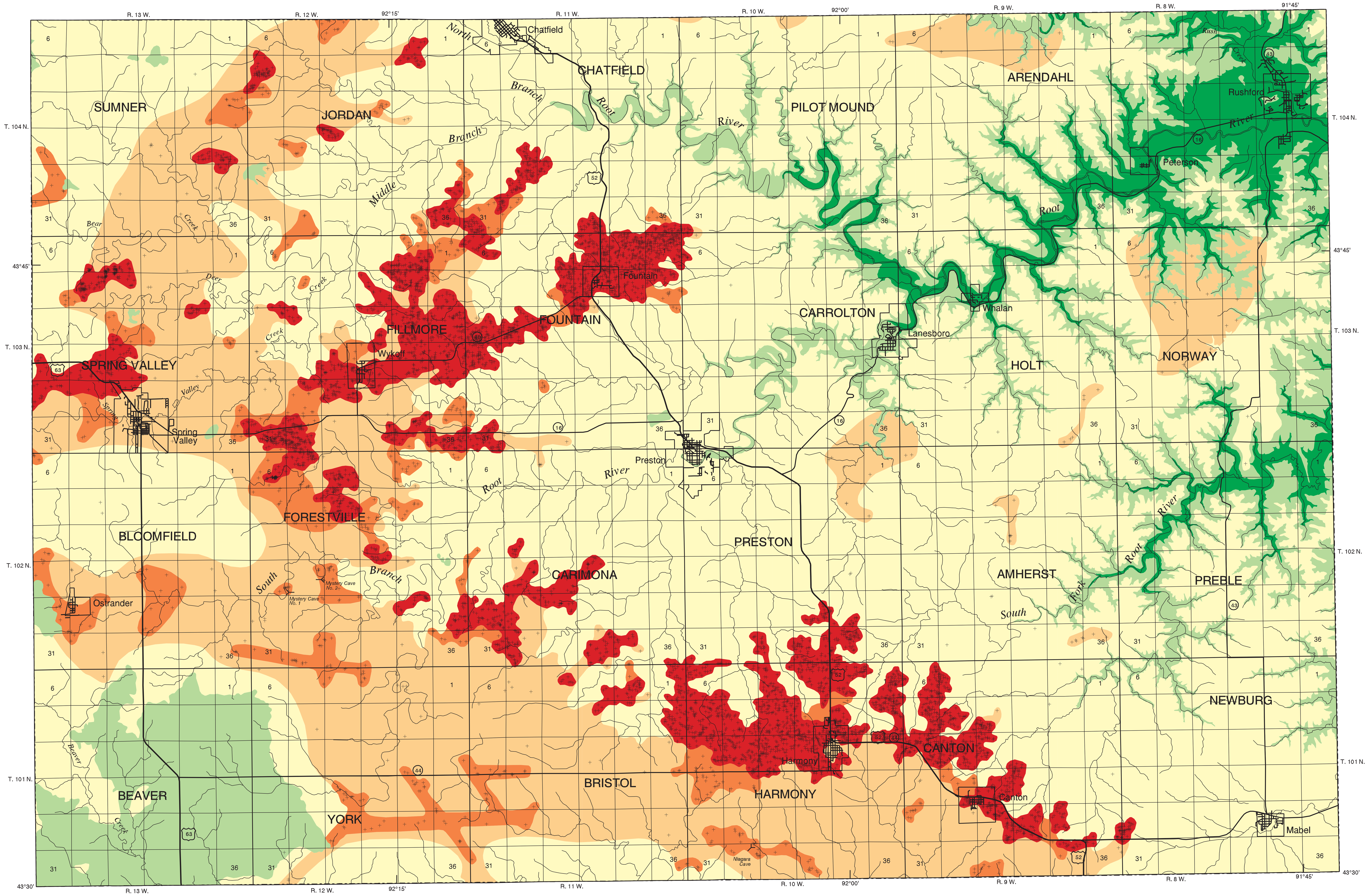
Prepared and Published with the Support of
THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND



Digital base modified from 1990 Census TIGER/Line Files of the U.S. Bureau of the Census (source scale 1:100,000); digital base annotation by the Minnesota Geological Survey.

