EXERCISE 12

Groundwater Hydrology

INTRODUCTION

Groundwater is an important component of the hydrologic cycle. It feeds lakes, rivers, wetlands, and reservoirs; it supplies water for domestic, municipal, agricultural, and heating and cooling systems. Groundwater resources at a site vary with natural and artificial recharge and discharge conditions. Because we dispose of wastes improperly or mishandle materials on the land surface, we pollute some groundwater reservoirs. For resource planning and waste management, it is essential that we understand the quantity, quality, and movement of water in bedrock and regolith or surficial aquifers. This exercise is an introduction to the basics of groundwater hydrology (hydrogeology) and to interpretation of the subsurface with geologic cross sections.

PART A. GROUNDWATER

Part of the water that reaches the land in the form of precipitation infiltrates to become groundwater. Groundwater occurs in openings in rocks and unconsolidated materials (Figure 12.1) and moves under the influence of gravity or pressure. An *aquifer* or groundwater reservoir is a water-saturated geologic unit composed of rock or unconsolidated materials that yields water to wells or springs. Generally, unconsolidated materials such as sand and gravel have more spaces than solid rock; the openings are due to incomplete cementation of the grains or to fracturing or partial solution of the rock. Openings in igneous and metamorphic rocks are generally due to fractures and joints. The ratio of the open spaces relative to the rock or regolith volume is called *porosity* (n), which is expressed as a percentage (Table 12.1). Porosity is a storage factor.

Not all the pores of a rock or regolith are available for flow of water. Some water does not flow because of molecular forces, surface tension, and dead-end pores. *Effective porosity* (n_e) is the amount of pore space that is available for transmitting water. (In some coarse-grained materials effective porosity approximates specific yield and gravity drainage.) Effective porosity is difficult to measure and is often approximated from total porosity and lab test data. Effective porosity is a factor in velocity of groundwater flow and is expressed as a percentage (Table 12.1).

The movement of water through a rock is also controlled by its permeability or hydraulic conductivity. The term *hydraulic conductivity* (K) is used in hydrogeology to describe the ease with which water can move through a formation and is often measured in units of length/time. Both fine grained and poorly sorted materials have low K values. Values for K are obtained in the lab and in the field. Representative values for different rock and unconsolidated materials are given in Table 12.1 in ft/day or ft d^{-1}. Sometimes values for K are given in m/d, m/s, or gal per day/ft^2. Some materials, such as clay and silt, may have a high porosity and hold much water; however, they have low effective porosity and low hydraulic conductivity because the openings are very small or not connected. Such units are aquitards because they retard the flow of water. Aquifers that have high hydraulic conductivity provide large quantities of water to wells.

In some aquifers groundwater occurs under *water table* or unconfined conditions (Figure 12.2). In this case the water table is the boundary between the *zones of aeration and saturation*. Where the water table intersects the land surface, *springs*, seeps, streams, and lakes are formed. The position of the water table can be determined by measuring the depth to water in a well tapping an *unconfined aquifer*.

Layers of low permeability confine many aquifers, and water in them is stored under pressure (Figure 12.2). When a well is drilled into such a *confined or artesian aquifer*, water rises in the well to some level above the base of the confining bed. In some cases the well may even flow at land surface. The water level (also known as the *potentiometric, piezometric, or water-pressure surface*) represents the artesian pressure in the confined aquifer.

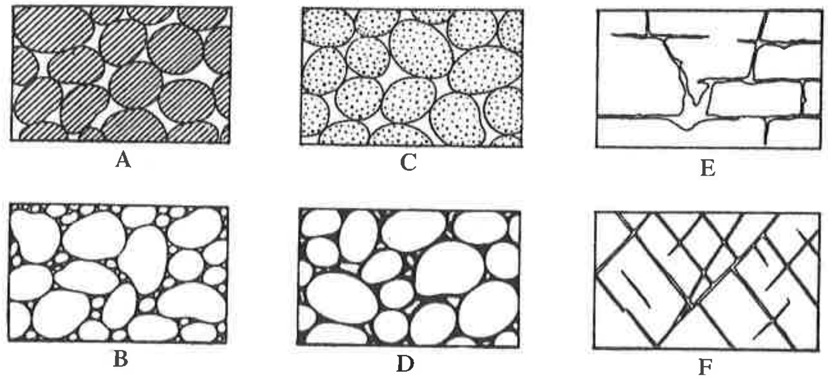

FIGURE 12.1 Types of primary (A–D) and secondary (E, F) porosity. A, well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing (Meinzer, 1923, p. 3).

