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Modification of karst depressions by urbanization in Pinellas County, Florida

Kelly V. Wilson

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Modification of Karst Depressions by Urbanization in Pinellas County, Florida

by

Kelly V. Wilson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
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Keywords: sinkhole, gis, karst, aerial photographs, florida

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Table of Contents

List of Tables ii

List of Figures iii

Abstract iv

Chapter One – Purpose and Introduction 1

Purpose 1
Introduction 1
Karst Landscape 2
Karst Formation 3
Karst Morphology 4
Florida Geology, Geomorphology, Hydrology 6
Florida Geology 6
Florida Geomorphology 7
Florida Hydrology 9
Florida Karst 10
Geomorphology of Sinkholes 11
Classification of Sinkholes 12
Sinkholes in Florida 13
Karst and Sinkholes in Pinellas County 15

Chapter Two – Methodology 19

Methodology 19
Data Management 20
Sinkhole Delineation 21
Morphometric Analysis 23

Chapter Three – Results 26

1926 Aerial Photos 26
Density, Total Features, Total Area, Percent Area 26
1926 Black and White Aerial Photo Descriptions 28
Northeastern Pinellas County 28
Central Pinellas County 32
Southern Pinellas County 35
2000 Aerial Photos 35
Density, Total Features, Total Area, Percent Area 35
2000 Color Aerial Photo Descriptions 37
Northeastern Pinellas County 41
Central Pinellas County 41
Southern Pinellas County 44

Chapter Four – Discussion 46

1926 and 2000 Aerial Photo Comparison 46
Percent Loss 46
Retention Areas 52
Sinkhole Elevations 52

Chapter Five - Conclusions and Suggestions for Further Research 55

Conclusions 55
Suggestions for Further Research 56

References 58
List of Tables

Table 1  Karst Landscapes and Descriptions  5
Table 2  1926 Aerial Photo Data  28
Table 3  2000 Aerial Photo Data  37
Table 4  Percent of Sinkholes lost by 2000  52
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Age of Geologic Units in Florida</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Geologic Map of Pinellas County</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Data Management Chart</td>
<td>20</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Map of Florida – Pinellas County Highlighted</td>
<td>27</td>
</tr>
<tr>
<td>Figure 5</td>
<td>1926 Sinkhole Map</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6</td>
<td>1926 Areas of Exclusion</td>
<td>30</td>
</tr>
<tr>
<td>Figure 7</td>
<td>1926 Developed Areas</td>
<td>31</td>
</tr>
<tr>
<td>Figure 8</td>
<td>1926 Aerial Photo – Northeastern Pinellas County</td>
<td>33</td>
</tr>
<tr>
<td>Figure 9</td>
<td>1926 Aerial Photo – Central Pinellas County</td>
<td>34</td>
</tr>
<tr>
<td>Figure 10</td>
<td>1926 Aerial Photo – Southern Pinellas County</td>
<td>36</td>
</tr>
<tr>
<td>Figure 11</td>
<td>2000 Sinkhole Map</td>
<td>38</td>
</tr>
<tr>
<td>Figure 12</td>
<td>2000 Storm Water Retention Areas</td>
<td>39</td>
</tr>
<tr>
<td>Figure 13</td>
<td>2000 Undeveloped Areas</td>
<td>40</td>
</tr>
<tr>
<td>Figure 14</td>
<td>2000 Aerial Photo – Northeastern Pinellas County</td>
<td>42</td>
</tr>
<tr>
<td>Figure 15</td>
<td>2000 Aerial Photo – Central Pinellas County</td>
<td>43</td>
</tr>
<tr>
<td>Figure 16</td>
<td>2000 Aerial Photo – Southern Pinellas County</td>
<td>45</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Possible Sinks Present on Both 2000 and 1926 Aerial Photos</td>
<td>47</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Sinks Present on Both 2000 and 1926 Aerial Photos</td>
<td>48</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Total Sinkholes Present in Both 1926 and 2000 w/ Intersecting Areas</td>
<td>49</td>
</tr>
</tbody>
</table>

iv
| Figure 20 | Intersecting Areas of Sinkholes Present in both 1926 and 2000 | 50 |
| Figure 21 | Sinkholes which formed after 1926 | 51 |
| Figure 22 | 1926 Sinkholes Intersecting 2000 Storm Water Retention Ponds | 53 |
| Figure 23 | Topographic Map with Sinkhole Locations | 54 |
Modification of Karst Depression by Urbanization in Pinellas County, Florida

Kelly V. Wilson

ABSTRACT

This thesis analyzes some of the effects of urbanization in Pinellas County, Florida on the karst landscape. Many sinkholes have been obscured and/or modified for storm water retention by urbanization in Pinellas County, with a few sinkholes still identifiable by characteristic zoning of vegetation, soil moisture, and circular shape. Using aerial photos from 1926 and 2000, karst features were identified by circularity, vegetation, and moisture conditions. Mapping karst surface features using historic aerial photos and maps is a useful exercise that will assist our scientific understanding of karstification in Florida and the nature and extent of karst processes that have acted in the pre-urbanized past. The final product of this research is a digital spatial database and metadata of karst features discernable on the 1926 and 2000 aerial photos; a description of the karst landscape mapped for each time period; and a morphometric description (including sinkhole area, density, and topography) of the karst landscape mapped for each time period.

A total of 2,703 sinkholes were identified on the 1926 aerial photos. By 2000 only 900 sinkholes were still visible, a loss of 87.31%. Most of the loss of these sinkholes was due to the rapid urbanization that happened between 1926 and 2000. A total of 499 sinkholes that had been identified in 1926 have now been modified into storm water retention ponds.
CHAPTER 1
PURPOSE AND INTRODUCTION

Purpose

The purpose of this thesis is to analyze the effects of urbanization in Pinellas County, Florida, on the karst landscape and to map sinkholes modified through urbanization from 1926 to the present. I believe that the urbanization of Pinellas County has resulted in the filling or modification of sinkholes that were present in the 1926 aerial photos to be filled or modified. I think many of the sinkholes which were modified have become storm water retention ponds. This modification can allow untreated water to enter aquifer systems and thus affect not only Pinellas County, but the rest of Florida as well. The results of this research will be useful to land managers in addressing karst issues in the County and to karst scientists interested in predevelopment karst geomorphology. This introduction will review various aspects of Florida karst systems.

Introduction

Over 17,000 square miles of the United States has been directly affected by land subsidence with eighty percent of this subsidence being a direct result of development and exploitation of groundwater resources (Galloway and others, 1999). The increasing development of land and water resources threatens to aggravate existing land subsidence problems and initiate new ones. The development of karst terrains is riddled with both environmental and engineering hazards (Wilson and Beck, 1988). Extraction and drainage of ground water play a direct role in land subsidence by causing the compaction of vulnerable aquifer systems and the dewatering of organic soils (Galloway and others,
In Florida more than 10 million people and countless agricultural interests rely on groundwater supply, thus increasing the possibility of land subsidence and sinkhole formation (Scott, 2002).

