Digital-Simulation and Projection of Water-Level Declines in Basalt Aquifers of the Odessa-Lind Area, East-Central Washington

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ABSTRACT

A digital computer program using finite-difference techniques simulates an intensively pumped, multilayered basalt-aquifer system near Odessa. The aquifers now developed are in the upper 1,000 feet of a regionally extensive series of southwesterly dipping basalt flows of the Columbia River Group. Most of the aquifers are confined. Those in the depth range of about 500 to 1,000 feet are the chief source of ground water pumped from irrigation wells. Transmissivity of these aquifers ranges from less than 2,700 feet squared per day to more than 40,000 feet squared per day, and storage coefficients range from 0.0015 to 0.006. Shallower aquifers are generally much less permeable, but they are a source of recharge to deeper aquifers with lower artesian heads; vertical leakage occurs along joints in the basalt and down uncased wells, which short circuit the aquifer system. For model analysis, the deeper, pumped aquifers were grouped and treated as a single layer with drawdown-dependent leakage from an overlying confining layer. Verification of the model was achieved primarily by closely matching observed pumpage-related head declines ranging from about 10 feet to more than 40 feet over the 4-year period from March 1967 to March 1971.

Projected average annual rates of decline in the Odessa-Lind area during the 14-year period from March 1967 to March 1981 are: from 1 to 9 feet per year if pumpage is maintained at the 1970 rate of 117,000 acre-feet per year; or, from 3 to 33 feet per year if 1970 pumpage is increased to 233,000 acre-feet per year, which includes 116,000 acre-feet per year covered by water-right applications held in abeyance. In each case, projected drawdown on the northeast side of a major ground-water barrier is about double that on the southwest side because of differences in transmissivity and storage coefficient and in sources of recharge.

INTRODUCTION

The Odessa-Lind area is a semiarid, chiefly dryland wheat-farming area near the center of the Columbia Plateau in eastern Washington (fig. 1). The average annual precipitation of only about 10 inches occurs mostly during the winter months. The general shortage of precipitation, particularly during the hot summer months, has created a demand for irrigation water. During the early 1960's, farmers started drilling deep irrigation wells, and, despite pumping lifts of 300 to 500 feet, they had sufficient success in terms of crop yield and profit to foster a rapid growth in drilling activity. During the mid-1960's pumpage almost doubled every 2 years, and as early as 1965 water levels started to decline over broad areas.

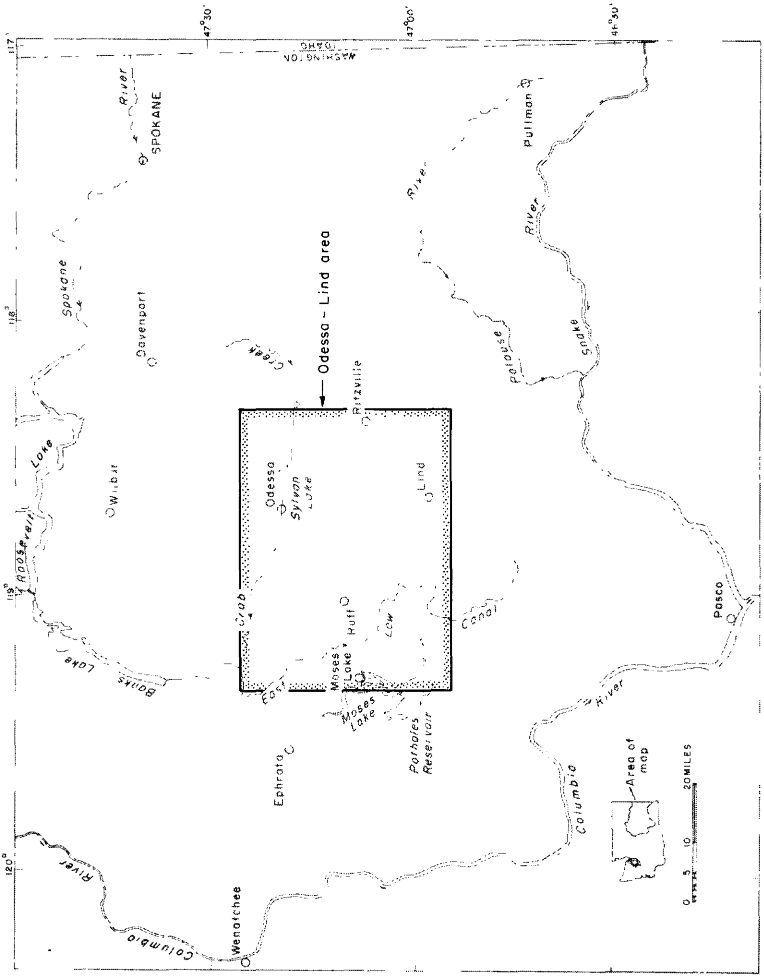


FIGURE 1.—Location of the Odessa-Lind area and the major surface-water features in east-central Washington.

For the most recent 4-year period from March 1967 to March 1971, the net water-level decline in parts of the area has approached 40 feet in wells tapping the deeper aquifers. Meanwhile, the pumping lifts have increased significantly because of the decline and drawdown interference between wells. Rising costs are being incurred by the irrigators because of the frequent need to ream and deepen wells and to extend pump columns. These increased costs have forced many irrigators to switch part of their acreage, traditionally planted in wheat, to more profitable row crops such as peas, beans, potatoes, and sugar beets. However, because these crops generally require more water than does wheat, the basic problem of declining water levels has continued.

The State of Washington Department of Ecology (formerly the Department of Water Resources) recognized the potential hardships associated with the continuing severe water-level declines in the area. In 1968 the Department suspended authorization of further deep-well irrigation development in part of the area of this study and designated it the "Odessa Hold Area," the boundaries of which are shown by stipple pattern on all maps in this report following figure 7. Issuance of additional ground-water rights for this part of the area was withheld pending further study to develop information needed for effective management of the ground-water resources.

PURPOSE AND SCOPE

The purpose of this study was to develop a predictive model of the ground-water system as a management tool for use in evaluating the effects of alternative methods of controlling or developing the ground-water resource in the Odessa-Lind area. The approach was to develop a digital model, which is simply a digital computer program that solves mathematical equations describing ground-water flow. The model "simulates" numerically the flow of ground water through the interstices of rock material. The use of such a model helps to improve the understanding of the physical system. Once it is calibrated, it can be used to predict the response of the aquifer system to man-induced stresses such as pumping withdrawal or artificial recharge. New plans of irrigation or methods of recharge can be tried by merely changing the rates of withdrawal or recharge in the model. Such computer-model predictions are rapid and relatively inexpensive.

The reasons for the development of the model are not only economy and speed, however. Because it incorporates virtually all available pertinent information about the real hydrologic system, the model described here is believed to be the most accurate and practical way at the present time to predict the ground-water response in the basalt aquifers of east-central Washington.

The digital model described in this report was used to simulate and evaluate conditions in the deeper aquifers (about 500–1,000 ft below land surface) penetrated by existing irrigation wells. The relatively shallow aquifers (about 100–400 ft) are considered in the model only as a possible source of leakage to the deeper aquifers.

This report discusses (1) the general ground-water system; (2) the digital model and how it was used and modified to simulate observed water-level changes over a 4-year verification period, 1967–71; (3) an evaluation of two 10-year model projections; and (4) possible future uses or extensions of the model and the data on which it is based.

As of 1970, the pumpage requested in water-right applications held in abeyance (116,000 acre-feet per year) is approximately equal to the actual pumpage (117,000 acre-feet per year) under existing permits and certificates. Therefore, withdrawal covered by pending permits, in addition to existing pumpage, poses a potential stress far greater than that experienced to date. As a necessary first step in ground-water management, the predicted effects of the pumping stresses at both the actual pumpage rates and actual rates plus pumpage covered by pending applications are included for 1971–81.

RELATION TO OTHER STUDIES

The model development is an outgrowth of two previous ground-water studies in this area and has benefitted from the information developed by related studies. The first study was a general appraisal of ground-water conditions and withdrawals in the Odessa area during 1964 and 1965 (Garrett, 1968). The findings of that appraisal led to an intensification of the ground-water study through 1969 and to the expansion of the coverage to include most of east-central Washington. An updated summary of the ground-water situation in the Odessa-Lind area was prepared by Luzier and others (1968) and was followed by a more comprehensive appraisal (Luzier and Burt, 1974) of ground water throughout the east-central region of the State. Luzier and Burt emphasized areas of depletion and their report contains rough empirical projections of water-level declines in the Odessa and Pullman areas based on the assumption that pumping was to continue at the 1968 or 1969 rate. Most of the basic data developed during the studies by Garrett (1968) and Luzier and Burt (1974) were utilized in the development of the digital model.

The model development also was guided by information from other investigations. A comprehensive study of the geology of the adjacent Columbia Basin Irrigation Project Area (Grolier and Bingham, 1971) provided significant knowledge of the basalt sequence and its water-yielding character. Insight to the rates of movement of water through the basalt-aquifer system was provided by research of hydrogeological applications of naturally occurring mineral isotopes (Silar, 1969). An evaluation of the economic and social impact of continued decline of pumping levels in the Odessa-Lind and adjacent areas was completed by Butcher and others (1971), utilizing preliminary information from the present study.

The present work has been conducted by the U.S. Geological Survey in cooperation with the State of Washington Department of Ecology (formerly the Department of Water Resources).

ACKNOWLEDGMENTS

The study was facilitated by the cooperation of many well owners in the region who made their wells available for periodic measurements, borehole surveys, and discharge measurements. The assistance and records provided by the well drillers of the region, and the generous help of the power companies in furnishing power-consumption records, also are greatly appreciated. Contributions to the study were made by other hydrologists of the U.S. Geological Survey, particularly H. E. Pearson and C. J. Londquist.

THE GROUND-WATER SYSTEM

REGIONAL GROUND-WATER RESERVOIR

Basalt aquifers of the Odessa-Lind area are part of a much larger ground-water reservoir occuring in a thick series of lava flows known as basalt of the Columbia River Group. The basalt was laid down in widespread sheets over a roughly circular 55,000-square-mile area in eastern Washington, northeastern Oregon, and west-central Idaho. In east-central Washington the basalt flows slope gently southwestward from near Roosevelt Lake and the Spokane River, where the basalt abuts older hills of granitic and metamorphic rocks (fig. 2). The thickness of the basalt is highly irregular near the older rocks, but it increases to the southwest (fig. 3), and is nearly 4,500 feet thick in the Odessa-Lind area (at Basalt Explorer well 1), and more than 10,000 feet near Pasco. The basalt surface in much of the Odessa-Lind area is thinly mantled by loess, but in areas to the north, east,and southeast, much of the plateau was scoured by enormous floods of glacial melt water during the Pleistocene Epoch, exposing wide belts of basalt within the channeled scabland of Bretz (1959). Along the line of the diagrammatic geologic section shown in figure 3, most of the surface northeast of Basalt Explorer well 1 is part of the channeled scabland. Although the individual basalt flows are shown in the section as being approximately parallel to land surface, the flows may actually be in an offlap relationship (Grolier, 1965, p. 186-188), with the edges of progressively older flows exposed toward the northeast margin of the plateau. This relationship is rarely observed in the field, especially because of the extremely low southwesterly dips (1° to 2°) of individual basalt flows.

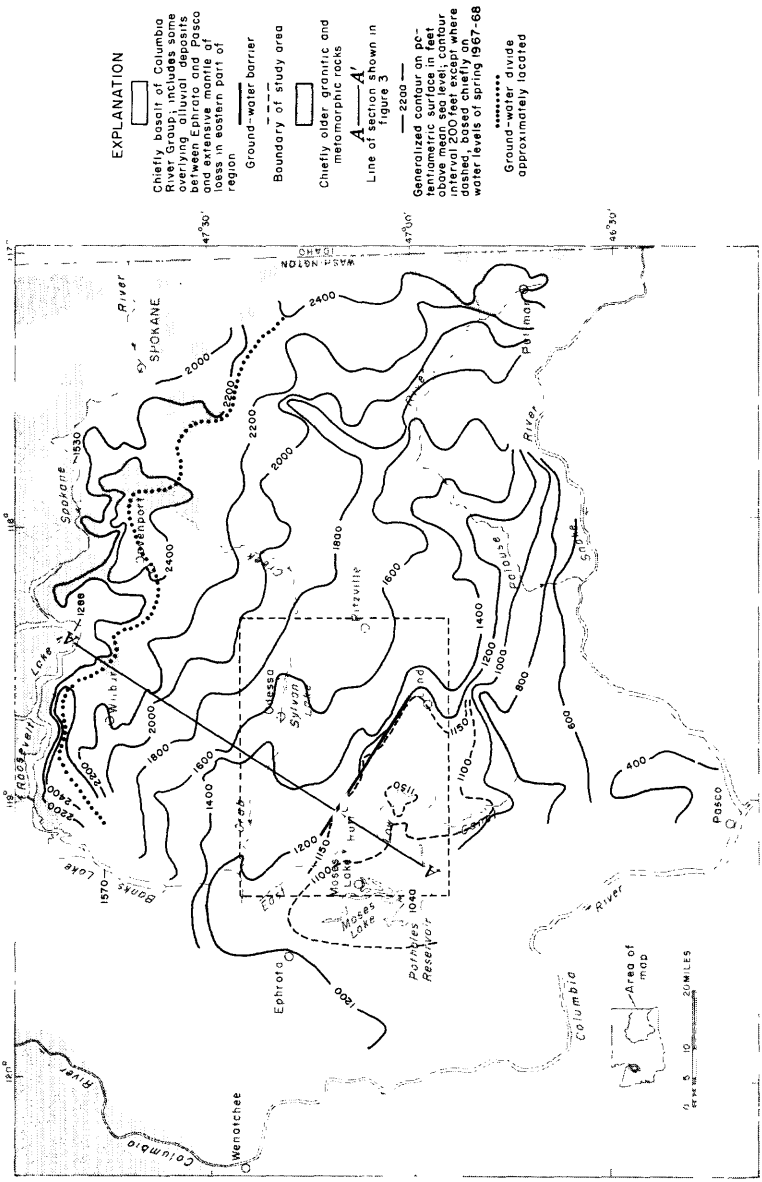


FIGURE 2. —Extent of regional basalt ground-water reservoir in east-central Washington, and generalized contours on the potentiometric surface.

