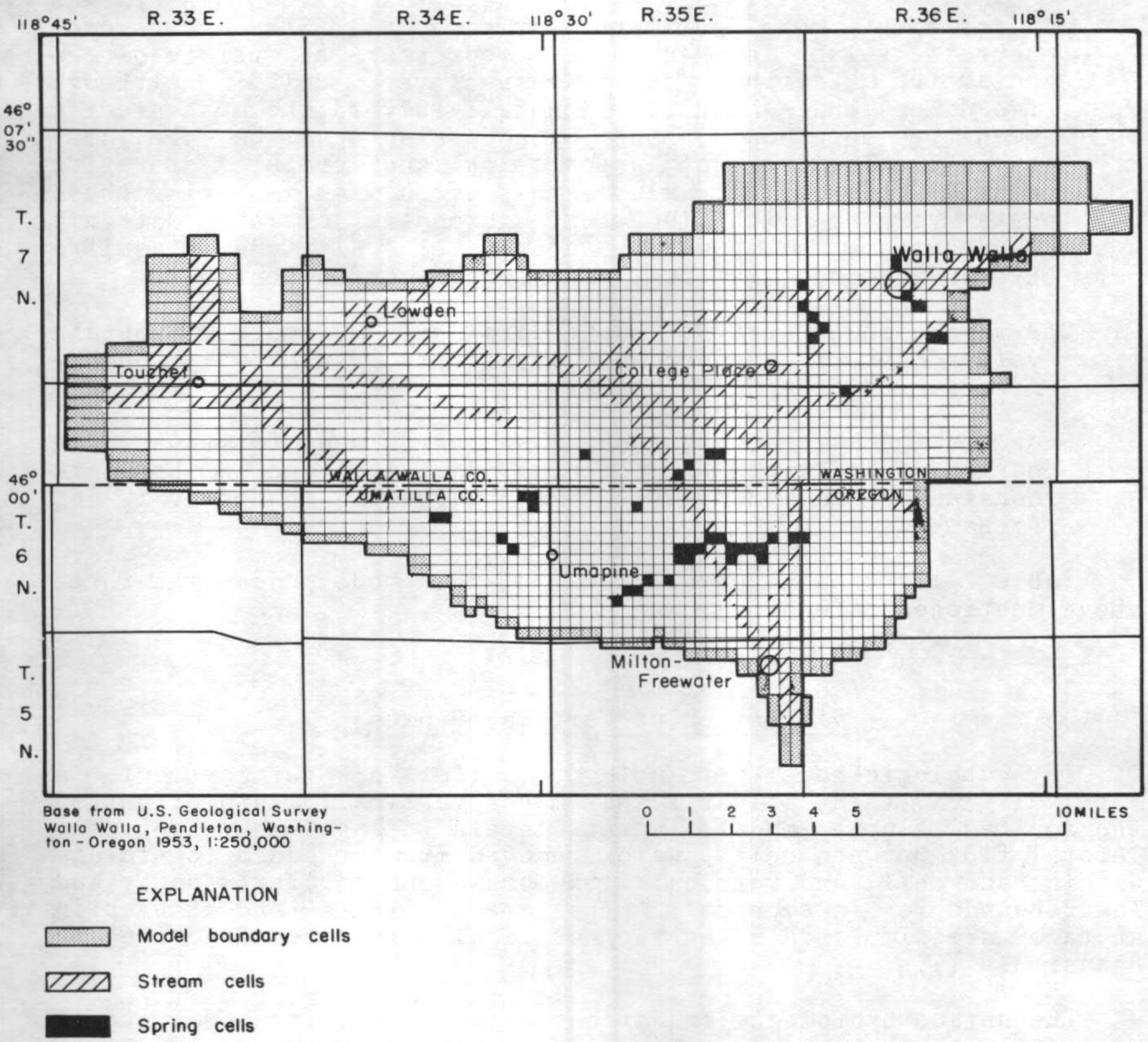


FIGURE 15.--Hydrologic subareas of the modeled area.

Data Entry

The three data formats used in the model were:

1. Two-dimensional matrices; such data sets contain values describing a model parameter for each cell. The assigned or computed value for any cell represents an average of the parameter within the respective cell. Although two-dimensional matrices generally afford the most precise means to enter data, the method also can be the most expensive in terms of preparation and computer-operation costs. This format was used most often for entering those data varying with location. Examples of such data are land-surface altitudes, water-level altitudes, aquifer hydraulic conductivities, and storage coefficients.

