Karst GeoHazards, Beck (ed.) © 1995 Balkema, Rotterdam, ISBN 90 5410 535 6

Sinkhole distribution in Winona County, Minnesota revisited

SUZANNE MAGDALENE & E.CALVIN ALEXANDER, JR Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minn., USA

ABSTRACT

The sinkhole distribution in Winona County, Minnesota was first mapped by Dahlgleish and Alexander (1984). They used the distribution of 535 sinkholes to define sinkhole probability zones. In 1992, a new survey identified an additional 73 sinkholes -- 39 older sinkholes missed in the first survey and 34 new sinkholes that have developed since 1983. All 73 sinkholes are located in the two highest sinkhole probability zones, supporting the criteria by which the original zones were delineated.

The mean density of the Winona County sinkholes is 0.52 sinkholes/km^2 in the area underlain by the Prairie du Chien. Sinkholes only occur over the Prairie du Chien Group. A moving window analysis, using a 1.69 km^2 window and a 0.1 km step, was applied to determine the spatial distribution of sinkhole densities. The resulting sinkhole densities were contoured and range from 0 to 14.8 sinkholes/km^2.

A nearest-neighbor analysis was applied to the sinkhole data set. The observed mean distance between nearest-neighbors is 385 m. The range of nearest neighbor distances is 6 m to 3999 m. Test statistics by Skellam (1952) and Clark and Evans (1954) were used to test the nearest-neighbor distances against the values expected from a spatially random data set. Random data sets were created and analyzed for comparison. The observed sinkhole locations are significantly different than a random distribution in visual spatial distribution, in nearest-neighbor distance histograms, and in tests for randomness. With near certainty, the observed sinkholes are clustered. The observed mean nearest-neighbor distance is about half the distance expected for a random population with the same number of sinkholes.

The 34 new sinkholes often develop in clusters and their nearest neighbors are usually another new sinkhole. The observed directions to nearest neighbor do not have preferred orientations along regional joint sets and are similar to the direction distribution calculated from random data sets. Sinkhole genesis does not appear to be structurally controlled in Winona County. Bedrock lithology, surficial geology, and topography of the land surface appear to be significant controlling factors.

INTRODUCTION

Those who live and work in karst regions often depend on groundwater as their primary water source. However, sinkholes (or dolines) serve as direct links between the land surface and karst aquifers, causing the groundwater to be highly susceptible to contamination. The travel time of water moving from the surface to karst aquifers via sinkhole run in can be as short as minutes. Water pollution in the aquifer can return to the land surface in springs, where it affects wildlife, domestic animal, and human populations alike.

Water resource managers and land use planners seek to protect water resources from potential pollution or to minimize existing pollution problems. Effective resource management decisions in karst regions depend on detailed knowledge of karst hydrogeology. It is in the context of resource management that this study attempts to improve the understanding of karst hydrogeologic processes and environmental implications in Winona County, Minnesota.

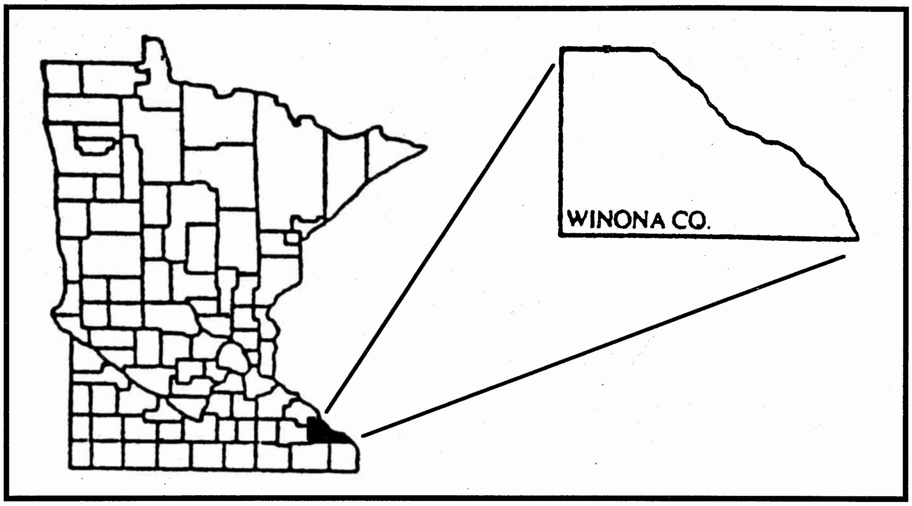


FIGURE 1. Location of Winona County, Minnesota.

