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Geostatistical Analysis of Sinkhole Occurrence Due to Increased Groundwater Pumping during Freeze Events in Plant City, Florida

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GEOSTATISTICAL ANALYSIS OF SINKHOLE OCCURRENCE DUE TO INCREASED GROUNDWATER PUMPING DURING FREEZE EVENTS IN PLANT CITY, FLORIDA

By

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If one advances confidently in the direction of his dreams, and endeavors to live the life which he has imagined, he will meet with success unexpected in common hours.

Henry David Thoreau

Although this is not where I imagined I would end up, I am thankful for the path I have taken and more importantly for the people that have lined the way. I would like to acknowledge the people listed below for helping me achieve my goals.

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At times I have dreaded my decision to pursue this degree, but I can now at the end stand back and be proud of where I have been, what I have done, and who I have become. I look forward to what the future has in store and forge on knowing that I have a tremendous support system behind me all the way.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Located in West Central Florida, Plant City is an agriculturally dominated region, growing strawberries and citrus. Due to temperatures during winter months, when they often fall below freezing, farmers in the area must use freeze protection techniques to protect their crops. The method of choice is pump-irrigation in which farmers pump large quantities of warm groundwater from subsurface aquifers and apply it directly to the crops. The water forms a protective layer of ice that prevents the crops from spoiling during the cold spells. The extraction of vast amounts of groundwater correlates with cover-collapse sinkholes. This is due mainly to the underlying limestone platform of Florida and also to loss of buoyant support. Previous freeze events have occurred in January of 1977, 1985, and 2010. The event of January 2010 was by far the most catastrophic; the freeze lasted eleven days and caused over 140 sinkholes. By examining water level data from monitoring wells in the area, sinkhole reports, and overburden thickness for the events of January 1985 and January 2010, this research describes the geostatistical relationships between groundwater withdrawal during freeze events and sinkholes. Results show that amount of drawdown is the main factor in predicting sinkholes.

CHAPTER ONE

INTRODUCTION

Located in West-Central Florida, between the cities of Tampa and Lakeland, Plant City (Figure 1) is a municipality of approximately 35,000 residents (US Census Bureau). Much of its rural area is dedicated to agricultural practices, mainly citrus and strawberry farming. Both farming and residents have a high demand for water, which is supplied from the underlying groundwater. Plant City sits atop one of the most productive aquifer systems in the country, the Floridan aquifer. With increased productivity and urbanization, the demands for water have increased. Strawberry crops are planted in November and harvested in March (Peres et al., 2010). Although the area is considered a warm temperate region, it does experience a great deal of temperature fluctuations. During the winter months, temperatures in the area drop below freezing (32°F) 6.5 days out of the year on average (Florida Climate Center, 2012). The crops become vulnerable causing farmers to implore freeze protection techniques, the most common being groundwater pumping. Warm groundwater is extracted from the subsurface and sprayed on the crops, creating a thin layer of ice. By spraying the crops, the temperature is held at 32°F. However, in order to ensure the crops survive the freezing temperatures the water must be applied constantly. In a study by North Carolina State University (New York Berry News,

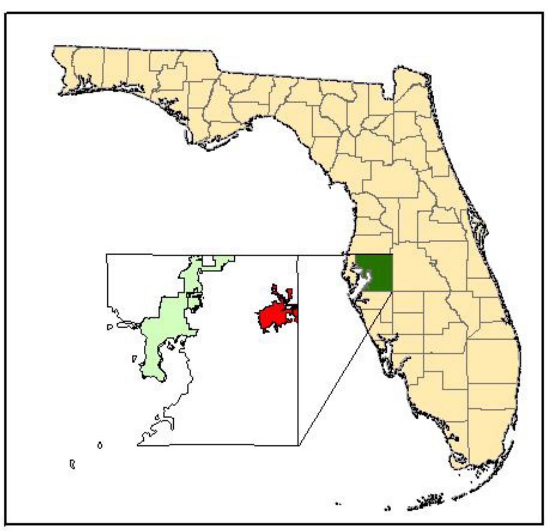


Figure 1: Location of Plant City, Florida

2006), application rates were calculated using different temperature and wind velocity data (Table 1). An application rate of 0.1-0.15 in/hr is needed to protect crops in conditions for 0-1 wind speeds and temperatures between 18°F and 27°F (New York Berry News, 2006). This translates to a removal of 45-60 gal/min-acre. During such drawdown events, the potentiometric surface is significantly lowered at the same time the surface sediments are loaded. This can result in catastrophic sinkhole collapse. It is this interaction, the lowering of the potentiometric surface and the occurrence of sinkholes that this research seeks to better understand.

