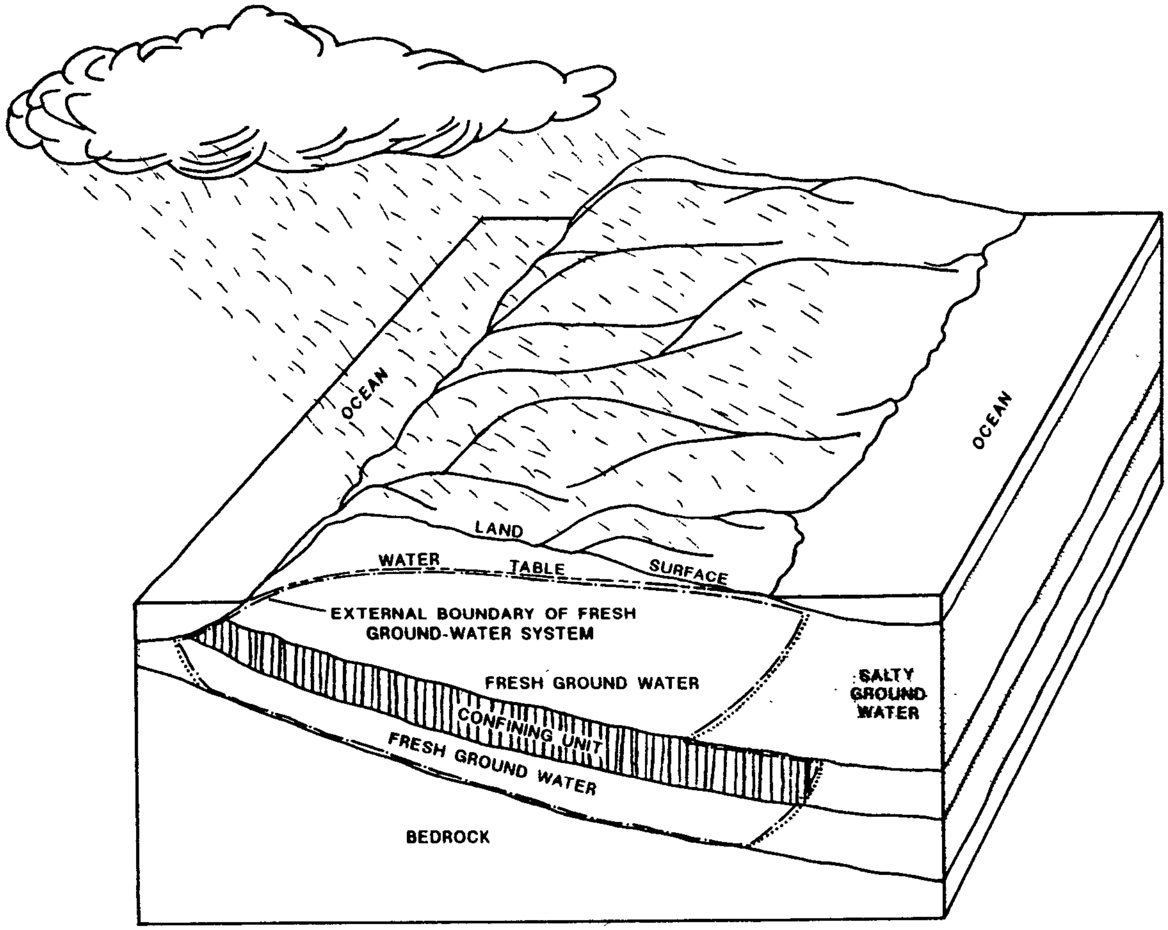
STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART I -- COURSE PARTICIPANTS



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Further field investigation of this phenomenon reveals an irregular hole in the confining unit in the northwest corner of the area (fig. 3-15). This hole results in a direct hydraulic connection locally between the water-table and confined aquifers. Although the vertical gradient between the aquifers is least in the area of the hole, the flux between the aquifers probably is greatest there. An additional effect of this hole on the flow system might be that, to a limited degree, water converges above the hole in the water-table aquifer, flows through the hole, and disperses (flowlines diverge) within the confined aquifer.

Question 7.--Using your current understanding of the structure and operation of this ground-water system, construct a set of maps that depict its three-dimensional head distribution. Construct maps for the water-table and potentiometric surfaces and section A-A' (figs. 3-13, 3-15, and 3-16. Draw equipotential lines at 5-ft intervals.

Locate the line of transition between regions of downward and upward flow between aquifers, and mark it as a dashed line on figure 3-15. Compare this transition line with the one determined in question 5 (for unstressed conditions with continuous confining unit); also compare the head maps constructed for both scenarios. What does this comparison indicate about the effect of the hole in the confining unit on the operation of this system?

Analysis of Ground-Water Systems Using Flow Nets

Assignments

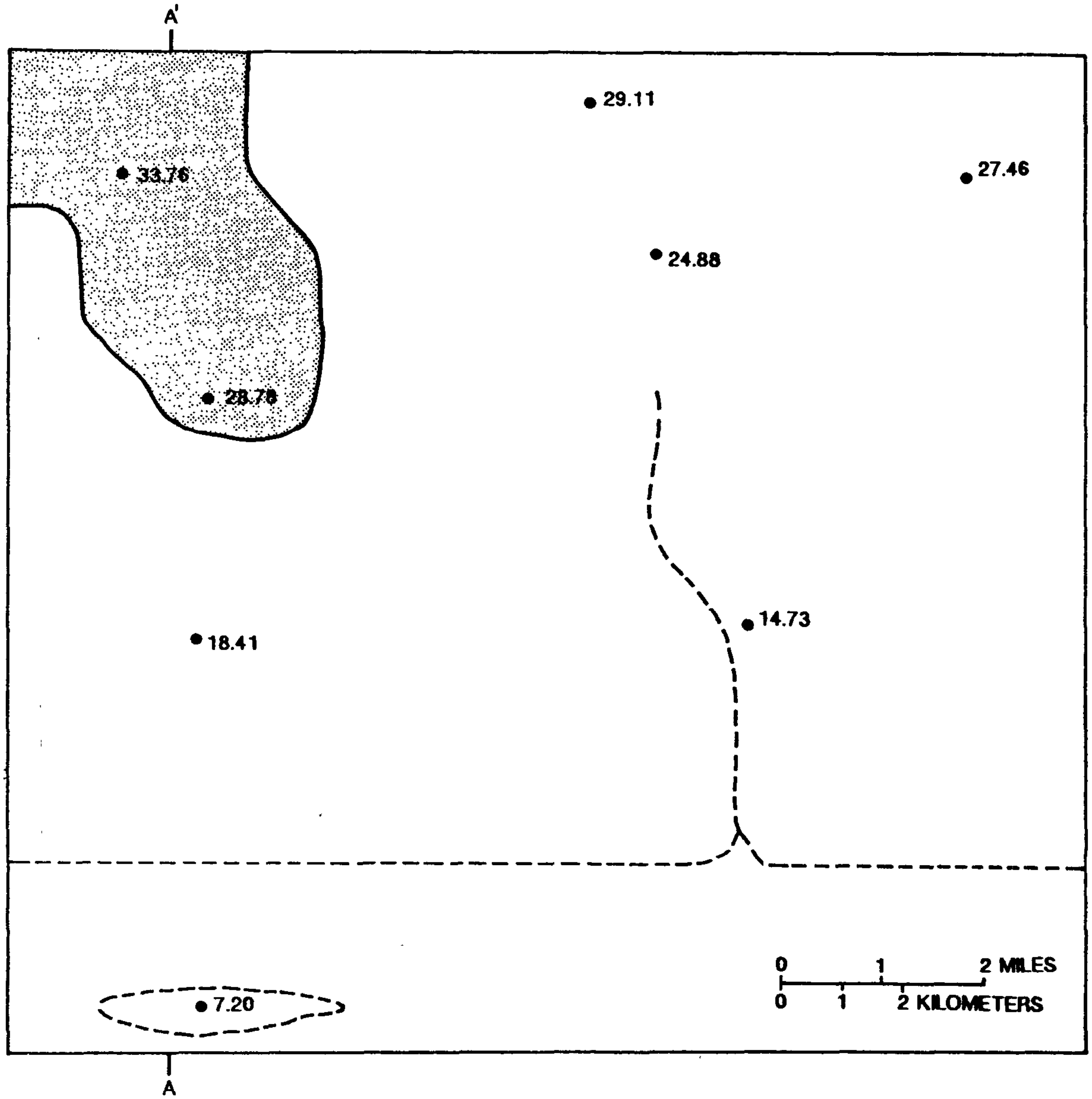
*Study Fetter (1988), p. 137-141, 218-229; Freeze and Cherry (1979), p. 168-185; or Todd (1980), p. 83-93.

*Study Note (3-4)--Introducton to discretization.

*Work Exercise (3-2)--Flow net beneath an impermeable wall.

*Study Note (3-5)--Examples of flow nets.

Flow nets depict a selected number of accurately located flowlines and equipotential lines in the flow system, which provide in total a quantitatively useful, graphical representation of the ground-water flow field. In fact, problems that involve ground-water flow often can be considered as solved if an accurate flow net is developed. Flow nets can be applied conveniently only in two-dimensional flow problems, and the technique is particularly useful in analyzing vertical sections of flow systems that are oriented along a regional "streamline" (actually, stream surface).



EXPLANATION

AREA OF HOLE IN CONFINING UNIT

• 14.73 OBSERVATION WELL SCREENED IN THE CONFINED AQUIFER -- Number is altitude of water level, in feet above sea level

A-A' TRACE OF SECTION

Figure 3-15.--Measured heads in the confined aquifer and location of hole in the overlying confining unit.

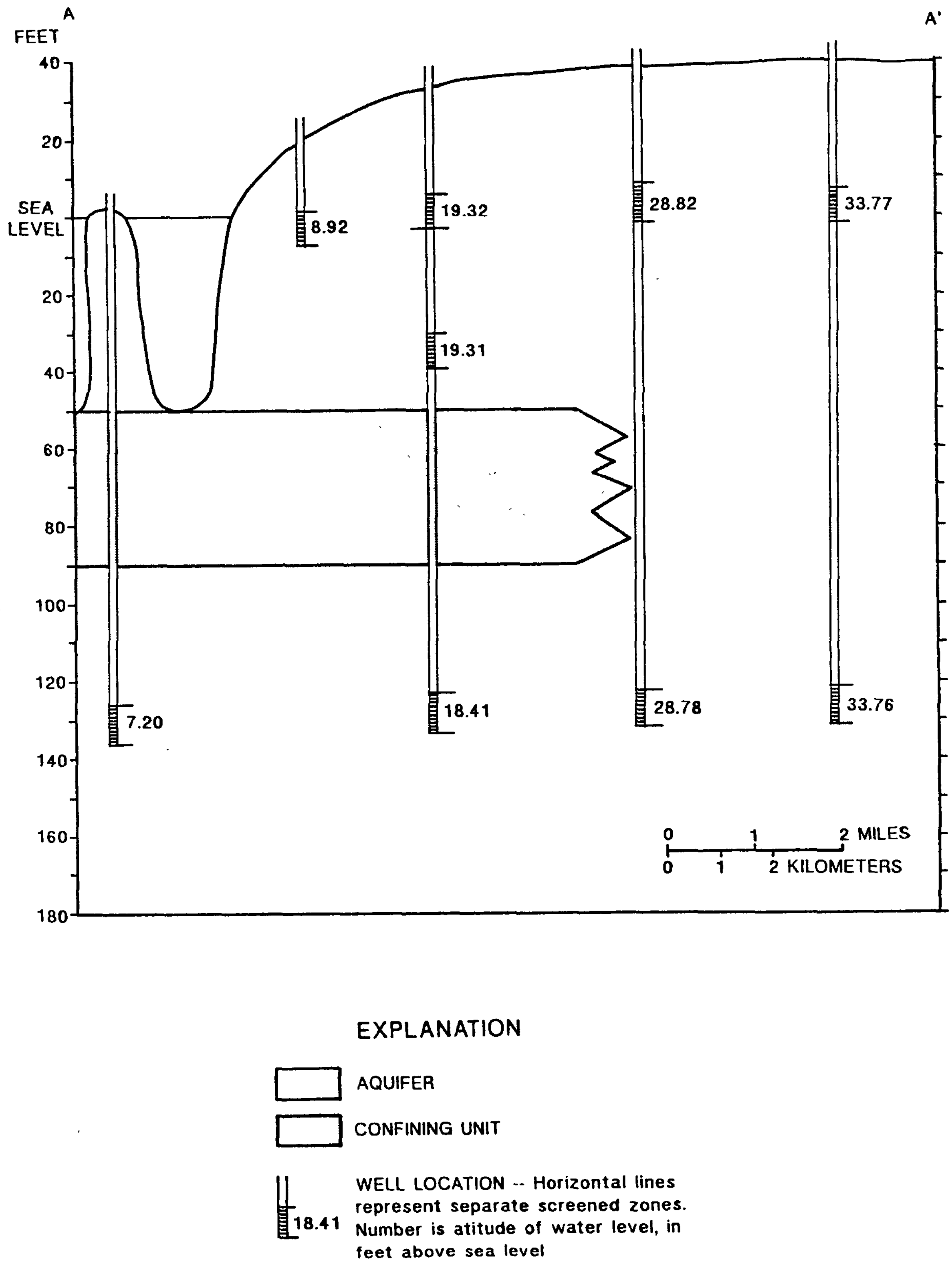


Figure 3-16.--North-south-trending hydrogeologic section showing heads measured in a ground-water system with a discontinuous confining unit. (Location of section A-A' is shown in fig. 3-2.)

Note (S-4).--Introduction to Discretization

The purpose of this note is to provide an introduction to "square-mesh" finite-difference discretization that is sufficient to permit the calculation of flows in the subsequent impermeable wall flow-net exercise (Exercise 3-2). First, we will review some of the important concepts related to discretization.

1. What is discretization?

Discretization is the breaking up of a continuous system into blocks or lumped "discrete" elements. A map of a space-discretized system consists of a network of lines (branches) which intersect at points (junctions or nodes) (fig. 3-17). Flow in a discretized system can occur only along branches. Head values in a discretized system can be measured or calculated only at nodes.

