MORPHOMETRIC AND SPATIAL DISTRIBUTION PARAMETERS OF KARSTIC DEPRESSIONS, LOWER SUWANNEE RIVER BASIN, FLORIDA

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This study describes an application of Geographic Information Systems (GIS) to examine the morphometric and spatial distribution of karstic depressions in the lower Suwannee River basin. Morphometris analysis of some 25,000 karstic depressions in an area covered by twenty-four 1:24,000 scale standard USGS topographic quadrangles were made possible by the analytical capabilities of the GIS. The parameters calculated for the study area include length, width, orientation, area, depth, circularity index, depression density, pitting index, and nearest neighbor index. Analysis of ~25,000 depressions in the lower Suwannee River basin reveals that the Florida karst is represented by broad, shallow depressions with an average density of 6.07 depressions/km² and an average pitting index of 14.5. Morphometric and spatial distribution parameters of karstic depressions within the lower Suwannee River basin show significant variations.

The robust GIS methodology used in this study provides not only a rapid analysis of spatial data on a large population of karstic depressions, but also an objective approach with consistent measurement and calculation processes in which human errors and bias were eliminated. In accordance with the increasing use of GIS in analyzing spatial data on diverse applications, this study shows that the GIS environment can also be efficiently used for karst landform studies.

Surrounded by submarine escarpments from both east and west, the Florida Platform consists of a thick sequence of limestone and dolomite deposited during the Tertiary Period. The generally unconfined or semiconfined hydrogeologic conditions of the Floridan aquifer system in the lower Suwannee River Basin have produced a fascinating collection of karst depressions illustrating a complex evolutionary history controlled by the lower sea-level stands of the Pleistocene and the formation of the Suwannee River (Denizman & Randazzo 2000).

Morphometry can be defined as the measurement and mathematical analysis of the configuration of the Earth's surface and of the shape and dimensions of its landforms (Bates & Jackson 1987: 235). Application of morphometric techniques to karst landforms provides an objective and quantitative system of karst landform description and analysis. Morphometric techniques have been applied to a variety of karst regions and proven to be very effective in placing many karst landforms, especially depressions, in perspective (Williams 1972a, 1979; Day 1983; Troester *et al*. 1984; Magdalena & Alexander 1995).

There have been few quantitative investigations of Florida's complex karst features. Certainly, little attention has been given to the morphometric and spatial distribution parameters of enclosed depressions. The work of Troester *et al.* (1984), Beck and Jenkins (1985), and Bahtijarevic (1996) on depression morphometry and spatial distribution were of local scale with small depression populations. In this study, morphometric analysis of a relatively large part of the lower Suwannee River karst area (4063 km²) was made possible by the powerful and rapid analytical capabilities of Geographic Information Systems (GIS). Application of GIS to spatial data has proven to be instrumental in the analysis of complex problems in earth and environmental sciences (ESRI 2000). GIS provide rapid access, integration, and analysis of spatially referenced data stored in large numerical databases. It also display the results graphically in maps and charts.

Methodology

Morphometric and spatial distribution parameters of karstic depressions in the lower Suwannee River basin were evaluated in the GIS environment, using ArcInfo 7.0 and ArcView 3.0. In this study, morphometric analysis of ~25,000 karstic depressions in an area covered by twenty-four 1:24,000 scale standard USGS topographic quadrangles (4063 km²) was made possible by the powerful and rapid analytical capabilities of the GIS. The topographic quadrangles analyzed in this study are shown in Figure 1. The procedure followed in this study consists of extensive manual and computer work.

The first stage of the study involved detailed topographic map analysis. All the natural depressions depicted by hachured closed contours on topographic maps along the Suwannee River were delineated on transparent papers. Depressions delineated on topographic quadrangles were then transferred to ArcInfo (GIS) environment. Digital layers (coverages) of depressions were produced. In order to utilize GRID functions of ArcInfo, vector coverages of depressions were converted to raster files. GRID is a cell-based module of ArcInfo. It manipulates raster files in which a regular "mesh" is draped over the

