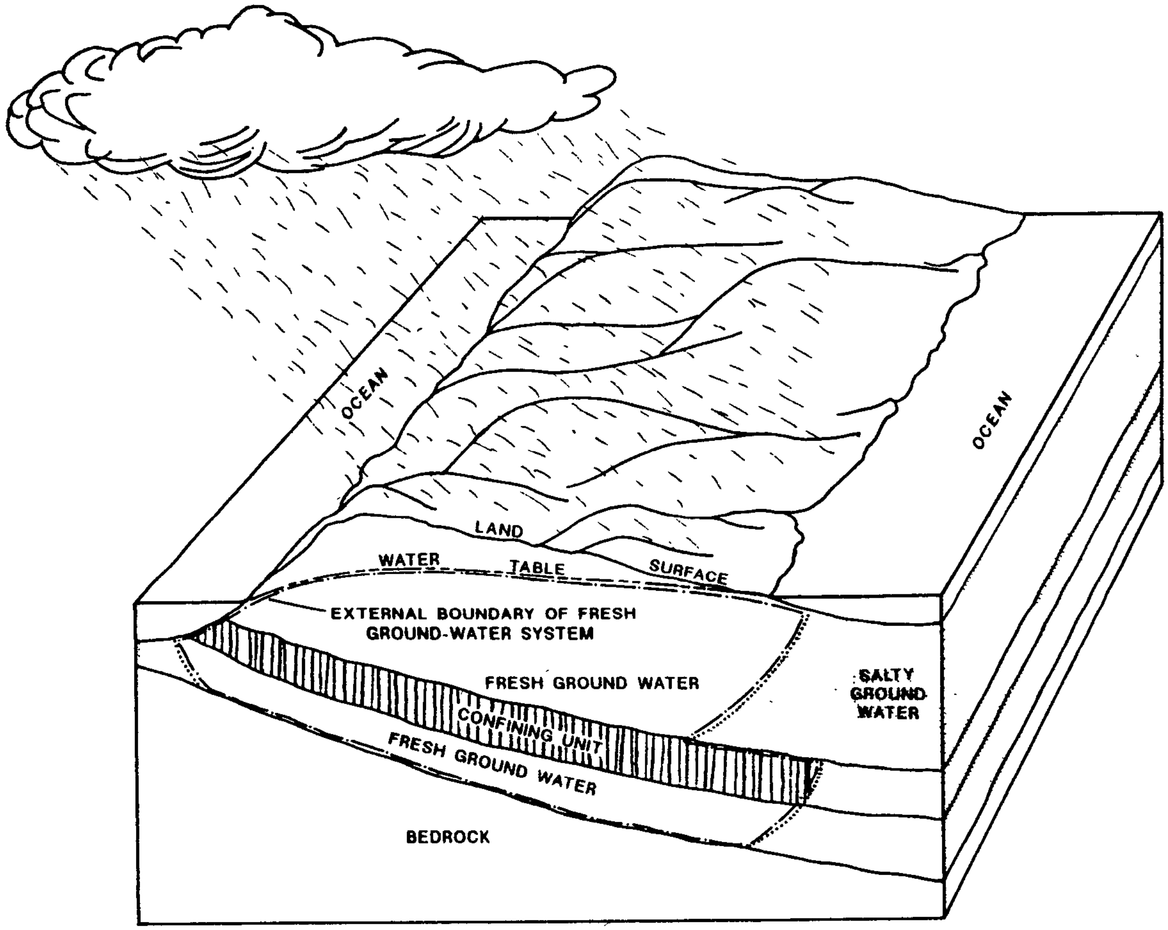
STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART I -- COURSE PARTICIPANTS



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EXTRA COPIES

OF

WORK SHEETS

FOR

PROBLEMS

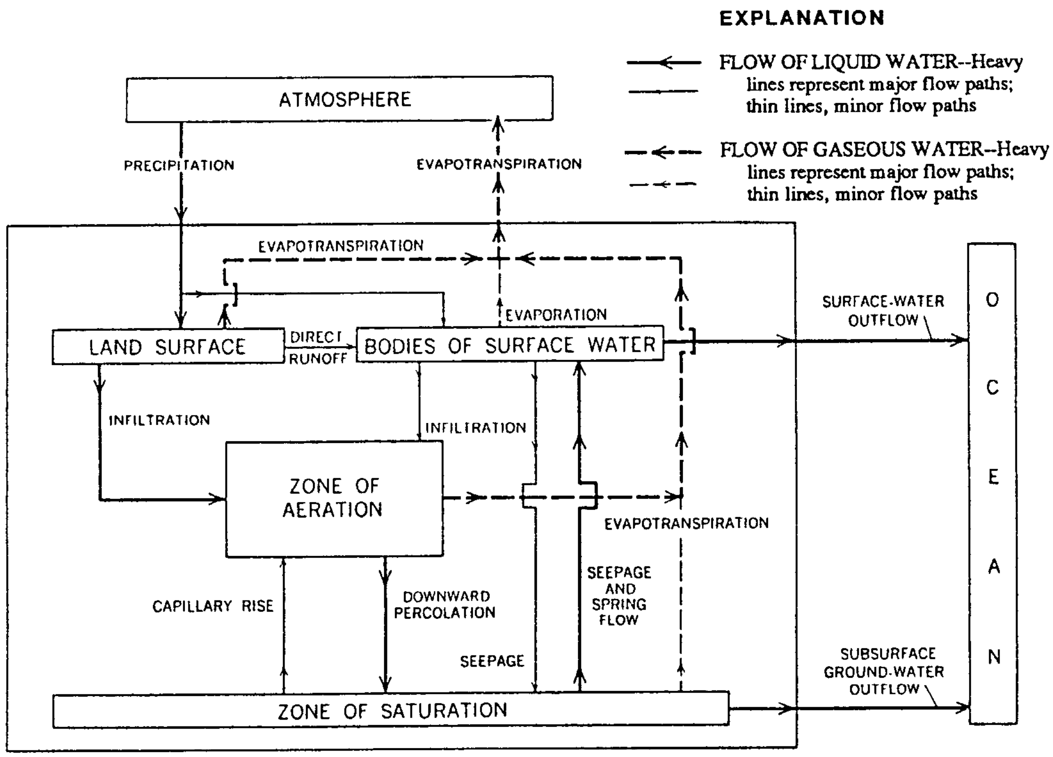


Figure 1-1.--Flow diagram of the hydrologic system, Nassau and Suffolk Counties, Long Island, New York, under predevelopment conditions. (From Franke and McClymonds, 1972, fig. 13.)

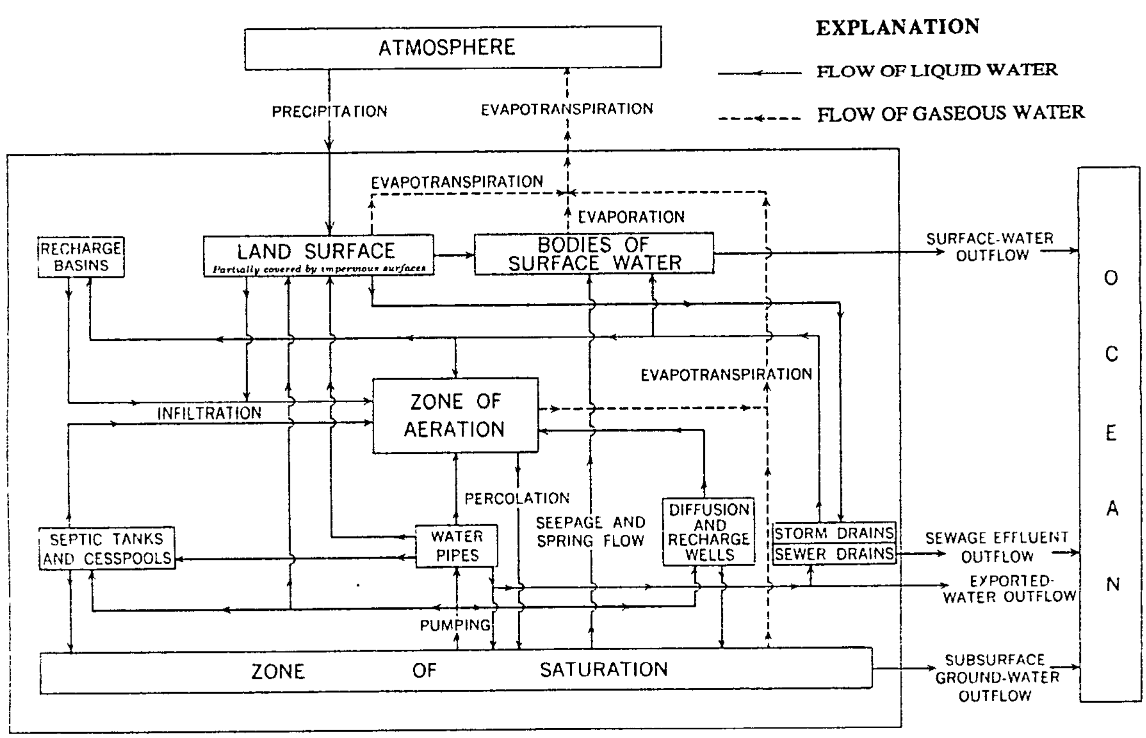


Figure 1-2.--Flow diagram of the hydrologic system, Nassau and Suffolk Counties, Long Island, New York, after noticeable influence from human activities. (From Franke and McClymonds, 1972, fig. 33.)

The relation between heads at the water table and heads in adjacent wells whose screened intervals lie at some depth below the water table depends on the position of the observation-well pair in the associated ground-water system. A general interpretation of the head relations depicted in figure 1-7 must wait for a more comprehensive discussion of ground-water systems in Section (3) of this course. The purpose of presenting figure 1-7 at this time is to emphasize that, in general, hydraulic head in ground-water systems varies not only with geographic location but also with depth.

Exercise (1-4)--Hydraulic Head

The purpose of this exercise is to provide practice in differentiating between the two components of head--pressure head and elevation head. The elevation head at a point in a ground-water system is arbitrary in that it depends on the altitude of an arbitrary datum. Sea level generally is used as head datum, the same datum used for land-surface topographic maps. However, the pressure head at a given point and a given time is not arbitrary, but is a physical quantity that can be measured directly. It is directly proportional to the height of the fluid column above the point of pressure measurement in a piezometer or observation well.

The data below are available for three closely spaced (in map view) observation wells with short well screens.

(1) Determine the missing entries in table 1-2.

(2) Make a careful sketch of each observation well on the accompanying worksheet (fig. 1-8). Plot and designate on each sketch the pressure head, elevation head, and total hydraulic head.

Table 1-2.--Head data for three closely spaced observation wells

Well	Land-surface altitude (feet above sea level)	Depth of top of screen below land surface (feet)	Depth to water (feet)	Altitude of water-level surface in well[1] (feet above sea level)	Pressure head (p/γ) (feet)	Elevation head (z) (feet)
1	50	25	15			
2	45	90	9			
3	51	350	13			

[1] Altitude of water-level surface in observation well equals hydraulic head at point of pressure measurement of observation well.

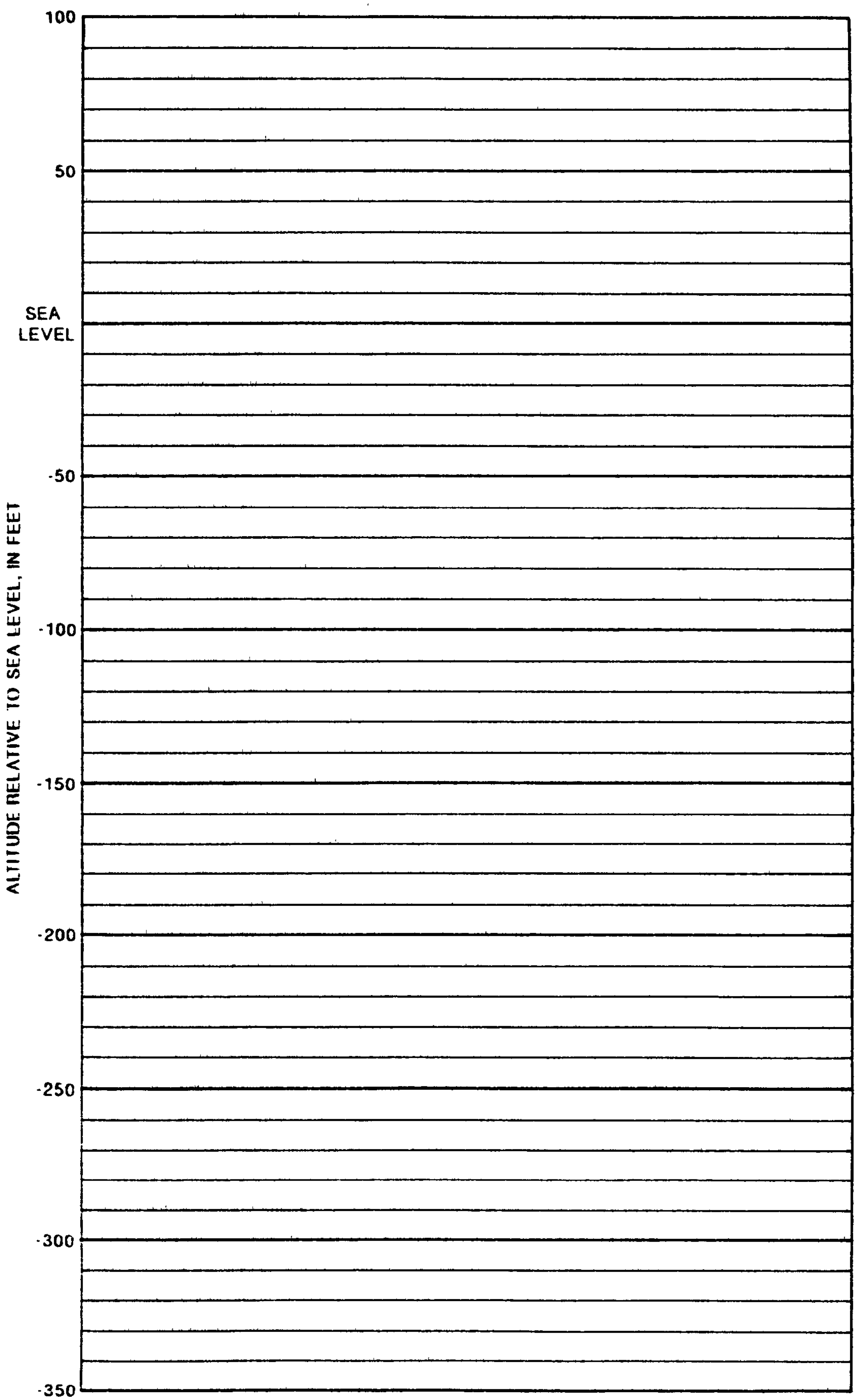


Figure 1-8.--Worksheet for head exercise.

