INTRODUCTION

Water that seeps into the ground is pulled downward by the force of gravity through spaces in the soil and bedrock (rock that is exposed at the land surface or underlies the soil). At first, the water fills just some spaces and air remains in the other spaces. This underground zone with water- and air-filled spaces is called the zone of aeration (Figure 12.1; also called the unsaturated zone or vadose zone). Eventually, the water reaches a zone below the zone of aeration, where all spaces are completely saturated with water. This water-logged zone is called the zone of saturation, and its upper surface is the water table (Figure 12.1). Water in the saturated zone is called groundwater, which can also be withdrawn from the ground through a well (a hole dug or drilled into the ground). Most wells are lined with casing, a heavy metal or plastic pipe. The casing is perforated in sections where water is expected to supply the well. Other sections of the casing are left impervious to prevent unwanted rock particles or fluids from entering the well.

Recall the last time that you consumed a drink from a fast-food restaurant (a paper cup containing ice and liquid that you drink using a plastic straw). The mixture of ice and liquid (no air) at the bottom of the cup was a zone of saturation, and your straw was a well. Each time you sucked on the straw, you withdrew liquid from the drink container just as a homeowner withdraws water from a water well. After you drank some of the drink, the cup contained both a zone of saturation (water and ice in the bottom of the cup) and a zone of aeration (ice and mostly air in the upper part of the cup). The boundary between these two zones was a water table. In order to continue drinking the liquid, you had to be sure that the bottom of your straw was within the zone of saturation, below the water table. Otherwise, sucking on the straw produced only a slurping sound, and you obtained mostly air. Natural water wells work the same way. The wells must be drilled or dug to a point below the water table (within the zone of saturation),
A. Groundwater Zones and the Water Table

Zone of aeration
Zone of saturation

Well B
Well A
Water table
Water table

Lake

Hydraulic gradient = \( \frac{h_1 - h_2}{d} = 10 \text{ ft/mi} \)

\( h_2 = 110 \text{ ft} \)
Well B

\( h_1 = 120 \text{ ft} \)
Well A

Elevation above sea level (foot)
Distance between wells (d)

B. Normal Water Table Contours and Flow Lines:
Note that flow direction is downhill to streams and the lake

Surface of water table

Flow line (arrow indicates direction of flow)

C. Water Table Contours and Flow Lines Changed by a Cone of Depression Developed Around a Pumped Well

Surface of water table

Cone of depression around pumped well

FIGURE 12.1 Water movement through an unconfined (water table) aquifer. A. Rainwater seeps into the zone of aeration (unsaturated zone, vadose zone), where void spaces are filled with air and water. Below it is the zone of saturation, where all void spaces are filled with water. Its upper surface is the water table. Water in the saturated zone is called groundwater, which always flows down the hydraulic gradient in unconfined aquifers. B. A water table surface is rarely level. Contour lines (contours) are used to map its topography and identify flow lines—paths traveled by droplets of water from the points where they enter the water table to the points where they enter a lake or stream. Flow lines with arrows run perpendicular to contour lines, converge or diverge, but never cross. C. A pumped well is being used to withdraw water faster than it can be replenished, causing development of a cone of depression in the water table and a change in the groundwater flow lines.
so that water can flow or be pumped out of the ground.

The volume of void space (space filled with water or air) in sediment or bedrock is termed porosity. The larger the voids, and the greater their number, the higher is the porosity. If void spaces are interconnected, then fluids (water and air) can migrate through them (from space to space), and the rock or sediment is said to be permeable. Sponges and paper towels are household items that are permeable, because liquids easily flow into and through them. Plastic and glass are impermeable materials, so they are used to contain fluids.

Permeable bedrock materials make good aquifers, or rock strata that conduct water. Some examples are sandstones and limestones. Impermeable bedrock materials prevent the flow of water and are called confining beds (or aquitards). Some examples are layers of clay, mudstone, shale, or dense igneous and metamorphic rock. But how does groundwater move through aquifers?

Confined aquifers are sandwiched between two confining beds, the groundwater fills them from confining bed to confining bed, so there is no water table. The weight of the groundwater (being pulled downward by gravity) in a confined space creates water pressure, like the pressure inside of a garden hose or kitchen sink faucet. If a confined aquifer is penetrated by a well, then water flows naturally from the well. When aquifers are not confined (i.e., they are unconfined aquifers), the groundwater establishes a water table just beneath the surface of the land (Figure 12.1). For this reason, unconfined aquifers are also called water table aquifers. If an unconfined aquifer is penetrated by a well, then the water must be pumped from the ground using a submersible pump lowered into the well on a cable. An electric line runs from the top of the well to the submersible pump, and a water hose runs from the submersible pump to the top of the well.

