SINKHOLES, SINKHOLE PROBABILITY, AND SPRINGS AND SEEPS

By

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FIGURE 1. *Sinkhole MN25:D0363. A typical Galena sinkhole in the woodlands of the western half of Leon Township. D363 consists of an old, bowl-shaped sinkhole about 30 feet in diameter and 3 feet deep. In the center, it has a currently active, funnel-shaped collapse measuring 10 feet in diameter by 3 feet deep.*

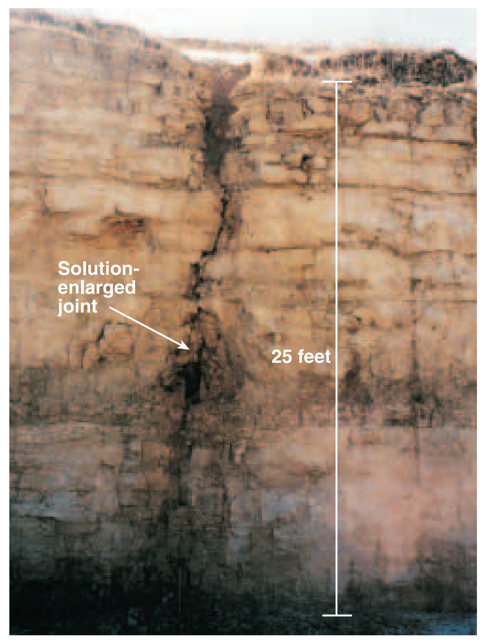
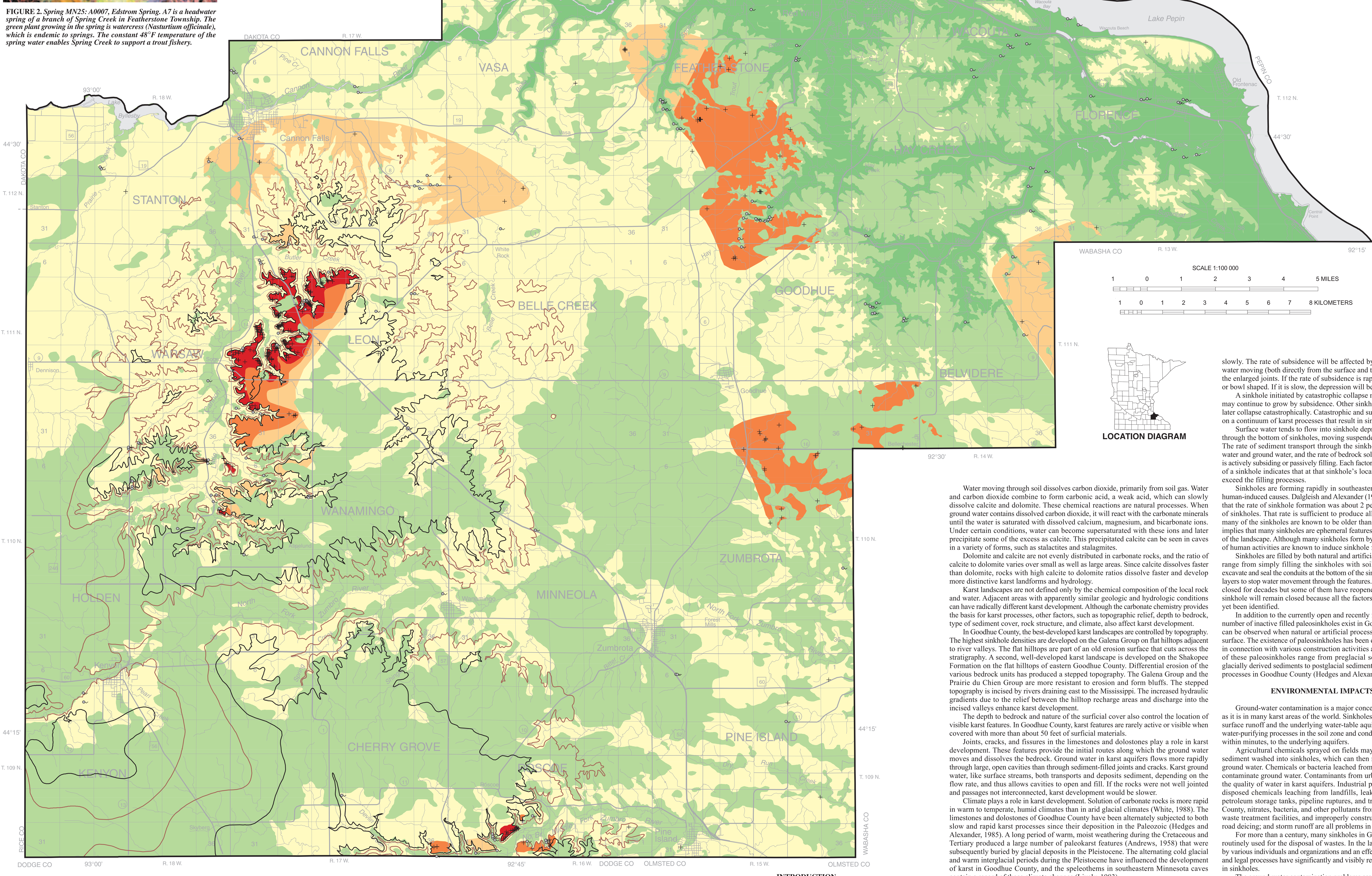


