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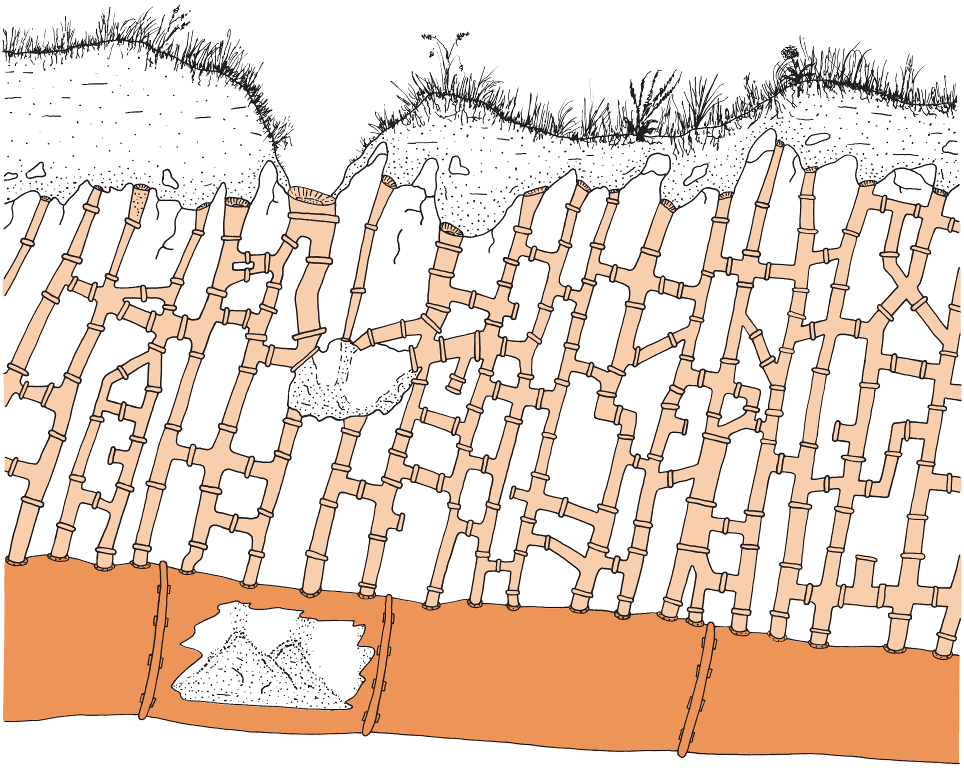
Educational Series 11

Sinkholes in Pennsylvania



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FRONT COVER: The sketch on the front cover likens the natural breaks in limestone bedrock to a plumbing system. Surface water permeates the soil and travels through the breaks (smaller pipes) to the water table, which is represented by the top of the large pipe at the bottom of the sketch. A sinkhole forms over one of the pipes where the overlying soil has collapsed.

Educational Series 11

SINKHOLES IN PENNSYLVANIA

by William E. Kochanov

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SINKHOLES IN PENNSYLVANIA

by William E. Kochanov

Introduction

What are sinkholes? A farmer may view them as naturally forming holes that occasionally open up in the fields. Some people see sinkholes as sites for dumping trash. In urban areas, the sudden appearance of a sinkhole is a hazard that can disrupt utility services, hamper transportation, and cause severe damage to nearby structures. In anyone's backyard, a sinkhole is a safety risk to the curious who may find it exciting to explore this new "cave."

Information about sinkholes in Pennsylvania is pertinent to planning for future land development and for the protection of private and public property. It also provides a fascinating story for those who are interested in learning more about geologic conditions and earth processes.

The first 17 pages of this booklet contain an explanation of how sinkholes develop. In order to tell the sinkhole story, it is important to discuss a number of related geologic disciplines. The words used to describe sinkholes and these disciplines may be a bit unfamiliar. However, general explanations are given throughout the booklet to help clarify their meanings. Key words are printed in **bold** type for emphasis.

The remaining sections, starting with "Sinkholes in the Urban Environment" (page 17), deal with sinkholes and their impact on our environment. This includes recognition of subsidence features and sinkhole repair.

As you read, keep in mind that the formation of sinkholes is part of the natural weathering process and that this process has worked on the limestone bedrock over a very long period of time.

What are Sinkholes?

A **sinkhole** is a subsidence feature. **Subsidence** is the downward movement of surface material; it involves little or no horizontal movement. Subsidence occurs naturally due to the physical and chemical weathering of certain types of **bedrock** (solid rock that underlies soil or other unconsolidated surface material). Subsidence can also occur as a result of underground mining, excessive pumping of groundwater, or subsurface erosion due to the failure of existing utility lines. All of these can produce surface features that appear similar, but not all are naturally occurring. Some are solely the result of human activities.

Subsidence and the Old Farmhouse

Subsidence usually occurs slowly over a relatively long period of time. Imagine an old, abandoned, two-story, wooden farmhouse (Figure 1). Over a period of time, the wooden crossbeams and joists that support the house dry and begin to deteriorate. As time goes on, the framework that underlies the floors loses its integrity and the floors sag. If this process is allowed to continue, the house eventually collapses due to the removal of the wooden supports. Although the actual subsidence process may have taken a long time, the final collapse of the structure can occur very rapidly.

Figure 1. The slow removal of support for this abandoned Pennsylvania farmhouse has caused the roof and sidewalls to tilt and sag.

Sinkhole development is comparable to the subsidence process just described. In the case of a sinkhole, the support for the land surface is gradually removed over a period of time, causing the land surface to sag and finally collapse, leaving a hole or cavity as a result. Overlying surface materials then move downward into the hole.

The mechanism of subsidence can help define a sinkhole. A sinkhole can be defined as a subsidence feature that can form rapidly and is characterized by a distinct break in the land surface and the downward movement of surface materials into the resulting hole or cavity.

Questions now arise. What causes the underlying support for the land surface to be removed? Where does it go? Do sinkholes occur everywhere?

Case histories of sinkhole occurrence reveal that sinkholes occur only in certain parts of Pennsylvania. By examining these records, we learn that sinkholes are found in areas underlain by **carbonate bedrock**. Large areas of central and eastern Pennsylvania are underlain by this type of bedrock (Figure 2).

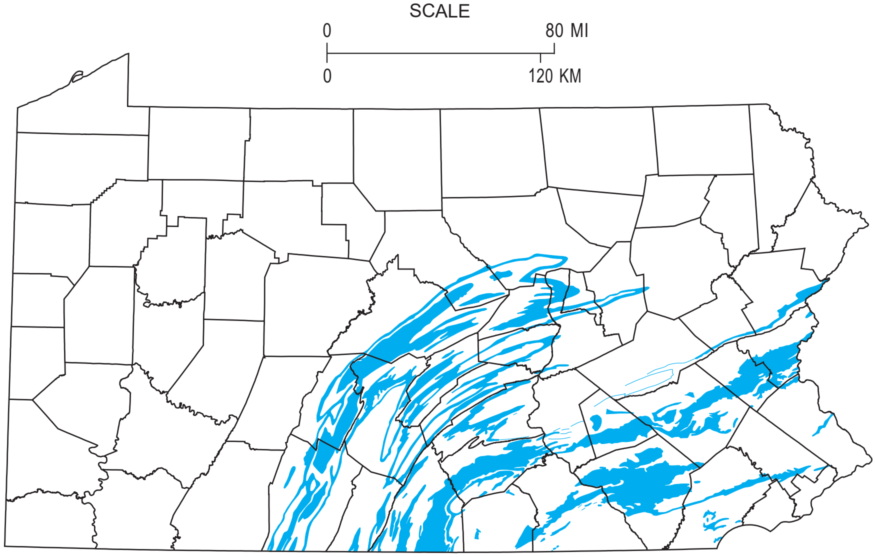

Figure 2. Areas (blue) where carbonate bedrock occurs at or near the surface in central and eastern Pennsylvania.

