Factors Affecting Areas Contributing Recharge to Wells in Shallow Aquifers

USGS
science for a changing world

United States Geological Survey Water-Supply Paper 2412

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may be no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from U.S. Geological Survey ESIC—Open-File Report Sales, Box 25286, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave. - Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey offices:

- **FAIRBANKS, Alaska**—New Federal Bldg., 101 Twelfth Ave.
- **ROLLA, Missouri**—1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**—Bldg. 3101

Factors Affecting Areas Contributing Recharge to Wells in Shallow Aquifers

By THOMAS E. REILLY and DAVID W. POLLOCK

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2412

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
DALLAS L. PECK, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1993

For sale by
U.S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Library of Congress Cataloging in Publication Data

Reilly, Thomas E.
Factors affecting areas contributing recharge to wells in shallow aquifers / by
Thomas E. Reilly and David W. Pollock.
p. cm. — (U.S. Geological Survey water-supply paper ; 2412)
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2412
1. Groundwater flow. 2. Aquifers. I. Pollock, David W. II. Title. III. Series.
GB1197.7.R45 1993
551.49—dc20 93–7410
CIP

CONTENTS

FIGURES

METRIC CONVERSION FACTORS

Multiply	By	To obtain SI metric unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic feet per day (ft^3/d)	0.0283	cubic meters per day (m^3/d)

Factors Affecting Areas Contributing Recharge to Wells in Shallow Aquifers

By Thomas E. Reilly *and* David W. Pollock

Abstract

The source of water to wells is ultimately the location where the water flowing to a well enters the boundary surface of the ground-water system. In ground-water systems that receive most of their water from areal recharge, the location of the water entering the ground-water system is at the water table. The area contributing recharge to a discharging well is the surface area that defines the location of the water entering the ground-water system at the water table that flows to the well and is eventually discharged from the well.

The calculation of areas contributing recharge to wells is complex because flow paths in ground-water systems change in response to development, and the aquifer material in ground-water systems is heterogeneous and is hidden from direct observation. Hypothetical experiments were undertaken to show the complexities in the delineation of areas contributing recharge to wells. Four different "cases" are examined to demonstrate the effect of different conceptualized aquifer frameworks on deterministically calculated areas contributing recharge. The main conclusion drawn from the experiments is that, in order to understand the cause and effect relations that affect the quality of water derived from wells, the importance and nature of the variability in the ground-water-flow system must be considered and accounted for in any efforts to "protect" the water supply.

INTRODUCTION

Ground water is the source of drinking water for about 50 percent of the population of the United States (Solley and others, 1988). Ground water is generally obtained through wells and, because of the natural filtering properties of the rocks, commonly does not require treatment before use. Widespread contamination of shallow ground-water supplies from various land-use practices is affecting this resource. To address this concern, the U.S. Environmental Protection Agency (USEPA), in response to the Safe Drinking Water Act Amendments of 1986, has encouraged the States to develop "Well-head Protection" strategies (U.S. Environmental Protection Agency, 1987). The objective of these strategies is to define the area where water carrying potential contaminants can enter the ground-water system and flow to a supply well and then to set regulations to minimize the opportunity for contamination to occur in areas defined as sources of water to wells.

Although the concept of "wellhead protection" is straightforward and consistent with the ideals of protecting our water supplies, in many cases there are technical and conceptual difficulties in actually defining, with a reasonable amount of certainty, a fixed area that defines the recharge location of water that flows to a particular well. These difficulties arise because of the inherent complexity of ground-water systems. Wellhead-protection strategies that are based on overly simplified characterizations of the ground-water-flow system may needlessly protect areas that do not contribute water to a well and instead fail to protect areas that do contribute water.

This report describes and illustrates some of the inherent difficulties in the determination of the areas contributing recharge to wells. Simulation techniques are used to calculate the areas contributing recharge under a variety of conditions defined for hypothetical aquifer systems. The areas contributing flow to wells as determined for the hypothetical systems are delineated in a series of figures. The use of simple hypothetical systems provides the mechanism to illustrate and compare the cause and effect relations among the many factors examined. All the systems analyzed are unconfined valley-fill-aquifer systems that are undoubtedly much less complex than actual systems that would be encountered in nature.

AREAS CONTRIBUTING RECHARGE AND SOURCES OF WATER TO WELLS

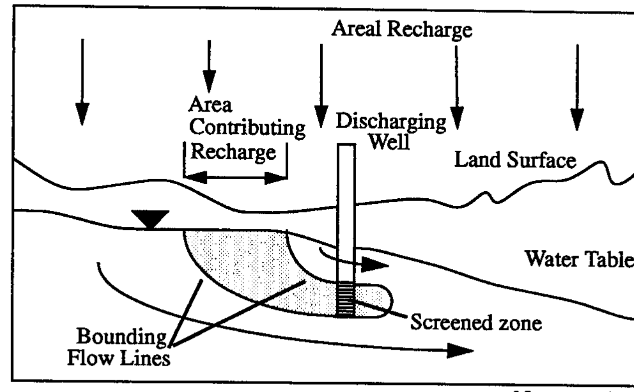
The withdrawal of water from a well in a ground-water system creates drawdown throughout the aquifer. The only limit to the areal and vertical extent of drawdown is the physical boundaries of the ground-water system (Brown, 1963). Drawdown occurs in three dimensions and decreases with distance away from the point of withdrawal. The change in head caused by the withdrawal of water causes flow to the well. The location of pathlines that define the flow paths to the well depend on the hydrogeologic characteristics of the flow system, the well location and discharge rate, and the boundary conditions of the flow system.

For three-dimensional systems, the area contributing recharge to a discharging well is defined in this report as the surface area that delineates the location of the water entering the ground-water system at the water table that eventually flows to the well and discharges. For example, figure 1 illustrates the flow paths to a well in a simplified aquifer system with areal recharge. The ultimate source of water being discharged at a constant rate from a partially penetrating well is recharge to the water table. The area of this source of water must provide an amount of recharge that balances the amount of water being discharged from the well. Thus, for this simple case,

$$Q = WA,$$

where

Q = discharge rate of well (L^3/T),
W = areal recharge rate (L/T), and
A = area contributing recharge (L^2).



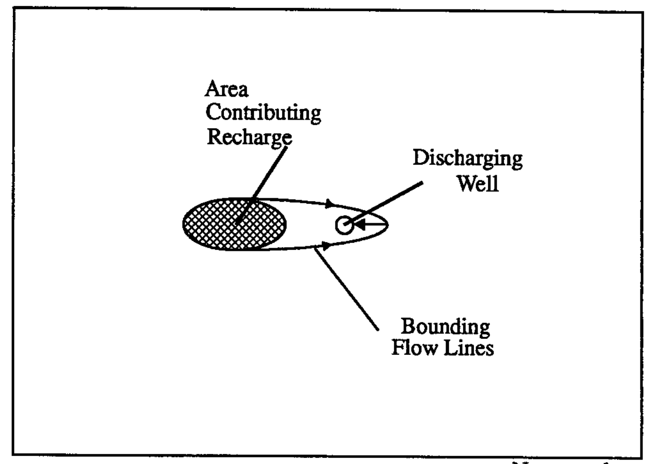


Figure 1. Area contributing recharge to a single discharging well in a simplified hypothetical ground-water system. *A*, Cross-sectional view. *B*, Map view.

The location of this area depends on many factors that describe the ground-water system and the well. Depending on factors that describe the three-dimensional flow system and the placement of the well in the three-dimensional system, the area contributing recharge to a well does not necessarily have to include the location of the well (fig. 1).

The area contributing recharge to a well in the vicinity of a stream is shown in figure 2. In this case, the well is capturing water that was flowing in the stream, so the contributing area is not a function of the areal recharge rate only but is also a function of the amount of water obtained from the stream. Any contamination entering the river valley upstream from the well could affect the quality of the water in the stream and ultimately affect the water discharged from the well.

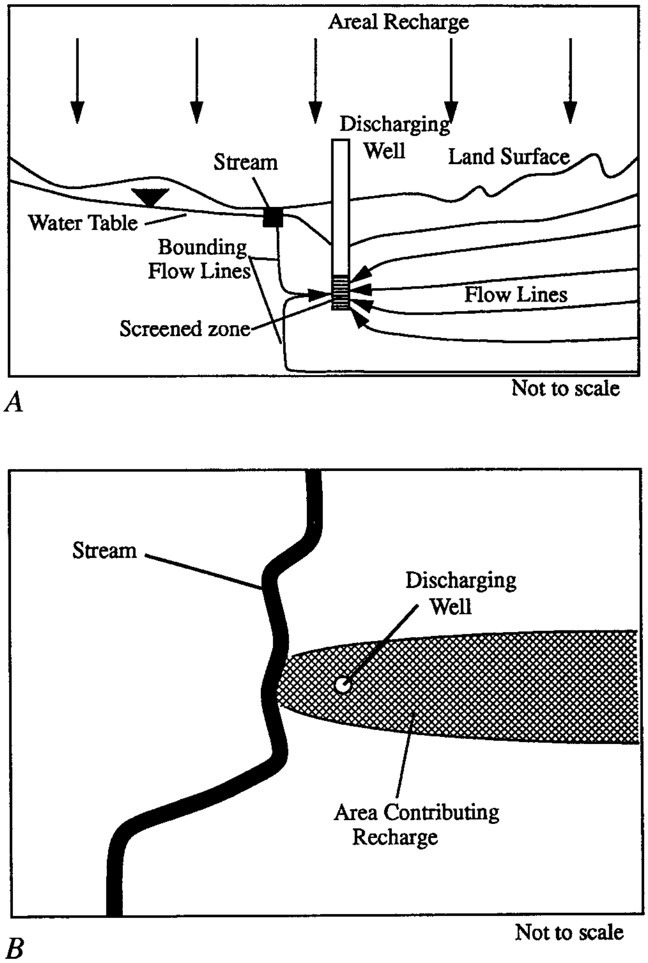


Figure 2. Area contributing recharge to a single discharging well in a simplified hypothetical ground-water system with a stream. *A*, Cross-sectional view. *B*, Map view.

An obvious point is that the quality of the water withdrawn from a well is a function of (1) the quality of the water entering the area that contributes recharge to the well and (2) any chemical or biological transformations that take place during its transit to the well. The movement of water is usually relatively slow, and traveltimes are commonly long in most ground-water systems. During the long residence time, chemical and biological activity often changes the quality of the water. In some instances, the quality of the water can improve with time as the water flows through the system. Another process that can affect the chemical quality of the water is mixing, both natural, as a result of the heterogeneity of ground-water systems, and human induced, as a result of the installation of wells and other construction.

PREVIOUS RELATED WORK

The quantitative estimation of flow paths to and from wells has been the subject of investigation since the work of Slichter (1899, p. 368) at the turn of the century. The description of flow lines near an injection or withdrawal well in a two-dimensional infinite aquifer is available in works by Slichter (1899), Jacob (1950, p. 344), Milne-Thomson (1955, p. 199), Ogata (1963), Bear and Jacobs (1965), and others. The description of flow lines around a three-dimensional point source or sink is available by Streeter (1948, p. 53), Milne-Thomson (1955, p. 436), Bear and Jacobs (1965), and others. These descriptions all deal with idealized, uniform, and infinite systems that have no local sources of water.

