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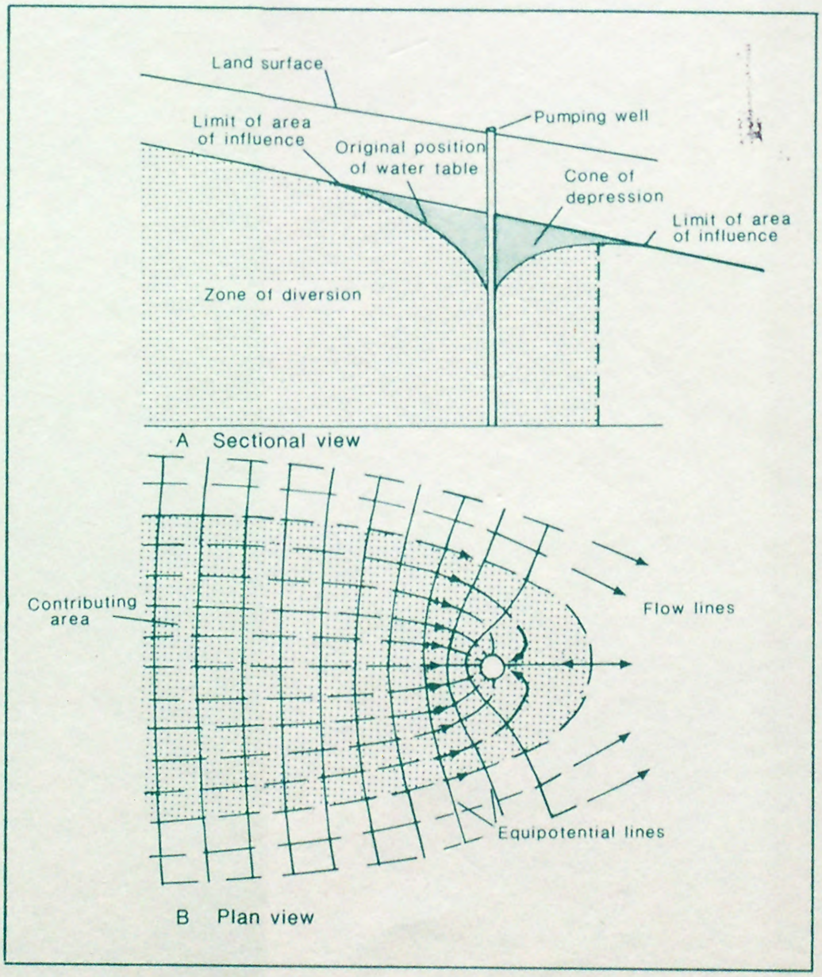
U.S. GEOLOGICAL SURVEY

Open-File Report 86-543



Prepared in cooperation with the

RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

ESTIMATION OF THE RECHARGE AREA CONTRIBUTING WATER TO A PUMPED WELL IN A GLACIAL-DRIFT, RIVER-VALLEY AQUIFER

By Daniel J. Morrissey

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RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

Providence, Rhode Island

1987

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors.

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
foot per year per square mile [$(ft/yr)/mi^2$]	0.7894	meter per year per square kilometer [$(m/yr)/km^2$]

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

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ABSTRACT

The highly permeable, unconfined, glacial-drift aquifers that occupy most New England river valleys constitute the principal source of drinking water for many communities that obtain part or all of their public-water supply from ground water. Recent events have shown that these aquifers are highly susceptible to contamination that results from a number of sources, such as seepage from wastewater lagoons, leaking petroleum-product storage tanks, and road salting.

To protect the quality of water pumped from supply wells in these aquifers, it is necessary to ensure that potentially harmful contaminants do not enter the ground in the area that contributes water to the well. A high degree of protection can be achieved by application of appropriate land-use controls within the contributing area. However, the contributing areas for most supply wells are not known.

This report describes the factors that affect the size and shape of contributing areas to supply wells and evaluates several methods to delineate contributing areas of wells in glacial-drift, river-valley aquifers. Analytical, two-dimensional numerical and three-dimensional numerical models were used to delineate contributing areas. These methods of analysis were compared by applying them to a hypothetical aquifer having the dimensions and geometry of a typical glacial-drift, river-valley aquifer. In the model analyses, factors that control the size and shape of a contributing area were varied over ranges of values common to glacial-drift aquifers in New England.

These controlling factors include the rate of well discharge, rate of recharge to the aquifer from precipitation and from adjacent till and bedrock uplands, distance of a pumping well from a stream or other potential source of induced recharge, degree of hydraulic connection of the aquifer with a stream, horizontal hydraulic conductivity of the aquifer, ratio of horizontal to vertical hydraulic conductivity, and degree of well penetration.

Analytical methods proved easiest to apply but gave results that are considered to be significantly less accurate than those obtainable by means of numerical-model analysis. Numerical models of valley aquifers are deemed best suited to determine the approximate contributing area of a well because of their capability to simulate more accurately the variable geohydrologic conditions typical of glacial-drift valley aquifers.

For "average" conditions in the hypothetical aquifer, the analytical method predicts a contributing area that is limited to the well side of the river. This is caused by using a constant-head boundary simulated with image wells in the analytical model. For typical glacial-drift, river-valley aquifers, this is an unrealistic simulation because drawdowns caused by a pumping well and the contributing area of the well can extend beneath and beyond a river or stream.

On the basis of results obtained with the two-dimensional numerical model, for which a wide range of hydrologic conditions were simulated, it seems that the contributing area in a typical glacial-drift, river-valley setting for a well pumped at a rate of 1.0 million gallons per day--a common pumping rate--may be expected to range from about 0.9 to 1.8 square miles. Model analysis also shows that the

contributing area of pumped wells may be expected to extend to the opposite side of the river and to include significant areas of till uplands adjacent to the aquifer on both sides of the valley.

Simulations with the three-dimensional model allow a full three-dimensional delineation of the zone of contribution for a pumped well. For the relatively thin (100 feet or less) unconfined aquifers considered in this analysis, the three-dimensional model showed that the zone of contribution extended throughout the entire saturated thickness of aquifer. Because of this, the two-dimensional simulations were considered adequate for delineating contributing areas in this particular hydrologic setting. For thicker aquifers (greater than 100 feet), this may not be the case.

Values for several of the factors that affect the size and shape of contributing areas generally are not known with a high degree of certainty. Therefore, determination of the recharge area that contributes water to a pumped well by any method is an approximation at best. Nevertheless, in river valleys where a reasonable amount of accurate geohydrologic data are available, methods described in the report can be used to estimate the extent of contributing areas with sufficient accuracy to be of use to planners and water-resource managers.

Control of land-use activities by State and local governments within the contributing areas to supply wells alone will not guarantee that water pumped from a well is of a quality suitable for human consumption. Many supply wells in river-valley aquifers derive substantial portions of their water from induced infiltration of streamflow. Thus, if the quality of streamflow entering the contributing area of a well is unsuitable for human consumption, the quality of water pumped from the well also may be unsuitable.

INTRODUCTION

Traditional strategy by State and local water managers to protect ground-water quality in New England has been to regulate land use in a circular area around supply wells with little regard for geohydrologic factors operating at specific sites. The inadequacy of this approach has been demonstrated by numerous instances of well contamination that have occurred throughout the area. From 1978 through 1981, 25 public-supply wells in Massachusetts with a combined capacity of 23 Mgal/d were taken out of service because of ground-water contamination (U.S. Geological Survey, 1985). At least five municipal-supply wells in Rhode Island have recently been abandoned because of contamination (Herbert Johnston, U.S. Geological Survey, written commun., 1985). Wells located in highly permeable, shallow, sand and gravel aquifers that are characteristic of New England are particularly susceptible to contamination from a variety of sources, including sanitary landfills, industrial waste and municipal sewage lagoons, road-salting operations, subsurface wastewater disposal, and underground petroleum-product storage tanks.

To absolutely protect ground-water quality at an individual well or well field, an entire aquifer and its recharge area would have to be protected from possible sources of contamination. Because this level of protection is difficult to implement, especially in extensive stratified-drift aquifers, a need exists to know the approximate area of the aquifer and areas adjacent to the aquifer that contribute water to individual supply wells. Only when the sources of water for a well and the detailed pattern of ground-water flow to the well are fully understood can State and local government regulate land use to protect the well, at least to some extent, from contamination.

Purpose and Scope

Because of a need to better protect water-supply wells, from contamination, the Rhode Island Department of Environmental Management entered into a cooperative study with the U.S. Geological Survey. This report presents the results of the cooperative study. The specific objectives of this report are to (1) describe the sources of water that sustain well yields, (2) analyze factors that affect the size and shape of areas that contribute water to supply wells, and (3) demonstrate and evaluate various methods of delineating approximate areas that contribute water to supply wells. Although the report is based upon work done in Rhode Island, the methods presented are applicable to similar hydrogeologic settings.

Previous Investigations

Jacob (1949) described an analytical method for determining the effects of a single well in a uniform flow field. The area of diversion for a well is computed with equations that describe the down-gradient stagnation point and limiting stream lines. This technique assumes a homogeneous, isotropic, confined aquifer of infinite areal extent. Jacob (1949) also described the area of diversion for a well located in an unconfined aquifer bounded by two streams. Jacob showed how the location of the well with respect to the streams caused changes in the size and shape of the diversion area.

DaCosta and Bennett (1960) examined the problem of flow between a pair of wells, one discharging and the other recharging, in a uniform flow field. They showed that distance between the wells, their location with respect to areal flow directions, and the rates of recharge and discharge affect the flow pattern and quantities of flow between the wells. The analysis assumed a homogeneous, isotropic, confined aquifer of infinite areal extent.

The contributing area to a well in an infinite strip aquifer subject to uniform recharge was investigated with an analytical technique by Brown (1963). Brown's work pointed out the difference between the area of diversion (contributing area) and the area of influence for a pumping well.

D. L. Mazzaferro, (U.S. Geological Survey, written commun., 1985) used a finite-difference numerical model to delineate the contributing area for a well in a hypothetical stratified-drift aquifer and showed that variations in recharge and aquifer hydraulic conductivity affect the size of the contributing area. D. L. Mazzaferro (U.S. Geological Survey, written commun., 1985) also used a finite-difference model to delineate the contributing area for a proposed well field in an extensive stratified-drift aquifer in Farmington, Connecticut.

Horsley (1983) describes a procedure that was used to delineate the contributing areas for wells located on Cape Cod, Mass.

Keely and Tsang (1983) describe the use of velocity distribution plots for determining the capture zone (contributing area) of a well pumping in a uniform flow field under steady-state conditions. Methods of analysis presented by Keely and Tsang (1983) assume a homogeneous, isotropic aquifer of infinite areal extent with steady-state, uniform-flow conditions.

Keely (1984) discusses factors that can affect flow fields around pumping wells, the difference between capture zones (contributing areas) and cones of depression, and the use of velocity distribution plots for determining capture zones of pumping wells utilized to control contamination plumes.

Acknowledgments

The author wishes to express appreciation to Herbert Johnston of the U.S. Geological Survey in Providence, Rhode Island, for his support and helpful discussions of hydrologic conditions in Rhode Island. Special thanks to Lehn Franke of the Office of Ground Water, U.S. Geological Survey, for important suggestions on technical aspects of the study and for guidance and encouragement throughout the study.

GEOHYDROLOGY OF GLACIAL-DRIFT, RIVER-VALLEY AQUIFER SYSTEMS

The most productive aquifers in Rhode Island and in other parts of New England are composed of sand and gravel deposited by glacial meltwater during the most recent glacial period. The large majority of high-yield municipal and industrial supply wells are located in such aquifers. A generalized discussion of aquifers is presented here to provide a framework for the following discussions of the contributing areas of wells.

Physical Properties

Glacial drift consists of fine to coarse rock materials, which may be sorted or unsorted, depending on the mode of deposition. Unsorted deposits, known as till, consist of a heterogeneous mixture of materials, ranging in size from clay to boulders that were deposited directly by a glacier. Because till usually is very dense and relatively impermeable, it does not yield large quantities of water to wells.

Other materials, known collectively as stratified drift, were deposited by glacial meltwater and, as a result, generally are uniform and well-sorted compared to tills. Depending on the velocity of the glacial meltwater in which the materials were transported and deposited, the stratified drift may range in size from cobbles, gravel, and coarse sand (associated with fast moving water) to fine-grained sand, silt, and clay (associated with slow moving water, such as in lakes or estuarine environments). Saturated, coarse-grained, stratified-drift deposits typically yield large quantities of water to wells.

The glacial-drift deposits usually lie between valley walls bounded by till-covered bedrock uplands, as depicted in figure 1. Along parts of coastal New England, the drift deposits may completely bury valleys in the bedrock.

The stratigraphic sequence shown in figure 1 is typical of those observed in the field. In general, coarse-grained, stratified-drift deposits, interspersed with fine-grained materials, overlie till and bedrock. The contact between the stratified drift and till or bedrock defines the bottom and side boundaries of the aquifers; the water table defines the top boundary. The thickness of an entire stratified-drift deposit typically ranges from about 10 ft or less near valley walls to about 100 ft or more in the deepest part of a valley.

In some places, the stratigraphic sequence consists of relatively coarse sand and gravel overlying thick deposits of fine-grained sand, silt, and clay which overlie till and bedrock. In this situation, the upper coarse portion of the stratified drift constitutes the aquifer. The bottom boundary is defined by the contact with fine-grained deposits. The top boundary is defined by the water table and side boundaries by the contact with till or bedrock.

Occasionally, coarse-grained deposits occur between a thick layer of fine-grained sediment and till or bedrock, and constitute an aquifer. These aquifers are usually not well defined because they are buried and relatively thin. Ground water in such aquifers would occur under confined conditions.

The widths of stratified-drift, valley-fill deposits can vary from less than 1 mi to as much as 4 or 5 mi, and they can extend for several miles along major river valleys. Locations of major glacial-drift, river-valley aquifers in New England are presented by Lyford and others (1984).

Hydraulic Properties

The hydraulic properties of an aquifer include hydraulic conductivity, storage coefficient or specific yield, and transmissivity. The range of reported values of hydraulic conductivity for stratified-drift aquifers in the northeastern United States is from about 10 to 10,000 ft/d (Lyford and others, 1984). Hydraulic conductivities of silt, clay, and till are generally less than 1 ft/d. The specific yield for unconfined stratified-drift aquifers ranges from about 0.05 to 0.35 (Lyford and others, 1984). Stratified-drift, river-valley aquifers that are capable of yielding 500 gal/min or more to individual wells generally have transmissivities of at least 10,000 ft^2/d (Lyford and others, 1984)

Recharge

Major sources of recharge to stratified-drift, river-valley aquifers include infiltration of rainfall and snowmelt, natural or induced infiltration from surface water, and ground- and surface-water runoff from adjacent and underlying till or bedrock (fig. 2).

Where sand and gravel is present at land surface, MacNish and Randall (1982) estimated that about half of total annual precipitation recharges the ground water. Lyford and others (1984) report recharge rates for stratified-drift aquifers in the northeastern United States ranging from approximately 1 to 31 in/yr. Recharge from adjacent hillsides and tributary streams may exceed recharge from precipitation (MacNish and Randall, 1982). Randall (1978) reported natural tributary stream losses of about 1 ft^3 per 1,000 ft of stream channel in the Susquehanna River basin, New York. Similar losses have been observed along tributary streams in the Saco River valley in New Hampshire and Maine (D. J. Morrissey, U.S. Geological Survey, written commun., 1986).

The amount of natural or induced infiltration from surface-water bodies is controlled in part by the difference in head between surface water and ground water and the hydraulic conductivity of bordering deposits. In many locations, induced infiltration, caused by pumping near surface water, is the largest potential source of recharge to an aquifer (MacNish and others, 1969).

Discharge

Natural discharge of ground water from stratified-drift, river-valley aquifers is to surface-water bodies, wetlands, and through evapotranspiration.

Ground-water discharge to streams and rivers maintains flow in periods of little or no surface runoff. The amount of total streamflow made up by ground water was shown to be directly proportional to the percentage of total drainage area covered with stratified-drift deposits (Cervione and others, 1972). Ground-water runoff provides as much as 95 percent of streamflow in drainage areas covered entirely with stratified drift, and about 35 percent in till covered drainage areas.

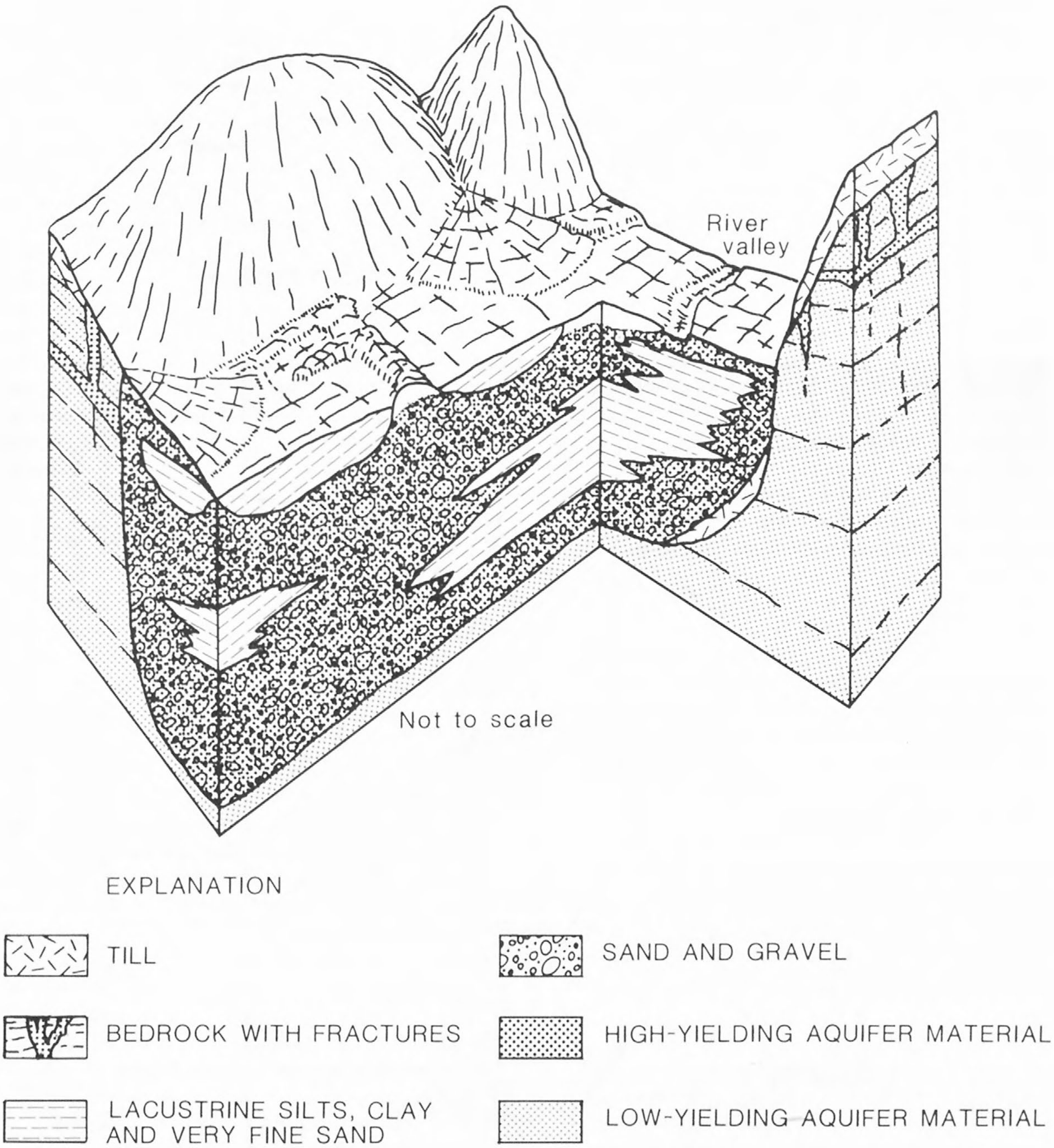


Figure 1.--Generalized geologic setting for glacial-drift, river-valley aquifers.

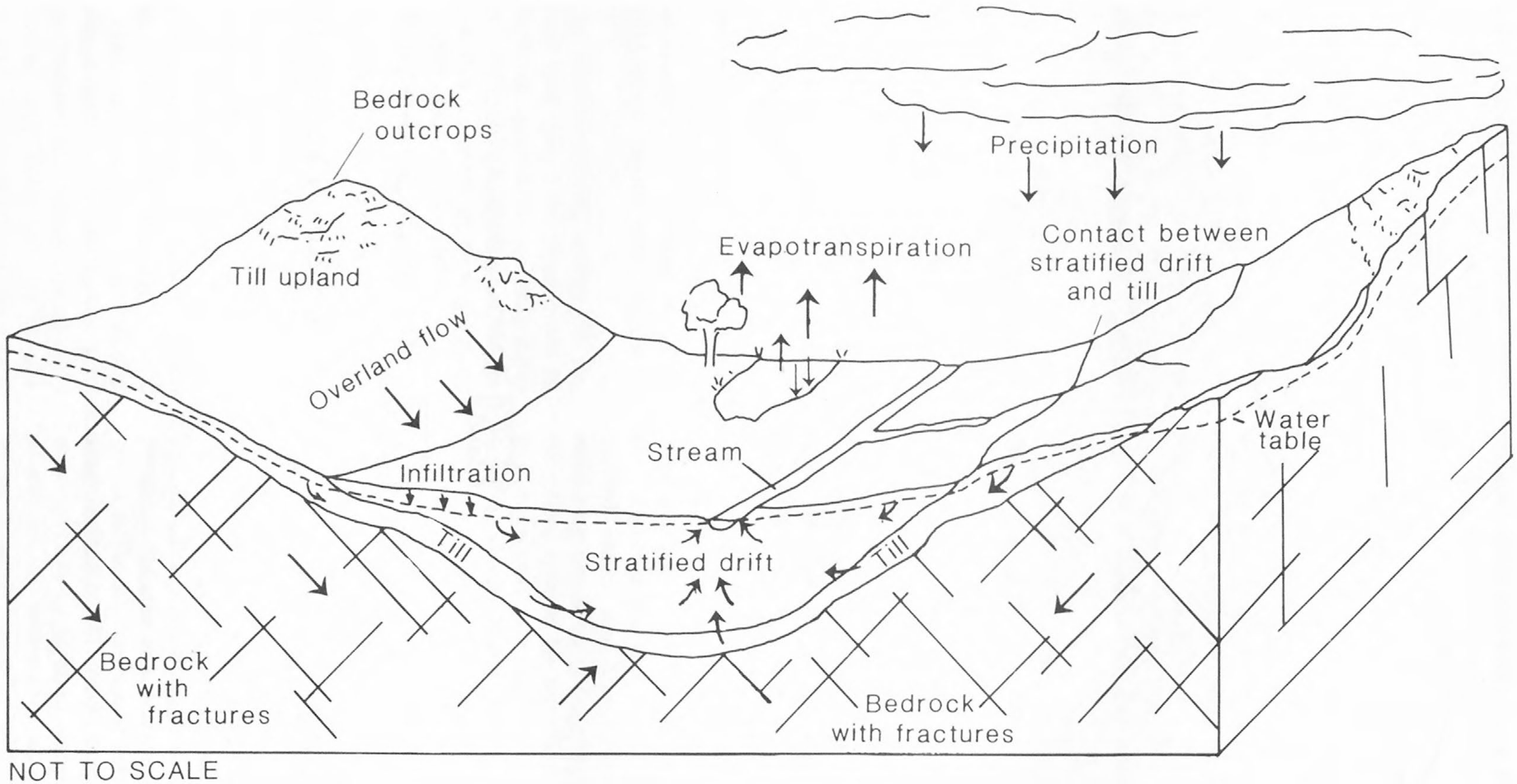


Figure 2.--Recharge/discharge relations and generalized flow patterns in glacial-drift, river-valley aquifers.

Estimates of ground-water evapotranspiration from stratified-drift aquifers in the northeastern United States range from 1 to 9 in/yr (Lyford and others, 1984). One of the major factors affecting ground-water evapotranspiration losses is depth to the water table below land surface. Where the depth to water is about 10 ft or greater, the loss is probably not significant.

Despite the large variation in factors that describe the geometry and hydraulic properties of glacial-drift, river-valley aquifers, some generalizations can be made. When a pumping well stresses one of these aquifers, the hydraulic response is controlled by certain essential features of the system. The next section of the report discusses these system features and describes how they operate within the geohydrologic framework described above.

SOURCES OF WATER IN WELLS

Before the technical discussions on delineating contributing areas are presented, it is important to review some of the general concepts that describe how a ground-water system responds to pumping stress. The following discussion has been taken largely from Heath (1983). Heath's description of the sources of water derived by wells provides an excellent review of the essential factors that control the response of an aquifer to development.

Both the economical development and the effective management of any ground-water system require an understanding of the response of the system to withdrawals from wells. The first concise description of the hydrologic principles involved in this response was presented by C. V. Theis in a paper published in 1940.

Theis pointed out that the response of an aquifer to withdrawals from wells depends on:

1. The rate of expansion of the cone of depression caused by the withdrawals, which depends on the transmissivity and the storage coefficient of the aquifer.

2. The distance to areas in which the rate of water discharging from the aquifer can be reduced.

3. The distance to recharge areas in which the rate of recharge can be increased.

Over a sufficiently long period of time under natural conditions (prior to the start of withdrawals) the discharge from every ground-water system equals the recharge to it. In other words,

natural discharge (D) = natural recharge (R)

This situation is represented diagrammatically in figure 3. For unconfined stratified-drift, river-valley aquifers in the humid northeastern part of the United States, the amount and distribution of ground-water recharge is such that the period of time that is required for recharge to balance discharge is usually 1 year or less.

Over shorter periods of time, differences between discharge and recharge involve changes in ground-water storage. In other words,

1. When the total volume of discharge (D_V) exceeds the total volume of recharge (R_V) over a given period of time, ground-water storage (S) is reduced by an amount ΔS equal to the difference between the volumes of discharge and recharge. Thus,

$$D_V = R_V + \Delta S$$

2. Conversely, when the total volume of recharge exceeds the total volume of discharge over a given period of time ground-water storage is increased. Thus,

$$D_V = R_V - \Delta S$$

When withdrawal through a well begins, water is removed from storage in its vicinity as the cone of depression develops (fig. 4). Thus, the total volume of withdrawal (Q_V) is balanced by a reduction in ground-water storage. In other words,

$$Q_V = \Delta S$$

As the cone of depression expands outward from the pumping well, it may reach an area where water is discharging from the aquifer. The hydraulic gradient will be reduced toward the discharge area, and the rate of natural discharge (D) will decrease.