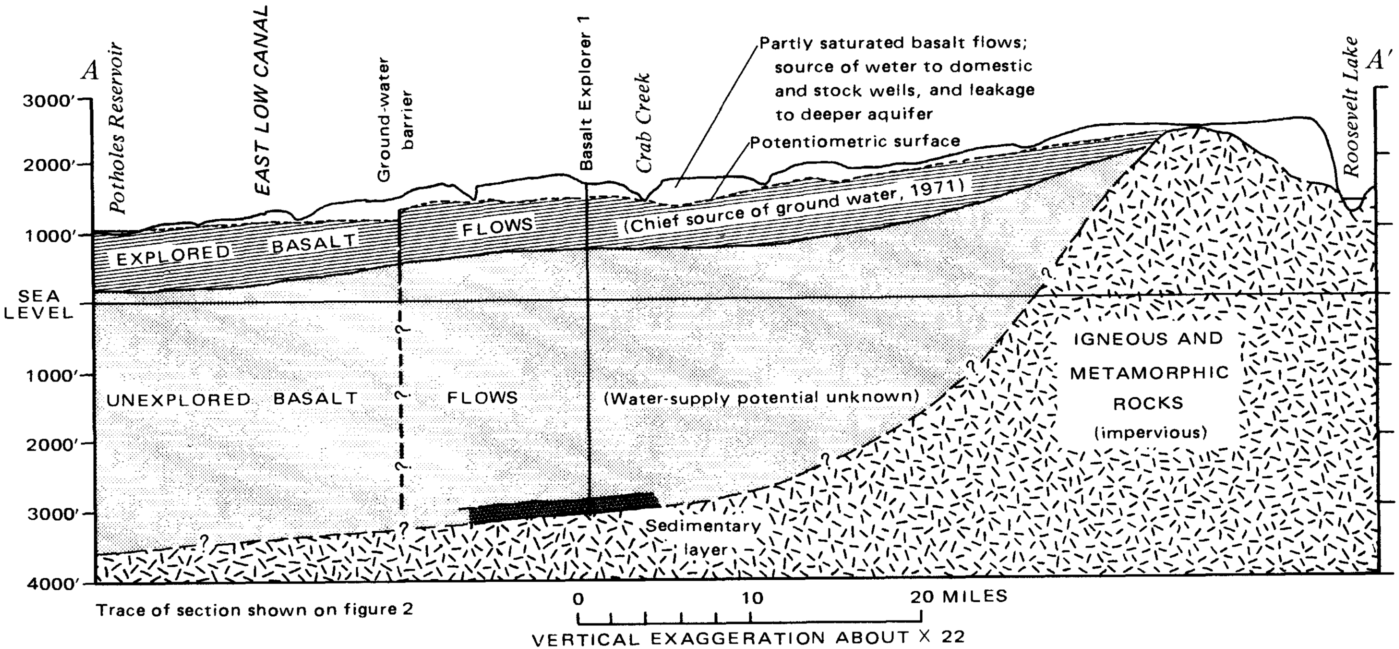


FIGURE 3. —Generalized geologic section from Potholes Reservoir to Roosevelt Lake, showing thickness of the basalt ground-water reservoir in relation to the zone tapped by irrigation wells as of 1971. Trace of section shown in figure 2.

GROUND-WATER RECHARGE AND MOVEMENT

The basalt is recharged mainly by water from precipitation, which increases gradually from about 8 inches between Potholes Reservoir and Pasco to about 16 inches near Davenport and about 22 inches along the Washington-Idaho border. Recharge is by direct infiltration and by seepage from the channels of intermittent streams. Thin rocky soils of scabland probably are more conducive to recharge than are the fine loess soils elsewhere. In the western part of the Odessa-Lind area, a substantial amount of recharge is derived from the East Low Canal and land irrigated under the Columbia Basin Irrigation Project (Luzier and Burt, 1974, p. 16).

The regional potentiometric contours (fig. 2) show that ground water moves generally to the southwest, except in an area west and north of Potholes Reservoir and Moses Lake where the general direction of movement is southeastward. In all these areas, the direction of ground-water movement is influenced by the dip of basalt flows, although to the west of Potholes Reservoir and Moses Lake, recharge from canals and irrigation since about 1952 has accentuated the easterly movement of ground water. Recharge from irrigation also has induced more southward flow in areas to the south of the Odessa-Lind area.

BASALT AQUIFERS IN ODESSA-LIND AREA

Basalt aquifers in the Odessa-Lind area have been explored by irrigators to maximum depths of about 1,000 feet, or less than one-fourth of the total known thickness of the basalt (4,465 ft at Basalt Explorer well 1, fig. 3). Most of the several hundred irrigation wells have obtained adequate supplies of ground water—1,000–2,000 gpm (gallons per minute)—from two or more confined aquifers in the depth range of about 500 to 1,000 feet. Aquifers in the first 400 to 500 feet of basalt in most parts of the Odessa-Lind area are not sufficiently permeable or areally extensive enough to supply such large yields. However, these aquifers have been adequate sources of water supplies for domestic and stock wells and, locally, for small irrigation wells.

Heads are highest in the shallowest aquifer zones in the basalt and become progressively lower in the deeper zones. During the drilling of a deep well in the basalt, the water level in the well commonly drops several feet, or several tens of feet, as deeper aquifer zones are penetrated. The drop in water level may be 100 feet or more in some places. Such large changes in head usually occur only once during the drilling of a well, commonly within the first 500 to 600 feet. Additional changes in head, but of smaller magnitude, are likely to occur with continued drilling. The differences in head reflect the very low permeability of the intervening dense basalt and largely represent the head loss as the ground water slowly migrates across these layers. Low vertical permeability of individual basalt flows partly accounts for the extremely high position of water levels adjacent to parts of Roosevelt Lake along the northern margin of the project area (fig. 2). For example, water levels in deep irrigation wells at Wilbur and Davenport are 900 to 1,100 feet higher than the altitude of Roosevelt Lake. Near Ruff, a ground-water barrier of unknown origin was delineated by Luzier and Burt (1974).

The known aquifers in the area have been grouped into upper and lower depth intervals, aquifer zones A and B, respectively, by Luzier and Burt (1974, p. 10). The delineation of the two zones was based chiefly on (1) distinct differences in static heads (those of zone A usually are at a higher level), and (2) degree of response to large head changes induced by deep-well pumping. Figure 4 shows how the two zones are typically related. Rarely are wells cased to more than 100 feet below land surface and, therefore, they form interconnections or hydraulic short-circuits between all aquifers penetrated. The deep wells, being open to the deeper aquifers of lower artesian head of zone B as well as to the higher aquifers of zone A, cause significant drainage of ground water from zone A. This short-circuiting effect of deep well bores, according to Luzier and Burt (1974) has contributed to the widespread lowering of artesian head in zone A that, in places, has been sufficient to nearly dewater parts of the upper aquifer zone.

As shown in figure 4, the downhole leakage causes a local buildup of heads in the deeper aquifers. In most cases, the leakage from the zone A aquifers is small enough, that the head buildup is minor and can be disregarded in analyses of water-level changes. However, in a few of the wells from which water-level data were obtained for this study, the local buildup of water levels seems to have been great enough to significantly affect the interpretation of water-level declines related to pumping.

For the local buildup of heads to have a significant effect on the interpretation, the following conditions would be required: (1) The transmissivity of the zone B aquifers would have to be in the lower part of the range suitable for a successful irrigation well in this area—certainly less than 5,000 feet squared per day; and (2) the downhole flow would have to be relatively great initially—probably more than 100 gpm—and to have decreased greatly during the period of measurements. Under this set of conditions, the decline in zone B head at a well due to the decrease in downhole leakage could amount to 10 feet or more and would be a significant addition to the declines in levels that have resulted from pumping.

The apparent local buildup in head due to downhole leakage would tend to be even greater where bubbles of air were entrained in water that was cascading down the well bores into zone B aquifers. Clogging of basalt aquifers by bubbles of air, causing increased buildup of water levels in wells while they were receiving water, has been observed in at least two artificial-recharge experiments in the region (Price and others, 1965, p. 45–46). In the Odessa-Lind area, the conditions for this type of clogging were greatest where downhole cascading occurred at relatively large rates and involved a substantial distance of free fall.

THE DIGITAL MODEL

Use of the digital model as a predictive tool is based on the premise that if past conditions can be simulated in the model, then so can future

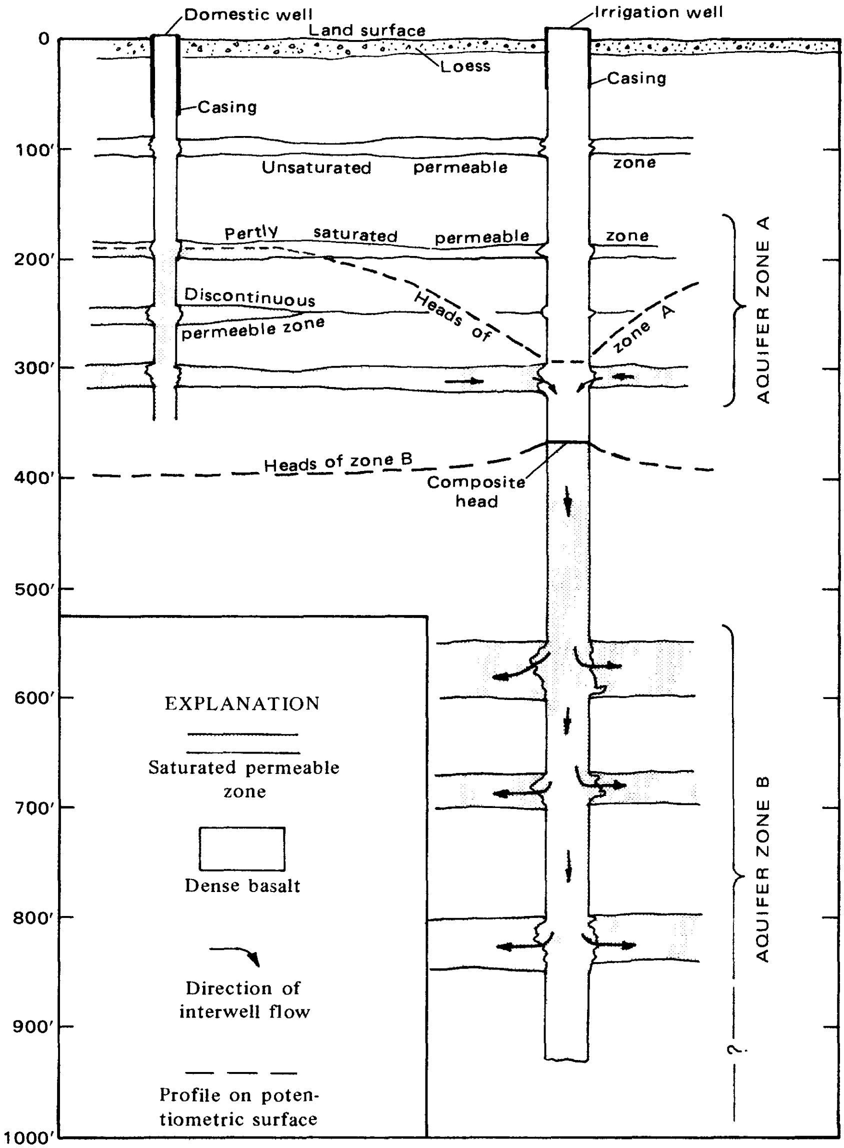


FIGURE 4. —Diagrammatic section showing relationship between aquifer zones A and B near typical nonpumping wells in Odessa-Lind area.

conditions. In practice, water-level changes in response to pumpage in each of the past several years were duplicated, after which, it is assumed, the model will simulate the response of the real system to predicted pumping or other stresses. However, it is not sufficient to merely develop a mathematical formula to duplicate a specific pattern of water-level changes. To be suitable, the model must (1) function within the constraints of theoretically valid equations of ground-water flow, (2) be based on reasonable simplifying assumptions and technically sound hydrologic rationale, and (3) utilize model parameters whose values do not exceed reasonable limits.

SIMULATION OF AQUIFER ZONE B

The multilayered aquifer system in the Odessa-Lind area, as depicted in figure 4, has been generalized in the model. Although methods are available for modeling multilayer aquifer systems, the costs of a multiple-layer analysis are quite high, and the available data for this area are not sufficiently detailed to warrant a multilayer approach. Because most of the irrigation wells are uncased, it is impractical to isolate and collect information on individual aquifers. Instead, the zone B aquifers are grouped and treated as a single layer which receives vertical leakage from an upper zone (fig. 5).

As shown in figure 5, zone A and zone B are assumed to be connected hydraulically by leakage through a confining layer. When pumping begins, the heads in zones A and B are assumed to be equal, and the head in zone A is held constant. As drawdown in zone B increases, so does the vertical leakage, which depends on the head difference between the two zones. Figure 5 only shows the model representation for one well. The model, of course, includes representation of multiple wells and simulates the response of the entire system as idealized. The vertical leakage is described in the "Sources of Recharge" section of this report.

DIGITAL COMPUTER PROGRAM

To model the aquifer system in the Odessa-Lind area, the writers adapted a digital computer program written by Pinder (1971), based on the techniques described by Pinder and Bredehoeft (1968). This program solves the differential equation which describes nonsteady groundwater flow for either a confined or unconfined aquifer. It uses an alternating-direction implicit technique to solve a set of finite difference equations which approximate the differential equation.

Pinder successfully tested his program using theoretical aquifers with known solutions. The digital-program solutions also compare favorably with solutions by analog-model analysis. In addition, an aquifer at Musquodoboit Harbour, Nova Scotia, was simulated and verified using Pinder's program (Pinder and Bredehoeft, 1968).

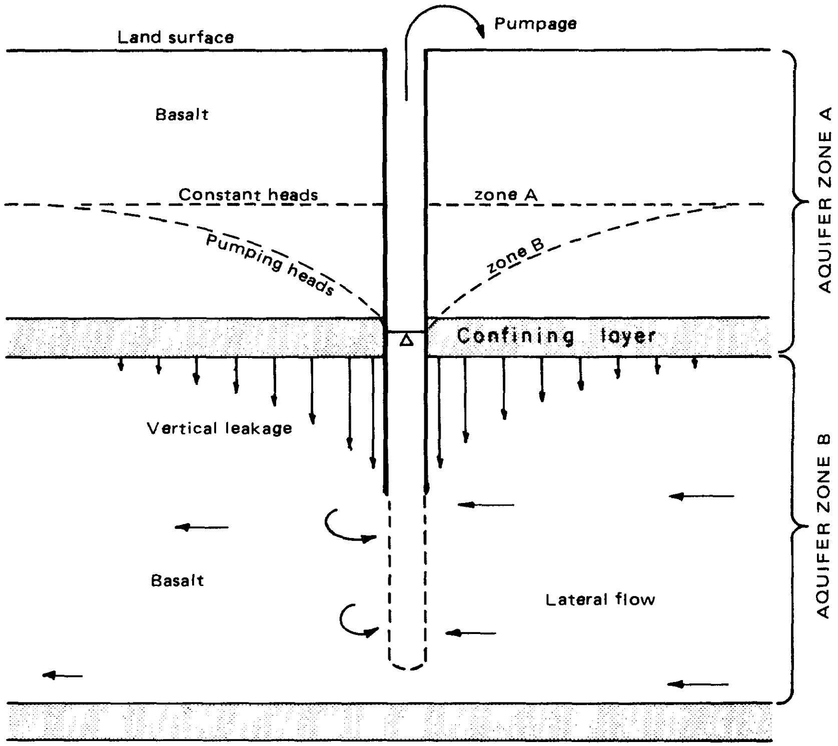


FIGURE 5. —Model representation of the Odessa-Lind aquifer system under pumping conditions.

For simulation of aquifer zone B in the Odessa-Lind area, modifications of Pinder's program[1] included the following:

1. Vertical leakage to every node was used to simulate leakage from an upper aquifer. (See "Sources of Recharge" section for further discussion.)
2. Since the transmissivity does not change with time in confined aquifers, such as those near Odessa, average transmissivities were computed once and were stored for further use in the computer to save computer time.
3. Constant-head nodes were incorporated to simulate areas where heads were known or at least were not expected to change with time.
4. Actual heads were automatically compared with computed heads to indicate where the model was and was not matching the field data.
5. A capability was added for plotting computed and measured heads at selected locations to produce hydrographs with which computed data can be compared to the historical data.

[1]The reader is referred to Pinder (1971) for a more comprehensive description of his program and its use; Skrivan (written commun., 1972) describes program documentation of Pinder's model as modified for the Odessa aquifer.

MATHEMATICAL DESCRIPTION

The nonsteady flow of ground water in a confined aquifer can be stated mathematically with the partial differential equation

$$\frac{\delta}{\delta x}\left(T\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(T\frac{\delta h}{\delta y}\right)=S\frac{\delta h}{\delta t}+\frac{Q}{\Delta x\cdot\Delta y}+\frac{K}{m}\left(H_0-h\right) \quad (1)$$

where

h = potentiometric head, in feet;
T = transmissivity, in feet squared per day;
S = storage coefficient (dimensionless);
Q = rate of withdrawal, in cubic feet per day;
K = vertical permeability of the confining layer, in feet per day;
m = thickness of the confining layer, in feet;
H_0 = initial head at the top of the confining layer, in feet;
x,y = rectangular coordinates, in feet;
$\Delta x,\Delta y$ = space increments, in feet; and
t = time, in days.

