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Sinkhole distribution based on pre-development mapping in urbanized Pinellas County, Florida, USA

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Abstract: Locating sinkholes in Pinellas County, Florida, is confounded by the presence of a cover of Quaternary sediments that mute the surface appearance of these sinkholes. As a first step in addressing the sinkhole hazard in the county, we analysed aerial photographs from 1926 and 1995 that covered the entire county. We digitized all identifiable sinkholes in each set of photographs in a GIS (Geographical Information System) using a set of criteria established to differentiate between karst depressions and depressions resulting from other geological processes. The 1926 photographs, although of low quality, helped to establish a baseline prior to urbanization. The 1995 photographs provided a post-urbanization distribution of natural sinkholes and man-made depression features (e.g. retention ponds). From these two data sets, we are able to assess natural and anthropogenic changes in the karst landscape of the study area. In particular, we discovered that 87% of the sinkhole features identified in the 1926 photographs are no longer present in the photographs from 1995. Many of the lost depressions have been incorporated into retention ponds.

Pinellas County, in west-central Florida (Fig. 1), in the USA, is located in one of the most active karst regions of the world. Karst, a collection of surface and subsurface landforms produced from the dissolution of limestone and other soluble rocks, is present in many regions throughout the world and is of distinct interest to individuals and organizations associated with these landscapes. This is due, in part, to unique engineering difficulties and contaminant transport properties of karst aquifers. Pinellas County is a peninsula and is underlain by distinct layers of Cenozoic limestone that are covered in most areas by Quaternary sands. The county is modified by coastal processes on the current shoreline, and marine terraces indicate the presence of higher sea levels. In the interior portions of the county, numerous karst depressions are present.

The most identifiable surface features in the karst landscape of west-central Florida are sinkholes. However, in contrast to classical karst landscapes of the Central Lowlands and Appalachian Mountains in the USA, the topographic expression of these depressions is partially masked by Quaternary sediments deposited by eolian processes or during higher sea levels. Within the past century, humans have filled many depressions and modified others for storm-water retention as part of the rapid and intense urbanization of this coastal area. Mapping and analysis of sinkholes was not completed prior to or after development to assess the distribution of karst features in Pinellas County or to document changes in topography as a result of urbanization. Pinellas County, like much of the Tampa Bay region and Florida in general, is rapidly urbanizing. Construction projects significantly impact the karst landscape and vice versa. Without a clear understanding of where karst features are located it is difficult to implement appropriate land-use strategies and management decisions that are suitable for the site geology and of benefit to the citizens of the county. As Pinellas County loses remaining green space, increases densities in existing developments and redevelops brownfields, it will be critical to understand the landscape that exists beneath the veneer of human development because the underlying geological processes that created the original surface features will continue to modify the soil, bedrock and topography.

In Florida, sinkholes occur in clusters or 'sinkhole regions' (Tihansky 1999). These clusters represent areas of past sinkhole formation and are locations where future sinkholes may develop, although the occurrence of topographic sinkholes does not predict the development of new cover collapses. Certainly, sinkhole regions may be hidden by geological deposition or human development, and may extend into or exist within urbanized regions. A useful method of identifying

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Fig. 1. Location of Pinellas County, Florida.

masked (obliterated) areas affected by subsidence is to map topographic depressions and wetland features that are probably the result of karst processes using historic air photographs and maps. Such an exercise will not only assist county planners, it will aid our scientific understanding of karst processes in Florida and the extent of sinkhole regions that existed in the pre-urbanized past. Such an exercise has rarely been conducted over such a large area.

Pinellas County is underlain by the unconfined Floridan Aquifer System and, as in most carbonate terrain, karst processes exert significant control on the geomorphology (White 1970, 1988; Schmidt & Scott 1984; Lane 1986; Miller 1986). Aggressive groundwater circulation and diagenetic alteration has dissolved limestone and increased porosity within the stratigraphic framework of the Floridan Aquifer. This solution porosity dominates groundwater flow. The complex nature of conduit systems in the unconfined Floridan Aquifer is becoming better understood (Miller 1997). However, the difficulty of locating and exploring submerged conduits and the complex porosity makes analysis and modelling difficult.

