10 groundwater

Topics

A. What is groundwater? Why is the composition of geyserite variable within Yellowstone National Park? How does the total amount of groundwater on Earth compare with that of surface water?
B. How do the dynamics of groundwater in humid regions differ from those in arid regions?
C. What are the two common problems with the saturated zone described here? What is hydraulic gradient, and how does its measurement differ from the way in which geologists measure slope? What is hydraulic conductivity? What is Darcy's Law, and how does it apply in computing the rate at which groundwater flows through a saturated zone?
D. How can one map a water table from well data? How can one use such a map to decipher the direction and rate of flow of contaminants within the saturated zone?
E. What is a confined aquifer, and what does it have to do with artesian conditions? What is a potentiometric surface, and how does it apply to flowing and nonflowing artesian wells?
F. What is a perched water table? What is the purpose of a reservoir liner?
G. What is karst topography, and what are its features? How are the direction and rate of flow of groundwater exposed within sinkholes in Florida determined?

A. Groundwater defined.

In its broadest definition **groundwater** is all water contained in vacant spaces within rocks and sediments. Groundwater that originates from precipitation (e.g., rain and snow)—the topic of this exercise—is called **meteoric water**. In addition to meteoric water, there are two minor sources of subterranean water: *connate water* (aka *sediment water*), which is water entrapped within sediments that accumulated in ancient seas; and *juvenile water*, the water that is born of magmatic activity. Neither connate water nor juvenile water is quantitatively important. (Exception: Connate water is invariably produced along with petroleum and can present environmental management problems on land because of its high salinity.)

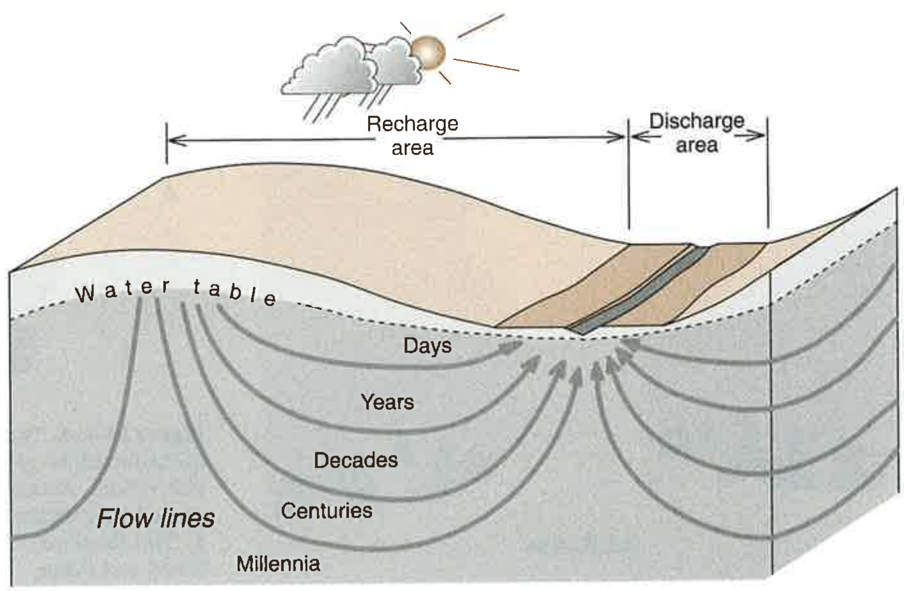


Figure 10-1. The vast majority of groundwater is meteoric in origin and is free to move with vagaries of climate. Rates of groundwater flow differ with depth, ranging from days to thousands of years to traverse an area the size of a county.

Groundwater—the great dissolver and precipitator

Groundwater is physically and chemically *dynamic*. It is constantly on the move, constantly dissolving and/or precipitating a host of rocks and minerals—depending on the chemistry of the water and the chemistry of the rocks and sediments through which it moves (Fig. 10-2).

Dissolves some things	Precipitates many things
• Limestone, gypsum, salt (makes caves and landscapes in these rocks) • Few minerals from sandstones, shales, and igneous and metamorphic rocks (does not make caves in these rocks)	• Cave deposits (stalactites, travertine, etc.) • Cements that hold sedimentary rocks together (calcareous, siliceous, ferruginous) • Spring and geyser deposits • Concretions and geodes

Figure 10-2. Groundwater dissolves rocks and minerals, groundwater precipitates rocks and minerals—depending on the composition of the water and on the composition of the rocks and sediments through which it circulates.

The variability of groundwater is illustrated by the variety of **geyserites** in Yellowstone National Park. (Geyserite is precipitated from groundwater as it spouts from the ground and evaporates, leaving behind whatever elements were in held in solution.)

Old Faithful

Q10-1. In the southern part of Yellowstone National Park (e.g., at and around Old Faithful), geyserite consists of varicolored siliceous material; whereas in the northern part of the park (e.g., at Mammoth Hot Spring), geyserite consists of snow-white calcareous material. Examine the details of Figure 10-3 and try to explain why this difference in the mineral compositions of Yellowstone geyserites.

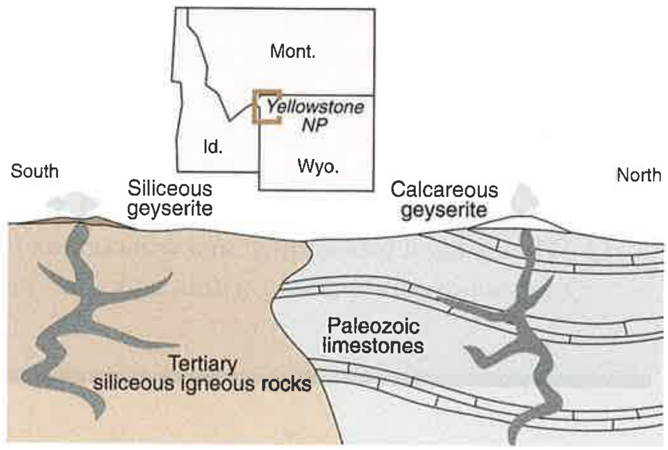


Figure 10-3. This is a schematic north–south cross-section showing the general stratigraphy of geysers and their plumbing systems in Yellowstone Park.

Groundwater and geologic wonders—Minerals that grow within cavities in rocks are precipitated by groundwater (Fig. 10-4A and B). And, petrifaction of trees of Triassic age in the Petrified Forest of northern Arizona reflects the work of groundwater as well (Fig. 10-4C). In the world of geologic wonders, stories of the effects of groundwater are endless.

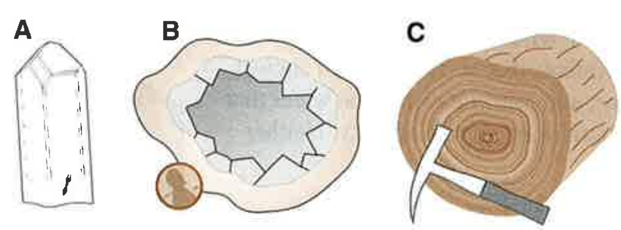


Figure 10-4. A. This faceted quartz crystal was precipitated, unobstructed, by groundwater within cavities in sandstone near Hot Springs, Arkansas. **B**. This geode was precipitated by groundwater within gas-bubble cavities in volcanic rocks of Brazil. **C**. This fossil tree was petrified by groundwater in the Petrified Forest in Arizona.

The impending global water shortage not only requires that the world develop all available potable water resources in the near future, but we must also do a better job of minimizing waste and preventing pollution.

Groundwater will play a growing role in efforts to provide water for our growing global population, given the fact that it quantitatively competes with other fresh water resources (Fig. 10-5).

COLUMBIA DAILY TRIBUNE, MARCH 24, 2002

U.N. water report warns of impending shortages

Crisis will affect 5 billion worldwide by 2025.

VIENNA, Austria (AP)—Warning that 2.7 billion people face a critical shortage of drinkable water by 2025, the United Nations marked World Water Day on Friday with a call for a "blue revolution" to conserve and tap the seas for new supplies.

In fewer than 25 years, about 5 billion people will be living in areas where it will be difficult or impossible to meet all their needs for fresh water, creating "a looming crisis that overshadows nearly two-thirds of the Earth's population," a U.N. report said.

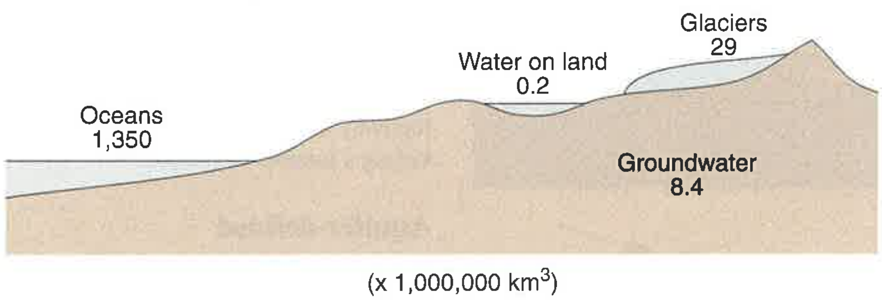


Figure 10-5. This is a comparison among the four vast reservoirs of accessible water on Earth. (A single unit is one million cubic kilometers.) Surface water consists of streams, rivers, lakes, and ponds.

Q10-2. (A) How many cubic kilometers of water reside within groundwater? (B) How many more times abundant is groundwater than surface water?

Groundwater has its advantages over surface water when it comes to providing for municipalities.

Q10-3. Imagine that you are a member of a city council and your town is in need of a new and larger municipal water supply. Discussion has turned to the merits of well water compared to those of impounding a stream. How do you imagine groundwater might be superior to surface water as concerns the following points?

(A) Paying for the cost of drilling a well, as compared to that of building a dam.
(B) Contending with the occasional drought in your semiarid region.
(C) Minimizing contamination from surface runoff and from the atmosphere.
(D) Surveillance of your water supply to prevent vandalism.

B. Anatomy of water tables.

Saturated and unsaturated zones—Within the subterranean realm of groundwater there are two principal *zones*:

(1) The **saturated zone** (Fig. 10-6) is the zone in which open spaces in sediments and rocks are filled with water. The top of the saturated zone is the **water table**. The movement of groundwater—*toward streams in humid regions and away from streams in arid regions*—accounts for the fact that water tables are rarely flat. The shape of a water table in a humid region mimics that of the land surface above—high under hills and low under valleys, intersecting perennial streams and lakes.

(2) The **unsaturated zone** is the zone in which intergranular spaces and fractures are filled with air and, in some cases, films of descending water.

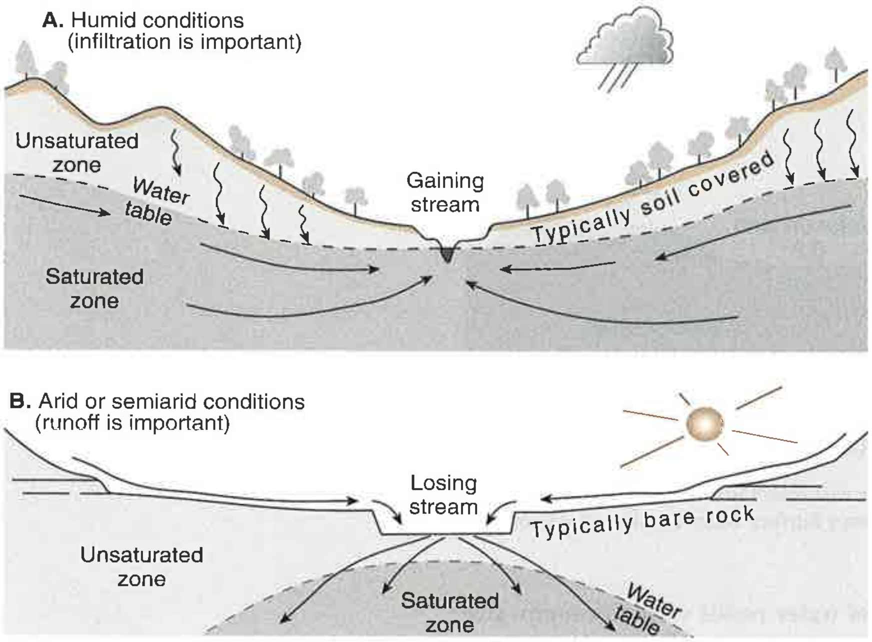


Figure 10-6. A. In a humid region, water moves (seeking its own level as it were) in an effort to develop a horizontal water table, and so the saturated zone feeds a *gaining stream*. **B.** In an arid or semiarid region, the water table slopes downward away from a *losing stream*, which is the source of water for the saturated zone.

A word about arid and semiarid streams

Q10-4. Judging from the information accompanying Figure 10-6, which kind of stream do you suspect might rise faster for a given amount of rain, that in a humid region or that in an arid or semiarid region?

If you answered "in an arid or semiarid region," to the above question, you were correct. Flat-bottomed losing streams like that in Figure 10-6B (Spanish *arroyos* or *barrancos*) can be dangerous. There is little rain in arid and semiarid regions, but when rain does come, it is *torrential*. Commonly, the entire annual amount of rainfall arrives in a single afternoon—often creating disastrous "flash floods." In August 2003 this kind of flash flood swept automobiles and highway dividers from I-35 in Kansas, killing a number of people.

Aquifer defined

Before going further in our discussion of groundwater, best we define the concept of **aquifer**—*a body of sediments or rocks that yields water sufficient to satisfy specific needs*. The saturated zone in Figure 10-6 might or might not be an aquifer. The definition is qualitative, rather than quantitaive. An aquifer meeting the needs of a city might cease to be viewed as an aquifer if the population were to grow beyond the carrying capacity of that aquifer.

Much of western United States lies within the North American Desert (Fig. 10-7), a region in which the groundwater situation is like that in Figure 10-6B. In contrast, eastern United States is characterized by conditions shown in Figure 10-6A.