For a given point in the aquifer at a given time, the head is calculated based on estimates of the other variables. In general, the head depends on lateral flow in the aquifer, downward leakage through an upper confining layer, change in quantity of ground water in storage, and the quantity of pumping.

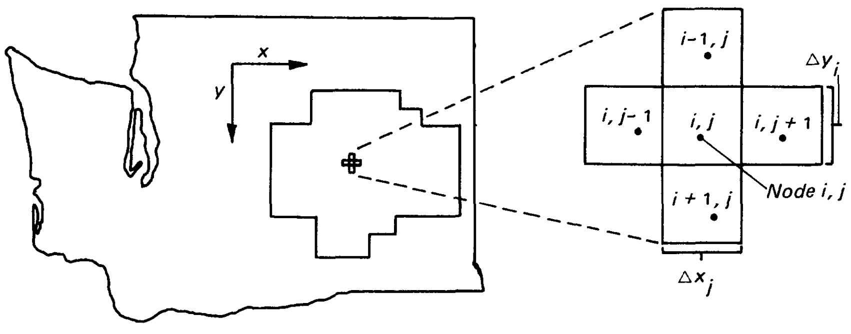


FIGURE 6. —Nodal array for finite-difference approximations.

The well-known finite-difference method is used to approximate equation 1. (For example, see Pinder and Bredehoeft, 1968, p. 1073–1075.) This method represents the aquifer as a two-dimensional mesh of elements i, j (fig. 6). A typical element is 1 square mile. At the center of the element is a node which is a hypothetical point where data values are given.

Using finite differences for the partial derivatives, equation 1 is approximated by:

$$T_{i+½,j}\frac{(h_{i+1,j}-h_{i,j})}{\Delta y_i} - T_{i-½,j}\frac{(h_{i,j}-h_{i-1,j})}{\Delta y_i} + T_{i,j+½}\frac{(h_{i,j+1}-h_{i,j})}{\Delta x_j}$$

$$- T_{i,j-½}\frac{(h_{i,j}-h_{i,j-1})}{\Delta x_j} = S_{i,j}\frac{(h_{i,j}-\overset{\text{Prev}}{h_{i,j}})}{\Delta t} + \frac{Q_{i,j}}{\Delta x_j\,\Delta y_i} + \frac{K(H_0-h_{i,j})}{m_{i,j}} \qquad (2)$$

where $\overset{\text{Prev}}{h_{i,j}}$ is the potentiometric head at the node i, j at the previous time step, Δx and Δy are space increments, Δt is the time increment and

$$T_{i+½,j} = \frac{2T_{i+1,j}\,T_{i,j}}{T_{i+1,j}\,\Delta y_i + T_{i,j}\,\Delta y_{i+1}}, \qquad T_{i-½,j} = \frac{2T_{i,j}\,T_{i-1,j}}{T_{i,j}\,\Delta y_{i-1} + T_{i-1,j}\,\Delta y_i},$$

$$T_{i,j+½} = \frac{2T_{i,j+1}\,T_{i,j}}{T_{1,j+1}\,\Delta x_j + T_{i,j}\,\Delta x_{j+1}}, \qquad T_{1,j-½} = \frac{2T_{i,j}\,T_{i,j-1}}{T_{i,j}\,\Delta x_{j-1} + T_{i,j-1}\,\Delta x_j}.$$

An equation similar to equation 2 is written for each node. The result is a system of simultaneous linear equations in which the unknown head is solved over the entire area, using the alternating-direction implicit method. Since equation 1 is also time dependent, time is advanced by an increment of 10 days, for example, and the process is repeated to give heads 10 days later.

Equation 1 also can be solved for drawdowns and, through the principle of superposition, potentiometric heads can still be calculated. In general, superposition means that the addition of any two solutions of equation 1 representing independent stresses is itself a solution representing the sum of the stresses. Any measured head-distribution map is a solution which reflects the response of the system at the time of measurement. If the system has reached steady state, drawdowns calculated from additional stress, such as new pumping, can then be added to the measured heads. The result is a potentiometric surface reflecting the original stress plus the new pumping stress.

The unique data for the Odessa-Lind model consist of two types: fixed and variable. Fixed-model data include the geometric description of the aquifer, such as dimensions of the model, grid size, and boundaries. Also considered fixed data are the locations of constant-head areas, pumpage for each particular year, and measured water-level changes and potentiometric surfaces. All these data were defined or calculated at the beginning of the analysis and consequently were rarely changed.

The variable data are those model parameters that are more tentative and are subject to modification in attempting to achieve a match of the model to the real system. Data of this type include transmissivity, storage coefficient, thickness of the assumed confining layer, and the rates and cumulative volume of vertical leakage. These are the quantities which can be varied within rational limits in attempting to verify the model.

GRID SIZE AND BOUNDARIES OF THE MODEL

The nodal arrangement of the Odessa-Lind model consists of a central fine grid of 1,764 elements or nodes, each representing 1 square mile, and a surrounding variable grid of 1,502 nodes (fig. 7). Each row and column of nodes contains rectangular land areas which increase in size outward to the model boundaries.

No-flow boundaries are used in the Odessa-Lind model. The east and north boundaries represent a natural thinning or termination of basalt at the arc of granitic or metamorphic rocks, which extend from the Pullman area northward and westward to Banks Lake and Grand Coulee Dam (fig. 2). The major regional boundaries on the west and south — the Columbia and Snake Rivers — are so distant from the fine-grid area that their effects on pumping and resultant drawdown can be practically disregarded. In addition to the peripheral boundary nodes, the model contains some internal constant-head nodes that are described in the section "Sources of Recharge."

The selection of the 1 square-mile size of the fine-grid nodes was made to strike a proper balance among the following three important factors: (1) The density of field data available for input to the node, (2) overall costs of developing and operating the model, and (3) the planned uses of the model as a predictive tool. The density of wells (and thus of field data) is not great enough in the Odessa-Lind area to justify a grid size finer than 1 square mile per node. Well density is no greater than 15 per township and, in many instances, there are less than four wells per township. A finer grid, in addition, would be far more costly in terms of increased computer storage and computer execution time. Finally, the basic use of the model is for a regional analysis and thus a finer grid detail is unnecessary.

AQUIFER TRANSMISSIVITY AND STORAGE COEFFICIENT

Transmissivity values for the Odessa-Lind aquifer were obtained by conversion of specific-capacity data obtained from 2- to 8-hour aquifer tests by drillers and from long-term tests (several months or longer) reported by Luzier and Burt (1974, p. 17). Specific capacities for areas with no supporting data were calculated by computer averaging of surrounding specific capacities. As stated by Luzier and Burt (1974, p. 24), estimates of transmissivity in feet squared per day were obtained by multiplying specific capacity by 270 (equivalent to conversion factor of 2,000 for obtaining transmissivity, in gallons per day per square foot), in accordance with a method described by Theis, Brown, and Meyer (1963).

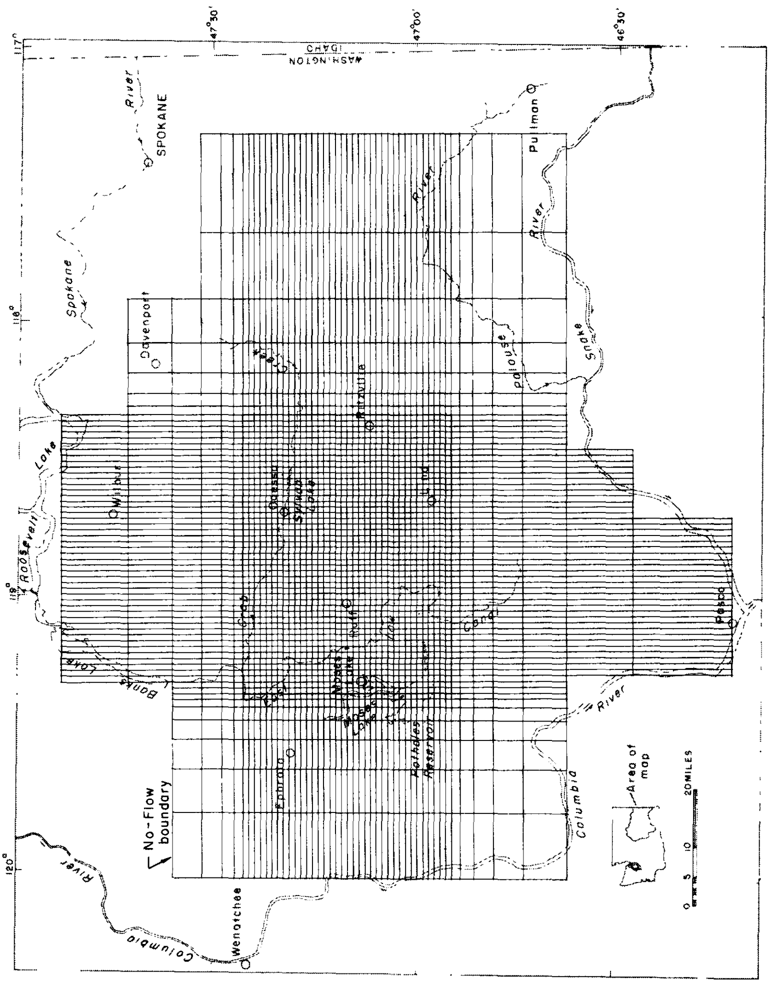


FIGURE 7. —Grid system used for the ground-water model.

Initially, the specific capacities based on long-term tests were favored over those based on the short-term tests; in general, the long-term data produced lower transmissivity estimates than the short-term tests. However, early model runs indicated the need for higher transmissivities than the original estimates. As a result, transmissivities were then recalculated from both types of specific-capacity data, and average values were used. The resulting transmissivity map was not modified greatly during subsequent runs, except in the area of T. 19 N., Rs. 32 and 33 E., where it was found necessary to raise transmissivity. The ground-water barrier near Ruff was approximated by lowering the transmissivity to 134 feet squared per day, or 1,000 gpd (gallons per day) per foot at the appropriate nodes. The final transmissivity distribution used in the fine grid of the model is shown in figure 8.

Storage coefficients calculated by Luzier and Burt (1974, p. 24) for two large areas adjacent to the ground-water barrier are 0.002 for the northeast side of the barrier and 0.006 for the southwest side. These values were extended to other nodes of the model with a dividing line running east from the southeast end of the barrier and west from the other end.

During the model runs, the storage coefficient was adjusted on the northeast side of the barrier from 0.002 to 0.0015 in one large area, and in another area near the southeast end of the barrier from 0.002 to 0.006. The final storage-coefficient distribution used in the model is shown in figure 9.

These values for storage coefficient are clearly within the leaky artesian aquifer range and agree with the concept of addition of water to zone B by leakage from aquifer zone A. An alternative approach in the model might be to reduce the storage coefficient to a value typical for a pure artesian situation and then adjust the vertical leakage parameter upward. However, in the judgment of the writers there would be very little difference in the overall model results using this approach.

PUMPAGE

Pumpage in the area increased from about 26,000 acre-feet in 1963 to a maximum of about 122,000 acre-feet in 1968; it decreased to 114,000 and 117,000 acre-feet in 1969 and 1970, respectively (fig. 10). Closure of most of the Odessa-Lind area in 1968 to further drilling of new irrigation wells apparently was an important factor in stopping the rapid growth of pumpage. Most of the pumpage was used for irrigation, and only a small fraction was used for municipal and industrial demands. The 117,000 acre-feet of water pumped in the area in 1970 was distributed within the model, as shown in figure 16.

Simplification was made in the model to compensate for the various lengths of pumping seasons. Although pumping wells in the real system

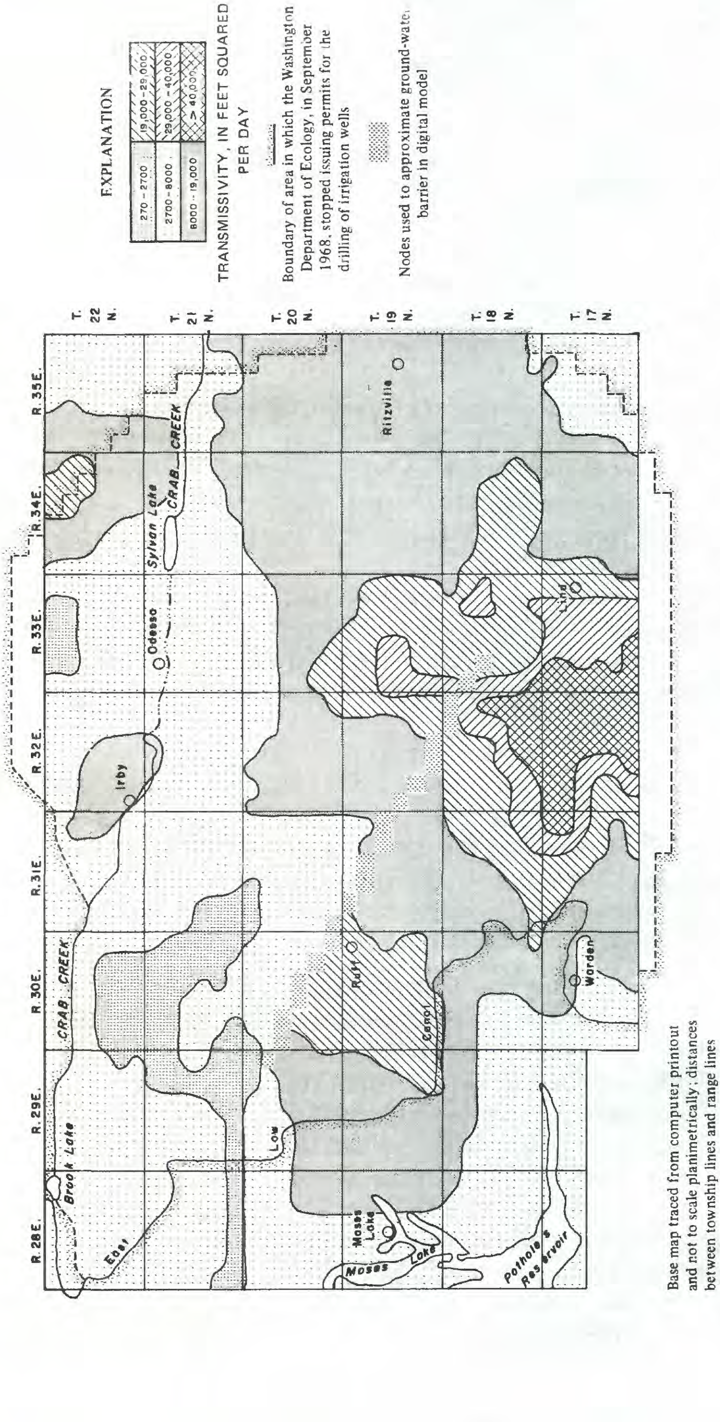
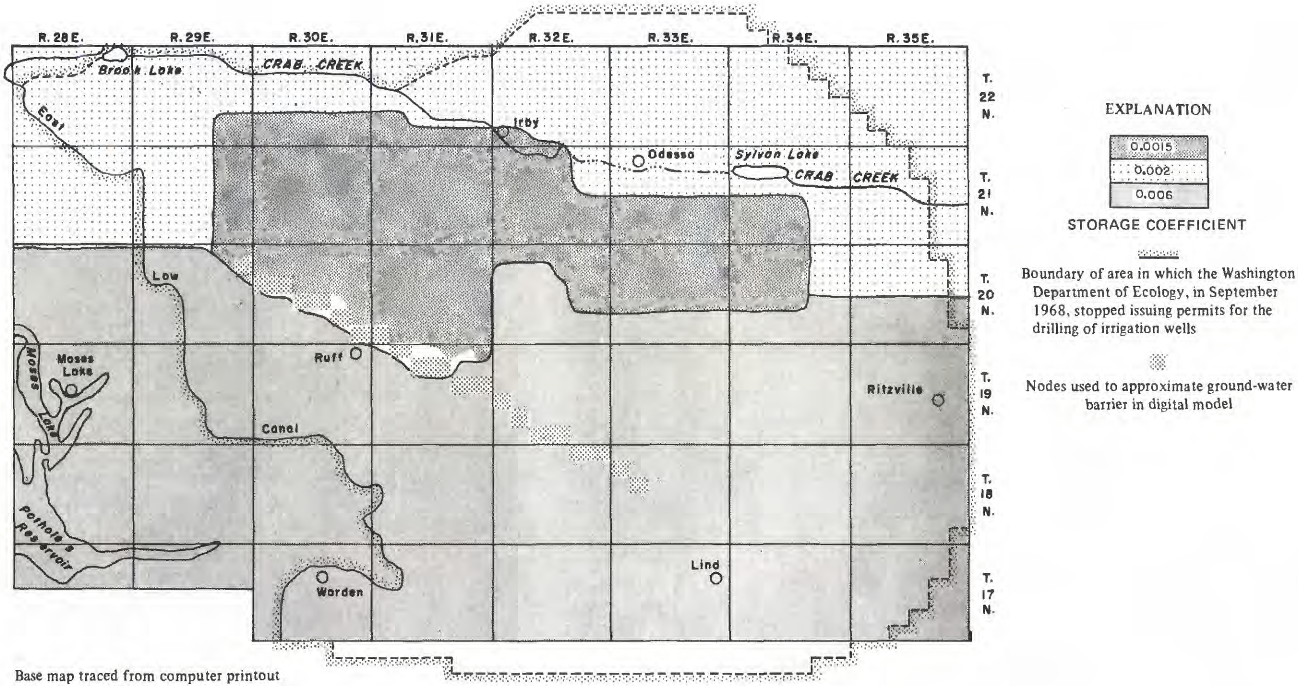


FIGURE 8. —Final transmissivity distribution used to verify the ground-water model.



