UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# NUMERICAL SIMULATION OF GROUND-WATER FLOW IN LOWER SATUS CREEK BASIN, YAKIMA INDIAN RESERVATION, WASHINGTON

By Edmund A. Prych

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(Plate in pocket)

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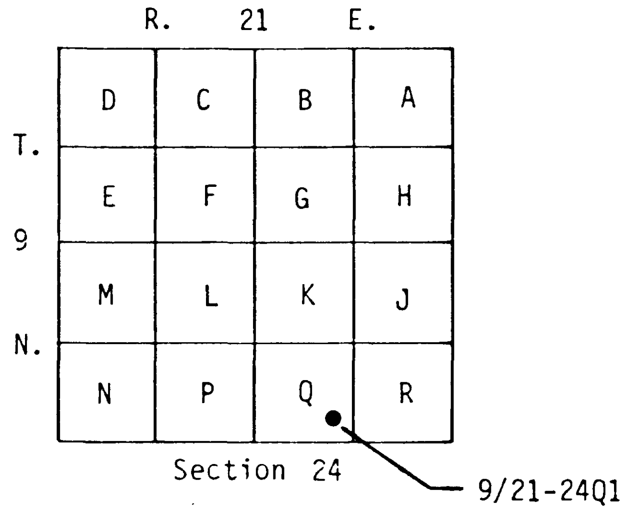
## DEFINITION OF SYMBOLS

| Symbol | Definition | Units |
|---|---|---|
| A | Area | $L^2$ |
| K | Vertical leakage coefficient | $t^{-1}$ |
| L | Unit of length | L |
| $Q_x$, $Q_z$ | Water discharge in horizontal and vertical directions, respectively | $L^3/t$ |
| S | Storage coefficient of group of geologic units of | 1 |
| T | Transmissivity of group geologic of units | $L^2/t$ |
| W | Source and sink function | L/t |
| $\bar{W}_s$ | Time-averaged source and sink function corrected for change in storage | L/t |
| b | Thickness of geologic unit | L |
| h | Altitude of ground-water head | L |
| $\bar{h}$ | Time-averaged altitude of ground-water head | L |
| $k_x$,$k_z$ | Hydraulic conductivity in horizontal and vertical directions, respectively | L/t |
| m | Saturated thickness of geologic unit | L |
| s | Model-computed drawdown of water table corrected for change in saturated thickness | L |
| s' | Model-computed drawdown of water table | L |
| t | Time | t |
| w | Width | L |
| x,y | Horizontal cartesian coordinates | L |
| z | Vertical cartesian coordinate | L |
| $\Delta_x$, $\Delta_y$, $\Delta_z$, $\Delta_t$ | Denote changes over finite distances $\Delta x$, $\Delta y$ and $\Delta z$, or finite time $\Delta t$ | |
| $(\ )_d$,$(\ )_u$ | Denote differences relative to layer below and above, respectively | |

## WELL- AND LOCATION-NUMBERING SYSTEM

Wells used in this study have been assigned numbers that identify their location within a section, township, and range. For example, in the well number 9/21-24Q1, the part preceding the hyphen indicates, successively, the township and range (T.9 N., R.21 E.) 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. 24), and the letter "Q" gives the 40-acre subdivision of the section, as shown in the figure below. The numeral "1" indicates that this well is the first one inventoried in the 40-acre subdivision.

The same numbering system is used in this report to indicate the location of certain geologic and hydrologic features described in the text. Occasionally, a well or location is referred to using part of the well number.



# METRIC CONVERSION TABLE

| Multiply | By | To obtain |
|---|---|---|
| inches (in.) | 25.4 | millimeters (mm) |
| | 2.54 | centimeters (cm) |
| feet (ft) | 1.609 | kilometers (km) |
| square miles ($mi^2$) | 2.590 | square kilometers ($km^2$) |
| acres | 4,047. | square meters ($m^2$) |
| acre-feet (acre-ft) | 1,233. | cubic meters ($m^3$) |
| cubic feet per second ($ft^3/s$) | 28.32 | liters per second (L/s) |
| | 0.02832 | cubic meters per second ($m^3/s$) |
| gallons per minute (gal/min) | 0.06309 | liters per second (L/S) |
| gallons per minute per foot (gal/min)/ft | 0.2070 | liters per second per meter (L/s)/m |
| feet per second (ft/s) | 0.3048 | meters per second (m/s) |
| feet per day (ft/d) | 0.3048 | meters per day (m/d) |
| feet squared per second ($ft^2/s$) | 0.0969 | meters squared per second ($m^2/s$) |
| degrees Fahrenheit (°F) | 0.555, after subtracting 32 | degrees Celsius (°C) |

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

# A NUMERICAL MODEL OF GROUND-WATER FLOW IN THE LOWER SATUS CREEK BASIN, YAKIMA INDIAN RESERVATION, WASHINGTON

By Edmund A. Prych

## ABSTRACT

Lower Satus Creek basin is a 51-square-mile agricultural area in the Yakima River valley on the Yakima Indian Reservation in south-central Washington. In some areas of the basin waterlogging, caused by high ground-water levels, has made land unsuitable for agriculture.

A multilayer numerical model of steady-state ground-water flow in lower Satus Creek basin was constructed, calibrated using time-averaged data, and used to estimate the long-term effects of proposed irrigation-water management plans on ground-water levels in the area. Computations with the model showed that irrigation of new lands in the Satus uplands would raise ground-water levels in lower Satus Creek basin and thereby increase the size of the waterlogged areas. The model also demonstrated that pumping water from wells, reducing the amount of irrigation water used in the lowlands, and stopping leakage from Satus Nos. 2 and 3 Pump Canals are all effective methods for alleviating present waterlogging in some parts of the basin and for counteracting some of the anticipated ground-water-level rises that would be caused by irrigating the uplands. The proposed changes in water use affected model-computed ground-water levels most in the eastern part of the basin between Satus No. 2 and No. 3 Pump Canals. The effects on ground-water levels in the western part of the basin between Satus Creek and Satus No. 2 Pump Canal were comparatively less.

# INTRODUCTION

## Background

Ground-water levels in lower Satus Creek basin are of interest because the water table in some locations is so high that the land is unsuitable for agriculture because of waterlogging. This condition exists when a high water table saturates the root zone of crops, preventing vertical drainage and aeration of the plants' roots. Additional problems can arise from waterlogging if evaporating ground water leaves salt residues in the soil. According to an unpublished report by the U.S. Bureau of Indian Affairs, more than 15 $mi^2$ of lower Satus Creek basin (more than one-quarter of the basin) are affected by waterlogging.

## Purpose

The purpose of this investigation was to develop a numerical model of ground-water flow in the lower Satus Creek basin and to use the model to estimate the effects of proposed ground-water pumping and of other irrigation-water management plans on ground-water levels in the lower Satus Creek basin. This report documents the procedures and data that were used for constructing and calibrating the model, and presents estimates of ground-water-level changes that might occur as a result of some proposed irrigation-water management plans.

## Method and Scope

A three-layer, steady-state, numerical model of ground-water flow in lower Satus Creek basin was constructed by using an existing generalized model (Trescott, 1975). Initial estimates of the hydraulic properties of the geologic units, which are part of the model input data, were obtained from drillers' logs, aquifer pump tests, and water-level data. These estimates were changed in a systematic way during a model-calibration procedure to find which values of the properties gave the best agreement between model-computed ground-water heads and time-averaged observed heads for the 12-month period March 1979 through March 1980. Ground-water recharge for this period by percolation of applied irrigation water was estimated using data from the files of the local irrigation project. Recharge by leakage from the major irrigation canals was estimated using data from tests that were made specifically for that purpose.

The calibrated model was used to estimate the long-term effects on ground-water levels of various irrigation-water management plans. They included: (1) irrigating lands in the Satus uplands; (2) reducing the amount of applied irrigation water; (3) pumping ground water at selected locations and rates; and (4) stopping leakage from Satus Nos. 2 and 3 Pump Canals.

## GEOGRAPHY

### Location and Topography

Lower Satus Creek basin is located on the southwest side of the Yakima River on the Yakima Indian Reservation in south-central Washington. The term lower Satus Creek basin as used in this report refers to the 51 $mi^2$ that is bounded (see pl. 1) on the southeast by the Yakima Indian Reservation boundary, on the southwest by Satus Nos. 2 and 3 Pump Canals, on the northwest by Toppenish Ridge and Toppenish Creek, and on the northeast by the Yakima River. The area included in the numerical model is nearly the same as the above area, except that the model also includes a 1-mile-wide strip of land on the northeast side of the Yakima River (see pl. 1). The area within the model boundries is 71 $mi^2$, of which 57½ $mi^2$ are south of the Yakima River.

Land-surface altitudes in the study basin range from a maximum of about 800 ft above sea level near the upstream end of Satus No. 3 Pump Canal to about 650 ft at the Yakima River near Mabton. Typically, the land slopes gently downward from near the pump canals, which usually either butt up against or are cut into the toe of the Satus Creek basin uplands. Breaks in slope occur at terraces along the Yakima River and along Satus No. 2 Pump Canal downstream of Satus Pump House No. 3.

## Climate

Lower Satus Creek basin is in a semiarid region lying in the rain shadow of the Cascade Mountains. Table 1 gives a summary of the climatological data from a station near the basin and the estimated potential evapotranspiration. Precipitation during the 12-month period shown was 8.87 in., which was about 30 percent more than the long-term average. The last column in the table shows that precipitation exceeded the potential evapotranspiration during November through February. The precipitation excess of 4.41 in. for this period was considerably greater than the long-term amount of 1.32 in.

TABLE 1.--Monthly and long-term annual climatological data for Sunnyside, Washington[1]

| Month | Precipitation (inches) | Temperature (°F) | Computed potential evapotranspiration[2] (inches) | Precipitation less potential evapotranspiration (inches) |
|---|---|---|---|---|
| 1979 | | | | |
| April | 0.36 | 52.2 | 2.35 | -1.99 |
| May | .13 | 62.1 | 4.28 | -4.15 |
| June | trace | 68.1 | 5.47 | -5.47 |
| July | .40 | 73.1 | 6.52 | -6.12 |
| August | .36 | 71.8 | 5.75 | -5.39 |
| September | .45 | 65.9 | 4.02 | -3.57 |
| October | 1.03 | 55.7 | 2.35 | -1.32 |
| November | 1.46 | 35.3 | .40 | 1.06 |
| December | .82 | 35.8 | .40 | .42 |
| 1980 | | | | |
| January | 2.10 | 24.2 | .23 | 1.87 |
| February | 1.43 | 34.0 | .37 | 1.06 |
| March | .33 | 45.0 | 1.35 | -1.02 |
| Sum or average | 8.87 | 51.9 | 33.49 | -29.03 +4.41 |
| Long-term annual average | 6.81 | 51.9 | 32.14 | -26.65 +1.32 |

[1]Sunnyside, altitude 747 ft, about 9 miles north of Mabton. Data from National Oceanic and Atmospheric Administration (1979-80). Long-term data for the years 1941-70.

[2]Average of values computed by methods of Blaney and Criddle (U.S. Soil Conservation Service, 1967) and of Thornthwaite (Thornthwaite and Mather, 1957).

## Agriculture

Irrigated agriculture is the major economic activity and use of water in lower Satus Creek basin. Most irrigation water is supplied by the Wapato Irrigation Project, which is under the administration of the U.S. Bureau of Indian Affairs. Major crops are alfalfa, field corn, hops, mint, small grains, and vegetables such as asparagus and sweet corn that are grown for commercial processing. Some of the land is used for pasture, part of which is irrigated. Of the 51 $mi^2$ in the lower Satus Creek basin, 33 $mi^2$ are irrigated; 26 $mi^2$ are flood irrigated, and the remaining 7 $mi^2$ are irrigated with sprinklers. Irrigation usually begins in early April and continues into October.

The number of total and sprinkler-irrigated acres in each quarter section are shown on figure 1. The majority of the data were obtained from the Wapato Irrigation Project 1978 Crop Report (written commun., Wapato Irrigation Project, 1979). Locations of sprinkler-irrigated areas were spot-checked in the field during the summer of 1979. The amount of irrigated land in 1979 (the period when other hydrologic data were collected) should not have been significantly different from that in 1978. The Sunnyside Irrigation District supplies water to 713 acres in three sections at the extreme west end of the basin. It was assumed that all this area was sprinkler irrigated.

Most of the irrigation water in the basin is derived from surface waters and is distributed by a canal system. The canal-distribution system for irrigation water and the drain system for irrigation-return flows are described in the following section.

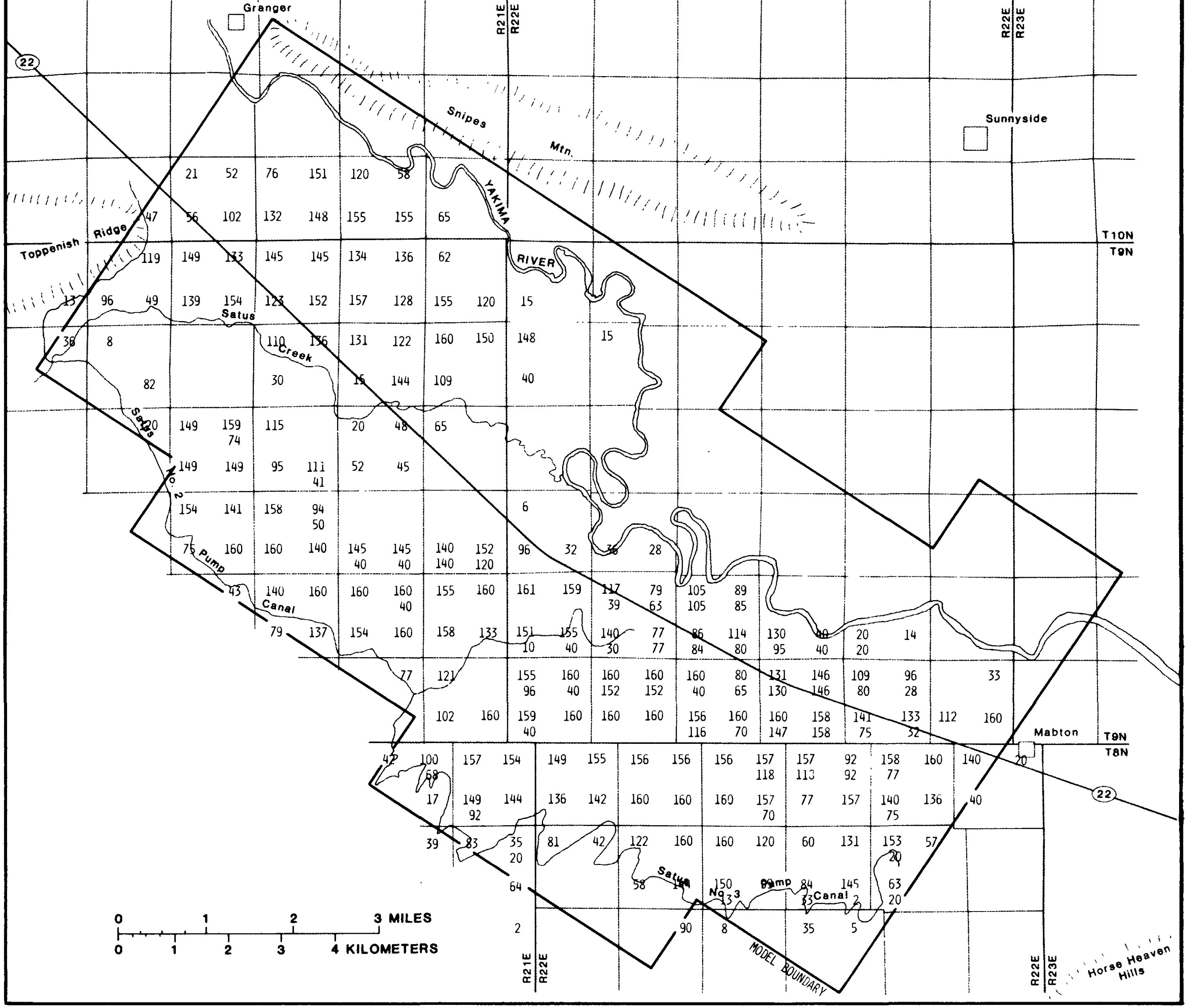



FIGURE 1.--Lower Satus Creek basin showing numbers of total (upper number) and sprinkler (lower number) irrigated acres in each quarter section.

# SURFACE WATER

## The Surface-Water Network

A schematic diagram of the surface-water network in lower Satus Creek basin is shown in figure 2. Triangles designate points where the irrigation districts provided estimates of water discharge. Table 2 lists monthly discharge volumes at the locations shown in figure 2 for the period April 1979 through March 1980. There are no storage reservoirs in the network.

The Yakima River, which forms the northeast boundary of the study area, is the ultimate recipient of nearly all the surface and subsurface drainage from the study basin. Satus Creek is its only major natural tributary. The other tributaries convey mostly excess surface irrigation water, subsurface drainage from agricultural lands, and water spilled during normal operation of irrigation canals.

Most of the canals, laterals, and drains are part of the Wapato Irrigation Project. The Mabton West Lateral is part of the Sunnyside Valley Irrigation District. The majority of the water supplied to the basin by the Wapato Irrigation District is diverted from Toppenish Creek, which, during the irrigation season, carries mostly irrigation return flows from the Toppenish Valley. This valley lies immediately north of Lower Satus Creek basin and is separated from the basin by Toppenish Ridge. The water imported from Toppenish Valley is augmented with water diverted from Satus Creek through the Satus Feeder Canal and with water pumped from a few wells. These wells will be discussed in a later section entitled "Ground-Water Pumpage."

TABLE 2.--Monthly discharge volumes, in acre-feet, in the surface-water network of lower Satus Creek basin

[Data furnished by Wapato Irrigation Project, U.S. Bureau of Indian Affairs]

| | East lateral | West lateral | Well 14G1 | Satus No. 2 Pump station | Satus Feeder Canal | Upper Satus Creek | Satus No. 3 Pump station | Wells 25Q1, 35H1, 29L1, 30L1 | Coulee Drain | Lower Satus Creek | South Drain | Drain 302 | Drain 303 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | | | | | | | | | | | | | |
| April | 3,670 | 730 | 0 | 7,100 | 3,320 | 5,980 | 7,000 | 0 | 250 | 5,780 | 4,190 | 440 | 690 |
| May | 9,360 | 1,060 | 0 | 7,400 | 4,230 | 6,620 | 11,700 | 0 | 760 | 5,280 | 3,860 | 1,020 | 1,310 |
| June | 9,290 | 1,800 | 0 | 14,900 | 1,180 | 4,160 | 13,400 | 112 | 1,180 | 5,140 | 2,850 | 1,620 | 1,030 |
| July | 9,540 | 910 | 0 | 17,200 | 610 | 3,290 | 13,400 | 559 | 1,470 | 4,970 | 3,220 | 1,550 | 990 |
| August | 7,470 | 820 | 136 | 17,000 | 180 | 3,070 | 13,800 | 747 | 1,100 | 5,000 | 3,500 | 1,580 | 680 |
| September | 5,050 | 400 | 131 | 13,500 | 180 | 3,020 | 11,700 | 1,006 | 650 | 3,330 | 4,210 | 1,450 | 1,060 |
| October | 2,480 | 290 | 0 | 5,900 | 0 | 3,440 | 5,000 | 732 | 220 | 2,650 | 2,540 | 290 | 980 |
| November | 0 | 0 | 0 | 0 | 0 | 3,980 | 0 | 0 | 0 | 1,780 | 890 | 0 | 0 |
| December | 0 | 0 | 0 | 0 | 0 | 7,760 | 0 | 0 | 0 | 6,350 | 690 | 0 | 0 |
| 1980 | | | | | | | | | | | | | |
| January | 0 | 0 | 0 | 0 | 0 | 14,080 | 0 | 0 | 0 | 246,700 | 810 | 180 | 90 |
| February | 0 | 0 | 0 | 0 | 0 | 32,860 | 0 | 0 | 0 | 21,000 | 2,530 | 1,080 | 250 |
| March | 0 | 0 | 0 | 0 | 0 | 38,670 | 0 | 25 | 320 | 30,400 | 1,060 | 820 | 370 |
| Sum | 46,860 | 6,010 | 267 | 83,000 | 9,700 | 126,930 | 76,000 | 3,181 | 5,950 | 116,280 | 30,350 | 10,030 | 7,450 |

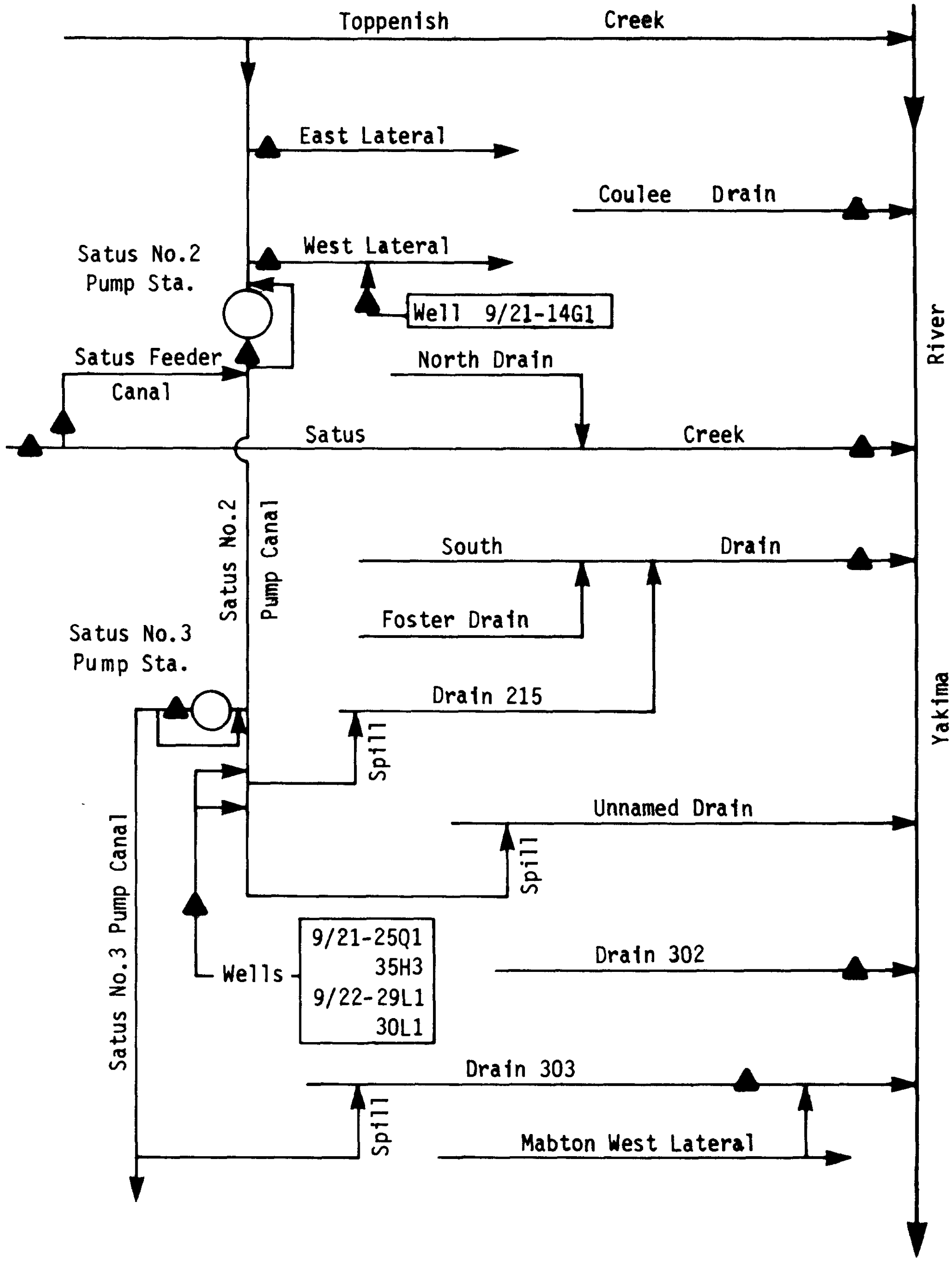



FIGURE 2.--Schematic diagram of surface-water network in lower Satus Creek basin. Triangles denote locations where discharges are gaged or estimated.

## Canal Leakage

Because leakage from irrigation canals was suspected as being a major source of ground-water recharge in lower Satus Creek basin, tests were conducted on Satus No. 2 Pump Canal to provide data for estimating the leakage rates. These tests were conducted in March 1980, after maintenance dredging and before the start of the irrigation season. At that time the canals had been dry, except for scattered pools of water, for about 5 months. During the tests three segments of Satus No. 2 Pump Canal (see pl. 1) were isolated with temporary earth dams and filled with water from adjacent wells. Water levels in two of the canal segments were kept at near-operating levels by periodically adding water. Water levels were monitored in all segments by reading staff gages. Figure 3 shows the observed water levels, and table 3 gives the locations of the segments and summarizes data from the tests.

The canal segments near wells 9/21-25Q1 and 9/22-30L1 were filled to approximately normal operating level and refilled to about that level once a day during the first few days of the tests. The test on the segment near well 9/21-35H3 was conducted with a water level about 5 feet below normal because the dam at the upstream end failed. To minimize errors that might be caused by variations in leakage with water level in the canal and by effects caused by a dry canal bed during the initial part of the tests, the rates of water-level decline given in table 3 were computed from data collected during the 24-hour period after the final refilling.

Water levels in wells adjacent to the canals during these tests and during the irrigation season were always below the altitude of the bottom of the canal. Therefore, at these locations flow beneath the canal bed was vertical, the hydraulic gradient was unity, and the material was probably, but not necessarily, unsaturated. Thus, canal leakage rates should not have been a function of the ground-water level. Also, the data in figure 3 show that the rates of water-surface decline were only a weak function of the water level in the canal. Leakage rates with the lower water levels at the end of the tests in segments near wells 25Q1 and 30L1 were 17 and 14 percent lower, respectively, than the rates with higher water levels after the final fillings.

Leakage rates for the entire lengths of the Nos. 2 and 3 Pump Canals were estimated (table 4) by multiplying the average water-level- decline rate for the three canal segments, 0.6 ft/d, by the products of canal lengths and widths. Although the bottom sediments along the lengths of both canals were similar (both canals are in the Touchet Beds of Flint, 1938; see the section Geologic Units), these estimates of leakage rates should be considered speculative because they were based on data collected only at three relatively closely spaced segments in the No. 2 Pump Canal. Other sources of error include using data from the canal segment near well 35H3, which was below normal operating level during the test, and performing the tests after maintenance dredging, which would have removed any surface seal of fine material that might develop during normal canal usage. These two errors are of opposite sign and would tend to cancel each other. Therefore, including the value from the test near well 35H3 probably gives a better estimate of the leakage rate than if it were deleted.