To the extent that the decrease in natural discharge compensates for pumpage, the rate at which water is being removed from storage will also decrease, and the rate of expansion of the cone will decline. If and when the reduction in the rate of natural discharge (ΔD) equals the rate of withdrawal (Q), a new balance will be established in the aquifer. This balance in symbolic form is:

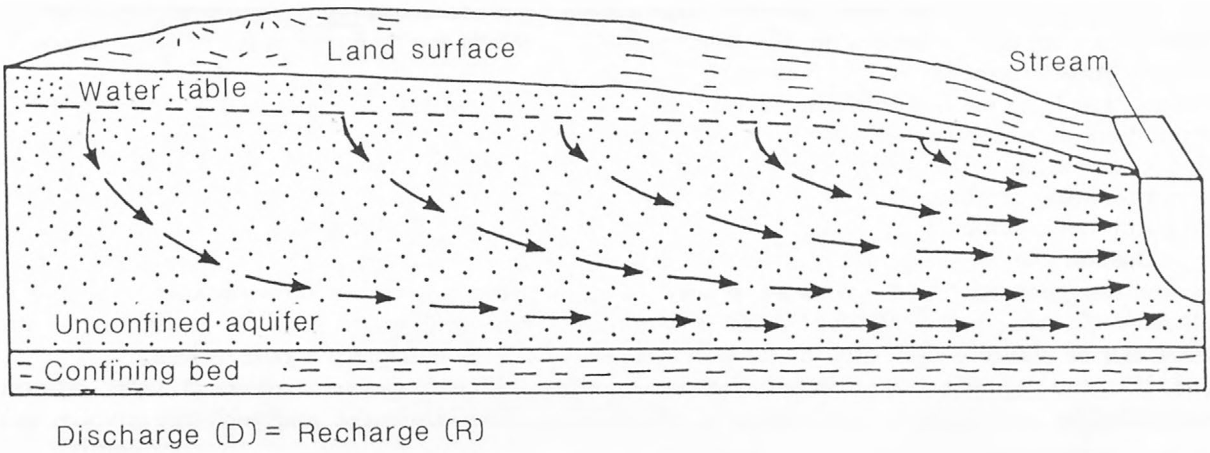


Figure 3.--Ground-water flow at various stages of aquifer development natural equilibrium conditions, previous to aquifer development.

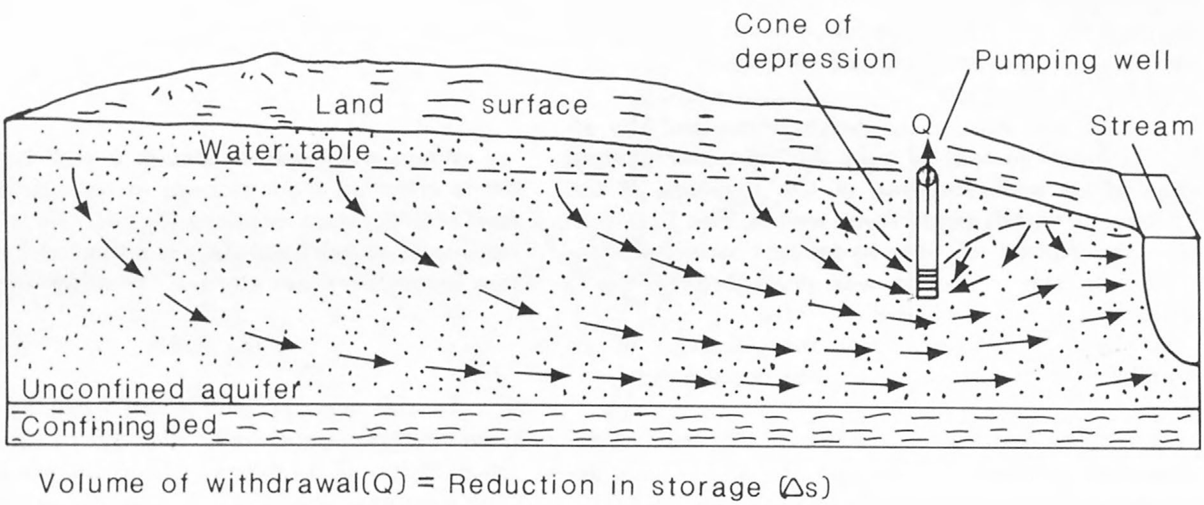


Figure 4.--Ground-water flow at various stages of aquifer development pumping conditions, early time.

$$(D - \Delta D) + Q = R$$

Conversely, if the cone of depression expands into a recharge area rather than into a natural discharge area, the hydraulic gradient between the recharge area and the pumping well will be increased. If, under natural conditions, more water is available in the recharge area than the aquifer could accept (the condition Theis referred to as one of rejected recharge), the increase in gradient away from the recharge area will permit more recharge to occur, and the rate of growth of the cone of depression will decrease. If and when the increase in recharge (ΔR) equals the rate of withdrawal (Q), a new balance will be established in the aquifer and the expansion of the cone of depression will cease. The new balance in symbolic form is:

$$D + Q = R + \Delta R$$

In the northeastern United States, rejected recharge has not been considered to be a major source of water to wells. More commonly, captured natural discharge from an aquifer is the major source of water to a well and will tend to be the factor that limits the expansion of the cone of depression.

If the pumping wells are near a stream or if withdrawals are continued long enough, ground-water discharge to a stream may be stopped entirely in the vicinity of the wells, and water may be induced to move from the stream into the aquifer. In other words, the tendency in this region is for withdrawals to change discharge areas into recharge areas. This consideration is important where streams contain brackish or polluted water or where streamflow is committed or required for other purposes (fig. 5).

To summarize, the withdrawal of ground water through a well reduces the water in storage in the source aquifer during the growth of the cone of depression. When and if the cone of depression ceases to expand, the rate of withdrawal is being balanced by a reduction in the rate of natural discharge and (or) by an increase in the rate of recharge. Under this condition:

$$Q = \Delta D + \Delta R$$

As an additional note of clarification, a ground-water divide exists between the well and the stream in figure 4 (indicated by directions of flow in opposite directions) which signifies a reduction in natural discharge to the stream by the pumping well. In contrast, flow directly from the stream to the well is indicated in figure 5.

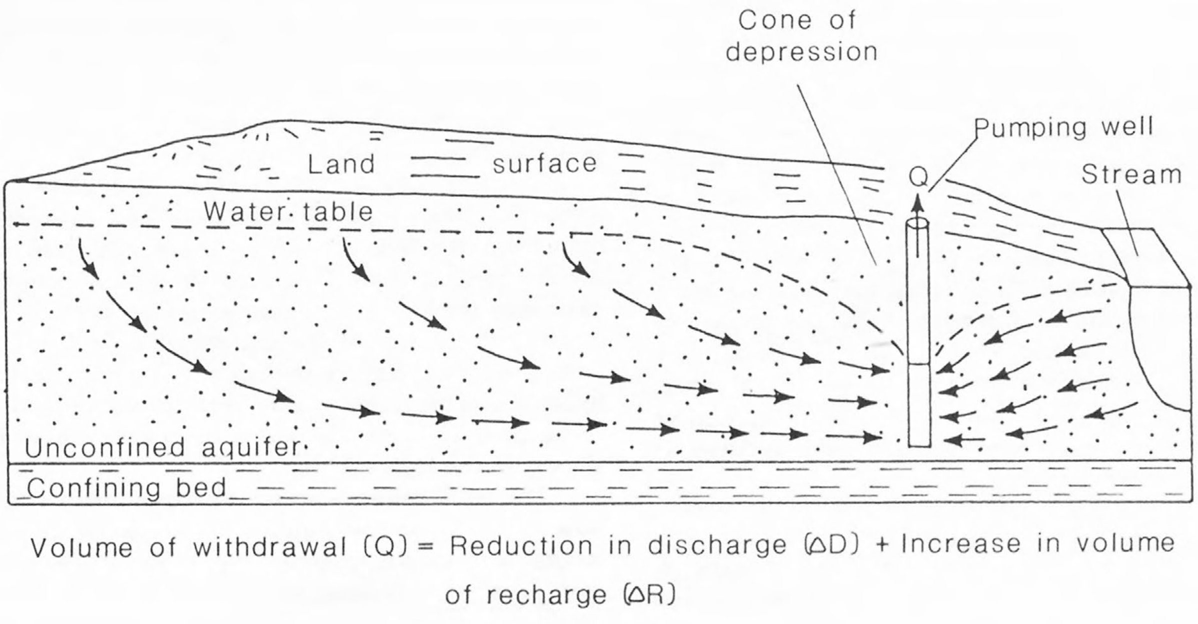


Figure 5.--Ground-water flow at various stages of aquifer development pumping conditions, late time (equilibrium).

These concepts, as applied to stratified-drift, river-valley aquifers in Rhode Island and elsewhere in New England, have several important ramifications. In this area water pumped from wells will be derived from (a) storage in the aquifer, (b) a reduction of ground-water flow to nearby streams, and (c) possibly induced infiltration from streams. Both of the latter two mechanisms (one or both of which must be operative during extended periods of pumping) will reduce streamflow and thus could produce an undesirable result where downstream user rights are affected. Furthermore, if the quality of the surface water is distinctly inferior to the quality of ground water, induced infiltration from the stream could have important and undesirable consequences on the quality of water pumped from the well.

THE CONCEPT OF CONTRIBUTING AREA

Definition of Contributing Area and Related Terms

The *cone of depression* is the geometric solid included between the water table or other potentiometric surface after a well has begun discharging and the hypothetical position the water table or other potentiometric surface would have had if there had been no discharge by the well (Theis, 1938). Although the first effect of pumping travels radially outward with a speed approaching that of sound in the saturated sand, the measurable influences travel much more slowly (Jacob, 1949). This depression in the water table or other potentiometric surface can be visualized as a cone shaped geometric solid as shown in figure 6a.

The *area of influence* of a pumping well is the land area that directly overlies and has the same horizontal extent as the part of the water table or other potentiometric surface that is perceptibly lowered by the withdrawal of water (Meinzer, 1923). The area of influence can be visualized as a two-dimensional area on the land surface as shown in figure 6b.

The *zone of contribution* of a pumping well is here defined as the volumetric portion of an aquifer from which ground-water flow is diverted to a pumping well. The zone of contribution can be visualized as a three-dimensional volume of aquifer as depicted in cross-section and plan view in figure 7.

The *contributing area* (sometimes referred to as area of diversion) of a pumping well is here defined as the land area that has the same horizontal extent as that part of an aquifer, or adjacent areas, from which ground-water flow is diverted to the pumping well. The contributing area for a pumping well can be visualized as a two-dimensional area on the land surface as shown in figure 7b.

The typical high yield aquifer in New England is made up of coarse-grained, unconsolidated, stratified drift with a thin, highly permeable unsaturated zone. In this geohydrologic setting, significant amounts of recharge to the water table can occur near pumping wells. Of course, recharge containing contaminants in a contributing area can adversely affect the quality of water obtained from a well. Therefore, efforts to protect the quality of water obtained from a well must be at least partly directed toward protection of these important source areas.

The fallacious idea that contributing area and area of influence are identical persists despite an excellent discussion by Brown (1963). (This confusion may have contributed to the use of circular areas around wells as buffer zones for ground-water-quality protection.) Actually these areas can be the same only in the hypothetical circumstances where the pre-pumping water table is perfectly flat and all aquifer properties are uniform within the area of influence. When the pre-pumping water table has a gradient, as it does under most natural conditions, the contributing area to a well will be distorted to extend to a greater distance on the upgradient side and to a lesser distance on the downgradient side.

Consider the hypothetical aquifer shown in figure 8. The aquifer is unconfined and recharged only from precipitation (W). Discharge from the aquifer is to a river that cuts through the entire saturated thickness of the aquifer and to a well located in the center of the aquifer at a distance (d) from the river. Values that describe the geometry, hydraulic properties, boundary conditions, and recharge and discharge rates for the aquifer are shown on the figure 8.

The equilibrium water-table configuration and flow directions in the aquifer for nonpumping conditions are shown in figure 9a. The drawdowns and area of influence for steady-state pumping conditions are shown in figure 9b. (For the purpose of this discussion the area of influence is defined as that area where drawdowns caused by the well are 0.1 ft or greater.) Theoretically, very

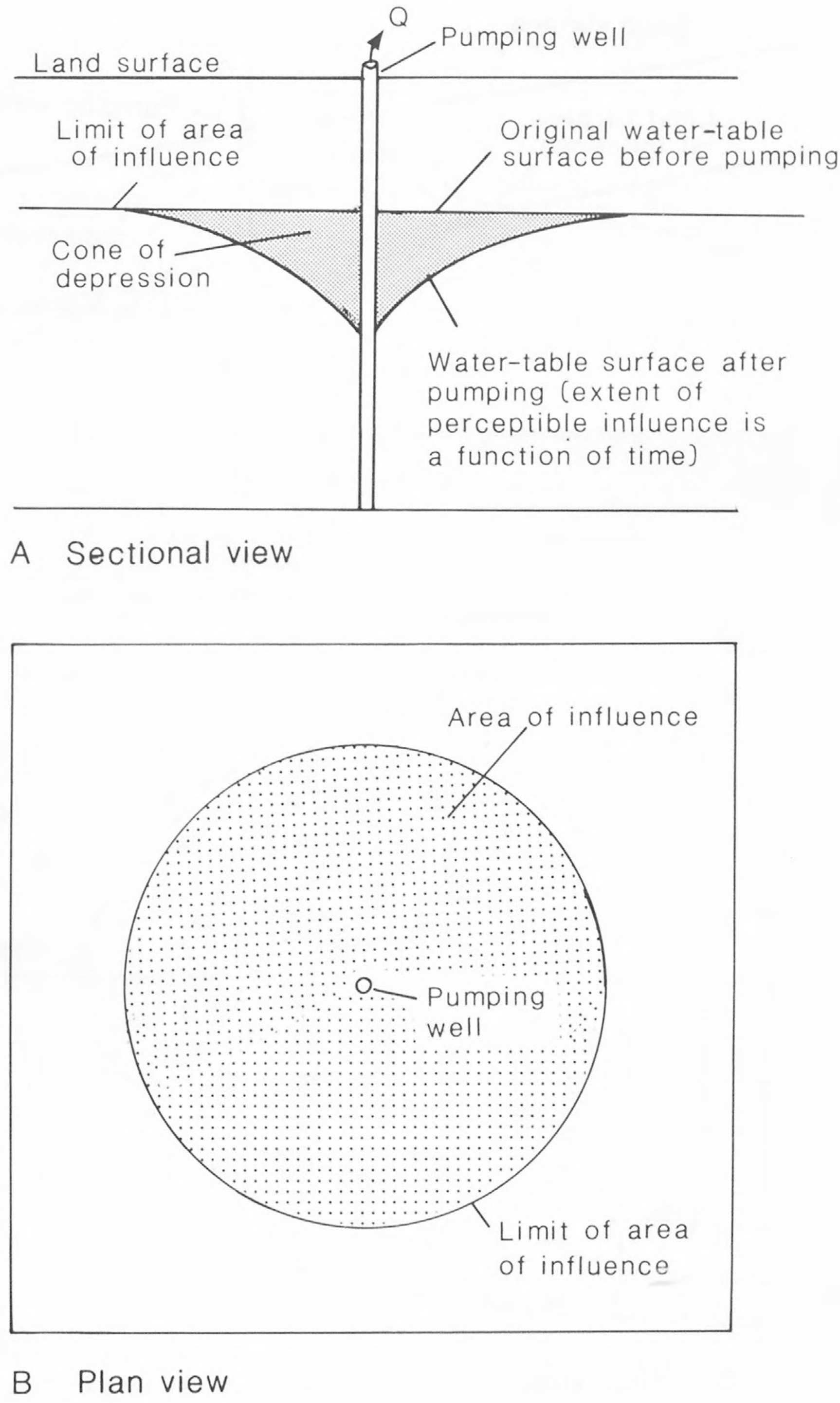


Figure 6.--Diagram of a pumped well showing (a) cross-sectional view of the cone of depression and (b) plan view of the area of influence.

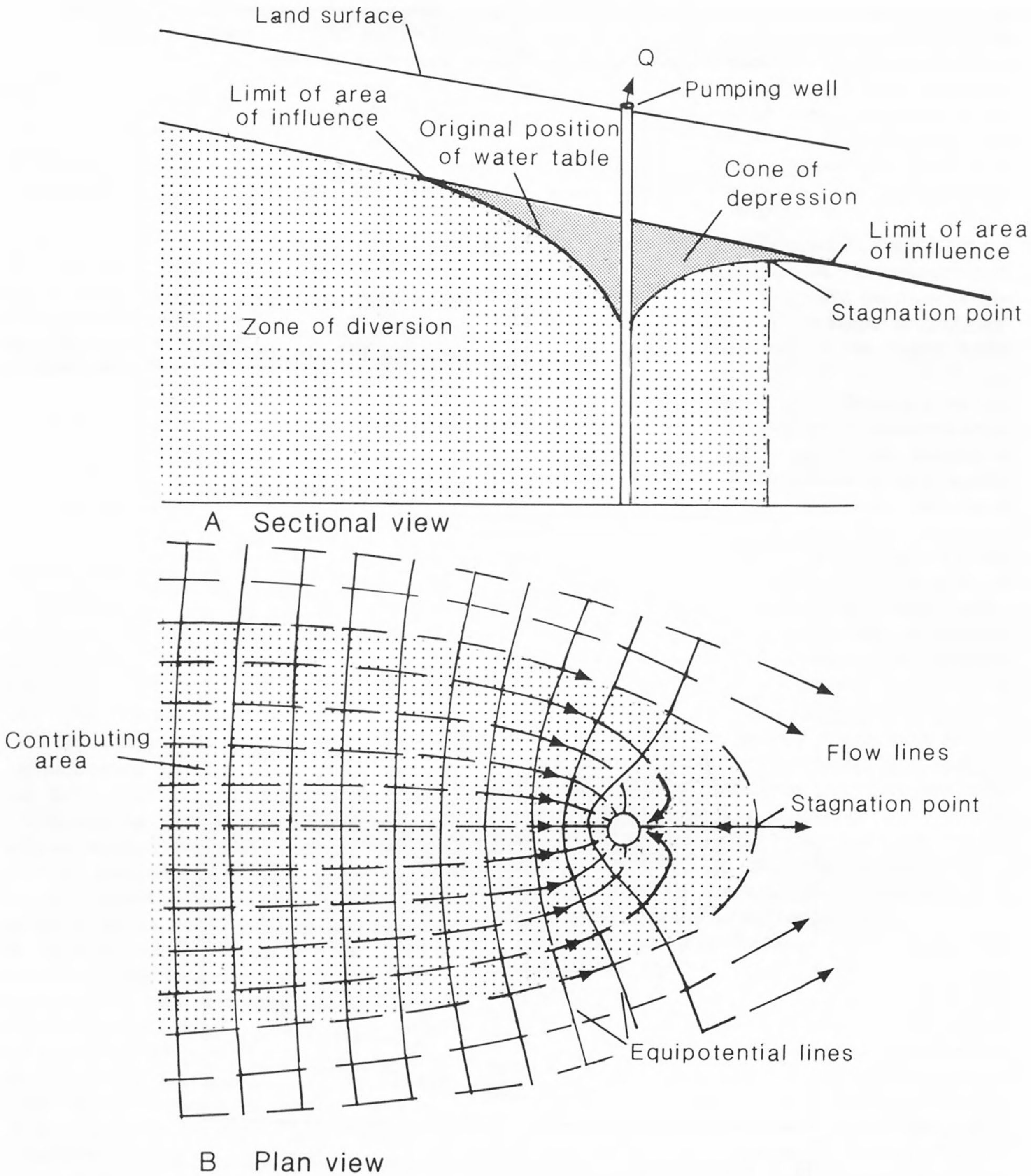
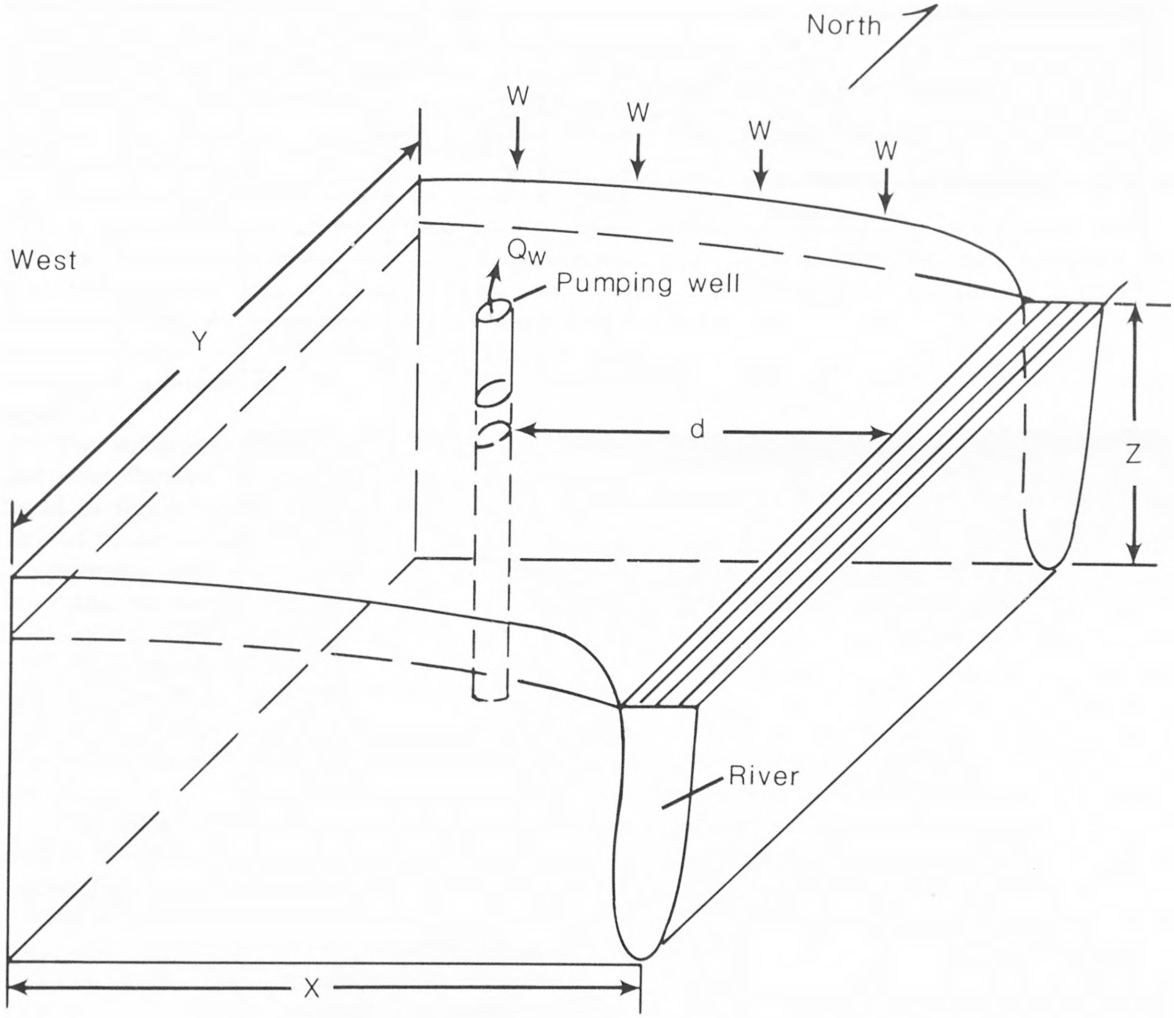


Figure 7.--Diagram of a pumped well showing (a) cross-sectional view of the zone of diversion and (b) plan view of the contributing area.



AQUIFER GEOMETRY

$X = 5000$ feet

$Y = 12{,}000$ feet

$Z = 100$ feet

$d = 1600$ feet

BOUNDARY CONDITIONS

North → inflow of water 0

South → inflow of water 0

West → inflow of water 0

East → constant-head river

AQUIFER HYDRAULIC PROPERTIES

Hydraulic conductivity = 50 feet per day

Specific yield = 0.2

AQUIFER RECHARGE

From precipitation (W) = 3 feet per year

WELL DISCHARGE

$Q_W = 0.25$ million gallons per day

Figure 8.--Geohydrologic features of a hypothetical aquifer used to illustrate the difference between the area of influence and the contributing area of a pumped well.

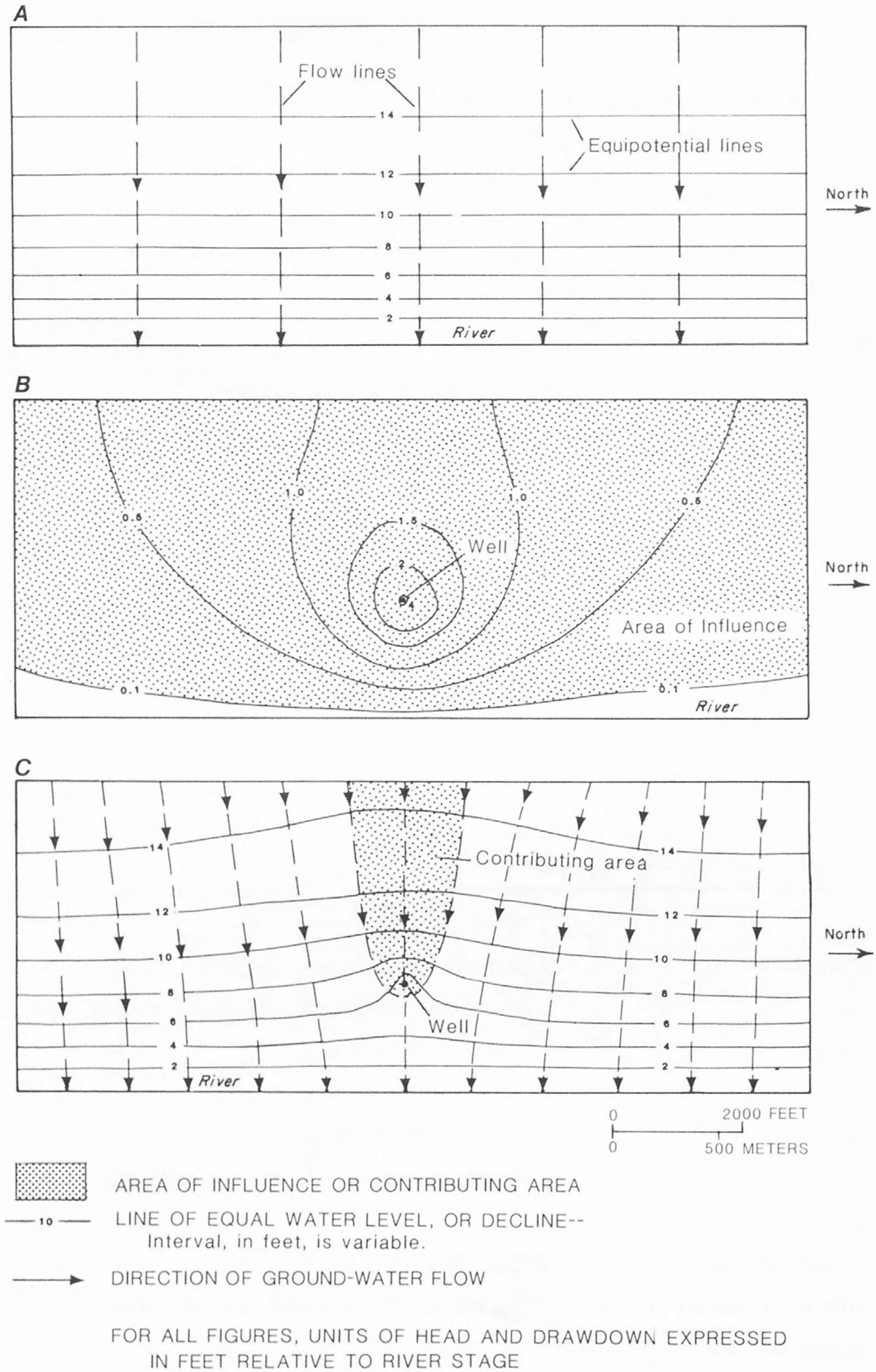


Figure 9.--Hypothetical aquifer illustrated in figure 9 showing (a) prepumping equilibrium water-table configuration, (b) steady-state drawdowns and the area of influence of the pumped well, and (c) the contributing area of the well.

small drawdowns occur to the boundaries of the aquifer even though they might not be reliably measured in the field. The equilibrium water-table configuration, flow directions in the aquifer, and contributing area for pumping conditions are shown in figure 9c.

