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# A SIMPLE MAP INDEX OF KARSTIFICATION AND ITS RELATIONSHIP TO SINKHOLE AND CAVE DISTRIBUTION IN TENNESSEE

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*We here introduce a readily determined index of surface karstification, termed "sinkhole" index, based on the mean spacing of closed contours in a given area. The index shows a high correlation with total sinkhole area and a moderate correlation with total volume. The index was measured in 5056 blocks with dimensions of 2.5' of latitude by 2.5' of longitude, covering much of Tennessee. A new map showing the distribution of this index in the state is similar to one previously published karst map of Tennessee, but shows the variation of karstification in a more detailed manner. The sinkhole index was also used to compare the distribution of sinkholes and caves in Tennessee, using cave data compiled by the Tennessee Cave Survey. Maps of the sinkhole index and the number and total length of caves in each 2.5' x 2.5' block show strong regional similarities. However, there are dramatic exceptions. In addition, using blocks as the basic unit of analysis, the correlation coefficients between the sinkhole index and the two measures of cave abundance are low, generally explaining less than 10% of the variance. Thus, although similar geologic conditions appear to favor both sinkhole development and cave formation, the actual processes involved in the development of these two types of features seem to be only weakly related.*

Sinkholes are the most common surface feature of karstification that can be recognized on topographic maps, and their abundance and size are indicators of the degree to which the local bedrock has undergone solution. Below we use an index of sinkhole abundance to construct a map showing the variation in karstification across Tennessee. We also address the relationship between sinkhole and cave distribution by relating our sinkhole index to cave-location data from the Tennessee Cave Survey.

## PREVIOUS WORK

Sinkholes are the diagnostic karst landform (Cvijic 1893; Ford & Williams 1989), and thus the abundance of closed depressions provides an important measure of karstification. Several measures of sinkhole abundance have been used (White 1988). A common one is sinkhole density, defined as the total number of sinkholes divided by the total area studied. Another is the sinkhole area ratio, which is the ratio of the total sinkhole area to the total area studied. Of these, density has been more commonly used, as counting sinkholes is much faster than measuring their areas. White and White (1979) measured sinkhole densities in 62 drainage basins in the Appalachians, including a number in Tennessee. Kemmerly (1982) measured sinkhole densities on 1-km grids in 42 quadrangles in the Western Highland Rim and Pennyroyal plateau of south-central Kentucky and northcentral Tennessee, counting more than 25,000 sinkholes.

Miller (1977) has published a karst hazards map of Tennessee showing two levels of karstification: "karst areas," based mainly on the observed association between bedrock geology and karst (see below), and "areas with a high density of karst features," based on examination of topographic maps and ground observations (Miller, pers. comm. 2000).

The relationship between sinkhole and cave development is an important question in karst geomorphology. One effort to investigate this relationship was made by Ford (1964), who studied sinkholes and caves on the Mendip plateau, southern England. He found that 80% of the sinkholes lie in dry valleys with low gradients. Mapping of the caves in the area showed that they did not underlie the dry valleys, and collapses in them did not correspond with surface depressions. Another effort was made by Palmer and Palmer (1975), who studied sinkholes overlying Blue Spring Cave in southern Indiana. Although deeper sinkholes are preferentially located over or close to cave passages, maps of sinkhole density do not closely correspond with cave passages, but show only a general relationship to the known caves. Jennings (1985) infers that this finding suggests some mutual interdependence of sinkhole and cave development but with only a small proportion of the sinkholes being directly connected with underground passages. Based on these studies, the relationship between cave and sink-

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**Figure 1. Physiographic provinces and counties of Tennessee. Highlighted/labeled counties and cities are those mentioned by Miller (1977), and are discussed in text.**

hole development seems to be a weak one.