The formation of sinkholes, one of the greatest karst hazards found in Florida, although fundamentally a natural process, can also be triggered by groundwater level declines caused by pumping, infiltration from reservoir impoundments, surface water diversions, or storm water runoff channels (Galloway and others, 1999). The economic losses due to karst hazards, such as sinkholes, are largely hidden because they are spread across an area the size of a state. The only way to completely avoid economic and environmental damage from human activity on karst terrain is to avoid building on karst, but the demands of economic growth are applying overwhelming pressure to develop these areas (Cobb and Currens, 2001). According to a report published by the Florida Sinkhole Research Institute (FSRI)...

“Florida’s rapid urban development dramatically increases the threat and the dangers of sinkhole collapse, particularly in the state’s urban areas. Unprecedented growth, patterns of drought, and increased water well pumping increase the likelihood of extensive future sinkhole formation activity. Increased risks will accompany continued development.” (FSRI, 1983)

**Karst Landscape**

The term karst (Slavic kras) means literally, a bleak waterless place (Sinclair and others, 1985). Karst is defined in the *Glossary of Geology* as “a type of topography that is formed on limestone, gypsum and other rocks, primarily by dissolution, and that is
characterized by sinkholes, caves, and underground drainage” (Bates and Jackson, p.337, 1980). Karst is terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well-developed secondary porosity. Karst is synonymous with limestone landscapes; however, other soluble rocks such as dolomite, gypsum, and salt show karstification in some regions (Bloom, 1998). A true karst area has predominately underground drainage with a poorly developed surface network of streams. Karst landscapes are common in humid, temperate climates where ample free water is available to circulate, but the greatest abundance and variety of karst landscapes are located in warm, tropical environments with lush vegetation and abundant rainfall, and are underlain by other soluble rock (Kochel and others, 1995).

About 15 percent of the area of the conterminous United States has karst-prone rocks at or near the surface, and about 12 percent of the earth’s land area has exposed carbonate rocks although not all of it shows karst landforms. The most notorious karst region in the United States for construction and groundwater problems is Florida and parts of Georgia, Alabama, and Kentucky. Other areas of the world facing karst problems include Turkey, Greece, Italy, France, Spain, the Middle East, and northern Africa (Kochel and others, 1995).

**Karst Formation**

Two things are necessary to create the karst terrain present in Florida: carbonate rocks and slightly acidic water to dissolve them (Lane, 1986). The solution of limestone in a karst terrain is essentially the solution of CaCO₃, by downward moving water which is accomplished through the CaCO₃-CO₂-H₂O chemical reaction. This is an epigenic process that is driven by the hydrologic cycle. Limestone solution, and therefore karst, is
also affected by biologically generated CO₂ in decaying humus. Animals and plants can corrode limestone directly as well as create biochemical conditions that slow down solution or promote deposition of sediments (Bloom, 1998).

The solution process can create and enlarge cavities within karst rocks. This leads to the progressive enlargement of voids beneath the surface allowing large amounts of water to be directed into an underground drainage system, possibly disrupting the pattern of surface flow. Creation of karst depends on how much water any rock can hold and how easily the water moves through the rock system; these two characteristics are known as porosity and permeability. Open textures and higher secondary porosity facilitate the solution process and the development of karst (Kochel and others, 1995).

Karst Morphology

Two important physical characteristics of karst are lithology and rock permeability. Most karst forms on limestone, which is an extremely diverse rock type. To be defined as a limestone, a rock should contain more than 80 percent calcium and magnesium carbonate, but many limestones contain sand, silt, and clay (Bloom, 1998). Limestones can have granular textures and considerable porosity and permeability (Lane, 1986). Karst limestones in general are quite pure. Karst landscapes can develop their own distinctive geomorphology. Table-1 lists several landscape types and their characteristics.

An estimated 25 percent of the Earth’s human population is supplied with most or all of their waters from karst aquifers (Galloway and others, 1999). Much of the water flows rapidly through conduits from point sources in the bottom of sinkholes, and discharges at springs or into rivers or the sea. The complex conduit system of karst
Aquifers are not all interconnected as explained in the following paragraph (Bloom, 1998).

Aquifers are subsurface zones of rocks or sediments that yield water in sufficient quantities to be economically useful for man’s activities. Aquifers can be unconfined, semi-confined, or confined. Unconfined aquifers contain water that is in direct contact with the atmosphere. The zone of sediments or rocks saturated with water is the vadose zone, and is referred to as a surficial or water-table aquifer. The water table

<table>
<thead>
<tr>
<th>Aquifer Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doline karst</td>
<td>Most common and widely distributed landscape; are spotted with sinkholes of varying size</td>
</tr>
<tr>
<td>Cockpit karst</td>
<td>Typically found in sub-tropical and tropical climates; very similar to doline karst but have low depression densities with high sinkhole area ratios</td>
</tr>
<tr>
<td>Cone and Tower karst</td>
<td>Thick massive limestone and well-developed fracture system. Isolated blocks surrounded by alluvial plains.</td>
</tr>
<tr>
<td>Fluvio karst</td>
<td>Abnormal drainage, blind valleys, swallow holes, large springs, closed depressions, and caves. Larger rivers maintain their surface courses and are often fed by underground tributaries.</td>
</tr>
<tr>
<td>Pavement karst</td>
<td>Areas of bare limestone, usually sculpted into karren of various types. Occur in alpine terrains where soils are thin or stripped by glaciation.</td>
</tr>
<tr>
<td>Polje karst</td>
<td>Covers very large areas; Consists of poljes which are very large closed depressions; requires a great thickness of carbonate rocks.</td>
</tr>
<tr>
<td>Labyrinth karst</td>
<td>Dominated by intersecting solution corridors and solution canyons.</td>
</tr>
<tr>
<td>Cave karst</td>
<td>Regions where limestones and other soluble rocks crop out at the surface, there are caves and a well-developed underground drainage, and little surface expression in the form of closed depressions or other karst landforms is found.</td>
</tr>
</tbody>
</table>

Table 1. Karst landscapes and descriptions (White, 1988 – p. 107 - 117).

is the top of the zone of saturation. Semi-confined or confined aquifers are separated from direct contact with the atmosphere by impermeable material, such as clay beds or
consolidated rocks. Confinement may impose pressure on the contained water and create artesian conditions (Lane, 1986)

Springs are expressions of flow from a water-table, semi-confined, or a confined aquifer. When downward percolation of water is impeded by a confining layer the water is forced to move laterally, downslope, and discharge where the permeable sand and less permeable clay intersect the land surface (Lane, 1986). These terms are important when discussing Florida karst systems.

A review of Florida karst hydrology and geomorphology follows.

