Effect of Seasonal and Long-Term Changes in Stress on Sources of Water to Wells

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By THOMAS E. REILLY and DAVID W. POLLOCK

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2445

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CONTENTS

FIGURES

TABLE

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
gallon (gal)	3.785	liters
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Effect of Seasonal and Long-Term Changes in Stress on Sources of Water to Wells

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 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. Water entering the system at the water table flows to the well and is eventually discharged from the well. Many State agencies are currently (1994) 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. In the analyses of ground-water flow systems, steady-state average conditions are frequently used to simplify the problem and make a solution tractable. Recharge is usually cyclic in nature, however, having seasonal cycles and longer term climatic cycles. A hypothetical system is quantitatively analyzed to show that, in many cases, these cyclic changes in the recharge rates apparently do not significantly affect the location and size of the areas contributing recharge to wells. The ratio of the mean travel time to the length of the cyclic stress period appears to indicate whether the transient effects of the cyclic stress must be explicitly represented in the analysis of contributing areas to wells. For the cases examined, if the ratio of the mean travel time to the period of the cyclic stress was much greater than one, then the transient area contributing recharge to wells was similar to the area calculated using an average steady-state condition. Noncyclic long-term transient changes in water use, however, and cyclic stresses on systems with ratios less than 1 can and do affect the location and size of the areas contributing recharge to wells.

INTRODUCTION

The determination of sources of water to wells has been the subject of investigation since the late 19th century (Slichter, 1899). With the enactment of the U.S. Environmental Protection Agency's (USEPA) Wellhead Protection Program in the 1986 Amendments to the Safe Drinking Water Act, understanding and quantifying the source of water to wells has become a major task undertaken by State governments. This task of "wellhead protection" is aimed at limiting the potential for contaminants from land surface to move with the water and discharge at the supply well. Whereas the concept of this approach of "wellhead protection" is straightforward and consistent with the ideals of protecting our water supply, in many cases, technical and conceptual difficulties or uncertainties impede the definition of these areas.

In a previous report (Reilly and Pollock, 1993), the spatial factors affecting areas contributing recharge to wells in shallow aquifers were enumerated and quantitatively evaluated. This report examines the effect of temporal variability on our ability to determine quantitative areas that are the sources of water to wells. Temporal variability can be cyclical or a long-term trend. Cyclic stresses, such as those caused by diurnal pumping, seasonal precipitation patterns, and multiyear weather cycles, have different time scales. It is useful to examine the different time scales and evaluate their relative importance in the determination of specific recharge areas.

Goode and Konikow (1990) evaluated the effect of transient ground-water flow on the determination of effective dispersion coefficients. Their work showed that the transient effects could indeed be significant in causing contaminant spreading that mimicked increased transverse dispersion. These transient effects also introduce uncertainty in attempts to determine locations that are the source of water to wells. The purpose of this report is to examine the explicit effect of transient conditions on recharge areas to wells.

This report describes and illustrates the effect of temporal changes in stress on 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.

DEFINITION OF AREA CONTRIBUTING RECHARGE

The withdrawal of water from a well in a ground-water system creates drawdown throughout the aquifer. The only limits to the areal and vertical extent of drawdown are 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 flow paths of water that discharges 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.

In the hydrologic literature, the term "source of water to wells" has been used in two distinct and quite different contexts: a water-budget context and a transport context. Theis (1940) discussed the source of water to wells in a water-budget context. The water-budget context addresses the water-budget components affected by water withdrawn from the ground-water system (for example, water withdrawn from a well caused a net decrease in discharge from the ground-water system to a stream). The water-budget context does not address the paths of the water that discharge to the well but, rather, addresses the effect on the systemwide water budget. This report uses the term in a transport context. The source of water in a transport context represents the location where the water entered the ground-water system and flowed to the well. The transport context focuses on the paths of water to the actual point of discharge but does not address the effect on the systemwide water budget.

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. Thus, the area contributing recharge to a well is the source of water to the well in a transport context. The definition and meaning of this source area is different for steady-state and transient-state systems.

Steady-State Systems

For steady-state conditions, the size of the area contributing recharge to a well is constant, and the quantity of water entering the area equals the quantity discharged at the well. For a ground-water system that is subject to areally uniform recharge, the area contributing recharge to a well (if no additional sources of water are present) must provide an amount of recharge that balances the amount of water being discharged from the well (Reilly and Pollock, 1993). This area and the flow paths to a well in a simple hypothetical ground-water system are shown in figure 1. For this simple case,

$$Q = WA, \qquad (1)$$

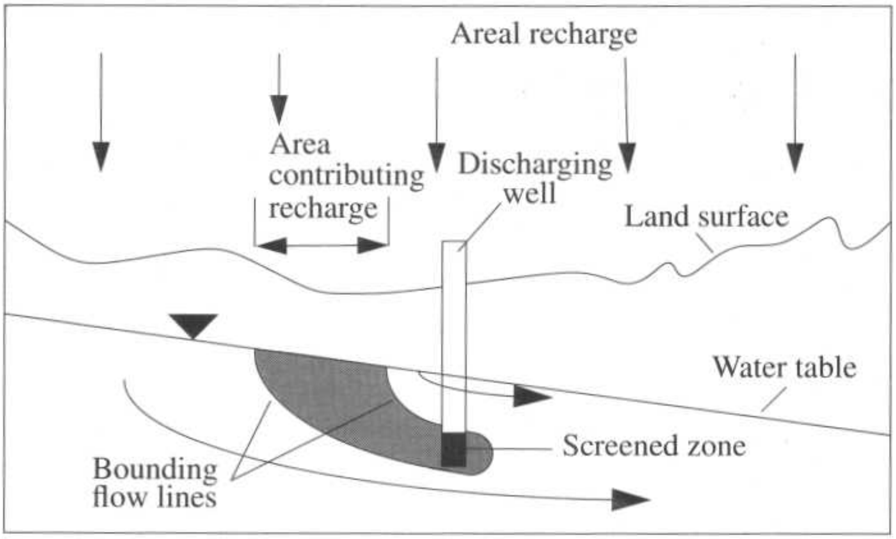
where

Q = discharge rate of well (L^3/T),

W = areal recharge rate (L/T), and

A = area contributing recharge (L^2).

The location of this area depends on many factors that describe the ground-water system and the well. The shape and location of areas contributing recharge to wells can be complex because of the three-dimensional nature of the ground-water system. In particular, the area contributing recharge to a well, screened below the water table, does not necessarily



A

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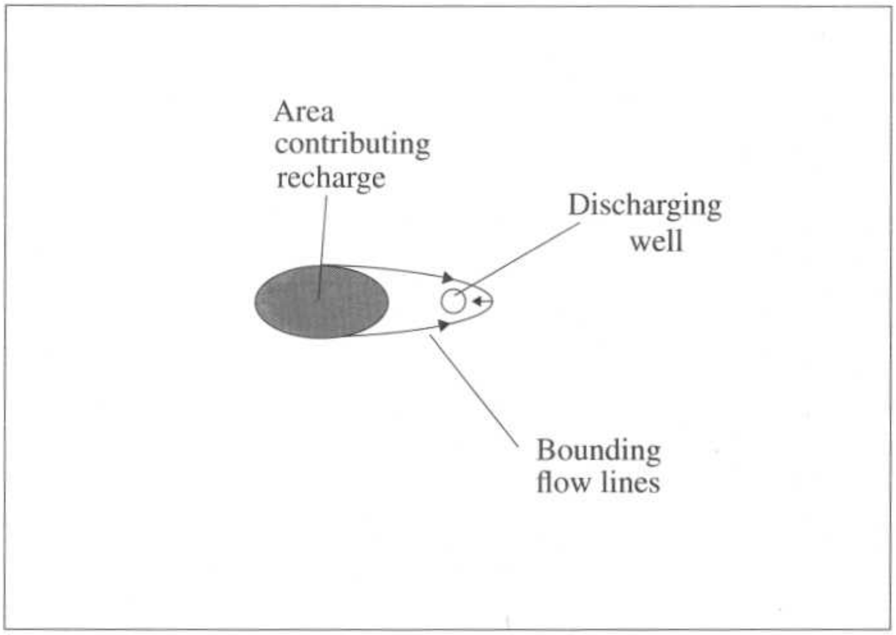


B

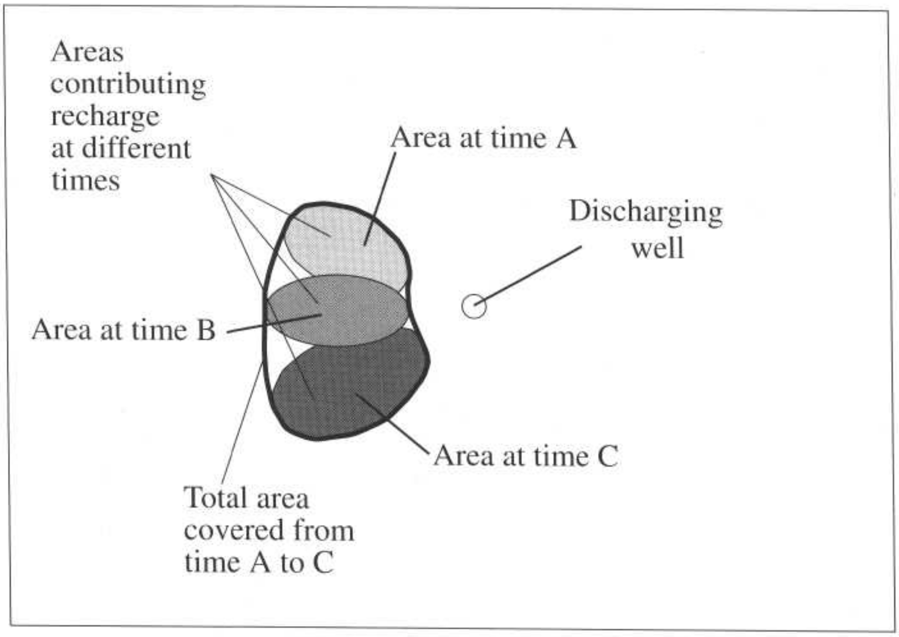
Not to scale

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

include the area immediately surrounding the well (fig. 1).

Transient-State Systems

For the case of temporally varying stresses (that is, either the well discharge rate changes or the rate or distribution of recharge entering the system changes), the area contributing recharge can change size and location through time. For example, if the recharge rate and direction of flow in the system shown in figure 1 changed from time A to time B, then the area contributing recharge might move as shown in figure 2. As the system changes through time, the area where the water that discharges to the well entered the system moves in a continuous manner. Every point within the total recharge area shown in figure 2 contributes at least some water to the well during the period from time A to time C. Some parts of the total recharge area may contribute water to the well throughout most of the time period, whereas other parts may contribute recharge to the well for only a small fraction of the



Not to scale

Figure 2. Composite area contributing recharge to a single discharging well in a simplified hypothetical ground-water system due to changing conditions over time.

period. In contrast to the steady-state condition, the size of the total recharge area in a transient system is not related in any simple way to recharge and discharge rates.

The time-varying conditions, the response time of the ground-water system, and the flow paths affect how this area changes over time and how rapidly these changes take place. Two response times must be considered when evaluating the temporal variability of areas contributing recharge to wells: the hydraulic-response time and the transport-response time.

Ground-water systems contain water in storage and gradually change from one steady state to a new steady state in response to changes in stress or boundary conditions. The time required to evolve between equilibrium steady-state conditions is related to the Fourier number (Domenico and Schwartz, 1990). A time constant can be defined as

$$\tau = \frac{S_s L^2}{K} = \frac{SL^2}{T} \qquad (2)$$

where

τ = time constant for basin (T),
S_S = specific storage (1/T),
K = hydraulic conductivity (L/T),
S = storativity (dimensionless),
L = characteristic length (L), and
T = transmissivity (L^2/T).

Domenico and Schwartz (1990, p. 137) state, "If the time t_e at which we wish to observe some transient is significantly larger than τ, the transient will not be observable, and the basin would appear to be in some steady state." This time constant serves as a reference to determine how quickly a system changes from one steady state to another in response to a change in stress. This time constant gives an estimate of the time required for a system to re-equilibrate in response to changes in hydraulic conditions.

Transport-response time is related to the time of travel through the ground-water system. One such measure of transport-response time is the mean travel time from the area contributing recharge to the point of discharge. In many ground-water systems, especially alluvial valley systems such as those examined here, the hydraulic-response time is much shorter than the transport-response time, and the rate of change in recharge areas to wells and other discharge features is controlled primarily by the transport-response time of the system.