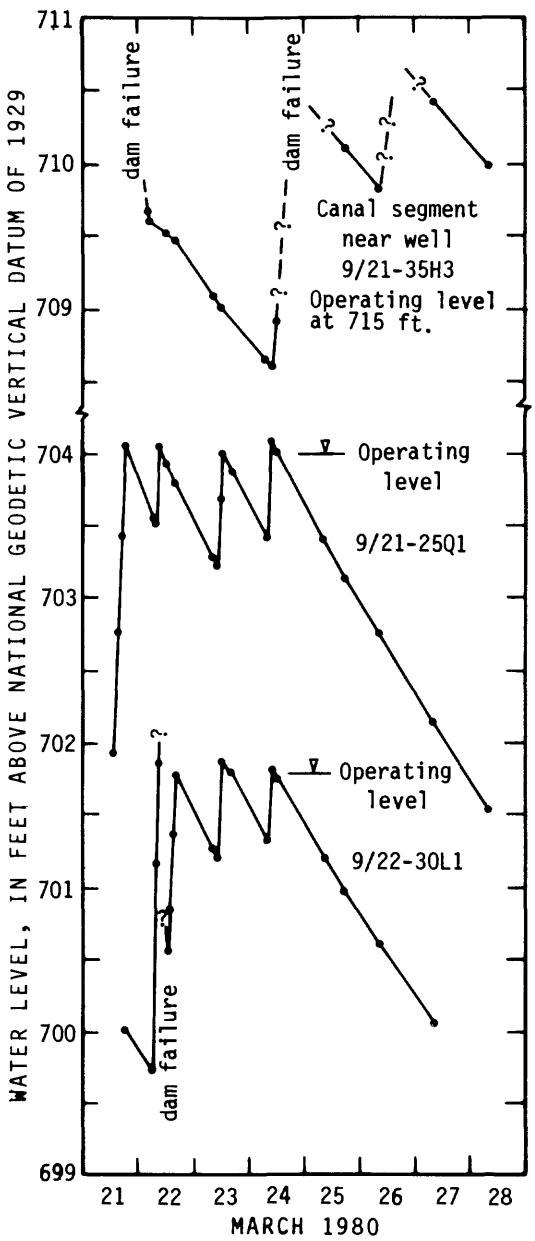



FIGURE 3.--Variations in canal water levels during leakage tests.

TABLE 3.--Summary of data for March 1980 leakage tests on Satus No. 2 Pump Canal

| Identification number of adjacent well | Location of canal segment (also see pl. 1) | Water level decline rate (ft/d) | Segment length (ft) | Approximate water level during normal operation (ft) | Water-surface width during normal operation (ft) | Approximate maximum depth during normal operation (ft) |
|---|---|---|---|---|---|---|
| 9/21-35H3 | From entrance to forebay at No. 3 pump station to a point 1,590 ft upstream | 0.45 | 1,590 | 715 | 36 | 8.5 |
| 9/21-25Q1 | From west side of Roberts Rd to a point 3,060 ft upstream | .72 | 3,060 | 704 | 16 | 5.5 |
| 9/22-30L1 | From west side of Roberts Rd to a point 3,850 ft downstream | .64 | 3,850 | 701.8 | 17 | 5.5 |
| Average of three segments-------------------------------------- | | | | 0.60 | | |

TABLE 4.--Estimated leakage rates of Satus No. 2 and No. 3 Pump Canals

| Leakage rate ($ft^3/s$) | Canal |
|---|---|
| 11 | No. 2 Pump Canal from No. 2 pumping station to spill about 0.5 mile downstream from No. 3 pumping station. |
| 1 | No. 2 Pump Canal from spill to end. |
| 11 | No. 3 Pump Canal |
| 23 | Sum for No. 2 and No. 3 Pump Canals |

# GEOHYDROLOGY

## Geologic Units

Lower Satus Creek basin is a structural and topographic basin underlain with basalt and filled with sediments. The basaltic rocks are upfolded to the north to form Toppenish Ridge and Snipes Mountain and to the south to form the Horse Heaven Hills.

The stratigraphic sequence is shown in figure 4 and is described in table 5. Most of the wells in the area obtain water from the upper part of the Ellensburg Formation called upper Ellensburg in this report, the old alluvium, or the young alluvium. The Touchet Beds of Flint (1938) usually do not yield water except in a few areas where they are unusually sandy. Unirrigated areas in the western part of the basin (in fig. 1; see for example, 9/21-8,9,10,23, and 24) are commonly sandy near the surface. Of the wells in the basin that penetrate the basalts, only those into the Wanapum or Grande Ronde Basalts yield sufficient water for irrigation. Both the Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation, a sedimentary unit, are poor aquifers in this basin.

Contours of the top of the Saddle Mountains Basalt are shown in figure 5. These contours were drawn using three types of data:

1. Data from the few wells that penetrated the basalt (mostly along the southwest boundary) gave altitudes of the top of the basalt at those locations;

2. Data from the many shallower wells that did not reach the basalt gave upper limits of the top of the basalt at many locations in the basin; and

3. Data from a gravity survey (Z. F. Danes, University of Puget Sound, written commun., 1979) gave qualitative data on the topography of the top of the basalt over most of the area. The contours show that the top surface of the basalt forms a trough where the axis is roughly along the Yakima River in the western half of the basin, but diverges from the river in the eastern half and heads northeast on the east side of Snipes Mountain.

Contours of the contact between the old alluvium or upper Ellensburg Formation and the Touchet Beds of Flint (1938) or young alluvium are shown on figure 6. This figure also shows the approximate lateral extent of the Young Alluvium. The contours show a trough-shaped surface with an axis that approximately parallels the Yakima River and dips in the downstream direction. The relief on this surface is less than that on the basalt (fig. 5); consequently, the maximum thickness of the combined old alluvium and upper Ellensburg Formation is near the axis of the basalt trough.

Differences between the contours on figures 5 and 6 and on similar figures presented by Mundorff, MacNish, and Cline (1977) are due mostly to the availability of additional data from wells drilled since the writing of their report. Logs of many new wells appear in the report by the Boyle Engineering Co. (1978). Names of basalt units used in this report differ from those used by Mundorff, MacNish, and Cline (1977) because the official nomenclature was revised by Swanson and others (1979).

TABLE 5.--Summary of geologic units and their water-yielding characteristics, lower Satus Creek basin. (Modification of table 6, Mundorff, Mac Nish, and Cline (1977)

| ogic and e | Maximum thickness (ft) | Description | Water-yielding characteristics | Grouping of geologic units into layers for model |
|---|---|---|---|---|
| g alluvium locene) | a36 | Chiefly sand and gravel, with some boulders and a few sand and silt layers. Limited extent along Yakima River, lower Satus and Toppenish Creeks. | Capable of yielding several hundred gallons per minute to properly constructed drilled or dug wells where saturated thickness is 20 to 25 feet. | III |
| het Beds of it (1938) istocene) | b150 | Thin-bedded strata of silt, very fine sand, and clay with a few coarser sand layers and scattered pebbles and cobbles. Forms a blanket over older deposits in the lowland of the basin up to an altitude of about 1,150 feet. | Will yield 5 to 10 gal/min of water to relatively shallow wells. In some places may yield as much as 50 gal/min. Its chief significance in the lowland is its poor permeability and retarding of vertical ground-water flow. | III |
| alluvium istocene?) | a62 | Chiefly sand and gravel with some sand and silt. Deposited by Yakima River and Satus and Toppenish Creeks. | Capable of yielding 500 to 2,000 gal/min to properly constructed wells at some places | II |
| ifferentiated r part of nsburg Formation, ed upper nsburg in (Miocene) | c450<br>d750 | Mostly poorly sorted and roughly stratified, partly cemented sand and gravel, with some strata of sand silt, pumice, and clay. At many places quartzite and light-colored volcanic rocks predominate in the gravel. | Supplies water to many wells in lowland. The cleaner, less cemented strata generally yield 250 to 500 gal/min to properly constructed wells, and in some places in excess of 2,000 gal/min. | II |
| lle Mountains lt of Columbia r Basalt Group cene) | a150 | Basalt generally similar to basalt described below. | Generally yields some water where saturated, possibly as much as 100 gal/min in places. | |
| rly er of nsburg ation (Miocene) | a250 | Generally fine-grained sedimentary strata of clay, silt, volcanic ash, and pumaceous sand. | Generally not considered an aquifer in the Satus Creek basin, although in places sand strata may yield some water. | |
| fferentiated pum Basalt Grande Ronde lt of the mbia River lt Group cene) | a1,000<br>e5,000 | Thick sequence of dark gray to black lava flows, each generally 20 to 100 feet thick. Basal parts of flows are generally dense and fine grained; upper parts are in many places vesicular and locally rubbly. Flows have both horizontal and vertical joint. | Water-bearing zones occur at and near the tops of some flows. Wells drilled 500 to 1,000 feet below the water table or potentiometric surface generally will yield 500 to 1,000 gal/min with moderate drawdown. Water level may be at great depths beneath parts of the upland. | I |

From well logs.
Composite thickness, from well logs and outcrops.
Based on data for well 9/22-8A1.
From Laval (1956).
Based on data from outside Satus Creek basin.

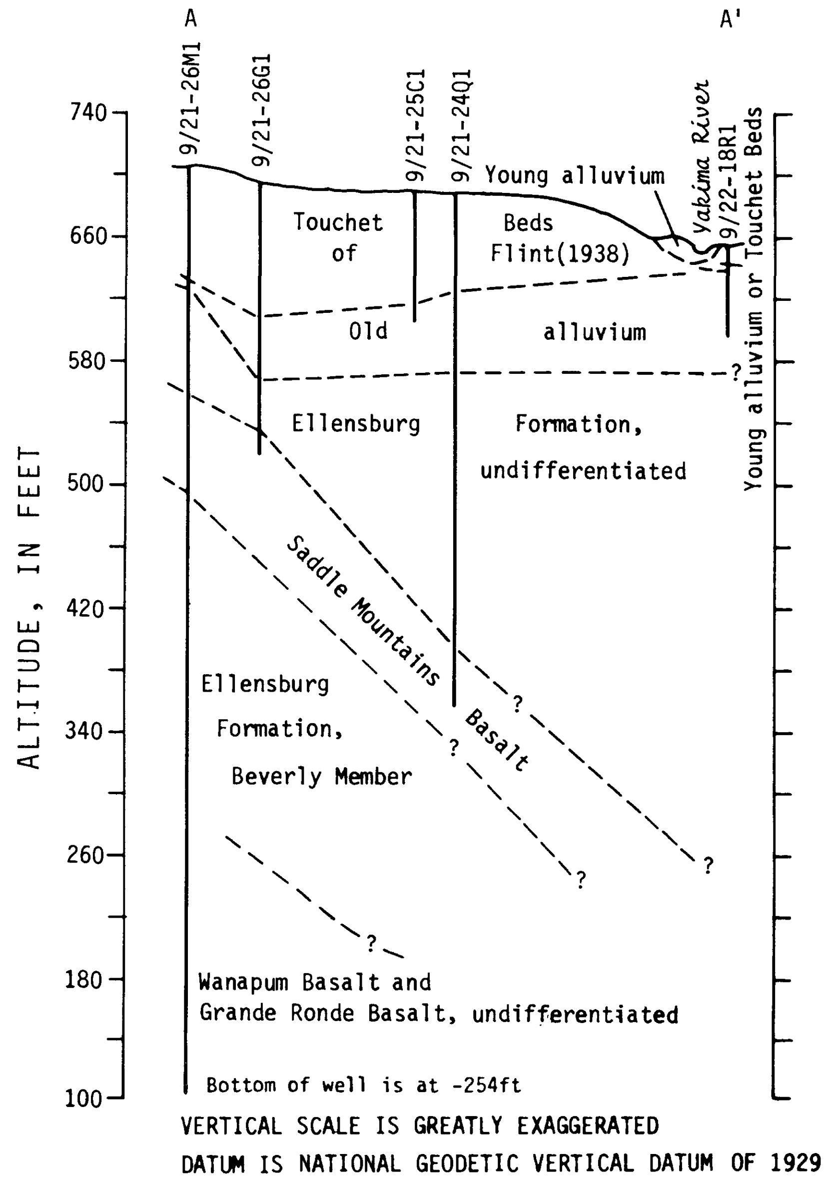



FIGURE 4.--Diagrammatic geologic cross section in lower Satus Creek basin along line A-A' of plate 1. Vertical exaggeration is about x50. (Modification of figure 11 in Mundorff, Mac Nish, and Cline, 1977).

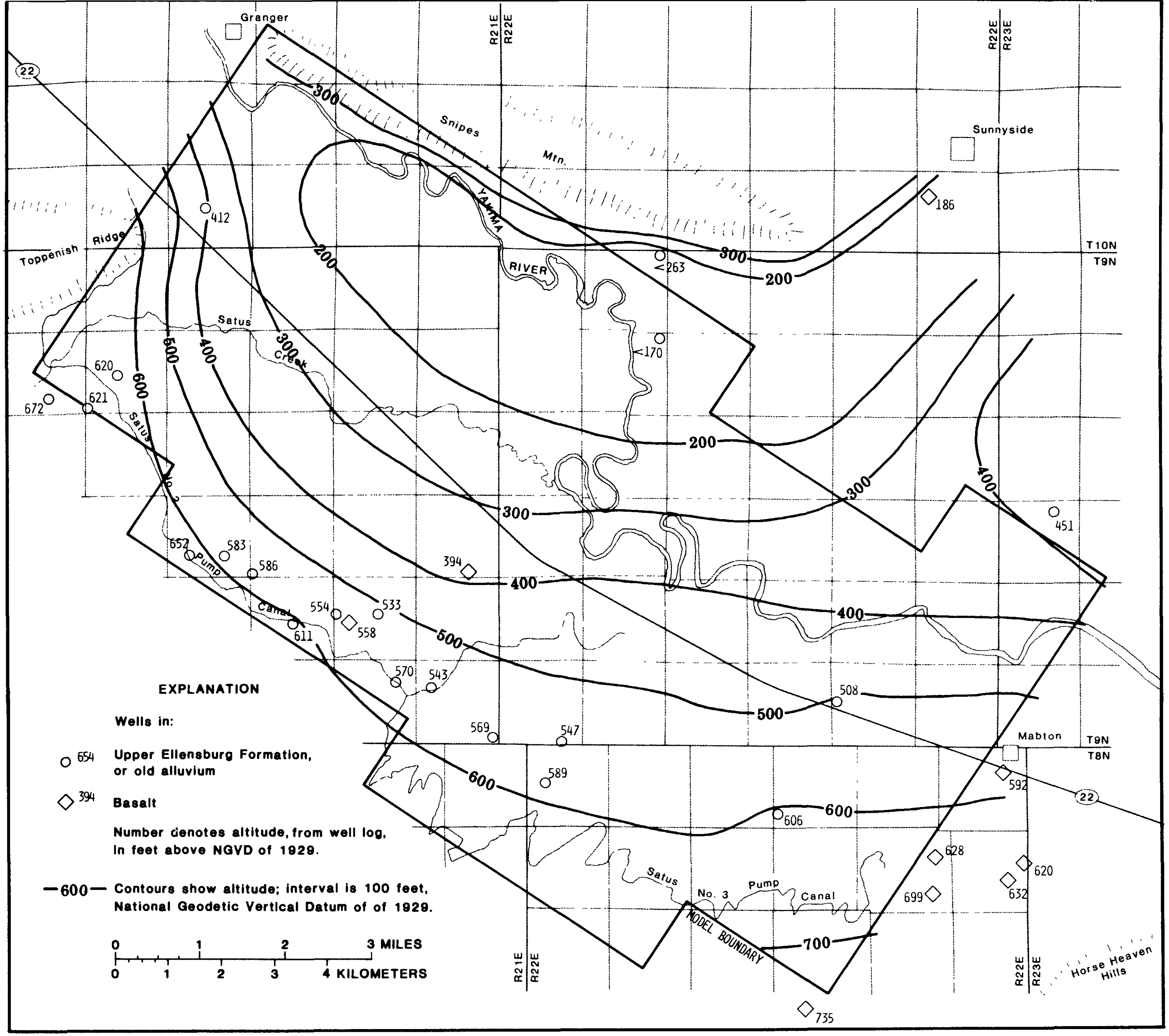



FIGURE 5.-- Lower Satus Creek basin showing altitudes on top of Saddle Mountains Basalt.

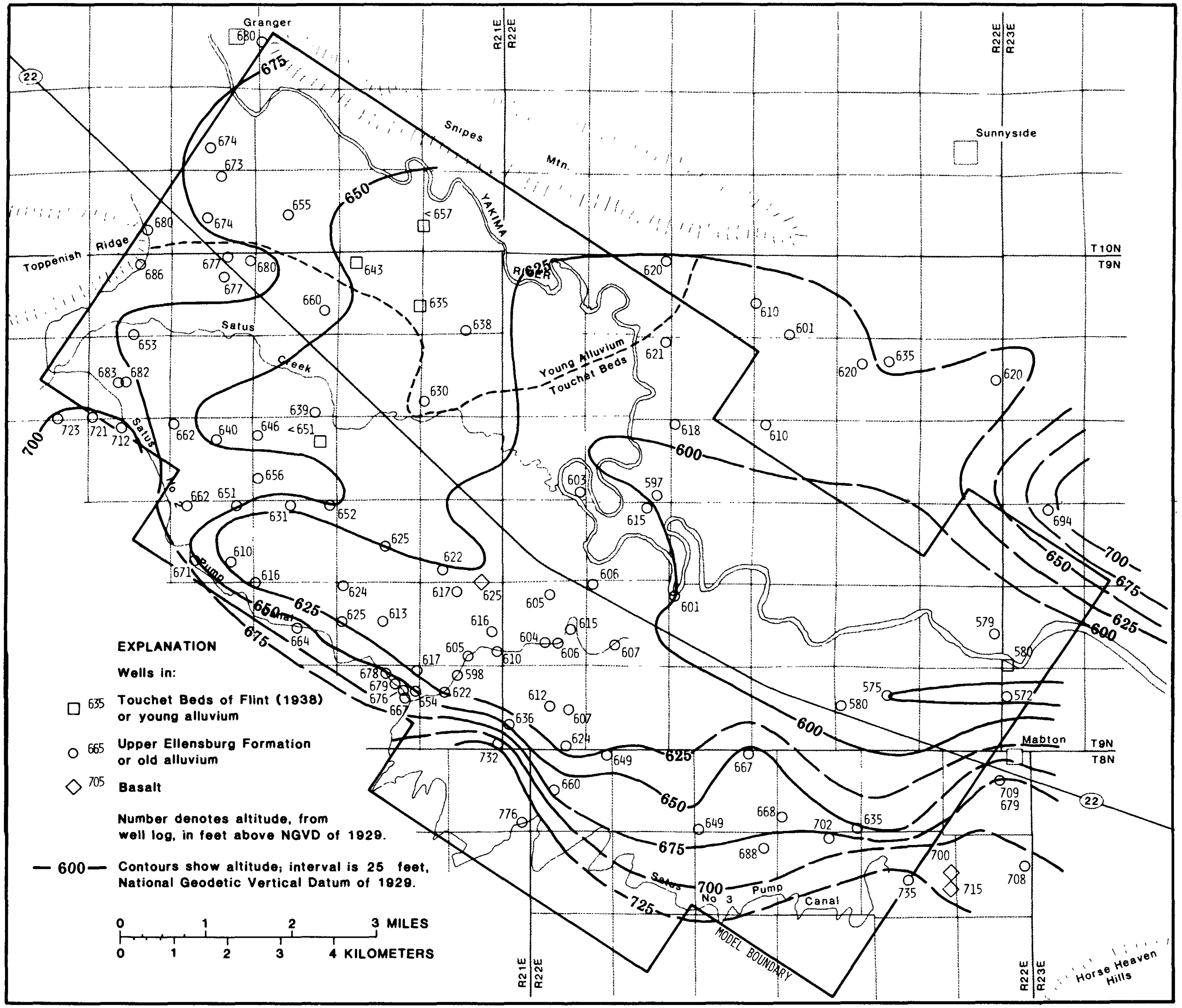



FIGURE 6.--Lower Satus Creek basin showing altitudes on contact between upper Ellensburg Formation or old alluvium and Touchet Beds of Flint (1938) or young alluvium.

## Ground-Water Levels

Figure 7 shows 12-month averages of observed water levels in wells and of streams and ponds for the period mid-March 1979 through mid-March 1980. The contours in this figure were fit to data from wells in the upper Ellensburg Formation and Old Alluvium. In areas where wells do not exist in these geologic units, such as in the northwest part of the study basin, data from shallower wells were used as a guide for drawing the contours. Figure 8 shows ranges in water levels at most observation sites during the 12-month period, and figure 9 shows the minimum observed depths below land surface to water. Figures 10 through 16 show the seasonal variations in water levels at selected sites. The average range for wells not markedly affected by pumping was about 4 ft.

Water levels were observed monthly at most locations. In a few wells observations were made only in March and October, the approximate times of highest and lowest ground-water levels. Most water levels were measured relative to reference marks whose altitudes were estimated from topographic maps with 10-ft contour intervals. Therefore, the datum, and hence the absolute head, at each well or group of wells could easily be in error by 5 ft. However, vertical control surveys with an accuracy of 0.01 ft were run between closely spaced wells and surface-water gages so that small differences between ground-water levels at different depths and between ground-water and surface-water levels could be measured accurately.

Seasonal variations of water levels in many wells in lower Satus Creek basin are similar to those in wells 9/21-16D1 and D2, (fig. 10a). Typically, water levels start to rise in the spring in response to recharge by irrigation water and reach their maximum in late summer. Water levels also rise in many wells between February and March 1980 (figs. 11-14), probably in response to natural recharge following the spring thaw.

There are many exceptions to the typical annual variation in water levels as described above. Water levels in wells adjacent to Satus Creek and the Yakima River usually fluctuated with the stages of these streams, (figs. 10b and c). The highest levels occurred during winter and early spring runoff. Water levels in wells 9/21-35H4 through H7, adjacent to Satus No. 2 Pump Canal, rose after April 1, 1979, in response to the filling of the canals (fig. 15). However, no immediate response was evident in the data for wells 9/22-30K1 through K4 (fig. 16), which were also adjacent to the canal. The slow rise of water levels in these wells during the summer months could be due to either canal leakage or recharge of excess applied irrigation water. Pumping of ground water also affected water levels in nearby wells, as shown by the data for summer months (figs. 13, 15, and 16).

Between March 1979 and March 1980, ground-water levels rose an average of 1.3 ft (fig. 17), indicating an increase in the amount of ground-water storage. The generally higher water levels could be due to above-average precipitation during this 12-month period. The March 1980 levels were higher in nearly every well except those in the vicinity of well 9/21-35H3. There, water levels were as much as 2 ft lower, probably because this well was pumped for the first time during the 1979 irrigation season.

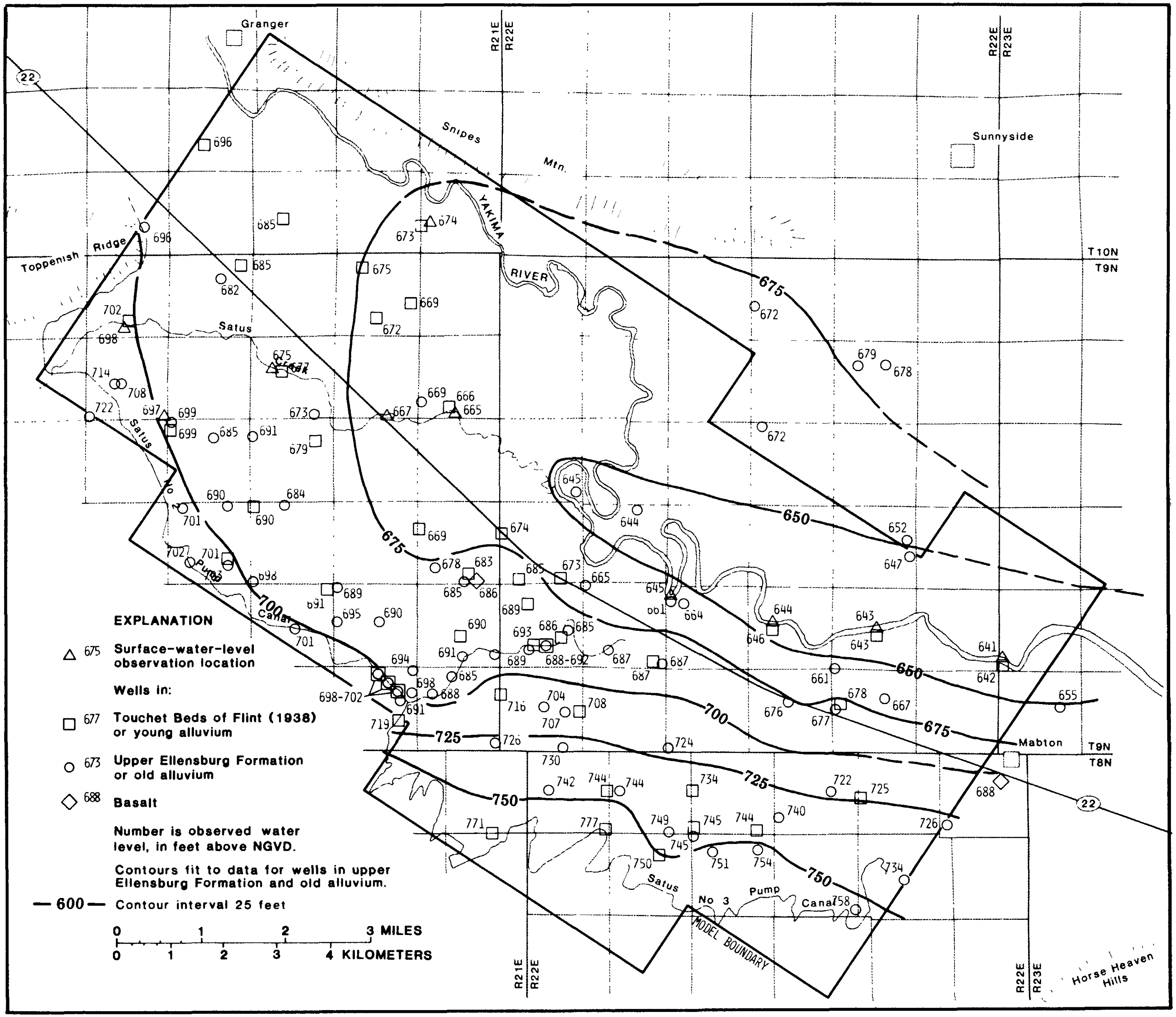



FIGURE 7.--Lower Satus Creek basin showing average observed water-level altitudes for the period March 1979 to March 1980.