In Pinellas County, surficial expression of karst is limited to sinkholes, sinkhole-associated features and springs. Karst features provide unique problems for planners and environmental scientists. Land stability is perhaps the issue citizens are most familiar with and are the most concerned about, although contaminant transport and water quantity are also important issues.

Sinkholes form from a variety of processes (e.g. White 1988; Upchurch & Randazzo 1997). The bulk of sinkholes in Pinellas County are categorized as cover-collapse sinkholes that form when Pleistocene sands above limestone ravel into void space in bedrock (Tihansky 1999). The spatial distribution of these sinkholes appears linear on many Florida maps. Sinkholes form in linear trends because they are localized by joints and fractures that facilitate groundwater flow through the soluble rock.

Previous efforts have described and/or mapped karst features in Pinellas County. For example, Sinclair *et al.* (1985) analysed sinkholes in west-central Florida and described their formation based on cover and bedrock type. They also reviewed data on recently formed sinkholes in the region. However, they did not map them. Frank & Beck (1991) assessed the causes of subsidence damage in a small area of the town of Dunedin in northern Pinellas County. They examined the mechanisms behind the formation of subsidence in the area in the years 1990–1991 and found that almost all of these damaging subsidences were cover-subsidence sinkholes, although this could not be guaranteed for 100% of the damage.

In 1991, Beck & Sayad (1991) published a summary of the sinkhole hazards in Pinellas County. They utilized reported sinkhole events to assess the overall hazard from subsidence. Stewart *et al.* (1995) examined foundation failures in Pinellas County to assess the causes of failures. More recently, the Florida Geological Survey mapped closed depressions on United States Geological Survey (USGS) 1:24 000 topographic maps as part of their overall Florida Aquifer Vulnerability Assessment (FAVA) programme. A variety of other attempts have been made to map sinkholes in other parts of Florida, including nearby Pasco County (Currin & Barfus 1989).

Although all of the past research is useful, to date, there has been no effort to map all sinkholes in Pinellas County, including those lost to urbanization. Therefore, the focus of this project is to develop a county-wide map of sinkholes present on historic and recent aerial photographs in order to assess the number and spatial distribution of depressions lost through development, and in order to understand how pre-existing sinkholes may have been modified through urbanization.

One measure of the human impact on karst landforms is to assess the number of obliterated depressions and particularly those modified to create storm-water retention ponds. Storm-water retention ponds are used to manage storm-water drainage to prevent flooding during common high-intensity storm events in the rainy season and to allow time for polluted runoff to clear up before discharging into the aquifer or surface streams. If natural depressions like sinkholes are used as sites for storm-water pond creation, the degradation of groundwater quality may be aggravated because polluted surface water can quickly enter aquifer systems through sinkhole-ravelling zones. The unfortunate use of the sinkholes may also result in the reactivation of the subsidence features, with the consequent rise in the sinkhole frequency. Storm-water retention ponds became the best management tool for urban storm water in the 1970s when the combined effects of flooding and surface-water pollution caused environmental problems. Thus, many areas of Florida are dotted with these ponds.

Recent rules preclude the use of the sinkholes as sites for pond construction. Yet, many sinkholes were used prior to the approved establishment of these rules. Thus, we seek to understand the extent of storm-water construction in natural depressions in Pinellas County in order to assess the potential detrimental effects on the karst aquifer. This is particularly important because water-retention ponds are more frequently being used as sites of storm-water storage to prevent polluted water from entering nearby surface-water bodies like the important Tampa Bay estuary or many of the lakes and small streams that flow in Pinellas County.

Methods

Karst features were mapped on aerial photographs from 1926 and photographs from 1995 imported into a GIS (Geographical Information System). Four GIS layers were created using the 1926 black and white photographs: sinkholes, possible sinkholes, exclusion areas (areas that were obscured or unclear in the photographs) and developed areas (those areas that showed notable development such as clusters of roads and/or structures). The 1995 aerial photographs are full-colour high-resolution infrared images. Using these images, four GIS layers were constructed: sinkholes, possible sinkholes, water retention ponds and undeveloped and/or non-urbanized areas (mainly wetlands and forest).