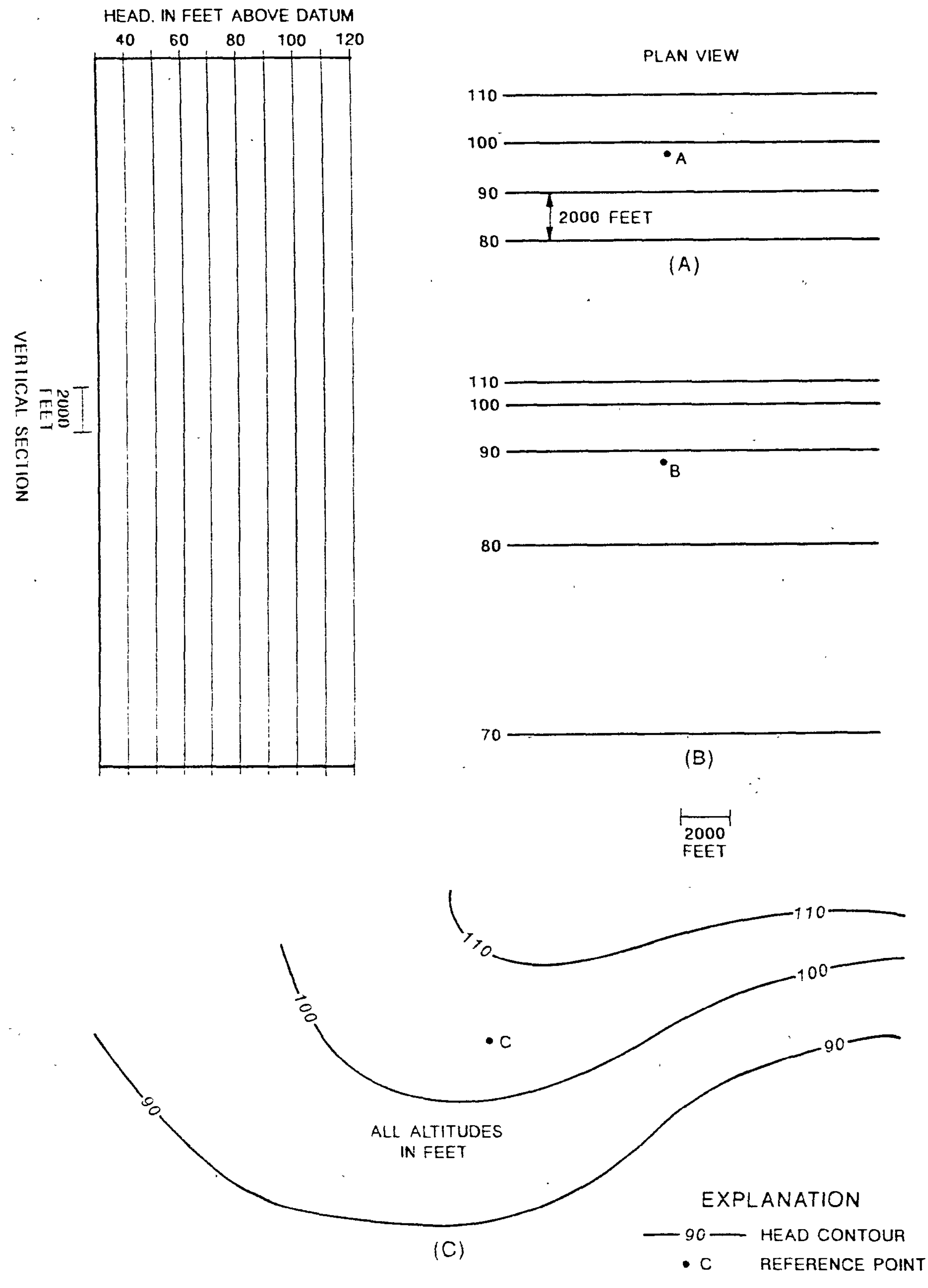


Figure 1-10.--Maps of ground-water head illustrating three different contour patterns.

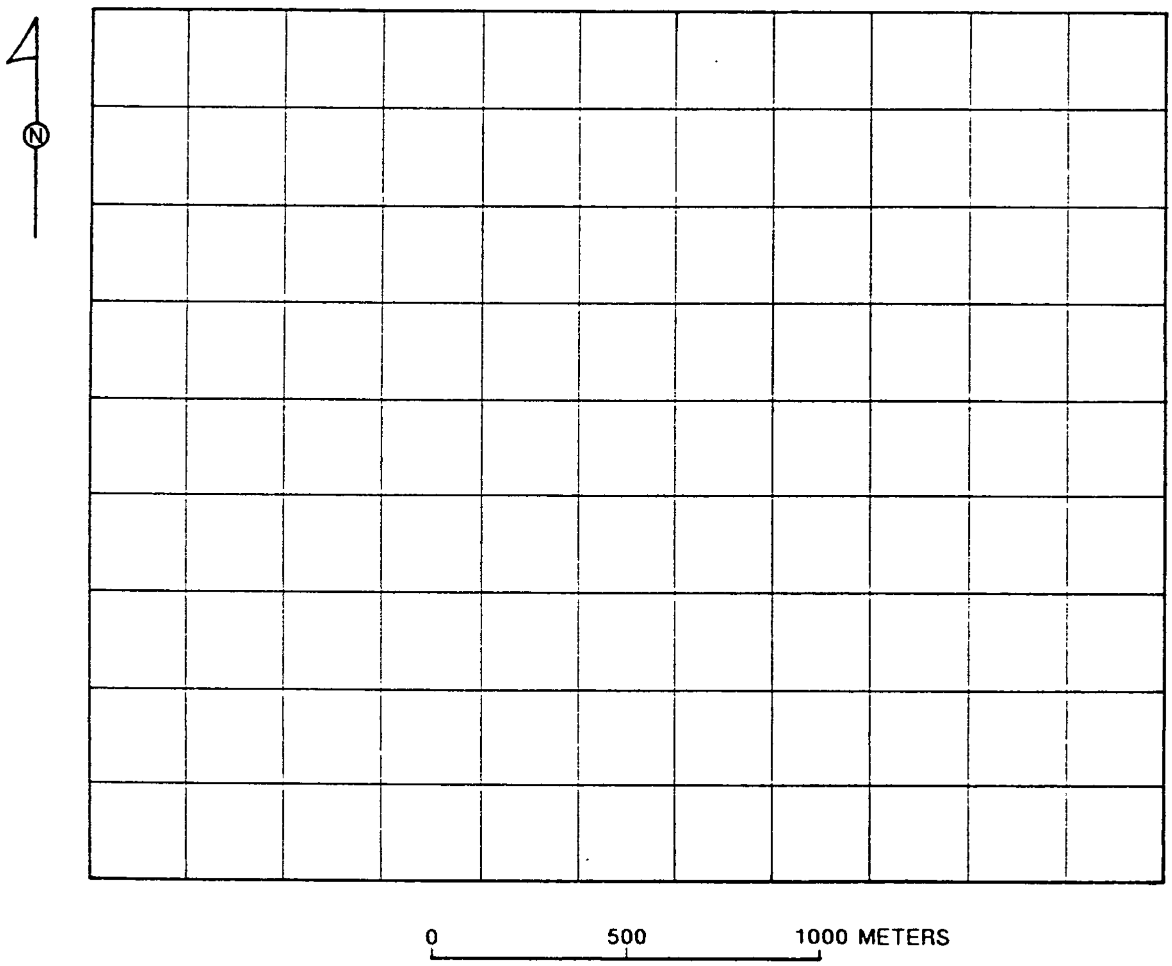
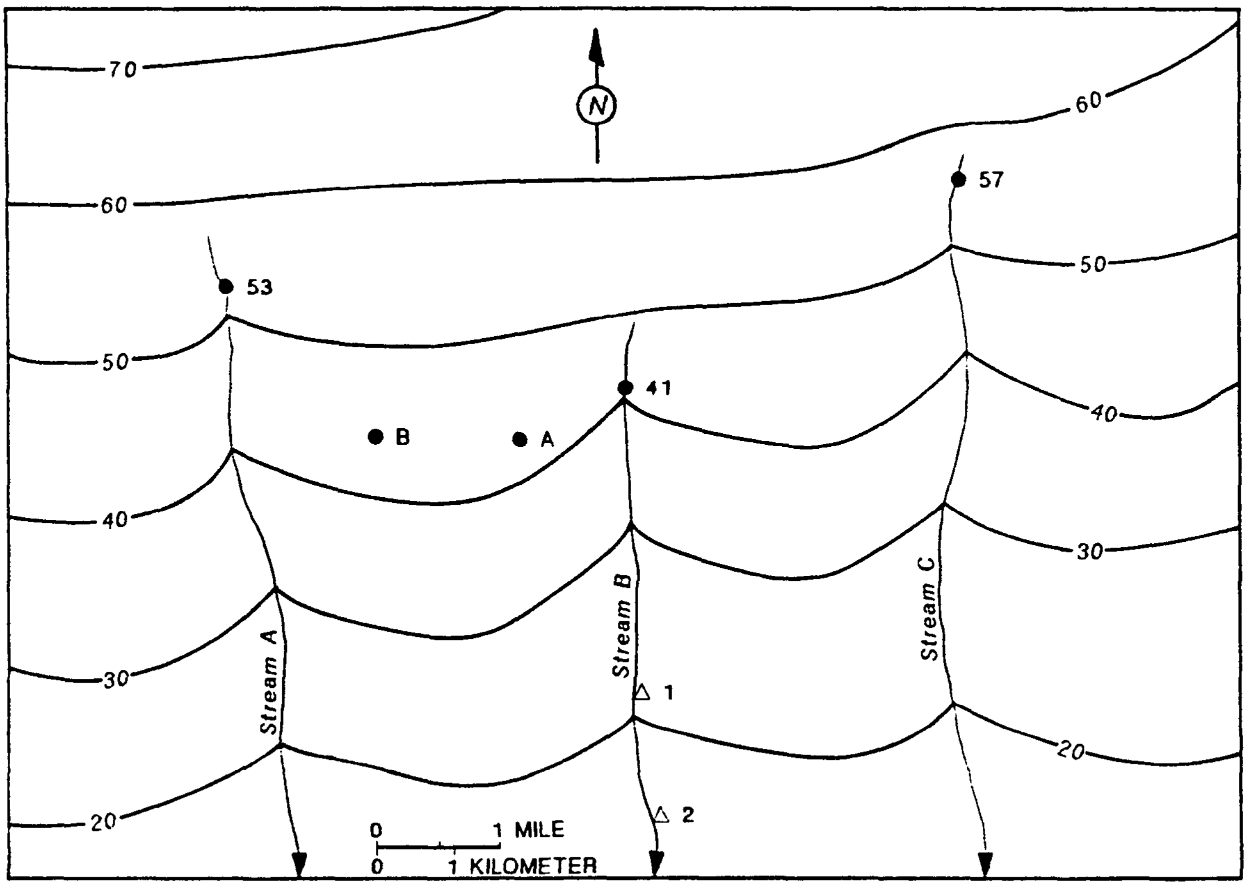


Figure 1-11.--Worksheet for the "three-point" head-gradient problem.



EXPLANATION

—20— WATER-TABLE CONTOUR -- Shows altitude of water table. Contour interval 10 feet. Datum is sea level

● 41 LOCATION OF START OF FLOW OF STREAM -- Number is altitude of stream, in feet above sea level

△ 2 LOCATION AND NUMBER OF STREAM DISCHARGE MEASUREMENT POINT

Figure 1-12.--Hypothetical water-table map of an area underlain by permeable deposits in a humid climate.

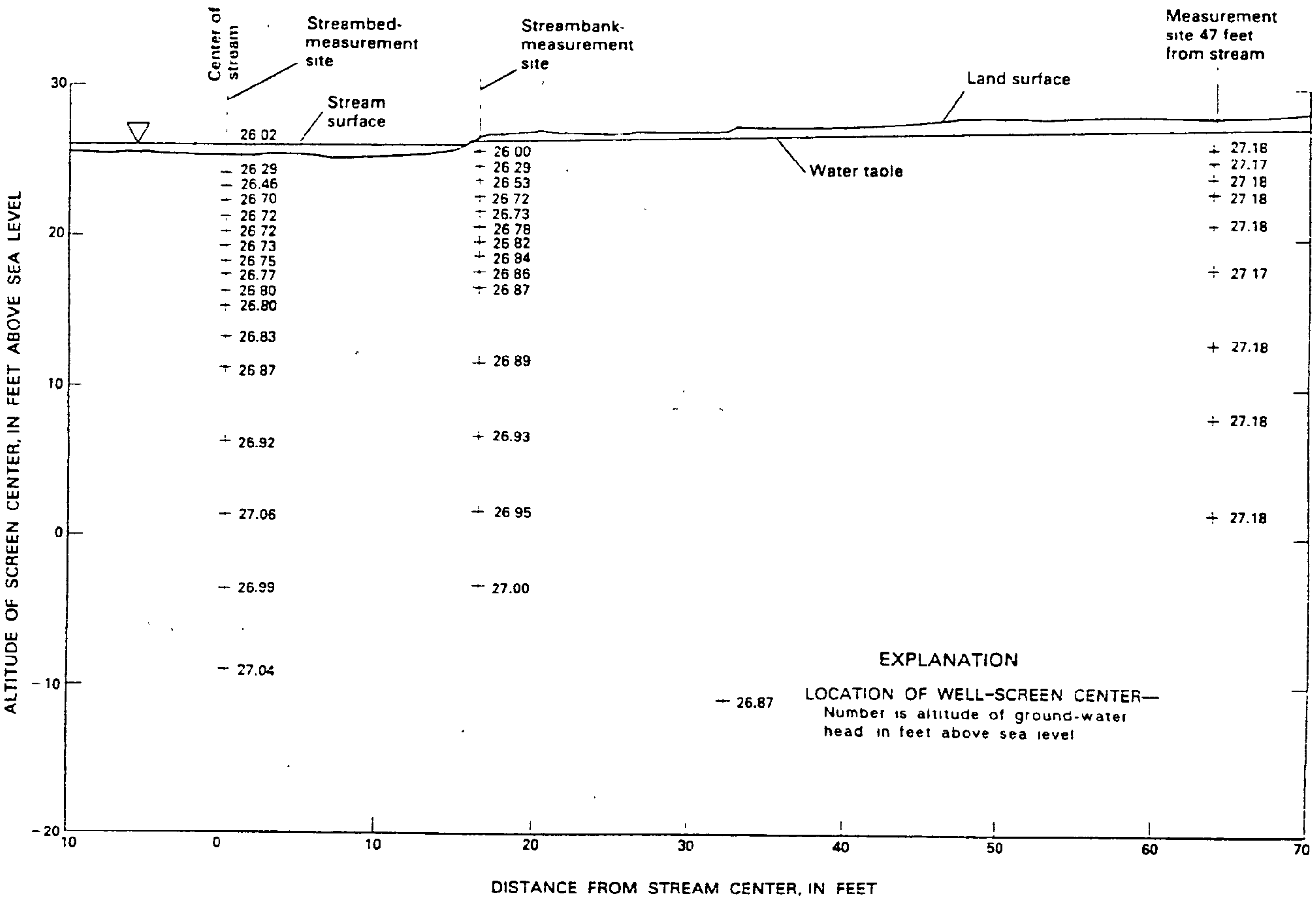


Figure 1-13.--Head measurements near Connetquot Brook, Long Island, New York, during a 3-day period in October 1978. (Modified from Prince and others, 1988, fig. 10.)

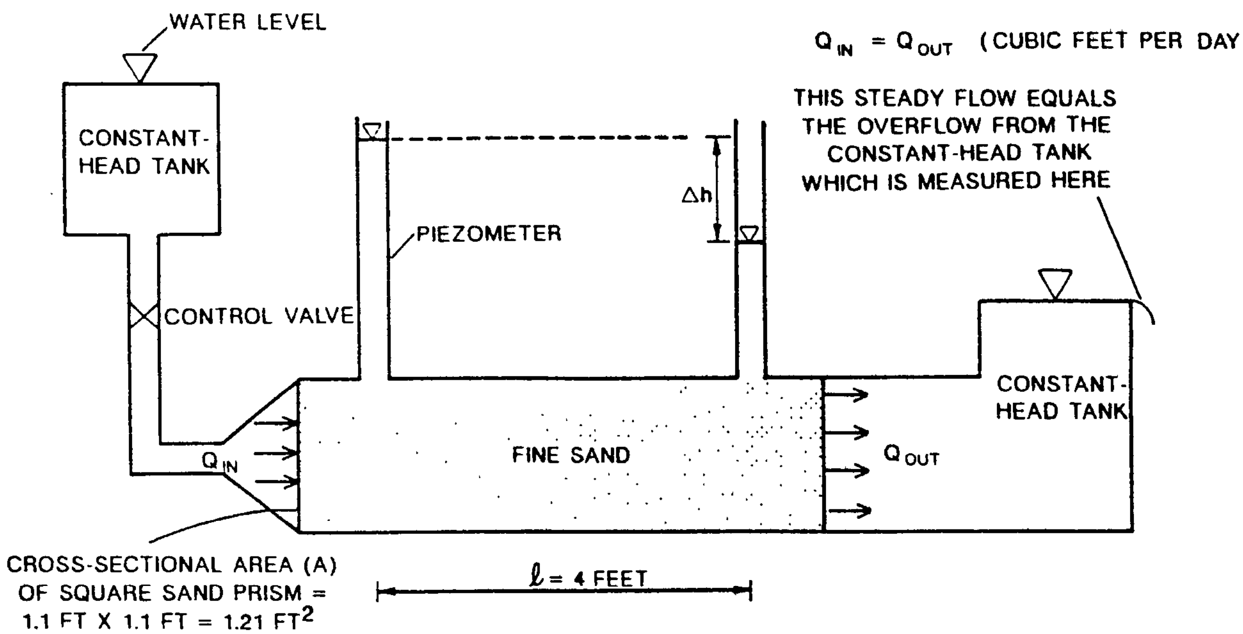


Figure 2-1.--Sketch of laboratory seepage system.