Study area

Winona County is located in southeastern Minnesota (Figure 1). Southeastern Minnesota is part of a karst region that includes southwestern Wisconsin and northeastern Iowa. The geology of the karst region is dominated by lower Paleozoic strata deposited in a shallow epicontinental sea which occupied the Hollandale embayment, extending northward out of the Iowa Basin. The Lower Ordovician Prairie du Chien Group, containing sandy dolomites and quartzose sandstones, forms a karst plateau across much of Winona County. The landscape is characterized by broad, flat-topped ridges, which are incised by steep, narrow drainageways. Based on the classification system of Sweeting (1973), the study area is a mantled fluviokarst. Karst bedrock is overlain by layers of unconsolidated surficial deposits. The surficial deposits in Winona County are Quaternary glacial till and loess (Hobbs, 1984). Productive silt loam soils have developed on top of the surficial deposits (Luethe, 1994). The climate is a temperate, continental type. The mean annual precipitation is 79 cm (31 in). The mean daily temperature is -9 °C (16 °F) in the winter and 21 °C (70 °F) in the summer (Luethe, 1994).

There are both regional and local groundwater flow systems in Winona County. Regional flow within the bedrock aquifers is to the northeast toward the Mississippi River (Kanivetsky, 1984). In addition, the overlying bedrock aquifers tend to have higher potentiometric levels than the underlying aquifers, producing downward flow from the upper aquifers to the lower aquifers (Broussard et al., 1975). Where stream valleys are incised into bedrock aquifers, groundwater discharges into streams (Kanivetsky, 1984). This creates local flow systems which recharge on the ridge tops and discharge toward the stream valleys.

The sinkholes which develop in Winona County range along the continuum between cover subsidence and cover collapse (Dahlgleish and Alexander, 1984). Cover subsidence sinkholes develop gradually from the slow ravelling of noncohesive cover deposits down cracks in the carbonate bedrock, and are characterized by gently sloping walls (Wilson and Beck, 1992; Ford and Williams, 1989; White, 1988; Beck, 1984). Cover collapse sinkholes develop rapidly from the sudden downward transport of cover deposits into underlying voids, and are characterized by vertical or steeply sloping walls (Wilson and Beck, 1992; White, 1988). Subsidence is a slow, continuous process due to low material strengths, while collapse is a sudden, sporadic process due to high material strengths. Material strengths occur along a continuum, as do the styles of sinkhole development. Any given sinkhole may exhibit a single style or a combination of styles during its lifespan.

Background

Dahlgleish (1985) conducted a survey of the county's sinkholes in the summer of 1983. Before 1983, little information was available regarding the location and physical characteristics of sinkholes in Winona County. The data collection effort of Dahlgleish identified, mapped, and described 535 sinkholes. Dahlgleish's survey was conducted as part of the Minnesota Geological Survey's development of the Winona County Geologic Atlas (Balaban and Olsen, 1984). The atlas included 1:100,000 maps of surficial geology (Hobbs, 1984), bedrock geology (Mossler and Book, 1984), bedrock hydrogeology (Kanivetsky, 1984), and sinkhole probability (Dahlgleish and Alexander, 1984), and other maps.

Dahlgleish (1985) characterized the sinkholes in Winona County as being open depressions located primarily on the ridges of the karst plateau. The 535 sinkholes surveyed in 1983 tended to be steep-sided and of moderate to large dimensions (larger than four meters along their long-axis). Dahlgleish found that the probable controlling factors in sinkhole occurence were primarily, bedrock stratigraphy, and secondarily, land surface topography and surficial stratigraphy. The depth to water table did not appear to be a significant controlling factor. A sinkhole probability map (Dahlgleish and Alexander, 1984) was created for the Winona County Geologic Atlas, with probability zones classified as High, Moderate-to-High, Low-to-Moderate, Low, and No Probability. The governing criteria for the probability zones was the distribution of sinkhole densities. This criteria was based on the observation of Kemmerly (1982) that many new sinkholes tend to form in the vicinity of older, well developed sinkholes. The boundaries of the probability zones were qualitatively delineated, based on general zones of higher and lower sinkhole densities.

Purpose of the study

The current study was undertaken to update the sinkhole database for Winona County. The specific objectives were: 1) to document the location and physical characteristics of sinkholes not previously identified in 1983, 2) to compare the physical characteristics of the newly identified sinkholes with the physical characteristics of the sinkholes identified in 1983, 3) to use the newly identified sinkholes to evaluate the validity of the original probability criteria of the sinkhole probability map, and 4) to evaluate the geographic distribution of the densities and physical characteristics of the sinkholes in Winona County to derive a more quantitative basis for the probability criteria. A secondary goal of the current study was to evaluate sinkhole treatment as a best management practice used to reduce nonpoint source pollution to karst groundwater.