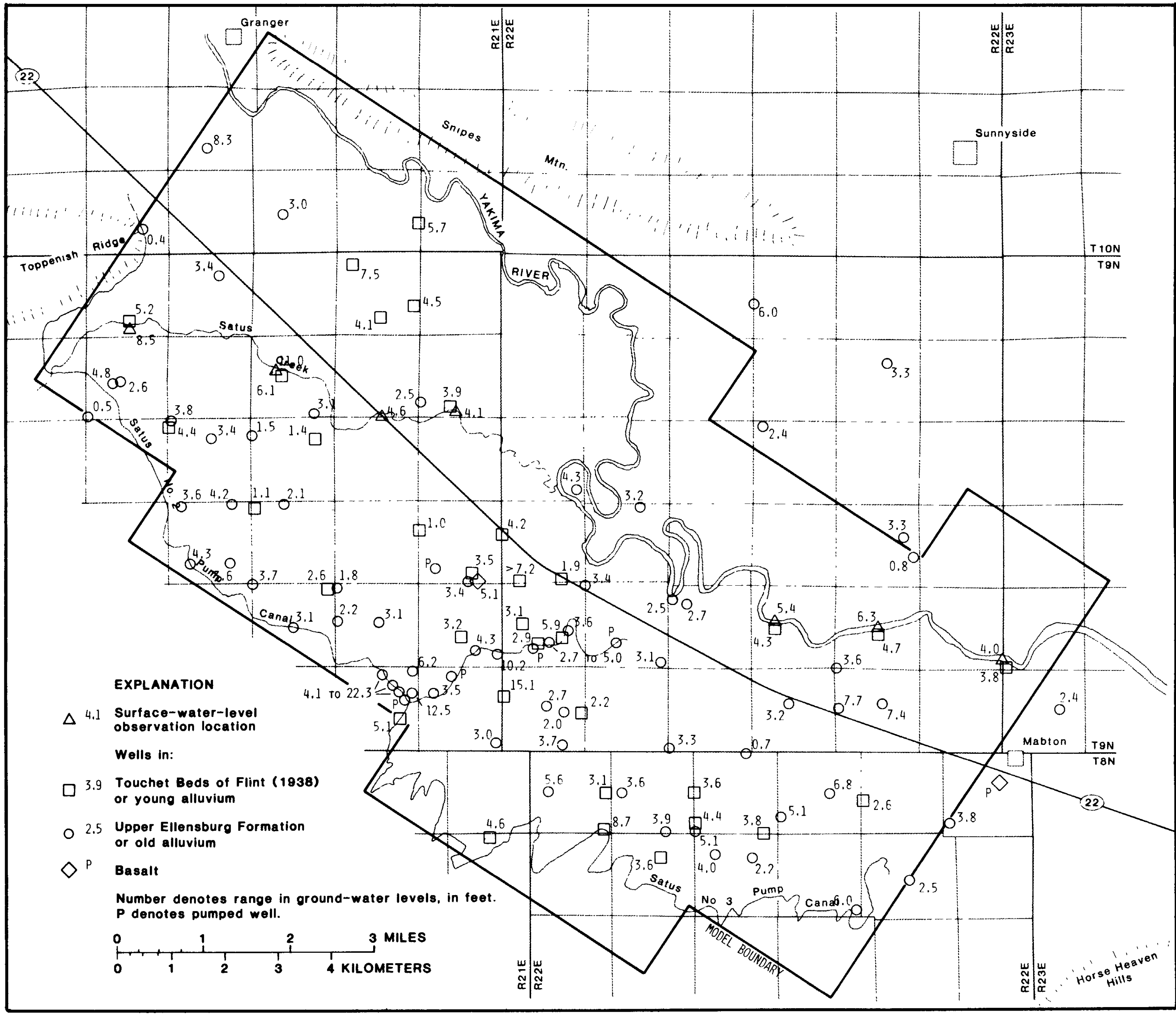



FIGURE 8.--Lower Satus Creek basin showing ranges in observed water levels for the period March 1979 to March 1980.

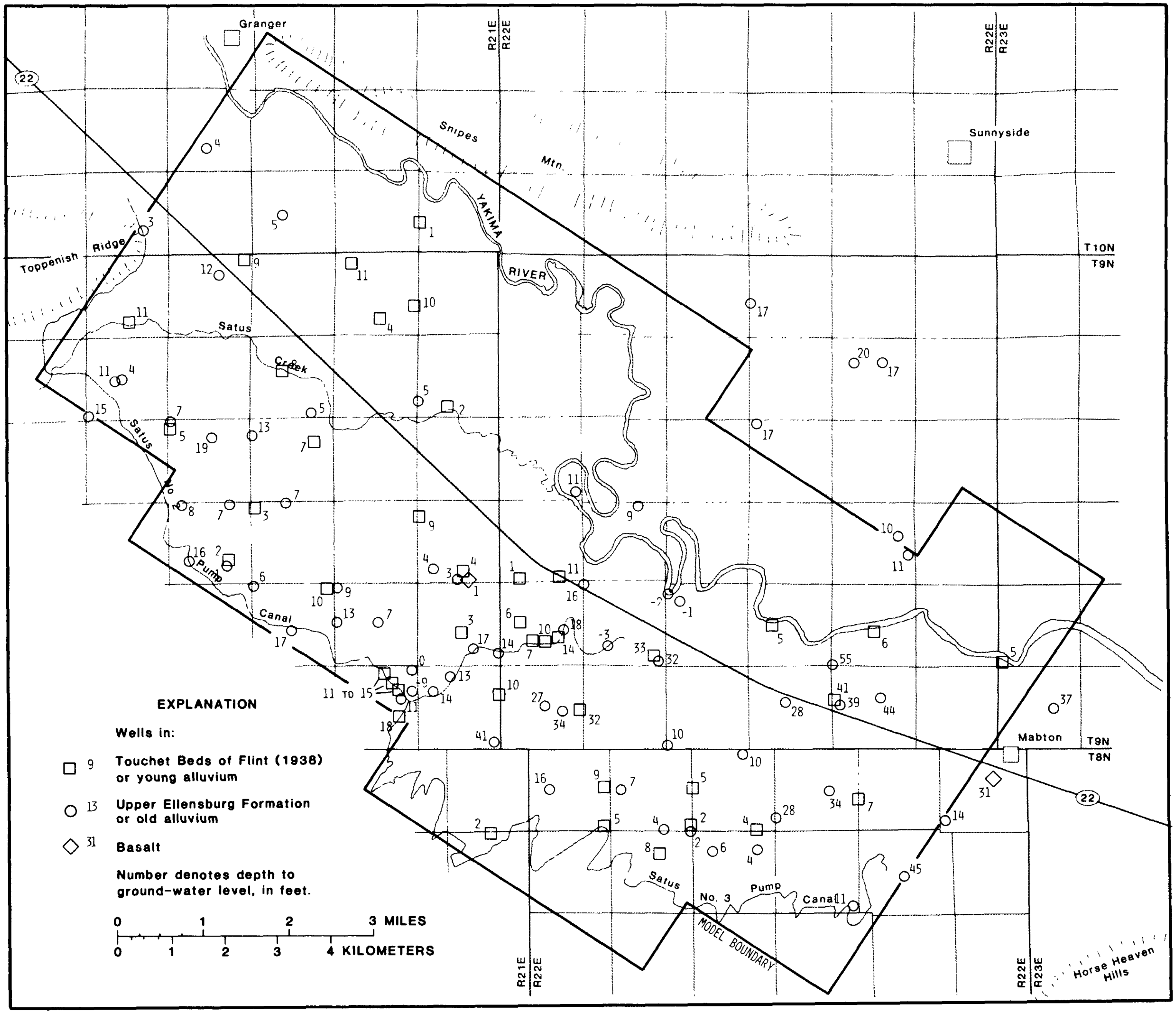



FIGURE 9.--Lower Satus Creek basin showing minimum depths below land surface of water levels in wells for the period March 1979 to March 1980.

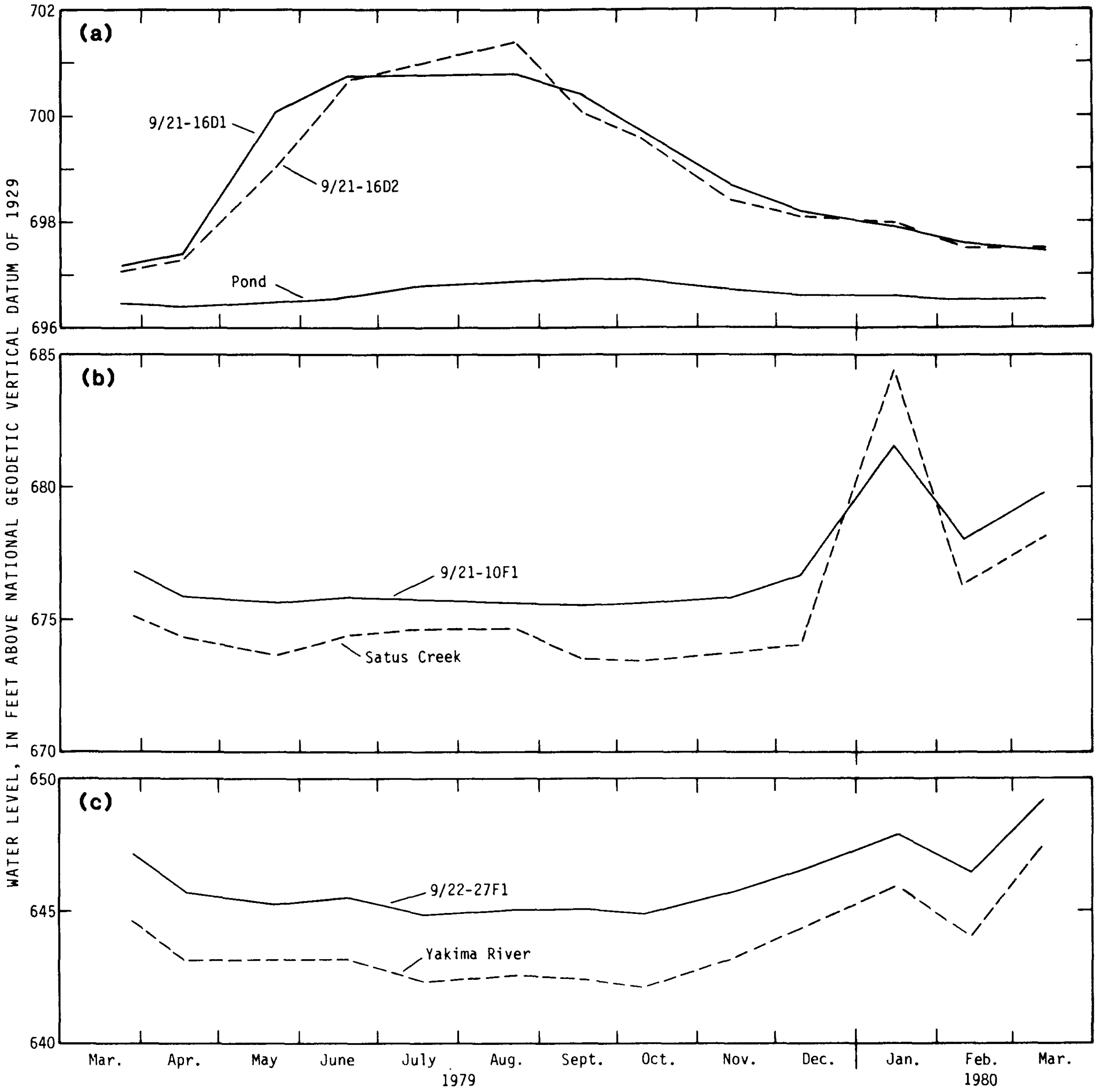



FIGURE 10.--Seasonal variations of water levels (a) in two wells and adjacent pond, one in the upper Ellensburg Formation (9/21-16D1) and one in Touchet Beds of Flint (1938) (9/21-16D2), (b) of Satus Creek and in adjacent well in Touchet Beds of Flint (1938), and (c) of Yakima River and in adjacent well in Touchet Beds of Flint (1938).

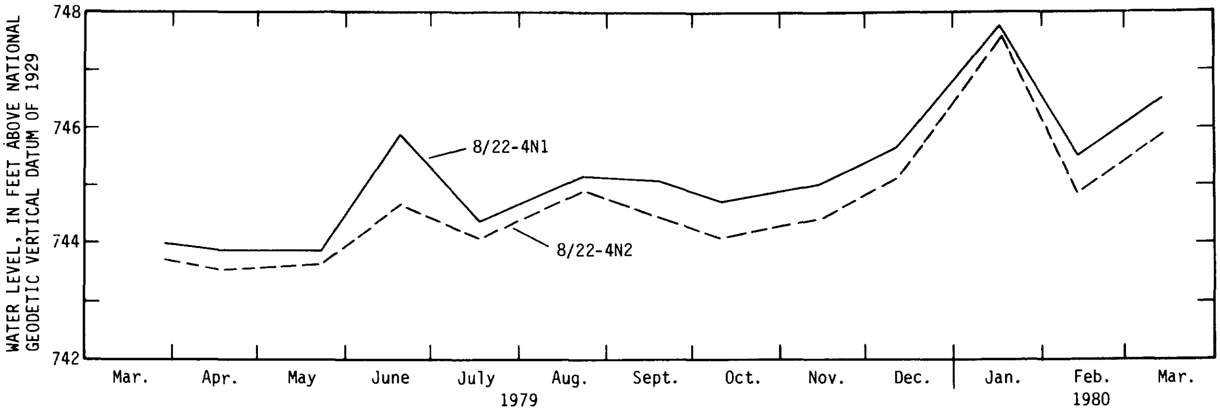



FIGURE 11.--Seasonal variations of water levels in adjacent wells in upper Ellensburg Formation (9/22-4N1) and in Touchet Beds of Flint (1938)(8/22-4N2).

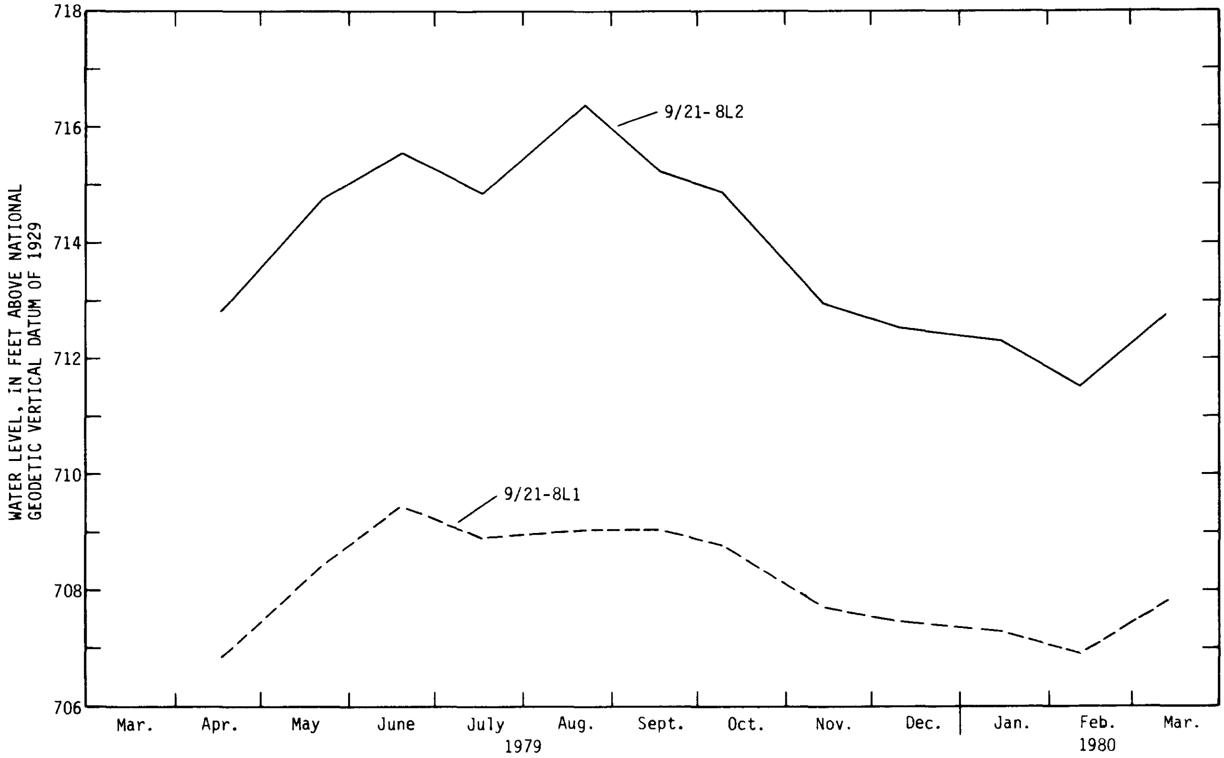



FIGURE 12.--Seasonal variations of water levels in adjacent wells near bottom (9/21-8L1) and near top (9/21-8L2) of old alluvium.

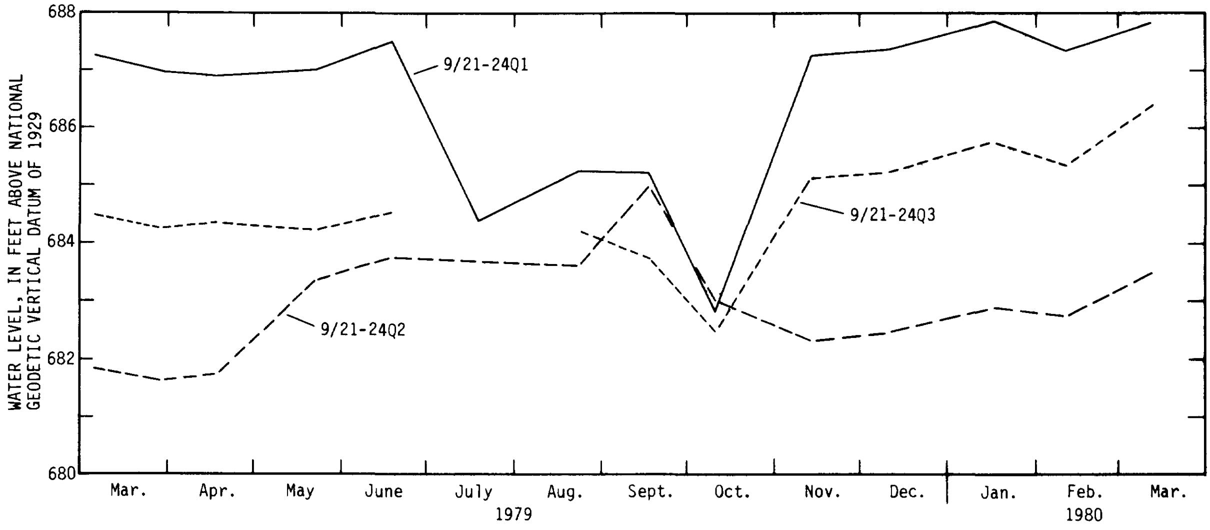



FIGURE 13.--Seasonal variations of water levels in three adjacent wells in Saddle Mountains Basalt (9/21-24Q1), in upper Ellensburg Formation (9/21-24Q3), and in Touchet Beds of Flint (1938)(9/21-24Q2).

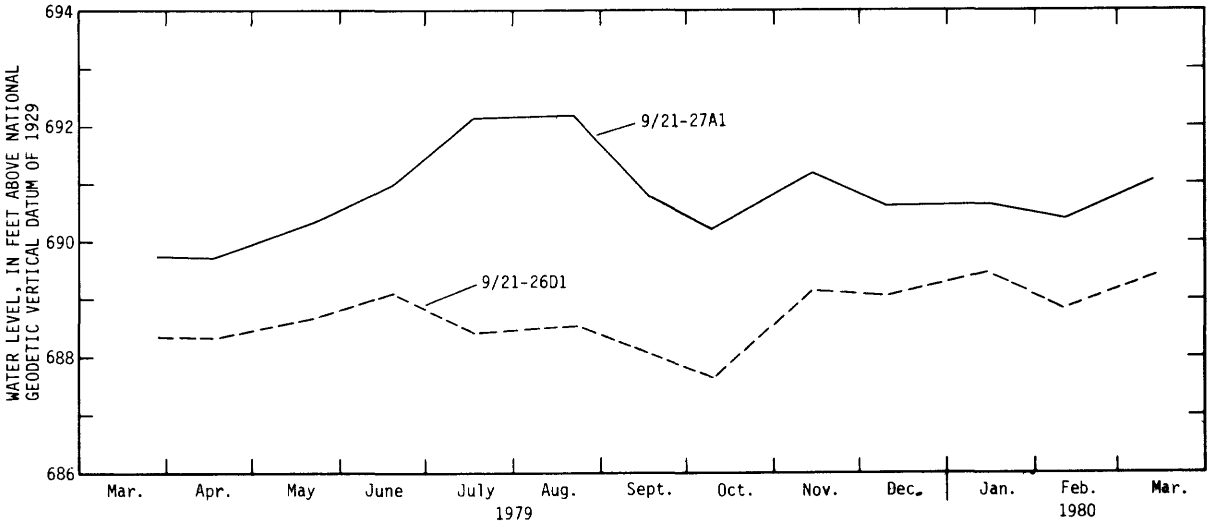



FIGURE 14.--Seasonal variations of water levels in adjacent wells in upper Ellensburg Formation (9/21-27A1) and in Touchet Beds of Flint (1938)(9/21-26D1).

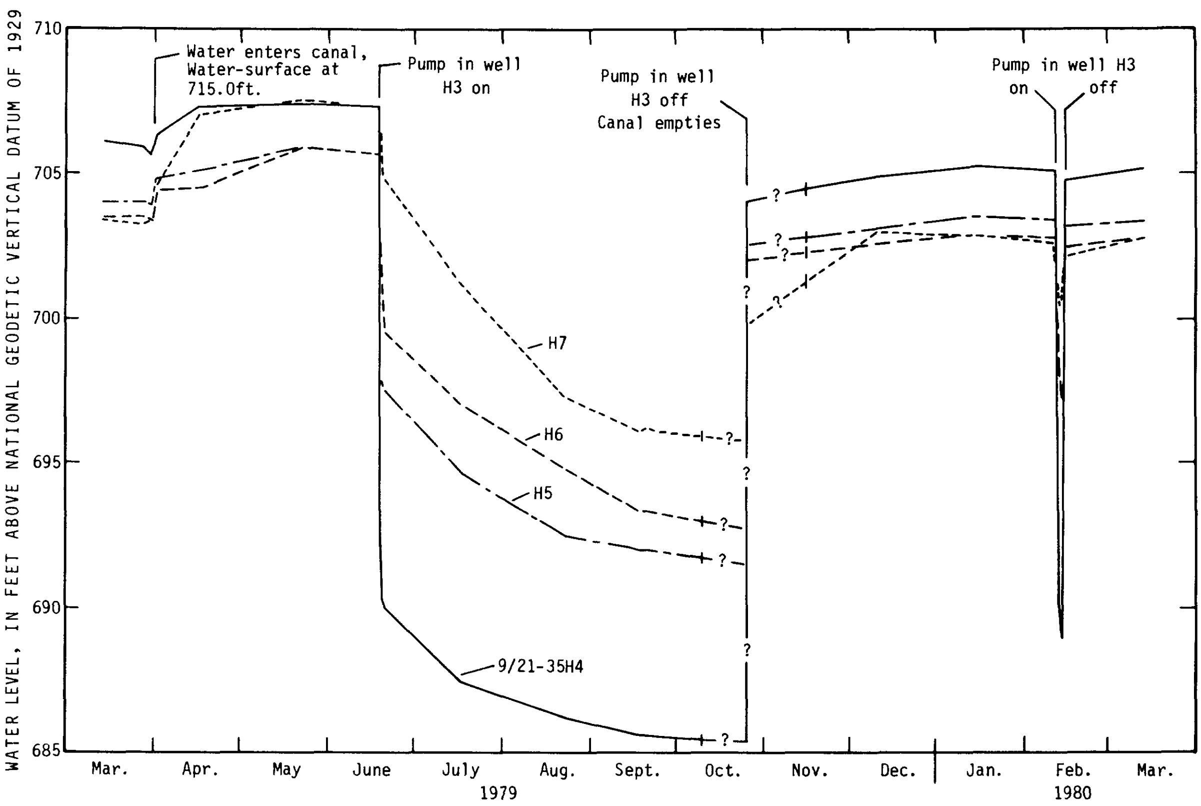



FIGURE 15.--Seasonal variations of ground-water levels in adjacent wells in upper Ellensburg Formation (9/21-35H4 and H5), and in Touchet Beds of Flint (1938)(9/21-35H6 and H7). Evident are the effects of filling Satus No. 2 Pump Canal in April and pumping from well H3.