The results shown in figure 9 were determined with a numerical ground-water-flow model developed by Trescott and others (1976). The flow nets, contributing area, and area of influence shown in the illustration were constructed graphically from model output. A detailed description of this method of analysis will be presented later in this report.

The difference between the areas of influence and contribution for the hypothetical conditions listed in figure 8 are clearly evident when figure 9b and 9c are compared. The contributing area of the pumping well covers about 0.15 mi^2 extending from the western boundary of the aquifer to a point about 350 ft downgradient from the well while the area of influence covers almost the entire aquifer (2 mi^2). Recharge into the contributing area from precipitation exactly balances well discharge for the equilibrium conditions shown in figure 9c.

The area of influence caused by a pumping well is limited only by the physical boundaries of the aquifer in which it is located. The contributing area of a pumping well will be limited to the area around the well in which captured water balances well discharge. The captured water can consist of a decrease in aquifer storage, increased recharge (usually in the form of induced infiltration from a surface-water body), and (or) decreased natural discharge from the aquifer. Many geohydrologic, climatic, and cultural factors can affect the size and shape of the area that contributes water to a well. The next section presents a partial list of such factors.

Factors Affecting the Contributing Area of a Pumping Well

Based on the discussion of the sources of water derived by wells and the work of previous investigators (Theis, 1940; Jacob, 1949; DaCosta and Bennett, 1960; Brown, 1963; D. L. Mazzaferro, U.S. Geological Survey, written commun., 1985; and Keely, 1984), several factors have been shown to affect the area that contributes flow to a pumping well. Among these factors are:

(1) Well discharge rate and duration of pumping period.

(2) Aquifer transmissivity.

(3) Aquifer storage coefficient or specific yield.

(4) Proximity of the pumping well to aquifer boundaries.

(5) Spatial and temporal variations in aquifer transmissivity and (or) storage coefficient.

(6) Spatial and temporal variations in aquifer recharge.

(7) Partial penetration of the pumping well.

(8) The presence of extensive confining layers.

All geohydrologic factors that can affect the two- or three-dimensional flow field around a pumping well can also affect the contributing area to the well. This list covers some of the major factors that can affect the contributing area to a well. For unusual geohydrologic conditions, there may be additional factors that have not been listed. Each of these factors will affect the contributing area to a well to some degree depending upon specific conditions at the site. The choice of a technique to estimate a contributing area will, in large part, depend upon the critical geohydrologic factors that must be considered at a specific site.

Selected Methods for Estimating the Contributing Area of a Pumping Well

Delineation of the contributing area for a pumping well involves the construction of a flow net. The flow net is used to differentiate between areas in an aquifer where ground-water flow is captured by a well or wells (contributing areas) from areas where it is not.

An example of a flow net is shown in figure 9c. The flow net consists of a set of equipotential lines and flow lines. The equipotential lines connect locations of equal head in the aquifer; and the flow lines, oriented perpendicular to the equipotentials (for an isotropic aquifer), show directions of ground-water flow. The flow net shown in figure 9c is two-dimensional, that is, it is drawn on a horizontal plane and assumes there are no vertical components of flow in the aquifer. This assumption can be made in most stratified-drift aquifers in New England because they are relatively thin.

Several methods are available for generating the data necessary to construct flow nets. These include graphical techniques, analog simulation (conductive paper, resistor-capacitor networks, sand box), analytical mathematical, and numerical mathematical simulations. Discussions of flow-net construction can be found in Freeze and Cherry (1979) and Todd (1980). The most commonly used methods, and the ones that will be described in this report, are analytical mathematical techniques and numerical mathematical simulation.

Analytical-Model Analysis

Analytical models commonly are used to evaluate aquifer characteristics from pumping test results, examples include the Theim, Theis and Hantush equations. If aquifer characteristics are known or can be estimated, the same analytical models can be used to predict drawdowns that will occur in the vicinity of a well due to a pumping stress. Generally, use of analytical methods requires simplifying assumptions be made about the geometry and hydraulic properties of an aquifer.

Some of the most typical assumptions require that aquifer properties be homogeneous, and isotropic and that the aquifer is confined. In addition, the analytical methods often assume that drawdowns caused by a well are unaffected by aquifer boundaries. If boundaries are present, they must be conceptualized as being perfectly straight with uniform properties. Another important consideration is that the results of analytical models are usually expressed in terms of drawdown.

To estimate a contributing area with analytical techniques the drawdowns determined with the model must be superimposed on (subtracted from) a prepumping water-table surface. The principle of superposition and its application in ground-water hydraulics is discussed in detail by Reilly and others (1984). An example of this procedure is illustrated in figure 10.

Assume the head distribution (h) and boundary flows (Q1) of an unstressed confined aquifer, depicted in cross-section in figure 10a, are known. Also known is the drawdown distribution (Δh), relative to an arbitrary datum, and boundary flows (Q2) in response to a hypothetical pumping stress (2Q2)--figure 10b. Both the natural-flow system and the stressed-flow system are assumed to be at steady-state. Superposition of the natural and stressed system results in the head distribution (h_t) and boundary flows (Q1$\pm$Q2) shown in figure 10c. Although this concept is illustrated here in cross-section, the procedure is carried out in plan view to determine the contributing area for a pumped well.

In general, if the regional drawdowns that will be caused by a pumping well are less than 10 percent of the total saturated thickness of an unconfined aquifer the use of superposition in an unconfined system may be acceptable (Reilly and others, 1984). In a strict sense superposition is mathematically correct only for confined aquifers because linear equations describe flow in confined aquifers. Superposition can be used for unconfined aquifers only as an approximation because flow in unconfined aquifers is described by nonlinear equations. The use of analytical models to estimate contributing areas of such unconfined aquifers requires that a prepumping water-table map be available and that the use of superposition is considered to be mathematically appropriate, that is, when the effects of nonlinearity are acceptable.

Typical glacial-drift, river-valley aquifers are almost never homogeneous, isotropic, or confined. They are characterized by abrupt changes in hydraulic properties in both horizontal and vertical directions. Pumping wells in glacial-drift, river-valley aquifers are usually affected by the presence of complicated boundaries such as surface-water bodies with leaky bottoms and semipermeable valley walls. Because of these problems, considerable errors can be made when analytical methods and superposition are used to estimate contributing areas in glacial-drift, river-valley aquifers.

Despite these problems, analytical techniques can provide reasonable estimates of flow patterns around wells in glacial-drift aquifers under certain conditions. With respect to the previously presented list of factors that can affect the contributing area of a well analytical models can be used to simulate factors 1-3. Factor 4 also can be simulated if the aquifer boundaries can be idealized. To use analytical models intelligently the inherent hydrological assumptions and their affects on results must be carefully considered. There is no analytical model that can be used in every situation to estimate contributing areas for wells in glacial-drift aquifers. The suitability of an analytical approach must be considered on a site-by-site basis.

The advantages of using analytical methods are that they require only pencil and paper to solve and they can be solved in a short amount of time. In addition, analytical solutions can provide insight into the dependence of a solution on input

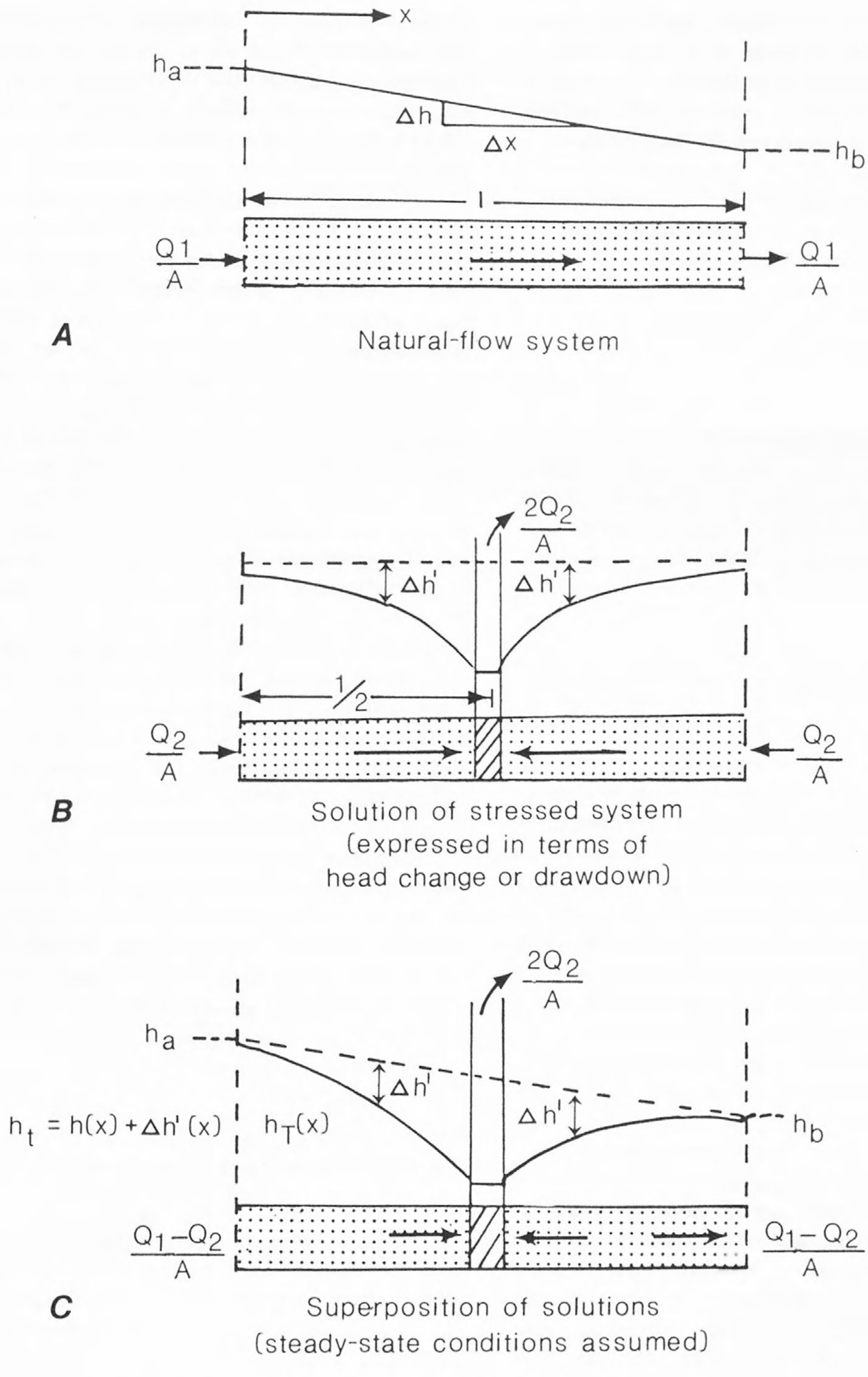


Figure 10.--Diagram showing (a) head distribution for a natural-flow system, (b) drawdowns caused by a pumping stress, and (c) head distribution resulting from superposition of (a) and (b).

data--such as boundary conditions, hydraulic properties, and the relative location of a point of interest with respect to spatial boundaries. Because of these advantages, analytical models are excellent to use for preliminary analyses or feasibility type studies.

Analytical models that might be useful for determining the effects of wells in glacial-drift, river-valley aquifers include the Theis equation as modified by image well theory (Ferris and others, 1962), a solution for a well located near a semipervious streambed (Hantush, 1965), and a solution for determining the effect of a well in a uniform flow field (Bear, 1979). Equations for determining steady-state drawdowns caused by a well in an infinite strip aquifer with various boundary conditions are given by Kirkham (1949; 1951) and Rorabaugh (1956). More complete listings of analytical models can be found in Bear (1979), Freeze and Cherry (1979), Lohman (1979), and Todd (1980).

Two-Dimensional Numerical-Model Analysis

Two-dimensional, mathematical numerical ground-water-flow models have become the most commonly used tool for analyzing the response of an aquifer to stress. The reason numerical models have gained such popularity is because of their capability to solve a very wide range of complicated field problems that cannot be analyzed with analytical methods. A two-dimensional ground-water-flow model can simulate all of the previously listed factors that can affect the contributing area for a well with the exception of those that involve vertical flow (factors 7 and 8). A zone of diversion estimated with a two-dimensional numerical model applies through the entire saturated thickness of aquifer.

Two-dimensional numerical models can be used to simulate horizontal flow of ground water in heterogeneous, anisotropic aquifers with either confined or unconfined conditions. They also can simulate irregular, mixed boundary conditions and complicated combinations of aquifer recharge and discharge. Model design allows detailed information to be obtained in areas of special interest.

An important limitation of two-dimensional numerical models is their inability to simulate vertical flow in an aquifer. For the relatively thin aquifers found in New England, this constraint is not serious except in areas where vertical flow is predominant such as near recharge or discharge areas. A general limitation of numerical models has been the need for a computer with sufficient storage to handle the necessary computer codes and data arrays. This problem has become less important with the advent of more powerful computers.

Another general limitation of numerical models results from the fact that the numerical solution is an approximation to the continuous solution and, therefore, some error (discretization error) may be involved. The accuracy of a finite-difference numerical solution is related to the choice of the size of the grid blocks used to represent the aquifer. In most real world applications of such approximation methods, the accuracy associated with an arbitrary choice of a grid cannot be determined exactly. In practice, what can be done to "select" an acceptable grid is, starting with an arbitrary grid, to make simulation runs with increasingly more refined grids until the computed results do not change more than a specified amount. Although the grid size was not varied for this study, it is presumed that the grid block size used is small enough that the qualitative character of the approximate solutions is acceptably close to that of the unknown exact solutions to give useful information. Remson and others (1971) provide a useful discussion on discretization error.

Some references that will provide an introduction to both the theoretical and the applied aspects of numerical ground-water-flow modeling are Bennett (1976), Mercer and Faust (1981), and Wang and Anderson (1982). Commonly used two-dimensional ground-water-flow models are those developed by Prickett and Lonnquist (1971) and Trescott and others (1976) as well as a variety of other finite-difference and finite-element codes.

Three-Dimensional Numerical-Model Analysis

A three-dimensional numerical ground-water-flow model can simulate all of the previously listed factors that can affect the contributing area for a well. In addition to the factors that can be simulated with a two-dimensional model, the three-dimensional model codes take into account vertical variations in geometry, hydraulic properties, and recharge or discharge within an aquifer. This type of model will allow estimation of the three-dimensional shape of a zone of diversion which, as noted previously, is not possible with a two-dimensional model. This could be particularly useful in very thick aquifers.

Depending upon the model that is used, three-dimensional simulation can be accomplished either with a "quasi" three-dimensional approach by stacking two-dimensional models and linking them with vertical leakage terms or by actually simulating the equations that describe the three-dimensional flow of ground water. Confining layers can be simulated with leakage terms or with discrete layers in the model. Because of the vertical layering inherent in a three-dimensional model, it is relatively easy to simulate partial penetration of a well or surface-water body. Partial penetration means that the well screen or surface-water body is not in contact with the entire saturated thickness of an aquifer.

The major limitations involved in the use of three-dimensional models are the need for extensive data for model construction and calibration and for a computer with sufficient storage to handle the computer program and associated data arrays.

A three-dimensional ground-water-flow model developed by Trescott (1975), and subsequently modified by Trescott and Larson (1976) and Torak (1982) has been successfully applied to solve a wide variety of problems. A more recent model, developed by McDonald and Harbaugh (1984) has a "modular" coding structure which allows simulation of various geohydrologic conditions, such as leakage to rivers and evapotranspiration, with individual packages that can be incorporated in the program as needed.

EVALUATION OF METHODS FOR ESTIMATING CONTRIBUTING AREAS AND SIMULATING GEOHYDROLOGIC FACTORS THAT AFFECT THE EXTENT OF CONTRIBUTING AREAS

The purposes of this section of the report are (1) to demonstrate the use of selected methods for estimating contributing areas of wells in stratified-drift, river-valley aquifers and (2) to show how variations in geohydrologic factors can effect the size and shape of the contributing area of a well in this setting. The techniques that will be demonstrated and the geohydrologic factors that will be tested are summarized below.

Selected techniques	Geohydrologic factors
Analytical mathematical	Well discharge
Two-dimensional numerical	Aquifer recharge
Three-dimensional numerical	Streambed permeability
	Aquifer permeability
	Proximity of well to source of induced infiltration
	Well penetration

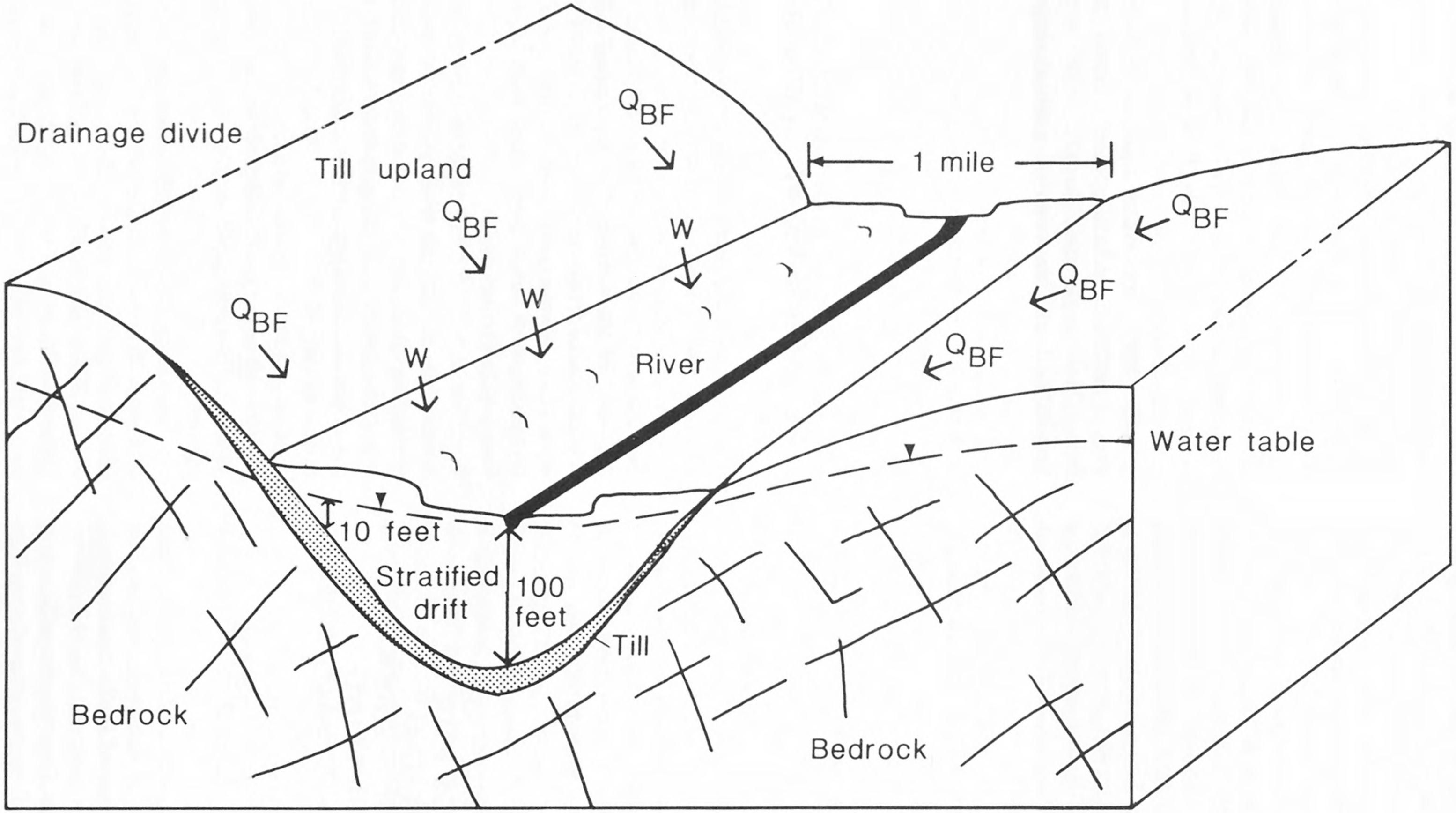
The most important aquifers in New England are unconfined, stratified-drift, river-valley aquifers. Most high yield supply wells in the region are located in this type of geohydrologic setting. For this reason, the contributing area analyses will concentrate on this type of setting. A detailed description of a hypothetical glacial-drift, river-valley aquifer that will form the basis for the following analyses is given in the next section of the report.

Description of a Generalized Glacial-Drift, River-Valley Aquifer System

The generalized aquifer is made up of stratified-drift deposits in which there are no extensive confining layers, and ground water exists everywhere under unconfined conditions. The drift deposits fill the bottom of a U-shaped valley cut in crystalline bedrock as shown in figure 11. A layer of relatively impermeable till forms a discontinuous layer between the drift and bedrock and over bedrock in upland areas.

The stratified-drift deposits are approximately 1 mi wide across the valley floor, extend for several miles along the river valley, and have a saturated thickness that ranges from about 20 ft near the till/drift boundary at the valley walls to 100 ft in the center of the valley. Aquifer hydraulic conductivity varies from about 10 ft/d along the till/drift boundary to 100 ft/d in the center of the valley. Specific yield equals 0.2 throughout the aquifer.

Recharge from precipitation averages 2 ft/yr, recharge from surface-water and ground-water runoff originating in the till uplands bordering the valley fill is assumed to be 0.6 (ft/yr)/mi^2 of till upland. Discharge from the aquifer is to a river that lies atop and is in hydraulic connection with the stratified-drift deposits through a permeable streambed. The river has a relatively flat gradient, with bottom deposits that have a permeability of 2 ft/d and a thickness of 2 ft.



EXPLANATION

W = 2 feet per year

Q_{BF} = 0.6 foot per year per square mile

Figure 11.--Geohydrologic features of the generalized stratified-drift, river-valley aquifer addressed in the model analyses.

The bottom of the generalized system is defined as the contact between stratified drift and till and is assumed to be an impermeable or no-flow boundary. In reality, there is probably some flow across this type of boundary; but because of the large contrast in permeability between the stratified drift and till, this flow is assumed to be negligible. The top of the aquifer is the water table, which is a free-surface boundary that can move up or down depending upon the balance of stresses within the aquifer. The lateral extent of the system is marked by the contact between saturated stratified drift and till or bedrock valley walls. Inflow of water from upland areas is assumed to occur along these boundaries.

In determining values for the geohydrologic factors used to describe this generalized aquifer, reference was made to several river-valley aquifer studies done in New England so that parameters would be reasonable and representative of actual field conditions. Examples include studies by Rosenshein and others (1968), Haeni (1978), Mazzaferro (1980), Morrissey (1983), Olimpio and de Lima (1984), and Dickerman and Ozbilgin (1985).

The following simulations will be concerned with the effects of a pumping well in the system described above. Various levels of stress and differing stress patterns will be investigated. The levels of stress that will be examined are defined by different pumping rates and different aquifer recharge rates. Other factors that will be analyzed involve the location of the well with respect to aquifer boundaries and variations in the hydraulic properties of the aquifer and streambed deposits.

Analytical-Model Analysis of the Contributing Area of a Pumped Well

This section of the report illustrates the use of an analytical model for estimating the contributing area of a well in the hypothetical stratified-drift, river-valley aquifer system. A description of the simplifying assumptions that must be made to use the analytical model and procedures for estimating a contributing area are included. The analysis shows how treatment of boundary conditions can affect the size and shape of the contributing area for a well.

The analytical model is based on the Theis nonequilibrium formula (Theis, 1940) as modified by image well theory for simulation of constant-head or impermeable boundary conditions (Ferris and others, 1962). The model provides corrections for partial penetration of the pumping well, for variations in transmissivity because of dewatering, and for the drawdowns of any nearby pumping wells.

The model requires the aquifer to be idealized as a rectangular area defined by various combinations of impermeable-barrier, line-source constant-head and "open" or infinite boundary configurations. The model is programmed in a code that is suitable for use on a variety of computers. A more detailed description of the model can be found in Mazzaferro and others (1979).

Procedure for Estimating a Contributing Area from Analytical-Model Results

The generalized procedure for applying an analytical model to estimate a contributing area is as follows:

(1) Make assumptions necessary to idealize the real aquifer for the analytical model analysis. For the analytical model used in this study, this included (a) idealizing the real aquifer as a rectangular area, (b) defining boundary conditions along each edge of the rectangle as either impermeable, constant-head or infinite, (c) defining of uniform hydraulic properties within the rectangle (transmissivity and storage coefficient) and, (d) specifying the rate and duration of pumping.

(2) Determine drawdowns caused by the pumping stress with the analytical model.