FIGURE 3. *Prairie du Chien karst features visible in MN25:X0001, a roadcut bedrock island between lanes of U.S. Highway 61 in the northwest corner of Section 13 in Welch Township. The wider parts of this solutionally widened vertical joint have been filled with preglacial sediment. Construction can reactivate such paleokarst features. Photograph contributed by Dan Bauer.*

FIGURE 2. *Spring MN25: A0007, Edstrom Spring. A7 is a headwater spring of a branch of Spring Creek in Featherstone Township. The green plant growing in the spring is watercress (Nasturtium officinale), which is endemic to springs. The constant 48° F temperature of the spring water enables Spring Creek to support a trout fishery.*



WARNING: This map provides an overview of the distribution of karst features and the relative probability that new sinkholes will form as interpreted from 1:100,000-scale geologic map information. THIS MAP SHOULD NOT BE THE BASIS FOR EVALUATION OF SPECIFIC SITES.

SCALE 1:100 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS

LOCATION DIAGRAM

MAP EXPLANATION

The construction of this sinkhole probability map was guided by and builds on earlier efforts in Winona County (Dalgleish and Alexander, 1984a, b), Olmsted County (Alexander and Maki, 1988), and Fillmore County (Witthuhn and Alexander, 1995). 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, springs, and seeps shown on this map were located primarily by fieldwork. Very few of the springs and sinkholes in Goodhue County are marked on U.S. Geological Survey (USGS) topographic maps or the Goodhue County Soil Survey (Poch, 1976). A small fraction of the features can be seen on aerial photographs and the USGS Digital Ortho Quads. Local residents and county staff provided information on where to find many of the mapped features. Most of the features shown on this map were field checked by the authors and the locations determined using global positioning system (GPS) technology. The uncertainty of the feature locations varies from about 30 meters to about 1 meter. Time, staff, and access limitations did not permit a visit to every sinkhole and spring in Goodhue County. This effort was focused more on sinkholes than springs and seeps. There are many small, unmapped springs and seeps, often ephemeral, in the county. Filled sinkholes were mapped where their locations could be accurately determined. The locations and descriptive information for the mapped features are available in the Minnesota Karst Features Data Base (Gao, 2002), which can be accessed from links on the web pages of the Minnesota Geological Survey and Minnesota Department of Natural Resources.

The Karst Features Data Base contains information on 371 sinkholes, nine stream sinks, and 160 springs in Goodhue County. About two-thirds of the active sinkholes and maybe one-quarter of the larger springs were visited and mapped in Goodhue County. The Karst Features Data Base will be updated as additional information is received. That information is one starting point for any site investigation, but each site will need a careful karst inventory conducted by qualified personnel trained in karst hydrogeology.

+ Sinkholes

Springs and seeps

Contact between the Prosser Limestone and the Cummingsville Formation

Contact between the Cummingsville Formation and the Decorah Shale

No Probability—The only places in Goodhue 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 northeastern part of the county where the Mississippi and Cannon rivers and Spring, Hay, Wells, Bullard, and Sugar Loaf creeks 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 Goodhue County, few sinkholes have developed where more than 50 feet of surficial sediments covers the bedrock or where the Oneota Dolomite is the first bedrock. The Oneota Dolomite is first bedrock along the sides of the Mississippi River valley in the northeastern 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. Extensive areas with more than 50 feet of sediment over bedrock occur throughout Goodhue County.