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 9. —Final storage-coefficient distribution used to verify the ground-water model.

have different starting and stopping times, all pumping simulated in the model starts and stops simultaneously. In addition, pumpage from all wells in a particular node is added together and is treated as if it

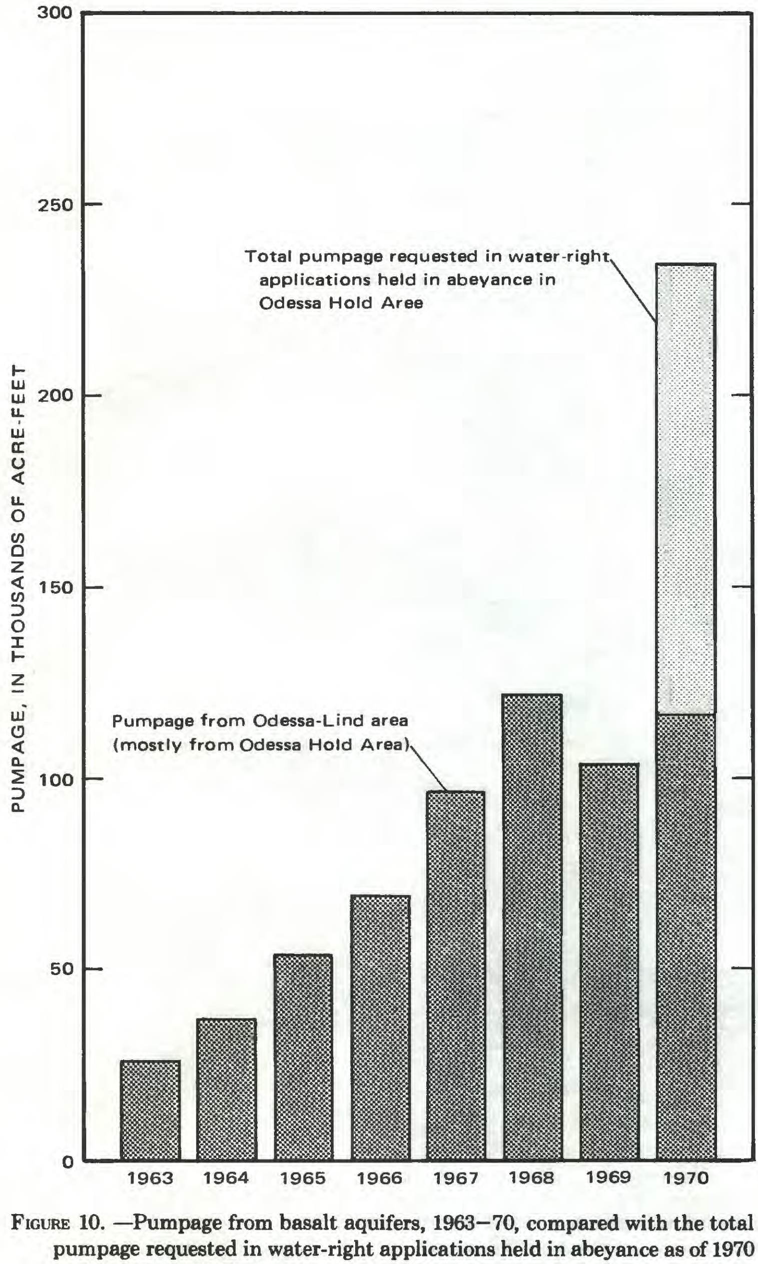


FIGURE 10. —Pumpage from basalt aquifers, 1963–70, compared with the total pumpage requested in water-right applications held in abeyance as of 1970 in the Odessa Hold Area.

were coming from one central well. Then, the pumping rate for each node is held constant throughout each pumping season; the rate is changed, of course, from node to node and from year to year. These simplifications greatly reduced data preparation and computer time and had negligible effects on the final results.

All pumpage was computed by conversion of electric-power consumption records for individual wells by Luzier and Burt (1974, p. 25) and is assumed to be accurate within 10 percent. For each year of the model-verification period (1967–70), the lengths of seasonal pumping periods were estimated from monthly electrical power-consumption records at two major substations owned by Lincoln Electric Cooperative. The average lengths are included in the following table:

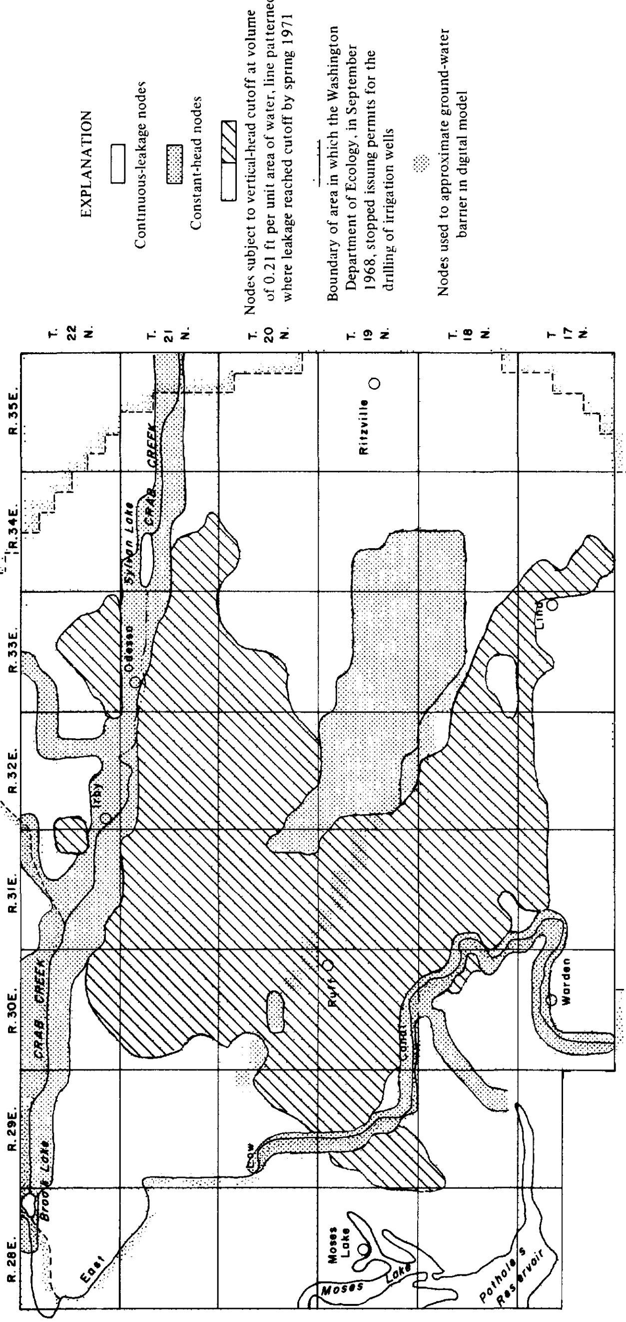
Average date pumps start	Average date pumps stop	Average pumping period (days)
Apr. 1, 1967	Sept. 28	180
Apr. 6, 1968	Oct. 22	200
Apr. 21, 1969	Oct. 6	170
Mar. 28, 1970	Oct. 12	200

As the table shows, the length of the pumping season varies. The variation is usually caused by climatic factors; the relatively short pumping season in 1969, for instance, was due in large part to an unusually wet spring.

SOURCES OF RECHARGE

Simulation of recharge to aquifer zone B consists primarily of (1) a vertical flux derived from a simplified upper aquifer zone (fig. 5), assumed to be present everywhere within the model boundaries, and (2) a series of constant-head nodes extending from Potholes Reservoir (fig. 11) generally northward to Banks Lake (fig. 2).

Vertical leakage is possible at every node in the model except at the constant-head nodes and represents either (1) interception of natural runoff in Crab Creek and adjoining coulees, (2) continual leakage from the East Low Canal area and an area near the ground-water barrier centered around T. 19 N., R. 32 E. and R. 33 E., or (3) restricted leakage (in cumulative volume) from the aquifer zone A (fig. 11). An apparent progressive decrease in the low flow of Crab Creek at Irby (Luzier and Burt, 1974, p. 44) suggests that some of the ground water formerly discharging from the upper basalt aquifers to Crab Creek now is being diverted to recharge aquifer zone B. There is also geologic evidence of scoured and fractured flow layers in coulee bottoms which may enhance vertical leakage through the basalt. Recharge attributed to the East Low Canal includes leakage from unlined parts of the canal itself as well as from the Columbia River Irrigation Project area to the west of



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 11.—Sources of recharge represented in ground-water model.

Odessa (Luzier and Burt, 1974, p. 17). Zone B aquifers in the area near T. 19 N., Rs. 32 and 33 E., apparently are receiving unusually large quantities of recharge water in a manner not fully understood at this time. The authors chose to approximate this source as continuous vertical leakage. This is based on the postulation that the vertical connection between zone A and zone B aquifers may be better in this part of the area than elsewhere and that, consequently, downward leakage to zone B at that location is occurring at an unusually rapid rate. Additional study is needed to understand more fully the source and nature of this recharge and its probable future dependability and duration.

The model is quite sensitive to recharge variations. During the study, vertical leakage was the parameter that was most often varied and which posed the biggest problem. Very little supportive data are available on vertical leakage, despite its importance as a source of water to aquifer zone B. As a result, when leakage was added to the model, estimates had to be made about both the rate and extent of vertical leakage in the Odessa-Lind area. The principal adjustments that were used to fine tune the model were the vertical permeability rate, which differed areally, and the maximum leakage rate and maximum cumulative volume, which were chosen uniformly for the entire area. In addition, some areas were selected to receive continuous leakage which probably will not continue indefinitely in the real system.

Vertical leakage in the model is induced by drawdown, as shown in figure 5. As indicated in figure 12, the leakage rate is directly proportional to drawdown until some arbitrary maximum drawdown is reached. The rate is then held constant as long as drawdown exceeds the maximum limit. The need for this limitation was established

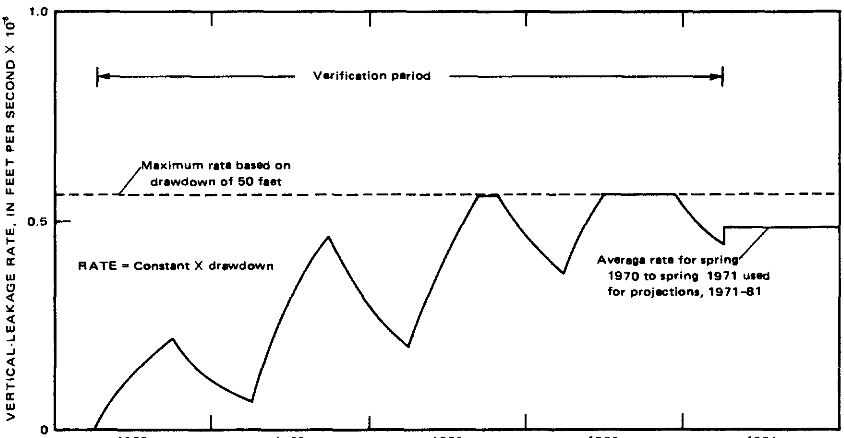


FIGURE 12. —Vertical-leakage rate versus time, for a typical node where leakage is allowed to continue.

through trial-and-error runs in attempting to get a good match of the model with the field conditions. Best overall results were obtained by using a maximum drawdown of 50 feet for the leakage-rate calculation.

Nodes receiving leakage from the upper aquifer zone were further restricted to a total cumulative volume of leakage, after which leakage was cut off. This refinement simulates the dewatering of parts of the upper aquifer zone, which apparently has occurred recently at some places in the Odessa-Lind area. The total volume of zone A water available for leakage to zone B cannot be easily determined for the real system. However, after many computer runs during simulation, a maximum cumulative volume was established at 0.21 foot of water. This amount, equivalent to about 2½ inches of rain reaching the aquifer, was the total allowed to leak to nodes receiving leakage from the upper aquifer zone. Figure 11 shows the nodes that had received 0.21 foot of water by March 1971. Consequently, those nodes would receive no more leakage during the period of the model projections.

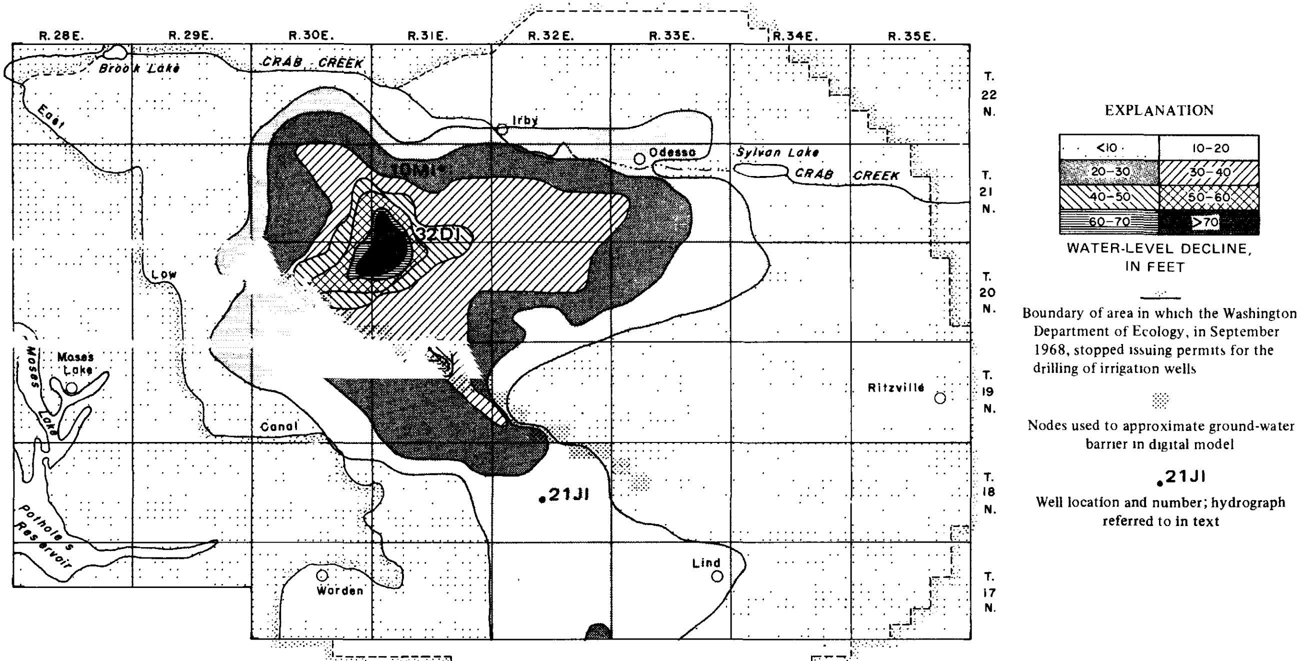
VERIFICATION OF THE MODEL

In order to develop a mathematical model suitable for projecting future stresses on the Odessa aquifer, historical responses had to be duplicated reasonably well. The primary emphasis in this phase of analysis was placed on achieving the best possible match between measured and model-generated head changes over the longest time period for which sufficient data were available.

