THE DEVELOPMENT OF A KARST FEATURE DATABASE FOR SOUTHEASTERN MINNESOTA

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A karst feature database of southeastern Minnesota has been developed that allows sinkhole and other karst feature distributions to be displayed and analyzed across existing county boundaries in a geographic information system (GIS) environment. The central Database Management System (DBMS) is a relational GIS-based system interacting with three modules: GIS, statistical, and hydrogeologic modules. Data tables are stored in a Microsoft Access 2000 DBMS and linked to corresponding ArcView shape files. The current Karst Feature Database of Southeastern Minnesota was put on a Windows NT server accessible to researchers and planners through networked interfaces.

Initial spatial analyses and visualizations of karst feature distributions in Southeastern Minnesota were conducted using data extracted from the karst feature database. A series of nearest-neighbor analyses indicates that sinkholes in southeastern Minnesota are not evenly distributed (i.e., they tend to be clustered). ArcInfo, ArcView and IRIS Explorer™ were used to generate a series of 2D and 3D maps depicting karst feature distributions in southeastern Minnesota using data exported from the GIS-based karst feature database. The resulting maps allow regional trends to be visualized and extend county-scale trends to larger state-wide scales.

Southeastern Minnesota is part of the Upper Mississippi Valley Karst (Hedges & Alexander 1985) that includes southwestern Wisconsin and northeastern Iowa. Karst lands in Minnesota developed in Paleozoic carbonate and sandstone bedrock. A significant sandstone karst has developed in Pine County (Shade *et al.* 2000). Most surficial karst features, such as sinkholes, are only in those areas with less than 50 ft (~15 m) of sedimentary cover over bedrock surface (Fig. 1). Few scientific descriptions of the Upper Mississippi Valley Karst exist. Nevertheless, the karst lands of southeastern Minnesota present an ongoing challenge to environmental planners and researchers and have been the focus of a series of research projects and studies for over 30 years.

Since the early 1980s, the Minnesota Geological Survey and Department of Geology and Geophysics at the University of Minnesota have been mapping karst features and publishing various versions of their results in the form of 1:100,000 scale County Geologic Atlases. In the mid-1990s, the Minnesota Department of Natural Resources was assigned responsibility for the hydrogeology portions of the County Atlases and is now responsible for the karst mapping. Dalgleish and Alexander (1984a), Alexander and Maki (1988), Witthuhn and Alexander (1995), Green *et al.* (1997), Shade *et al.* (2001), and Tipping *et al.* (2001) published sinkhole distribution maps for Winona, Olmsted, Fillmore Counties, Leroy Township, Pine and Wabasha Counties respectively. Published atlases of Washington, Dakota, and the counties of the Twin Cites Metro area contain limited information on sinkhole occurrences.

As geographic information systems, (GIS), global positioning systems, and web tools became more accessible to resource managers in the 1990s, the need for a state-wide, Web-accessible, and GIS-compatible karst feature base has become increasingly evident. Several factors hindered the development of this database. Karst features have not been inventoried in significant areas. Where data exist, they are often decades old and exist as difficult to obtain paper copies in researchers' files. Several generations of students and workers have gathered the data, and the format, quality, and completeness vary greatly. The data were organized into county databases and incompatibilities between adjacent counties were introduced. All of these challenges only serve to emphasize the need for state-wide data sets and, indeed, for interstate compilations.

A successful model for such a database already exists in Minnesota. The Geological Survey's County Water-Well Index (CWI) successfully supplies current users with readily accessible information about Minnesota's millions of water wells while continually updating and improving the database and delivery system. The Database Management System (DBMS) we are building builds on the lessons that have been learned from the CWI project. Experts in GIS, computer science and geology have constructed a karst feature GIS database that displays and allows analysis of sinkhole and other karst feature distributions across existing county boundaries. The ongoing research focused on the management of the GIS-based Karst Feature Database of Southeastern Minnesota, statistical analysis of karst feature distribution and sinkhole formation, and 2D and 3D visualization of karst feature distribution in southeastern Minnesota.