**Florida Geology, Geomorphology, Hydrology**

The following section discusses the geology, geomorphology, and hydrology in Florida. The Florida Platform is believed to have been part of the West African continental margin near Sengal and was rifted from that margin during a Triassic breakup. Geochemical and geochronologic data have provided support for the proposed correlations of Florida basement terrains with the West Africa and northeastern South America (Heatherington and Mueller, 1997).

**Florida Geology**

The entire Florida Platform is covered by a blanket of carbonate sediments ranging in age from Miocene to Holocene. Older sediments are exposed only along rivers and streams and in sinkholes that cut through younger sediments. Younger sediments were deposited under marine conditions (Scott, 1997). The Florida peninsula most likely emerged from a submarine environment during the Neogene (Smith and Lord, 1997).
The carbonate formations of Florida are generally dolomitic limestones, with varying amounts of interbedded evaporites; they represent peritidal and subtidal shelf environments of deposition, reflecting small and large scale sea-level fluctuation (Randazzo, 1997). Dolostones are the dominant carbonate sediments in the northern two-thirds of the peninsula while limestone predominates in the southern peninsula and in the eastern panhandle area (Scott, 1992). Figure - 1 visually depicts the geology of the state of Florida.

Florida Geomorphology

Marine and coastal processes have been the dominant factors in shaping and modifying the Florida platform as well as the exposed peninsula (Scott, 1988). The western edge of the Florida platform lies over 160 kilometers west of Tampa. The eastern edge lies only 4 or 6 kilometers off the coast of Miami, dropping off steeply to abyssal depths of more than 3 kilometers, creating what is known as the Florida escarpment (Lane, 1994). The portion of the Platform that is above sea level, the peninsula, comprises the state of Florida. Sediments were eroded from the southeastern coastal plain and southern Appalachians as the siliciclastic coastal plain advanced southward toward the Gulf of Mexico. Sediments eventually filled the Gulf trough and spilled onto the carbonate platform. These sediments covered the limestone and formed the spine of clayey sands on the peninsula.

Subsequent sea-level changes altered these deposits and modified the elongated system of upland ridges identified on Florida’s present landscape (Schmidt, 1997).

The following section describes the hydrology of the Florida peninsula.
Figure 1. Age of Geologic Units in Florida. (FGS website, taken on 9/9/2003).
Florida Hydrology

Across most of the state, highly permeable soil or rock is present at or near the land surface. Drainage density is low, but surface-water features include extensive wetlands and more than 7,700 lakes. Many of the lakes that occur in central and western Florida occupy basins formed by sinkholes that are the result of dissolution of part of the limestone bedrock. Water levels in these lakes fluctuate directly with variations in aquifer levels. Water levels in many Florida streams also depend on aquifer levels. The rise and fall in the river stage is generally paralleled by rise and fall in aquifer water levels – both of which change in response to precipitation (Miller, 1997).

There are five principal aquifers or aquifer systems in Florida. Four of these crop out at the land surface or are covered by a thin layer of soil and/or weathered rock; the fifth, the intermediate aquifer system of southwestern Florida, is completely buried by shallower aquifers or confining units. The Floridan aquifer system extends in the subsurface throughout the state and is the most prolific aquifer system in the region (Miller, 1997). Miocene sediments compose the confining unit of the Floridan aquifer system, Miocene-Pliocene sediments form the intermediate aquifer system, and Pliocene-Pleistocene sediments make up the shallow aquifer system (Scott, 1997). Recharge to the aquifer system occurs over approximately 55 percent of the state as rainwater infiltrates the overlying sediments. Recharge rates vary from less than 2.5 cpy to more than 25 cpy depending on location (Scott, 1992).

The geomorphology of the state, along with the geologic framework, controls the distribution of springs throughout the state. The springs occur where karst features are common and the surface elevations are low enough to allow groundwater to flow at the
surface (Scott & others, 2002). Florida has 300 known springs with a combined estimated discharge of about 12,600 cfs or eight billion gpd (Lane, 1986). Florida has 33 first-magnitude springs, more than any other state or country. First-magnitude springs discharge more than 64 million gallons of water per day or more than 100 cfs (Scott, 2002). All of Florida’s major springs discharge from the Floridan Aquifer, which is estimated to hold more than 2.2 quadrillion gallons of fresh water. The water flowing out of these springs allows a window into the aquifer, thus assisting in determining the health of the aquifer (Scott, & others, 2002).

The following section will summarize the many karst features found in Florida.

**Florida Karst**

Karst development in west-central Florida is controlled by lithology and water movement, dissolution by chemically aggressive water, aquifer material, and sea levels (Sinclair and others, 1985). Limestone dissolution in Florida has been intense because of the warm climate, heavy precipitation, low relief that encourages infiltration, and multiple Pleistocene sea-level changes of 100 meters or more (Bloom, 1998). Florida is almost entirely underlain by carbonate rocks, almost all of which are limestone or dolomite. The carbonate-evaporite sequences of Florida are extremely vulnerable to recrystallization, replacement, dissolution, and cementation. This diagenesis of Florida’s carbonate rocks has produced significant changes in rock makeup and has facilitated the development of many types of pore spaces including moldic, vug, and interparticle pore. Areas with extensive dissolution can create caves and caverns, which are the underlying essentials of karst landscapes (Randazzo, 1997; Lane, 1986; Scott, 1992).
Karst drainage in Florida is characterized by sinkholes, springs, caves, disappearing streams, and underground drainage channels. Chemical weathering is the predominant erosive process that forms the karst terrains like the ones found in Florida. Limestones, by nature, tend to be fractured, jointed, laminated, and have units of differing texture, all characteristics which, from the standpoint of percolating ground water, are potential zones of weakness, which can be enlarged and extended by acidic rain water (Lane, 1994; Scott, 1992).

Chemical weathering of limestone is the ultimate cause of land subsidence such as sinkhole development, but localized stress may also trigger overburden collapse into preexisting cavities. Most of Florida’s more than 7,700 lakes are solution-based lakes created by groundwater solution of underlying limestone and subsequent lowering of local land surface. These lakes as a result, have physical characteristics of sinkholes such as relatively steep sloping sides, no surface streams into or out of them, and circular outlines (Lane, 1986).

**Geomorphology of Sinkholes**

The term doline (sinkhole) describes a particular landform produced by karst processes. Dolines are characterized by circular depressions and underground water drainage networks (Tihansky, 1999). Identically shaped closed depressions can form by subsidence, volcanism, wind deflation, glaciation – or any other process that selectively displaces a mass of rock and permits the surrounding material to slump into the excavation.

Some sinkholes have gently sloping sides, while others, especially those known as collapse sinks, have vertical or overhanging cliffs. Sinkholes are usually circular in plan.
view and less commonly elongate or oval. Sinkholes range in size from shallow soil depressions a few meters in diameter and a meter deep to major landforms several kilometers in diameter and hundreds of meters in depth (Bloom, 1998).