(3) Check to see if drawdowns predicted by the analytical model are small (10 percent or less) with respect to the saturated thickness of the unconfined aquifer. If they are, proceed to next step. If drawdowns are greater than 10 percent of saturated thickness, superposition may yield incorrect results. In this case, a different method of analysis should be utilized, such as numerical modeling, that can account for the changes in transmissivity caused by dewatering of the aquifer.

(4) Superimpose (subtract) the drawdowns determined with the analytical model on a water-table map of the natural system that does not reflect the pumping stress under study. If a conservatively large contributing area is desired, the prepumping water-table map should reflect lowest expected ground-water altitudes for the aquifer being studied.

(5) Construct a flow net from the resulting water-table map. For a flow net in homogeneous, isotropic media, the rules for graphic construction of flow nets are as follows: (a) flow lines and equipotential lines must intersect at right angles throughout the system; (b) equipotential lines must meet impermeable boundaries at right angles; and (c) equipotential lines must parallel constant-head boundaries.

(6) Determine the dividing flow lines between the regional flow field and the flow field around the pumping well.

(7) Estimate areas adjacent to the aquifer that may be included in the contributing area of the pumping well, such as till upland areas.

It is important to emphasize the limitations involved with using an analytical method, such as the one described here, for estimating the contributing area of a well in a stratified-drift, river-valley aquifer. The most important limitation is that simplification of the real system required for analytical model analysis can affect the size and shape of a contributing area and yield misleading results. These simplifications could be related to aquifer geometry, hydraulic properties, and especially to boundary conditions. An example of how treatment of boundary conditions in the analytical model can affect results is illustrated in the next section of the report.

Another limitation involved with use of analytical models for estimating contributing areas in unconfined stratified-drift, river-valley aquifers is that superposition is only an approximation. The degree to which this approximation affects results should be examined on a case-by-case basis. Finally, the prepumping water-table map upon which drawdowns are superimposed will have an affect on the size and shape of a contributing area. In many cases, these maps may not be available for extreme low-water conditions. As a result, the estimated contributing area for a well will not be as large as it might possibly be under low-water conditions.

Example of How to Determine Contributing Areas with an Analytical Model

The contributing area for a well pumping 1.0 Mgal/d in the hypothetical stratified-drift, river-valley aquifer was determined with an analytical model based upon the Theis equation and image well theory. In this simulation, the river was treated as a constant-head boundary which, in effect, acts as an unlimited source of water for the pumping well. In reality, this situation would occur where a river cuts through the entire saturated thickness of an aquifer (fully penetrating) or if a streambed and aquifer are so highly permeable they do not impede flow between the river and aquifer. The idealized version of the hypothetical aquifer for this boundary configuration is illustrated in figure 12.

In this simulation, the well was located near the center of the valley, 200 ft from the "river" and the contact between the stratified-drift deposit and the valley walls was treated as an impermeable boundary. Because the hypothetical aquifer is several miles long, the end boundaries in the model were left "open" to simulate infinite conditions. Transmissivity was assumed to average 7,500 ft^2/d and specific yield 0.2 over the entire area of the idealized aquifer.

The assumed prepumping water-table configuration for the hypothetical aquifer is shown in figure 13a. This water table was estimated by numerical-model-analysis conditions described in the section of the report entitled "Description of a generalized glacial-drift, river-valley aquifer system". Therefore, the water levels shown in figure 13a reflect all of the "real world" features such as recharge from precipitation and upland areas and hydraulic properties of the aquifer. Steady-state drawdowns determined with the analytical model, in which the river is treated as a constant head, are illustrated in figure 13b. The contributing area for the well and water table configuration that results when the drawdowns (fig. 13b) are superimposed on the prepumping water table (fig. 13a) are shown in figure 13c.

Comparison of figures 13b and 13c shows that the area of influence is much larger than the contributing area for the well, a point that has already been discussed in this report. Both the area of influence and the contributing area determined with this analytical model are limited to the well side of the river because of the way the river boundary has been simulated. A constant-head boundary acts as an unlimited source of water for the well and thus limits the spread of the cone of depression. Although this particular model doesn't indicate how much of the pumped water is obtained from the river, techniques are available for determining this quantity (Theis and Conover, 1963; Wilson, 1981).

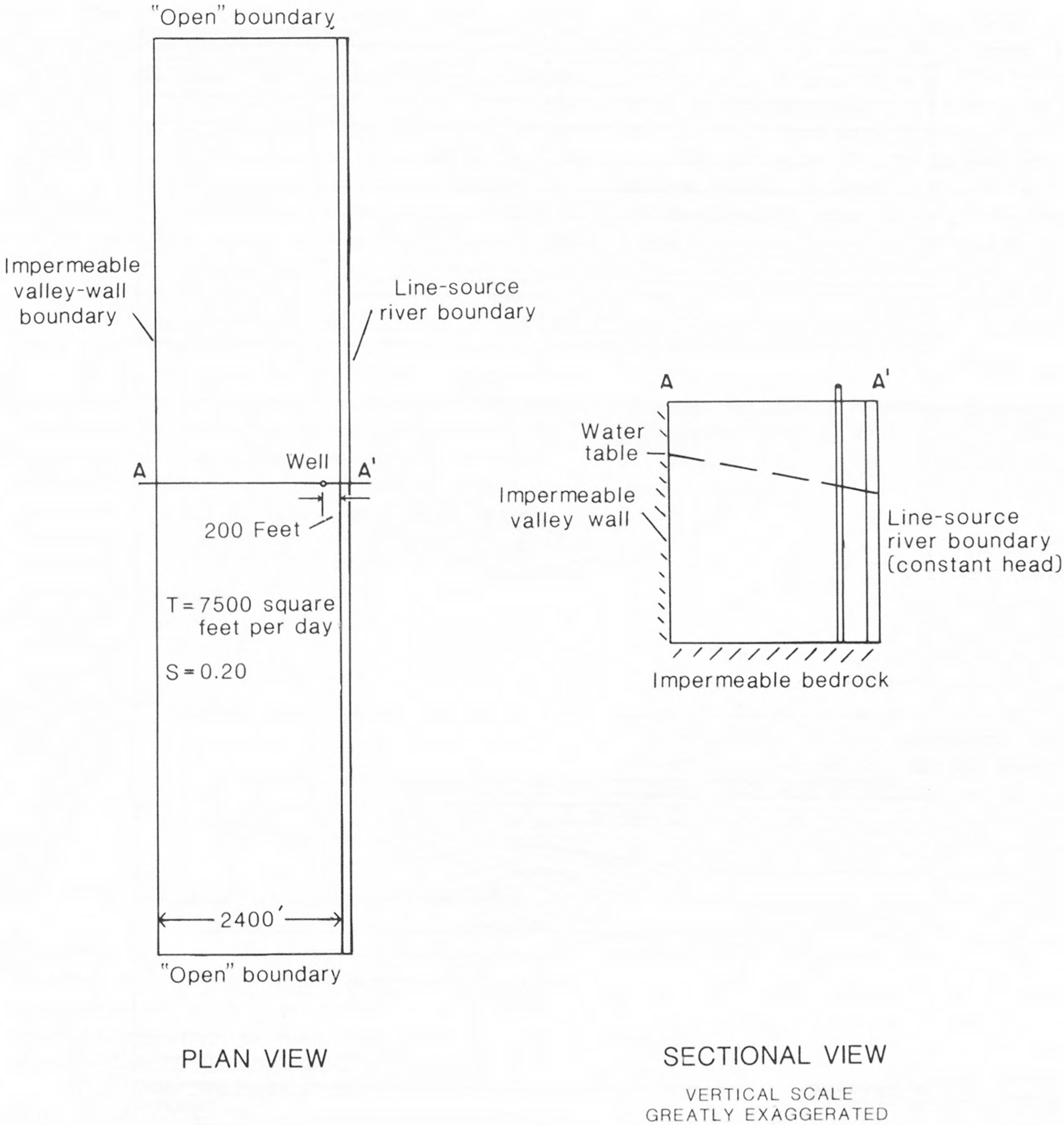


Figure 12.--Idealized version of the aquifer for analysis with an analytical model using a line-source river boundary.

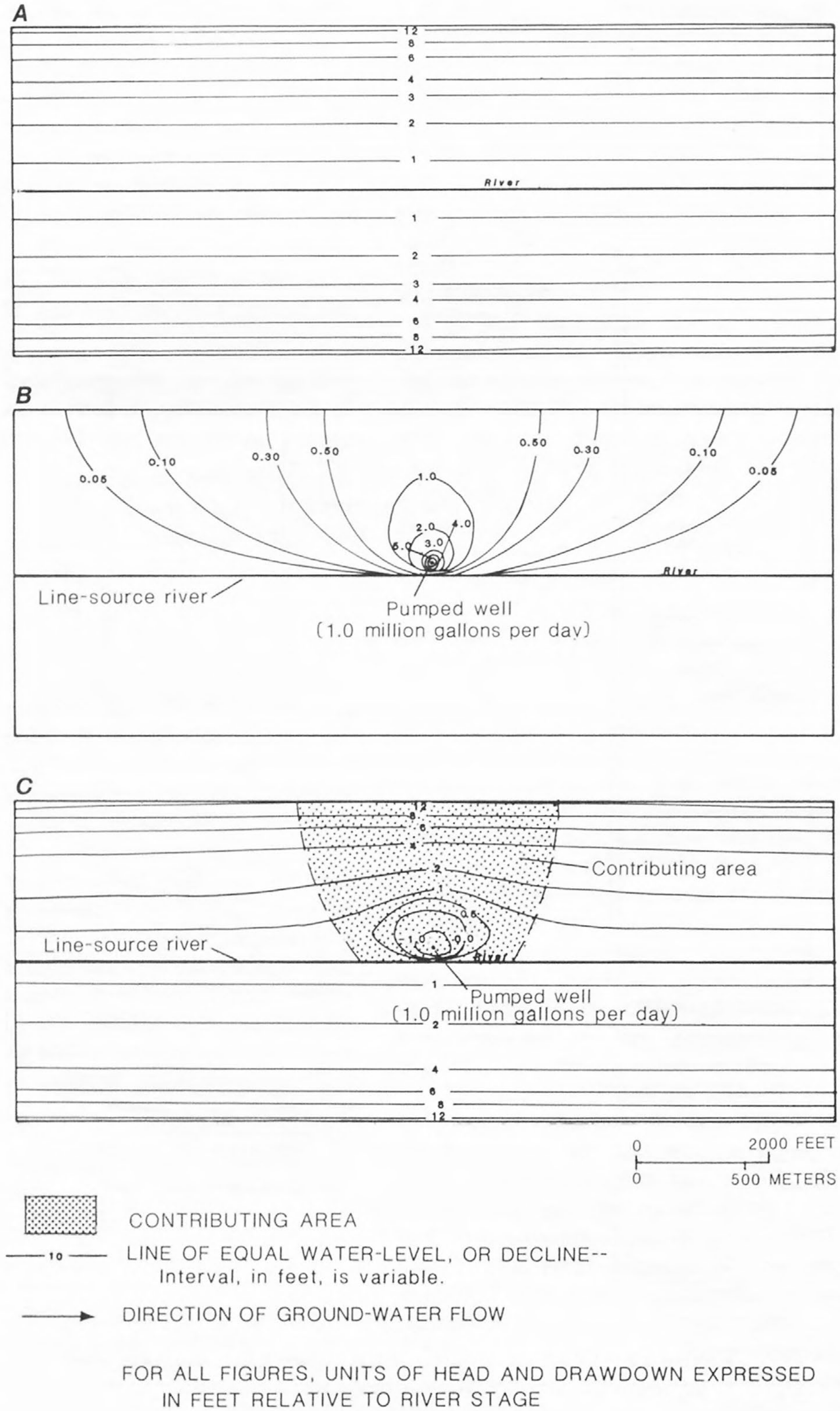


Figure 13.--Idealized aquifer showing (a) prepumping water-table altitudes, (b) drawdowns computed with the analytical model, and (c) water-table altitudes and contributing area resulting from superposition of (a) and (b) for the line-source river-boundary condition.

The suitability of a given boundary condition for analytical model analysis of contributing areas depends upon actual field conditions. In a situation where a surface-water body totally limits the spread of drawdown caused by a well, either because the surface water fully penetrates the aquifer or because of very high aquifer and streambed permeability, the use of constant-head river boundary would produce realistic results. However, if drawdowns caused by a well can extend beneath and beyond a surface-water body the constant-head boundary model would predict an unrealistic contributing area.

In a typical stratified-drift, river-valley aquifer in New England, the river partially penetrates the aquifer and has semipermeable bottom deposits. Under these conditions, drawdowns caused by a well can extend beneath and beyond the river. It follows that contributing areas for a well also can extend beneath and beyond a river. If a constant-head river-boundary analytical model is used to estimate a contributing area under these conditions, areas on the opposite side of the river would be overlooked. The use of a numerical model to simulate semipermeable stream deposits is illustrated in the next section of the report.

Two-Dimensional Numerical-Model Analysis of the Contributing Area of a Pumped Well

This section of the report describes the use of a two-dimensional numerical model to estimate the contributing area for a well in the hypothetical aquifer. The effects that variations in specified geohydrologic factors have on the size and shape of contributing areas is illustrated with the use of steady-state model simulations.

The finite difference model for aquifer simulation developed by Trescott and others (1976) was used to simulate ground-water flow in the hypothetical aquifer. The computer code is written in FORTRAN language and has been adapted for use on a wide variety of computers. This model has been used here for reasons of convenience. Several other computer codes are available that can be used to accomplish the same type of analysis.

One of the major differences between an analytical and numerical ground-water-flow model is that numerical models allow simulation of areal variations in the hydraulic properties of an aquifer. Analytical models assume that hydraulic properties of an aquifer are uniform throughout the entire aquifer area. Numerical-model analysis requires that the area of interest be divided (discretized) into small blocks. The hydraulic properties within each block are assumed to be uniform but may vary from block to block.

The grid network used to discretize the hypothetical aquifer is shown in figure 14. The blocks are assumed to extend through the the full saturated thickness of the aquifer and have a uniform areal spacing of 200 ft on a side. The grid network is designed to cover the hypothetical aquifer from valley wall to valley wall (5,000 ft) along a length of valley about 12,000 ft long.

The boundary between stratified drift and till beneath the aquifer was treated as a no-flow impermeable boundary in the model. Although there is probably some flux across this boundary in real aquifer systems, it is assumed to be small compared with flow in the aquifer.

The end boundaries that terminate the extent of the aquifer along the valley axis (at each end of the aquifer) are treated as impermeable boundaries in the numerical model because they are parallel to flow lines. Under actual field conditions, flux across these boundaries could occur in response to drawdown caused by a pumping stress. Pumping wells in the numerical model of the aquifer were located far enough from these end boundaries so that drawdowns and changes in flow direction along them were minimal to nonexistent.

The lateral boundaries of the model, located along the aquifer/valley wall contact, were treated as inflow boundaries to simulate inflow from the adjacent till uplands. Grid block locations where lateral inflow was simulated are shown in figure 14. The amount of inflow applied at each block was determined based upon the size of the adjacent upland drainage area and the estimate that average annual runoff was equal to 0.6 (ft/yr)/mi^2. The total upland area adjacent to the aquifer was assumed to be 4 mi^2, 2 mi^2 on each side of the valley. The upland area and the recharge along the boundary was distributed equally along each boundary block.

The river was simulated as a leaky boundary to allow flow between it and the aquifer. Grid block locations where leakage between the river and aquifer was simulated are shown in figure 14. The river was assumed to be 200 ft wide and 5 ft deep, and to have a flat gradient throughout the modeled area. The streambed deposits were assumed to be 2 ft thick with a permeability of 2 ft/d.

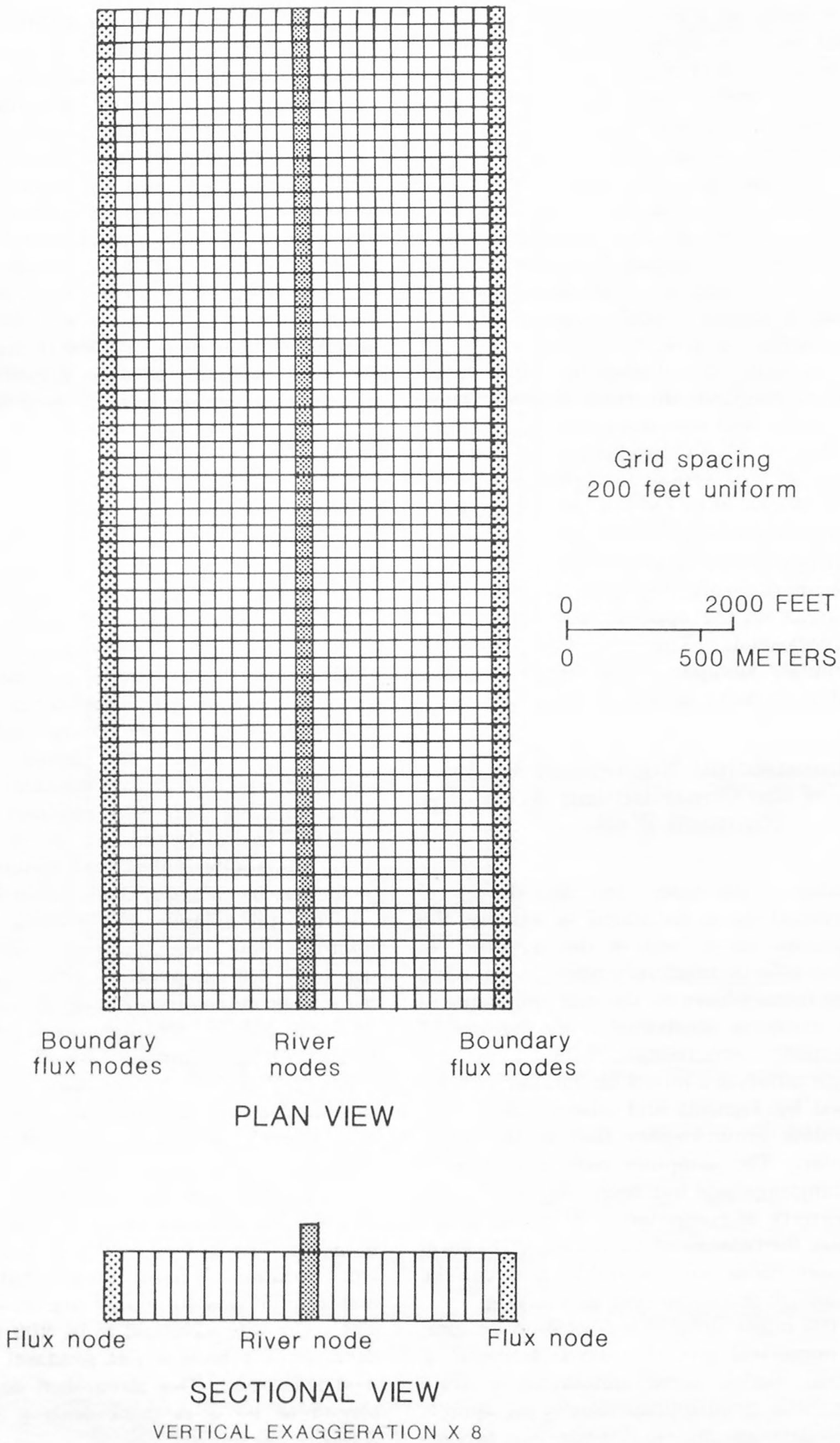


Figure 14.--Finite-difference grid used for the two-dimensional numerical-model analyses in (a) plan and (b) cross-sectional views.

The assumption of a flat river combined with flow across lateral boundaries causes ground-water contours in the aquifer to be exactly parallel to the river, a condition which usually does not exist in real aquifers. For the purposes of this study (the delineation of contributing areas), such assumed conditions are considered acceptable. However, it should be kept in mind that, under certain field conditions, the actual shape of contributing areas will be different from those shown here because of this assumption. This concept is illustrated in figure 15.

Figure 15a (same as fig. 9c) shows the contributing area for a well pumping 0.25 Mgal/d in an idealized stratified-drift, river-valley aquifer in which the river gradient is small. The geohydrologic conditions for the aquifer are shown in figure 8. The contributing area shown in figure 15b was determined for the same conditions except that the river has a gradient of 10 ft/mi. The effect that water-table configuration and river gradient have on the shape of the contributing area for the well is obvious when figures 15a and 15b are compared. It should be noted that, despite the difference in shape, the contributing areas in figures 15a and 15b are equal in size.

The two-dimensional numerical model allows simulation of water-table conditions by adjusting aquifer transmissivity for changes in the saturated thickness of the aquifer. To accomplish this, values of hydraulic conductivity, aquifer-bottom altitude, and starting water-table altitudes are assigned to each grid block in the model. In addition, recharge from precipitation was applied uniformly over each grid block in the model at the rate of 2 ft/yr.

With all of this information incorporated into suitable data arrays, the model was run until steady-state conditions were reached. The resulting water-table configuration is shown in figure 16. The corresponding steady-state water budget for the aquifer is shown in table 1.

The steady-state water-table conditions shown in figure 16 and the computed water budget seem reasonable when compared with the actual conditions found in the field. These results define the "average" long-term conditions for the hypothetical aquifer and will form the basis of comparison for the following examples in which the contributing area of a well will be estimated for various pumping rates, well locations, and aquifer hydraulic properties.

Table 1.--*Average annual water budget for the hypothetical aquifer computed with the two-dimensional numerical model*

Average annual water budget, in cubic feet per second			
In		Out	
Recharge from precipitation	= 3.4	Leakage to river	= 5.6
Inflow from till uplands	= 2.2		
Total in	= 5.6	Total out	= 5.6

Procedure for Estimating a Contributing Area from Numerical-Model Results

The general procedure used for delineating the contributing area of a well using the two-dimensional numerical-model results follows:

(1) Introduce a pumping well into the prepumping steady-state model. Steady-state pumping conditions were utilized because they illustrate the maximum impact of a given stress.

(2) Construct a flow net based on the steady-state water-table altitudes computed by the model. For a flow net in homogeneous, isotropic media, the rules for graphic construction of flow nets are as follows: (a) flow lines and equipotential lines must intersect at right angles throughout the system; (b) equipotential lines must meet impermeable boundaries at right angles; and (c) equipotential lines must parallel constant-head boundaries.

(3) Determine the dividing flow lines between the regional flow field and the flow field created by the pumping well on the well side of the river.

(4) Determine aquifer blocks where induced infiltration occurs and tabulate the amount of total infiltration.

(5) Construct dividing flow lines on the opposite side of the river perpendicular to water-table contours at aquifer block locations where ground-water flow passes under the river toward the pumping well.

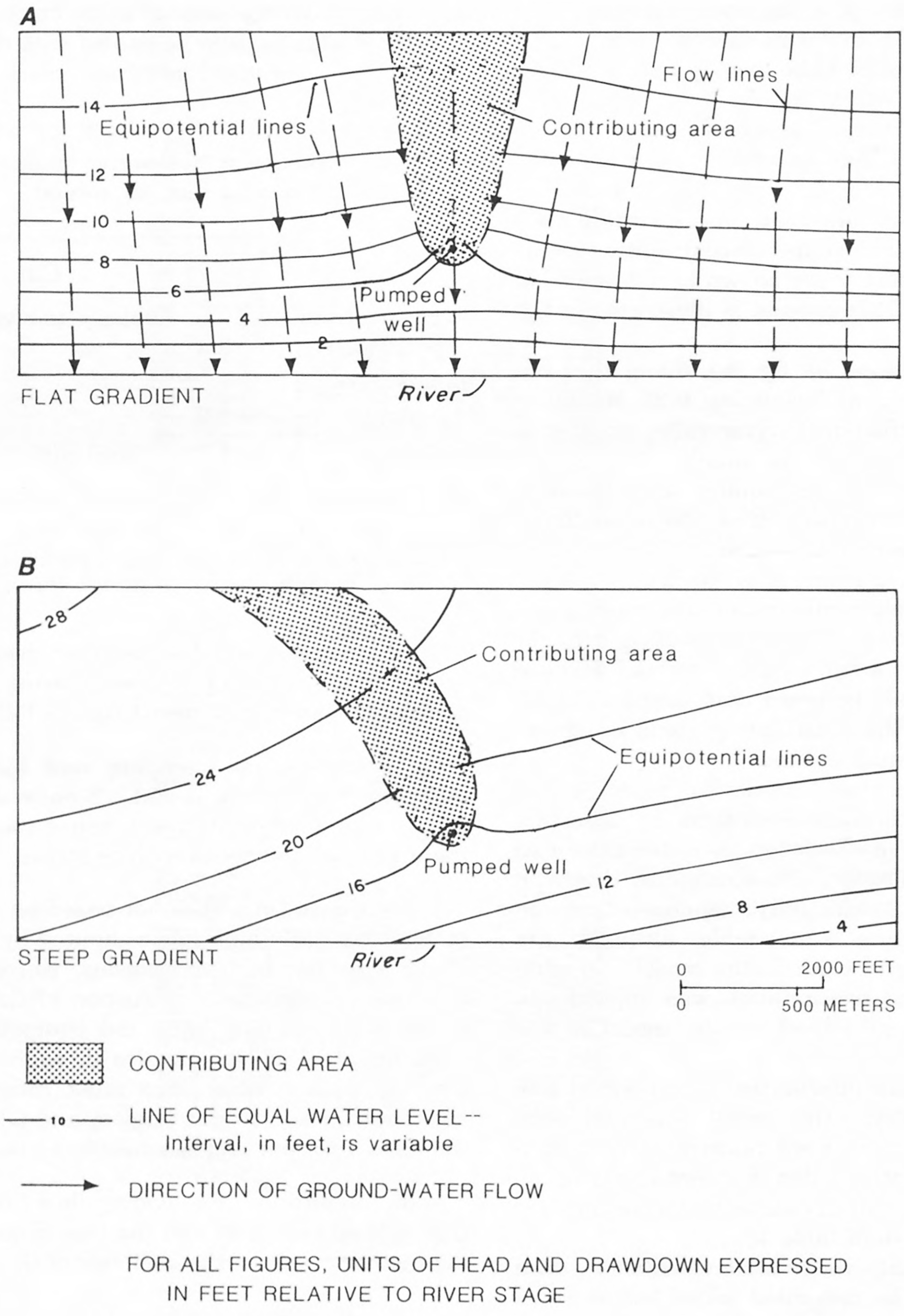
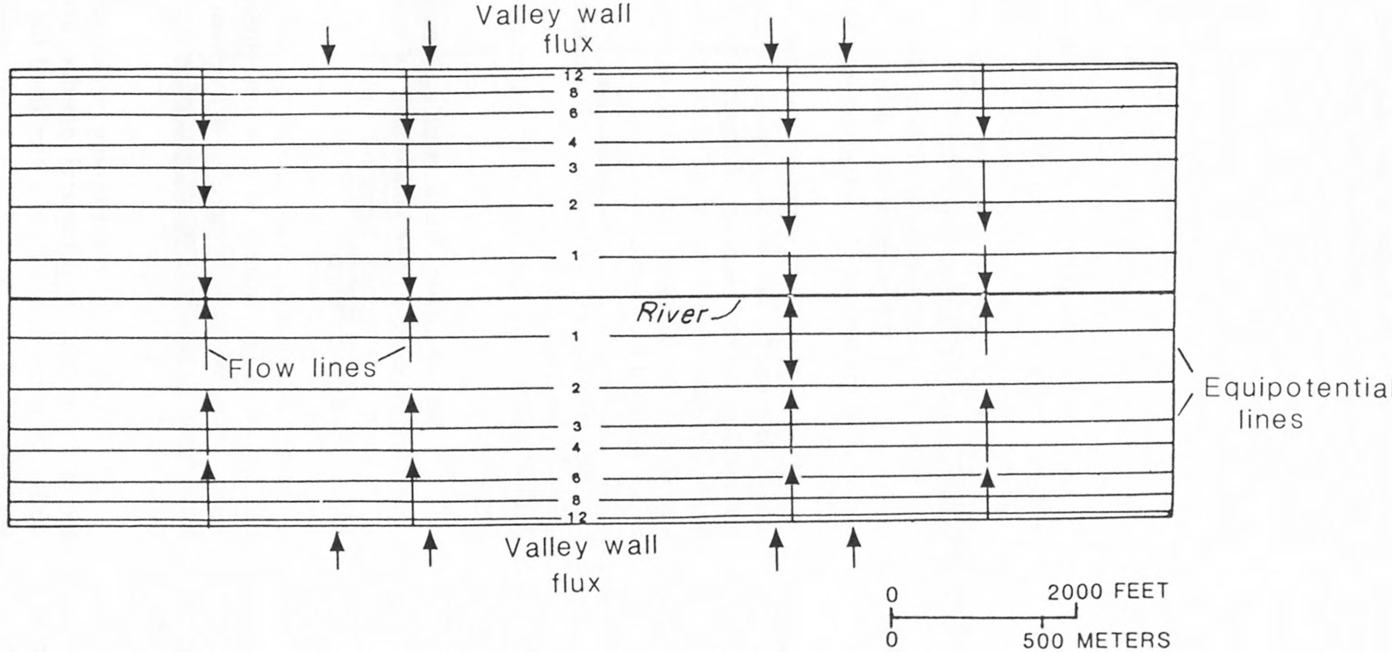


Figure 15.--Effect of water-table configuration and river gradient on the shape of a contributing area in a stratified-drift, river-valley aquifer.



