# Fracture Mapping and Ground Subsidence Susceptibility Modelling in Covered Karst Terrain: Dougherty County, Georgia

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ABSTRACT

Dougherty County is a covered karst with 1,011 subsidence sinkholes that are developed in surface residuum over fracture-located cavities in the Eocene Ocala limestone. One possible consequence of a recent upsurge in the use of groundwater in the Ocala aquifer for irrigation, is accelerated sinkhole development due to a lowering of the regional piezometric surface or due to the formation of cones of depression at irrigation wells. Ground subsidence susceptibility maps have therefore been developed using sinkhole and bedrock fracture data. Dougherty County was partitioned into 855 cells each 1.18 $km^2$ in area. Five cell variables were used in modelling: the number of sinkholes, sinkhole area, the number of fractures, the number of fracture intersections, and the total length of fractures. Cells with moderate values for sinkhole area and high values for the other four variables were considered to be the most susceptible to ground subsidence. Broadly similar subsidence susceptibility models were developed from cell data by intersections, and separately by linear combination.

## INTRODUCTION

The Dougherty Plain is the prime agricultural region of southwest Georgia, including some 5,250 $km^2$ of the county. It is also a major recharge area for the Principal Artesian Aquifer, which is the most important source of groundwater in the southeastern United States. The Dougherty Plain is underlain by the upper Eocene Ocala limestone, a sub-aquifer of the Principal Artesian Aquifer. The limestone is covered almost everywhere by Oligocene to Recent residuum which in places exceeds 50 m in thickness. The area is a highly developed covered karst region with numerous

dolines, uvalas, semi-blind and blind valleys, sinking streams, and springs. Closed depressions have developed by subsidence and/or suffosion of residuum into cavities in the underlying Ocala limestone.

Subsidence sinkholes develop through the progressive collapse of arches or domes which span air-filled voids in the surface residuum. A void in the Ocala limestone, roofed by residuum, moves towards the surface by the collapse of roof material until it finally breaks through to the surface to form a sinkhole. Collapse of the roof temporarily produces a cylindrical hole which rapidly weathers into a gentler conical or bowl-shaped depression. Suffosion sinkholes are funnel-shaped depressions, which develop in residuum through spasmodic minor subsidences and more continuous piping of unconsolidated materials into widened joints and solution pipes in the Ocala limestone beneath.

As a result of severe droughts during the 1954 and 1977 growing seasons, agriculture in the Dougherty Plain has become increasingly dependent upon groundwater from the Ocala aquifer for irrigation. In 1970 less than 8 million $m^3$ of water were withdrawn for irrigation, in 1977 more than 150 million $m^3$ were withdrawn. Almost unheard of prior to 1970, center pivot irrigation systems increased to 376 in 1976 and to more than 1,000 in 1979 (Pollard et al., 1979; Kundell, 1980).

Increased use of the Ocala aquifer for irrigation could, in the long term, result in a lowering of the regional piezometric surface. In the short term cones of depression will be developed around center pivot and other irrigation wells. In either case one possible cause for concern could be accelerated development of subsidence sinkholes in the region. At cones of depression, surface residuum loses hydrostatic support and steep hydraulic gradients are produced. Increased groundwater flow velocities cause erosion of subsurface residuum into bedrock cavities. Natural and artificial recharge (in the form of irrigation water) percolates freely through the newly established vadose zone eroding the roofs of air-filled voids.

In Alabama an estimated 4,000 man-induced sinkholes are thought to have formed since 1900, most of them induced by a decline in the water table due to groundwater withdrawals (Newton, 1977). In some cases man-induced sinkholes near discharging wells have resulted in groundwater contamination (Spigner and Graves, 1977). A further problem is that some sinkhole subsidences are catastrophic. On the Far West Rand, South Africa, on December 12, 1962, a three-storyed crusher plant belonging to the West Driefontein Gold





Mine was engulfed by a huge sinkhole. The disaster took 29 lives. On August 3, 1964, another sinkhole formed suddenly in the same general area swallowing a house at the Blyvooruitzicht Mine, 5 persons were killed (Jennings, 1966). Accelerated sinkhole development in the Far West Rand is in response to a lower water table. Pumping of water from the gold mines has produced cones of depression 75-305 m below the former piezometric surface. In addition, many sinkhole collapses were triggered by large volumes of artificial recharge when water was discharged at the surface by the gold mines in the course of underground pumping (Brink and Partridge, 1965).

Because of the threat of accelerated sinkhole development on the Dougherty Plain, as a result of increased irrigation, there is a need for ground subsidence susceptibility maps, which can be used by land use and water resource planners. An attempt has been made to develop such maps in a sample area--Dougherty County--using easily acquired sinkhole and bedrock fracture data.

THE STUDY AREA: DOUGHERTY COUNTY

Dougherty County is approximately 43 km E-W, 21 km N-S, and covers 845 $km^2$. It is underlain by Cretaceous to Recent sedimentary rocks, which dip souteastwards at 2 m/km. These rest on crystalline basement rocks and older Paleozoic sediments. Only the extreme souteastern corner of the county lies outside the Dougherty Plain topographic province. This area is a part of the Tifton Upland and is capped by clays of the Miocene Hawthorne Formation. It is separated from the rest of the county by the Pelham Escarpment. Elevations on the Tifton Upland reach 100 m , on the Dougherty Plain they range from 50-75 m (Fig. 1).

The topography of the upper surface of the Ocala limestone in Dougherty County is highly irregular because it has been differentially weathered. The limestone may be less than 15 m thick in the west, where it occasionally outcrops, but increases to more than 75 m in the east. The Ocala is covered almost everywhere by surface residuum averaging 13 m in thickness in the northwest and 19 m in the southeast. Residuum thickness is highly variable and may increase by more than 30 m over a distance of less than 3 km (Wilson and Pickering, 1973). The residuum is sandy, silty clay and contains boulders of weathered siliceous limestone up to 2 m in diameter; it is thought to be primarily derived from the weathering of the Ocala limestone.