Factors that initiate and enlarge sinkholes include: groundwater recharge, secondary porosity, overburden thickness and sheer strength, and hydraulic gradient. The initiation and enlargement of primary sinkholes leads to the generation of secondary sinkholes. Mixed sinkhole populations, those with primary and secondary sinks, can exist within the same karst area (Kochel and others, 1995). Sinkholes not only have an impact on surface land features but also have an impact on hydrological systems such as lakes, streams, and wetlands by changing water chemistry and rates of recharge or runoff (Tihansky, 1999).

Classification of Sinkholes

Five major classes of sinkholes or dolines are recognized. The two most contrasting types are the funnel-shaped solution/subsidence doline and the steep or cliffed collapse doline. Subsidence dolines and collapse dolines are surface forms in non-soluble rock, caused by solution of buried karst (Bloom, 1998). Most sinkholes are a combination of the solutional and collapse types.

Solution sinkholes form as water infiltrating into joints and fissures enlarges the cracks by corrosion. A cone depression is produced in the perched water table as downward flow rates in the enlarged fractures exceed that of the surrounding area. Collapse sinkholes are depressions that are initiated by solution that occurs beneath the surface. The expansion of caverns, caused by corrosion and reduction of buoyant support
may lead to collapse by decreasing the support of the overlying rock material (Kochel and others, 1995).

The following section discusses sinkhole formation in Florida.

**Sinkholes in Florida**

Sinkholes are a predominant landform in Florida; with west-central Florida being delineated as having the highest frequency of sinkhole activity. Sinkhole formation commonly damages buildings, roads, and utilities, diminishing the usefulness of the affected land. Millions of dollars are lost each year in Florida because of structural damage caused by sinkholes (Upchurch and Randazzo, 1997). The Florida Sinkhole Research Institute conservatively estimated that sinkholes cause approximately $10 million in damage each year in the state of Florida (Beck and Sayed, 1991).

The occurrence of sinkholes has become more frequent with the increased development of ground water and land resources (Tihansky, 1999). Dissolution of limestone in Florida appears to occur preferentially in recharge areas, such as sinkholes and wetlands, and near the saltwater/freshwater coastal mixing zone. Recharge environments are the more important of these two environments for sinkhole development (Upchurch and Randazzo, 1997). Sinkholes are more common where the Floridan aquifer system is unconfined or thinly confined (Miller, 1997).

The multiple stages of the development of karst in Florida have resulted in a number of different types of sinkholes present in the state. The most common are collapse and solution sinkholes. Collapse sinkholes form when limestone substrate has layers of clays and sands overlying it, and a cavern below. If the cover is cohesive and thick enough, it may be able to bridge a cavern in the absence of a limestone roof. When
the cover eventually collapses, a large funnel shaped depression results. Solution sinkholes form as a result of dissolution of rock. The geologic framework is similar to that of a collapse sinkhole, with the exception that a group of nearly vertical joints is present. If water passes vertically along the joints, they will become enlarged by dissolution. The removal of rock by dissolution allows settling of rock and washing of overburden into the cavern. Consequently slow subsidence occurs (Tihansky, 1999).

Because there is a long history of karstification in Florida, sinkholes vary in age and degree of development. Many of the older sinkholes have been partially filled by marine and wetland sediments. These older, partly to completely filled sinkholes are called alluvial sinkholes (Upchurch and Randazzo 1997). Where the water table is shallow, they form lakes and cypress domes. Rejuvenated alluvial sinkholes are sometimes called “raveling sinks.” Alluvial sinkholes are reactivated by a number of different processes. Where heavy pumping is present, especially for agricultural freeze protection when the water table is low, many sinkholes become reactivated. Turbulent flow causes erosion and reduction of the hydraulic head in the limestone aquifer reducing buoyancy and support of the overburden. The erosion is initially accompanied by loss of cohesion and upward piping. Settling and cracking begins, the failure works upward until the cover can no longer be supported, and finally rapid subsidence begins (Tihansky, 1999).

Sinkholes can operate as pathways of local or regional groundwater contamination. In the past, sinkholes were considered to be convenient, low-cost waste-disposal sites. Because karst areas typically have internal drainage, agricultural wastes, lawn fertilizers, and other sources of nutrients are unintentionally washed into the
sinkholes, and eventually into the aquifers below. These excess nutrients can cause enrichment of surface waters and groundwater (Upchurch and Randazzo, 1997).

**Karst and Sinkholes in Pinellas County**

Surficial evidence of a karst landscape in Pinellas County is limited to sinkholes, sinkhole associated features, and springs. These features provide distinct problems for planners and environmental scientists in the region. Land stability is perhaps the largest issue for citizens of Pinellas County; with contaminant transport through karst features, water quality, and hurricanes on the forefront as well (Schmidt, 1997).

At least 500 homes have been damaged by sinkholes in Pinellas County, Florida between 1990 and 1994, according to the county property appraiser (Hutchinson, 1994), with more forming every year. Sinkholes can form from a variety of processes. Those found in Pinellas County are cover-collapse sinkholes that form when Pleistocene sands above limestone collapse into cavities in the bedrock (Schmidt, 1997).

Pinellas County is a peninsula, consisting of a mainland and several barrier islands or keys, and is part of the Gulf Coastal Lowlands physiographic region as described by White (1970). This area consists of low-angle scarps and terraces formed during several Pleistocene sea-level stands as illustrated in Figure 2 (White, 1970). In Pinellas County the overburden materials are generally thicker, 9 – 60 meters thick, and less permeable than in other areas of this region. Greater cohesion of the clay in this area postpones failure, and ultimate collapse tends to occur more abruptly in the form of cover collapse sinkholes (Tihansky, 1999; Frank and Beck, 1991). The uppermost consolidated rock in Pinellas County is Tampa limestone, which is white to light yellow, soft, moderately sandy and clayey, finely granular, and locally fossiliferous, with high
porosity. Recharge to the aquifer in areas where this limestone is present is likely concentrated at sinkholes. The water table in the surficial aquifer in this area generally lies within a few meters of the land surface. Water in the Floridan aquifer in Pinellas County is under artesian pressure and will rise in tightly cased wells to a level above the clay confining layer.

Movement of water from the surficial to the Floridan aquifer is greatly accelerated where the clay is absent or has been breached by sinkhole collapse or subsidence (Lane, 1986). Pinellas County has limited potable water supplies and depends on water delivered from the surrounding counties of Pasco and Hillsborough (Broska and Barnette, 1999).

Recent occurrence of sinkholes has been related to abrupt water-level declines caused by pumping. Collapse and subsidence is caused, not by recent solution of limestone but by downward movement of the unconsolidated surficial material that overlies and fills existing cavities in the rock filling voids in which water has been removed (Sinclair, 1982).