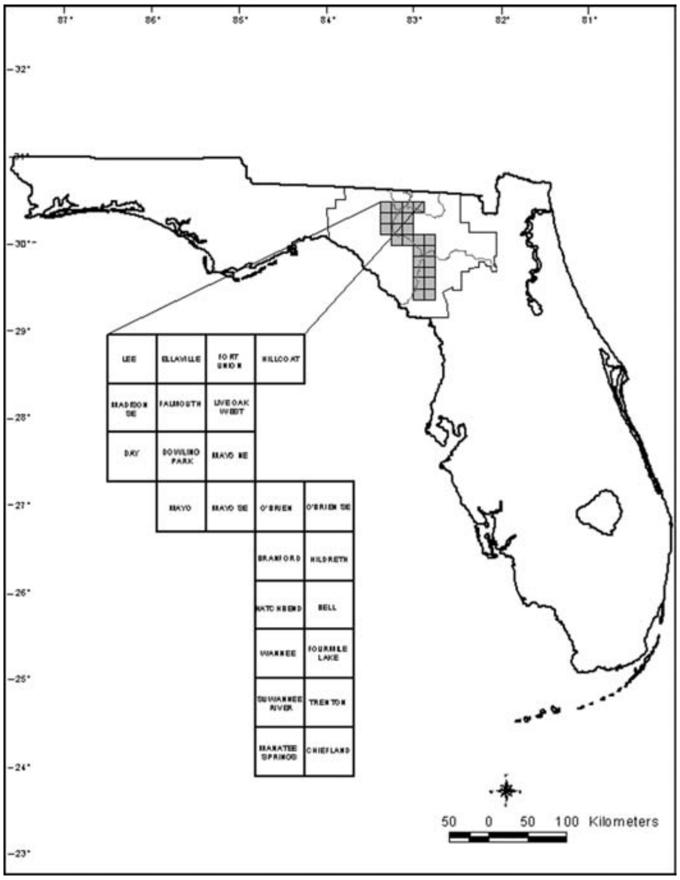

Figure 1. General location of the Suwannee River basin and the study area.

landscape. Morphometric measurements (length, width, area, perimeter, major axis orientation) were performed on each depression using zonal functions (zonalgeometry and zonalcentroid) of GRID. Depressions were represented by their highest contour for measurements of length, width, depth, area, perimeter, and major axis orientation.

Nearest neighbor analysis was performed for each quadrangle as well as the whole study area. Compound depressions were divided into their components and each depression was taken into account individually. Nearest neighbor distances for each quadrangle were calculated by using Fragstats, a powerful spatial analysis software originally created for landscape pattern analysis of digital data. Calculations for the whole study area were made using the Euclidian functions of GRID. In these analyses, depressions were represented by their centroids, determined by the "zonalcentroid" function of GRID. Ideally, karstic depressions are represented by their deepest points, i.e., swallets as in Williams (1972a) for an accurate spatial description that is of paramount importance in spatial analysis. Williams (1972a, 1972b) was able to detect the swallets and drainage patterns in the polygonal karst of New Guinea. However, they are not detectable in the low-relief karst of Florida, which is covered by at least several meters of soil and thick vegetation. Therefore, in order to maintain consistency and avoid subjectivity in assessing point locations for depressions, they were represented by their centroids that were readily and precisely determined by GRID functions in GIS.

As explained above, two GIS databases for karstic depressions were created in ArcView: The morphometric database includes morphometric parameters such as depression area, perimeter, length, width, mean diameter, length/width ratio, circularity index, major axis orientation, and approximate depth. The spatial distribution parameters database includes

Table 1. Spatial distribution parameters of depressions per topographic map quandrangle.