Universal Transverse Mercator projection, grid zone 15, 1927 North American Datum. Vertical datum is mean sea level. Compiled 1994.

SCALE 1:100 000

1 0 1 2 3 4 5 6 MILES

1 0 1 2 3 4 5 6 KILOMETERS

Partial funding for this project approved by the Minnesota Legislature M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd. 4(f) and M.L. 93, Ch. 172, Sec. 14, Subd. 11(g) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund. Base funding established by the 1989 Groundwater Protection Act, M.L. 89, c. 326, art. 10, sec. 1, subd. 6, item a. and b.

EXPLANATION

The contruction of this sinkhole probability map was guided by, and builds on, earlier efforts in Winona County (Dalgleish and Alexander, 1984a, b) and Olmsted County (Alexander and Maki, 1988). The relative probability of future sinkhole development is estimated primarily from the observed density of sinkholes. New sinkholes are most likely to form in areas where sinkholes are concentrated (Kemmerly, 1982; Beck, 1991). In places where fewer sinkholes occur, a chance still exists that new sinkholes will open in apparently random locations. Depth to bedrock, bedrock geology, and position on the landscape were secondary factors to estimate future sinkhole development. The division of the county into areas of varying sinkhole probability is approximate and boundaries are not sharply defined.

The sinkholes were primarily mapped from closed depressions shown on both U. S. Geological Survey (USGS) 7.5 minute topographic maps and the Fillmore County Soil Survey (Farnham and others, 1958). Not all of the closed depressions shown on the topographic maps and the Soil Survey are sinkholes, however; some are associated with mining or other human activities and were eliminated from the database when they could be identified. This process was not exhaustive, however, and some individual features mapped as sinkholes may have other origins. Sinkholes were also mapped from field investigations of selected areas; information provided by local residents, township and county staff; and air photos. Time and staff limitations did not permit a detailed survey of each mapped depression. Field checks were limited to sinkholes in unusual locations and those visited during other hydrogeologic investigations. Local residents reported several previously open sinkholes that had been filled. When accurate locations could be obtained, filled sinkholes were mapped.

The sinkhole database contains 6022 locations. A comparison of the sinkholes found through detailed field work and those shown in the same areas on the USGS topographic maps and the Soil Survey indicates that about 60 percent of the currently active sinkholes have been mapped; therefore, about ten thousand sinkholes are probably present in Fillmore County. The sinkhole data base is on file with Fillmore County, the Department of Natural Resources, and the Minnesota Geological Survey.

For further information on karst processes, landscape features and hydrogeology see the accompanying *Supplement to the Fillmore County Geologic Atlas.*

+ **Sinkholes**

—< **Public Caves**

NO SINKHOLE PROBABILITY

The only places in Fillmore County where karst sinkholes cannot form are areas in which the first bedrock is the Jordan Sandstone or a stratigraphically lower unit. Such areas occur only in the northeast and east parts of the county where the Root River and the South Fork of the Root River have eroded valleys through the Prairie du Chien Group into the underlying Jordan Sandstone and deeper formations. All other parts of the county have some potential for sinkhole development.

LOW PROBABILITY

Areas underlain by carbonate bedrock, but in which very few sinkholes are found, are shown as Low Probability for sinkhole development. In Fillmore County, few sinkholes have developed where the Oneota Dolomite is the first bedrock or where more than 50 feet of surficial sediments covers the bedrock. The Oneota Dolomite is first bedrock along the sides of the Root River valley in the eastern part of the county. The Oneota cliffs contain evidence of karst activity such as enlarged joints and small caves but few sinkholes are found on the steep slopes. The only extensive area with more than 50 feet of sediments over bedrock occurs in the southwestern corner of Fillmore County.