The sinkholes in Winona County were re-surveyed in 1992. Seventy-three previously unidentified sinkholes were mapped and described. Of these 73 sinkholes, 39 had developed before 1983 and 34 had developed since 1983. In this paper, the Winona County Sinkhole Data Set A refers to the sinkholes surveyed in 1983, mapped by Dahlgleish and Alexander (1984), and described by Dahlgleish (1985). The Winona County Sinkhole Data Set B refers to the newly identified sinkholes surveyed in 1992, and mapped and described in Magdalene (1994) and in this paper. Finally, the Winona County Sinkhole Data Set C is a combination of Data Set A, updated from 1992 fieldwork, and Data Set B. Magdalene (1994) is a more detailed description of Data Sets B and C.

METHODOLOGY

Field investigation

The U.S. Department of Agiculture (USDA)-Soil Conservation Service (SCS) in Winona County was a source of information for many of the newly developed and/or recently treated sinkholes in Data Set C. Landowners in the county occasionally request assistance of the SCS engineers in the treatment of sinkholes located on their land. The SCS staff provided records of these activities, including the location of sinkholes investigated by the SCS, and some information about sinkhole dimensions and treatment dates. When these sites were visited, landowners were questioned regarding neighboring and/or previously sealed sinkholes that SCS staff might not have known about. Although landowner memories may not be as precise or quantifiable as the USDA-SCS records, this information source has proven reliable and the information is not available from any other source. A few previously unidentified sinkholes were found through this method.

Data analysis

Sinkhole density was calculated by two methods: as an average sinkhole density estimated for a portion of the study area, and as the variation of sinkhole densities across the study area. In Winona County, no sinkholes are found beyond the stratigraphic lower boundary of the Prairie du Chien Group. Therefore, the areal extent of this strata was selected for the estimation of average sinkhole density.

Moving window average analysis was used to calculate the distribution of sinkhole densities across the study area. The size of the window was selected to be larger than most sinkhole clusters, but small enough to give local detail between clusters. On topographic maps, sinkhole clusters were usually less than 1200 meters in diameter and some of the clusters were spaced 1700 meters apart. Therefore, a step size of 0.1 km and a window size of 1.69 km^2 (1300 meters squared) were selected.

A nearest-neighbor program used the Universal Transverse Mercator (UTM) coordinates of the Data Set C sinkhole locations to calculate the direction and distance to each sinkhole's nearest neighbor. To avoid the edge-effect (Cressie, 1991; Clark and Evans, 1954), the sinkholes were evaluated for proximity to the county boundary. In an infinite population, sinkholes close to the boundary may have nearest-neighbors outside of the boundary. Limiting one's data analysis to the sinkholes within the boundaries might result in nearest-neighbor values that are too high. The convoluted, stream-cut boundary of the Prairie du Chien was not considered to be subject to the edge-effect. It is a real, geologic boundary to the extent of the sinkholes. The straight boundaries along the northwest, west, and south borders of the county are political and not geologic. Along these boundaries, only four sinkholes were identified that were closer to the county boundary than they were to their nearest neighbor. Therefore, it appeared unnecessary to apply the buffer zone recommend by Cressie (1991). For these four sinkholes, the nearest neighbors were not calculated and were not included in the nearest neighbor statistics, but the four sinkholes were included in the pool of potential neighbors.

A set of random sinkhole locations was generated to compare against the observed sinkhole locations in Data Set C. Random number sets were generated that ranged between the minimum and maximum Universal Transverse Mercator (UTM) coordinates for Winona County. The point locations covered a rectangular area. The Prairie du Chien boundary was applied as a cookie cutter to eliminate the parts of the rectangular area where sinkholes are known to not occur. The result was random sinkhole locations on the Prairie du Chien plateau. Random number sets were successively generated until the "cookie-cutter" gave approximately 608 random sinkhole locations. A random number set of n=1250 resulted in 605 random sinkhole locations on the karst plateau. The random sinkhole locations were compared visually and statistically against the observed locations.

RESULTS

Sinkhole characteristics

The sinkholes in Data Set B are similar to those in Data Set A in their shape and dimensions: steep-walled with less than 10 m (30 ft) diameters. However, the Data Set A sinkholes were more than 25 years old, open holes without apparent in-filling, and located on the ridges of the karst plateau. In contrast, the Data Set B sinkholes were less than 5 years old, closed holes due to sinkhole treatment, and located on slopes and in waterways.