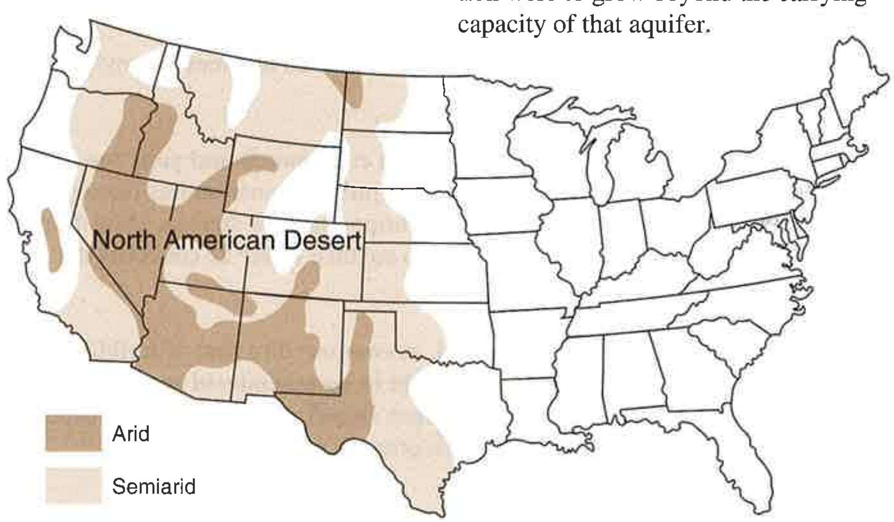


Figure 10-7. Because of arid to semiarid climate, approximately one-half of the lower 48 states is at risk as concerns the development and management of water resources.

C. Dynamics of water tables.

Common problems

In Los Angeles County, a 3.5-mile section of I-105 was constructed below ground level in an effort to minimize noise and sight pollution. Caltrans (Calif. Dept. of Transportation) believed the water table to be 30 feet below road level at the time of construction (Fig. 10-8). However, what Caltrans failed to learn was that the water table had been drawn down by overpumping in the 1950s, and another state agency had recently mandated that the overpumping cease. *(Ref: Calif. State Auditor rep't #99113, 1999.)*

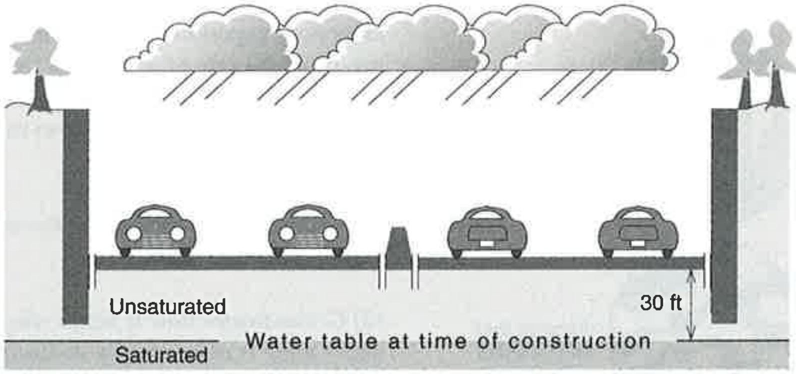


Figure 10-8. Highway engineers recessed a section of I-105 in Los Angeles County in an effort to mitigate noise and sight pollution. At that time, the water table was 30 ft deep.

Q10-5. So what do you suppose happened when overpumping of the saturated zone was stopped by that other California state agency?

On more than one occasion a gas station in a low topographic setting has allowed the level of gasoline in its storage tanks to become too low (Fig. 10-9). Then came the rains, with runoff making its way into the saturated zone.

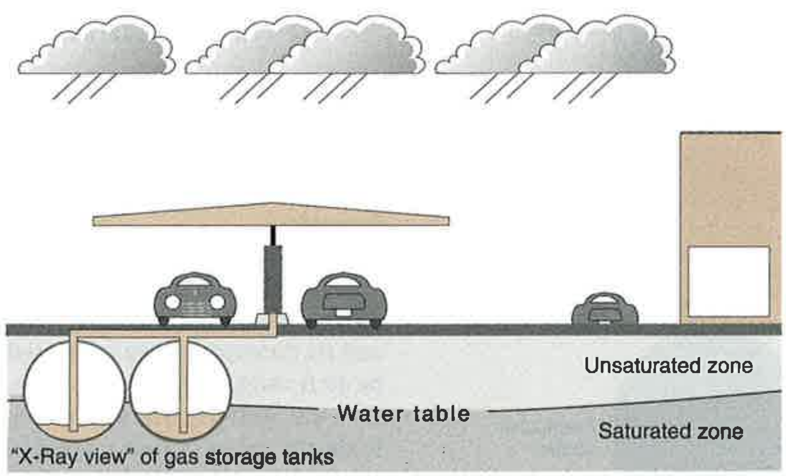


Figure 10-9. This gas station is very near the water table, which presents a threat to fuel storage tanks.

Q10-6. Can you imagine what happened when the rains came? *Hint*: Asphalt and concrete are only so strong.

Hydraulic gradient

Geologists describe the magnitude of slope as the vertical angle between slope and the horizontal (Fig. 10-10).

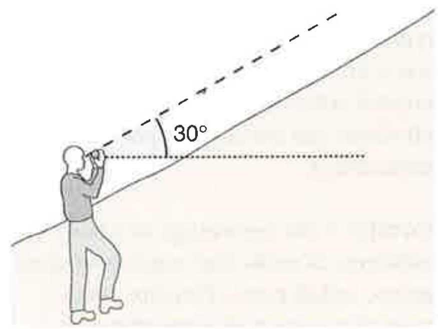
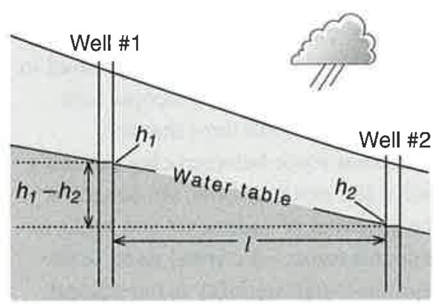


Figure 10-10. A Brunton compass enables a geologist to measure the vertical angle between slope and the horizontal.

But engineers describe the magnitude of slope as the ratio of vertical drop to horizontal distance, aka the *percent of grade*. Thus, a gradient of 0.05, or 5 percent, designates a vertical drop of 5 feet per 100 feet of horizontal distance. This same convention is used in describing the **hydraulic gradient** of groundwater (Fig. 10-11).



$$\text{Hydraulic gradient} = \frac{h_1 - h_2}{l}$$

Figure 10-11. h_1 is the elevation of the water table in well #1, h_2 is the elevation of the water table in well #2, and l (for length) is the horizontal distance between wells.

Q10-7. If, for the model in Figure 10-11, h_1 were 506 ft, h_2 were 497 ft, and l were 150 ft, what would be the hydraulic gradient (in percent) between well #1 and well #2?

Hydraulic conductivity

Like surface water flowing down steeper slopes, groundwater moves faster down steeper gradients. But hydraulic gradient is not the only factor affecting the rate of groundwater movement. Equally important is **hydraulic conductivity**, which is the ease with which sediments or rocks transmit water. Hydraulic conductivity introduces the concepts of *porosity* and *permeability*.

Porosity is the percentage of a body of sediments or rocks that consists of open spaces, called pores. Porosity determines the amount of water that sediments or rocks can *hold*. There are many kinds of pores—ranging from pores in sediments, to pores in volcanic rocks, to cavities in soluble rocks, to fractures in any rock (Fig. 10-12). And any of these pores can be occluded to differing degrees by cements.

Permeability is the ability of soil, sediment, or rock to *transmit* fluid. Material with low porosity is likely to have low permeability as well, but high porosity does not necessarily mean high permeability. In order for pores to contribute to a permeability, they must be (a) interconnected, and (b) not so small that they restrict flow. For example, clay commonly has high porosity, but clay grains are so broad in proportion to their microscopic size (i.e., around 0.005 mm) that the molecular force between clay particles and water restricts flow. As concerns the potential of sediments and rocks to transmit water—a critical issue in the aquifers—*permeability* is paramount.

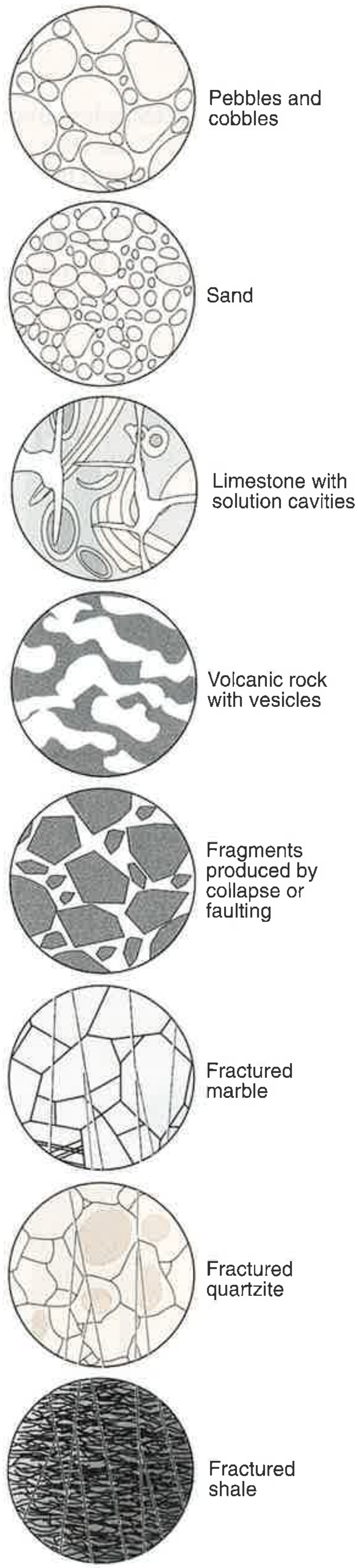


Figure 10-12. (White space is open space available to water. Open space along fractures is too thin to illustrate.) Porosity and permeability can result from sedimentation, volcanism, solution, collapse, faulting, and fracturing. Subsequent cementation can reduce the volumes of any of these pores. (Magnification is 5–10x.)

Darcy's Law

The most fundamental questions in targeting a prospective groundwater resource are, "How much, and how often?" This *volume per time* issue is analogous to the discharge of a stream.

In 1856, **Henri Darcy**, a French engineer, attempted to determine whether a prospective aquifer could yield water sufficient for the city of Dijon. Darcy undertook a series of laboratory experiments in which he measured the rate of water flow through a variety of sediments in tubes tilted at various angles. Not surprising to us now, Darcy concluded:

(1) Groundwater flows faster through more permeable rocks.

(2) Groundwater flow is faster where a water table is more steeply inclined.

Darcy identified the four key variables in groundwater flow (or discharge) as...

- Discharge *(Q)*
- Hydraulic conductivity *(K)*
- Hydraulic gradient $(h_1 - h_2 / l)$
- Area *(A)* (thickness x width)

...and crafted an algebraic expression of their relationship:

$$Q = (K)\,(h_1 - h_2 / l)\,(A)$$

Darcy's Law enables one to calculate the maximum amount of water that an aquifer might yield to an array of wells.

Example:

Q10-8. Hydraulic conductivity of an aquifer is known to be 8 ft/day, and its dimensions are estimated to be 40 ft thick and 18,000 ft wide. Two test wells drilled one mile apart in the direction of flow encountered the water table at elevations 5030 ft and 5050 ft. *Question*: How many gallons of water flow through the aquifer per day? (To convert ft^3 to gal, see page *ii*.)

D. Mapping a water table.

Directions of groundwater flow within your mapped area

Figure 10-23 on Answer Page 176 includes the locations of 26 water wells (Fig. 10-23). At each well there is recorded the depth to the water table within that well—as a negative value in feet.

Procedure:
For each well location:
(1) Estimate the *surface elevation* from contours.

(2) Subtract the *depth to the water table* from that elevation in order to determine the *elevation of the water table* within the well, and record the elevation of the water table at the well site.

(3) After doing the above for all 26 wells, *contour groundwater elevations* with a contour interval of 20 feet. (A "getting started" sample is framed in the southwest corner of the map.)

Q10-9. Draw an arrow between Well A and Well B indicating the direction in which groundwater is likely to be moving. In which direction is the arrow pointing, northeastward or southwestward?

Q10-10. (A) At what coordinates is the difference between the elevation of the ground and the elevation of the water table the greatest? (B) Give the coordinates of a place where you might expect to find a marsh or spring.

Q10-11. If liquid waste finds its way into groundwater at Acme Industries, in which well is it more likely to appear—that at the Smith farmhouse, or that at the Jones farmhouse?

Rates of groundwater flow—applying Darcy's Law to your map of the water table

Q10-12. What is the difference in elevation of the water table between Well A and Well B?

Q10-13. What is the map distance (in feet) between Well A and Well B?

Q10-14. What is the hydraulic gradient ($h_1 - h_2 / l$) between Well A and Well B?

Q10-15. If the hydraulic conductivity (*K*) of the aquifer is 10 ft/day, and the cross-sectional area (*A*) of the aquifer is 200 ft x 5,000 ft, what is the rate of flow, or discharge, (*Q*) through the aquifer in cubic feet per day?

E. Confined aquifers and artesian flow.

Water seeks its own level—You can probably surmise that water within glass tubing such as that shown in Figure 10-13A will rise to the same level within all three conduits—realizing the *potential* for each in defining a horizontal surface. But, if that same tubing is (a) filled with sand and (b) opened at its downstream end (Fig. 10-13B), water will not rise as high within the vertical tubes. And, the farther from its source, the less high the water will rise because of the progressive reduction in hydrostatic pressure. This progressive reduction in *potential* away from the source defines a *sloping surface*, rather than a horizontal surface.

In the real world, an artesian aquifer is more like the situation shown in Figure 10-13B in that (a) an artesian aquifer is filled with sediments and/or rocks, and (b) water within an artesian aquifer is free to circulate within that aquifer.

Q10-16. In sum, and in few words, list the *two* things that account for less pressure in Conduit B than in Conduit A. *Hint*: Those few words are scattered around labels and the caption of Figure 10-13.