TABLE 12.1 Range in Hydrologic Properties of Selected Geologic Materials

Material (rock or regolith)	Porosity (n) %	Effective Porosity (n_e) (%)	Hydraulic Conductivity (K) (ft/day)
Gravel	25–40	15–30	100–10000
Sand	30–40	10–30	0.1–1500
Clay, silt	45–60	1–10	10^{-7}–10
Till	20–40	6–16	10^{-7}–0.1
Sandstone	10–30	5–15	10^{-4}–1
Shale	1–10	0.5–5	10^{-8}–10^{-3}
Limestone	1–20	0.5–5	10^{-3}–10^{4}
Igneous rocks	0–40	0–30	10^{-8}–10
Metamorphic rocks	0–40	0–30	10^{-8}–10

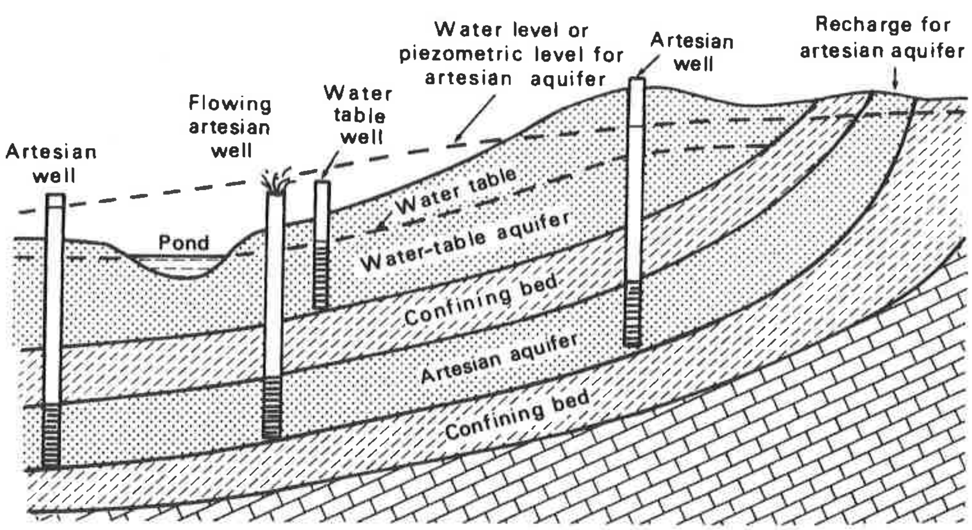

FIGURE 12.2 Schematic diagram of artesian and water table aquifers. Horizontal lines show well screen.

Most commonly the water table forms a gently sloping surface that follows the land surface (i.e., higher under hills than adjacent valleys). The water-pressure surface in artesian systems also generally follows topographic contours but in a more subdued manner. When the water table is at or near the land surface, groundwater may evaporate or be transpired by plants in large quantities and thus returned to the atmosphere.

The water table or water-pressure surface controls the direction of groundwater flow and can be mapped in a manner similar to contouring surface topography (Figure 12.3). In this case, however, control points are water elevations in wells, springs, lakes, or streams. Groundwater flows in the direction of decreasing head, which means that it flows from high to low pressure in a groundwater system. The high-pressure areas are where the water table is high or the water-pressure surface has a high value. On the contour map of the water table the flow lines cross the contour lines at right or 90° angles; the flow of groundwater effectively moves down slope or down gradient. Note how the flow lines curve to maintain the 90° crossing of each contour line in Figure 12.3.

The *hydraulic gradient* (I) is the difference in water level per unit of distance in a given direction. It can be measured directly from water-level maps in feet per foot or feet per mile. It is the slope of the water table surface or the water-pressure surface. (See "Slope or Gradient" in Part B of Exercise 3).

By using water-level maps in conjunction with topographic maps, the depth to the water table or water-pressure surface can be determined. This depth will vary with time depending on the season and the amount of recharge supplied by precipitation infiltrating the aquifer and the amount of discharge by pumping and by natural outflow to springs and streams. If discharge exceeds the rate of recharge to the aquifer, the water level in the aquifer will decline, and some wells could become dry.