LOW TO MODERATE PROBABILITY

More than half of Fillmore County contains areas where only widely scattered individual sinkholes or isolated clusters of two or three sinkholes occur. The average sinkhole density in Low to Moderate Probability areas is less than one sinkhole per square mile. These areas are underlain by carbonate rock covered with less than 50 feet of surficial material. The expected future sinkhole development is generally low in these areas, but is moderate where small sinkhole clusters have developed. Despite the low density of sinkholes, karst aquifers occur; they are rapidly recharged by infiltration through the relatively thin surficial materials.

MODERATE TO HIGH PROBABILITY

In these parts of Fillmore County, sinkholes are common landscape features. They occur as diffuse clusters of three or more sinkholes, with an average sinkhole density of about one per square mile. These Moderate to High Probability areas are particularly challenging to resource managers since sinkholes in these areas are sufficiently far apart that a sinkhole may not be visible from a specific location. This lack of visible sinkholes may encourage development that ignores the land-use constraints imposed by karst.

HIGH PROBABILITY

Sinkholes are a prominent part of the landscape when their densities reach 5 to 20 per square mile. In these areas, new sinkholes routinely appear. In some High Probability areas, sinkholes occur in linear arrays that suggest structural control. Clusters of new sinkholes may develop in response to local water table changes, either natural or human-induced. Natural changes include droughts and unusually wet periods. Human-induced changes include fluctuations of the water table due to the construction of a building or water-retention facility, or by diverting natural drainage into sinkholes.

SINKHOLE PLAINS

Sinkholes are the dominant landform when their densities exceed about 20 per square mile. In Fillmore County, areas with sinkhole densities from about 20 up to several hundred per square mile are mapped as Sinkhole Plains. New sinkholes often appear in these areas. Sinkholes are major agricultural problems preventing the cultivation of significant fractions of many fields. Sinkhole collapse is a major, ongoing concern for roads and structures. Sheet and gully erosion into the sinkholes is a significant problem. All of the precipitation that is not lost to evapotranspiration either infiltrates through the soil or drains into a sinkhole.

SINKHOLES AND SINKHOLE PROBABILITY

By
Kathleen M. Witthuhn and E. Calvin Alexander, Jr.
1995

INTRODUCTION

In Fillmore County, mildly acidic ground water slowly dissolves the carbonate bedrock and produces distinctive ground-water conditions and landscapes known as karst (White, 1988; Ford and Williams, 1989). Karst landscapes are characterized by sinkholes, caves, sinking streams and subsurface drainage with an associated lack of surface water in all but base-level streams and large springs. Cavities and voids in the bedrock cause problems for many human activities on karst landscapes and the unanticipated collapse of materials into sinkholes can cause damage to structures. This plate shows the distribution of sinkholes in Fillmore County and the relative probability that new sinkholes will form.

Karst aquifers are aquifers in soluble bedrock in which solution produces a significant portion of the aquifers' porosity and permeability (Quinlan and others, 1992). In Fillmore County, the limestones and dolostones are karst aquifers because solution-enlarged joints, bedding planes, and conduits provide the only hydraulically significant porosity and permeability.

Karst aquifers are highly susceptible to pollution because contaminated surface water can rapidly infiltrate through soils or directly enter the subsurface via sinkholes. Once in a karst aquifer, polluted waters can move laterally much faster than in non-karst aquifers. Water in karst aquifers may move several miles per day. However, in deep karst aquifers flow velocities may be comparable to those in non-karst aquifers such as sandstones in which water may move at inches or feet per day. The hydrologic characteristics of karst aquifers are extremely variable at all scales up to tens of miles.

The effects of karst development extend well beyond the landscape and underlying karst aquifers. Ground water flowing through karst aquifers can move into adjacent, non-karst aquifers. The water flowing from karst aquifers commonly carries surface contaminants, and is high in ions dissolved from carbonate bedrock. When the karst ground waters return to the surface, the characteristic chemistry and contaminants are added to surface streams and rivers.