Table 2-1.--Data from hypothetical experiments with the laboratory seepage system

Test number	Q[1] (cubic feet per day)	Δh (feet)	$\Delta h/l$	Q/A (feet/day)
1	2.2	0.11		
2	3.3	.17		
3	4.6	.23		
4	5.4	.26		
5	6.7	.34		
6	7.3	.38		
7	7.9	.40		

[1] Q is steady flow through sand prism, Δh is head difference between two piezometers; l is distance between two piezometers; A is constant cross-sectional area of sand prism (fig. 2-1).

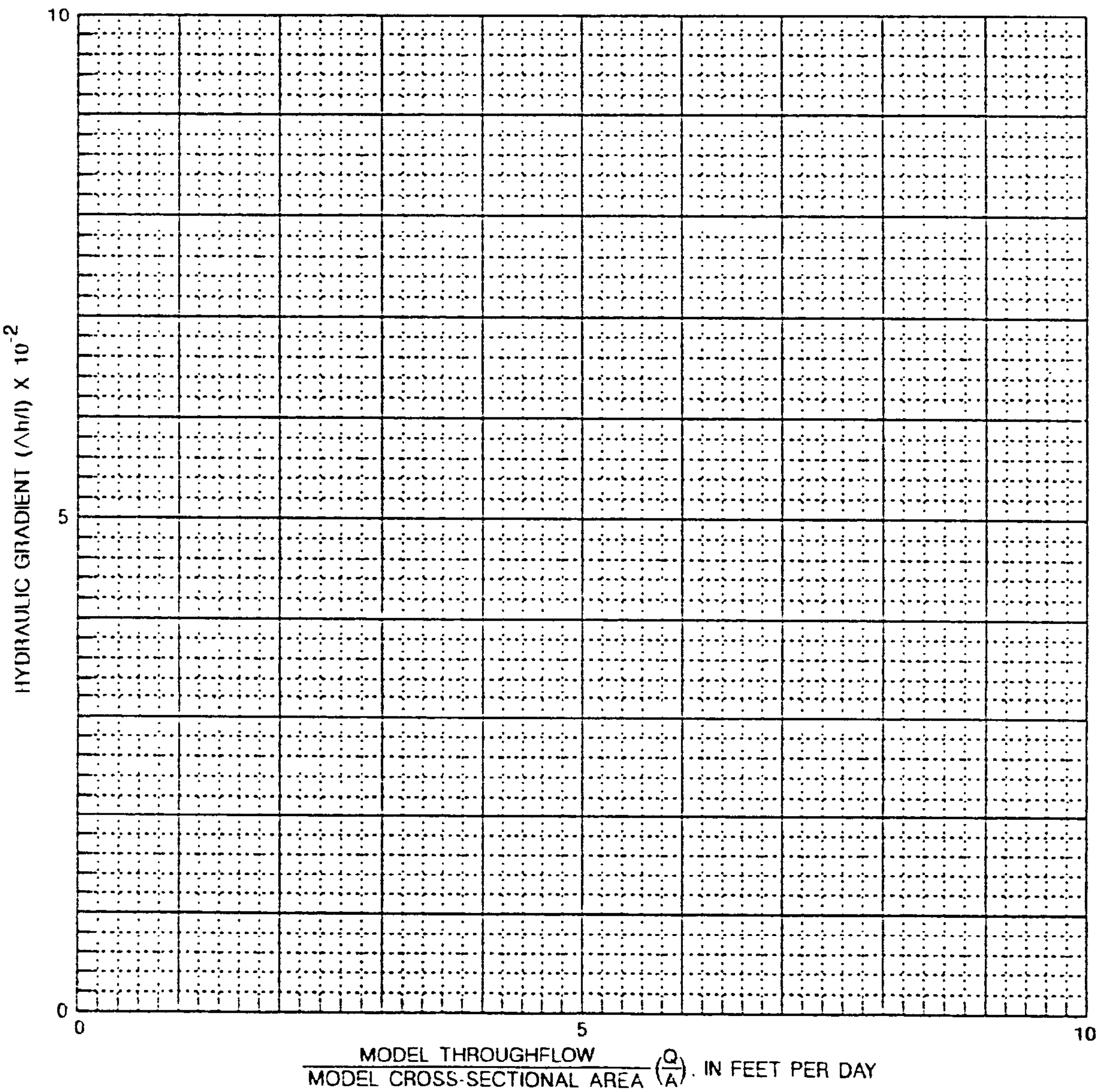


Figure 2-2.--Worksheet for plotting data from hypothetical experiments with the laboratory seepage system.

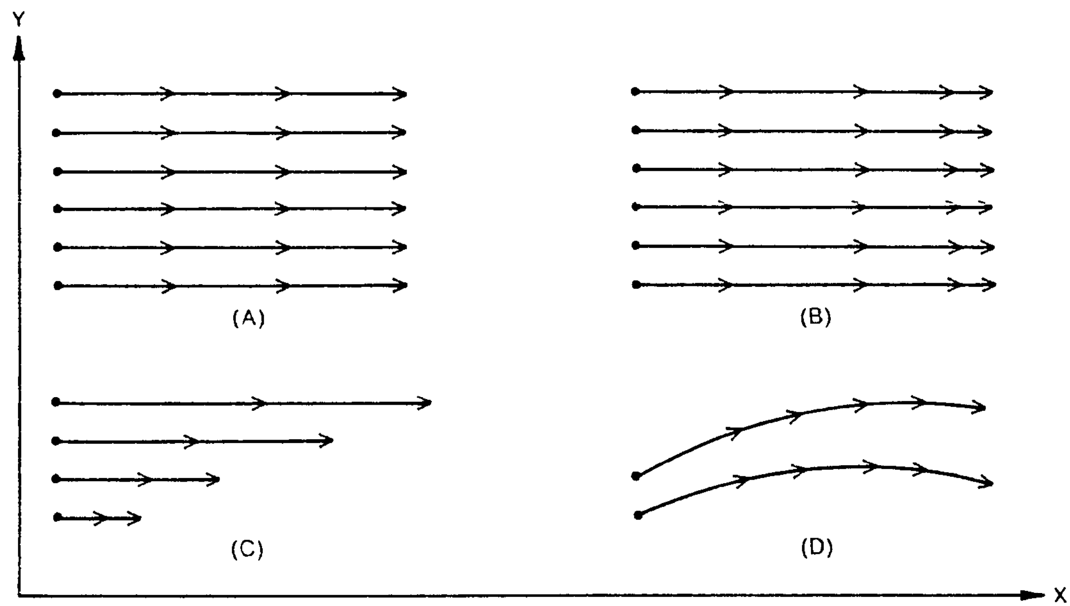


Figure 2-3.--Examples of ground-water flow fields depicted by velocity vectors at selected points: (A) and (B) are one-dimensional flow fields; (C) and (D) are two-dimensional flow fields.

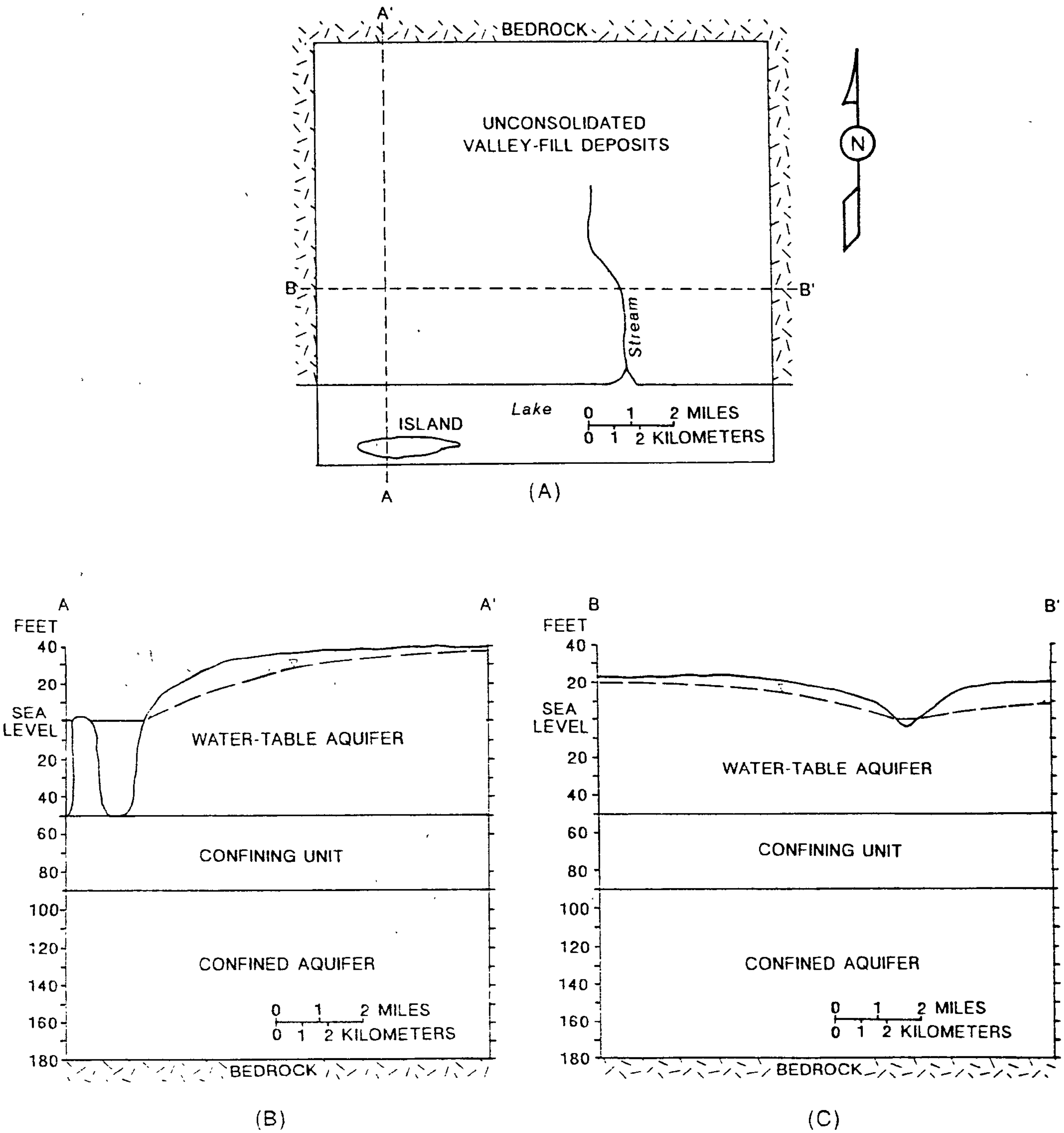
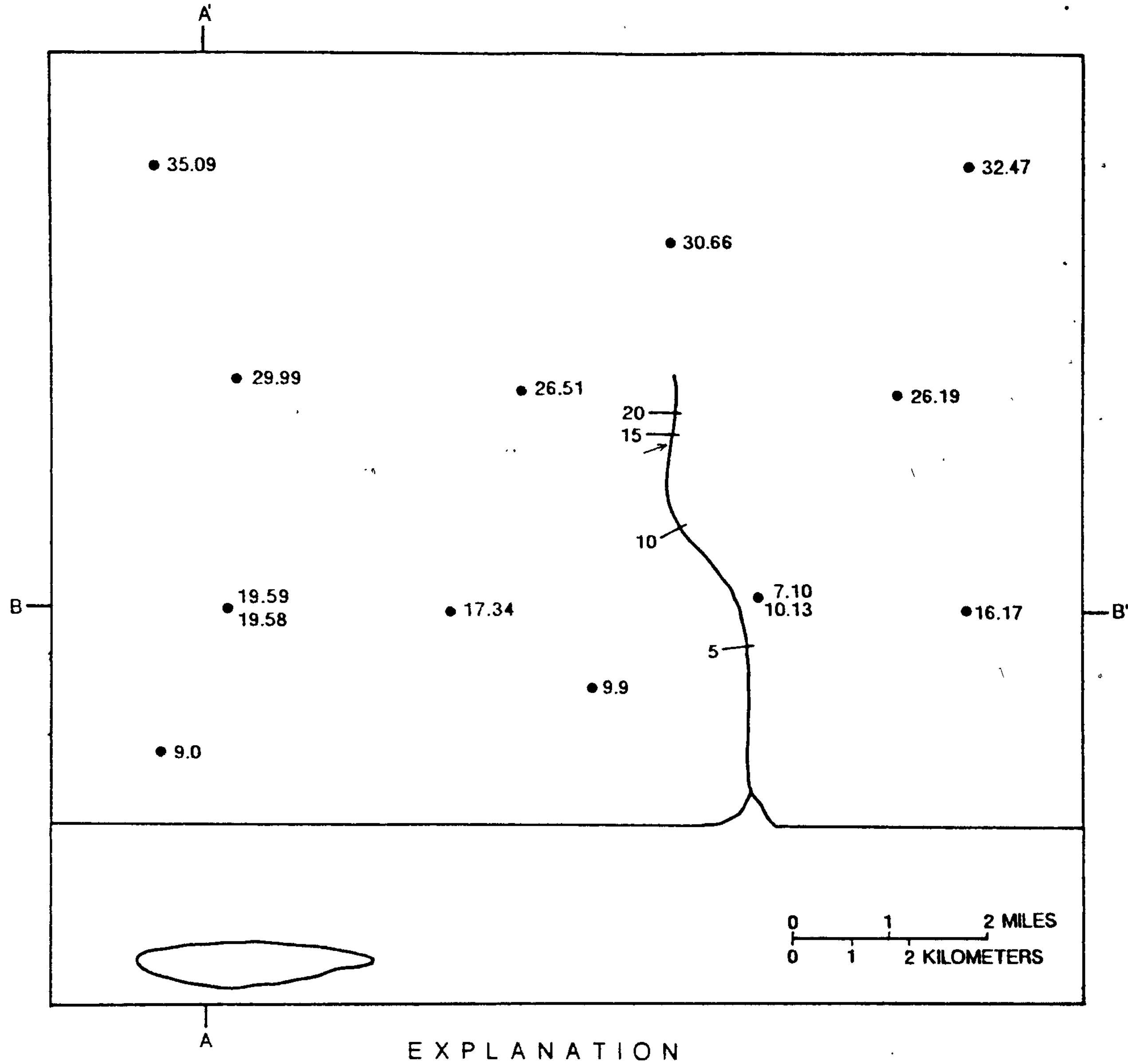


Figure 3-2.--Hydrogeologic framework of hypothetical ground-water system: (A) plan view, (B) north-south-trending section, (C) east-west trending section.