Sinkhole probability map

The sinkholes in Data Set B were plotted on the sinkhole probability map (Dahlgleish and Alexander, 1984) of the Winona County Geologic Atlas. All 73 sinkholes are in the High or Moderate-to High sinkhole probability zones. The location of all of the newly identified sinkholes in the High or Moderate-to-High sinkhole probability zones is an encouraging test of the criteria used to develop the original map.

Moving window analysis

The areal extent of the Prairie du Chien plateau is 1167 km^2 (452 mi^2), and the average sinkhole density of Data Set C is 0.52 sinkholes/km^2 (1.35 sinkholes/mi^2). Using moving window analysis with a 1.69 km^2 window size, the range of sinkhole densities across the study area are 0 to 14.8 sinkholes/km^2.

Nearest neighbor analysis

Of the 608 sinkholes in the pool of potential neighbors, 430 were the nearest-neighbor for at least one other sinkhole. About 63%, or 272 sinkholes, were the nearest-neighbor for only one other sinkhole. About 33%, or 142 sinkholes, were the nearest neighbor for two other sinkholes, and the remaining 16 sinkholes were the nearest neigbor for three other sinkholes. No sinkhole was nearest neighbor for more than three sinkholes. This result is not an indication of the limit to the number of sinkholes in each cluster, but it is an indication of the limit to the number of sinkholes clustered around any individual sinkhole.

Using the cookie-cutter method described above, a set of random sinkhole locations was generated for comparison with the observed Data Set C sinkhole locations. The comparison is shown in Figure 2. The observed locations show a marked degree of clustering relative to the random locations. The map of the observed locations (Figure 2a) contains areas of high and low sinkhole densities. In contrast, the random locations (Figure 2b) are more evenly distributed across the study area.

A histogram of the nearest-neighbor distances for the Data Set C sinkholes is shown in Figure 3a. The mean distance to nearest neighbor is 385 ± 485 (1σ) meters. The values range from 6 to 3999 meters. The histogram displays a log-normal distribution. Most of the sinkholes are located near another sinkhole, while a few sinkholes occur as isolated individuals. Figure 3b is a histogram of the nearest-neighbor distances for the random sinkholes mapped in Figure 2b. The distribution in Figure 3b is distinctly different from the distribution in Figure 3a. There are many more close nearest-neighbors in the distribution of observed sinkholes than in the distribution of random sinkholes. The mean nearest-neighbor distance for the random sinkholes, 798 ± 444 (1σ) meters, is nearly twice the mean distance of the observed sinkholes. In addition, there are fewer isolated individual sinkholes in the random data set. The distances between the random sinkholes range from 28 to 2722 meters, a smaller range than for the observed sinkholes.

The mean value of the distance to nearest neighbor measurements was used for the Skellam (1952) and Clark-Evans (Clark and Evans, 1954) tests for complete spatial randomness. The Skellam random spatial index B is,