The surficial aquifer system in the area is recharged almost entirely from local precipitation. In much of west-central Florida water moves downward from the surficial aquifer system to recharge the Upper Floridan aquifer. The karst is mantled and less apparent at the land surface, except when the overburden collapses or subsides into a subsurface cavity. Many small sinkhole-like depressions occur in Pinellas County, but only a few are directly connected to the underlying limestone. The ones that are directly connected to the Floridan aquifer are near the coast and the Upper Floridan aquifer contains saline water in these areas. (Trommer, 1987)
Figure 2. Geologic Map of Pinellas County, Florida. Qbd – beach ridge and dune; Qh – Holocene sediments; Qu – undifferentiated sediments; TQsu – shelly sediments of Plio-Pleistocene age; Th – Hawthorn Group; Arcadia Formation, Tampa Member. (Modified from the FDEP Geodata Library, taken on 09/09/03).
Because of its mild subtropical climate, Pinellas County has become the most densely populated county in the State of Florida, with a population that is currently more than 900,000.

The following chapter describes the methodology used to perform the digitization of sinkholes and to determine the loss of sinkholes to urbanization in Pinellas County, Florida.
CHAPTER 2
METHODOLOGY

Methodology

Pinellas County, in west-central Florida, is located in one of the more active and least understood karst region of the world. Some of the more common karst features found in this area are dolines, also known as sinks and sinkholes. The topographic expression of these depressions is partially masked by Holocene sand deposits and recent urban development. Urbanization results in filled depression features and modifications for storm water retention. Mapping and analysis of pre-and post-development sinkholes have not been completed in order to assess the distribution of sinkholes and document changes in topography due to urbanization in Pinellas County. This is problematic in that Pinellas County, like much of the Tampa Bay region continues to urbanize rapidly and is likely to undertake significant construction projects that have the potential to directly impact the karst landscape. Without a clear understanding of where karst processes are still active, it is difficult to implement the appropriate land use and management decisions suitable for the geology and population of the region. As Pinellas County moves toward redevelopment of lands, it will be important to understand the former landscape that once existed in order to make appropriate land use decisions.

It is clear from studies of sinkholes in undeveloped portions of Florida that they occur in particular clusters or “sinkhole regions”. Regions of past sinkhole formation are locations where modern doline formation may also occur. Certainly there are such regions that are hidden by the urbanized nature of areas such as Pinellas County. In this
study, karst features will be identified by circularity, vegetation and soil moisture variations.

Mapping karst surface features using historic aerial photos and maps will be a useful exercise that will assist our scientific understanding of karstification in Florida and the nature and extent of karst processes that have acted in the pre-urbanized past. The methods for completing this research follow and are outlined in Figure 3.

Figure 3. Data Management Chart.

**Data Management**

I have constructed a spatial database for this project. The database includes historic aerial photos from 1926 and more recent photos from 2000. The photos were acquired from the Pinellas County government. The digital topographic maps that are the framework for the GIS maps in the County were obtained from the Florida Geographic Data Library, University of Florida. The metadata for these base maps are the foundation on which GIS layers were created for this study.
The 1926 aerial photos required georeferencing within ARCGIS (ESRI) due to their age and lack of a geographic projection. The 1926 aerial photos are georeferenced first by being projected into the Albers coordinate system, using Datum D North American 1983 (NAD83). I then inserted them into the table provided by Pinellas County to their approximate locations. Next, I had to georeference each photo to either a geomorphic detail found on the topographic maps or anthropogenic markers, such as bridges and roads. The photos are then rectified to their actual geographic location. This was accomplished by stretching the photos within ArcGIS. Finally, I constructed GIS layers of karst features identifiable on the historic, black and white 1926 air photos. There are four layers in this map including features I have discerned as sinks and possible sinks, a layer for exclusions, or areas that were obscured or unclear in the photos and a layer for developed areas, these areas showed notable development such as clusters of roads and/or structures, with the smallest identifiable area being 0.027 km².

I then constructed GIS layers of karst features identifiable on the 2000 air photos, which are full-color high-resolution infrared images. Theses images were already georeferenced and thus required nothing more than simple insertion into a new ArcGIS map. This map contains four layers including the features I have identified as sinks, possible sinks, storm water/retention ponds, and undeveloped areas. These areas consisted of wetlands and forests, with the smallest identifiable area being 0.32 km².

Sinkhole Delineation

Specific karst features, such as sinkholes are often recognized by their signatures, or combination of image characteristics, which include tone, texture, shape, size, shadow, height, and spatial relationship. Many sinkholes have been obscured by urbanization in
Pinellas County, but numerous sinkholes should be definable by characteristic zoning of vegetation and soil moisture, which will still persist even after human alteration or infilling (Lyon and McCarthy, 1995).

Surface properties such as mineralogy, textures, color, and moisture differences can be identified on aerial photos (Coker, 1969). Sinkhole indicators that I will be using include: vegetation – changes/variation; water – presence/absence; soil moisture; and shapes. The sinks layer on both the 1926 and 2000 aerial photo maps are features that I concluded were most likely sinkholes. The criteria used to identify these features were circular and/or combined circular shapes, forming uvalas or coalescing sinkholes. Where a depression contour enclosed two of more subsets of closed depressions, the entire feature is treated as a single sinkhole. The possible sinks layer on both the 1926 photos and 2000 photos are areas of possible sinkhole activity lacking an entirely circular shape, but showed other signs such as soil moisture variations, some circular form, presence of water and indicator vegetation. Lakes that appeared to be depressions on the aerial photographs were treated as karst features and according to their shape where categorized as either sinks or possible sinks. The sinks and possible sinks layers were each identified in layers of different colors.

On the 2000 aerial photos I also created a retention pond layer, identifying areas that I considered man-made structures. The criteria I used to identify these areas were straight edges on at least one side of the depression, and the presence of water or soil moisture. The smallest identifiable retention pond feature identifiable on the 2000 aerial photos had an area of 260 m².
The 1926 aerial photos were taken during the dry season in Florida - March, April, and May - so it must be noted that many of the sinks which would normally contain water, and thus be more easily identified, were dry, so vegetation patterns and geomorphology were used to identify the circular patterns. It must also be noted that these criteria were difficult ones with which to work. The 1926 aerial photos are black and white and of very poor quality due to age, technology available and loss of resolution due to scanning of images (pixilation). Consequently many areas of these photos are completely blacked out and thus an exclusion layer was created to remove these areas when carrying out density estimates and other analyses about sinkholes in the County. Complete resolutions of some of the photos, both 1926 and 2000, is obscured on some frames by cloud cover and reflection from water bodies and thus were unreadable.

Littlefield (1988) defined sinkholes as an area on topographic maps enclosed by closed depression contours, whether circular or irregular in shape. The minimal diameter at which a sinkhole could be recognized on the topographic maps used in his study was estimated to be 0.027 kilometers. Small sinkholes were not identifiable due to small surface areas (Littlefield, 1988). The resolution of the 1926 aerial photos allowed sinks and possible sinks with a minimal area of approximately 89 m² to be identified. The high quality resolution of the 2000 aerial photos would seem to allow for greater recognition of sinkholes with a minimal area smaller than those in the 1926 aerial photos, but the smallest identifiable sinks and possible sinks were approximately 170 m² in area.