We can now add this information to the definition of a sinkhole. A sinkhole is a subsidence feature in an area underlain by carbonate bedrock. It can form rapidly and is characterized by a distinct break in the land surface and the downward movement of surface materials into the resulting hole or cavity.

What is Carbonate Bedrock?

Carbonate bedrock includes **limestone, dolomite,** and **marble**. Limestone and dolomite are **sedimentary** rocks, and marble is a **metamorphic** rock. Marble forms from limestone and dolomite when they are subjected to significant amounts of pressure, heat, or stress. It is present in Pennsylvania but not nearly as common as its sedimentary counterparts. Although sinkholes are associated with all of the carbonate rock types, limestone will be used as the primary example throughout much of this booklet.

Being a sedimentary rock, limestone is composed of grains of sediment, much like the individual sand grains that make up sandstone. The difference is that the sediment grains of limestone are chemically different and are derived from a different source.

Limestone is composed of **carbonate sediment**. Carbonate sediment is commonly found in relatively shallow, subtropical and tropical oceans around the world. A good example of a carbonate environment is a coral reef, such as the reefs that lie east of the Florida Keys, or the Great Barrier Reef of Australia.

Ocean-dwelling organisms such as corals, clams, and algae use the various elements within seawater to form hard, rigid skeletons composed of the carbonate mineral **calcite**. When these organisms die, their skeletons accumulate on the ocean floor as sediment. Movement of this sediment by wave action and ocean currents breaks it into smaller pieces and transports it from one place to another.

The sediment can be further reduced in size by the action of burrowing and grazing organisms. The sediment is ingested by these organisms, available nutrients are removed, and the undigested portion of the sediment is returned to the ocean floor.

How Does Carbonate Sediment Become Rock?

When building a brick wall, one needs some type of **cement,** such as mortar or concrete, to hold the bricks together. Similarly, **unconsolidated** (loose) sediment needs something to hold the grains together in order for it to become a rock. Limestone is the result of carbonate sediment being cemented together, generally by the mineral calcite. This cement can be produced by chemical reactions that take place in the fluids that move through the pore spaces of the sediment after deposition. Cementation is more likely to occur when fresh water, as opposed to ocean water, moves through the sediment.

Look at Figure 2 again, and note that there are many places in Pennsylvania where limestone is at or near the surface. You can see limestone in outcrops along the highway, in fields, or in quarries. How did the limestone get there if it was formed in the ocean?

The answer is that during the earth's history, the continents and the oceans have changed in shape and location. Shallow seas covered all of Pennsylvania in past geologic time and produced layer upon layer of carbonate sediments. These sediments were **lithified** (turned to rock), and the layers were later uplifted, tilted, fractured, folded, and twisted by the forces unleashed during the formation of the Appalachian Mountains. Erosion has worn away most of the ancient mountains, leaving the landscape as we see it today, including exposures of carbonate rock.

Chemical Composition of Carbonate Bedrock

The chief constituent of limestone is the mineral calcite. The chemical composition of calcite is **calcium carbonate** ($CaCO_3$). The rock dolomite is similar to limestone but has dolomite as the dominant mineral. Note that the term “dolomite” is used for both the rock and the mineral. The chemical composition of the mineral dolomite is **calcium magnesium carbonate** [$CaMg(CO_3)_2$]. The minerals calcite and dolomite both have CO_3 as part of their chemical formulas. CO_3 represents an electrically charged group of atoms known as the **carbonate ion**.

Generally, limestone and dolomite rocks are not made up entirely of calcite or dolomite. In addition to these minerals, they contain minor amounts of impurities—typically noncarbonate minerals. Among the more common noncarbonate minerals are clay, quartz, and pyrite.

Acids, Bases, and Limestone

Carbonate rocks have a shared chemical property; they can be dissolved by certain **acids**. When dilute hydrochloric acid (HCl) is placed in contact with limestone, it fizzes. The HCl reacts with the calcium carbonate, breaking it down into ionic form and releasing the gas **carbon dioxide** (CO_2). This release of carbon dioxide is what is observed when the limestone fizzes.

Limestone is considered a **base**. A base is the chemical opposite of an acid. If an acid is added to a base, the two chemicals will counteract one another. If an acid is added to limestone, the limestone will react until the acid has been neutralized by the limestone. An example of a common acid is household vinegar, which contains 4 percent acetic acid. Acetic acid reacts with limestone the same way as dilute hydrochloric acid but at a much slower rate. The fizz produced by the release of CO_2 may not even be noticeable at first. The chemical reaction rate is slower because the vinegar is a weaker acid.

Acids react differently when placed in contact with limestone than they do when placed in contact with dolomite. If we put acids of similar strength on both limestone and dolomite, we would observe that the limestone reacts more vigorously than the dolomite. Remembering that limestone is mostly calcium carbonate, we can deduce that the more calcium carbonate in a rock, the greater its reaction will be with certain acids.

The **pH** of a substance is a general indicator of whether it is **acidic** or **basic**. A pH of 7.0 is considered neutral. A pH greater than 7.0 is considered basic, and a pH less than 7.0 is considered acidic. The pH also indicates the relative strength of an acid or base. An acid with a pH of 3.5 is ten times as acidic as an acid with a pH of 4.5. To put acid strengths into perspective, the pH value for laboratory-grade, concentrated hydrochloric acid is 0.1, whereas household vinegar has a pH of about 3.0. Rainwater in Pennsylvania has an average pH of 4.5, so we see that rainwater is an acid.

What makes rainwater acidic? Within the earth's atmosphere there is a small amount of carbon dioxide gas. The carbon dioxide gas reacts with water to form **carbonic acid** (Figure 3). Carbonic-acid production can increase as carbon dioxide gas that is also present in the soil reacts with infiltrating water. Carbonic acid is a weak acid and reacts with limestone and dolomite. In fact, it is the main acid that dissolves carbonate bedrock.

Beds, Bedding, and Laminae

Sedimentary rock such as limestone is arranged in distinct layers of varying thicknesses. These distinct layers are called **beds,** and the arrangement of these layers, one bed overlying another bed, is called **bedding**. Bedding can be thick or thin. Where the layers are less than 1 centimeter thick, they are called **laminae**.

Bedding is horizontal in rocks that have not been disturbed since they were deposited as sediment, but in central and eastern Pennsylvania, bedding is commonly tilted. The tilting of the bedrock was caused by the mountain-building forces that were active at various times during Pennsylvania's geologic past. The strong forces moved the beds from their original horizontal position to an angular position (Figure 4A).