The rate of groundwater flow generally ranges from 5 ft/day to 5 ft/year. It is usually less than 1 ft/day, but velocities greater than 400 ft/day have been measured. Groundwater *velocity* (v) depends on *hydraulic conductivity* (K), the hydraulic gradient (I), and the *effective porosity* (n_e). Sometimes permeability (P) and specific yield (a) are used in place of hydraulic conductivity and effective porosity, respectively. The

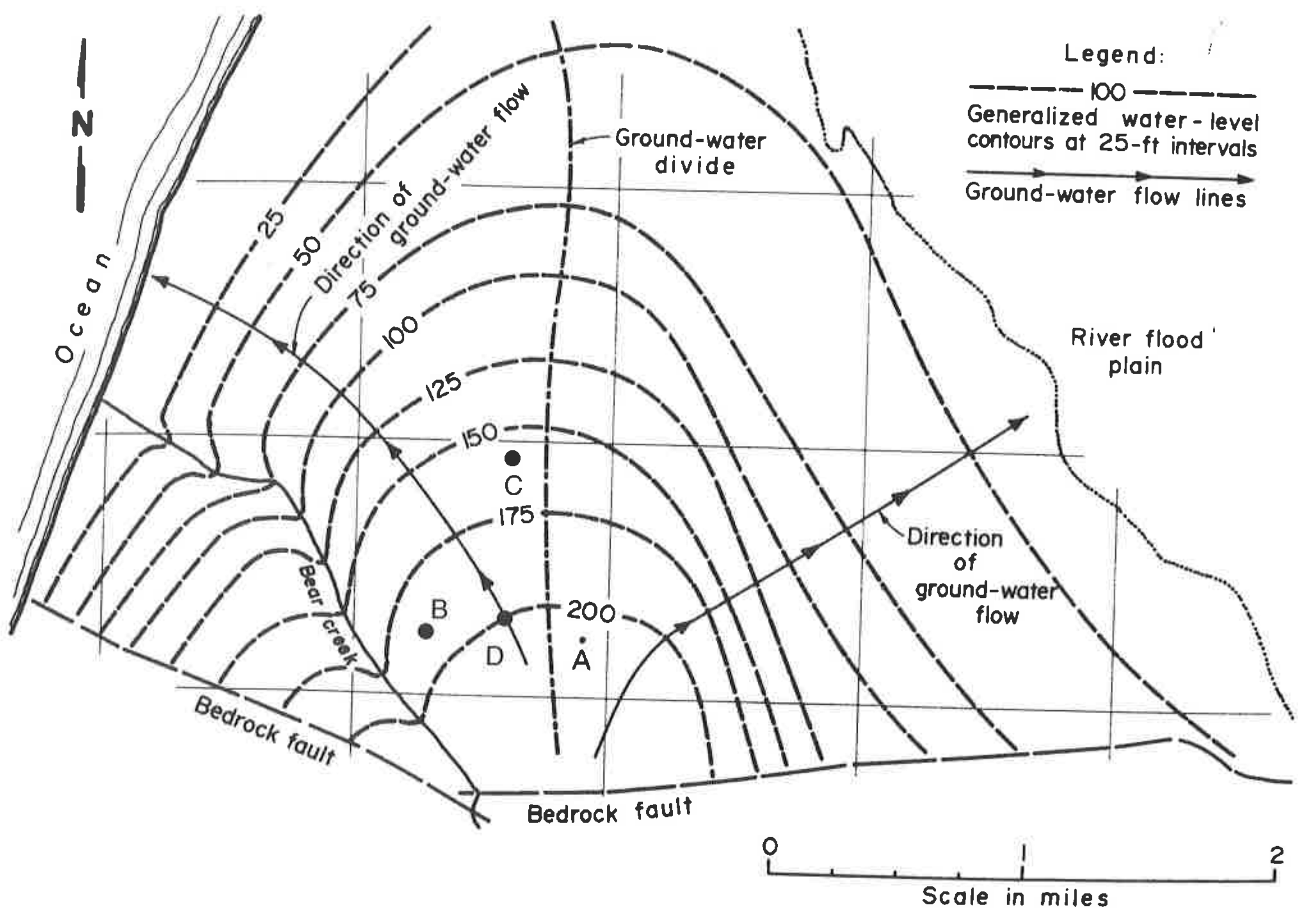

FIGURE 12.3 Water-level contour map showing elevation of the upper surface of the saturated zone (the water table). Groundwater flows down-gradient at right angles to the contours, as shown by the two flow lines that have been added to the map. One mile = 5,280 feet.