**Morphometric Analysis**

I calculated morphometric characteristics of the identified features using ArcGIS. ArcGIS automatically calculated the area within the attributes table. The sinkhole
density in Pinellas County is determined for 1926 and 2000 using numbers supplied by ArcGIS. US Census Bureau figures (2000) for the Pinellas County estimate the total area to be 1,574 km², with a land area of 725 km² (the figure I used to determine the density). ArcGIS automatically calculated the total area in square kilometers for each layer. I then used these numbers to calculate the density for each layer in 1926 and 2000, using the following calculation:

\[ D = \frac{N}{T} \]

\( D \) = density  
\( N \) = number of sinks  
\( T \) = total land area

I then determined the percent of land area that was covered by the sinks for each layer in 1926 and 2000, using the following calculation:

\[ P = \frac{K}{T} \]

\( P \) = land area covered  
\( K \) = total square kilometers of each individual layer  
\( T \) = total land area

To assess the effects that urbanization has had on the sinks of Pinellas County I then combined many of these calculations and maps to assess the modifications that have occurred. First I calculated the loss of the features that were identified. The calculation used:

\[ L = \frac{A}{B} \]

\( L \) = loss of sinkholes  
\( A \) = 1926 identified sinkhole area  
\( B \) = 2000 identified sinkhole area
I then created a map with a layer consisting of the total sinks from 1926 and a layer of the total sinks from 2000. I then used the intersect function in ArcGIS, and the results were the sinks that are still present in 2000. I then used the map previously described and intersected it with the 1926 total sinkholes map. This map illustrated sinkholes that have formed since the 1926 aerial photos were taken. I also attempted to determine which sinkholes that were identified in 1926 have now been converted into storm water and/or retention pond areas in the 2000 aerial photos. To do this I created a new map which consisted of a layer of the total sinks identified in 1926 and the retention pond layer from 2000, and preformed an intersect function in ArcGIS. This intersected the areas from the 1926 total sinks layer and the 2000 retention pond layer that overlapped.

Finally, I took the 1926 sinkhole map and the 2000 sinkhole map and combined them with a topography map. This illustrated the sinkholes and at what elevation they occurred.

The final product of this research is a digital spatial database of karst features discernable on the 1926 and 2000 air photos; a description of the karst landscape mapped for each time period; and a morphometric description (including sinkhole area, density, and circularity) of the karst landscape mapped for each time period. With these data I hope to be able to characterize the karst landscape and determine a loss of karst landforms due to urbanization.
CHAPTER 3
RESULTS

Pinellas County, in West Central Florida (Figure 4), is located in one of the more active and least understood karst region of the world. Surficial evidence of a karst landscape is limited to sinkholes, sinkhole associated features, and springs in this county. The topographic expression of these depressions is partially masked by Holocene sand deposits and recent urban development. Urbanization results in filled depression features and modifications to others for storm water retention.

The following information is the result of the digitization of the 1926 and 2000 aerial photos of Pinellas County.

1926 Aerial Photos

The 1926 aerial photos acquired from Pinellas County are the foundation of the calculations, inferences, and results within this thesis.

Density, Total Features, Total Area, Percent Land Area

The number of sinks identified in the 1926 aerial photos is 1,570. They cover 19.34 km$^2$. The density is 2.20 sinks per km$^2$. 2.70% of Pinellas County is covered by sinks (Table 2, Figure 5). The number of possible sinks identified is 1,133. They cover 24.56 km$^2$. The density is 1.59 possible sinks per km$^2$. 3.44% of Pinellas County is covered by possible sinks (Table 2, Figure 5).

Together, the identified sinks and possible sinks (collectively called sinkholes in this thesis) are 2,703 in number, 43.9 km$^2$ in area, and 3.79 km$^2$ in density. They cover 6.20% of the total land area of Pinellas County (Table 2).
Figure 4. Map of Florida – Pinellas County highlighted.
Areas of exclusion covered 11.26 km² of Pinellas County, which accounted for 1.58% of the total land area of the county (Table 2, Figure 6).

<table>
<thead>
<tr>
<th>Total # of Features</th>
<th>Total Area (km²)</th>
<th>Density (per/km²)</th>
<th>Percent Land Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinks</td>
<td>1570</td>
<td>19.34</td>
<td>2.20</td>
</tr>
<tr>
<td>Possible Sinks</td>
<td>1133</td>
<td>24.56</td>
<td>1.59</td>
</tr>
<tr>
<td>Exclusions</td>
<td>N/A</td>
<td>11.26</td>
<td>N/A</td>
</tr>
<tr>
<td>Undeveloped</td>
<td>N/A</td>
<td>609.99</td>
<td>N/A</td>
</tr>
<tr>
<td>Combined Sinkholes</td>
<td>2703</td>
<td>43.90</td>
<td>3.79</td>
</tr>
</tbody>
</table>

Table 2. 1926 Aerial Photo Data. Total area, density, and percent land area of sinkholes, combined sinkholes, possible sinkholes, exclusion areas, and undeveloped land mapped using the 1926 air photos.

As part of the analysis of the 1926 aerial photos, I examined the amount of land that was undeveloped in the county. The undeveloped areas of Pinellas County accounted for 609.99 km². This accounts for 85.46% of the total land area in Pinellas County (Table 2, Figure 7).

1926 Black and White Aerial Photo Description

A total of 36 black and white aerial photos were taken in 1926. The following photos and descriptions are a sample of 3 photos from the northeastern, central, and southern parts of Pinellas County. The barrier islands were excluded in this comparison due to the lack of karstic formations and sinkhole activity.

Northeastern Pinellas County

The photo in Figure 8 is located in the northeastern portion of Pinellas County. To the East is Hillsborough County, and to the North is Pasco County. In 1926 this portion of Pinellas County was completely undeveloped, except for one road which is
Figure 5. 1926 sinkholes.
Figure 6. 1926 Areas of Exclusion.
Figure 7. 1926 Developed Areas.
is visible in the southwestern area of the photograph. Karstic formations are clearly visible in this aerial photo. The majority of this photo is covered by a highly karstified landscape. In the eastern portion of this aerial photo many sinkhole features are visible, most of which have formed into uvalas or coalescing sinkholes. The majority of this photo appears to be wetlands, although it is difficult to determine due to age and quality of the photo. These wetlands likely formed as a result of the karstic activity.