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

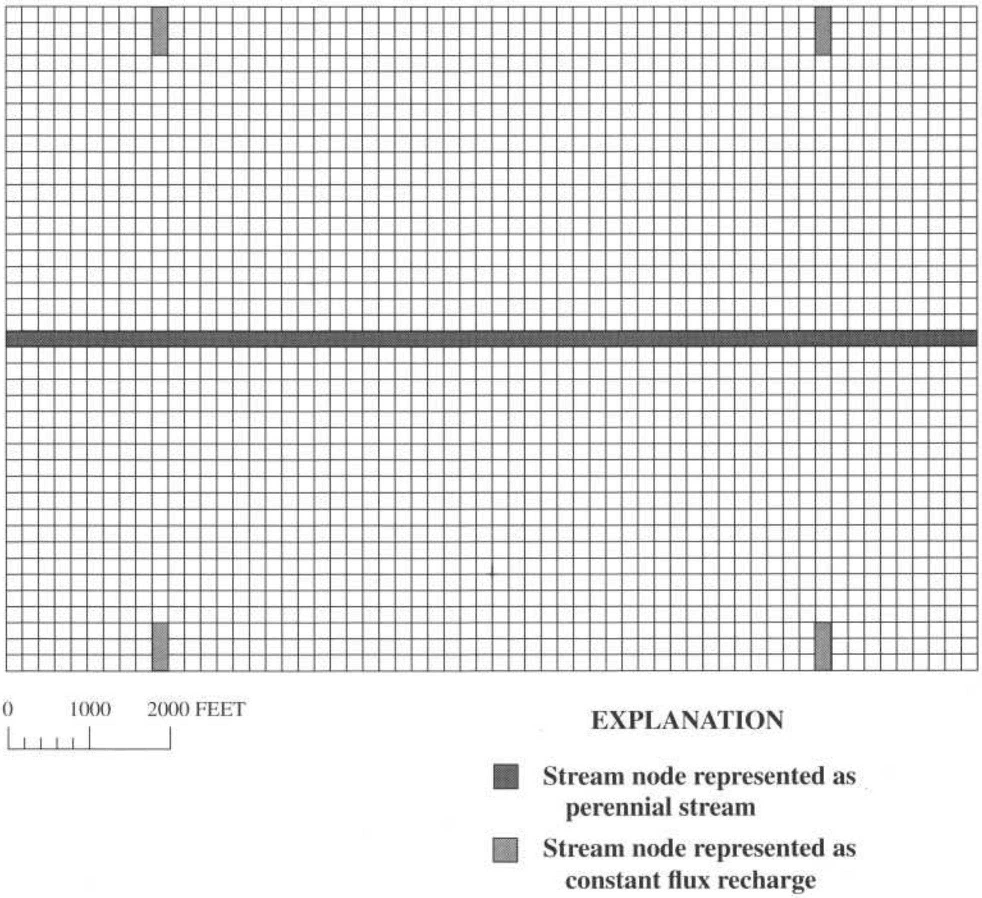


Figure 3. Model grid for simplified alluvial valley showing stream locations.

conducted to determine areas contributing recharge that 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, and Pollock, 1994) is then used to calculate steady-state or transient pathlines in the simulated three-dimensional ground-water system. The computer program MODPATH-PLOT (Pollock, 1990, and Pollock, 1994) is used to plot the computed pathlines. The methodologies used for MODFLOW, MODPATH, and MODPATH-PLOT are described in their separate documentation as referenced.

DEFINITION OF HYPOTHETICAL GROUND-WATER SYSTEM

The setting for the hypothetical ground-water systems used for the calculation of areas contributing recharge is a simplified alluvial valley. Permeable alluvial deposits are underlain and laterally bounded by impermeable bedrock and a straight perennial stream flows through the valley. The valley segment simulated is 12,000 feet (ft) long, and the permeable deposits are about 200 ft thick and extend 8,200 ft across the valley. The steady-state average areal recharge rate is 0.00411 foot per day (ft/d) from infiltration of precipitation directly on the valley, and runoff from the impermeable bedrock valley walls into four drainage channels that extend 600 ft into the valley contributes 0.6 cubic feet per second (ft^3/s). The streams are not deeply incised into the deposits.

The numerical model used to represent this system consists of a three-dimensional array of cells with 41 rows, 60 columns, and 8 layers (fig. 3). Each model layer is 25 ft thick, and each grid cell is 200 ft by 200 ft. The hydraulic conductivity is represented as uniform throughout the valley fill material and has a value of 100 ft/d horizontally and 20 ft/d vertically. The recharge from the valley walls that enters the drainage channels is represented as a constant leakage from the four channels by increasing the recharge to the top layer at those cell locations (fig. 4). The main perennial stream is treated as a nonpenetrating stream with a depth of 2 ft, a streambed conductance of

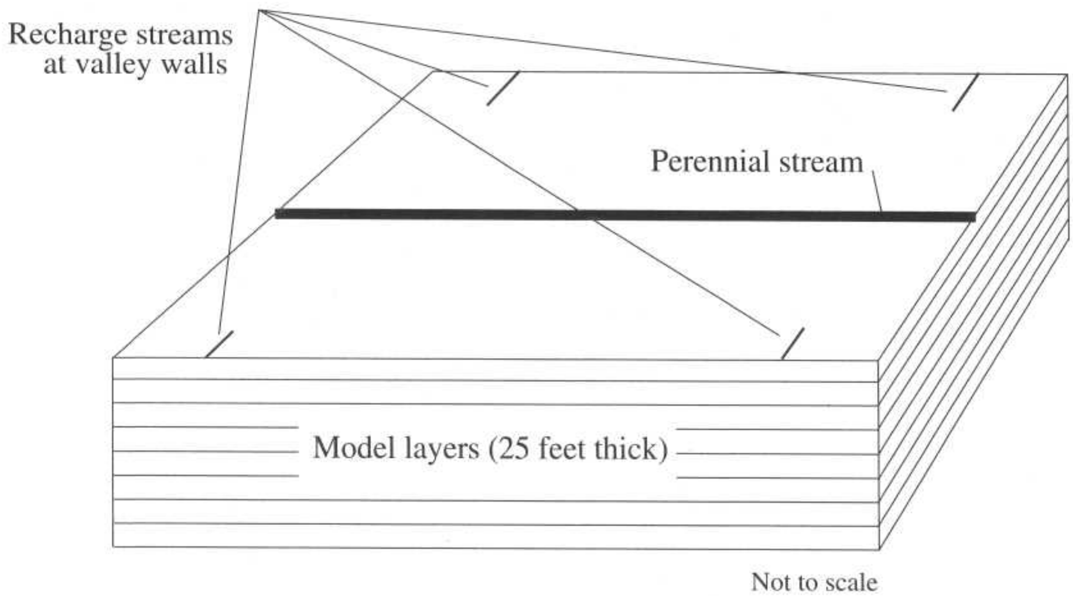


Figure 4. Block diagram showing three-dimensional system with eight layers and streams on top.

15,000 ft^2/d, and a stream stage that varies from 3.54 to 0.00 ft (a slope of 0.0003 ft/ft) above an arbitrary datum from left to right (column 1 to column 60).

Under natural or predevelopment conditions, water recharges the aquifer from areally distributed precipitation and from losing streams at the valley walls that drain the surrounding uplands. All natural discharge is to the perennial stream that runs through the center of the basin. The steady-state water-table surface is symmetric with respect to the perennial stream and varies from a high of over 6 ft to a low of less than 2 ft (fig. 5).

This hypothetical ground-water system will be examined to determine the importance of a suite of transient stresses. The resultant sources of water under the transient conditions are then compared to equivalent "average" steady-state systems to determine their differences. The magnitude of any differences is indicative of the importance of the type of cyclic stress in the determination of sources of water to wells.

AREA CONTRIBUTING RECHARGE TO A WELL UNDER STEADY-STATE AVERAGE CONDITIONS

The locations of areas contributing recharge to discharging wells are dependent on factors determined by the three-dimensional ground-water system and characteristics of the well (Reilly and Pollock, 1993). The ground-water system 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, and (4) stresses and changes in stresses (water withdrawals and changing boundary conditions). The well characteristics 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 and also determines the extent to which flow paths in the ground-water-flow system are altered to supply water to the well.

As control cases, the areas contributing recharge to wells under steady-state conditions are determined for three wells, all screened in layer 7 (150 to 175 ft below datum) and in different areal locations (fig. 6). Wells 1 and 2 discharge at a rate of 0.1 ft^3/s, and well 3 discharges at 0.5 ft^3/s. The areas contributing recharge for each well (when each is the only discharging well in the system) and also when all three wells are discharging simultaneously are depicted in figure 6. As previously discussed, the location and shape of each area contributing recharge differs, as shown in figure 6, because the wells are in different locations with respect to the boundary conditions and sources of water.

The calculated areas shown in figure 6 illustrate some interesting characteristics of the areas contributing recharge to wells in three-dimensional systems. The area for well 1 (fig. 6*A*) extends from about 500 ft upgradient of the well all the way up to the small