Groundwater in an unconfined (water table) aquifer is pulled down by gravity and spreads out through the ground until it forms the water table surface (such as the one in the drink cup full of crushed ice described above). You can see the water table where it leaves the ground and becomes the level surface of a lake (Figure 12.1A) or springs flowing from a hillside. However, because groundwater is continuously being replenished (recharged) upslope, and it takes time for the water to flow through the ground, the water table is normally not level. It is normally higher uphill, where water flows into the ground, and lower downhill, where water seeps out of the ground at a lake or springs. The slope of the water table surface is called the hydraulic gradient (Figure 12.1A)—the difference in elevation between two points on the water table (observed in wells or surfaces of lakes and ponds) divided by the distance between those points.

To better understand the topography of the water table in a region, geologists measure its elevation wherever they can find it in wells or where it forms the surfaces of lakes and streams. The elevation data is then contoured to map the water table contour lines (Figure 12.1B). Since water always flows down the shortest and steepest path it can find (path of highest hydraulic gradient), a crop of water on the water table surface will flow perpendicularly to the slope of the water table contour lines. Geologists use flow lines with arrows to show the paths that water droplets will travel from the point where they enter the water table to the point where they reach a lake, stream, or level water table surface. Notice how flow lines have been plotted on Figures 12.1B and 12.1C. In Figure 12.1C, notice how water is being withdrawn (pumped) from a well in an unconfined aquifer faster than it can be replenished. This has caused a cone-shaped depression in the water table (cone of depression) and a change in the regional flow of the groundwater. Thus, water table contour maps are useful for determining:

- Paths of groundwater flow (flow lines on a map), along which hydraulic gradients are normally measured.
- Where the water comes from for a particular well.
- Paths (flow lines) that contaminants in groundwater will likely follow from their source.
- Changes to groundwater flow lines and hydraulic gradients caused by cones of depression at pumped wells.

**PART 12A: CAVES AND KARST TOPOGRAPHY**

The term karst describes a distinctive topography that indicates dissolution of underlying soluble rock, generally limestone (Figure 12.2). Limestone is mostly made of calcite (a carbonate mineral), which dissolves when it reacts with acidic rainwater and shallow groundwater.

Rainwater may contain several acids, but the most common is carbonic acid (H_2CO_3). It forms when water (H_2O) and carbon dioxide (CO_2) combine in the atmosphere (H_2O + CO_2 → H_2CO_3). All natural rainwater is mildly acidic (pH of 5–6) and soaks into the ground to form mildly acidic groundwater. There, bacteria and other underground organisms produce carbon dioxide (CO_2) as a waste product of their respiration (metabolic process whereby they convert food and oxygen into energy, plus water and carbon dioxide waste). This carbon dioxide makes the groundwater even more acidic, so it easily dissolves the calcite making up the limestone by this reaction:

\[
\text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^{-}
\]

where calcite (calcium carbonate) dissolves in groundwater.
FIGURE 12.2 Stages in the evolution of karst topography, which forms by dissolution of soluble bedrock (usually limestone).
A typical karst topography has these features, which are illustrated in Figure 12.2 and visible on the US Topo orthoimage of the Park City, Kentucky Quadrangle in Figure 12.3.

- **Sinkholes**—surface depressions formed by the collapse of caves or other large underground void spaces.

- **Solution valleys**—valley-like depressions formed by a linear series of sinkholes or collapse of the roof of a linear cave.

- **Springs**—places where water flows naturally from the ground (from spaces in the bedrock).

- **Disappearing streams**—streams that terminate abruptly by seeping into the ground.

Much of the drainage in karst areas occurs underground rather than by surface runoff. Rainwater seeps into the ground along fractures in the bedrock (Figure 12.4), whereupon the acidic water dissolves the limestone around it. The cracks widen into narrow caves (underground cavities large enough for a person to enter), which may eventually widen into huge cave galleries. Sinkholes develop where the ceilings of these galleries collapse, and lakes or ponds form wherever water fills the sinkholes. The systems of fractures and caves that typically develop in limestones are what make limestones good aquifers.

Eventually, the acidic water that was **dissolving** limestone becomes so enriched in calcium and bicarbonate that it turns alkaline (the opposite of acid) and may actually begin **precipitating** calcite. Caves in karst areas often have **stalactites** (Figure 12.5), icicle-like masses of chemical limestone made of calcite that hang from cave ceilings (Figures 12.5, 6.8). They form because calcite precipitates from water droplets as they drip from the cave ceiling. Water dripping onto the cave floor also can precipitate calcite and form more stout **stalagmites**.