Quadrangle Name	Number of Depressions	Density (#/km^2)	Total Depression Area (km^2)	Mean Depression Area (km^2)	Mean Nearest Neighbor Distance (m)	Nearest Neighbor Index (R)	Distribution Pattern	Pitting Index	Length/ Width
WANNEE	904	5.3	10.7	0.012	186.2	0.9	Tending to cluster	15.83	1.70
FOURMILE LAKE	588	3.4	8.5	0.014	212.6	0.8	Tending to cluster	20.15	1.81
SUWANNEE RIVER	953	5.6	9.8	0.010	164.4	0.8	Tending to cluster	17.35	1.72
TRENTON	1283	7.5	20.5	0.016	174.8	1.0	Near random	8.35	1.74
MANATEE SPRINGS	953	5.6	12.4	0.013	170.8	0.8	Clustered	13.72	1.82
CHIEFLAND	1742	10.2	8.5	0.005	129.7	0.8	Tending to cluster	20.23	1.62
LEE	593	3.5	18.0	0.030	235.4	0.9	Tending to cluster	9.41	1.70
MADISON SE	405	2.4	13.0	0.032	245.4	0.8	Tending to cluster	12.84	1.99
ELLAVILLE	622	3.6	14.1	0.023	214.7	0.8	Tending to cluster	12.18	1.89
FORT UNION	482	2.9	16.6	0.034	255.5	0.9	Tending to cluster	10.20	1.80
FALLMOUTH	1002	5.8	11.4	0.011	174.9	0.8	Tending to cluster	15.06	1.80
LIVE OAK WEST	1389	8.1	19.1	0.014	161.3	0.9	Near random	8.97	1.69
HILLCOAT	444	2.6	4.2	0.009	178.8	0.6	Clustered	40.91	1.90
DAY	388	2.7	7.3	0.019	241.4	0.8	Tending to cluster	19.49	1.84
DOWLING PARK	1514	8.9	21.7	0.014	159.6	1.0	Near random	7.89	1.76
MAYO NE	2721	15.8	23.5	0.009	128.9	1.0	Near random	7.32	1.61
MAYO	1273	7.5	13.2	0.010	160.9	0.9	Tending to cluster	12.86	1.77
MAYO SE	1187	6.9	11.6	0.010	179.7	0.9	Near random	14.81	1.72
O'BRIEN	1724	10.1	16.6	0.010	160.3	1.0	Near random	10.27	1.72
O'BRIEN SE	1663	9.8	25.4	0.015	158.5	1.0	Near random	6.70	1.74
BRANFORD	766	4.5	8.4	0.011	191.0	0.8	Tending to cluster	20.15	1.81
HILDRETH	971	5.7	11.7	0.012	189.1	0.9	Near random	14.47	1.80
HATCHBEND	753	4.4	8.8	0.012	205.3	0.9	Tending to cluster	19.60	1.82
BELL	837	4.9	16.4	0.020	187.0	0.8	Tending to cluster	10.37	1.89
TOTAL	25157								