(Modified from Johnson, 1966, p. 40)

following formula is used to determine groundwater velocity in ft/day, where n_e is unitless and given as a decimal (i.e., 10 percent = 0.10), and I is in ft/ft.

$$v\ (\text{ft/day}) = [K\ (\text{ft/day})\ I\ (\text{ft/ft})]/n_e$$

Knowing the amount of groundwater moving in an aquifer under a property may be of interest for resource development. The quantity of groundwater (Q), in cubic feet per day (ft^3/day) or cubic feet per second (cfs, if multiplied by 0.0000115), that passes through a cross-sectional area of an aquifer can be determined by means of *Darcy's Law*:

$$Q\ (\text{ft}^3/\text{day}) = K\ (\text{ft/day})\ A\ (\text{ft}^2)\ I\ (\text{ft/ft})$$

where A, the cross-sectional area through which flow occurs in ft^2, is equal to the width of the aquifer times its saturated thickness. Darcy's Law shows that the quantity of flow increases with an increase in K, A, or I.

These two equations, for the velocity and quantity of groundwater flow, are useful for estimating the movement and potential availability of water in an aquifer. More sophisticated computer models, which account for geologic variations in the subsurface, are used by professionals to predict groundwater flow. The velocity equation, based on Darcy's Law, may not apply where: (1) groundwater flows through low hydraulic conductivity materials at low gradient, and (2) turbulent flow occurs through large fractures or openings. The following questions are based on the conditions shown in Figure 12.3.

QUESTIONS 12, PART A

1. What is the average water-level gradient or slope along the eastern flow line of Figure 12.3 between the 200-ft and 50-ft contour? Give your answer in ft/ft and ft/mi and show your work.

2. If an aquifer near the floodplain in the eastern part of Figure 12.3 is 30 ft thick and has a porosity of 10 percent, how much water is *stored* in a 0.1 mile by 0.1 mile area of the aquifer? Give your answer in cubic feet and gallons; show your work (see Appendix A for Conversions).

3. If the hydraulic conductivity (K) of the aquifer is 150 ft/day, and the effective porosity (n_e) is 15%, what is the average groundwater velocity in the vicinity of the eastern flow line! Show your work.

4. On Figure 12.3, construct a groundwater flow line downslope from each of sites A, B, and C. (See the instructor for other possible sites).

5. a. If gasoline were spilled at A, would it discharge with groundwater directly into the ocean? Explain.

b. If gasoline were spilled at B, would it discharge with groundwater directly into the ocean? Explain.

c. If gasoline were spilled at C, would it discharge with groundwater directly into the ocean? Explain.

6. In the western part of the aquifer, at and down gradient from D, the hydraulic conductivity is 100 feet per day and the effective porosity is 30 percent.

a. What is the average velocity along the flow line from D? Show your work.

b. If the velocity of the groundwater is assumed to also represent the movement of the contaminant, what is the time required for gasoline spilled at site D to travel to the end of the flow path? Show your work (time-distance/velocity D).

7. Using Darcy's Law, what is the quantity (Q) of groundwater flowing horizontally through a 2ft × 2ft square of an aquifer with K = 180 ft/day and an hydraulic gradient of 1 ft/1000 ft?

PART B. SUBSURFACE GEOLOGY

In addition to looking at the flow of groundwater, it is important to have a mental understanding of what the distribution of subsurface geologic units may be like. Different geological units will allow different amounts of water to flow through them depending on their hydraulic conductivity (Table 12.1). Understanding the relationships among subsurface geologic units is very important in developing an understanding of how groundwater moves in complex subsurface environments. Although there is much difference in the geology of subsurface units in different geological settings, the example below illustrates how sedimentary units might be related in many parts of the northern United States where glaciation has modified or formed the regolith.