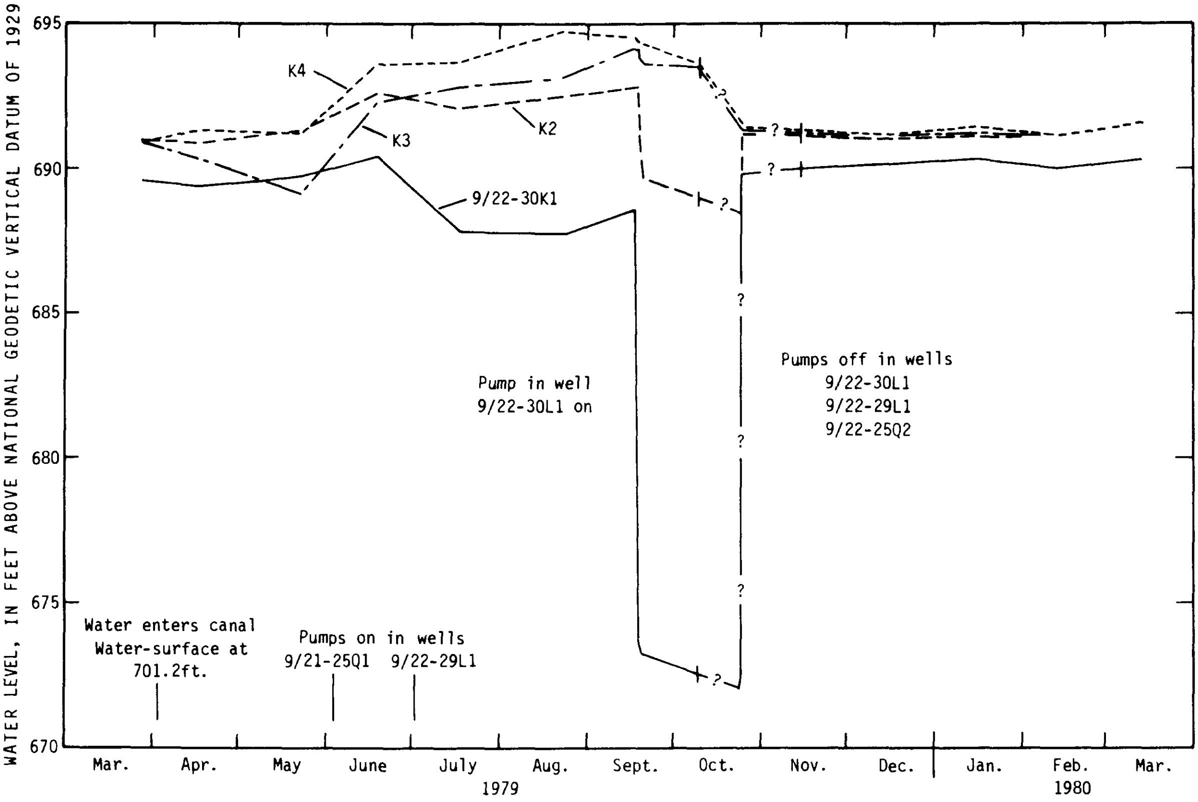



FIGURE 16.--Seasonal variations of water levels in adjacent wells in upper Ellensburg Formation (9/22-30K1) and in Touchet Beds of Flint (1938)(9/22-30K2, K3, and K4). Evident are the effects of pumping nearby well, but not of filling canal.

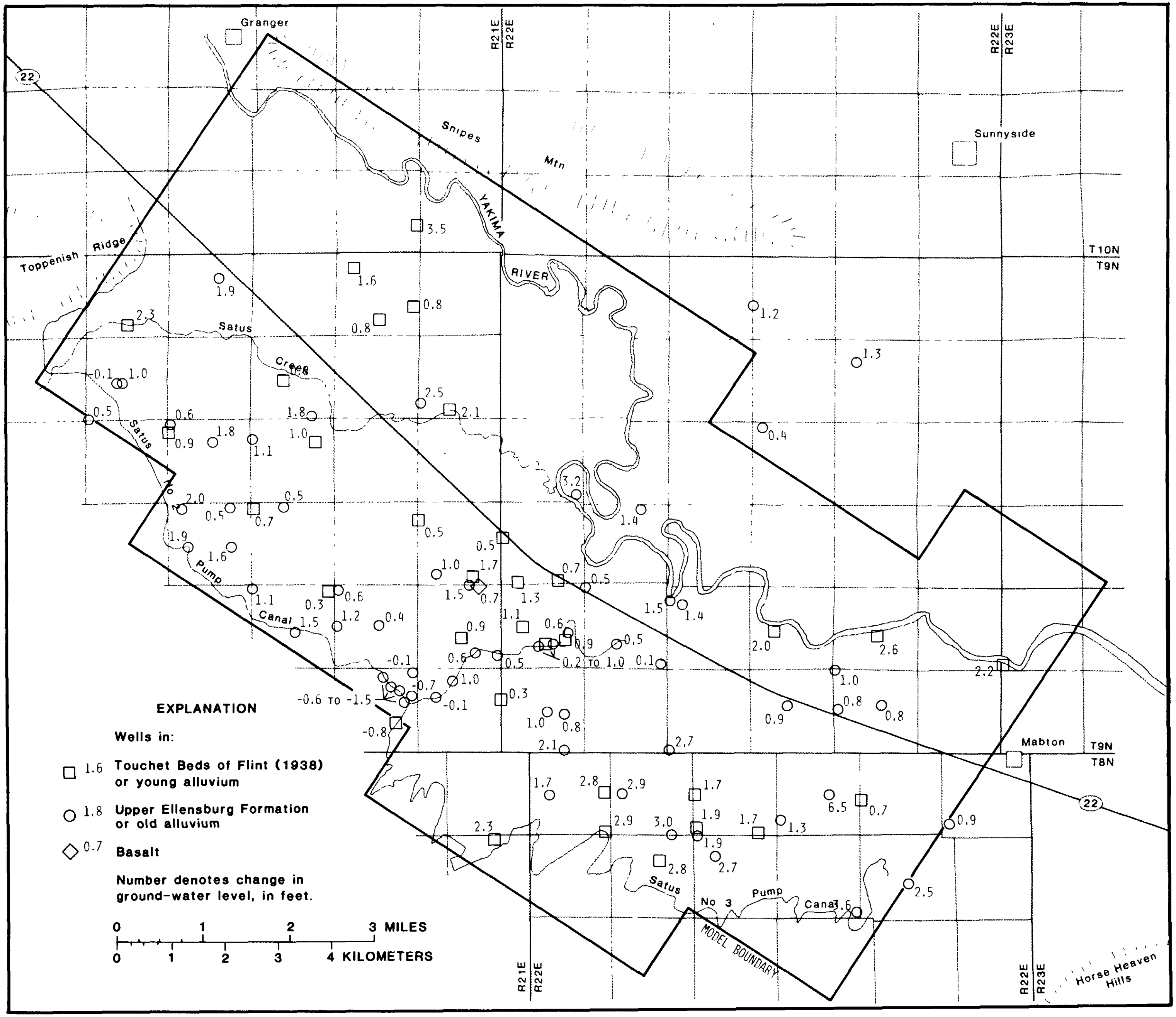



FIGURE 17.--Lower Satus Creek basin showing differences between water levels in wells observed in March 1979 and in March 1980.

## Horizontal Ground-Water Movement

Contours of ground-water heads fit to the data from wells in the old alluvium and the upper Ellensburg Formation are shown in figure 7. Because ground water flows in the general direction of decreasing head, these data show that the general flow of water in the Old Alluvium and upper Ellensburg is from the pump canals towards the Yakima River, although some flow is towards Satus Creek and the large drains in the northeast corner of the basin. The regional flow pattern in the Touchet Beds of Flint (1938) is undoubtedly similar, because water levels in this geologic unit seldom differ by more than a few feet from those in deeper wells. However, local flow directions near drains could be quite different in the shallower system.

Few data are available on water levels and, hence, flow direction in the basalts. However, Mundorff, MacNish, and Cline (1977) reported that precipitation in the Satus uplands percolates to the basalt and approximately 30,000 acre-ft/yr flows into lower Satus Creek basin. As the water flows northeast through the basin, about 20,000 acre-ft/yr discharges vertically from the basalts to the sediments, and eventually to the Yakima River. The remaining 10,000 acre-ft/yr, together with ground water from other sources, leaves the basin as ground-water outflow near Mabton. Ground-water inflow from the Toppenish Valley probably occurs at all depths near the Yakima River in the northwest corner of the basin.

## Vertical Ground-Water Movement

Mundorff, MacNish, and Cline (1977) postulated that the Old Alluvium and upper Ellensburg were being recharged from above through the Touchet Beds of Flint (1938) and also from below via the basalt. This concept was checked by computing differences between water levels in adjacent wells of different depths. Because ground water moves in the direction of lower head, these differences indicate the direction of vertical water movement. Table 6 lists differences of time-averaged water levels for adjacent wells. The seasonal variation in the differences at selected sites can be inferred from the data in figures 10 through 16. The averaging periods for computing the differences were selected to exclude the local effects of nearby pumping wells or canal leakage so that the differences would more likely indicate regional flow directions. The data from most sites for which data are available for a 12-month period show that the vertical flow is unidirectional most of the year. Therefore, averages of data from only part of a year usually can be expected to indicate the correct mean-annual-flow direction.

At the one location, 9/21-24Q, where one well in the set is in the basalt, the data show that the old alluvium is being recharged from below, as was expected. In 6 of the 11 sections where water levels are available in the Touchet Beds and the old alluvium or upper Ellensburg Formation, the data show that the flow is definitely downward. In another section (9/21-16, fig. 10) the annual-average flow is down, but the gradient is small and its direction changes during the year (fig. 10). The indicated movement is upward at 9/21-24Q, where the Touchet Beds are unusually sandy and permeable. In this area water probably discharges freely to South Drain. Part of the discharged water is probably transmitted from the deeper geologic units.

The data in table 6 indicate an upward flow of water from the Ellensburg Formation to the Touchet Beds in the northeastern part of 9/21-35. Note that the head in well H1 is 6.6 ft above land surface. However, Satus No. 2 Pump Canal still leaks water to the ground-water system in this region (see fig. 15). Here the canal is cut into the foothills and the normal canal water level is about 15 ft above the land surface at well H1. The reason for the upward flow of ground water in this area is probably a combination of a relatively low land surface altitude and recharge in higher altitudes of the southern halves of 9/21-35 and 36 and in 8/21-01 and 02. The sources of the recharge are probably leakage from Satus No. 3 Pump Canal, which begins in 9/21-35 at an altitude of about 100 ft higher than the land surface at well H1, and percolation of irrigation water applied to the higher lands.

No explanation can be given for the apparent upward flow to the Touchet Beds of Flint (1938) at 8/22-4N or 9/21-21K. These are irrigated areas and the expected vertical flow direction is downward.

TABLE 6.--Differences in water levels (a) between adjacent wells at different depths; and (b) between surface waters and adjacent wells. Positive differences denote upward flows; negative differences denote downward flows. Geologic unit numbers denote (1) Saddle Mountains Basalt, (2) old alluvium or upper Ellensburg, and (3) young alluvium or Touchet Beds of Flint (1938)

(a)

| LOWER WELL | | UPPER WELL | | AVERAGE WATER LEVEL DIFF. LOWER-UPPER (FT) | AVERAGING PERIOD |
|---|---|---|---|---|---|
| WELL NUMBER | GEO-LO-GIC UNIT | WELL NUMBER | GEO-LO-GIC UNIT | | |
| 8/22-04N1 | 2 | 8/22-04N2 | 3 | 0.31 | MAR79-MAR80 |
| 8/22-05E1 | 2 | 8/22-06H1 | 3 | -0.52 | SEP79-MAR80 |
| 9/21-08L1 | 2 | 9/21-08L2 | 2 | -5.73 | APR79-MAR80 |
| 9/21-16D1 | 2 | 9/21-16D2 | 3 | 0.09 | MAR79-MAR80 |
| 9/21-21K1 | 2 | 9/21-21K2 | 3 | 1.99 | DEC79-MAR80 |
| 9/21-24Q1 | 1 | 9/21-24Q3 | 2 | 2.06 | NOV79-MAR80 |
| Q3 | 2 | Q2 | 3 | 2.67 | NOV79-MAR80 |
| 9/21-26D1 | 2 | 9/21-27A1 | 3 | -2.12 | MAR79-MAR80 |
| 9/21-35B1 | 2 | 9/21-35B4 | 2 | -0.01 | NOV79-MAR80 |
| B4 | 2 | B2 | 3 | -0.14 | NOV79-MAR80 |
| 9/21-35H1 | 2 | LAND SURFACE | | 6.6 | NOV79-MAR80 |
| 9/21-35H3 | 2 | 9/21-35H4 | 2 | 0.42 | NOV79-MAR80 |
| H4 | 2 | H5 | 2 | 1.75 | NOV79-MAR80 |
| H5 | 2 | H6 | 3 | 0.54 | NOV79-MAR80 |
| H6 | 3 | H7 | 3 | -0.03 | NOV79-MAR80 |
| 9/21-35H8 | 2 | 9/21-35H9 | 3 | 1.51 | NOV79-MAR80 |
| H9 | 3 | H10 | 3 | 0.17 | NOV79-MAR80 |
| H10 | 3 | H11 | 3 | 0.27 | NOV79-MAR80 |
| 9/22-29R1 | 2 | 9/22-29R2 | 3 | -1.14 | DEC79-MAR80 |
| 9/22-30J1 | 2 | 9/22-30J2 | 3 | -0.13 | NOV79-MAR80 |
| 9/22-30L1 | 2 | 9/22-30L2 | 3 | -2.27 | NOV79-MAR80 |
| 9/22-30K1 | 2 | 9/22-30K2 | 3 | -0.72 | NOV79-MAR80 |
| K2 | 3 | K3 | 3 | -0.36 | NOV79-MAR80 |
| K3 | 3 | K4 | 3 | -0.06 | NOV79-MAR80 |
| 9/22-35E1 | 2 | 9/22-35E2 | 3 | -0.50 | DEC79-MAR80 |

(b)

| GROUNDWATER | | SURFACEWATER | AVERAGE WATER LEVEL DIFF. GW-SW (FT) | AVERAGING PERIOD |
|---|---|---|---|---|
| WELL NUMBER | GEO-LO-GIC UNIT | WATER BODY | | |
| 9/21-16D2 | 3 | POND 9/21-08R | 2.39 | MAR79-MAR80 |
| 9/21-35H7 | 3 | SATUS NO.2 CANAL | -7.53 | APR79-JUN79 |
| 9/22-30K4 | 3 | SATUS NO.2 CANAL | -7.67 | MAY79-SEP79 |
| 9/21-05Q2 | 3 | SATUS CR. | 2.45 | APR79-MAR80 |
| 9/21-10F1 | 3 | SATUS CR. | 1.38 | MAR79-MAR80 |
| 9/21-12P1 | 3 | SATUS CR. | 1.11 | APR79-MAR80 |
| 9/22-26K1 | 3 | YAKIMA R. | 0.45 | MAR79-MAR80 |
| 9/22-27F1 | 3 | YAKIMA R. | 2.93 | MAR79-MAR80 |
| 9/22-28D2 | 2 | YAKIMA R. | 15.20 | APR79-AUG79 |
| 9/23-30N1 | 3 | YAKIMA R. | 0.33 | MAR79-MAR80 |
| 10/21-36M1 | 3 | OX-BOW POND | -0.81 | MAR79-NOV79 |

## Ground-Water/Surface-water Interaction

The direction of flow between the ground-water system and surface waters was determined from the differences between surface-water levels and water levels in adjacent wells. Table 6 lists time-averaged differences in observed water levels; the seasonal variations in the differences at selected sites are graphed in figure 10.

Data from all three sites along Satus Creek indicate that water normally flows from the ground-water system into the creek. Only during January 1980, and only at wells 9/21-05Q and 9/21-10F1, did the observed water levels indicate flow from the creek into the ground-water system.

Data from both sites along Satus No. 2 Pump Canal indicate that the canal leaks water to the ground-water system. Tests conducted to estimate the leakage rates were described earlier in subsection Canal Leakage, page 10.

Data from the four sites along the Yakima River indicate that flow is from the ground-water system to the river. Only during December 1979, and only at well 9/23-30N1, do the data indicate a flow from the river into the ground-water system.

All the observation sites along the Yakima River were in the downstream or eastern half of the study basin. The closest well to the river in the upstream half was 10/21-36M1, which is about 1,500 ft from the main river channel, but is adjacent to an ox-bow pond, through which part of the river flows during periods of high water. Water-level measurements in this well and data from a topographic map indicate that the ground-water level at this site was about 3 ft higher than the river; unfortunately, the accuracy of altitudes obtained from the maps is only 5 ft. Observed water levels in the well were below the pond level from March through November 1979. During this period the pond did not appear to be connected to the river. No pond levels were available for periods of higher river stages when part of the river flowed through the pond. Therefore, there are no conclusive data to show that ground-water discharges to the Yakima River in the western half of the study basin. Nevertheless, the regional ground-water head distribution (fig. 7) strongly suggests that it does.

## Ground-Water Pumping

The locations of wells and amounts of ground water pumped for the period April 1979 through March 1980 are listed in table 7. Four of the wells - 35H3, 25Q1, 29L1, and 30L1 - were used for the first time in the summer of 1979. These are four of about 31 drought-relief wells in lower Satus Creek basin that were drilled in 1977 and 1978 by the Wapato Irrigation District. The four discharge directly into Satus No. 2 Pump Canal, so that the water from them is distributed by the present canal system. Presently (1980), the other drought-relief wells are unused. It was the intent of the Irrigation District to use water from drought-relief wells to augment the present supply for irrigating existing farmlands during years of water shortage and to supply water for irrigating newly developed lands during years with normal or excess water. An additional anticipated benefit of pumping these wells is the lowering of ground-water levels in waterlogged areas.

TABLE 7.--Major withdrawals of ground water in and near lower Satus Creek basin during April 1979 through March 1980

| Well number | Model layer and node | Amount pumped (acre-ft) | Average rate ($ft^3/s$) | Geologic unit | Comments |
|---|---|---|---|---|---|
| 8/22-1G1, G2, G3 | | 210 | -- | Wanapum and Grande Ronde Basalts | Mabton municipal supply; outside basin boundary. Amount from 1975 records, partly estimated. |
| 9/21-14G1 | II 5-5 | 270 | 0.37 | Old alluvium(?) | Irrigation, Wapato Irrigation District. |
| 9/21-24N1 | II 6-7 | 460 | .64 | Old alluvium | Irrigation, amount estimated, privately owned. |
| 9/21-25Q1 | II 6-8 | 1,510 | 2.10 | Upper Ellensburg | Irrigation, Wapato Irrigation District. |
| 9/21-26J | I 7-7 | 140 | .2 | Touchet Beds of Flint (1938) | Drain-field sump; amount estimated. |
| 9/21-35A | I 7-7 | 360 | .5 | ---do.--------- | Do. |
| 9/21-35H3 | II 7-7 | 690 | .95 | Upper Ellensburg | Irrigation, Wapato Irrigation District. |
| 9/22-29L1 | II 5-9 | 520 | .71 | ---do.--------- | Do. |
| 9/22-30L1 | II 6-8 | 440 | .61 | ---do.--------- | Do. |

## Hydraulic Properties of Geologic Units

### Definitions

The hydraulic properties of the geologic units needed in the numerical model of ground-water flow are those that quantify the ability of the geologic unit to conduct and to store water.

Darcy's Law is an equation used to compute flow rates through porous material. For flow in a horizontal, x, direction one writes

$$Q_x = -Ak_x\Delta_x h/\Delta x, \qquad (1)$$

where $Q_x$ is the flow rate through an area A perpendicular to x; $\Delta_x h$ is the change in hydraulic head across the distance $\Delta x$ that is parallel to the flow direction; and $k_x$ is the hydraulic conductivity in the x-direction, which is a function of the material. The hydraulic conductivity of a geologic unit is usually also a function of direction. Typically, the hydraulic conductivity in the horizontal direction, called $k_x$ in this report, is larger than in the vertical direction, $k_z$.

To calculate the horizontal flow through a part of a geologic unit that has a thickness b and an arbitrary width w, one substitutes in equation 1 the product wb for A,

$$Q_x = -wbk_x\Delta_x h/\Delta x = -wT\Delta_x h/\Delta x\ , \qquad (2)$$

where $T = bk_x$ is called the transmissivity of the geologic unit.

To calculate the vertical flow, $Q_z$, through a part of a geologic unit of thickness b, equation 1 becomes

$$Q_z = -A\,k_z\Delta_z h/b = -AK\Delta_z h\ , \qquad (3)$$

where $K = k_z/b$ is called a leakage coefficient and $\Delta_z h$ is the difference between the hydraulic heads above and below the unit.

A geologic unit gains or loses water from storage in response to changes in hydraulic head. The storage coefficient, S, is defined as the volume change in storage per unit horizontal area of the geologic unit per unit change in hydraulic head. Changes in storage are due to the elasticity of the geologic unit and the water and, in the presence of a water table, due to the filling and draining of pore spaces that occurs with a raising and lowering of the water table. The storage coefficient for a water-table aquifer is much larger than for a confined aquifer.

## Transmissivity of Wanapum and Grande Ronde Basalts

The only available data for estimating the transmissivity of the lower basalt formations, which form layer I in the numerical model, are specific capacities of wells that are located outside the eastern boundary of the study area. (The specific capacity of a well is defined as the pumping rate divided by the drawdown in the well.) A rough estimate of the transmissivity of an aquifer can be obtained by using the rule-of-thumb formula,

$$\text{Transmissivity in } ft^2/s = 0.003 \times \text{specific capacity in (gal/min)/ft.} \qquad (4)$$

Equation 4 is a simplification of a more precise expression given by Brown (1963), and has been used by Tanaka and others (1974) to estimate transmissivities of formations in the Columbia River Basalt Group. Table 8 lists specific capacities of wells in the Wanapum and Grande Ronde Basalts and the estimated transmissivities.

TABLE 8.--Specific capacities of wells in Wanapum and Grande Ronde Basalts, and transmissivities estimated using the formula: Transmissivity in square feet per second equals 0.003 times specific capacity in gallons per minute per foot of drawdown

| Well number | Pumping rate (gal/min) | Draw-down (ft) | Specific capacity (gal/min/ft) | Trans-missivity ($ft^2/s$) |
|---|---|---|---|---|
| 8/22-1G1 | 300 | 15 | 20 | 0.060 |
| -1G2 | 950 | 23 | 41 | .12 |
| -1G3 | 450 | 74 | 6.1 | .018 |
| -11J1 | 1,300 | 276 | 4.7 | .014 |
| -12H1 | 210 | 120 | 1.8 | .0054 |
| -12J1 | 180 | 237 | .76 | .0023 |
| 9/21-26M1 | 325 | 104 | 3.1 | .0093 |
| Average | | | | .033 |

## Leakage Coefficients of Saddle Mountains Basalt and Beverly Member of Ellensburg Formation

As mentioned earlier (p. 13), the Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation are relatively poor conductors of water. Consequently, their ability to convey water horizontally is not included in the numerical model. However, their ability to hinder the vertical flow of water between the lower basalt unit and the upper Ellensburg or old alluvium is a necessary feature of the model and must be included in the value of the leakage coefficient for computing vertical flow between these two layers.

An average leakage coefficient, $K = 2 \times 10^{-9} s^{-1}$, was computed using equation 3. The horizontal area, A, used was 58.5 $mi^2$, which is the area south of the Yakima River that is included in the model; a vertical flow rate, Q, of 20,000 acre-ft/yr was used, which is the previously estimated total flow from the lower basalt to the upper Ellensburg unit. The difference in head, $\Delta_z h$, was assumed to be 10 ft, which is known only to within an order of magnitude. This estimate was obtained from data at these locations: (1) at well 8/22-1G1, where the heads in the Ellensburg had to be estimated from poorly defined contours, 12 ft; (2) at well 9/21-24Q, where the lower well was in the upper rather than lower basalt, 5 ft; and (3) at well 9/21-26M1, where the only water-level measurement in this basalt well was made in 1972, 14 ft.

The average vertical hydraulic conductivity for the geologic section consisting of the Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation was estimated by multiplying the leakage coefficient by the thickness of the section (approximately 200 ft) to give $k_z = 4 \times 10^{-7}$ ft/s. This value was within the expected range for fine-grained sediments and for basalts of poor hydraulic conductivity (Freeze and Cherry, 1979, p. 29).

## Hydraulic Conductivities of Upper Ellensburg and Old Alluvium

Estimates of the horizontal hydraulic conductivity of the upper Ellensburg and old alluvium were made from specific capacities of wells located throughout the study area and from aquifer tests at wells 9/21-35H3 and 9/22-30L1. A representative value for the horizontal hydraulic conductivity for these geologic units was found to be about $10^{-3}$ ft/s.

Specific capacities for most of the Wapato Irrigation District's 31 drought-relief wells and for a few other wells in the basin can be computed using drillers' pump-test data. Estimates of the horizontal hydraulic conductivities at these well sites were obtained by dividing transmissivities computed with equation 4 by the lengths of well screen or perforated well casing. These conductivities appear in figure 18. Hydraulic conductivities computed with data from wells in the old alluvium or Upper Ellensburg Formation ranged from less than $0.01 \times 10^{-3}$ ft/s to $35 \times 10^{-3}$ ft/s; the median was $0.83 \times 10^{-3}$ ft/s. There were no obvious large-scale areal groupings of the data.

Horizontal hydraulic conductivities were also estimated from drawdowns measured in the vicinity of pumped wells. Two different techniques, both described by Bennett and others (1967), were used to make estimates from data collected during pumping from wells 9/21-35H3 and 9/22-30L1. These estimates are probably more accurate than those obtained from the specific capacities of the wells.

In one method, the drawdowns of all affected wells in the pumped aquifer were plotted as a function of the radial distance from the pumped well. These data were fitted to an analytic curve that was derived by Jacob under the assumption that a steady-state flow throughout the entire thickness of the pumped aquifer is maintained by leakage from a water-table aquifer through a semipervious layer. Analyses of data from tests of wells 9/21-35H3 and 9/22-30L1 both yielded horizontal hydraulic conductivities of $1.4 \times 10^{-3}$ ft/s. The conductivities given by this method are averages over the entire thickness of the aquifer.