Brown (1963) laid the foundation for explaining the source of water to wells in shallow aquifers subject to areal recharge in bounded two-dimensional systems. This work, although for a simplified two-dimensional system, defined the basic problem for shallow systems subject to areal recharge. Brown illustrated the distinction between the cone of depression (which he called the area of influence) and the area that contributes water to the well (which he called the area of diversion).

Transport to wells in the immediate vicinity of the well was investigated by Mundorff and others (1972), Kirkham and Sotres (1978), Phillips and Gelhar (1978), Reilly (1978), and others. These studies examined the effects of partial penetration and the vertical movement of water from the water table or boundaries on the traveltime of the water to a single well. These investigations did not account for the effects of regional boundaries on the flow to a well, but they did account for the important local effects in determining the flow paths and traveltimes to a single, partially penetrating, discharging well.

The estimation of surface areas that are the source of water to discharging wells received considerable renewed interest with the enactment of the USEPA's Wellhead Protection Program in the 1986 Amendments to the Safe Drinking Water Act. USEPA provided "Guidelines for the Delineation of Wellhead Protection Areas" (U.S. Environmental Protection Agency, 1987) to enable the States to begin their wellhead protection efforts. Extensions of the basic analytical solutions have been made by some investigators; for example, Javandal and Tsang

(1986) used complex potential theory to analyze capture zones for multiple wells. In addition, work with numerical models to calculate areas contributing flow to wells has recently increased; for example, see Morrissey (1989), Barlow (1989), and Bair and Roadcap (1992).

Morrissey (1989) uses analytical, two-dimensional, and three-dimensional flow models to determine the area that contributes flow to a discharging well. His careful definition of terms and discussion of the various methods forms a foundation for future work. Barlow (1989) demonstrated the use of flow simulation and particle tracking (Pollock, 1989) to determine contributing areas. Barlow's (1989) work introduces the variability in the areas that is due to factors such as the geologic environment and the dimensionality of the method used. This report expands on this theme and attempts to address the uncertainties in determining the areas that contribute flow to discharging wells.

FACTORS AFFECTING AREAS CONTRIBUTING RECHARGE TO WELLS

The factors that influence the location of areas contributing recharge to wells can be categorized as dependent either on the ground-water system or the well. The ground-water factors that affect the paths of water movement in three-dimensional ground-water systems are (1) the hydrogeologic framework of the system, (2) system boundary conditions, (3) system transmitting and storage properties, (4) stresses and change in stresses (water withdrawals), and (5) other transient effects. The well factors are the location of the well and the depth of the screened zone or open hole section of a well. In addition, the rate at which the well discharges determines the size of the area contributing recharge, as discussed previously, and also determines the extent to which flow paths in the ground-water-flow system are altered to supply water to the well.

The extents and thicknesses of the various layers in the system of interest define its hydrogeologic framework. Once the extents and thicknesses are defined, the description of the boundary conditions explains how water enters and leaves the ground-water system. For example, if areal recharge is the primary source of water to the ground-water system, the top boundary (the water table) of the three-dimensional ground-water system is where most (or all) of the water flowing to the system will originate. The system's transmitting properties, in conjunction with the boundary conditions and framework, determine the rates at which water flows through the system. It is important to visualize ground-water systems as three-dimensional and composed of materials of different transmitting properties. Water that enters at the top boundary can flow deep into the system before eventually returning to the surface as discharge.

Because ground-water systems are dynamic, human-induced stresses cause the flow of water in the system to adjust in response to these stresses. Drawdown caused by well discharges changes the head and flow patterns. Thus, as water withdrawals change, so too do the sources of water to the wells. This is shown quantitatively in following sections. And just as human-induced changes affect the paths of water, so too do natural variations in boundary conditions, such as recharge. Changes in rates of recharge over time affect the paths of flow and, ultimately, the source of water to wells.

METHOD OF ANALYSIS

Numerical simulation is used to show the cause and effect relations among the various factors that affect the location, shape, and extent of areas contributing recharge to wells. Simulations of selected hypothetical systems are controlled experiments that are conducted to determine areas contributing recharge; these areas can then be compared to one another.

The U.S. Geological Survey's ground-water-flow model called MODFLOW (McDonald and Harbaugh, 1988) is used for these experiments. The results of the flow simulation are simulated heads and flows. A postprocessing model called MODPATH (Pollock, 1989) is then used to calculate steady-state pathlines in the simulated three-dimensional ground-water system. The computer program MODPATH-PLOT (Pollock, 1990) is used to plot the computed pathlines. The methodologies used for MODFLOW, MODPATH, and MODPATH-PLOT are described in their separate documentation as referenced.

DELINEATION OF AREAS CONTRIBUTING RECHARGE TO WELLS IN HYPOTHETICAL GROUND-WATER SYSTEMS

The setting for the hypothetical ground-water systems used for the calculation of areas contributing recharge is a simplified alluvial valley (fig. 3). Permeable alluvial deposits are underlain and laterally bounded by impermeable bedrock, and a meandering stream flows through the valley. The simulated valley segment is 8,625 feet long, and the permeable deposits are about 150 ft thick and extend 6,750 ft across the valley. The areal recharge rate is 0.005 ft/d from infiltration of precipitation directly on the valley, and runoff from the impermeable bedrock valley walls accounts for inflow at the lateral boundary of the permeable deposits of 2 (ft^3/d)/ft. The stream is not deeply incised into the deposits.

The numerical model used to represent this system consists of a three-dimensional array of cells with 54 rows, 69 columns, and 6 layers (fig. 4). Each model layer is 25 ft thick, and each grid cell is 125 ft by 125 ft. The lateral inflow is simulated as entering the top layer. The stream is treated as a nonpenetrating stream with a depth of 2 ft, a streambed conductance of 15,000 ft^2/d, and a stream stage that varies from 152.75 to 148.85 ft above an arbitrary datum from left to right (column 1 to column 69).

Several hydrologic and (or) hydraulic conditions that could exist in alluvial valleys are simulated as individual cases. Each simulated "case" has a different hydraulic-conductivity distribution. The results of these simulations as they pertain to areas contributing to wells are described in the remainder of this paper.

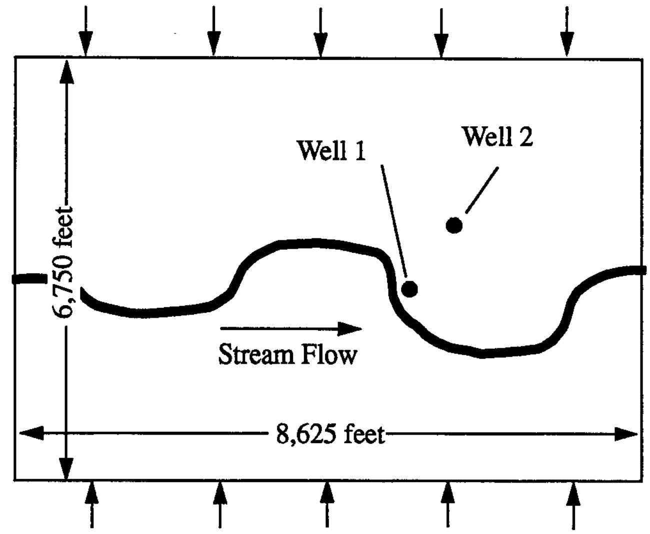


Figure 3. Map view of hypothetical alluvial valley.

Case 1—Homogeneous System

For Case 1, the alluvial deposits are assumed to be homogeneous and vertically anisotropic. The hydraulic conductivity is 100 ft/d laterally and 25 ft/d vertically, and the deposits have a uniform porosity of 0.3. To examine areas contributing recharge to discharging wells, the system is assumed to be in equilibrium (steady state), and the wells are pumped continuously at specified discharge rates.

The simulated water-table contours for the system when no wells are being pumped is shown in figure 5. The system has a net areal recharge of 291,090 ft^3/d and a lateral inflow of 34,500 ft^3/d. The areal recharge comprises 89.4 percent of the water entering the system and is the most significant part of the water budget for the system for the condition of no discharging wells. All the water entering the system (325,590 ft^3/d) discharges to the stream under such an unstressed condition.

Well 1 is screened at different depths at node 30,44 (row 30, column 44) in the following variations of the simulations for Case 1. The areas contributing recharge are determined for discharge rates of 2,000, 10,000, and 30,000 ft^3/d. The source area (area contributing recharge) for the water discharged is calculated by using MODPATH and MODPATH-PLOT (Pollock, 1989,1990). The pathline calculation method is used to determine the paths of the water through the modeled system, thereby allowing identification of the paths that eventually discharge to the well. The location where the paths entered the ground-water system are then determined and plotted for each case.

The "areas contributing recharge" delineated on maps for each simulation indicate the area at the water table where water flowing to the well originates. A component of flow to the well can also originate at the lateral inflow boundary or at the stream; these components are not shown on most of the figures but are discussed as water-budget components to the well.

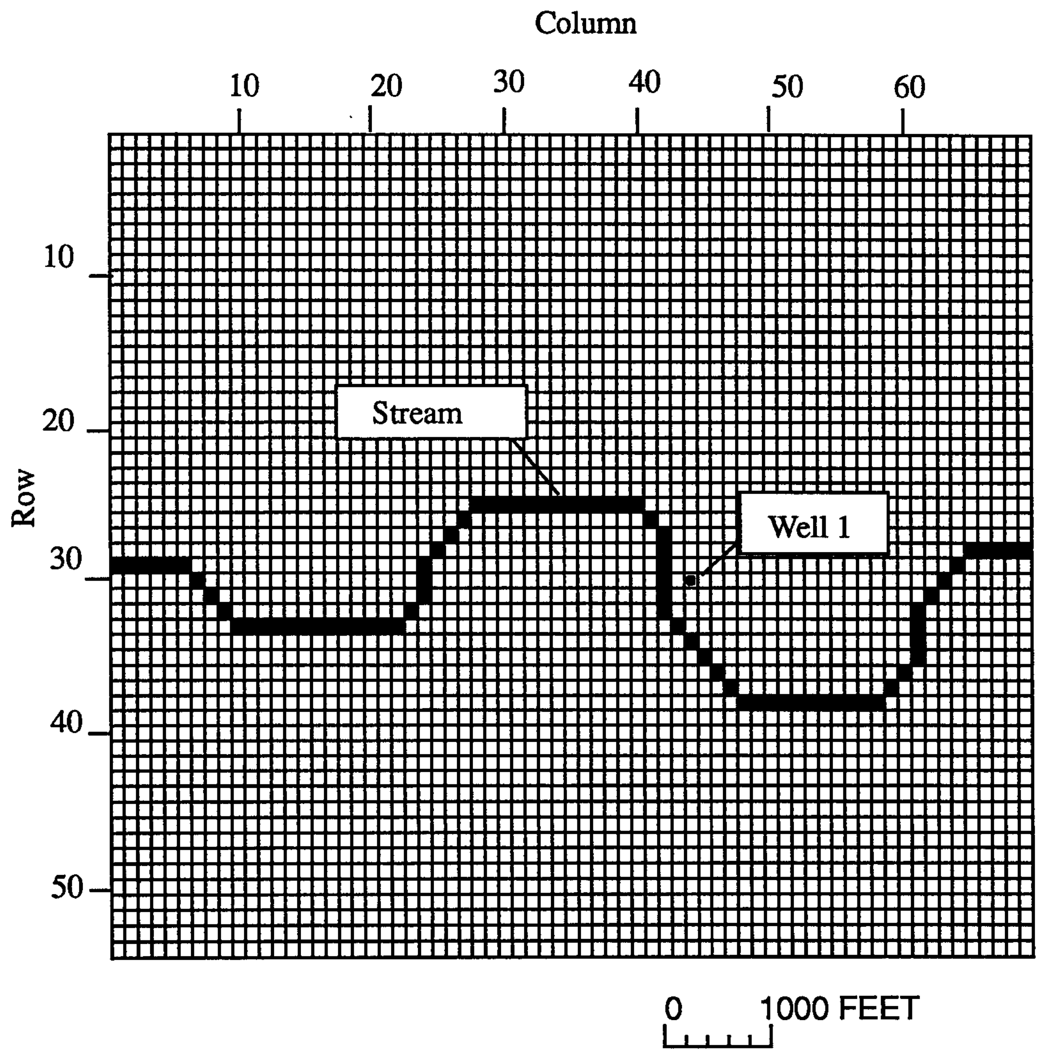


Figure 4. Model grid for simplified alluvial-valley system showing stream and well location.