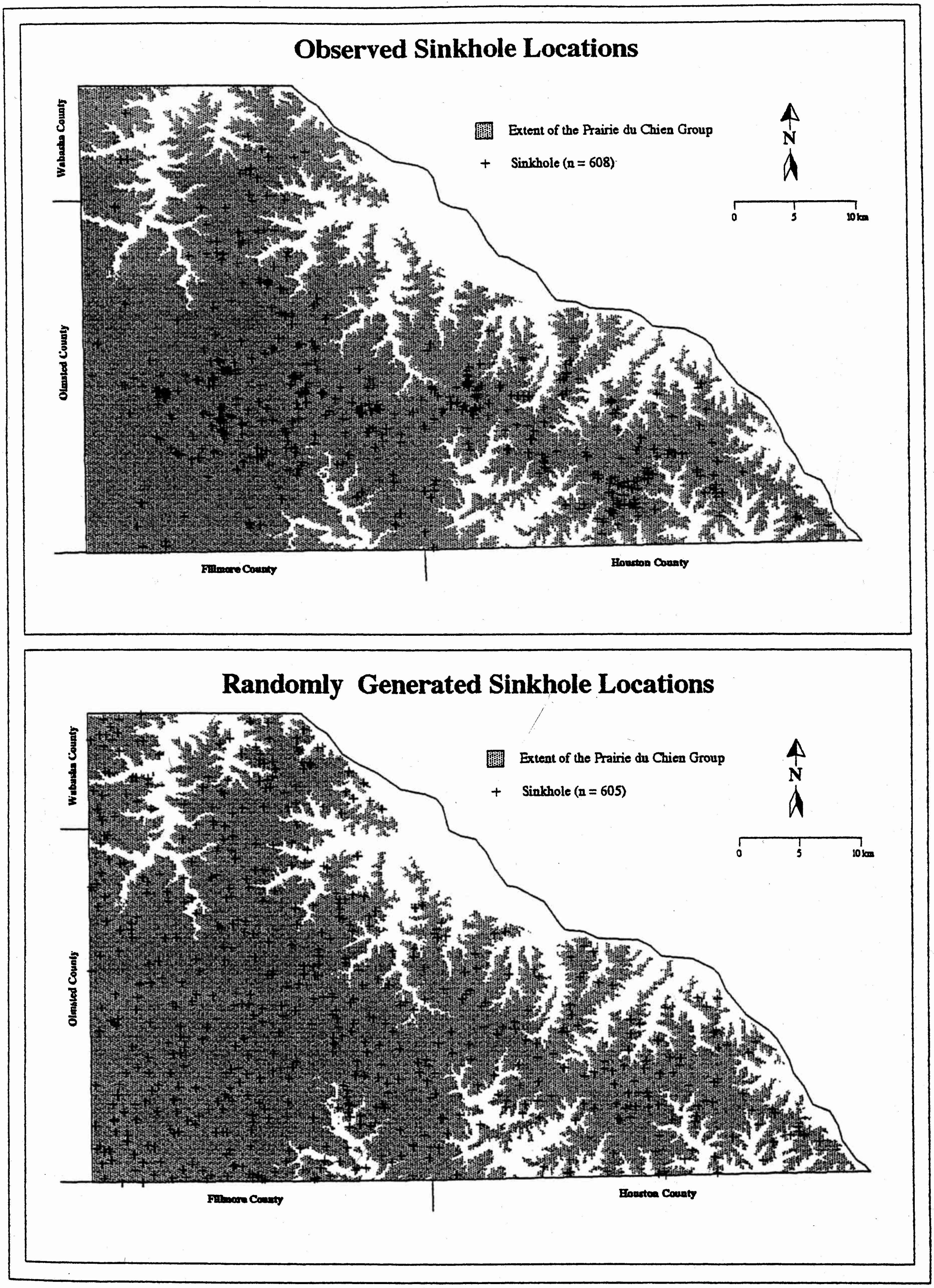
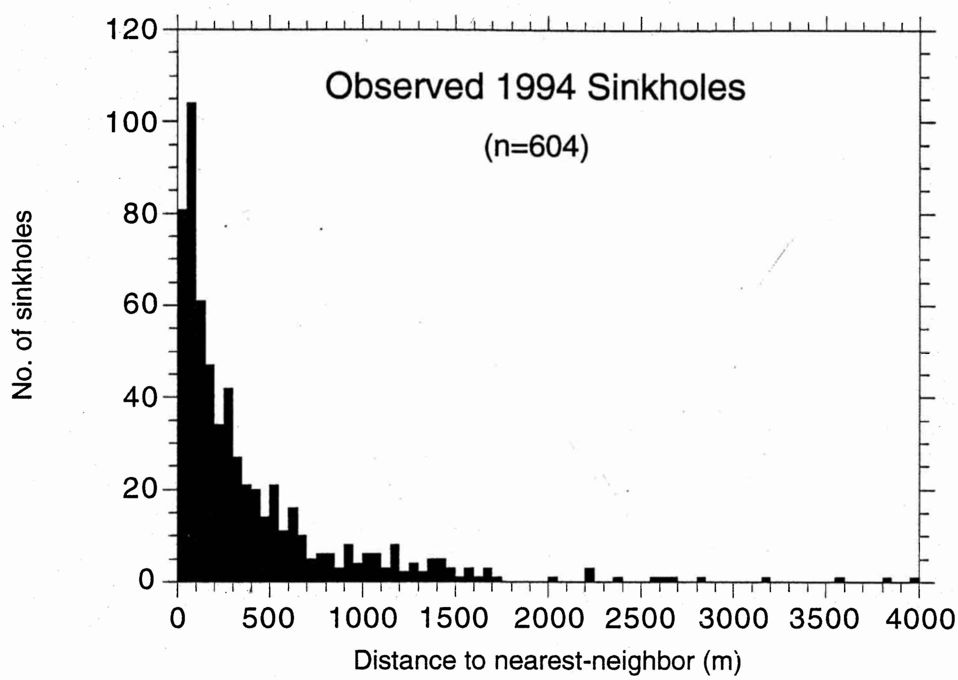


FIGURE 2: Sinkhole locations in Winona County, a) observed 1994 sinkhole locations, and b) randomly generated locations.