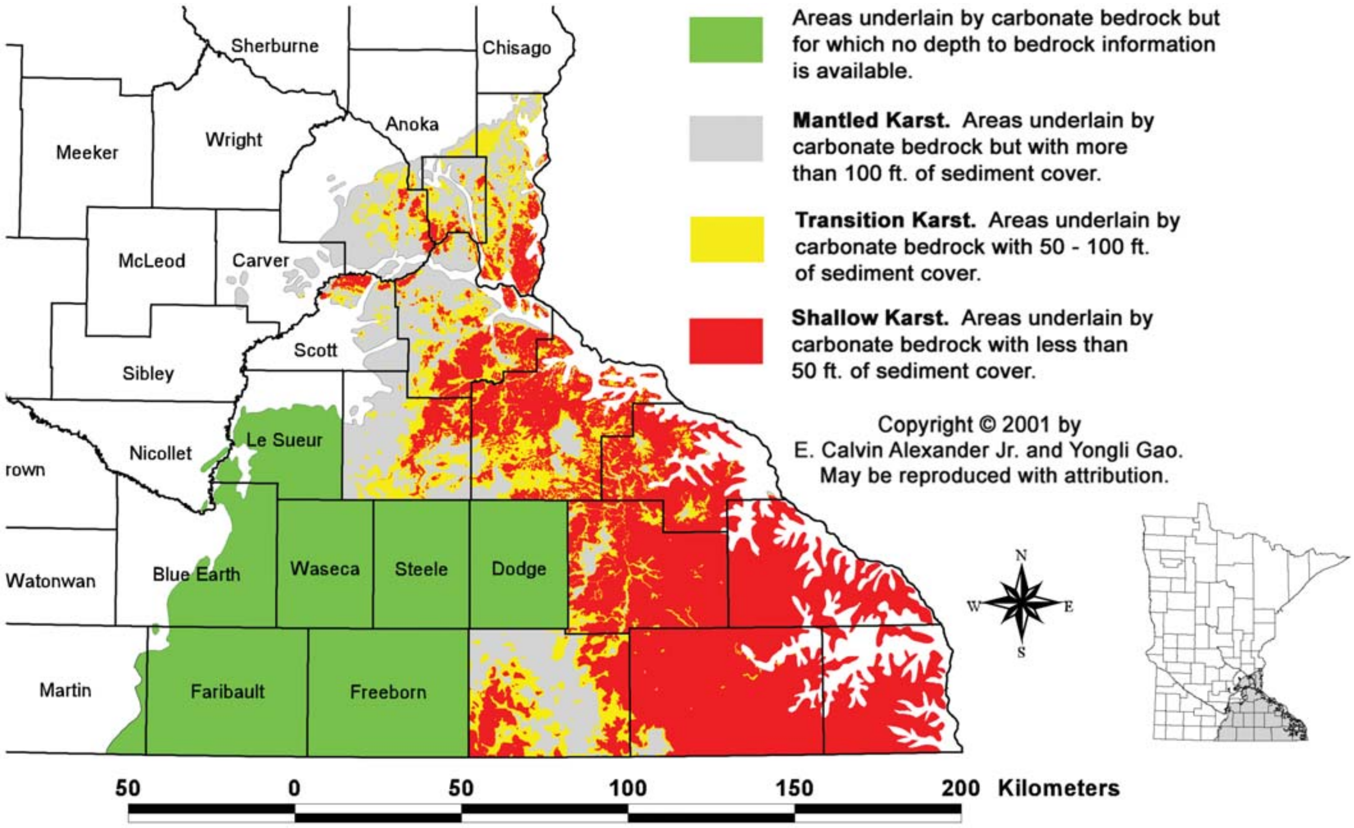


Figure 1. Minnesota Karst Lands. This map overlays the areas with < 50 feet, 50 to 100 feet, and > 100 feet of surficial cover over the areas underlain by carbonate bedrock. Featureless green counties in the southwestern portion of this map are underlain by carbonate bedrock but the depth to bedrock has not mapped with sufficient accuracy to draw informative maps. This map emphasizes the patchy nature of the thick sediment cover and the importance of site-specific information for land-use decisions.

Research goals

This research integrated geology, groundwater hydrology, statistics, GIS, and DBMS to study karst feature distribution in southeastern Minnesota. The main goals of this interdisciplinary research are: 1) to look for large-scale patterns in the sinkhole distribution; 2) to conduct statistical tests of hypotheses about the formation of sinkholes; 3) to create Web-accessible management tools for land-use managers and planners; and 4) to deliver geomorphic and hydrogeologic criteria for making scientifically valid land-use policies and decisions in karst areas of southeastern Minnesota.