2. One-dimensional arrays; such data sets primarily contain values for time-dependent parameters, such as monthly percentages of annual totals.

3. Single-value parameters; such an entry was used for those data having no spatial or temporal variation and is therefore constant. An example is the hydraulic conductivity of streambeds.

Table 2 lists all data used in the model under the three above-mentioned categories.

Simulation of Vertical Fluxes

In hydrologic-model terminology, a flux is water movement. A vertical flux, then, is water that moves vertically into or out of the aquifer. In the model, water levels change in response to lateral flux between cells, water removed from or added to storage within each cell, and vertical flux across the aquifer's upper and lower boundaries in each cell. The lateral fluxes and changes in storage are simulated using the numerical procedures described by Pinder (1971).

The unique hydrologic conditions associated with the gravel aquifer in the Walla Walla River basin required some modification of the basic Pinder method of simulating vertical flux. Figure 16 provides a flow chart showing the sequence of vertical-flux computations used in the gravel aquifer model.

TABLE 2.--Classification of data in the gravel-aquifer model

Two-dimensional matrices	One-dimensional arrays
Altitudes of aquifer bottom	Cell dimensions
Altitudes of land surface	Time-step lengths
Altitudes of streambeds and springs	Time distribution of:
Hydraulic conductivities of aquifer	Canal and ditch usage
Coefficients of storage	Irrigation application
Steady leakage to/from bedrock system	Consumptive use
Water levels	Precipitation
Annual well pumpage totals	Well pumpage
Infiltration potential	
Irrigated areas/ditch locations	
Hydrologic subareas	

Single-value parameters
Conductivities of:
Streambed
Canal and ditch bottoms
Spring areas
Thickness of streambeds