The main objective of this research is to describe and define areas, within Plant City and its surroundings, which are vulnerable to sinkhole collapse, during freeze events and intense groundwater pumping. By using sinkhole incidence reports and groundwater data, a statistical model was generated to correlate the amount of drawdown, water level, and overburden thickness with the number of new sinkholes. The study focuses on the events of January 1985 and January 2010, with comparisons to non-events within the same years.

Table 1: Water application rate (in/hr) from Pritts (2006)

	Wind Speed				
Temp (F)	**0-1**	**2-4**	**5-8**	**10-14**	**18-22**
Relative humidity of 50%					
27	0.10	0.20	0.30	0.40	0.45
24	0.10	0.30	0.35	0.45	0.60
20	0.15	0.35	0.45	0.60	0.75
18	0.20	0.40	0.50	0.65	0.80
Relative humidity of 75%					
27	0.05	0.10	0.20	0.25	0.25
24	0.10	0.20	0.30	0.35	0.40
20	0.10	0.25	0.40	0.45	0.60
18	0.15	0.30	0.45	0.55	0.70

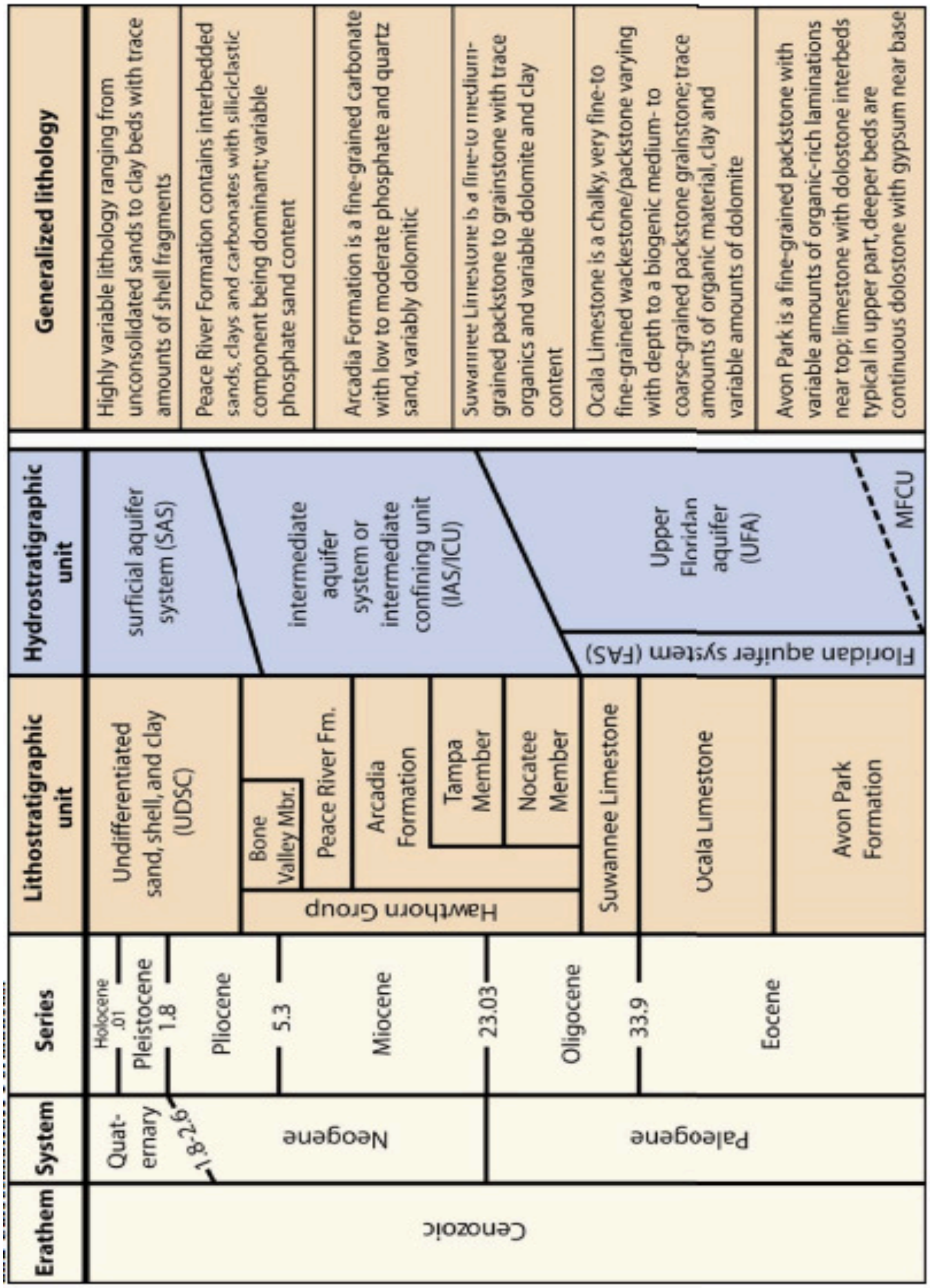
CHAPTER TWO

STRATIGRAPHY

Arthur et al (2008) describe the stratigraphy of the entire Southwest Florida Water Management District (SWFWMD), Figure 2. The district includes the counties of Levy, Marion, Citrus, Sumter, Hernando, Lake, Pasco, Pinellas, Hillsborough, Polk, Manatee, Hardee, Highlands, Sarasota, Desoto, and Charlotte. Stratigraphically, the region is characterized by a series of limestone and dolostone units, which vary in thickness and extent throughout the region due to erosional unconformities. The units present in the Plant City study area include the Avon Park Formation, Ocala Limestone, Suwannee Limestone, Tampa Member of the Hawthorn Group, Bone Valley Member of the Peace River Formation, and undifferentiated sands, shells, and clays. A generalized table with the correlation of lithostratigraphic and hydrologic units is provided in Table 2.

Figure 2: Map of the Southwest Florida Water Management District (from SWFWMD)

Table 2: Litholostratigraphic and hydrostratigraphic units with discription and ages (Arthur et al., 2008)



Erathem	System	Series	Lithostratigraphic unit	Hydrostratigraphic unit	Generalized lithology
Cenozoic	Quat-ernary	Holocene .01 Pleistocene 1.8	Undifferentiated sand, shell, and clay (UDSC)	surficial aquifer system (SAS)	Highly variable lithology ranging from unconsolidated sands to clay beds with trace amounts of shell fragments
	1.8-2.6 Neogene	Pliocene 5.3	Hawthorn Group: Bone Valley Mbr.; Peace River Fm.	intermediate aquifer system or intermediate confining unit (IAS/ICU)	Peace River Formation contains interbedded sands, clays and carbonates with siliciclastic component being dominant; variable phosphate sand content