Distinct breaks known as **fractures** are found within the

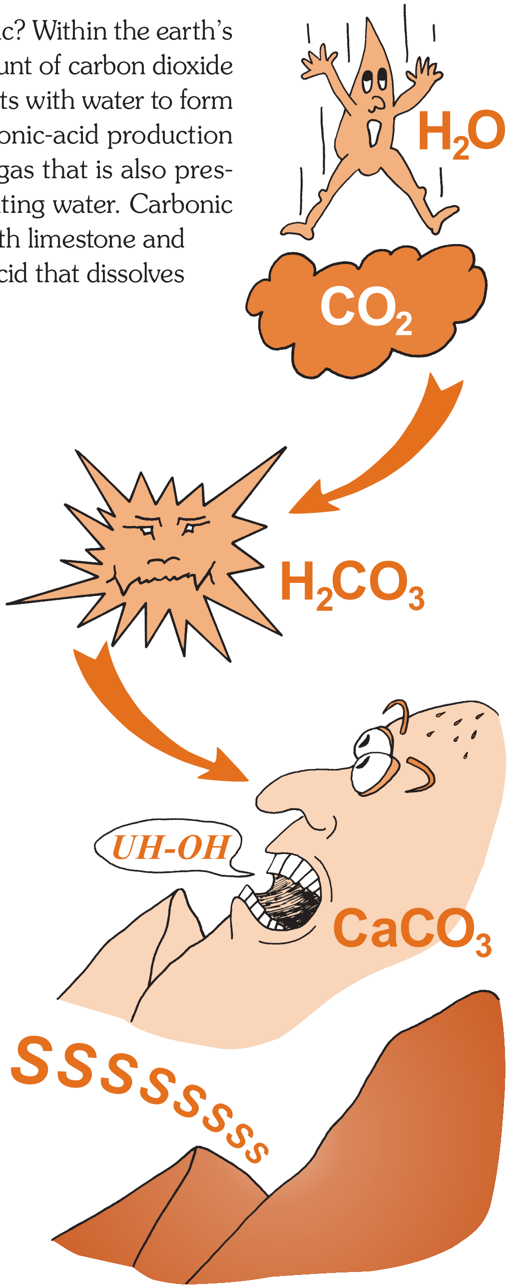

Figure 3. Water (H_2O) combines with carbon dioxide (CO_2) to form carbonic acid (H_2CO_3). This is the acid that dissolves limestone ($CaCO_3$).

bedrock (Figure 4A). Where individual beds meet one another, there are commonly noticeable planar surfaces between them called **bedding planes** (Figure 4A). Bedding can be broken and displaced in a horizontal or vertical direction; the surface along which such movement occurs is known as a **fault**. In some places, you may see rock layers that have been bent, or **folded** (Figure 4B). Folds, faults, fractures, and bedding planes are all classified as inherent weaknesses within the bedrock.

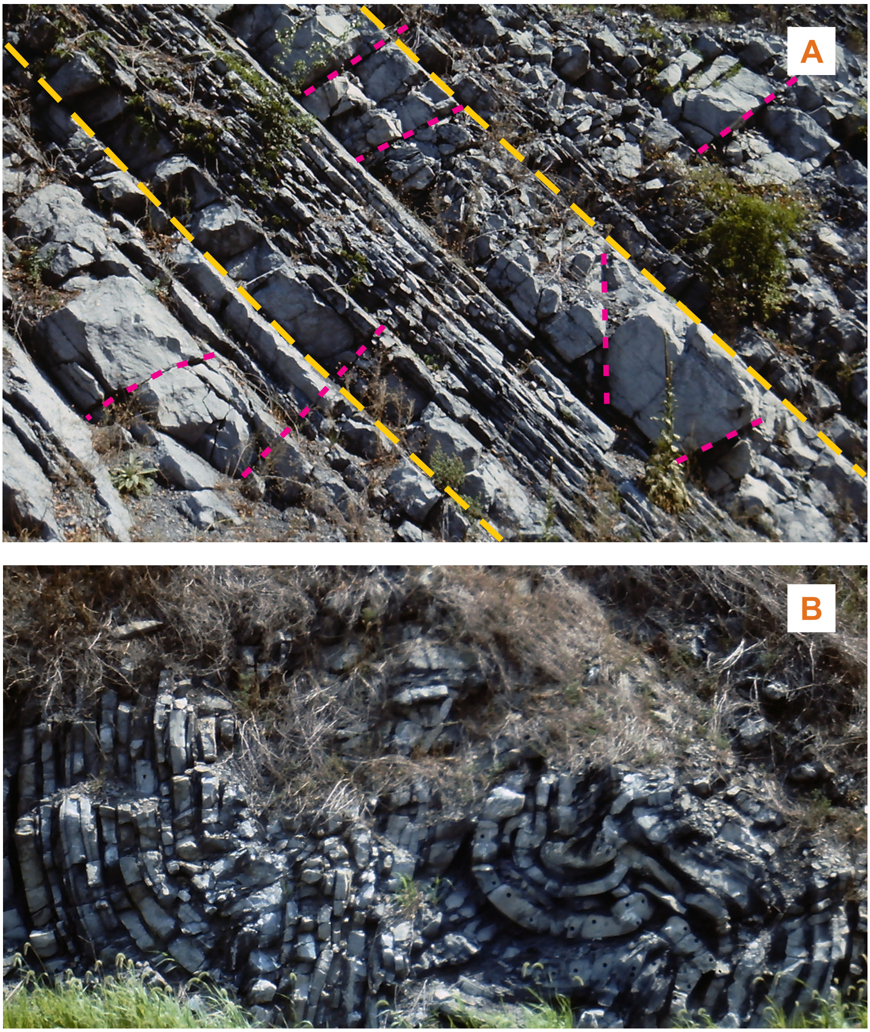

Figure 4. A. Tilted limestone beds of various thicknesses. Pink dashed lines highlight fractures, and gold dashed lines show bedding planes. B. Tightly folded beds of limestone.

All of these natural features indicate that limestone is not necessarily a simple rock layer. It can be thick or thin, laminated, folded, faulted, or fractured, or it can have various combinations of these characteristics. In addition, layers of limestone can alternate with layers of dolomite or other rock types.

Now imagine the acidic water coming into contact with limestone bedrock. What happens? If a bed of limestone was just one flat-lying, thick layer of rock, the acidic water would react only with the topmost layer. However, this is not generally the case. Water also enters the natural breaks in the bedrock and moves downward through these fractures.

As the acidic water enters the fractures, it comes into contact with additional surfaces of the limestone and begins to dissolve them. This **dissolution** widens the fractures. As they get wider, more water can enter. This process is repeated over and over. The acidic water continues to react with the basic limestone bedrock until it is neutralized.

Because water flows along the natural breaks within the limestone bedrock, the surfaces exposed along these breaks are preferentially dissolved. Limestone bedrock normally has many breaks as part of its structure. Fractures may cross one another and intersect laminae and bedding (Figure 5). This may result in uneven dissolution of the limestone bedrock as the acidic water follows different paths. Unusually shaped limestone bedrock may result as the bedrock is dissolved at various levels. Some portions of the carbonate bedrock can appear as abstract sculptures or can become pointed columns called **pinnacles** (Figure 6).

Not all of the limestone bedrock will be dissolved. Remember that there are noncarbonate minerals within limestone. Carbonic acid has a negligible effect on these minerals; thus, they are not dissolved and remain as insoluble residue. As the process of dissolution continues, these insoluble minerals accumulate on top of the limestone bedrock and become part of the soil. The insoluble minerals also fill the widened fractures and voids that are formed by the dissolution process.

Figure 5. Intersecting fractures.