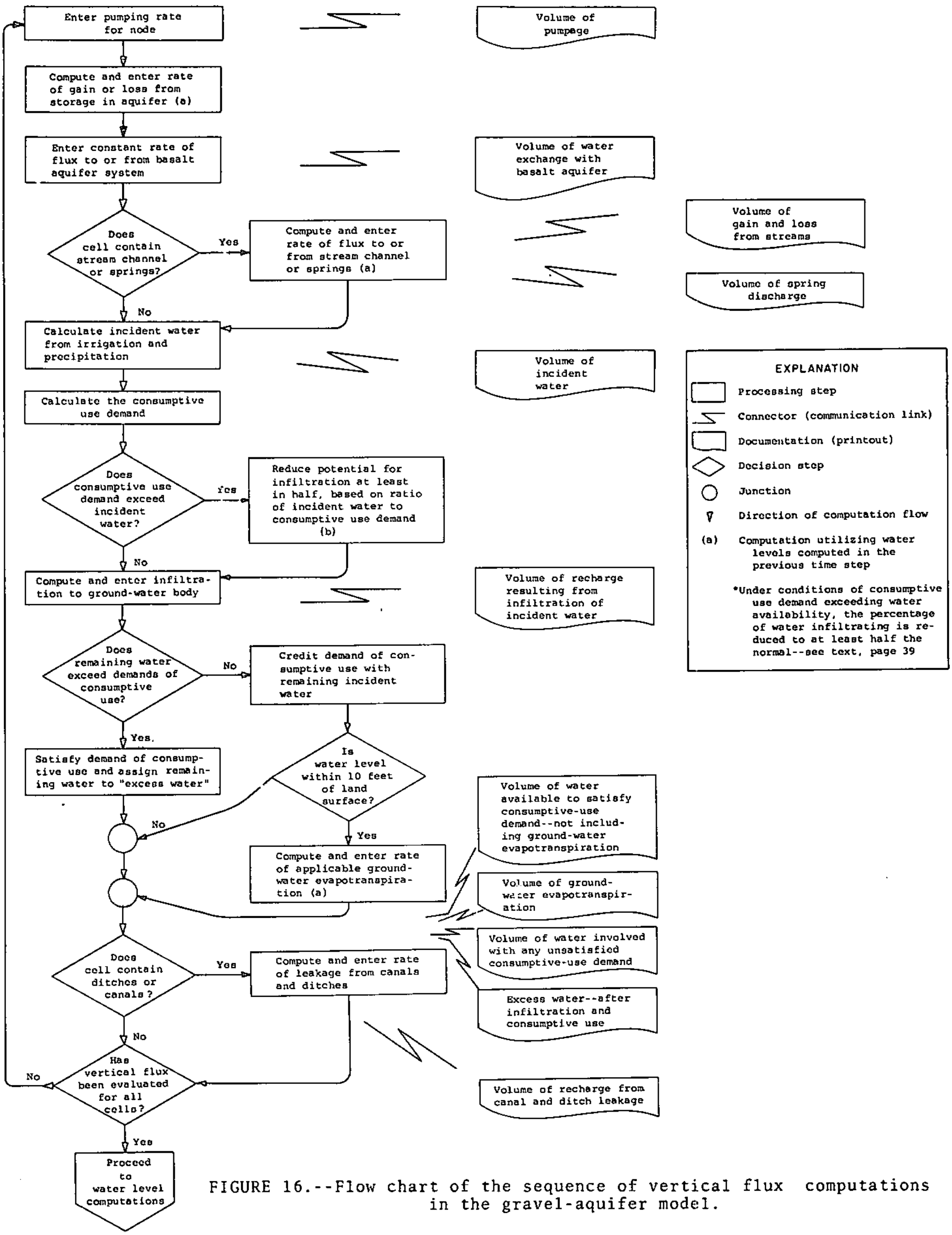


FIGURE 16.--Flow chart of the sequence of vertical flux computations in the gravel-aquifer model.

Assumptions inherent in the diagrammed procedure are:

1. A certain percentage of precipitation and applied irrigation water (collectively called incident water) always reaches the water table and that percentage (called infiltration potential) does not change as long as the demands of consumptive use are equaled or exceeded by the incident water. If the demands are not met, the percentage is reduced by the ratio of incident water to consumptive use, or 0.5, whichever is smaller. For example, if the percentage of expected infiltration were 30 percent of the incident water, and the ratio of incident water to consumptive-use demand was 2 to 3, the infiltration potential would be reduced to 15 percent, or half its original values. If the ratio of incident water to consumptive-use demand was 1 to 3, the infiltration potential would be reduced to 10 percent, or one-third its original value. This empirically derived reduction formula helped produce the best match between observed and simulated water levels.

2. The infiltration of incident water occurs immediately upon application, with no time lag allowed for seepage through unsaturated parts of the aquifer. This assumption causes some difficulty--when attempting to match well hydrographs--where the water table is far below land surface and is unrealistic for conditions of high soil-moisture deficiency. However, irrigation practices in the basin normally do not permit excessive soil-moisture shortages to occur.

3. No evapotranspiration occurs directly from the ground-water reservoir unless consumptive-use demands are insufficiently met by available incident water and the ground-water level is less than 10 feet below land surface.

4. In reality, incident water still remaining after the requirements of infiltration and evapotranspiration have been met could either: (1) run off, (2) evaporate, or (3) go into storage in the soil zone. Because the model has no capability to simulate any of these possibilities, the excess is totaled as "runoff."

CONCLUSIONS

Real Versus Modeled System

Before the model could be considered suitable for evaluating aquifer response to future stresses, it was necessary that it demonstrate a reasonable ability to simulate historical response to associated historical stresses. During calibration a continuing evaluation of the model's validity was maintained by comparing simulated water levels and water-budget items to those supported by field measurement.

The model was developed under the assumption that seasonal hydrologic variations are duplicated from one year to the next. This assumption required close agreement between January water levels used as initial conditions for simulation (fig. 10) and those computed for the succeeding January--in order for the model to be considered "calibrated."

After calibration efforts were completed, January levels could be computed to differ from those contoured in figure 10 by less than 10 feet over about 95 percent of the modeled area and to be within 5 feet over about one-half the area. For model cells where measured water levels were available for comparison with computed levels, the match was generally within 3 feet, and in only a few cases were the differences more than 5 feet. The greatest deviations between computed and contoured January water levels (14 to 20 ft) occurred in an area between the northern city limits of Walla Walla and the northern boundary of the modeled area (fig.2). When simulation was continued for another year (without resetting initial January water levels) the deviations remained virtually unchanged except in the area north of State Highway 12 between Lowden and Walla Walla (fig.2). There, the computed levels rose higher than the originally contoured levels--but at a much smaller rate than during the first year of simulation, suggesting an approaching condition of equilibrium.