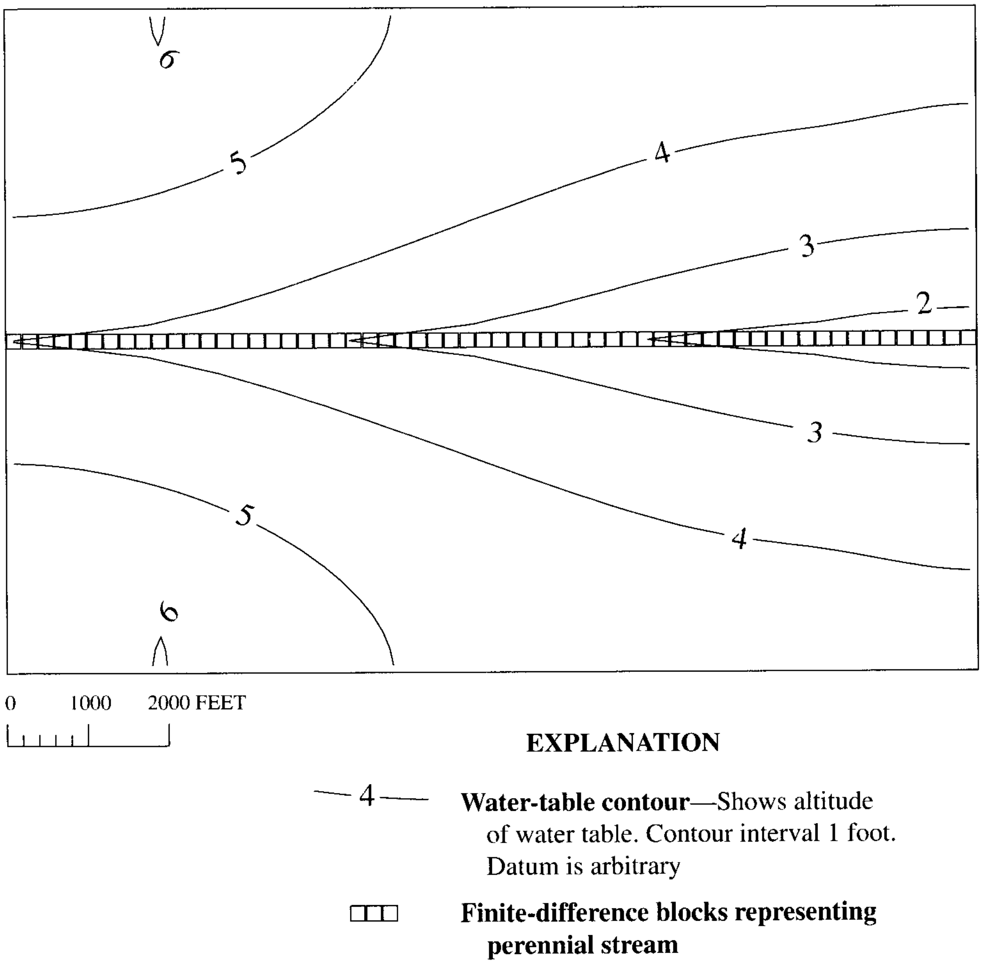


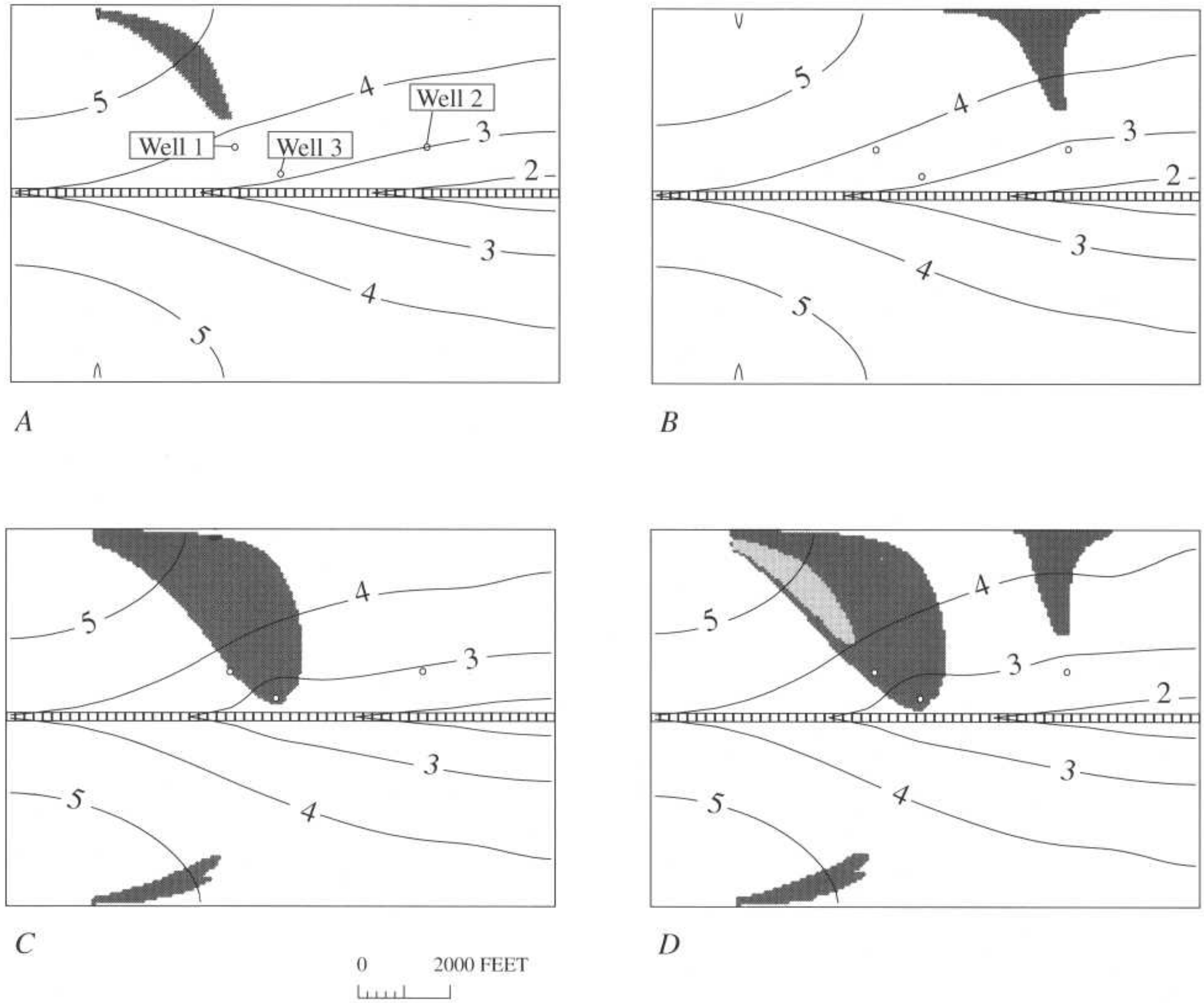
Figure 5. Configuration of the water table for the simulated alluvial valley under steady-state conditions with no ground-water withdrawals.

recharging stream at the valley wall. The area does not include the well location. The area contributing recharge to well 2 (fig. 6*B*) is shaped differently than the area for well 1 because the boundaries affecting the head distribution are in a different location relative to well 2. The area contributing recharge to well 3 (fig. 6*C*) is divided into two distinct areas, each on a different side of the perennial stream. Because of the location and discharge rate of well 3, water originating far from the perennial stream on the side opposite the well flows under the stream and discharges at well 3, resulting in separate areas on both sides of the stream that contribute recharge to the well. When all three wells discharge simultaneously (fig. 6*D*), source areas for the three wells are intertwined and contributing areas must be analyzed in the context of all the stresses on the system (Reilly and Pollock, 1993).

AREA CONTRIBUTING RECHARGE TO A WELL UNDER CONDITIONS OF ANNUALLY VARYING RECHARGE

True steady-state conditions never exist in natural systems; some variability in stresses or boundary conditions in time always results in transient flow. One such variable stress is a seasonal climatic cycle that causes recharge rates and patterns to change over an annual cycle. A question arises: does an annual recharge cycle affect the sources of water to wells significantly enough to make any simplified steady-state analyses of areas contributing recharge to wells invalid?

To investigate the effect of annually changing conditions, the sources of water to wells under transient cyclic conditions will be quantitatively calculated for the hypothetical system previously described.



EXPLANATION

Area contributing recharge to well

Area contributing recharge to well 1, imbedded in area contributing recharge to well 3

—4— **Water-table contour**—Shows altitude of water table. Contour interval 1 foot. Datum is arbitrary

Perennial stream location

Well location

Figure 6. Simulated configuration of the water table and areas contributing recharge to a well for the following: *A.* Well 1 screened from 150 to 175 feet below datum and discharging at 0.1 cubic foot per second, *B.* Well 2 screened from 150 to 175 feet below datum and discharging at 0.1 cubic foot per second, *C.* Well 3 screened from 150 to 175 feet below datum and discharging at 0.5 cubic foot per second, and *D.* Wells 1, 2, and 3 discharging simultaneously at 0.1, 0.1, and 0.5 cubic foot per second, respectively.

Although this evaluation is not exhaustive, it should provide some insight into potential processes that could be important.

A simplified, seasonally changing system is represented by reducing recharge to 0.00211 ft/d during a 6-month dry season and increasing it to 0.00611 ft/d

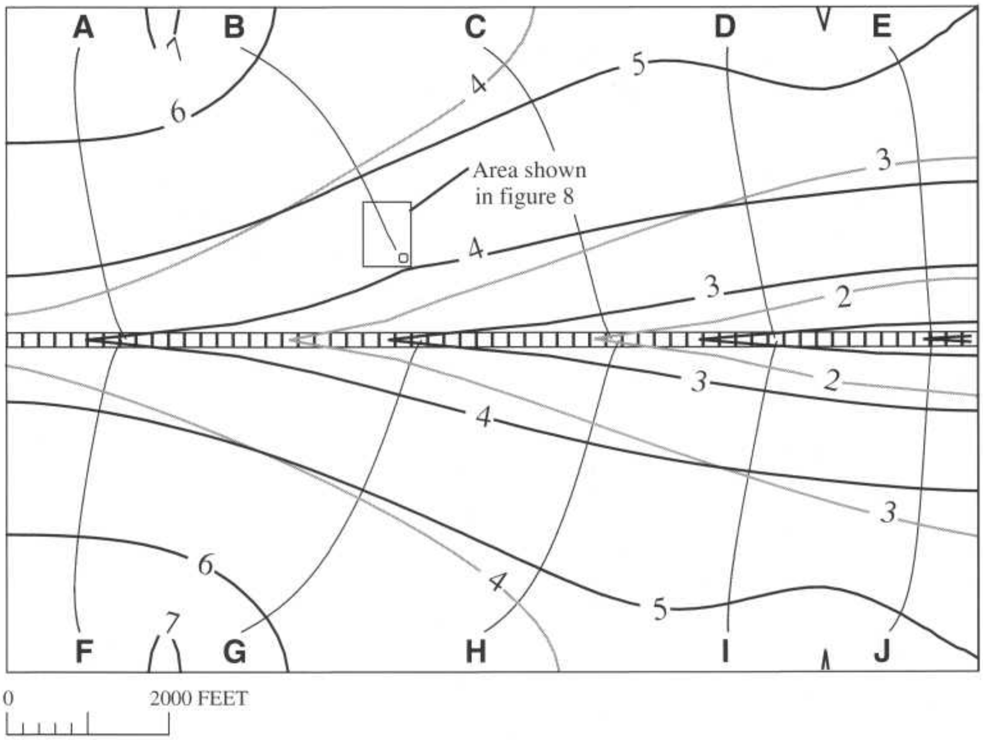


Figure 7. Transient pathlines from 10 different locations resulting from a seasonal fluctuation of areal recharge.

EXPLANATION

— 4— **Seasonal high water-table contour**—Shows altitude of water table. Contour interval 1 foot. Datum is arbitrary

— 4— **Seasonal low water-table contour**—Shows altitude of water table. Contour interval 1 foot. Datum is arbitrary

A **Transient pathline**

Perennial stream

○ **Well location**

during a 6-month wet season. The average annual recharge for this transient system is 0.00411 ft/d, which is identical to the rate used in the previous steady-state analysis. The streams along the valley walls will fluctuate between being dry during the dry season and recharging 1.2 ft^3/s during the wet season (the annual average is 0.6 ft^3/s as in the steady-state analysis). A specific yield of 0.25 and a specific storage of 1.0×10^{-6} 1/ft are used for the storativity of the aquifer materials. The hydrologic response time is 200 days, calculated using the distance from the stream to the valley walls as the characteristic length. The simulation used half-year stress periods (with one time step in each stress period) for a 100-year simulation. Although the half-year stress periods may neglect some of the fine-scale detail of the transient changes during each dry and wet season, the major effect of the seasonal changes was represented. The more important time discretization design consideration was the transport-response time. The 100-year period was simulated with an additional 100-year steady-state time step concluding the simulation to ensure that all particles had time to be affected by the cyclic variation along their flow paths and discharge from the system.

The seasonally varying recharge had very little effect on the flow paths to well 1. The water-table level changed significantly in magnitude over the year, but changes in the flow directions appeared to be minor (fig. 7). The area contributing recharge to well 1 was almost identical to that for steady-state average conditions (fig. 6*A*) but was minimally larger due to the seasonal changes. The flow paths (as shown on fig. 7) were the same as under steady-state average conditions at the scale shown. When examined in detail, the flow paths do show some minor differences between the transient cyclic path and steady-state average path due to the seasonal fluctuations (fig. 8).

The half-year recharge cycle is short compared to the multiyear travel times involved in flow to a well from the recharge area. The time of travel to the well from the recharge area under steady-state recharge ranged from 10.0 to 87.8 years for well 1. Apparently,

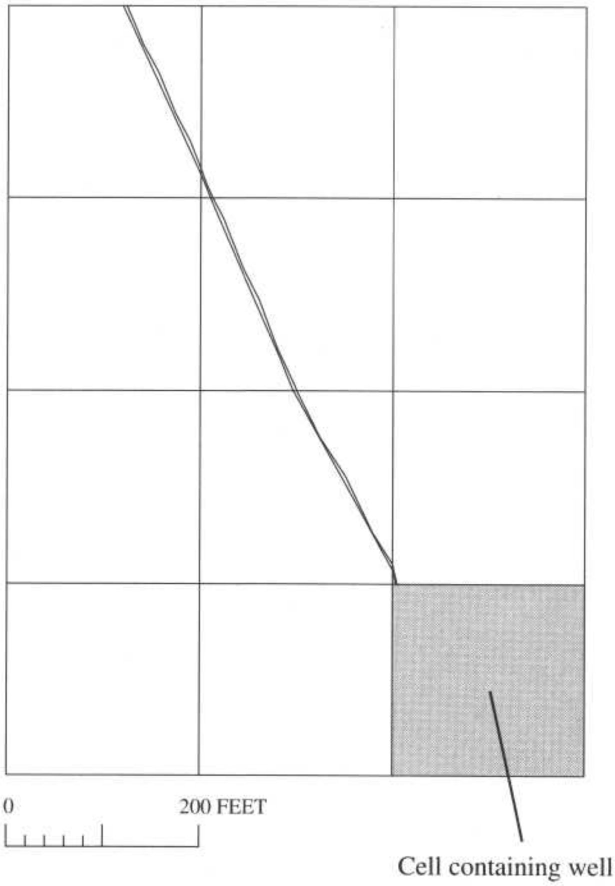


Figure 8. Comparison of steady-state and seasonally transient pathlines near the discharging well.

the half-year cyclic recharge variation is present at a frequency that gets smoothed out over the time scale of the flow to the well. As such, the seasonal changes do not appear to affect the location or size of the recharge area in many cases. The simulation described represents only one of an infinite number of possible system configurations. This anecdotal evidence seems to indicate, however, that steady-state analyses to determine the areas contributing recharge to discharging wells may be sufficient to characterize systems where variations in recharge are primarily seasonal.