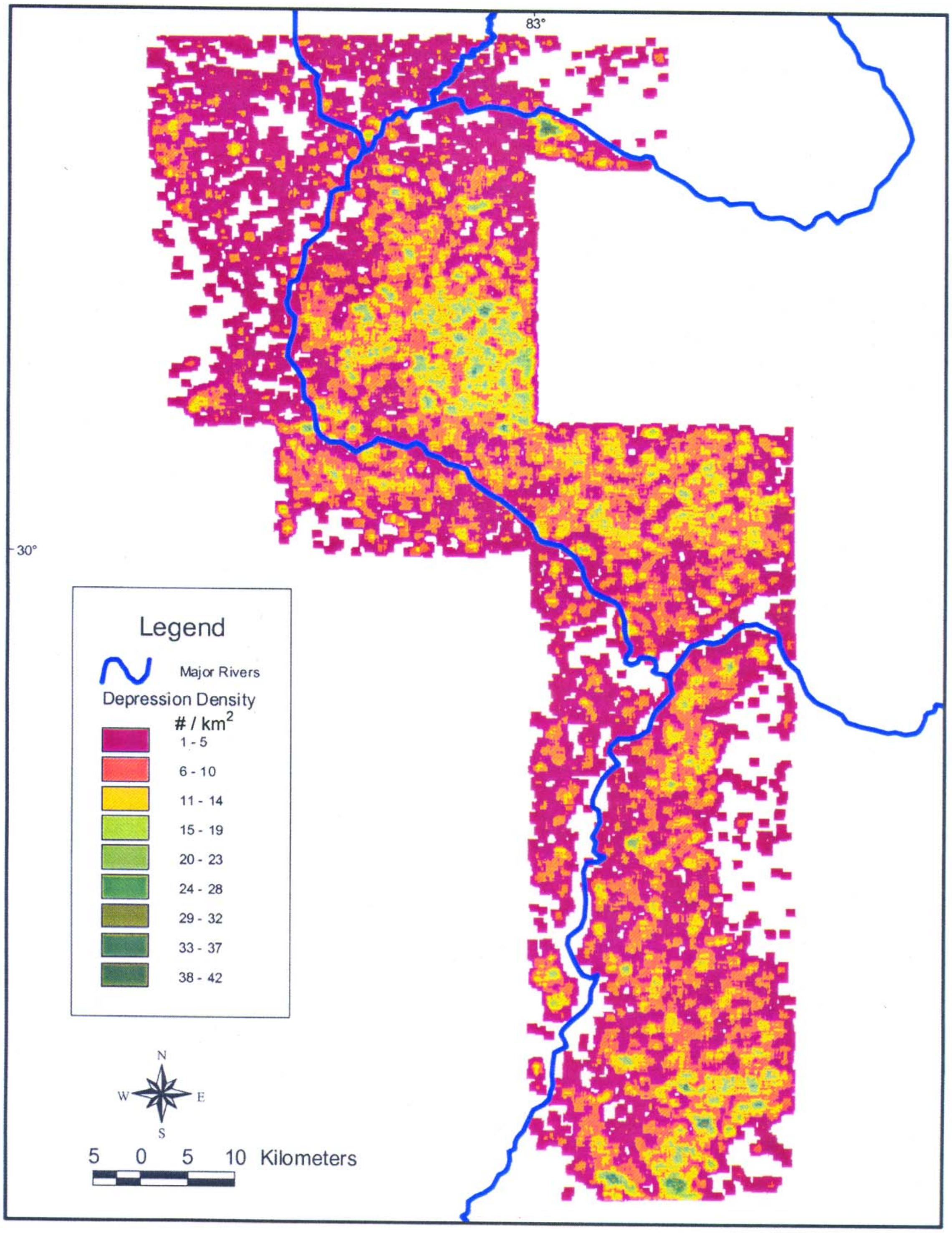

Figure 2. Depression density distribution within the study area.

centroid locations of depressions, nearest neighbor distances, and azimuth values for nearest neighbor vectors for individual depressions.

Among a great number of morphometric parameters proposed by various karst geomorphologists, only those that are possible to be measured or calculated by GIS based on the available data were included in this study:

Length: length of the major axis of an ellipsoid representing the depression.

Width: length of the minor axis of an ellipsoid representing the depression.

Orientation: orientation of the major axis. Originally expressed by GRID as the angle from the east, counterclockwise, it was converted to regular azimuth values.

Area: area of each depression measured in m^2.

Pitting index: (Area of karst)/(Total depression area).

Circularity index: the measure of the circularity of a depression.

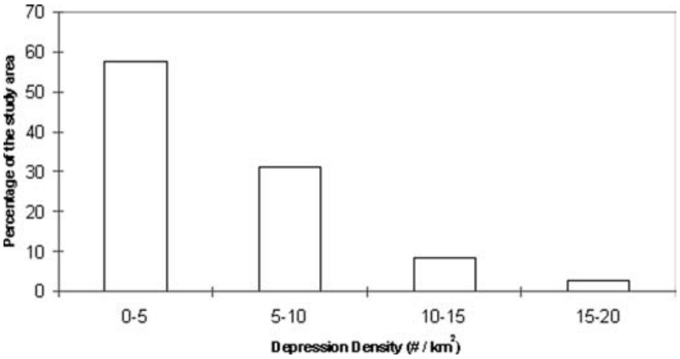

Figure 3. Distribution of depression density.

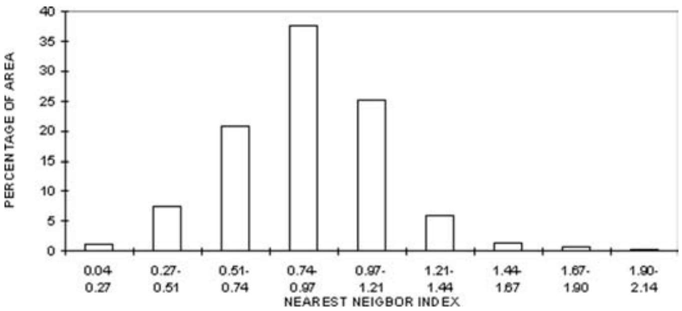

Figure 4. Distribution of nearest neighbor index.

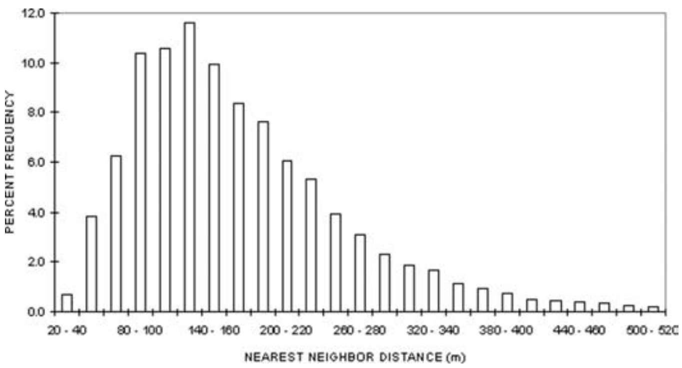

Figure 5. Frequency distribution of nearest neighbor distance.