Central Pinellas County

Figure 9 is located in central Pinellas County. By 1926 development was rapidly spreading to this area, thus much of the karst landscape was being converted into urban areas as well as farmlands. This photo is very dark and thus some features are difficult to discern, but there are several sinkholes still visible in this area. Many roads have been cut into the landscape, as well as several homes. In the southeastern portion of this photo there are six sinkholes visible, with roads or possibly trails, connecting them. It is possible that they were used as a water supply for the human population or farming activities. In the central area of the photo it appears as though there are several karst features including sinkholes and uvalas. Five of these sinkholes are single sinks with the most northern being a coalescing sink. The individual sinks range from approximately 50 to 150 meters in diameter, with the coalescing sink being approximately 300 meters in diameter. In the south-central portion of this photo is a perfectly formed sinkhole, as well as another in the southwestern portion of the photo. Both of these sinks appear to be approximately 150 meters in diameter. In the southwestern portion of the photo there also appears to be a coalescing sinkhole approximately 5 meters from a road bed. This sinkhole is approximately 500 meters in diameter.
Figure 8. 1926 Aerial Photo – Northeastern Pinellas County photo.
Figure 9. 1926 Aerial Photo – Central Pinellas County.
Southern Pinellas County

Figure 10 is southern Pinellas County. This area was, and is now, known as St. Petersburg. This is the largest city in Pinellas County, and by 1926 was almost completely developed. As can be seen in the image, this area of Pinellas County was fully developed, thus many of the sinkholes that may have previously existed most likely have been filled or modified. There are still several sinkholes that appear in the photo. In the northeastern corner of the photo there is a sinkhole which has been named Mirror Lake. It appears to be a coalescing sink and is approximately 500 meters in diameter. In the west-central portion of this photo there appears to be several sinks within close proximity of each other. They range from approximately 50 to 300 meters in diameter.

2000 Aerial Photos

The 2000 aerial photos acquired from Pinellas County are the basis for the following calculations and maps.

Density, Total Features, Total Area, Percent Land Area

The number of sinks identified in the 2000 aerial photos is 261, covering 1.60 km², with a density of 0.36 sinks per km². This land area accounts for 0.22% of Pinellas County (Table 3, Figure 11). The number of possible sinks identified was 639, covering 3.97 km², with a density of 0.88 possible sinks per km². The possible sinks cover 0.55% of Pinellas County (Table 3, Figure 11). As noted previously, sinks and possible sinks are collectively going to be called sinkholes throughout the rest of this section. A combined total of 900 sinkholes were identified with a combined total area of 5.57 km², a combined density of 1.24 sinkholes per km². The sinkholes covered a combined 0.77% of the
Figure 10. 1926 Aerial Photo - Southern Pinellas County.
total land area of Pinellas County (Table 3). The areas identified as retention ponds/storm water features are areas that had at least one straight edge and appeared to be manmade. There were 1,646 retention ponds identified, covering 13.25 km² of Pinellas County with a density of 2.27 retention pond features per km². They accounted for 1.83% of the total land area of the county (Table 3, Figure 12). I also calculated the area of undeveloped land in the County. The undeveloped areas of Pinellas County accounted for 19.54 km², which is 2.74% of the total land area in Pinellas County (Table 3, Figure 13).

<table>
<thead>
<tr>
<th></th>
<th>Total # of Features</th>
<th>Total Area (km²)</th>
<th>Density (km²)</th>
<th>Percent Land Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinks</td>
<td>261</td>
<td>1.60</td>
<td>0.36</td>
<td>0.22</td>
</tr>
<tr>
<td>Possible Sinks</td>
<td>639</td>
<td>3.97</td>
<td>0.88</td>
<td>0.55</td>
</tr>
<tr>
<td>Retention Ponds</td>
<td>1646</td>
<td>13.25</td>
<td>2.27</td>
<td>1.83</td>
</tr>
<tr>
<td>Undeveloped</td>
<td>N/A</td>
<td>19.54</td>
<td>N/A</td>
<td>2.74</td>
</tr>
<tr>
<td>Combined Sinkholes</td>
<td>900</td>
<td>5.57</td>
<td>1.24</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 3 – 2000 Aerial Photo Data. Total area, density, and percent land area of sinkholes, combined sinkholes, possible sinkholes, exclusion areas, and undeveloped land mapped using the 2000 air photos.

2000 Color Aerial Photo Descriptions

The following photos and descriptions are a sample of 3 of the 2000 aerial photos. They are located in the northeastern, central, and southern parts of Pinellas County. The barrier islands were excluded in this comparison due to the lack of karstic formations and sinkhole activity.
Figure 11. 2000 Sinkholes.
Figure 12. 2000 Storm Water Retention Areas.
Figure 13. 2000 Undeveloped Areas.
**Northeastern Pinellas County**

Figure 14 is a 2000 aerial photo located in northeastern Pinellas County and corresponds to the 1926 photo that was previously described in Figure 8. As can be seen in this photo this portion of Pinellas County is still partially undeveloped. There are large areas in this photo that are still natural wetland areas. Due to the colorization of these photos the karstic features, including sinkholes can be identified by vegetation. As can be seen, there are several large storm water retention features in this photo. All of these retention features were former sinkholes as will be seen in the next chapter. The east-central region of this photo is scattered with various sinkholes identified by a greenish-gray color. The rest of the photo is covered by urbanization, including housing developments and golf courses.

**Central Pinellas County**

Figure 15 is a 2000 aerial photo located in Central Pinellas County and corresponds to the 1926 aerial photo that was previously described in Figure 9. This photo is a very good example of what has become of Pinellas County by the year 2000. This area of Pinellas County has undergone rapid urbanization as can be seen when compared with Figure 9. This area would most likely be considered a build out, with no areas left for development. As a result of the urbanization, most of the sinkholes in this area have been modified by being completely filled, or turned into storm water retention areas. Most of the water features visible in this photo are storm water retention areas. There are few sinkholes left unmodified in this area. One such sinkhole is located in the northeastern corner of this
Figure 14. 2000 Aerial Photo – Northeastern Pinellas County
Figure 15. 2000 Aerial Photo – Central Pinellas County.
photo, and is approximately 15 meters in diameter. It is possible that this sinkhole is also used for storm water retention but has retained a circular shape. There is another sinkhole that is visible in the southwestern portion of this photo. It is also surrounded by what appears to be a park. This sink seems to be a coalescing sink with a diameter of approximately 50 meters. It is possible that other smaller sinks exist in this photo but it is difficult to determine from an aerial photo.