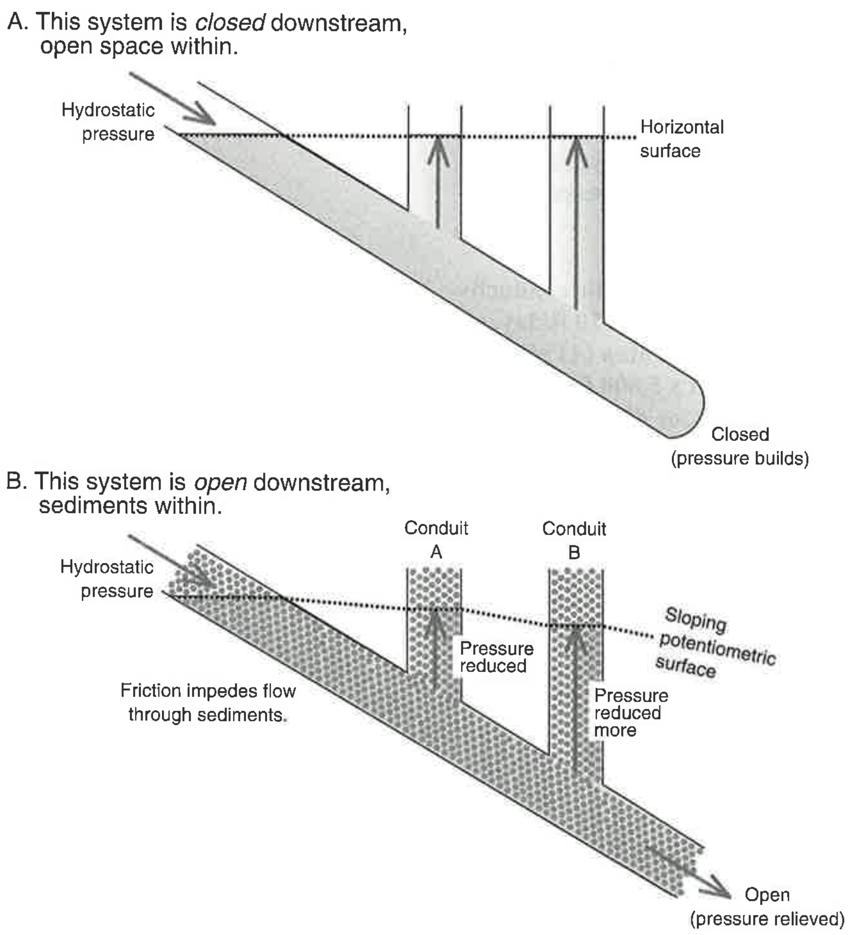


Figure 10-13. Glass tubing illustrating principles of artesian flow. **A**. This tubing illustrates the simple principle, "water seeks its own level." **B**. This tubing illustrates the variation of this principle that is applicable to the real world of artesian flow of groundwater.

Notable artesian examples

When deep wells were first drilled in London *circa* 1900, fountains at Trafalgar Square were flowing artesian wells (Fig. 10-14). But hydrostatic pressure has since declined, so now water must be pumped to the surface.

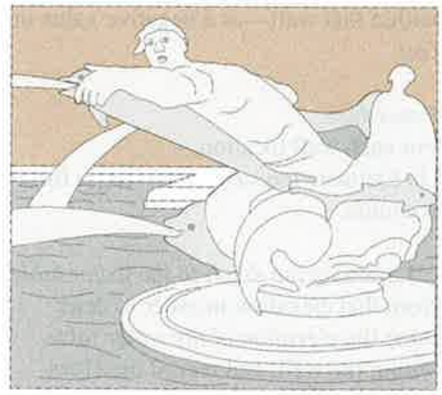


Figure 10-14. Fountains at Trafalgar Square are a graphic reminder of the famous London artesian basin.

Thermal waters at Hot Springs National Park, Arkansas, owe their heat to deep circulation through Devonian sandstone (Fig. 10-15). Normal geothermal gradient is sufficient to bring hot water spouting from springs along famed Bathhouse Row on picturesque Central Avenue.

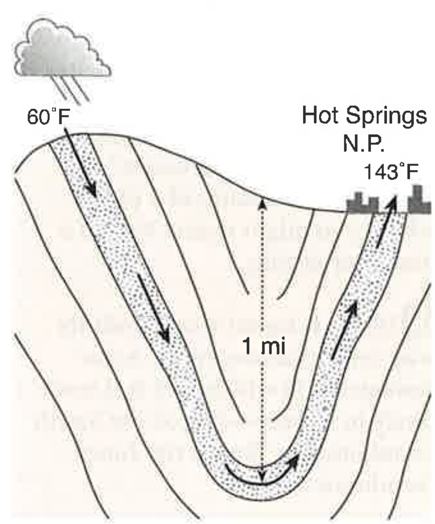


Figure 10-15. Within the folded rocks of the Ouachita Mtns., rainwater enters an artesian aquifer at 60°F, descends to a depth of one mile, and emerges at 143°F.

Details of confined aquifers—But first, a look back at **unconfined aquifers**. In Sections B and C, dealing with the anatomy and dynamics of water tables, the aquifers (i.e., saturated zones) are unconfined; i.e., the top of the zone of saturation (the water table) is free to rise and fall with the vagaries of climate. But in a confined aquifer, such is not the case. A **confined aquifer** is one in which water is prevented from rising and falling by relatively impermeable intervals of rock called **aquitards** (from Latin, meaning *retards water*). (A visual metaphor: Swiss cheese sandwiched between slices of dense bread.) Aquitards typically consist of shale—the most common and least permeable of all sedimentary rocks.

Note: Older literature made reference to *aquicludes* (i.e., intervals of rock that exclude water). But then it was acknowledged that all rocks are permeable to some degree, so the concept of *aquitard* was adopted.

A confined aquifer receives its water in an area where it intersects the land surface, called the **recharge area** (Fig. 10-16). Where a well is drilled into a confined aquifer, water rises toward the elevation of the water table in the recharge area, a condition called **artesian.** Water will not rise quite as high as the water table in the recharge area because (a) friction is associated with water moving through the aquifer, and (b) the water, even within a confined aquifer, is moving within the aquifer. The imaginary level to which water in a group of artesian wells tends to rise is the **potentiometric surface** (aka the *piezometric* surface.) In Figure 10-16 the potentiometric surface is *below* ground level in the vicinity of Wells A and B, so the two are **nonflowing artesian wells**. The potentiometric surface is *above* ground level in the vicinity of Well C, so that well is a **flowing artesian well.**

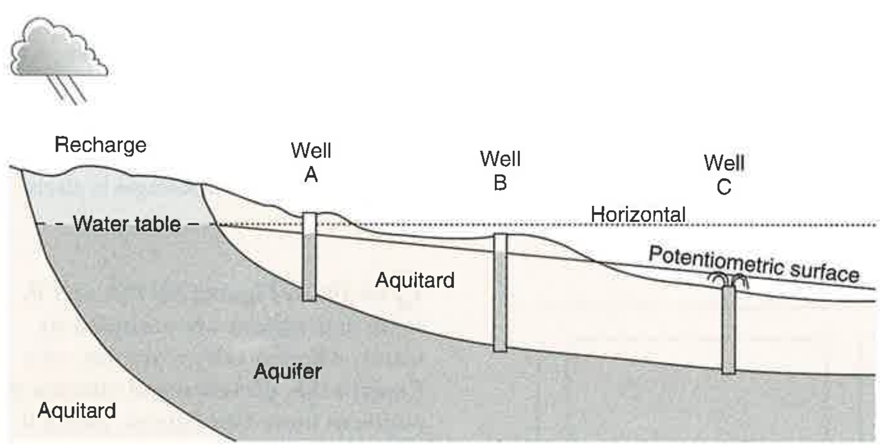


Figure 10-16. The dotted line is a horizontal projection of the water table in the recharge area. The solid line is the potentiometric surface, the level to which water tends to rise if free to move upward. Well A is near the recharge area, so the water in it rises almost to the elevation of the water table. Well B is farther away, so more friction accounts for the water's not rising as high as in Well A. The mouth of Well C is below the potentiometric surface, so it is a flowing artesian well.

Q10-17. On Figure 10-24 on Answer Page 176, label each well with the correct letter as described in the text beside that figure.

Mapping a potentiometric surface—Figure 10-25 on Answer Page 177 shows six wells on a contour map in the area of a confined aquifer. The map includes a second set of contours drawn on the aquifer's potentiometric surface. Flowing artesian wells should occur where the potentiometric surface is *higher* than ground elevation. Nonflowing artesian wells should occur where the potentiometric surface is *lower* than ground elevation.

Procedure:
At every place where an elevation of a surface contour line crosses a potentiometric contour line of the *same value*, place a small circle. Then connect the circles with a line. Ground elevations of wells on one side of that line will be *lower* than the potentiometric surface, and, thus, should be *flowing* artesian wells.

Q10-18. (A) Which of the six wells shown, all of which penetrated the confined aquifer, should be *flowing* artesian wells? (B) Darken the area of the map (like the swatch in the legend) in which the wells that penetrated the confined aquifer are *flowing* artesian wells.

P.S. Such a map is useful in assessing land use values. Who wants a building site in a swamp?

F. Perched water tables and basement flooding.

Where descending surface water encounters an aquitard, it can accumulate as a local saturated zone with its own local **perched water table** (Fig. 10-17). This is one of the more common explanations for the occurrence of springs.

In areas of flat-lying sedimentary rocks where relatively impermeable shales alternate with permeable sandstones and limestones, perched water tables (and related springs) are common.

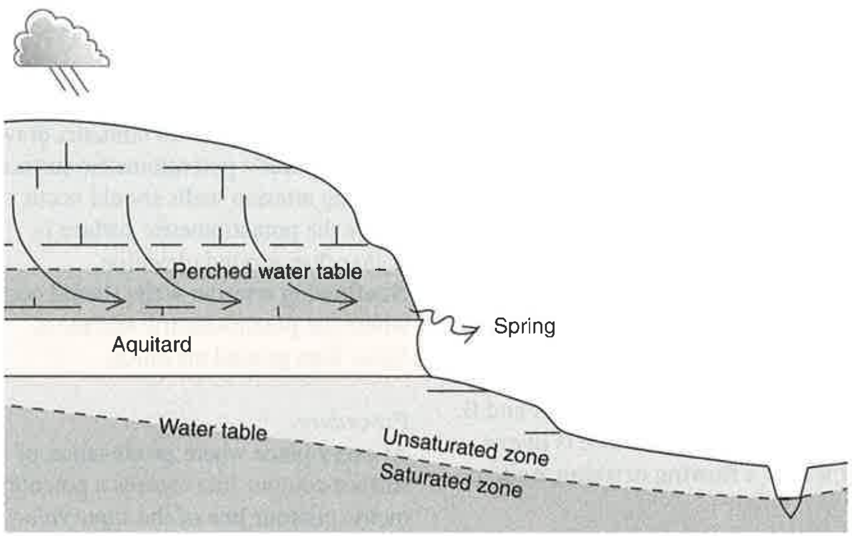


Figure 10-17. Here, descending water is deflected by an aquitard to emerge as a spring. The general water table is some deeper.

Trouble for construction sites—Perched water tables can cause water in the basement for homes and buildings. At St. Louis University, excavation for two buildings breached a perched water table (Fig. 10-18). The only remedy: installation of sump pumps to lift the water out and away to the nearest storm drains.

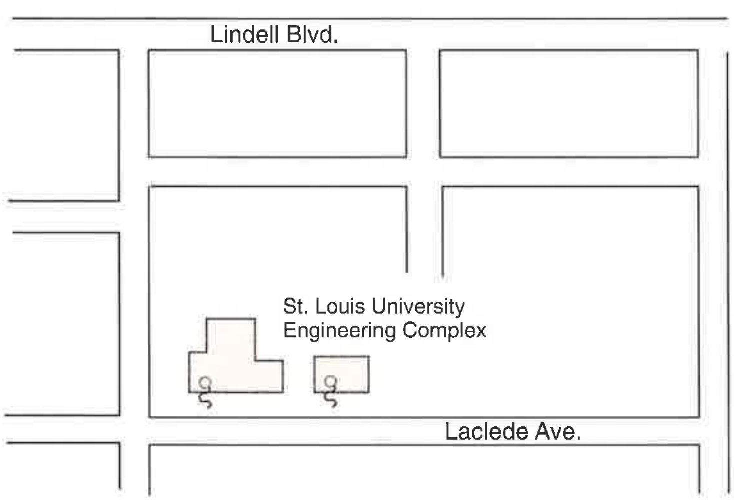


Figure 10-18. Perched water tables can cause springs in basements. *(The map symbol for a spring is a small circle with a wiggly tail.)*

Ephemeral ponds occur where water is temporarily prevented from sinking into the zone of saturation by relatively impermeable soil or sediments (Fig. 10-19). Such ponds can disappear by either drying up or eventually sinking into the unsaturated zone.

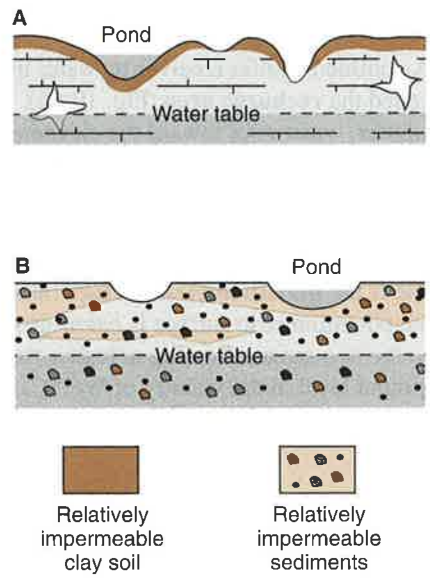


Figure 10-19. **A**. An ephemeral pond within a sinkhole formed by the collapse of a cave roof. **B**. An ephemeral pond within a depression typical of landscapes in glacial deposits.

Q10-19. In Figures 10-19A and B, some depressions are occupied by water, whereas others are dry. (A) Explain this presence and absence of ponds in these two figures. (Keep it simple.) (B) If these ponds were *perennial* ponds intersecting a water table, how would the presence/ absence of water in depressions in these two figures differ from that which is shown?

Reservoir liners and the Erin Brockovich case

A rancher can build a stock pond (with proper local permits) by simply bulldozing an earthen dam across a stream course. If stream flow is considerable, an added feature might be a metal tube or concrete spillway to handle excess water and prevent the water's topping the dam and washing it away. A second matter, especially common in cases of marginal water supply, is *leakage*, which can result in pond water vanishing into the unsaturated zone (Fig. 10-20).

Q10-20. Judging from what you learned from the previous page, how might one repair a leaking stock pond? *Hint*: There should be at least *three* steps in remedying this situation.

The Erin Brockovich case grew out of the undisputed fact that Pacific Gas and Electric used water containing an alleged carcinogen, chromium-6, to cool pipes that were heated by the compression of gas at its pumping station near Hinkley, California. (Chromium-6 was added to the water to minimize corrosion of the cooling towers.) A group of plaintiffs alleged that chromium-rich water was placed in evaporating ponds that lacked proper liners. PG&E admitted that there was, in fact, seepage of pond water into the groundwater, but disputed the alleged health effects of such water. Hydrologic and geochemical data marshalled by Erin Brockovich, legal assistant with the Masry law firm, which represented the plaintiffs, are not a matter of public record because the case was settled out of court.