The first intensive mapping of the potentiometric surface of aquifer zone B was developed in March 1967 (Luzier and Burt, 1974, p.11). Within 4 years, by March 1971, the potentiometric surface had declined by amounts ranging from 10 to 40 feet or more over large parts of the Odessa-Lind area (fig. 13). This 4-year period was selected as the most appropriate time interval for verification of the model.

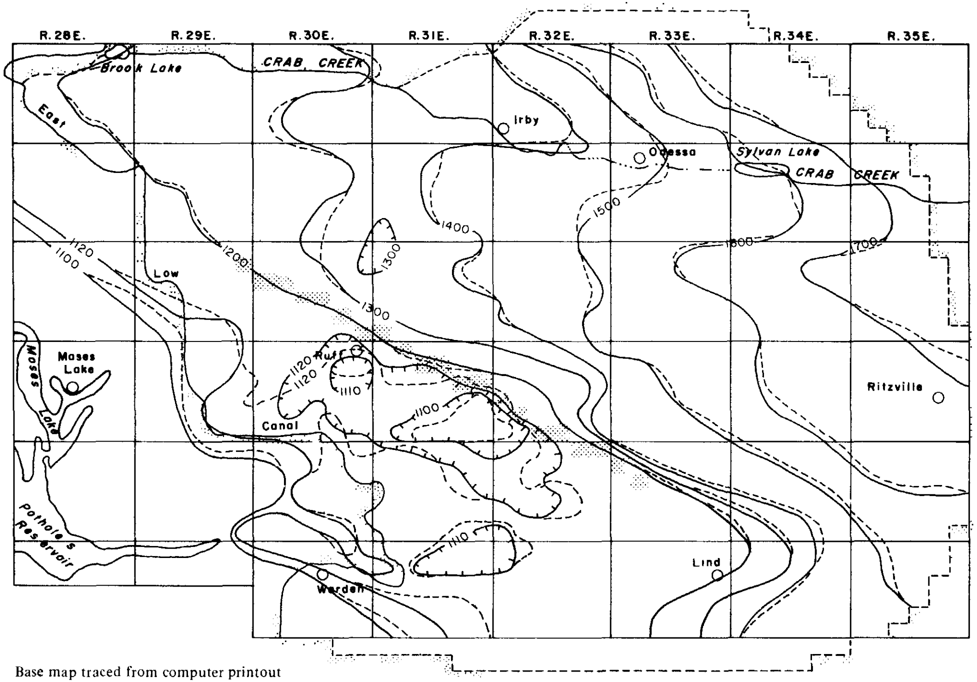
Two objectives were used to determine verification success. First, the March 1971 head-distribution map had to be predicted reasonably well by the model. Second, four selected hydrographs spanning the 4 years had to agree generally with the computed hydrographs.

Most parts of the 4-year decline map (fig. 13) were matched within ±5 feet, as shown by figure 15. However, where the measured decline was greatest (60 ft or more, fig. 13), the match by the model at the end of 4 years was not as good. This anomalous area is apparent in figure 14 where the 1,300-foot depression contour (hachured) was not duplicated by the model. In that part of the area, the zone B transmissivity is relatively low (fig. 8), and the apparent head reduction may have been magnified by a preexisting buildup of composite water levels in the wells and a subsequent decrease in downward leakage from zone A. (See previous discussion of head relationships in the section "Basalt Aquifers in Odessa-Lind area.") This conclusion is supported by un-



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

Figure 13. —Generalized decline in the potentiometric surface of aquifer zone B, March 1967 to March 1971.



EXPLANATION

---- 1200 ---- Computed potentiometric contour

—— 1200 —— Potentiometric contour drawn from water level measurements in individual wells

Shows altitude of potentiometric surface. Contour interval 10 and 100 feet. Datum is mean sea level. Hachures indicate depressions

Boundary of area in which the Washington Department of Ecology, in September 1968, stopped issuing permits for the drilling of irrigation wells

Nodes used to approximate ground-water barrier in digital model

Base map traced from computer printout and not to scale planimetrically, distances between township lines and range lines about 6 miles

FIGURE 14. —Comparison of computed and measured potentiometric surfaces of aquifer zone B after 4-year model run ending March 1971.

usually large increases in the temperatures of water pumped from wells in the immediate vicinity—as much as 6°C (11°F) during the 4-year period. Such large temperature changes indicate a substantial increase in the proportion of the pumped water that was derived from the deeper, warmer aquifers and a corresponding decrease in the contribution from the shallower, cooler ground water.

The hydrographs of selected wells (fig. 15) generally show a good match between computed and measured water levels during periods of nonpumping, but they show a divergence, during periods of pumping. The fact that the computed values for periods of pumping remain above the lower measured levels is related to the basic model design and does not necessarily imply a shortcoming in the model. A computed level in the model represents an average water level for the entire 1-square-mile nodal area, whereas the level measured during pumping at any specific well is likely to be lower than the average for the entire square mile. During periods of recovery, however, measured levels in the individual wells begin to approach the average water level for the node and will usually be closer to the computed values. Normally, a good match throughout both the pumping and recovery phases of the hydrographs

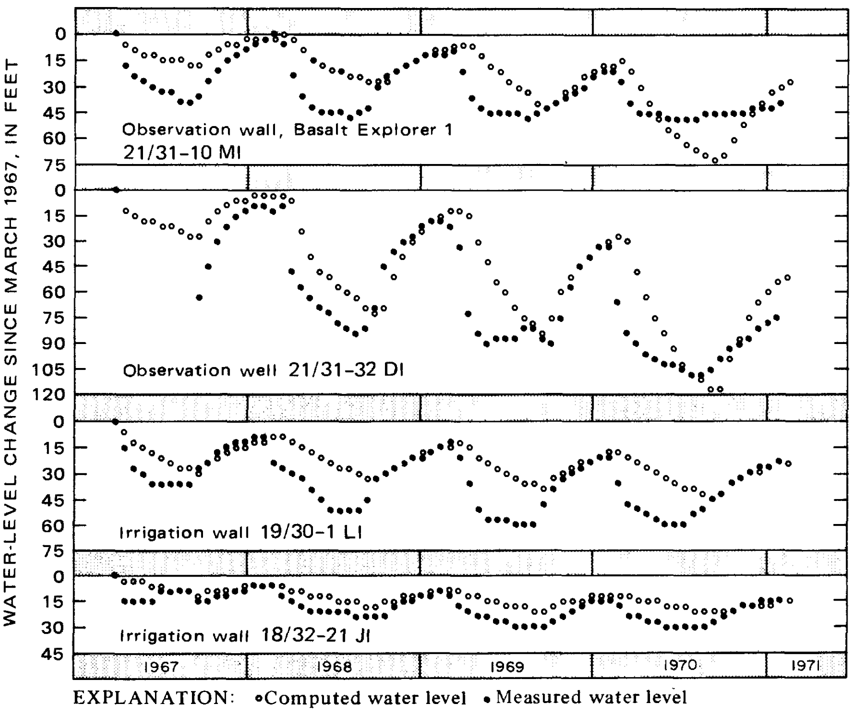


FIGURE 15. —Comparison of computed and measured water levels in selected wells, during the verification period March 1967 to March 1971.

would not be expected unless (1) the measured levels were from wells in an area remote from pumping, or (2) the drawdown caused by pumping was very small because of exceptionally high transmissivity or a low pumping rate. Of the four wells represented in figure 15, the upper two are observation wells situated immediately adjacent to pumping nodes (fig. 16); the lower two are seasonally pumped irrigation wells.

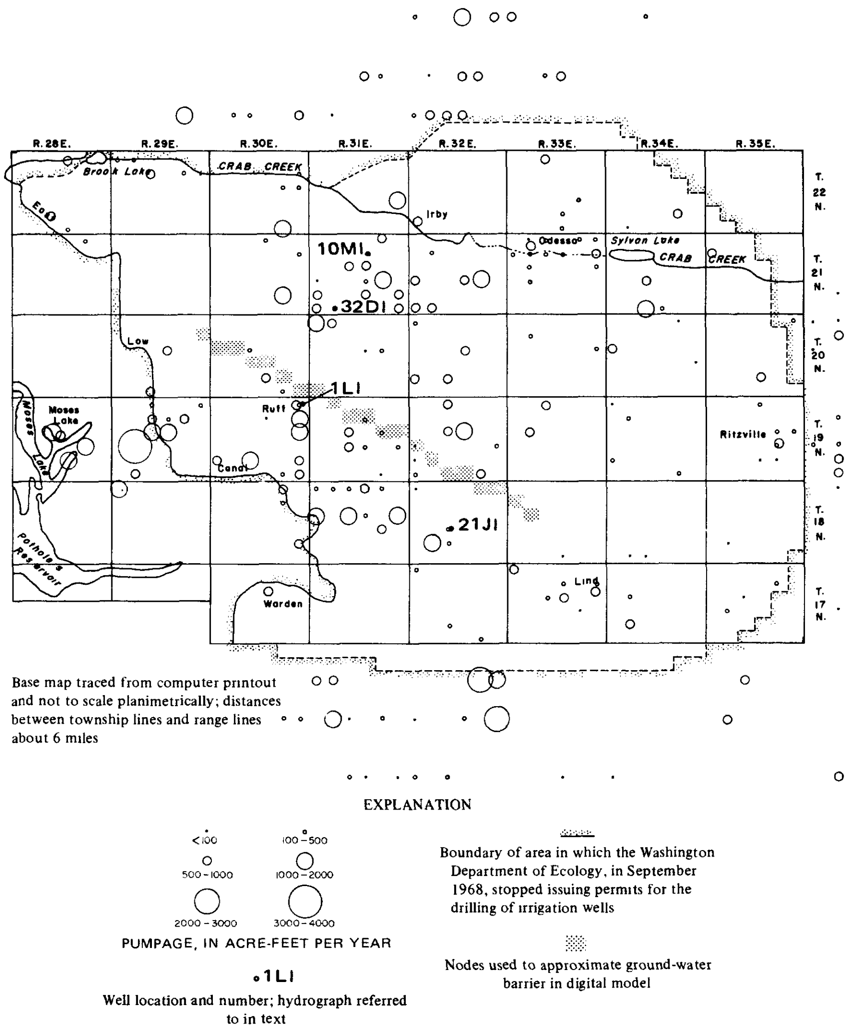


FIGURE 16. —Distribution of 1970 pumpage totaling 117,000 acre-feet.

PROJECTED DECLINE, 1971 TO 1981

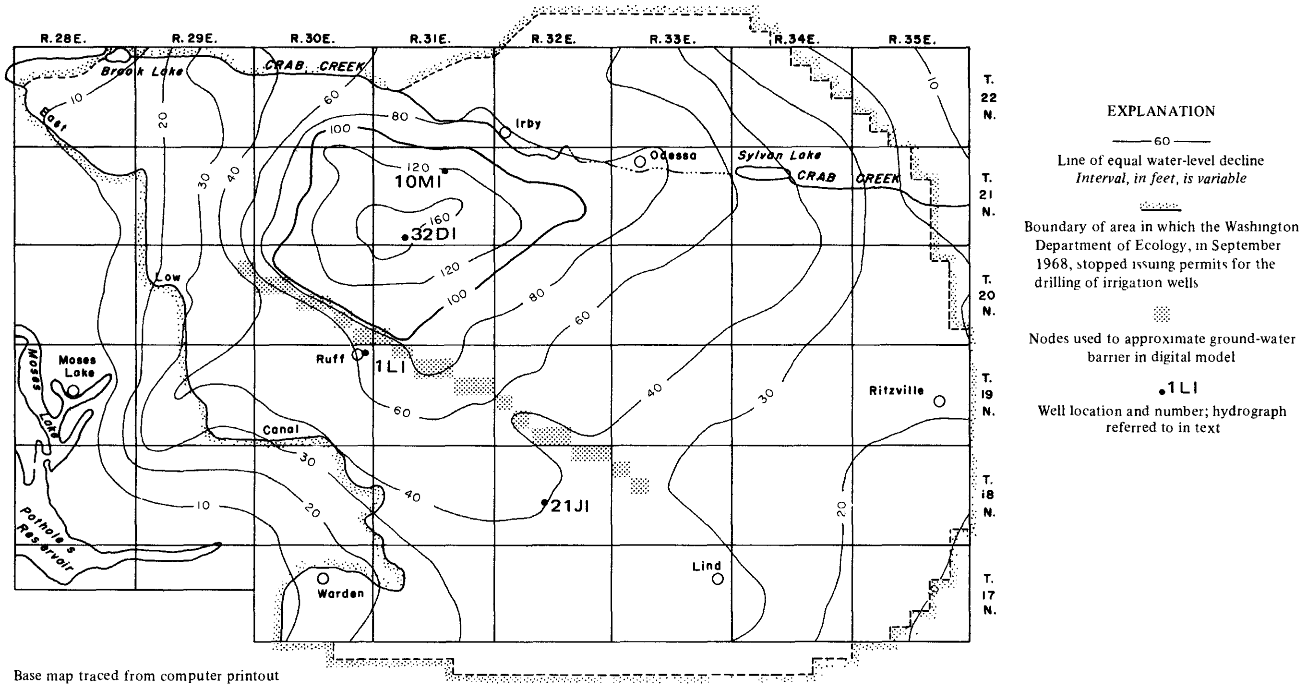
This section describes the use of the verified model for projecting aquifer response over a 10-year period, using each of two cyclic pumping stresses lasting 200 days and starting April 1 each year. The last measured pumping rate for the Odessa-Lind and adjacent areas (117,000 acre-ft in 1970) is used for the first projection. For the second projection, pumpage is increased for 1971 to 233,000 acre-ft (fig. 10), a rate that includes 1970 pumpage and that requested in water-right applications held in abeyance by the Department of Ecology since 1968 in the Odessa Hold Area. Each projection starts with 1967 (the beginning of the initial base period of 1967–71) and, therefore, drawdowns given for any point in time are figured from the March 1967 levels. For each projection, drawdown maps are included for October 1975, March 1976, October 1980, and March 1981. Also, potentiometric-surface maps are included for March 1981.