Well Discharge of 2,000 Cubic Feet per Day from Three Different Screened Intervals

The vertical placement of the well screen affects the location of the area contributing recharge. Figure 6 shows the calculated areas contributing recharge to a well discharging 2,000 ft^3/d and located in the same place areally but with three different vertical screen intervals. All three screened intervals are 25 ft. The areas contributing recharge for all three intervals are on the same side of the stream as the well.

With the screen at the shallowest position (0–25 ft below the water table), the area contributing recharge to the well lies directly above the well. The area contributing recharge does not extend to the valley walls. All of the water flowing to the well screened at this shallow depth is derived from areal recharge at the water table; the contributing area, therefore, equals the discharge rate divided by the areal recharge rate—4.0×10^5 ft^2. The maximum time required for a particle of water to travel from its origin at the water table to the well is 41.8 years, and the minimum time is 0.0 years.

With the screen at an intermediate depth (50–75 ft below the water table), the area contributing recharge to the well does not directly overlie the well but extends from near the well to the valley walls. With this intermediate screen depth, the well derives 97 percent of its flow from areal recharge at the water table and 3 percent from the lateral inflow at the valley wall. The maximum time required for a particle of water to travel from its origin at the

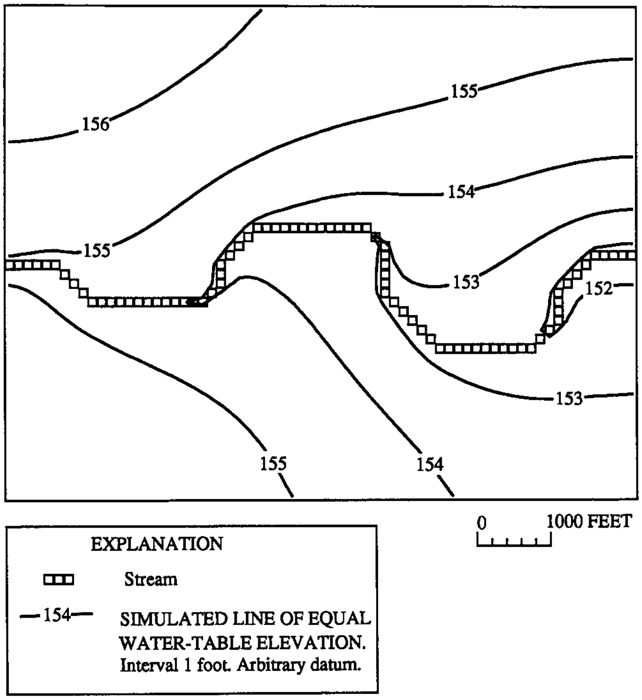


Figure 5. Configuration of the water table for the simulated alluvial valley with no ground-water withdrawals.

water table to the well is 54.2 years, and the minimum time is 4.0 years. Water derived from lateral inflow takes longer to flow to the well than the maximum time required for water derived from the water table.

With the deep screen (125–150 ft below the water table), the area contributing recharge to the well lies at some distance from the well and extends to the valley wall. The area contributing recharge is distant from the well because, for the specified screen depth and discharge rate, the well intercepts deep pathlines that originate far upgradient in the system. These pathlines are shown in cross section in figure 7. Well 1 is capturing some of the lateral inflow, which represents flow from the valley walls, and some of the areal recharge occurring over the entire valley. In this case, the area contributing recharge is located on the same side of the river as the well. No water is derived directly from the stream, but the total discharge to the stream from the ground-water system is decreased by the amount discharged (captured) by the well, which is 2,000 ft^3/d. With this screen interval, the well derives 68 percent of its flow from areal recharge at the water table and 32 percent from lateral inflow at the valley wall. The maximum time for a particle of water to travel from the water table to the well is 58.9 years, and the minimum time is 18.8 years.

This series of figures (figs. 6 and 7) for a well having its screened interval at different depths highlights the importance of recognizing the three-dimensional aspect of a flow system in determining paths of ground-water flow to a well.

Well Discharge of 10,000 Cubic Feet per Day from Three Different Screened Intervals

The area contributing recharge to well 1 discharging at a rate of 10,000 ft^3/d with a 25-ft-long screened interval located at depth intervals of 0 to 25 ft, 50 to 75 ft, and 125 to 150 ft below the water table is shown in figure 8. The area contributing recharge is not contiguous at this discharge rate for all the screened intervals, and water that flows to the well originates on both sides of the stream. Most of the contributing area is on the same side of the stream as the well, but a part is on the opposite side of the stream. Because the stream is only partially penetrating, water can flow beneath the stream to the well. The water-table contours shown on figure 8 do not reflect these deep flow patterns for any of the screened intervals. No water is derived directly from the stream for any of the screened intervals, but the total discharge to the stream from the ground-water system has decreased by 10,000 ft^3/d, the amount discharged (captured) by the well. The three-dimensional aspect of the water movement in ground-water systems is evidenced by the flow of some of the water beneath the stream to the well discharging at a rate of 10,000 ft^3/d.

The vertical position of the well screen in the three-dimensional domain affects where the water flowing to the well originates, as shown previously for a well discharging at 2,000 ft^3/d. Examination of the effect of the position of the screened interval on a well with a discharge greater than 2,000 ft^3/d provides some additional insight into understanding the location of areas contributing recharge. Although the location of the areas contributing recharge are similar for the different screened intervals, there are some obvious differences. In particular, the location of the area contributing recharge to the well screened at 0 to 25 ft below the water table overlies the well, and the range in time for water to travel to the well from its entrance at the water table is 0.0 to 81 years. For the deepest well screen, at a depth interval of 125 to 150 ft below the water table, the

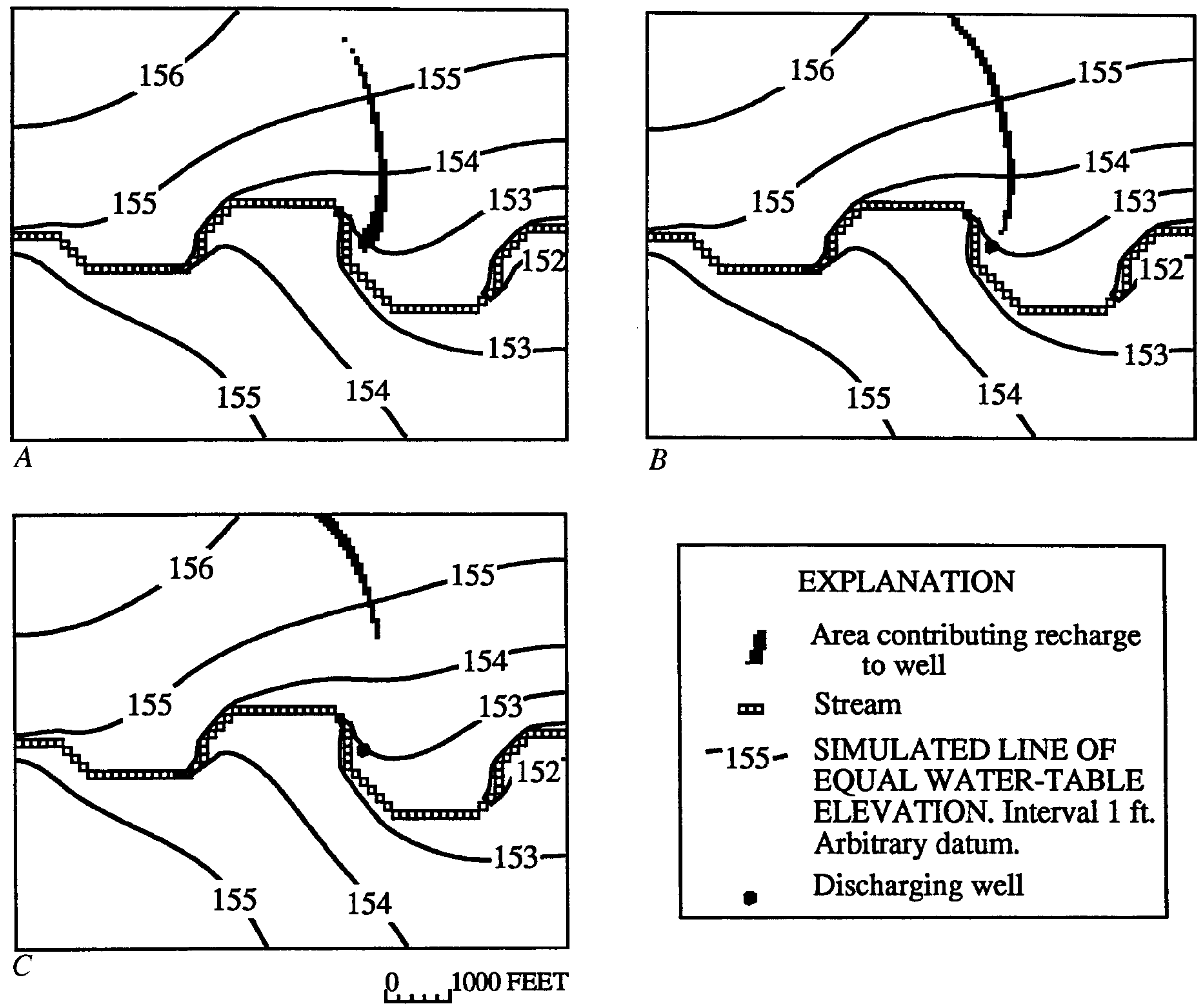


Figure 6. Simulated configuration of the water table and areas contributing recharge for a well discharging at a rate of 2,000 cubic feet per day screened at three different depths. *A*, Screened interval=0–25 ft below water table. *B*, Screened interval=50–75 ft below water table. *C*, Screened interval=125–150 ft below water table.

area contributing recharge is not located at the well bore, and the time of travel of water flowing to the well from its point of recharge at the water table ranges from 3.5 to 83 years. Thus, the area contributing recharge and three-dimensional flow paths are again affected by the vertical location of the well screen.