—— 10 —— LINE OF EQUAL WATER LEVEL-- Interval, in feet, is variable.

——→ DIRECTION OF GROUND-WATER FLOW

FOR ALL FIGURES, UNITS OF HEAD AND DRAWDOWN EXPRESSED IN FEET RELATIVE TO RIVER STAGE

Figure 16.--Average steady-state water-table altitudes, without pumping, computed with the two-dimensional numerical model.

(6) Determine a water budget for the pumping well by summing the amount of recharge entering the contributing areas for the well. This includes recharge from precipitation, flux across the valley wall boundaries, and induced infiltration.

(7) Compare the amount of recharge entering the contributing area for the well with the pumping rate as a general check on the proper delineation of the contributing area. If the rates were not similar, an error would be indicated. (In general, if recharge into the contributing area was within ±5 percent of the pumping rate, the contributing area delineation was considered as being reasonable.)

Steady-State Analysis of Factors that Affect the Extent of Contributing Areas

The following sections of the report will show how variation in levels and patterns of stress will affect the size and shape of the contributing area for a well in the hypothetical aquifer. The types of geohydrologic factors that can be simulated with a two-dimensional model are illustrated.

Well discharge

To demonstrate the effects that variations in well discharge rate have on the extent of the contributing area and the sources of water to a well, steady-state simulations were run in which a well, located in the center of the aquifer and 200 ft from the river, was pumped at rates of 0.5, 1.0 and 2.0 Mgal/d. These pumping rates are typical of those that occur in the field.

The resulting steady-state water-table configurations and contributing areas are shown in figure 17. The sources of water derived by the well as a percentage of total water pumped, and the sizes of contributing areas for different pumping rates are shown graphically in figure 18.

When the pumping rate is increased from 0.5 to 2.0 Mgal/d, the total contributing area grows from 0.7 to 1.6 mi^2. The total contributing area consists of areas underlain by till adjacent to the aquifer and stratified-drift aquifer areas. The drift areas can be determined directly from the maps shown in figure 17. The size of contributing areas underlain by till adjacent to the aquifer are determined based on the assumptions that recharge to till is 0.6 $(ft/yr)/mi^2$, that 2 mi^2 of upland underlain by till border each side of the aquifer, and that this area and the resulting recharge are distributed evenly along the boundary of the aquifer.

Induced infiltration from the river increased from 16 to 55 percent of the water pumped by the well as the rate withdrawal increased from 0.5 to 2.0 Mgal/d. Conversely, the percentage of contribution from till and drift areas decreased from 84 to 45 percent of water pumped by the well over the same rates. In general, in this sequence of examples, the contributing area increased by a factor of about two and the amount of induced infiltration increased by a factor of about three when pumping increased by a factor of four.

Several important observations about the delineation of contributing areas about a pumping well can be made from the foregoing analyses:

(1) The maximum expected yield for a well or well field must be known to properly delineate the contributing area because changes in the well-discharge rate can cause significant change in the size of the contributing area and in the sources of water pumped by a well.

(2) If induced infiltration of surface water occurs, protection of contributing areas alone will not be sufficient to ensure good water quality at the well.

(3) Source areas for a well can extend beneath and beyond a river which acts as a source of infiltration and include adjacent upland areas on both sides of the valley.

(4) Contributing areas estimated for wells in the hypothetical aquifer are much different in shape than the simple circular drawdown or formula areas typically used for ground-water protection.

(5) The size of contributing areas estimated for wells in the hypothetical aquifer are much larger than the areas historically used for bacteriological or sanitary ground-water protection about wells in New England.

A summary of the areas currently used for ground-water protection around municipal-supply wells in sand and gravel aquifers in each of the New England states is included in table 2.

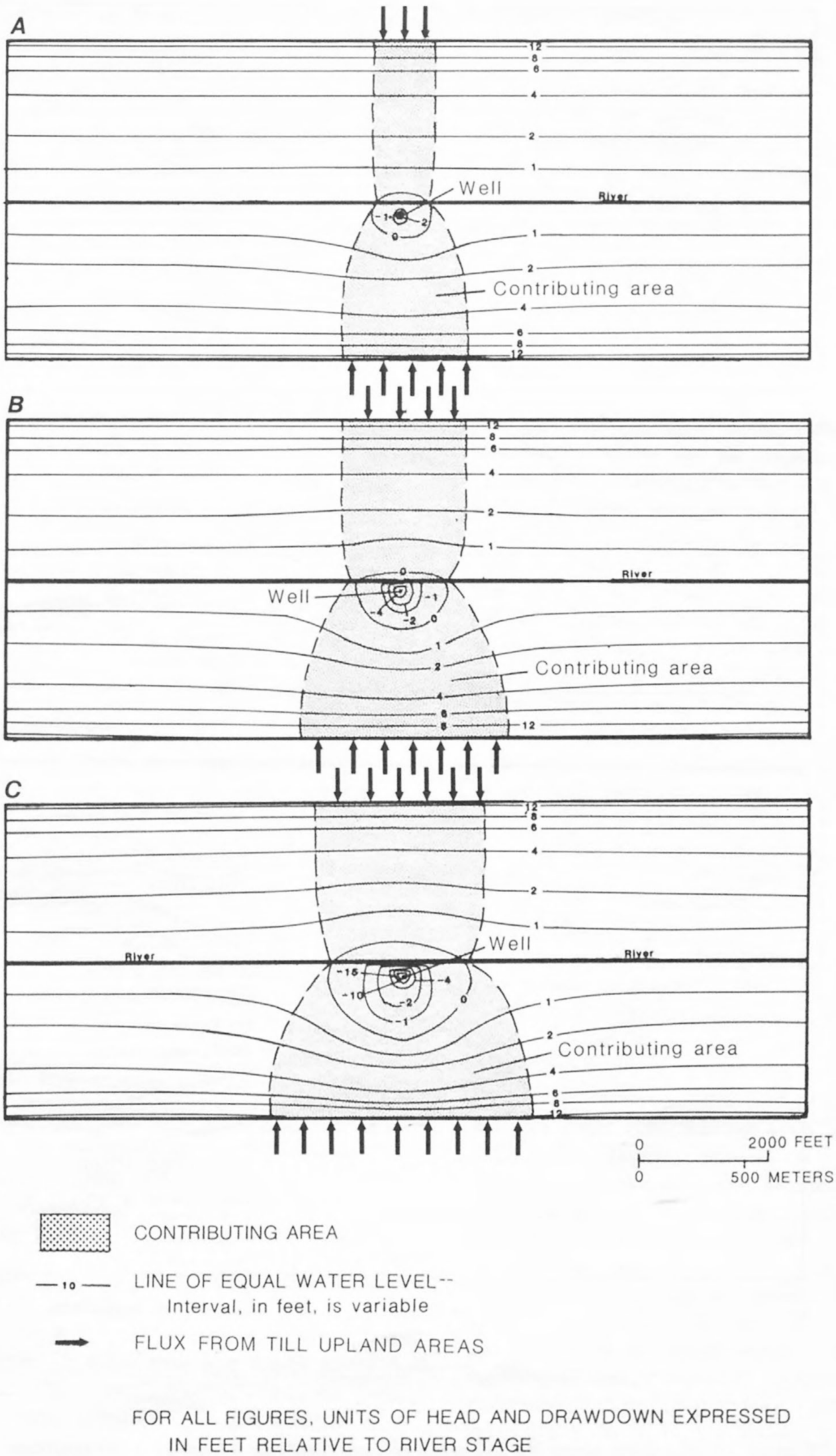


Figure 17.--Water-table altitudes and contributing areas of a well pumped at (a) 0.5, (b) 1.0, and (c) 2.0 million gallons per day.

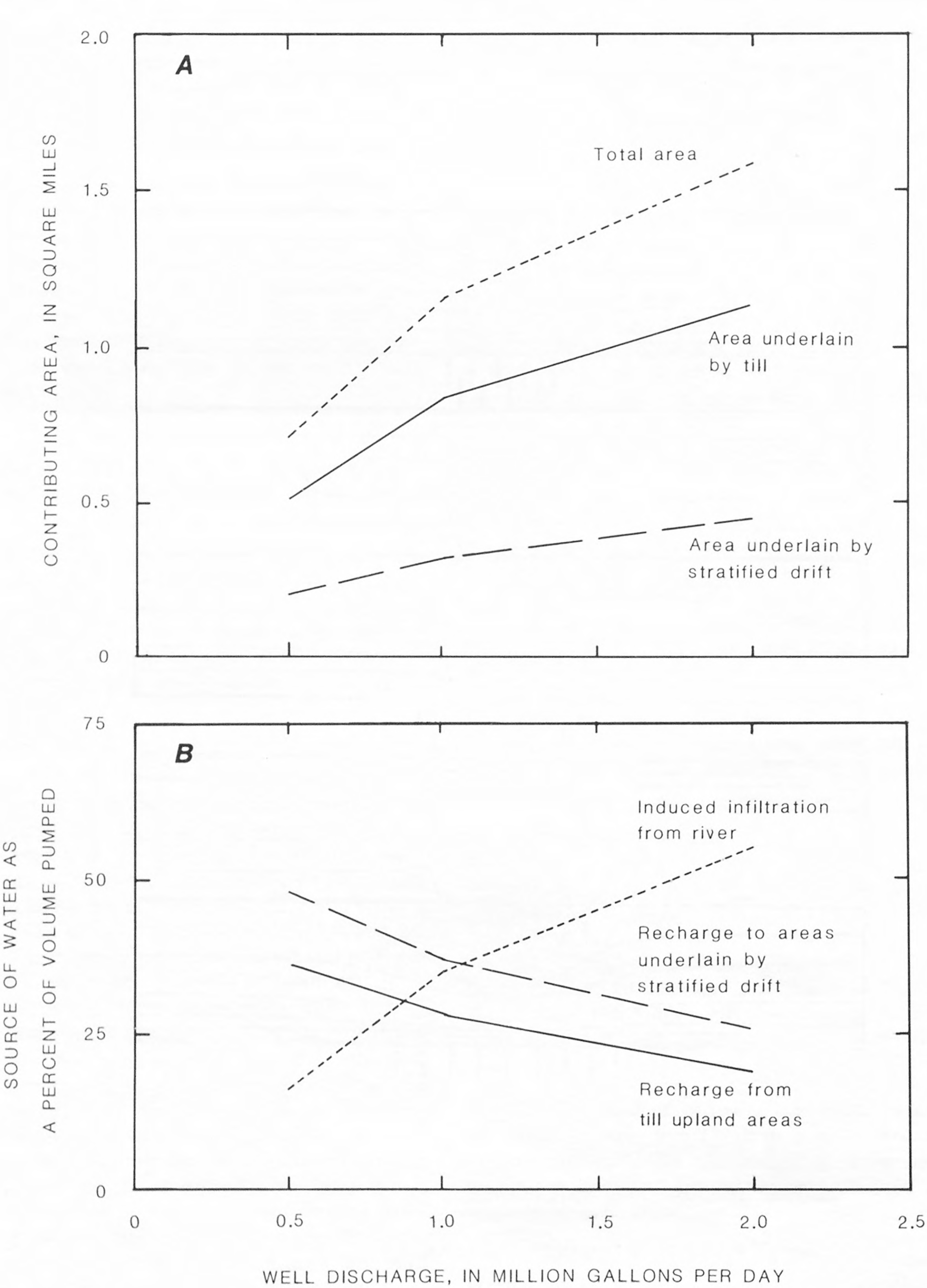


Figure 18.--Graphs showing (a) sizes of contributing areas and (b) sources of water pumped from the well as a function of well discharge.

Table 2.--*Summary of ground-water-protection areas for municipal-supply wells in New England*

State	Protection area
Connecticut	[1] 200-foot radius
Maine	[2] Not specified
Massachusetts	[3] 400-foot radius
New Hampshire	[4] 400-foot radius
Rhode Island	[5] 400-foot radius
Vermont	[6] 200-foot radius or APA

[1] For wells discharging at greater than 50 gallons per minute (Connecticut Public Health Code 19-13-B51, *Water Supply Regulations*).

[2] The actual radius is determined based upon an engineering report required for each new municipal well. This generally is interpreted to be a 400-foot radius. Municipal-supply wells in bedrock are required to have a 300-foot radius. (*Maine State Health Code 10-144A, Rules Related to Drinking Water.*)

[3] Radius of protection zone depends on well discharge. A well pumping 1.0 million gallons per day requires a 400-foot radius protection zone. (Commonwealth of Massachusetts, Department of Environmental Quality Engineering, *Guidelines for Public Water Systems.*)

[4] Protective radius for bacteriological contaminants. Protection zones for hazardous chemicals are more stringent but not specified exactly. (New Hampshire Water Supply and Pollution Control Commission guidelines WS 309.04 and 309.5. *Drinking Water Regulations, 1984.*)

[5] Recommended distance for gravel-packed wells. Distance may be modified at the discretion of the State depending upon site conditions. (Rhode Island Rules and Regulations pertaining to public drinking water R46-13 DWS Section 3.0.)

[6] Aquifer protection areas have been determined for 209 of 316 municipalities in the State of Vermont which utilize ground water. Aquifer protection areas range in size from 4 to 2,649 acres and average about 120 acres. *Vermont Aquifer Protection Area Reference Document, March 1983.*

Aquifer recharge

Variations in the recharge rate to an aquifer can occur for several reasons including natural seasonal fluctuations in precipitation and evapotranspiration, longer term climatic changes or urbanization. Resulting changes in water levels and ground-water flow will affect the contributing area to a well. To illustrate these effects, a series of simulations were run in which recharge to the hypothetical aquifer was varied.

Steady-state simulations were made in which the average rate of recharge from precipitation of 24 in/yr was varied by a factor of 0.5 and 1.5 with proportional changes in the rate of recharge from areas underlain by till adjacent to the aquifer. These values represent the approximate expected range in the average annual recharge rates to stratified-drift aquifers in New England. In addition, to imitate an extreme drought condition, a simulation was made of a 6-month period in which all recharge ceased and the river "dried up". In all of these simulations the well was located 200 ft from the river in the center of the aquifer and pumped at a rate of 1.0 Mgal/d.

The resulting water-table contours and contributing areas for the steady-state simulations of maximum, average, and minimum annual recharge rates are shown in figure 19.

The percentage of pumpage derived from different sources and the sizes of contributing areas for the various recharge rates are shown graphically in figure 20.

Variations in the average annual recharge rate cause a change in the amount of water flowing through the hypothetical aquifer, and in the ground-water gradient from the valley wall to the river. When recharge is at a maximum (1.5 X average), the ambient flow and gradient are greatest and the total contributing area for the well is 0.9 mi^2. When average annual recharge is at a minimum (0.5 X average) the ambient flow and gradient also are at a minimum and the contributing area for the well covers 1.7 mi^2.

The sources of water to the well also change as the recharge rate is varied. When recharge is at a maximum, induced infiltration makes up 26 percent of pumped water. At the minimum recharge rate, induced infiltration comprises 56 percent of pumped water. When less water is available from recharge (decrease in recharge from precipitation and inflow from till covered areas adjacent to the aquifer), the contributing area

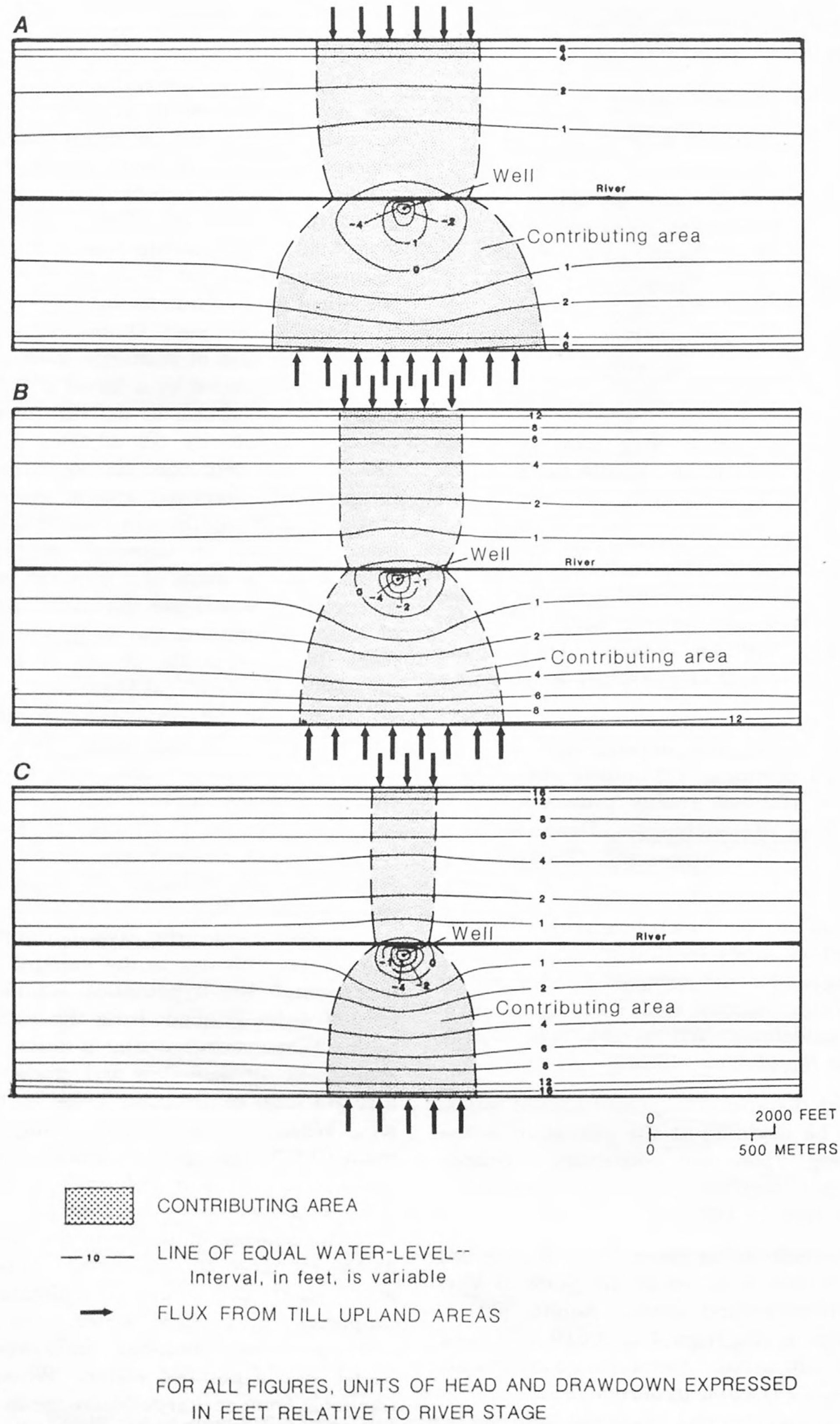


Figure 19.--Water-table altitudes and contributing areas of a well pumped at 1.0 million gallons per day for (a) 0.5 times average, (b) average, and (c) 1.5 times average recharge.

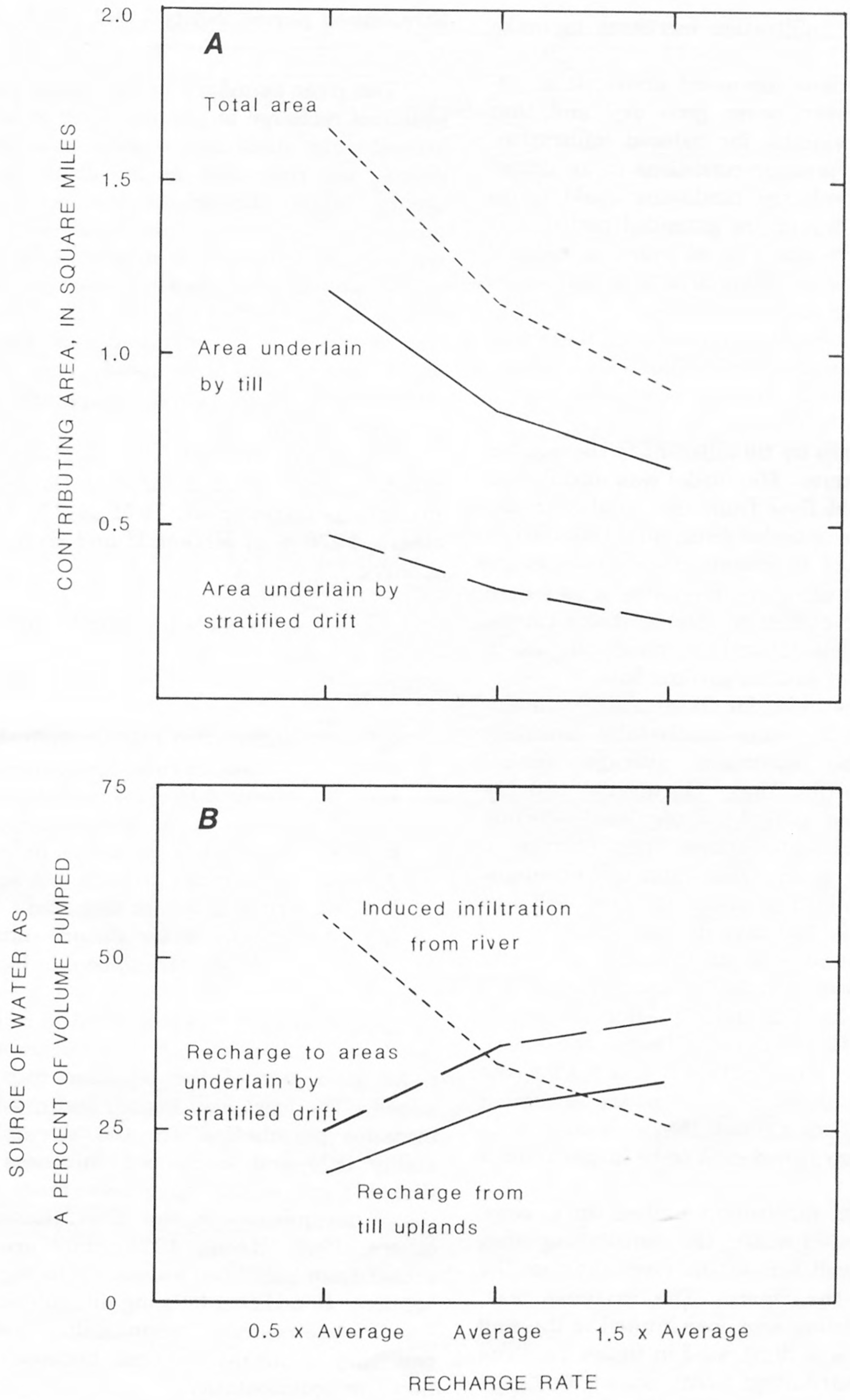


Figure 20.--Graphs showing (a) sizes of contributing areas and (b) sources of water pumped from the well as a function of recharge rate.

grows and induced infiltration increases to make up for the deficit.

In the simulations discussed above, it is assumed that the river never goes dry and that water is always available for induced infiltration. Depending upon hydrologic conditions in an actual basin, minimum recharge conditions could cause surface waters to dry up for extended periods. If this happened, there would be no source of induced infiltration so the contributing area to a well would increase to make up the deficit.

A 180-day transient simulation of the hypothetical aquifer was designed to illustrate the condition described above. During the period of simulation, recharge from precipitation and inflow from areas underlain by till adjacent to the aquifer were set equal to zero. The model was modified so ground water could flow from the aquifer to the river but not in the opposite direction. This modification was designed to imitate a condition where evapotranspiration along the river (the area where the water table is closest to land surface) causes ground water to flow toward the river, but not in sufficient amount to sustain surface flow.

The initial conditions for the transient simulation were the steady-state water-table altitudes computed for the minimum average annual recharge condition (fig. 19a). During the 180-day transient-simulation period, water levels decline steadily as ground water moves from storage to the well and river area. The water-table configurations and contributing areas for the well are shown after 30, 90, 180 days in figure 21.