2. Why discretize?

Differential equations describe ground-water flow in continuous space. These equations cannot be solved directly for complicated field problems. Discretization (in this case, the finite-difference method of discretization) allows the use of a set of linear algebraic equations to represent the continuous differential equation that governs a specific problem in ground-water flow. For each node in a discretized system, one algebraic equation expresses the principle of continuity in the vicinity of that node. For a system with n nodes, n simultaneous linear equations are solved to obtain a solution, which consists of a calculated head value at each node.

3. How is a system discretized?

A system can be discretized in space by the finite-difference method using either uniform-grid spacing, in which network branches form squares (fig. 3-17), or variable-grid spacing, in which network branches form rectangles.

The purpose of the following paragraphs is to describe the procedure for calculating flows through branches in a square finite-difference network. The first step is to determine the top or map area (vector area) associated with each branch (fig. 3-18), which along with the "thickness" defines the block of aquifer material associated with each branch. As will be seen later, this area associated with the branch is not the area needed to calculate the branch flow.

Square-mesh networks (fig. 3-18) are a special case of rectangular-mesh networks. The following procedure for determining the top or map area associated with branches in rectangular networks is applicable to both network types and is illustrated in figure 3-18. As an example in applying the following instructions, refer to branch AB and start at node B.

1. Starting at a node at either end of the branch under consideration, draw a line that is perpendicular to the branch halfway to the next node. This line is coincident with another branch.

2. From this point, draw a line equal in length and parallel to the branch under consideration.

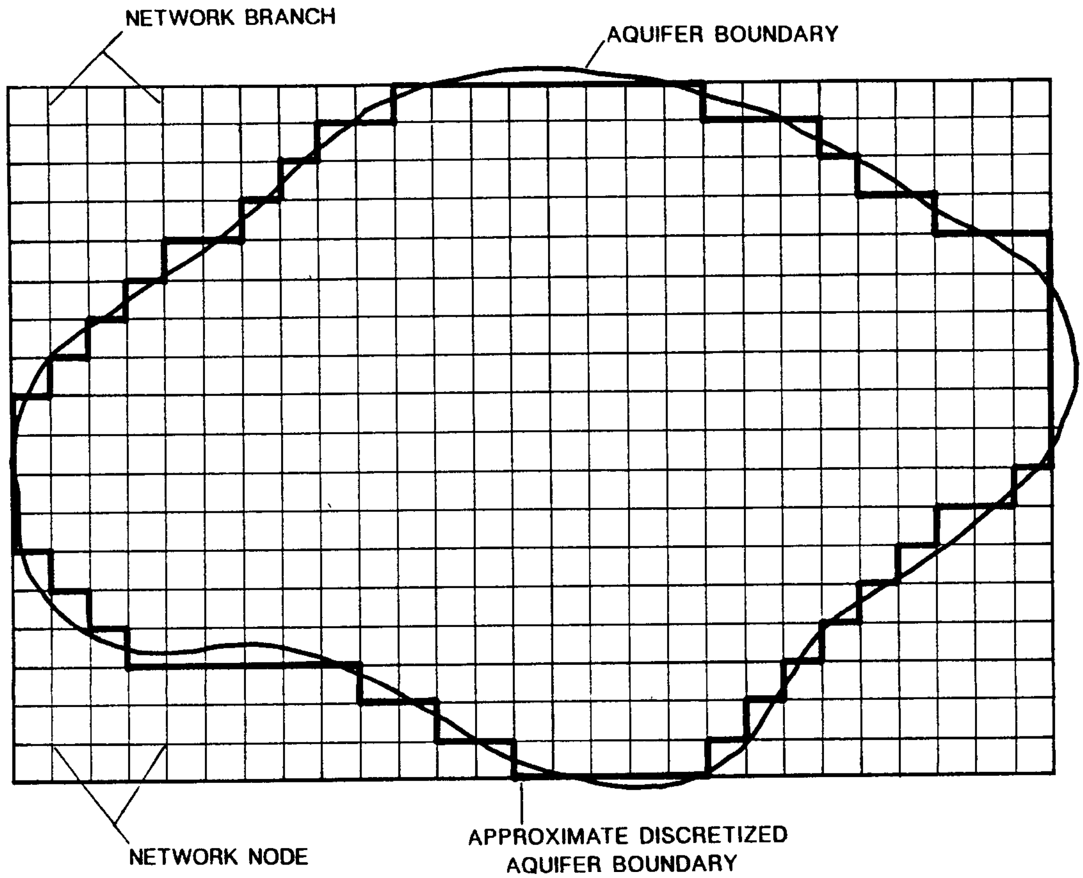
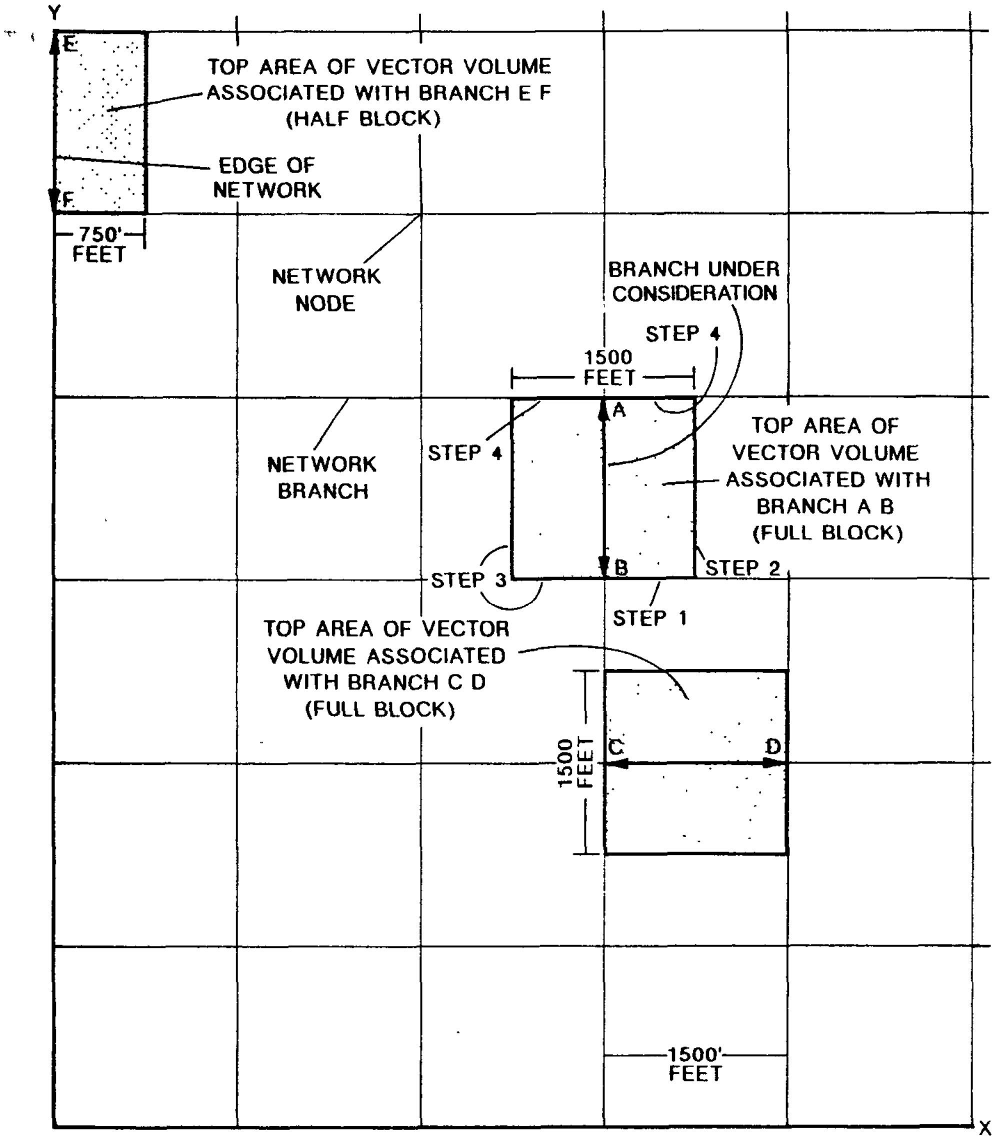


Figure 3-17.--Plan view of a square-mesh finite-difference grid over a map of an aquifer system. (From Prickett and Lonnquist, 1971, fig. 7.)



EXPLANATION

A, B, C, D, E, F -- JUNCTIONS OR NODES IN SQUARE-MESH NETWORK

A B -- INTERIOR NETWORK BRANCH IN Y DIRECTION

C D -- INTERIOR NETWORK BRANCH IN X DIRECTION

E F -- BRANCH AT EDGE OF NETWORK IN Y DIRECTION

K = HYDRAULIC CONDUCTIVITY

K_x = 40 FEET PER DAY

K_y = 60 FEET PER DAY

b = THICKNESS OF AQUIFER MATERIAL ASSOCIATED WITH A BLOCK = 35 FEET

STEP 1, 2, 3, 4 -- SEE ACCOMPANYING TEXT

Figure 3-18.--Vector areas associated with branches in a square-mesh finite-difference grid.

3. Return to the starting node and repeat steps 1 and 2 in the opposite direction. 4. Three sides of a square are drawn in steps 1-3. Complete the square. The fourth side of the square is perpendicular to the branch under consideration (fig. 3-18).

The resulting square (fig. 3-18) represents the vector area (area on network "map" of discretized system) associated with the branch. The vector volume of earth material associated with the branch is obtained by multiplying this area by the aquifer thickness.

Calculations of the areas and volumes associated with branches for the examples shown in figure 3-18 are given in table 3-3. Note the "half block" associated with branch EF at the boundary of the network.

The blocks of earth material whose volumes are calculated in table 3-3 can be thought of as Darcy prisms that are represented by branches between nodes in the network map where head is measured. Darcy's law can be written

$$Q = KA \frac{\Delta h}{L} = \frac{KA}{L} \Delta h \qquad (1)$$

where Δh is the difference in head at the two ends of the prism. The combination of parameters KA/L is called the hydraulic conductance. Note particularly that the area A in this combination (and in Darcy's law) does <u>not</u> refer to the map area associated with the branch, but to the area of the vertical prism face perpendicular to the branch and perpendicular to the plane of the network map. Values of hydraulic conductance for the same network branches shown in figure 3-18 also are listed in table 3-3. The hydraulic conductance is a "lumped" coefficient, obtained directly from Darcy's law, that represents the transmitting capability of a block of earth material.

In summary, application of Darcy's law as written in equation (1) to a discretized finite-difference network permits calculation of the flow through any branch in the network.

Table 3-3.--Areas, volumes, and hydraulic conductances associated with network branches in figure 3-18

Branch	Area associated with branch (square feet)	Volume associated with branch (cubic feet)	Hydraulic conductance associated with branch (feet squared per day)
AB	(750+750)(1,500) = 2,250,000	(1,500)(1,500)(35) = 78,750,000	$\frac{60[35(750+750)]}{1,500} = 2,100$
CD	(750+750)(1,500) = 2,250,000	(1,500)(1,500)(35) = 78,750,000	$\frac{40[35(750+750)]}{1,500} = 1,400$
EF	(750)(1,500) = 1,125,000	(750)(1,500)(35) = 39,375,000	$\frac{60[35(750)]}{1,500} = 1,050$

Exercise (3-2)--Flow Net Beneath an Impermeable Wall

A cross section of a ground-water flow system near a partially penetrating impermeable wall is shown in figure 3-19. This section depicts a two-dimensional flow field. Flow is assumed to occur only in the plane of the figure; that is, there is no flow perpendicular to the plane of the figure. The flow field has unit thickness--that is, the thickness of the flow system perpendicular to the page is 1 ft. The wall is impermeable, as are the bottom and lateral boundaries. The "top" of the ground-water flow system to the left of the impermeable wall lies 5 ft beneath a standing body of water whose surface elevation remains constant at 55 ft above the impermeable bottom boundary (datum). To the right of the impermeable wall the surface of the aquifer material is at an elevation of 25 ft above datum; ground water discharges at this surface to nearby surface drains and by evaporation. The earth material near the impermeable wall is fine sand, which is assumed to be isotropic and homogeneous.

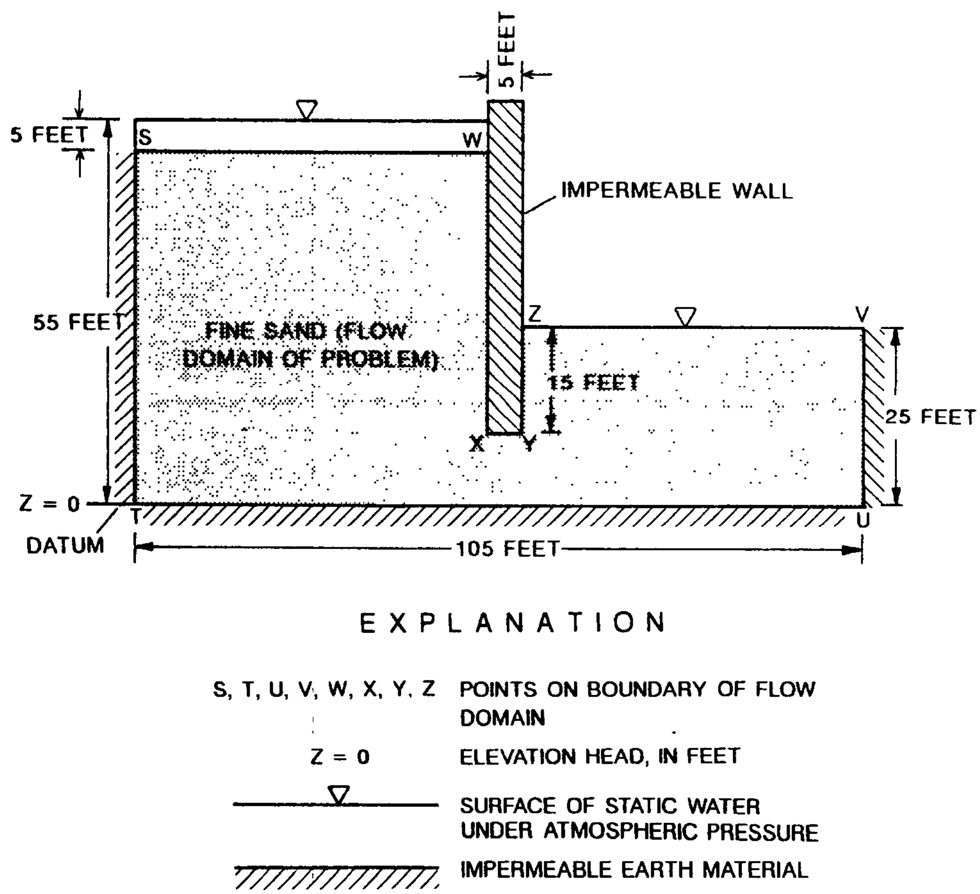


Figure 3-19.--Vertical section through a ground-water flow system near a partially penetrating impermeable wall.