It is believed that the discrepancies between computed and contoured water levels for areas north of State Highway 12 should not warrant major concern at this time because (1) the computed water levels may be more accurate than the contoured levels, which were mostly estimated due to the meager amount of available hydrologic data available for the area (pl. 1); and (2) amounts of water involved are relatively small.

To insure the most reliable projected results, the computed, or "calibrated," January water levels need to be used as initial conditions for future management runs. These computed levels provide more consistent results from one year to the next in those areas where the match between contoured and computed water levels was most difficult to obtain. Because the differences between contoured and computed water levels were almost everywhere less than 5 feet for those areas having adequate water-level control for the contours, the substitution is felt to be justified. At best, the contoured water levels could be considered accurate only to within 10 feet, because this was the contour interval of the base maps used to define land-surface altitudes in the project area.

A model run was made to simulate hydrologic conditions during 1970. This was accomplished by (1) beginning the simulation with the "calibrated" January water levels and (2) substituting 1970 precipitation data (fig.8) for the long-term precipitation (figs.3d and 7) originally programmed into the model to represent climatological conditions during a typical year. No other changes in the data input were necessary; there were no data available to indicate any significant difference between other 1970 fluxes and stresses and those already incorporated into the model. How well the computed results of the 1970 simulation compared to or meshed with measured water levels and water-budget items for the same period of time can be seen in figure 17 and table 1.

A comparison of hydrographs that typify the match between observed and computed seasonal water-level fluctuations in different parts of the gravel aquifer is given in figure 17. The locations of wells providing the observed water levels used in the comparison are shown in figure 18. To provide an equal basis for comparison, the observed water levels are plotted as though they were measured from land-surface altitudes at the center of cells enclosing the wells to which the computed levels relate.

Computed water levels deviate from observed water levels most significantly during the summer months. However, much of the apparent disparity was caused by the effects of frequent, but sporadic pumping in the same wells that were used to observe the water levels. Water-level drawdown due to pumping most wells in the aquifer is typically confined within a radius of about 100 feet around the pumped wells, whereas the simulated water levels reflect the net effect of all hydrologic activity programmed (as average monthly fluxes) over the area of an entire cell. Because the minimum cell size in the modeled area is 1,320 by 1,320 feet, the computed hydrographs cannot possibly show the full effects of well pumping, which is generally confined to relatively small areas around the well bores. As long as the observation wells (or nearby wells) were not pumped shortly before or while the measurements were obtained, the observation wells provided a good means of monitoring water-level changes over a large area of the aquifer. In such cases computed water levels generally compare favorably with measured water levels through most of the year (fig.17, well 4).

The model's validity might be assessed further by comparing simulated water-budget items with those measured or estimated before development of the model. A comprehensive water budget involving surface- and ground-water interactions during 1970 is presented in table 1. Included are the simulated items such as stream gains and losses, subsurface recharge and discharge, spring discharge, ground-water evapotranspiration, infiltration of incident water, and canal leakage. The reasonably good meshing of