EFFECTS OF LONG-TERM 18.6-YEAR LUNI-SOLAR CYCLICAL STRESS

Just as diurnal fluctuations in temperature and evapotranspiration, and seasonal fluctuations in recharge are evident, probably a longer term periodic element to climate variability (Mitchell, 1976) is also present. It has been suggested (Currie and O'Brien, 1992) that one such deterministic periodic element is the 18.6-year luni-solar cycle (known as the M_n cycle). In this section, the potential effect of a longer term cyclic stress, such as the luni-solar cycle, is examined.

The same hypothetical system that was previously tested is subjected to a 18.6-year periodic stress. The area contributing recharge to a well and the pathlines from that area to the well are compared with the results from the steady-state analysis of average conditions. The area contributing recharge to a well under transient conditions can be represented as either a time-varying area or as a combined total area that encompasses all water that flows to the well at any time. This combined total area is shown in this report and is greater than or equal to the steady-state area because water from different areas can be "captured" by the well as the system undergoes the cyclic variation and the system adjusts to changing recharge conditions (as shown in fig. 2). The temporal areal-recharge distribution for the luni-solar simulations has a 18.6-year period and varies from 0.00206 ft/d to 0.00617 ft/d (fig. 9). Thus, the recharge rate changes from 50 percent of the average to 150 percent of the average over 9.3 years. Although purely hypothetical, this scenario is similar to the range observed in the base-flow records of streams on Long Island, New York, in the water years between 1940 and 1967 (Cohen and others, 1969). On Long Island, New York, the combined flows of the principal streams averaged 291 ft^3/s (over the water years 1940–67) and ranged from a high of 401 ft^3/s (138 percent of average) in 1956 to a low of 155 ft^3/s (53 percent of average) in 1966 (Cohen and others, 1969, p. F10). The recharging streams at the valley walls are also represented as periodic, and their combined flows cycle between a maximum of 1.2 ft^3/s and a minimum of 0.0 ft^3/s.

Well 1

The hypothetical ground-water system responds to this cyclic stress—heads and discharge to the perennial stream change on a cyclic basis. For the case of well 1 discharging at 0.1 ft^3/s, the cyclic change in head in the block containing the well ranges from 4.66 to 2.76 ft (fig. 10). The total area contributing recharge to well 1 over time is shown in figure 11. Also shown on figure 11 is the average steady-state area contributing recharge to well 1 as shown in figure 6*A*. The transient area is larger because some of the water that enters the system outside the steady-state area is sufficiently affected by the lower recharge head

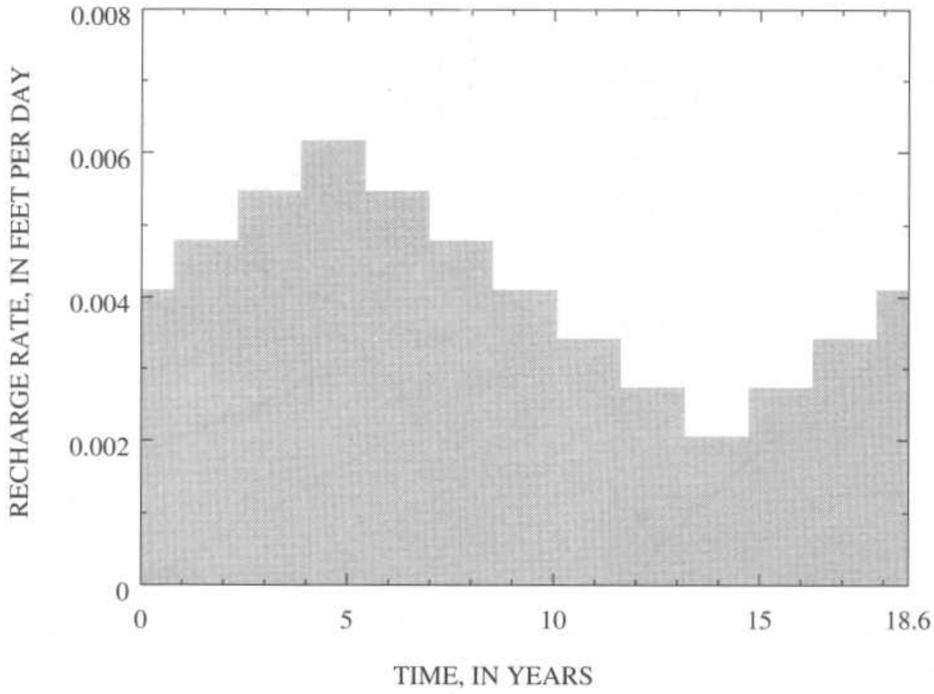


Figure 9. Recharge cycle used in the luni-solar simulation.

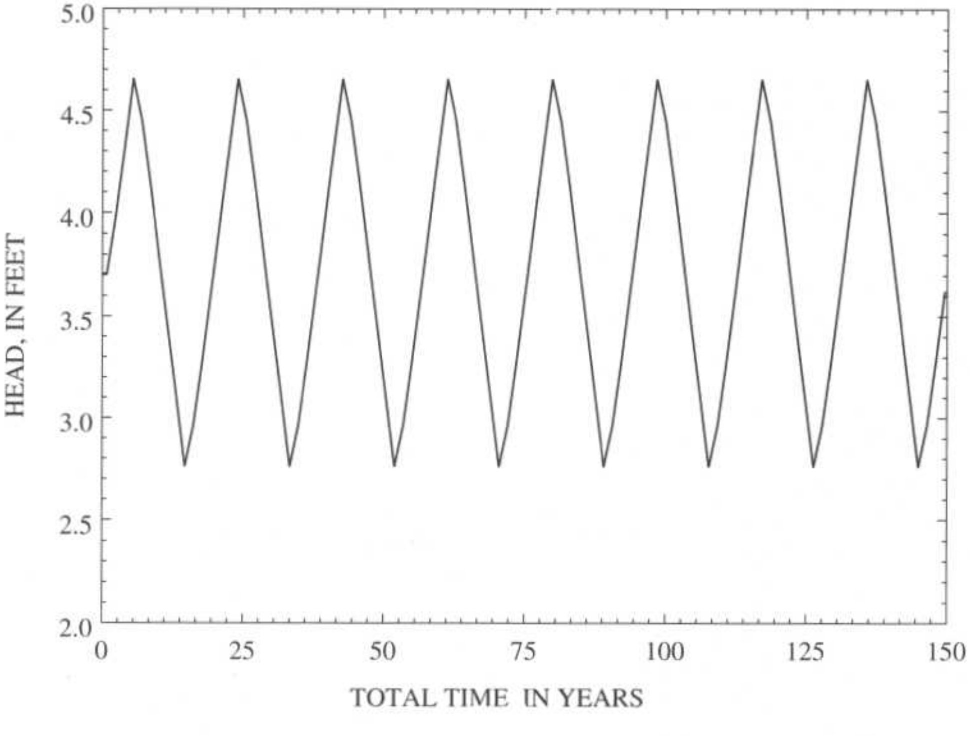
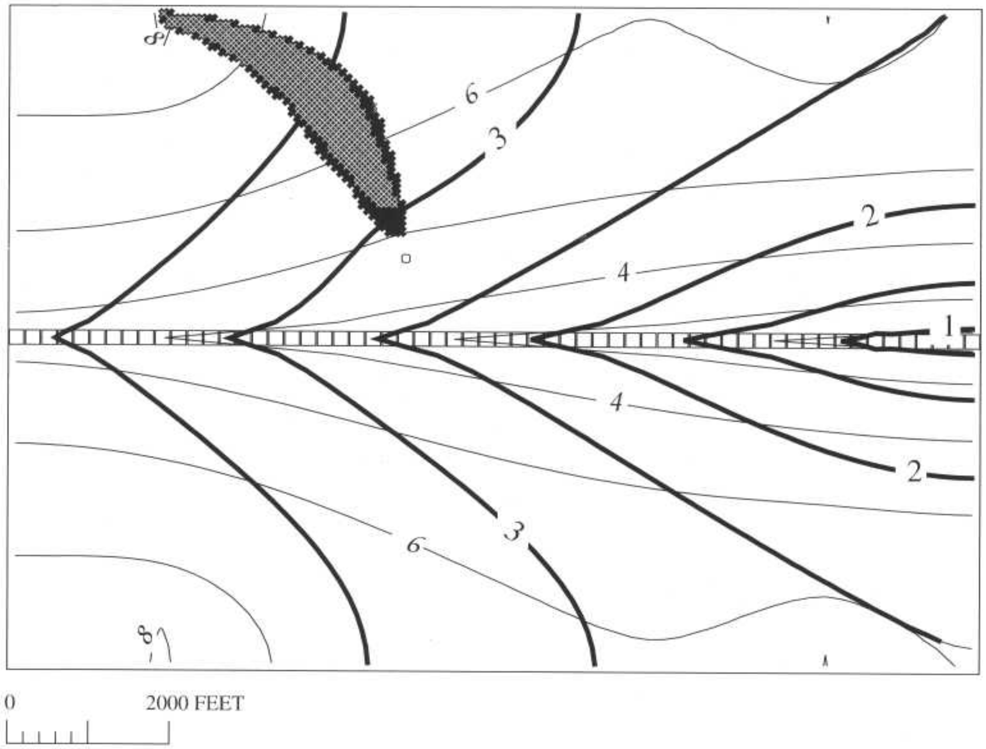


Figure 10. Hydrograph of head at well 1 under luni-solar cyclic recharge distribution.



EXPLANATION

- Average steady-state area contributing recharge
- Area contributing recharge under luni-solar cyclic conditions that also encompasses the steady-state area
- — 3 — **Water-table contour**—Shows altitude of water table at its minimum. Contour interval 0.5 foot. Datum is arbitrary
- — 4 — **Water-table contour**—Shows altitude of water table at its maximum. Contour interval 1 foot. Datum is arbitrary
- **Location of perennial stream**
- o **Location of well 1**

Figure 11. Area contributing recharge to well 1 under luni-solar cyclic conditions and the high and low water-table altitude.

distribution so that at some point in time, it discharges to the well.

A surprising result of this simulation is that for the scale of investigation (that is, the scale of flow to a discharging well), not much difference is noted between the contributing area and flow paths as calculated under transient cyclic conditions and the contributing area and flow paths as calculated under average steady-state conditions. A comparison of 10 representative flow paths at the system scale is given in figure 12. The difference in flow path at a particular site and at a particular time may be significant (on the order of 10 to 100 ft between flow lines perpendicular to the direction of flow). The cyclic stress, however, causes the flow to remain close to the average conditions over the spatial and time scales that are important in the determination of areas contributing recharge to wells.