The head distribution in this cross section, obtained by numerical simulation, is shown on figures 3-20 and 3-21. The "node" at which each head value applies is located at the decimal point of the head value. All head values are in feet above datum. The nodes form a square discretization grid with an equal 5-ft spacing between nodes.

The head values on figures 3-20 and 3-21 represent the standard output of a digital simulation of this problem. Often, or perhaps usually, these head data can be contoured to improve insight into the flow pattern. In this exercise, we will use these head data as the starting point for calculating the position of streamlines--an essential step in developing a flow net for this system. Approximate times of travel and residence times within the flow system will be calculated from these head data in a later exercise.

The first step in analyzing any ground-water problem is to develop a simple (compared to the complexity of the real system) conceptual "picture" or model of the operation of the ground-water system. To attain a reasonable conceptual model of the flow system, the minimum required information is (1) the shape (geometry) of the flow system and (2) the boundary conditions. The geometry of the flow system already has been defined in figure 3-19. The next step is to define the boundary conditions of the problem.

Delineate carefully with colored pencils, the extent and type of the boundaries in the impermeable wall problem in figure 3-19. You will find four boundaries and two different boundary conditions. Remember that your designations of the boundaries by means of colored pencils must result in a loop or closed curve without gaps in color. A "gap" without color would represent a portion of the boundary surface for which you have not defined the governing boundary condition.

Where does ground water enter the system? Where does ground water discharge from the system? Sketch the approximate pattern of several flowlines and equipotential lines on figure 3-19. Does your conceptual model of the flow system "make sense"?

Make a table of p/γ, z, and h values for the upper left and upper right horizontal boundaries. What is the total head drop (Δh) in the ground-water system? Is this information consistent with your concept of the flow system?

Flow Net

1. Our goal in this exercise is to construct a fairly accurate flow net from the head data shown on figure 3-21. It is advisable to make copies of this worksheet before you begin in case you make errors. Contour the head data using a contour interval of 2.5 ft--that is, draw contour lines for 52.5, 50, 47.5, 45, . . . 27.5 ft. The contour lines should be smooth curves that intersect streamline boundaries at right angles. Draw all contours in pencil so that corrections and improvements can be made easily. Draw these contour lines carefully because later work depends on their position.

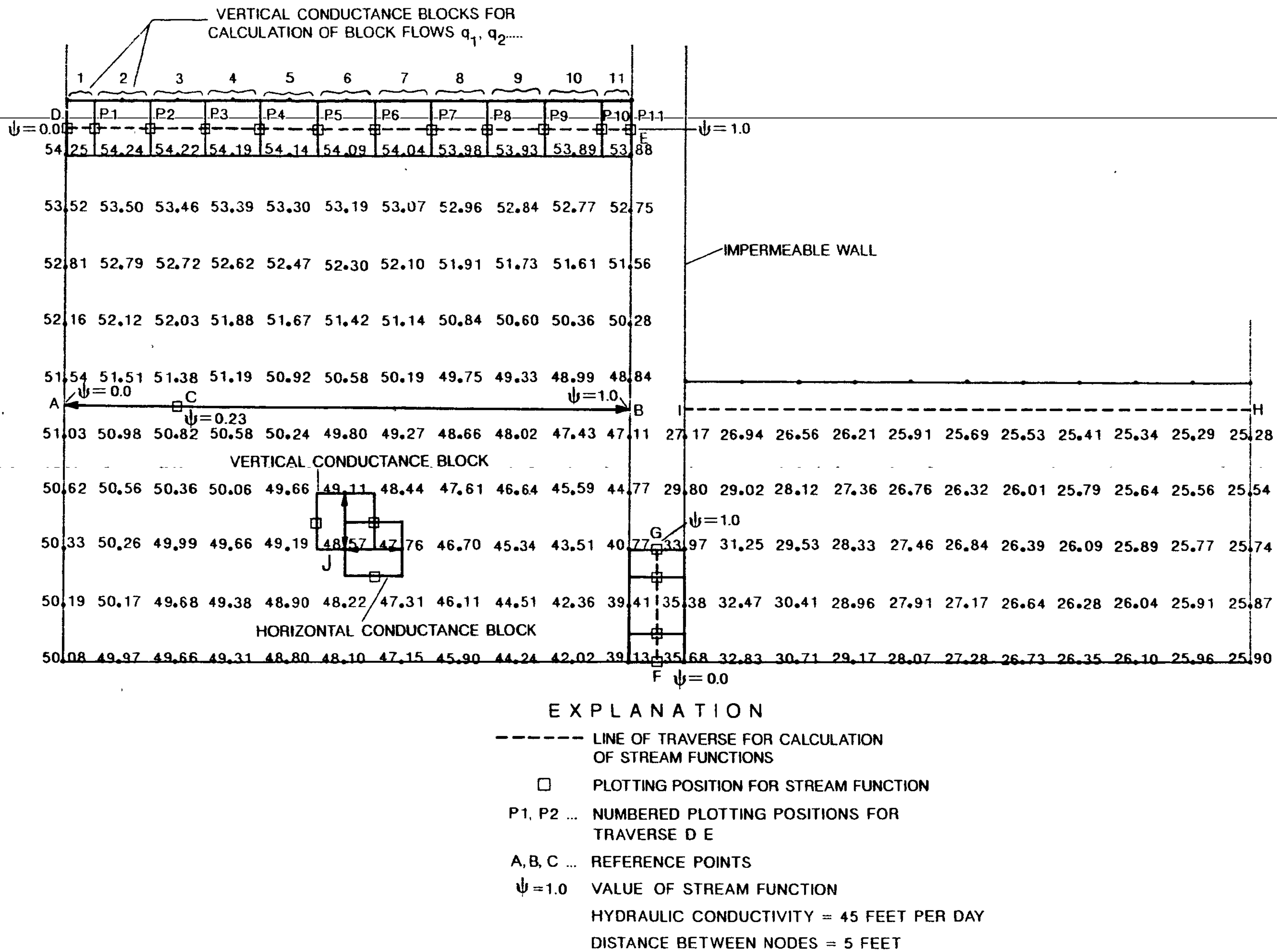
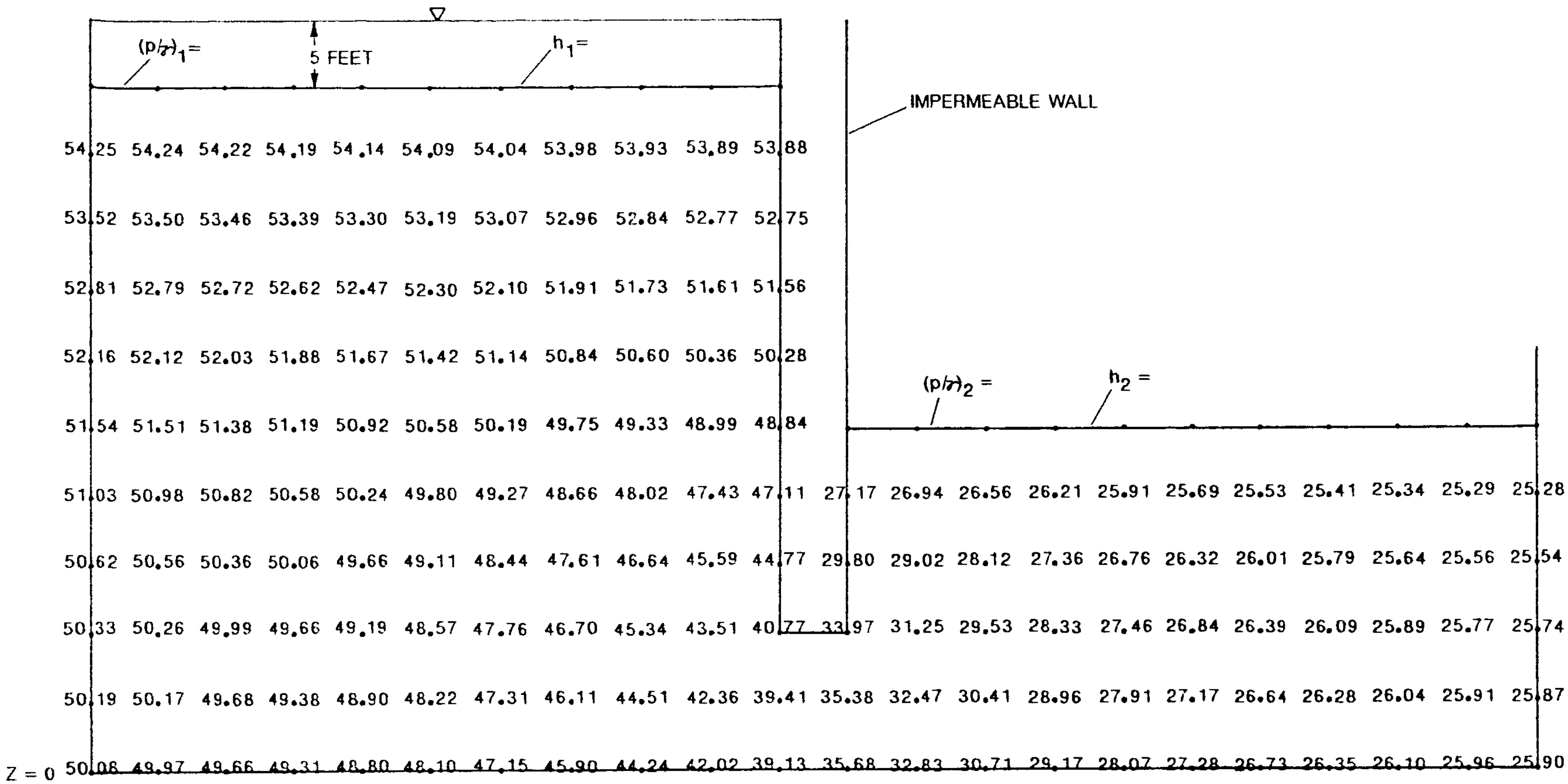


Figure 8-20.--Aquifer blocks for calculating block conductances and block flows, and for plotting positions of calculated values of stream functions.



EXPLANATION

- ▽ SURFACE OF STATIC WATER UNDER ATMOSPHERIC PRESSURE
- —— IMPERMEABLE MATERIAL
- • NODE IN DISCRETIZED SYSTEM AND DECIMAL POINT OF HEAD VALUE AT NODE
- 53.39 HEAD AT NODE, IN FEET

Z IS ELEVATION HEAD, p/γ IS PRESSURE HEAD, h IS TOTAL HEAD, IN FEET

DISTANCE BETWEEN NODES = 5 FEET

HYDRAULIC CONDUCTIVITY = 45 FEET PER DAY

Figure 3-21.--Worksheet for preparation of a flow net for a ground-water system near an impermeable wall.

2. The next step is to determine the position of several interior streamlines in the flow system. These streamlines intersect the head contours at right angles, and generally are constructed so that the flows between adjacent streamlines are equal. (Two adjacent streamlines define a flow tube.)

To begin, identify the two bounding streamlines in the system. Next, we have decided arbitrarily to draw four interior streamlines, so that the system is divided into five flow tubes. Thus, the internal streamlines must be positioned so that one-fifth of the total flow Q beneath the impermeable wall or 0.20Q is transmitted through each flow tube.

In order to locate the four internal streamlines, we will calculate stream functions along selected traverses across the flow field. However, before considering the procedure for calculating stream functions, we will discuss what the stream function represents.

Assume that our flow system is the original continuous system composed of fine sand--that is, we have not yet discretized the system for the purpose of obtaining a numerical solution for head values at nodes. Also assume that we know the total flow through the system. Now, make an arbitrary traverse from one bounding streamline to the other bounding streamline. To do this, designate a point on one bounding streamline as the starting point of the traverse. All traverses across the system must begin on the same bounding streamline. For example, let a traverse start at A on the outside bounding streamline and traverse the system to point B on the other bounding streamline, as shown in figure 3-20. Even though the direction of ground-water flow may not be perpendicular to the traverse line at any given point, we must, nevertheless, intersect the total flow through the system along the traverse from A to B.

Assume further that we measure each increment of flow as we proceed along the traverse. Because we know the total flow, we can assign to any point on the traverse the proportion of the total flow that we have encountered to that point. This proportion is equal to the stream function, Ψ. For example, at point C, assuming that we started at point A, we have encountered 0.23Q, where Q is the total flow--that is, 0.23Q is behind us on the traverse and 0.77Q remains in front of us on the traverse. Clearly, at point A we have intersected none of the flow and the stream function $\Psi = 0$, (Ψ is the Greek letter psi used as a symbol for stream function.) At B, we have intersected the total or 100 percent of the flow, and $\Psi = 1.0$.[1]

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[1] The stream function is actually the total flow traversed to a given point on a traverse line such as point C on traverse AB. We have defined a dimensionless proportion-of-total-flow function which is the stream function divided by a constant, the total flow in the system. For convenience, we will refer to this ratio simply as the stream function.

The stream function is constant along a streamline. Consider a number of closely spaced traverses through the flow field similar to AB and assume that we know the value of the stream function at every point on the traverses. By connecting points of equal stream function--for example, $\Psi_1 = 0.40$ and $\Psi_2 = 0.60$--we are drawing a flow tube bounded by the streamlines $\Psi_1 = 0.40$ and $\Psi_2 = 0.60$ such that 20 percent (0.20 Q) of the total flow is found within this flow tube ($\Psi_2 - \Psi_1 = 0.60 - 0.40 = 0.20$). The stream function is a scalar[2] function of position, just as head is a scalar function of position. A unique value of the stream function may be defined for every point in a continuous flow field. We could write the ground-water flow equations using stream functions instead of head as the dependent variable, although this is seldom done.