When geologists begin to investigate the subsurface geology of an area, they often are limited to data gathered from existing wells. These data are in the form of well logs, which are a driller's or a geologist's written records of the different types of rock materials encountered as a well was drilled. By using logs from one well, a graph can be drawn that shows units encountered, as is illustrated in Figure 12.4. The depths at which different geologic units are encountered are shown. Depths below ground surface often are converted to elevations, so multiple wells can easily be plotted and compared. The transition from one geologic unit to another is called a contact.

Data from multiple wells can be connected (correlated) to form a geologic cross section. A cross section illustrates the subsurface relationships among different geologic units.

Where data are available from multiple wells, lines linking the geology in one well with the geology in another well can be sketched between the wells. Although there are no data between wells to suggest at what depth a particular geological unit may be encountered, it is reasonable to sketch a straight line where units can reasonably be connected (wells are vertical lines in Figure 12.5). If a unit is encountered in one well, but not in the next, the section must be drawn to indicate that it has not been encountered in the latter well. This is illustrated in Figure 12.5. Note that the sand unit at 760 ft was only found in one well on the right. Either it was not deposited elsewhere, or it has been eroded.

QUESTIONS 12, PART B

Your assignment is to interpret the well logs in Table 12.2, draw a topographic map, draw a geologic map, draw cross sections that illustrate the subsurface geology, and answer related questions about how water may move in the subsurface. The distribution of wells is shown on the map in Figure 12.6.

1. List the five different types of sediment or rock found in the wells (see Table 12.2).

2. Which sediment has the highest hydraulic conductivity? Which two have the lowest? (See Table 12.1 for hints.)

3. In Table 12.2, complete the data for *Depth* (to the bottom of each unit) and *Elevation* (height above sea level for the bottom of each unit) for wells 4–8. Wells 1–3 are completed in the table as guides.

4. On Figure 12.6, put the land elevation beside each well. Draw topographic contours showing the configuration of the land surface. Use a contour interval of 20 feet for your *topographic map*. The 260-foot contour is given on the map.

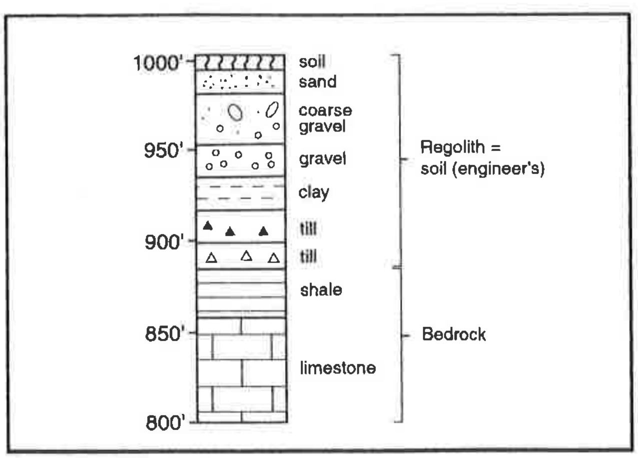

FIGURE 12.4 Typical log from a well, showing geologic materials and contacts.

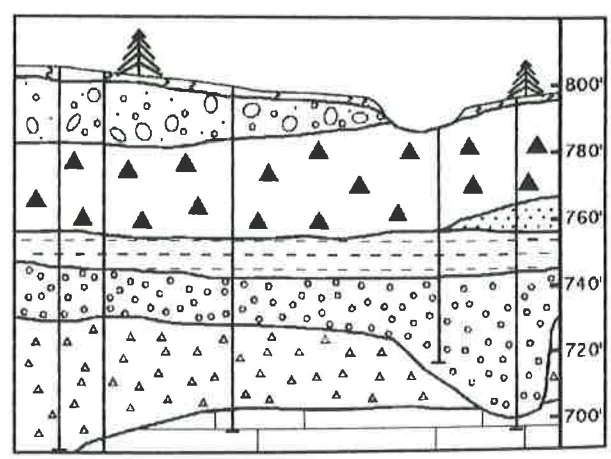

FIGURE 12.5 Geologic cross section, showing the correlation (connection) of geologic units in the subsurface between wells.