Depth information was obtained by counting the number of closed contours for each depression.

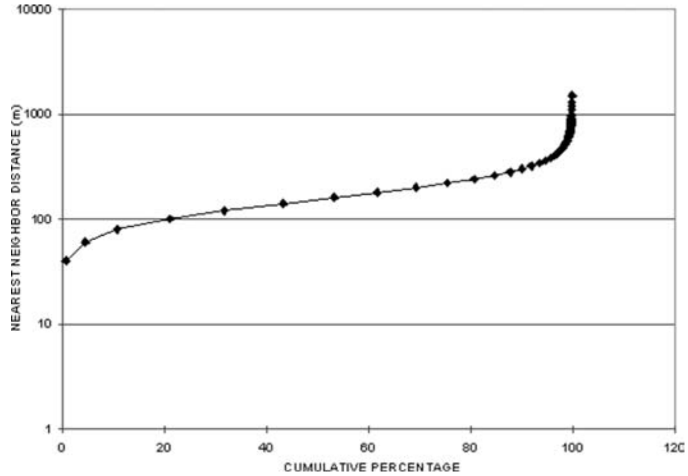

Figure 6. Cumulative percentage of nearest neighbor distance.

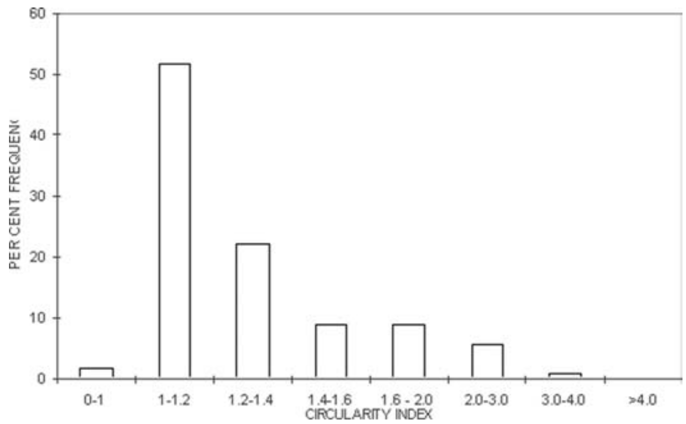

Figure 7. Frequency distribution of circularity index.

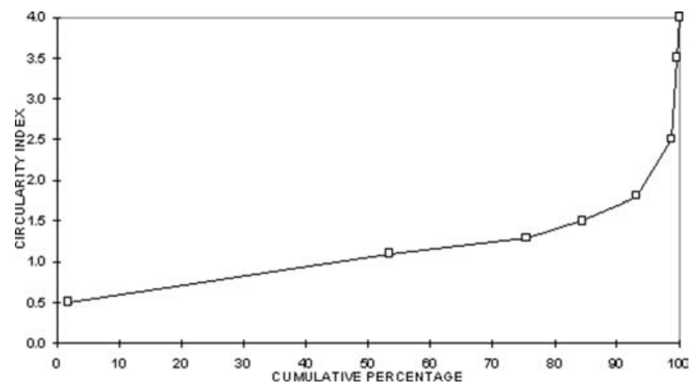

Figure 8. Cumulative percentage of circularity index.

RESULTS

DEPRESSION DENSITY

Depression densities were calculated for each topographic quadrangle by dividing the number of depressions by area (Table 1). Mean depression density for the 4063 km² area is 6.1/km². It ranges from 2.4 (Madison SE) to 15.8 (Mayo NE) with a standard deviation of 3.2.

Distribution of depression density is also presented as a GIS layer with a spatial resolution of 10 m (Fig. 2). It was created by calculating the number of depression centroid points in a 1 km² window moving 10 m at each step. Nearly half of the study area (~1900 km²) is represented by a depression density between 1 and 5 /km² (Fig. 3).