Next, we will develop a procedure for calculating stream functions in the discretized impermeable wall problem (fig. 3-20) along three traverses--DE (near the upper left constant-head boundary), FG (beneath the impermeable wall), and HI (near the upper right constant-head boundary). The calculation of stream functions is facilitated by using the format in table 3-4. We will begin with traverse DE (fig. 3-20). Note that blocks 1 and 11 are "half" blocks. Calculate the conductance of the blocks on the traverse using the formula C = KA/L. Determine the flow through each block using the head differences across the blocks. Next, calculate the cumulative flow for the blocks along the traverse from D to E (see format in table 3-4). Divide the cumulative flow at the right-hand edge of each block by the total flow. This calculated value is the stream function at the right-hand edge of that particular block--that is, the percent of the total flow across line DE at the right-hand edge of that particular block on the traverse. Note that the plotting positions of the stream functions are at the right-hand edges of the blocks. For example, the stream function along traverse DE for block 1 is plotted at "p1" (fig. 3-20); the stream function for block 11 is plotted at "p11," the boundary of the flow system.

This choice of plotting positions permits a unique value of the stream function to be plotted on the discretized grid no matter how we make a traverse across the flow field. Compare the two plotting positions of the stream functions at two edges of a typical vertical conductance block and the two plotting positions at two edges of an overlapping horizontal conductance block near J in figure 3-20. One plotting position is shared by both blocks. By extension of this pattern, the stream function plotting positions form a square array of points throughout the flow domain that is offset from the square array of points that constitutes the head nodes. Complete the stream function calculations for traverses FG and HI in table 3-4.

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[2] A scalar quantity can be identified by a single number and has no implied direction; a scalar may be contrasted to a vector quantity, which has direction and requires more than one number for its description.

Table 3-4.--Format for calculation of stream functions in impermeable wall problem (page 1 of 2).

[For locations of numbered blocks, traverse DE, and plotting positions for stream functions p1, p2, ..., see figure 2; C_{block} is hydraulic conductance of discretized block which equals KA/L, where K = hydraulic conductivity of earth material in block, A = cross-sectional area of block perpendicular to direction of ground-water flow, and L = length of block; h_1 and h_2 are head values at nodes located at ends of block; $\Delta h = h_1 - h_2$; q_{block} = flow through a single block; Σq_{block} = flow in a numbered block plus the flows through all lower-numbered blocks (cumulative sum of block flows in traverse); Q_{total} = total flow through the ground-water system beneath the impermeable wall; ft= feet; ft^2 = square feet; ft^3 = cubic feet; Ψ = stream function]

	BLOCK NUMBER	C_{block} = KA/L (ft^2/day)	h_1 (ft)	h_2 (ft)	Δh_{block} (ft)	$q_{block} = C\Delta h$ (ft^3/day)	Σq_{block} (ft^3/day)	$\Psi = \frac{\Sigma q_{block}}{Q_{total}}$	PLOTTING POSITION FOR STREAM FUNCTIONS
TRAVERSE D E	1	22.5	55.00	54.25	.75	16.88	16.88		P1
	2								P2
	3								P3
	4								P4
	5								P5
	6								P6
	7								P7
	8								P8
	9								P9
	10								P10
	11							1.00	P11

Table 3-4.--Format for calculation of stream functions in impermeable wall problem (page 2 of 2).

BLOCK NUMBER	$C_{block} = KA/L$ (ft^2/day)	h_1 (ft)	h_2 (ft)	Δh_{block} (ft)	$q_{block} = C\Delta h$ (ft^3/day)	Σq_{block} (ft^3/day)	$\Psi = \frac{\Sigma q_{block}}{Q_{total}}$

3. The procedure for completing the flow net is the following. Plot the individual stream function values on figure 3-21 at the appropriate points. By interpolation mark on each traverse line the position of the stream functions $\Psi = 0.20$, $\Psi = 0.40$, $\Psi = 0.60$, and $\Psi = 0.80$. After completing this, you have established three points on the four streamlines that you wish to draw. Now sketch the four streamlines on figure 3-21, being careful to draw the streamlines perpendicular to the already existing equipotential lines. Starting at the left end of the upper-left horizontal boundary (fig. 3-21), label the streamlines "a" through "f" (the designations on the two streamline boundaries). The result should be a respectable flow net. Of course, you can improve the flow net by calculating additional values of stream functions along additional traverses through the flow system and refining, thereby, the positions of the four internal streamlines.

Note (3-5).--Examples of Flow Nets

Study of flow nets provides valuable information about and insight into typical flow patterns in ground-water systems. It is advisable to study systematically all the flow nets that you encounter. To obtain the greatest possible return from studying flow nets, the following sequence of steps is suggested: (1) differentiate between the equipotential lines and flowlines, (2) identify exactly where water enters the ground-water system and where water leaves the system, (3) designate the boundary conditions of the ground-water system, first for the inflow and outflow boundaries in (2), and then for the remainder of the system boundaries, and (4) study the actual pattern of flowlines and equipotential lines, asking questions such as (a) where ground-water velocities are greatest and least, (b) where "resistance" to flow in the system is greatest, which corresponds to where head drops (head dissipation) in the system are concentrated, and (c) how flowlines refract at boundaries between layers within the system that have different values of hydraulic conductivity.

Examples of flow nets are given in figures 3-22, 3-23, and 3-24. Go through the thought sequence above for each of these flow nets and for the flow net beneath the impermeable wall in Exercise (3-2).

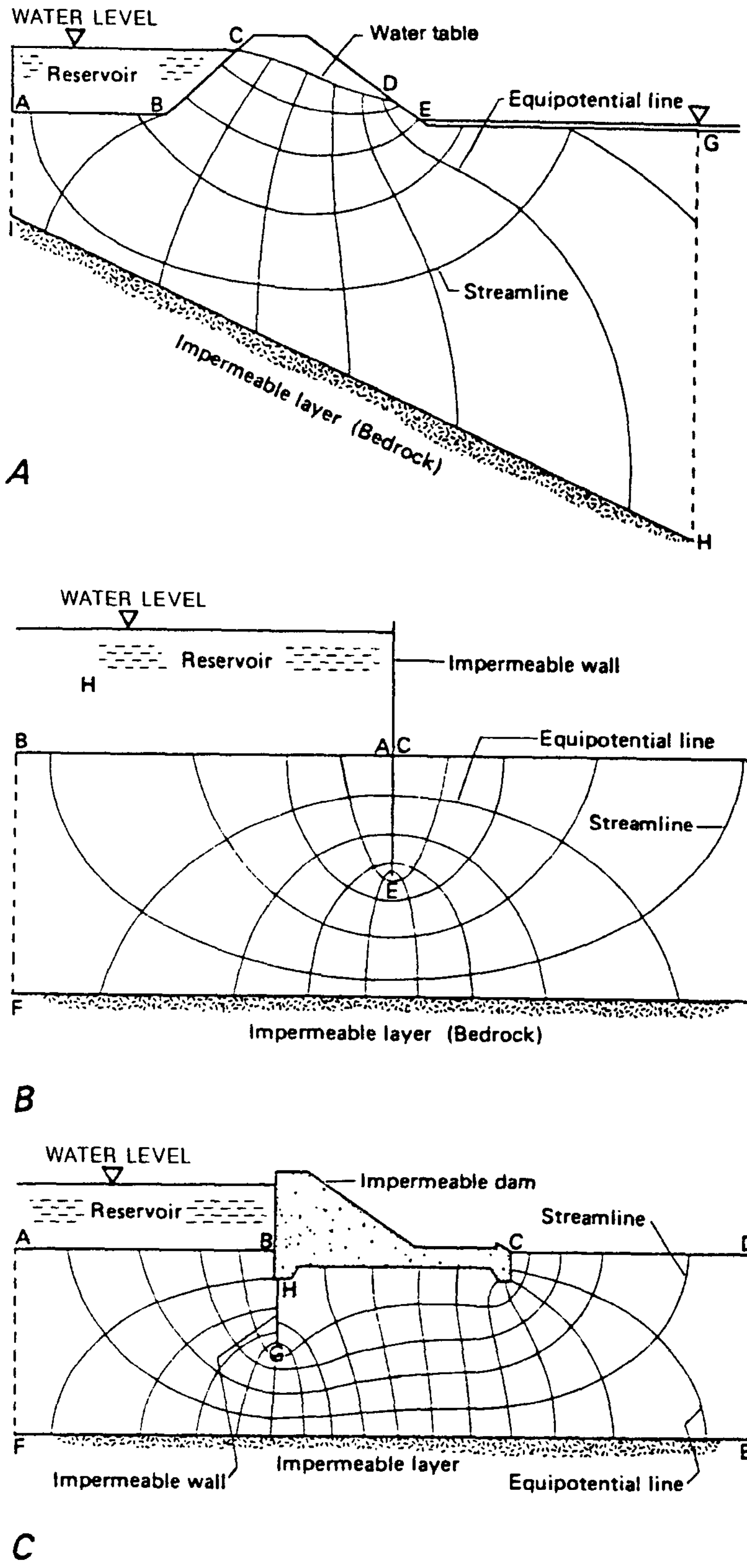


Figure 3-22.--Flow net within three different hydraulic settings: A, through and beneath an earth dam underlain by sloping bedrock; B, beneath a vertical impermeable wall; and C, beneath an impermeable dam and a vertical impermeable wall. (From Franke and others, 1987.)

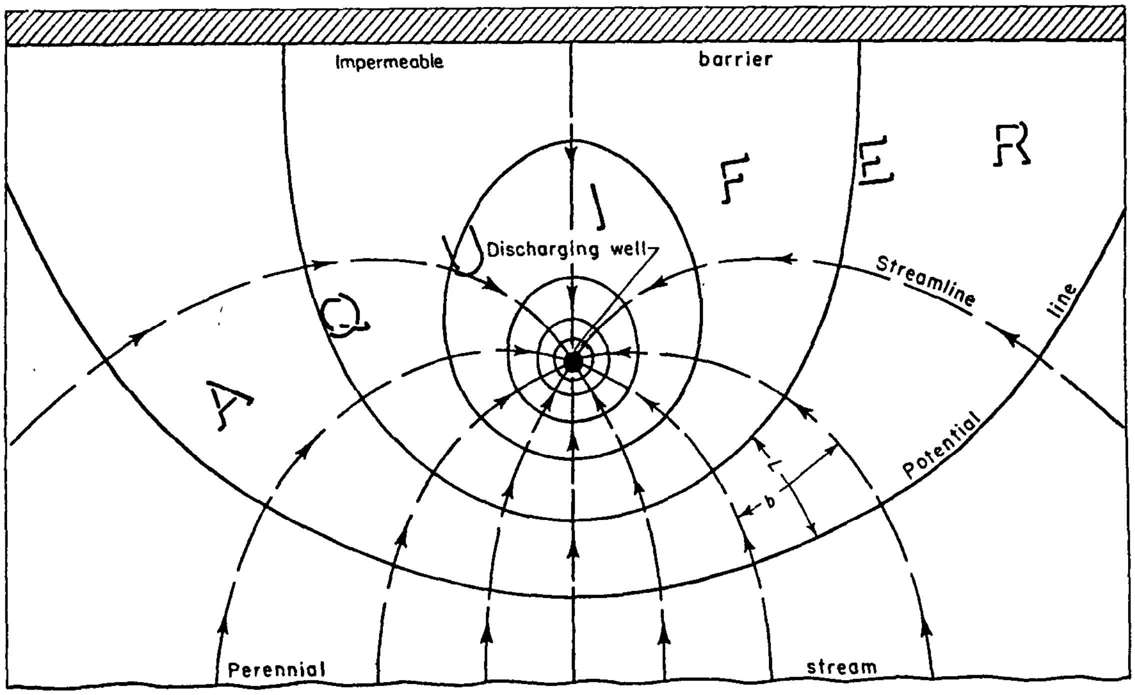


Figure 3-23.--Flow net for a discharging well in an aquifer bounded by a perennial stream parallel to an impermeable barrier. (From Ferris and others, 1962, fig. 3.)

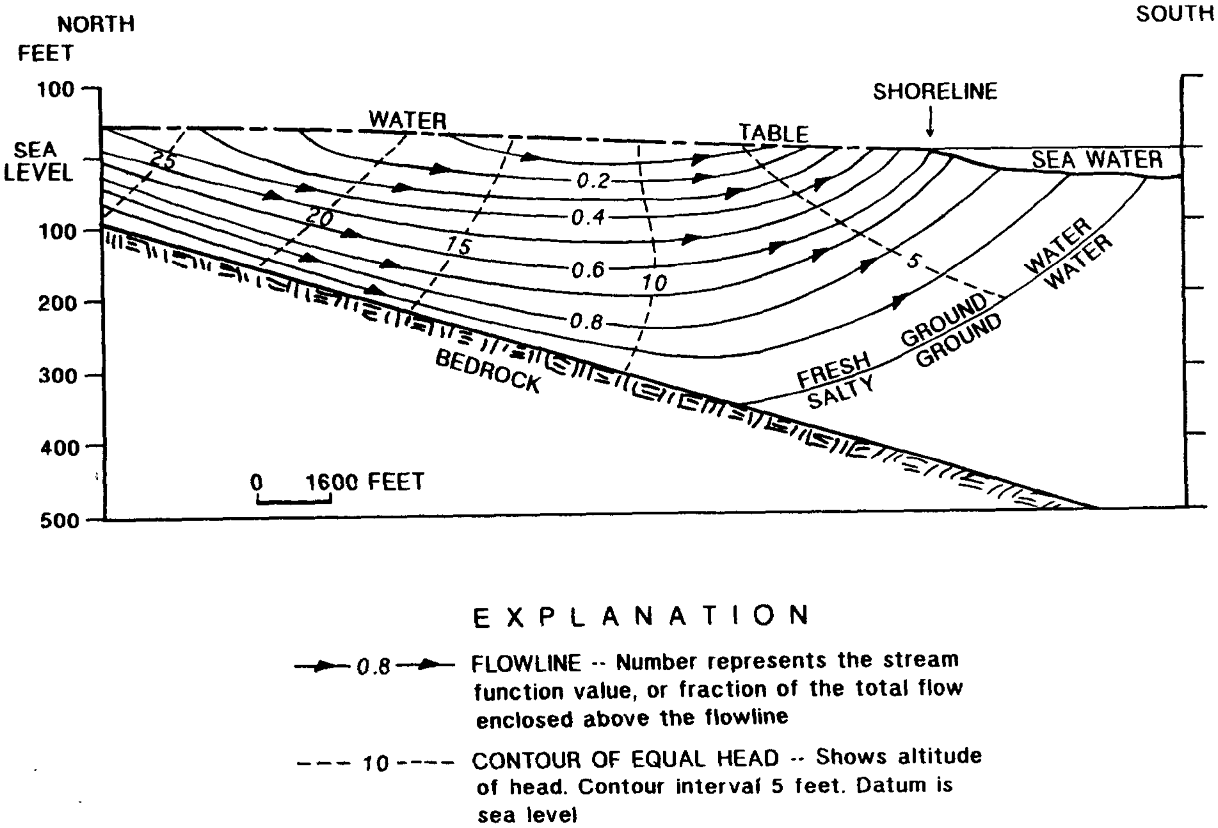


Figure 3-24.--Analog simulation of coastal ground-water flow pattern near Ponce, Puerto Rico, assuming a homogeneous ground-water reservoir. (From Bennett and Giusti, 1971.)