Well Discharge of 30,000 Cubic Feet per Day

The area contributing recharge becomes larger if the well is screened at the bottom of the aquifer (125- to 150-ft depth interval) and discharges 30,000 ft^3/d (fig. 9). At this discharge rate, part of the contributing area directly overlies the well, and some of the water must travel vertically downward from the water table to the screened interval. The range in traveltimes from the water table to the well for the area contributing recharge is 1.5 to 87 years. The area is in two parts, one on each side of the stream. The area is adjacent to the stream, but no water is derived directly from the stream at this discharge rate.

Well Discharge of 30,000 Cubic Feet per Day in the Presence of an Additional Well Discharging 130,000 Cubic Feet per Day

Ground-water systems are dynamic, and flow patterns within them change in response to changes

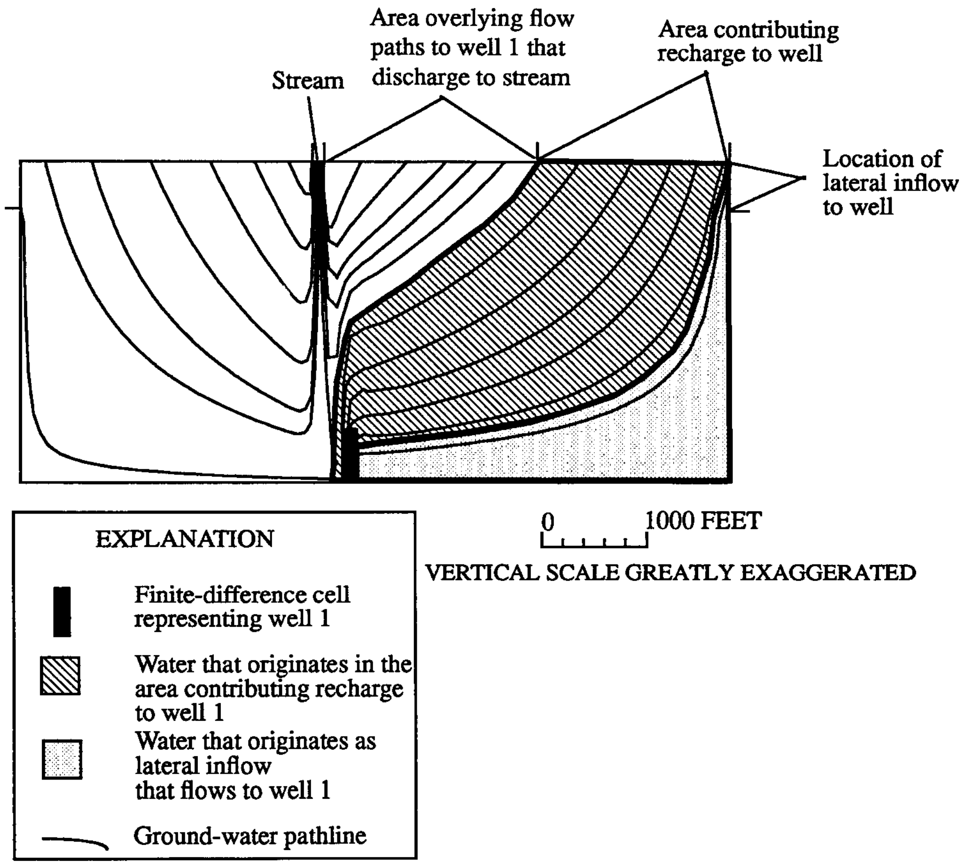


Figure 7. Pathlines in the ground-water system with well 1 screened at 125 to 150 feet below the water table and discharging at a rate of 2,000 cubic feet per day.

in stress. This is illustrated by simulating the same hypothetical system as the one just discussed but with the addition of a second discharging well.

The original well (designated well 1) continues to discharge at a rate of 30,000 ft^3/d. However, a second well (well 2, located at row 22, column 49) discharges at a rate of 130,000 ft^3/d from the bottom of the aquifer at a depth interval of 125 to 150 ft below the water table. The heads throughout the entire aquifer system respond to this new stress, and the shape and location of the area contributing recharge change. The area contributing recharge to well 1 changes, as shown in figure 10, even though the discharge rate of well 1 has not changed.

The area contributing recharge to well 1 under these conditions is contiguous, but most of it is on the opposite side of the stream from the well location. Also, some of the water flowing to well 1 comes directly out of the stream. This means that the quality of the water in the stream may affect the quality of the water eventually discharged from well 1.

The area contributing recharge to well 2 is very complex (even for this simplified hypothetical system). The water-table contours reflect the well's effect on the flow system on the same side of the stream, but the parts of the area contributing recharge to well 2 that surround the area contributing recharge to well 1 on the opposite side of the stream cannot be inferred readily from the water-table contours.

Case 2—Low-Hydraulic-Conductivity Local Confining Unit

Case 2 uses a hypothetical alluvial aquifer system similar to that in Case 1, except for the inclusion of a low-hydraulic-conductivity layer at 100 ft beneath the stream. The low-hydraulic-conductivity layer, which acts as a confining unit, does not

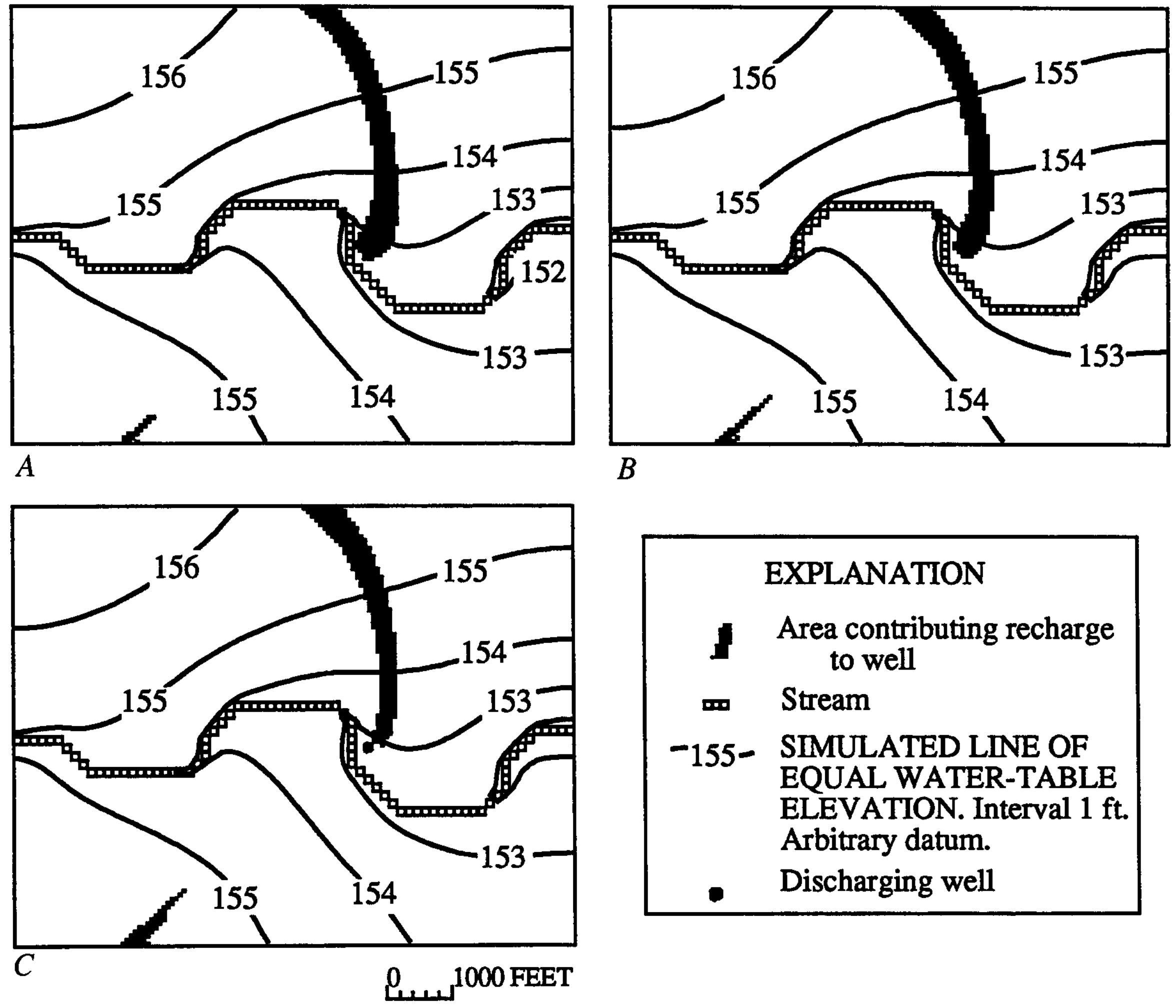


Figure 8. Simulated configuration of the water table and areas contributing recharge for a well discharging at a rate of 10,000 cubic feet per day screened at three different depths. *A*, Screened interval=0–25 ft below water table. *B*, Screened interval=50–75 ft below water table. *C*, Screened interval=125–150 ft below water table.

extend over the entire basin but is present only in the vicinity of the stream. The confining unit is simulated as a 1-ft-thick layer with a vertical hydraulic conductivity of 0.0001 ft/d.

If a well is simulated as being screened at the bottom of the aquifer and discharging at a rate of 10,000 ft^3/d, the resultant area contributing recharge is as shown in figure 11*B*. This contributing area differs from that for a well discharging at the same rate from a homogeneous aquifer (fig. 8). Of particular interest is that, although the area contributing recharge remains in two parts, both parts are on the same side of the stream, in contrast to a well in a homogeneous aquifer. The reason that water from the area contributing recharge on the left of figure 11*B* (up valley) flows to the well under these conditions is that the water flows under the confining unit and then cannot discharge until it reaches the well.