	Neogene	Miocene	Hawthorn Group: Arcadia Formation	intermediate aquifer system or intermediate confining unit (IAS/ICU)	Arcadia Formation is a fine-grained carbonate with low to moderate phosphate and quartz sand, variably dolomitic
		23.03	Hawthorn Group: Arcadia Formation: Tampa Member; Nocatee Member		
	Paleogene	Oligocene	Suwannee Limestone	Floridan aquifer system (FAS): Upper Floridan aquifer (UFA)	Suwannee Limestone is a fine-to medium-grained packstone to grainstone with trace organics and variable dolomite and clay content
	Paleogene	33.9 Eocene	Ocala Limestone	Floridan aquifer system (FAS): Upper Floridan aquifer (UFA)	Ocala Limestone is a chalky, very fine-to fine-grained wackestone/packstone varying with depth to a biogenic medium- to coarse-grained packstone grainstone; trace amounts of organic material, clay and variable amounts of dolomite
	Paleogene	Eocene	Avon Park Formation	Floridan aquifer system (FAS): Upper Floridan aquifer (UFA); MFCU	Avon Park is a fine-grained packstone with variable amounts of organic-rich laminations near top; limestone with dolostone interbeds typical in upper part, deeper beds are continuous dolostone with gypsum near base

The Avon Park Formation marks the stratigraphic bottom of the section and is a Middle Eocene limestone and dolostone unit (Arthur et al., 2008; Miller, 1986). Limestone layers are partially dolomitized and interbedded with very fine-grained to coarse grained, vuggy, and fossiliferous dolostones (Arthur et al., 2008). Allochems within the limestone include peloids and skeletal remnants. Varied mud content from unit to unit creates a series of wackestones, grainstones, and minor mud stones. Minor clay beds and organic rich laminations exist at the top of the unit, as do the accessory mineral gypsum. Porosity with in the Avon Park Formation is an average of 31.7% (Aruther et al., 2008). In the limestone units it is primary intergranular porosity, while the dolostone porosity is due in part to secondary fractures. Some of the dolostone porosity is also from the sucrosic nature of the rock. Although the Avon Park Formation is the oldest exposed unit in Florida, it is commonly encountered at depths of -2400 to -1000 feet MSL within the study area. Thickness ranges between 1000 and 1600 feet. Basal contact of the Avon Park Formation is considered to be conformable since differentiation with the Oldsmar Formation is difficult. The basis for the distinction is often the abundance of the foraminifer *Helicostegina gyralis*, which is more abundant in the Oldsmar Formation (Arthur et al., 2008). The upper contact with the overlying Ocala Limestone is unconformable and dolomitized in most areas. Where the contact may be less obvious, characteristics such as color, organic and peat content, and grain support are used (the Avon Park is more grain supported with organic and peat beds).