The area of each depression for each quadrangle was cal-

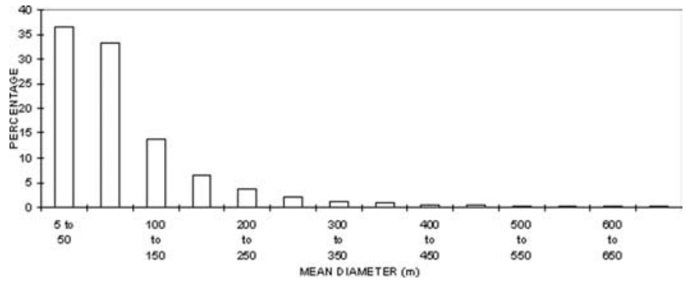

Figure 9. Distribution of mean diameter.

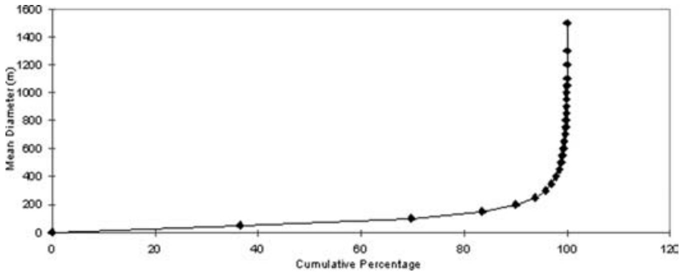

Figure 10. Cumulative percentage of mean diameter.

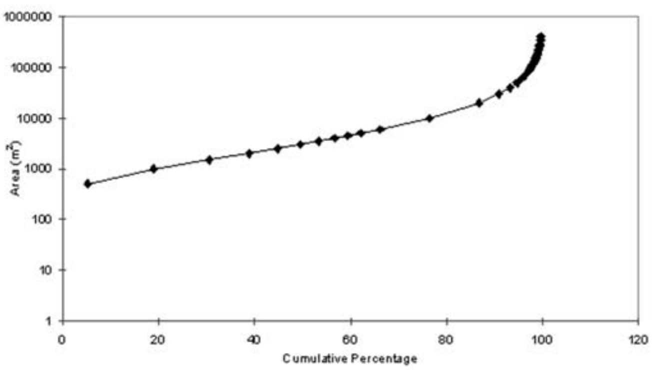

Figure 11. Cumulative percentage of depression area.

culated by GIS functions (Table 1). Total depression area varies from 4.2 km² (Hillcoat) to 25.4 km² (O'Brien SE) with a mean of 13.8 km² and a standard deviation of 5.4 km². Grand total of the depression area is 331.4 km², corresponding to 8.2% of the study area (4063 km²).

As a measure of surficial karst development, the pitting index (total area of karst/total depression area) provides information about the extent of karstification. For the polygonal karst landscapes covered by tightly spaced depressions, the pitting index approaches unity. The pitting index varies from 6.7 (O'Brien SE) to 40.91 (Day) with a mean of 14.5 and a standard deviation of 7.0 (Table 1).

Spatial distribution of depression centroids was analyzed using the simple nearest neighbor technique (Williams 1972a, 1972b). The mean nearest neighbor distance (La) for karstic depressions within each quadrangle was calculated using Fragstats (Table 1). It ranges from 129.0 m (Mayo NE) to

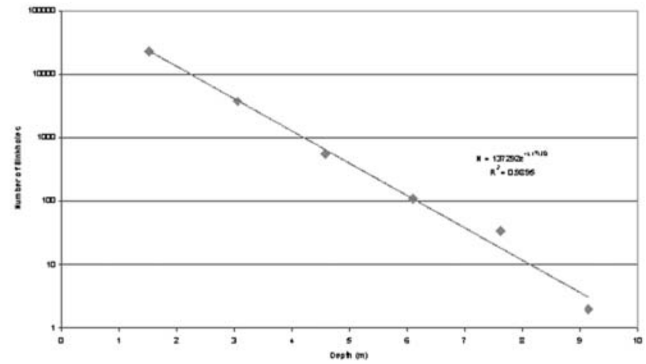

Figure 12. Depression depth frequency.

255.5 m (Fort Union) with an overall mean and standard deviation of 186.1 m and 33.3 m respectively. The expected mean nearest neighbor distance (L_e) in an infinitely large, randomly located population with same depression density, D, is given by $L_e = 1/(2\sqrt{D})$ and ranges from 125.8 m (Mayo NE) to 321.0 m (Madison SE).