An examination of specific pathlines in Case 2 helps in visualizing the details of the flow system that cause the area contributing recharge to be two separate areas on the same side of the stream. Pathlines that represent the path taken by the water originating at the water table along the top boundary of the aquifer system are shown in figure 11*B*. Pathline A extends from the water table deep into the system beneath the confining unit and then emerges on the opposite side of the stream, where the water discharges into the stream. Pathline B extends from the water table deep into the system beneath the confining unit, where the flow path is affected by the discharging well, and the water flows downgradient

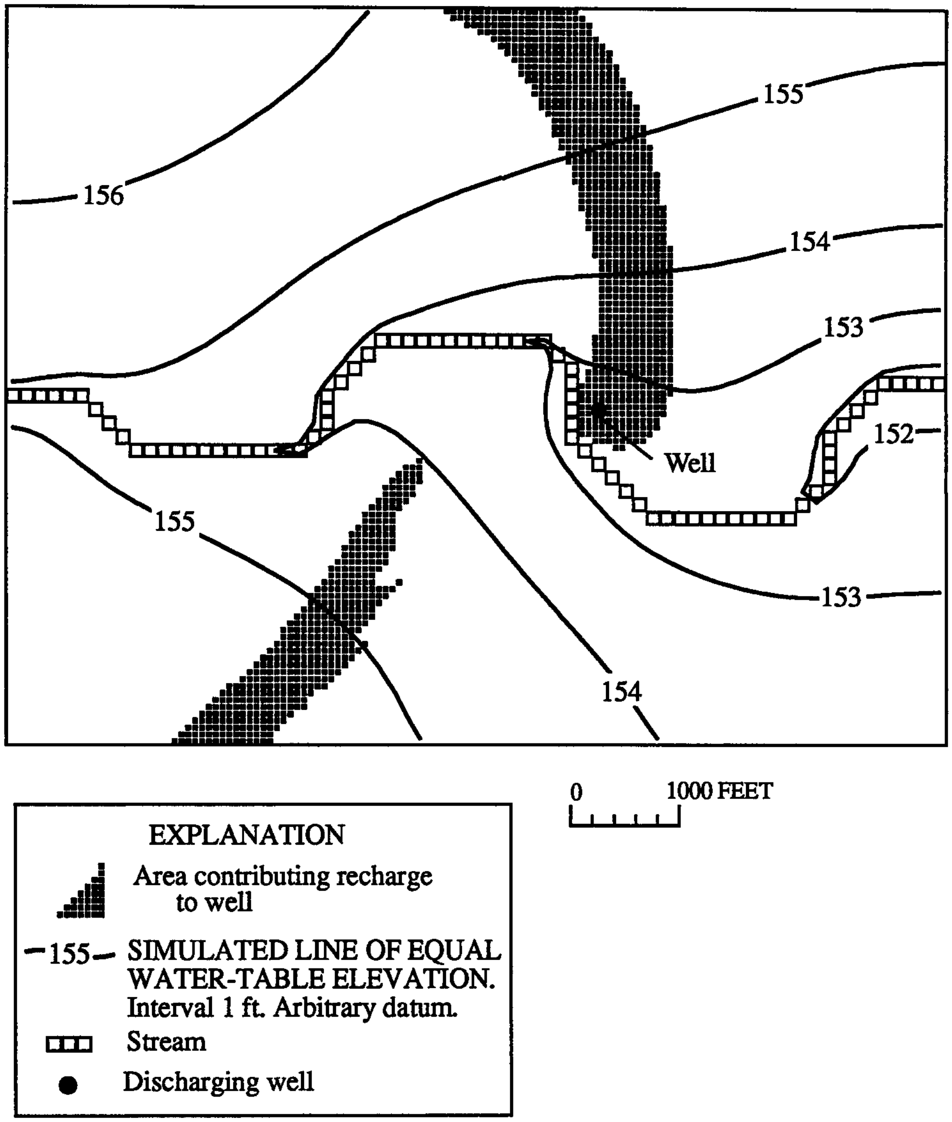


Figure 9. Simulated configuration of the water table and area contributing recharge for a well discharging at a rate of 30,000 cubic feet per day.

beneath the confining unit to the well, where the pathline ends. The water movement represented by pathline C is from the water table to the section of stream that is near the edge of the confining unit, so that the flow path never gets under the confining unit to be "captured" by the well. It is important to note that, although no water from the water table in the area of pathline C flows to the well, some of the lateral inflow from the north (top of the figure) boundary does flow under the confining unit and flows to the well, as shown by the area of lateral inflow on the cross section in figure 11*A*. Pathline D extends from the water table deep into the system beneath the clay layer and ends at the well.

In this case, most (71 percent) of the water flowing to the well originates as lateral inflow along the valley walls. Areal recharge accounts for 29 percent of the water discharged by the well. The minimum traveltime from the area that contributes recharge to the well is 41 years—a significant increase from the 3.5 years for the homogeneous system of Case 1.

The presence of the 1-ft-thick confining unit is not indicated by the water-table configuration. In fact, the water-table configuration is similar to that for the case of a homogeneous aquifer (fig. 8*C*). However, even with similar water-table configurations, the localized confining unit significantly

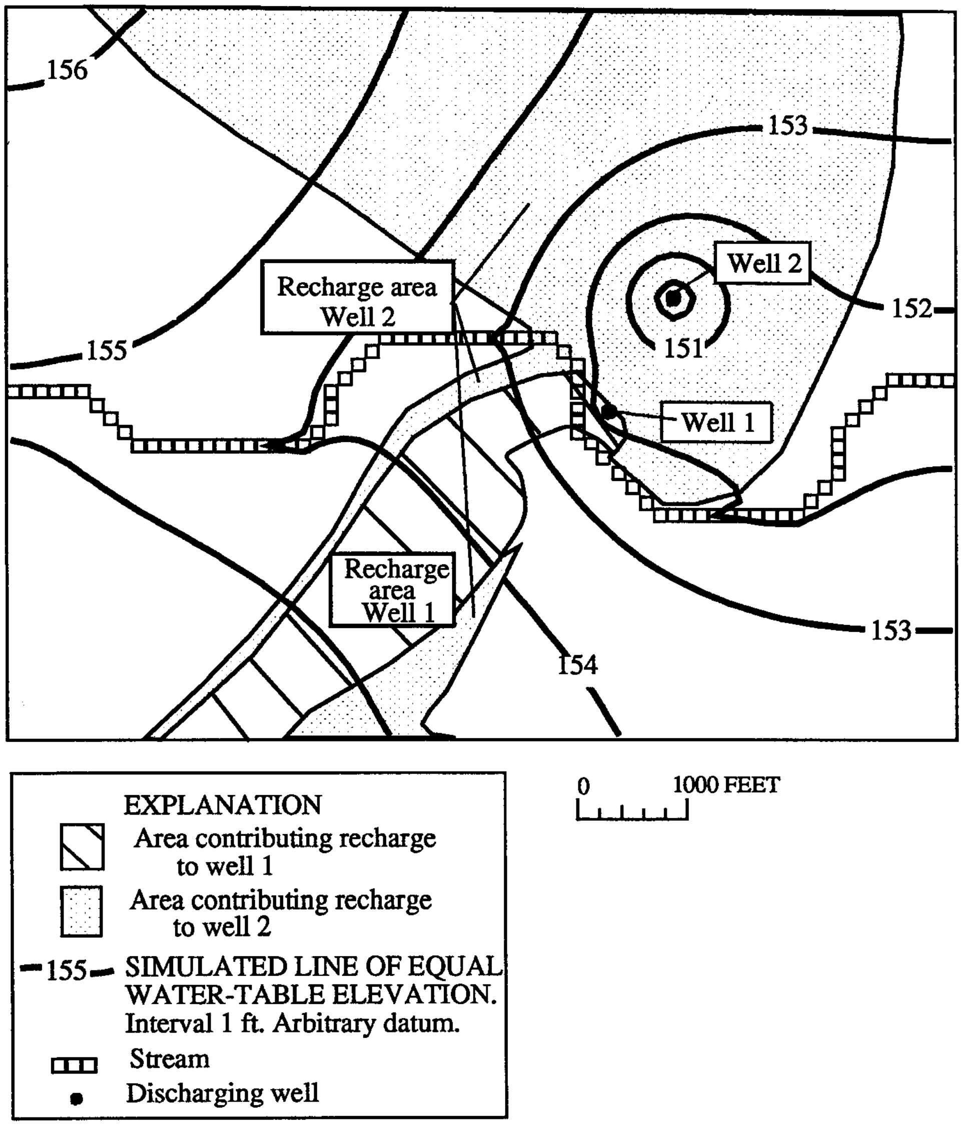


Figure 10. Simulated configuration of the water table and areas contributing recharge for two wells discharging simultaneously: well 1 discharges at a rate of 30,000 cubic feet per day, and well 2 discharges at a rate of 130,000 cubic feet per day.

affects the location of the area contributing recharge and the time of travel to well 1.

Case 3—High-Hydraulic-Conductivity Units

In Case 3, a hypothetical alluvial system similar to that in Case 1 is simulated, but the system now includes a zone of high hydraulic conductivity beneath and (or) adjacent to the stream. The well discharges at a rate of 10,000 ft^3/d. Two different systems are evaluated for Case 3—one with the zone of high hydraulic conductivity beneath the stream only in layer 6 (the 25-ft-thick screened interval at the bottom of the aquifer) and the other with the zone of high hydraulic conductivity extending throughout the total thickness of the aquifer (approximately 150 ft) beneath the stream. In both cases, the background horizontal hydraulic conductivity is simulated as 100 ft/d, and the deposits with a high hydraulic conductivity have a horizontal hydraulic conductivity of 500 ft/d. The vertical hydraulic conductivity is one-fourth the horizontal conductivity everywhere.

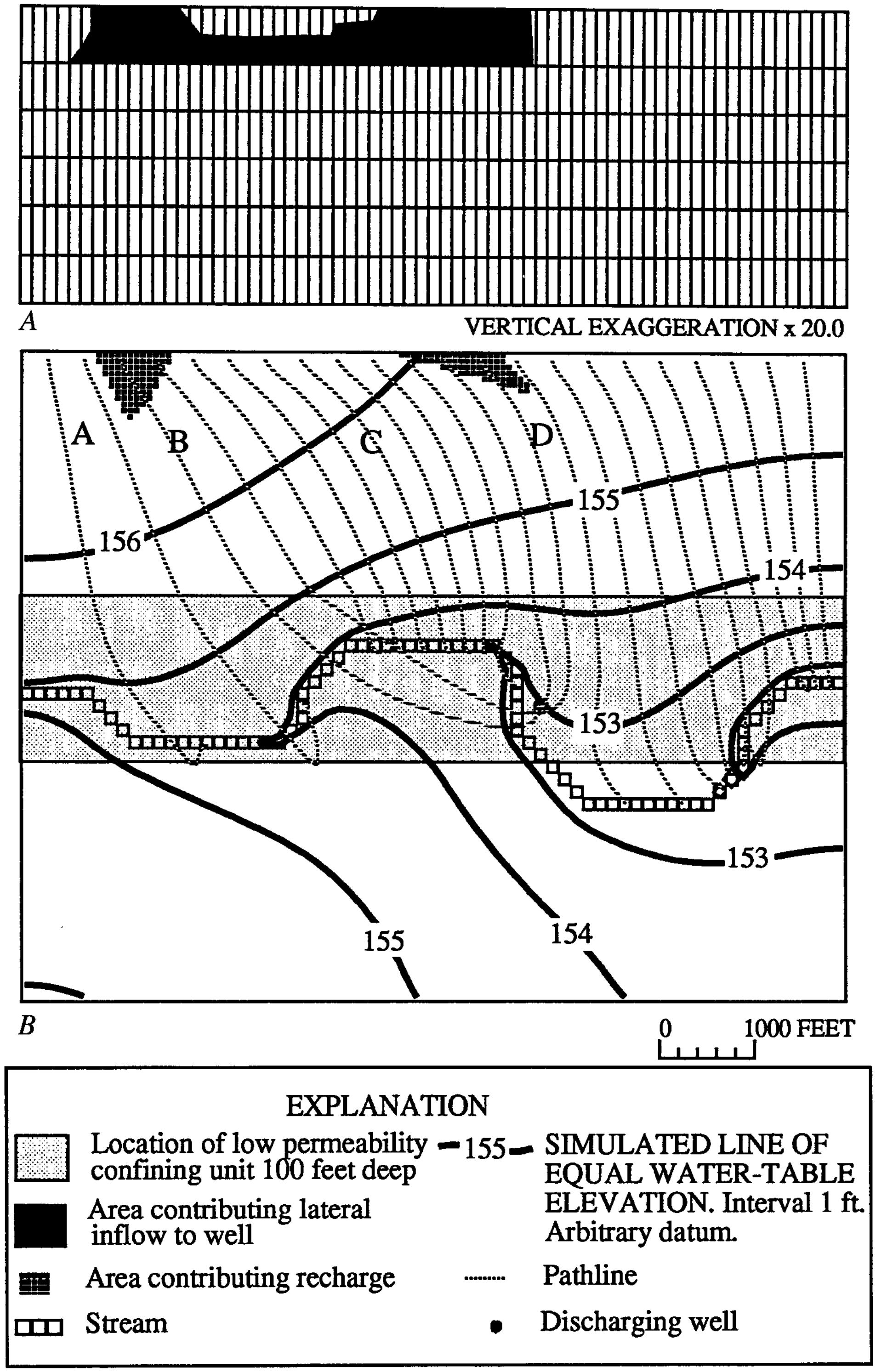


Figure 11. *A*, Cross section showing area of lateral inflow on finite-difference grid. *B*, Simulated configuration of the water table and area contributing recharge for a well discharging at a rate of 10,000 cubic feet per day, in the presence of a discontinuous confining unit. See text for discussion of pathlines A–D.