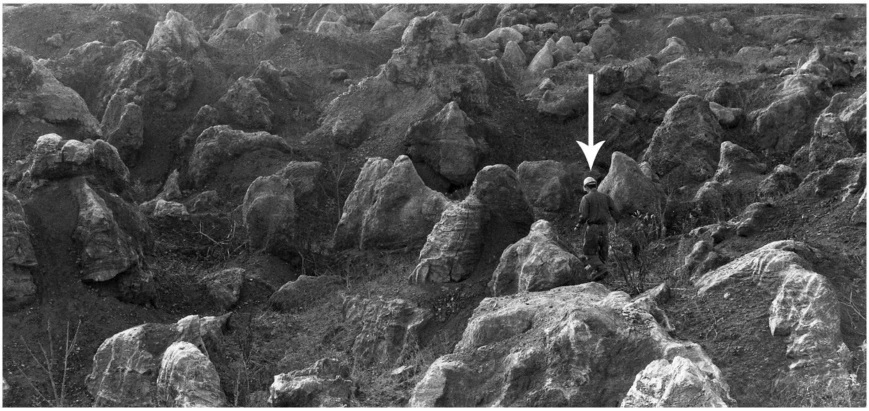

Figure 6. Pinnacles of limestone exposed on the property of the former J. E. Baker quarry in York County. Man (below arrow) is approximately 6 feet tall. Photograph by Helen Delano.

Groundwater and the Plumbing Network

Imagine a plumbing system where the natural breaks in the limestone bedrock (fractures, faults, and bedding contacts) are replaced by pipes (Figure 7). Water migrates downward through the pipes in the limestone bedrock until it meets with other water that has flowed through similar pipes in the area. This meeting place for water is the **water table**.

The water table is a dividing line; essentially, above this line, there is little water, and below this line, the ground is saturated (filled) with groundwater. If a drinking glass is filled with sand and then colored water is poured onto the sand, we can see that the water moves downward or **percolates** through the sand by means of gravity and accumulates at the bottom of the glass. The same process occurs in nature. Water infiltrates through the **regolith** (any unconsolidated sediment above the bedrock, including the soil), then migrates along breaks in the limestone bedrock until it reaches the water table. Groundwater then flows laterally, following the natural **gradient** (slope) of the land surface from high areas to low areas as it makes its way toward the lowest surface elevation, or **base level**. Groundwater generally flows in the same direction as surface water.

The ultimate base level is sea level, but local or regional base levels with higher elevations also can be established. During the evolution of Pennsylvania's landscape, the local and regional base levels changed. This allowed dissolution of the limestone to occur at different depths and, in turn, caused the voids and pathways of the associated plumbing networks to also develop at different depths.

Figure 7. Fractures behave as though they were pipes in limestone bedrock, conveying water to the water table.

The water-table level fluctuates during the year, depending on how much water is available to replenish what flows away. During periods when the water table is high, the pipes in the limestone bedrock may be filled with water. When the water table is low, the pipes may be open or free of water to a greater depth. In the latter case, as new weakly acidic water enters the open pipes, the acid reacts with the limestone, widening the fracture at a deeper level.

Pipes and Drains

Over time, the entry point of rainwater and surface water into a pipe serves as a drain. Drains complete the plumbing network, providing a means to convey water into fractures (pipes) that will carry it through the subsurface to the water table (Figure 8).

Not all of the pipes lead to the water table, however. Fractures may not continue all the way through a bed of limestone. In other instances, the composition of the limestone may result in dissolution only in certain parts of the limestone bedrock. As a result, some of the pipes become dead ends, whereas other pipes are open and interconnected.

The plumbing system in limestone bedrock can be quite complex. Depending upon the orientation and direction of the pipes, groundwater follows the natural gradient of the land in a regular or irregular pattern and can flow to a surface discharge point or points. These discharge points are **springs,** which are common in limestone areas. A substantial area is usually drained by each spring; thus, a spring can be quite large.

In some cases, a stream may enter a drain, flow in the subsurface, and emerge at the surface some distance from where it first entered the drain.

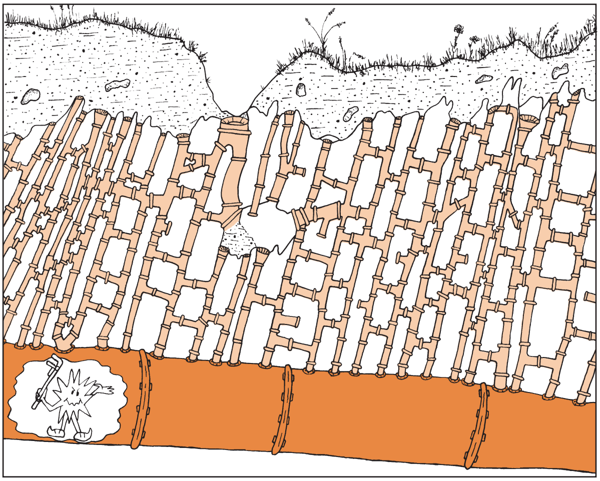

Figure 8. Mr. Carbonic Acid shows off his plumbing network in the limestone bedrock. Groundwater flows through the pipes until it reaches the water table (top of the large pipe).

These streams are called **disappearing streams.** Names such as Sinking Creek or Lost Creek are common in limestone areas throughout the state.

Sinkholes and the Plumbing Network

The drains and pipes in our limestone-bedrock plumbing network play an important part in sinkhole development. Remember that subsidence was described previously in the example of the old farmhouse. The farmhouse began to sag after removal of its support, and eventually it collapsed. Now, think about our plumbing network.

First, consider the function of a drain. In a bathtub or sink, the drain is where the water goes once we pull the plug. At one time or another, most of us probably have encountered the nemesis of bathtubs, the clogged drain. We observe in those situations that water will drain very slowly and, at times, not at all. The bathwater just remains there until we use the proper unclogging agent to open the drain.

Clogged drains in limestone bedrock are very common. Soil typically clogs the drains and retards the movement of water into them. Because surface water moves naturally to the drains, the water may collect in the general area of a clogged drain. After a heavy rain or during the spring thaw or snowmelt, standing water may take on the appearance of a pond or a **ghost lake** (Figure 9). After a few days, the impounded water will slowly drain into the subsurface.

Surface water might also aid in the removal of ghost lakes. It can act as a natural unclogging agent, periodically flushing material down into the limestone drains.

Figure 9. This ghost lake in Lebanon County resulted from a clogged drain. The impounded water may prevent vegetation from growing.

Subsidence and Piping: the Bathtub Model

Imagine a bathtub filled with soil. The bathtub represents the limestone bedrock, and the soil represents soil in a fracture that has been widened by dissolution of the bedrock (Figure 10). If we slowly add water to the bathtub, the water will infiltrate through the soil and migrate toward the drain (Figure 10A). The water then moistens the soil in the area around the open drain. As a result, the moistened soil begins to lose its cohesive properties and begins to break apart. Some of the soil falls down into the open drain.

As the soil enters the drain, it leaves behind a void or open area in the bathtub soil (Figure 10B). If the water source is removed, this void may remain suspended in the soil profile. If water is continually added to the bathtub, the soil above the void (the roof) is moistened and collapses into the void. As the soil fills the void below it, another void is created directly above it (Figure 10C).

As water continues to enter the bathtub, the process is repeated, and the void migrates toward the surface. As the void gets closer to the surface, the surface may begin to sag. (Remember the farmhouse sagging as the support is removed?) At some point, the roof of the void cannot support itself, and it finally collapses (Figure 10D). The result is a hole in the ground.

The actual size and orientation of voids in the soil depend on the thickness of the soil and the source of water. If the water source is continual, the flow may keep the void open to the drain in the limestone bedrock (Figure 10E).