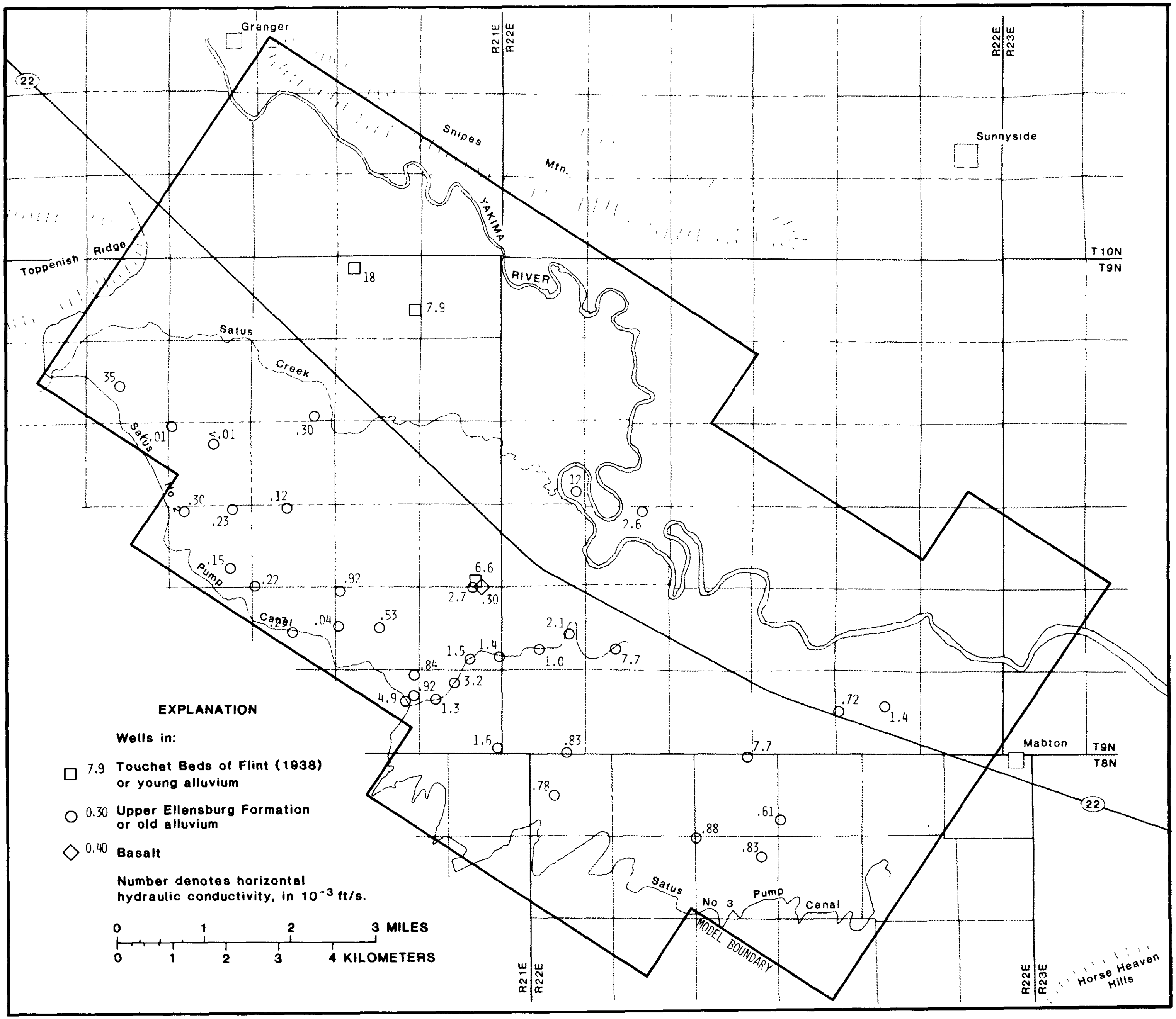



FIGURE 18.--Lower Satus Creek basin showing horizontal hydraulic conductivities estimated from specific capacities of wells.

In the other method it was assumed that all flow is radial and within the screened interval of the pumped well. Drawdowns in wells close to (within a few hundred feet) and within the screened interval of the pumped well were plotted as a function of the logarithm of the distance from the pumped well. The horizontal hydraulic conductivity was estimated from the slope of the plotted data (Bennett and others, 1967, eq. 24). This analysis, performed only with data from the test with well 9/21-35H3, indicated that the horizontal hydraulic conductivity of the material in the screened interval is $7.8 \times 10^{-3}$ ft/s. The difference in values given by the two techniques is partly due to the fact that the first method gives an average value for the entire thickness of the layer, but the other gives a value for only the screened interval, which would normally be more permeable than the average. If one assumes that the hydraulic conductivity of the nonscreened interval is so small that it adds little to the transmissivity of the layer, then the depth-averaged horizontal hydraulic conductivity for the layer can be obtained by multiplying the value $7.8 \times 10^{-3}$ ft/s by the thickness of the screened interval (20 ft) and dividing by the layer thickness (87 ft) to give $k_x = 1.8 \times 10^{-3}$ ft/s. This value is much closer to the $1.4 \times 10^{-3}$ ft/s obtained by the first (Jacob's) method. The remaining difference could easily be due to inaccuracies in the methods that result from failures to fulfill exactly all the assumptions that are made in the derivations of the equations used in the methods.

No data were available for directly estimating the vertical hydraulic conductivity, $k_z$, of the material composing the old alluvium or upper Ellensburg. The order of magnitude of $k_z$ can be estimated by dividing the horizontal hydraulic conductivity, $k_x$, by the ratio $k_x/k_z$, which was assumed to be $10^3$, to give:

$$k_z = (10^{-3} \text{ ft/s})/(10^3) = 10^{-6} \text{ ft/s}.$$

This ratio is about 10 times the average found by Bennett and others (1967) in the Punjab Plain of West Pakistan. The larger value was used because the sediments in the upper Ellensburg Formation are believed to be more heterogeneous and to contain more fine material than those in the Punjab Plain.

## Hydraulic Conductivity of Young Alluvium

Two of the Wapato Irrigation District wells, 9/21-2C1 and 2J1, are in the young alluvium. The horizontal hydraulic conductivity of the material at those two sites, as determined from specific capacities of the wells, is also shown in figure 17. The conductivities at these two locations (7.9 and $18 \times 10^{-3}$ ft/s) are higher than the typical value computed with data from wells in the upper Ellensburg Formation or old alluvium.

## Hydraulic Conductivities of Touchet Beds of Flint (1938)

Waterlogging occurs in the Touchet Beds, the surficial material in most of the study area. Therefore, the ease with which waterlogging can be alleviated by pumping ground water depends, among other things, on the vertical conductivity of these beds.

Vertical hydraulic conductivities were computed using data from a number of different locations and by a variety of techniques. The methods used to compute these conductivities are discussed below, and the results are summarized in table 9.

The analysis of data from pump tests on wells 9/21-35H3 and 9/22-30L1 by the method of Jacob as described by Bennett and others (1967) gives estimates of the vertical hydraulic conductivity of the overlying semipervious layer as well as the transmissivity of the pumped aquifer. The conductivities estimated with this method were 1.8 and 1.5 x $10^{-6}$ ft/s, respectively.

TABLE 9.--Estimates of vertical hydraulic conductivity of the Touchet Beds of Flint (1938)

| Location | Estimated vertical hydraulic conductivity ($10^{-6}$ ft/s) | Method of estimate |
|---|---|---|
| 9/21-35H | 1.8 | Analysis of data from pump test on well 9/21-35H3, using method of Jacob as described by Bennett and others (1967). |
| 9/22-30L | 1.5 | Analysis of data from pump test on well 9/22-30L1, using method of Jacob as described by Bennett and others (1967). |
| 9/21-35H | 1.9 to 3.6 | Darcy's Law with flow rate equal to evapotranspiration rate, and other data from well 9/21-35H1 |
| -35H | $\geq$5.2 | Leakage rate from Satus No. 2 pump canal. |
| -25Q | $\geq$8.3 | Do. |
| 9/22-30L | $\geq$7.4 | Do. |
| -26K | 52 | Darcy's Law with flow rate equal to ground-water discharge to Yakima River, and other data from water levels in river and adjacent wells. |
| -27F | 14 | Do. |
| -28D | 4.0 | Do. |
| 9/23-30N | 140 | Do. |

During the leakage tests on Satus No. 2 Pump Canal, the hydraulic gradients beneath the canal were probably near unity. Therefore, the effective vertical hydraulic conductivities of the Touchet Beds underlying the canal segments during the tests equaled the leakage rates. However, if the material beneath the canal was not saturated, then the observed hydraulic conductivities ($5.2$ to $8.3 \times 10^{-6}$ ft/s) would be less than the conductivities for the material when saturated.

Another estimate of the vertical hydraulic conductivity was made with data in the vicinity of well 9/21-35H1 where the ground-water head in the upper Ellensburg has usually been above the land surface. At that site the ground is marshy during most of the year but often is dry in late summer. Therefore, in late summer the vertical flow to the land surface is approximately equal to the rate of evapotranspiration. Equation 3 can then be used to estimate the vertical hydraulic conductivity, $k_z$, by substituting: the July evapotranspiration rate, about 6.5 inches per month, for Q; unity for the area; 8 ft, the height of the ground-water head above land surface before well 9/21-35H3 was pumped, for $\Delta_z h$; and for b, a number between 77 ft, the depth to the center of the well screen, and 41 ft, the thickness of the Touchet Beds at this location. With an appropriate conversion of units, $k_z$ is found to be between 1.9 and $3.6 \times 10^{-6}$ ft/s. The hydraulic conductivity of the Touchet Beds equals the lower limit if $k_z$ for the upper Ellensburg Formation is the same as for the Touchet Beds, and equals the upper limit if $k_z$ for the upper Ellensburg is much larger than for the Touchet Beds.

Other estimates of the vertical hydraulic conductivity of the Touchet Beds can be made using equation 3 and information on the discharge of ground water to the Yakima River. In making these estimates, which are also summarized in table 9, the discharges used were those computed with the numerical model (the model is described in the next chapter) for 1- to 2-mile reaches of the river centered at observation wells; the horizontal areas were that of the river; the head differences, $\Delta_z h$, were those between the river surface and the water levels in the observation wells (table 6); and the vertical distances, b, were the differences in altitudes between the screened intervals in the wells and estimated altitudes of the river bottom.

The data in table 9 show that the vertical hydraulic conductivities that were computed using data from pump tests and evapotranspiration are similar to each other but are lower than those calculated using canal leakage or ground-water discharge to the Yakima River.

A reason that the first two methods give the lowest values may be that the methods give the effective vertical conductivities for the entire thickness (65 to 90 ft) of the geologic unit, which is known to contain horizontal layers of clayey material of low hydraulic conductivity. The conductivities obtained from the canal leakage data are representative of only the upper 5 to 15 ft of material of the unit which, in some places, contains less clayey material than exists at depth. Three of the conductivities computed using the ground-water discharge to the Yakima River are also only for the upper 10 ft or less. The fourth value, at 9/22-28D, is for the upper 30 ft. The value at this location is much lower than the others; the log for well 9/22-28D2 shows clayey material throughout most of this thickness.

In summary, the effective vertical hydraulic conductivity of the Touchet Beds is of the order 1 to $2 \times 10^{-6}$ ft/s. However, locally, layers within the unit could have conductivities 50 times as high.

Data for estimating the horizontal hydraulic conductivity of the Touchet Beds are scant. One estimate, $6.6 \times 10^{-3}$ ft/s, can be made from the specific capacity of well 9/21-24Q2 (see fig. 18). The log of this and adjacent wells Q1 and Q3 indicate that the geologic material at the depth of the screen in well Q2 ranges from fine to coarse sand, which is consistent with the estimated conductivity. Because the Touchet Beds at this site are more sandy than in most other parts of the basin, this value of hydraulic conductivity is probably higher than the average for the basin, but may be typical of the sandy areas.

An estimate of the typical horizontal hydraulic conductivity can be made by multiplying the estimated vertical hydraulic conductivity by an assumed ratio of the horizontal to vertical conductivities $10^3$. Thus,

$$k_x = (2 \times 10^{-6} \text{ ft/s})(10^3) = 2 \times 10^{-3} \text{ ft/s} .$$

## Discussion of Estimated Hydraulic Conductivities

In their study of the Satus Creek basin, Mundorff and others (1977) found that wells in the upper Ellensburg Formation and old alluvium were typically more productive than wells in the Touchet Beds. To many, this implies that the hydraulic conductivity of the Touchet Beds is less than that of the other units. However, the hydraulic conductivities for the different units that were estimated in the earlier sections of this report are similar and are assumed to be the same in the numerical model that is described in the next chapter.

This apparent discrepancy can be explained if the highly productive zones occur as thin layers or as unconnected lenses or pockets of highly conductive material within a mass of material of low conductivity. The gross effective hydraulic conductivity of such a unit would be considerably less than the local conductivity of the material in the productive zones. Such is probably the case in the upper Ellensburg Formation. Typically, well logs show that productive zones in this unit occupy only a fraction of the total thickness of the unit, are not readily correlatable between wells that are more than ½ mile apart, and are not found at every well site.

The old alluvium is also stratified and nonhomogeneous, but not as much so as the upper Ellensburg Formation. Therefore, the above reasoning may also be used, but with less certainty, for explaining the similarity in the estimated conductivity for the old alluvium and Touchet Beds.

## Storage Coefficients

Only the storage coefficient of the geologic unit with the water table is of importance in the computations performed in this study. Because this unit, typically the Touchet Beds, is mostly silt and fine sand, the average storage coefficient is probably between 0.05 and 0.15 (Johnson, 1967). A value of 0.1 was used in this study.

# MODEL CONSTRUCTION AND CALIBRATION

## Description of General-Purpose Model

A multilayer numerical model of steady-state ground-water flow in the lower Satus Creek basin was constructed using the general-purpose model and program for three-dimensional ground-water flow described by Trescott (1975). The option employed solves numerically a set of equations of the type:

$$\frac{\partial}{\partial x}(T\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T\frac{\partial h}{\partial y}) + (K\Delta_z h)_u - (K\Delta_z h)_d = S\frac{\partial h}{\partial t} - W, \qquad (5)$$

where there is one equation for each layer. The variables x and y are rectangular coordinates in the horizontal plane, and t is time. By using finite difference methods, the computer program solves the equations for h, the ground-water heads at points on a rectangular grid in each of the layers. Most of the other variables in the equation are input data to the model or are calculated by the computer program from the input data. They are: T, transmissivity; K, leakage coefficient between layers; S, storage coefficient; and W, a source and sink function expressed as a discharge rate per unit horizontal area. The function W usually includes such things as pumping from wells and recharge by percolating irrigation water or precipitation. The quantity $\Delta_z h$ is the difference in head between adjacent layers, and the subscripts u and d refers to the layers above and below, respectively. Layer thickness is not explicity required as input data to the model; however, the thickness does appear implicitly in the definitions of T and K. All the above variables can be functions of x and y and be different for each layer, and W can also be a function of time. Although the general-purpose model has the capability to automatically adjust the transmissivity of the top layer to account for changes in saturated thickness that accompany changes in water-table altitude, this feature was not incorporated into the lower Satus Creek basin model because water-level changes were small relative to saturated thickness. Errors caused by this omission were reduced by correcting the model-computed heads as described in the section on model use.

To use the general model, a rectangular grid is overlayed on a map of the study area, and values of the input variables are specified for each rectangular block (node) in every layer. The grid dimensions are part of the input data. The model, in turn, computes ground-water heads for every node of each layer.

In addition to specifying the above input data, a solution to equation 5 requires that boundary conditions be specified. In physical terms this means that on all the model's external boundaries, either the ground-water heads or the flows through the boundaries must be given.

In this study the model was used mostly to estimate changes in steady-state ground-water heads. Because of seasonal variations in recharge, the ground-water system is never truly in steady-state; therefore, a time-averaged model, which is nearly identical to a steady-state model, was used for calibration. The time-averaging period was 12 months.

To compute steady-state heads one need only to delete the term with the time derivative from equation 5. In the model this is done by setting $S = 0$ in the input data. To compute time-averaged heads one must make a slight modification to equation 5. Time-averaging equation 5 yields the expression:

$$\frac{\partial}{\partial x}\left(T \frac{\partial \bar{h}}{\partial x}\right) + \frac{\partial}{\partial y}\left(T \frac{\partial \bar{h}}{\partial y}\right) + (K \Delta_z \bar{h})_u - (K \Delta_z \bar{h})_d = - \bar{W}_s \text{ ,} \qquad (6)$$

where

$$\bar{W}_s = \bar{W} - s \Delta_t h / \Delta t$$

and the overbars denote time-averaged quantities. The term $\Delta_t h$ is the net change in head over the averaging period of length $\Delta t$, and $-S\Delta_t h/\Delta t$ represents the average rate of release of water from storage during this period. Because equation 6 is of the same form as the steady-state equation (eq. 5 with $S\partial h/\partial t$ deleted), the general-purpose model program can be used to compute time-averaged heads if one sets $S = 0$ in the input data (just as for computing steady-state heads). However, the actual values of S must still be used to evaluate the change-in-storage component of $\bar{W}_S$.

The general-purpose model is capable of computing the variation of ground-water heads with time that occur when the function W changes with time (for example, because of seasonal variations in recharge or when new wells are pumped). This feature was used very little in this study.

## Geometry of Lower Satus Creek Basin Model

### Ground-Water System

The 71 $mi^2$ included in the lower Satus Creek basin model and the uniform 1-mile square grid are shown on plate 1. A particular grid, or node, is referred to by giving the row and column indices. For example, the city of Mabton is at (4,14).

Vertically, the model contains three layers, which are numbered from bottom to top using Roman numerals. Layer I contains the Wanapum and Grande Ronde Basalts; layer II contains the upper Ellensburg and old alluvium, and layer III contains the Touchet Beds and the young alluvium (see table 5). The ability of each of these layers to convey water horizontally and to leak water vertically to adjacent layers is modeled, as well as the ability of the top layer to leak water to, or to receive leakage from, parts of the surface-water system in the basin. The Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation have relatively low hydraulic conductivities and the amount of water moving horizontally through them is small. Therefore, it is not necessary to simulate their capability to convey water horizontally. However, the amount of water moving vertically through them and their ability to hinder the vertical flow of water between layers I and II is important, so that vertical flow through them is incorporated in the model through the value of the leakage coefficient for vertical flow between layers I and II.

The variations in total thickness of layer II and of the saturated thickness of layer III were computed from the data in figures 5, 6, and 7 and appear in figure 19. No data are available for the thickness of layer I.

### Surface-Water System

An important hydrologic process in the basin is flow between the ground-water and surface-water systems. In the model, the surface-water system is represented by a fourth layer (above layer III). Included are the Yakima River, Satus Creek, and miscellaneous drains and swamps. Leakage to or from the streams in this layer is computed with equation 3. The head difference is that between layer III, which is computed by the model, and the surface-waters, which are specified in the input data. The area used in equation 3 is the horizontal area of stream surface. The irrigation canals are not included in the fourth layer, but leakage rates from the canals are input data to the model.

Figure 20 shows the surface-water altitudes and areas at each node where the model computes a leakage rate. Some of the elevations were from observations (fig. 7), but most were estimated from topographic maps. The leakage coefficients used in equation 3 were determined by model calibration.

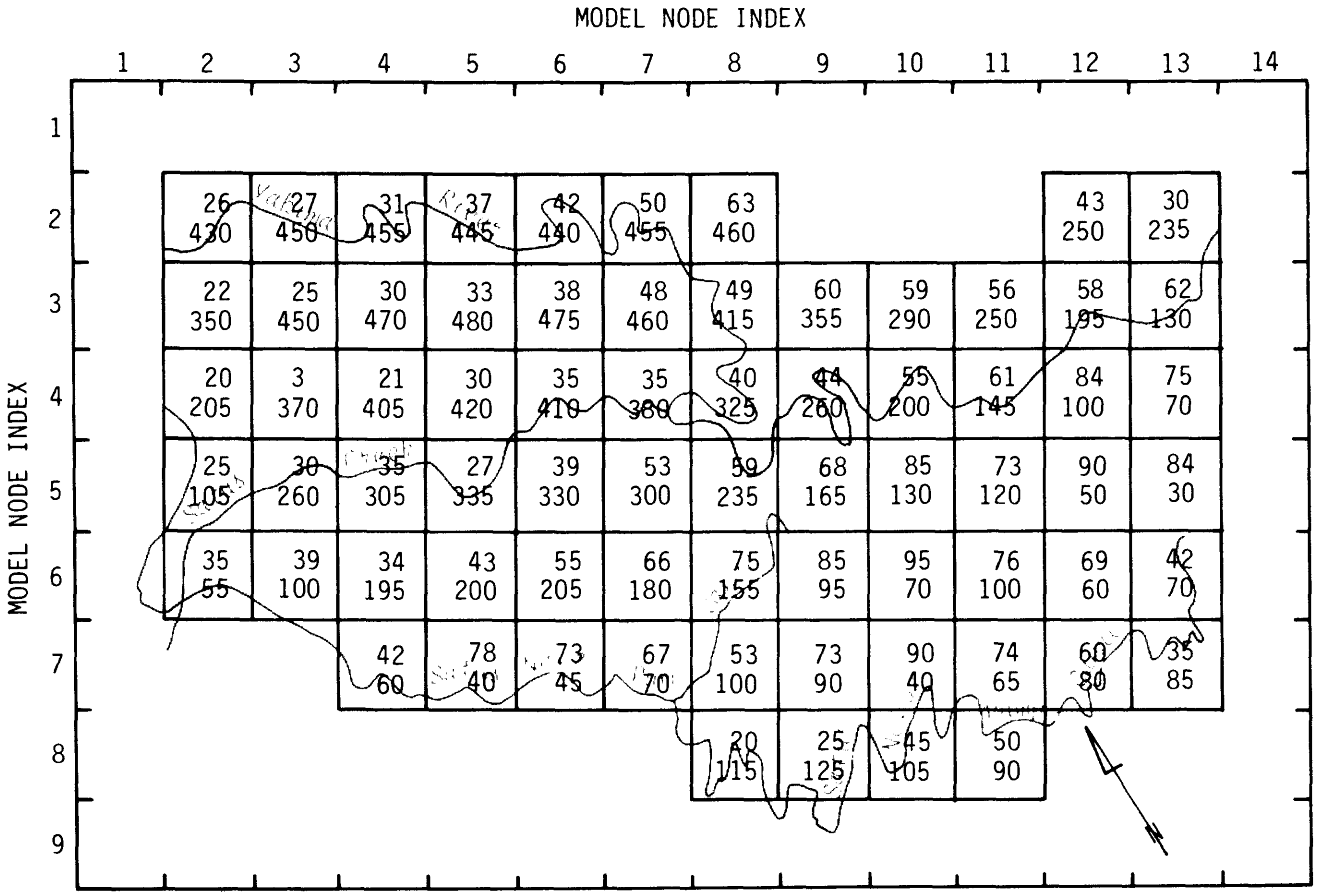



FIGURE 19.--Saturated thickness of layer III (upper number) and thickness of layer II (lower number) for each node in numerical model of lower Satus Creek basin. Thicknesses are in feet.

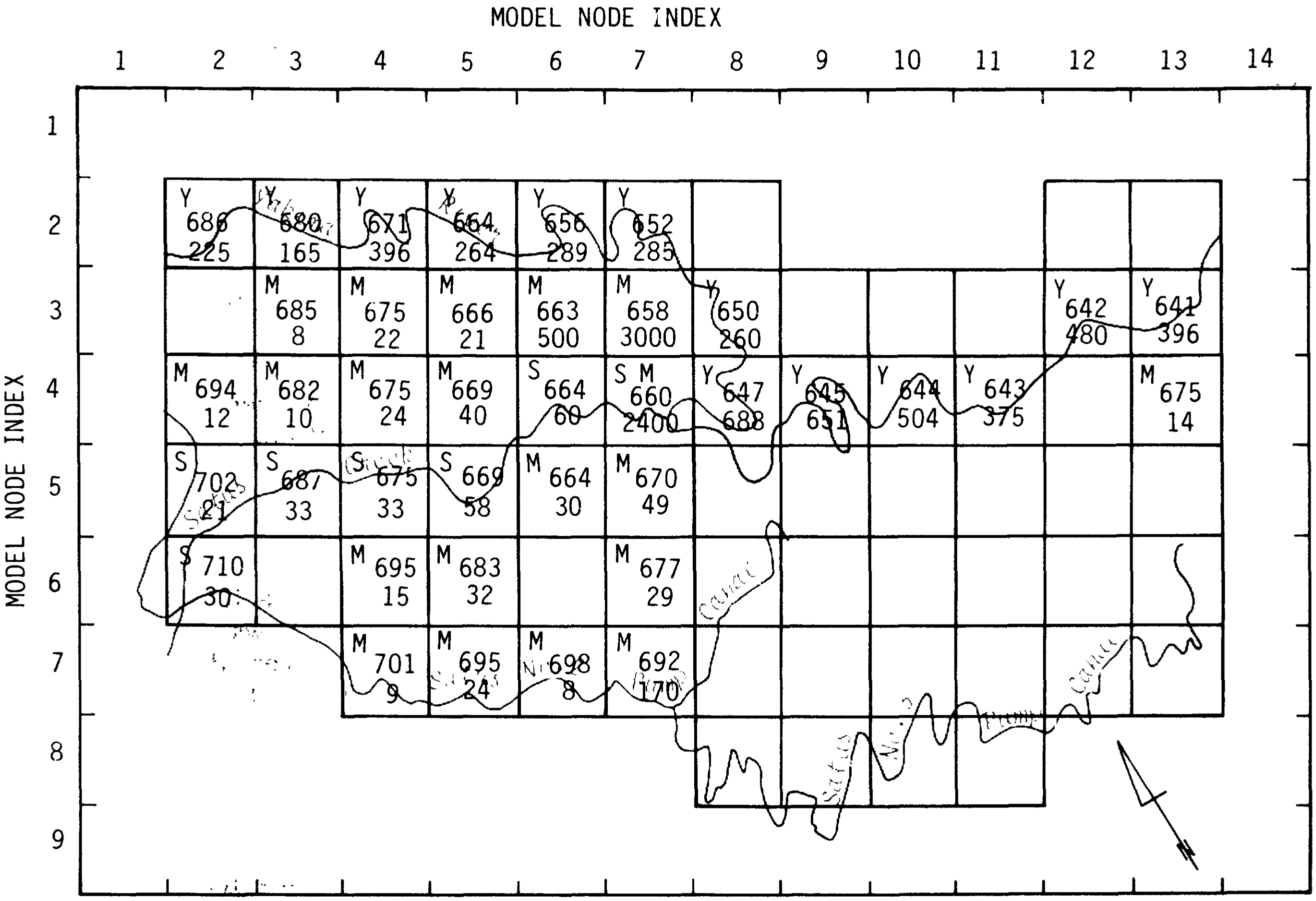



FIGURE 20.--Water-surface altitude (upper number) and water-surface area (lower number) of Yakima River (Y), Satus Creek (S), and miscellaneous drains and swamps (M) for each node in numerical model of lower Satus Creek basin. Altitudes are in feet, areas are in mile-feet.

## Model-Calibration Procedure and Data

The model of lower Satus Creek basin was calibrated to time-averaged observed water levels for the 12-month period March 1979 through March 1980. Values of the time-averaged source and sink function in equation 6, $\overline{W}_S$, were calculated for each node from available data for this period.