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**Activity 12.1**

**Karst Processes and Topography**

Conduct this activity to analyze karst processes and topography in Kentucky using an orthoimage and topographic map.

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**PART 12B: LOCATION AND MOVEMENT OF GROUNDWATER IN THE FLORIDAN LIMESTONE AQUIFER**

Figures 12.6 and 12.7 show karst features developed in the Floridan Limestone Aquifer in the northern part of Tampa, Florida. Notice in both figures that most of the lakes occupy sinkholes. They are indicated on Figure 12.6 with hachured contour lines (contours with small tick marks that point inward, indicating a closed depression). These depressions intersect the water table and the subjacent limestone bedrock, as shown in Figure 12.7. By determining and mapping the elevations of water surfaces in the lakes, you can determine the slope of the water table and the direction of flow of the groundwater here (as in Figure 12.1B).

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**Activity 12.2**

**Floridan Limestone Aquifer**

Analyze karst topography and groundwater flow through this important Florida aquifer in a region near Tampa, Florida.

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**PART 12C: LAND SUBSIDENCE HAZARDS CAUSED BY GROUNDWATER WITHDRAWAL**

Land subsidence caused by human withdrawal of groundwater is a serious problem in many places throughout the world. For example, in the heart of Mexico City, the land surface has gradually subsided up to 7.6 m (25 ft). At the northern end of California’s Santa Clara Valley, 17 square miles of land have subsided below the highest tide level in San Francisco Bay and must be protected by earthworks. Other centers of subsidence include Houston, Tokyo, Venice, and Las Vegas. With increasing withdrawal of groundwater and more intensive use of the land surface, we can expect the problem of subsidence to become more widespread.

Subsidence induced by withdrawal of groundwater commonly occurs in areas underlain by stream-deposited (alluvial) sand and gravel that is interbedded with lake-deposited (lacustrine) clays and clayey silts (Figure 12.8A). The sand-and-gravel beds are aquifers, and the clay and clayey silt beds are confining beds. In Figure 12.9, the water in the lower aquifer (“sand and gravel”) is confined between impermeable beds of clay and silt and is under pressure from its own weight. Thus, water in wells A and C rises naturally from the confined aquifer to the potentiometric (water-pressure) surface. Such wells are termed **artesian wells** (water flows naturally from the top of the well). The sand in the water table aquifer (Figure 12.9) contains water that is not confined under pressure, so it is an **unconfined aquifer** (also called a water table aquifer). The water in well B stands at the level of the water table and must be pumped up to the land surface.

Land subsidence (Figure 12.8B) is related to the compressibility of water-saturated sediments. Withdrawing water from wells not only removes
FIGURE 12.4  Looking east toward the Arkansas River from Vap’s Pass, Oklahoma (15 miles northeast of Ponca City). The Fort Riley Limestone bedrock crops out (is exposed at the surface) here. There is no soil, but plants have grown naturally along linear features in the bedrock.

FIGURE 12.5  Stalactites on part of the ceiling of Cave of the Winds, which has formed in Paleozoic limestones near Manitou Springs, Colorado.
water from the system, it also lowers the potentiometric surface and reduces the water pressure in the confined artesian aquifers. As the water pressure is reduced, the aquifer is gradually compacted and the ground surface above it is gradually lowered. The hydrostatic pressure can be restored by replenishing (or recharging) the aquifer with water. But the confining beds, once compacted, will not expand to their earlier thicknesses.

The Santa Clara Valley (Figure 12.10) of California is a very important center of agriculture that depends on groundwater for irrigation. It was one of the first areas in the United States where land subsidence due to withdrawal of groundwater was recognized. The Santa Clara Valley is a large structural trough filled with alluvium (river sediments) more than 460 m (1500 ft) thick. Sand-and-gravel aquifers predominate near the valley margins, but the major part of the alluvium is silt and clay. Below a depth of 60 m (200 ft), the groundwater is confined by layers of clay, except near the margins.

Initially, wells as far south as Santa Clara were artesian, because the water-pressure surface was above the land surface. However, pumping them for irrigation lowered the water-pressure surface 40–60 m (150–200 ft) by 1965. This decline was not continuous. Natural recharge of the aquifer occurred between 1938 and 1947. As of 1971, the subsidence had been stopped due to a reversal of the water-level decline.

