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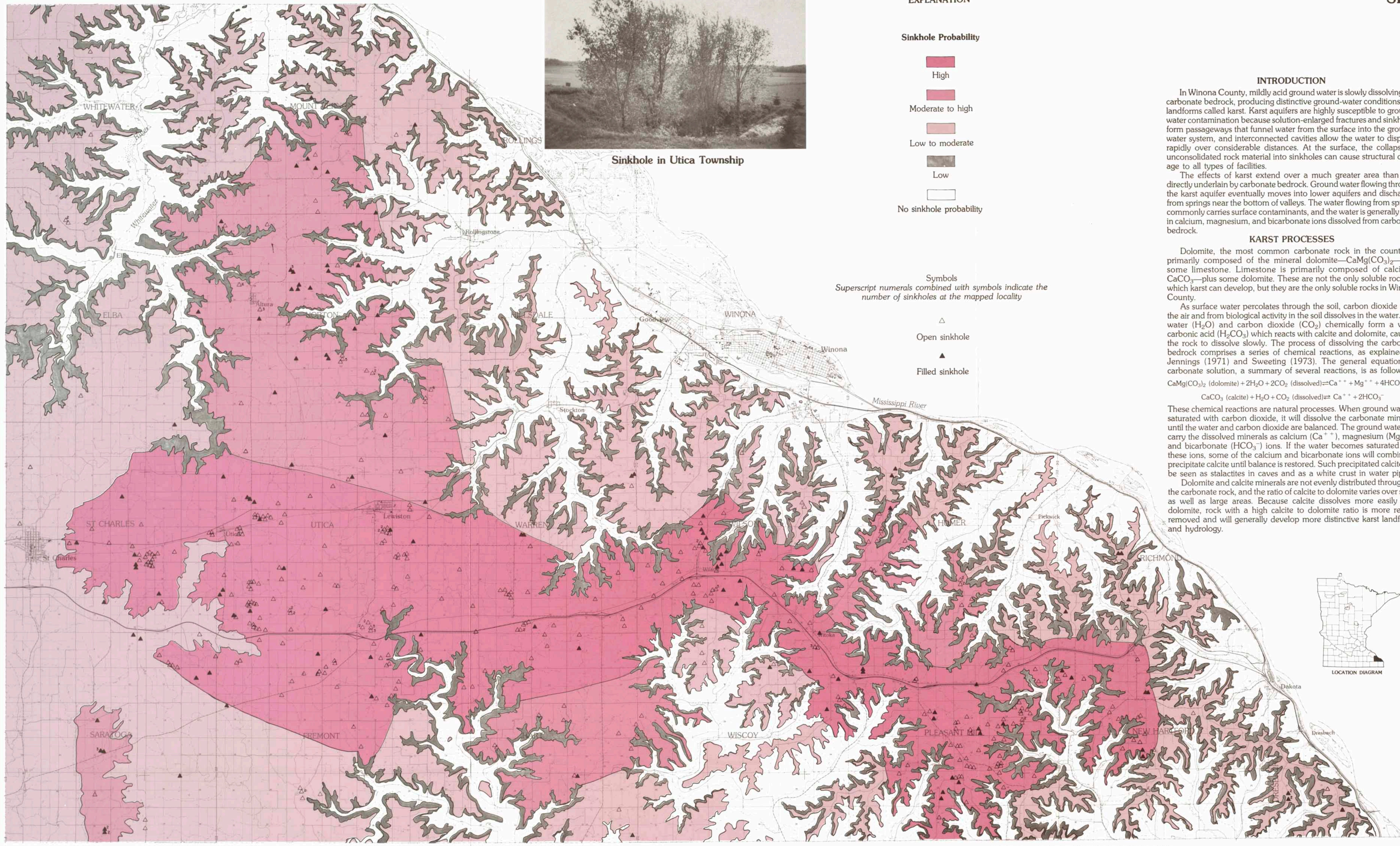

Base modified from U.S. Geological Survey 1:24,000-scale topographic quadrangle maps; see index on Plate 1 for dates.