KARST PROCESSES

Dolostone and limestone are the common carbonate rocks. Dolostone is the mineral dolomite ($CaMg(CO_3)_2$) plus some calcite ($CaCO_3$), while limestone is calcite plus some dolomite. These are not the only soluble rocks in which karst develops, but they are the only important soluble rocks in Fillmore County.

Water moving through soil dissolves carbon dioxide, primarily from soil gas. Water and carbon dioxide combine to form carbonic acid, a weak acid which can slowly dissolve calcite and dolomite. These chemical reactions are natural processes. When ground water contains dissolved carbon dioxide, it will react with the carbonate minerals until the water is saturated with dissolved calcium, magnesium, and bicarbonate ions. Under certain conditions, water can become supersaturated with these ions, and later precipitate some of the excess as calcite. This precipitated calcite can be seen in caves in a variety of forms, such as stalactites and stalagmites.

Dolomite and calcite are not evenly distributed in carbonate rocks, and the ratio of calcite to dolomite varies over small as well as large areas. Since calcite dissolves faster than dolomite, rocks with high calcite to dolomite ratios dissolve faster and develop more distinctive karst landforms and hydrology.

Karst landscapes are not defined only by the chemical composition of the local rock and water. Adjacent areas with apparently similar geologic and hydrologic conditions can have radically different karst development. Although the carbonate chemistry provides the basis for karst processes, other factors, such as topographic relief, depth to bedrock, type of sediment cover, rock structure, and climate also affect karst development.

In Fillmore County, the best-developed karst landscapes are controlled by topography. The highest sinkhole densities are on flat hilltops between or adjacent to river valleys. The flat hilltops are part of an old erosion surface that cuts across the stratigraphy. Differential erosion of the various bedrock units has produced a stepped topography. The Galena Group and the Prairie du Chien Group are more resistant to erosion and form bluffs. The stepped topography is incised by rivers draining east to the Mississippi. The increased hydraulic gradients due to the relief between the hilltop recharge areas and discharge into the incised valleys enhances karst development.

The depth to bedrock and nature of the surficial cover also control the location of visible karst features. In Fillmore County, karst features are rarely active or visible when covered with more than about 50 feet of surficial materials.

Joints, cracks, and fissures in the limestones and dolostones play a role in karst development. These features provide the initial routes along which the ground water moves and dissolves the bedrock. Ground water in karst aquifers flows more rapidly through large, open cavities than through sediment-filled joints and cracks. Karst ground water, like surface streams, both transports and deposits sediment, depending on the flow rate, and thus allows cavities to open and fill. If the rocks were not well-jointed and passages not interconnected, karst development would be slower.

Climate plays a role in karst development. Solution of carbonate rocks is more rapid in warm to temperate, humid climates than in arid glacial climates (White, 1988). The limestones and dolostones of Fillmore County have been alternately subjected to both slow and rapid karst processes since their deposition in the Paleozoic (Hedges and Alexander, 1985). A long period of warm, moist weathering during the Cretaceous and Tertiary produced a large number of paleokarst features (Andrews, 1958) that were subsequently buried by glacial deposits in the Pleistocene. The alternating cold glacial and warm interglacial periods during the Pleistocene have influenced the development of karst in Fillmore County and the speleothems in local caves contain a record of those climate changes (Lively, 1983).

SINKHOLES

Sinkholes are closed depressions that form by the solution of the underlying soluble bedrock and function as connections between surface and ground waters. Sinkholes are intermediate in size between larger karst features such as blind valleys and smaller karst features such as solution pits. In Fillmore County, sinkholes range from less than 3 feet to more than 100 feet in diameter and from 1 foot to about 60 feet in depth. The majority of them are 10 to 40 feet in diameter and 5 to 40 feet deep. Sinkholes are circular or elliptical with walls that range from nearly vertical through cone and bowl shapes to shallow dish-like shapes. In Fillmore County, sinkholes occur in all of the bedrock units between the Cedar Valley Group and the Jordan Sandstone.