## PHYSIOGRAPHY AND GEOLOGY OF THE STUDY AREA

Davies and LeGrand (1972) have summarized the karst topography of the Appalachian Highlands and the Interior Low Plateaus, and Miller (1977) has summarized it for the State of Tennessee, including its relation to stratigraphy. Miller (1977) notes that karst is most extensively developed in the Central Basin, Eastern and Western Highland Rim, and Valley and Ridge physiographic provinces (Fig. 1). In the Central Basin, karst development is especially associated with Ordovician Ridley Limestone and Lebanon Limestone outcrops. On the Highland Rim two areas show the best developed karst. The first is in the northern part of the Western Highland Rim, in northern Montgomery and Robertson Counties (Fig. 1). This area represents a southern extension of the Pennyroyal plateau of Kentucky, where karst is best developed on the Mississippian St. Louis Limestone and the Ste. Genevieve Limestone. The second area is the eastern part of the Eastern Highland Rim, adjacent to and including the lower slopes of the Cumberland Plateau escarpment, chiefly involving the Mississippian St. Louis Limestone and the Monteagle Limestone (equivalent to the Ste. Genevieve Limestone). In the Valley and Ridge province of east Tennessee, the Ordovician Knox Group, some formations of the Ordovician Chickamauga Group (e.g., the Holston Formation), and the Cambrian Honaker Dolomite support the best-developed karst. Specific areas with highly developed karst include the Powell River Valley (principally Claiborne, Campbell, and Union Counties), the lower Holston River Valley (Knox and Jefferson Counties), the Ft. Loudon Lake area (Knox, Loudon, and Blount Counties), and the upper Holston River Valley in the area of Boone Lake.

Quaternary deposits in the karst areas range in thickness from nearly zero to several tens of meters. They consist largely of clay-rich residuum derived from insoluble materials left behind by the dissolution of the limestone units or let down from overlying clastic units. Also present are colluvium and, in the western part of the study area, thin loess deposits.

## METHODS

Measures of surface karstification, at least those that can be measured from 1:24,000-scale maps, obviously involve the extent of closed depressions. The total area of closed depressions in a given study area would be a good index, but the time required would be prohibitive, and the available digital elevation models lack the resolution to allow this task to be done by computer. An alternative approach is to count closed depressions, a method used by many researchers. Although somewhat faster than area measurement, this technique is also just too time consuming for evaluating an area covering most of a state, and also encounters difficulties as a measure of karstification where sinkhole size varies greatly from one area to another.

We sought a rapid sampling technique that did not require sinkhole area measurements or actual sinkhole enumeration, and, in particular, a method that would reflect size as well as number of sinkholes. Also desirable was a method requiring as little interpretation by the operator as possible. We devised the following approach. Our unit of study was a block 2.5' of latitude by 2.5' of longitude (area of about 17.4 km$^2$), or one ninth of the standard 7.5' by 7.5' topographic quadrangle. Over each 2.5' by 2.5' block, we placed a transparent grid with 12 horizontal lines and counted the total number of closed (hachured) contour lines crossed by the grid lines. Scanning the lines required no more than a minute or so on maps with no or very few sinkholes, up to 20 minutes on maps with hundreds of sinkholes. For a sinkhole index, we then divided the total length of the grid lines (45.36 km) by the total number of hachured contour lines crossed, thus giving the mean spacing between closed contour lines, a closer spacing indicating a greater degree of karst development (note that by defining it in this manner, the index is relatively independent of either the number or total length of grid lines.) We did this for 5056 blocks covering all but about the western one-fifth of Tennessee (Fig. 2).

Counts were made by two geomorphology classes taught by Mills in 1998 and 2000. Quadrangles were assigned alphabetically rather than by area in order to minimize the effects of bias. The reliability of all operators was checked by having some maps counted by multiple operators and by means of random checks by Mills. Data of unreliable operators were