SCALE 1:100 000

KILOMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
MILES 0 1 2 3 4 5 6 7 8 9

1 CENTIMETER ON THE MAP REPRESENTS 1 KILOMETER ON THE GROUND
1 INCH ON THE MAP REPRESENTS NEARLY 1.6 MILES ON THE GROUND

Sinkhole in Utica Township

EXPLANATION

Sinkhole Probability

High

Moderate to high

Low to moderate

Low

No sinkhole probability

Symbols

Superscript numerals combined with symbols indicate the number of sinkholes at the mapped locality

△ Open sinkhole

▲ Filled sinkhole

LOCATION DIAGRAM

SINKHOLES AND SINKHOLE PROBABILITY

By
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INTRODUCTION

In Winona County, mildly acid ground water is slowly dissolving the carbonate bedrock, producing distinctive ground-water conditions and landforms called karst. Karst aquifers are highly susceptible to ground-water contamination because solution-enlarged fractures and sinkholes form passageways that funnel water from the surface into the ground-water system, and interconnected cavities allow the water to disperse rapidly over considerable distances. At the surface, the collapse of unconsolidated rock material into sinkholes can cause structural damage to all types of facilities.

The effects of karst extend over a much greater area than that directly underlain by carbonate bedrock. Ground water flowing through the karst aquifer eventually moves into lower aquifers and discharges from springs near the bottom of valleys. The water flowing from springs commonly carries surface contaminants, and the water is generally high in calcium, magnesium, and bicarbonate ions dissolved from carbonate bedrock.

KARST PROCESSES

Dolomite, the most common carbonate rock in the county, is primarily composed of the mineral dolomite—$CaMg(CO_3)_2$—plus some limestone. Limestone is primarily composed of calcite—$CaCO_3$—plus some dolomite. These are not the only soluble rocks in which karst can develop, but they are the only soluble rocks in Winona County.

As surface water percolates through the soil, carbon dioxide from the air and from biological activity in the soil dissolves in the water. The water (H_2O) and carbon dioxide (CO_2) chemically form a weak carbonic acid (H_2CO_3) which reacts with calcite and dolomite, causing the rock to dissolve slowly. The process of dissolving the carbonate bedrock comprises a series of chemical reactions, as explained by Jennings (1971) and Sweeting (1973). The general equation for carbonate solution, a summary of several reactions, is as follows:

$$CaMg(CO_3)_2 \text{ (dolomite)} + 2H_2O + 2CO_2 \text{ (dissolved)} \rightleftharpoons Ca^{++} + Mg^{++} + 4HCO_3^-$$

$$CaCO_3 \text{ (calcite)} + H_2O + CO_2 \text{ (dissolved)} \rightleftharpoons Ca^{++} + 2HCO_3^-$$

These chemical reactions are natural processes. When ground water is saturated with carbon dioxide, it will dissolve the carbonate minerals until the water and carbon dioxide are balanced. The ground water will carry the dissolved minerals as calcium (Ca^{++}), magnesium (Mg^{++}), and bicarbonate (HCO_3^-) ions. If the water becomes saturated with these ions, some of the calcium and bicarbonate ions will combine to precipitate calcite until balance is restored. Such precipitated calcite can be seen as stalactites in caves and as a white crust in water pipes.

Dolomite and calcite minerals are not evenly distributed throughout the carbonate rock, and the ratio of calcite to dolomite varies over small as well as large areas. Because calcite dissolves more easily than dolomite, rock with a high calcite to dolomite ratio is more readily removed and will generally develop more distinctive karst landforms and hydrology.

However, karst processes cannot be simply defined by the chemical composition of the rock and water. Most of the sinkholes in Winona County have developed in the Prairie du Chien Group, which is chiefly dolomite, rather than in the limestones of the Platteville and Galena Formations. A few sinkholes have even formed in the St. Peter Sandstone, but are probably the result of cavities in the underlying Prairie du Chien Group. Although the carbonate chemistry provides the basis for karst processes, many environmental conditions, such as rock structure, the nature of unconsolidated sediments, and climate, also affect karst development.