Research approach

Existing county and sub-county karst feature datasets have been assembled into a large GIS-based database capable of analyzing the entire data set. Figure 2 illustrates the logical design of the Karst Feature DBMS of Southeastern Minnesota. The central DBMS is a relational GIS-based system interacting with three modules: GIS, statistical, and hydrogeologic modules. The GIS module uses ArcInfo and ArcView to manipulate spatial transformation and map generation. The statistical module is used to analyze and test karst feature distribution and hypothesis about the formation of sinkholes. The hydrogeologic module helps to understand groundwater flow and solute transport in carbonate aquifers and investigate the hydrogeologic controls on the sinkhole distribution. As can be seen in Figure 2, the three modules and the central DBMS are interconnected to each other instead of standing alone. A series of software packages have been developed in the last decade to integrate two or three modules in Figure 2. For example, a "close coupling" between statistics package S-Plus and ArcInfo has been developed to conduct both GIS and statistical processes (Trevor 1995).

DBMS and GIS modeling

GIS-based DBMS have been widely used to manage and analyze karst features on both regional and national scales (Denizman 1997; Kochanov & Kochanov 1997; Whitman & Gubbels 1999; Cooper *et al.* 2001; Lei *et al.* 2001). The databases used in this research have been built over the past 20+ years. The most complete sinkhole database was constructed by Dalgleish and Alexander (1984b), and updated by Magdalene and Alexander (1995) using spreadsheet format for

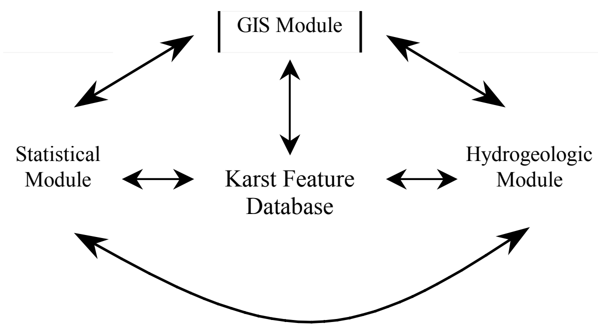


Figure 2. Logic design of Minnesota Karst Feature Database. See Figure 3 for the logical design of the central Karst Feature Database.

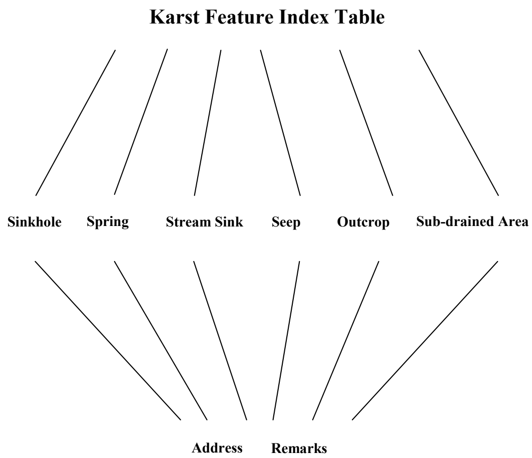


Figure 3. Database Structure of the Karst Feature Database of Southeastern Minnesota (Updated from Gao *et al.*, 2001). The top level karst feature index table stores basic and location information for each karst feature. The middle level tables, sinkhole - sub-drained area, store specific information for different features. The bottom level tables, address and remarks store owners' address and additional comments of each karst feature. See Figure 6 and 7 for applications built upon this structure.

Winona County. That inventory continues to be the model for subsequent work.

Existing county and sub-county sinkhole databases have been assembled into a large GIS-based relational database capable of analyzing the entire data set. Several other karst features in Winona County, including springs, seeps, and outcrops, have been mapped and entered into the Karst Feature Database of Southeastern Minnesota. The Karst Feature Database of Winona County is being expanded to include all the mapped karst features of southeastern Minnesota. Figure 3 illustrates the design and relationships of the Karst Feature Database of southeastern Minnesota. Tables are stored in a Microsoft Access 2000 DBMS and linked to corresponding