TABLE 12.2 Darcyville Well Logs. All measurements are in feet. Material is the type of geologic deposits (sediments). Thickness records how many feet of a particular unit were encountered when the well was drilled. Depth is how far down it is from the surface to the bottom contact of the specific type of geologic deposit. *Elevation is the height above sea level for the bottom of the geologic deposit.* Data for wells 1, 2 and 3 are filled in. Till is a poorly sorted silt and clay-rich sediment deposited by a glacier.

Well 1; Darcyville (land elev. 265)

Material	Thickness	Depth	Elevation
coarse gravel	40	40	225
till	45	85	180
clay	10	95	170

Well 2; Darcyville (land elev. 275)

Material	Thickness	Depth	Elevation
till	15	15	260
coarse gravel	25	40	235
till	15	55	220
fine sand	10	65	210
till	30	95	180
clay	25	120	155

Well 3; Darcyville (land elev. 290)

Material	Thickness	Depth	Elevation
till	60	60	230
fine sand	25	85	205
till	25	110	180
clay	25	135	155

Well 4; Darcyville (land elev. 305)

Material	Thickness	Depth	Elevation
coarse gravel	45		
till	20		
fine sand	45		
till	15		
clay	10		

Well 5; Darcyville (land elev. 310)

Material	Thickness	Depth	Elevation
coarse gravel	15		
till	40		
medium sand	40		
till	35		
clay	10		

Well 6; Darcyville (land elev. 290)

Material	Thickness	Depth	Elevation
till	70		
fine sand	15		
till	25		
clay	4		

Well 7; Darcyville (land elev. 265)

Material	Thickness	Depth	Elevation
coarse gravel	15		
till	35		
fine sand	10		
till	25		
clay	15		

Well 8; Darcyville (land elev. 255)

Material	Thickness	Depth	Elevation
coarse gravel	40		
till	35		
clay	10		

5. On Figure 12.6, beside each well, place the name of the material that is found at the land surface. These materials are those found in the top unit for each well.

6. Make a *geologic map* of the area in Figure 12.6 by interpreting the distribution of sediment (material) types and grouping any areas with similar materials. Do this by drawing a line to show the approximate contact between any two different materials at the surface. Without knowing the exact location of contacts, there will be more than one way to show the extent of materials. Your geologic map provides the distribution of sediments at the surface in this map area.

7. Draw two *geologic cross sections* (x to x', and y to y', for the map on Figure 12.6). The first cross section is through wells 1, 2, 3, and 4 (x–x'). The second cross section is through wells 5, 6, 7, and 8 (y–y'). Construct the cross sections on Figure 12.7 following the instructions below.

a. Draw the *profile* of the land surface; the profile for y–y' is given as an example. On the upper diagram in Figure 12.7 at the locations of the wells on the lower axis, draw a light line vertically above each well to the top of