Regional Ground-Water Flow and Depiction of Ground-Water Systems Using Hydrogeologic Maps and Sections

Assignments

*Study Fetter (1988), p. 230-258; or Freeze and Cherry (1979), p. 253.

*Study Note (3-6)--Examples of hydrogeologic maps and sections.

A comprehensive introduction to many of the most areally extensive regional aquifer systems in the United States is provided in U.S. Geological Survey Circular 1002 edited by Sun (1986).

Common types of hydrogeologic maps and sections include (a) structure-contour maps that depict the topographic surfaces corresponding to the tops and bottoms of hydrogeologic units; (b) isopach (thickness) maps, which can be regarded as difference maps between two selected structure contour maps; (c) cross sections that depict hydrogeologic units--sometimes cross sections show actual lithologic or borehole geophysical logs; (d) fence diagrams and block diagrams, which extend the geometric representation of hydrogeologic units to three dimensions; (e) head maps of a single hydrogeologic unit; and (f) cross sections showing both hydrogeologic units and head information. Examples of some of these types of hydrogeologic illustrations are given in Note (3-6), figures 3-25 through 3-32.

Note (3-6).--Examples of Hydrogeologic Maps and Sections

The following series of figures, figures 3-25 through 3-32, is a collection of representative hydrogeologic maps and sections that depict hydrogeologic features of the ground-water system beneath Long Island, New York. This ground-water system is used as an example primarily because it has been studied intensively and a great deal of hydrogeologic information about this system is available.

Ideally, an intensive study of a ground-water system includes preparation of a series of internally consistent hydrogeologic maps and cross sections. As a start, this series might include (a) structure-contour maps on tops of all hydrogeologic units, (b) isopach maps for all hydrogeologic units, (c) head maps of all aquifers for predevelopment conditions and at subsequent times, (d) transmissivity maps for all aquifers, and (e) selected hydrogeologic sections showing the geologic framework and associated equipotential lines.

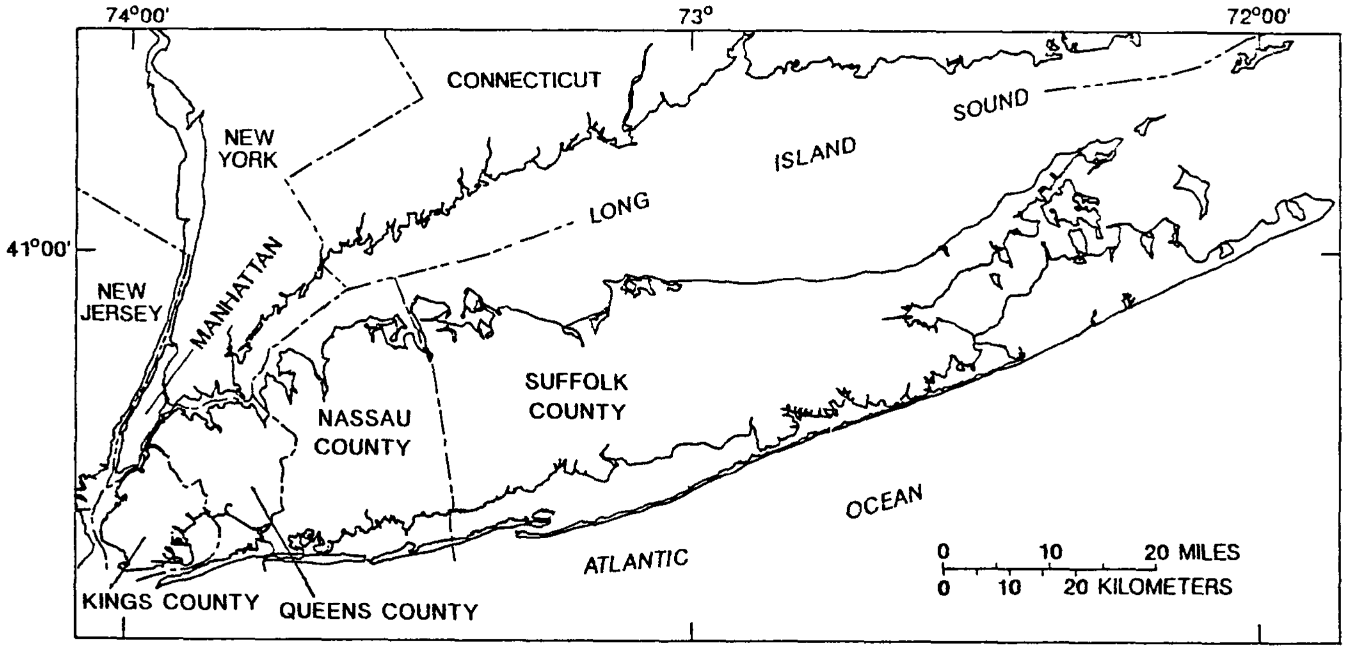


Figure 3-25.--Location and general geographic features of Long Island, New York. (From Franke and McClymonds, 1972, fig. 1.)

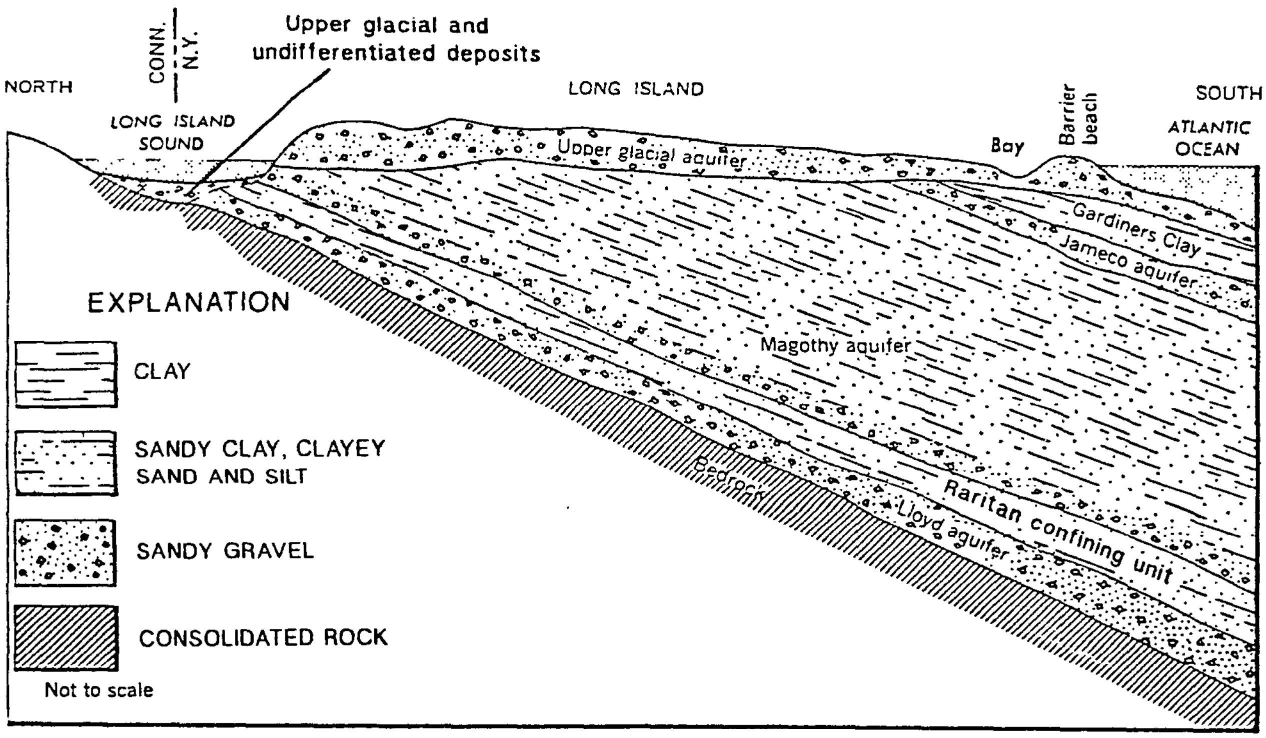


Figure 3-26.--Geologic features of the Long Island ground-water reservoir. (From Franke and McClymonds, 1972, fig. 8.)

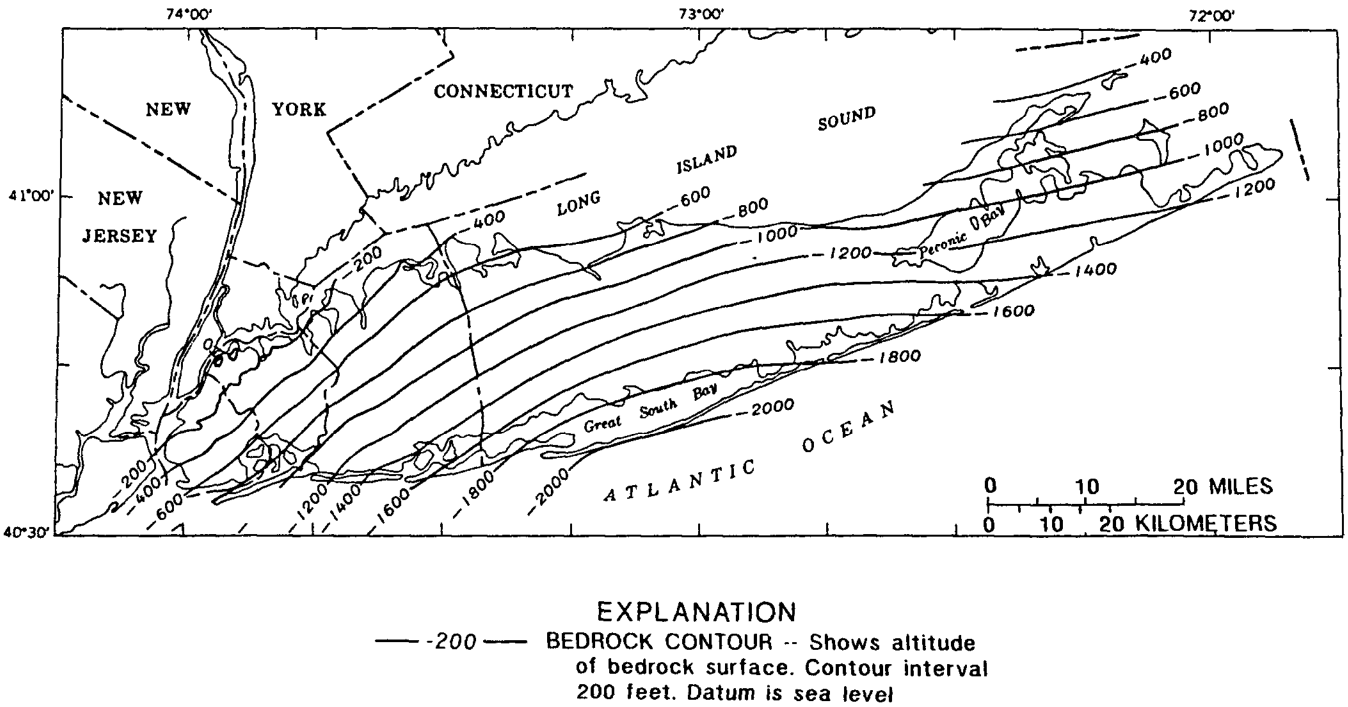


Figure 3-27.--Contour map of the bedrock surface, Long Island, New York. (From Franke and McClymonds, 1972, fig. 11.)