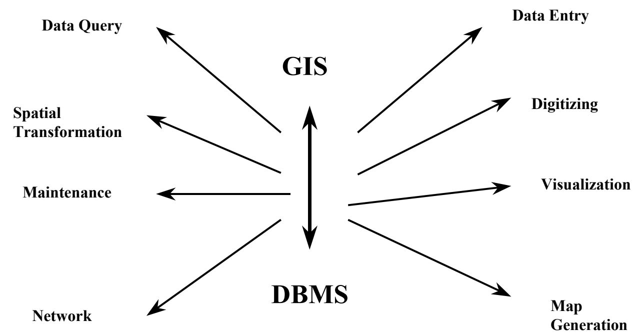
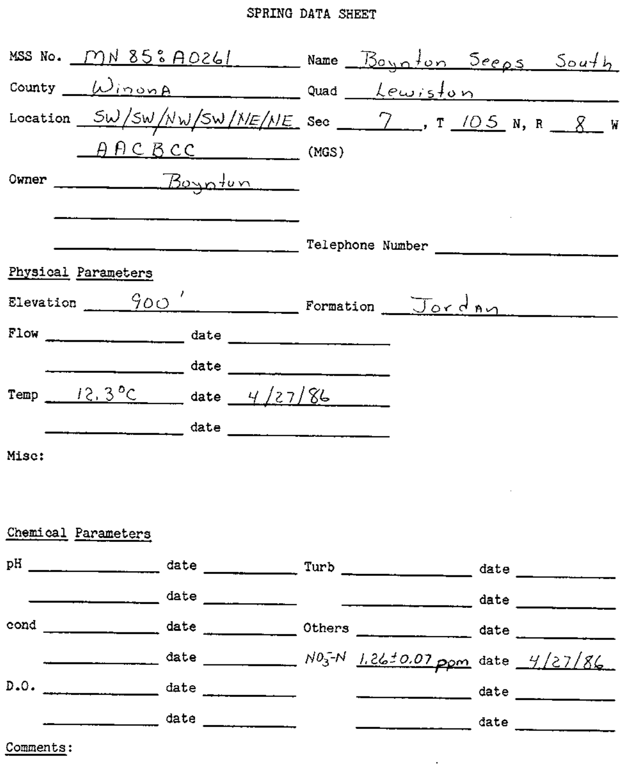


Figure 4. Applications built for GIS-based DBMS. See Figures 6 and 7 for examples of data entry, digitizing, and editing interfaces

ArcView shape files. A Karst Feature Index Table, primary table of the database, has a series of one to many and 1-to-1 cascading downward relationships to the other data tables. Codes are stored in a separate database and are accessed by Structured Query Language (SQL) requests. The code database contains lookup tables for code types. Code types are numerous, but cover all field entries where a specific text value is required. Examples would be fields such as quadrangle, stratigraphy, and surface strata. Figure 6 shows some of the codes used for sinkhole data represented by pull-down menus. Users can click the arrows of those pull-down menus and get the definitions of the codes used for different attributes. Using codes in this database significantly reduces storage space and improves performance of applications built on the DBMS.

In order to make a secure database, only the database management administrator (DBA) has the full-control permission to access all data and codes of the karst feature database. Other users will be assigned different permissions to access the database through different interfaces. Figure 4 shows some applications built for the central DBMS and the GIS module. These interfaces were written in Visual Basic, ArcInfo AML, and ArcView Avenue programming languages to interact with the karst feature database.

Most of the karst feature datasets of Southeastern Minnesota were inventoried as paper files and/or surveyed and marked on USGS 1:24,000 topographic maps (Fig. 5). Figure 5a is a paper-file record of a spring (ID number is MN85:A0261) in Lewiston, Winona County. This spring, also marked on a USGS 1:24,000 topographic map (Fig. 5b), was surveyed and recorded on April 26, 1986. Since some existing karst feature datasets are in either paper-file format or marked on topographic maps, two kinds of interfaces were created to enter and manipulate these two different dataset formats. One set of interfaces was written in Visual Basic programming language and linked to the Karst Feature Database under Microsoft Access 2000 DBMS. These interfaces were used to process karst feature records in paper-file format. The other set of interfaces was written in ArcView Avenue programming language and linked to the Karst Feature Database under


SPRING DATA SHEET

MSS No. MN 85:A0261 Name Boynton Seeps South
County Winona Quad Lewiston
Location SW/SW/NW/SW/NE/NE Sec 7, T 105 N, R 8 W
AACBCC (MGS)
Owner Boynton
Telephone Number