This process of moving soil is called **piping**. The shapes and directions of soil pipes are determined by the infiltration of water through various types of unconsolidated sediments overlying the limestone bedrock. Keep in mind that once a soil pipe has been established, water will continue

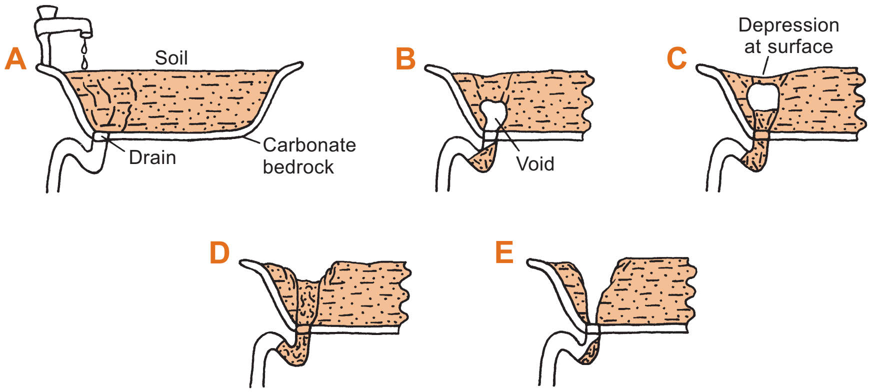

Figure 10. The bathtub model. A. Water infiltrates through the soil. B. As soil enters the drain, a void is left behind. C. Over time, the soil moves into the void, and the void "migrates" toward the surface. D. Support is removed and collapse occurs. E. If enough water is supplied, an open connection to the drain results.

to use it. There also may be more than one soil pipe leading to a common drain. Understanding this has a bearing on planning sinkhole repairs, as discussed later.

Remember that the drain in the bathtub may connect to other limestone-bedrock pipes and other drains. Also remember that water that enters the drains flows through the plumbing network and collects at the water table. During and immediately following periods of heavy precipitation, the water-table level will rise, and then it will lower slowly after the rainfall has ended. This fluctuation of the water table can loosen the soil walls and roof of the void, and pieces can fall off. Conversely, prolonged drought may cause the water-table level to drop, allowing soil to dry, shrink, and fall into existing voids, perhaps causing further collapse.

Sinkhole Characteristics

Sinkholes come in many different sizes and shapes. They occur in unconsolidated sediments (regolith) and are commonly circular in outline, but they can also be elliptical, linear, or irregular in shape. Some sinkholes will look as if someone scooped out a hole with a backhoe. Other sinkholes may resemble a funnel. The stem of the funnel, or **throat,** may be visible within the hole (Figure 11). This throat represents a soil pipe that leads to the bedrock drain. If the regolith is thin, the bedrock or the bedrock drain may be exposed (Figure 12). If a sinkhole occurs in an urbanized area, utility lines may be exposed (Figure 13).

Figure 11. A throat and soil arch in a shallow sinkhole.

The size of a sinkhole depends on how much material has been flushed down the drain and on the size of the pipes. On average, sinkholes in Pennsylvania range from 4 to 20 feet in diameter and have approximately the same range in depth. Surface water can induce erosion along the rim of a sinkhole and cause enlargement of the sinkhole to as much as several hundred feet long. Due to the interconnected nature of the karst plumbing system, a group of small sinkholes can also coalesce to form a larger sinkhole (Figure 14).

The shapes of sinkholes change over time. Initially, sinkholes have steep or nearly vertical sidewalls. Portions of the sidewalls can break off over time and fall into the sinkholes. As this process continues, sinkholes get wider. If water continues to be added to a sinkhole, it can also get deeper.

Figure 12. A sinkhole having an open drain.

Figure 13. This sinkhole in Dauphin County has exposed a utility pipeline.

Figure 14. A group of sinkholes in the Saucon Valley of Lehigh County have joined to form a larger sinkhole. Each individual sinkhole was approximately 30 feet in diameter.

Commonly, one side of a sinkhole remains steep, and the opposite side has a more gentle slope; the sinkhole resembles a funnel that has been cut in half along its length. An **arch** of soil may be apparent along the sidewall (Figure 11). This arch forms over the throat of the sinkhole and represents the roof of the void described in the bathtub model.

Initially, the area above the soil arch and throat, the steep side, is the most stable. Over time, the sides of the sinkhole will continue to fall and fill in the hole. The sinkhole may fill in to the point that it will appear as a depression on the land surface, or it may have very little difference in surface relief from the surrounding area. In the latter case, the evidence that there was once a sinkhole is gone. If there is a constant supply of water entering a sinkhole (from a stream, for example), the sinkhole can remain open for years.

Karst Topography

We now know that a sinkhole is a complex subsidence structure formed by a variety of chemical and physical processes. The process of limestone dissolution over a large area results in a distinct landscape that is called **karst topography**. Karst topography includes features such as sinkholes, **surface depressions,** and **caves**.

A Bit About Caves

Caves are probably the most aesthetic of karst features. The dissolution of the limestone bedrock, coupled with both the abrasive action of sediment that is transported by moving groundwater and the lowering of base level, forms cave passages along fractures, faults, and bedding planes. Additional chemical processes take place once passages have been developed and form the unique features observed in caves. Sinkholes can occur as a result of the collapse of the roof of a cave, but this is rare. For more information about caves, see White (1976).

Redefinition

To put things into perspective, let's go back to our definition (page 3) and modify it to read, "A sinkhole is a hole formed in a karst area by localized, gradual or rapid sinking of the land surface to a variable depth; it is characterized by a roughly circular outline and a distinct break in the land surface. The collapse feature is a result of soil or related materials being transported by water into voids within carbonate bedrock or in the overlying regolith."

Still too technical? How about this? "A sinkhole is a roughly circular hole in the ground in an area underlain by limestone bedrock. It varies in depth, acts as a drain for surface water, and is a result of the periodic flushing of soil, rocks, or other surface materials by water down into voids either in the limestone bedrock or in the soil profile."

Does Karst Topography Develop Everywhere?

According to our definition, karst develops in areas underlain by carbonate bedrock. One would think that if we knew where all the carbonate rocks in the state are located, we would have a fairly good idea of where sinkholes can occur. Figure 2 shows that the major carbonate bedrock areas of Pennsylvania are in the central and eastern parts of the state. Do all of these areas have karst topography? Generally, yes. However, carbonate rocks are not the same everywhere. There are several factors that can influence karst development.

One of the main factors that permits development of karst in Pennsylvania is the percentage of calcium carbonate (calcite) within a limestone or other rock. Generally, the higher the percentage, the greater the dissolution rate and the volume of rock that is dissolved. The percentage of calcite can vary widely in different limestones. Variations can even be at the atomic level, where magnesium, manganese, or iron ions can be substituted for calcium ions.

Shale and sandstone can also be calcareous. That means that there is some calcite present in the rock. If dilute hydrochloric acid comes into contact with it, the rock will fizz to some degree. However, since most of the rock is noncarbonate in composition, most of it is unaffected. The larger the percentage of noncarbonate material in a rock, the less it is affected by the dissolution process caused by carbonic acid. Extensive and large caves exist in some of the **calcareous sandstone** bedrock in Pennsylvania, such as along Chestnut Ridge in the southwestern part of the state.

Another factor influencing the development of karst terrain is the number of bedrock fractures. Generally, dolomite is more brittle than limestone and may have a larger number of natural fractures. The fractures provide more pipes, thereby exposing more of the dolomite bedrock to the carbonic acid. Because of this, even though dolomite reacts more slowly to carbonic acid than does limestone, it may dissolve to a greater extent.