The calibration process consisted of making a number of calculations with the model using different values of leakage coefficients and transmissivities to determine which combination of these parameters gives the best agreement between calculated and observed ground-water heads. In the first computation, leakage coefficients and transmissivities were estimated using the information in the section entitled "Hydraulic Properties of Geologic Units." The leakage coefficient between layers I and II was then varied to obtain desired differences in heads between these two layers. Similar procedures were followed to find the optimum leakage coefficients between layers II and III, and layer III and the surface waters. Next, all transmissivities were adjusted proportionally and simultaneously to obtain the minimum difference between computed and observed time-average ground-water heads. Parameters were adjusted in the above sequence until the parameters no longer changed. Parameter values found by the calibration process are presented and discussed later in this section.

## Boundary Conditions

At each external model boundary node the user must specify for each layer either the ground-water head or flow through the boundary. Flows were specified at all boundaries in the final calibrated Satus model. However, during calibration, heads were specified along boundaries in the northern part of the model because the flows across these boundaries were unknown.

### Southern part of model

Along the model's southern boundary the lower Satus Creek basin receives an estimated 30,000 acre-ft/yr of ground-water inflow from the Satus uplands. Most of this flow probably occurs in the Wanapum and Grande Ronde Basalts, with a small fraction in the overlying sediments. In the model this flow is distributed nearly uniformly (horizontally but not vertically) across the southern boundary, as noted by the letter Q in figure 21. Because the model axis is not perfectly alined with the flow direction, some boundary flow, Q/2, was allotted to each of two stacks of model nodes on the southeasterly boundary. Also, because Satus Creek is a perennial stream, there is probably considerably more ground-water inflow through the sediments (layers II and III) along the creek than elsewhere on this boundary. Therefore, a ground-water inflow of 2Q was assigned to the vertical stack of boundary nodes centered on Satus Creek.

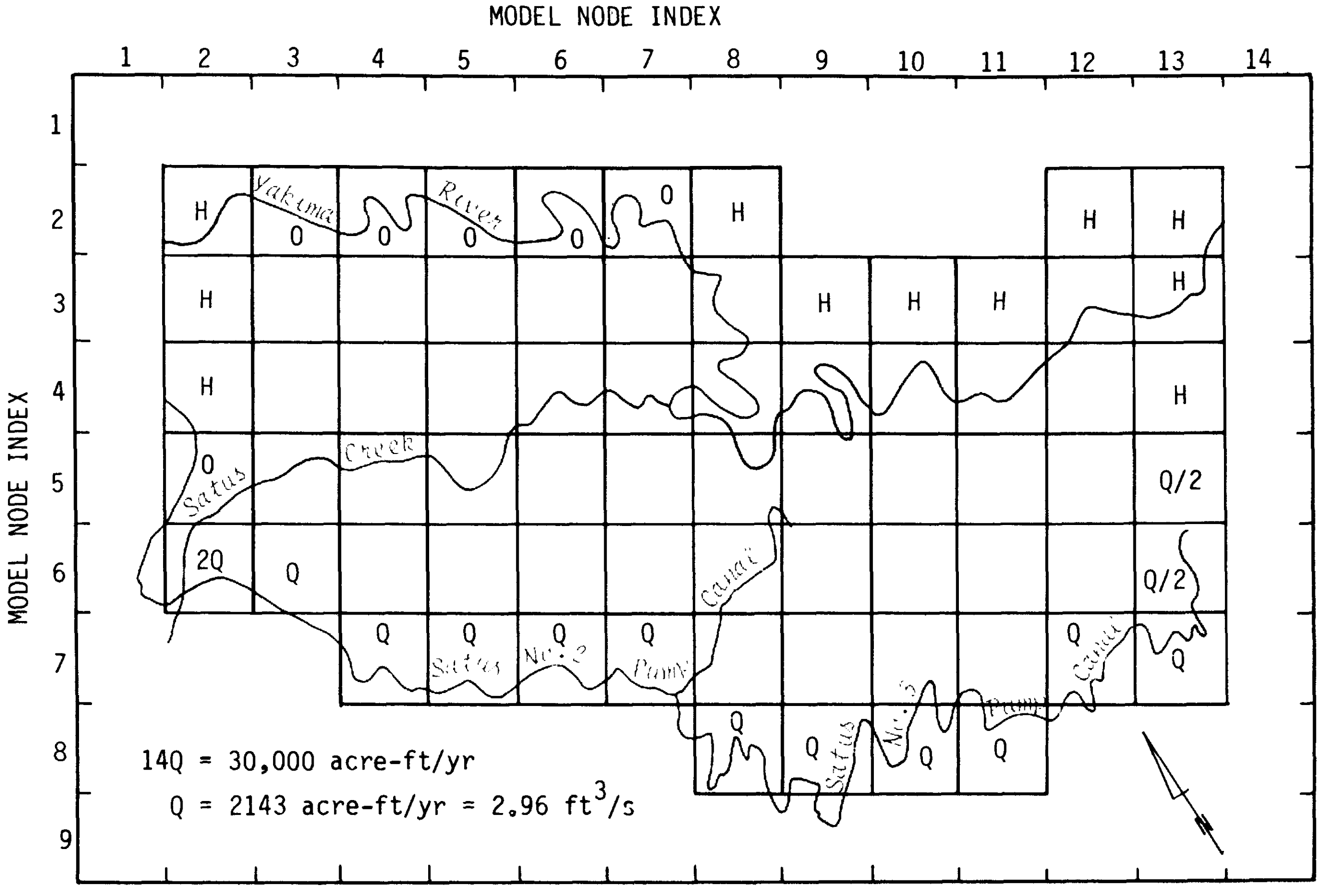



FIGURE 21.--Specification of boundary conditions for calibration of model of lower Satus Creek basin. Q denotes specified boundary flow from Satus uplands; O denotes no-flow boundary; H denotes that heads are specified during model calibration.

Table 10a gives the assumed vertical distribution of ground-water inflow. Although most of the 30,000 acre-ft/yr inflow probably enters the basin in the basalt (layer I), some small but unknown fraction probably enters in the overlying sedimentary layers. Therefore, for all boundary nodes except the one on Satus Creek, 5 percent of the boundary flow for that node was assigned to layer II and the remaining 95 percent to layer I. No flow was assigned to layer III because the water table probably lies below the bottom of this layer, not far south of the model boundary. For the node on Satus Creek where the total boundary inflow was assumed to be 2Q, the assigned inflow through the basalt was the same as for the other southern boundary nodes, but the balance was equally divided between layers II and III.

Northern part of model

Ground-water also enters lower Satus Creek basin from Toppenish Valley and leaves the basin in the vicinity of Mabton. There probably is also ground-water inflow to the modeled area from the north that most likely discharges to the Yakima River. Because the magnitudes of these boundary flows were unknown during the calibration process, the ground-water levels were specified at these boundary nodes. The locations of these nodes are denoted by the letter H in figure 21. Zeros denote nodes at which the boundary flows were assumed to be zero.

The heads specified during model calibration appear in table 10b. Nearly all specified heads in layer I were estimated as being 10 ft above the heads in layer II, and heads in layer III as 2 ft below those in layer II. The latter were taken from figure 7.

Once the model was calibrated, flows at the specified-head nodes were estimated with the model. The estimated ground-water inflow from Toppenish Valley was 12 $ft^3/s$, the down-valley flow near Mabton was 5 $ft^3/s$, and the inflow on the north side of the river was 14 $ft^3/s$. The vertical and horizontal distributions of the estimated flows were erratic, probably because of the sensitivity of the boundary flows to the distribution of the assumed specified heads. The effects of the erratic flow distributions were not evident more than one node from the specified-head boundaries.

TABLE 10.--Boundary conditions for calibration of numerical model (a) specified flows, (b) specified heads

(a)

| Model layer | Discharge, in cubic feet per second | | |
| --- | --- | --- | --- |
| | model-node indicies | | |
| | (6,2) | (6,3)(7,4)(7,5)(7,6) (7,7)(8,8)(8,9)(8,10) ((8,11)(7,12)(7,13) | (5,13)(6,13) |
| III | 1.55 | 0 | 0 |
| II | 1.56 | 0.15 | 0.07 |
| I | 2.81 | 2.81 | 1.41 |
| Sum | 5.92 = 2Q | 2.96 = Q | 1.48 = $\frac{Q}{2}$ |

(b)

| Model node | Head, in feet | | |
| --- | --- | --- | --- |
| | Layer I | Layer II | Layer III |
| (4,2) | 700 | 690 | 688 |
| (3,2) | 701 | 691 | 689 |
| (2,2) | 706 | 696 | 694 |
| (2,8) | 683 | 673 | 671 |
| (3,9) | 665 | 655 | 653 |
| (3,10) | 659 | 649 | 647 |
| (3,11) | 656 | 646 | 644 |
| (2,12) | 663 | 653 | 651 |
| (2,13) | 655 | 645 | 643 |
| (3,13) | 653 | 643 | 671 |
| (4,13) | 685 | 675 | 673 |

## Recharge, Ground-Water Pumping, and Change in Storage

The variable $\bar{W}_s$ in equation 6 includes water pumped from wells, recharge from precipitation, irrigation, and canal leakage, and changes in storage. Water volumes and rates withdrawn from wells during April 1979 through March 1980 are listed in table 7.

Recharge from precipitation was assumed to be uniform over the model area and to occur only during November through February, when precipitation exceeded potential evapotranspiration. The annual amount was estimated as the precipitation excess (4.4 in.; table 1) less the amount that runs off and that which goes to increase soil moisture. Runoff in the study areas is probably less than 10 percent because most of the land surface is flat and is cultivated. Runoff was assumed to be 0.6 in. The amount of water that goes to soil moisture is that amount required to bring the soil moisture in November up to field capacity. The amount is probably small because irrigation continues into October; it was assumed to equal 0.5 in. Thus, the estimated precipitation recharge rate during the 12-month study period is 4.4 - 0.6 - 0.5 = 3.3 in./yr, which is equivalent to 0.24 $(ft^3/s)/mi^2$. The rate in an average year is probably closer to 1 in./yr because the average precipitation excess is only 1.3 in. (table 1).

Canal-leakage rates were computed for each model node by multiplying the product of the canal length and width for each node by a leakage rate of 0.6 ft/d. These rates were then adjusted to give average rates for the 12-month period by multiplying by 214/365, the fraction of the year during which the canals held water. The 12-month averaged canal-leakage rates for each node appear in figure 22.

Figure 22 also shows the estimated recharge rate of irrigation water for each node during the calibration period. These rates were obtained by summing for each node the products of irrigated areas (estimated from the data in fig. 1) and recharge amounts for the corresponding distribution systems and irrigation methods (table 11).

Change in storage during model calibration, as represented by the term $S\Delta_t h/\Delta t$, was included in the model for layer III, the layer with the water table. The change in head, $\Delta_t h$, for the calibration period was assumed to be uniform at 1.3 ft everywhere except at the node (7,7), where $\Delta_t h = -1$ ft. Using the estimated storage coefficient of 0.1 gave $S\Delta_t h/\Delta t = 0.12$ and -0.09 $(ft^3/s)/mi^2$ when $\Delta_t h$ was 1.3 and -1.0 ft, respectively.

TABLE 11.--Estimated ground-water recharge of irrigation water applied to farmlands in lower Satus Creek basin during the 1979 irrigation season, in feet

| | Irrigation Method | |
|---|---|---|
| Distribution system: | flood | sprinkler |
| East Lateral | *3.33 | -- |
| West Lateral | *2.74 | -- |
| Satus Pump Canals 2 and 3 | 1.28 | 1.13 |
| Mabton West Lateral | -- | .72 |

*Includes leakage from laterals

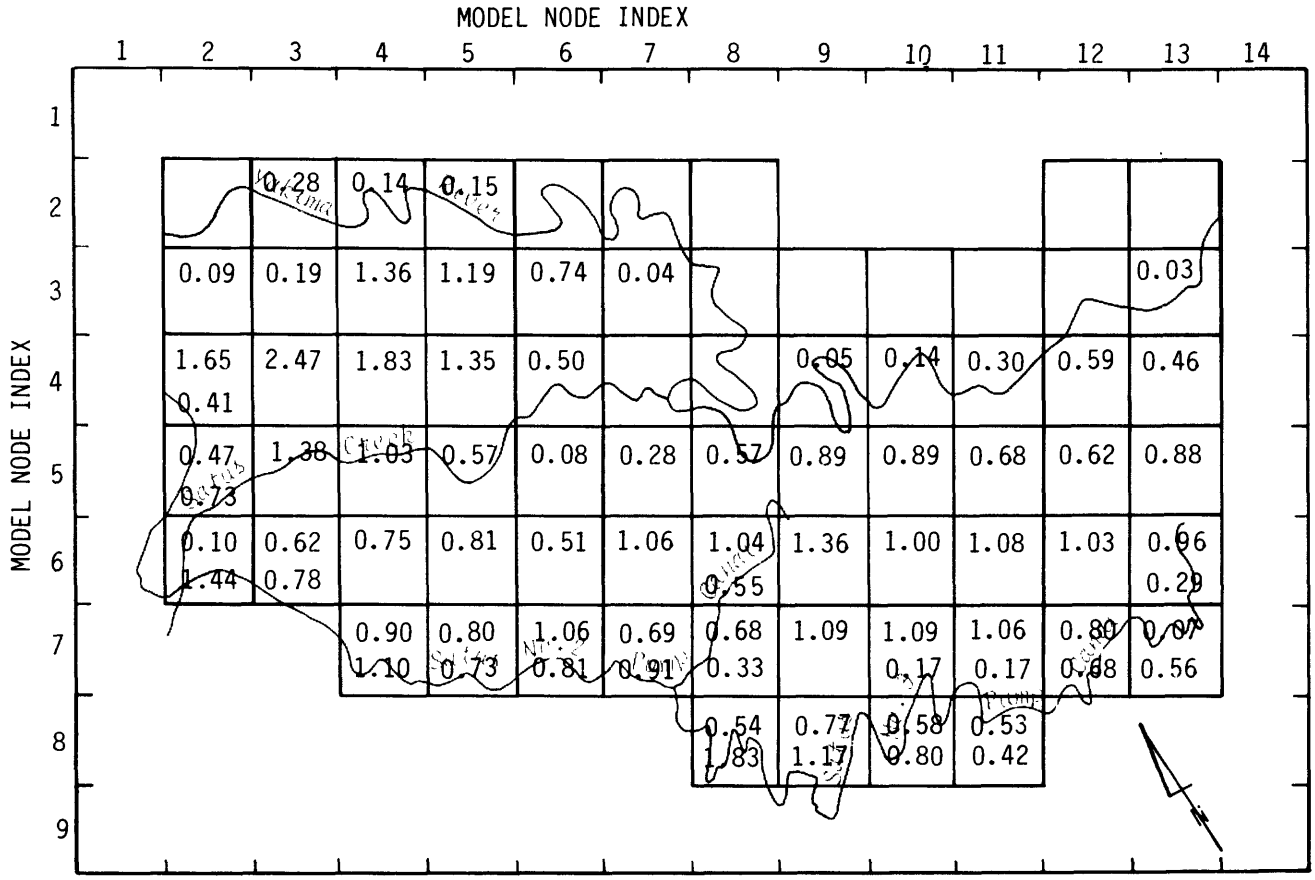



FIGURE 22.--Estimated annual average ground-water-recharge rates from irrigation (upper number) and from leakage of Satus No. 2 and No. 3 Pump Canals (lower number) for each node in numerical model of lower Satus Creek basin. Rates are in cubic feet per second.

## Leakage Coefficient between Layers I and II

Lack of data on the areal variability of the thickness and composition of the Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation required assuming that the value of leakage coefficient between layers I and II was uniform over the modeled area. The value of the leakage coefficient was selected by making a number of computations with the model, each with a different leakage coefficient, and choosing the one that gave the best approximation of the head difference between layers I and II. Three different values of the leakage coefficient were tried, $2 \times 10^{-10}$, $2 \times 10^{-9}$ and $2 \times 10^{-8}$ $s^{-1}$. The best value was $2 \times 10^{-9}$ $s^{-1}$, which was the value estimated in a previous chapter. The head differences computed using this value ranged from 3 to 30 ft. The computed differences using $2 \times 10^{-10}$ and $2 \times 10^{-8}$ $s^{-1}$ were 20 to 106 ft and 1 to 5 ft, respectively. Although accurate data on the actual head differences were not available, they were estimated to be of the order of 10 ft. The changes in head differences that occurred with changes in the leakage coefficient were due primarily to changes in the computed heads in layer I. Head changes in layer II were of secondary importance.

## Leakage Coefficient Between Layers II and III

The leakage coefficient between layers II and III was computed as the quotient $k_z/b$ (see equation 3). Because of the generally uniform lithology horizontally and similar estimates of hydraulic conductivities for the geologic units in layers II and III, the vertical hydraulic conductivity, $k_z$, was assumed to be the same in both layers II and III and to be uniform over most of the model area. The thickness, b, is the distance between the centers of the layers and was computed from the thicknesses in figure 19. The effect of the more permeable young alluvium in layer III in the northeast corner of the model was accounted for by using only half the thickness of layer II for b in that area. This is the same as assuming that all the head loss due to vertical flow in that area occurs in layer II.

Table 12 compares observed differences in heads between layers II and III (from table 6) with head differences computed using different values of vertical hydraulic conductivity. The value of $k_z$ that gave the best agreement (based on the root-mean-square error) between model-computed and observed head differences is $4 \times 10^{-6}$ ft/s. Although the error was not extremely sensitive to $k_z$, the selected value is probably physically realistic because it is within the range of the independently made estimates for the Touchet Beds (table 9). Unfortunately, the errors in the computed head differences are the same order of magnitude as the differences themselves. Some errors could be due to spacial variations in the vertical hydraulic conductivity that are not accounted for in the model. Table 12 also shows that the direction of vertical flow between layers II and III, as indicated by the algebraic sign, is usually the same for the computed and observed data.

TABLE 12.--Comparison of average observed differences in ground-water heads between layers II and III and differences computed with numerical model for three values of the vertical hydraulic conductivity, $k_z$, for the upper Ellensburg Formation, old alluvium, and Touchet Beds of Flint (1938); the values of $k_z$ for the young alluvium were 10 times these values

| Model node | Well in layer II | Observed difference in water levels, in ft | Computed difference in water levels, in feet, between layers II and II for different values of $k_z$, the vertical hydraulic conductivity | | |
|---|---|---|---|---|---|
| | | | $k_z$, in $10^{-6}$ ft/s | | |
| | | | 2 | 4* | 8 |
| 7-11 | 8/22-4N1 | 0.31 | -0.48 | -0.08 | -0.11 |
| 7-10 | -5E1 | -.52 | -.19 | -.12 | -.04 |
| 6-3 | 9/21-16D1 | .09 | -1.18 | -.64 | -.33 |
| 7-5 | -21K1 | 1.99 | 1.24 | .61 | .31 |
| 6-7 | -24Q3 | 2.67 | 2.06 | .99 | .48 |
| 7-6 | -26D1 | -2.12 | .17 | -.04 | .00 |
| 7-7 | -35B1 | -.15 | | | |
| 7-7 | -35H1 | 6.6 | | | |
| 7-7 | -35H3 | 2.71 | | | |
| 7-7 | -35H8 | 1.68 | | | |
| 7-7 | Average | 2.7 | 2.31 | 1.16 | .58 |
| 5-10 | -29R1 | -1.14 | -1.77 | -1.13 | -.66 |
| 6-8 | 9/22-30J1 | -.13 | | | |
| 6-8 | -30K1 | -1.08 | | | |
| 6-8 | -30L1 | -2.27 | | | |
| 6-8 | Average | -1.16 | -3.45 | -2.06 | -1.11 |
| 5-12 | -35E1 | -.50 | .48 | -.24 | -.12 |
| Average | | 0.22 | -0.08 | -0.16 | -0.09 |
| Root-mean-square error | | | 1.22 | 1.15 | 1.32 |

*Value chosen for calibrated model.

### Leakage Coefficient Between Layer III and Surface Waters

The leakage coefficient between layer III, the top geohydrologic layer, and the surface waters was also computed as a quotient $k_z/b$. However, because of the mechanics of model operation the leakage coefficients in the model input data were the above quotient multiplied by the fraction of the nodal area covered by the surface-water body. The distance b in the above quotient was set equal to half the thickness of layer III (fig. 19). A uniform value of vertical hydraulic conductivity was assumed.

In table 13 observed differences between heads in layer III and the surface waters (from table 6) are compared with differences computed using those values of vertical hydraulic conductivity. A vertical hydraulic conductivity of 20 x $10^{-3}$ ft/s gave the best agreement between model-computed and observed head differences. This value is 5 times as large as the vertical hydraulic conductivity between layers II and III. The ratio of these conductivities is less than that suggested by the data in table 9, but is consistent in that the vertical hydraulic conductivity used for computing leakage between layer III and the surface-water system is larger than that used to compute leakage between layers II and III. Again, the errors in head differences are of the same magnitude as the head differences themselves.

TABLE 13.--Comparison of average observed differences in water levels between Satus Creek or the Yakima River and layer III, and differences computed with numerical model for various values of $k_z$, the vertical hydraulic conductivity

| Model node | Well in layer III | Observed difference in water levels, in ft | Computed difference in water levels, in feet, between streams and layer III for different values of $k_z$, the vertical hydraulic conductivity: $k_z$ in $10^{-6}$ ft/s, 10 | 20* | 40 |
|---|---|---|---|---|---|
| 5-2 | 9/21-05Q2 | 2.45 | 0.13 | -0.05 | -0.06 |
| 5-4 | -10F1 | 1.36 | 3.48 | 1.90 | 1.01 |
| 4-6 | -12P1 | 1.11 | 1.02 | .51 | .25 |
| 4-11<br>3-12 | 9/22-26K1 | .45 | 1.07 | .54 | .28 |
| 4-11 | -27F1 | 2.93 | 1.53 | .78 | .40 |
| Average | | 1.66 | 1.45 | 0.74 | 0.38 |
| Root-mean-square error | | | 1.56 | 1.52 | 1.65 |

*Value chosen for calibrated model.

TABLE 14.--Variations of root-mean-square errors in computed water levels and of hydraulic properties of geologic units for different multipliers of transmissivities used during model calibration

| Multiplier for transmissivities in all layers----- | 0.7 | 0.8* | 0.9 |
|---|---|---|---|
| Transmissivity of Wanapum and Grande Ronde Basalts (layer I), in ft²/s | 0.049 | 0.056 | 0.063 |
| Horizontal hydraulic conductivity of upper Ellensburg Formation and old alluvium (layer II) and of Touchet Beds of Flint 1938 (layer III), in $10^{-3}$ ft/s | .7 | .8 | .9 |
| Horizontal hydraulic conductivity of young alluvium (layer III), in $10^{-3}$ ft/s. | 7 | 8 | 9 |
| Root-mean-square errors in computed ground-water levels, in feet, | | | |
| for layer II, 25 nodes | 7.61 | 6.44 | 7.98 |
| for layer III, 26 nodes | 4.53 | 4.49 | 7.35 |
| for layers II and III, 51 nodes | 6.29 | 5.57 | 7.67 |

*Value chosen for calibrated model.

## Transmissivities

Transmissivities in the model were determined by a calibration procedure in which an initial estimate of transmissivities was made using the information in the previous chapter. Then a single multiplier, common to all nodes in all layers, was varied in a search for the best agreement between computed and observed ground-water heads. Transmissivities in all layers were varied simultaneously because the effects on heads of varying the transmissivities of any one layer are correlated with the effects of varying the transmissivities of another. Consequently, the optimum transmissivities in one layer cannot be determined independent of the others. Typically, increasing the transmissivities in any layer of the lower Satus Creek basin model decreases the gradient toward the Yakima River. The changes in heads caused by varying transmissivities were most apparent in the eastern part of the basin. In the western part, where most of the drains are located, values of the computed heads depended less on transmissivities and more on the value of the leakage coefficients between layer III and the surface water.

The initial estimate of the transmissivity of layer I was 0.07 $ft^2/s$, and was assumed to be uniform over the model area. This value was obtained by doubling the average value in table 8 to account for the fact that most of the wells penetrated only a fraction of the basalt thickness in this layer. The transmissivity at each node in layer II was computed as the product of the non-uniform layer thickness (fig. 19) and a uniform horizontal hydraulic conductivity. The initial estimate of the conductivity was $1.0 \times 10^{-3}$ ft/s. Transmissivities in layer III were also computed as the products of layer thicknesses (from fig. 19) and a horizontal hydraulic conductivity. The initial estimate of the conductivity over most of layer III was $1.0 \times 10^{-3}$ ft/s, the same as for layer II. However, in the northwest corner of the basin where layer III contains the young alluvium the initial estimate was 10 times this value, $1.0 \times 10^{-2}$ ft/s.

Table 14 gives the root-mean-square errors in computed heads for the different transmissivities. Computed and observed heads agreed best when the initial estimates were multiplied by 0.8. Thus, the optimum transmissivities for the model do not differ greatly from the independent estimates of the previous chapter.

A contour map of water levels in layer III computed with the calibrated model is shown in figure 23. For comparison, the 12-month averages of observed data are also shown.