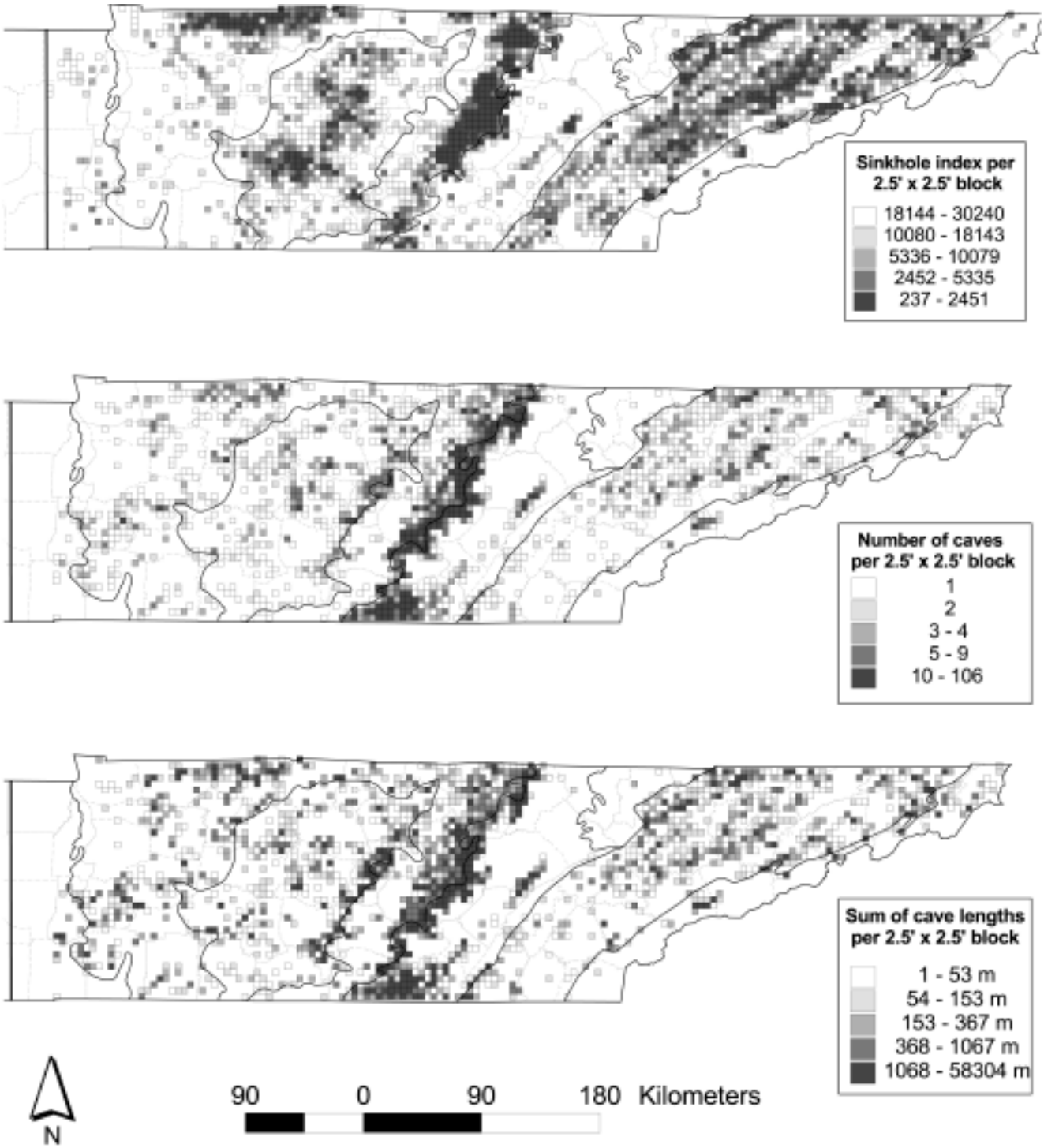



**Figure 2. Map showing sinkhole index, number of caves, and sum of cave lengths for each 2.5' x 2.5' block. Note: a *lower* sinkhole index indicates greater karstification, as lower values mean closer spacing of closed contour lines. Regions with no blocks represent "zero" values, i.e. no closed contours measured/observed, or no caves recorded. Heavy vertical line to the extreme left delimits the western extent of the study area. Heavy irregular lines show physiographic province boundaries; provinces are identified in figure 1.**

rejected. The total labor represented in making the counts was about 250 hours.

The block counts were entered into a plain-text database that was manipulated by custom FORTRAN code to produce

**Figure 3.**

**Enlarged map showing sinkhole index and number of caves in each 2.5' x 2.5' block for portions of the Western Highland Rim and Central Basin physiographic provinces. CLARK = Clarksville, CMB = Cumberland River, DK = Duck River, MURF = Murfreesboro. Physiographic provinces are identified in figure 1.**