The highest sinkhole densities occur as Sinkhole Plains in a northwest to southeast band across the central part of Fillmore County and are part of a sinkhole trend extending from southeastern Olmsted County into northeastern Iowa. Sinkhole Plains occur where the first bedrock is the Spillville, Maquoketa/Dubuque, or Stewartville Formations or the Prosser Limestone and are restricted to flat hilltops adjacent to or between stream valleys. High Probability areas occur over the same bedrock units and are adjacent to and southwest of the Sinkhole Plains. Moderate to High Probability areas are scattered through the county. Part of these areas define a continuous arcuate band across the county that is adjacent to and connects High Probability and the Sinkhole Plains areas. Extensive areas over the Spillville, Maquoketa/Dubuque, and Stewartville Formations and smaller areas over the Prosser Limestone are also Moderate to High Probability. In the eastern part of Fillmore County, these areas occur over the Shakopee Formation, both the lower part of the formation associated with the New Richmond Sandstone as well as the upper part associated with the overlying St. Peter Sandstone.

If subsurface erosion is rapid compared to surface adjustment, voids form in the sediments and a catastrophic sinkhole develops. The collapse of cavities in the bedrock itself is rare. Most catastrophic sinkholes are initially cylindrical with vertical walls and erode into cone shapes. If the subsurface erosion is slow compared to the surface adjustment, a subsidence sinkhole forms. Subsidence sinkholes form slowly, as sediment subsides into enlarged joints, or even more slowly as the bedrock surface itself dissolves. Subsidence sinkholes can start as subtle dish-shaped depressions and may develop very slowly. The rate of subsidence will be affected by the amount of sediment carried by water moving (both directly from the surface and through the unsaturated zone) toward the enlarged joints. If the rate of subsidence is rapid, the sinkhole will be cone or bowl-shaped. If it is slow, the depression will be shallow for a longer period of time.

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 end-members on a continuum of karst processes that result in sinkholes.

Surface water tends to flow into sinkhole depressions and then into the subsurface through the bottom of sinkholes, moving suspended sediment 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 solution determine whether the sinkhole is actively subsiding or passively filling. Each factor may change with time. The existence of a sinkhole indicates that at that sinkhole's location, the erosion processes currently exceed the filling processes.

Sinkholes are forming rapidly in southeastern Minnesota from both natural and human-induced causes. Dalgleish and Alexander (1984a, b) and Magdalene (1995) found that the rate of sinkhole formation was about two percent per year of the total inventory of sinkholes. That rate is sufficient to produce all of the sinkholes in 50 years. Since many of the sinkholes are known to be older than 50 years, the high rate of formation implies that many sinkholes are ephemeral features that do not become a permanent part of the landscape. Although many sinkholes form by entirely natural processes, a number of human activities are known to induce sinkhole formation (Aley and others, 1972).

Sinkholes are filled by both natural and artificial processes. The artificial techniques range from simply filling the sinkholes with soil, through sophisticated attempts to excavate and seal the conduits at the bottom of the sinkholes, to installation of impermeable layers to stop water movement through the features. Many filled sinkholes have remained closed for decades but some of them have reopened. It is difficult to predict whether a sinkhole will remain closed, because all the factors causing sinkhole collapses have not yet been identified.

In addition to the currently open and recently filled active sinkholes, a much larger number of inactive filled paleosinkholes exist in Fillmore County. These paleosinkholes can be observed when natural or artificial processes strip sediments from the bedrock surface. The existence of paleosinkholes has been confirmed by dense arrays of borings in connection with various construction activities and by mining activities. The fillings of these paleosinkholes range from pre-glacial sediments (Andrews, 1958) through glacially derived sediments to post-glacial sediments and reflect the long history of karst processes in Fillmore County (Hedges and Alexander, 1985).

ENVIRONMENTAL IMPACTS OF SINKHOLES

Ground-water contamination is a major concern in Fillmore County's karst areas, as it is in many karst areas of the world. Sinkholes serve as direct connections between surface runoff and the underlying water-table aquifers. Karst systems bypass potential water-purifying processes in the soil zone and conduct surface water directly, sometimes within minutes, to the underlying aquifers.