Physical Parameters
Elevation 900' Formation Jordan
Flow date
date
Temp 12.3°C date 4/27/86
date
Misc:

Chemical Parameters
pH date Turb date
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cond date Others date
date NO_3^--N 1.26±0.07 ppm date 4/27/86
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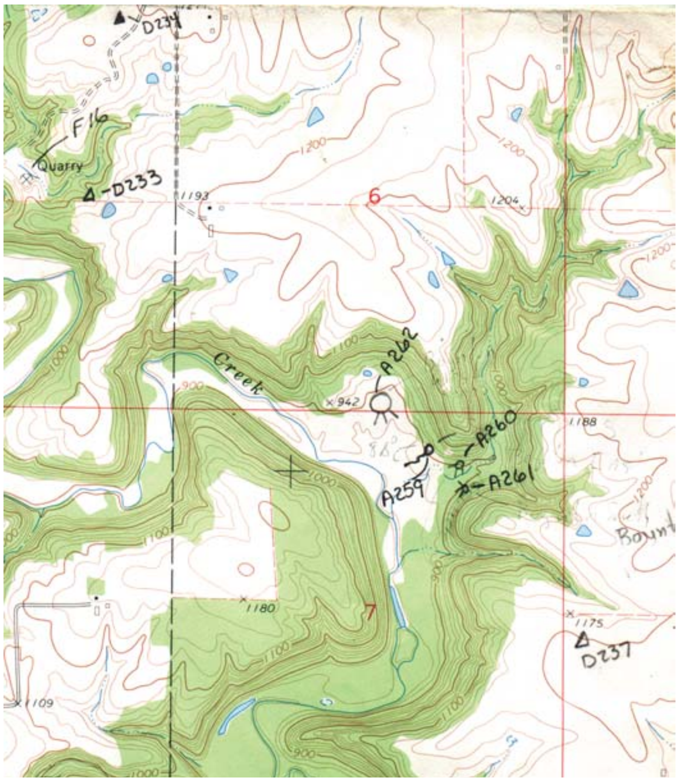

Figure 5a (left). Karst features recorded in a paper data sheet format. Figure 5b (right). Karst features compiled on USGS 1:24,000 topographic maps. This example is from the Lewiston Quadrangle, Minnesota - Winona Co., 7.5 minute series topographic map, 1974. The area of section 6 is 1 square mile.

ArcView 3.2 environment. These interfaces were used to process karst feature records surveyed and stored on topographic maps. Both kinds of interfaces would allow users to enter, edit, and query karst feature data stored in the karst feature database.

Figure 6 illustrates a data-entry interface for karst features in paper-file format. “BASE INFO” and “POSITIONING” in Figure 6 correspond to the top-level karst feature index table on Figure 3. The tabs (Sinkhole – Remarks) at the bottom section of Figure 6 are linked to the lower level data tables specific for each karst feature and its owner’s address and additional remarks through sub-form interfaces. These sub-form tabs correspond to the lower level tables on Figure 3.

Figure 7 shows a digitizing-editing interface written in ArcView Avenue programming language. This interface was used under ArcView 3.2 environment and connected to our karst feature database. Users can digitize karst features based on their location on USGS 1:24,000 topographic map or USGS Digital Orthoquad (DOQ). If a user clicks the “save” button on the interface, a karst feature’s location information such as geographic coordinates, quadrangle, township, and range will be automatically entered into the database. Users can also enter or modify some base information of a karst feature such as organization, digitizer, program, and data type. This information will be saved into the karst feature database when the “save” button is clicked. In addition, users can adjust the location of a karst feature and change some attributes of a karst feature through this interface.

Figure 6 demonstrates that information about a spring in Lewiston, Winona County, (see original data on Fig. 5a), is entered through the data entry interface. Figure 7 displays that users can find this spring and its corresponding USGS 1:24,000 topographic map through the digitizing-editing interface, which allows users to adjust the spring’s location and modify some attributes of the spring.