Several experimental 10-year model projections were made prior to those described above to determine average cumulative rates of leakage in nodes along Crab Creek and other areas of continuous leakage outlined in figure 11. As mentioned previously, leakage rates at these nodes gradually increase until drawdown reaches 50 feet (fig. 12), whereupon the leakage rate was held constant. By the end of the verification period, drawdown in the continuous-leakage nodes was generally less than 10 feet and had reached a maximum of about 20 to 30 feet in small areas. (Compare figs. 11 and 13.) The experimental runs generally showed that leakage rates in those continuous-leakage areas were becoming substantial within a few years after the verification period because of continued drawdown, and perhaps these rates could not be justified on the basis of low-flow records or other available information. For example, the total indicated leakage along Crab Creek was starting to exceed the actual streamflow during low-flow periods. The writers chose to limit the overall rate of leakage on the assumption that leakage rates reached during verification are the most reasonable approximation to use over the long term. Therefore, the average leakage rates were computed for the continous-leakage nodes during the last year of the verification period (fig. 12, for example), and they were incorporated as constant rates in the appropriate nodes of the model for each of the projections described in this report.

PROJECTION USING 1970 PUMPAGE

Projected water-level declines produced by the digital model, using cyclic pumping at the rate of 117,000 acre-feet per year beyond the verification period, are included in figures 17 through 20. Areal distribution of the pumpage was the same as that in 1970 (fig. 16). Projected hydrographs also are included for the same wells discussed previously (fig. 21).

The projected-decline maps (figs. 17–20) indicate that under these conditions future declines north of the ground-water barrier would be about double those on the south side—a condition similar in form to the head change observed during the verification period (fig. 13). The large difference in drawdown is primarily related to significant differences in



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 17. —Water-level decline from March 1967 to October 1975, computed with cyclic pumpage held at the 1970 rate of 117,000 acre-feet per year.

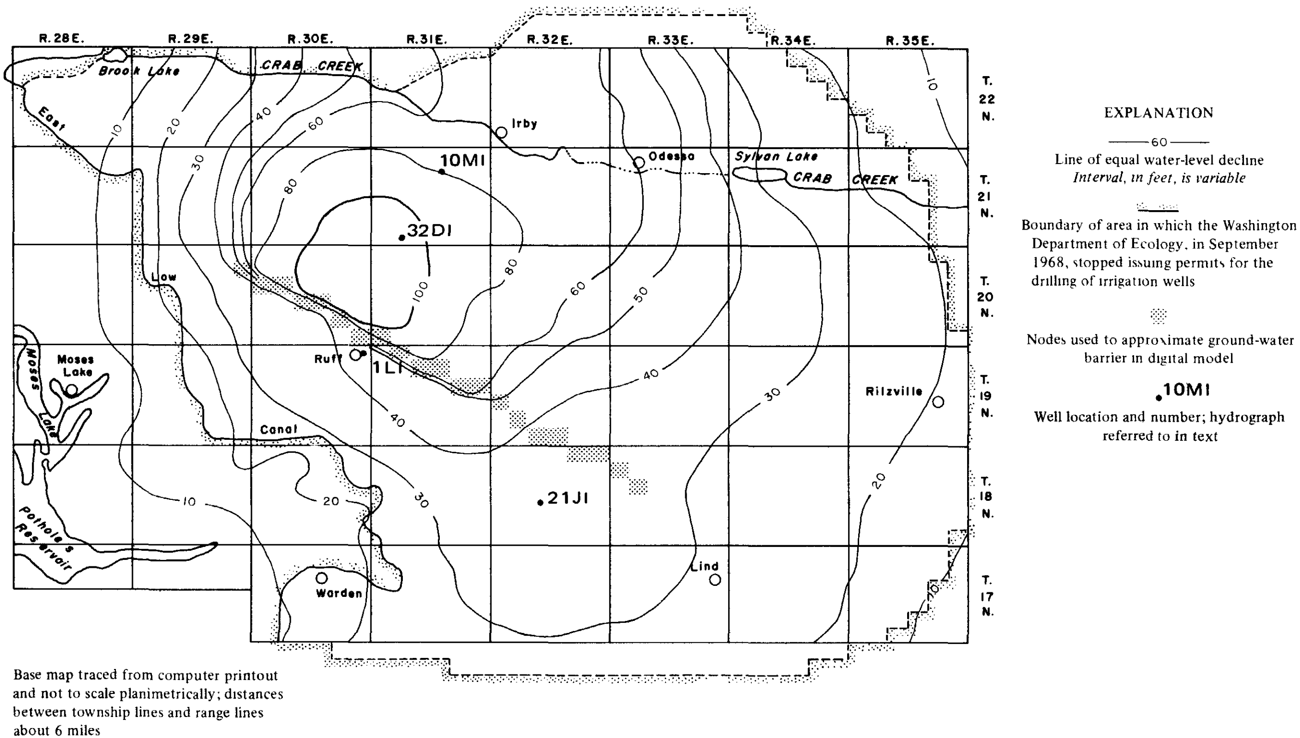
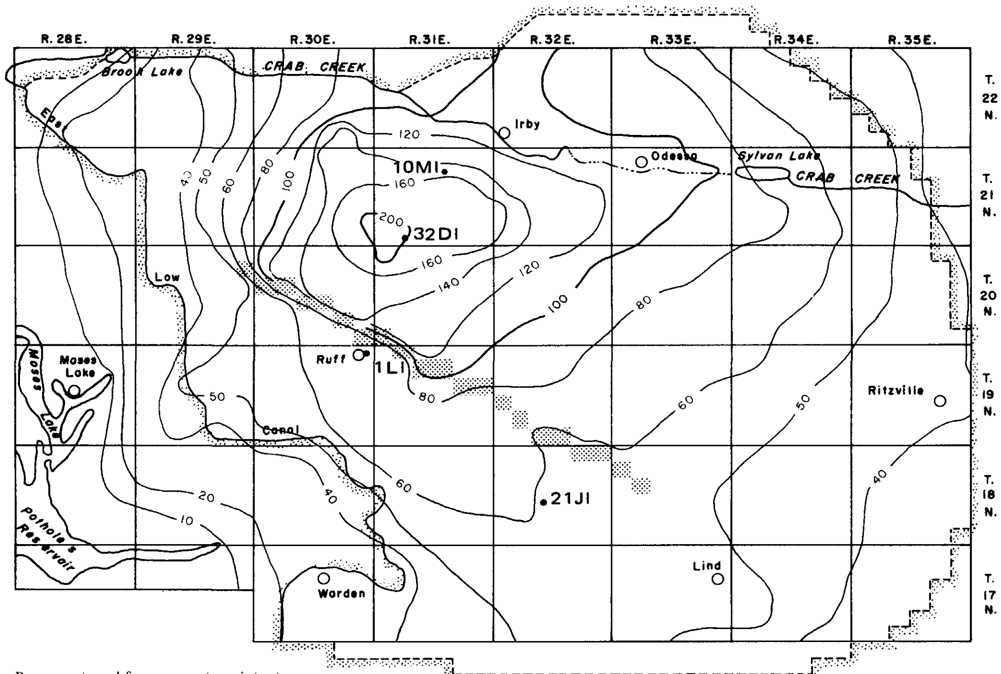


FIGURE 18. —Water-level decline from March 1967 to March 1976, computed with cyclic pumpage held at the 1970 rate of 117,000 acre-feet per year.



EXPLANATION

——60—— Line of equal water-level decline
Interval, in feet, is variable

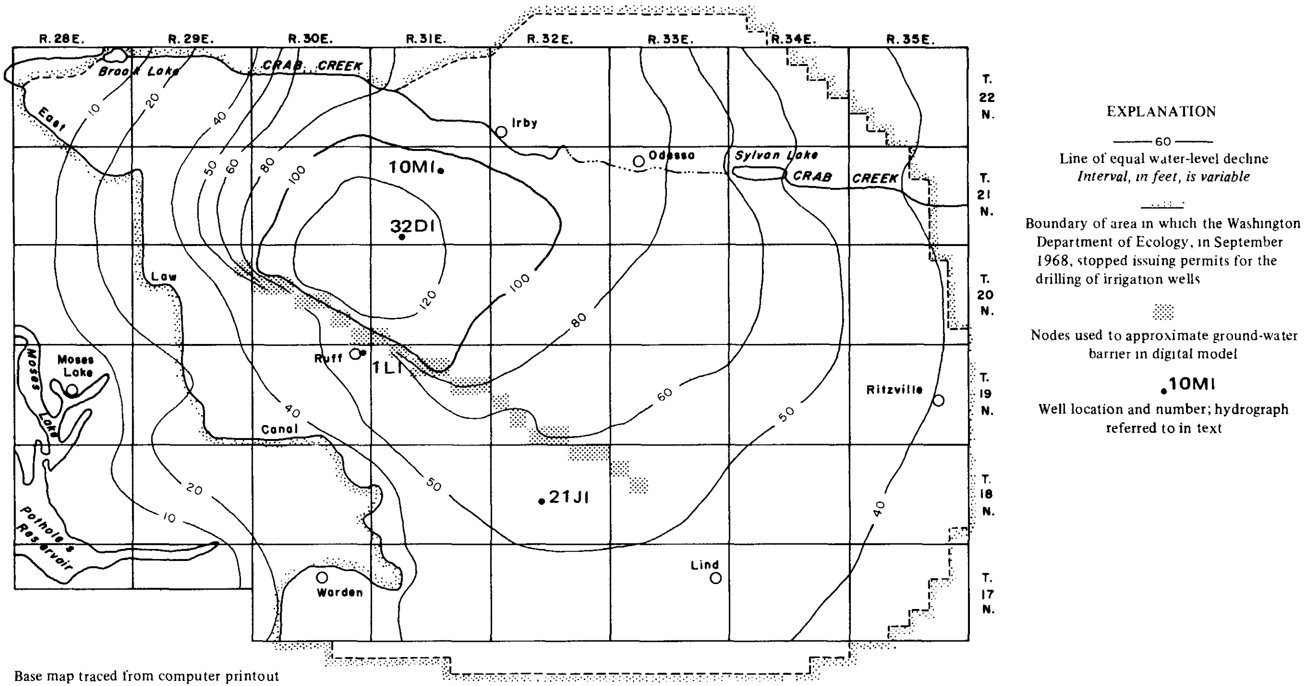
Boundary of area in which the Washington Department of Ecology, in September 1968, stopped issuing permits for the drilling of irrigation wells

Nodes used to approximate ground-water barrier in digital model

•32D1 Well location and number; hydrograph referred to in text

Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 19. —Water-level decline from March 1967 to October 1980, computed with cyclic pumpage held at the 1970 rate of 117,000 acre-feet per year.



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

Figure 20. —Water-level decline from March 1967 to March 1981, computed with cyclic pumpage held at the 1970 rate of 117,000 acre-feet per year.

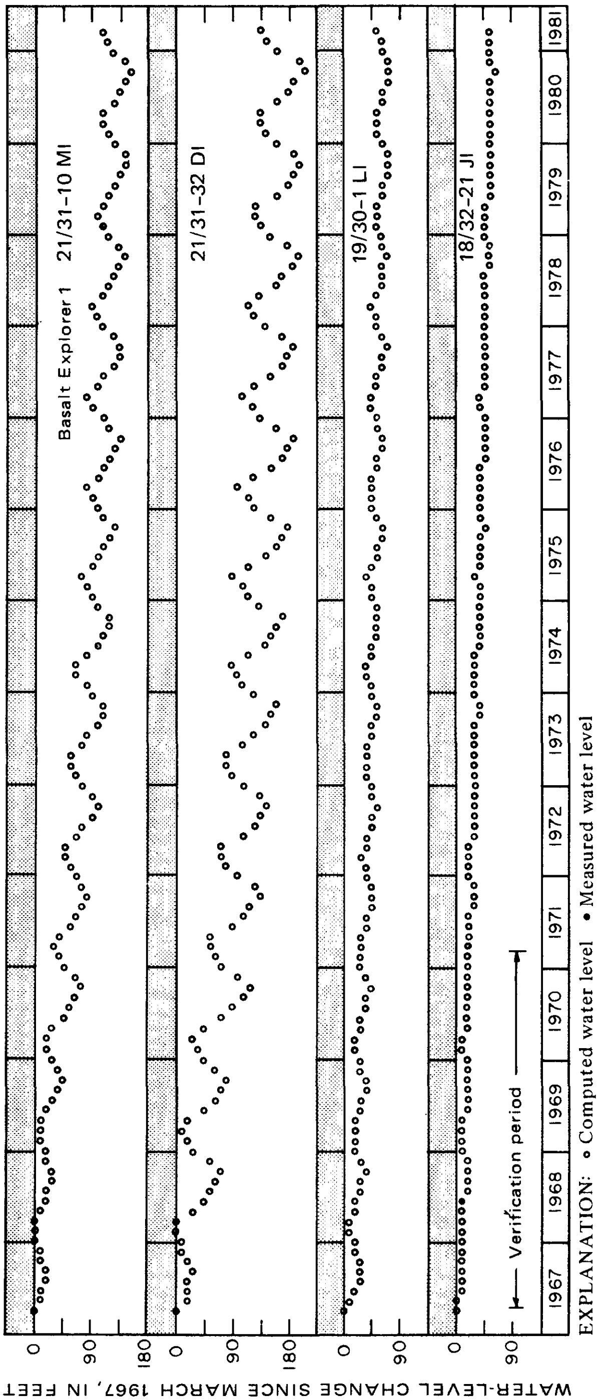


FIGURE 21. —Water-level trends at selected wells, projected beyond the verification period to 1981, computed with annual pumpage held at 1970 rate of 117,000 acre-feet.

transmissivity and storage coefficient of the aquifers on either side of the barrier (figs. 8 and 9), the partial boundary effect of the barrier itself, and the expected recharge from the Columbia Basin Irrigation Project on the southwest side. Computed rates of decline from March 1967 to March 1976 range from about 2 to 5 feet per year on the southwest side of the barrier and from about 3 to 11 feet per year on the northeast side. For the full 14-year period ending March 1981, computed rates of decline are about 1 to 4 and 4 to 9 feet per year, respectively. At the 1970 rate of pumpage, the indicated maximum water-level decline since March 1967 at places on the northeast side of the ground-water barrier exceeds 100 feet by March 1976 and 160 feet by October 1975. A comparison of figures 18 and 20 indicates that the present large area of pumping depression would still spread and the cone of depression would become deeper after 1975, but changes would occur at a more uniform rate and at a slower pace. The projected hydrographs at four selected well locations (fig. 21) generally show the same trend through March 1981.

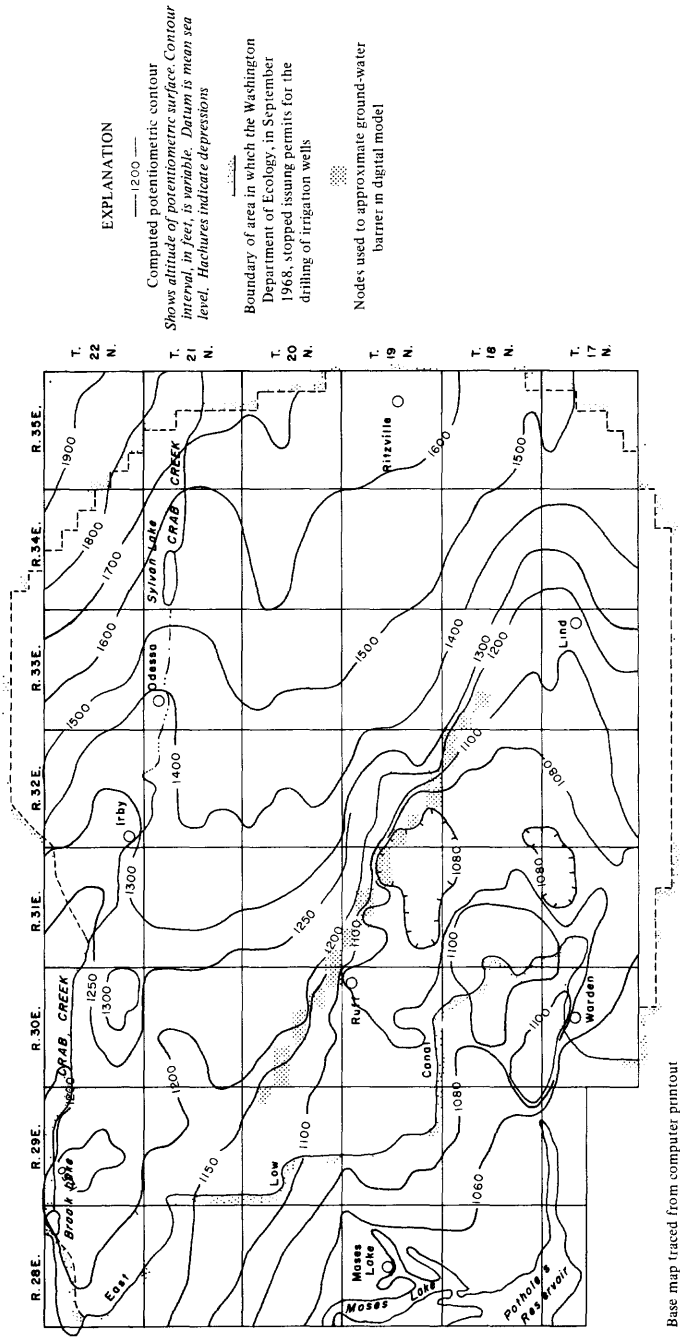
Comparison of the potentiometric surface computed for March 1981 (fig. 22) with the surface developed from levels measured in March 1971 (fig. 14) shows that most contours north of the barrier would shift in an upgradient direction (northeasterly) 3 to 4 miles; to the south the shift would be much greater, despite lower rates of decline, because of the low ground-water gradients. For example, the indicated shift of the 1,100-foot potentiometric contour was about 8 miles at places, from a position just west of the East Low canal to the edge of the ground-water barrier.