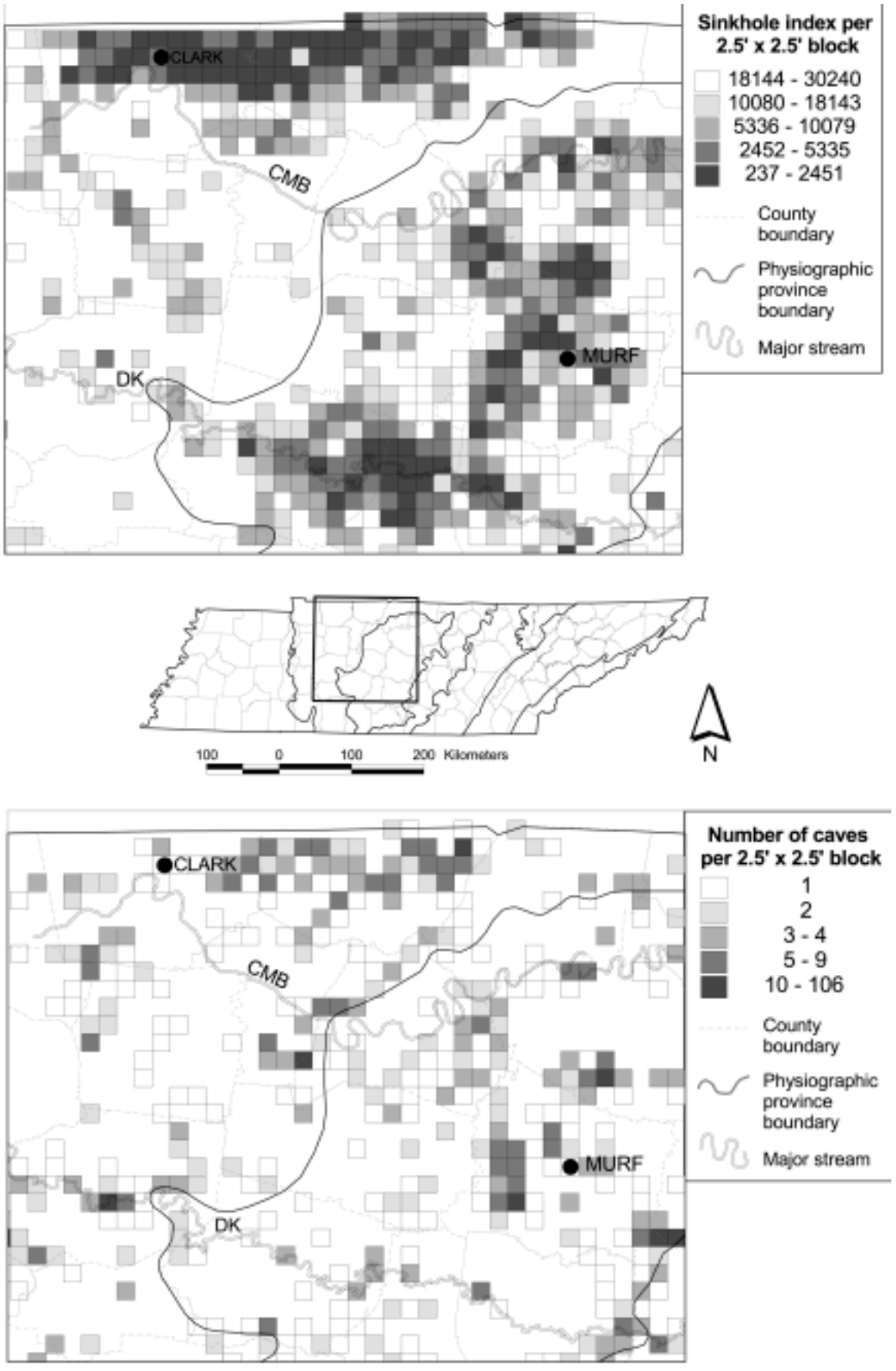


**Table 1. Mean values by physiographic province.**

| Physiographic province | N | Karst index = mean spacing of closed contours (m) | Mean number of caves | Mean sum of cave lengths (m) |
|---|---|---|---|---|
| Unaka Mts | 362 | 42,293 (41,241-43,346) | 0.44 (0.29-0.59) | 117.5 (34.4-200.5) |
| Valley & Ridge | 1134 | 17,949 (16,915-18,983) | 1.13 (0.97-1.29) | 182.0 (142.4-221.7) |
| Cumberland Mts | 136 | 43,631 (42,432-44,831) | 0.04 (0.00-0.07) | 5.8 (0.0-13.1) |
| Cumberland Plateau | 655 | 38,998 (37,930-40,066) | 3.77 (3.08-4.46) | 912.7 (538.0-1187.4) |
| E Highland Rim | 431 | 20,398 (18,568-22,228) | 4.29 (3.53-5.06) | 912.5 (559.3-1265.7) |
| Central Basin | 863 | 28,836 (27,260-30,035) | 0.85 (0.73-0.97) | 213.3 (148.0-278.5) |
| W Highland Rim | 1047 | 36,653 (35,397-37,909) | 0.61 (0.52-0.69) | 150.9 (109.3-192.5) |
| All provinces | 4628 | 30,077 (29,370-30,783) | 1.54 (1.40-1.68) | 342.0 (286.9-397.1) |

The 95% confidence interval is given in parentheses.