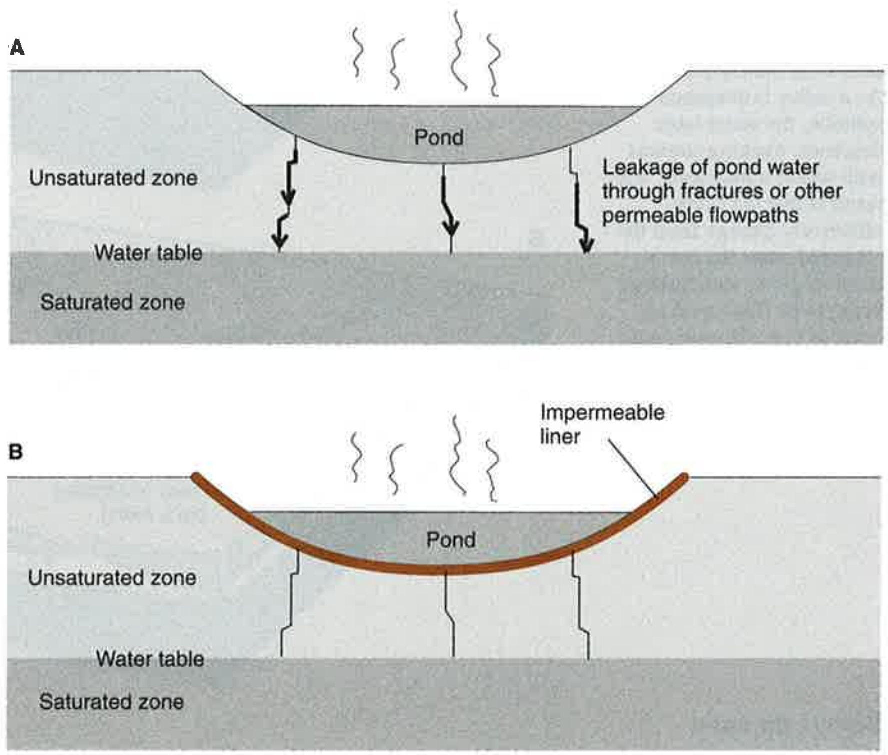


Figure 10-20. **A**. A pond without an impermeable liner might leak water into the unsaturated zone. **B**. The same pond with an impermeable liner loses water only through evaporation. Such liners are essential in the preparation of landfill sites.

G. Karst topography.

In humid areas where there is an abundance of limestones and/or dolostones (more rarely, gypsum or salt), solution of these relatively soluble rocks accounts for **caves** and cave-related features (Fig. 10-21). **Sinkholes** commonly develop through the collapse of cave roofs, and surface streams commonly disappear into underground passages, only to reappear as springs.

Topography characterized by caves, sinkholes, solution valleys, captured streams, and underground drainage is called **karst** topography, a name taken from the region of Slovenia where such features abound. Karst landscapes are in fact solution landscapes. Very little detrital sediment occurs in streams exiting karst landscapes.

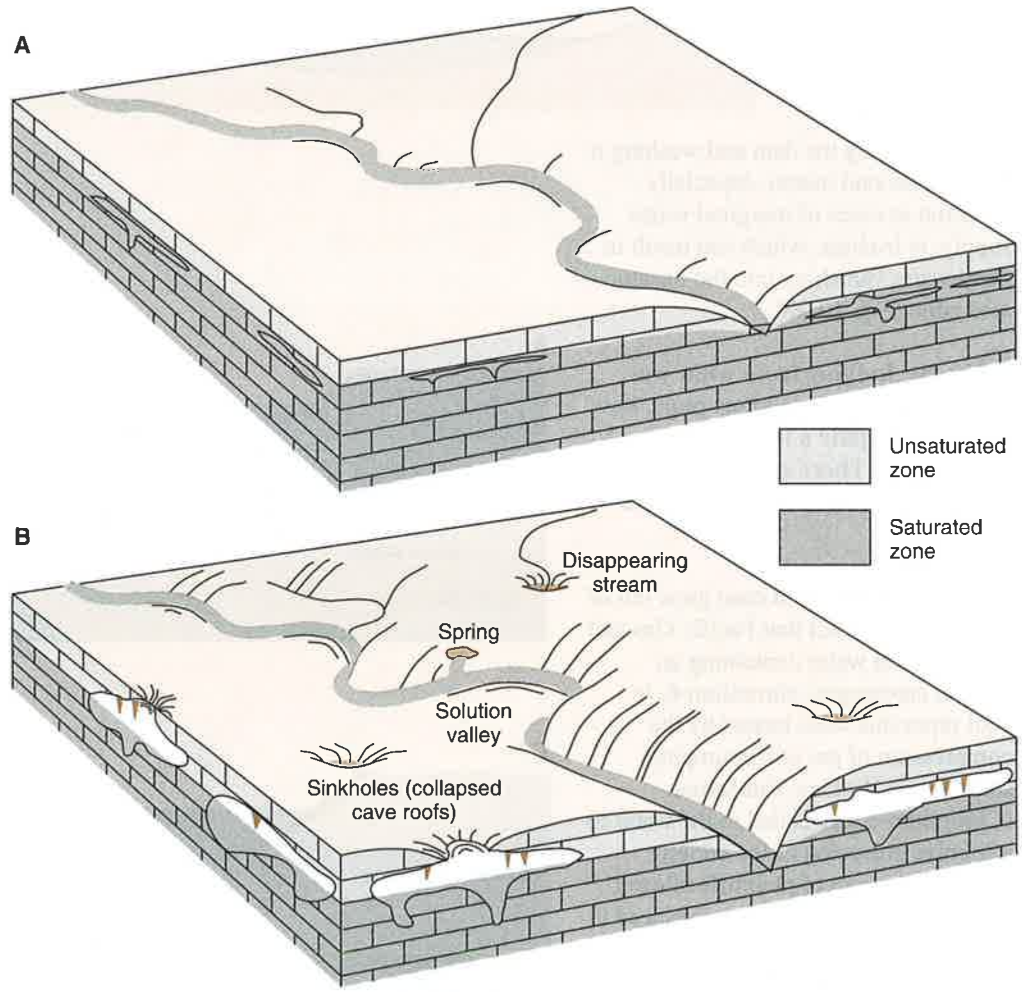


Figure 10-21. A. Incipient cave development in a karst area. The solution of limestone occurs within the uppermost part of the saturated zone (just below the water table) because it is there that carbonic acid (rainwater plus atmospheric and soil carbon dioxide) enters the saturated zone. **B.** As a valley is deepened by solution, the water table descends, tracking streams with which it intersects. The result is that the caves effectively emerge from the saturated zone, the caves cease to grow, and, instead, begin to be filled with an array of cave deposits (e.g., stalactites, stalagmites, columns, flowstone, curtains, cave pearls).

Beware the karst

Karst is a proverbial red flag in almost every imaginable kind of land use. In karst terrain, special care should be taken in an effort to contend with the following threats.

- Pollution of groundwater (practically instantaneous flow of waste effluent to wells and reservoirs)
- Catastrophic collapse of sinkholes (swallowing people and buildings)
- Construction problems (failure of foundations)

Of these several foregoing problems, the pollution of groundwater is the most universal.

The movement of groundwater through soil and sediments magically cleanses the water of ordinary waste such as that in municipal and home sewage systems—provided that the **residence time** within the soil and sediments is sufficiently long (i.e., measured in weeks and months). Not only does movement through soil and sediments filter solid particles, but slow movement typical of fine-grained media provides time for pathogenic bacterial and other microbial organisms to die.

In striking contrast is cavernous limestone, where solution channels can transport effluent effectively instantaneously.

Karst topography in stereogram

An example of karst topography occurs in Rock Bridge State Park, Missouri. Figure 10-22 is a stereogram that includes part of Rock Bridge Park. This area is at the northern margin of the Ozark Plateau, the most spectacular karst region between Mammoth Cave, Kentucky, and Carlsbad Caverns, New Mexico.

Q8-21. Examine Figure 10-22. At a glance the ponds might be mistaken for stock ponds. However, there is a relationship between one large pond and a highway that indicates that the pond was there before the highway, and, so, is probably a sinkholw. Explain this relationship.

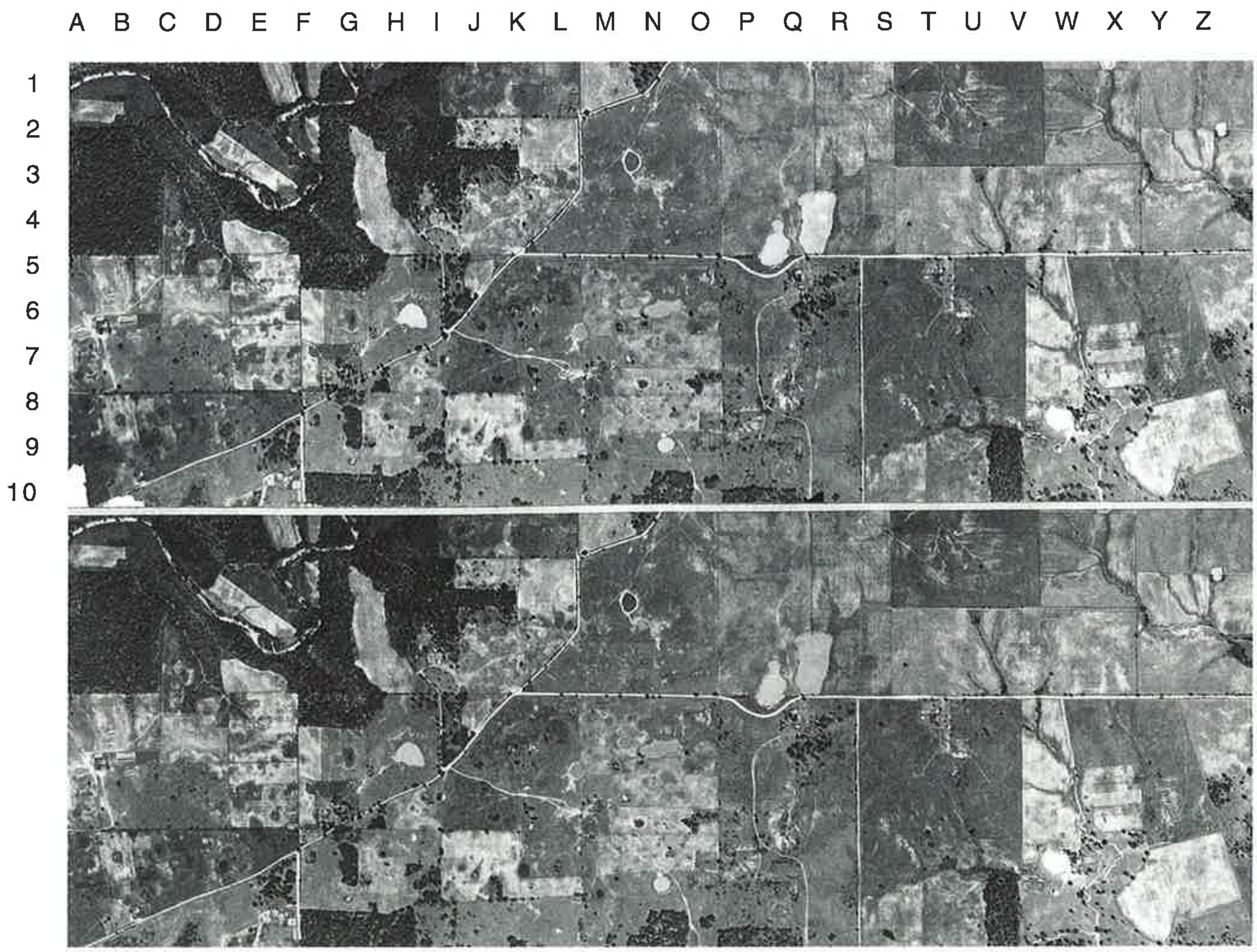


Figure 10-22. Sinkholes characterize karst topography at Rock Bridge State Park, Missouri. Some sinkholes are lined with relatively impermeable clay soil, so they can hold water in times of drought. In contrast, other sinkholes are without benefit of such natural liners, so they fail to retain rainwater for long periods of time.

Karst topography on a map—Putnam Hall, Florida, quadrangle

See the Putnam Hall, Florida, quadrangle on the facing page (p. 173)—a region underlain by limestone of the Florida Aquifer. A thin veneer of sandstone covers the surface, so the limestone largely goes unnoticed to residents of this community.

Countless sinkholes (some with ponds, some without) are marked by bundles of crudely concentric contours with hachures indicating depressions. Some of these bundles are pinched on opposite sides of depressions (creating a bird's eye appearance; e.g., at C-6 and E-3) that suggests solution of the limestone along fractures, aka **joints**.

Q10-22. Do these probable joints appear to be oriented northeast–southwest, or northwest–southeast?

Q10-23. Ther appears to be no through-flowing streams on this map. Why do you suppose that is?

Q 10-24. What is the elevation of the surface of (A) Chipco Lake? (B) Mariner Lake? (C) Junior Lake?