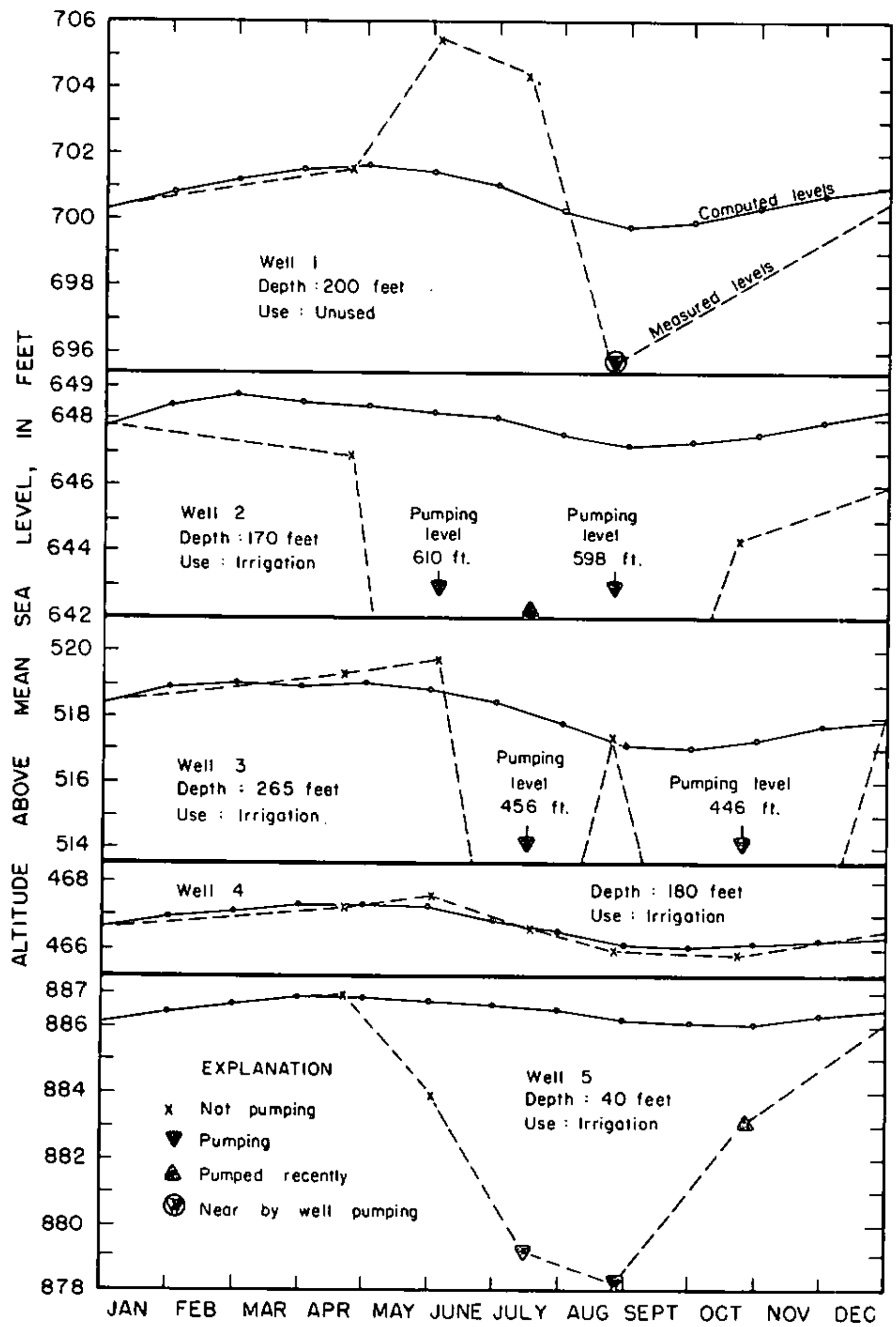


FIGURE 17.--Hydrographs of measured and computed water levels for five areas of the gravel-aquifer model.

simulated values with estimated and measured values is a positive indication that the model could satisfactorily predict the response of the aquifer system to similar manmade and natural stresses in future years.

Precipitation in the modeled area during 1970 exceeded the long-term average annual precipitation by approximately 30 percent. This produced about 33,000 acre-feet more incident water during the 1970 simulation than was made available during runs with the calibrated model using "typical" precipitation. Because the greatest percentage of the increase in incident water came in January and February--when consumptive-use demand was essentially nonexistent--most of the 33,000 acre-feet was treated as excess water (runoff) in the model. Compared to a simulation run with the normal quantity and distribution of precipitation (figs. 3d and 7), the 1970 run resulted in about 28,000 acre-feet more runoff, about 1,000 acre-feet more ground-water evapotranspiration and about 4,000 acre-feet more water being infiltrated to the water table.

Due mostly to the increased infiltration of precipitation in 1970, approximately 5,000 acre-feet of additional water was being stored in the aquifer by the end of the year. In other words, water levels computed for January 1971 were higher in some areas than those used as initial conditions to represent January 1970. Generally these water-level differences were less than 1 foot and the greatest differences (as much as 5 ft) occurred around the edges of the aquifer near the eastern and northern borders of the modeled area--areas for which no water-level data exists in either January of 1970 or 1971. In general, however, for areas where water-level data do exist, the computed differences are less than 1 foot and are in reasonable agreement with measured differences.

The water budget in table 1 includes various gaged and ungaged surface-water quantities. The quantity of 15,000 acre-feet is added to the gaged inflow to the area as a correction to the gaged part of the Touchet River inflow. This correction accounts for a historic relationship between the surface-water gage on the Touchet River at Bolles (fig. 1) and a discontinued (1955) gage near the town of Touchet (just above the Touchet River's confluence with the Walla Walla River). Published discharges (U.S. Geological Survey, 1963) for both gages indicate that there is an average annual gain in flow of about 15,000 acre-feet between the gage at Bolles and the discontinued gage near Touchet. As shown in figure 1, Bolles is at least 30 miles upstream from Touchet; Touchet is less than 3 miles above the lower gage on the Walla Walla River, which records the basin's outflow.