Agricultural chemicals sprayed on fields may be dissolved in water or carried on sediment washed into sinkholes which can then move downward through joints into ground water. Chemicals or bacteria leached from wastes placed in sinkholes can also contaminate ground water. Contaminates from urban and industrial sources can affect the quality of water in karst aquifers. In Fillmore County, nitrates, bacteria and other pollutants from community drainfields, municipal waste treatment facilities, and improperly constructed domestic drainfields, salt from road deicing, and storm runoff are all problems in urban areas. Industrial pollution sources include improperly disposed chemicals leaching from landfills, leaking under and above-ground petroleum storage tanks, pipeline ruptures, and transportation accidents.

For over a century, many of Fillmore County's sinkholes were improperly but routinely used for the disposal of wastes. In the last fifteen years, public education efforts by a wide variety of individuals and organizations and an effective mix of community involvement and legal processes have significantly and visibly reduced the incidence of waste disposal in sinkholes.

The ground-water contamination problems associated with karst extend into regions without sinkholes and can influence water quality in springs and wells in non-carbonate aquifers. Hallberg and others (1983) and Libra and others (1984) 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. The lack of surface streams in many parts of Fillmore County indicates that infiltration into the karst aquifers through relatively thin soils is a major source of ground-water recharge. Water chemistry and residence time studies conducted as part of the Fillmore County Geologic Atlas indicate that the recently recharged water in Fillmore County aquifers usually shows varying levels of anthropogenic pollutants. These human-induced chemical changes are absent in the water from aquifers recharged more than about 40 years ago.

Other environmental problems created by sinkholes are physical. Soil loss can be a significant problem if sheet and gully erosion are allowed to develop around the sinkholes. Potentially hazardous incidents have occurred when new sinkholes open catastrophically under farm equipment being driven over fields.

Any facility may be structurally damaged if a sinkhole opens under or adjacent to it. Home owners have experienced economic losses from sinkholes collapsing near or under house foundations, roads, or sewer lines. Water retention structures, such as lagoons and ponds, are highly susceptible to sinkhole collapse (Aley and others, 1972). A number of ponds in Fillmore County have failed due to sinkhole formation. Animal-waste storage facilities in Fillmore County and municipal waste treatment facilities elsewhere in southeastern Minnesota (Alexander and others, 1993) have been damaged when sinkholes developed catastrophically.

SUMMARY

Bedrock composition, topographic position in the landscape, and depth of surficial cover are the main controls on sinkhole formation in Fillmore County. The highest sinkhole densities occur where the Spillville, Maquoketa/Dubuque, and Stewartville Formations and the Prosser Limestone form uplands adjacent to entrenched stream valleys. Other combinations of first bedrock and topographic position result in locally greater sinkhole densities. Sinkholes appear to form only where there is less than 50 feet of surficial cover over the carbonate bedrock. The pre-Pleistocene paleokarst may also be influencing sinkhole formation. Many existing sinkholes may represent reactivation of paleokarst sinkholes.

Sinkholes can form anywhere in Fillmore County except in the stream valleys that have eroded down below the Oneota Dolomite. Nearby sinkholes remain the single best predictor of new sinkhole development. However, many sinkholes are not shown on existing maps or may have been filled.