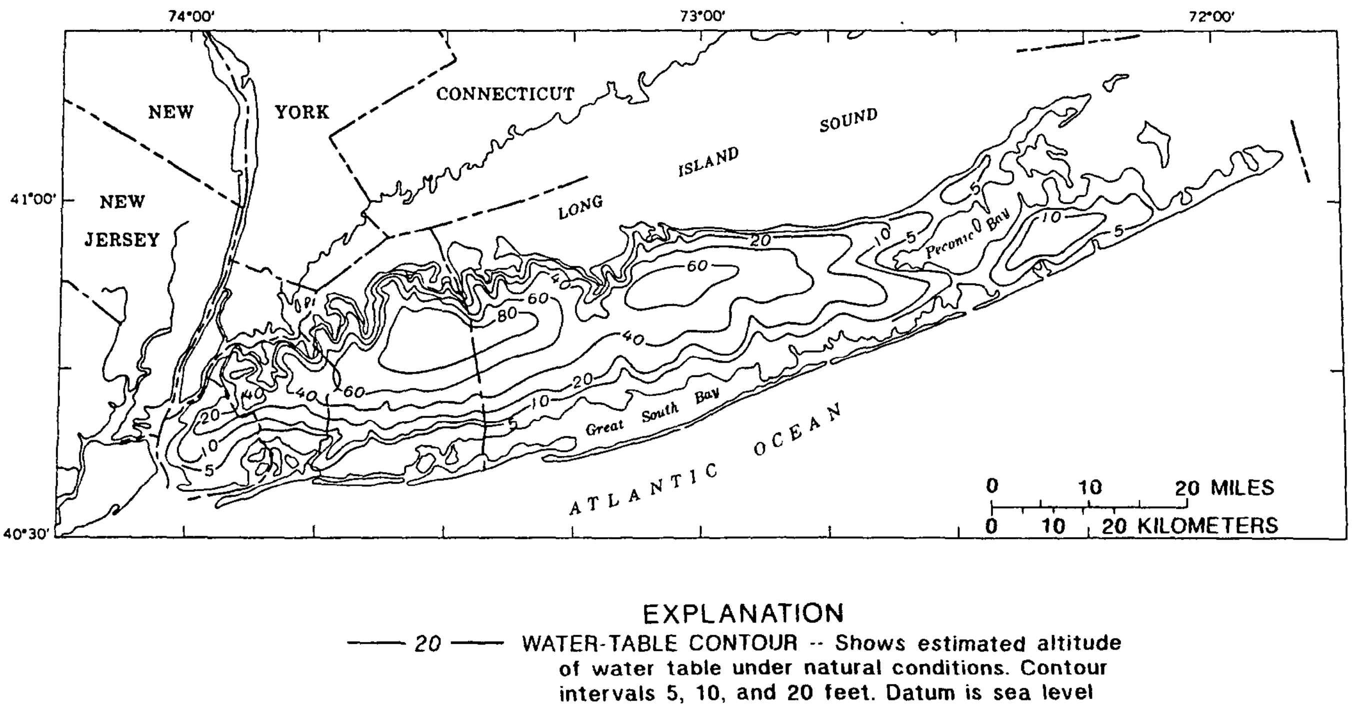
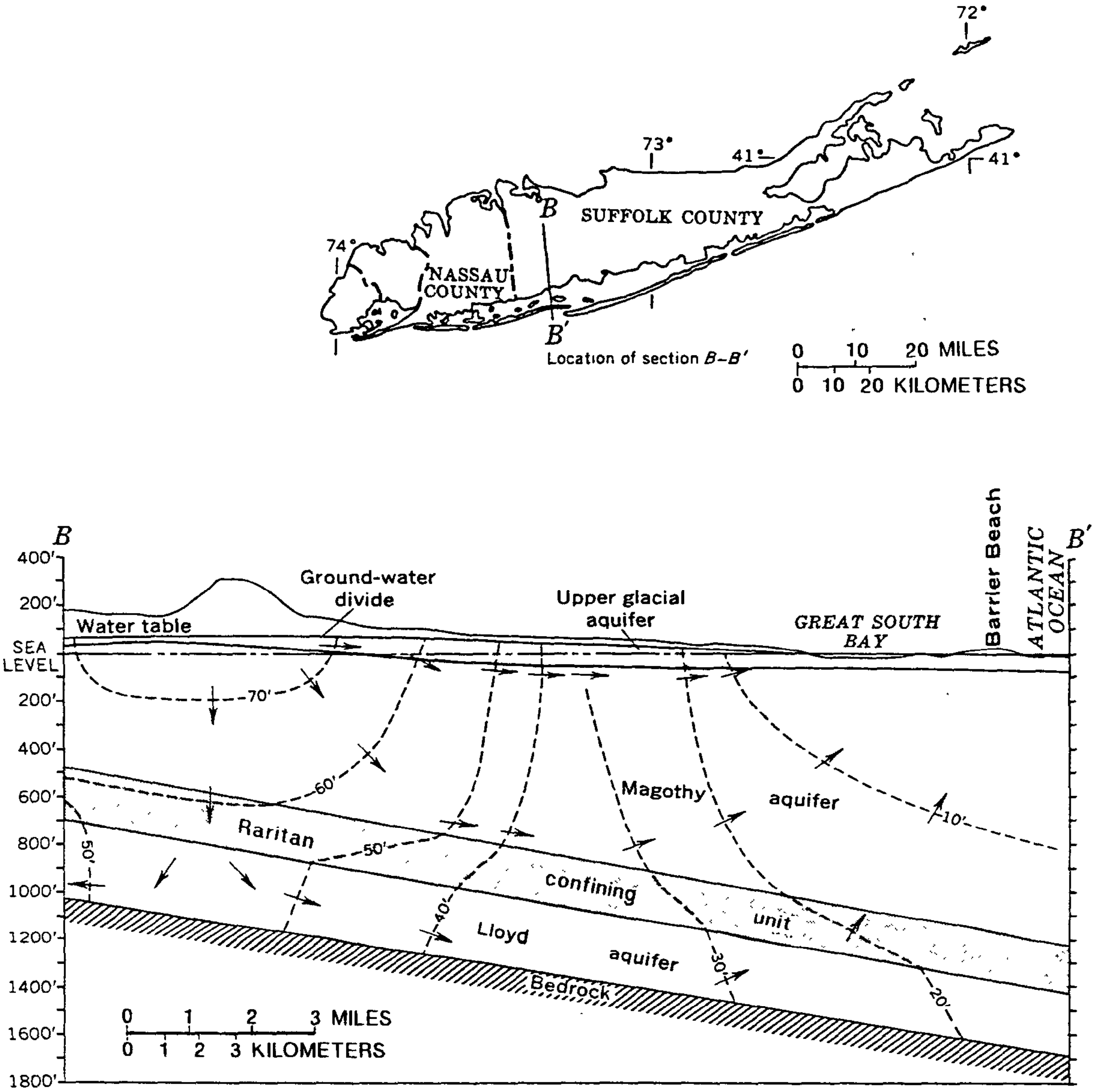


Figure 3-28.--Estimated average position of the water table under natural conditions. (From Franke and McClymonds, 1972, fig. 9.)



VERTICAL SCALE GREATLY EXAGGERATED

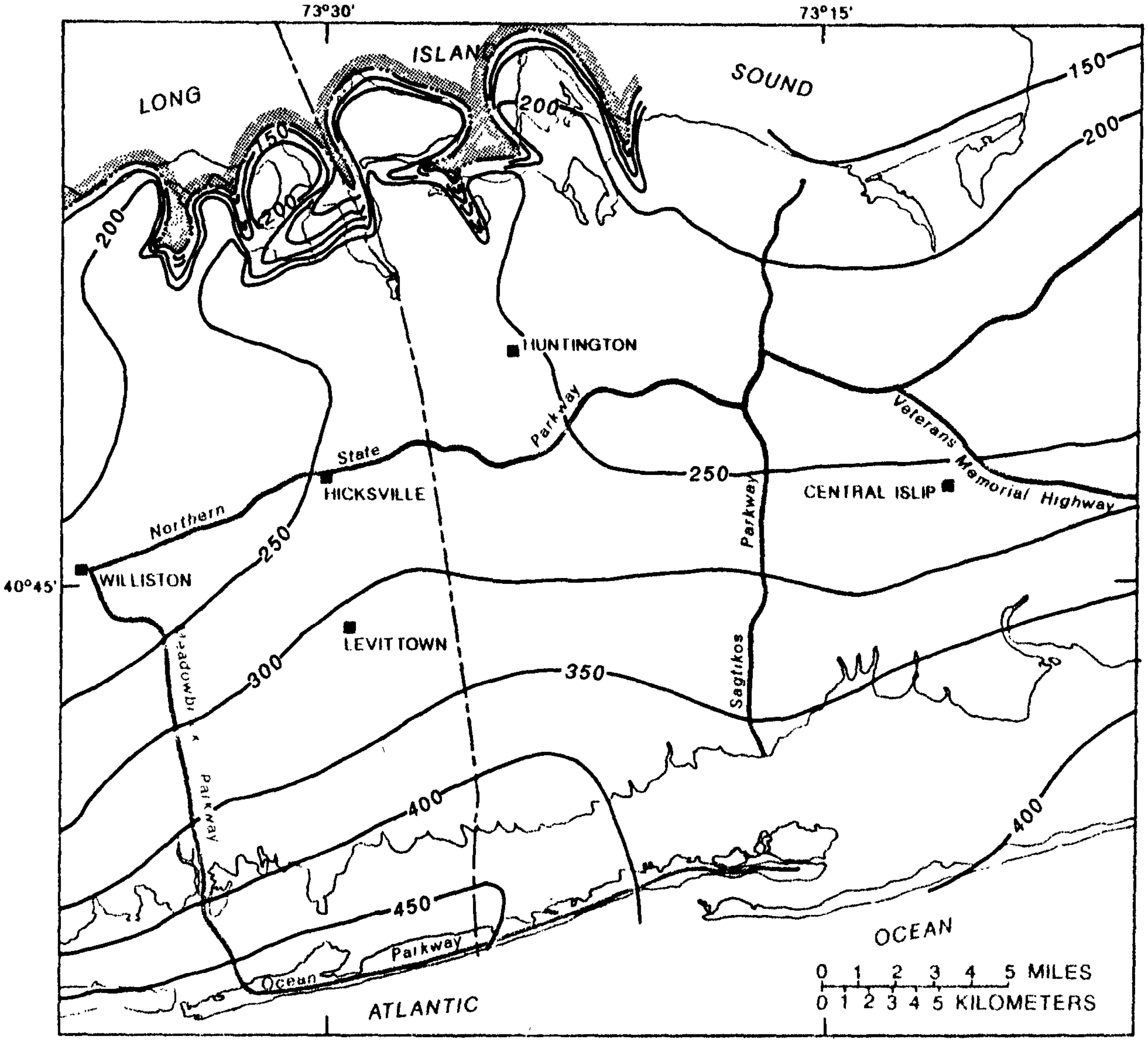
EXPLANATION

---40--- POTENTIOMETRIC CONTOUR -- Shows altitude of equipotential surface. Contour interval 10 feet. Datum is sea level

→ DIRECTION OF GROUND-WATER FLOW

——— HYDROGEOLOGIC BOUNDARY

Figure 3-29.--Geohydrologic section of the ground-water reservoir in southwestern Suffolk County, Long Island, New York, in October 1960. (From Franke and McClymonds, 1972, fig. 21.)



EXPLANATION

—450— LINE OF EQUAL THICKNESS OF LLOYD AQUIFER -- Interval is 50 feet

APPROXIMATE LIMIT OF LLOYD AQUIFER

Figure 3-30.--Thickness map of the Lloyd aquifer in west-central Long Island, New York. (From McClymonds and Franke, 1972, pl. 3A.)

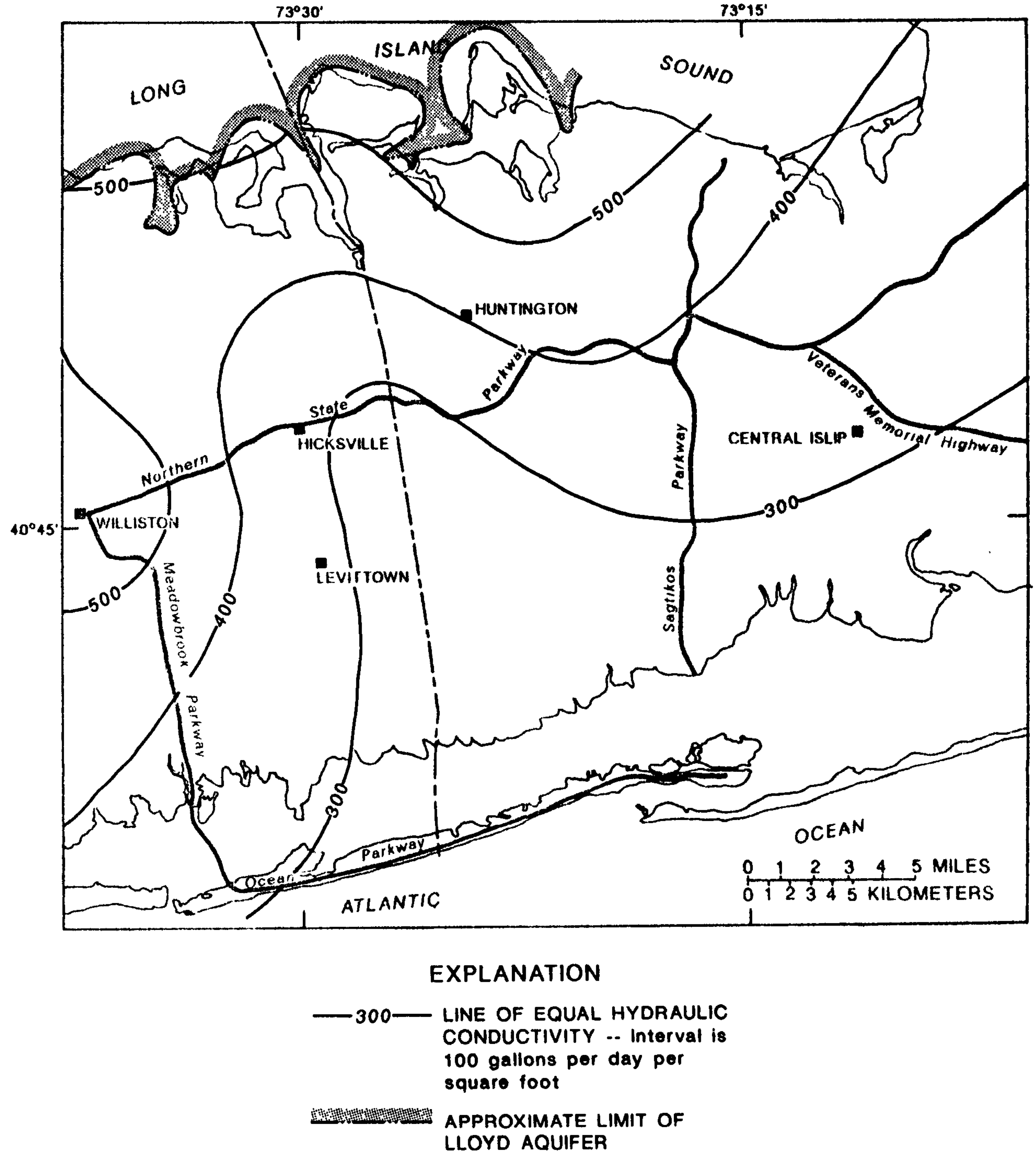
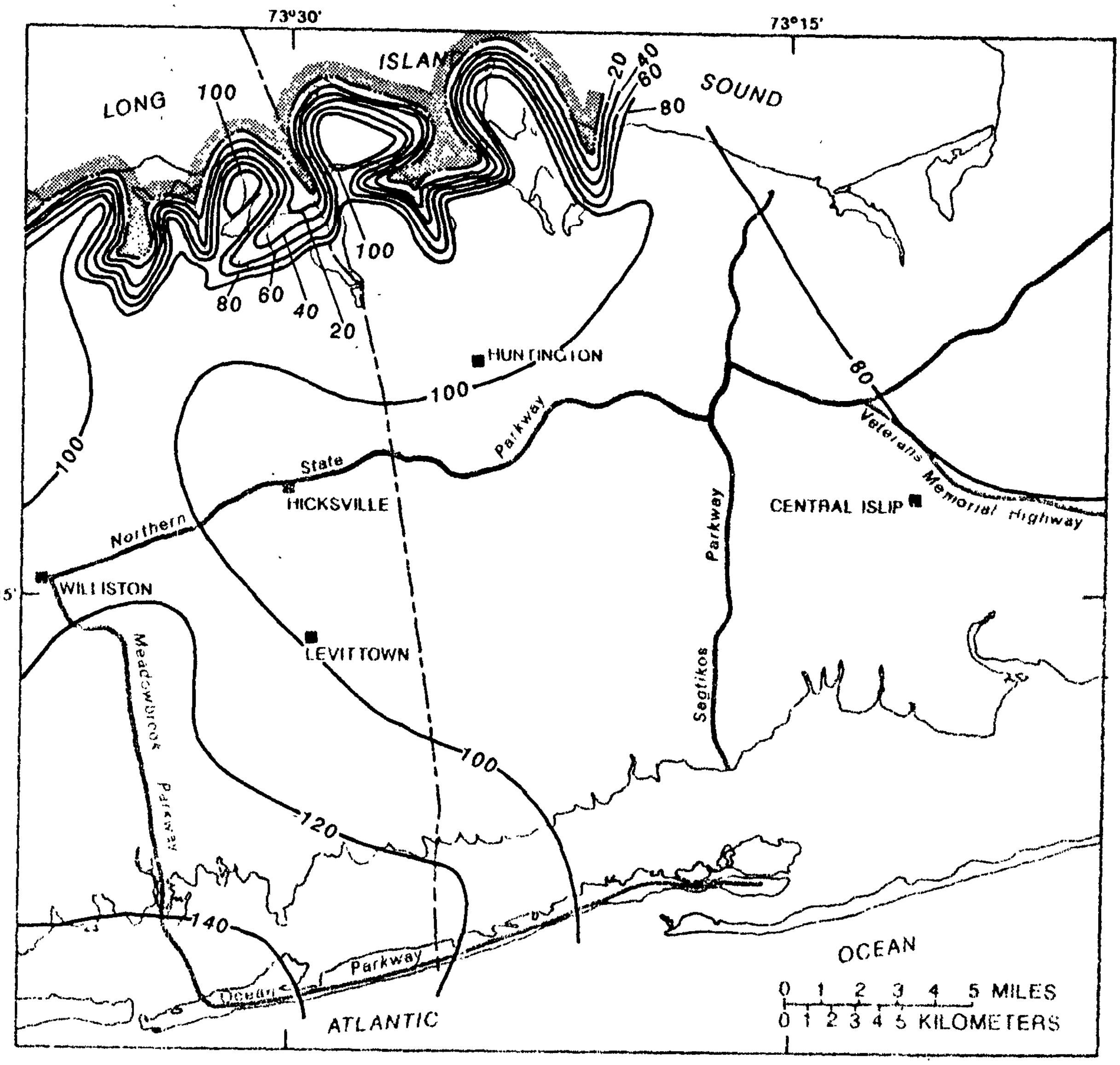