**Table 2. Correlation coefficients ( r values).**

| Physiographic province | N | Karst index vs. number of caves | Karst index vs. length of caves | Number of caves vs. length of caves |
|---|---|---|---|---|
| Unaka Mts | 362 | 0.394 | 0.251 | 0.439 |
| Valley & Ridge | 1134 | 0.235 | 0.153 | 0.623 |
| Cumberland Mts | 136 | 0.298 | 0.296 | 0.866 |
| Cumberland Plateau | 655 | 0.409 | 0.267 | 0.572 |
| E Highland Rim | 431 | 0.286 | 0.106 | 0.364 |
| Central Basin | 863 | 0.105 | 0.005 | 0.531 |
| W Highland Rim | 1047 | 0.268 | 0.178 | 0.511 |
| All provinces | 4628 | 0.204 | 0.100 | 0.515 |

the sinkhole index, including normalization to a common contour interval of 20-ft, that being the most common interval on Tennessee maps. Thus, counts done on a map with 10-ft intervals were halved, and counts done on a map with 40-ft intervals were doubled. (One possible inadequacy with such normalization is addressed below.)

To compare the distribution of sinkholes and caves, we used data provided by the Tennessee Cave Survey (TCS), specifically the location of the entrance and the length of each recorded cave in Tennessee. (Only one entrance was used for caves with multiple entrances.)

Microsoft Access was used to parse the TCS cave data to produce a data set usable within ArcView. The point locations of the cave entrances and the corresponding cave lengths were transformed into indices based on the same 2.5' x 2.5' blocks as the sinkhole index, by means of spatial queries within ArcView. Because it was not possible to constrain the spatial orientation of the caves, the entire length of any given cave was attributed to the same block as its entrance. All analyses in ArcView, including these queries, were based on a shapefile comprised of 5056 rectangular polygons.

Although intuitively obvious that the index is related to the abundance of sinkholes, we sought to define more precisely just what attributes of sinkholes the index reflects. To do this we generated 20 synthetic maps, representing sinkholes as inverted cones of varying area, depth, and density. (The advantage of conic sinkholes is that area and volume can be determined exactly.) We then overlaid grids on these maps and measured the sinkhole index of each. We then correlated the index with the total area and total volume of sinkholes on each map. The log-log correlation coefficient between the index and total sinkhole area was -0.974 ($R^2$ = 0.949), whereas that between the index and total volume was -0.803 ($R^2$ = 0.645). Thus, the index seems to be an excellent indicator of sinkhole area, and is a fairly accurate indicator of sinkhole volume.

## RESULTS AND DISCUSSION

On a small scale, the distribution of the sinkhole index in Tennessee (Fig. 2) generally agrees with Miller's (1977) karst map. However, whereas Miller's map delineates only two levels of karstification, the quantitative approach used here provides more detail on the degree of karstification. Figures 3 and 4 show enlarged views of selected areas of figure 2, focusing on the Western Highland Rim/Central Basin and the Eastern Highland Rim/Cumberland Plateau, respectively (Figures 3 and 4 show only the plot of cave numbers. However, as figure 2 shows, plots of sum of cave lengths and cave numbers are