EXPLANATION

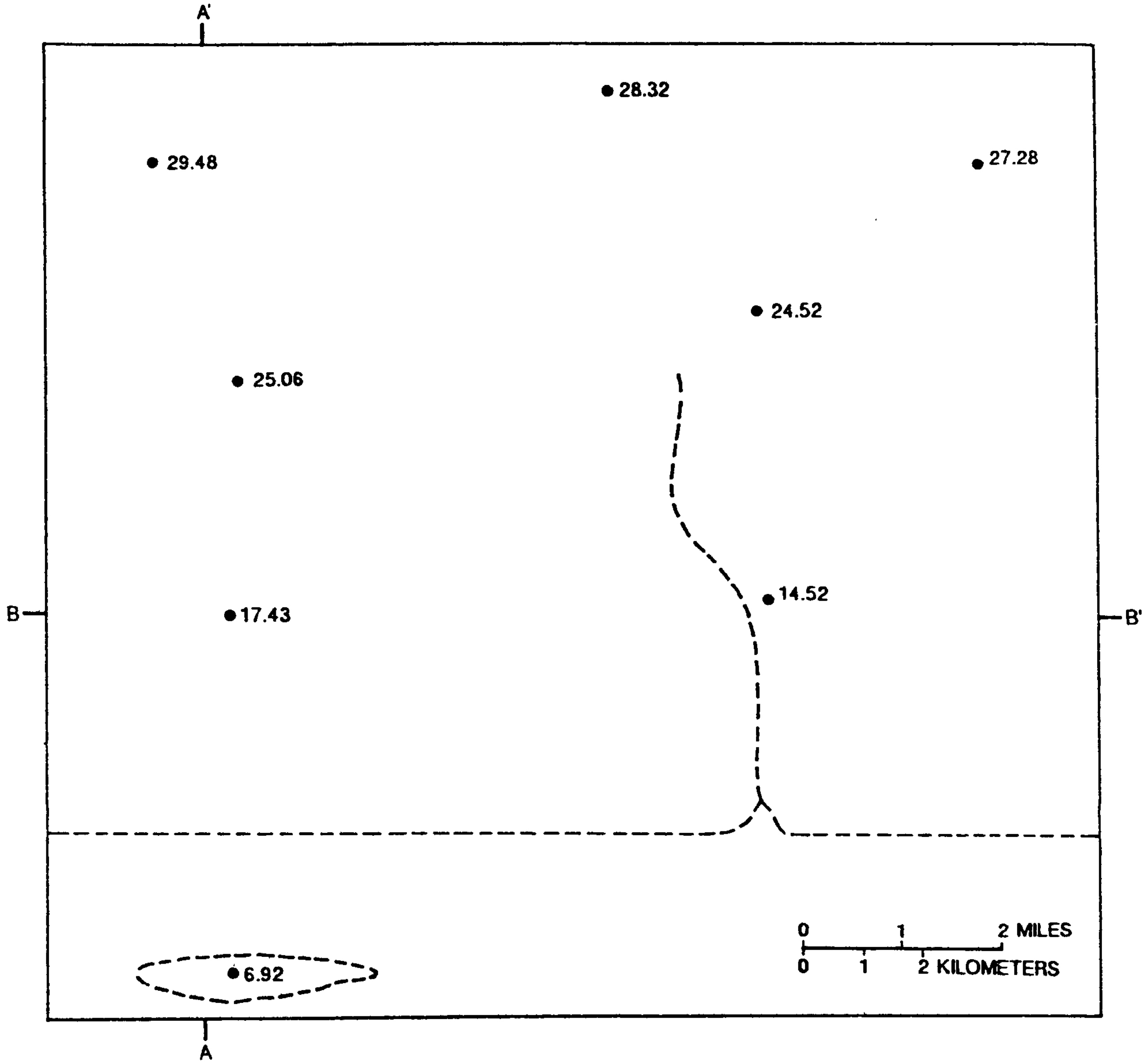
● 9.9 WATER-TABLE OBSERVATION WELL -- Number is altitude of water level, in feet above sea level

5 STREAMBED LEVEL -- Number is altitude of streambed, in feet above sea level

POINT OF START OF FLOW OF STREAM

A-A' TRACE OF SECTION

Figure 9-4.--Water-table heads obtained during a synoptic measurement of water levels in observation wells.



EXPLANATION

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

A-A' TRACE OF SECTION

Figure S-6.--Heads in the confined aquifer obtained during a synoptic measurement of water levels in observation wells.

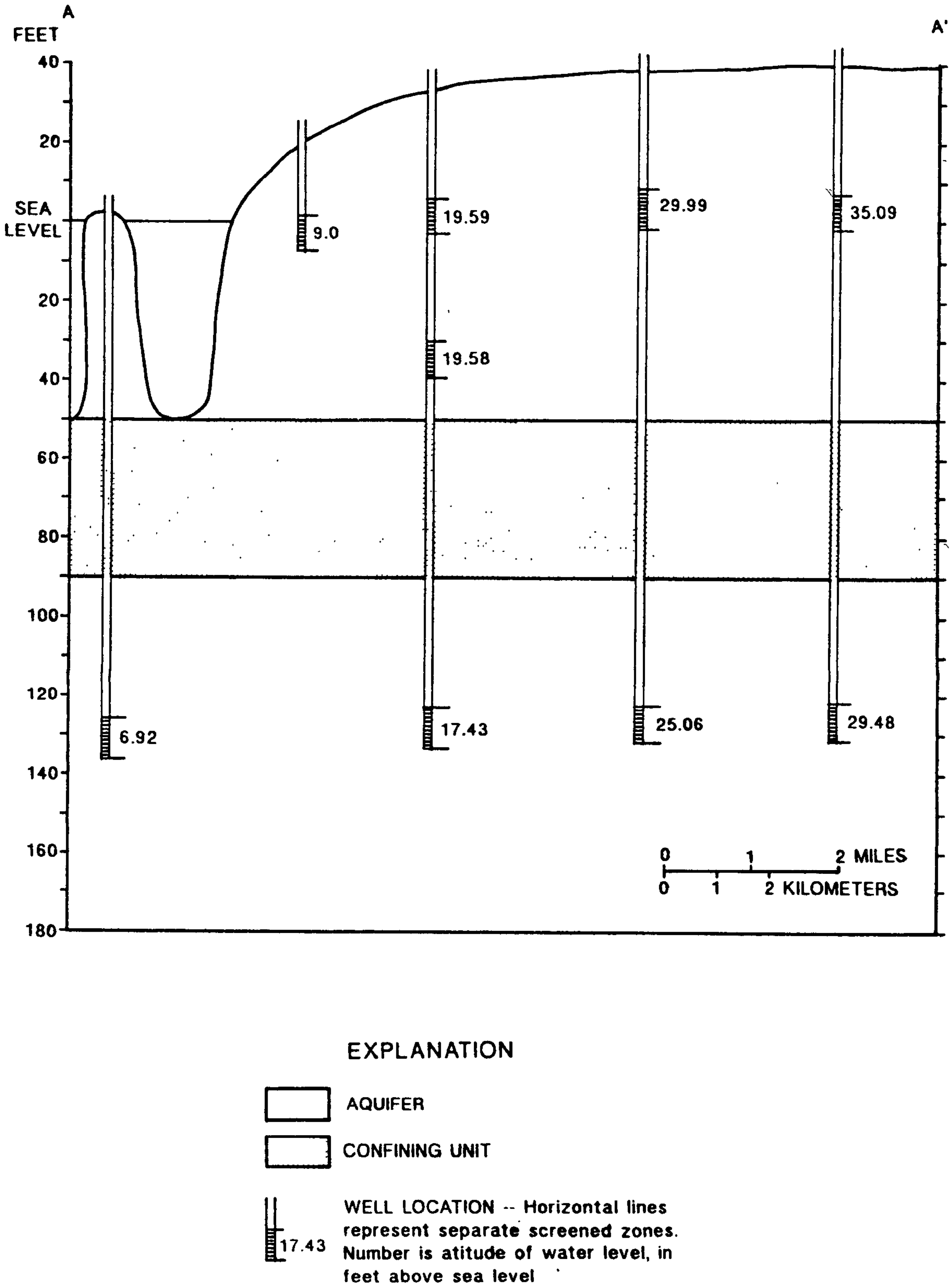


Figure 3-7.--North-south-trending hydrogeologic section showing heads obtained during synoptic measurement of water levels in observation wells. (Location of section A-A' is shown in fig. 3-2.)

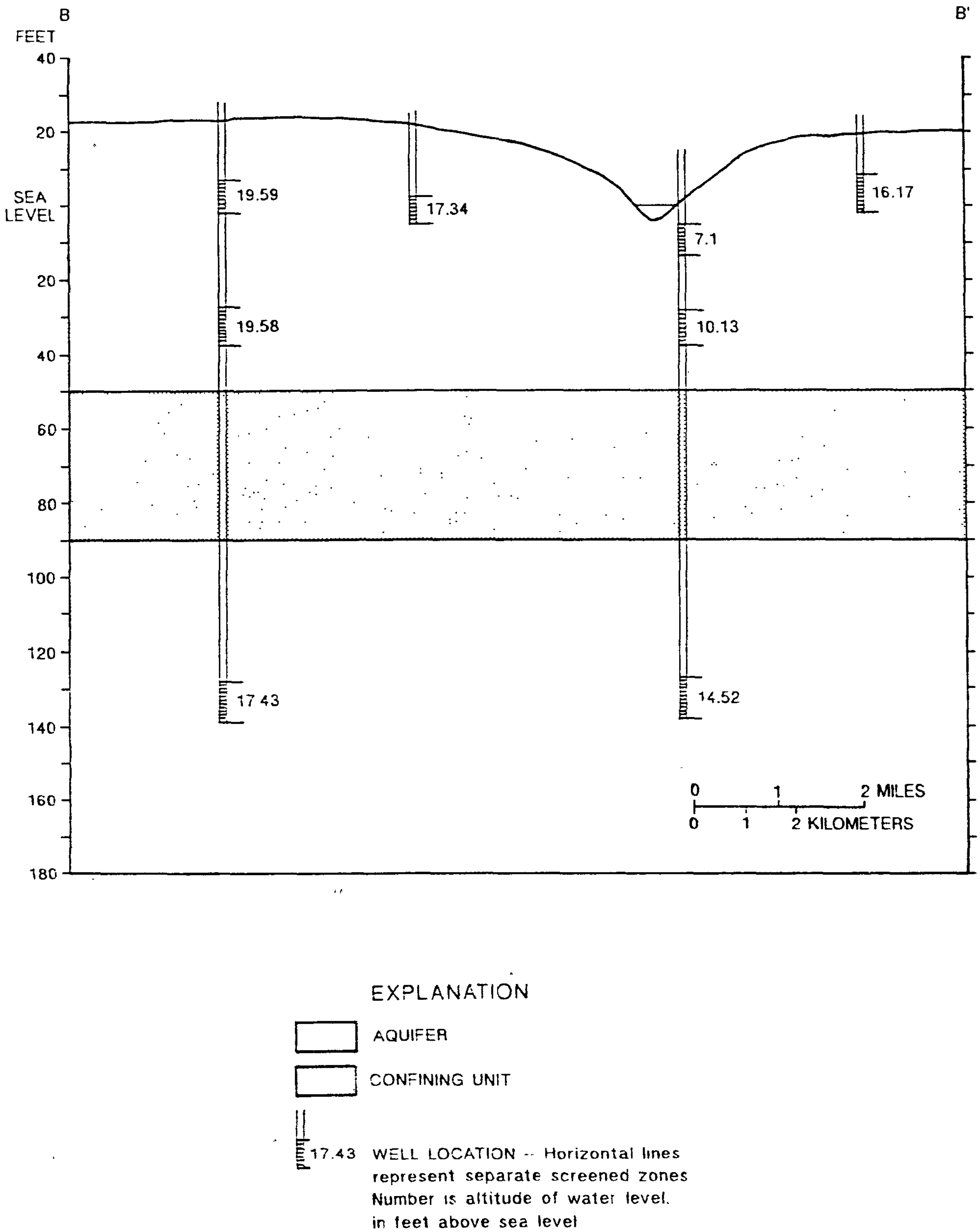


Figure 3-8.--East-west-trending hydrogeologic section showing heads obtained during synoptic measurement of water levels in observation wells. (Location of section B-B' is shown in fig. 3-2.)

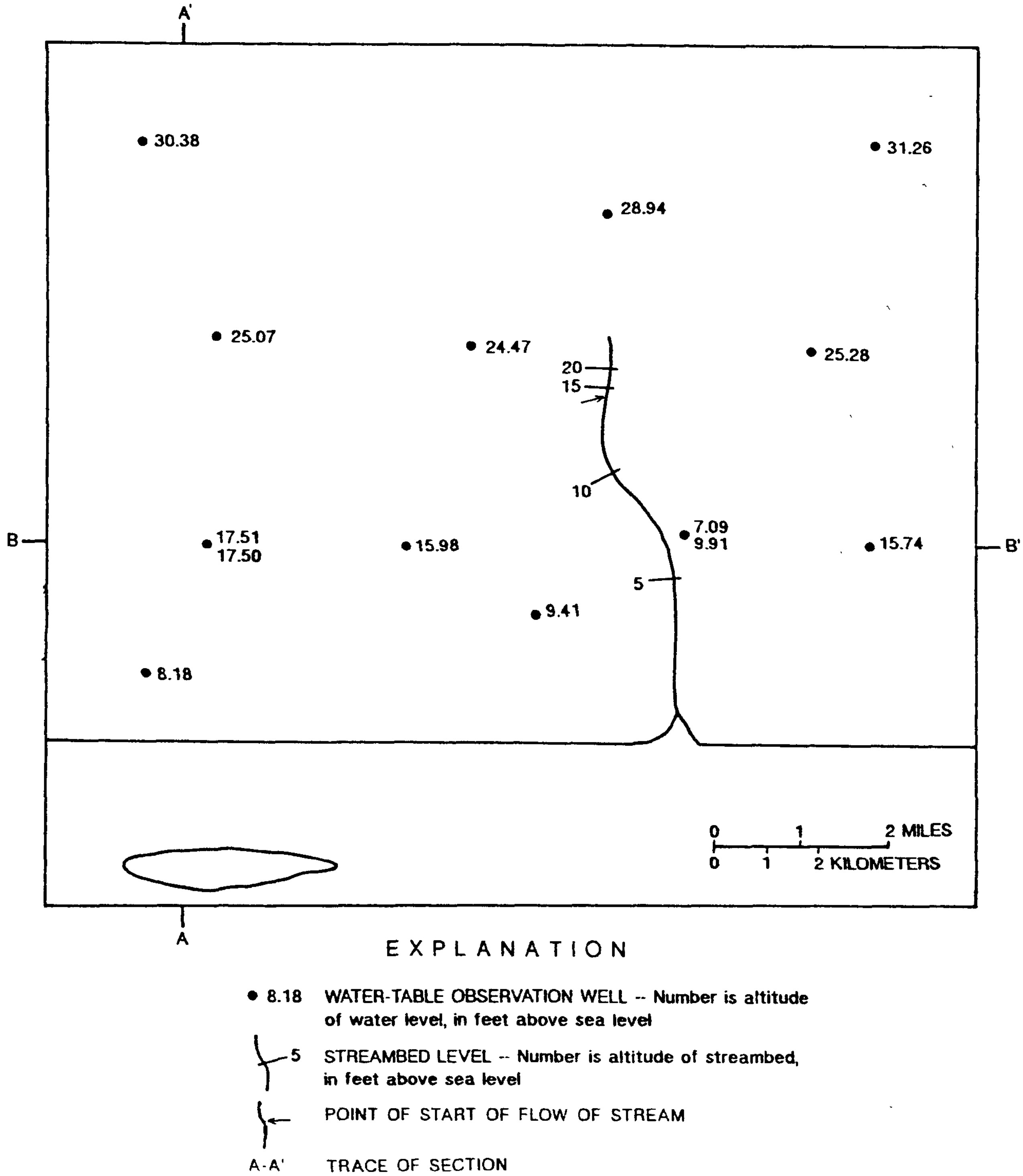
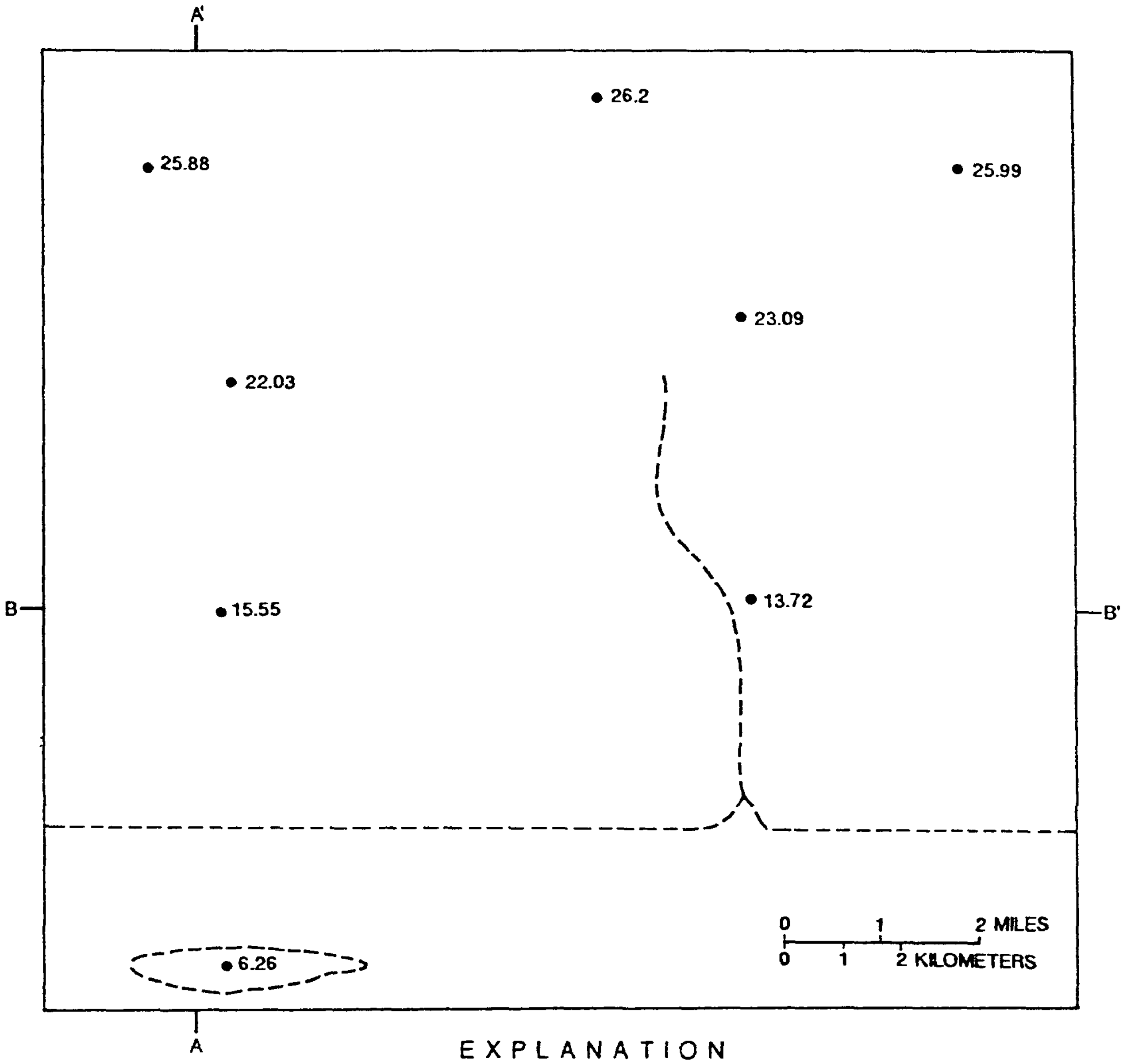