Figure 3-31.--Map of estimated average hydraulic conductivity of the Lloyd aquifer in west-central Long Island, New York. (From McClymonds and Franke, 1972, pl. 3B.)



EXPLANATION

—140— LINE OF EQUAL TRANSMISSIVITY IN THOUSANDS -- Interval is 20,000 gallons per day per foot

APPROXIMATE LIMIT OF LLOYD AQUIFER

Figure 3-32.--Map of estimated transmissivity of the Lloyd aquifer in western Long Island, New York. (From McClymonds and Franke, 1972, pl. 3C.)

Geology and the Occurrence of Ground Water

Assignment

*Study Fetter (1988), p. 259-324; Freeze and Cherry (1979), p. 144-166; or Todd (1980) p. 37-42.

Much has been written about the role of rock type, depositional environment of sediments, geologic structure and climate on the occurrence of ground water. The reading assignment listed above deals with these aspects of ground-water hydrology in sufficient detail for the purposes of this course.

Description of a Real Ground-Water System

At this point in the course we suggest that the instructor or someone else make a formal presentation that describes in detail the operation of a real ground-water system, preferably one that is of particular interest to the participants. Some of the information that such a presentation might contain is listed below. Of particular importance in the context of this course is a clear conceptualization of the natural system, which includes a careful description of the system's physical boundary conditions (items (2) and (3) in the following list).

(1) Location of study area, geography, and climate.

(2) Geologic framework--pertinent features but not lengthy stratigraphic descriptions.

(3) Natural hydrologic system--how the system operates; inputs and locations; areas of discharge; head maps for pertinent hydrogeologic units; careful designation of boundaries and boundary conditions of natural hydrologic system; data available, and methods to estimate distribution of hydraulic properties.

(4) Human effects on hydrologic system--brief historical survey.

(5) If the presentation includes discussion of a model simulation, reason for developing model or definition of problem to be solved by model.

(6) Description of model--areal extent; areal discretization scheme; number of model layers; careful designation of model boundaries and boundary conditions; compare with boundaries in (3) and justify any differences; definition of initial conditions; time-discretization scheme if unsteady model; superposition versus absolute heads; preliminary model runs and what one might learn from them; calibration procedures; and subjective evaluation of reliability of final model results to solve the problem posed.

Source of Water to a Pumping Well

Assignment

*Work Exercise (3-3)--Source of water to a pumping well.

What is the source of water to a pumping well placed at different locations within the ground-water system? Answering this question qualitatively in the early part of a ground-water investigation can be a productive part of the conceptualization of a ground-water system. As some thought about the question may suggest, the response of a system to stress ultimately must depend on that system's physical boundary conditions.

Exercise (3-3)--Source of Water to a Pumping Well

The points made by C. V. Theis (1940) in his paper "The source of water derived from wells--essential factors controlling the response of an aquifer to development" may be summarized and extended as follows. Consideration of the hydrologic equation Inflow = Outflow $\pm$ ΔStorage suggests that, in principle, there are three possible sources of water to a pumping well--a decrease in ground-water storage, an increase in inflow to the ground-water system, or a decrease in outflow from the ground-water system. This abstract statement of principle can be clarified by application to a concrete example.

Consider a simple hydrologic system under predevelopment conditions in a state of dynamic equilibrium for which inflow = outflow (fig. 3-33(A)). When a well is added to the system and pumping starts at a rate Q_1, initially water is withdrawn only from storage. As water levels continue to fall and hydraulic gradients are reduced in areas of natural discharge, natural discharge is reduced (fig. 3-33(B)). These processes reduce the amount of water that must come from storage--in effect, flow is rerouted from the original discharge area, the stream, to the pumping well. As the rate of storage depletion decreases, the rate of water-level decline slows and the system approaches a new equilibrium (fig. 3-33(C)).

At a later time the equilibrium condition depicted in figure 3-33(C) is further disturbed by a higher rate of pumpage (Q_2). After an initial removal of ground water from storage accompanied by a further decline in water levels, in contrast to the situation depicted in figure 3-33(C) in which a water-table divide exists between the well and the stream, the new equilibrium condition exhibits no divide; that is, a hydraulic gradient exists between the stream and the pumping well (fig. 3-33(D)). This condition induces movement of water from the stream into the aquifer. Thus, the stream, which formerly was a gaining stream under natural conditions and a lesser rate of pumpage Q_1 (fig. 3-33(C)), is now locally a losing stream (fig. 3-33(D)).

In summary, the source of water to the well at the initial rate of pumpage Q_1, after a new equilibrium condition had been achieved, was reduced outflow of ground water to the stream. However, in contrast, the source of water to the well at the higher rate of pumpage Q_2 includes both reduced outflow to the stream and induced inflow from the stream to the aquifer.

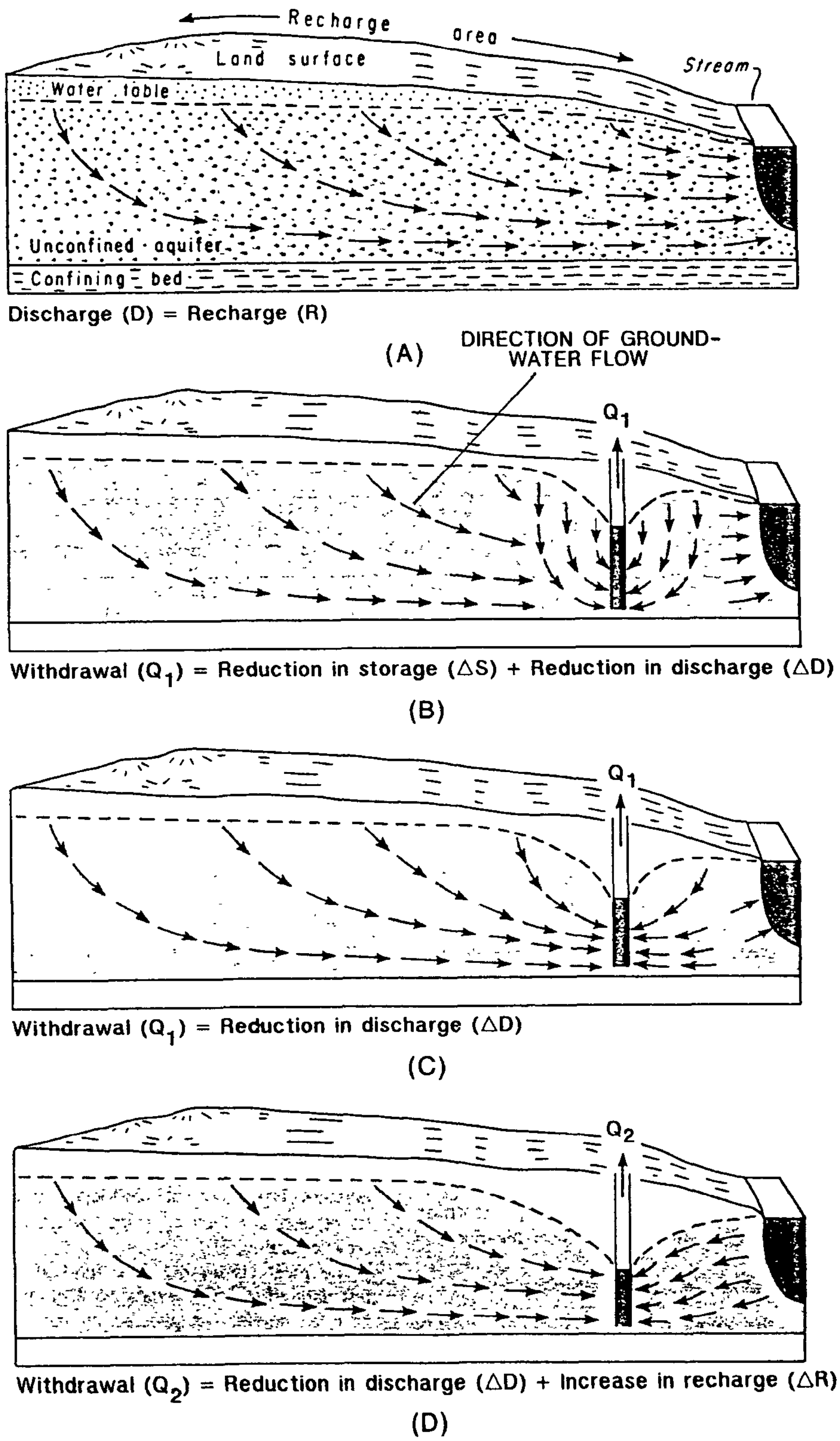


Figure 3-33.--Ground-water flow patterns in a hypothetical system (A) under natural conditions and (B, C, and D) in response to different levels of stress resulting from local pumping of ground water. (Modified from Heath, 1983, p. 33.)

In some cases, the pumpage may exceed the increases in recharge and decreases in natural discharge that can be induced. In these cases, withdrawal from storage continues until falling water levels or exhaustion of the supply force a reduction in the pumping rate. A new equilibrium is then attained in which the reduced pumping rate equals the increases in recharge and decreases in discharge that have been achieved.

If pumpage is not held constant, but rather is increased from year to year, new periods of withdrawal from storage accompany each increase in pumpage.

The following exercise will help to clarify some of these concepts. In this exercise only equilibrium (steady-state) states of the system will be considered--that is, transient conditions in the system, in which some of the water pumped is obtained from ground-water storage, will not be analyzed.

A square confined aquifer with a uniform transmissivity is shown in figures 3-34(A) and 3-34(B). The aquifer is bounded laterally by two impermeable rock walls and two surface-water bodies. The earth materials above and below the aquifer are assumed to be impermeable. The surface-water bodies are a river and a reservoir whose stages remain constant. Thus, a constant head is exerted by the surface-water bodies on their surfaces of contact with the aquifer. The natural head distribution with the river stage at zero altitude and the reservoir stage at 200 ft is a straight line in cross section, as shown in figure 3-35(B). The long-term average increase in flow in the river due to inflow of ground water from the aquifer is 3.1 ft^3/s.

A steady-state simulation of the system with a well (figs. 3-34(B), 3-35(A)) that is pumped at 3.1 ft^3/s (discharge of well is equal to the natural steady-state flow through the aquifer before pumping) using a numerical model solved by a digital computer resulted in the head distribution shown in figure 3-35(A). The steady-state increase in flow in the river opposite the aquifer with this steady rate of pumpage is decreased to 2.0 ft^3/s from its original value of 3.1 ft^3/s.

(1) What is the transmissivity of the aquifer, in ft^2/s?

(2) Contour the head values in figure 3-35(A) using a 20-ft contour interval.

(3) Draw a head profile along AC on figure 3-35(B).

(4) What hydrologic feature may be observed at point B on the head profile?

(5) Draw two streamlines (perpendicular to contours of equal head) from point B to the reservoir on figure 3-35(A).

   (a) What hydrologic feature is represented by these two streamlines?

   (b) What hydrologic feature is represented by the area enclosed by the two streamlines and the reservoir?

(6) Using the information given above, what must be the total inflow to the aquifer from the reservoir when the well is being pumped?