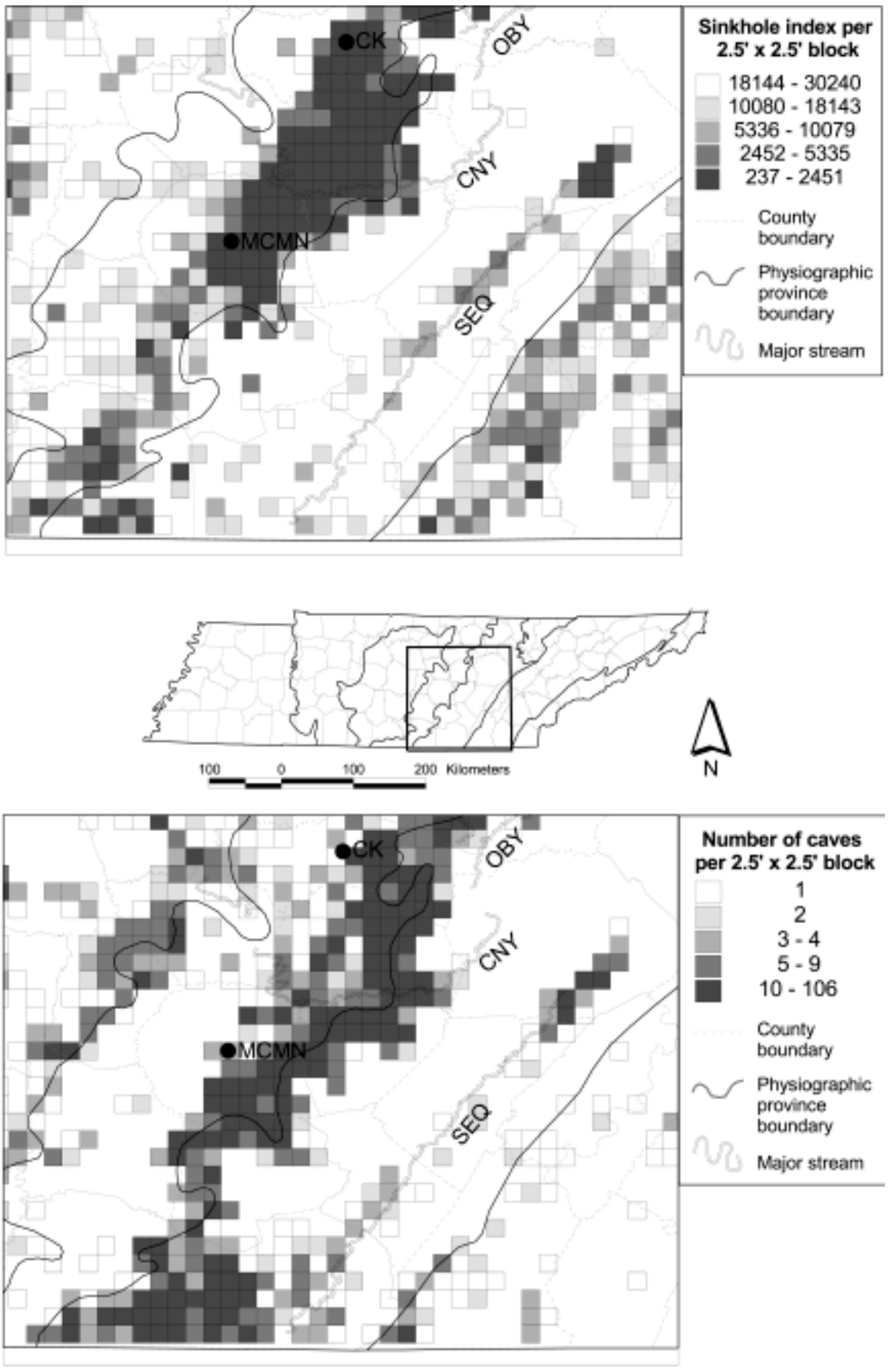



**Figure 4.**

**Enlarged map showing sinkhole index and number of caves in each 2.5' x 2.5' block for portions of the Eastern Highland Rim and Cumberland Plateau physiographic provinces. CNY = Caney Fork River, CK = Cookeville, MCMN = McMinnville, OBY = Obey River, SEQ = Sequatchie River. Physiographic provinces are identified in figure 1.**