Low to Moderate Probability—Large parts of Goodhue County contain 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 Goodhue 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. 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 Plain—Sinkholes are the dominant landform when their densities exceed about 20 per square mile. In Goodhue 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.

INTRODUCTION

In Goodhue 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 karst features in Goodhue 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 Goodhue 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 nonkarst aquifers. Water in karst aquifers may move several miles per day. However, in deep karst aquifers, flow velocities may be comparable to those in nonkarst aquifers such as sandstones. 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, nonkarst 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 Goodhue 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 Goodhue County, the best-developed karst landscapes are controlled by topography. The highest sinkhole densities are developed on the Galena Group on flat hilltops adjacent to river valleys. The flat hilltops are part of an old erosion surface that cuts across the stratigraphy. A second, well-developed karst landscape is developed on the Shakopee Formation on the flat hilltops of eastern Goodhue County. 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 enhance karst development.

The depth to bedrock and nature of the surficial cover also control the location of visible karst features. In Goodhue 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 Goodhue 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 Goodhue County, and the speleothems in southeastern Minnesota caves contain a record of those climate changes (Lively, 1983).

SINKHOLES

Sinkholes are closed depressions that form as the result of the solution of the underlying soluble bedrock and function as connections between surface water and ground water. Sinkholes are intermediate in size between larger karst features such as blind valleys and smaller karst features such as solution pits. In Goodhue 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. Most of them are from 10 feet to 40 feet in diameter and from 5 feet to 40 feet deep. Sinkholes are circular or elliptical with walls that range from vertical through cone and bowl shapes to shallow dish-like shapes. In Goodhue County, sinkholes occur in all of the bedrock units between the Galena Group and the top of the Jordan Sandstone.

The highest sinkhole densities in Goodhue County occur as Sinkhole Plains along the bluffs on the eastern side of the Little Cannon River primarily in the western half of Leon Township. Small areas of the Sinkhole Plains unit also occur on the bluffs along the north side of the North Branch of the Middle Fork of the Zumbro River in southern Roscoe Township. Both Sinkhole Plains areas are developed on the Prosser Formation of the Galena Group. The extent of the Prosser Formation is shown by the solid black line on the map. The Leon Township Sinkhole Plains areas are the northern end of a band of high sinkhole densities that extends southeastward through Dodge, Olmsted, and Fillmore counties and continues into northeastern Iowa. This Sinkhole Plains trend is developed along the northeastern edge of the Galena Group outcrop belt. A second concentration of sinkholes occurs as a diffuse band on the Prairie du Chien bluffs along the Mississippi River and its tributaries. This band of sinkholes is developed mainly where the Shakopee Formation is the first bedrock. This band of sinkhole development consists of broad areas of Low to Moderate areas with Moderate to High Probability areas interspersed.

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 shaped 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 2 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 Goodhue 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 preglacial sediments (Andrews, 1958) through glacially derived sediments to postglacial sediments and reflect the long history of karst processes in Goodhue County (Hedges and Alexander, 1985).

ENVIRONMENTAL IMPACTS OF SINKHOLES

Ground-water contamination is a major concern in Goodhue 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. Contaminants from urban and industrial sources can affect the quality of water in karst aquifers. Industrial pollution sources include improperly disposed chemicals leaching from landfills, leaking underground and aboveground petroleum storage tanks, pipeline ruptures, and transportation accidents. In Goodhue 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.

For more than a century, many sinkholes in Goodhue County were improperly but routinely used for the disposal of wastes. In the last 15 years, public education efforts by various 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 noncarbonate aquifers. Hallberg and others (1983) and Libra and others (1984) concluded that most of the ground-water contaminants in the karst region of northeastern Iowa enter the aquifers through soil infiltration and not through direct runoff into sinkholes. The fast flow of surface streams in many parts of Goodhue County indicates that infiltration into the karst aquifers through relatively thin soils is a major source of ground-water recharge.