A 5,000-acre-foot disparity exists between the actual surface-water outflow during 1970 (521,000 acre-ft) and the computed quantity of 526,000 acre-ft). Because the 5,000 acre-feet is only about 5 percent of the estimated inflow, it was not considered feasible to further calibrate the model in an attempt to lessen this disparity.

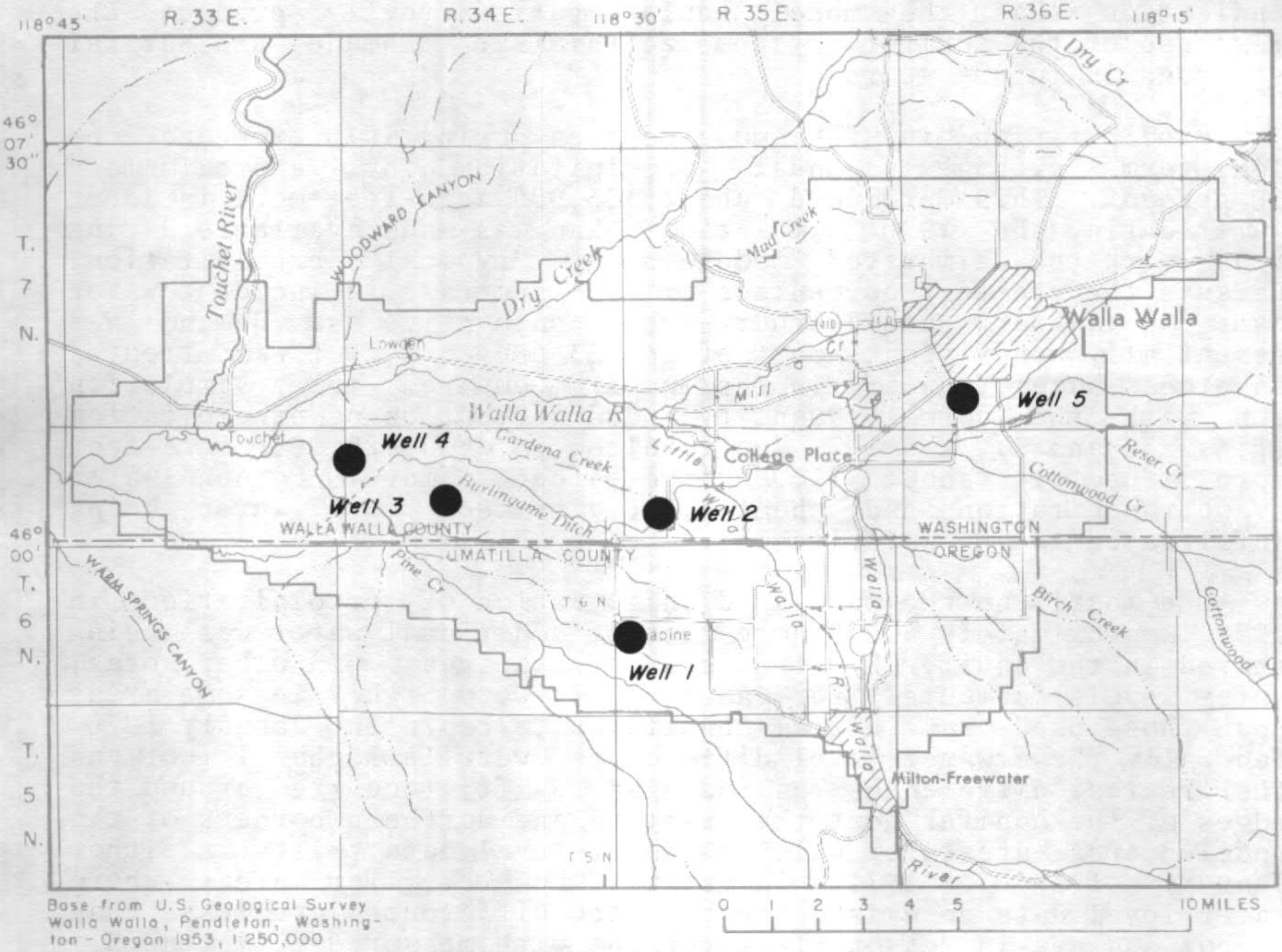


FIGURE 18.--Locations of wells that provided water-level data for hydrographs in figure 17.