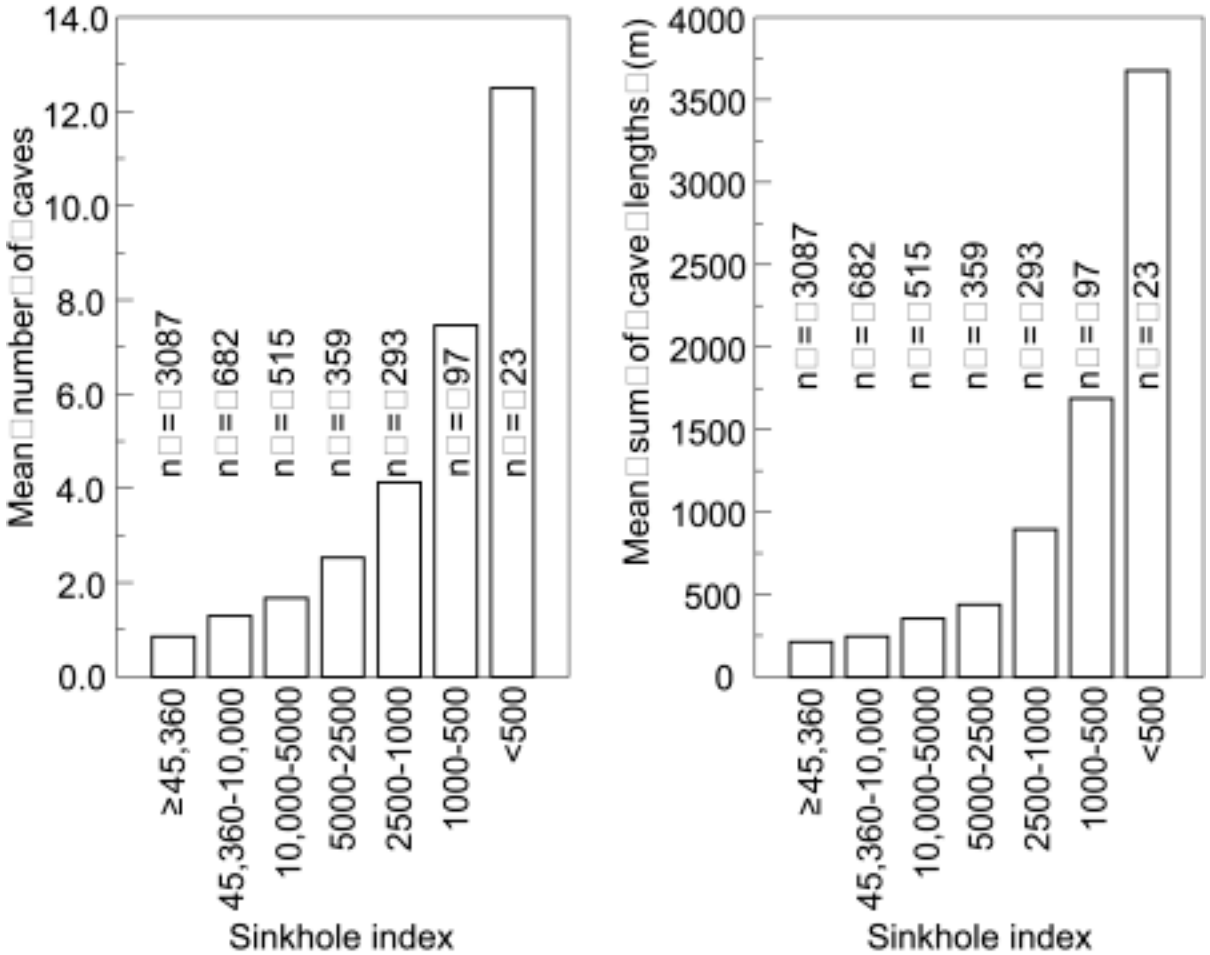



**Figure 5.**

**Histograms showing variation in mean number of caves per block and mean sum of cave lengths per block as a function of sinkhole index. The *n* values are the number of blocks in each interval.**

very similar). Table 1 shows the mean sinkhole index, mean number of caves, and mean sum of cave lengths for the major physiographic provinces of Tennessee, excluding the westernmost ones. Note that the physiographic boundaries shown in the figures have been simplified for presentation; more detailed boundaries were used for calculations.

Karstification generally is closely associated with areas underlain by carbonate bedrock. The sinkhole distribution map of figure 2 shows that the Highland Rim, Central Basin, and Valley and Ridge physiographic provinces, which are largely characterized by carbonate bedrock, all show extensive sinkhole development. But sinkholes are sparse in many carbonate areas, especially in the Central Basin and Highland Rim provinces. Extensive sinkhole development in the Central Basin is restricted to two areas, one centered around Murfreesboro, the other following along the course of the Duck River to the south (Fig. 3). This may be bedrock related, as the Ridley Limestone and Lebanon Limestone both crop out in these areas, and the intensity of sinkhole development diminishes where younger units are present. In the Western Highland Rim, the most intensive sinkhole development is limited to a small region in the northern part of the state, yet the entire region is predominantly limestone. In the Eastern Highland Rim, the intensity of sinkhole development ends fairly abruptly along a line trending southwest-northeast through Cookeville and McMinnville, with the sinkhole concentration lying to the east of this line (Fig. 4). Bedrock also seems to play a role in both of these cases, as the Eastern Highland Rim trend and the Western Highland Rim zone correspond to the stratigraphic contact between the Warsaw Formation and the overlying St. Louis Limestone (both Mississippian), with the sinkholes occurring mostly in the St. Louis.