The Flint River and other surface streams in the county occupy channels that cut into the Ocala aquifer.

For most of the year these are effluent streams but at times of peak flow they may become influent. The Ocala aquifer is recharged through sinkholes and blind valleys. Sinkholes vary from 6-8 m deep and from 150-300 m in diameter. Many are alluviated, some containing perched water bodies. Other depressions with open ponors are sites of rapid recharge and therefore sites of potentially rapid groundwater pollution.

In recent years man-induced ground subsidences have become more frequent in Dougherty County, particularly in the county seat Albany. In one incident, Hilsman Park, located in a sinkhole, was selected by Albany city officials as an ideal location for a recreational lake. Clay was hauled in to make an impervious floor and logs and tree stumps were placed in the center of the sinkhole in an attempt to plug it. A well was drilled immediately adjacent to the area and water was pumped into the depression for several days forming a small lake. The lake lasted only a short time, the water eventually drained underground when part of the depression floor, including filling material, logs, and tree stumps, subsided into a subsurface cavity (Wait, 1963). A second subsidence occurred near Banks Halley Art Gallery in Albany. During heavy rains, storm runoff is funnelled into a sinkhole on the grounds of the gallery and is then pumped out through sewer lines. On June 6, 1973, during an especially heavy rain, one of the pumps failed and 2-3 m of storm water was ponded in the depression. This water triggered a subsidence only 15 m from the art gallery (Wilson and Pickering, 1973).

## MODELLING PROCEDURE

The relative susceptibility of an area in Dougherty County to ground subsidence was considered to depend on the number of subsurface cavities in the Ocala limestone, and on the liklihood of subsidence or suffosion of residuum into them. Ogden and Reger (1977) concluded from studies in Monroe County, West Virginia, that areas underlain by the most cavernous rock display the most dolines. They found that the percent of the limestone area in dolines and the doline density were useful indicators of areas of potential subsidence. Ford (1964) has demonstrated that in the central Mendip Hills of England the formation of one doline (the "mother") tends to promote subsurface conditions that are conducive to the formation of additional dolines (the "daughters") in the same area. Data on sinkhole density and on the percent of area in sinkholes were therefore used in modelling as being indicative of both the number of cavities in limestone and of the liklihood of further subsidence or suffosion of residuum occurring. In addition, as there is





potential development of solution voids along zones of high secondary permeability because these concentrate ground water flow, data on fracture density, fracture intersection density, and the total length of fractures in an area were also used in modelling the presence of solution cavities in the limestone.

A geographic information system DBMANG/CONGRID was used in sinkhole and bedrock fracture data analysis (Hokans, 1977). The program DBMANG (Data Base Manager Grid) was used to build and maintain a grid-format data base. The program accomodates up to 30 variables and any number of cells. CONGRID (Conversational Grid) was used to display grid-format data in grey-scale choropleth map form via a line printer. It is presently dimensioned for 29 variables and a maximum of 20,000 cells.

CONGRID has four map output options: (1) simple variable display (a data file map), (2) intersections of variables, (3) unions of variables, and (4) linear combinations of variables. Cells in the grid-format data base with 3-5 sinkholes form a set, cells with 6-8 fractures form another set. The intersection of these two sets (map option 2) includes all cells with 3-5 sinkholes AND 6-8 fractures. The union of these two sets (map option 3) includes cells with 3-5 sinkholes OR 6-8 fractures. The linear combination option is used when weighting of variables and values is needed in data analysis. For example, if the decline in the ground water table is considered to be twice as important in triggering sinkhole collapse as the depth of surface residuum, these two variables can be weighted 10 and 5 respectively in modelling ground subsidence susceptibility. Map options (1), (2), and (4) were used in this study.

In order to develope sinkhole and bedrock data files in DBMANG, Dougherty County was partitioned into 855 cells in 19 rows and 45 columns. Cell size was 1.0 X 1.1 km.

## SINKHOLE AND FRACTURE DATA COLLECTION

The U.S. Geological Survey 7.5 minute quadrangles show approximately 40% of the sinkholes in Dougherty County, the remainder are too shallow to be depicted on these maps which have only a 10 foot (3.05 m) contour interval. Sinkholes were therefore mapped from February, 1973, 1:24,000 scale, color infrared images (NASA Project 1473). Color infrared transparencies were viewed stereoscopically at 2X magnification. Sinkholes were identified by the presence of surface water bodies, from vegetation and soil moisture patterns, and from topographic expression. Sinkhole boundaries were drawn at the break of slope with the

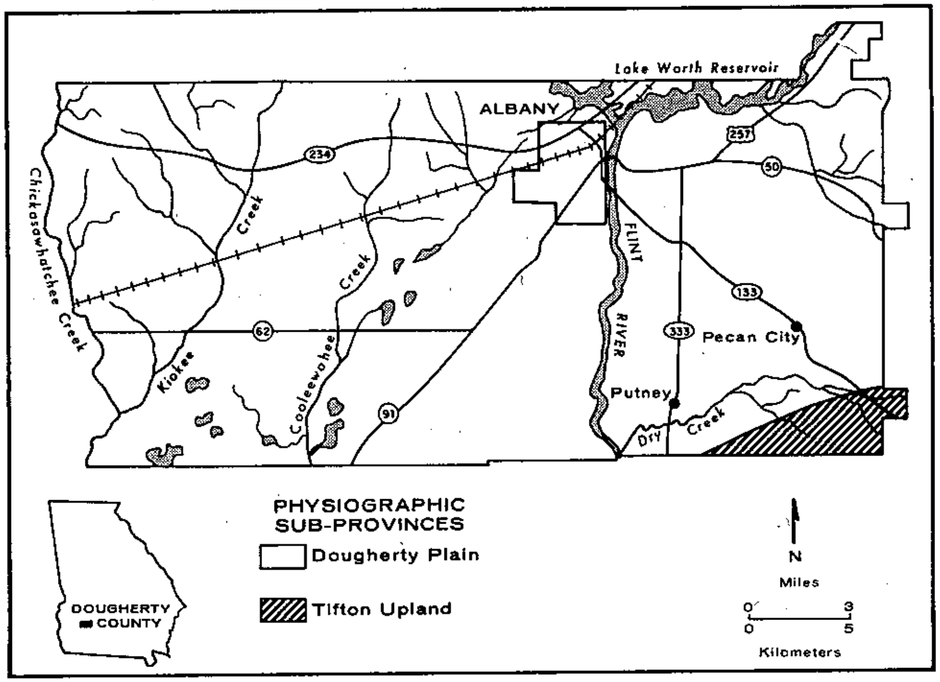


Fig. 1. The physical and built environment of Dougherty County, Georgia.