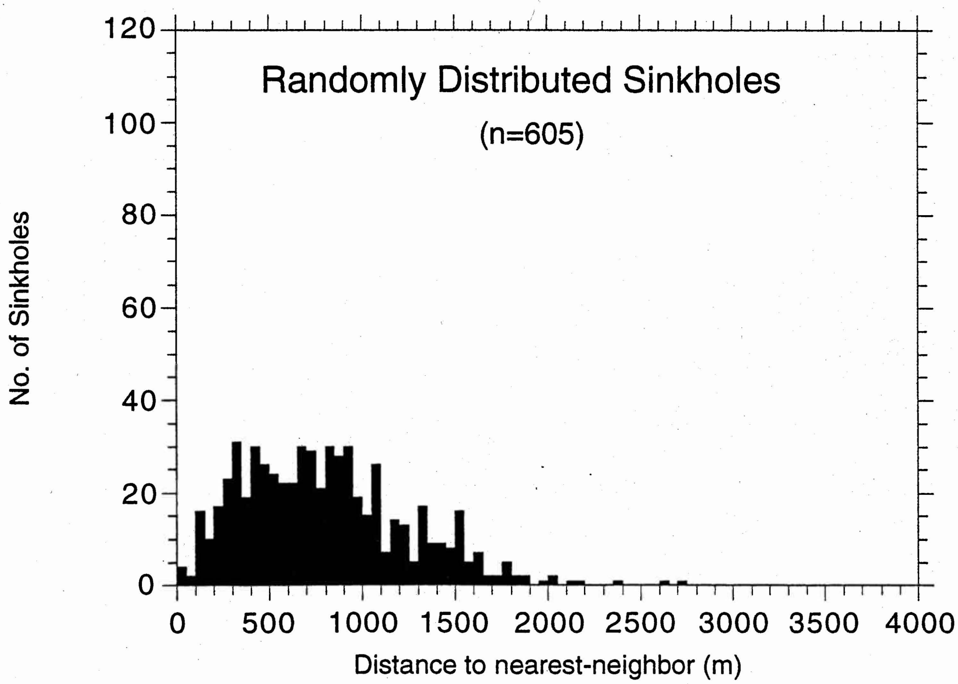


FIGURE 3: a) Distance to nearest-neighbors of the observed 1994 sinkholes in Data Set C. The mapped locations of the sinkholes are shown in Figure 2a. b) Distance to nearest-neighbors of the randomly located sinkholes. The mapped locations of the sinkholes are shown in Figure 2b.

$$B = 2\pi D \sum_{i=1}^{n} L_i^2$$

where D is 0.52 sinkholes/km^2, the sinkhole population density, L_i is the distance to nearest-neighbor for sinkhole i, and n is 604, the number of sinkholes with nearest-neighbor measurements. For the Data Set C sinkholes, B=831.2. The index B has a chi-square distribution in 2n degrees of freedom. For n=604, the χ^2 distribution is approximated by:

$$\Pr\left[\chi^2_{2n} < B\right] \approx \Phi\left[\sqrt{9n}\left\{\left(\frac{B}{2n}\right)^{1/3} - 1 + \frac{2}{9}(2n)^{-1}\right\}\right] \quad \text{or} \quad \Pr[B < 831.2] = \Pr\left[\chi^2_{1208} < 831.2\right] \approx \Phi(-8.625)$$

where Φ is the unit normal probability function. The values of ±1.96 and ±2.58 correspond to the 0.05 and 0.01 significance levels. According to the Skellam index, the probability that the Winona County sinkholes are randomly distributed is effectively zero.

The observed sinkhole locations in Data Set C were also evaluated with the Clark-Evans (Clark and Evans, 1954) test for complete spatial randomness. The Clark-Evans random spatial index, R, is the ratio between the observed mean distance to nearest-neighbor (L_a) and the expected mean distance to nearest-neighbor (L_e) for an infinitely large random population with density D, where

$$R = \frac{L_a}{L_e} \quad \text{and} \quad L_e = \frac{1}{2\sqrt{D}}.$$

R ranges from 0 (maximum aggregation or clustering) to 1.0 (complete spatial randomness) to 2.149 (hexagonal regular pattern). If the value of R is significantly less than 1.0, the points are more clustered than random. If the value of R is significantly greater than 1.0, the points are more regular than random. The expected mean distance to nearest neighbor, L_e, is 0.693 km for 608 sinkholes distributed across 1167 km^2. The observed mean distance to nearest neighbor is 0.385 km, so the Clark-Evans ratio is,

$$R = \frac{L_a}{L_e} = \frac{0.385}{0.693} = 0.555.$$

Since R has a normal probability distribution, the significance of departure from 1.0 can be tested with the standard normal curve,