Ground water in karst aquifers flows more rapidly through large cavities than through sediment-filled joints and cracks. Karst ground water, like surface streams, transports and deposits sediment depending on the flow rate, and thus allows cavities to open and close. If the rocks were not well jointed and passages interconnected, karst development would be very slow.

Dissolution of carbonate rocks is generally more rapid during humid periods of warm to temperate climates than during glacial climates (Sweeting, 1973). Records of soil borings made for construction of Interstate Highway 90 and observations of sediments filling exposed joints and bedrock depressions suggest that a karst formed as a result of intense weathering during a warm, humid climate prior to the Pleistocene. The pre-Pleistocene karst had an irregular bedrock surface with sinkholes spaced at intervals of tens to hundreds of feet. Residual material from pre-Pleistocene bedrock dissolution, together with glacial sediments deposited during the Pleistocene, temporarily filled the pre-Pleistocene depressions and bedrock cavities. Karst and stream processes during the present temperate interglacial period are returning the land to a more irregular topography as sinkholes reopen and streams cut into the sediments and bedrock.

CAVES

Dissolution of carbonate rock at depth produces cavities within the bedrock which commonly are partly filled with sediments carried into them by the ground water. Caves are cavities that have grown to human scale. Cave sediments generally are a combination of unconsolidated materials from the surface and the insoluble residue from dissolution of the carbonate bedrock (Milske, 1982; Jennings, 1971).

The water flowing through caves may be slightly acid, particularly if the cavity contains air rich in carbon dioxide, or it may be neutral if the water is saturated with bicarbonate, calcium, and magnesium ions. Dissolution or precipitation will occur, depending on the balance between the carbon dioxide and the carbonate ions.

Many small caves consisting of less than a few hundred feet in continuous passageways occur in Winona County. Most of the cave entrances are along the steep bluffs of the Oneota Dolomite. Only a few cave entrances are known in sinkholes on the uplands. Many large cavities, which do not currently connect to the surface, have been detected in rocks of the Prairie du Chien Group by water well contractors.

SINKHOLES

Sinkholes in Winona County range in size from less than 3 feet to as much as 100 feet in diameter and from 1 foot to about 30 feet in depth. Most sinkholes are 2 to 40 feet in diameter and 5 to 10 feet deep. Sinkholes are circular or elliptical at the land surface, and the walls range from nearly vertical to shallowly inclined. Most sinkholes in the county are cone-shaped depressions.

Many sinkholes formed catastrophically when the soil collapsed under its own weight. Most catastrophic sinkholes are initially cylindrical, and later become cone shaped as the vertical walls begin to erode. However, not all sinkholes in Winona County have formed catastrophically. Surface depressions, referred to as subsidence sinkholes, occur slowly as sediment subsides into enlarged joints. The rate of subsidence will be affected by the amount of sediment carried by water flowing toward the enlarged joints, both from the surface and through the unsaturated zone. In general if the rate of subsidence is rapid, the sinkhole will be cone or bowl shaped, and if it is slow, the depression will be shallow.

A sinkhole initiated by catastrophic collapse may periodically collapse again, or it may continue to grow by subsidence. Other sinkholes may begin with subsidence and later collapse catastrophically. Catastrophic and subsidence sinkholes are two end-members on a continuum of karst processes that result in sinkholes.

Once a sinkhole forms, it will grow as long as unconsolidated material continues to move through horizontal and vertical joints in the bedrock. The sinkhole will begin to fill if sediment transport into the depression exceeds sediment removal through joints in the bedrock. A sinkhole that has been filling may collapse again if the rate of sediment removal increases or if the sediment input decreases.