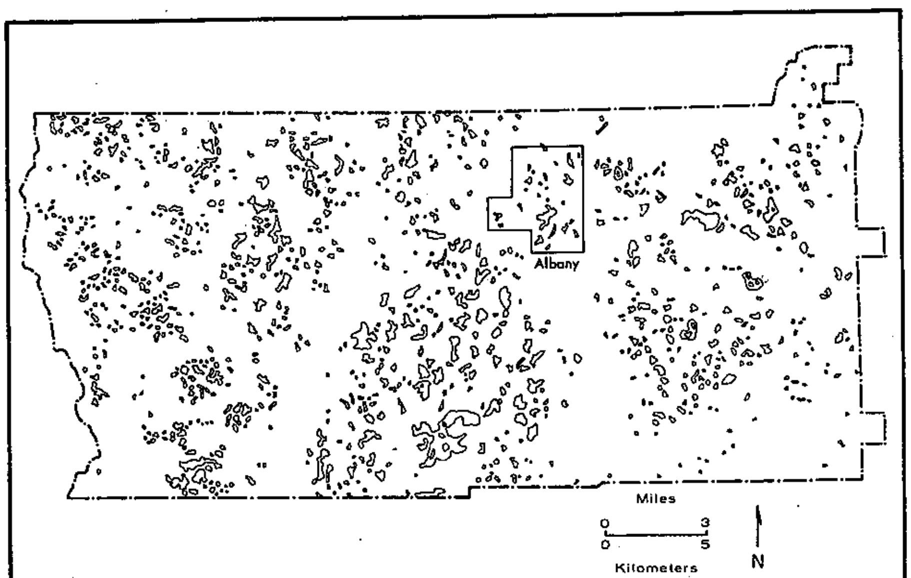


Fig. 2. The sinkholes of Dougherty County, Georgia.





surrounding flat terrain. Planimetric control was established by also mapping roads and railway lines. Photographic distortion was removed and sinkhole boundaries were transferred to 1:24,000 scale topographic maps using a Bausch and Lomb zoom transfer scope. In total 1,011 sinkholes were mapped, the mean density for the county being 1.1 sinkholes/km$^2$ (Figure 2). DEMANG data files were developed for the number of sinkholes in each cell (sinkholes lying in more than one cell were counted in each cell they occupied), and for the percent area of each cell occupied by sinkholes. The maximum number of sinkholes in any cell was 15, 32 cells contained more than 10 sinkholes (Figure 3). Five cells had more than 30% of their area covered by sinkholes, 26 cells had more than 20% covered.

The relationship between the number of sinkholes in a cell and the area occupied by them provides an insight into the evolution of sinkhole topography in Dougherty County (Figure 4). It suggests that there are two distinct stages in sinkhole development. In the first stage there is a gradual increase in the number of sinkholes in a cell and in the area they occupy. When the number of sinkholes reaches 14-15, a threshold is reached beyond which the topography enters a second stage of evolution. In this stage the lateral growth of sinkholes and their coalescence to form uvalas becomes more important than the formation of new sinkholes. The area of the cell occupied by sinkholes continues to increase but the number of separate depressions decreases.

A most important characteristic of the sinkholes in Dougherty County is that they have pronounced linear shape elements. To test whether these show statistically significant preferred orientations, the azimuths of prominent long axes or other linear shape elements in 205 sinkholes, in randomly selected cells, were measured and grouped into 10-degree classes (Figure 5). Chi-squared analysis was used to test for non-randomness in the distribution (Pincus, 1953). Six classes, their midpoints at 325, 315, 305, 5, 25, and 35°, were found to be significantly non-random at the 0.05 level. When adjacent significant classes were grouped, three preferred orientations emerged at 315, 5, and 30°.

Wilson (Doug Wilson, personal communication) reports joint directions at 300, 10, and 30° in Ocala limestone visible along the banks of the Flint River in Dougherty County during periods of low flow. The close agreement between measured joint directions and the orientations of linear sinkhole shape elements suggests that sinkholes in Dougherty County have developed above, and are elongated parallel to fractures in the