Southern Pinellas County

Figure 16 is located in southern Pinellas County in the area that is known as St. Petersburg and corresponds to the 1926 aerial photo in Figure 10. As can be seen in this photo from 2000 the area continued to urbanize remaining land areas and is now a complete build out with no land left for any more development. Any other development activities in this area would be refurbishment or redevelopment of existing structures. In this photo there are very few water structures other than large inlets and marinas. In the south central portion of this photo there is a large tract of land that has been specified as non-development due to wetland regulations. In this area, which can be identified by the red coloration, two large sinkholes are visible by the vegetation patterns. The larger of the sinks has a diameter of approximately 200 meters and is in the northwestern part of this undeveloped area. The other sink, which is located in the southern portion of this area, is approximately 100 meters in diameter. Other than these two sinks, no others are clearly visible. This area also has a lack of storm water retention ponds due to the rapid urbanization in the early 1900’s when regulations for inclusion of such structures with development did not exist. Other smaller sinkholes are possible in this area but are once again difficult to discern due to small size or lack of vegetation indicator patterns.
Figure 16. 2000 Aerial Photo – Southern Pinellas County.
CHAPTER 4
DISCUSSION

1926 and 2000 Aerial Photo Comparison

The following is a comparison of the 1926 aerial photo and the 2000 aerial photo digitization. In ARCGIS the intersect function was executed to intersect sinks and possible sinks from 1926 that still exist in 2000. Figure 17 illustrates the comparison of possible sinks between 1926 and 2000. There is a total of 114 possible sinks present in both 1926 and 2000 with a total area of 0.46 km$^2$. Figure 18 illustrates the comparison of sinks between 1926 and 2000. This allowed only sinks that were present in both 1926 and 2000 to be revealed. There is a total of 118 sinks present in both 1926 and 2000 with a total area of .43 km$^2$. Figure 19 illustrates all possible sinks, and sinks, as well as the intersecting areas from 1926 and 2000 aerial photos. Figure 20 illustrates intersecting areas of sinkholes (possible sinks and sinks) from 1926 and 2000 aerial photos. This map illustrates all sinkholes present in both 1926 and 2000. There is a total of 457 total sinkholes present in both 1926 and 2000 with a total combined area of 2.66 km$^2$. Figure 21 illustrates sinkholes which most likely formed after the 1926 aerial photos were taken and now appear in the 2000 aerial photos. It appears as though approximately 400 sinkholes have formed since 1926. This could be a misinterpretation because this number seems abnormally high.

Percent Loss

Table 4 illustrates the percent loss of sinkholes between 1926 and 2000. The number of sinks loss to urbanization by the year 2000 is 92%. A total of 84% of the possible sinks were lost over the same period. The total loss of sinkholes between 1926 and 2000 is
Figure 17. Possible Sinks present on both 1926 and 2000 aerial photos.
Figure 18. Sinks present on both 1926 and 2000 aerial photos.
Figure 19. Total sinkholes in both 1926 and 2000 aerial photos, with intersecting areas.
Figure 20. Total intersecting areas of sinkholes present in both 1926 & 2000 aerial photos.
Figure 21. Sinkholes which have formed since 1926, and appear on the 2000 aerial photos.
87% (Table 4). Undeveloped area lost to urbanization by the year 2000 is 97% (Table 4). As can be seen, there has been a dramatic loss in sinkholes and an explosion in development.

<table>
<thead>
<tr>
<th>Percent sinkholes remaining in 2000</th>
<th>8.27%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent possible sinkholes remaining in 2000</td>
<td>16.16%</td>
</tr>
<tr>
<td>Undeveloped area lost by 2000</td>
<td>96.80</td>
</tr>
</tbody>
</table>

Table 4. Percent of Sinkholes Lost by 2000. Sinkholes and possible sinkholes left in 2000. This figure was determined by comparing the overlap of sinkholes mapped in 1926 and sinkholes mapped in 2000. Also shown is rural area lost by 2000.

Retention Areas

The areas identified as retention ponds were areas on the 2000 aerial photos that appeared to be man made and functioned as storm water retention areas. It is likely that many of these storm water retention areas were former sinkholes with a possible connection to the aquifer underlying Pinellas County.

When the intersect function was executed for the retention pond layer from the 2000 aerial photos and the 1926 sinks and possible sinks layers the map in Figure 22 was created. Figure 22 illustrates the areas which intersected. These areas may possibly be sinkholes that have now been converted into storm water retention areas. Approximately 21.76 km² of retention pond features overlapped with 1926 sinks and possible sinks with a total of 499 sinkholes that have now been formed into retention pond areas.

Sinkhole Elevations

Figure 23 illustrates sinkhole locations with the contour lines of Pinellas County. This map was created with the hopes of defining a pattern of sinkhole development. Unfortunately, even after much scrutiny, this map did not show a pattern of sinkhole development which related to elevation.
Figure 22. 1926 Sinkholes intersecting 2000 storm water retention ponds.
Figure 23. Topographic Map with Sinkhole Locations
The results of this study have provided new information on the sinkholes, past and present, as well as the effects of urbanization on the karst landscape of Pinellas County, Florida. The conclusions reached from this research provide justification for further sinkhole research in Pinellas County, which will assist land planners and local governments with future development and redevelopment projects.

**Conclusions**

The mapping of sinkholes on historic 1926 aerial photos within ArcGIS proved to be a useful exercise in determining the landscape that existed prior to the urbanization of Pinellas County. A total of 2,703 sinkholes were identified on the 1926 aerial photos. These sinkholes accounted for 43.90 square kilometers and 6.14% of the total land area. By 2000 only 900 sinkholes remained, with approximately 400 sinkholes forming since the 1926 aerial photos were taken. The sinkholes identified on the 2000 aerial photos accounted for only 5.57 square kilometers and 1% of the total land area of Pinellas County. This accounted for a total loss of 87% of sinkholes between 1926 and 2000. It is likely that this loss is due to the rapid urbanization that occurred since 1926. Many of the existing sinkholes were likely filled, while others have been modified into storm water retention areas.

The 2000 aerial photos of Pinellas County revealed 1,646 storm water retention areas. These areas cover 13.25 square kilometers and account for 2% of the total land area. It is probable that many of these were former sinkholes and thus have a direct
connection to the aquifers located beneath Pinellas County. When 1926 sinkholes were intersected with 2000 retention ponds in ArcGIS, the sinkholes which have been modified in retention areas were revealed. A total of 499 of the 1,646 storm water retention ponds now present in Pinellas County were former sinkholes. They account for 21.76 square kilometers and 3% of the total land area.

**Suggestion for Further Research**

There are many opportunities for further research on the sinkholes in Pinellas County, as well as the state of Florida. Some suggestions follow.

Further research is needed in Pinellas County to verify sinkholes and exact locations and sizes. This could be accomplished by on-site analysis or ground truthing. The sinkholes that appear to be present in both the 1926 aerial photos should be located, measured, and verified as sinkholes. It would be wise to verify the 1926 sinkholes that appear to be retention ponds on the 2000 aerial photos with the same methods listed previously.

Dye traces in the 1926 sinkholes that are now retention ponds would also provide useful information. This would allow researchers to determine if contaminated water from the storm water retention areas is flowing into the aquifer and at what velocity. This would help to understand the aquifer dynamics below Pinellas County as well as determine where and when pollution will show up.

Pinellas County also has a collection of aerial photos taken in 1945. If these photo’s were digitized within ArcGIS and the sinkholes identified, they could then be compared to the sinkholes identified on 1926 and 2000 aerial photos. This would allow
researchers to see a progression of urbanization as well as possibly identify sinkholes that developed between 1926 and 2000.

It would also be useful to conduct a historic air photo analysis of the entire state of Florida. A comprehensive inventory of the sinkholes in the state of Florida mapped during different time periods would greatly facilitate the understanding of the state’s complex karst systems.
References