The nearest neighbor index R, described as the ratio of L_a/L_e, was derived for corresponding quadrangles (Table 1). It ranges from 0.6 (Hillcoat) with a clustered distribution to 1.0 (Mayo NE and O'Brien), which represents randomly distributed depressions. Mean nearest neighbor index for the whole area is 0.9. Most of the topographic quadrangles reveal a depression distribution significantly different from random expectation (R=1) at the 0.05 level. All the depressions except those in Trenton, Live Oak West, Dowling Park, Mayo NE, Mayo SE, O'Brien, O'Brien SE, and Hildreth indicate a tendency towards clustering.

Nearest neighbor analysis was also performed for the whole area by using map algebraic functions of the GIS. Based on the centroid locations of depressions, layers of measured nearest neighbor distance, L_a, and expected nearest neighbor distance, L_e, were created. The distribution of nearest neighbor index (R) was obtained by the ratio of two GIS layers (L_a/L_e). A greater part of the study area is represented by a nearest neighbor index less than 1, indicating a trend towards clustering (Fig. 4).

A histogram of nearest neighbor distance data set for depression centroids is shown in Figure 5. The mean distance to nearest neighbor is 188.1 m. The values range from 20-2956.0 m with a standard deviation of 116.5 m. A cumulative percentage graph of depression nearest neighbor distance values shows that 90% of depressions are located closer than 500 m to their nearest neighbor (Fig. 6).

PLANIMETRIC SHAPE

As an indicator of planimetric shape, circularity index was utilized. The circularity index is a measure of the circularity of a depression. It is the ratio between the measured depression area and the area of a circle with the same perimeter. Using GIS-measured area and perimeter values for each depression,

Table 2. Statistical summary of morphometric parameters.

	Area (m^2)	Mean Diameter (m)	L/W	Circularity Index
Mean	14571.4	98.6	1.74	1.33
Maximum	5,804,750.0	2785.9	14.1	8.86
Minimum	75.0	10.1	1.0	0.006
Standard Deviation	71355.2	106.6	0.68	0.455

the circularity index was calculated in ArcView 3.0 by Table operations. It approaches unity as depressions become circular. For a perfectly circular depression, the index of circularity would be unity. The greater it departs from one, the less circular is the depression. Elongated features have values smaller than one whereas convoluted shapes present values greater than one.

Most depressions are nearly circular in plan with the major modal ratio class between 1-1.2 (Fig. 7). Mean circularity index value is 1.33 with a standard deviation of 0.45. Approximately 85% of the total population have a circularity index smaller than 1.5 (Fig. 8).

MEAN DIAMETER

Mean depression diameters were estimated in ArcView tables by obtaining the mean of length and width also measured in the GIS environment for each depression. In karst morphometry, the use of mean diameter is more helpful than major and minor axes, because these measures represent maximum rather than average dimensions.

Mean diameter distribution for the total population is shown in Figure 9. The values range from 5.6 - 2785.9 m with a standard deviation of 106.6 and a mean of 98.6 m. The major modal class is 5-50 m. Cumulative frequency distribution of mean diameter (Fig. 10) indicates that some 95% of the total population have a mean diameter of less than 300 m.

PLANIMETRIC AREA

The cumulative frequency distribution of depression areas for the total measured population is given in Figure 11. The mean value is 14,570 m^2, the standard deviation 71,349 m^2, and the range of values from 25 - 5,804,750 m^2. Within the total measured population, 50% of depressions are smaller than ~5000 m^2.

DEPTH OF KARSTIC DEPRESSIONS

In their comparative study of various karst regions, Troester *et al.* (1984) concluded that depression depth distributions in temperate and tropical karst regions could be explained by an exponential equation as follows:

$$N \text{ (number of sinkholes)} = N_o e^{-Kd}$$

where N_o and K are constants, and d is depth. The N_o coefficient is affected by the number of depressions, whereas the K coefficient varies within ranges corresponding to temperate and tropical karst areas. Comparing the internal relief within various karst regions, Troester *et al.* (1984) found that the Florida karst is very flat, represented by broad, shallow depressions with a K value of 1.18 m^{-1} (0.362 ft^{-1}).

The depth-frequency distribution for 23,031 depressions in the study area is shown in Figure 12. Depth values were estimated by manually counting the number of contours, representing the maximum depth values for depressions. The depth-frequency distribution was found to be changing exponentially with depth, expressed as:

Table 3. Spatial distribution parameters of karstic depressions in various karst regions of the world (Modified after Ford & Williams 1989).