Surface water tends to flow into the sinkhole, moving sediment deeper into the bedrock. Sediment transport is also affected by fluctuations in the water table. A high water table tends to support joint-filling sediments in position, but when the water table drops, sinkhole sediments move deeper into the bedrock. The rate of sediment transport through the sinkhole, the interaction between surface water and ground water, and the rate of bedrock dissolution determine whether the sinkhole is actively subsiding or passive. Each of these factors may change with time.

People have filled many sinkholes with unconsolidated materials to smooth the land surface. Most of these filled sinkholes have remained closed for the past 5 to 15 years, although some of them periodically collapse again. It is difficult to predict whether a sinkhole will remain closed, because it is not possible to measure all of the factors causing sinkhole collapses.

ENVIRONMENTAL IMPORTANCE OF KARST

Ground-water contamination is a major environmental problem in Winona County's karst. The funnelling of surface contaminants into the ground water is increased by erosion around a sinkhole as it develops and forms a small surface drainage basin. Agricultural chemicals sprayed on fields may be dissolved in water or carried on sediment washing into the sinkhole, and move downward through joints into the aquifers. When waste products are thrown into sinkholes, any chemicals or bacteria from these products will also contaminate the ground water. Indicators of such ground-water contamination entering through sinkholes may be the high nitrate and coliform levels which have been observed in many wells that use the Prairie du Chien-Jordan aquifer.

Other environmental problems created by sinkholes are physical. Sinkholes can cause rapid erosion by soil sliding into the hole. Soil loss removes farmland from production and thins the valuable top soil. Potentially hazardous incidents have also occurred when new sinkholes opened catastrophically under farm equipment being driven over fields.

All types of facilities may be structurally damaged when a sinkhole opens. Home owners may experience economic losses from sinkholes collapsing near or under a house foundation, road, or sewer line. Water-retention facilities are highly susceptible to sinkhole collapse, inasmuch as these structures change the water saturation and lower the shear strength of the surficial materials (Aley and others, 1972). Sinkholes that develop under facilities storing potential ground-water contaminants will drain the pollutants into the ground water.

The rate of sinkhole formation has significantly increased in the past 50 years. Of the 535 sinkholes located, 47 have formed in the past 5 years. At the present rate of about 9 per year, all of the sinkholes could have formed in the last 50 to 60 years. This is not the case, because many sinkholes are more than 100 years old. Although the specific causes of sinkhole collapse in Winona County are uncertain, human activities elsewhere have significantly increased the rate of sinkhole formation (Aley and others, 1972).

The ground-water contamination problems associated with karst extend into regions without sinkholes and can influence water quality in springs and wells in noncarbonate aquifers. Hallberg and others (1983) and Libra and others (1984) have concluded that most of the ground-water contaminants in northeastern Iowa's karst region enter the aquifers through soil infiltration and not through direct runoff into sinkholes. Although similar studies have not been conducted in Winona County, the lack of surface streams in the upland dry valleys indicates that infiltration through relatively thin soils into the karst aquifers is probably a major source of ground-water recharge in Winona County. Recharge of the Jordan aquifer takes place through the Prairie du Chien Group in most of Winona County. Although the Jordan is not a carbonate aquifer, the quality of the water currently in the Jordan was largely determined when that water passed through the overlying Prairie du Chien.

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SINKHOLES AND PROBABILITY FOR FUTURE DEVELOPMENT

Local residents provided most of the information on sinkhole histories and locations. Other sources of sinkhole locations include the Soil Conservation Service, air photos, and U.S. Geological Survey topographic maps. Although the entire county was systematically searched for sinkholes, coverage of the county was least complete in forested areas and where access to the land was unobtainable. The 535 sinkholes inventoried probably include about 75 to 80 percent of the sinkholes, both open and closed, in Winona County.

The relative likelihood for future sinkhole development was estimated on the basis of the observed density of sinkholes, together with information on the bedrock geology (Plate 2), surficial geology (Plate 3), and hydrogeology (Plate 4).