From the initial size of 0.9 mi^2, the contributing area grows in time to a maximum of 1.7 mi^2 after 180 days of "drought". After 180 days, the well diverts flow from practically the entire area of aquifer. (It should be noted that the method of simulation did not account for storage in upland areas. This caused the estimated contributing area in stratified drift to be larger than it might actually be.)

When induced infiltration makes up a large proportion of pumped water, the contributing area is larger on the well side of the river than on the opposite side of the river. The extreme case, where the contributing area was limited to the well side of the river, was illustrated in figure 13. The shapes of the contributing areas shown in figure 21 reflect the lack of induced infiltration as they extend across the entire valley and are almost symmetrical along the axis of the river.

Streambed permeability

The river boundary in the model can act as a source of recharge to ground water or as a sink for ground-water discharge. Under nonpumping conditions, the river acts as the discharge point for ground water throughout the aquifer. When pumping lowers the ground-water level below the river stage, natural-flow directions in the vicinity of the well are reversed and surface water flows into the aquifer. If the aquifer head falls below the elevation of the stream bottom, flow from the river will reach a maximum steady rate provided all other factors, such as river stage and water temperature, remain the same.

In equation form, flow through the streambed can be expressed as a form of Darcy's law (see Prickett and Lonnquist, 1971 p. 33; Trescott and others, 1976 p. 4; McDonald and Harbaugh, 1984, p. 209):

$$Q' = (k'/b')\,A\,(h' - h) \qquad (1)$$

where:

Q' = infiltration rate through the streambed, in cubic feet per second;
k' = vertical hydraulic conductivity of the streambed, in feet per second;
b' = streambed thickness, in feet;
A = streambed area, in feet squared;
h' = river stage, in feet; and
h = ground-water altitude immediately below streambed, in feet

To simulate a leaky streambed in the numerical model, values for each of the parameters on the right hand side of the equation must be determined. The least well known and most difficult to measure parameters are the streambed permeability (k') and streambed thickness (b'). Although some efforts have been made to measure these parameters in the field (Rosenshein and others, 1968; Haeni, 1978) they are often estimated from published values or during model calibration. In addition to being difficult to measure in the field, streambed permeability and thickness can vary naturally in time because of scouring floods or sedimentation.

To test the effect of variation in streambed permeability on the size of the contributing area of a well in the hypothetical aquifer a series of simulations were run in which the ratio of streambed

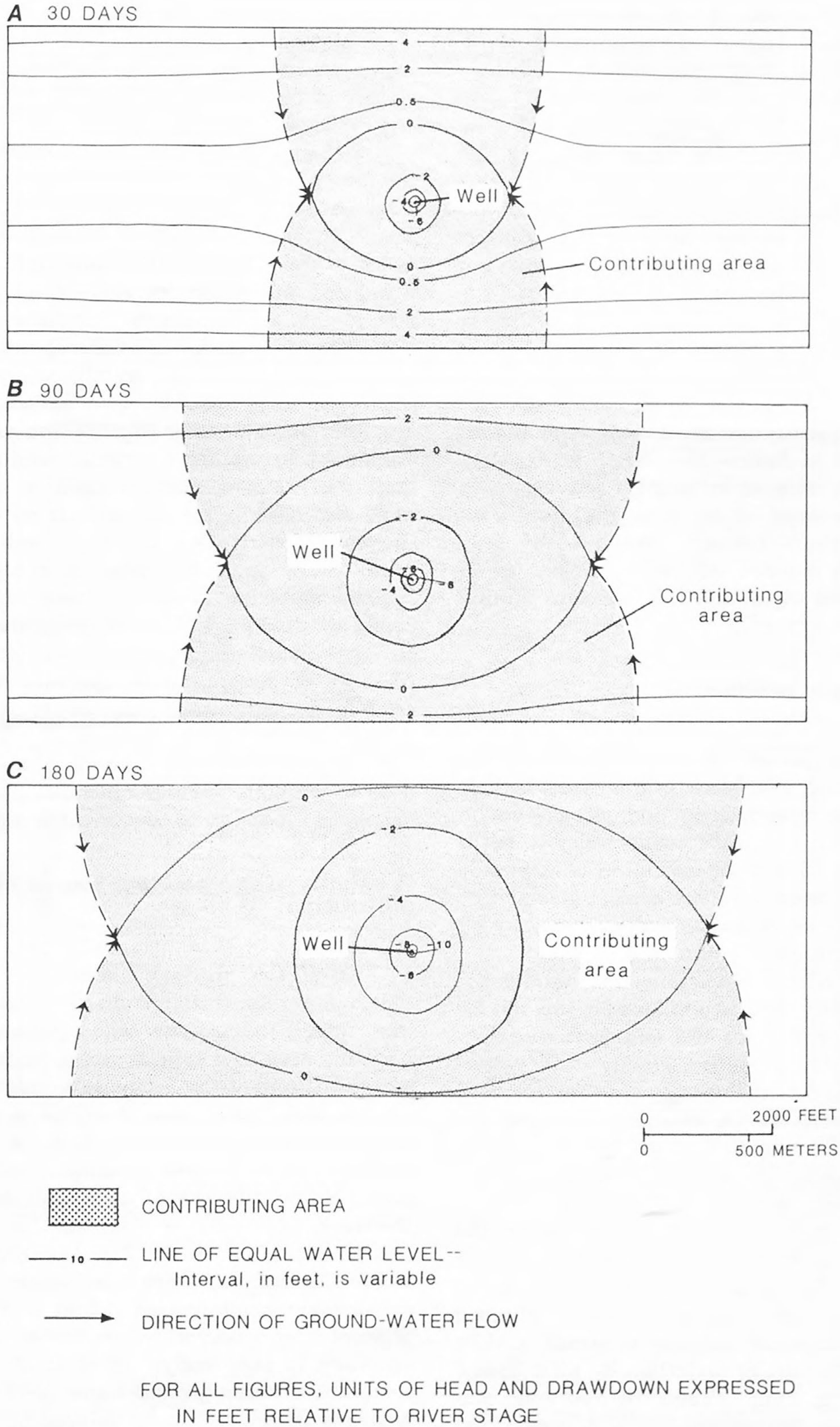


Figure 21.--Water-table configuration and contributing area of a well pumped at 1.0 million gallons per day after (a) 30, (b) 90, and (c) 180 days of drought.

permeability to thickness (k'/b') was set at 0.1, 1.0, and 10. This variation was assumed to cover the range of reasonably expected values.

Steady-state water-table contours and contributing areas for a well pumping 1.0 Mgal/d with different values of k'/b' are shown in figure 22. The variations in k'/b' cause changes in the water-table gradient from the valley wall to the river throughout the modeled area. The maximum head difference from the valley wall to the river during pumping is 13.1 ft when k'/b' is 0.1, 11.8 ft when k'/b' is 1.0, and 11.6 ft when k'/b' is 10.0.

Variations in k'/b' cause substantial variation in the rate of induced infiltration from the river and consequently on the size of contributing areas, as shown in figure 23. When k'/b' is a minimum (0.10), induced infiltration provides only 8 percent of pumped water and the total contributing area covers 1.8 mi^2. When k'/b' is a maximum (10.0) induced infiltration makes up 45 percent of pumped water and the total contributing area is 0.9 mi^2.

Aquifer hydraulic conductivity

Hydraulic properties of the aquifer that must be assigned to each grid block in the model include aquifer hydraulic conductivity and storage coefficient. In general, hydraulic conductivity is not a very well known parameter and often is estimated during model calibration. In a typical glacial-drift aquifer, hydraulic conductivity values can vary by an order of magnitude or more.

To test the effects of variations in aquifer hydraulic conductivity, average values for the aquifer were increased by a factor of 3 and decreased by a factor of 0.3. The resulting steady-state water-table contours and contributing areas for the well are shown in figure 24. A summary of variations in the sizes of contributing areas and sources of water pumped from the well as a function of hydraulic conductivity is shown in figure 25.

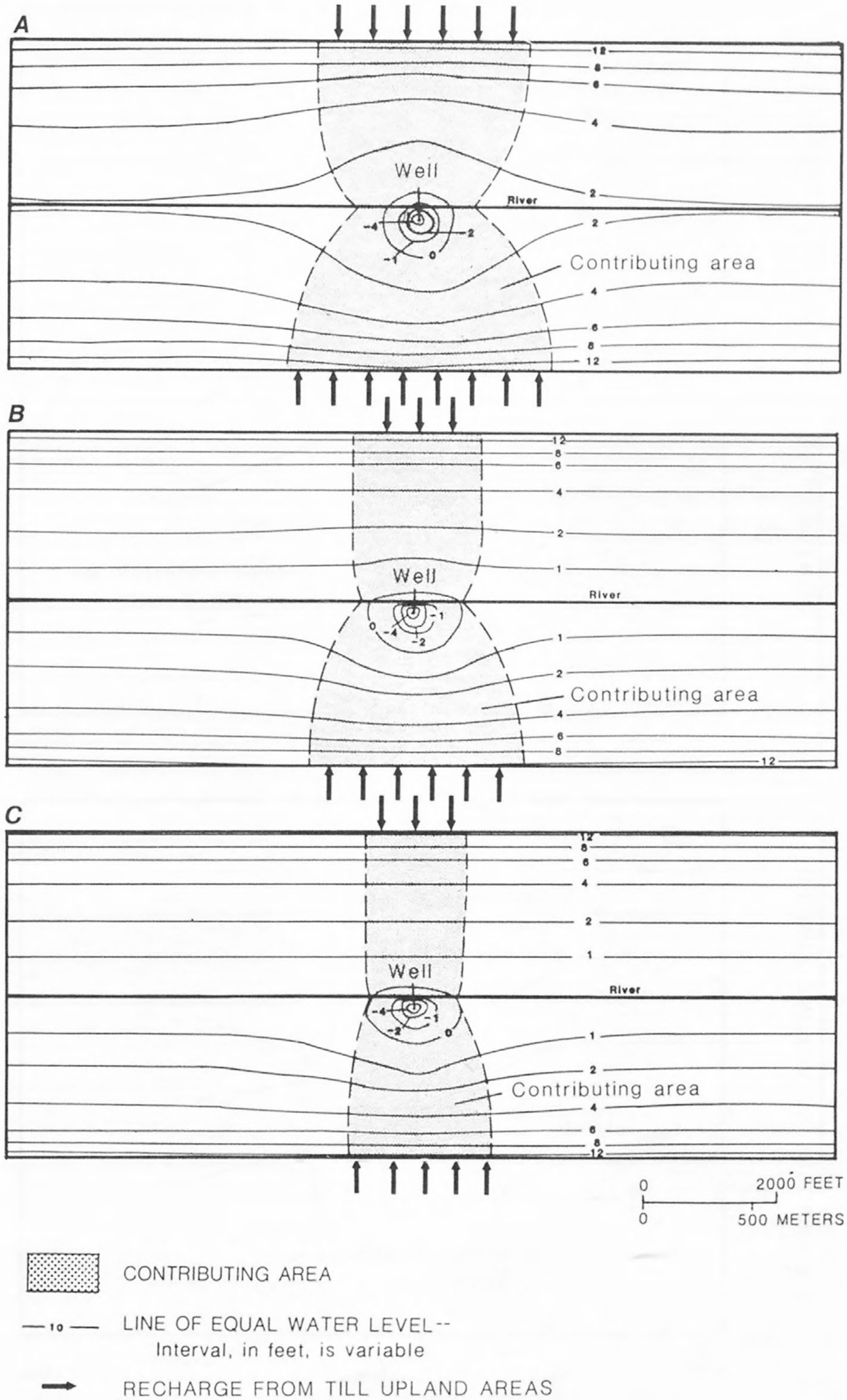
When the hydraulic conductivity is at the maximum (3 X average), the contributing area is largest 1.3 mi^2 for these simulations (fig. 24a-c) and the predominant sources of water pumped from the well are areal recharge to stratified drift and recharge from areas underlain by till adjacent to the aquifer (fig. 25b). When the hydraulic conductivity is at the minimum (0.3 X average), the contributing area is smallest (1.0 mi^2) and the major source of pumped water is induced infiltration from the river (fig. 25b). Decreasing the average hydraulic conductivity by a factor of 0.3 has a greater effect on the size contributing area and sources of pumped water (fig. 25) than an equivalent increase.

A change in the hydraulic conductivity of the aquifer by one order of magnitude, from 0.3 X average to 3.0 X average, causes a 44 percent increase in the size of the area that contributes water to the well. At the same time, the amount of induced infiltration decreases from 44 to 26 percent of the water pumped from the well. When hydraulic conductivity is at a minimum (0.3 average) drawdowns caused by the well are greatest which, in turn, causes more induced infiltration (fig. 25b) and a smaller contributing area (fig. 24a) Variations in aquifer hydraulic conductivity other than the uniform changes used in this analysis could also have interesting effects on the sizes and shapes of contributing areas. A well located in a linear coarse-grained deposit surrounded by fine-grained materials (esker in lacustrine or marine deposits) could have a contributing area with much different shape than those illustrated here. The presence of discontinuous layers of low hydraulic conductivity (silt or clay) also could change the size and distort the shape of a contributing area. As discussed earlier, the numerical models can be used to simulate such complicated patterns of hydraulic conductivity in two or three dimensions.

Proximity of the well to a source of induced infiltration

All of the previous simulations have shown that induced infiltration from the river is an important factor to consider when delineating a contributing area in a typical glacial-drift, river-valley aquifer. In all of the previous simulations the well was located 200 ft from the river, a distance that is commonly observed in the field. A question naturally arises about the quantity of induced infiltration if the well is located at greater distances from the river.

D. L. Mazzaferro (U.S. Geological Survey, written commun., 1985) delineated contributing areas for a well located 1,500 ft from a leaky streambed in a hypothetical aquifer similar to the one used in this study. In most of those simulations, there was a ground-water divide between the well and the river and no induced infiltration from the river was occurring. The source of water to the well in Mazzaferro's hypothetical model was



FOR ALL FIGURES, UNITS OF HEAD AND DRAWDOWN EXPRESSED IN FEET RELATIVE TO RIVER STAGE

Figure 22.--Water-table altitudes and contributing areas of a well pumped at 1.0 million gallons per day with streambed coefficients (k'/b') of (a) 0.1, (b) 1.0, and (c) 10.0.

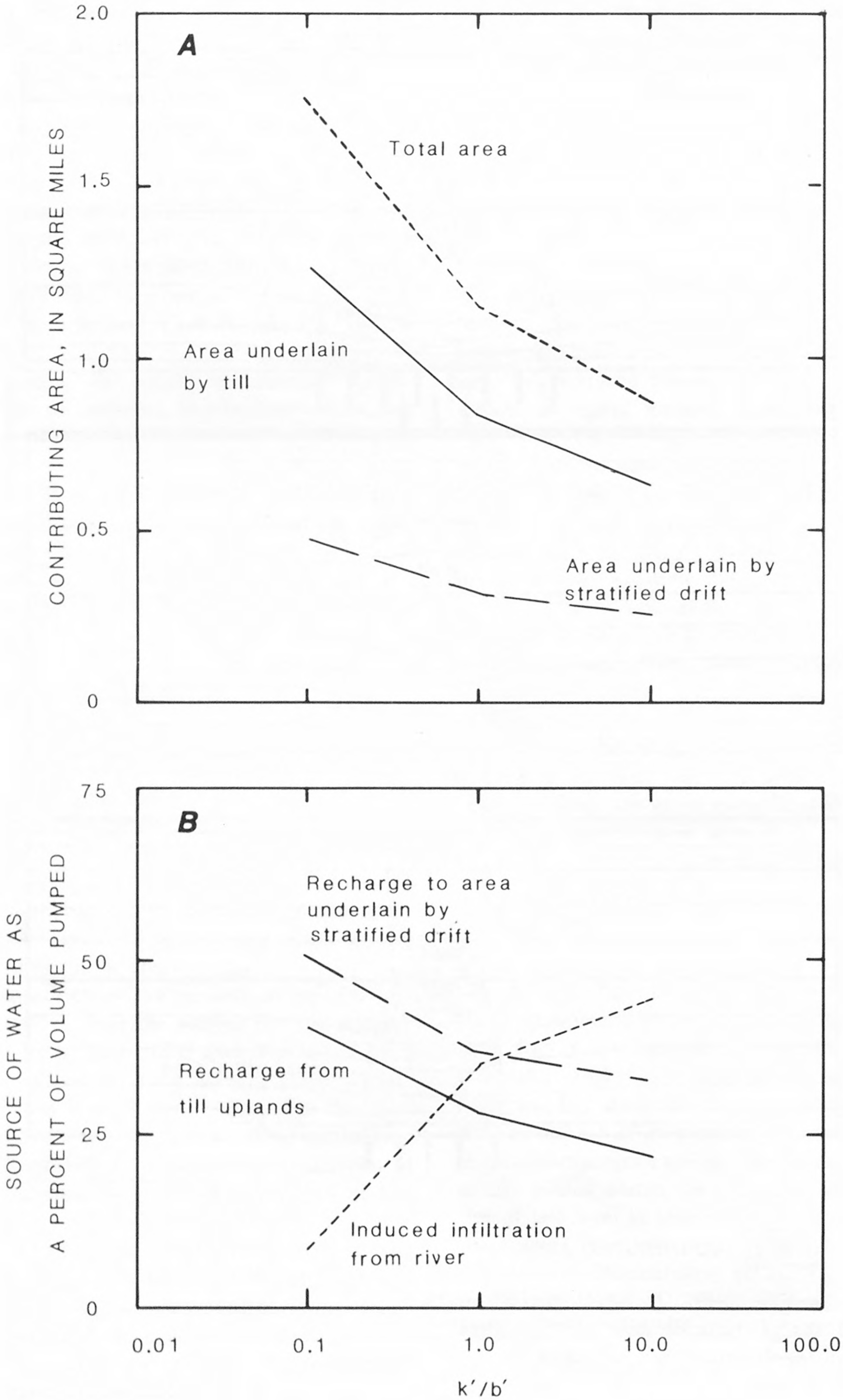


Figure 23.--Graphs showing (a) sizes of contributing areas, and (b) sources of water pumped from the well as a function of streambed coefficient (k'/b').

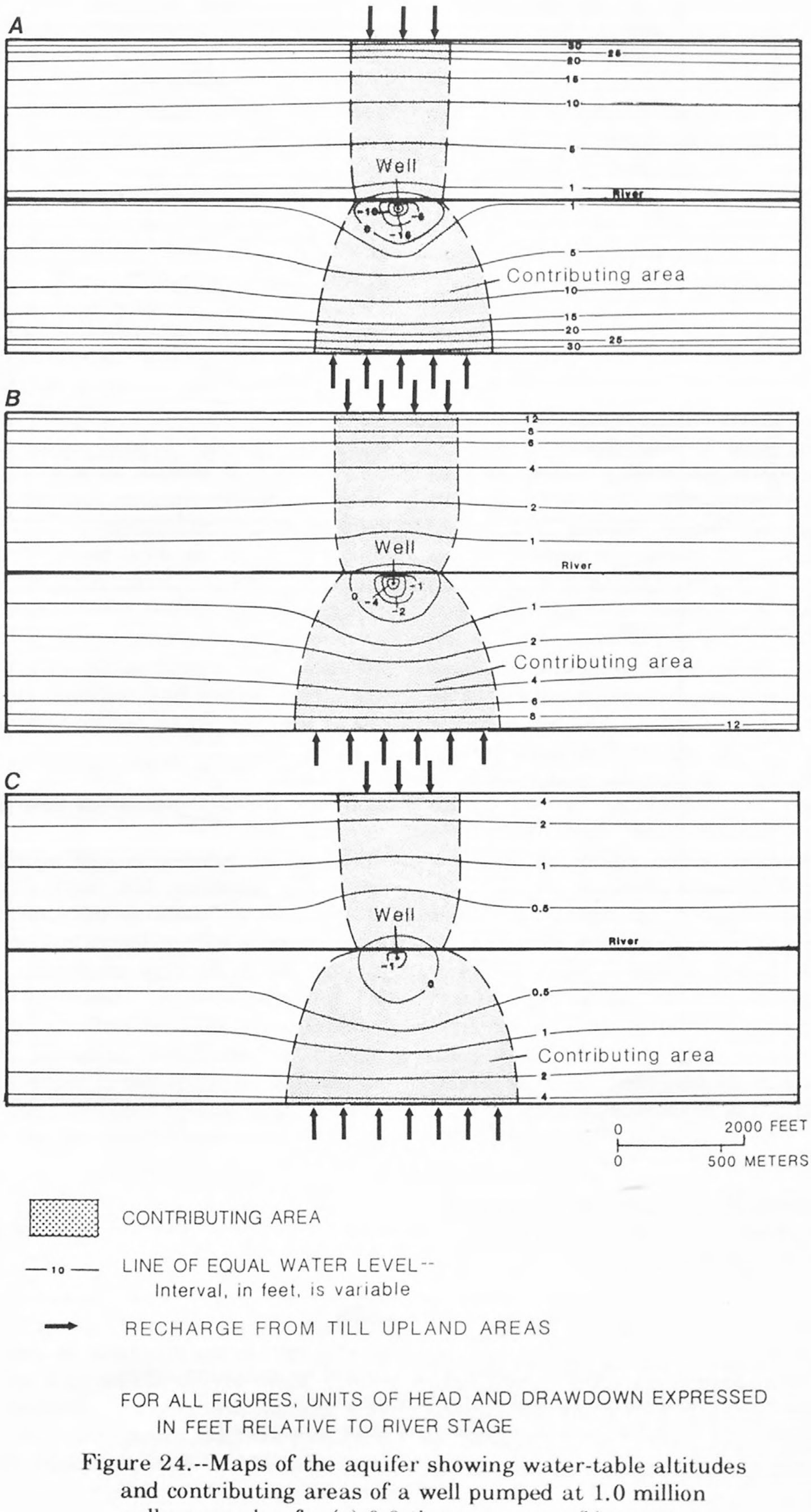


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Figure 24.--Maps of the aquifer showing water-table altitudes and contributing areas of a well pumped at 1.0 million gallons per day for (a) 0.3 times average, (b) average, and (c) 3.0 times average hydraulic conductivity.

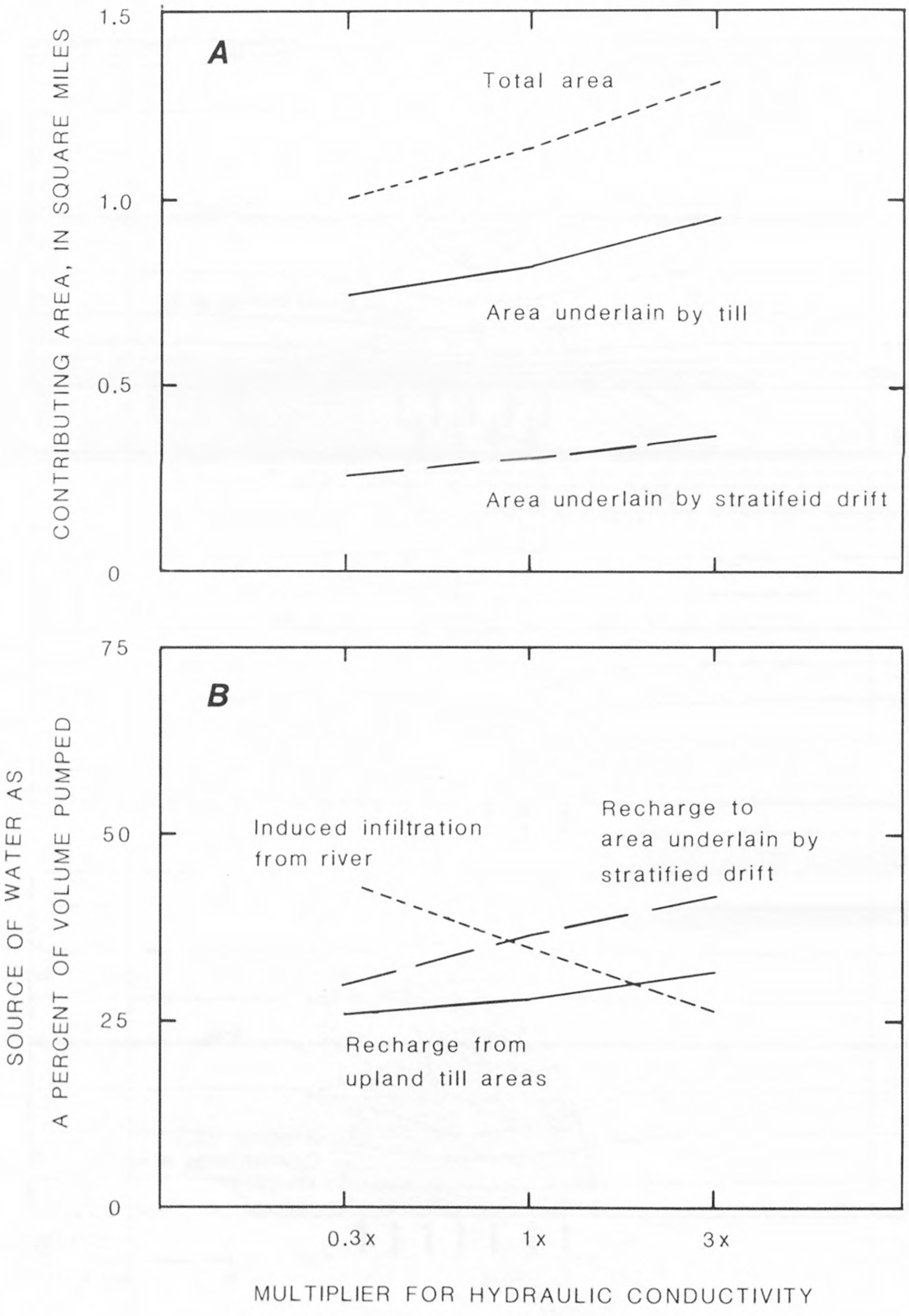

Figure 25.--Graphs showing (a) sizes of contributing areas and (b) sources of water pumped from the well as a function of aquifer hydraulic conductivity.

ground-water capture (reduced discharge to the river on the well side of the river).

To investigate how proximity of the well to the river affects the contributing area for a well, a series of simulations were made in which a well pumping 0.5 Mgal/d was located at 200, 600, and 1,400 ft from the river.

With the well located 200 ft from the river, induced infiltration made up 16 percent of the pumped water and the total contributing area was 0.7 mi^2 (fig. 26a). When the well is located 600 ft from the river, pumped water is derived entirely from captured flow in the aquifer (fig. 26b). Some of the captured flow is from the opposite side of the river but it is difficult to determine the exact shape of this area.