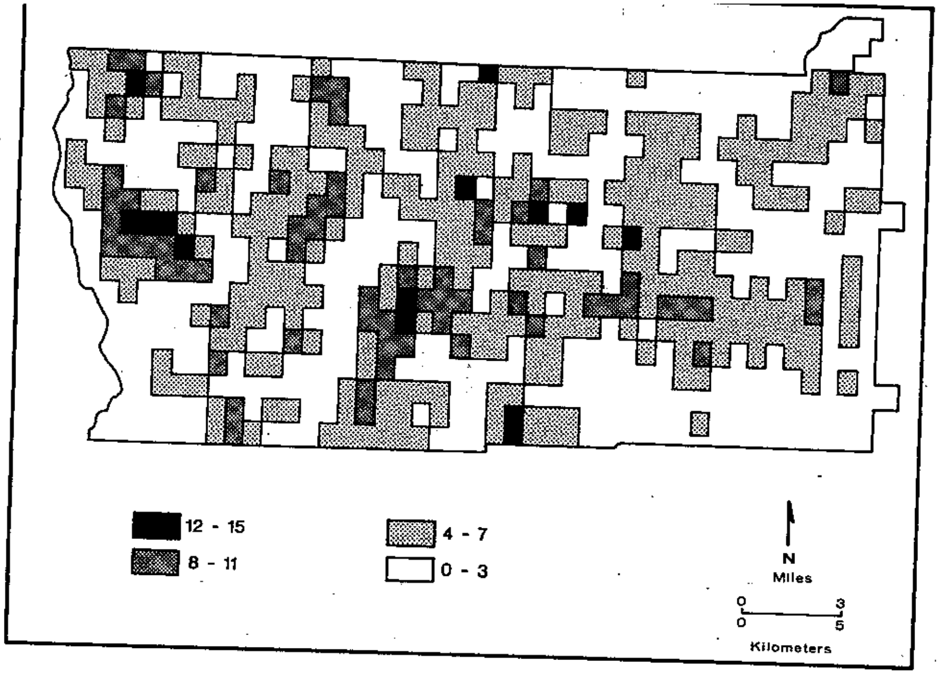


Fig. 3. Number of sinkholes by cell, Dougherty County, Georgia.

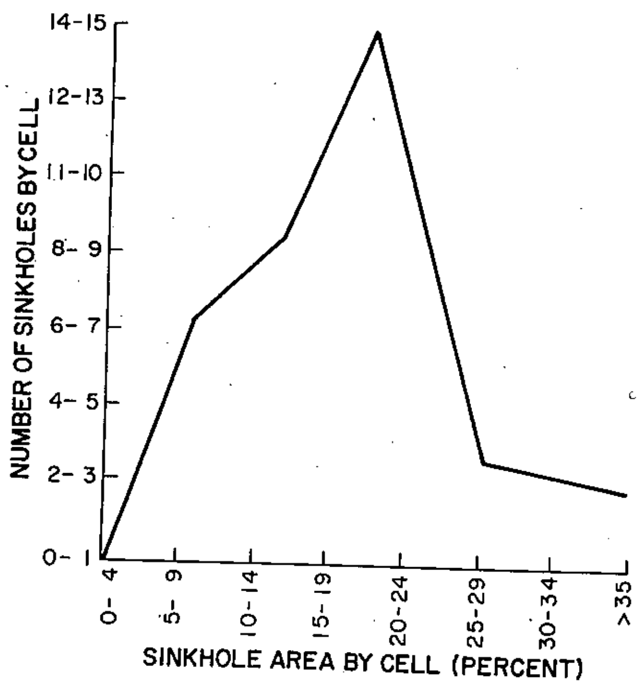


Fig. 4. Relationship between the number of sinkholes in a cell and the area of the cell occupied by sinkholes, Dougherty County, Georgia.





underlying Ocala limestone. As the sinkholes have formed by subsidence or suffosion of surface residuum into subsurface cavities, this implies that joints and faults are also the major avenues of ground water movement and solution.

FRACTURE DATA

The distribution and shapes of sinkholes in Dougherty County were used to map possible fractures in the Ocala limestone. Mapping was completed in three stages. In the first stage, all pronounced sinkhole long axes and other linear shape elements were identified and marked. In the second stage, linear shape elements were connected where these appeared to lie along a single fracture. In addition, fractures were drawn where several sinkholes fell along a straight line. In the final stage of mapping the color infrared images of the county were examined for additional evidence of fractures in the underlying bedrock and for evidence which might suggest modifications to the fracture map prepared from sinkhole data. In total, 1,298 possible fractures were mapped, the mean length being 1.9 $km/km^2$ (Figure 6). DBMANG data files were developed for the number of fractures, the number of fracture intersections, and the total length of fractures in each cell. Thirty cells had more than 9 fractures and 276 cells more than 5 fractures; 155 of the 855 cells had no fractures. Three cells had more than 15 fracture intersections and 20 cells more than 4.5 km of fractures. (Fractures lying in more than one cell were counted in each cell they occupied.)

In an attempt to explain the fracture pattern in Dougherty County, fracture end point coordinates were digitized and lengths and orientations calculated. Fractures were then grouped in 10-degree classes and the number and total length of fractures in each class estimated (Figure 7). Chi-square analysis was used to test the non-randomness of these distributions (Pincus, 1953). In both data sets the same six classes, their midpoints at 315°, 325°, 335°, 5°, 35°, and 40°, were significantly different from random at the 0.05 level. When adjacent classes were grouped three major preferred fracture orientations emerged at 325°, 5°, and 40°.

Preferred fracture orientations in Dougherty County agree well with those measured in nearby areas of Florida and Georgia. Vernon (1951) recognizes a fundamental regional pattern of two systems of fractures trending NW-SE and NE-SW in northern Florida and parts of southwest Georgia. Work by Ellwood in Climax Blowing and Glory Hole Caves beneath the Pelham Escarpment, near Cairo, Georgia, 75 km south of Albany, has revealed two preferred passage orientations at 317°