The only areas in the county without potential for sinkhole formation are the deep river valleys where erosion has removed all of the carbonate bedrock. The rest of the county has some potential for sinkhole development. Surface collapse is most likely in areas where sinkholes are concentrated (Kemmerly, 1982). In places where fewer sinkholes occur, a chance still exists that new sinkholes will open in apparently random locations. The lines dividing the county into areas of varying sinkhole probability should be viewed as approximate outlines of these areas.

Low Probability

Sinkholes have not developed in the Oneota Dolomite on the steep slopes along deeply incised valleys, because surface water tends to run off instead of infiltrating into the bedrock. If sinkholes do form, they may not be noticed because of the rapid erosion of the downslope rim of the sinkhole and filling of the sinkhole with sediments.

Low to Moderate Probability

Sinkholes are either widely scattered or occur as small isolated clusters of 2 to 3 sinkholes on the ridges between deeply entrenched rivers. The expected future sinkhole development is low over most of these areas, but moderate where small sinkhole clusters have developed. Although the ridges are mostly underlain by the Oneota Dolomite and small remnants of the Shakopee Formation, sinkhole density generally decreases sharply away from the upland plain. The surficial overburden varies in type, but in general is thinner than on the broad plain. The water table is very deep and should have little or no effect on sinkhole formation, whereas surface water would have a greater impact.

In the southwestern corner of the county, most of the bedrock is overlain by calcareous till and loess, which tend to neutralize the water. Much of Saratoga Township is underlain by the Platteville Formation, which is a thin unit (Plate 2) of interlayered, thinly bedded limestone and shale. The shale is less soluble than limestone, and the thin beds tend to disperse, rather than concentrate the water percolating from the surface. It is not clear why so few sinkholes have developed in the overlying Galena Formation, because sinkholes are actively forming in the Galena in other parts of southeastern Minnesota's karst. The reason may involve the relative thinness of the formation in this area due to erosion, the calcareous nature of the glacial till, and the depth to the water table.

Moderate to High Probability

Sinkholes in the areas of moderate to high probability include several clusters of 4 to 8 sinkholes. In Saratoga Township they have developed along a well-defined north-south trend west of the Platteville plateau. It is believed that these sinkholes are forming in the Oneota Dolomite in a major joint, and new sinkholes may develop along this joint and in response to changes in surface drainage caused by existing sinkholes.

Other areas designated as moderate to high sinkhole probability have varied geologic conditions. In general all of them are underlain by the noncalcareous sandstone member of the Shakopee Formation or by the Oneota Dolomite. Most of these areas are on broad, regionally flat plains, which are mantled with noncalcareous residuum and glacial till (Plate 3), so the mildly acid water is not neutralized before it reaches the bedrock. Most of the sinkholes have formed where the depth to the water table is greater than 160 feet, and thus its fluctuation probably has little effect on sinkhole development. It is not clear what topographic or geologic conditions are responsible for the difference in sinkhole density in these areas versus the density in the high-probability region.

High Probability

The region of high probability of continued sinkhole formation extends across the central part of the county. Sinkhole density is high, and large clusters of more than eight sinkholes occur. Several new sinkholes formed in this region during the 1-year study, and more are expected to form. Small areas where sinkholes are less common were included in this category because they do not differ in geology or topography from the rest of the region. Clusters of sinkholes may develop in these areas in response to local changes, such as fluctuation of the water table, construction of a building or water-retention facility, or hydraulic changes being created now by isolated sinkholes.