In addition to those areas shown on the map in Figure 2, there are also some relatively thin units of limestone in western Pennsylvania that exhibit solution features in the form of widened fractures and small caves. In general, however, they are too thin to have a well-developed karst surface.

Sinkholes in the Urban Environment

If we add to the information in Figure 2 and show the locations of the larger towns and cities in central and eastern Pennsylvania, we see that large population areas are on or adjacent to areas underlain by carbonate bedrock (Figure 15).

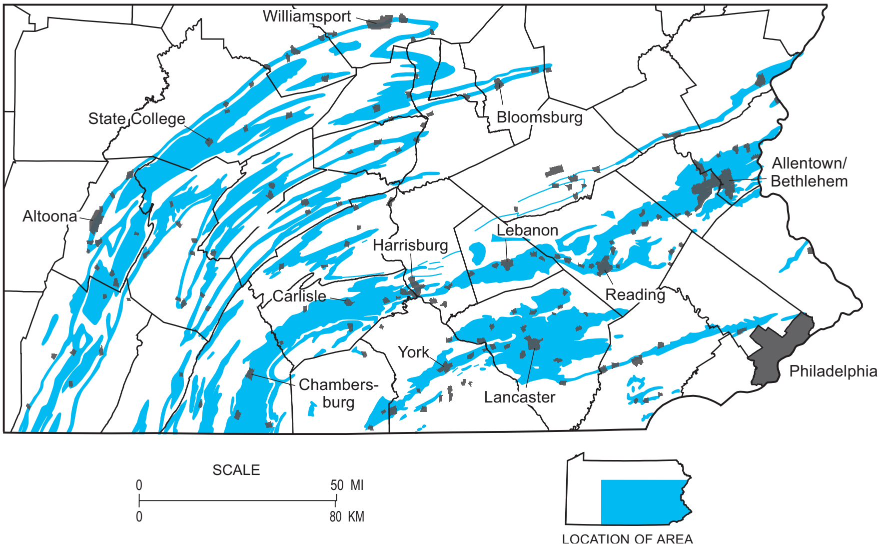

Figure 15. Carbonate bedrock distribution (blue) and major population centers (gray) in central and eastern Pennsylvania.

When populated areas undergo development, land is cleared, soil and rocks are moved, foundations are dug, utility lines are laid, and roadways are established. The landscape is altered to accommodate residential, commercial, or industrial structures.

Let us consider a residential area that has been developed on karst topography. What are the potential problems? How does urban development interact with karst topography?

Storm-Water Drainage

Storm-water drainage is a major urban concern. Where does the storm water go after a heavy rain? It runs off roofs, down storm gutters, along streets, over parking lots, and then either enters the ground by percolating through the soil or is directed toward a natural or artificial drainageway.

The storm-water-drainage problem is compounded in karst areas by the fact that development reduces the surface area available for rainwater to infiltrate naturally into the ground. A typical residential development having quarter-acre lots may reduce the natural ground surface by 25 percent, whereas a shopping center and parking lot may reduce it by 100 percent. If storm water, gathered over a specific area, is collected and directed into a karst area, the concentration of water may unplug one of the karst drains (Figures 16 and 17).

Figure 16. A sinkhole resulting from water discharging from a storm gutter. Sinkhole formation can be attributed to storm-water runoff throughout central and eastern Pennsylvania.

Figure 17. Sinkholes in a storm-water retention basin along U.S. Route 22 in Lehigh County.

Utility Lines

Buried utility lines can also serve as a focus for sinkhole development. Normally, a trench is dug to accommodate the utility lines, and the bottom of the trench is lined with compacted soil or crushed stone. The utility lines are placed in the trench, service lines are connected, and the trench is backfilled. Infiltrating water from precipitation or from leaky storm sewers, sanitary sewers, and water mains can flow through the crushed rock along the length of the trench or pipeline until it comes to a karst drain. The water can slowly flush out a drain over a period of time and cause slow subsidence and eventual collapse. This type of occurrence can take on added importance if there are natural gas pipelines in a karst area. Rupturing of natural gas lines by sinkhole collapse can have tragic results.

Storm sewers and water mains have a great potential for causing collapse because of the large volume of water carried in the lines. Water mains are also under pressure. Water mains can leak because of deterioration of the metallic pipes by oxidation. Storm sewers are normally large-diameter, jointed pipes. Leaks around seams can result in localized settlement, which causes offsetting at the joints of the pipes and in turn increases the amount of water leaking out of the pipes. Over a period of time, the leaks can wash away large amounts of soil and cause the pipes to subside and ultimately fail.

The failure of a water main in a karst area can be quite dramatic. The pressurized water can rapidly flush out nearby karst drains, resulting in a sudden removal of support of the land surface. It is not uncommon in these instances to have large sections of roadway collapse. Nearby structures can also be affected (Figure 18).

Although it is arguable that a sinkhole is the immediate cause of a break in a utility line, or vice versa, we must keep in mind that the karst landscape has taken thousands or perhaps millions of years to develop. It is the momentary action of moving water that triggers most sinkholes. This makes urban areas and newly developing areas more susceptible to subsidence problems. Problems can arise from modifying or diverting water from established natural drainageways, collecting and diverting storm-water runoff, underdesigning storm-water-management systems, and neglecting utility-line maintenance.

Figure 18. Sudden collapse of a city street attributed to a water-line break in the karst area of Northampton County.

Groundwater Withdrawal

The extraction of carbonate-mineral resources can create problems when mining or quarrying extends below the water table. Surface water and groundwater in such cases must be pumped out of a quarry or deep mine to allow removal of the resource. Large volumes of groundwater are sometimes pumped from the lowest part of a mine, which can affect the level of the water table over a localized area. Aside from affecting the yields of public and private water wells, fluctuations of the water table can affect karst drains and cause subsidence.

Sinkholes can also occur in close proximity to private or public water wells. Water wells are commonly drilled in areas that correspond to fracture zones, the pipes and drains of the karst plumbing network. Local fluctuations in groundwater level caused by pumping from a water well may enhance the migration of voids (as in the bathtub model) or cause flushing of surface materials into pre-existing subsurface voids.

Groundwater Contamination

Carbonate rocks are important sources of groundwater in Pennsylvania, yielding millions of gallons of water to commercial and domestic wells. However, because water moves readily from the earth's surface down through solution cavities and fractures, and undergoes very little filtration, groundwater in limestone is easily polluted. It would be easy to contaminate the groundwater by discharging waste materials into a karst drain. This process would be similar to pouring waste down the drain in our homes. The waste enters the drain and is essentially unchanged as it makes its way to the sewer line. Similarly, as waste enters the karst drains, it follows the pipes to the water table. If the waste happens to be an organic chemical that does not mix well with water, such as oil or gasoline, contamination can be widespread, and the contaminating substance can remain in the groundwater for a long time.

Contamination of groundwater is not restricted to industrial sources. Other contaminants, such as sewage, fertilizers, herbicides, and pesticides, can be traced back to municipal, agricultural, and household sources. And according to Pennsylvania Code, even storm water may be considered a polluting substance (Commonwealth of Pennsylvania, 2015).

Recognizing a Developing Subsidence Problem

There are clues that can indicate ongoing subsidence. Within a building, cracks may be evident along walls and floors, particularly in the basement. Cracks may also be noticeable along brick and mortar joints. You might see gaps where porches join with a house. Doors and windows could jam, not opening and closing properly. Keep in mind, however, that other factors that existed during construction, such as soil moisture, soil compaction, and slope of the land surface, can also have a bearing on subsidence and foundation problems.