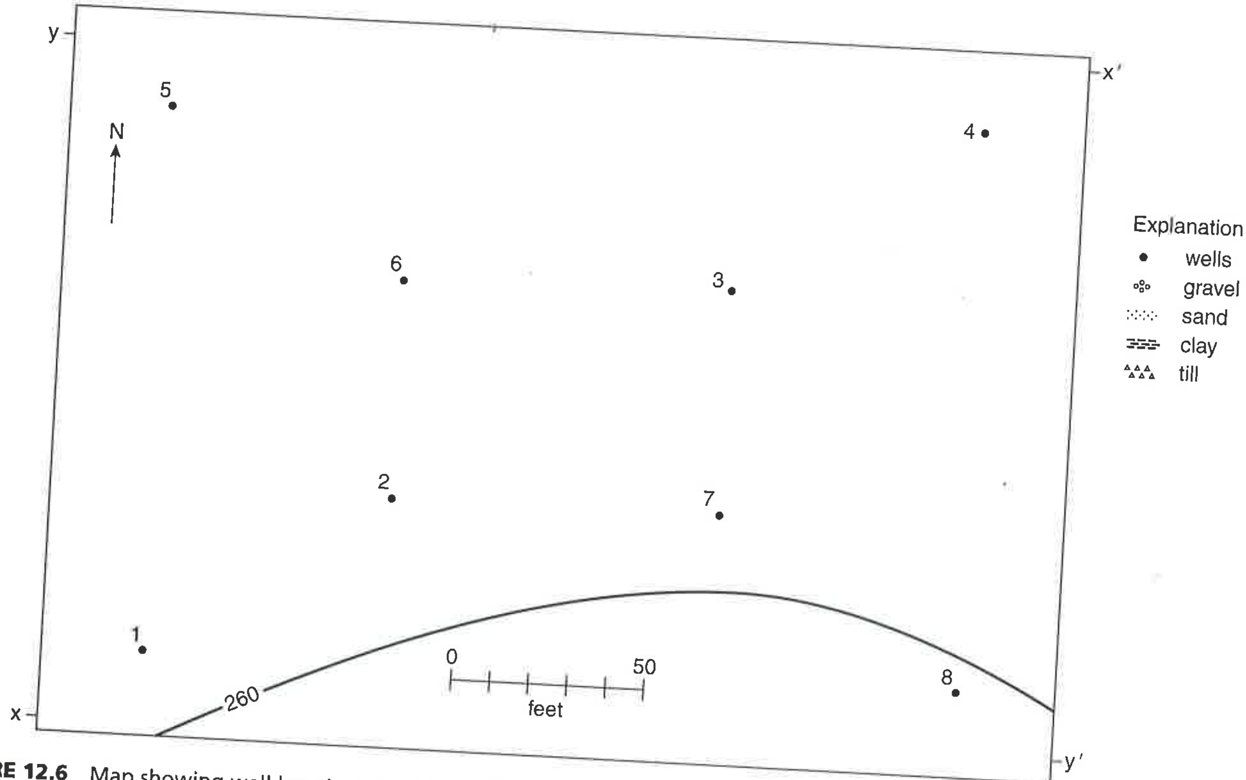

FIGURE 12.6 Map showing well locations near Darcyville, for completion of topographic and geologic maps. The 260-foot contour line is given.

the diagram (the line for well 1 is given). Mark the land elevation at the top of each well on this line with a short bar and label the elevation. Obtain the land elevation value for each well from Table 12.2.

Note: Optional: You could check agreement between your profile and a profile made from the topographic map constructed in Question 4, but this is optional. The points on profile y–y′ between wells were obtained from the contour map.

b. Add the stratigraphy for each well (wells 2–4 and 5–8). Starting from the topographic profile, place a tick mark on the vertical line for each well corresponding to the elevations where the geologic units change (i.e., the contacts of the units). The contacts for well 1 are entered on Figure 12.7.

c. Label each layer of each well as done for well 1.

d. Now complete the *geologic cross sections*. Look at the labeled geologic units in each well. Draw lines between wells to connect the same contacts separating geologic units. Not all units can be connected because some units may not occur in adjacent wells. Such units must "pinch out" before reaching an adjacent well when you construct your cross section.

8. Where is the best location to drill a water well for a house (domestic use well)? Briefly explain your choice based on the cross sections and geologic map that you constructed.

9. Assuming that all wells obtain water from every sand or gravel unit they intersect, which wells have the greatest potential for pollution from a nearby spill of toxic liquids? Explain your choices on the basis of the geology in your cross sections (Figure 12.7).