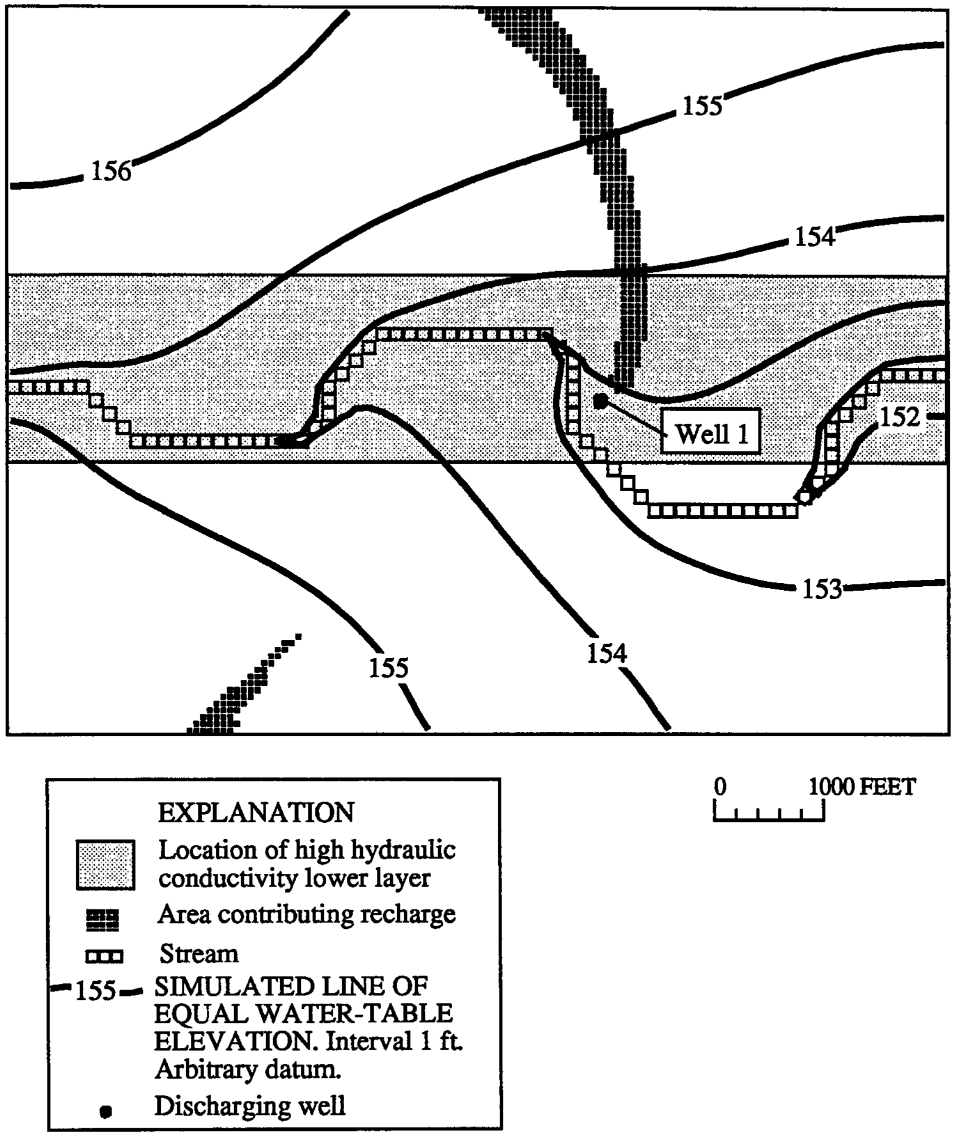


Figure 12. Simulated configuration of the water table and area contributing recharge for a well discharging at a rate of 10,000 cubic feet per day, with a layer of high hydraulic conductivity at the bottom of the aquifer.

Figure 12 shows the calculated area contributing recharge for the case of a layer of high hydraulic conductivity in the screened zone at the bottom of the aquifer in the vicinity of the stream. This contributing area and the water-table configuration are almost identical to those for the homogeneous system as shown in figure 8*C*. As simulated, the 25-ft-thick layer of high hydraulic conductivity has very little effect on the location of the area contributing recharge to the well. However, if the entire thickness of aquifer adjacent to the stream has a high hydraulic conductivity, the resultant area contributing recharge is quite different, as shown in figure 13. The area contributing recharge now comprises three distinct parts. Recharge water from the part in the upper left corner now flows toward the stream along the left boundary of the valley, and, once under the stream, it flows in the high-hydraulic-conductivity section of aquifer until it discharges at the well. The water-table configuration differs from that shown in figures 8*C* and 12, but the difference is not great, even though the difference in the locations of the areas contributing recharge is significant.

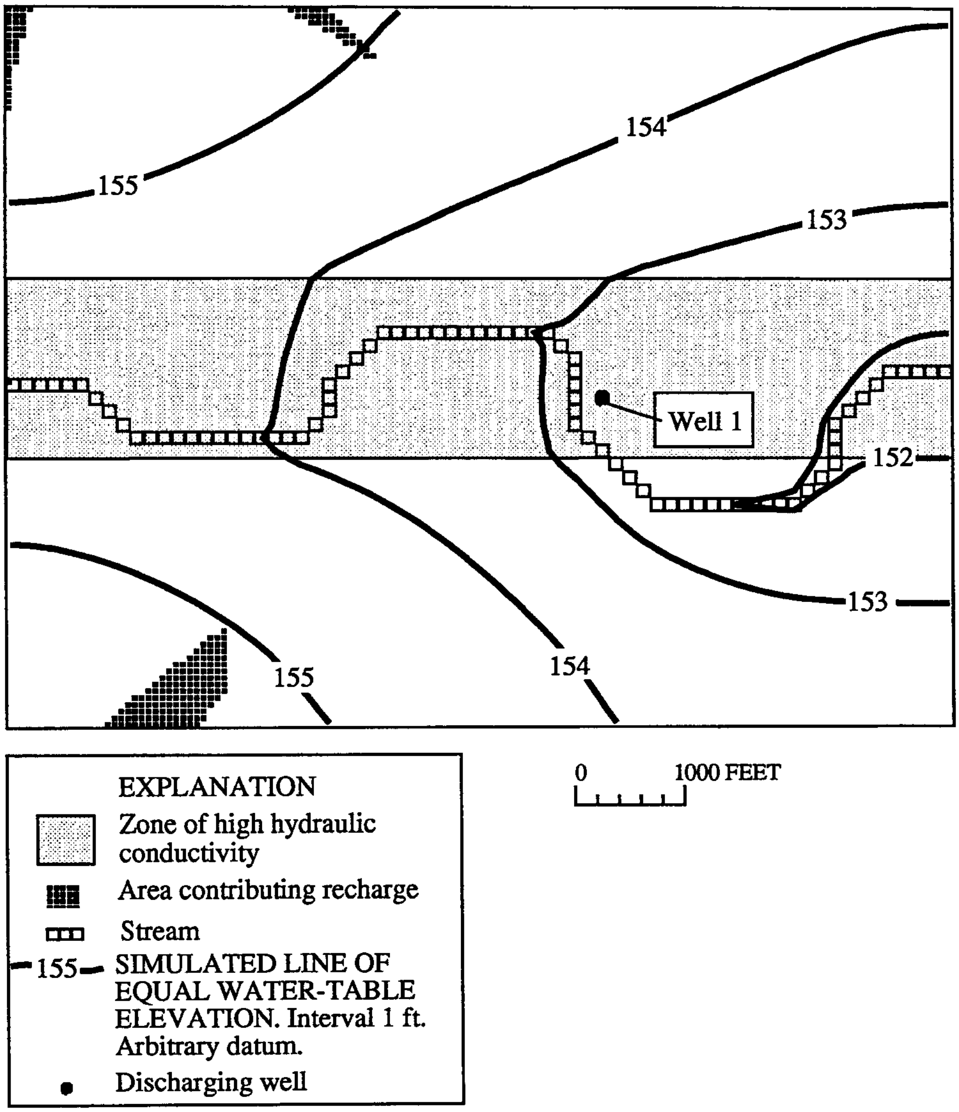


Figure 13. Simulated configuration of the water table and area contributing recharge for a well discharging at a rate of 10,000 cubic feet per day, with a zone of high hydraulic conductivity (500 feet per day) 150 feet thick along the stream.