On the land surface, depressions may be evident, particularly in drainage areas. You might see depressions in yards and streets. Offset or uneven sidewalks and curbs are other possible indicators of ongoing subsidence, as are large, open cracks in soil, lawns, sidewalks, parking lots, and streets, and noticeably leaning trees and shrubbery.

Is it a Sinkhole?

A feature that some people interpret as a sinkhole could be something completely different. Knowing the history of a particular piece of property may provide an explanation for those "strange discoveries" that property owners come across now and then. Some items that you might wish to consider are discussed below.

* * *

Age of the structure. Associated with newer structures may be holes or depressions in the land surface due to natural settling of soil fill that was deposited or redistributed during construction. Was clean fill used during construction? During the process of construction, organic material such as trees, wood, or even trash may have been buried. Trees may have also been removed so that the stumps and roots were left in the ground. Over time, the organic debris will decompose and leave voids in the soil. These voids may collapse, much like the migrating voids in the bathtub model. In some instances, you may be able to find wood in the hole as evidence that a tree had once been there.

If the structure has been there for some time, it may have gone through any number of modifications. Many houses have used or are using a septic system for sewage disposal or a water well for drinking. If these were abandoned in order to connect to a municipal service, was the septic system removed? Was the well plugged? Aside from the actual septic tank or water-well structures, there are also the pipes to consider. Were the buried pipelines removed? Over time, they may deteriorate and collapse, resulting in surface features that can resemble sinkholes. You may be able to find out answers to some of these questions from your local municipality, neighbors, or former property owners.

Drainage areas. Wet or impounded areas do not necessarily indicate a clogged karst drain on your property. Construction typically changes the landscape from its original state and in turn, changes the way in which surface water flows or gathers.

Burrowing animals. Is the hole an animal burrow? Animal burrows are fairly easy to identify. Generally, the hole is small, a few inches to perhaps a foot and a half in diameter. It is common to see ejected material at the entry point, usually soil and bits of rock.

Abandoned or active underground mines. Is it an old mine? Subsidence due to underground mining can result in features similar to sinkholes. Knowing the local history of the area can provide valuable information as to whether or not the area had been mined in the past. There are a number of sources that can be used to help track down mining information. Local municipal offices, libraries, or historical societies are good places to start, and state and federal government agencies that deal with mining and abandoned mines are listed in the Appendix.

* * *

What if you have completed your research and have concluded that the hole is not construction-related settling or collapse, an animal burrow, or subsidence over a mine? What is next?

Remember the definition of a sinkhole. The key to identifying a sinkhole area is to consider the location of carbonate bedrock. Is your property in an area underlain by carbonate bedrock? Where can you find out that sort of information? Specific and generalized geologic information can be found by searching the Internet, and some primary sources of geologic information are listed in the Appendix. These sources include state and federal agencies and libraries, which may have detailed geologic reports and maps that pertain to your area. If so, look for the key words limestone, dolomite, or carbonate. Most maps will be in color, so you can identify an area that is underlain by carbonate bedrock by looking for a particular color. Other maps may be in black and white, and you may have to be more careful in your inspection of the map to locate areas of carbonate bedrock.

Another option is to talk to your local municipal government. Most municipalities have a board of supervisors or a council that governs activities within a given area. Engineering firms are often employed by a municipality to handle the technical duties associated with permitting, utility design, and land management. These firms may have information on the type of bedrock in your area. Public works and road maintenance offices may also have pertinent information.

At this point, you may have gathered as much information as you can by making a few telephone calls and talking with the neighbors. Let us assume that the collected evidence indicates that a sinkhole is present. Now you have to decide what to do with it.

Safety Precautions

One of the first things to do is to secure the area. If it seems unlikely that you will be filling the hole anytime soon, erect a barricade around it. Sawhorses work fine, as does fencing. Brightly colored flags can be used as warning markers. If possible, cover the hole with a piece of plywood or some other type of firm cover. The main objective is to keep the curious away from the hole, particularly children. It is a good idea to inform your neighbors. If the hole is very large, contact the local police department and ask for assistance in securing the area. Unless there are compelling circumstances, *no one* should enter a sinkhole. This is particularly true for newly formed sinkholes. It is common for the sinkhole sidewalls to continue to collapse, creating an unstable and dangerous condition.

In addition, remember that the soil pipes that lead to the drain are *not* caves. They *should not* be entered regardless of how safe they may look. **Spelunking,** or caving, is an entirely separate issue and is an activity that requires special training in technique and safety.

Does your house use natural gas? If so, the gas company should be notified immediately if any type of disturbance to the line is suspected. The degree of potential danger depends on the magnitude and location of the subsidence event. Is the sinkhole close to the house or is it a hundred feet away? Is a throat visible? In which direction does the throat trend?

A thorough examination of the property, utilities, and structures should be done to assess damage, potential damage, and threats to safety. Gather as much data as you can, including photographs. This will help you when you start making telephone calls. Below is a general discussion of items that may be helpful in repairing a sinkhole.

Repairing a Sinkhole

There is no such thing as a typical sinkhole and, therefore, one standard method of repair may not apply. It is important to remember that a sinkhole is nothing more than a large natural drain that has suddenly opened. For a sinkhole to occur there has to be some other opening in the subsurface to accept the lost material, and there needs to be some medium to move the material into that opening; this is commonly water. When initiating a repair, the objectives are to stop loose material from movng down into the drain and then to remove the triggering mechanism.

Once the safety issues have been addressed, you may wish to contact your insurance carrier, inform them of the incident, and suggest a site visit. This should help clarify what is covered. Most standard homeowner policies do not include sinkhole coverage, and if sinkhole coverage is included, there may be limitations.

There are normally a number of engineering firms and general contractors listed in local telephone directories. Some may have experience in evaluating sinkhole damage and in sinkhole repair. Municipalities may be able to help with references. Check with more than one firm and contractor to get estimates.

Repair methods are varied, and the method used may depend largely on economics and the location of the sinkhole (Figure 19). The method and materials needed to repair a small sinkhole in a backyard or in a farmed field may be quite different than those needed to repair a sinkhole in the middle of a highway in a highly urbanized area. Repair tools can range from heavy machinery to hand shovels. Materials can include concrete, soil, grout, synthetic liners, and various sizes and mixtures of crushed stone. Be aware that sinkholes serve as major recharge areas for groundwater, particularly in rural areas. Plugging these recharge areas may not be desirable, and alternative methods may need to be employed.

One method of repair is to simply plug the hole with clean fill materials. Filling in a sinkhole with one size of crushed rock may address the volume issue, but over a period of time, the crushed rock may act as a French

Figure 19. Sinkholes often affect utility lines. In this instance, the void between the exposed bedrock has been filled with concrete to provide a stable base for additional backfill materials and for the overlying utility pipelines.

drain, allowing water to easily flow through it and causing subsidence to progress, albeit at a slower pace.

In a natural state, storm water infiltrates the soil and follows the easiest pathway to the water table. Modifying subsurface conditions, as with a sinkhole repair, can alter these pathways and cause the water to find alternative routes. The water is blocked and, as a consequence, is directed around the plug in an attempt to find another route to the water table. This rerouting can initiate additional subsidence in areas close to the repaired site, oftentimes abutting the repaired sinkhole.

To make a more permanent repair, it is common to combine methods and materials. Plugs constructed of large rocks and concrete or combinations of filter fabric and different sizes of crushed rock have been used successfully to repair sinkholes.