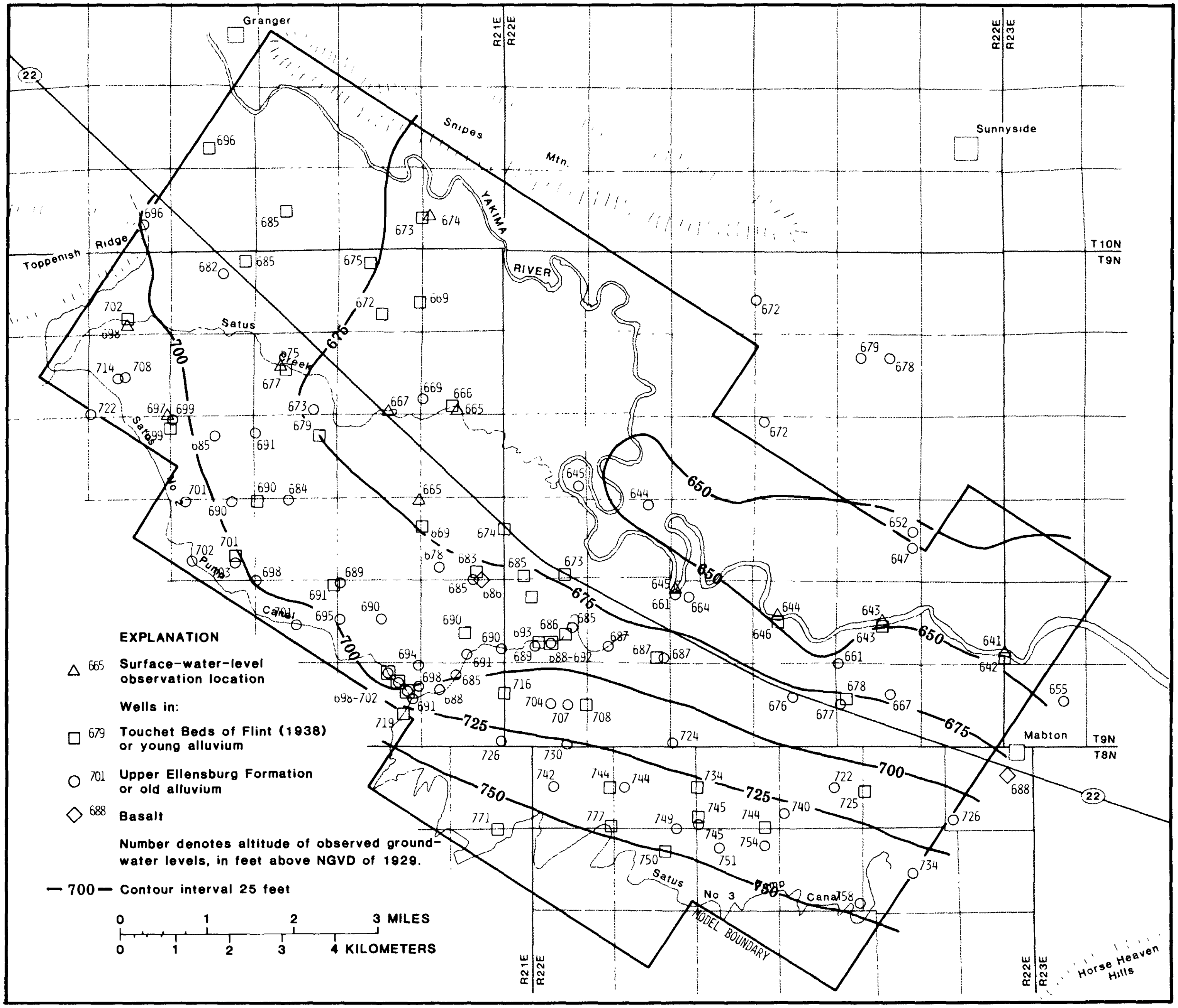



FIGURE 23.--Contours of model-computed ground-water levels in the top geohydrologic layer (III) and averages of observed ground-water levels for lower Satus Creek basin during the period March 1979 to March 1980.

# MODEL UTILIZATION

## General Discussions

The calibrated ground-water-flow model was used to estimate long-term average changes in ground-water levels that might occur in response to different possible irrigation-water development plans. The plans investigated were: (1) irrigating three different amounts of presently (1980) unirrigated land in the Satus uplands; (2) reducing, by two different amounts, the quantity of irrigation water used in lower Satus Creek basin; (3) pumping three different amounts of ground water from wells in lower Satus Creek basin; and (4) stopping all leakage from Satus Nos. 2 and 3 Pump Canals.

Figures 24 through 27 show the estimated changes in water-table altitudes. These are model-computed changes for layer III that have been corrected for changes in saturated thickness as described in the following section. The number at each node is probably best interpreted as the long-term change in mean-annual water-table altitude averaged over the 1 square mile represented by the node. Changes close to a pumped well would be larger than the average for the node in which the well is located.

The water-level changes that are presented were computed directly by the model rather than by taking differences between two sets of computed water levels. In order to compute water-level changes directly with the model, only the changes in the source and sink function, $W_s$, and only the changes in flows or heads are specified at the boundaries. Although not given in this report, absolute water levels can be obtained by algebraically adding the computed water-level changes to either computed or observed water levels for the base period.

## Correcting Computed Water-Level Changes

Because the lower Satus Creek basin model does not automatically adjust the transmissivities in layer III to account for changes in saturated thickness that occur with changes in water-table altitudes, the model-computed water-level changes require corrections. The computed water-level changes presented in this report were corrected to account for changes in saturated thickness by using the method proposed by Jacob (1963):

$$s' = s - s^2/2m \quad , \qquad (7)$$

where s and s' are the corrected and model-computed drawdown (negative changes in water levels), and m is the original saturated thickness. In this study the sum of the thicknesses of layers II and III was used for m. None of the corrected water-level changes differed from the uncorrected changes by more than 10 percent.

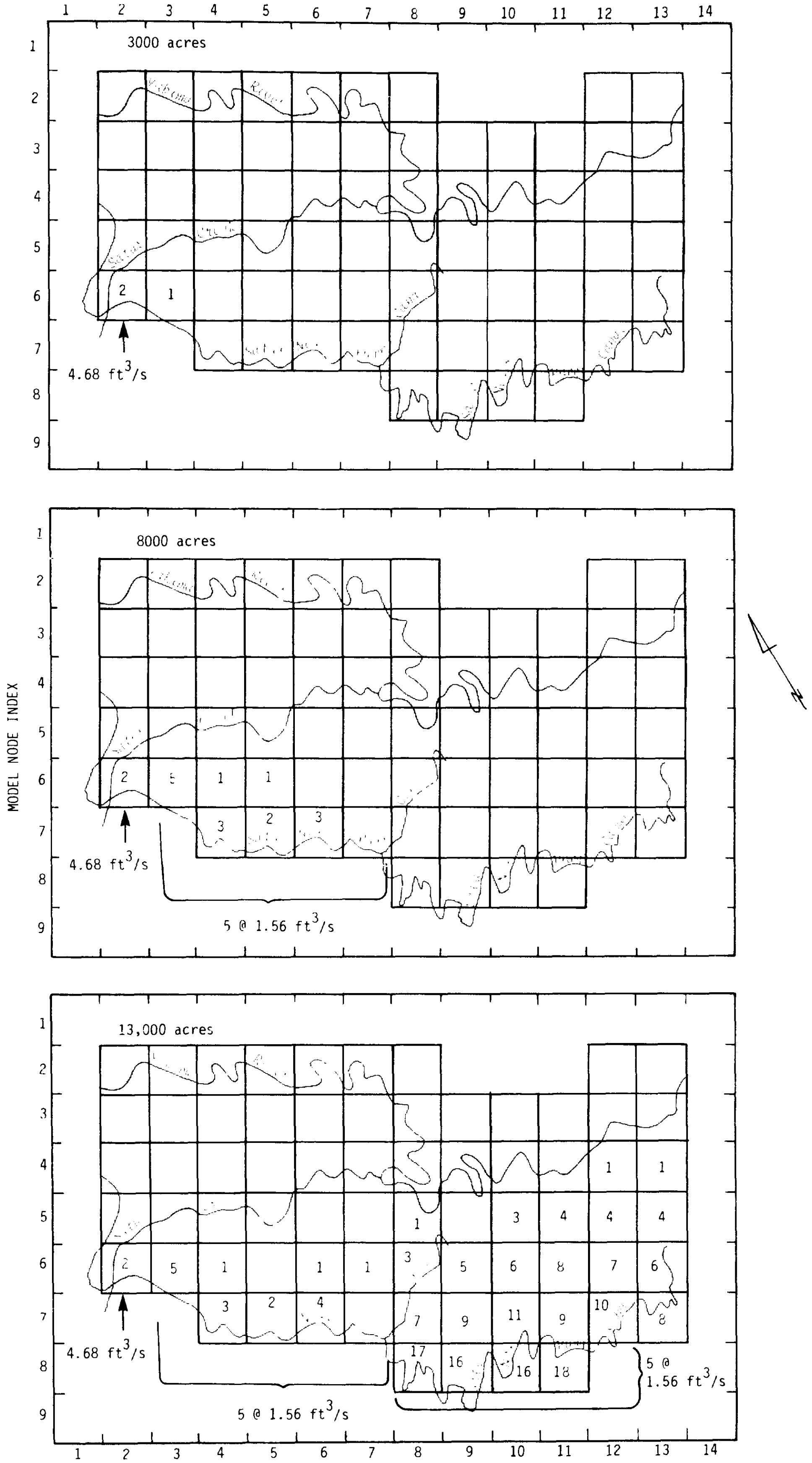



FIGURE 24.--Estimated changes in water-table altitudes in lower Satus Creek basin caused by irrigating three different amounts of land in the Satus uplands.

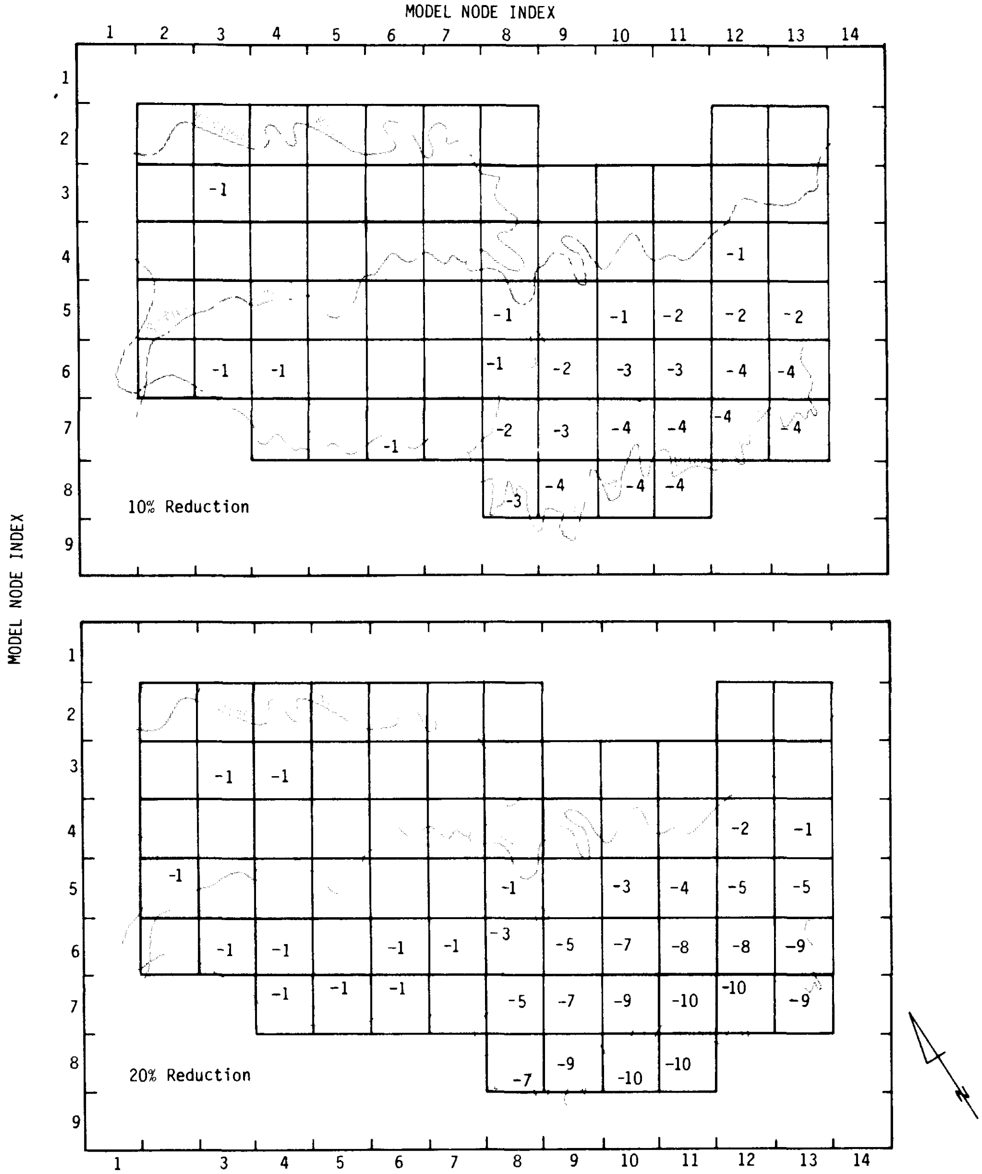



FIGURE 25.--Estimated changes in water-table altitudes in lower Satus Creek basin caused by reducing the amount of irrigation water used in lower Satus Creek basin by two different amounts.

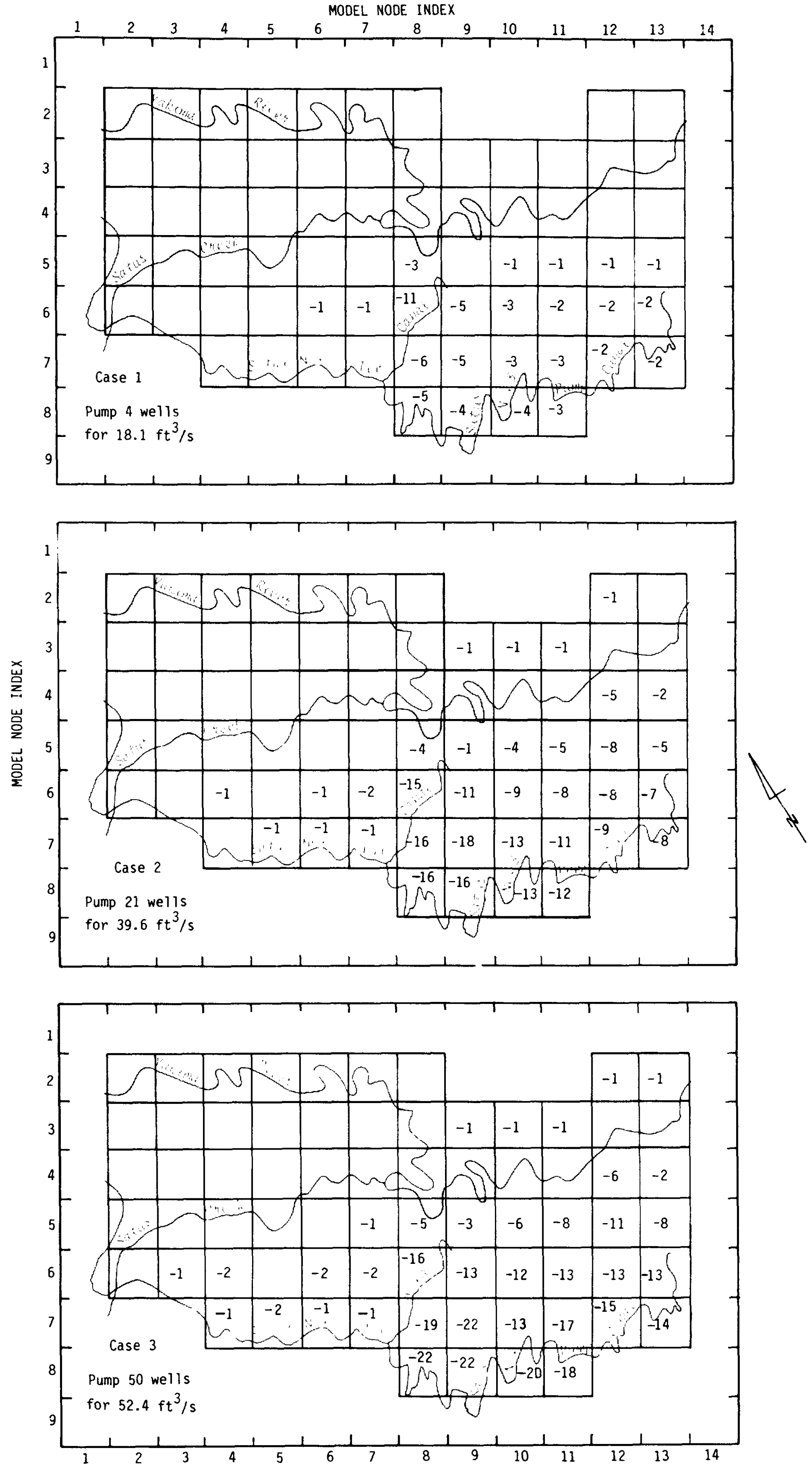



FIGURE 26.--Estimated changes in water-table altitudes in lower Satus Creek basin caused by pumping three different amounts of ground water.

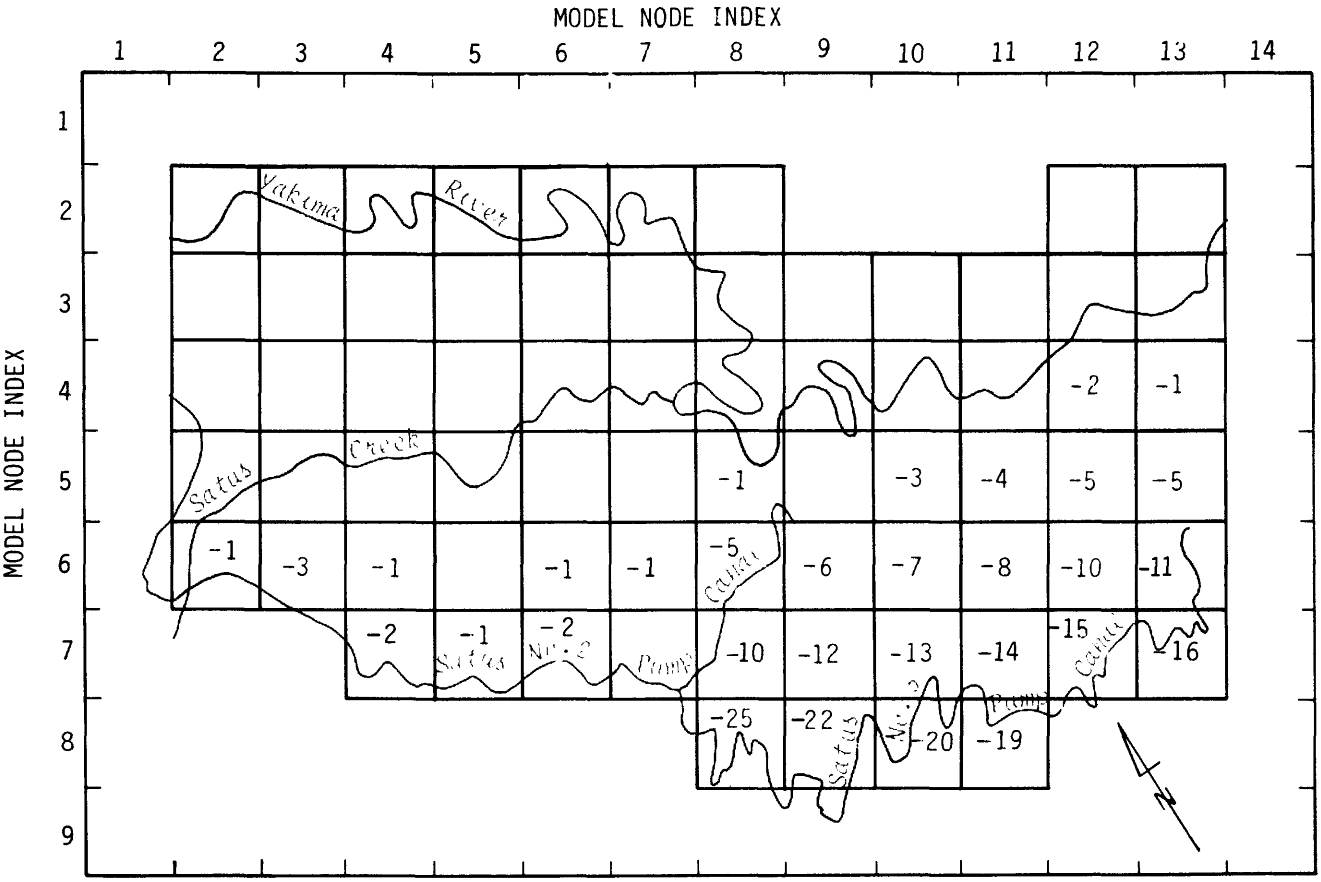



FIGURE 27.--Estimated changes in water-table altitudes in lower Satus Creek basin caused by stopping leakage from Satus Nos. 2 and 3 Pump Canals.

## Boundary Conditions

In preparing the model-input data for estimating changes in ground-water heads, it was assumed that in most cases ground-water flows across the model boundaries would not change in response to implementation of the different irrigation-water development plans. Therefore, the specified changes in boundary flows were zero except for the plan to irrigate the Satus uplands.

Although it is nearly certain that the inflows from the Satus upland, Toppenish Valley, or north of the Yakima River would not be affected by changes in irrigation-water use in lower Satus Creek basin, the down-valley ground-water outflow probably would be different for each of the irrigation-water development plans. However, because most ground water leaves lower Satus Creek basin by discharging to streams, the change in ground-water outflow probably would be less than the change in net recharge or pumpage. Although the ground-water outflow cannot be predicted for the various plans, upper and lower limits can be established. One limit is the computed discharge through the specified-head boundary during the calibration period; the other limit is the discharge at the outflow boundary that would be computed for a development plan if the boundary heads were specified equal to those during the calibration period. If the down-valley boundary flow is assumed to be the same as that computed during model calibration (zero change in boundary flow specified), the model will overestimate the head change at the outflow boundary. The maximum possible error in the computed head anywhere in the model caused by approximating the boundary condition will be the computed head change of the boundary. These changes were always less than 2 and usually less than 1 foot (see figs. 24 through 27).

## Areas With a High Water Table

The purpose for estimating changes in ground-water levels was to provide information to help evaluate the effects of different irrigation development plans on waterlogging in lower Satus Creek basin. Therefore, as an aid to the reader, figure 28 was prepared from the data on figure 9 and shows minimum observed depths below land surface to the water table in the same format used in figures 24 to 26 to show estimated water-level changes.

Areas with a high water table (less than 5 ft below land surface) are: (1) the southwest part of the basin along Satus No. 3 Pump Canal; (2) a central area north and east of Satus No. 3 Pump Station; (3) the northwest corner along Satus No. 2 Pump Canal; and (4) the low lying areas along the Yakima River, especially near the mouth of Satus Creek. None of the development plans is expected to affect the areas along the river; they will not be discussed further in this report.

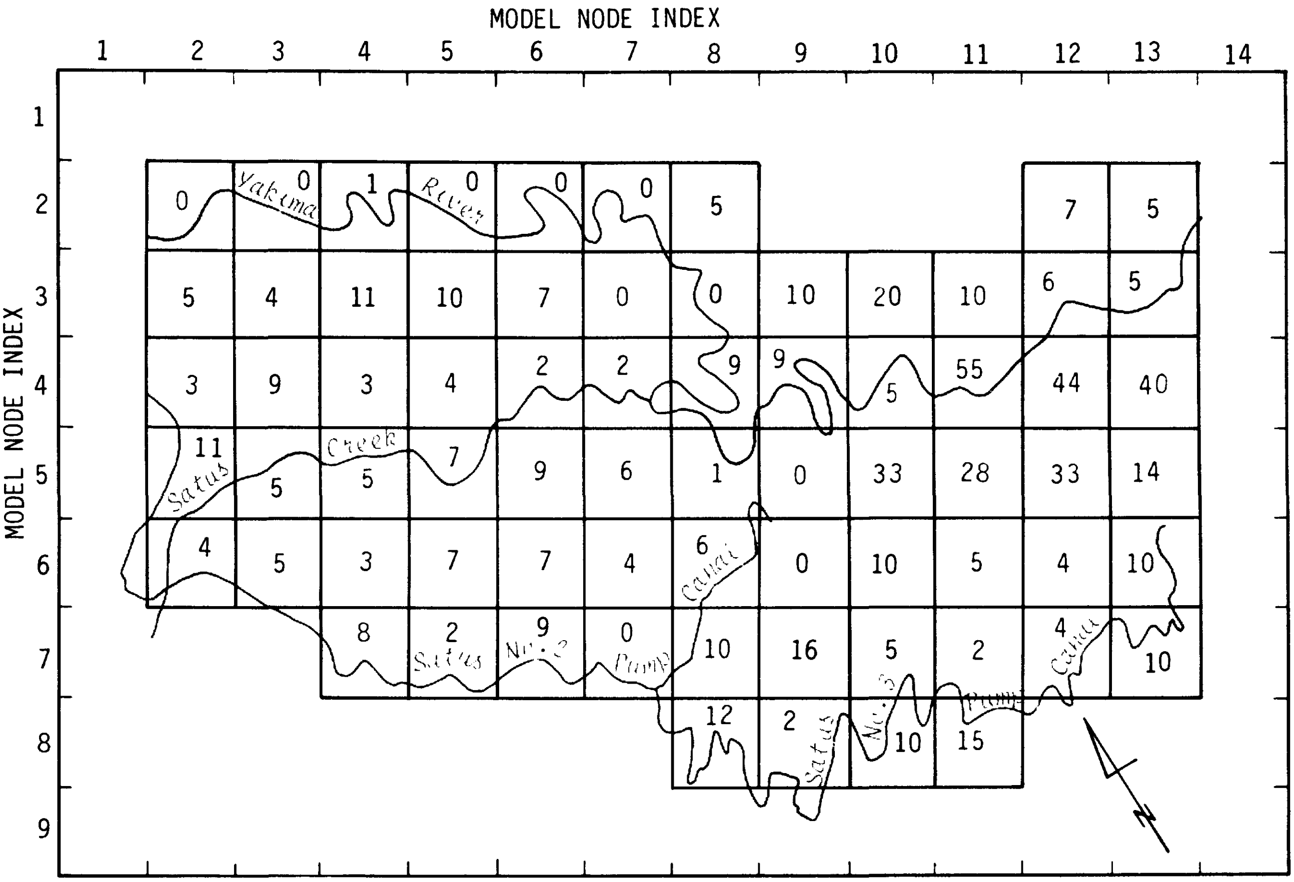



FIGURE 28.--Minimum observed depths below land surface to water table in lower Satus Creek basin during the period March 1979 to March 1980.

## Effects of Irrigating Satus Uplands

The estimated changes in ground-water levels in lower Satus Creek basin that would be caused by irrigating 3,000, 8,000, and 13,000 acres in the foothills of the Satus uplands are shown in figure 24. Although the area is outside the model boundaries, irrigation water that recharges the ground-water system in the uplands would appear as an increase in ground-water inflow to lower Satus Creek basin. The estimated increases in ground-water inflow appear in figure 24. The amount of recharge was estimated by assuming that 4 ft of irrigation water would be provided per year, that about 10 percent (0.4 ft/yr) would be lost as evaporation from sprinkler systems and as runoff, and that 2.47 ft/yr would be consumed by evapotranspiration. The remaining 1.13 ft/yr would be ground-water recharge. Thus, the estimated recharge rate is 1.56 $ft^3/s$ for each 1,000 acres irrigated.