PROJECTION USING 1970 PUMPAGE PLUS THAT REQUESTED IN WATER-RIGHT APPLICATIONS HELD IN ABEYANCE

Present pumpage and the anticipated pumpage requested in water-right applications held in abeyance (116,000 acre-ft per year) in the Odessa Hold Area in 1970 totaled about 233,000 acre-feet, or about double that actual pumpage of 1970 in the larger area of this study (see fig. 16). This pumpage is distributed as shown in figure 23.

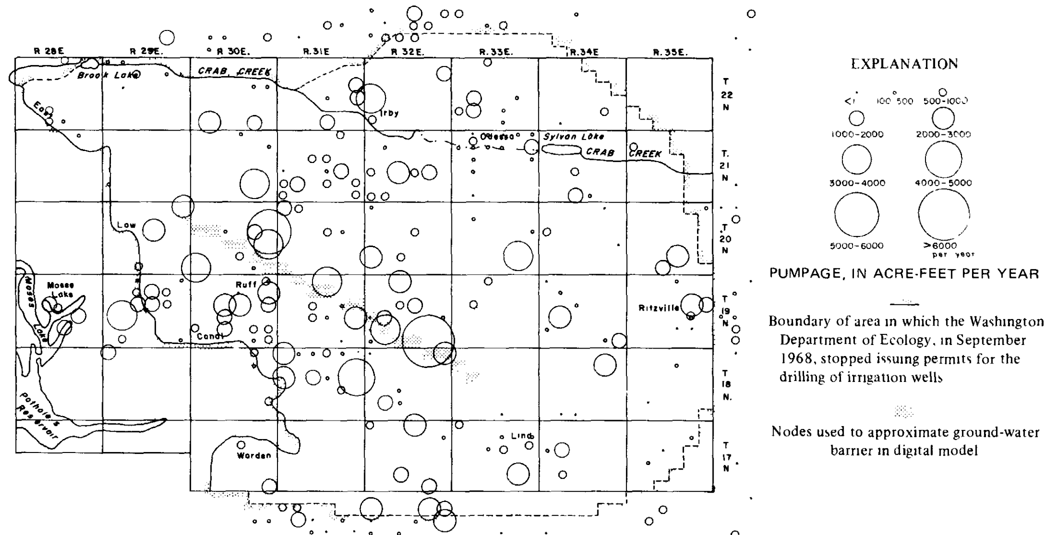
The Odessa-Lind model was verified using yearly pumpages ranging from 70,000 to 117,000 acre-feet. Because the additional pumpage requested in water-right applications approximately doubles these values, the projections using this greater pumpage are more tenuous than the previous projection using 1970 pumpage. The results, therefore, should be used only as a general guide for what may happen under these pumping conditions.

Projected water-level declines, produced by the digital model simulating cyclic pumping of 233,000 acre-feet beyond the verification period, are included in figures 24 through 27. Computed hydrographs for four wells already discussed are included in figure 28.



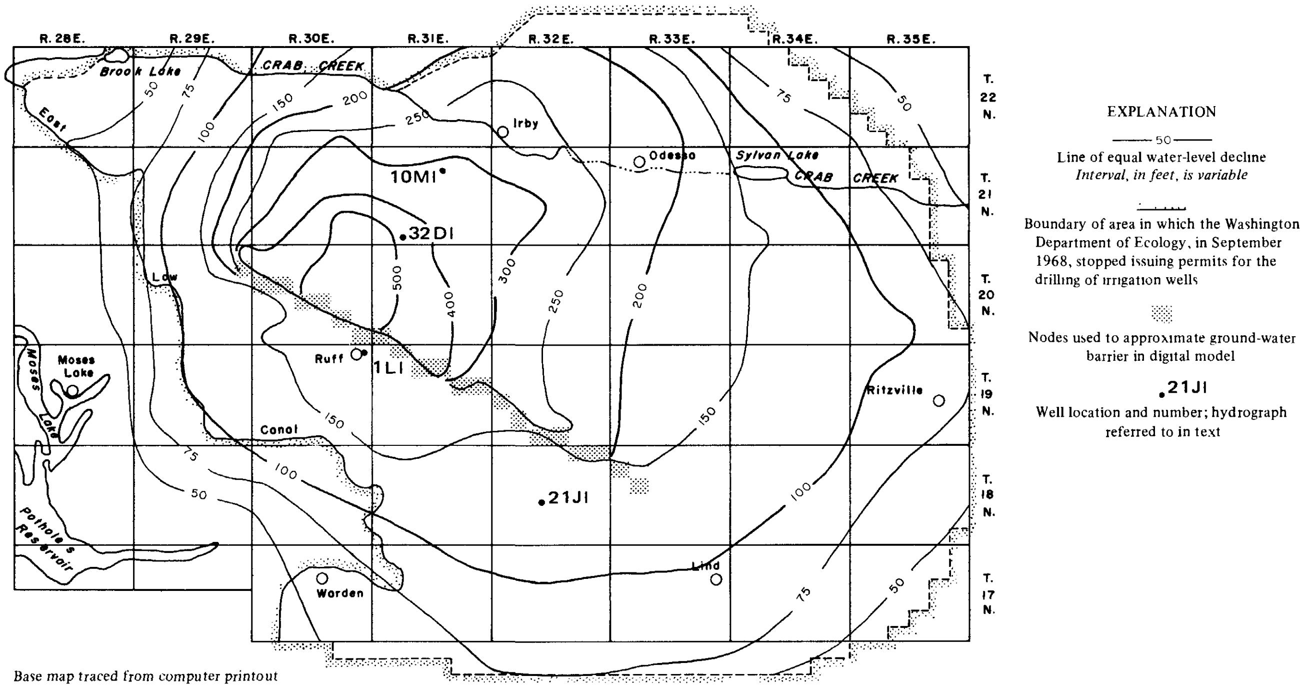
Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

Figure 22. —Projected potentiometric surface of aquifer zone B in March 1981, computed with annual pumpage held at 1970 rate of 117,000 acre-feet.



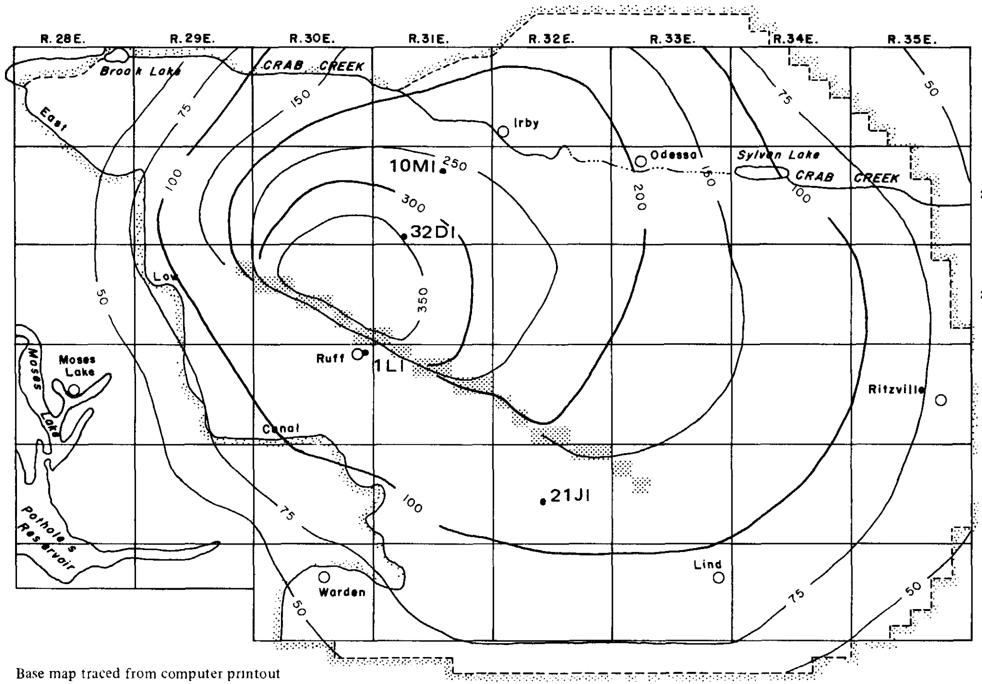
Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 23. —Distribution of pumpage totaling 233,000 acre-feet, including 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology as of 1970 in the Odessa Hold Area.



Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

FIGURE 24. —Water-level decline from March 1967 to October 1975, computed with cyclic pumpage since 1971 held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.



EXPLANATION

—— 50 ——

Line of equal water-level decline
Interval, in feet, is variable

Boundary of area in which the Washington Department of Ecology, in September 1968, stopped issuing permits for the drilling of irrigation wells

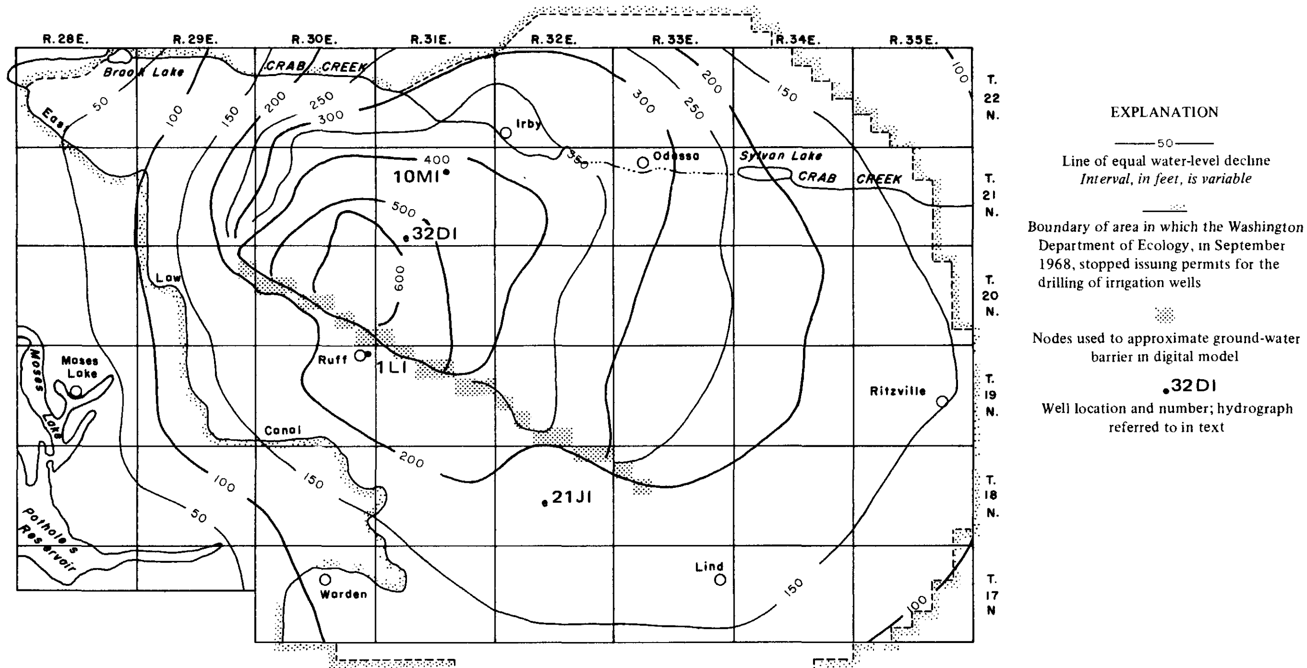
Nodes used to approximate ground-water barrier in digital model

•32DI

Well location and number; hydrograph referred to in text

Base map traced from computer printout and not to scale planimetrically; distances between township lines and range lines about 6 miles

Figure 25. —Water-level decline from March 1967 to March 1976, computed with cyclic pumpage since 1971 held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.



Base map traced from computer printout and not to scale planimetrically, distances between township lines and range lines about 6 miles

FIGURE 26.—Water-level decline from March 1967 to October 1980, computed with cyclic pumpage since 1971 held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.