Figure S-10.--Measured heads in the water-table aquifer in response to steady pumping from a well screened in the lower part of the water-table aquifer.



EXPLANATION

● 6.26 OBSERVATION WELL SCREENED IN CONFINED AQUIFER -- Number is altitude of water level, in feet above sea level

A-A' TRACE OF SECTION

Figure 9-11.--Measured heads in the confined aquifer in response to steady pumping from a well screened in the lower part of the water-table aquifer.

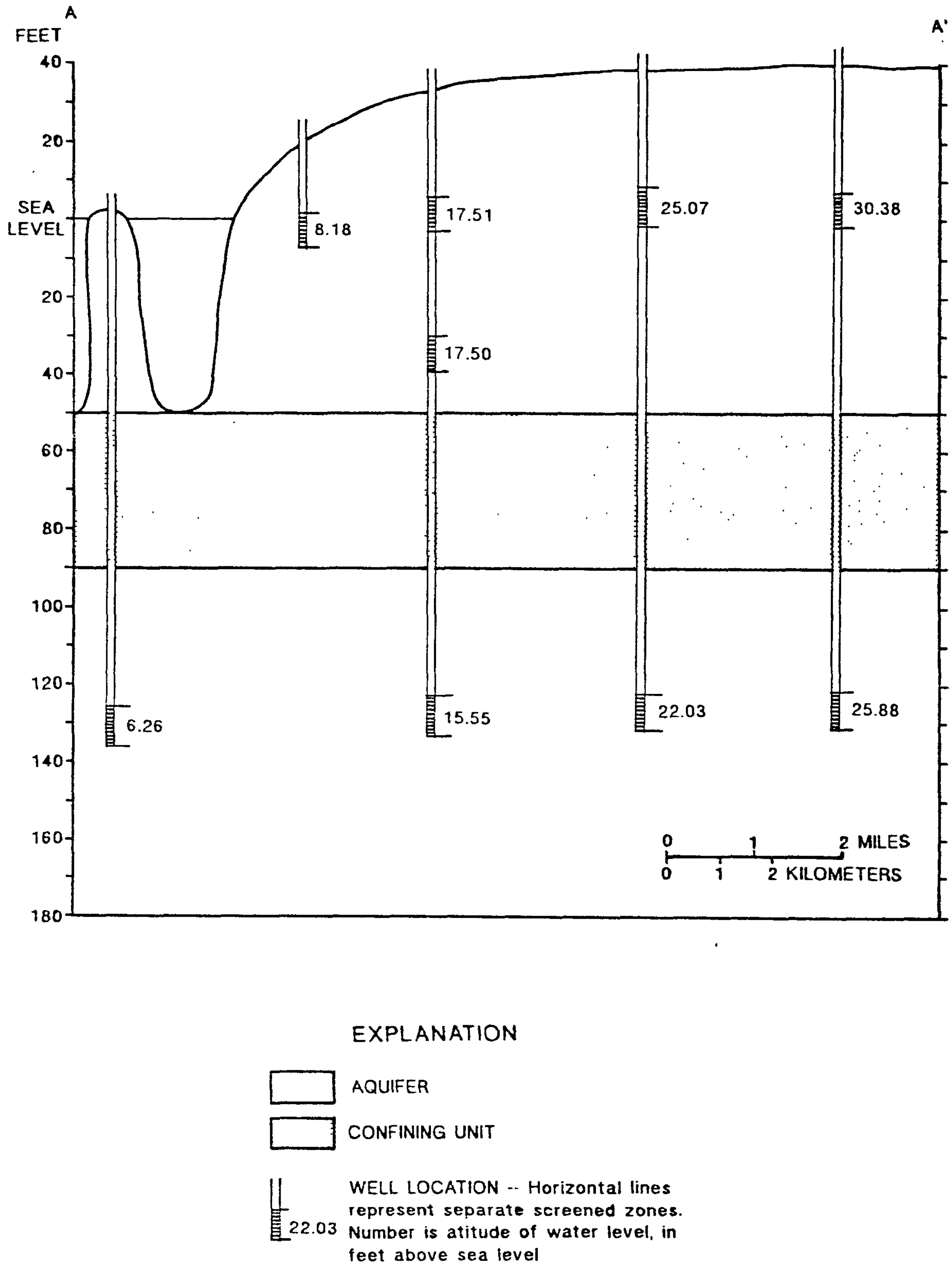
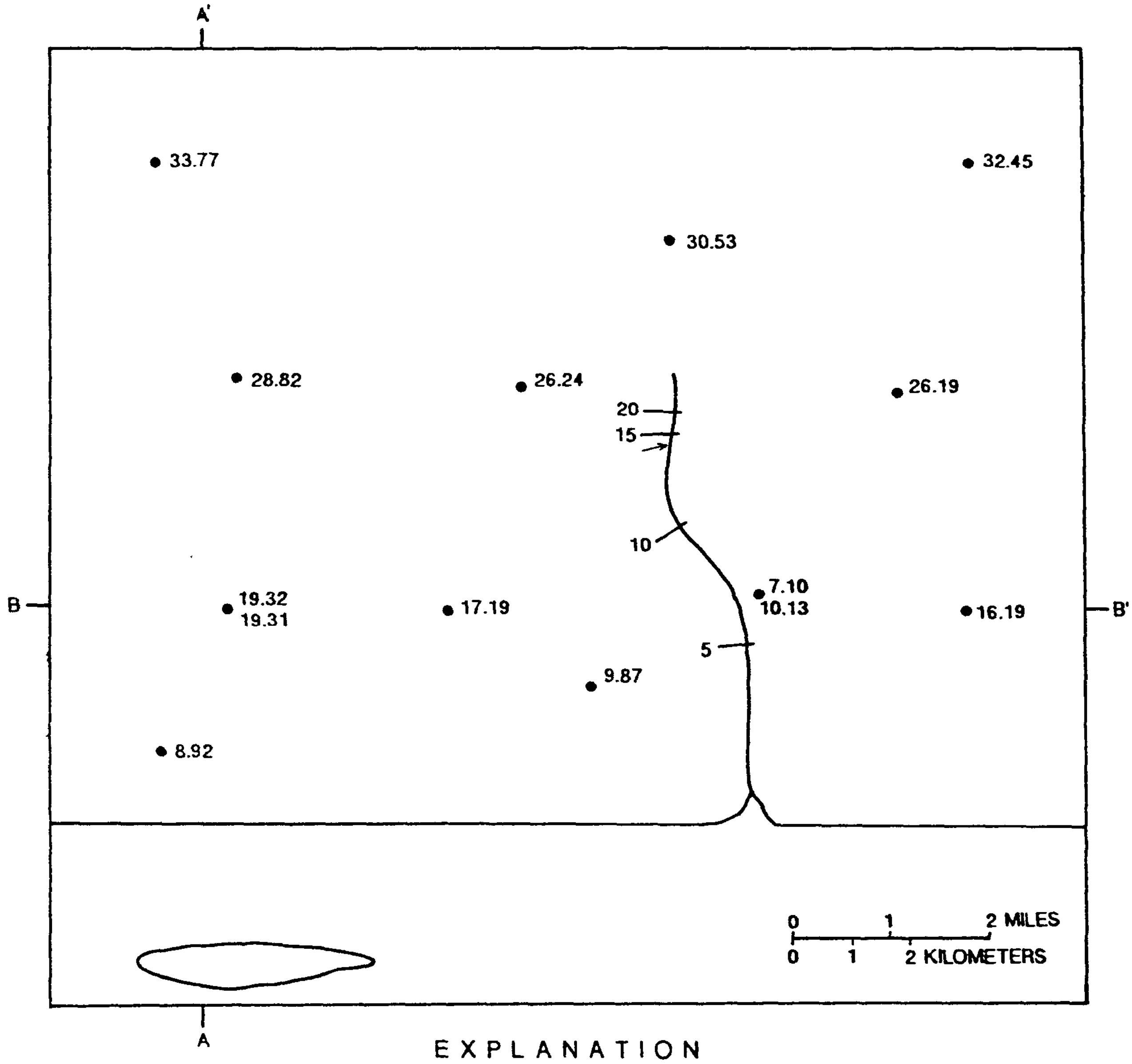


Figure S-12.--North-south-trending hydrogeologic section showing measured heads in response to steady pumping. (Location of section A-A' is shown in fig. S-2.)



EXPLANATION

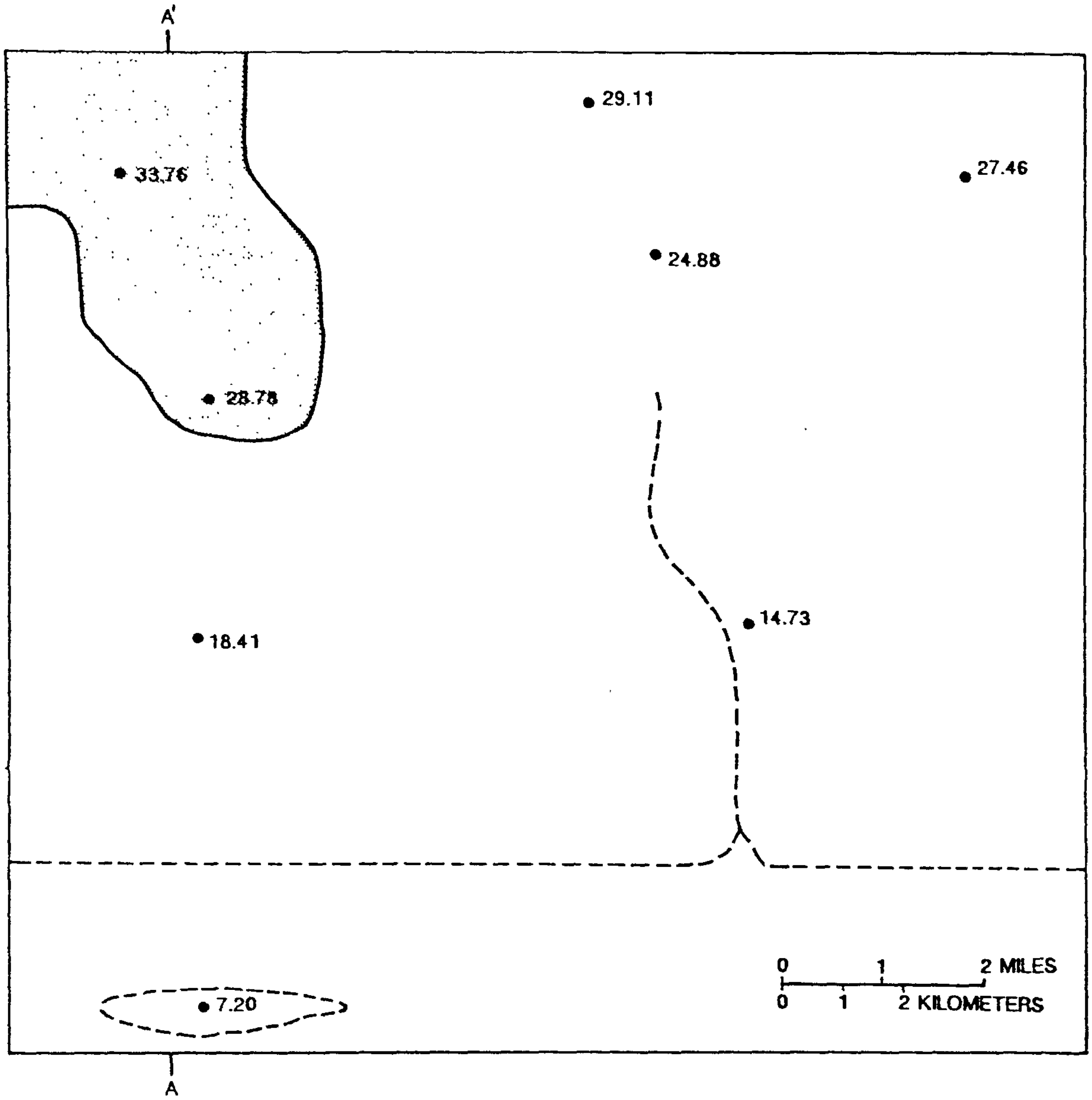
● 8.92 WATER-TABLE OBSERVATION WELL -- Number is altitude of water level, in feet above sea level

5 STREAMBED LEVEL -- Number is altitude of streambed, in feet above sea level

POINT OF START OF FLOW OF STREAM

A-A' TRACE OF SECTION

Figure 8-18.--Measured heads in the water-table aquifer in a ground-water system with a discontinuous confining unit.