$$z = \frac{L_e - L_a}{\sigma_{Le}} \quad \text{and} \quad \sigma_{Le} = \frac{0.26136}{\sqrt{nD}}$$

where σ_{Le} is the standard error of L_e in a random population of density D, and n is 604, the number of sinkholes with nearest-neighbor measurements. The standard error of the 1994 sinkhole dataset is 0.0147, and the z-value is 20.9. For a two-tailed test, the z-values of ±1.96 and ±2.58 correspond to the 0.05 and 0.01 significance levels. The probability that the Winona County sinkholes are randomly distributed and R=0.555 is effectively zero. The sinkholes in Winona County are clustered. The value of R is also an indication of the degree of clustering of the sinkholes. The mean observed nearest-neighbor distance is about half the mean expected distance for a random population with the same average density.

The random sinkhole locations in Figure 3b were evaluated for complete spatial randomness using the Clark-Evans index. The observed mean distance between nearest-neighbors for the random number set was 0.798 km. The expected mean sinkhole density for n=605 is 0.518 sinkholes/km^2. The expected mean distance between nearest-neighbors is 0.695 km. The index R is the ratio between the observed and the expected, or 1.148. The value of R under conditions of randomness is 1.0. Whether 1.148 is a significant departure from 1.0 can be tested with the above equation for the z-value. The standard error in this case is 0.01476, so the z-value is -6.98. The probability that the "random" number set satisfies complete spatial randomness is nearly zero. The cookie-cutter method appears to result in a population that has a slightly regular spatial distribution. To test this observation, the original random number set of n=1250 was evaluated with the Clark-Evans index. The original random number set hasa value of R =1.023, with a z-value of -1.58. Therefore, the original random number set is a truely random distribution, and the "cookie-cutter" imposes a slightly regular distribution on the random locations.

Reporting ages

Sinkhole investigators have identified differences in the spatial distribution of ancient and modern sinkholes. Ancient sinkholes are those which developed before modern record-keeping. Modern sinkholes developed since record-keeping began and, presumably, better information is available regarding their genesis. The best predictor of where new sinkholes will develop is the location of other recently developed sinkholes (Beck, 1991; Upchurch and Littlefield, 1987). Beck (1991) recommends using only recently reported (within three to five years after collapse) sinkholes to calculate temporal development rates and spatial occurence rates for sinkholes.

There are 34 sinkholes that developed in the time interval between the 1983 and 1992 sinkhole surveys. The nearest-neighbors of these sinkholes were evaluated to determine which reporting-age group is the best predictor of the location of newly developed sinkholes. The reporting-age is known for the nearest-neighbor of 28 of the 34 new sinkholes. Of these 28 , 57%, or 16 nearest-neighbors had developed in the last 5 years. Fifteen of the 16 new sinkholes are in three clusters of 4 , 5, and 6 sinkholes. In the cluster of six sinkholes, no other sinkhole was known in that immediate area. In the other two clusters, spaced less than 30 meters away from the new sinkholes, were older sinkholes that had been filled. The newly developed sinkholes tend to form in clusters. And, instead of being clustered around an older sinkhole, the majority of new sinkholes are nearest to another new sinkhole. However, two of the clusters of new sinkholes developed within 30 meters of an older, filled sinkhole.

CONCLUSIONS

The distribution of sinkholes in Winona County are not random but are strongly clustered. Nearest neighbor analyses indicate that the average distance between the mapped sinkholes is about half of that expected from a spatially random distribution of the same average density. The Skellam (1952) and Clark and Evans (1954) statistical tests for complete spatial randomness indicate clustering at better than the 0.01 significance level. On the scale of several kilometers, new sinkholes tend to develop in the areas of existing sinkholes. However, new sinkholes do not necessarily develop clustered around older sinkholes. A majority of the newly developed sinkholes in Winona County were clustered around another newly developed sinkhole. The location of newly developed sinkholes mapped in 1992 supports the criteria of the probability zones that were delineated using the 1983 sinkhole survey.

ACKNOWLEDGEMENTS

We thank Paul Williams for a critical review of this work. This study was funded by the Garvin Brook Rural Clean Water Project via the Minnesota Pollution Control Agency.

REFERENCES

Balaban, N.H., and Olsen, B.M., (eds.), 1984. Geological Atlas of Winona County, County Atlas Series, C-2. Minnesota Geological Survey, 8 plates.

Beck, B.F., 1984. Sinkhole terminology, in Beck, B.F., (ed.), Sinkholes: Their Geology, Engineering and Environmental Impact: Proceedings of the First Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, FL, October 15-17, 1984, A.A. Balkemea, Rotterdam and Boston, p. IX-X.