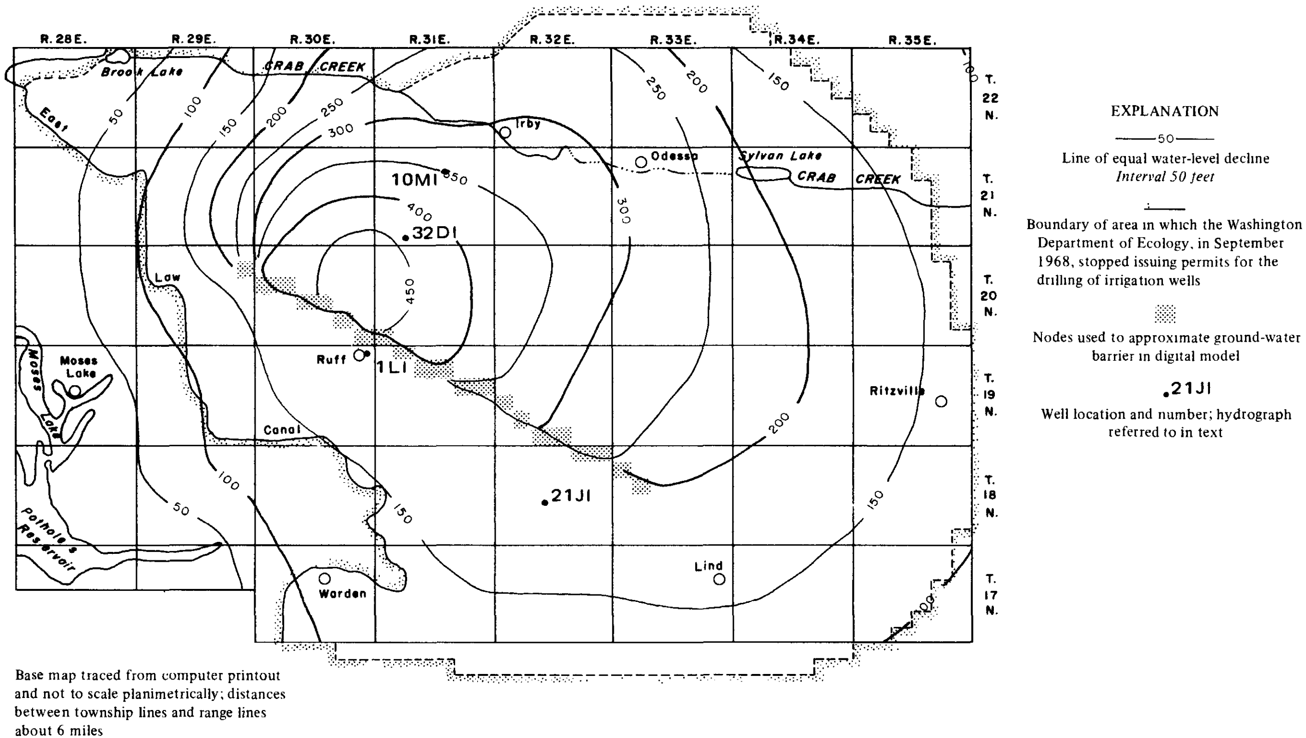
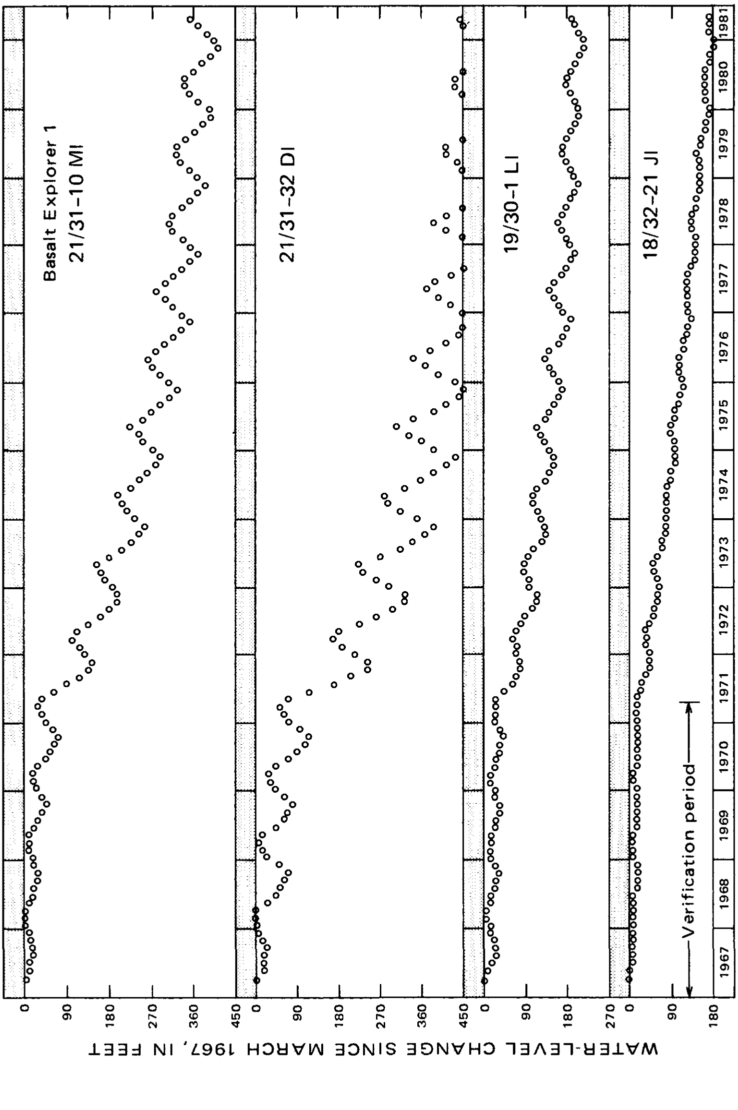


FIGURE 27. —Water-level decline from March 1967 to March 1981, computed with cyclic pumpage since 1971 held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.



EXPLANATION: ∘ Computed water level • Measured water level

FIGURE 28. —Water-level trends projected beyond the verification period to 1981 at selected wells, computed with pumpage held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.

As in the previous projection, declines northeast of the ground-water barrier generally are at least double those on the southwest, largely for the same reasons (that is, large differences in transmissivity and storage coefficient, the presence of the barrier, and differences in sources of recharge).

Computed rates of decline from March 1967 to March 1976 range from about 5 to 15 feet per year on the southwest side of the barrier and from about 14 to 40 feet per year on the northeast side. For the full 14-year period ending March 1981, computed rates of decline are about 3 to 13 feet and 14 to 33 feet per year, respectively. At the annual pumpage rate of 233,000 acre-feet the maximum indicated water-level declines since March 1967, at places on the northeast side of the ground-water barrier, would exceed 450 feet by March 1981 and 600 feet by October 1980. In comparing figures 25 and 27, it is apparent that the indicated rates of decline have decreased toward the end of the period, but the area of pumping depression is still spreading and deepening. Hydrographs in figure 28 show the dramatic impact that the sudden increase in simulated pumping rate (1971) had on the projected rate of decline.

Comparison of the computed potentiometric surface, March 1981 (fig. 29), with the surface developed from measurements in March 1971 (fig. 14) shows a shift in the 1,100- and 1,200-foot contours all the way from the barrier upgradient to a position near Odessa. Furthermore, the indicated direction of ground-water flow (formerly southwestward) is completely reversed between Moses Lake and Potholes Reservoir and the large closed depression along the north side of the ground-water barrier.

EXTENSION OF MODEL USE AND SUGGESTIONS FOR FURTHER STUDY

There are a variety of possible uses of the Odessa-Lind ground-water model, even though certain constraints are imposed by the model design and there is need for periodic additional verification of the model against field data. For example, the model may be used to develop the optimum spacing of wells in an area to allow a specific amount of pumping, and at the same time it can be used to avoid some undesirable results such as drawdown beyond a certain limit. Data on altitudes of tops of individual aquifers and altitudes of well bottoms can be incorporated, and the model can be used to identify areas where water levels are likely to decline to the top of a given aquifer zone. Also, the model can be used to evaluate alternative areal distributions of pumping or the effects of staggering pumping schedules.

Artificial-recharge proposals also may be evaluated with the model, since a recharge node is simply a withdrawal node of opposite algebraic sign. Various plans for injecting surface water into wells can be analyzed, although the model will not provide a basis for evaluating

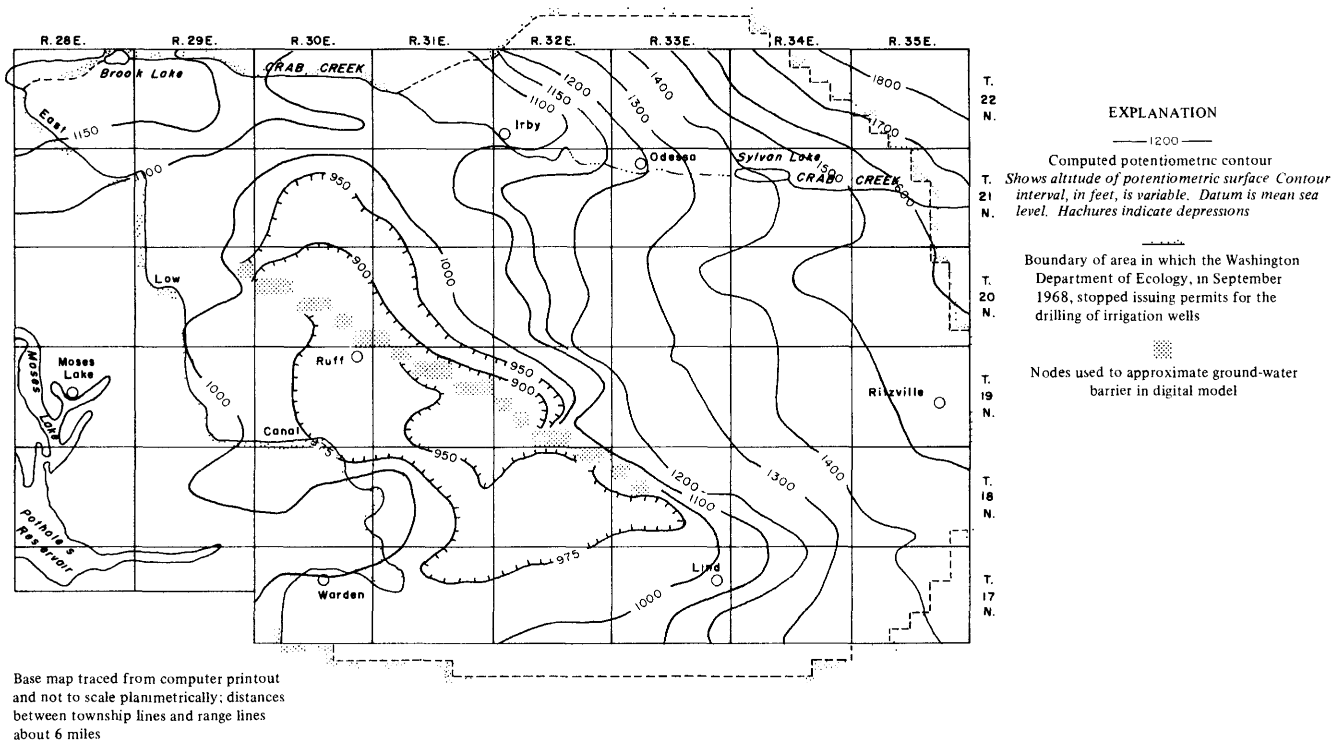


FIGURE 29.—Potentiometric surface of aquifer zone B, March 1981, computed with pumpage since 1971 held at 233,000 acre-feet per year, which includes 1970 pumpage and that requested in water-right applications held in abeyance by the Washington State Department of Ecology.

possible undesirable effects on surface-water supplies for this diversion to shallow ground water. Inasmuch as there is potentially a large untapped source of ground water below the existing zone of pumping (fig. 3), schemes can also be evaluated for recharging aquifer zone B by upward injections through the boreholes that penetrate the deeper sources.

To retain its validity and effectiveness, the model must be updated periodically. Water-level measurements should be made every year, especially during the annual high-water period, so that the model can be reverified to the latest and longest period of water-level record. This annual collection of water-level data comparable to the previous data doubtless will be hampered by changing conditions at the various wells. That is, as water levels continue to decline, some of the wells used for water-level measurements will be deepened and may tap aquifers containing water at different heads, thereby destroying the comparability of the new with the previous water-level measurement. If this problem becomes serious, it may justify the cost of separate observation wells to monitor aquifer zone B. Pumpage data also will need periodic updating and, if possible, should be refined by means of a greater number of direct discharge measurements at wells in the area.

Conditions may change so drastically that major redesign of the model or a new ground-water model may be needed. Future investigators may consider a two-layer (or more) model analysis of the Odessa-Lind area. The two-layer approach would require a more complete quantitative description of aquifer zone A, including a description of transmissivity, storage coefficient, and recharge sources. If a two-layer digital model were used, a steady-state analysis of both aquifer zones A and B would be necessary to establish head relationships for calculation of leakage. It must be noted, however, that the real ground-water system includes multiple aquifer zones, and even a two-layer approach is still an approximation of the real system.

One of the greatest needs for improvement of the present model is the refinement in the estimates of vertical leakage (borehole leakage as well as crossbed leakage). Also, the area represented in the model as having continuous leakage, centered at T.19 N., Rs. 32 and 33 E., should be studied in greater detail to evaluate the validity of, and improve the rationale for simulation of, continuous leakage in this part of the area. No method is available for directly measuring the total vertical leakage, although careful monitoring for declines in zone A water levels, intensive borehole-flow measurements, and measurement and analysis of vertical temperature profiles hold promise for considerable improvement in our estimates of vertical leakage.

If a new or extensively redesigned model is needed, the experience gained during this study should be helpful. First, the investigator should select reasonable limits for each parameter to be used in the model and then stay within those selected limits insofar as possible. In the case of parameters for which the original estimates are little better than educated guesses, this, of course, may not be possible. Nevertheless it seems advisable to stay within the reasonable limits until all possibilities of verifying the model have been exhausted. In the writers' experience, failure to verify when the parameters are held within the reasonable limits generally indicates a need for critical review of either the hydrologic rationale or the mathematics of the digital model.

In adjusting the model, it is best to alter only one parameter at a time (per computer run) and hold the others constant. A model of the type described here is too complex for a high degree of success in predicting the overall result of changing more than one of the interacting parameters at a time. Attempts to make a few changes per computer run often lead to a delay of the overall verification effort.

For this and future models, opportunities should be sought to improve estimates of transmissivity and storage coefficient by means of aquifer tests. Also, any subsequent models presumably will need a vertical-leakage parameter and probably will be sensitive to this parameter in the manner of the present model. Therefore, the vertical leakage should receive special attention in future modeling as should data collection in support of the model.

As new field data on all parameters are collected and longer term net-change maps are prepared, the original estimates and interpretations no doubt will require some modifications. The overall result should be a continually improving model that reflects, at any particular stage (as does this model), use of the best techniques and model type available.

SUMMARY AND CONCLUSIONS

A digital-computer program using finite-difference techniques was used to simulate an intensively pumped, multilayered basalt-aquifer system near Odessa. For model analysis, the system included two aquifer groups, upper zone A and lower zone B. Aquifers in zone B, the heavily pumped zone, are treated as a single-layer aquifer receiving vertical leakage from zone A. The model was verified primarily by matching observed head declines ranging from about 10 to more than 40 feet over a 4-year period (March 1967 to March 1971). A close match was achieved except for one small area that had the greatest net decline for the period (60 ft or more).

Projections using the digital model clearly show that the decline of heads which started in 1965 in aquifer zone B, will continue for some years even if pumpage is held at the 1970 rate of 117,000 acre-feet per year. If this rate of pumpage is projected beyond 1970, computed rates of decline for a 14-year period, March 1967 to March 1981, will average about 1 to 4 feet per year on the southwest side of a local ground-water barrier, and about 4 to 9 feet per year on the northeast side. At the 1970 rate of pumpage, the indicated maximum water-level decline in the area by March 1981 is greater than 100 feet at places on the northeast side of the barrier.

If the projected pumpage is increased to 233,000 acre-feet per year in 1971 (the total of 1970 pumpage and that requested in water-right applications held in abeyance), computed rates of decline for the 14-year period ending March 1981 would average about 3 to 13 feet per year on the southwest side of the ground-water barrier and about 14 to 33 feet per year on the northeast side. At that increased pumpage rate, the indicated maximum water-level decline in the area by March 1981 exceeds 500 feet on the northeast side of the barrier.

Both projections generally show that drawdowns north of the barrier are double or more those on the south, owing to differences in transmissivity, storage coefficient, and sources of recharge.

The digital model described here is a reasonable simulation of the ground-water system in this part of east-central Washington. Various projections of the response of the system to pumpage and (or) recharge situations can be made for regional analysis.

There are a variety of possible additional uses of the Odessa-Lind model. These uses include: evaluations of the effects that different patterns and amounts of pumping will have on water levels; definition of optimum spacing of wells; and projection of times when water levels will decline to a certain altitude. However, the reliability of the model projections may be reduced drastically in cases where the test conditions differ radically from the conditions in which the model was verified.

The validity of the model will diminish with significant departures from the verification conditions. These departures might include pumpage in much greater amounts or in a drastically different areal pattern. The combination of these two was encountered in the projection of declines in the Odessa Hold Area and, as previously stated, the reliability of those projections was weakened. Continued dewatering of aquifer zone A will change the vertical leakage, to which the model is especially sensitive. The vertical-leakage situation also will be altered by new, deeper wells tapping deeper aquifers which, if uncased, may begin either recharging or draining aquifer zone B, depending on their relative potentiometric heads. To retain its validity and effectiveness, the model must be updated periodically, using additional data on water levels, pumpage, and improved estimates of vertical leakage. Additional models may be needed and these can be enhanced by the experiences gained during the present study. However, in dealing with such a complex, multilayered, multiple-head aquifer system as that underlying the Odessa-Lind area, it must be recognized that the present data samples and interpretive techniques allow only a general and imprecise approximation of the real system.

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