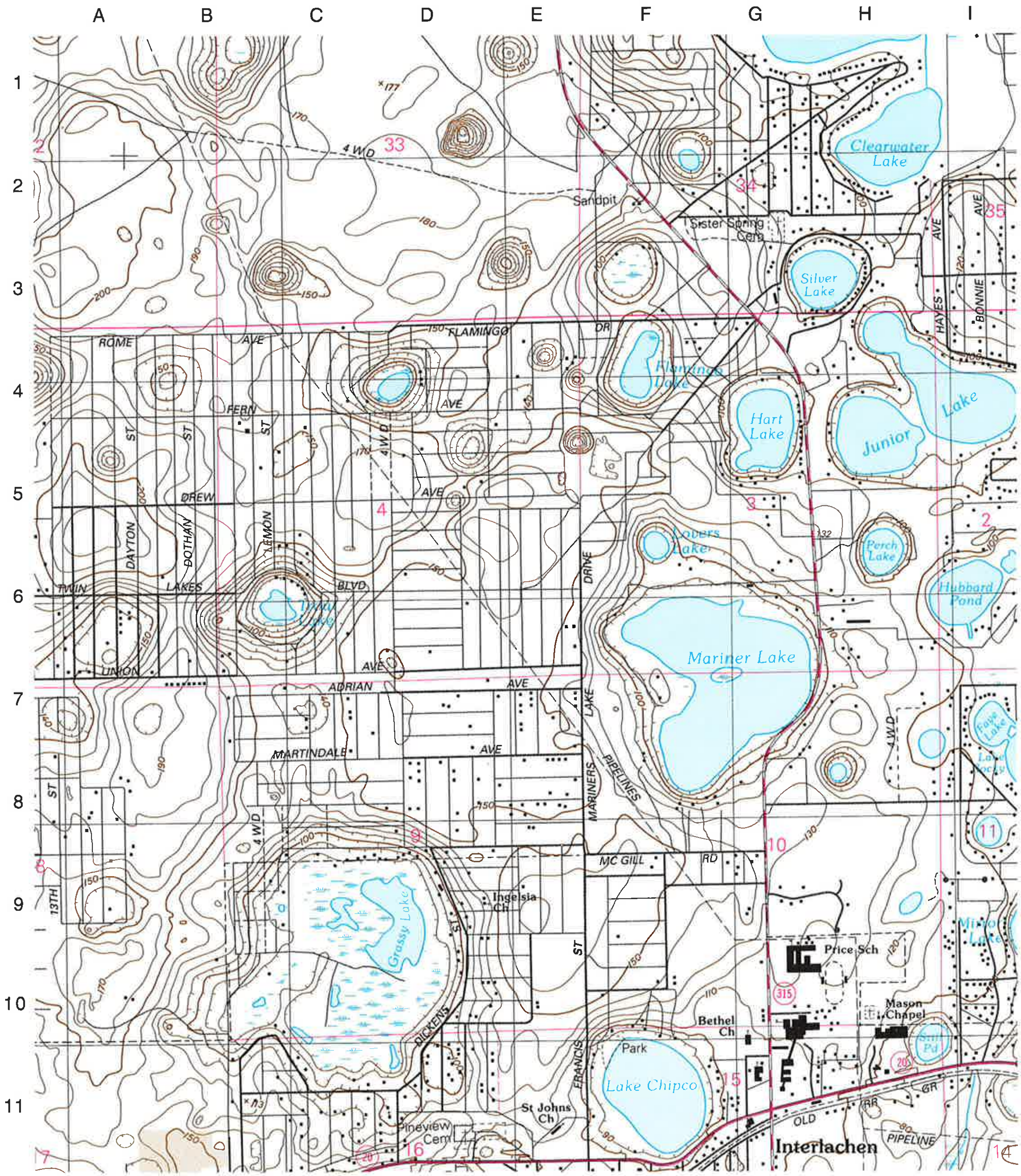
Q 10-25. Do water levels in these three lakes (as well as others) appear to be governed by the vagaries of spotty rainfall and random surface drainage, or do they appear to mark systematic elevations on a water table?

Q 10-26. (A) What is the elevation of the surface of Grassy Lake? (B) What is the distance (in feet) between the center of Chipco Lake and the center of Grassy Lake?

Q 10-27. Blue biodegradable fluorescent dye was once added to Chipco Lake. Twenty-four hours later the dye appeared in Grassy Lake. What is the approximate velocity of groundwater flow between these two lakes in feet per day?

Q 10-28. Would you expect to detect that same fluorescent dye in Mariner Lake? Why, or why not?

For a comprehensive short course in groundwater, go to EPA site http://www.epa.gov/seahome/groundwater/src/geo.htm.



Putnam Hall, Florida, 7 1/2' Quadrangle

SCALE 1:24,000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

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(Student's name) (Day) (Hour)

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(Lab instructor's name)

ANSWER PAGE

10-1

10-2 (A) (B)

10-3 (A)

(B)

(C)

(D)

10-4

10-5

10-6

10-7

10-8

10-9 ______________________

10-10 (A) __________ (B) __________

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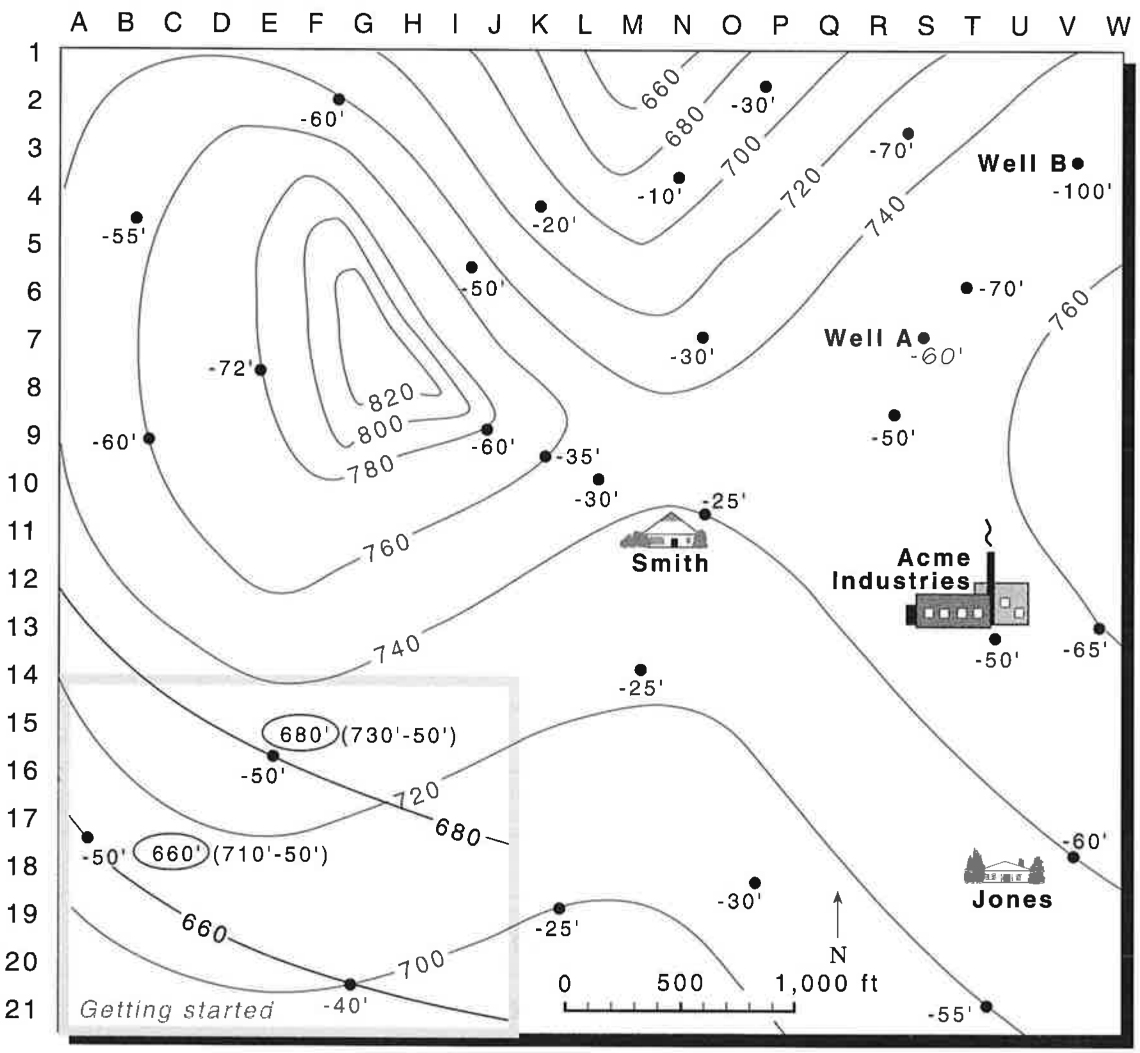

Figure 10-23. A contour map of a humid area. The contour interval is 20 ft. Each dot represents a water well with the depth to the water table indicated in feet with a negative value (e.g., -70').

10-16 ______________________

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10-17 (Label Fig. 10-24.) A—Possibly a flowing artesian well.
B—Possibly a nonflowing artesian well.
C—A well that might produce from an unconfined aquifer.

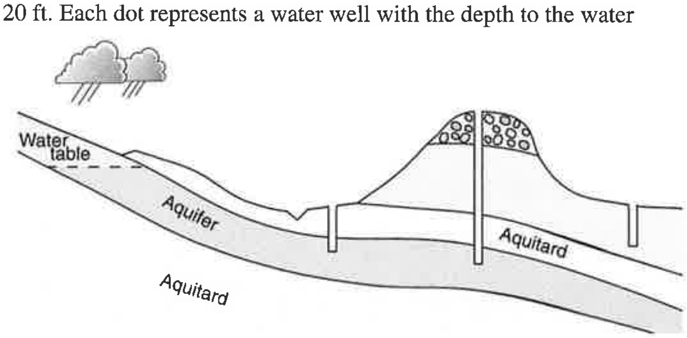

Figure 10-24. Three wells with different hydrologic settings.

10-18 (A) ______________________

10-19 (A) ______________________

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(B) ______________________

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10-20 ______________________

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10-21 ______________________

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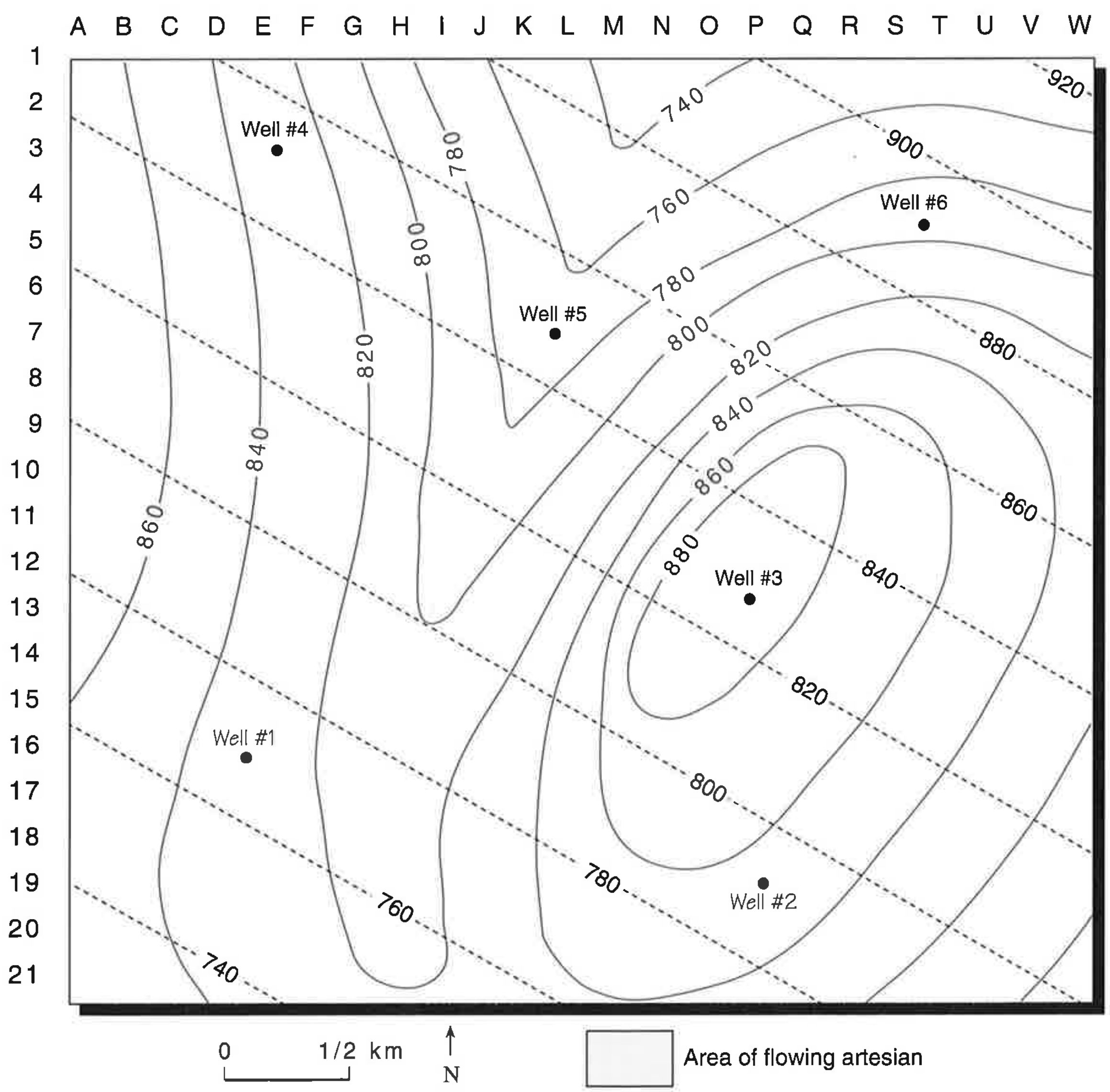

Figure 10-25. This is a contour map (with an interval of 20 ft) of an area underlain by a confined aquifer. The black dashed lines are drawn on the aquifer's potentiometric surface, also with a contour interval of 20 feet.

10-22 ______________________________

10-23 ______________________________

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10-24 (A)__________ (B)__________ (C)__________

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10-25 ______________________________

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10-26 (A) ______________________________

(B)______________________________

10-27 ______________________________

10-28 ______________________________

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11 waste and water

Topics

A. What are two ways in which water can complicate waste management?
B. What is porosity, and how can it be quantitatively measured in the laboratory? What is permeability, and how can it be qualitatively measured in the laboratory?
C. Of what two main components does a home septic system consist, and what are their functions? Within the leach field of a septic system, why should the odor of rotten eggs and the presence of cattails be matters of concern for a buyer? What complication does slope present in designing a septic drain field, and how is that complication mitigated? What is the preferred grain-size of soil in a septic drain field, and why? How is a soil percolation test conducted?
D. What are the three phases of a municipal sewage-treatment plant, and what goes on within each?
E. What is the anatomy of a simple landfill? What is the anatomy of a sanitary landfill?
F. What causes the Gulf of Mexico "dead zone"? How might its severity be mitigated?

A. Biggest player in waste management.

The biggest player in waste management is *water*.

Flood waters can drown waste repositories and broadcast waste from treatment plants—thereby disrupting operation of such facilities.

Water is the universal solvent that *mobilizes* toxic chemicals within all types of waste repositories.

Water operates within two broad domains—the *surface* and the *subsurface*.

The behavior of surface water is predictable. Water runs downhill. The carrying capacity of streams and rivers can be readily observed and measured. But the dynamics of subsurface water (aka **groundwater**) are more enigmatic because of the web of earth materials through which groundwater moves—a web characterized by **porosity** and **permeability** and their spatial distribution.

B. The nature of earth materials.

Porosity and permeability

Porosity is the ratio—*stated as a percentage*—of void space in a sample of sediment or rock to the total volume of that sample. The volume of void space plus the volume of solid material = 100% of the total volume of the sample.

Porosity can be either of two broad types.

Primary porosity develops at the time sediment and/or rock originates. Two common types of *primary* porosity:

(1) Pore spaces that develop among grains of clay, silt, sand, and pebbles at the time those grains are deposited

(2) Pore spaces that develop from gas bubbles within lava, producing irregular cavities before the rock crystallizes

Secondary porosity develops long after a rock originates. Two common types of *secondary* porosity:

(1) Pore spaces that develop as open space along fractures, which are common in all rocks

(2) Pores that develop as cavities produced by the dissolving of soluble rocks (e.g., limestone) by groundwater

Q11-1. Review: (A) Which of the drawings in Figure 11-1 illustrate primary porosity? (B) Which of the drawings illustrate secondary porosity?