Case 4—Random Distribution of Hydraulic Conductivity

Properties of natural systems can vary significantly in space. The manner in which these properties vary in aquifers can be very complex, depending on the depositional environment of the rock or unconsolidated materials that constitute the aquifer. One conceptualization that accounts for the variability in hydraulic conductivity treats hydraulic conductivity as a random variable. To obtain a sense of the effect of this randomness on the location of the area contributing recharge, a correlated random field of hydraulic conductivity is simulated in Case 4. A correlated random field assumes that the parameter of interest is a random variable but that the parameter values at adjacent points are related. This relation is specified such that, as the distance between two points increases, they become less related (or correlated). The deposition processes of unconsolidated porous media would produce a hydraulic-conductivity distribution that would probably be correlated spatially. The simulation of a correlated random distribution of hydraulic conductivity is a simplified means to test the significance of variabil-

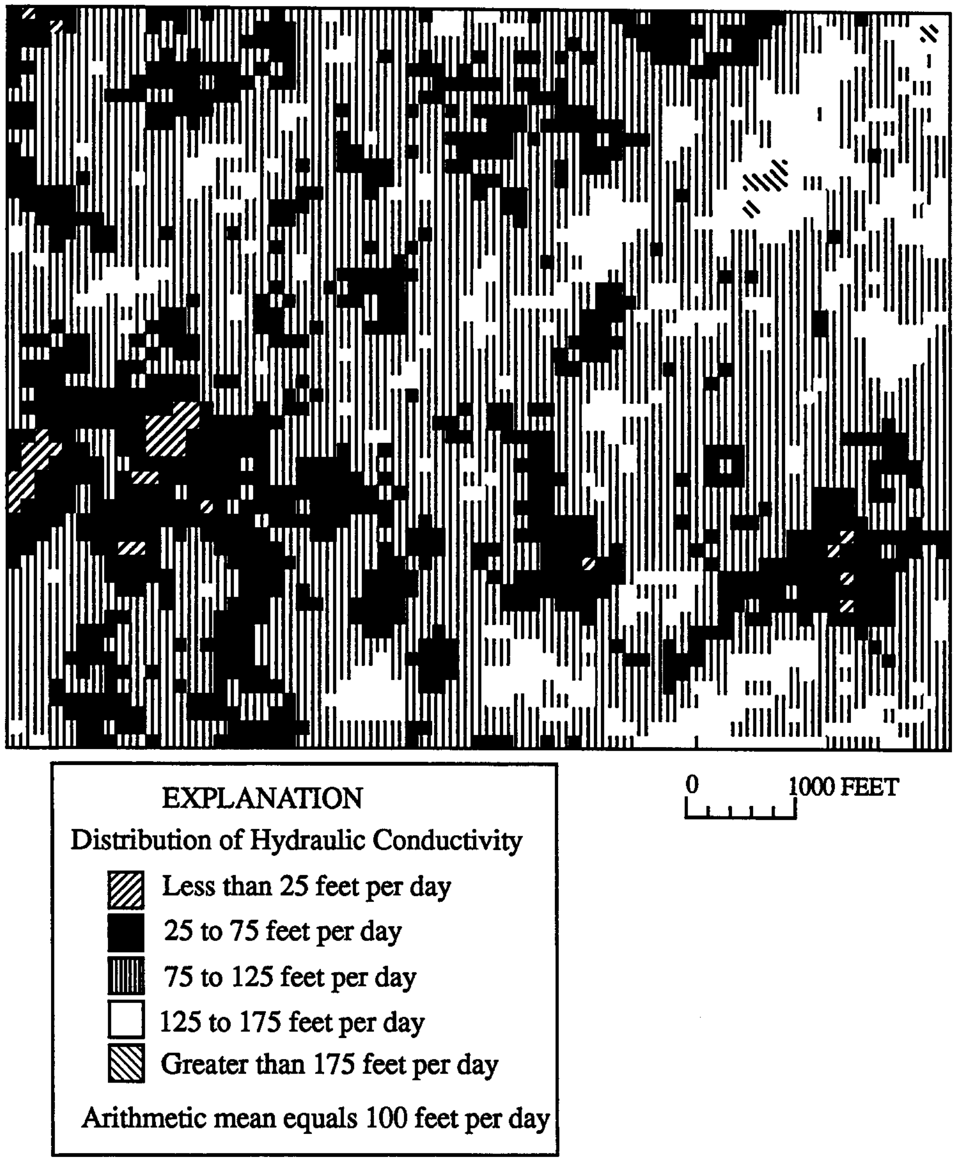


Figure 14. Random two-dimensional hydraulic-conductivity distribution in a hypothetical alluvial-valley aquifer.

ity in hydraulic conductivity on the areas contributing flow to a well in aquifer systems.

The hydraulic conductivity used in Case 4 varies areally but is the same for each layer. This two-dimensional hydraulic-conductivity field was generated using the program TUBA (Mantoglou and Wilson, 1982; Zimmerman and Wilson, 1989), which generates two-dimensional spatially correlated random fields by the turning-bands method. For the purposes of this report, three realizations (or three specific distributions out of the infinity of possible distributions) of a random hydraulic-conductivity field that has a normal distribution with a 1,000-ft correlation length, an arithmetic mean of 100 ft/d, and a standard deviation of 30 ft/d are calculated and used to illustrate potential effects of hydraulic-conductivity variability on areas contributing recharge. Again, the well is screened over the bottom 25 ft of the aquifer and discharges at a rate of 10,000 ft^3/d.

The first realization of the hydraulic conductivity distribution used is shown in figure 14. The hydraulic conductivity ranged from approximately 10 ft/d to 190 ft/d. The resultant area contributing recharge for this first realization is shown in figure 15*B*. The area contributing recharge consists of two

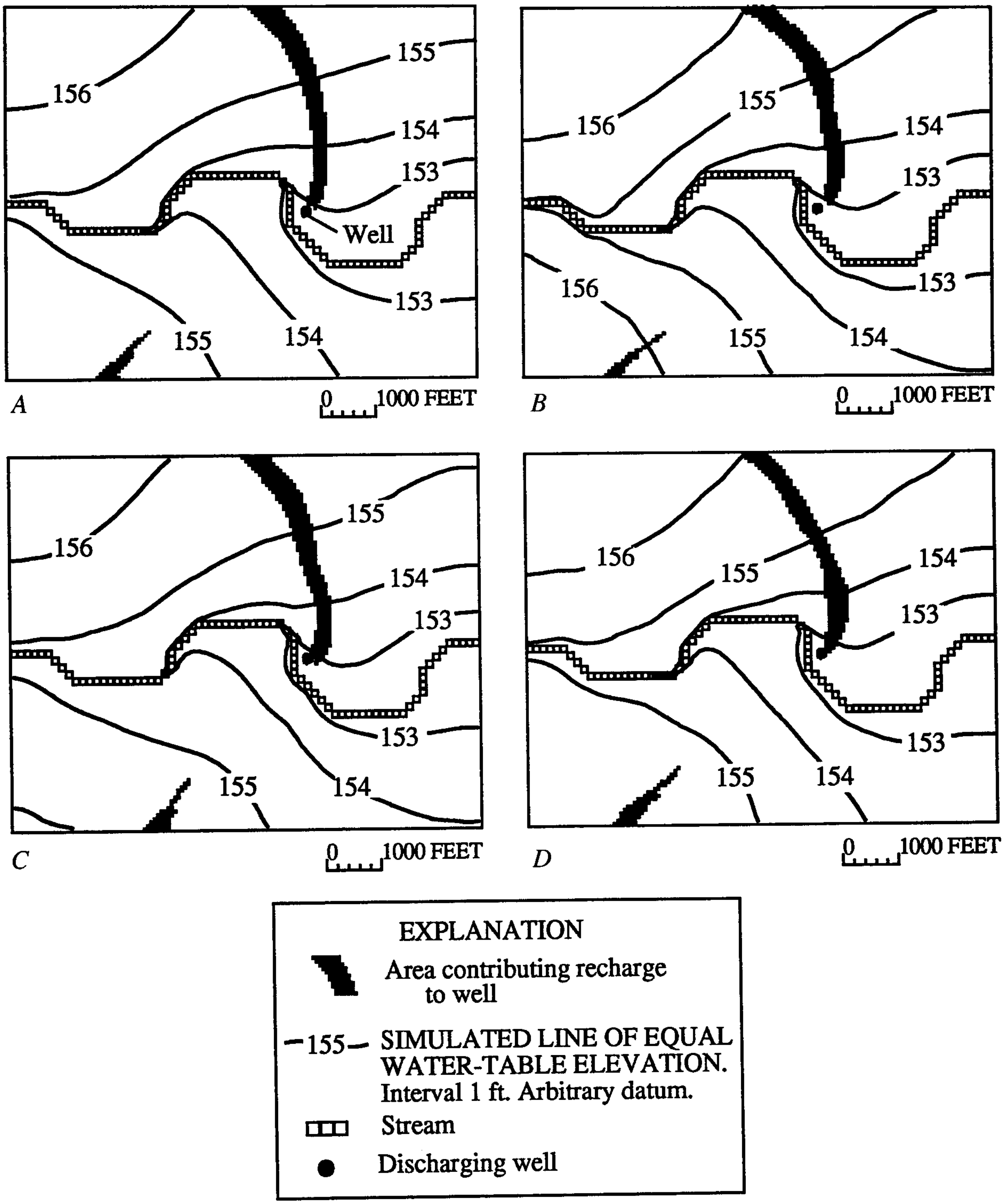


Figure 15. Simulated configuration of the water table and areas contributing recharge for four cases. *A*, Homogeneous hydraulic conductivity of 100 feet per day, *B–D*, Three realizations of a random hydraulic-conductivity distribution with an arithmetic mean of 100 feet per day and the same variance.

parts, one on each side of the stream. The location is similar to the area calculated for the homogeneous case (fig. 8*C*, which is reproduced as fig. 15*A*), but it differs slightly at some locations. The water-table configurations in figures 15*A* and 15*B* have the same general shape that reflects the stream gradient

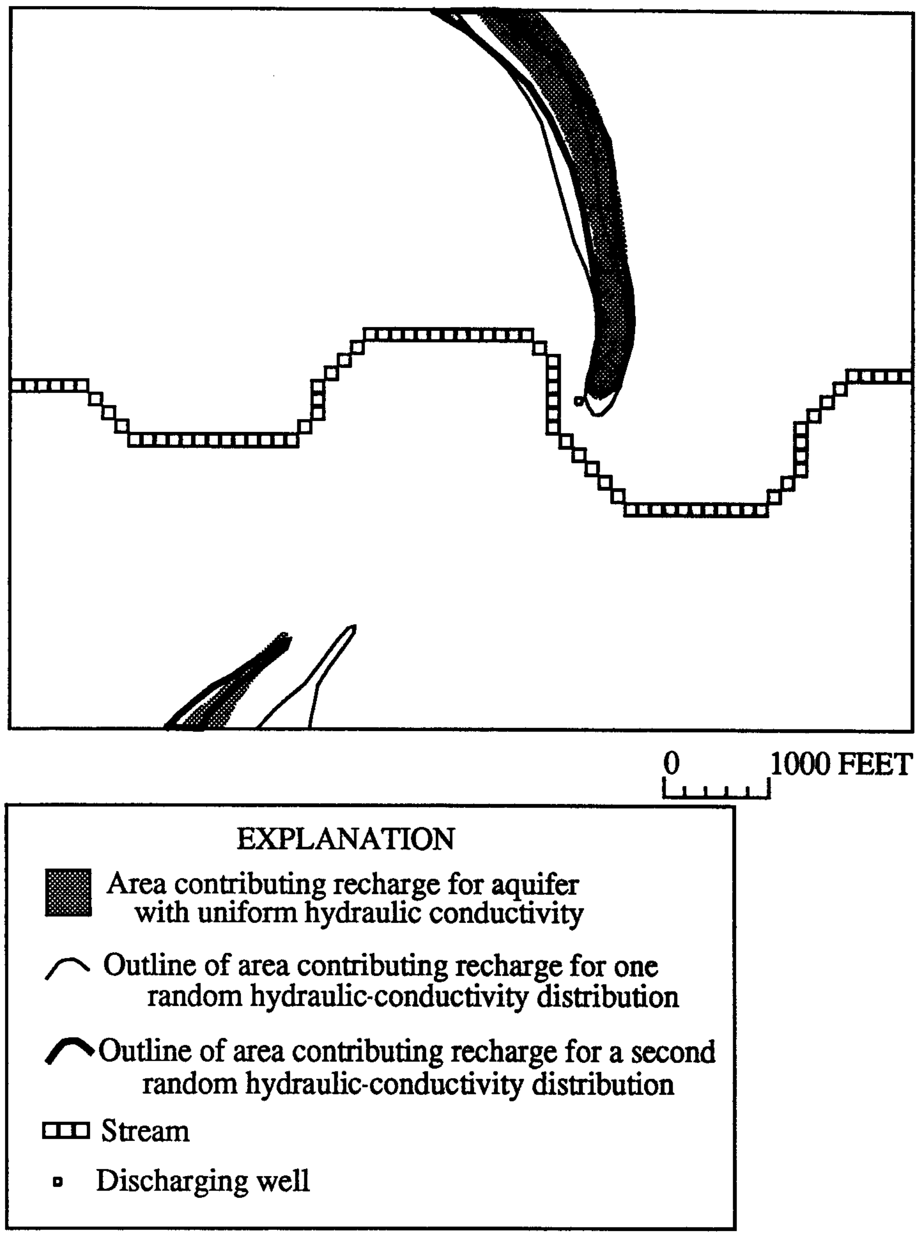


Figure 16. Areas contributing recharge to a discharging well in an aquifer with two different randomly distributed hydraulic-conductivity fields and in an aquifer of uniform hydraulic conductivity.

and geometry; any differences probably could not be detected by field measurements.