The lateral distribution of the increased ground-water inflow to lower Satus Creek basin, as shown in figure 24, was assumed to be similar to the assumed distribution of irrigated land in the uplands. The 4.68 $ft^3/s$ inflow in the southeast corner along Satus Creek, which would be caused by irrigating the first 3,000 acres, was assumed to be distributed equally (vertically) between layers II and III of the model. The remaining model inflows were assumed to be mostly in layer II, and only 10 percent assigned to layer III.

Irrigating 3,000 acres of Satus uplands causes a water-table rise of more than 1 ft in the lowlands over an area of about 2 $mi^2$ (fig. 24). The data in figure 28 show that the 1979-80 water table in this area was within 4 to 5 ft of land surface. Therefore, even a 1 or 2 ft rise in water-table altitude in this area would increase the likelihood of waterlogging. However, the model computations also showed that about 90 percent of the estimated increase in ground-water inflow discharged to Satus Creek within 1 mile of the model boundary. Therefore, it is possible that much of the ground-water recharge from irrigating 3,000 acres would actually discharge to Satus Creek somewhere upstream of the model boundary. If so, then the increase in water-table altitudes within the modeled area would be less than estimated.

If 8,000 acres of the uplands are irrigated, the estimated rise in altitude is 1 ft or more over a total of 7 $mi^2$ (see fig. 24). At two of the nodes, (6,3) and (7,5), the estimated rise is sufficient to bring the water table to the land surface. Of the 12.5 $ft^3/s$ increase in boundary inflow caused by the irrigation, more than 90 percent was computed to discharge either to Satus Creek or to drains in the area south of the creek.

If 13,000 acres of the uplands are irrigated, the estimated rise in water-table altitude is 1 or more feet in 31 of the 71 1-square-mile nodes (see fig. 24). At 11 of the nodes, most of which are in the model's southeast corner, the estimated rise is sufficient to bring the water table to the land surface. At many of these nodes the estimated water-table altitude would be a number of feet above land surface. In reality, swamps and surface drainage systems would develop and the computed condition could never exist. However, a seriously high ground-water-level problem would develop over a large area.

## Effects of Reducing Irrigation-Water Usage in Satus Lowlands

Figure 25 shows the estimated decreases in water-table altitudes that might occur if the amount of irrigation water brought into lower Satus Creek basin by the Wapato Irrigation District were reduced. In the first case the amount used for flood irrigation was assumed to be reduced by 10 percent. In the second case the amount used for flood irrigation was reduced by 20 percent and the amount used for sprinkler irrigation was reduced slightly to equal the amount used for flood irrigation.

Table 15 summarizes the annual amounts of water used, and the amounts and changes in amounts of ground-water recharge for each case. The reduction in water use for flood irrigation was assumed to reduce the runoff and the ground-water recharge equally. In the sprinklered areas the runoff and evaporation losses were assumed to be reduced by the same proportion as the overall reduction in water use. The balance in the reduction was assumed to be a reduction in ground-water recharge. In all cases, the amount available for use exceeded that required for evapotranspiration.

Figure 25 shows that reducing the amount of irrigation water used in lower Satus Creek basin would lower the water tables in the southeastern part of the basin as much as 4 ft for the 10 percent reduction and as much as 10 ft for the 20 percent reduction. The relatively small changes in water levels in the northwestern half of the basin, both in response to reductions in water usage in the lower basin and to irrigation in the uplands, is probably due to control of water levels by the drains.

The reductions in ground-water recharge that occur as a consequence of the reductions in irrigation-water use result in a decrease in ground-water discharge to drains and to Satus Creek more than in a reduction in direct ground-water discharge to the Yakima River.

## Effects of Pumping from Wells

The estimated decreases in ground-water levels that might occur as a result of pumping from wells are shown in figure 26. Three different cases were considered. Locations of wells that were assumed to be pumped for each case are shown on figure 29, and pumping rates are listed in table 16. It was assumed that the wells would be pumped only 6 months per year; therefore, the time-averaged pumping rates used in the model computations were one-half of those in table 16. It was also assumed that the two field-drain sumps at 9/21-26J and 35A would no longer operate.

Figure 26 shows that pumping four wells at a combined rate of 18.1 $ft^3/s$ (case 1) would lower the water table 2 to 4 ft in the high water-table areas in the southeast corner of the basin. However, this pumping would not substantially reduce water levels elsewhere. Figure 26 also shows that even increasing the pumpage to 39.6 and 52.9 $ft^3/s$ (cases 2 and 3) lowers the water table in the southwest by only 2 ft or less. However, ground-water pumping is effective in lowering the water table at nodes (5,8), (5,9), and (6,9), the area of high ground-water levels in and around 9/22-29.

TABLE 15.--Estimated annual irrigation-water budgets for 1979 and for hypothetical years in which irrigation-water use is reduced by 10 percent and 20 percent; data are for areas served by different laterals or canals and are expressed in feet

| | Irrigation water use | | | | | |
|---|---|---|---|---|---|---|
| | 1979 | | 10-percent reduction | | 20-percent reduction | |
| | Flood | Sprinkler | Flood | Sprinkler | Flood | Sprinkler |
| East Lateral | | | | | | |
| Total | 12.23 | -- | 11.01 | -- | 9.78 | -- |
| Runoff and losses | 6.89 | -- | 6.28 | -- | 5.67 | -- |
| Evapotranspiration | 2.47 | -- | 2.47 | -- | 2.47 | -- |
| Ground-water recharge | 2.87 | -- | 2.26 | -- | 1.65 | -- |
| Change in recharge from 1979 | -- | -- | -.61 | -- | -1.22 | -- |
| West Lateral | | | | | | |
| Total | 4.95 | -- | 4.46 | -- | 3.96 | -- |
| Runoff and losses | 1.01 | -- | .76 | -- | .51 | -- |
| Evapotranspiration | 2.47 | -- | 2.47 | -- | 2.47 | -- |
| Ground-water recharge | 1.47 | -- | 1.22 | -- | .97 | -- |
| Change in recharge from 1979 | -- | -- | -.25 | -- | -.50 | -- |
| Satus No. 2 & No. 3 Pump Canals | | | | | | |
| Total | 4.67 | 4.00 | 4.20 | 4.00 | 3.74 | 3.74 |
| Runoff and losses | .92 | .40 | .69 | .40 | .46 | .37 |
| Evapotranspiration | 2.47 | 2.47 | 2.47 | 2.47 | 2.47 | 2.47 |
| Ground-water recharge | 1.28 | 1.13 | 1.04 | 1.13 | .81 | .90 |
| Change in recharge from 1979 | -- | -- | -.24 | 0 | -.47 | -.23 |

TABLE 16.--List of wells and assumed pumping rates used to estimate the effect of pumping ground water on ground-water levels

| Well number | Pumping rate during test ($ft^3/s$) | Specific capacity (gal/min/ft) | Assumed pumping rates for computation ($ft^3/s$) Case I | Case 2 | Case 3* |
|---|---|---|---|---|---|
| 9/21-25Q1 | 6.4 | 39 | 6.4 | 5.2 | 5.1 |
| -35H3 | 2.2 | 33 | 2.7 | 2.4 | 2.3 |
| 9/22-29L1 | 2.8 | 26 | 3.3 | 3.3 | 3.2 |
| -30L1 | 6.3 | 33 | 5.7 | 3.8 | 3.6 |
| 8/22-4N1 | 1.1 | 7.0 | 0.0 | .8 | .7 |
| -6F1 | 2.6 | 14 | 0.0 | 1.3 | 1.2 |
| 9/21-2C1 | 1.7 | 60 | 0.0 | 1.5 | 1.5 |
| -2J1 | 1.1 | <110 | 0.0 | 1.5 | 1.5 |
| -21A1 | .62 | 3.5 | 0.0 | .5 | .5 |
| -22C1 | 1.2 | 7.6 | 0.0 | .7 | .7 |
| -25R1 | .67 | 10 | 0.0 | 1.0 | 1.0 |
| -26D1 | 3.3 | 20 | 0.0 | 2.2 | 2.2 |
| -26G1 | .98 | 5.3 | 0.0 | .7 | .7 |
| -35A1 | 2.2 | 11 | 0.0 | 1.4 | 1.4 |
| -36C1 | 2.8 | 22 | 0.0 | 2.4 | 2.4 |
| -36E2 | 2.4 | 13 | 0.0 | 1.2 | 1.2 |
| -36R2 | 2.0 | 33 | 0.0 | 1.3 | 1.1 |
| 9/22-30J1 | 2.1 | 14 | 0.0 | 1.3 | 1.2 |
| -31R1 | 3.3 | 20 | 0.0 | 2.1 | 2.0 |
| -35E1 | 2.7 | 14 | 0.0 | 2.0 | 1.9 |
| -36G1 | 3.1 | 22 | 0.0 | 3.0 | 3.0 |
| Sum | | | 18.1 | 39.6 | 52.9 |

*In addition to the above wells, wells at the following locations were assumed pumped at a rate of 0.5 $ft^3/s$. If a well location in this list does not have a sequence number following the letter designation, the well is hypothetical. These wells are included in the sum.

8/21-1E,1P
8/22-3H,4B,6P,8F,9G,10G
9/21-2N,4R,5F,8E,8P,10Q1,11R,12J,13Q,16B2,21D1,22N1,23C,24Q,26P,36N
9/22-19R,32A,32R,33A
10/21-34P

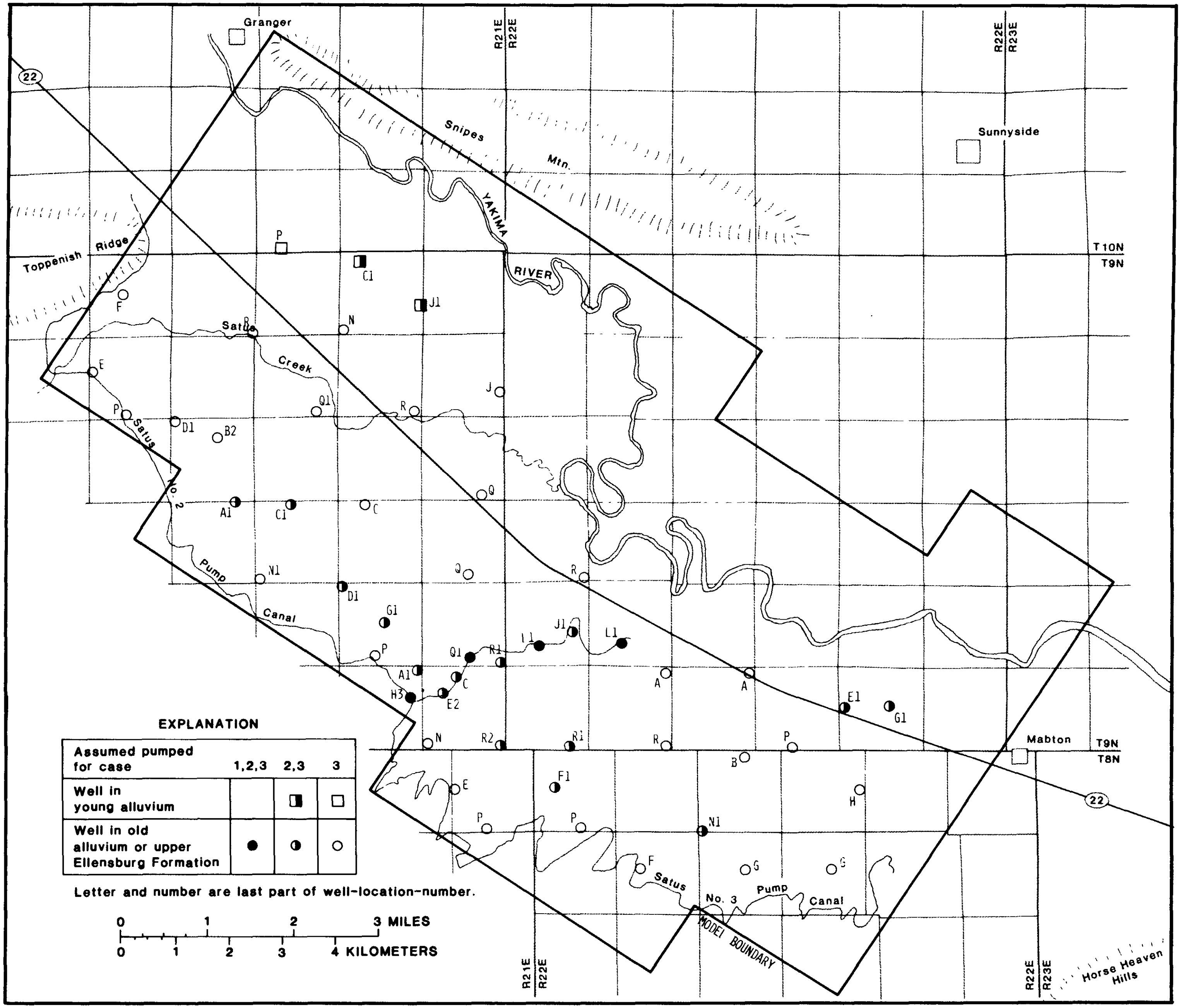



FIGURE 29.--Locations of wells in lower Satus Creek basin that were assumed pumped in the various computations that were made to estimate the change in water-table altitudes caused by pumping ground water.

For the first case, the only wells that were assumed to be pumped were the four drought-relief wells that were pumped during 1979. The assumed pumping rates were the actual pumping rates at the end of the summer.

For the second case all the drought-relief wells that would yield 0.5 $ft^3/s$ (225 gal/min) or more were assumed to be pumped. In order to avoid assuming unrealistically high pumping rates, the rate for each well was selected so that the drawdown inside each well would be two-thirds of the distance from the water level at the time the well was drilled to the top of the well screen or perforations in the casing. The drawdown in each well was estimated as the sum of the model-computed water-level decrease (corrected for the change in saturated thickeness) and the drawdown computed by dividing the pumping rate by the specific capacity of the well. The model-computed water-level change represents the regional change caused by pumping all wells, and to some extent approximates the drawdown at one well caused by pumping other wells. The component of drawdown that is computed by using the specific capacity approximates the depth of the local cone of depression in the aquifer around the pumped well plus the well entrance loss, which is the head drop across the well screen or perforated casing.

The advantages of computing the local drawdown by using the specific capacity of a well rather than more sophisticated analytic methods is that the first method automatically includes many effects that are difficult to treat analytically or that require data that are either unavailable or must be estimated from the same data that were used to compute the specific capacity. These include the effects of: (1) variations in the hydraulic conductivity of the geologic units; (2) the well screens not extending over the full thickness of the aquifer; (3) change in saturated thickness of the aquifer; (4) turbulent flow in the aquifer close to the well; and (5) well-entrance losses. The disadvantages of using the specific capacity to estimate the local drawdown are that: (1) estimates are for the wells as constructed; more hydraulically efficient wells cannot readily be considered; (2) the relation between well-entrance loss and the pumping rate is not linear; and (3) the relation between head loss in the turbulent flow part of the aquifer and the pumping rate is not linear. However, if the assumed pumping rate is close to or less than the pumping rate during the test from which the specific capacity is computed, as is the case for most of the wells, the error caused by nonlinearity will be small or conservative, respectively.

Two exceptions to the above method of selecting pumping rates were the two relatively shallow wells in the young alluvium, 9/21-02C1 and J1. Both these wells were assumed to be pumped at 1.5 $ft^3/s$, which is slightly more than the average of the pumping rates from these two wells during the tests.

The wells assumed pumped in the third case were all those wells pumped in the second case plus additional wells spaced about 1 mile apart. The pumping rates of the wells from case 2 were determined using the drawdown criteria explained earlier. The pumping rate of each of the additional wells was assumed to be 0.5 $ft^3/s$. These wells were assumed located in areas where there was a better-than-average (but unproven) likelihood of developing a productive well. Some of these wells are drought-relief wells that presently don't meet the drawdown criteria when pumped at 0.5 $ft^3/s$, but which might meet the criteria after some development work. Others are only fictitious wells at locations selected on the bases of data from nearby wells.

## Effects of Stopping Canal Leakage

Estimated decreases in water-table altitudes that would result if leakage from Satus Nos. 2 and 3 Pump Canals were stopped are shown in figure 27. Decreases exceeded 20 ft in a few locations and, in general, were largest in the southeast part of the basin between the two pump canals. Water-table altitudes along Satus No. 2 Pump Canal in the southwest part of the basin decreased by as much as 3 ft.

These estimated decreases in water-table altitudes are directly proportional to the estimated canal-leakage rates and, therefore, are very dependent on them. However, as explained earlier, the leakage rates were estimated using data from tests at only three locations on the downstream part of Satus No. 2 Pump Canal and none on the No. 3 Pump Canal. Therefore, one should be cautious in the use of the information on figure 27 until the canal-leakage rates that were used in this study are verified with additional data, especially for Satus Pump Canal No. 3.

## Effects of Combinations of Irrigation-Water Development Plans

To estimate the combined effects of two or more development plans on ground-water levels, one may, as a first approximation, algebraically add the water-level changes associated with each plan. For example, to estimate the effect at node (7,8) of irrigating 13,000 acres of Satus uplands and of pumping 52.9 $ft^3/s$ from 50 wells, one combines the 7-foot increase (from fig. 24) with the 19-foot decrease (from fig. 26) to obtain a 12-foot decrease in water-table altitude at that node.

By using this procedure with the data on figures 24 to 27, one would find that water-level rises caused by irrigating the Satus uplands can be prevented at many locations by pumping from wells, by reducing the amount of irrigation water used in the lowlands, or by stopping leakage from the canals.

The procedure of algebraically adding water-level changes is only approximate because the method used for adjusting water-level changes for changes in saturated thickness is nonlinear. Also, errors will be introduced by the method for computing leakage between a drain and layer III if the drain is dry in one computation but not in the other. One should also check that a well can be pumped at the assumed rate if one combines the effects of reduced irrigation-water usage or stopping canal leakage, which lower water levels, with pumpage.

## Sensitivity of Estimates to Geohydraulic Properties

The sensitivity of the estimated changes in water-table altitudes to the numerical values of the hydraulic properties of the geologic units was investigated by making a series of computations in which only the values of the hydraulic properties were varied. The results appear in table 17. In each of the computations all drought-relief wells that yield more than 0.5 $ft^3/s$ were assumed to be pumped at the same rates that were used earlier (table 15, Case 2). Because varying the hydraulic properties affected the computed water-level declines in different parts of the basin differently, table 17 shows the changes in water-level declines for two areas of the basin. One area, nodes (6,9), (6,10), (7,9), and (7,10), is between Satus Nos. 2 and 3 Pump Canals, where the various development plans had relatively large effects on the estimated water-table altitudes; the other area, nodes (6,5) and (5,6), is between No. 2 Pump Canal and Satus Creek, where the effects are less.

The results of the computations in table 17 show that the computed water-level declines in the area between the pump canals were most sensitive to changes in transmissivities. The computed declines between Satus Creek and No. 2 Pump Canal, where ground-water levels are controlled mostly by the drains and by Satus Creek, were more sensitive to the leakage coefficients between layer III and the surface waters, and between layers II and III. Although the percentage change in water-level decline in this area was relatively large (25 percent) for a 50-percent decrease in the leakage coefficient, the absolute change was not large (0.4 ft) because the absolute value of the computed water-level decline in this area is small.

## Ground-Water-Level Response Times

Results from a few preliminary calculations with a transient model for computing the variations of water levels with time indicate that from 1 to 2 years are required to achieve 50 percent of the estimated ground-water level changes and that 6 to 8 years are required to achieve 90 percent of the changes. These computations used an assumed storage coefficient, S, of 0.1 for layer III and $10^{-3}$ for layer I and for layer II. The computed response times are probably insensitive to the assumed values for S in layers I and II, but probably vary inversely with the value assumed for layer III.

TABLE 17.--Changes in model-computed water-level declines in response to changes in values of geohydraulic properties in numerical model of lower Satus Creek basin; water-level declines were computed for pumping all drought-relief wells that would yield more than 0.5 $ft^3/s$ (table 16, Case 2)

| Geohydrologic properties changed by multiplying: | | Average change, in percent, of model-computed water-level declines at nodes: (6,5) and (6,6) | (6,9)(6,10) (7,9)(7,10) |
|---|---|---|---|
| All transmissivities | by 0.75 | 5 | 29 |
| | by 1.25 | -5 | -18 |
| Leakage coefficients between layers: | | | |
| I and II | by 0.1 | -3 | 13 |
| | by 10.0 | 0 | -7 |
| II and III | by 0.5 | 19 | 3 |
| | by 2.0 | -12 | -2 |
| III and surface waters | by 0.5 | 55 | 3 |
| | by 2.0 | -32 | 2 |

## SUGGESTIONS FOR IMPROVING MODEL

The accuracy and reliability of most numerical models of hydrologic systems can be improved by using improved data for calibration. Most useful for improving the accuracy and reliability of the lower Satus Creek basin model would be better data on:

1. The amount and spacial distribution of ground-water inflow from the Satus uplands;

2. The amount and spacial distribution of ground-water recharge by canal leakage;

3. The amount and spacial distribution of ground-water recharge by applied irrigation water;

4. Water levels in the Yakima River and adjacent ground-water system in the western half of the basin;

5. Transmissivities of the Wanapum Basalt and Grande Ronde Basalt and ground-water heads in these formations; and

6. Horizontal hydraulic conductivities of the Touchet Beds of Flint (1938).

The existing calibrated steady-state model could be converted to a transient model for computing temporal changes in ground-water levels by including in the model-input data non-zero values for the storage coefficient, S. The model would need additional calibration by adjusting S so that computed and observed temporal changes in water levels agreed. The transmissivities and leakage coefficients would be the same as in the calibrated time-average model.

# SUMMARY AND CONCLUSIONS

A three-layer steady-state or time-averaged numerical model of ground-water flow in lower Satus Creek basin was constructed and calibrated with time-averaged data from the period March 1979 through March 1980. The best agreement between model-computed and observed ground-water levels was obtained when the following values for hydraulic properties of the geologic units were used in the model:

1. A depth-averaged horizontal hydraulic conductivity for the Touchet Beds of Flint (1938), the old alluvium, and the upper Ellensburg Formation of $0.8 \times 10^{-3}$ ft/s;

2. A transmissivity for the lower basalt of 0.054 $ft^2/s$;

3. An effective average vertical hydraulic conductivity of a column made up of the Touchet Beds of Flint (1938), old alluvium, and upper Ellensburg Formation of $4 \times 10^{-6}$ ft/s;

4. An effective vertical hydraulic conductivity of the Touchet Beds of Flint (1938) or young alluvium beneath Satus Creek, the Yakima River, and miscellaneous drains and swamps of $20 \times 10^{-6}$ ft/s;

5. Average horizontal and vertical hydraulic conductivities of the young alluvium of $8 \times 10^{-3}$ ft/s and $40 \times 10^{-6}$ ft/s, respectively; and

6. A vertical leakage coefficient for a combined layer consisting of the Saddle Mountains Basalt and the Beverly Member of the Ellensburg Formation of $2 \times 10^{-9}$ $s^{-1}$.

The calibrated model was used to estimate long-term average changes in ground-water levels that would occur in response to; (1) irrigating three different amounts of presently (1979) unirrigated land in the Satus uplands; (2) reducing, by two different amounts, the quantity of irrigation water used in lower Satus Creek basin; and (3) pumping three different amounts of ground-water from wells in lower Satus Creek basin.

Calculations with the model showed that irrigating land in the Satus uplands will raise water levels in lower Satus Creek basin. Irrigating 3,000 acres with 4 ft of water per year would probably raise the water table by no more than 1 or 2 ft over 2 $mi^2$ in an area where the present (1979-80) water table was 4 to 5 ft below land surface. As more land in the uplands area is irrigated, the affected area in lower Satus Creek basin increases. When 13,000 acres are irrigated the computed water-table position is at or above land surface at 11 of the 1-square-mile model nodes.

Model calculations also showed that decreasing the amount of irrigation water usage, pumping from wells, and stopping leakage from Satus Nos. 2 and 3 Pump Canals are effective methods for lowering the water table in some, but not all, areas where the water table is presently high. These methods are also effective in preventing, at some locations, rises in the water-table caused by irrigating the uplands.

Irrigating the uplands, reducing irrigation-water usage in the lowlands, pumping from wells, and stopping canal leakage affect ground-water levels most in the part of the basin between Satus Pump Canals No. 2 and 3. The effects on water levels in the western part of the basin are small by comparison.

# SELECTED REFERENCES


Bennett, G. D., Rehman, A., Sheikh, I.A., and Ali, Sabir, 1967, Analysis of aquifer tests in the Punjab region of West Pakistan: U.S. Geological Survey Water-Supply Paper 1608-G, 56 p.

Boyle Engineering Corporation, 1978, Final report on the drought relief program for the Wapato Irrigation Project, Wapato, Washington: San Diego, Calif., 31 p. plus unpaged appendices.

Brown, R. H., 1963, Estimating the transmissibility of an artesian aquifer from the specific capacity of a well, in, Benthal, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 336-338.

Flint, R. F., 1938, Origin of the Cheney-Palouse scabland tract, Washington: Bulletin of the Geological Society of America, v. 49, no. 3, p. 461-563.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

Jacob, C.E., 1963, Determining the permeability of water-table aquifers, in Bentall, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 245-271.

Johnson, A.I., 1967, Specific yield - compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662-D, 74 p.

Laval, W. M., 1956, Stratigraphy and structural geology of portions of south-central Washington: Washington University (Seattle) Ph.D. thesis, 223 p.

Molenaar, Dee, 1977, Outline of the water resources of the Satus Creek basin: U.S. Geological Survey Open-File Report 76-808, 34 p.

Mundorff, M. J., MacNish, R. D., and Cline, D. R., 1977, Water resources of the Satus Creek basin, Yakima Indian Reservation, Washington: U.S. Geological Survey Open-File Report 76-685, 102 p.

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.

Tanaka, H. H., Hansen, A. J., and Skrivan, J. A., 1974, Digital model of ground-water hydrology, Columbia Basin Irrigation Project areas, Washington: Washington State Department of Ecology Water-Supply Bulletin 40, 60 p.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Drexel Institute of Technology Laboratory of Climatology, Pub. in Climatology, v. 10, no. 3, p. 206, 210, 211, 228.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 103 p.

U.S. National Oceanographic and Atmospheric Administration, 1979-80, Climatological data for Washington: Ashville, N.C., vol. 83-84.

U.S. Soil Conservation Service, 1967, Irrigation water requirements: Technical Release No. 21, 83 p.

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