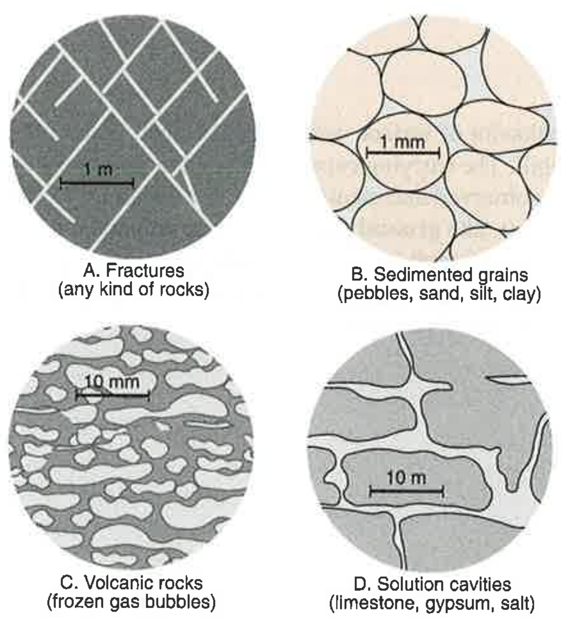


Figure 11-1. Common examples of primary and secondary porosity.

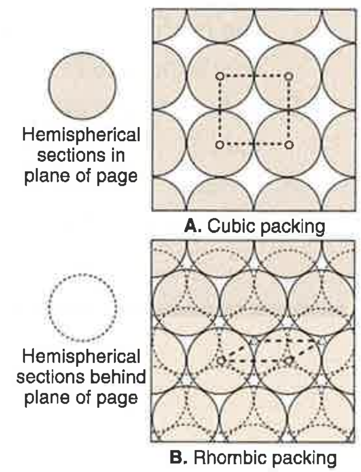
Intergranular porosity (Fig., 11-1B) is among the most common types of porosity that affect the behavior of groundwater. So let's examine some of its aspects.

The maximum theoretical intergranular porosity possible among spherical grains of equal size occurs in *cubic* packing, where imaginary lines connecting the centers of four contiguous grains form a cube (Fig. 11-2A).

Q11-2. Compute the porosity (i.e., percent of intergranular open-space volume) shown in Figure 11-2A. *Hint*: 4/3 • pi • r^3. (With Net connection, go to…)

http://www.1728.com/diam.htm.

Figure 11-2. These two views of equal diameter spheres show cubic and rhombic packing. Think 3-dimensionally.

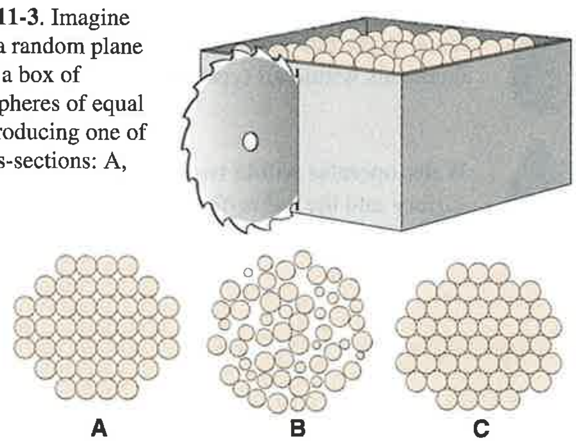


The idealized packing in Figure 11-2A rarely, if ever, occurs in nature. A more likely packing is the *rhombic* packing in Figure 11-2B (with its porosity of 25.95%).

In Figure 11-3, imaginary spheres of equal size have been poured into a box (so they are constrained by the bottom and four sides of the box), frozen in space, and sawed.

Q11-3. Which cross-section in Figure 11-3 is most likely to result from a random slice through a box of frozen spheres—A, B, or C?

Figure 11-3. Imagine sawing a random plane through a box of frozen spheres of equal size—producing one of the cross-sections: A, B, or C.



Porosity and permeability (cont.)

Does grain size affect porosity? Figure 11-4 shows cross-sections of two samples, each consisting of spheres of equal diameter in cubic packing.

Q11-4. How does porosity in Figure 11-4A compare with porosity in Figure 11-4B?

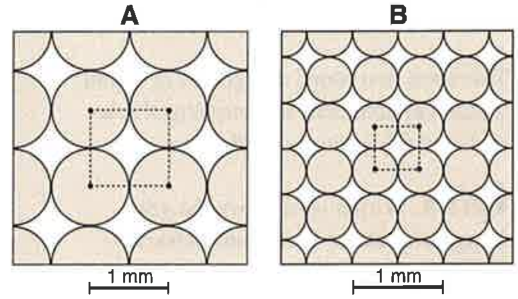


Figure 11-4. Illustration A consists of grains 1 mm in diameter, and illustration B consists of grains 1/2 mm in diameter. Each exhibits cubic packing.

Quantitatively measuring porosity

Q11-5. Refer to Figure 11-5. Write an outline of 7 or so steps you would take in quantitatively measuring the porosity in a sample of, say, the coarse spheres. *Hint*: For this mental exercise, you will need all of the items in the figure except the fine spheres, the fine screen, and the timer.

Qualitatively measuring permeability

Permeability is the fluid *transmissivity* of soil, sediment, or rock—i.e., the ease with which water moves through such material.

Q11-6. (A) Write an outline of the steps you would take in qualitatively measuring the permeability of each of two samples of spheres. (B) Which would you expect to find to be more permeable, the coarse spheres or the fine spheres? (C) Explain your expectation. *Hint*: You might include the terms *surface-area* and *friction* in your explanation.

Q11-7. In conclusion, (A) how do grain sizes of coarser spheres and finer spheres affect porosities? (B) How do grain sizes affect permeabilities?

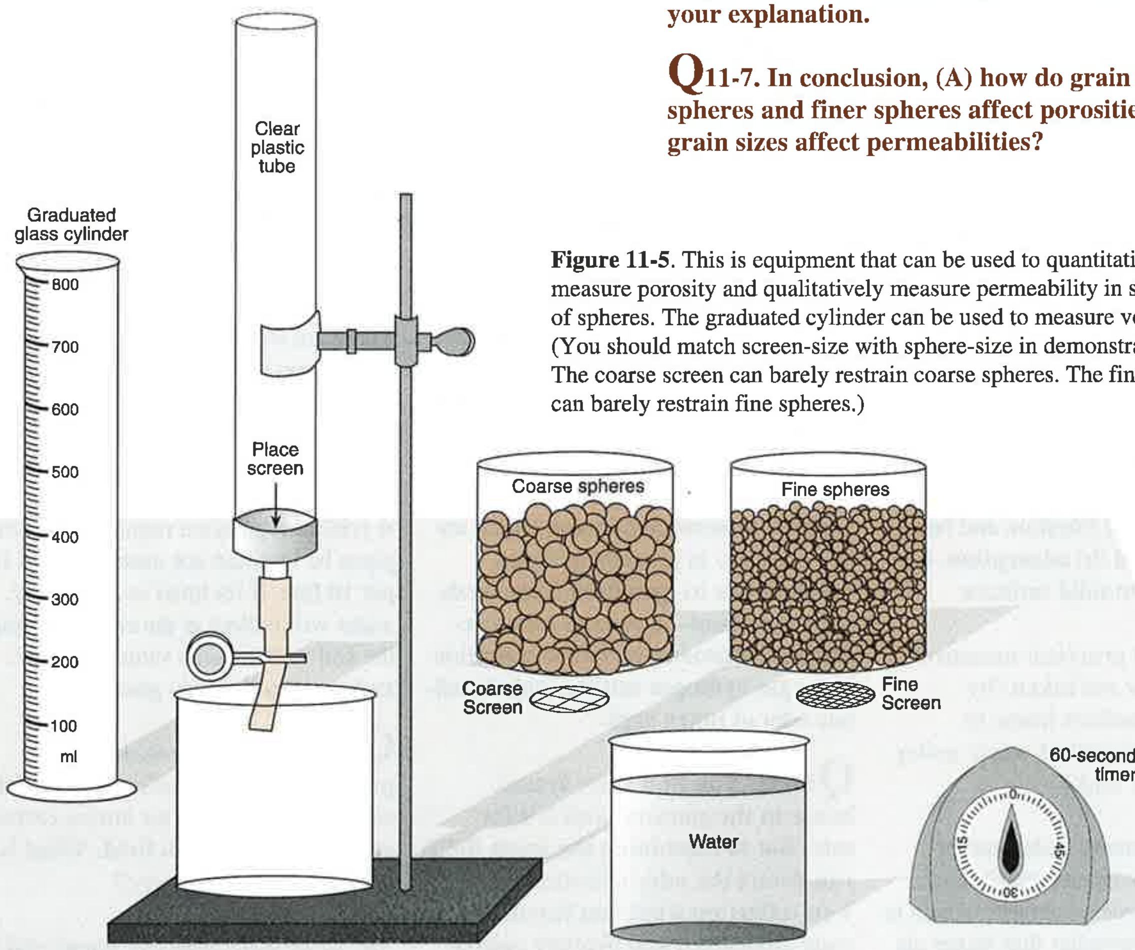


Figure 11-5. This is equipment that can be used to quantitatively measure porosity and qualitatively measure permeability in samples of spheres. The graduated cylinder can be used to measure volumes. (You should match screen-size with sphere-size in demonstrations. The coarse screen can barely restrain coarse spheres. The fine screen can barely restrain fine spheres.)

C. Home septic systems.

There are two broad categories of liquid waste: (a) *domestic and municipal sewage,* and (b) *industrial effluents.*

Q11-8. Which of the two do you imagine is more commonly characterized as *hazardous waste*?

Sewage includes all waste that exits a house, hotel, or apartment building through a pipe. On average, each person in the U.S. accounts for 550 liters of sewage per day.

Home septic systems

Approximately 25 percent of the U.S. population lives in areas where a home **septic system** is the only option for sewage disposal.

Q11-9. Migration from the family farm to the city reduced the number of rural septic systems, but a more recent demographic trend is adding septic systems. The total is now increasing. What is the colloquial term for this reverse migration? *Hint*: Growing cities are examples.

A septic system consists of two main components (Fig. 11-6):

(1) A tank in which solids settle out of the sewage, and which requires a pump-out every 5–7 years.

(2) A leach field that consists of perforated pipes that carry liquids away from the tank and into the soil. In passing through the soil, the liquid is purified by (a) physical filtration and bacterial processes; and (b) **adsorption**, the clinging of ions to solid surfaces.

Q11-10. What practical measure can be taken (or *not* taken) by residents of a modern home to minimize the amount of waste going into their septic tank?

In some areas, county codes and/or homeowners' covenants require that septic tanks include an aerator, which is a motor-driven propeller that mixes air with the liquid, thereby adding free oxygen that facilitates the activity of **aerobic** bacteria. Certain aerobic bacteria make their living through **oxidation** of organic waste, a process that is efficient in cleansing septic system liquids that otherwise can clog drain fields. In contrast, **anaerobic** bacteria, which are less effective in processing liquid waste, derive oxygen from compounds such as sulfates—a process called **reduction**. A product of sulfate reduction is the gas hydrogen sulfide, with its telltale odor of rotten eggs.

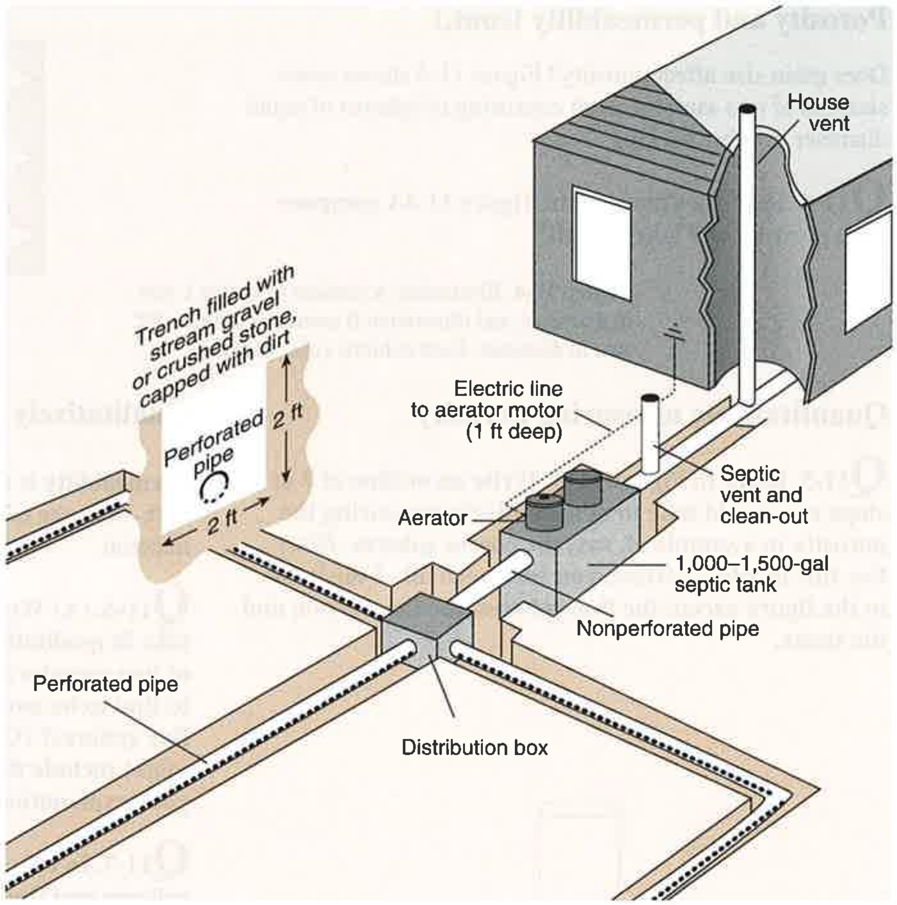


Figure 11-6. This is an example of a septic system with an aerator. The size of the tank depends upon the size of the house—as defined by the number of bedrooms. The total length of drain pipes is dictated by the size of the house and the condition of the soil.

Q11-11. You find your dream house in the country, and it's for sale. But in examining the leach field you detect the odor of rotten eggs. You reflect on what you learned in your environmental geology course, which is...?

There are strict specifications for the installation of a septic system, so the home builder should consult with county authorities early in order to assure an eventual occupancy permit.