Well 3

Well 3 discharges at a constant 0.5 ft^3/s (the same rate as in the previous steady-state simulation), whereas the ground-water system responds to the 18.6-year luni-solar climatic cycle. The transient area contributing recharge to well 3 (fig. 13) differs more from the steady-state contributing area than it did for

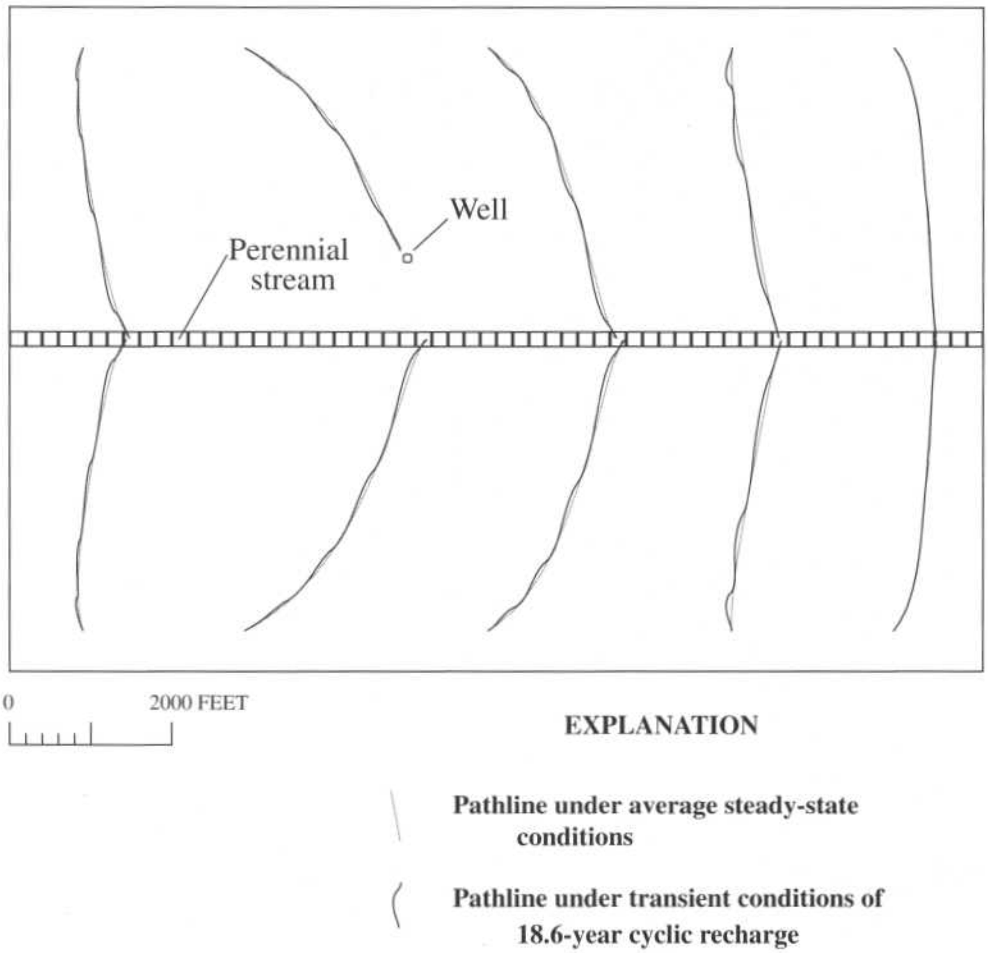


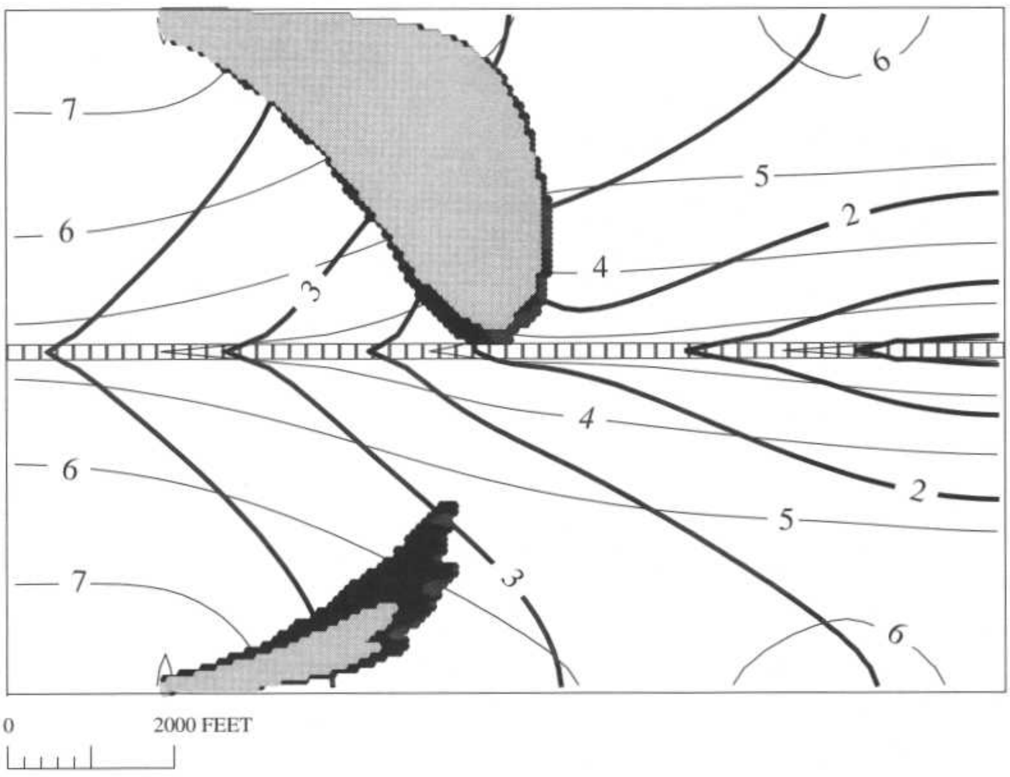
Figure 12. Comparison of pathlines calculated for average steady-state conditions and for transient conditions.

well 1. The larger transient area on the same side of the stream as the well is similar to the steady-state area, whereas the transient area on the opposite side of the stream is considerably larger than the steady-state area. This area on the opposite side of the stream is more sensitive to water-level fluctuations because they affect whether water will flow to the stream or flow under the stream and be captured by well 3.

Over the entire 18.6-year cycle, this larger transient area, on the opposite side of the stream from the well, probably shows considerable changes in shape and location over time. This variability over time is evident when the percentage of particles that originate in a finite-difference cell and flow to well 3 is calculated. The percentage, which is calculated for each finite-difference cell, is the number of particles from a cell that discharge to the well divided by the total number of particles released over time in that cell. This calculation is shown in figure 14; the darker areas contribute more particles to the well over the entire period (a more continuous contribution) and the lighter areas contribute fewer particles (a less frequent contribution). The gray scales in the area at the bottom of the figure indicate that this area does not always contribute flow to the well. The larger area at the top of the figure, however, is mostly dark, indicating that the temporal variation is small.

Three Wells Discharging Simultaneously

For the case of all three wells discharging, the areas contributing recharge to each well are shown in figure 15. These areas are also larger than the areas calculated for average steady-state conditions (fig. 6*D*). This increase in area is due to the fact that as the system undergoes the cyclic recharge, the location of the source of water can change. The area shown in figure 15 represents the total area for any location from



EXPLANATION

(shaded)	**Average steady-state area contributing recharge**	— 3 —	**Water-table contour**—Shows altitude of water table at its minimum. Contour interval 0.5 foot. Datum is arbitrary
(dark)	**Area contributing recharge under luni-solar cyclic conditions that also encompasses the steady-state area**	— 4 —	**Water-table contour**—Shows altitude of water table at its maximum. Contour interval 1 foot. Datum is arbitrary
		(boxes)	**Location of perennial stream**

Figure 13. Area contributing recharge to well 3 under luni-solar cyclic conditions and the high and low water-table altitude.

which water ever makes it to a well. The area contributing recharge to well 1 is completely enclosed by the area contributing to well 3. The boundary between these areas moves over time; the boundary shown in figure 15 represents the location that first discharged to either well 1 or 3. The part of the area contributing recharge to well 3 that is located on the opposite side of the perennial stream changed in size significantly.

The paths actually taken by particles of water under the 18.6-year recharge cycle provide some insight into why the areas contributing recharge have expanded slightly but are still relatively the same as the steady-state areas. Paths tracked from three different locations are shown in figure 16. The paths shown were generated by tracking particles released every 2 years from the same location. The cyclic recharge stress causes a significant change in the water-table surface, which affects the direction and rate of water movement. In this hypothetical system, however, all water eventually discharges to the perennial stream and the wells, so that all particles travel toward a discharging well or the stream. The paths shown in figure 16 diverge at their starting location depending upon the water-table surface at their time of release. Because the recharge stress is cyclic, however, the paths tend to cycle about the average steady-state path, and node points where the paths for all times cross each other are evident. These node points occur at 18.6-year intervals.

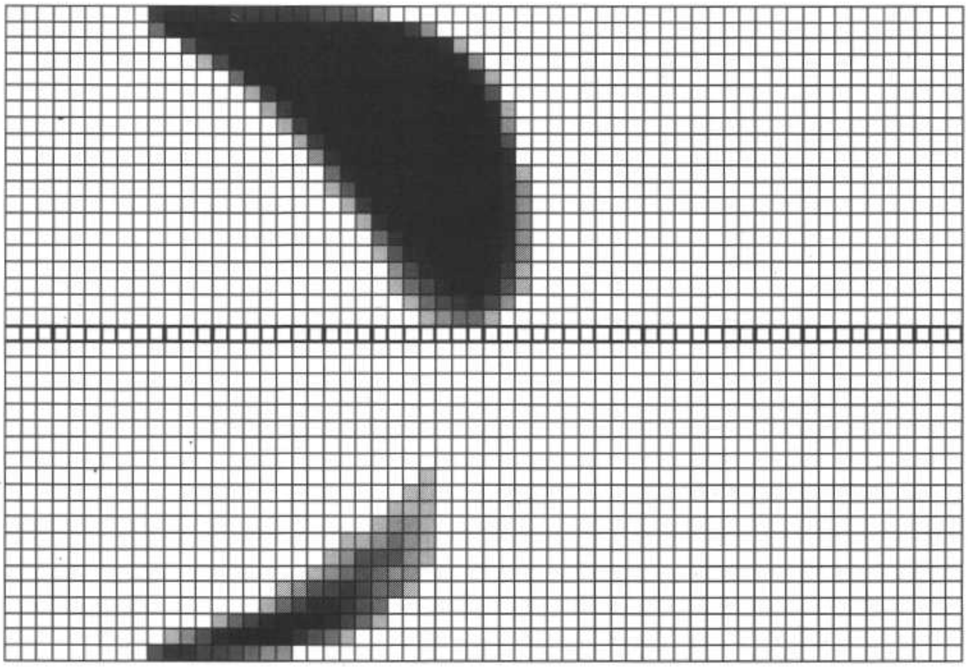


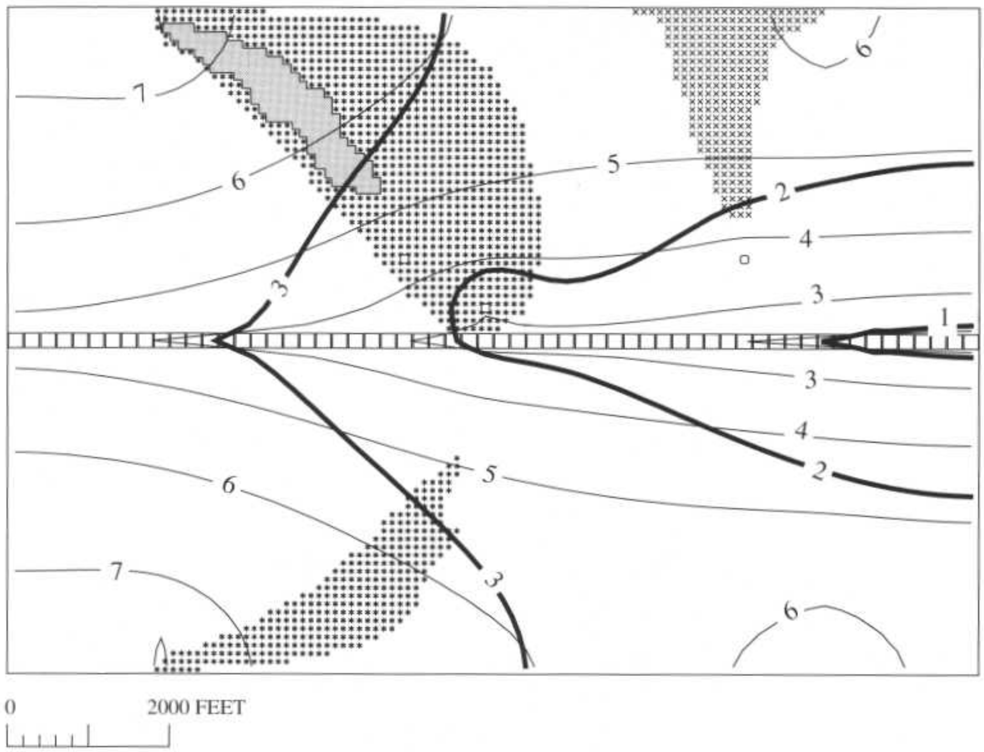
Figure 14. Frequency diagram indicating the percentage of particles that originate in the finite-difference cell and discharge to well 3 over the luni-solar cyclic stress, with the darker shades indicating larger percentages and the lighter grays indicating smaller percentages.

On a "regional" spatial and temporal scale, the significant recharge fluctuations about the average conditions do not greatly affect the areas contributing recharge to wells, although the fluctuations do increase the areas somewhat. When examined at a more local scale, however, the variation in flow path can be significant, as shown in figure 17, by the more detailed path for the particle released in the upper right of figure 16. The flow directions indicated by the water-table configuration change significantly between the high and low periods. The particles can take paths that are separated by 100 or more feet perpendicular to the direction of flow, but they do oscillate about the steady-state average path. This indicates that for local point-source problems, the cyclic climatic variations may have to be considered, but for the regional long-term estimation of areas contributing recharge to wells, the cyclic long-term climate variability may be less important.