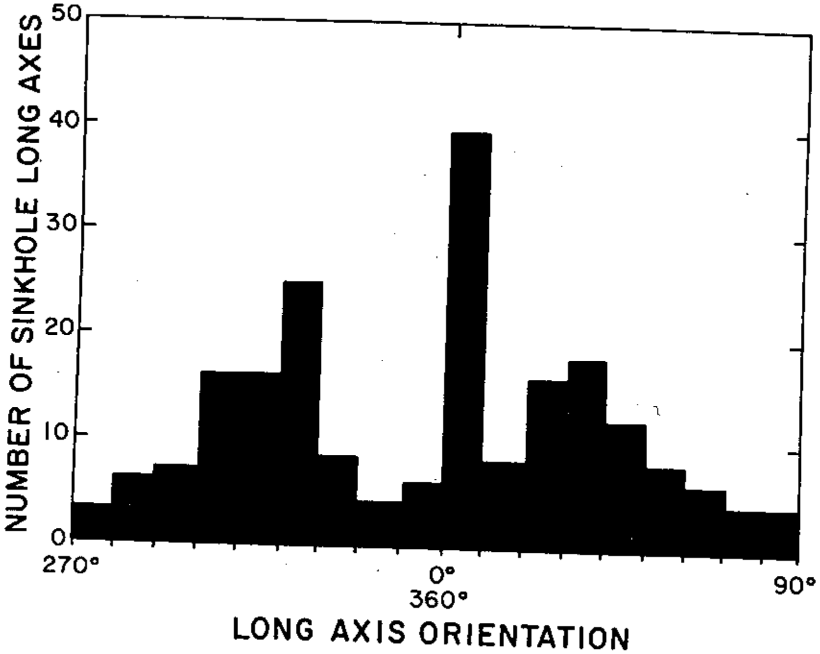

Fig. 5. Number of sinkhole linear shape elements by 10° orientation class for a random sample of 205 sinkholes, Dougherty County, Georgia.

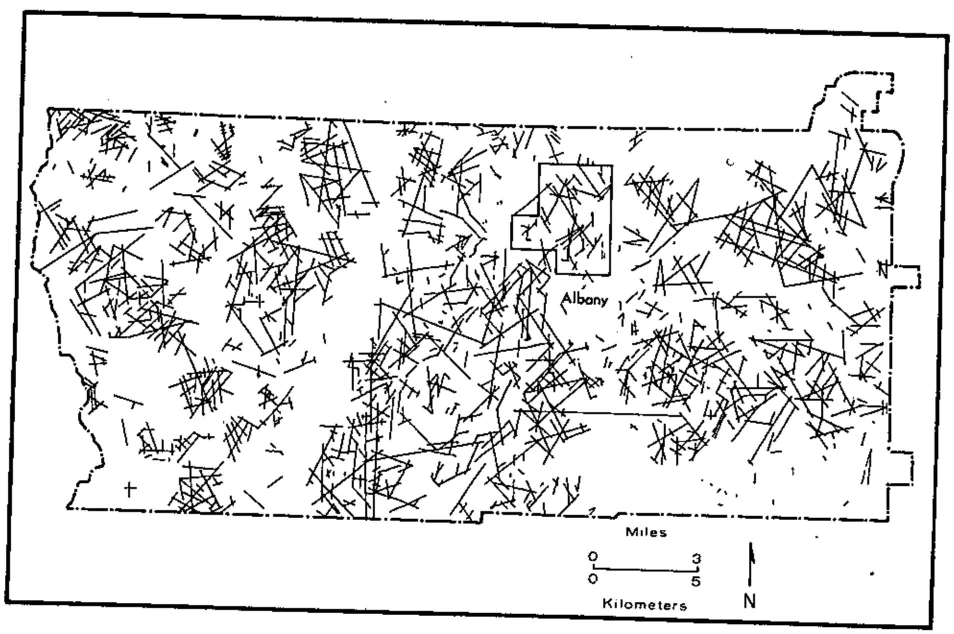


Fig. 6. Possible fractures in the Ocala limestone mapped for sinkhole data, Dougherty County, Georgia.



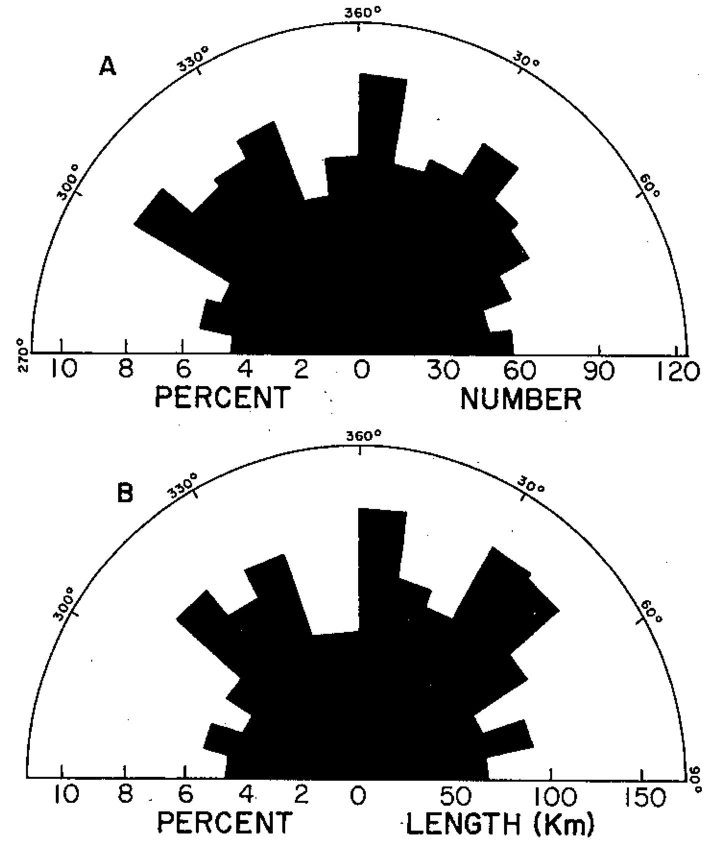

Fig. 7. Number (A) and length (B) of mapped fractures by 10° orientation class, Dougherty County, Georgia.

Table 1 Values of Variables Specified for Intersections 1-4

| VARIABLE | SPECIFIED VALUES OF VARIABLES | | | |
|---|---|---|---|---|
| | INTERSECTION 1 | INTERSECTION 2 | INTERSECTION 3 | INTERSECTION 4 |
| Number of Sinkholes | 12-15 | 10-15 | 4-15 | 2-15 |
| Percent Area of Cell Covered by Sinkholes | 15-24 | 10-29 | 5-35 | 5-35 |
| Number of Fractures | 7-9 | 5-9 | 3-9 | 1-9 |
| Number of Fracture Intersections | 12-19 | 8-19 | 4-19 | 2-19 |
| Length of Fractures (km) | 3.7-7.2 | 2.8-7.2 | 1.9-7.2 | 1.0-7.2 |

and 48°. Fault planes have been identified in Climax Cave at both orientations suggesting that passages have formed along a conjugate set of shear faults. Ellwood has tentatively interpreted the fracture directions in terms of a stress distribution with the axes of greatest and least stress horizontal and oriented at approximately 90° and 360° respectively, and the axis of intermediate stress vertical.