Sinkholes were defined by vegetation changes or variation, presence or absence of water, soil moisture and shape. The criteria used to identify these features on both the 1926 and 1995 photographs were moisture content and circular and/or combined circular shapes. The features in the possible sinkhole layer on both the 1926 and 1995 air photographs were identified as having some moisture and circularity conditions, but lacking clear indications of one of those factors (moisture condition or circularity). Lakes that appeared to be depressional on the photographs were considered to be sinkholes. It must be noted that the 1926 air photographs were taken during the dry season in Florida so many of the sinks that would normally contain water were dry. So, vegetation patterns and coloration from soil moisture were used to identify the circular patterns. The 1926 air photographs are black and white, and of poor quality. Many of the areas of these photographs are completely unusable for photographic interpretation. Thus, an exclusion layer was created to remove these areas when carrying out density estimates and other analyses.

The features identified in the retention pond layer in the 1995 air photographs were those depressions considered to be man-made with at least one straight edge.

The sinkhole density in Pinellas County was calculated using a total land area of Pinellas County of 725 km^2 for 1926 and 1995. In addition, the total area and percentage of land area of sinkholes was calculated for 1926 and 1995. From this we were able to calculate the percentage loss of the features that were identified. Then, a map with a layer consisting of all sinks in 1926 and a layer of all sinks from 1995 was constructed. An intersect was then performed in ArcGIS and the results were the sinks that are still present in 1995. We also attempted to determine which sinkholes that were identified in 1926 are now storm-water retention ponds. To do this, we created a map that consisted of the intersect of the layer of total sinks identified in 1926 and the retention pond layer constructed in 1995.

Table 1. *Total area, density and per cent land area of sinkholes using the 1926 and 1995 air photographs*

	Total number of features	Total area (km^2)	Density (per km^2)	Per cent land area (%)
1926				
Likely sinkholes	1570	19.34	2.20	2.70
Possible sinkholes	1133	24.56	1.59	3.44
Total	2703	43.90	3.79	6.20
1995				
Likely sinkholes	261	1.60	0.36	0.22
Possible sinkholes	639	3.97	0.88	0.55
Total	900	5.57	1.24	0.77
Retention ponds	1646	13.25	2.27	1.83

Results

We identified 1570 depressions using the 1926 air photographs of Pinellas County. These probable, or likely, sinkholes account for nearly 20 km^2 (2.7%) of land (Table 1, Fig. 2). In addition, we identified 1133 depressions that are possible sinkholes. While the number of possible sinkholes is smaller than likely sinkholes, the area covered is larger at nearly 25 km^2 (3.4%). Collectively, this accounts for a density of 3.8 sinkholes km^{-2}. It must be noted that several areas of Pinellas County were already developed in 1926 (Fig. 3). These areas account for some of the earliest urbanized areas of the Florida peninsula in the vicinity of present-day downtown St Petersburg and the fishing community of Tarpon Springs. However, the developed portions account for only 14.5% of the total land area. Certainly, some sinkhole modification occurred in these areas, but the

Fig. 2. Distribution of depressions in 1926 in Pinellas County, Florida.

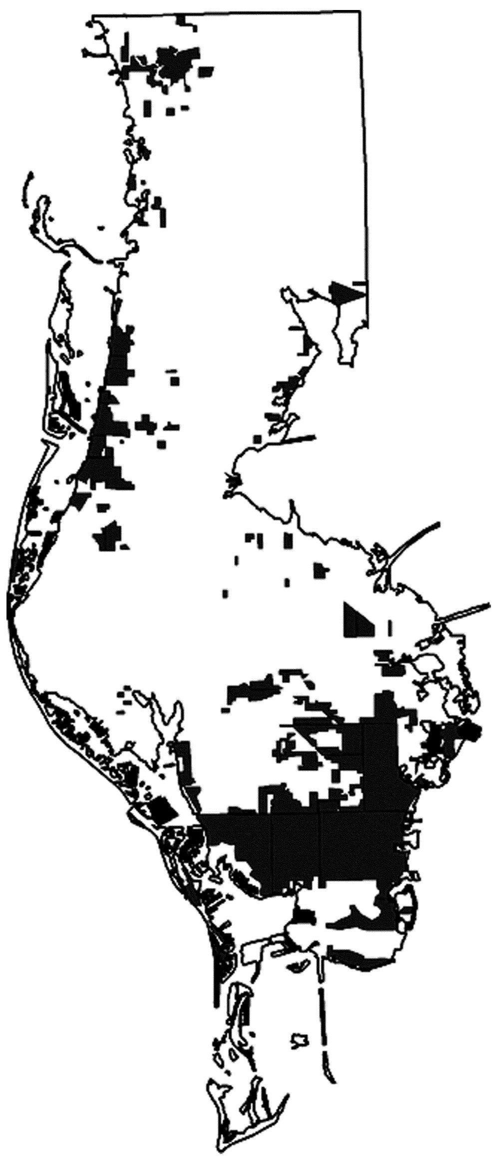

Fig. 3. Developed areas of Pinellas County, Florida.

vast majority of the county remained undeveloped at the time the air photographs were collected.