The reason that the areas contributing recharge to wells are larger than the steady-state areas under average conditions is clearly shown by the particle in the middle of figure 16. The pathlines for this particle in the immediate vicinity of the stream are shown in figure 18. The starting point for all these pathlines is within the transient area contributing recharge to well 3 but outside the steady-state recharge area for average conditions. The steady-state average pathline for this location discharges at the perennial stream (fig. 18*A*). Each of the other pathlines are for particles that were released every 2 years. Most of the pathlines also discharge to the perennial stream (fig. 18). At some time during the cyclic period, however, the flow to the stream is insufficient to capture the particle, and instead it flows to the well. Thus, most of the time, water originating at the starting location of these paths will discharge to the perennial stream, but occasionally during periods of low flow during the climate cycle, the water will be captured by well 3. Because the water sometimes discharges to well 3, it is included in the transient area contributing recharge to well 3.

CHANGES IN GROUND-WATER USE

The previous analyses examined cyclical climatic changes in recharge. Another type of temporal change in stress that occurs in ground-water systems is a change in water use over time. As populations increase and communities grow, the demand for water increases. Usually pumping rates are increased, and



EXPLANATION

- **Area contributing recharge to well 1**
- **Area contributing recharge to well 2**
- **Area contributing recharge to well 3**
- 3 **Water-table contour**—Shows altitude of water table at its minimum. Contour interval 1 foot. Datum is arbitrary
- 4 **Water-table contour**—Shows altitude of water table at its maximum. Contour interval 1 foot. Datum is arbitrary
- **Location of perennial stream**
- **Location of well**

Figure 15. Areas contributing recharge to all three wells for the condition of all wells discharging simultaneously and a 18.6-year cyclic recharge stress.

new wells are installed to supply increasing demands. As the water distribution system ages, older wells may be abandoned and replaced with newer, larger capacity wells.

An unavoidable consequence of changes in the rate and location of well discharge over time is that the areas contributing the recharge will change over time. To illustrate the potential effect of these types of water-use changes on the source of water to wells, a hypothetical water-development scheme is simulated using the same hydrologic system used in the previous examples with a constant steady average recharge. The same three wells will be stressed by pumping at well 1 starting at time 0 after a predevelopment steady-state period. Well 2 is added to the water-supply system after 30 years, and well 3 is added after 50 years.

Table 1. Discharge rates for three wells over a 100-year period, used in the hypothetical water-use trend simulation.

Well	Discharge (in cubic feet per second) for each 10-year period										
	Predevelopment	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Well 1	0.0	0.1	0.15	0.5	0.3	0.2	0.2	0.1	0.0	0.0	0.0
Well 2	0.0	0.0	0.0	0.0	0.2	0.5	0.2	0.2	0.5	0.5	0.5
Well 3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.5	0.5	0.6
Total discharge	0.0	0.1	0.15	0.5	0.5	0.7	0.7	0.8	1.0	1.0	1.1

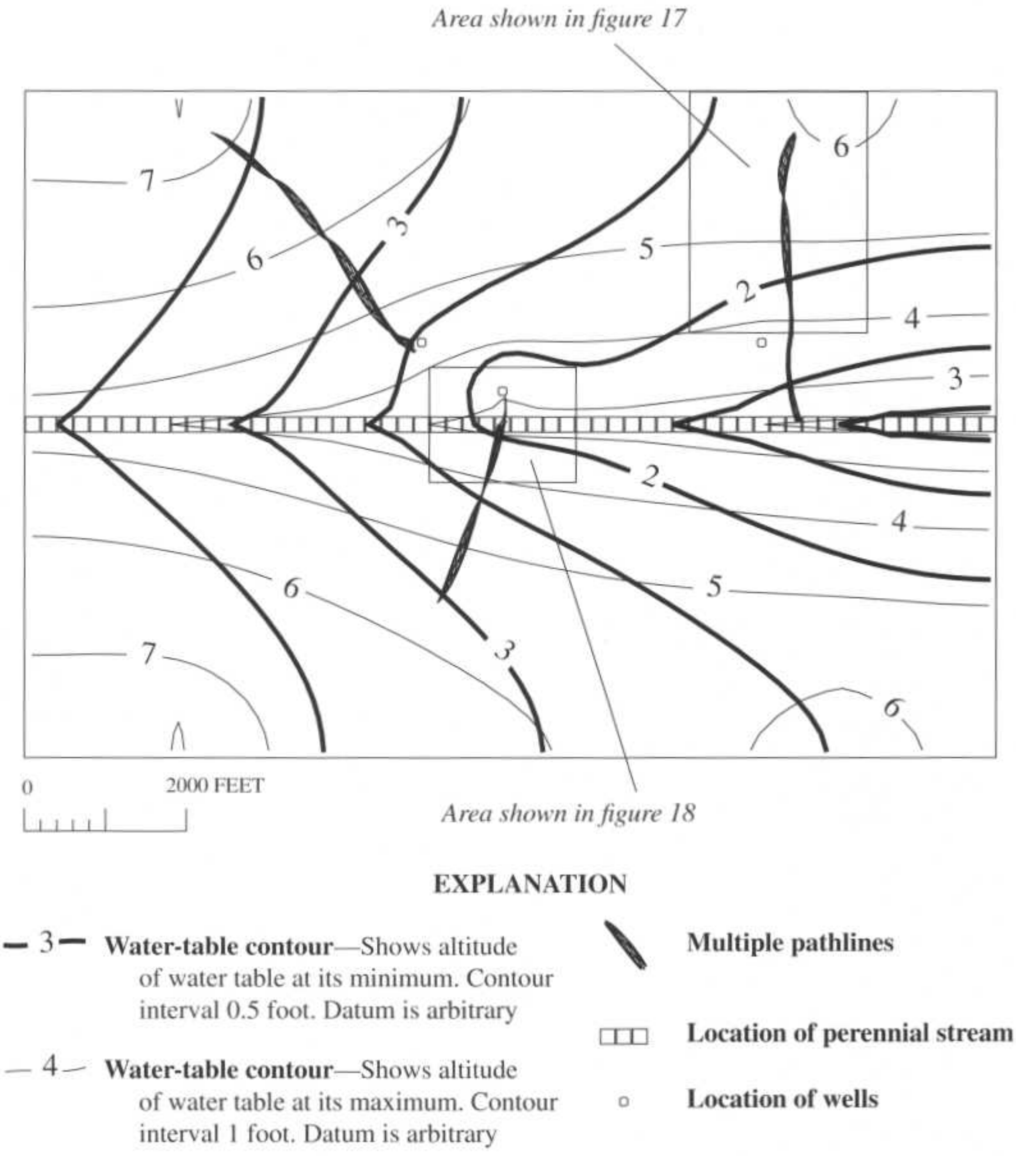
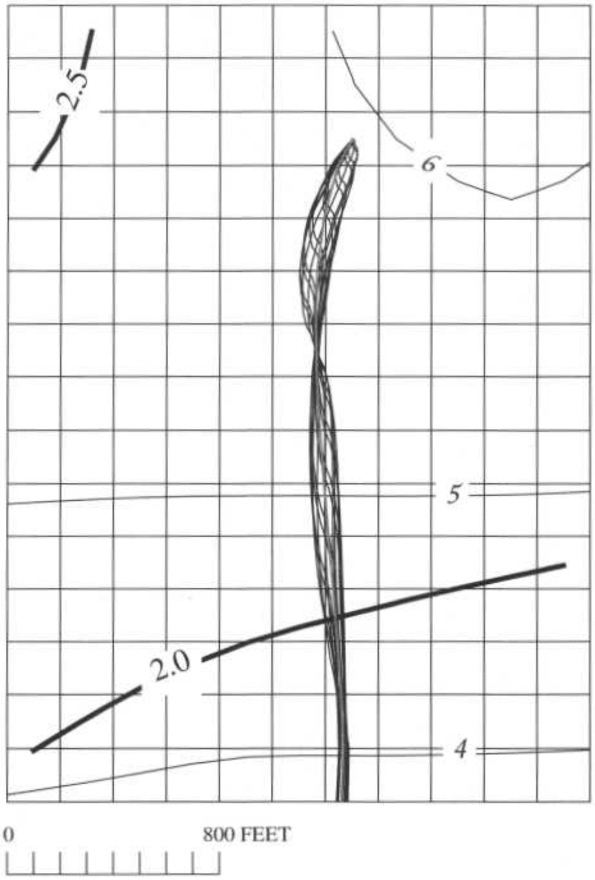


Figure 16. Pathlines from three points for particles released every 2 years under a 18.6-year cyclic stress.

Pumping is discontinued at well 1 after it has been in service for 70 years. The discharge rates for the individual wells change over time as listed in table 1. The total water use of the community increases over a 100-year period of analysis up to a maximum of 1.1 ft^3/s.

The recharge locations of the water particles that entered the wells at 10, 40, 70, and 100 years after



EXPLANATION

— 3 — **Water-table contour**—Shows altitude of water table at its minimum. Contour interval 0.5 foot. Datum is arbitrary

— 4 — **Water-table contour**—Shows altitude of water table at its maximum. Contour interval 1 foot. Datum is arbitrary

Pathline

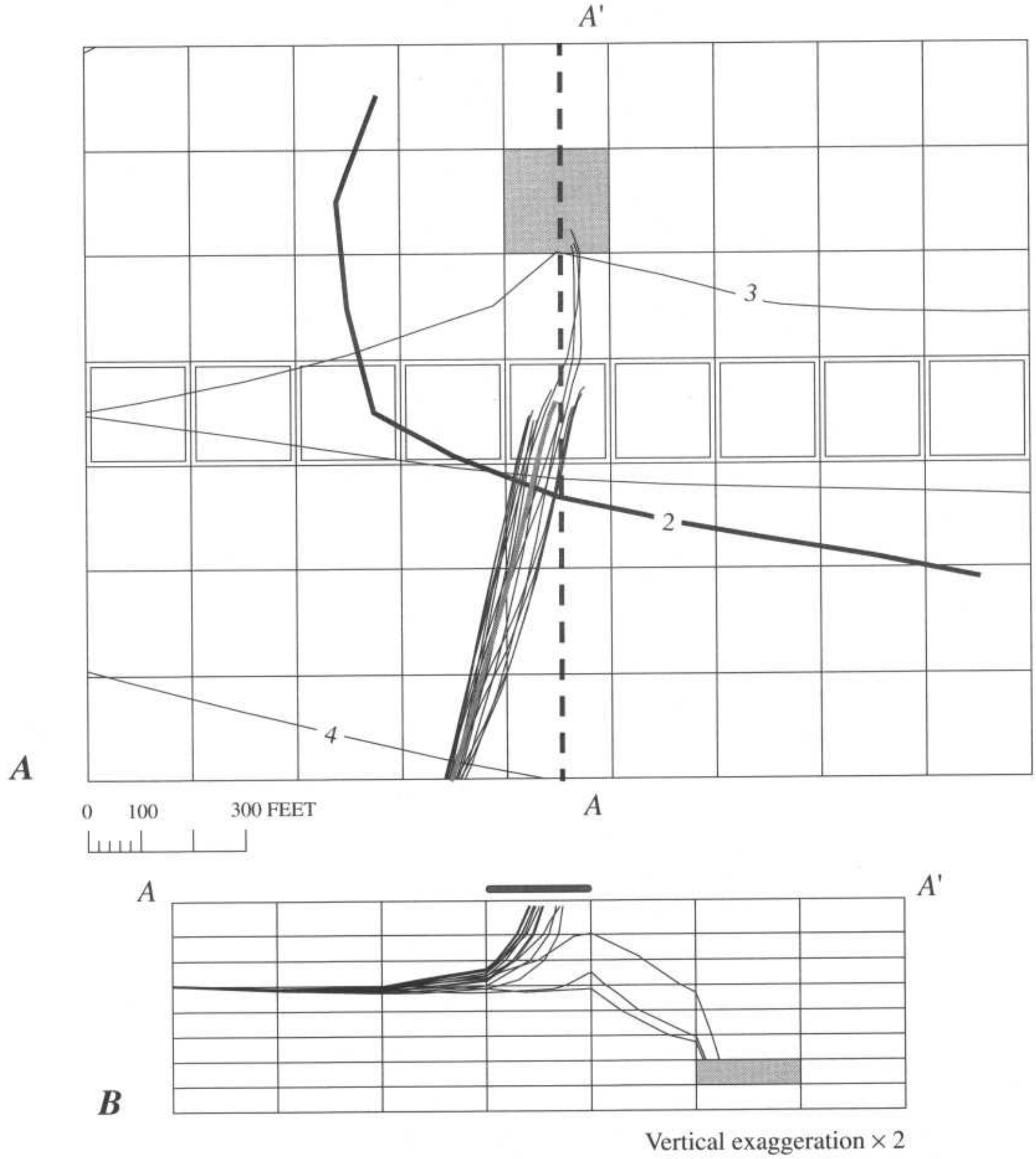
Pathline for steady-state average conditions

Figure 17. Pathlines from particles released every 2 years under a 18.6-year cyclic stress for the case of all wells pumping.

the start of pumping were determined by "back tracking" the transient flow paths from the well to the originating locations. These originating locations are shown for the four time periods in figure 19. The dot patterns in figure 19 indicate some of the processes that affect the areas contributing recharge to wells. The points plotted in figure 19 represent recharge locations of particles that discharge to the wells at the four points in time. The areas delineated in figure 19*A* through *D* can be thought of as maps of recharge areas for instantaneous water samples taken at the well (or grid cell) after 10, 40, 70, and 100 years of pumping, respectively. Although each area represents the spatial extent of recharge for water discharging to the well at a specific point in time, that recharge usually will have occurred over a wide range of time during a period of transient flow. Consequently, these areas have complex relations to one another in space and time. That complexity is enhanced by the long transport-response time in the ground-water system that causes changes in the shape and size of recharge areas to lag behind the transient hydraulic changes in the system.