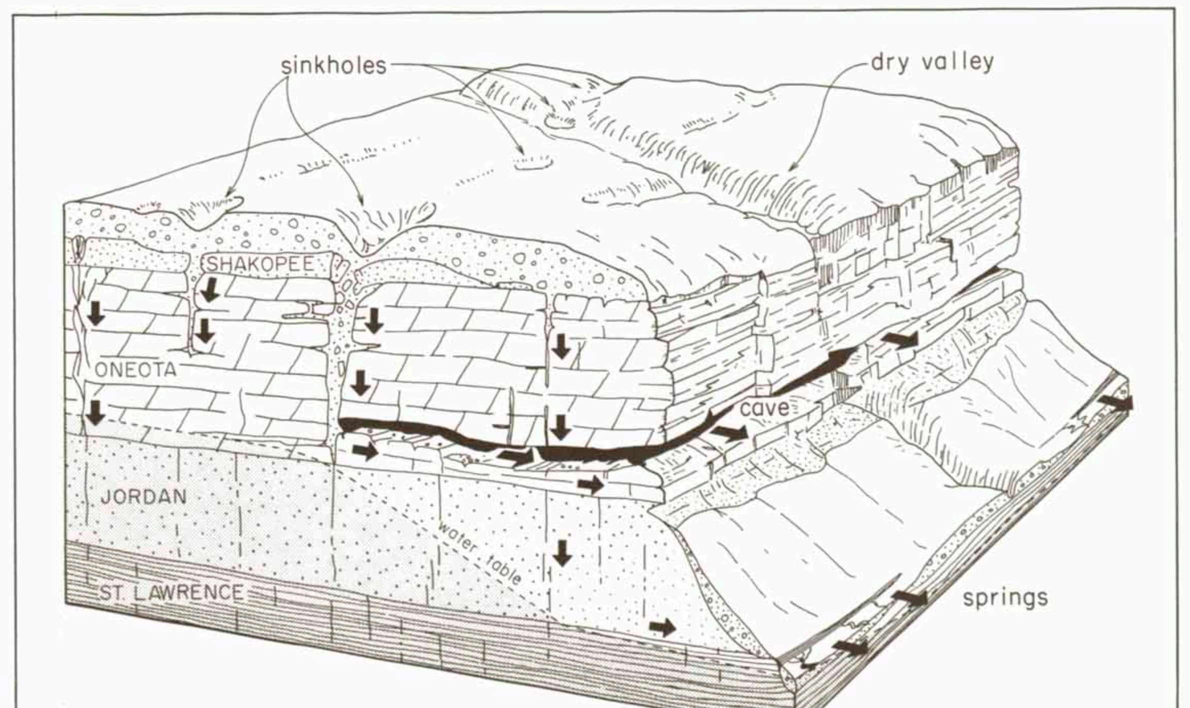
The region is generally underlain by the sandstone member of the Shakopee Formation and the Oneota Dolomite. The bedrock is mantled by calcareous till with and without a loess cover, and by loess, noncalcareous till and residuum. Depth to the water table ranges from about 30 to 370 feet, with sinkholes evenly distributed over almost the entire range. Two combinations of surficial and hydrogeological conditions may enhance sinkhole formation. In the western part of the region, large clusters of sinkholes have formed in the regional recharge area for the Prairie du Chien aquifer where the water table is closest to the surface. Fluctuation in the water table probably has a major positive effect on sinkhole development, overriding the negative effect of calcareous till.

In the eastern part of the high-probability region, sinkholes have formed in noncalcareous, thin tills and thicker residuum. These surficial sediments probably provide ideal conditions for continued carbonate dissolution and sinkhole collapse, even though deeply incised valleys and the very deep water table should inhibit sinkhole formation.

General Conclusions

The carbonate bedrock is the primary control on sinkhole formation. Areas where the Oneota Dolomite is overlain by the sandstone member of the Shakopee are the most susceptible to sinkhole formation. It appears that joints in the noncalcareous sandstone collect acid water without neutralizing it, and direct the water into the Oneota where it dissolves the bedrock. The surficial sediments, topography, and water table are secondary controls that vary in order of significance throughout the country.

Another factor which may be controlling sinkhole formation is the pre-Pleistocene karst, which developed during the warm, humid climate of the Tertiary. This old karst is called paleokarst. Many of the existing sinkholes probably have redeveloped on the sites of paleokarst sinkholes. The paleokarst surface seems to be directing water percolating through the formation today, especially to the northeast where the paleokarst would be more developed. Unfortunately this hypothesis cannot be documented on the basis of available data.



Typical relationships in Winona County between karst and topography