When the well is located 1,400 ft from the river (fig. 26c), there is no induced infiltration and no contribution from the opposite side of the river. In this case, the total contributing area is 0.98 mi^2, 0.24 mi^2 in drift and 0.74 mi^2 in till. Water pumped by the well is derived entirely of ground-water flow that is captured before it discharges to the river. The ultimate source of this ground-water flow is areal recharge from precipitation on the stratified-drift aquifer and recharge to the aquifer from areas underlain by till adjacent to the aquifer.

Despite the fact that no induced infiltration occurs when the well is located 1,400 ft from the river (fig. 26c) there is still an impact on streamflow. The reason for this is because the well captures ground-water flow that normally would discharge to the river. In actuality, streamflow is depleted by an amount equal to that pumped from the well. This is the case with all of the simulations previously discussed. A well pumping 1.0 Mgal/d reduces streamflow by that same amount under long-term pumping conditions, no matter how much of the water is derived from induced infiltration. This point has been discussed previously in this report in the section "Sources of water derived by wells".

Transient Simulation

All of the parameter testing thus far utilized steady-state simulations (with the exception of the drought simulation) so that the maximum effects of pumping, under a given set of hydrologic conditions, could be observed. As a result, nothing was learned about the transient response of the aquifer. To determine how long it takes the generalized aquifer to reach equilibrium conditions after pumping begins, a 3-year transient simulation was conducted.

For the transient simulation, "average" aquifer hydraulic parameters and recharge rates were specified. The well was located in the "standard" position, 200 ft from the river in the center of the aquifer, and pumped at the rate of 1.0 Mgal/d. A storage coefficient of 0.2 was specified uniformly over the modeled area.

Sources of water derived by the well as a function of time are shown in figure 27. The sources of water are categorized as storage depletion, captured discharge (flow from till and drift captured before it discharges to the river), and induced infiltration from the river.

At very early time (1 hour or less), all of the pumped water is from depletion of storage in the vicinity of the well. Subsequently, the well begins to capture ground water flowing through the aquifer before it reaches the stream. When approximately 9 hours have elapsed, induced infiltration from the river begins. Storage depletion remains the predominant source of pumped water until about 5 days have passed, after which captured discharge becomes the predominant source of water to the well.

Induced infiltration closely approaches the maximum rate after about 40 days. Equilibrium conditions are established in the aquifer after about 365 days have elapsed. At equilibrium, water is no longer being removed from storage, and pumped water is obtained from induced infiltration and captured ground-water discharge. If the pumping well was located at a greater distance from the river, a longer amount of time would be required for the aquifer to reach equilibrium conditions in response to pumping; and at equilibrium, the proportion of captured ground-water discharge would increase and induced infiltration from the stream decrease compared to the relations depicted in figure 27.

Three-Dimensional Numerical-Model Analysis of the Contributing Area of a Pumping Well

One of the essential assumptions inherent in the use of the two-dimensional model is that the predominant direction of flow in an aquifer is horizontal. For most thin stratified-drift aquifers, this is generally true except in recharge or discharge areas. In the hypothetical aquifer, vertical flow is

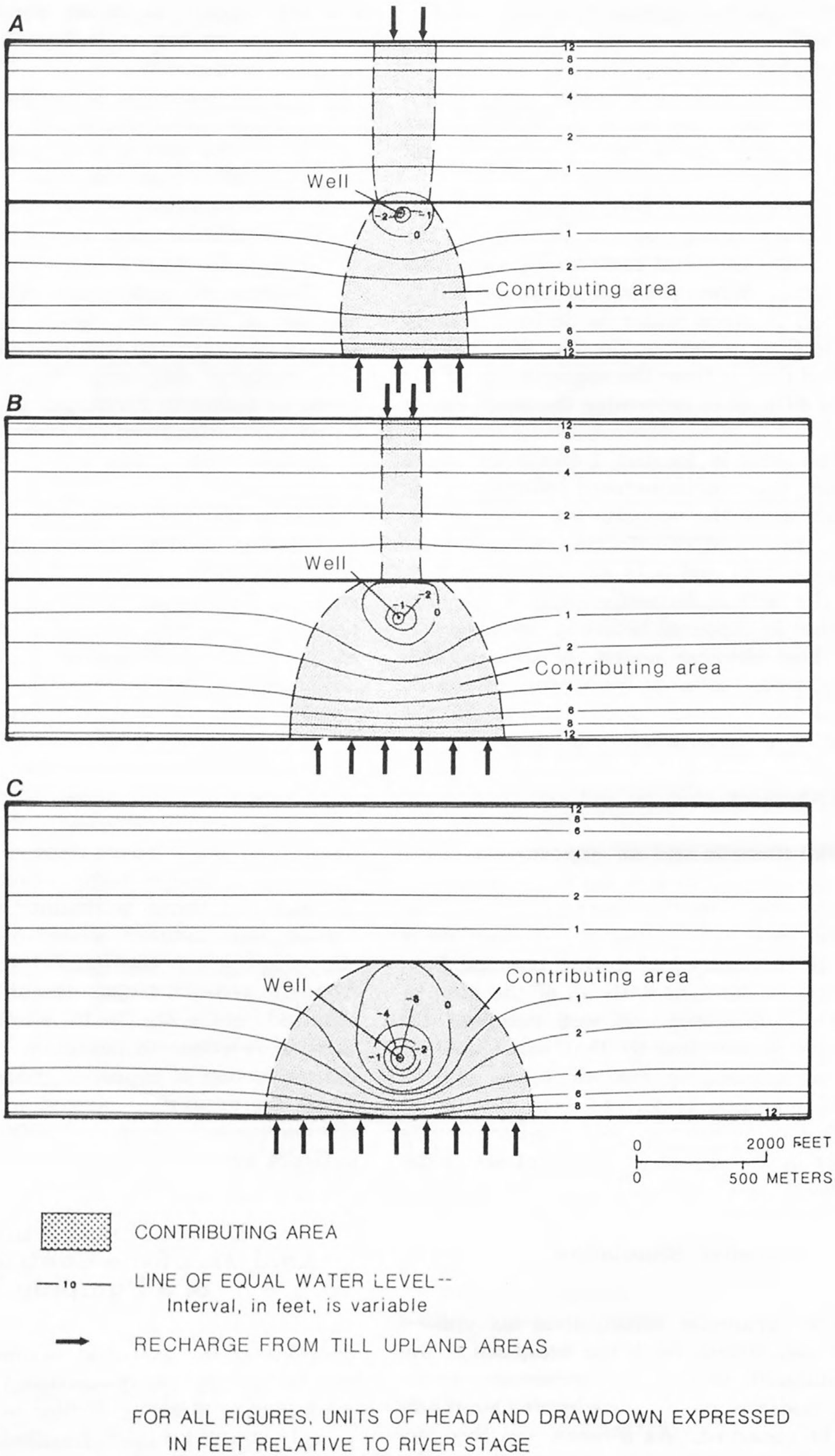

Figure 26.--Maps of the aquifer showing water-table altitudes and contributing areas for a well pumped at 0.5 million gallons per day located (a) 200, (b) 600, and (c) 1,400 feet from a source of induced infiltration.

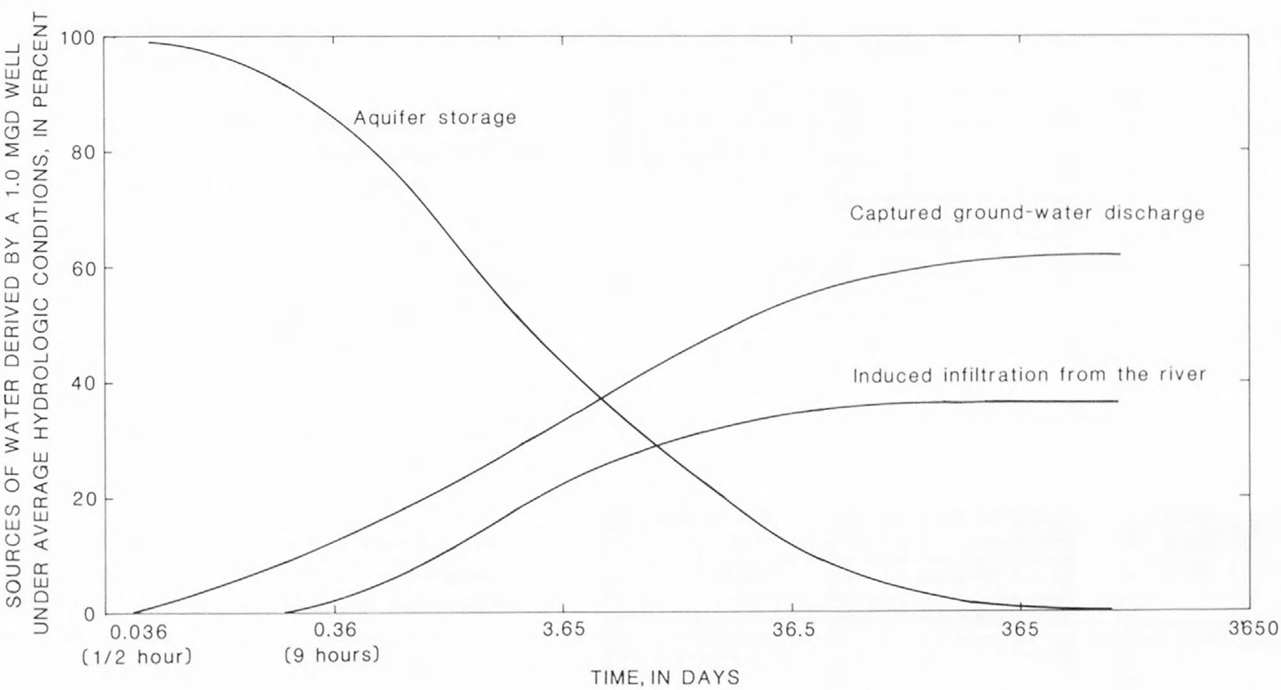

Figure 27.--Graph showing sources of water pumped by a well, under average conditions, as a function of time.

probably most significant near the leaky streambed and near the well. A three-dimensional flow model of the hypothetical aquifer was constructed to get better definition of flow patterns beneath and beyond the streambed and to determine the effects of vertical anisotropy and partial well penetration on contributing areas.

The numerical model used to simulate three-dimensional flow of ground water in the hypothetical aquifer was developed by McDonald and Harbaugh (1984). The model utilizes a finite-difference numerical method to solve the three-dimensional flow equation. In addition to the many options available with the two-dimensional model, the three-dimensional code allows simulation of vertical flow components between adjacent aquifer units. The units may or may not be separated by confining layers. Furthermore, the model simulates leakage to or from the aquifer through a leaky streambed in any model layer; the layers may be confined, unconfined, or a combination; and recharge may be applied to any model layer.

The three-dimensional model of the hypothetical aquifer is essentially the same as the two-dimensional model used previously with respect to hydraulic properties and recharge/discharge relationships except that it is divided vertically into five layers. The finite-difference grid used in the three-dimensional simulation is shown in plan and cross-sectional views in figure 28. Layer one of the three-dimensional model (top layer) has the same areal extent as the two-dimensional model (fig. 14), but the remaining layers are of lesser areal extent to more accurately simulate the geometry of the hypothetical aquifer. Horizontal grid spacing is uniform, 200 ft on a side, for each layer. Vertical grid spacing is uniform, 20 ft, for each layer.

The top layer in the model is simulated as having unconfined conditions. Transmissivity is computed as a function of saturated thickness and hydraulic conductivity after each model iteration. Nodes where the leaky streambed and recharge from areas underlain by till adjacent to the aquifer are simulated are also located in the top layer. Boundary conditions utilized in the top layer of the three-dimensional model are the same as described for the two-dimensional simulation. The bottom four layers of the model are simulated as having no-flow conditions along each side but can interact with layers immediately above or below.

Horizontal aquifer hydraulic conductivity (K_h) is the same as used in the two-dimensional model, vertical hydraulic conductivity (K_v) was modeled as 1/10 of the horizontal values. Recharge to the

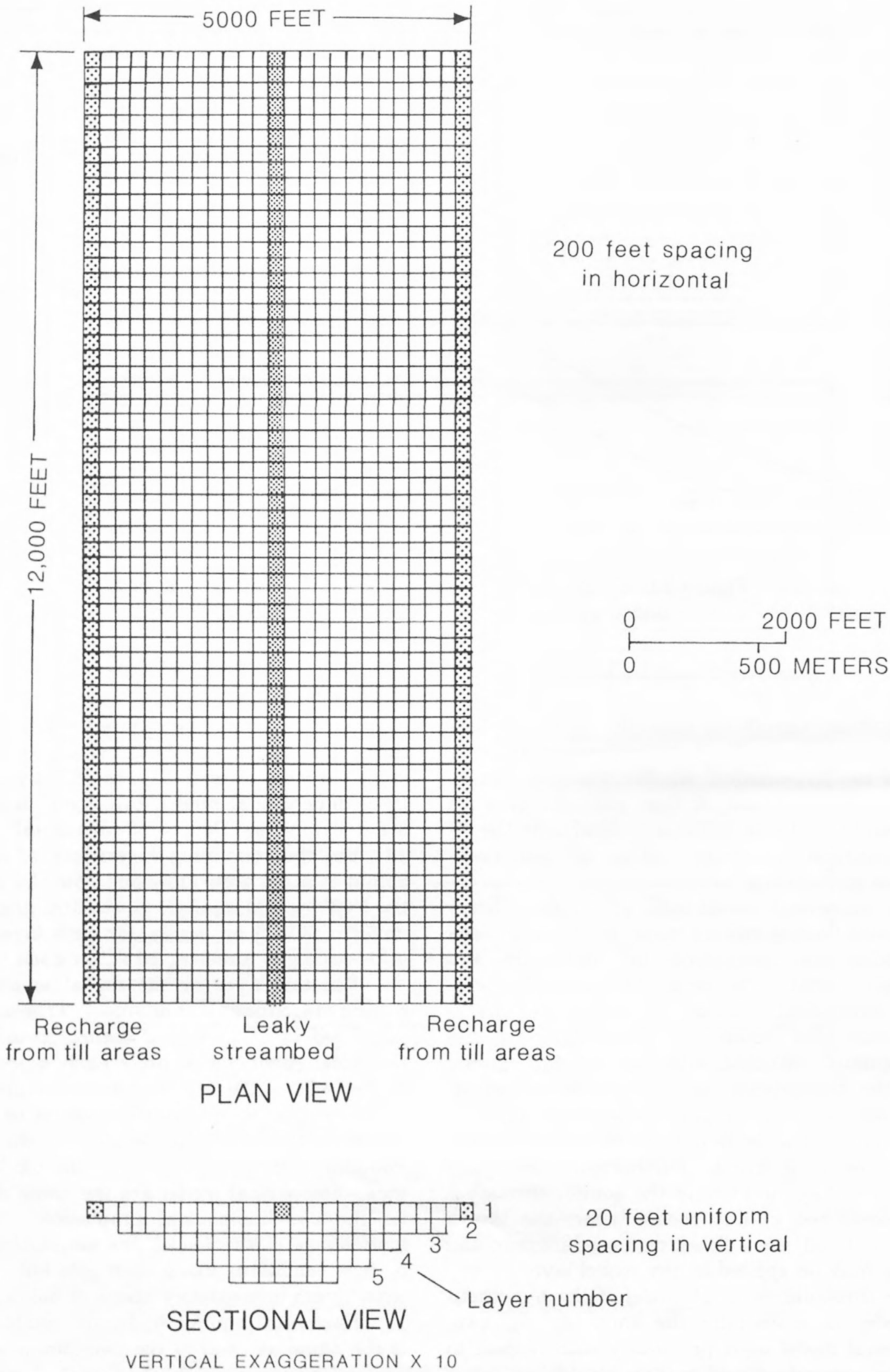

Figure 28.--Finite-difference grid used in the three-dimensional numerical-model analysis in (a) plan and (b) cross-sectional views.

model was applied uniformly on layer one at the same rate used in the two-dimensional simulation (2 ft/yr).

The resulting nonpumping steady-state water-table configuration that was computed with the three-dimensional model is shown in plan and cross-sectional views in figure 29. The steady-state water budget and water-table configuration computed with the three-dimensional model are essentially the same as those computed with the two-dimensional model.

Steady-State Analyses of the Effects of Vertical Anisotropy and Well Penetration on Contributing Areas

Wells completed in stratified-drift aquifers are usually screened over a small portion of available saturated thickness, a condition referred to as partial penetration. Partial penetration causes vertical flow components in an aquifer near the pumping well that cannot be accurately simulated with a two-dimensional flow model. The three-dimensional model allows analysis of the effects of partial penetration by providing the capability to locate the well screen in a specific vertical location (layer) within an aquifer.

The three-dimensional model also allows investigation of the effects of vertical variations in aquifer hydraulic conductivity. The alternate layering of coarse and fine materials within stratified-drift deposits creates a situation in which vertical hydraulic conductivity is generally less than horizontal hydraulic conductivity. The ratio of horizontal to vertical hydraulic conductivity in stratified drift is typically 10:1 but may be as high as 100:1 or 1000:1 (Rosenshein and others, 1968; Franke and Getzen, 1975; Larson and others, 1975; and Guswa and LeBlanc, 1981)

A series of simulations were run in which well penetration and the ratio of horizontal to vertical hydraulic conductivity were varied. The hydraulic conductivity ratio was varied from 1:1 to 100:1 and the well was located in either the top two layers or the bottom two layers of the model.

As with the two-dimensional modeling, simulations were run to steady-state so that the maximum effects of pumping could be observed. At steady-state, the sources of water to the well are induced infiltration from the river and captured ground-water discharge that originates as areal recharge from precipitation on the aquifer or runoff from upland till areas adjacent to the aquifer. Variations in the size of the contributing area for a well pumping 1.0 Mgal/d that result from changes in the ratio of K_h/K_v and well penetration are summarized in table 3.

Table 3.--*Total contributing area size as a function of well penetration and* K_h/K_v

Total contributing area, in square miles[1]		
K_h/K_v	Well in layers 1/2	Well in layers 4/5
1:1	[2]1.13	[2]1.13
10:1	1.27	1.39
100:1	1.40	1.72

[1]Includes contributing areas in stratified drift and till upland.

[2]Same rate as computed with the two-dimensional model for "average" conditions.

When K_h/K_v is 1:1, the vertical location of the well screen in the aquifer has a negligible effect on the size of the contributing area and the amount of induced infiltration caused by the well. In addition, the contributing area is the same size as that computed with the two-dimensional model. The reason for this is because the two-dimensional model simulations assumed a K_h/K_v of 1:1, and factors that control streambed leakage are identical in both models.

When K_h/K_v is increased from 1:1 to 10:1, the contributing area for a pumping well increases in size. The reason for this is because the increased resistance to vertical flow allows less induced recharge from the river. As a result, the contributing area gets larger to make up for this loss in recharge. For a well screen located in the bottom of the aquifer, the contributing area increased from 1.13 to 1.39 mi^2 when K_h/K_v increased from 1:1 to 10:1.

The vertical position of the well screen in the aquifer has a slight affect on the size of the contributing area when K_h/K_v is 10:1. Under these conditions, a well screen located in the top 40 ft of the aquifer has a contributing area of 1.27 mi^2. When the screen is moved to the bottom 40 ft of the aquifer, the contributing area encompasses 1.39 mi^2.

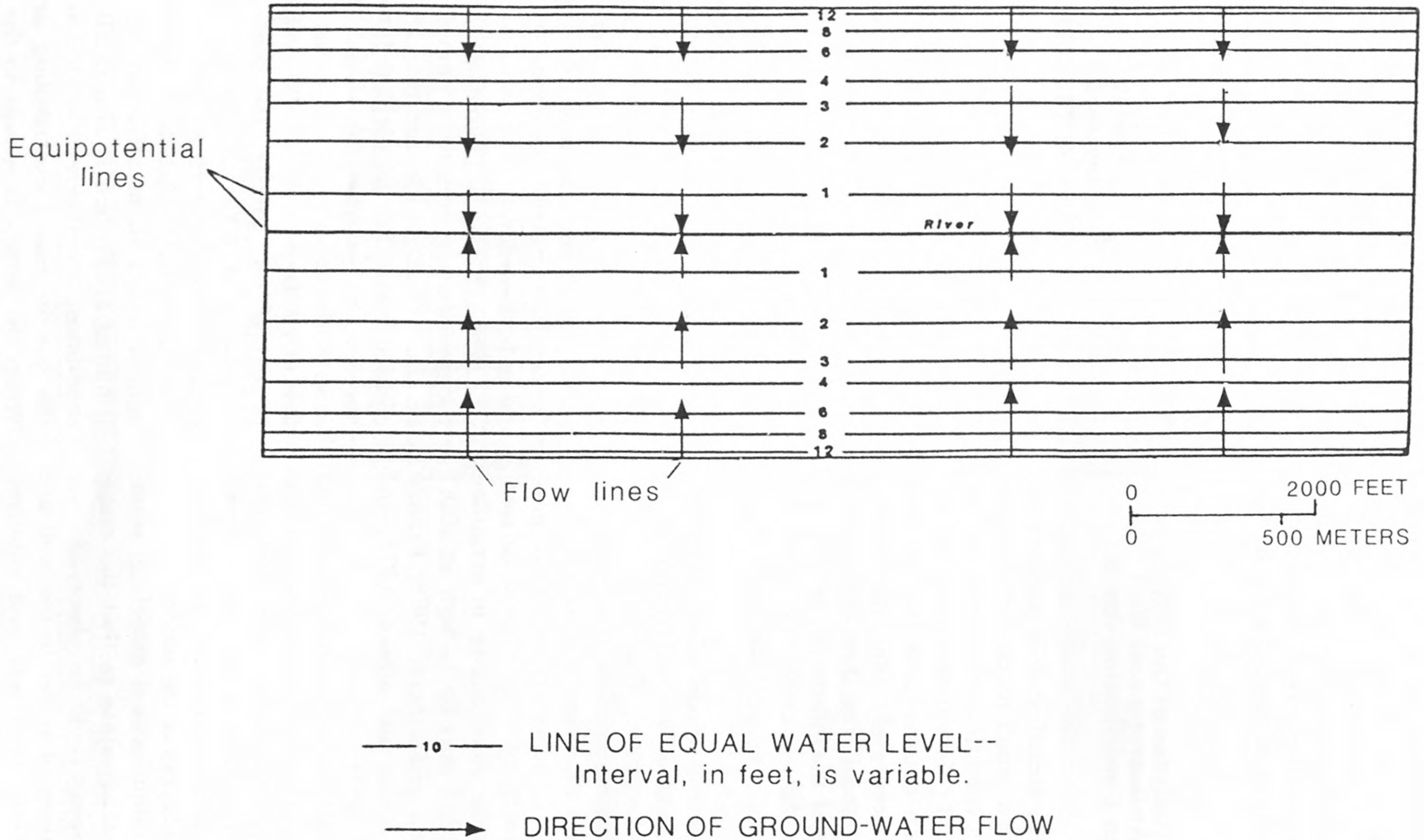

Figure 29.--Map of the aquifer showing steady-state nonpumping water-table altitudes computed with the three-dimensional numerical model.

When K_h/K_v is increased from 10:1 to 100:1, the contributing areas grow even larger. The areas increased in size by 0.13 mi² for a well located in the top 40 ft of the aquifer and 0.33 mi² for a well located in the bottom 40 ft of the aquifer. A well located in the bottom 40 ft of the aquifer receives less than 2 percent of pumped water from induced infiltration when K_h/K_v is 100:1. This means that essentially all of the water pumped by the well is made up of captured ground-water discharge. The contributing area for a well under these conditions is shown in plan and cross-sectional views in figure 30.

The three-dimensional model simulations point out several interesting facts about determination of the contributing area of a well in the hypothetical aquifer. Among these are the following:

(1) The two- and three-dimensional models produced identical results only when K_h/K_v was 1:1 in the three-dimensional model. For $K_h/K_v > 1$, the three-dimensional model estimates a larger contributing area for the well than the two-dimensional model. This is because of a decrease in the amount of induced infiltration caused by increased vertical resistance to flow in the aquifer that is accounted for with the three-dimensional model.

(2) The vertical location of the well in the three-dimensional model affected the rate of induced infiltration and hence the size of the contributing area for the well. When K_h/K_v is 1:1 or 10:1, this effect was negligible; but when K_h/K_v is 100:1, well penetration has a significant effect on the size of the contributing area.

(3) Two-dimensional numerical analysis will underestimate the size of the contributing area of a well in a stratified-drift aquifer in which $K_h/K_v > 1$ unless vertical components of flow in the aquifer are accounted for with the two-dimensional model. This can be accomplished by modifying equation 1 to account for vertical components of flow in the aquifer under the leaky riverbed. Details of how this can be done are described by Reilly and others (1983, pp. 23-26).

(4) The three-dimensional model allows estimation of the three-dimensional zone of contribution (fig. 30). However, for the relatively thin aquifer (100 ft or less) considered in these simulations, the zone of contribution extends throughout the entire thickness of the aquifer and the enveloping surface of the contributing area is close to vertical everywhere.

Summary of the Qualitive Effect of Selected Hydrogeologic Factors on the Contributing Area of a Pumped Well

All of the hydrogeologic factors that were tested had some effect on the size and shape of the contributing area for a well in the hypothetical aquifer. The magnitudes of these effects are summarized in table 4 for the steady-state two-dimensional numerical-model analyses. The initial set of hydrologic conditions, which formed the basis for subsequent comparisons, was described in the section entitled "Description of a generalized glacial-drift, river-valley aquifer system". The pumping rate of a well has a direct effect on the size and shape of its contributing area and on the sources of water pumped from the well. In the steady-state modeling simulations, sources of water for a well included captured ground-water discharge (that originated as recharge from areal precipitation on the stratified-drift aquifer and recharge from areas underlain by till adjacent to the aquifer) and induced infiltration from the river. With all other factors constant an increase in well discharge increased both the size of the contributing area and the amount of water obtained from induced infiltration. Depending upon the contrast in the quality of ground water and surface water at a given site, this indicates that well-discharge rate could be adjusted to influence the quality of pumped water.

When well discharge is held constant and recharge from areal precipitation on the aquifer and from runoff originating in areas underlain by till adjacent to the aquifer are reduced, the contributing area of a well increases in size to make up for the decreased availability of water. Under this scenario, the amount of induced infiltration also increases to make up for the loss in recharge.

When recharge from all sources stops entirely and the river goes dry, the contributing area grows continuously to capture enough water to balance the pumping rate. During this period, water pumped by the well is derived entirely from storage in the aquifer. The size of the contributing area under these conditions is controlled by the specific yield of the aquifer and the duration of the pumping. If this situation persists long enough, the contributing area for a well could be the entire aquifer area.