The areas shown in figure 19 are generated by locating 225 particles on each face of the finite-difference cell containing each of the three wells and "back tracking" the particles until their originating location is determined. Although the individual particles are not proportional to a specific volume or rate of flow, the relative density of particles does aid in interpreting the processes occurring. As the water use increases, the total area contributing to the wells increases as shown in the progression from figure 19*A* to 19*D*. The areas also change in size and shape through time as new wells begin pumping and discharge rates change. In the period between 40 and 70 years, as total water use increases from 0.5 to 0.8 ft^3/s, the area contributing water to the wells expands to include some area on the opposite side of the perennial stream. The density of the particles in the areas relates to three different factors: (1) the same number of particles was placed on all six faces of the finite-difference cells even though the quantity of water entering each face is different, (2) the number of particles was not proportional to well discharge, and (3) the areal recharge is not uniform because additional recharge occurs at the recharging streams at the valley walls.

Particle paths were calculated for all three wells even if the well was not supplying water. The areas identified by the letter "*N*" in figure 19 represent the origin of particles that flow through the cell in which the well is located. Because the well is not discharging, this flow path continues onward and eventually discharges either at the perennial stream or at another well. At the time represented by figure 19*A*, wells 2 and 3 are not discharging, and the water that originates in the areas identified by the letter "*N*" flows past the wells and discharges at the perennial stream. For the



EXPLANATION

— 3 — **Water-table contour**—Shows altitude of water table at its minimum. Contour interval 1 foot. Datum is arbitrary

— 4 — **Water-table contour**—Shows altitude of water table at its maximum. Contour interval 1 foot. Datum is arbitrary

Pathline

Pathline for steady-state average conditions

A- - - -A' **Trace of section**

Location of perennial stream

Finite-difference cell containing well

Figure 18. Pathlines from particles released every 2 years under a 18.6-year cyclic stress: *A*. Map view, and *B*. Cross-sectional view.

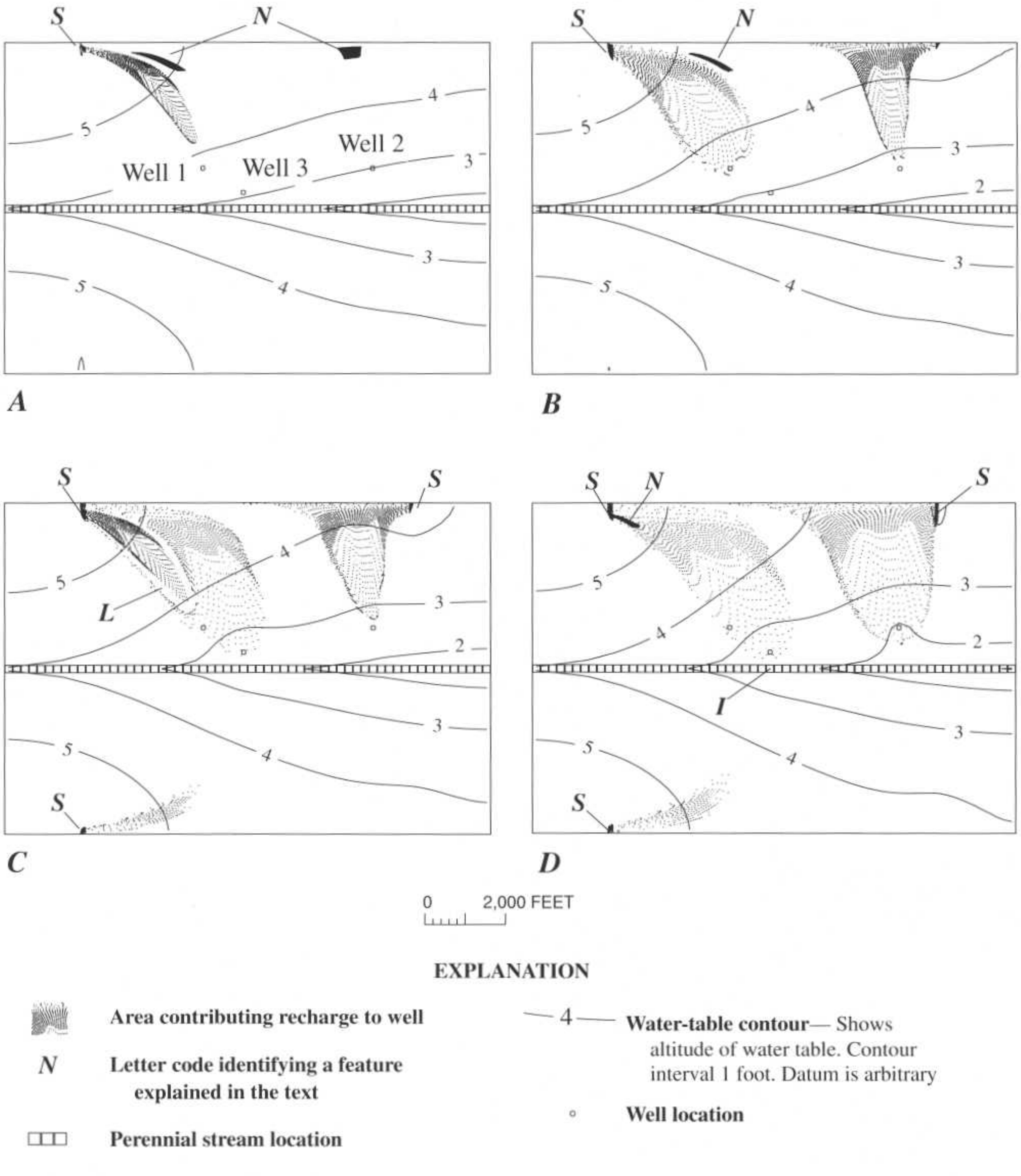


Figure 19. Recharge locations for water entering the three pumping wells at *A*. 10 years, *B*. 40 years, *C*. 70 years, and *D*. 100 years. (See text for explanation of letter codes.)

case in which well 1 is no longer discharging (as shown in fig. 19*D*), the water that originates in the area identified by the letter "*N*" flows past well 1 (through the finite-difference cell that represents well 1) and discharges at well 3.

The additional source of water from the recharging streams at the valley walls is indicated by the clustering or higher density of particles that originate at these streams. These areas from the recharging streams are identified by the letter "*S*" in figure 19.

When wells 1 and 3 are discharging at the same time (fig. 19*C*), the area contributing recharge to well 1 is enclosed by the area contributing recharge to well 3. The areas are separated by an area that is void of particles and is identified by the letter "*L*." This area did not contribute any of the water discharged from well 1 or well 3 at 70 years. The reason for this phenomenon is that the particles placed at the source location by "back tracking" enter the source area at different times, even though they discharge at the wells at the same time (70 years). The discharge of well 1 has been decreasing over time at this stage in the water-supply system (table 1). The water that entered this "void" area, identified by the letter "*L*," actually discharged to well 1 at a previous time. Thus, the particles shown in figure 19 each have a unique spatial and temporal location, but only their spatial location is shown on the figure.

As the total water use increases and the discharge to well 3 also increases, the contributing area gets closer to the stream as identified by the letter "*T*" in figure 19*D*. If discharge continues to increase, eventually water would be derived from the perennial stream, and it would become a losing stream near well 3.

Changing patterns in water use and increases in stresses over time will affect the shape and location of areas contributing recharge to wells. This quantitative examination of one hypothetical water-use scenario illustrates the importance of understanding the entire three-dimensional ground-water system and the relationship between stress and response in delineating recharge areas.

EFFECT OF SYSTEM TRAVEL TIME ON AREAS CONTRIBUTING RECHARGE UNDER CYCLIC CONDITIONS

The transport-response time is a key characteristic of the ground-water system in determining the number of cycles a particle travels through on its path from the point of recharge to the point of discharge. If a particle is affected by many cycles, then the transient path may closely compare with the steady-state average path. Conversely, if a particle is affected by only a partial cycle, it is not possible for its transient path to compare closely with the steady-state average path. The ratio of the mean travel time (from the area contributing recharge to the point of discharge) to the length of the cyclic stress provides a quantitative measure that may indicate the relative importance of the cyclic stress.

To investigate the role of transport-response time on the size of transient contributing areas, a series of simulations that isolate the transport-response-time variable is undertaken. This isolation of the transport-response-time variable is achieved by keeping the system geometry, transmission and storage properties, and boundary conditions constant and systematically changing the porosity. This change in porosity keeps all Darcian flow rates identical, but changes the velocity inversely proportional to the change in porosity. The direction of flow over each time step is determined by the Darcian flow, but the distance traveled over a time step depends on the actual velocity. In steady-state problems, the direction of flow does not change; therefore, the pathlines are independent of the porosity, but the time of travel is inversely proportional to the velocity. In the transient case, however, the particle paths move different lengths over each time step even though the direction is independent of velocity. The particle locations at the end of a time step are different for different porosities. At the start of a new time step, these particles have different locations and, therefore, will have different trajectories. This results in flow paths that differ as a function of the velocity (or porosity). Thus, the steady-state area contributing recharge to a well (for the same system geometry and boundary conditions) is independent of porosity, but the transient area is not.

The effect of the mean-travel-time/cycle-time ratio was determined for well 3 discharging at 0.5 ft^3/s. Simulations were undertaken with the luni-solar cyclic stress for porosities of 30 percent (the value used in all preceding simulations), 10 percent, and 3 percent. Simulations were undertaken with the seasonal cyclic stress for porosities of 30 percent and 3 percent. The porosities are being varied for the sole purpose of investigating transport-response times and do not reflect what are appropriate values for a sand-and-

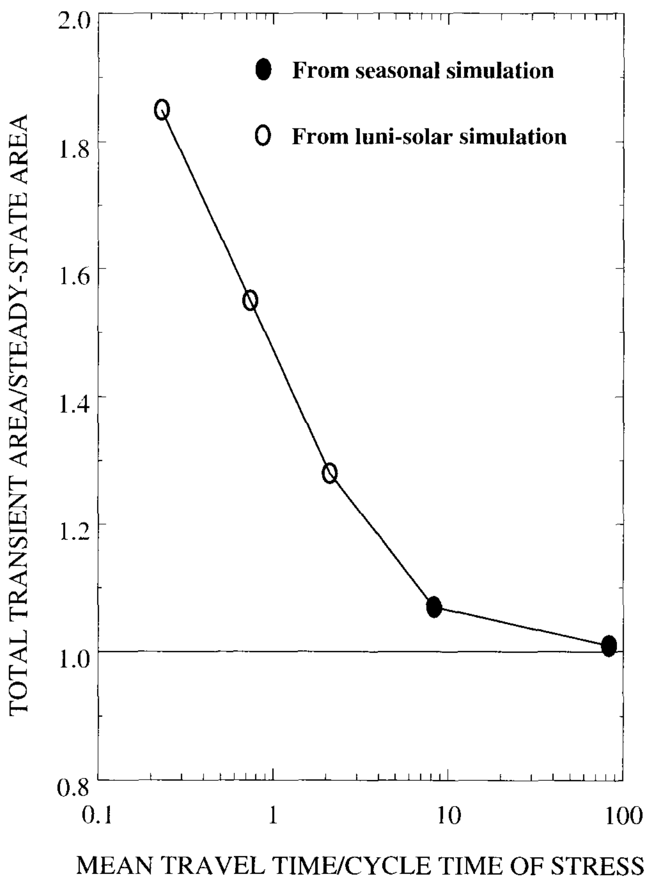


Figure 20. Relation between ratios of total transient contributing area to the steady-state area and mean travel time to the length of the cycle time of the stress.

gravel aquifer. The results of these simulations are shown in figure 20. Changing the porosity changes the frequency of the cyclic stress in relation to the mean travel time. The amplitude for both the luni-solar and seasonal stress simulations is similar. The relation shown in figure 20 indicates that as the ratio of mean travel time to the cycle time of the stress increases, the size of the transient area approaches that of the steady-state average area. As the ratio of mean travel time to the cycle time of the stress decreases to values of approximately 1 or less, however, the areas can become different depending upon the amplitude of the cyclic stress. This is because the particles experience only a part of the cyclic stress and behave in a manner similar to the changing-water-use scenario presented previously.