Two other realizations of the random hydraulic-conductivity field were analyzed. The areas contributing recharge and the water-table configurations for the homogeneous case (also shown as fig. 8*C*) and for the three realizations of the random hydraulic-conductivity field are shown in figure 15. All of the water-table surfaces for the four realizations (one homogeneous and three random) are indistinguishable, from a field perspective. Although subtle, differences are evident in the location of the areas contributing recharge (fig. 16).

The standard deviation of the hydraulic conductivity used in the three realizations is probably smaller than that for most actual ground-water systems. However, even this small variation in hydraulic conductivity about the mean causes differences in the location of the area contributing recharge (fig. 16). Because hydraulic properties of natural systems vary spatially and cannot be quantified exactly, the areas contributing recharge to discharging wells cannot be delineated without some degree of uncertainty. This uncertainty needs to be accounted for when attempting to define areas contributing recharge under field conditions.

DISCUSSION OF SIMULATION RESULTS

The variation in the size and location of the calculated areas contributing recharge to a well in the hypothetical alluvial-aquifer systems represented in Cases 1–4 illustrates the complexity of ground-water systems. Although the cases examined are not exhaustive, they do provide explicit examples, under specified conditions, of the cause and effect relations that must be considered in attempting to determine the sources of water (areas contributing recharge) to wells.

As illustrated in Case 1 (figs. 6–10), the location and size of the area contributing recharge depend on the overall geometry and boundary conditions of the system, as well as the location, screened interval, and discharge rate of the well. If the boundary conditions, such as recharge rates or the stream stage, change, then the area contributing recharge to a well will change. The location and size of the area contributing recharge to the well also will change as a function of the discharge rate, well location, and position of the screened interval.

Results of the simulation for all 4 of the cases show that the area contributing recharge to a single well is not necessarily one contiguous area and does not have to surround or be contiguous with the well. Even for the relatively simple systems considered here, flow paths to a well were shown to be a complex reflection of the subtle interactions among boundary conditions and hydraulic properties that take place in three-dimensional systems.

A discharging well is not an independent force on flow paths in a ground-water system. Flow within a ground-water system reflects all the stresses imposed on that system. Flow paths change in response to new stresses on the system, even if they are imposed at locations other than at the well of interest. Figure 10, for Case 1, illustrated that even though the discharge rate for well 1 did not change, the area contributing recharge to it changed in response to the addition of another well. Any calculations to determine the contributing area must evaluate the flow paths on a systemwide basis instead of on an individual well basis in order to delineate these areas correctly. Once areas contributing recharge to a well are delineated for a particular site, they must be reevaluated as new wells are added to the ground-water system.

Uncertainties in the definition of the hydrogeologic framework and transmitting properties of the aquifer system can have a major effect on the shape and location of areas contributing recharge. The specified heterogeneities in Cases 2 and 3 affected the shape and location of the area contributing recharge compared to the location and area delineated for the homogeneous system in Case 1 (fig. 8*C*). The relatively mild random distribution (a normal distribution with a small variance) of hydraulic conductivity in Case 4 also affected the location of the area contributing recharge.

The experimental results for Cases 1–4 show that the boundary conditions of the system and the location of the well screen (particularly if the well is partially penetrating) are very important in determining the area contributing recharge. In calculating and evaluating areas contributing recharge (or the contributing area and zone of contribution), it is important to consider the entire three-dimensional ground-water system. The volume of earth material and fluid that is associated with flow to a discharging well should be envisioned as a "bundle" of flow tubes that changes shape as it traverses from its starting point in the flow system to its exit point from the system at the discharging well. When using terms to describe this complex "bundle" of flow tubes, care needs to be taken to qualify the assumptions used and the three-dimensional volumes defined.

CONSIDERATIONS FOR THE PROTECTION OF GROUND WATER

Many State agencies are currently (1993) developing wellhead-protection programs. The thrust of some of these programs is to protect water supplies by determining the areas contributing recharge to water-supply wells and by specifying regulations to minimize the opportunity for contamination of the recharge water by activities at the land surface. The areas contributing recharge to wells delineated under specified hypothetical conditions illustrate that, at least under some conditions, the determination of areas contributing recharge is complex, because all ground-water systems are three-dimensional, and the transmitting properties, hydrogeologic framework, and boundary conditions are very difficult to determine with certainty. Thus, any determination of the areas contributing recharge needs to include an estimation of the uncertainties involved and the potential changes in stress on the system and needs to identify an area that comprises the combined areas under the suite of possible conditions for effective protection of a well's recharge area. The combined area, where recharge might occur under different conditions, could be considerably larger than the area contributing recharge for any one condition, but the combined area would account for the range of uncertainty in the estimation of a contributing area.

Even though the area contributing recharge to a well is distant from the location of the well, a potential exists for contamination outside of the contributing area to affect the quality of the water flowing to the well. For example, in the situation shown in figure 7, an area exists above the flow paths to the well where water entering the system discharges to the stream. Water entering this area does not flow to the well. However, if other wells, even nondischarging wells, have screens or are open holes that penetrate both the upper and lower zones, water can move downward through the well and "short circuit" the flow paths, allowing the mixing of the shallow and deep waters. In addition, unknown heterogeneities in the hydraulic-conductivity distribution can cause mixing in the vertical direction, or dense, immiscible contaminants may "sink" through the overlying water and affect the quality of the water flowing to the well. Additional stresses and variations in recharge over time can also induce mixing. Thus, the area of concern perhaps is not only the area where the water enters the ground-water system and flows to the well but also is the entire area overlying any flow paths to the well.

An implication of this discussion is that very large areas may have to be considered for protection, if protection is deemed the most appropriate means of ensuring high-quality ground water. Other options to ensure a high-quality ground-water supply could include relocation of wells as problems arise, a combination of regulating some aspects of the areas contributing recharge in conjunction with chemically treating (cleaning) the water discharged from wells before distribution, and complete reliance on water treatment to provide high-quality water. The overriding conclusion is that, for any management approach to be successful, the uncertainties associated with ground-water flow paths need to be considered.

REFERENCES CITED

Bair, E.S., and Roadcap, G.S., 1992, Comparison of flow models used to delineate capture zones of wells: 1, Leaky-confined fractured-carbonate aquifer: Ground Water, v. 30, no. 2, p. 199–211.

Barlow, P.M., 1989, Delineation of contributing areas to public supply wells in stratified glacial-drift aquifers, *in* Protecting ground-water from the bottom up: Proceedings, U.S. Environmental Protection Agency, Region I, Oct. 2–3, Danvers, Mass., p. 145–164.

Bear, J., and Jacobs, M., 1965, On the movement of water bodies injected into aquifers: Journal of Hydrology, v. 3, p. 37–57.

Brown, R.H., 1963, The cone of depression and the area of diversion around a discharging well in an infinite strip aquifer subject to uniform recharge: U.S. Geological Survey Water-Supply Paper 1545–C, p. C69–C85.

Jacob, C.E., 1950, Flow of ground water, *in* Rouse, Hunter, ed., Engineering hydraulics: New York, N.Y., John Wiley & Sons, p. 321–386.

Javandal, I., and Tsang, C., 1986, Capture-zone type curves: A tool for aquifer cleanup: Ground Water, v. 24, no. 5, p. 616–625.

Kirkham, D., and Sotres, M.O., 1978, Case depths and solute travel times to wells: Water Resources Research, v. 14, no. 2, p. 237–243.

Mantoglou, A., and Wilson, J.L., 1982, The turning bands method for the simulation of random fields using line generation by a spectral method: Water Resources Research, v. 18, no. 5, p. 1379–1394.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 6, chap. A1, 586 p.

Milne-Thomson, L.M., 1955, Theoretical hydrodynamics (3d ed.): New York, N.Y., The Macmillan Co., 632 p.

Morrissey, D.J., 1989, Estimation of the recharge area contributing water to a pumped well in a glacial-drift, river-valley aquifer: U.S. Geological Survey Water-Supply Paper 2338, 41 p.

Mundorff, M.J., Bennett, G.D., and Ahmad, M., 1972, Electric analog studies of flow to wells in the Punjab aquifer of West Pakistan: U.S. Geological Survey Water-Supply Paper 1608–N, 28 p.

Ogata, Akio, 1963, Effects of the injection scheme on the spread of tracers in ground-water reservoirs, *in* Short papers in geology and hydrology: U.S. Geological Survey Professional Paper 475–B, p. B199–B202.

Phillips, K.J., and Gelhar, L.W., 1978, Contaminant transport to deep wells: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 104, no. HY6, p. 807–819.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89–381, 188 p.

———1990, A graphical kernel system (GKS) version of computer program MODPATH-PLOT for displaying pathlines generated from the U.S. Geological Survey three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 89–622, 49 p.

Reilly, T.E., 1978, Convective contaminant transport to pumping well: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 104, no. HY12, p. 1565–1575.

Slichter, C.S., 1899, Theoretical investigation of the motion of ground waters, *in* U.S Geological Survey's 19th Annual Report, 1897–1898, Part II: p. 297–384.

Solley, W.B., Merk, C.F., and Pierce, R.R., 1988, Estimated use of water in the United States in 1985: U.S. Geological Survey Circular 1004, 82 p.

Streeter, V.L., 1948, Fluid dynamics: New York, N.Y., McGraw-Hill Book Co., 263 p.

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: Office of Ground-Water Protection, U.S. Environmental Protection Agency, June 22, 1987, 131 p.

Zimmerman, D.A., and Wilson, J.L., 1989, Description of and user's manual for TUBA, A computer code for generating two-dimensional random fields via the Turning Bands Method: Socorro, N.M., Hydrology Program, New Mexico Institute of Mining and Technology, 76 p.