Karst feature visualization and distribution derived from the karst feature database

Several 2D and 3D maps showing the relationships between sinkhole distribution and bedrock geology, depth to bedrock, surficial geology, and surface topography have been created using ArcInfo, ArcView, and IRIS Explorer™. Figure 1 shows one rendering of this combined data set. This map, compiled from a series of 1:100,000 scale depth to bedrock and bedrock topography datasets developed by Minnesota Geological Survey, emphasizes the patchy nature of the thick sediment cover and the importance of site-specific information for land-use decisions. Figure 8 shows sinkhole distributions across county boundaries on top of bedrock geology. Bedrock geology information was compiled from a series of 1:100,000 scale bedrock geology datasets published by Minnesota

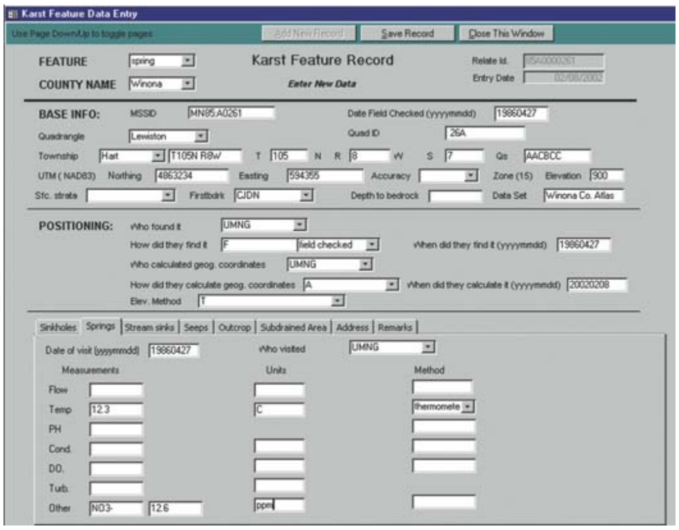

Figure 6. Data-entry interface written in Visual Basic programming language under Microsoft Access 2000 DBMS.

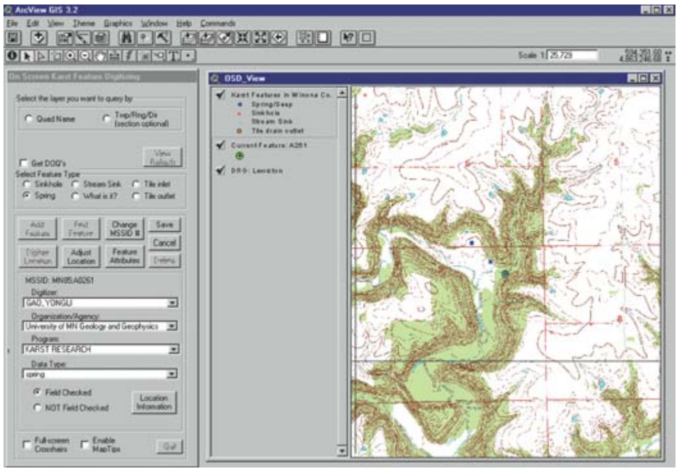

Figure 7. Digitizing-editing interface written in ArcView Avenue programming language under ArcView 3.2 environment. The background map is from the USGS Lewiston Quadrangle, Minnesota - Winona Co., 7.5 minute series topographic map, 1974.