Management Testing

To simulate the response of the gravel aquifer to hypothetical stresses, some change is imposed upon the model's "calibrated" data input (table 2). The simulated response to the change can be monitored using various computer outputs: maps, hydrographs, or budgetary tabulations. The simulated response is presumably indicative of the real response to a real change in the real system, and could aid management officials in decisions concerning further development of the water resources of the area.

The model could test alternative management proposals affecting the aquifer's vertical fluxes in time and space. For example, the model could test plans to irrigate areas that are currently nonirrigated and could simulate the effects of decreasing or increasing present rates of irrigation applications. By relocating stream reaches in the present pattern of hydrologic subareas (fig. 15), the effects of rechanneling streams (into abandoned stream depressions on the alluvial fans, for example) might be assessed. The general effects of discontinuing existing or forming new canal distribution systems might also be examined. An additional use could be to vary the existing time and space distribution of well pumping stresses and evaluate the responses with the resulting computed water levels and spring-flow rates.

The adequacy of the model to simulate the real system and to predict responses to changes within the system cannot be fully realized or evaluated until results of projections into the future can be tested against future observations. Although the model, in its present state of development, provides a useful aid for management planning and decisions, the model's capabilities could be expanded as the need arises. Some potential modifications for future improvement follow.

Future Modifications of Model

Any future modification of the present digital model could include some of the following:

1. Stream-aquifer leakage, spring discharge, and ground-water evapotranspiration are all approximated explicitly in the model. The explicit technique uses water levels computed in the previous time step to approximate the flux rates--in contrast to an implicit method which uses water levels computed within the same time step. The explicit procedure requires short time steps when the water levels are changing rapidly; as a consequence the method is somewhat inefficient and may introduce errors. The accuracy and efficiency of the model could be improved if the fluxes were simulated implicitly.

2. Rates of canal and ditch leakage do not vary with time in the model. However, in reality, canal and ditch bottoms leak significant volumes of water during the first few weeks of use and the leakage rates then drop to values near those used in the present model. If an approximation of this sharp variation in leakage rates were utilized in the model, it could improve the model's ability to simulate the rapid rise in water levels that occurs in the spring areas on the Walla Walla River alluvial fan.

3. Leakage to and from the underlying basalt aquifer system is approximated as a steady-state phenomena. The flux could be computed more accurately if it were treated as a transient variable--that is, as a function of changing water levels on either side of the confining bed. Such a treatment becomes more important as larger declines (or rises) in water levels in either aquifer are projected while simulating the effects of water-management proposals.

4. The time variation in streamflow and canal-flow rates are not presently incorporated in the model. The present model approximates fluxes to and from streams by assuming continuous channel flow for the "perennial" reaches of streams. Rates of surface-water flow could be incorporated in the model, so that management schemes involving joint use of ground and surface water might be analyzed more effectively.

5. The timing and spatial distribution of well pumpage is highly generalized in the model at present. Available data simply do not permit a precise simulation of all the aspects of pumping stress. The generalization of this stress dampens the amplitude of the simulated hydrographs as compared to hydrographs of actual water-level measurements.

6. The model has been calibrated with the assumption that some infiltration of incident water always occurs, whether or not the demands of consumptive use have been totally satisfied (p.39). Because present irrigation practices do not generally allow soil-moisture deficiencies to occur, results acquired with the incorporation of this assumption in the vertical flux computation (fig.16) appear to be reasonable and compatible with observations of the real system, as it presently exists. A more rigorous treatment in the model of the processes of infiltration, evapotranspiration, and runoff, based on more detailed, quantitative observations concerning the effects of soil moisture, would certainly provide a more accurate simulation of not only the present-day conditions but also the conditions which could exist in the future.

Of the six considerations discussed above, probably only the last three would require extensive data collection and substantial modification of the simulation procedures. Additional possibilities for future modification of the model include the incorporation of means to evaluate the effects of artificial recharge and the inclusion of economic variables related to crop type and water distribution. Finally, an important consideration with regard to the maintenance of the model is that it has been calibrated for a particular distribution of specific water-use practices and hydrologic conditions prevalent at this time (1974). As these phenomena change in the future, recalibration of the model with new data will be required.

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