The fracture sets in Dougherty County were most likely produced by a maximum stress from the west acting against the Chattahoochee Anticline, trending 350° in basement rocks west of Dougherty County. By this interpretation, fractures at 5° are extension fractures; those at 325° and 40°, a conjugate set of shear fractures. The broad range of the 325° and 40° fracture directions suggests that they may have been produced by a residual stress field in basement rocks, which caused upward migration of structural features and their impressment on the younger sediments.

SUBSIDENCE SUSCEPTIBILITY MODELS

The sinkhole and fracture data files in DBMANG were used to model via CONGRID the relative susceptibility of cells in Dougherty County to ground subsidence. Separate models were produced by intersections and by linear combination of the five variables. The susceptibility of a cell was assumed to increase with and increase in all variables except sinkhole area. For this variable, susceptibility is assumed to reach a maximum when 15-24% of the cell is occupied by sinkholes. This assumption is based on the observation that when 20% of the cell area is occupied by sinkholes, further development is dominated by lateral growth and coalescence of sinkholes rather than by the development of new sinkholes.

INTERSECTION

Intersection modelling of susceptibility involved the use of CONGRID to identify and map cells with specified values of the five variables. Four intersections were mapped. A broader range of values for each of the five variables was specified for successive intersections (Table 1). This meant that each intersection identified cells included in the previous intersection plus a number of additional cells. These additional cells were considered to be less susceptible to sinkhole development than the cells already identified. In the first intersection all cells having 12-15 sinkholes, 7-9 fractures, 12-19 fracture intersections, 3.7-7.2 km of fractures, and 15-24% of the area occupied by sinkholes were identified. Only one cell had all of these characterisics and by the criteria established, it is





the cell most susceptible to future sinkhole development. Intersection 2 identified cells with 10-15 sinkholes, 5-9 fractures, 8-19 intersections, 2.8-7.2 km of fractures, and 10-29% of the area occupied by sinkholes. Fourteen cells were identified, 13 more than were identified by intersection 1. Intersection 3 added 142 cells to those identified by intersection 2, and intersection 4 added 127 cells to those identified by intersection 3; specified values for intersections 3 and 4 are given in Table 1. Of the total 855 cells, 577 were not identified by intersection 4. These cells are considered to be the least susceptible to future ground subsidence (Figure 8).

LINEAR COMBINATION

In linear combination modelling the variables and the values for each variable were weighted according to their judged influence on the susceptibility of an area to future ground subsidence. Each cell was assigned a map value based on the equation:

$$\text{map value} = W_{k1} r_{k1} + W_{k2} r_{k2} + W_{k3} r_{k3} + \ldots W_{kn} r_{kn}$$

where w = variable weight r = value weight $k_{1-n}$ = index of the variable.

The linear combination model was generated using the variable and value weights listed in Table II. The number of sinkholes and the number of fractures in a cell were considered to be the most important measures of susceptibility to future sinkhole development and were assigned the highest weight 20. The number of fracture intersections was thought to be the next most significant variable, followed by the total length of fractures in a cell; these variables were assigned weights of 15 and 12 respectively. The area of the cell covered by sinkholes was considered the least useful in predicting future sinkhole development and was assigned the lowest weight, 6. Value weights for all variables ranged from 1 to 9.

For the variable and value weights shown in Table II, a cell with values of 5, 3, 7, 6, and 6 for the number of sinkholes, area occupied by sinkholes, number of fractures, number of fracture intersections and total fracture length respectively, would have a map value = (20)(4) + (6)(1) + (20)(9) + (15)(6) + (12)(9) = 464. A second cell with values of 2,1,3,4, and 3 for the same variables would have a map value = (20)(4) + (6)(1) + (20)(6) + (15)(4) + (12)(6) = 338. Map values for each cell were calculated by CONGRID and then were classified into five groups each covering an equal

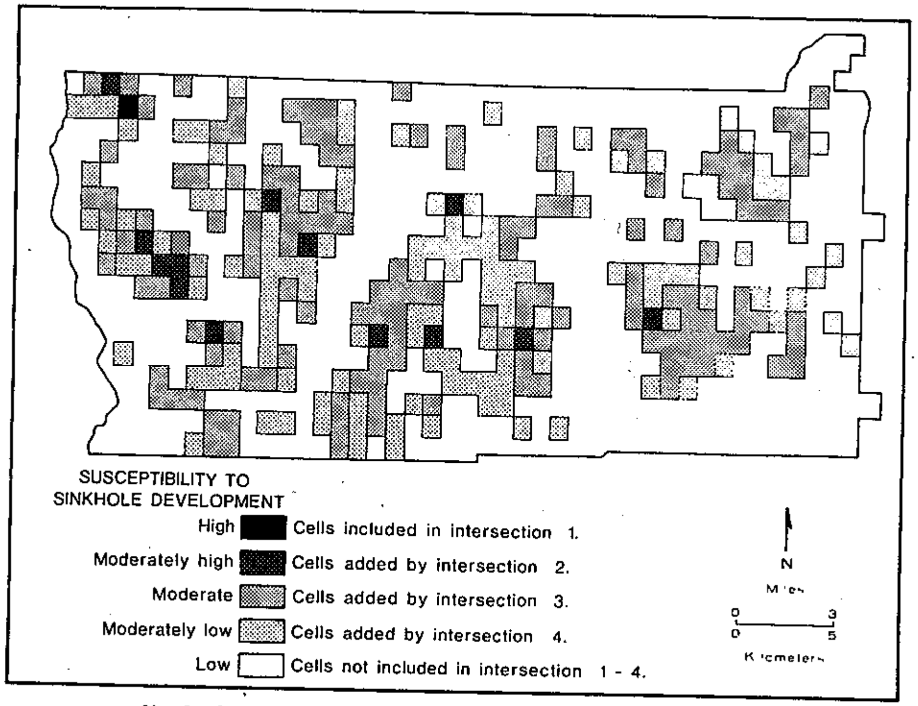


Fig. 8. Intersection model of ground subsidence susceptibility, Dougherty County, Georgia.