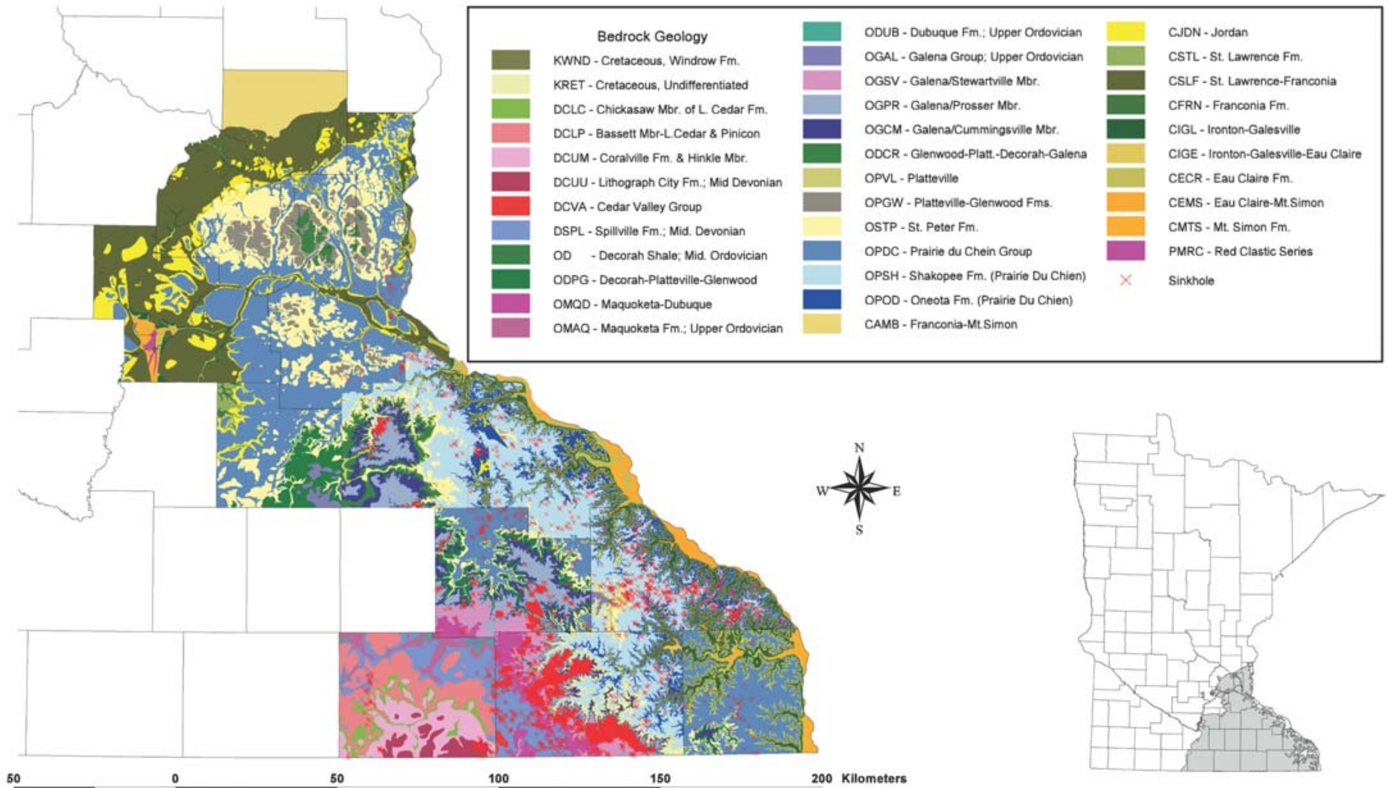

Figure 8. Sinkhole Distribution and Bedrock Geology of Southeastern Minnesota (Bedrock Geology information was compiled from 1:100,000 scale maps, Minnesota Geological Survey. Uncolored counties in the southwestern portion of this map have not been mapped with sufficient accuracy to draw informative bedrock geology maps.)

Geological Survey. A sinkhole dataset extracted from the karst feature database was superimposed on the bedrock geology map. The distributions of bedrock geology, depth to bedrock, and karst features form three bands of karst development that are arranged parallel to the Mississippi River. These bands of karst features extend into and correlate with similar distributions in northeastern Iowa. These three bands comprise the Prairie du Chien, Galena/Spillville, and Cedar Valley Karsts.

Figure 9. Histograms and cumulative fractions of the nearest-neighbor distances of the three stratigrapically distinct populations of sinkholes in southeastern Minnesota. Note the radically different numbers of sinkholes on the vertical axes of the three graphs. There are 146 Cedar Valley sinkholes, 6,940 Galena/Spillville sinkholes, and 1,161 Prairie du Chien sinkholes in these statistical analyses (Gao and others, 2001).