A critical regulation requires that drain pipes be inclined not more than 1/4 inch per 10 feet. If inclined more steeply, water will collect at the end of the pipe, the soil will become saturated there, and water will rise to ground level.

Q11-12. You are considering purchasing a particular house with a septic system, but you notice cattails growing in the leach field. What is probably going on here?

Tip: *Direct water from downspouts and lawn sprinklers away from your drain field.*

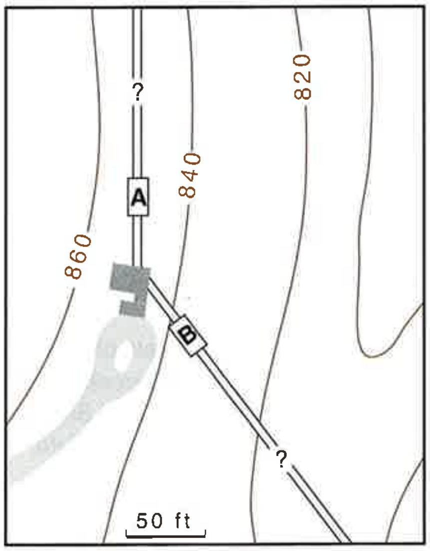


Figure 11-7. Two plans for drain pipes (A and B) appear on contoured topography.

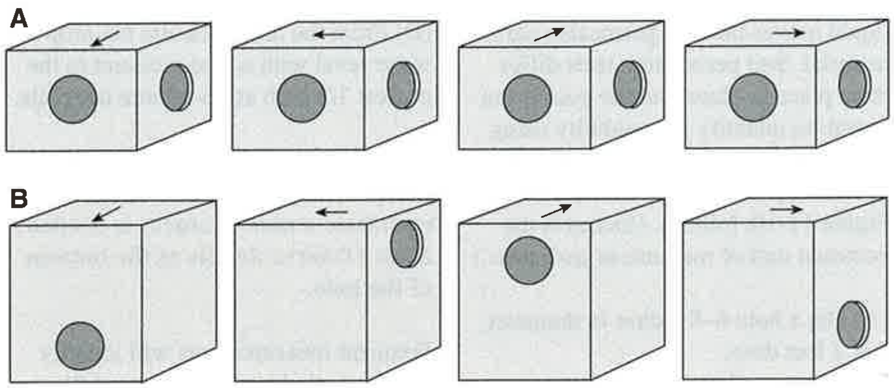


Figure 11-9. These are two of the types of boxes used in septic drain fields. Each is rotated (arrows) so as to show all four sides. Box A is called a distribution box. Box B is called a stepdown or drop-box.

Q11-13. At a glance, which drain pipe in Figure 11-7 is more advisable, A or B, and why?

Given the variety in distribution boxes (Fig. 11-9), there is a safe design for running a septic drain pipe downslope, where dictated by topography.

Q11-14. (A) How can a septic drain pipe be designed to safely run downslope as in Figure 11-8? (B) Sketch a cross-section running the length of the pipe in your design.

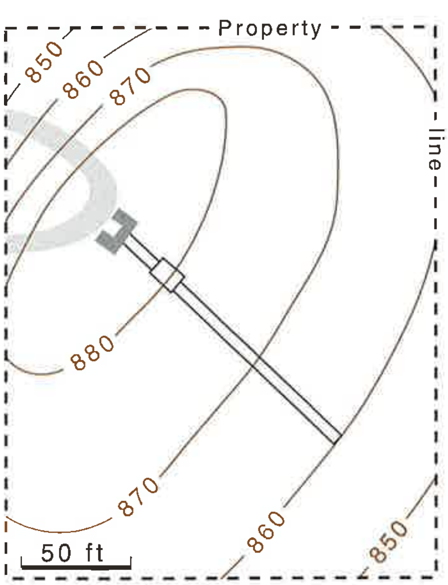


Figure 11-8. In this case, a drain pipe runs directly downslope, as shown by contours.

Q11-15. At a glance, which soil type in Table 11-1 would you intuitively expect to be the most efficient material for a septic drain field?

Table 11-1
Sediments and their porosity and permeability.

	Soil type	Absorption area needed (square meters per bedroom)
Decreasing grain size ↓	Gravel and coarse sand	6.5
	Fine sand	8.3
	Sandy loam	10.6
	Clayey loam	13.9
	Sandy clay	16.2
	Clay with sand or gravel	23.1
	Clay	Prohibited

After T. Dunne and L.B. Leopold, 1978.

Loam: Soil that consists of a mixture of clay, silt, sand, and organic matter. Absorption *area* will be explained later.

It turns out that the best soil for effective cleansing of sewage effluent is intermediate in its grain size. Reasons: (a) Bacteria require *time* to cleanse effluent liquids, and coarse sediments transmit effluent too fast. (b) Bacteria work better if they have *solid surfaces* (e.g., clay, silt, sand, pebbles) on which to attach themselves.

Q11-16. Consider two samples of soil—one fine-grained silt, the other coarse-grained sand. In which sample is there greater solid surface area per volume—the fine-grained silt or the coarse-grained sand? *Hint*: Recall your laboratory investigation of relative permeabilities.

But if grains are exceedingly small—as in clay—permeability is practically nil. So intermediate grain size provides an effective mix of permeability and surface area.

Testing soil percolation

Percolation is the process whereby a liquid moves through permeable earth material. Soil percolation tests differ from place to place, but the goal is universal: to quantify permeability using standardized procedures. An example of five steps, each of which is labeled in Figure 11-10, follows. (Inches is the common unit of measure in perk tests.)

(A) Dig a hole 6–8 inches in diameter and 2 feet deep.

(B) Drive a nail near the top of the hole.

(C) Fill the hole with water to the level of the nail and record the time.

(D) From the nail, measure the drop in water level with a tape measure to the nearest 1/8 inch at 10-minute intervals.

Q11-17. Why the nail? Why not just place a yardstick in the hole each time a measurement is needed? *Hint*: Observe details at the bottom of the hole.

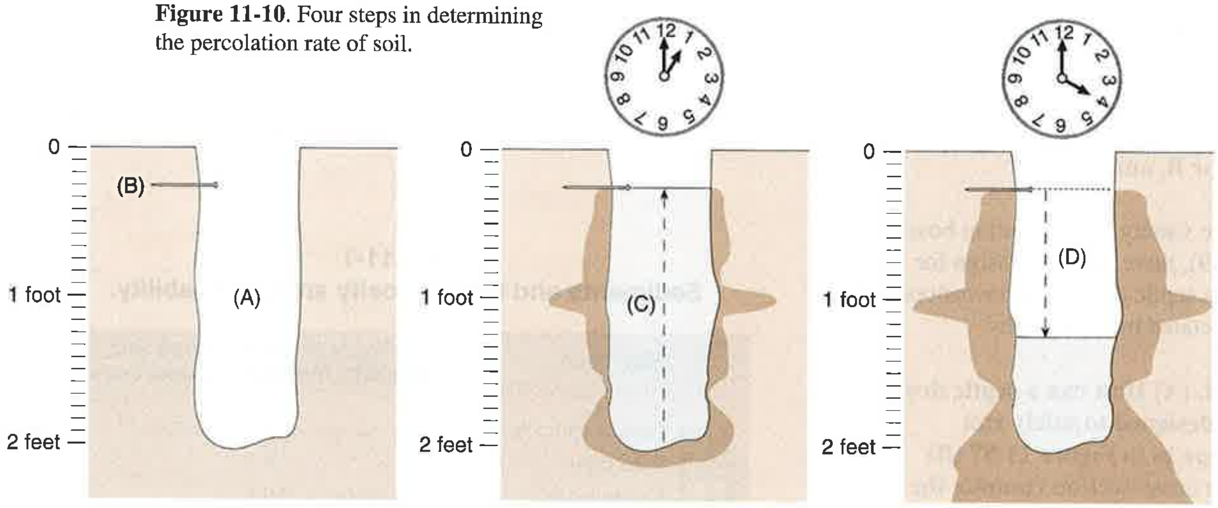
Frequent measurements will identify any vertical changes in permeability within the 2-foot interval.

Q11-18. Examine Figure 11-10. What is there about this illustration that visually indicates vertical differences in permeability within this 2-foot interval of soil?

(E) Calculate the rate of drawdown in *inches per hour*, which is the **percolation rate** of the earth material.

Perk-testing soil is most reliable during a wet period, so that true percolation is measured, rather than wicking. Several holes within the proposed drain field should be tested and then averaged together to derive a reliable perk rate.

Figure 11-10. Four steps in determining the percolation rate of soil.



Calculating trench and pipe requirements

Figure 11-11 is a typical graph showing *percolation rate* in inches per hour vs. *area required per bedroom*. But the cost basis for a trench and perforated pipe is *length*. So the question arises: How does one convert area to lineal feet?

As shown in Figure 11-6, a trench is typically two feet deep and two feet wide. By convention, "area" is that of trench bottom only, excluding areas of the sides of the trench. So the procedure for converting area (Fig. 11-11) to lineal feet is to simply divide the number of square feet by two.

The example shown in Figure 11-11 reveals the following:
A soil percolation rate of 5
= 180 sq ft, divided by 2
= 90 lineal feet of trench and pipe (required per bedroom)

Q11-19. How many total lineal feet of trench and pipe would be required if percolation were as illustrated in Figure 11-10, and the number of bedrooms were four?

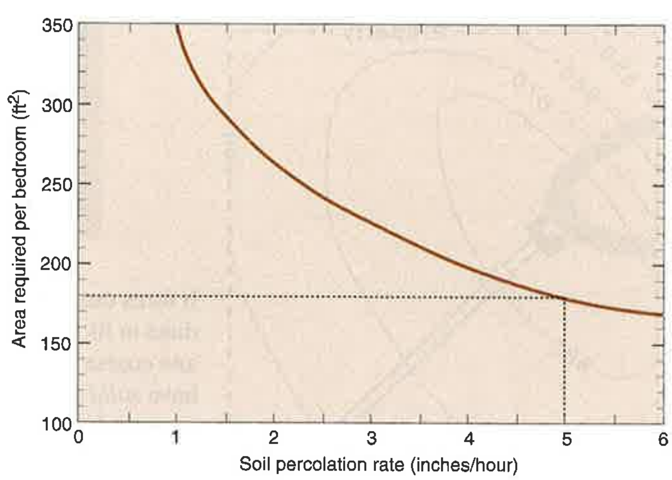


Figure 11-11. Graphs used in calculating the extent of a septic drain field typically plot percolation rate vs. area.

Incidentally, in some regions county regulators now require that a soil scientist provide a description of *soil morphology*, from which the length of trench and pipe is calculated.

D. Municipal sewage systems.

The U.S. Clean Water Act of 1977 set regulations dealing with discharges of contaminants into U.S. streams and rivers and established the Environmental Protection Agency (EPA) as the authority charged with setting standards for such discharges. This led to the development of the modern sewage-treatment plant, which operates in three phases (Fig. 11-12):

- *Primary phase*—Solids are screened and settle, then are physically removed.

- *Secondary phase*—Microbes break down biodegradable materials.

- *Tertiary phase*—Additional impurities are removed through carbon filtration,* evaporation, precipitation, and wetland microbial extraction of excess nitrogen.

Q11-20. Notice the aeration tank in the secondary phase of sewage treatment in Figure 11-12. Judging from what you have already learned in this exercise, (A) what's going on here? (B) What kind of bacteria are at work here?

**A handful of finely ground carbon can contain the surface area of one acre.*

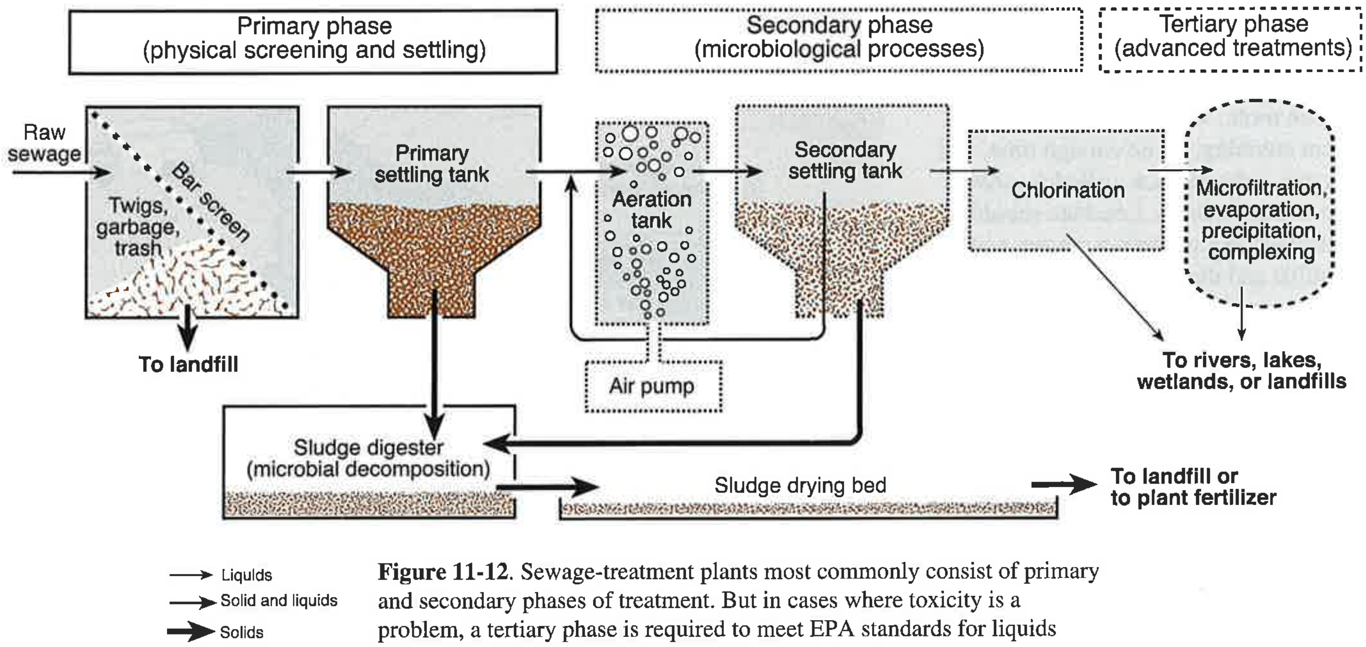


Figure 11-12. Sewage-treatment plants most commonly consist of primary and secondary phases of treatment. But in cases where toxicity is a problem, a tertiary phase is required to meet EPA standards for liquids released into the environment.