Beck, B.F., 1991. On calculating the risk of sinkhole collapse, in Kastning, E.H., and K.M. Kastning (eds.), Proceedings of the Appalachian Karst Symposium, Radford, Virginia, 23-26 March 1991: National Speleological Society, p. 231-236.

Broussard, W.L., Farrel, D.F., Anderson, H.W., Jr., and Felsheim, P.E., 1975. Water Resources of the Root River Watershed, Souteastern Minnesota. Hydrologic Investigations Atlas HA-548, U.S. Geological Survey.

Clark, P.J., and Evans, F.C., 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology, v. 35, p. 445-453.

Dahlgleish, J.B., 1985. Sinkhole Distribution in Winona County, Minnesota. M.S. Thesis, University of Minnesota, 95 pp.

Dahlgleish, J.B., and Alexander, E.C., Jr., 1984. Sinkhole and sinkhole probability map, Plate 5 of Balaban, N.H., and Olsen, B.M., (eds.), Geological Atlas of Winona County, County Atlas Series, C-2. Minnesota Geological Survey.

Ford, D.C., and Williams, P.W., 1989. Karst Geomorphology and Hydrology. Unwin and Hyman, London, 601 pp.

Hobbs, H.C., 1984. Surficial geology map, Plate 3 of Balaban, N.H., and Olsen, B.M., (eds.), Geological Atlas of Winona County, County Atlas Series, C-2. Minnesota Geological Survey.

Kanivetsky, 1984. Bedrock hydrogeology map, Plate 4 of Balaban, N.H., and Olsen, B.M., (eds.), Geological Atlas of Winona County, County Atlas Series, C-2. Minnesota Geological Survey.

Kemmerly, P.R., 1982. Spatial analysis of a karst depression population: Clues to genesis. Geological Society of America Bulletin, v. 93, p. 1078-1086.

Magdalene, S.C., 1994. Sinkhole Distribution in Winona County, Minnesota Revisited. M.S. Thesis, University of Minnesota, 108 pp.

Mossler, J.H., and Book, P.R., 1984. Bedrock geology map, Plate 2 of Balaban, N.H., and Olsen, B.M., (eds.), Geological Atlas of Winona County, County Atlas Series, C-2. Minnesota Geological Survey.

Skellam, J.G., 1952. Studies in statistical ecology: I. Spatial pattern. Biometrika, v. 39, p. 346-362.

Sweeting, M.M., 1973. Karst Landforms. Columbia Press, New York, 362 pp.

Luethe, R.A., 1994. Soil Survey of Winona County, Minnesota. U.S. Department of Agriculture Soil Conservation Service. 277 pp.

Upchurch, S.B., and Littlefield, J.R. Jr., 1987. Evaluation of data for sinkhole-development risk models, in Beck, B.F., and Wilson, W.L., (eds.), Karst Hydrogeology: Engineering and Environmental Applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, FL, February 9-11, 1987, A.A. Balkemea, Rotterdam and Boston, p. 359-364.

White, W.B., 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press, Oxford, 464 pp.

Williams, P.W., 1972a. The analysis of spatial characteristics of karst terraines, in Chorley, R.J., (ed.), Spatial Analysis in Geomorphology. Harper and Row, London, p. 135-163.

Williams, P.W., 1972b. Morphometric analysis of polygonal karst in New Guinea. Geological Society of America Bulletin, v.83, p. 761-796.

Wilson, W.L., and Beck, B.F., 1992. Hydrogeologic factors affecting new sinkhole development in the Orlando area, Florida. Ground Water, v. 30(6), p. 918-930.

PROCEEDINGS OF THE FIFTH MULTIDISCIPLINARY CONFERENCE ON SINKHOLES
AND THE ENGINEERING AND ENVIRONMENTAL IMPACTS OF KARST
GATLINBURG/TENNESSEE/2-5 APRIL 1995

KARST GEOHAZARDS

ENGINEERING AND ENVIRONMENTAL PROBLEMS IN KARST TERRANE

Edited by

BARRY F.BECK
P.E.LaMoreaux & Associates, Inc., Oak Ridge, Tennessee
(Formerly: Director of the Florida Sinkhole Research Institute)

Assisted by

FELICITY M.PEARSON

Sponsored by
P.E.LaMoreaux & Associates, Inc.
and Co-Sponsored by
The National Groundwater Association
The American Society of Civil Engineers, Tennessee Section
Institute for Geotechnology, University of Tennessee
Karst Waters Institute

A.A.BALKEMA/ROTTERDAM/BROOKFIELD/1995