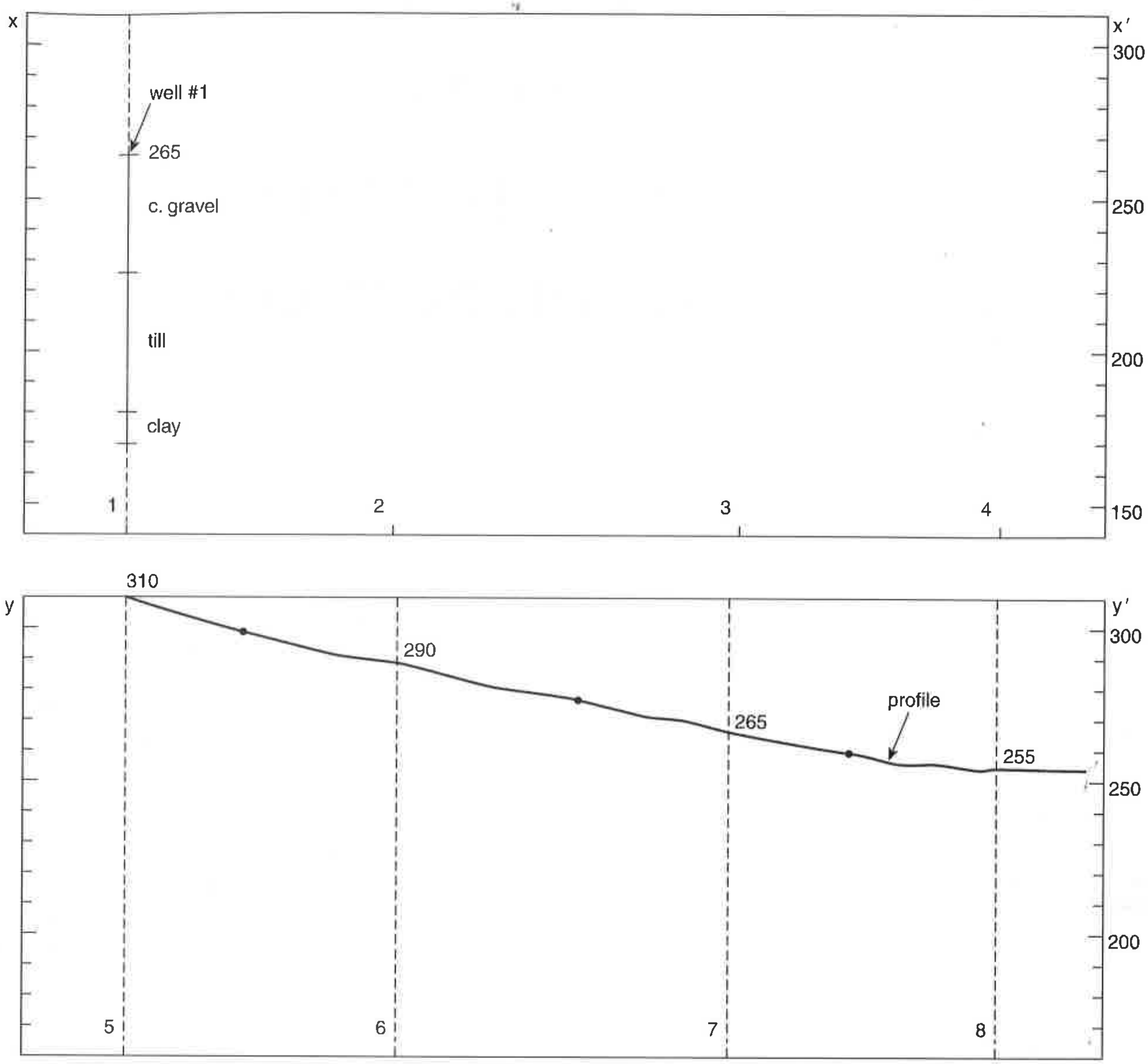

FIGURE 12.7 Geologic profiles and cross sections of the subsurface near Darcyville (x–x' and y–y'). See Figure 12.6 for location. Interpretation based on wells 1–8; elevation of land surface given in feet.

Bibliography

Clark, L., 1988, *Field guide to water wells and boreholes*: New York, John Wiley and Sons, 155 p.

Driscoll, F. G., 1986, *Groundwater and wells*: St. Paul, MN, Johnson Division, 1089 p.

Fetter, C. W., 1994, *Hydrogeology*: New York, Macmillan, 691 p.

Freeze, R. A., and Cherry, J. A., 1979, *Groundwater*: Englewood Cliffs, NJ, Prentice Hall, 604 p.

Heath, R. C., 1983, *Basic ground-water hydrology*: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Johnson, E. E., 1966, *Groundwater and wells*: St. Paul, MN, Edward E. Johnson, Inc.

Manning, J. C., 1987, *Applied principles of hydrology*: Columbus, OH, Merrill, 278 p.

McGuinness, C. L., 1963, *The role of groundwater in the national water situation*: U.S. Geological Survey Water-Supply Paper 1800, 1121 p.

Meinzer, O. E., 1923, *The occurrence of groundwater in the United States*: U.S. Geological Survey Water Supply Paper 489, 321 p.

Ohio EPA, 1995, *Technical guidance manual for hydrogeologic investigations and ground water monitoring*: Columbus, OH Environmental Protection Agency.

Price, M., 1985, *Introducing groundwater*: Boston, Allen and Unwin, 195 p.

U.S.EPA, 1990, *Handbook, ground water, volume 1: Groundwater and contamination*, EPA/625/6–90/016a.