A total of 261 depressions were identified on the 1995 air photographs that are likely sinkholes (Table 1, Fig. 4). This number contrasts sharply with the number of sinkholes identified on the 1926 air photographs and accounts for only 0.2% of the modern land surface. Likewise, only 639 possible sinks were identified in 1995. While this number is greater than the number of likely sinkholes found in 1995, these depressions only cover 0.6% of the land surface. Collectively, the sinkhole density in 1995 was only 1.2 sinkholes km^{-2}. A great deal of urbanization has taken place over the 1926–1995 period. The undeveloped land portions account for only 2.7% of the county. It is evident that development significantly altered the karst landscape over the 72 year period of study. Most of the undeveloped land areas were lowlying and adjacent to Tampa Bay or in terrestrial wetlands in the NE portion of the county. A total of 87% of the sinkholes and possible sinkholes mapped in 1926 were buried or masked by 1995.

It is striking to compare similar land areas in 1926 and 1995 in order to see the loss of depressions and the extent of urbanization that has taken place. One of the most obvious examples can be found in central Pinellas County and clearly demonstrates the dramatic loss of depressions through urbanization (Fig. 5). The dark areas in the older air graphphoto in Figure 5 largely represent depressional features probably formed through karstification and subsidence

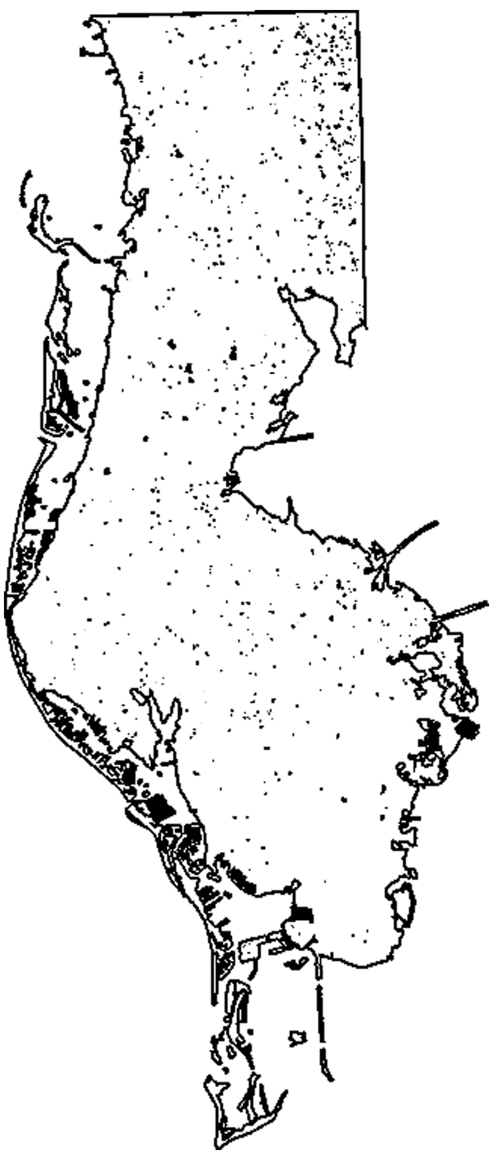

Fig. 4. Distribution of depressions in 1995 in Pinellas County, Florida.