REFERENCES

Alexander, E. C., Jr., Broberg, Jeffery S., Kehren, Andrew R., Graziani, Marco M., and Turri, Wendy L., 1993. Bellechester Minnesota lagoon collapses: Environmental Geology, v. 22, no. 4, p. 353-361.
Alexander, E. C., Jr., and Maki, G. L., 1988. Sinkholes and sinkhole probability, Plate 7 in Geologic Atlas of Olmsted County: Minnesota Geological Survey County Atlas Series C-3.
Aley, T. J., Williams, J. J., and Massello, J. W., 1972. Groundwater contamination and sinkhole collapse induced by leaky impoundments in soluble rock terrain: Missouri Geological Survey Engineering Geology Series 5, 32 p.
Andrews, George W., 1958. Windrow Formation of Upper Mississippi Region, a sedimentary and stratigraphic study: Journal of Geology, v. 66, no. 6, p. 597-624.
Beck, B. F., 1991. On calculating the risk of sinkhole collapse, in Kastning, E.H., and Kastning, K. M., eds., Proceedings of the Appalachian Karst Symposium, Radford, Virginia, 23-26 March, 1991, Huntsville, Ala., National Speleological Society, p. 231-236.
Dalgleish, J. D., and Alexander, E. C., Jr., 1984a. Sinkholes and sinkhole probability, Plate 5 in Balaban, N. H., and Olsen, B. M., eds., Geologic Atlas of Winona County: Minnesota Geological Survey County Atlas Series C-2.
Dalgleish, J. D., and Alexander, E. C., Jr., 1984b. Sinkhole distribution in Winona County, Minnesota, in Beck, B. F., ed., Sinkholes: Their geology, engineering and environmental impact: Boston, A. A. Balkema, p. 79-85.
Farnham, R.S., and others, 1958. Soil survey of Fillmore County, Minnesota: U. S. Department of Agriculture, Soil Conservation Service, 51 p., 72 maps, scale 1:20,000.
Ford, D. C., and Williams, P. W., 1989. Karst Geomorphology and Hydrology: London, Unwin Hyman, 601 p.
Hallberg, G. R., Hoyer, B. E., Bettis, E. A., III, and Libra, R. D., 1983. Hydrogeology, water quality, and land management in the Big Spring Basin, Clayton County, Iowa: Iowa Geological Survey Open File Report 83-3, 191 p.
Hedges, J., and Alexander, E. C., Jr., 1985. Karst-related features of the Upper Mississippi Valley Region: Studies in Speleology, v. 6, p. 41-49.
Kemmerly, P. R., 1982. Spatial analysis of a karst depression population; clues to genesis: Geological Society of America Bulletin, v. 93, p. 1078-1086.
Libra, R. D., Hallberg, G. R., Ressmeyer, G. G., and Hoyer, B. E., 1984. Groundwater quality and hydrogeology of Devonian carbonate aquifers in Floyd and Mitchell Counties, Iowa: Pt. 2 of Iowa Geological Survey Open File Report 84-2, p. 1-106.
Lively, R. S., 1983. Late Quaternary U-series speleothem growth record from southeastern Minnesota: Geology, v. 11, p. 259-262.
Magdalene, S., 1995. Sinkhole distribution in Winona County, Minnesota revisited: M.S. thesis, University of Minnesota, Minneapolis.
Quinlan, James F., Smart, Peter L., Schindel, Geary M., Alexander, E. C., Jr., Edwards, Alan J., and Smith, A. Richard, 1992. Recommended administrative/regulatory definition of karst aquifers, principles for classification of carbonate aquifers, practical evaluation of vunerability of karst aquifers, and determination of optimum sampling frequency at springs, in Quinlan, J., and Stanley, A., eds., Proceedings of the Third Conference on Hydrogeology, Ecology, Monitoring and Management of Ground Water in Karst Terranes. Nashville, TN, Dec. 4-6, 1991, Dublin, Ohio, NGWA, p. 573-635.
White, W. B., 1988. Geomorphology and hydrology of karst terrains: Oxford University Press, 464 p.

The DNR Information Center
Twin Cities: (612) 296-6157
MN Toll Free: 1-800-766-6000
Telecommunication Device for the Deaf:
(612) 296-5484
MN Toll Free: 1-800-657-3929

This information is available in an alternative format upon request.

This map was compiled and generated using geographic information system technology. Digital cartography by Joyce Meints, Minnesota Geological Survey, cartographic design by Jan Falteisek, Minnesota Department of Natural Resources, and digital layout by the Land Management Information Center. Digital data products are available from the Land Management Information Center, Minnesota Planning Office, St. Paul.