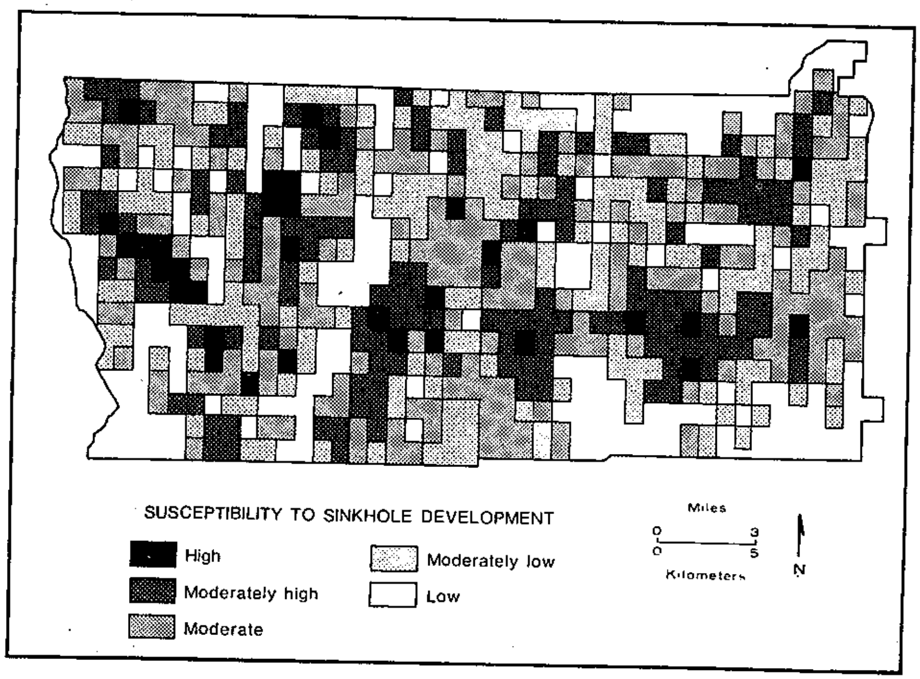


Fig. 9. Linear combination model of ground subsidence susceptibility, Dougherty County, Georgia.





portion of the total range of map values assigned. In a relative sense, these groups of cells were considered to have high, moderately high, moderate, moderately low, and low susceptibiliy to ground subsidence (Figure 9). It should be stressed that these terms are relative, cells designated as highly susceptible in the linear combination model may have a different susceptibility to cells designated highly susceptible in the intersection model.

DISCUSSION

Work in Dougherty County has shown that fractures in the Ocala limestone can be mapped from sinkhole data through >50 m of surface residuum. The fracture map of the county (Figure 6) should be useful in locating high yield, high specific capacity wells. If all irrigation wells were of high specific capacity this would minimize drawdown and reduce the possibility of ground subsidence. The most likely sites for such wells are at fracture intersections or along single fractures (Parizek, 1976). The fracture map of the county may also prove useful in selection of suitable sites for sanitary landfills. Improperly located landfills have already resulted in contamination of the Ocala aquifer in the Albany area. The most suitable locations for a landfill are those falling in interfracture areas where there is not rapid recharge to the aquifer via underground solution cavities located along fractures. As Figures 2 and 6 show, however, Dougherty County is a poor waste environment because a relatively permeable residuum with numerous sinkholes overlies a heavily fractured bedrock. The most suitable waste disposal sites are located on the Tifton Upland, 15-20 km southeast of Albany. This area is underlain by impermeable clays of the Hawthorne Formation.

The intersection and linear combination models of relative ground subsidence susceptibility are in broad agreement (Figs. 8 and 9). Furthermore, their accuracy is supported by independent data. In both models, cells considered most susceptible to ground subsidence correlate with: (1) areas of shallow residuum (particularly less then 10m (Doug Wilson, unpublished data on residuum thickness)), where subsidence may be more rapid; (2) two troughs in the piezometric surface of the Ocala aquifer to the west of the Flint River that Wait (1963) feels are areas in which the limestone is cavernous (Figure 10A); or (3) regions where the difference between the lowest piezometric surface on record (December, 1977) and the highest piezometric surface on record (March 1978) exceeds 3m (Figure 10B). In these areas there is a greater loss of hydrostatic support for the residuum during drought periods. These relationships suggest that easily acquired sinkhole and bedrock fracture data

| Variable | Variable Weight | | Values (V) and Value Weights (VW) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Sinkholes | 20 | V | 0-1 | 2-3 | 4-5 | 6-7 | 8-9 | 10-11 | 12-13 | 14-15 | | |
| | | VW | 1 | 4 | 4 | 6 | 6 | 9 | 9 | 9 | | |
| Percent Area Covered by Sinkholes | 6 | V | 0-4 | 5-9 | 10-14 | 15-19 | 20-24 | 25-29 | 30-34 | >35 | | |
| | | VW | 1 | 4 | 6 | 9 | 9 | 4 | 4 | 1 | | |
| Number of Fractures | 20 | V | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | VW | 1 | 4 | 4 | 6 | 6 | 6 | 9 | 9 | 9 | 9 |
| Number of Fracture Intersections | 15 | V | 0-1 | 2-3 | 4-5 | 6-7 | 8-9 | 10-11 | 12-13 | 14-15 | 16-17 | 18-19 |
| | | VW | 1 | 4 | 4 | 6 | 6 | 6 | 9 | 9 | 9 | 9 |
| Length of Fractures (km) | 12 | V | 0-0.9 | 1.0-1.8 | 1.9-2.7 | 2.8-3.6 | 3.7-4.5 | 4.6-5.4 | 5.5-6.3 | 6.4-7.2 | | |
| | | VW | 1 | 4 | 4 | 6 | 6 | 9 | 9 | 9 | | |