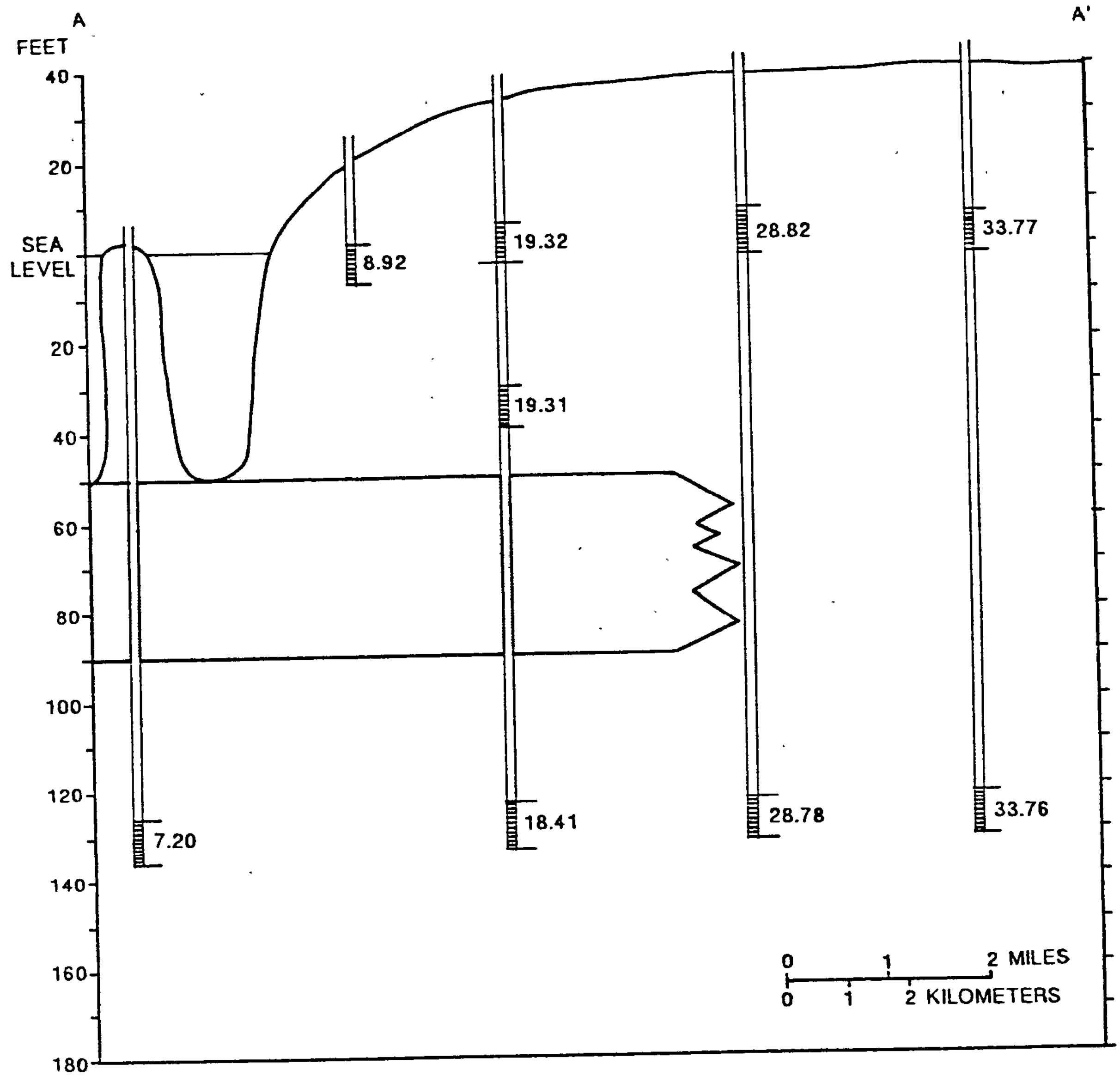
EXPLANATION

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 9-15.--Measured heads in the confined aquifer and location of hole in the overlying confining unit.



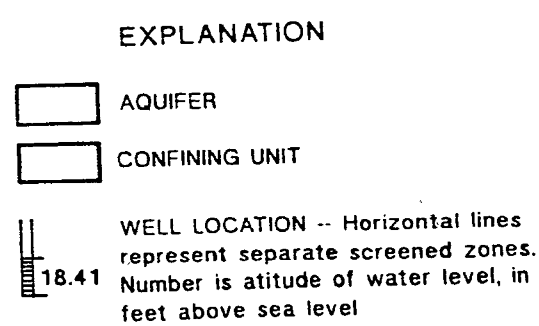


Figure 3-16.--North-south-trending hydrogeologic section showing heads measured in a ground-water system with a discontinuous confining unit. (Location of section A-A' is shown in fig. 3-2.)

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.

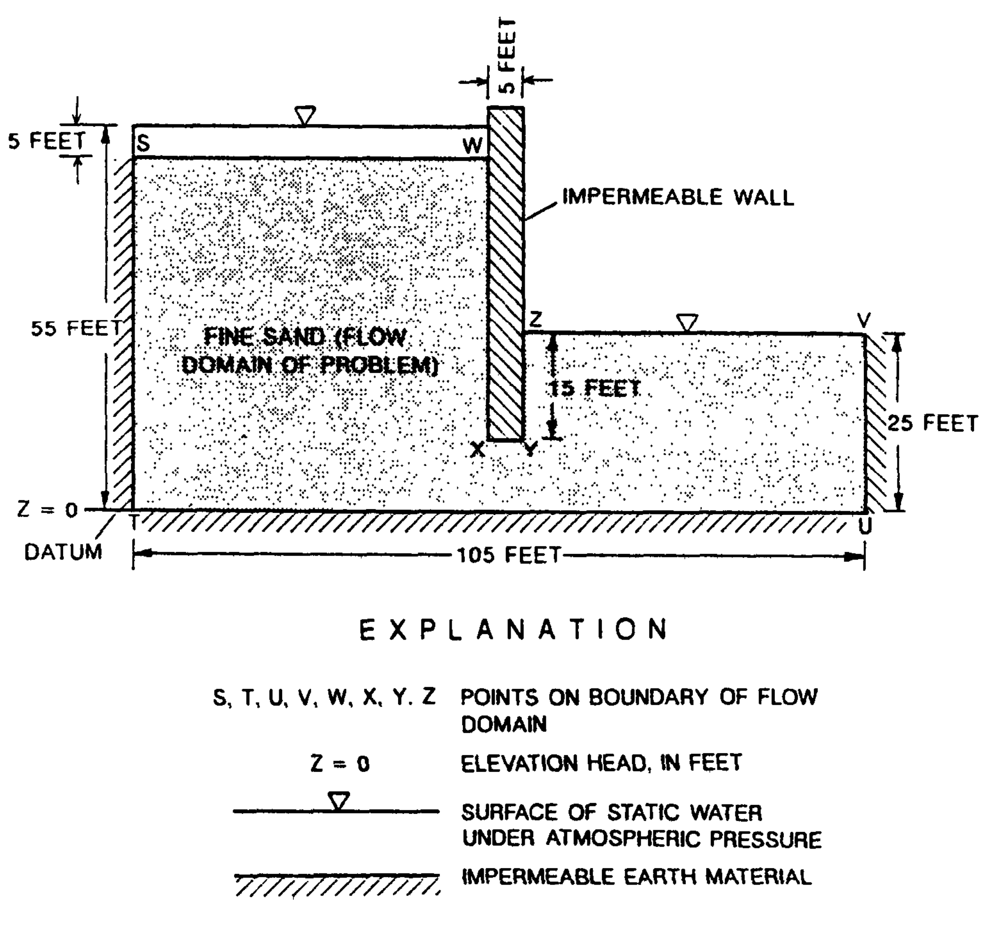
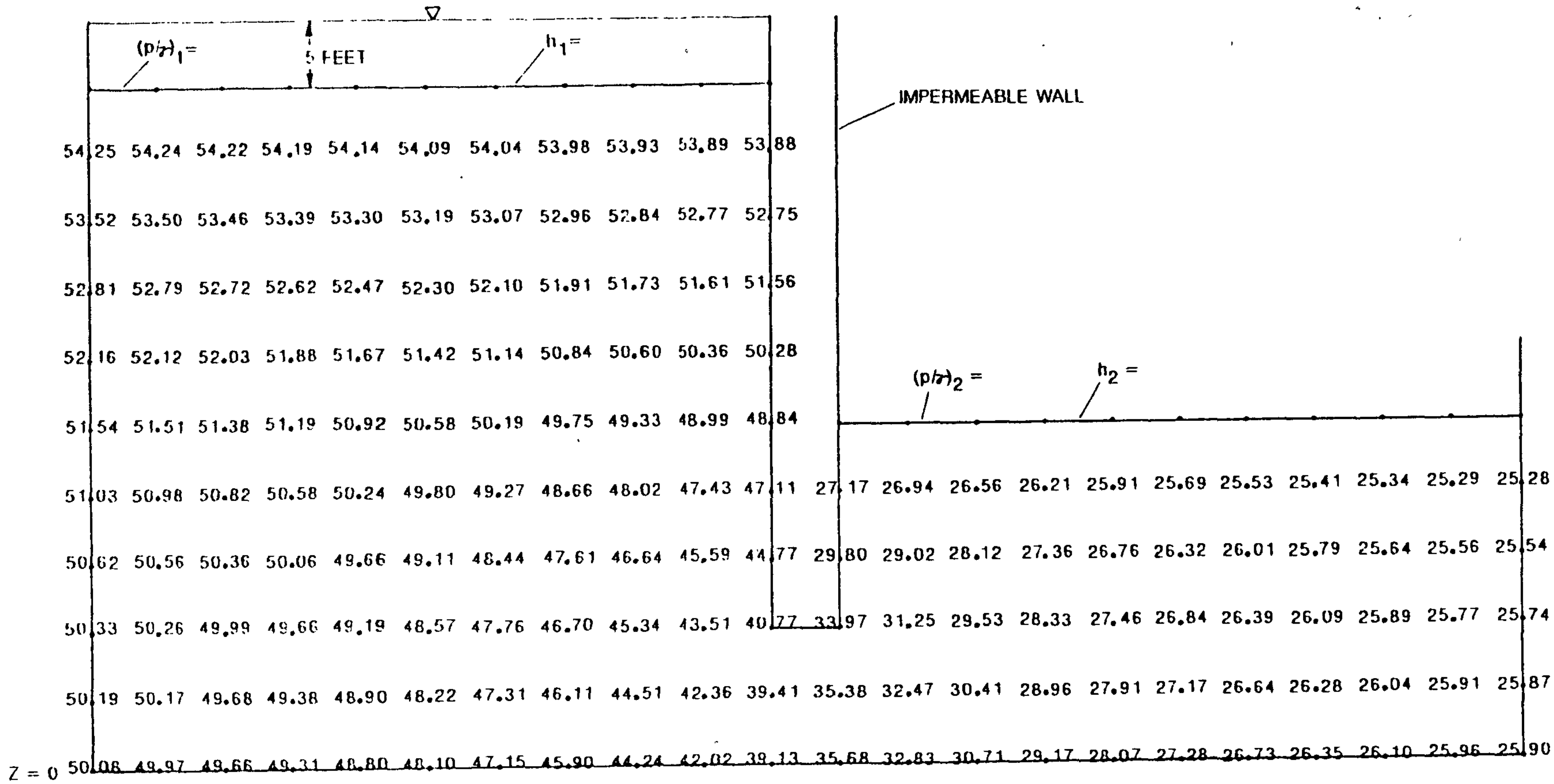


Figure 3-19.--Vertical section through a ground-water flow system near a partially penetrating impermeable wall.



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 9-21.--Worksheet for preparation of a flow net for a ground-water system near an impermeable wall.

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]

TRAVERSE D E

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
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)	$\Psi = \frac{\Sigma q_{block}}{Q_{total}}$

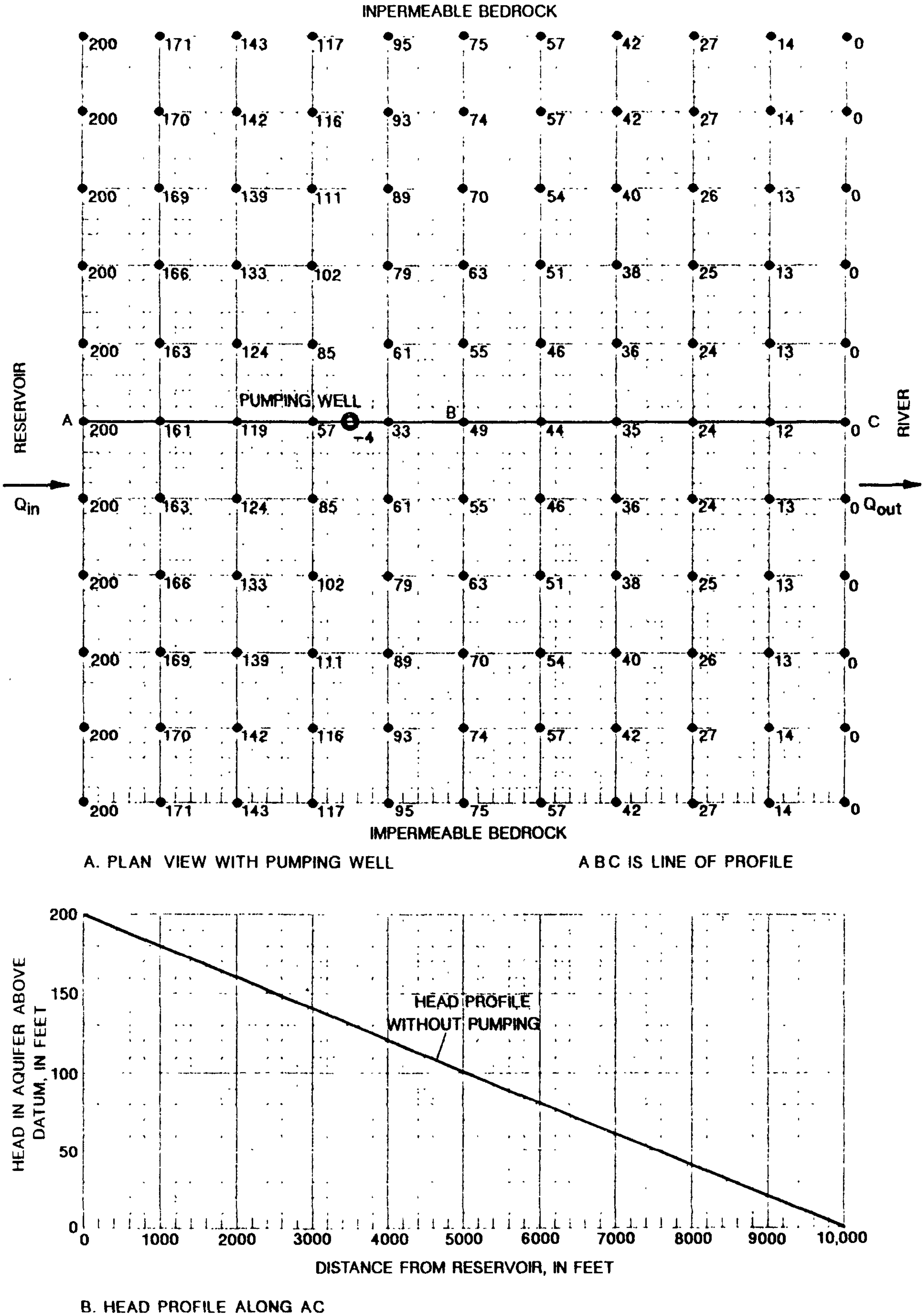
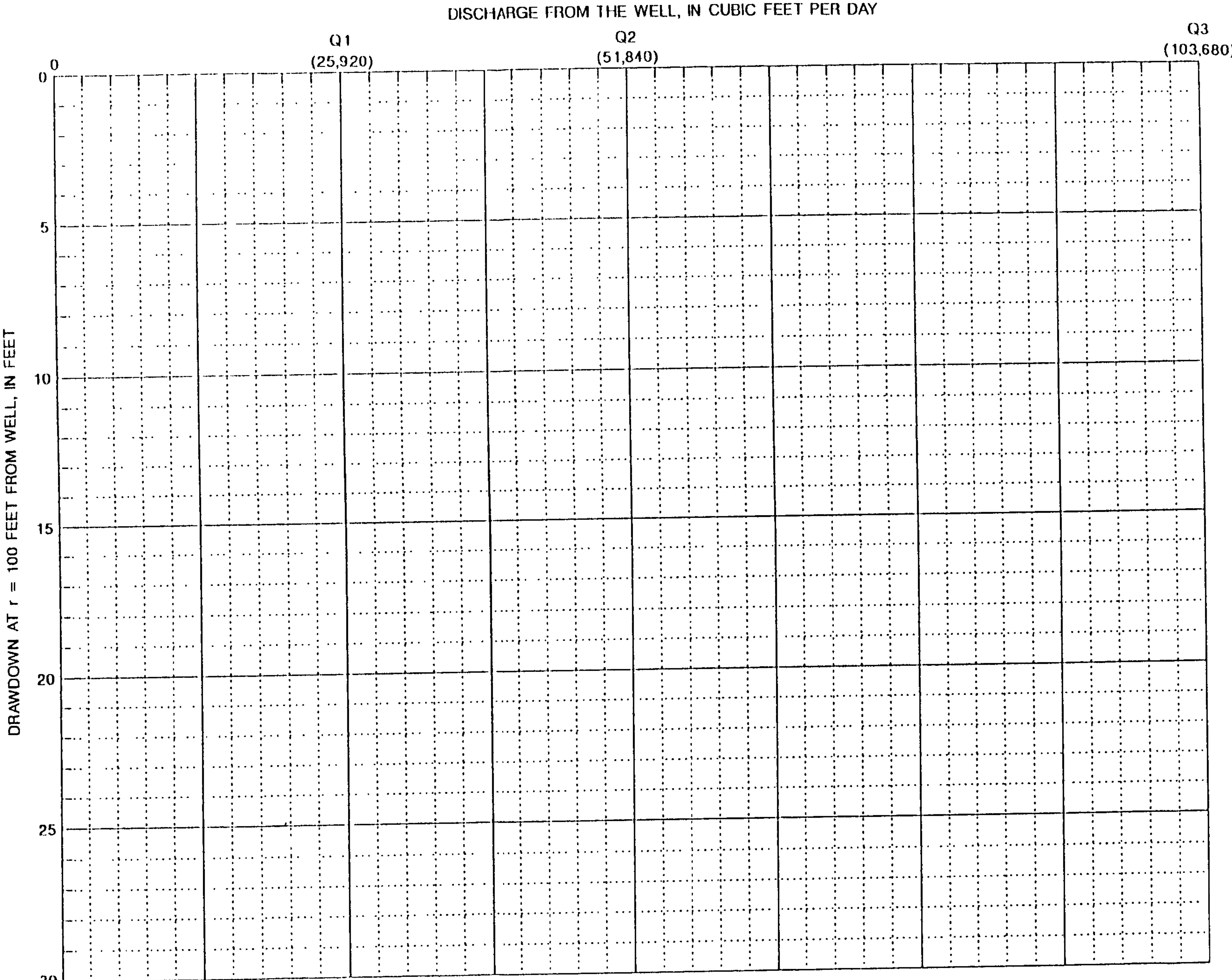