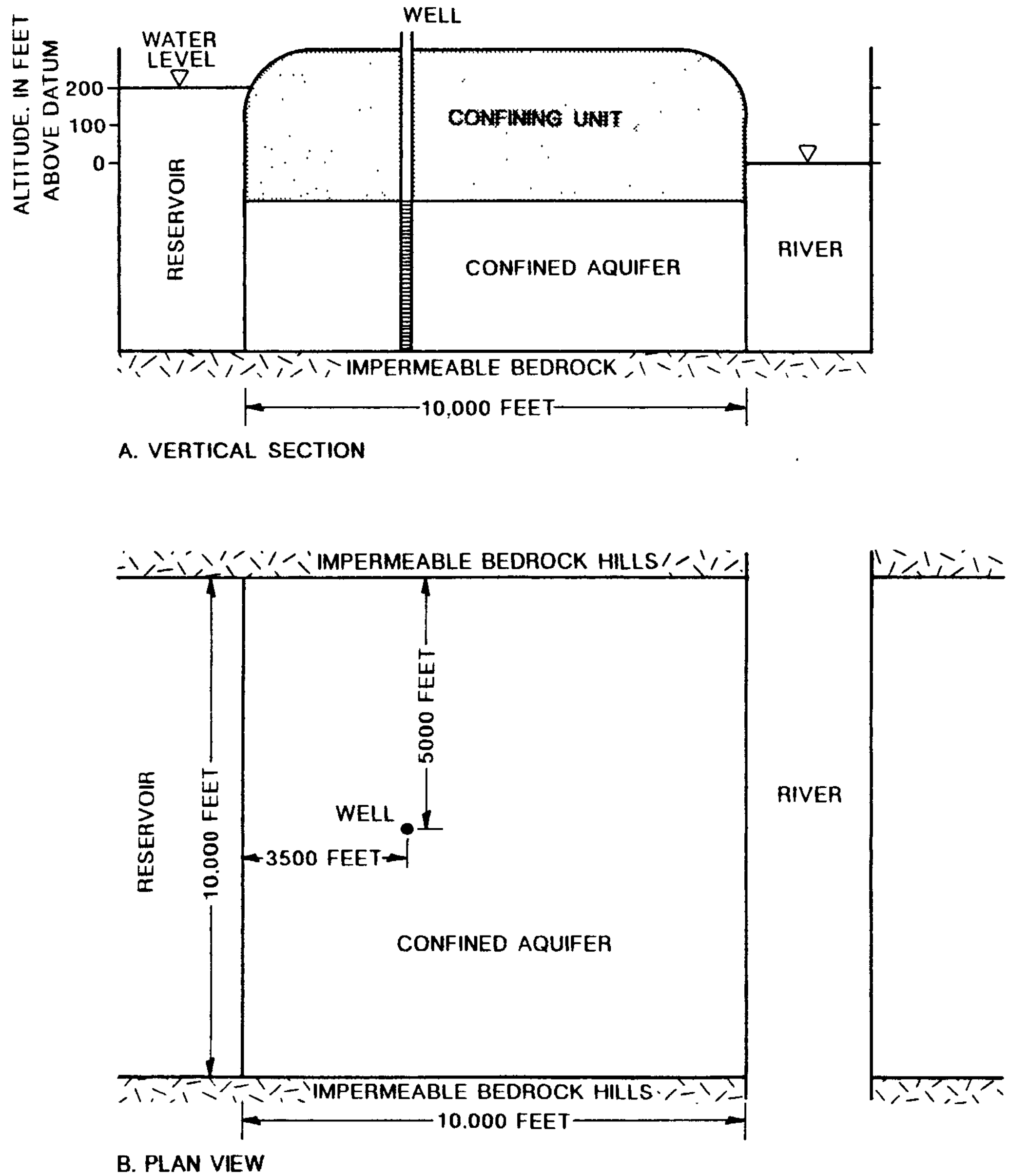


Figure 3-34.--A hypothetical aquifer system in (A) vertical section and (B) plan view.

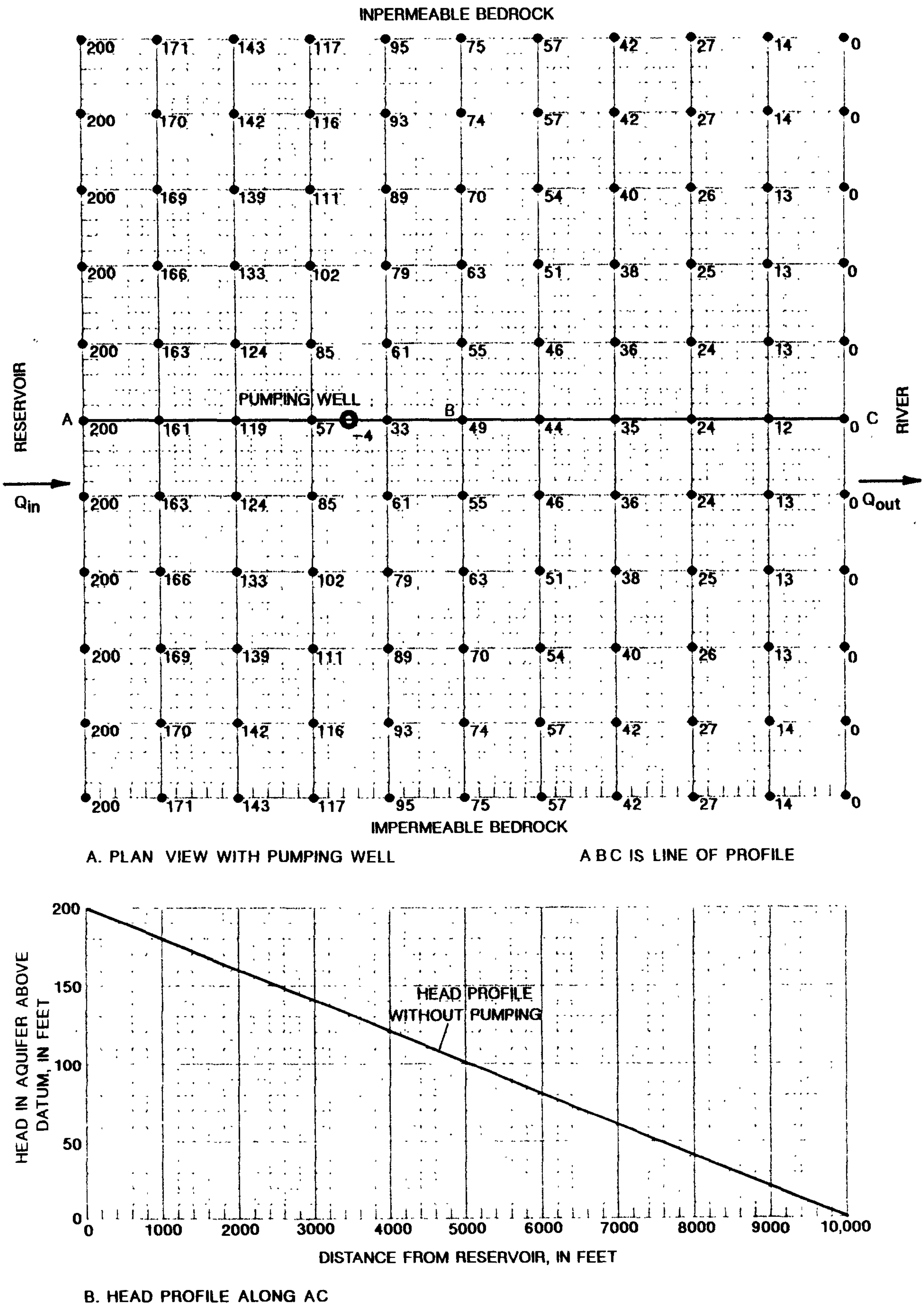


Figure 3-35.--(A) Heads in the stressed aquifer determined by numerical simulation when the pumping rate of the well is 3.1 cubic feet per second. (B) Graph for plotting head profile using data from (A).

(7) Applying the Theis concepts to this situation, what is the "source" of the water to the pumping well, in terms of increased inflow (or recharge) to the aquifer and decreased outflow from the aquifer?

(8) The pumping rate of the well is increased significantly. The resulting head profile along section AC is shown in figure 3-36.

(a) How does the head profile in figure 3-36 differ from the head profile in figure 3-35(B)?

(b) In terms of the Theis concepts, what are the three sources of water to the pumping well in figure 3-36?

(9) The following questions involve qualitative comparisons between the ground-water system described in this exercise and depicted in figure 3-34, designated for convenience as system (a), and the system depicted in figure 3-2 of Exercise (3-1), designated as system (b). Refer to item (6) in table 3-2 of Note (3-3).

(a) After reviewing the boundary conditions of both systems, list the differences in the two sets of boundary conditions.

(b) Place a hypothetical pumping well at two or more locations in both systems in order for (i) the drawdowns caused by the pumping well to be a minimum and (ii) the drawdowns caused by the well to be a maximum.

(c) List the probable sources of water to the pumping well at each location in (b).

(d) A pumping stress interacts with two boundaries in system (a). What is the corresponding situation in system (b)?

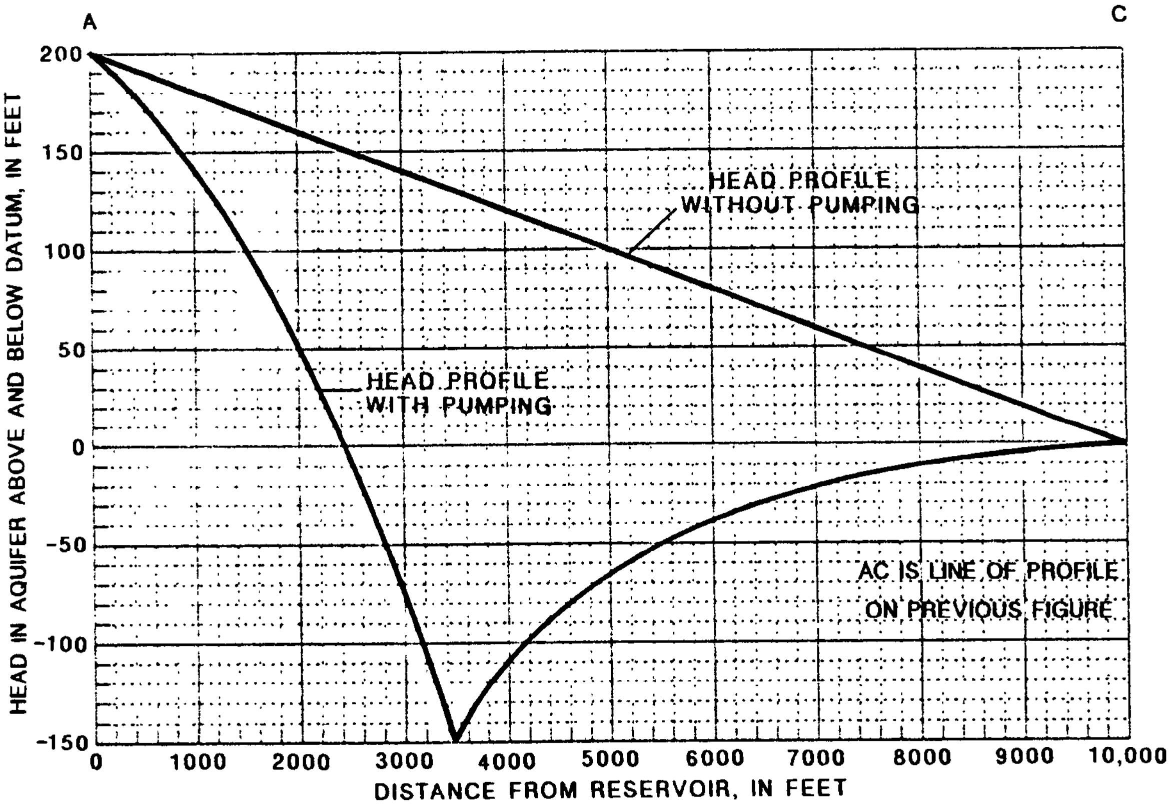


Figure 3-36.--Head profile in the aquifer when the pumping rate of the well is much greater than 3.1 cubic feet per second.

Role of Numerical Simulation in Analyzing Ground-Water Systems

Assignments

*Study Fetter (1988), p. 525-548; Freeze and Cherry (1979), p. 352-364, 540-541; or Todd (1980), p. 384-408.

*Study Note (3-7)--Role of numerical simulation in analyzing ground-water systems.

The most powerful quantitative tool that is available to the hydrologist is numerical simulation. An example of a well documented, general purpose three-dimensional numerical model for ground-water flow simulation is the U.S. Geological Survey Modular Model (McDonald and Harbaugh, 1988). The purpose of the brief comments in Note (3-7) is to suggest a number of ways in which this tool can be effectively utilized.

Simulation, however, can only be effectively utilized in the hands of a knowledgeable hydrologist. The authors have observed instances in which simulation was incorrectly applied. Unfortunately, although the results of these simulations are incorrect and misleading, the conceptual errors leading to these incorrect results may be difficult to identify, and the results may be perceived as correct because of their source.

Note (3-7).--Role of Numerical Simulation in Analyzing Ground-Water Systems

The following statement on the role of simulation in analyzing ground-water systems is an excerpt from an unpublished manuscript by Gordon D. Bennett (U.S. Geological Survey, written commun., 1983). We wish to emphasize two ideas expressed in this excerpt--(1) the importance of simulation as an investigative tool to increase our understanding of the functioning of the ground-water system, as opposed to the usual emphasis on using simulation for prediction, and (2) the idea that several different models of varying type and complexity can be used profitably in parallel early in an investigation to study specific features of the ground-water system.

> Simulation is the central activity in a modern ground-water resource evaluation. It is used ultimately in the predictive phases of the investigation to evaluate the effects of various proposed courses of development. More importantly, however, it is used throughout the study as an investigative tool to develop concepts and test hypotheses, to determine the sensitivity of the system to various parameters, to obtain estimates of parameters by inverse techniques, and to guide the collection and analysis of new data.

As working hypotheses are developed regarding system boundaries and parameter ranges, simulations are designed to test those hypotheses. The head values and ground-water flows obtained in the simulations are compared with corresponding observed heads or flow estimates, and the working hypotheses are modified as necessary. The simulations may be cross-sectional, areal, or three-dimensional, and may represent an original undisturbed equilibrium, a transient response to development, or a new equilibrium achieved after adjustment to development.

This use of simulation as an investigative tool should begin early in the investigation, in parallel with other project activities. Ground-water systems are always three-dimensional. In these early simulations, however, it is often preferable to focus first on individual aspects of the system which can be represented approximately through two-dimensional analysis. In general, both areal and cross-sectional models should be employed, and both steady-state and transient analyses should be made. This phase of the work should be carried on in a parallel, rather than a sequential mode; that is, it is usually a mistake to try to complete all areal simulations before undertaking cross-sectional simulations, or all steady-state analyses before undertaking transient analyses...

The general objectives of simulation remain the testing of hypotheses, establishment of parameter ranges, identification of sensitive parameters, and general insight into the operation of the ground-water system.