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. Homeowners 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). Numerous ponds in Goodhue County have failed because of sinkhole formation. Animal-waste storage facilities in Goodhue County and municipal waste treatment facilities elsewhere in southeastern Minnesota (Alexander and others, 1993) have been damaged when sinkholes developed catastrophically. Highways can be affected by sinkholes.

SPRINGS AND SEEPS

Springs and seeps are places where ground water returns to the surface. They occur where the ground-water table intersects the land surface. Springs and seeps come in a wide, overlapping range of sizes. The water flows range from tens to hundreds of gallons per minute to zero. Many of the important springs and seeps are ephemeral and only flow after large ground-water recharge events. Springs are generally taken to be point sources. The water at springs emerges as a distinct flow from a single point or a small area or pool. Seeps generally describe places where water oozes out of the ground over a broad area. Springs and seeps often, but not always, support distinctive plant and animal communities. Springs and seeps form the headwaters of many perennial streams of Goodhue County and support the coldwater trout fisheries. Springs and seeps often emerge from the bottoms and sides of streams, rivers, and lakes.

The location of springs in Goodhue County is strongly influenced by the interrelationships between aquifer stratigraphy and topography in the landscape. In southwestern Goodhue County, scattered springs and seeps flow from glacial sediments on top of the Galena Formation. Much of this landscape has been extensively tiled and it can be difficult to tell a buried tile outlet from a natural spring. Both typically drain to the lowest part of the local landscape. Many springs and seeps occur where the Decorah Shale, Platteville Limestone, and Glenwood Shale intersect the land surface (roughly following the brown crenulated line on the map). The headwaters of the Little Cannon River, Belle Creek, and the North and Middle Forks of the Zumbro River flow from Decorah edge and stratigraphically higher springs and seeps in the western and southwestern half of Goodhue County. The third major group of springs rises from the bottom of the Oneota Dolomite and the top of the Jordan Sandstone in eastern and northeastern Goodhue County. Such springs and seeps form the headwaters of Spring, Hay, and Wells creeks. A final group of springs emerges near and in the Mississippi River valley forming the northeastern edge of Goodhue County. The Mississippi River is the ultimate base level for the hydrogeology of Goodhue County. Some of the springs flow from glacial terraces and some flow from the St. Lawrence and deeper formations.

Springs are the natural outlets of the ground-water flow systems. They form ideal places to sample and monitor the overall water quality in the aquifers. Most springs drain the near-surface aquifers and, like wells in the near-surface aquifers, can be affected by human activities on the surface. Spring water should be assumed to be unpotable until proven otherwise.

SUMMARY

Bedrock composition, topographic position in the landscape, and depth of surficial cover are the main controls on sinkhole formation in Goodhue County. The highest sinkhole densities occur where the Prosser Limestone forms uplands adjacent to entrenched stream valleys. Other combinations of first bedrock and topographic position result in locally greater sinkhole densities. Sinkholes rarely form where there is more 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 Goodhue 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.

Springs and seeps form the headwaters of most of the flowing surface creeks, streams, and rivers in Goodhue County. Most of them emerge where specific parts of the bedrock stratigraphy intersect the surface topography. The three major concentrations of springs are along the Decorah edge in western and southwestern Goodhue County along the outcrop of the Oneota-Jordan contact and along the Mississippi River.

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FIGURE 4. *Sinkhole MN25:D0291. D291 was a 6-foot-diameter by 5-foot-deep vertical-sided collapse that formed after harvest in October 1996 in Welch Township. Field cultivation filled D291 in spring 1997 and 1998. It redeveloped each following autumn. Photograph contributed by Dan Bauer.*

Digital base composite:
Roads and county boundaries - Minnesota Department of Transportation GIS Statewide Base Map (source scale 1:24,000)
Hydrologic features - U.S. Geological Survey Digital Line Graphs (source scale 1:100,000)
Digital base annotation - Minnesota Geological Survey
Project data compiled from 1998 to 2001 at the scale of 1:100,000. Universal Transverse Mercator projection, grid zone 15, 1983 North American datum. Vertical datum is mean sea level.
GIS and cartography by Mike Tronrud and Yongli Gao. Edited by Nick Kroska.

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This information is available in an alternative format on request.

This map was compiled and generated using geographic information systems (GIS) technology. Digital data products are available from DNR Waters.

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