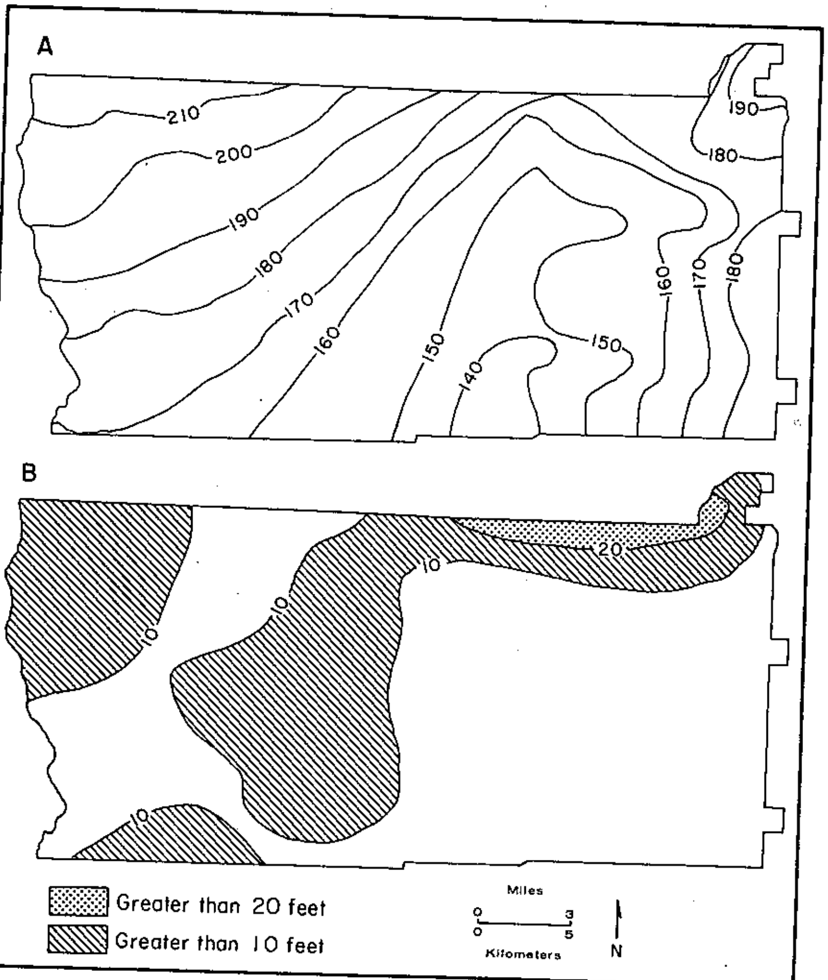


Fig. 10. Form and variability of the piezometric surface in the Ocala aquifer, Dougherty County, Georgia. The piezometric surface of August 1957 is shown in (A), the difference between the lowest piezometric surface on record (December, 1977) and the highest surface on record (March, 1978) is shown in (B). Elevations are given in feet. Diagram (A) is after Wait (1963), (B) is after Kwader and Wagner (1980).



can be used to develop relatively accurate ground subsidence susceptibility maps for covered karst areas.

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# Form as an Indicator of Origin of Karst Landscapes in Indiana

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ABSTRACT

Morphometric analysis of surface form is a viable approach to accounting for distinctions between different subtypes of karst. This approach is tested on sinkhole forms exhibited by two types of karst (i.e., normal fluviokarst and exhuming fluviokarst) developed on the Mitchell Plain of south central Indiana. By utilizing surveyed data and sophisticated morphometric techniques, it was possible to identify classes of sinkhole form types. The two karst landscapes were found to be form specific on the basis of a significant difference in the frequencies with which the representative form types occur in the two landscapes.

## INTRODUCTION

An important objective of geomorphic research is that of determining the relationship between form and origin in landscapes. This is the morphogenetic tradition in geomorphology. Common goals of morphogenetic studies include accounting for variation in surface forms and attempting to identify links between the landforms and the conditions and events which give rise to them. Two basic problems have hindered the accomplishment of these goals. First, inadequate description of surface morphology has often made it impossible to undertake meaningful comparisons between landscapes. Second, poor understanding of the geomorphic processes and how they work together to produce specific landforms has made it very difficult to account for variation in real world relief forms.

Unlike many other processes in geomorphology, the limestone solution process in karst is fairly well understood. Unfortunately, this understanding of limestone solution does not explain the variation in surface morphology in karst landscapes. Again, the problem is twofold. First, it is becoming increasingly apparent that limestone solution is but one of several interacting processes important in the karstification of a landscape. Second, in many cases the karst forms have not been adequately defined. Recent workers

# ENVIRONMENTAL KARST

Edited by Percy H. Dougherty

GeoSpeleo Publications Cincinnati, Ohio

## COVER PHOTO

COVER PHOTO: The cover photo shows the Pinnacles in the Gunong Mulu National Forest, Sarawak, Southeast Asia and is part of the illustrative material from the article by Michael J. Day on management problems in the park. The deeply-etched limestone spires rise up to 35 m through the forest covering the upper slopes of the mountainsides. The Pinnacles represent a well developed, large scale spitzkarren which is a function of the interaction between environmental conditions and geologic structure.


GeoSpeleo Publications, Box 389022, Cincinnati, OH 45238

Library of Congress Catalog Number: 84-80188

ISBN 0-9613107-0-7



Printed in the United States of America by Diversified Graphics Corporation, Wooster, OH 44691.

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