The effect of the transport-response time can also be visualized by examining the size of the transient contributing area and the percentage of particles that flow to the well from each finite-difference cell. This was shown for well 3 with a porosity of 30 percent under the luni-solar cyclic stress in figure 14. The frequency diagrams for the cases of the steady-state average conditions and the luni-solar cyclic stress with a porosity of 3 percent are shown in figure 21. The steady-state area (fig. 21*A*) shows that the core of the area constantly contributes water to the well whereas the cells along the boundary of the area contribute only partially. The cells along the boundary contribute only partially because the frequency is calculated on the basis of the total number of particles originating in a finite-difference cell, and when the contributing area is located in only part of the cell (as is usually the case around the edge of the contributing area), only a fraction of those particles will flow to the well. For the case with a porosity of 3 percent (fig. 21*B*), the mean travel time is 1,564 days and the ratio of mean travel time to cycle time is 0.23. This indicates that water moves through the system before one full cycle is completed, and the transient area is 1.85 times larger than the steady-state area. As the gray shades in figure 21*B* indicate, however, much of this area contributes flow to the well only part of the time. For the case with a porosity of 30 percent (fig. 14), the mean travel time is 10 times longer than the 3 percent porosity simulation, and the ratio of mean travel time to cycle time is also 10 times larger. This indicates that water moves through the system over more than two complete cycles, and the transient area is only about 1.28 times larger than the steady-state area.

DISCUSSION

Many ground-water systems are subject to cyclic climatic conditions. In the analyses of ground-water flow systems, steady-state average conditions are frequently used to simplify the problem and make a solution tractable. To our knowledge, the impact of cyclic changes on the estimate of the location of the area contributing recharge to wells has not been quantified. One of the difficulties in quantifying the effect of cyclic conditions is that many factors affect the flow paths taken in a ground-water system, and it is difficult to generalize. A few illustrative cases were rigorously analyzed in this report to give some insight into the potential importance of temporally changing conditions on the determination of sources of recharge to wells. Although these cases are by no means exhaustive, they nevertheless provide insight into how flow paths in ground-water systems respond.

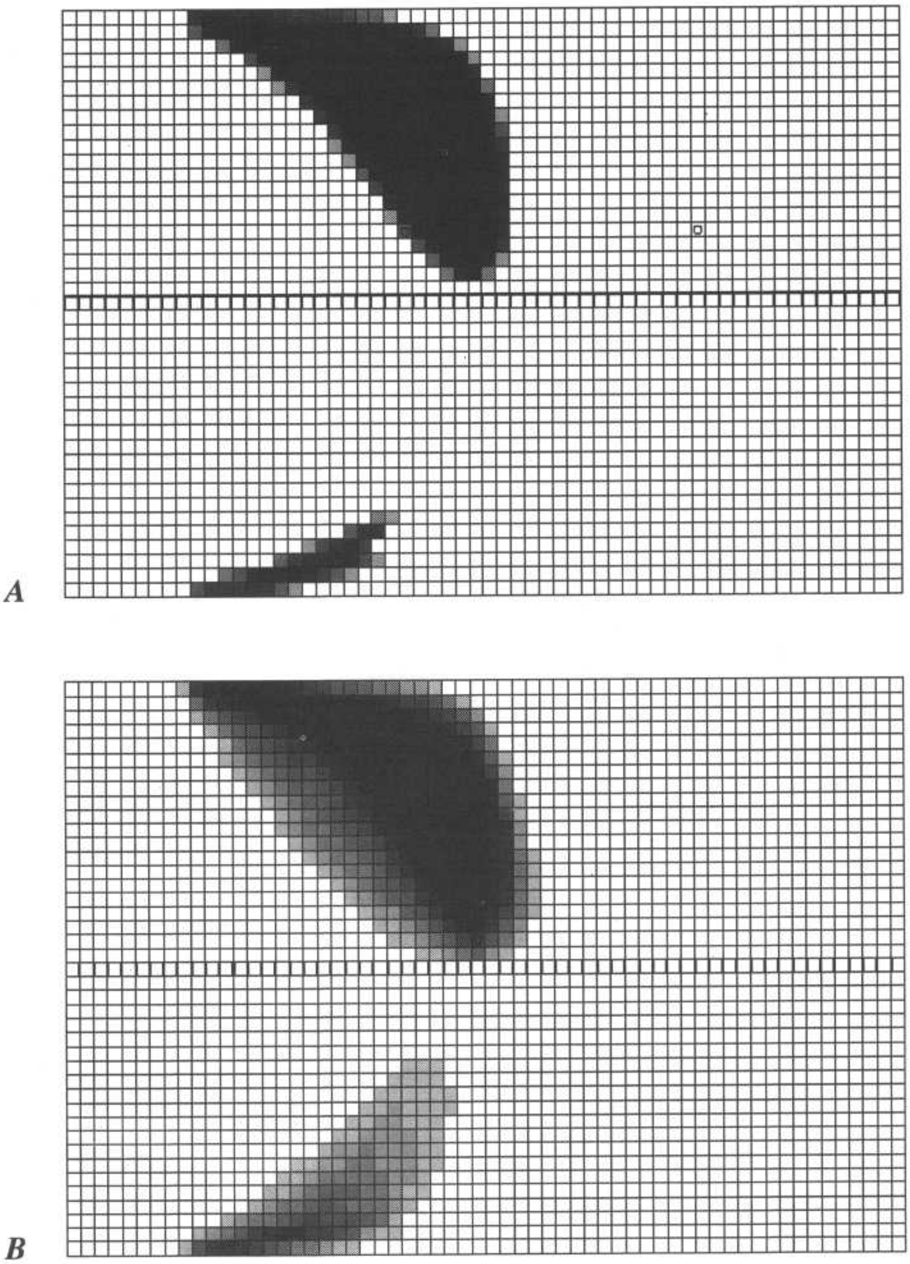


Figure 21. The percentage of particles that originate in the finite-difference cell and discharge to well 3: *A*. For steady-state conditions and *B*. For a luni-solar stress and a porosity of 0.03. The darker shades indicate larger percentages, and the lighter grays indicate smaller percentages.

The ratio of the mean travel time to the length of the cyclic stress period appears to be an indicator of whether the transient effects of the cyclic stress must be explicitly represented in the analysis of contributing areas to wells. For the cases examined in this report, if the ratio of the mean travel time to the period of the cyclic stress was much greater than 1, then the transient area contributing recharge to wells was similar to the area calculated using an average steady-state condition.

In particular, the case of a seasonally varying recharge distribution produced flow paths that were nearly identical to the steady-state flow paths for average conditions. This is a promising result, in that analyses for wellhead protection areas have been based on steady-state analyses to date. Thus, the high-frequency noise introduced by variations in recharge over months is almost completely smoothed over during a long flow path that takes decades to move through the system. Apparently, cyclic seasonal variations in recharge do not have to be explicitly accounted for in the determination of areas contributing recharge to wells for most ground-water systems.

The results of the simulation of long-term climatic cyclic variation in recharge over a 18.6-year cycle were less conclusive. The sensitivity of the area contributing recharge to the discharging well depended on the mean travel time from the area to the well. For the base case examined (that is, the system with a porosity of 30 percent), the travel times to well 1 for the seasonally transient condition ranged from 10.0 to 87.8 years. A significant difference between the steady-state pathlines and the 18.6-year cyclic condition pathlines was expected because of the large cycle-to-travel-time ratio. When examined on a scale appropriate for the calculation of contributing areas (for example, fig. 12), however, the differences between the steady-state pathlines and areas and the 18.6-year cyclic pathlines and areas were minimal. It is important to note that on a local scale, the differences could be significant, depending on the problem being examined. The areas that could potentially contribute recharge to a well were slightly larger because of the transient effects, but the difference in paths and areas would tend to introduce only some relatively minor uncertainty in the estimate of the location and size of the contributing area. No major qualitative differences in the shapes or locations of recharge areas were observed. Even when the system with short mean travel times was examined (the system with a 3 percent porosity and a mean travel time of 1,564 days), the transient area was similar in shape and was 1.84 times larger than the steady-state area. Although significant, the 1.84 times larger size shows that the areas are not very different even for the extreme case examined.

Cyclic trends in well discharge for either diurnal or seasonal changes in water use were not simulated. The insensitivity of the system to the cyclic changes in recharge, however, indicates that these short-term cyclic changes in pumping rates would not significantly alter the location of the area contributing recharge to the well.

An increasing trend in water use was simulated to highlight the difference in system response between climatic cyclic variations in recharge rates and other noncyclic anthropogenic stresses. The obvious result of increases in water use and the development of additional wells is that the contributing areas to these wells changed over time both in size and location. Ground-water systems are three-dimensional and dynamic in that water use in one part of the system affects flow paths in other parts of the system, depending upon the magnitude of the stress, the boundary conditions representing the sources of water to the entire ground-water system, the hydrogeologic framework, and the spatial relations within the system. The implication of the analyses is that transient effects can be important if the stress is not cyclical and that recognition of this implication is important in efforts to protect the quality of water discharging from wells. Also, if the travel time in a system is faster than the period of the cyclic stress, then the system will behave in a manner similar to changing trends rather than to a cyclic stress.

The analyses presented are for one hypothetical system and for the purpose of examining areas contributing recharge to wells under transient conditions. Although the cyclic stresses do not greatly affect the areas contributing water to wells if the mean travel time to cycle time ratio is greater than 1, the cyclic stresses could be important in the analysis of other phenomena at different time and spatial scales. In addition, the system for the analyses presented was designed to be a plausible representation of a general class of ground-water systems. Some systems, however, for example karst ground-water systems with high ground-water velocities, could behave very differently from the examples shown.

SUMMARY AND CONCLUSIONS

The factors that influence the location of areas contributing recharge to wells can be categorized as dependent on either the ground-water system or the well. The ground-water system factors that affect the paths of water movement in three-dimensional systems are (1) the hydrogeologic framework of the system, (2) system boundary conditions, (3) system transmitting and storage properties, and (4) stresses and change in stresses (water withdrawals and changing boundary conditions). Quantitative examples presented in this report test the effect of temporal variability (point 4) on the ability to determine quantitative areas that are the sources of water to wells. Temporal variability can be of a cyclic nature or a long-term trend.

Seasonal (half-year) cyclical changes in recharge caused relatively minor differences in contributing areas and flow paths as compared to the steady-state areas and flow paths for average conditions. Long term (18.6-year) cyclical changes in recharge caused a range of differences in contributing areas and flow paths as compared to the steady-state areas and flow paths for average conditions. For ground-water systems with a ratio of mean travel time (mean time of travel from the area contributing recharge to the discharging well) to the length of the cycle time of the stress much greater than 1, minimal differences between the transient contributing areas and the steady-state areas and flow paths were determined, but ground-water systems with mean travel-time-to-cycle-time ratios that were less than 1 (that is, the ground-water velocities were high) could have significantly different contributing areas and flow paths as compared to the steady-state areas and flow paths for average conditions. In contrast to cyclic changes in stresses, long-term trends in water use do cause major changes over time in the size and location of sources of recharge to wells. Thus, quantitative analysis of sources of water to wells may not have to be explicit in their representation (or simulation) of natural cyclic transient changes in stresses such as recharge in systems that have mean travel time (mean time of travel from the area contributing recharge to the discharging well) to cycle time ratios much greater than 1. But quantitative analyses of sources of water to wells probably have to account explicitly for long-term transient changes in discharge rates and well locations and cyclic stresses in systems with a mean travel-time-to-cycle-time ratio on the order of 1 or less than 1.

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