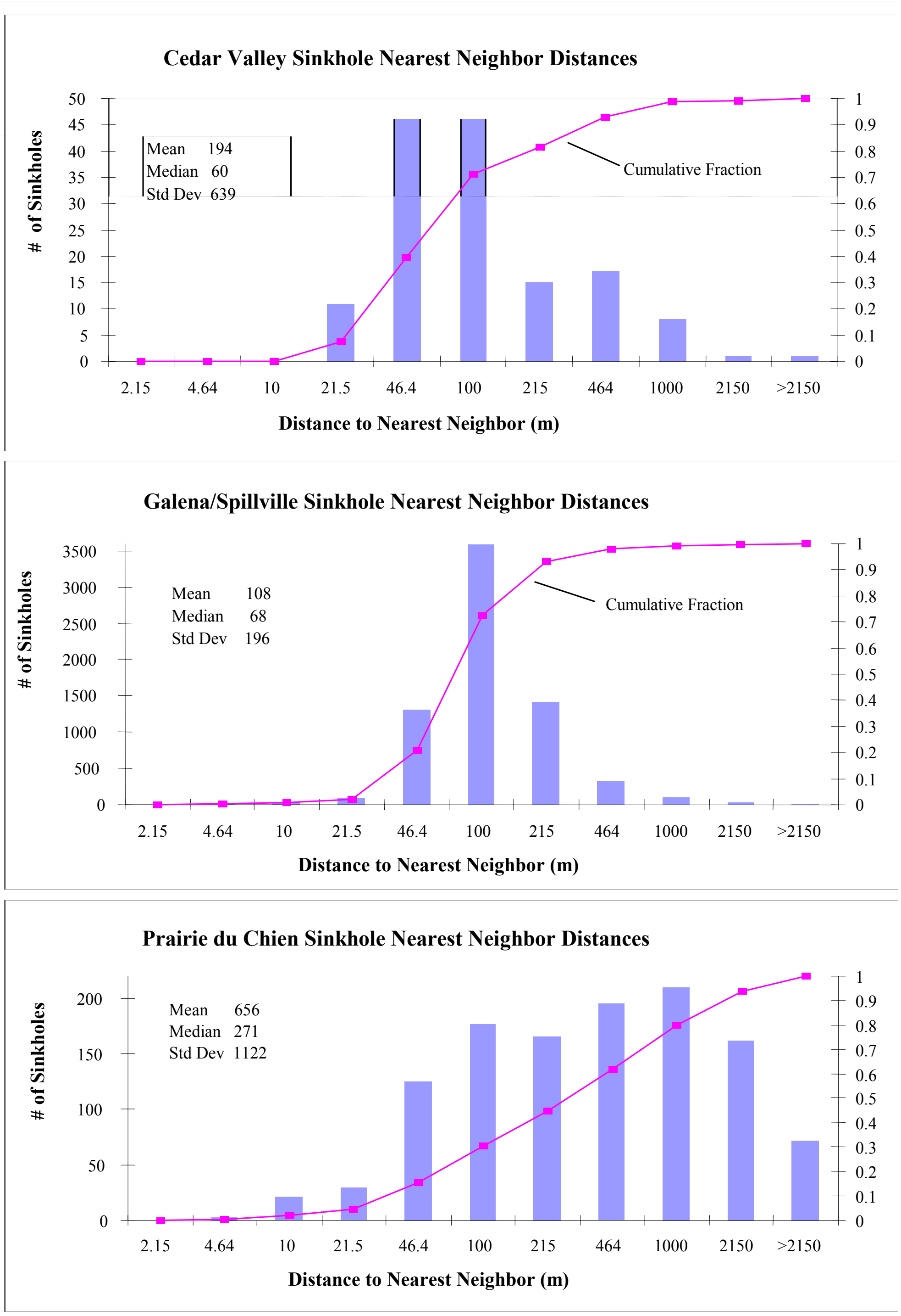

Figure 9 displays the histograms and cumulative fractions of the nearest-neighbor distances of the three sinkhole groups above. As can be seen in Figure 9, the median distance to the nearest neighbor is significantly less than the mean distance to the nearest neighbor of all the sinkhole groups. Our nearest-neighbor analyses on other sinkhole datasets all showed a highly skewed distribution. All the current nearest-neighbor analyses testify that sinkholes in southeastern Minnesota tend to cluster. This result confirms and expands Magdalene and Alexander's (1995) conclusion of clustered sinkhole distribution in Winona County to the entire Minnesota dataset. Figure 9 also reveals that the sinkholes in the Prairie du Chien Karst are spaced about 3-5 times further apart than are the sinkholes in the Cedar Valley and Galena/Spillville Karst. This implies that more isolated sinkholes occur in Prairie du Chien Karst.

FURTHER STUDY

All current nearest-neighbor analyses demonstrate that sinkholes in southeastern Minnesota are not evenly distributed in this area. Additional statistical methods such as cluster analysis, probability estimation, correlation and regression will be implemented to study the spatial distributions of mapped karst features of southeastern Minnesota. The results of these spatial analyses will provide evidence for karst hazard assessment.

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