A possible problem with the normalization technique used here to correct for map contour interval is that the number of sinkholes has been shown to increase exponentially with decrease in depth (Troester *et al*. 1984). In other words, a map with a 10-ft contour interval might show not merely twice as many sinkholes as a map with a 20-ft interval, but many times more, with a corresponding effect on the sinkhole index. However, at least in the present setting, this problem appears to be minor. First, 80% of the Tennessee maps have 20-ft contour intervals, 12.6% have 10-ft intervals, and most of the remainder have 40-ft intervals. The latter occur mainly in the Unaka Mountains, where karst areas are sparse, so the problem chiefly concerns the 20-ft vs. the 10-ft maps. The large difference between these two maps that might be expected from con-

sideration of Troester *et al*. (1984) simply does not occur. The mean sinkhole index for 10-ft maps is 23,294, only 26.1% different from the 31,522 value for 20-ft maps. Further, a large part of this difference appears to stem from the location of most 10-ft maps in karst areas (northernmost Western Highland Rim, central Central Basin, and southwestern part of the Eastern Highland Rim), whereas 20-ft maps are located in many non-karst as well as karst areas.

Concerning the relationship between sinkholes and caves, a comparison of the distribution of the sinkhole index, number of caves, and sum of cave lengths (Fig. 2) clearly shows a regional relationship between sinkholes and caves. However, there are also some pronounced differences. For example, note that the southern cluster of blocks in the Central Basin with high sinkhole densities shows little corresponding concentration of caves (Fig. 3). Perhaps the low relief in this province precludes access to many undiscovered caves that are present. Another discrepancy occurs in the southwestern part of the Cumberland Plateau, which shows a high cave density, yet a low sinkhole density (Fig. 4). An explanation probably involves the high degree of fluvial dissection in this part of the Plateau; sinkholes occur mainly only along the floors of narrow valleys. The walls of these valleys, however, provide access to many caves that have developed below the sandstone caprocks of the Plateau. Also note the concentration of sinkholes and caves near the boundary between the Eastern Highland Rim and the Cumberland Plateau. The sinkhole concentration is mainly on the Rim, but the cave concentration is somewhat farther to the southeast. This difference probably reflects the fact that many of the cave entrances occur along the escarpment where sinkholes are relatively few.

Figure 5 shows that as sinkhole index decreases (i.e., the density of closed contours increases), the number and length of caves rises, particularly for the higher ranges of sinkhole index values. However, on a block-by-block basis, the relationship is somewhat weaker. Table 2 shows the correlation coefficients between the sinkhole index and cave number and length for the major physiographic provinces. As can be seen, the correlation coefficients are low, although significant at the $p \leq 0.05$ level in most cases. The maximum percentage of variance explained is less than 17%, and less than 9% in most cases. The correlation between the sinkhole index and the mean sum of cave length is somewhat weaker than that between the index and the number of caves. This result may be partly due to the fact that the greater part of the cave length attributed to a given block may actually lie in a block different from that in which the cave entrance is located.

## CONCLUSIONS

The general correspondence between the maps of the sinkhole index and the previously compiled karst map by Miller (1977) supports the validity of this index. The present map based on a more quantitative method, shows the variation in karstification in more detail than does Miller's map. In addition, experiments with synthetic sinkhole maps suggest that the index accurately reflects total sinkhole area.

The visual correspondence between the sinkhole index and the abundance of caves indicated by the number and total length of caves in each block clearly indicates that conditions that favor sinkhole formation also favor cave formation. However, low correlation coefficients between the sinkhole index and number and length of caves show that this correspondence does not apply in a block-by-block manner. Thus, we must conclude that whereas similar conditions appear to favor both sinkhole development and cave formation, different and only weakly related processes are involved in the formation of the two types of karst features. This conclusion is similar to that of previous researchers.

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