Sewage sludge (aka "Metrogro") can in some cases be superior to commercial fertilizers. Sludge can be heat-treated to kill harmful bacteria. And, it can be treated to remove toxic metals and chemicals, but that is costly. Untreated sludge is acceptable as a fertilizer where plant nutrients will not directly find their way into a food chain.

Q11-21. (A) Given a situation of untreated toxic sludge, name a couple of soil applications where toxins might *directly* (i.e., in one step) find their way to our dinner table. (B) Name a couple of soil applications where toxins might only *indirectly* (i.e., in a number of steps) find their way to our dinner table.

E. Municipal effluents.

Sanitary landfills

The minimal objective of a *simple landfill* (Fig. 11-13) is out-of-sight, out-of-mind. But *sanitary landfill* practices (Fig. 11-14) include the management of **leachate** and **gases**—effluents that are invariably produced within landfills.

Actually, it isn't the solid waste per se that presents problems in waste management. It's rainwater and groundwater that find their way in and out of landfills, mobilizing hazardous chemicals en route. Water can dissolve just about anything, given enough time, and it's this garbage juice, called *leachate*, that is troublesome. Leachate should be collected via a plumbing system within landfills and then treated either on-site or at a remote facility.

Landfill gases—produced by bacterial decomposition of organic compounds—consist largely of **methane** (CH_4) and **carbon dioxide** (CO_2). These greenhouse gases are colorless and odorless, but there is sufficient hydrogen sulfide (H_2S) present to impart the stench of sewer gas.

Q11-22. In the world of aerobic and anaerobic bacteria, (A) which do you suppose produces methane? (B) Which produces carbon dioxide?

Methane, aka swamp gas, is the gas typically associated with oil. And it is methane, when mixed with oxygen, that accounts for coal mine explosions. Landfill methane can be bled off via pipes and burned in gas turbines. At the Fresh Kills landfill on Staten Island, NY, the burning of methane provides electricity for thousands of homes.

Q11-23. Before burning landfill gas, a gaseous component should be extracted and discarded. Its name?

Selecting a landfill site

When selecting a landfill site, the most essential requisite is that of **dryness** (i.e., minimal surface water and minimal groundwater).

Q11-24. How about using inexpensive flat land adjacent to soccer fields and a babbling brook?

Q11-25. Why should test holes be drilled before choosing an appealing site in a rolling country setting?

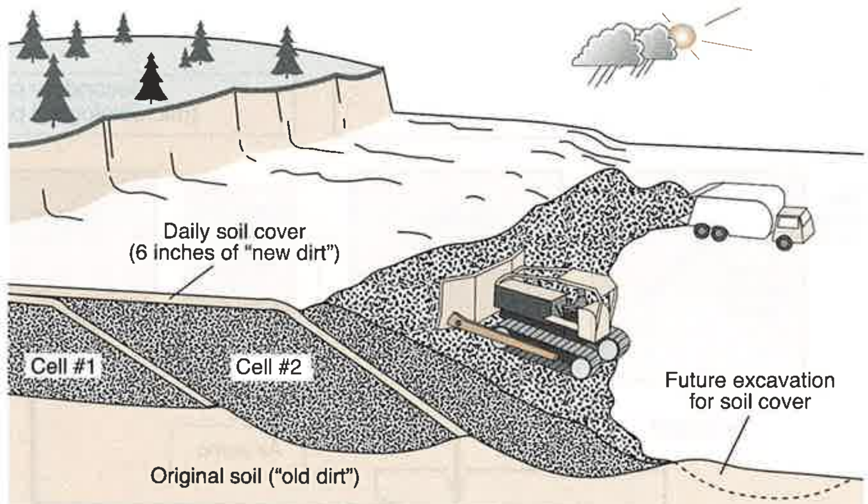


Figure 11-13. A simple landfill, designed to bury waste and recover (replant) the site. There are no provisions for managing leachate and gases.

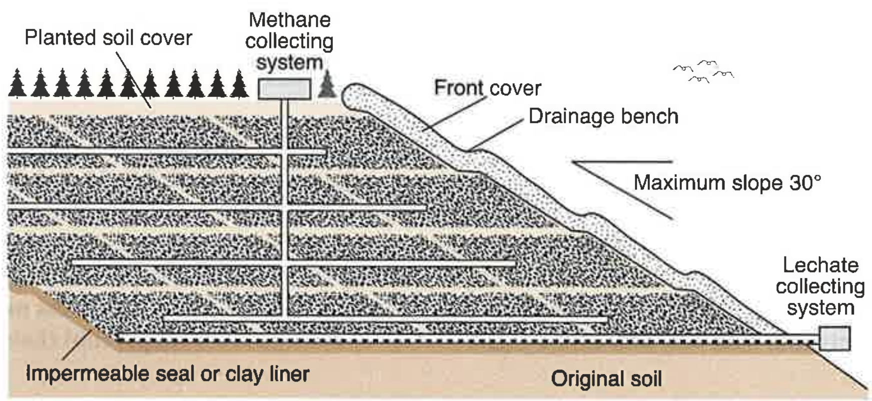
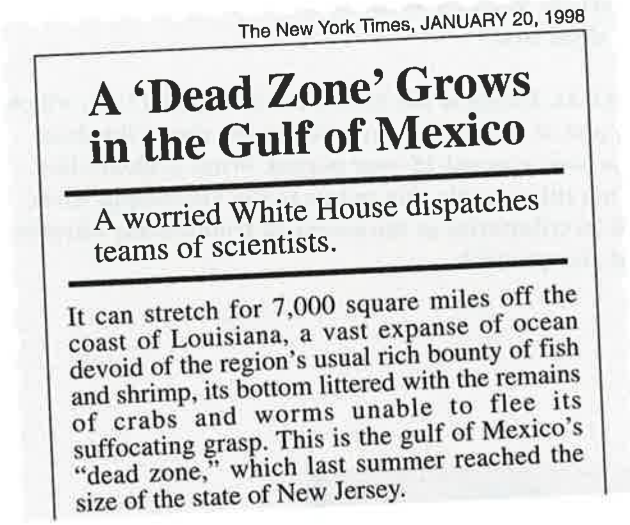


Figure 11-14. Elaboration of the sanitary landfill at Puente Hills, Los Angeles County, CA, with liner, leachate-collection system, and methane-collection system. *After B.W. Pipkin and D.D. Trent, 2001.*

Q11-26. Why do you suppose that there is a maximum slope angle dictated for the face of the landfill in Figure 11-14? *Hint*: This hazard is compounded in southern California by earthquakes.

Information about landfill gases is at http://www.epa.gov/outreach/lmop/products/factsheet.htm.

F. Gulf of Mexico "Dead Zone."



The New York Times, JANUARY 20, 1998

A 'Dead Zone' Grows in the Gulf of Mexico

A worried White House dispatches teams of scientists.

It can stretch for 7,000 square miles off the coast of Louisiana, a vast expanse of ocean devoid of the region's usual rich bounty of fish and shrimp, its bottom littered with the remains of crabs and worms unable to flee its suffocating grasp. This is the gulf of Mexico's "dead zone," which last summer reached the size of the state of New Jersey.

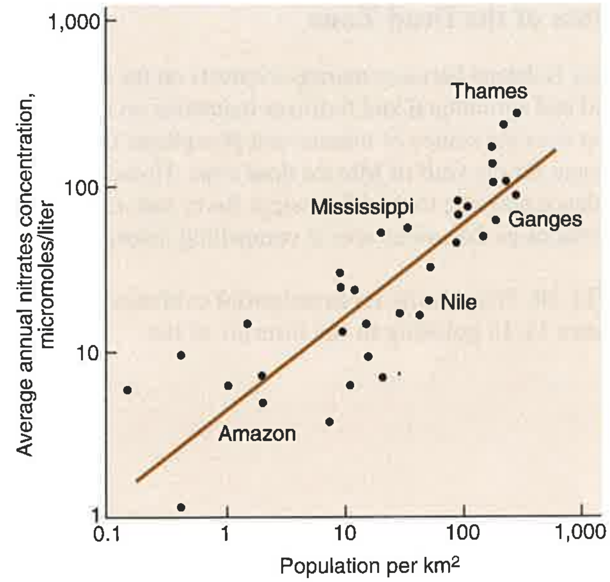


Figure 11-15. Human population density correlates with levels of pollutants in river waters. (*After B. Peierls, et al., 1991.*)

Mobile organisms flee, immobile organisms die. Such is the case within water in a state of **hypoxia** (Gr. *hypo*, under or less than—in this case, less than sufficient oxygen). Water is considered hypoxic when dissolved oxygen is less than 2 mg/L, which is about 20% of shallow sea water's capacity at mid-latitude salinity and temperature.

A number of aquatic environments can be naturally hypoxic, but coastal waters at the mouths of rivers are especially at risk owing to **anthropogenic** (human) activities (Fig. 11-15). The culprits appear to be nitrates and phosphates from developed lands. Perhaps you have noticed unsightly algae choking a suburban pond—algae that are nourished by runoff from fertilized lawns and shrubbery (a process called **cultural eutrophication**). Where such nutrients find their way into oceans, they promote similar overabundance of algae, which in turn promotes an overabundance of microscopic marine animals. Decay of such abundant organisms can deprive water of its dissolved oxygen. Such is the case in the Gulf of Mexico hypoxic **dead zone**, which has been growing since its discovery in the early 1980s (Fig. 11-16).

Q11-27. What is the apparent direction of flow of the longshore current along the Louisiana coast?

Water offshore of Louisiana consists of a surface layer of river water floating on a deeper layer of hypoxic water.

Q11-28. What is there about the compositions of river water and seawater that explains this stratification (i.e., layering) within water offshore of Louisiana (or offshore of any river, for that matter)?

Q11-29. (A) Why does hypoxia tend to develop in deeper water? *Hint*: What depletes deeper water of its oxygen? (B) Why does the hypoxic condition of deeper water tend to persist? *Hint*: What is the source of oxygen in seawater?

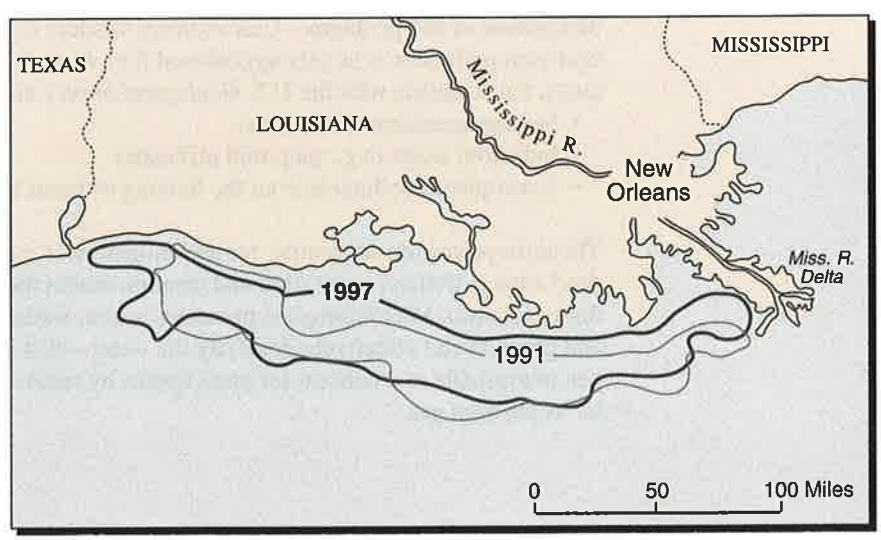


Figure 11-16. This map shows growth in the area of the hypoxic zone from 1991 to 1997. (*Based on data from Nancy Rabalais and her team at Louisiana Universities Marine Consortium.*)

Cause of the Dead Zone

There is debate between marine scientists on the one hand and agricultural and fertilizer industries on the other over the source of nitrates and phosphates that account for the Gulf of Mexico dead zone. However, evidence pointing to the Mississippi River and its tributaries as the source area is compelling indeed.

Q11-30. What is the circumstantial evidence in Figure 11-16 pointing to the interior of the American Midwest as the source of excessive nitrates in this dead zone?

Q11-31. Examine the histogram in Figure 11-17, which is a plot of the annual variation in the size of the dead zone over a recent 15-year period. What evidence lies within this graphic that points to the Mississippi River and its tributaries as the source of troublesome nitrates and phosphates?

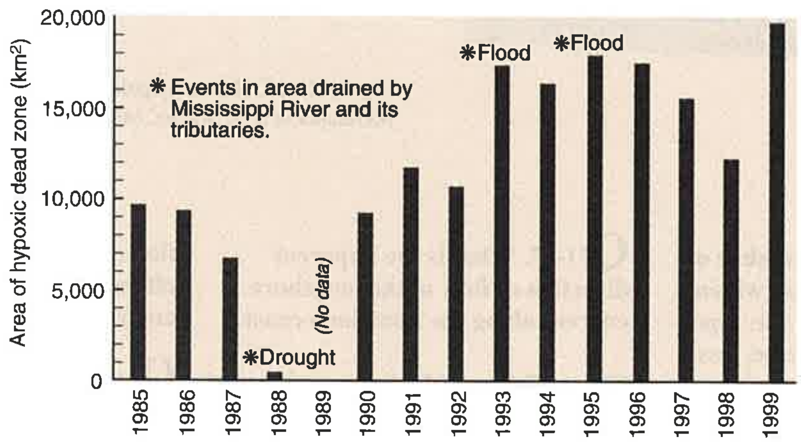


Figure 11-17. This histogram shows growth in the hypoxic dead zone year-by-year during the period 1985–1999. Added are three events that occurred within the Mississippi River drainage basin within this interval of time. (*From Nancy Rabalais and her team at Louisiana Universities Marine Consortium.*)

Mitigation of the problem—Conventional wisdom is that the source of upstream pollutants is largely agricultural (i.e., from fertilizers and manure), but scientists with the *U.S. Geological Survey* also list…

- Sewage treatment waste water
- Industrial waste (e.g., pulp mill effluents)
- Atmospheric pollutants from the burning of fossil fuels (e.g., NO_2)

The most promising suggestion for the mitigation of the Gulf of Mexico dead zone is wetland restoration and creation within the Mississippi River drainage basin. Microbiological processes within wetland surface water and groundwater effectively **denitrify** the water—that is, they make nitrogen unavailable as a nutrient for plant uptake by removing it from the water as nitrogen gas.

(Student's name) (Day) (Hour)

(Lab instructor's name)

ANSWER PAGE

11-1 (A) ______ (B) ______

11-2 ______

11-3 ______

11-4 ______

11-5 (a) ______

(b) ______

(c) ______

(d) ______

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