Most wells tapping the artesian system are 150–300 m (500–1000 ft) deep, although a few reach 365 m (1200 ft). Well yields in the valley are 500–1500 gallons per minute (gpm), which is very high.

**Activity 12.3**

**Land Subsidence from Groundwater Withdrawal**

Explore land subsidence in the Santa Clara Valley in more detail.
FIGURE 12.8 Before (A) and after (B) extensive pumping of a well. Note in B the lowering of the water-pressure surface, compaction of confining beds between the aquifers, and resulting subsidence of land surface. Arrows indicate the direction of compaction caused by the downward force of gravity, after the opposing water pressure was reduced by excessive withdrawal (discharge) of groundwater from the well.

FIGURE 12.9 Geologic cross section illustrating an unconfined (water table) aquifer and a confined aquifer. Vertical scale is exaggerated.
A. Analyze Figures 12.4 and 12.5.

1. In the area photographed in Figure 12.4 there is no soil developed on the limestone bedrock surface, yet abundant plants are growing along linear features in the bedrock. What does this indicate about how water travels through bedrock in this part of Oklahoma?

2. If you had to drill a water well in the area pictured in Figure 12.4, where would you drill (relative to the pattern of plant growth) to find a good supply of water? Explain your reasoning.

3. How is Figure 12.5 related to Figure 12.4?

B. It is common for buildings to sink into newly formed sinkholes as they develop in karst regions. Consider the three new-home construction sites (labeled A, B, and C) in Figure 12.2, relative to sinkhole hazards.

1. Which new-home construction site (A, B, or C) is the most hazardous? Why?

2. Which new-home construction site (A, B, or C) is the least hazardous? Why?

3. Imagine that you are planning to buy a new-home construction site in the region portrayed in Figure 12.2. What could you do to find out if there is a sinkhole hazard in the location where you are thinking of building your home?

C. Study the orthoimage of the Park City (Kentucky) topographic map in Figure 12.3. Almost all of this area is underlain by limestone. The limestone is overlain by sandstone in the small northern part of this image (Bald Knob, Opossum Hollow) that is covered by dense dark green trees.

1. How can you tell the area on this orthoimage where limestone crops out at Earth’s surface?

2. Notice that there are many naturally formed circular ponds in the northwest half of the image. (The triangular ponds are surface water impounded behind dams constructed by people.) How did these natural ponds form, and how could you use their elevation to determine how groundwater flows through this region?

D. Refer to the map on the back of this page, a topographic map of the orthoimaged area in Figure 12.3.

1. Compare the map and orthoimage, then draw a contact (line) on the map that separates limestone with karst topography from forested, more resistant sandstone. Color the sandstone bedrock with a colored pencil.

2. Gardner Creek is a disappearing stream. Place arrows along all parts of the creek to show its direction of flow, then circle the location where it disappears underground. Circle the disappearing end of two other disappearing streams.

3. Notice that there are nine different springs that flow from the east-west trending hill on which Apple Grove is located. Label the elevation of each spring (where it starts a stream), then use the elevation points to draw a flow line with a large arrow to show the direction that water travels down the hydraulic gradient within the hill.

4. Find and label a solution valley anywhere on the map.

5. Notice that a pond has been constructed on the sandstone bedrock on top of Bald Knob and filled with water from a well. If the well is located on the dark blue edge of the pond, then how deep below that surface location was the well drilled just to reach the water table? Show your work.
Refer to Figure 12.6 (Sulphur Springs Quadrangle) and the “sketch map” on the back of this page.

A. On the sketch map, mark the elevations of water levels in the lakes (obtain this information from Figure 12.6). The elevations of Lake Magdalene and some lakes beyond the boundaries of the topographic map already are marked for you.

B. Contour the water table surface (use a 5-foot contour interval) on the sketch map. Draw only contour lines representing whole fives (40, 45, and so on). Do this in the same manner that you contoured land surfaces in the topographic maps lab.

C. The flow of shallow groundwater in the sketch map is at right angles to the contour lines. The groundwater flows from high elevations of the hydraulic gradient to lower elevations, just like a stream. Draw three or four flow lines with arrows on the sketch map to indicate the direction of shallow groundwater flow in this part of Tampa. The southeastern part of Figure 12.6 shows numerous closed depressions but very few lakes. What does this indicate about the level of the water table in this region?

D. Note the Poinsettia Sinks, a pair of sinkholes in the southeast corner of the topographic map (see Figure 12.6). Note their closely spaced hachured contour lines. Next find the cluster of five similar sinkholes, called Blue Sinks, about 1 mile northwest of Poinsettia Sinks (just west of the WHBO radio tower). Use asterisks (*) to mark their locations on Figure 12.8, and label them “Blue Sinks.”