It is better to construct the plug directly at the location of the bedrock drain. This allows the plug to be in direct contact with the bedrock, providing a better seal. Sinkholes in which no bedrock is encountered, and where the soil cover is thick, require careful geologic analysis followed by various types of costly repair, ranging from pressure grouting in the subsurface to driven piles having concrete caps and gravel-mat backfilling.

Once a sinkhole has been filled, the repair is almost complete. To minimize the chances for additional subsidence, the triggering mechanism must be addressed. As water is generally the primary triggering mechanism, it is necessary to identify and remove to the extent possible the source of the water that may have caused the sinkhole. If the source is a storm gutter, you may need to change the discharge point. Keep in mind, however, that by moving the discharge point to another area, you may be shifting the problem to another part of your property or to someone else's property.

What Can You Do?

As with any geological hazard, most often it is the lack of awareness of the hazard (in this case, subsidence) that leads to the greatest problems. This is particularly true in residential development, but it also applies to industrial and highway construction. Land may be developed with minimal regard for the potential problem of sinkhole subsidence.

What can be done to prevent sinkholes and other subsidence problems or to minimize their impact in a local area? Described below are some options that will help.

* * *

Know the history of your property. Many subsidence features can be related to relic structures that have been left in the subsurface, conveying water and contributing towards the creation of voids as these structures decompose over time. Common examples are abandoned utility lines and septic tanks, cisterns, and a variety of buried organic materials.

Become informed about the geology of your area. Find out what is beneath the land surface. If purchasing property, your realtor should be able to identify if it is within a limestone area. Check with libraries, colleges and universities, county planning commissions, and state and federal agencies for information on the geology of your area. Maps showing locations of sinkhole-prone areas may be available.

Know the location of nearby underground mines. If you are in an area that was mined for either bituminous or anthracite coal, then subsidence can be related to those activities. If you suspect that there may be nearby subsurface coal mines, check the related sources of information listed in the Appendix.

Ensure that municipalities regularly inspect utility lines. Because moving water is a major triggering mechanism, it is logical to check water mains and connections, storm sewers, and sewage lines for leaks. This will minimize potential subsidence problems as well as groundwater contamination.

Ensure that development is regulated. When there is an understanding of the potential problems that are common to karst areas, development can then proceed in a safe and conscientious manner. Regulation is not meant to discourage development but to ensure that the proper steps are taken to minimize the potential for future problems. Regulation may mean that special foundations are required for residential and commercial structures, or that utility and storm-water facilities require special design. Specific zoning regulations and storm-water-management plans in karst areas should be established to provide guidance to individuals as well as to minimize future problems. Alternate land-use plans could also be considered.

Maintain sinkhole insurance. Just as with mine subsidence and flooding, insurance policies should be checked to determine if your property is covered for sinkholes. Finding out after the fact that your house is not covered by your insurance for damages attributed to subsidence is a hard lesson to learn. Sinkhole insurance could even be included as part of the mortgage process.

Conclusion

In summary, recall that the karst system can be thought of as a plumbing system. The karst system is developed by naturally occurring carbonic acid dissolving the carbonate bedrock along fractures over a long period of time. The drains and pipes of the plumbing network are established by the dissolution of the carbonate bedrock; they provide an entryway for surface water to infiltrate and migrate to the water table. Moving water is the primary triggering mechanism for flushing soil down karst drains and creating sinkholes. Sinkholes can result from the collapse of the roof of a cave, but typically it is the piping of unconsolidated material into subsurface voids that causes most land-subsidence events.

Sinkhole repair requires two components. The first one is to close the hole, and the second is to remove the triggering mechanism. Plugging the hole is the most common method used for sinkhole repair.

The rule of thumb for developing in a karst area is "look before you leap." Do some investigating before purchasing property. Understand potential or existing problems. If you proceed with development, consult with contractors and other professionals who have experience in karst areas. Preliminary subsurface investigations and carefully implemented construction techniques can eliminate or minimize future problems in a karst area. Sinkhole insurance is available.

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The present edition contains relatively minor changes from the 1999 version, clarifying some of the conceptual elements within the text, figures, and appendix. Special thanks to Caron O'Neil for her patience and expertise in guiding the author through these revisions.

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White, W. B., 1976, Geology and biology of Pennsylvania caves: Pennsylvania Geological Survey, 4th ser., General Geology Report 66, 103 p.

Wilshusen, J. P., 1979, Geologic hazards in Pennsylvania: Pennsylvania Geological Survey, 4th ser., Educational Series 9, 56 p.

Appendix—Sources of Information

Geology, groundwater, mineral resources, and geologic hazards:

Pennsylvania Department of Conservation and Natural Resources
Middletown, Pennsylvania
(717) 702–2017
dcnr.state.pa.us/topogeo/
dcnr.state.pa.us/topogeo/hazards/sinkholes

U.S. Department of the Interior
U.S. Geological Survey
Reston, Virginia
usgs.gov

Local information may be available from colleges and universities having departments in geology, earth sciences, physical sciences, planetary sciences, geography, or engineering (geological and civil), and from state, county, college, or university libraries.

Environmental regulations and permitted activities, including underground and surface mines:

Pennsylvania Department of Environmental Protection
Harrisburg, Pennsylvania
717–783–2300
www.portal.state.pa.us/portal/server.pt/community/dep_home/5968
Contact the regional or district DEP office for assistance.

Pennsylvania Mine Map Atlas
www.paminemaps.psu.edu/

Pennsylvania Historic Underground Mine Map Inventory System
www.ahs.dep.pa.gov/PHUMMISExternal/
Locations of underground mines and mine maps are available from the Mine Map Atlas. Information on active and abandoned mines is stored in the PHUMMIS database, whose data can also be accessed from the Mine Map Atlas.

National Mine Map Repository
Office of Surface Mining
Pittsburgh, Pennsylvania
412–937–2833
mmr.osmre.gov/Default.aspx
The NMMR maintains mine map information for the entire country, including data and maps specific to the bituminous and anthracite coal fields of Pennsylvania.

Caves and karst:

National Speleological Society
Huntsville, Alabama
256–852–1300
caves.org

Information on cave exploration, cave and karst research, and protection of caves and their environments. Includes contact details for the 13 local chapters (grottos) in Pennsylvania, access to bulletins published by the Mid-Appalachian Region (MAR) group, and a list of Pennsylvania caves maintained by the Pennsylvania Cave Conservancy.

Sinkhole repairs and storm-water management in rural areas:

U.S. Department of Agriculture
Natural Resources Conservation Service
Pennsylvania State Office
Harrisburg, Pennsylvania
717–237–2117
nrcs.usda.gov

Field Office Technical Guides (FOTG) contain technical information for specific geographic areas on a variety of soil, water, and air conservation practices. You can obtain FOTG as well as contact information for district offices through the website.

Safety and emergencies:

Safety protocols are established through many levels of federal, state, county, and municipal governments. This includes emergency management, police, fire, and ambulatory services. Contact information for these agencies is given in local telephone directories and online.

Local and regional history and archeology:

Pennsylvania Historical and Museum Commission
State Museum Building
Harrisburg, Pennsylvania
717–787–3362
www.phmc.state.pa.us

Local historical societies and municipal offices are other sources. Contact information for these groups should be available in telephone directories or online.

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https://elibrary.dcnr.pa.gov/GetDocument?docId=1752495&DocName=ES11_Sinkholes_Pa.pdf

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