Figure 3-35.--(A) Heads in the stressed aquifer determined by numerical simulation when the pumping rate of the well is 3.1 cubic feet per second. (B) Graph for plotting head profile using data from (A).



Note: Q1, Q2 is well discharge, in cubic feet per day;
r is distance from well, in feet.

Figure 4-5.--Graph for plotting calculated drawdowns.

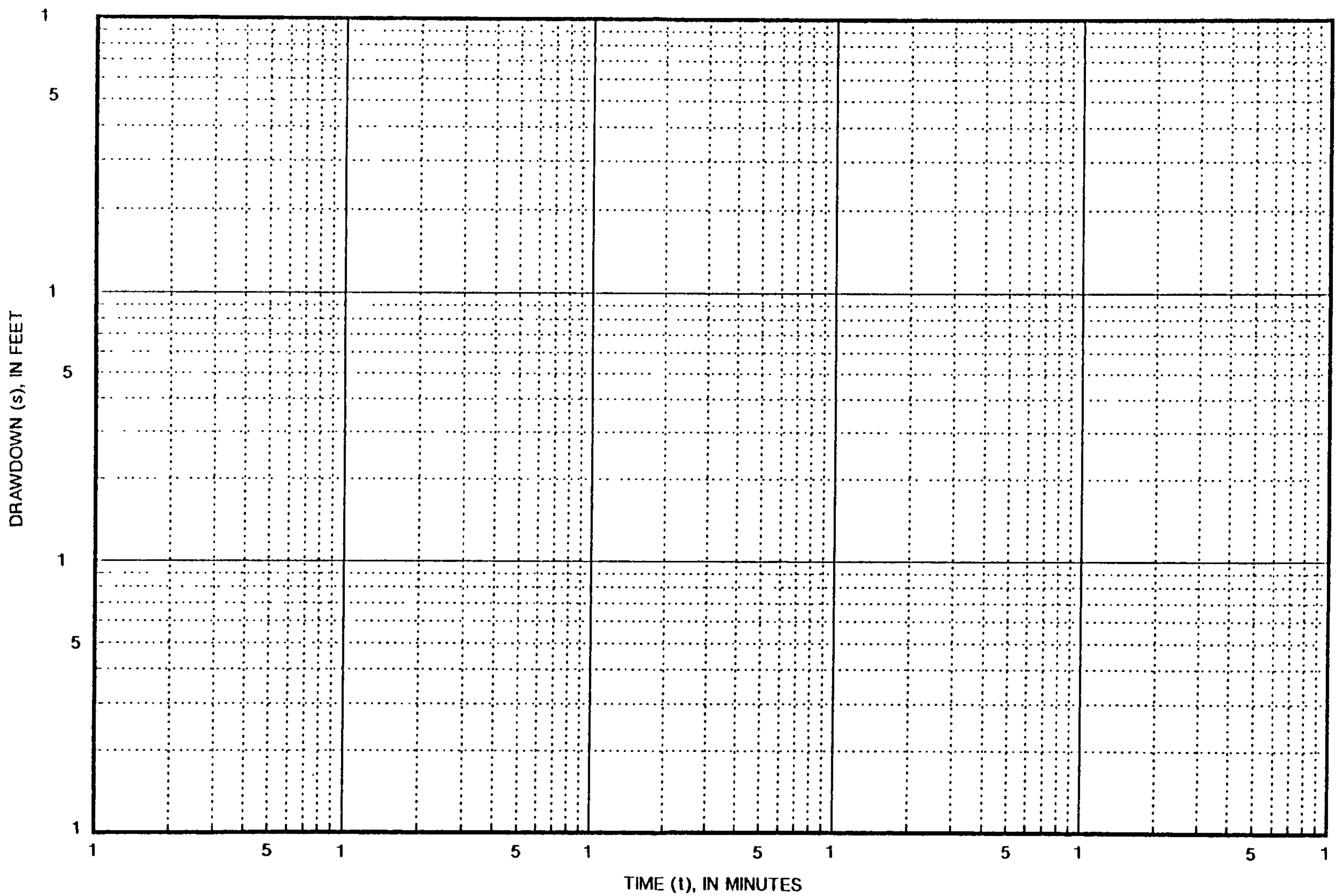


Figure 4-7.--Graph for plotting aquifer-test data from a single observation well in a Theis analysis (drawdown (s) against time (t)).

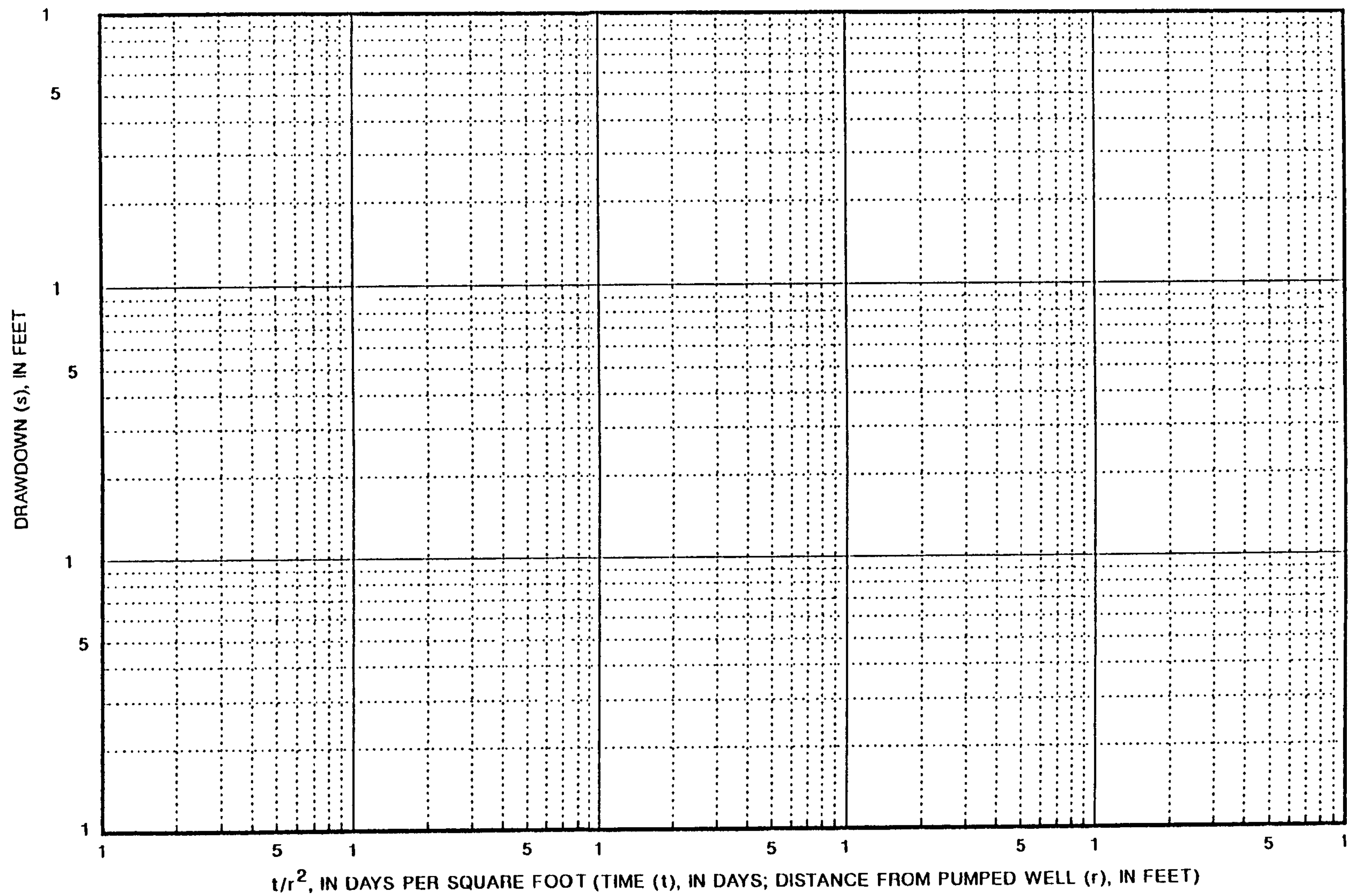


Figure 4-8.--Graph for plotting aquifer-test data from more than one observation well in a Theis analysis (drawdown (s) against t/rr).

Table 4-8.--Format for calculation of drawdowns at specified distances from the pumping well

[r_e is distance from pumping well at which drawdown is negligible; r_1 is distance from pumping well at which drawdown equals s_1; $\ln$ is natural logarithm; Q is pumping rate of well; T is transmissivity of aquifer]

Preliminary calculation: $\frac{-Q}{2\pi T}$ = constant =

r_1 (FEET)	$\ln(r_e/r_1)$	S_1 (FEET) $= -\frac{Q}{2\pi T} \ln(r_e/r_1)$
250		
500		
707		
1000		
1118		
1414		

Table 4-4.--Format for calculation of absolute heads at specified reference points

WELL IDENTIFICATION LETTER	INITIAL PREPUMPING HEAD (FEET)	DISTANCE FROM WELL (r), IN FEET	DRAWDOWN DUE TO PUMPING (FEET)	HEAD = INITIAL HEAD-DRAWDOWN, IN FEET
A				
B				
C				
D				
E				
F				
G				
H				
I				
J				
K				
L				
M				
N				
O				
P				
Q				
R				
S				
T				
U				
V				
W				
X				
Y				
Z				
AA				
BB				
CC				
DD				

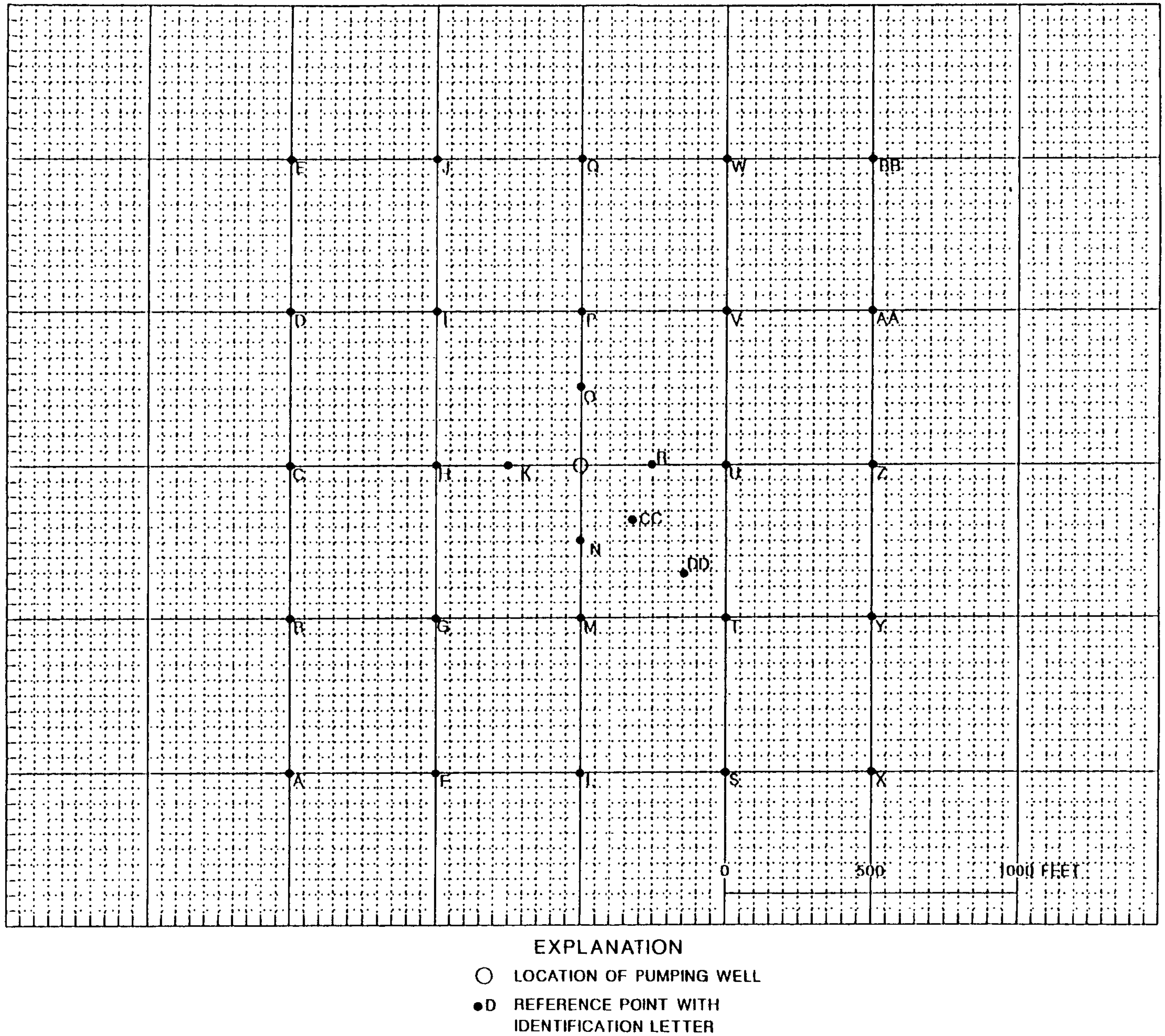


Figure 4-10.--Location map for plotting and contouring head distribution resulting from pumping.