AREA	NUMBER OF DEPRESSIONS	DENSITY	NEAREST NEIGHBOR INDEX	PATTERN
Papua New Guinea	1128	10 - 22.1	1.091 - 1.404	Near random to approaching uniform
Waitomo, New Zealand	1930	55.3	1.1236	Near random
Yucatan (Carrillo Puerto Formation)	100	3.52	1.362	Approaching uniform
Yucatan (Chicken Itza Formation)	25	3.15	0.987	Near random
Barbados	360	3.5 - 13.9	0.874	Tending to cluster
Antigua	45	0.39	0.533	Clustered
Guatemala	524	13.1	1.217	Approaching uniform
Belize	203	9.7	1.193	Approaching uniform
Guadeloupe	123	11.2	1.154	Near random
Jamaica (Browns Town-Walderston Formation)	301	12.5	1.246	Approaching uniform
Jamaica (Swanswick Fm)	273	12.4	1.275	Approaching uniform
Puerto Rico (Lares Fm)	459	15.3	1.141	Near random
Puerto Rico (Aguada Fm)	122	8.7	1.124	Near random
Guangxi, China	566	1.96 - 6.51	1.60 - 1.67	Approaching uniform
Spain, Sierra de Segura	817	18 - 80	1.66 - 2.14	Near uniform
Florida, Suwannee	25,157	6.06	0.854	Tending to cluster

N (number of depressions) = $137{,}292e^{-1.1713\,d}$.

It should be noted that the analysis of a much larger population of depressions in this study gives a K value of 1.1713 that is significantly close to 1.18 calculated by Troester *et al.* (1984) for Florida karst.

DISCUSSION

The landforms of the subtropical Suwannee River karst area can be compared to karst areas of different morphoclimatic settings. The application of GIS allows the capture, storage, analysis, and presentation of morphometric and spatial distribution parameters of karstic depressions. Despite the accurate, rapid, and objective data processing of GIS, it should be kept in mind that all the analyses performed here on karstic depressions are based on the resolution and precision of standard 7.5-minute USGS topographic quadrangles with a contour interval of 5 feet. Karstic depressions may have been underrepresented because of the constraints of map resolution, as well as the thick vegetation and sediment cover. Nevertheless, this study provides a quantitative expression of the morphometry and spatial distribution of karst depressions on a regional scale.

Spatial distribution parameters of the Suwannee River basin karst area are summarized as follows:

Total area: 4063 km².
Total depression area: 331 km².
Number of depressions: 25,157
Mean depression density: 6.1 depressions/ km².
Mean nearest neighbor distance: 186 m
Mean nearest neighbor distance index: 0.9
Mean pitting index: 14.5

A statistical summary of the morphometric parameters of karstic depressions is given in Table 2.

Table 3 compares the mean spatial distribution parameters obtained in this study with those of various karst regions from diverse morphoclimatic settings. It demonstrates the extraordinarily large database for the subtropical Florida karst, providing a comprehensive representation of karst landforms in a scale of 1:24,000. It should be noted that the values for depression density and the nearest neighbor index calculated for the study area show great variations. Depression densities calculated for individual quadrangles range from 2.4 (Madison SE) to 15.8 (Mayo SE), overlapping with values representing both temperate and tropical karst areas. Similarly, the nearest neighbor index, varying from 0.6 (Hillcoat) to 1.0 (Mayo NE), indicates a wide range of spatial distribution patterns of depressions in the study area ranging from clustered to uniform. These significant variations in morphometric and spatial distribution parameters along with the morphometry of depressions in a single morphoclimatic zone implicate other local factors (e.g., overburden thickness, potentiometric level fluctuation, fracture systems, soil types, recharge-discharge zones) in controlling the development of karstic depressions.

SUMMARY AND CONCLUSION

This study represents an application of GIS to examine the morphometric and spatial distribution of karstic depressions in the lower Suwannee River basin. The robust GIS methodology used in this study provides not only a rapid analysis of spatial data on a large population of karstic depressions, but also an objective approach with consistent measurement and calculation processes in which human errors and bias were eliminated. In accordance with the increasing use of GIS in analyzing spatial data on diverse applications, this study shows that the GIS environment can also be efficiently used for karst landform studies.

Analysis of the morphometric and spatial distribution parameters of karstic depressions reveals that the Florida karst is represented by broad, shallow depressions with an average density of 6.07 depressions/ km² and an average pitting index of 14.5. Morphometric and spatial distribution parameters of karstic depressions within the lower Suwannee River basin show great variations.

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