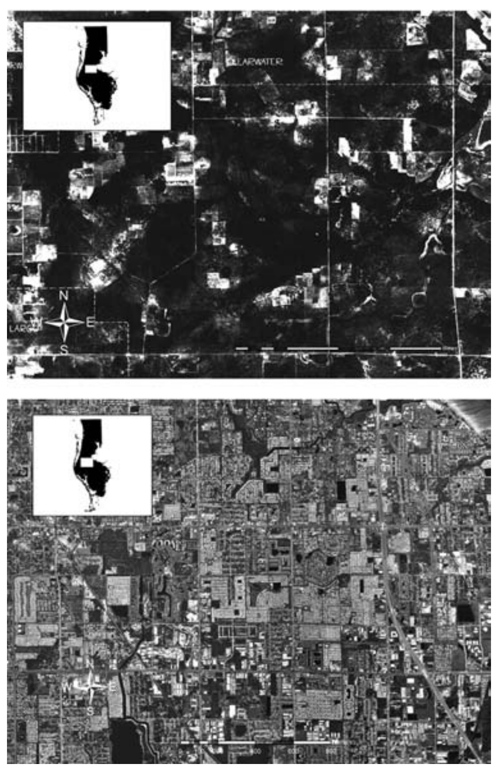

Fig. 5. Comparison of 1926 and 1995 air photographs. The photograph at the top is an image of an undeveloped portion of Pinellas County. The image below shows the same area in 1995. Note the loss of depressions throughout the area.

processes. Many of these features had gone by 1995, a time when urbanization and the associated regular grid system significantly modified the landscape, destroying many depressions. Sinkholes were most probably filled or otherwise modified as development progressed in the region.

Of particular interest is the presence of water retention ponds in Pinellas County present in the 2000 air photographs and how the distribution of these features coincides with depressions mapped on the 1926 air photographs. We identified 1646 water retention ponds on the 2000 air photographs. Approximately 21.8 km^2 of retention pond area overlapped with depressions mapped on the 1926 air photographs (Fig. 6). Of the 2703 depressions mapped in 1926, 499 of them have been converted or altered in some way into areas of water retention ponds. This figure, approximately 18% of all natural depressions in the county, does not necessarily mean that these water retention ponds pose a threat to groundwater. Indeed, we did not attempt to evaluate whether or not the retention ponds were lined or in some other way mitigated to prevent harmful effects of drainage through ravelling zones. However, it does demonstrate that there is a potential hazard to the subsurface system.

Although we did not intend to conduct any geomorphic description of sinkholes in the county, it is important to note that there are distinct differences in the karst landscape in the region (Fig. 2). The northern portion of the county had the most complex karst depressions. Many of these features were uvalas that certainly interconnected during high water flow. There may have been some fluvial modification of these features that occurred when subsurface drainage could not keep up with heavy rainfalls common during summer or during tropical storm events. Further south, the depressions are more rounded and exist in a less dense pattern than those in the north. It is not particularly surprising that the northern portion of Pinellas County is the last portion to undergo urbanization. Much of the area is in the form of low karst depressions and is thus difficult to develop.

Fig. 6. Distribution of water retention ponds in Pinellas County, Florida in 1995.

Conclusions and recommendations

The results of this study provides new information on the distribution of depressions in Pinellas County, Florida, as well on the effects of urbanization on Florida karst landscape. Specifically, a total of 2703 depressions were identified on the 1926 air photographs. These likely sinkholes accounted for 43.9 km^2 and 6.1% of the total land area. By 1995, only 900 of these depressions remained. These features totalled only 5.6 km^2 and 1% of the total land area of the Pinellas County. From these data we measured a loss of 87% of depressions between 1926 and 2000. It is likely that this loss is owing to the rapid urbanization that occurred since 1926. Many of the existing depressions were filled or modified into storm-water retention ponds.

We mapped 1646 storm-water retention ponds in Pinellas County. A total of 499 of these ponds are located in areas that were mapped as depressions in 1926. It is clear that there is a potential threat of subsurface pollution from leakage in the retention ponds owing to the overlap of these structures with ravelling zones of sinkholes. It must be noted that we did not evaluate individual water retention ponds to determine if they are lined or in some other way managed to prevent subsurface pollution. This would be a valuable future project.

The presence of so many buried or otherwise modified depressions in an urbanized area is rather striking. We are very interested in the impact of the modified depressions on overall ground stability, and surface-water and groundwater flow. Florida law mandates that insurance carriers cover damage to homes from subsidence caused by sinkhole activity (Eastman *et al.* 1995). There are dozens of claims filed each year in Pinellas County by property owners who have some form of structural damage to buildings caused by subsidence. While the focus of our research did not address the correlation between lost depressions and structural damage, we do believe that a follow-up study that addresses this issue is warranted.

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