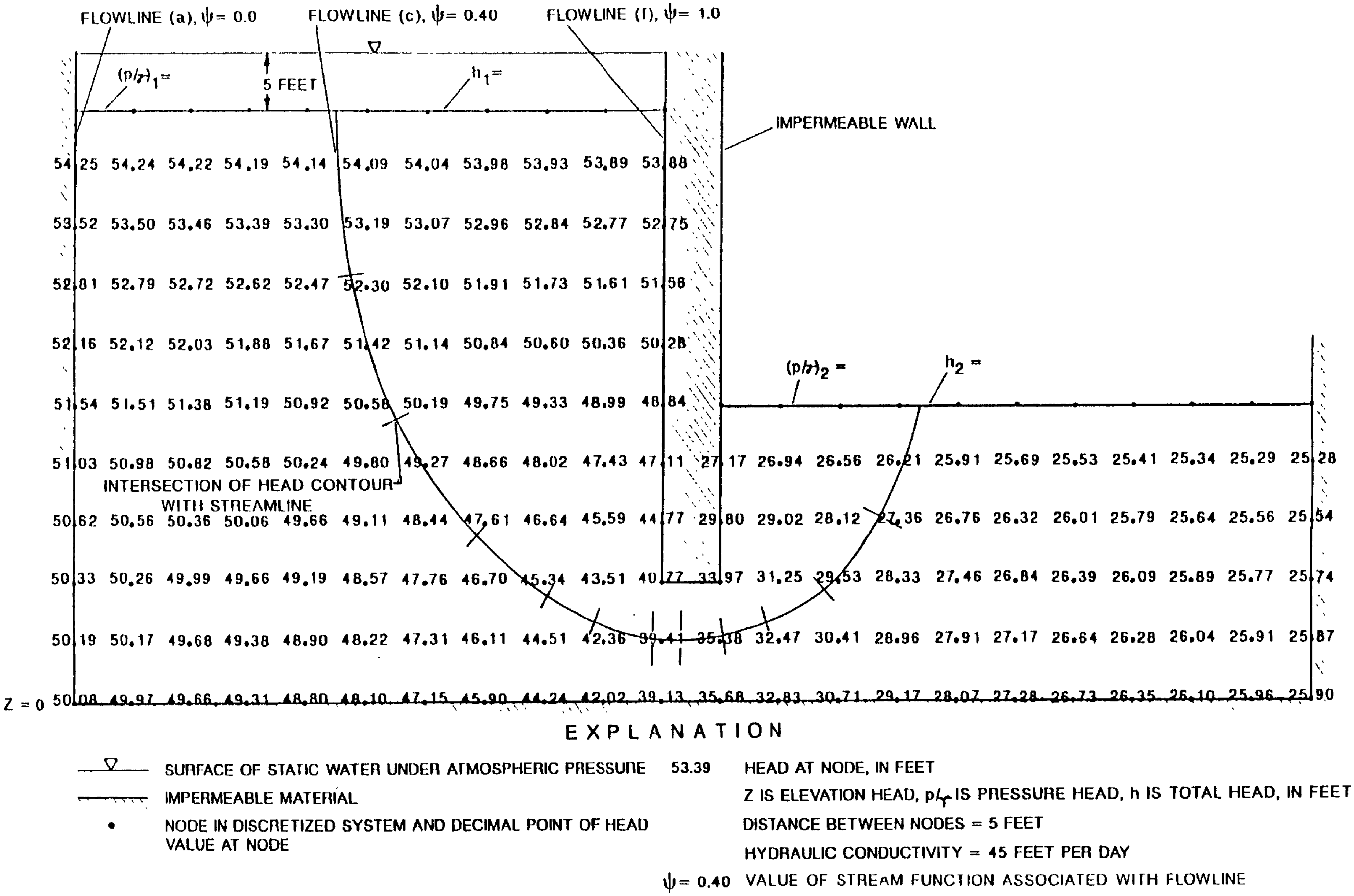


Figure 5-5.--Head "map" of a ground-water system with an impermeable wall for plotting cumulative time of travel from the system inflow boundary along two bounding flowlines and an internal flowline.

Table 5-1.--Format for calculation of time of travel along selected flowlines in impermeable-wall problem (page 1 of 3)

[h is head at a node or other point in flow system; L is distance between two points on a flowline at which head is known; Δh is difference in head between two points on a flowline; t is time of travel between two points on a flowline; Σt is time of travel from inflow boundary to point on flowline]

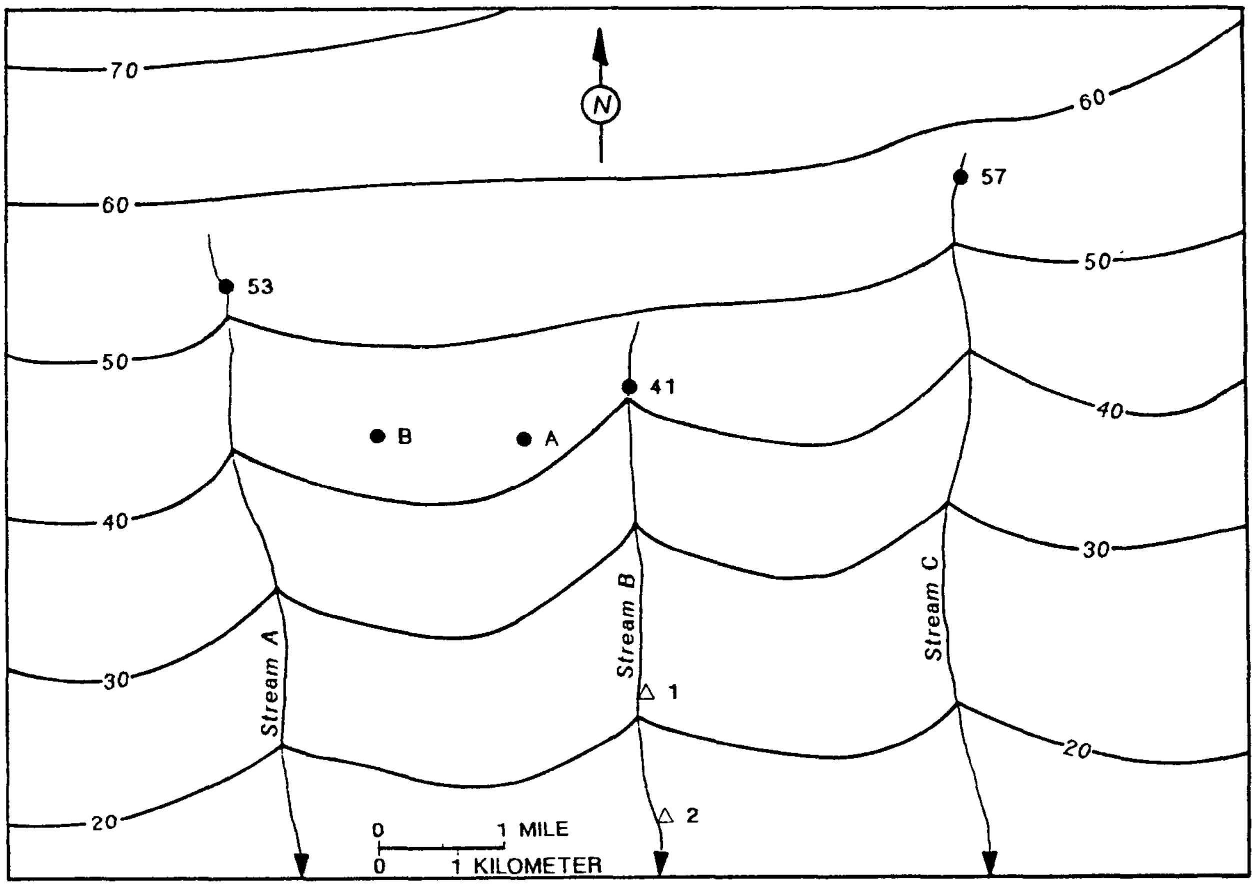
h (feet)	L (feet)	Δh (feet)	t (days) = $\frac{6.67 \times 10^{-3} L^2}{\Delta h}$	Σt (days)

Table 5-1.--Format for calculation of time of travel along selected flowlines in impermeable-wall problem (page 2 of 3)

h (feet)	L (feet)	Δh (feet)	t (days) = $\frac{6.67 \times 10^{-3} L^2}{\Delta h}$	Σt (days)

Table 5-1.--Format for calculation of time of travel along selected flowlines impermeable-wall problem (page 3 of 3)

h (feet)	L (feet)	Δh (feet)	t (days) = $\frac{6.67 \times 10^{-3} L^2}{\Delta h}$	Σt (days)



EXPLANATION

—20— WATER-TABLE CONTOUR -- Shows altitude of water table. Contour interval 10 feet Datum is sea level

● 41 LOCATION OF START OF FLOW OF STREAM -- Number is altitude of stream, in feet above sea level

△ 2 LOCATION AND NUMBER OF STREAM DISCHARGE MEASUREMENT POINT

Figure 5-6.--Hypothetical water-table map of an area underlain by permeable deposits in a humid climate.

Table 5-2.--Format for calculating solute concentrations when the dispersion coefficient D = 10 square feet per day and the elapsed time t = 1,000 days

[ft^2/d, square feet per day; mg/L, milligrams per liter]

Formula for calculations: $C = \frac{C_0}{2} \operatorname{erfc}\left(\frac{L - vt}{2\sqrt{Dt}}\right)$ where

C = concentration of solute at point in plume at specified time, in mg/L
C_0 = solute concentration of source, in mg/L
L = distance from source, in feet
v = average linear velocity of ground water, in ft/d
t = elapsed time since introduction of solute at source, in days
D = dispersion coefficient, in ft^2/d
erfc = complementary error function (see text)

Preliminary calculation:

For D = 10 ft^2/d, $\left(\frac{L - vt}{2\sqrt{Dt}}\right)$ =

L (feet)	$\frac{L-2,000}{200}$	$\operatorname{erfc}\left(\frac{L-2,000}{200}\right)$ [1]	C = 50 mg/L $\operatorname{erfc}\left(\frac{L-2,000}{200}\right)$
1,500			
1,600			
1,700			
1,800			
1,900			
2,000			
2,100			
2,200			
2,300			
2,400			

[1] erfc(-x) = 1 + erf(x).

Table 5-8.--Format for calculating solute concentrations when the dispersion coefficient D = 100 square feet per day and the elapsed time t = 1,000 days

[ft^2/d, feet squared per day; mg/L, milligrams per liter]

Formula for calculations: $C = \frac{C_0}{2} \operatorname{erfc}\left(\frac{L - vt}{2\sqrt{Dt}}\right)$ where

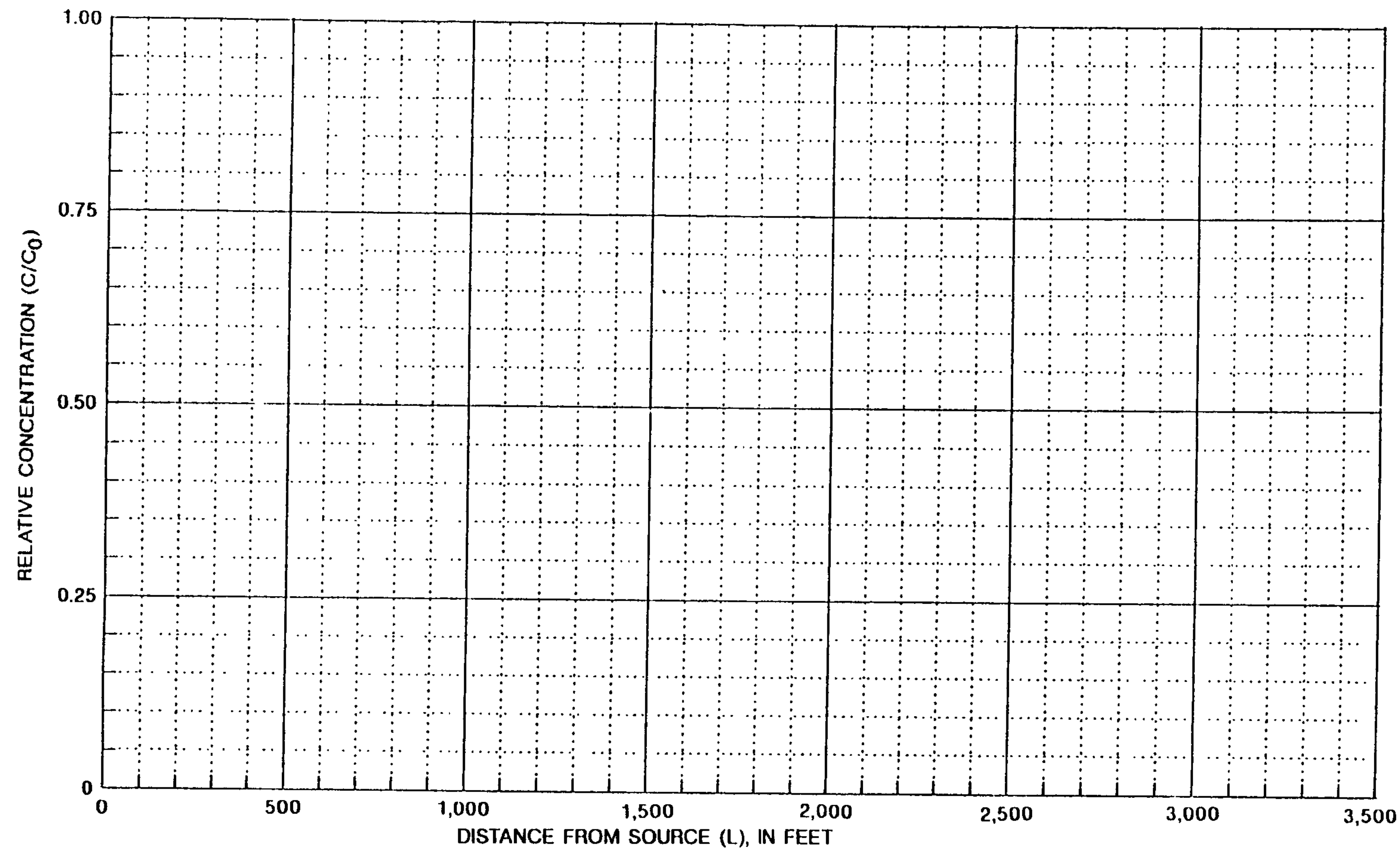
- C = concentration of solute at point in plume at specified time, in mg/L
- C_0 = solute concentration of source, in mg/L
- L = distance from source, in feet
- v = average linear velocity of ground water, in ft/d
- t = elapsed time since introduction of solute at source, in days
- D = dispersion coefficient, in ft^2/d
- erfc = complementary error function (see text)

Preliminary calculation:

For D = 100 ft^2/d, $\left(\frac{L - vt}{2\sqrt{Dt}}\right) =$

L (feet)	$\frac{L-2,000}{632.5}$	$\operatorname{erfc}\left(\frac{L-2,000}{632.5}\right)$ [1]	C = 50 mg/L $\operatorname{erfc}\left(\frac{L-2,000}{632.5}\right)$
1,000			
1,250			
1,500			
1,750			
2,000			
2,250			
2,500			
2,750			
3,000			

[1] erfc(-x) = 1 + erf(x).



EXPLANATION

C_0 = SOLUTE CONCENTRATION OF SOURCE

C = CONCENTRATION OF SOLUTE AT POINT IN PLUME

Figure 5-9.--Graph for plotting relative concentration against distance from source for two values of the dispersion coefficient and an elapsed time of 1,000 days.