E. On the sketch map, draw a straight arrow (vector) along the shortest path between Blue Sinks and Poinsettia Sinks. The water level in Blue Sinks is 15 feet above sea level, and the water level in Poinsettia Sinks is 10 feet above sea level. Calculate the hydraulic gradient (in ft/mi) along this arrow and write it next to the arrow on the sketch map. (Refer to the hydraulic gradient in Figure 12.1 if needed.)

F. On Figure 12.6, note the stream and valley north of Blue Sinks. This is a fairly typical disappearing stream. Draw its approximate course onto the sketch map. Make an arrowhead on one end of your drawing of the stream to indicate the direction that water flows in this stream. How does this direction compare to the general slope of the water table?

G. In March 1958, fluorescent dye was injected into the northernmost of the Blue Sinks. It was detected 28 hours later in Sulphur Springs, on the Hillsborough River to the south (see sketch map). Use these data to calculate the approximate velocity of flow in this portion of the Floridan Aquifer:

1. in feet per hour: __________  
2. in miles per hour: __________  
3. in meters per hour: __________

H. The velocities you just calculated are quite high, even for the Floridan Aquifer. But this portion of Tampa seems to be riddled with solution channels and caves in the underlying limestone. Sulphur Springs has an average discharge of approximately 44 cubic feet per second (cfs), and its maximum recorded discharge was 165 cfs (it once was a famous spa). During recent years, the discharge at Sulphur Springs has decreased. Water quality has also worsened substantially.

1. Examine the human-made structures on Figure 12.6. Note especially those in red, the color used to indicate new structures. Why do you think the discharge of Sulphur Springs has decreased in recent years?

2. Why do you think the water quality has decreased in recent years?

I. Name two potential groundwater-related hazards to homes and homeowners in the area that you can think of.
Sketch map of the area shown in Figure 12.6 (Sulphur Springs Quadrangle) and surrounding region.
A. On this map, solid brown contour lines show land surface elevation. Dashed blue lines represent the water-pressure surface (potentiometric surface) of a confined aquifer, as shown in Figure 12.9. This is the height to which water will rise in a well that is drilled into the aquifer.

1. Find and connect the points on the map where the two sets of contour lines have the same elevation.
2. Shade in the area on this map where wells would flow at the land surface without having to be pumped (i.e., where wells would be artesian).

B. Santa Clara Valley, California.
1. In Figure 12.10 on page 283, where are the areas of greatest subsidence in the Santa Clara Valley?

2. What was the total subsidence at San Jose (Figure 12.11) from 1934 to 1967? _______________ feet

<table>
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<td>1967</td>
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</tr>
</tbody>
</table>

**FIGURE 12.11** Subsidence at benchmark P7 in San Jose, California.
3. What was the average annual rate of subsidence for the period of 1934 to 1967 in feet per year? __________ feet/year

4. Analyze Figure 12.10. At what places in the Santa Clara Valley would subsidence cause the most problems? Explain your reasoning.

5. Would you expect much subsidence to occur in the darker shaded areas of Figure 12.10? Explain.

6. By 1960, the total subsidence at San Jose had reached 9.0 feet (Figure 12.11). What was the average annual rate of subsidence (in feet per year) for the seven-year period from 1960 through 1967? (Show your work.)

7. Refer to Figure 12.12 below. What was the level of the water in the San Jose well in:
   a. 1915? ________ feet
   b. 1967? ________ feet

**FIGURE 12.12** Hydrograph showing changes of water level in a well at San Jose, California.
8. During what period would the San Jose well have been a flowing artesian well? Explain.

9. How can you explain the minor fluctuations in the hydrograph (Figure 12.12) like those between 1920 and 1925?

10. In Figure 12.12, the slope of a line joining the level of the land surface in 1915 with subsidence that had occurred by 1967 gives the average rate of subsidence for that period. How did the rate of subsidence occurring between 1938 and 1948 differ from earlier rates?

11. Adolf Hitler came into power as head of the National Socialist German Workers’ Party (Nazi Party) in 1933 and German Troops invaded Austria in 1938 and Poland in 1939 to initiate World War II. Japan invaded China in 1932, withdrew, and then launched a full-scale invasion of China in 1937. The United States officially entered World War II in 1941 (when Japan attacked Pearl Harbor). Explain how these world events could have caused the change in subsidence rates noted in Question 10.

12. Subsidence was stopped by 1971. What measures might have been taken to accomplish this?