The model simulations show that in a typical stratified-drift, river-valley aquifer induced infiltration from the river provides significant quantities

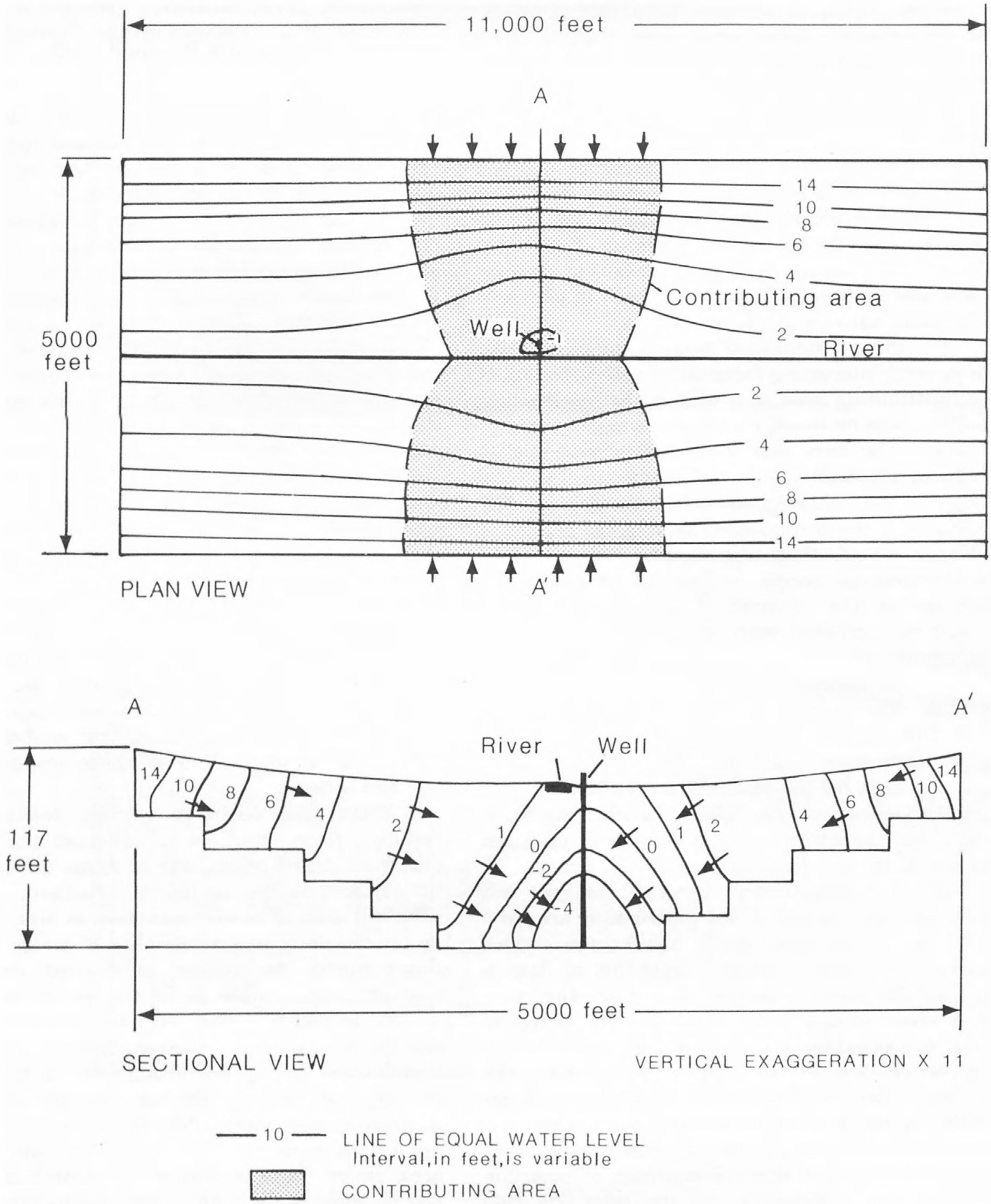

Figure 30.--Map of the aquifer showing the zone of contribution for a well, pumped at 1.0 million gallons per day, as determined with the three-dimensional numerical model.

Table 4.--*Summary of the effects of variations in selected geohydrologic factors on the size of the contributing area of a well in the hypothetical aquifer*

Simulation number:	1	2	3	4	5	6	7	8	9	10	11	12
GEOHYDROLOGIC CONDITIONS												
Well discharge, in million gallons per day:												
0.5		X									X	X
1.0	X			X	X	X	X	X	X	X		
2.0			X									
Aquifer recharge (average is 24 inches per year):												
0.5 x average					X							
Average	X	X	X				X	X	X	X	X	X
1.5 x average						X						
After 6 months of no recharge				X								
Ratio of streambed thickness to streambed permeability (k'/b'):												
0.1							X					
1.0	X	X	X		X	X			X	X	X	X
10.0								X				
0.0				[1]X								
Aquifer hydraulic conductivity (average is 10 to 100 feet per day):												
0.3 x average									X			
Average	X	X	X	X	X	X	X	X			X	X
3 x average										X		
Distance to well from river:												
200 feet	X	X	X	X	X	X	X	X	X	X		
600 feet											X	
1,400 feet												X
Aquifer specific yield:												
Steady-state, 0.0	X	X	X		X	X	X	X	X	X	X	X
Transient, 0.2				X								
RESULTS												
Size of contributing area, in square miles:												
Total area	1.13	0.73	1.57	[2]1.70	1.66	0.90	1.77	0.89	1.01	1.33	0.94	0.98
Area underlain by till	.78	.53	1.13	--	1.19	.67	1.29	.63	.75	.96	.74	.74
Area underlain by drift	.35	.20	.44	1.70	.47	.23	.48	.26	.26	.37	.24	.24
Sources of water to well by percent volume:												
Induced infiltration from river	35	16	56	0	56	26	8	45	44	26	0	0
Area recharge to areas underlain by drift	40	47	25	0	25	42	51	33	30	42	55	53
Runoff from areas underlain by till adjacent to the aquifer	25	37	19	0	19	32	41	22	26	32	45	47
Aquifer storage	0	0	0	100	0	0	0	0	0	0	0	0

[1]River assumed to be dry.
[2]Contributing areas in till not determined.

of water to supply wells. For average equilibrium conditions in the hypothetical aquifer with the well located 200 ft from the river induced infiltration makes up 35 percent of pumped water. Under other conditions induced infiltration comprises more than 50 percent of pumped water.

In general, any factor that increases the amount of induced infiltration obtained by a well will decrease the size of the contributing area and vice versa. This result was evident in simulations in which streambed permeability was varied and the well was moved further from the river in either a horizontal (two-dimensional numerical simulations) or vertical (three-dimensional numerical simulations) direction.

Variations in the horizontal hydraulic conductivity of the aquifer affected the size of the contributing area of a pumped well located 200 ft from the river such that an increase in hydraulic conductivity slightly increased the size of the contributing area. An increase in hydraulic conductivity also reduced the amount of induced infiltration obtained by the well.

When the contrast between horizontal and vertical permeability (K_h/K_v) was increased (three-dimensional simulations), the amount of induced infiltration caused by the well decreased and the size of the contributing area increased. This result was most evident when the well was screened in the bottom 40 ft of the aquifer. When the well was screened in the top 40 ft of the aquifer, variation in K_h/K_v had less affect on induced infiltration and size of the contributing area.

Certainly, there are other factors that can affect the area that contributes flow to a well that have not been tested in these model simulations. For example, under drought conditions the size of a contributing area depends in large part on the specific yield of the aquifer. Also, if pumping wells are introduced near an existing well, the flow patterns could change and affect the size and shape of a contributing area. A further consideration is the possible combined effect of variations in several factors at once, such as a simultaneous decrease in recharge and increase in pumping rate. The synergistic effect of such conditions could lead to much larger contributing areas than those shown in table 4.

Some of the factors that affect contributing areas can be controlled by man such as pumping rate, the distance of a well from a possible source of induced infiltration such as a river (Weeks and Appel, 1984), the degree of well penetration and the proximity of wells to one another. Other factors, such as natural variation in recharge from precipitation, length and severity of drought conditions, degree of interconnection between surface water and ground water, and aquifer permeability are generally beyond man's control. Because of the number of factors involved and an imperfect understanding of how these factors can vary, either naturally or at the hand of man, determination of contributing area is only an estimate.

The various model simulations utilized in this study show that the method of analysis can affect the size and shape of an estimated contributing area. The next section of the report will compare and contrast the different techniques used to estimate the contributing area for a well in a stratified-drift, river-valley aquifer. The suitability of various methods for differing field conditions will be discussed, and data requirements for each method will be described.

COMPARISON OF ESTIMATION METHODS AND GUIDELINES FOR ESTIMATING THE CONTRIBUTING AREA OF A PUMPED WELL IN A GLACIAL-DRIFT, RIVER-VALLEY SYSTEM

Three possible methods for estimating the contributing area of a well in a stratified-drift, river-valley aquifer have been discussed and illustrated in this report. These methods are analytical-mathematical model analysis, two-dimensional numerical simulation, and three-dimensional numerical simulation. Each of the methods is based upon hydraulic analysis of ground-water flow in the vicinity of a well or well field. The techniques represent a range of complexity in terms of speed of application and ability to handle typical geohydrologic conditions encountered in the field.

No technique should be applied universally for estimating the contributing area of a well in stratified-drift, river-valley aquifers. The essential geohydrologic features at a given site must be incorporated in the technique used to estimate a contributing area, and these features can change from site to site. The following discussion reviews each of the techniques used in this study and provides general guidelines for estimating the contributing area of a well in a typical stratified-drift, river-valley aquifer. A simple decision tree is presented to serve as a general guide for selecting a method to estimate contributing areas in a stratified-drift, river-valley aquifer (fig. 31). The final discussions

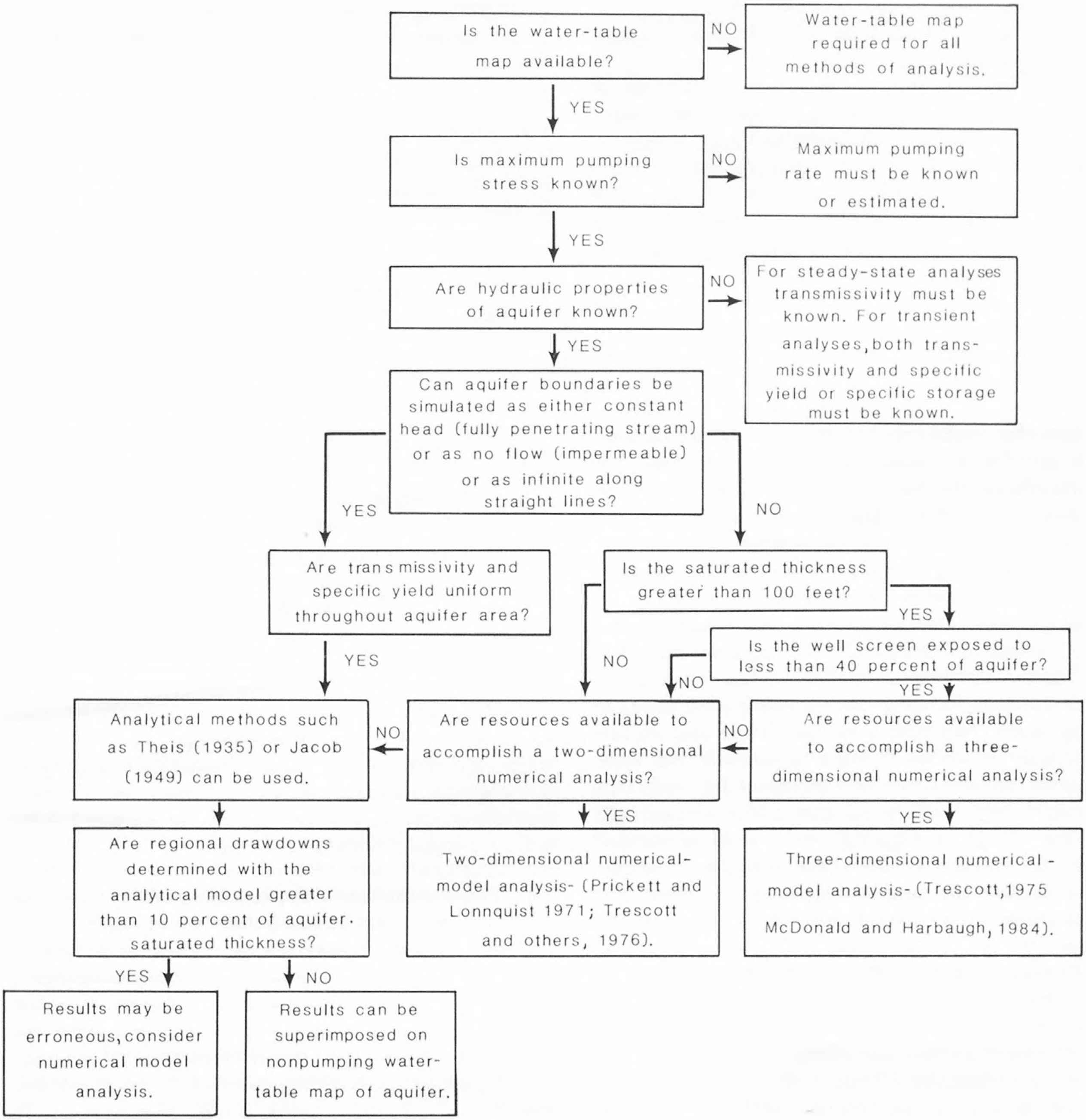

Figure 31.--Guide for selecting a hydraulic method of analysis to estimate the contributing area of a well in an unconfined stratified-drift, river-valley aquifer.

will address some of the problems involved in determining contributing areas of wells and the usefulness of results.

Analytical techniques have the advantage of being easy to apply in terms of time, necessary data, and computational complexity. Analytical methods can provide answers in a matter of hours using only pencil, paper, and a calculator. The serious disadvantages of analytical methods is the gross simplifications of field conditions required for their application.

Analytical model simulation of a partially penetrating surface-water body is limited to the use of a line source boundary. Although corrections can be made for the "effective distance" to the boundary so that aquifer response is reasonable on the well side of the river (Rorabaugh, 1956) aquifer response beneath and beyond the streambed cannot be correctly simulated (Walton and Ackroyd, 1966). The result, for the purpose at hand, is a contributing area limited to the well side of a river. This result was clearly illustrated when an analytical model with a line source river boundary was used to estimate the contributing area of a well in the hypothetical aquifer (fig. 13).

Another serious limitation in the use of analytical methods for estimating contributing areas in the "typical" river-valley aquifer is the assumption that aquifer response is linear (confined). In these thin systems, the combined stress of low recharge rates and high well yield can cause drawdowns that are large compared with total saturated aquifer thickness. Under these conditions the, assumption of linear aquifer response is violated and superposition may yield unacceptably incorrect results.

The analytical methods are most applicable where key simplifying assumptions are met or closely approached by field conditions. Such situations can exist in thick aquifers, in which wells are located far from the effects of aquifer boundaries such as in a very wide valley or broad outwash plain. If boundaries are close to the pumping well and simple, such as a fully penetrating river, an analytical method that uses image well boundaries might provide useful results.

If constraints--time and (or) money--force the use of an analytical method to estimate a contributing area, the analysis can be designed to provide a conservative estimate (largest contributing area) by using very conservative values for data required in the analysis. Analytical methods might provide a worthwhile preliminary analysis that could be followed with more complex modeling. The basic data needed for analytical model analysis of a contributing area are as follows:

(1) *Water table map* that shows water-table altitudes in the aquifer before pumping begins. Drawdowns determined with the analytical model are subtracted (superimposed) from the prepumping water-table map to determine the contributing area for a well. If the largest possible contributing area is to be estimated, the water-table map should reflect extreme low water conditions.

(2) *Boundary conditions* in an analytical model will be idealized as straight lines with either no-flow impermeable barrier or constant-head stream with constant stage.

(3) *Well field design criteria* that describe the pumping rate, pumping schedule, and well construction are needed for model analysis. As illustrated in model simulations, the maximum expected pumping rate must be known to determine the largest possible contributing area of a well.

(4) *Aquifer hydraulic properties* for an analytical model will include the average aquifer transmissivity and specific yield. Sensitivity testing of a range of possible values for these parameters will show how they affect the size of a contributing area for a specific field problem.

Two-dimensional numerical models have become the most widely used tool for aquifer analysis because they overcome many of the limitations of analytical methods. Complex boundary conditions, nonlinear aquifer response and heterogeneity can be simulated in a more realistic manner with the numerical model. A two-dimensional numerical-model analysis takes more time than an analytical model analysis and requires a digital computer. In addition, numerical models require more data for construction and calibration because aquifer hydraulic properties, recharge, and discharge must be specified for each block in the grid network (fig. 14).

The decision to use a two-dimensional numerical model for estimating the contributing area of a well will be based on many factors. Among these are time constraints, personnel, hardware and software availability, degree of accuracy required, and data availability. If all necessary data, hardware, software, and personnel are available, a two-dimensional numerical-model analysis to estimate a contributing area might require anywhere from a few days to a few months of time. The minimum hardware requirement would be a microcomputer with sufficient memory to execute a standard ground-water-flow model code that allows simulation of the essential hydrologic features of the system under consideration--several suitable codes have been previously mentioned in this report.

On the basis of model simulations done for this study and the work of previous investigators, the hydrologic data necessary for a two-dimensional numerical-model simulation (in approximate order of importance) are:

(1) *Water-table map* is probably the most important data element for construction and calibration of any numerical-flow model. The water-table map shows the upper limit of an unconfined aquifer, directions of ground-water flow, and recharge and discharge areas. A map of average water-table altitudes is usually sufficient, but maps that show extreme conditions aid model calibration.

(2) *Boundary conditions* that specify the location and hydrologic conditions along model boundaries can significantly affect model results. For a typical unconfined river-valley aquifer, the bottom of the aquifer and the lateral boundaries must be defined. Hydrologic conditions along each of these boundaries must also be specified. Boundary conditions that could be used in a numerical simulation included specified head or specified flux boundaries or more specialized conditions such as a head-dependent flux across a leaky streambed or till/stratified-drift boundary.

(3) *Well field design criteria* that describe the locations and maximum expected yield of a well or well field are important for estimating a contributing area. Locations and discharge of nearby wells that can affect flow patterns, and contributing areas should be incorporated in model simulation.

(4) *Aquifer hydraulic properties* such as hydraulic conductivity and specific yield (for transient analyses) must be assigned to each block in the numerical-model grid. Usually these values are determined at a few discrete locations and interpolated over the rest of the area or estimated during model calibration. For contributing area determination in the hypothetical aquifer, variations in hydraulic conductivity had less effect on model results than other parameters tested.

(5) *Recharge from areal precipitation* on stratified drift and runoff from adjacent areas underlain by till are given a low rank in relative importance because they can usually be estimated from available data. The most conservative result (largest contributing area) estimated for the aquifer resulted from a 180-day period in which all recharge had ceased.

A comparison of results obtained with the analytical model that used a line source river boundary (fig. 13c) with a two-dimensional numerical simulation in which the river was simulated as a partially penetrating boundary (fig. 17b), shows how choice of method can affect the size and shape of a contributing area estimated for the same geohydrologic conditions. The numerical model more realistically simulates the partially penetrating streambed by allowing drawdowns and the contributing area to extend beneath and beyond the stream. In general, the numerical approach provides the most widely applicable method for aquifer-wide analysis of ground-water flow and estimation of contributing areas in an unconfined stratified-drift, river-valley aquifer.

Three-dimensional numerical-model analysis is the most complex method of those investigated for estimating the contributing area of a well in a typical stratified-drift, river-valley aquifer. Three-dimensional modeling is more complicated because of the additional data necessary for model construction and calibration. In general, the amount of data required for the three-dimensional analysis (of the hypothetical aquifer) was approximately equal to the number of layers in the model multiplied by the amount of data used in the two-dimensional analysis. Because of the additional data required for three-dimensional simulation, more computer storage is also necessary.

The advantages of using a three-dimensional model for estimating the contributing area of a well in a stratified-drift, river-valley aquifer are the ability to simulate vertical components of flow in the aquifer and to simulate confining layers. The layering in a three-dimensional model also allows more detailed description of variations in aquifer properties. The result of an analysis using a three-dimensional numerical model is a three-dimensional representation of the zone of contribution of a pumping well (fig. 30).

A comparison of results obtained with the two- and three-dimensional models shows differences in the computed rates of induced infiltration from the river and in the sizes of estimated contributing areas. When K_h/K_v is equal to 1, results obtained with the two- and three-dimensional models are very similar. When K_h/K_v is greater than 1, the three-dimensional model estimates a larger contributing area for a well than the comparable two-dimensional simulation. The capability of the three-dimensional model for simulating resistance to vertical flow in the aquifer beneath the partially penetrating streambed results in less induced infiltration and a larger contributing area for a given pumping condition.

The most widely applicable and, at the same time, the most practical method of those investigated for estimating the contributing area of a well in a glacial-drift, river-valley aquifer is the two-dimensional numerical-model analysis. This type of analysis provides a compromise between the analytical and three-dimensional methods in terms of speed of application, applicability to typical field conditions and data requirements. Because most of these aquifers are relatively thin (100 ft or less), the two-dimensional model analysis is usually adequate. If there is a high degree of vertical anisotropy and the well partially penetrates the aquifer, the two-dimensional model may underestimate a contributing area. However, this condition could be approximated in a two-dimensional model with the proper modification (Reilly and others, 1983).

Exact determination of the contributing area of a pumping well is a very difficult task. There is, in reality, no such thing as a fixed contributing area for a pumping well. In nature, the contributing area is constantly changing in response to changing hydrologic conditions--such as variation in aquifer recharge, variation in pumping rate and change in the stage of a surface-water body that acts as a source of induced infiltration.

Methods of analysis used to estimate contributing areas require that simplifying assumptions be made about natural ground-water-flow systems. In general, the assumptions required for analysis do not coincide exactly with the real world conditions. This report has shown how the size and shape of a contributing area can change in response to different geohydrologic conditions. In the worst case, during an extended period of drought, the contributing area expanded in time to include virtually the entire aquifer.

Despite the uncertainty involved in determining the contributing area for a pumping well, a carefully executed hydraulic analysis will provide valuable information. Clearly, the contributing area for a well in a typical stratified-drift, river-valley aquifer is much more extensive than the simple circular areas that are currently used to protect ground-water quality. The most conservative contributing area (largest expected area) can be estimated by using the most reasonably conservative values for geohydrologic parameters that are included in the method of analysis.

SUMMARY AND CONCLUSIONS

The major sources of water for wells in unconfined, stratified-drift, river-valley aquifers include storage, capture of ambient ground-water flow, and induced infiltration of surface water. Ambient ground-water flow captured by a well can originate as precipitation that recharges the aquifer directly through infiltration or from runoff in upland areas adjacent to the aquifer that recharges aquifer boundaries.

The contributing area of a well is not the same as the area of influence of a well. The area of influence is the land area that has the same horizontal extent as the cone of depression caused by the well. Recharge that enters the aquifer through the area of influence of a well will not necessarily travel to the well, and recharge that enters the aquifer outside the area of influence may travel to the well.

The contributing area of a well is the land area that has the same horizontal extent as that part of an aquifer from which flow is diverted to the well. Recharge that enters an aquifer through the contributing area of a well will eventually be discharged by the pumped well. The extent of an area of influence is limited only by the physical boundaries of an aquifer; whereas, the extent of a contributing area is limited to the area around a well in which captured recharge equals well discharge.

Factors that can influence the size and shape of the contributing area of a well in stratified-drift, river-valley aquifers include (but are not limited to) the duration of pumping, well discharge rate, aquifer recharge rate, proximity of the well to sources of induced infiltration, degree of well penetration in the aquifer, aquifer hydraulic conductivity, ratio of horizontal to vertical hydraulic conductivity, and specific yield of the aquifer. The size and shape of the estimated contributing area of a well also depends on the assumptions implicit in the method of analysis, such as the way in which boundaries are simulated and the ability to vary hydraulic properties spatially.

To evaluate the applicability of methods for estimating contributing areas and to determine the effects of variations of selected geohydrologic factors on the sizes and shapes of contributing areas, simulations of a pumping well in a hypothetical aquifer were performed. The hypothetical system was designed to represent a major class of aquifers common to New England--namely, unconfined, glacial-drift, river-valley aquifers. Most high-yield supply wells in the region are located in this type of setting.

The methods used to estimate contributing areas included analytical, two-dimensional numerical and three-dimensional numerical models. The most widely applicable method of those tested was the two-dimensional model analysis. This method provides a compromise between the analytical and three-dimensional numerical analyses in terms of speed of application, applicability to field conditions typical of glacial-drift aquifers, and data requirements.

In general, the analytical methods lack flexibility for simulating geohydrologic factors that affect the contributing area of a well in a typical glacial-drift, river-valley aquifer. They are also subject to the limitations involved in the use of superposition. The analytical methods are best suited to situations where important simplifying assumptions are met or closely approached by field conditions.

Three-dimensional model analysis for estimating contributing areas is the most rigorous but complicated and time-consuming technique of those investigated. In situations where the required data are available for model construction and calibration, this technique can be used to provide the most complete analysis. This is especially true for very thick aquifers in which vertical components of flow affect well response. Such conditions can be caused by a combination of partial well penetration and aquifer anisotropy.

Because of the large number of factors that can affect contributing areas and an imperfect understanding of how these factors can vary, determination of contributing areas is an approximation at best. If sources of induced infiltration, such as streams, go dry and recharge ceases for extended periods, the size of a contributing area can include the entire extent of an aquifer.

Estimation of contributing areas generally should incorporate the most conservative values for geohydrologic factors that control aquifer response so that the maximum probable area is predicted. However, protection of contributing areas alone will not ensure that the quality of water obtained will remain acceptable if induced infiltration of surface water of unacceptable quality occurs.

All of the methods used to estimate contributing areas in this study involve hydraulic analysis of ground-water flow, whereby solute-transport phenomena have been neglected. The assumption inherent in this approach is that contaminants will move with the ground water and will not be subject to diffusion and dispersion. An obvious area for continued study would be to use solute-transport models to investigate the fate of specific contaminants in the idealized aquifer. Other areas for continued research would include delineation of contributing areas for wells located in fractured rock aquifers and investigation of the effects of multiple wells and cyclic pumping on the size and shape of contributing areas.

Estimation of contributing areas is an imperfect science because of our limited understanding of geohydrologic factors and the inability to predict future hydrologic conditions. Despite these problems, the use of reasonable methods of analysis can provide important information about the general sizes and shapes of areas that contribute flow to wells.

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