The Ocala Limestone is Upper Eocene in age and divided into upper and lower sections. The lower section is variable in induration and ranges from packstone to grainstone. Dolomite content increases with depth. The dolomite is either friable and sucrosic or indurated and crystalline. The upper section is more mud supported and chalky with dominant rock types being mudstones and wackestones. As a whole, the Ocala Limestone is dominantly calcite with low siliclastics although chert and trace organics and clays are present. The pyrite content is elevated. Diverse fossil assemblages of echinoids, mollusks, and foraminifera are present as well. The porosity of the unit is moldic and intergranular and averages 39.8 % (Arthur et al., 2008). Within the study area, the depth of the Ocala Limestone range from land surface (0 feet MSL) to -1275 feet MSL and is over 400 feet thick. It is bound by unconformities, which allows clear differentiation from the overlying Suwannee Limestone. Characteristics such as color and its mainly calcite composition are also helpful. In rare cases where the contact is gradational, foraminifera species can be used.

Next in the stratigraphic sequence is the Suwannee Limestone formed during the Lower Oligocene. This unit is composed of moldic packstones and grainstones with miliolod and peloid calcite grains. Variable amounts of dolomitization of the limestone occur. In areas where the Hawthorn Group overlies the Suwannee limestone, sand and clay content increases to 3 percent (Arthur et al., 2008). Missimer (2002) identifies sand beds within the Suwannee Limestone. Chert is present throughout along with silicified limestone. The majority of the porosity within this unit is moldic and intergranular, with average porosity of 36.3% (Arthur et al., 2008). This unit extends from 75 feet to -825 feet MSL and reaches a maximum thickness of 450 feet (Arthur et al., 2008). The contact with the overlying Tampa Member of the Hawthorn Group is locally gradational and difficult to discern. In some instances green clays at the base of the Tampa Member can be used, or where the Tampa is not present, the phosphate sands of the undifferentiated Hawthorn are used.

Upper Oligocene to Lower Miocene rocks from the Tampa Member of the Arcadia Formation overlie the Suwannee Limestone. These are dominated by wackestones and packstones composed of quartz sand and clay with minor phosphate, dolomite, chert, and fossil mold components. Dolostones and sporadic sand and clay beds are also present. Porosity within the Tampa Member is intergranular and moldic and averages 32.3% (Arthur et al., 2008). The rocks of this unit extend from 100 feet to -350 feet MSL in the study area. The maximum thickness is 292 feet. Other undifferentiated units of the Arcadia Formation conformably overlie the Tampa Member in some areas. Hawthorn Group clays or undifferentiated sands and clay overlie others. Lateral gradation of the Tampa Member into the Nocatee Member occurs with increased sand content.

The Peace River Formation of the Hawthorn Group, which disconformably overlies the Arcadia Formation, is described by Scott (1988) as a series of interbedded quartz sand, clay and carbonate units. It ranges in age from Middle Miocene to Lower Pliocene. These units extend from 175 to -150 MSL in the study area with maximum thicknesses of 120 feet (Arther et al, 2008; Scott, 1988). Siliclastic components are dominant, comprising approximately two-thirds of the formation (Scott, 1988). The quartz sands are poorly consolidated, clayey, calcareous to dolomitic, and phosphatic. Grain size varies from fine to medium. The color ranges from light to yellow to olive shades of grey. Phosphate content increases down section. Quartz sandy, silty calcareous to dolomitic, phosphatic clay beds are common throughout. Smectites and palygorskite are the two main mineral components (Scott, 1988). Carbonates make up less than one third of the Peace River Formation, with dolostone sections more prevalent than limestone. Sporadic chert beds are also present.

The stratigraphic top of the area is composed of undifferentiated sediments of Pliocene or younger age. Two distinct types are recognized, undifferentiated sand and clay (UDSC) and undifferentiated sand and shell (UDSS). UDSC sediments are predominantly sand and clay while UDSS are sand and shell. Thickness and elevations of the undifferentiated sediments vary significantly. In Plant City, according to the geologic map provided by Scott et al. (2001) in Arthur et al. (2008) (Figure 3), the Bone Valley Member of the Peace River Formation is the top most unit.

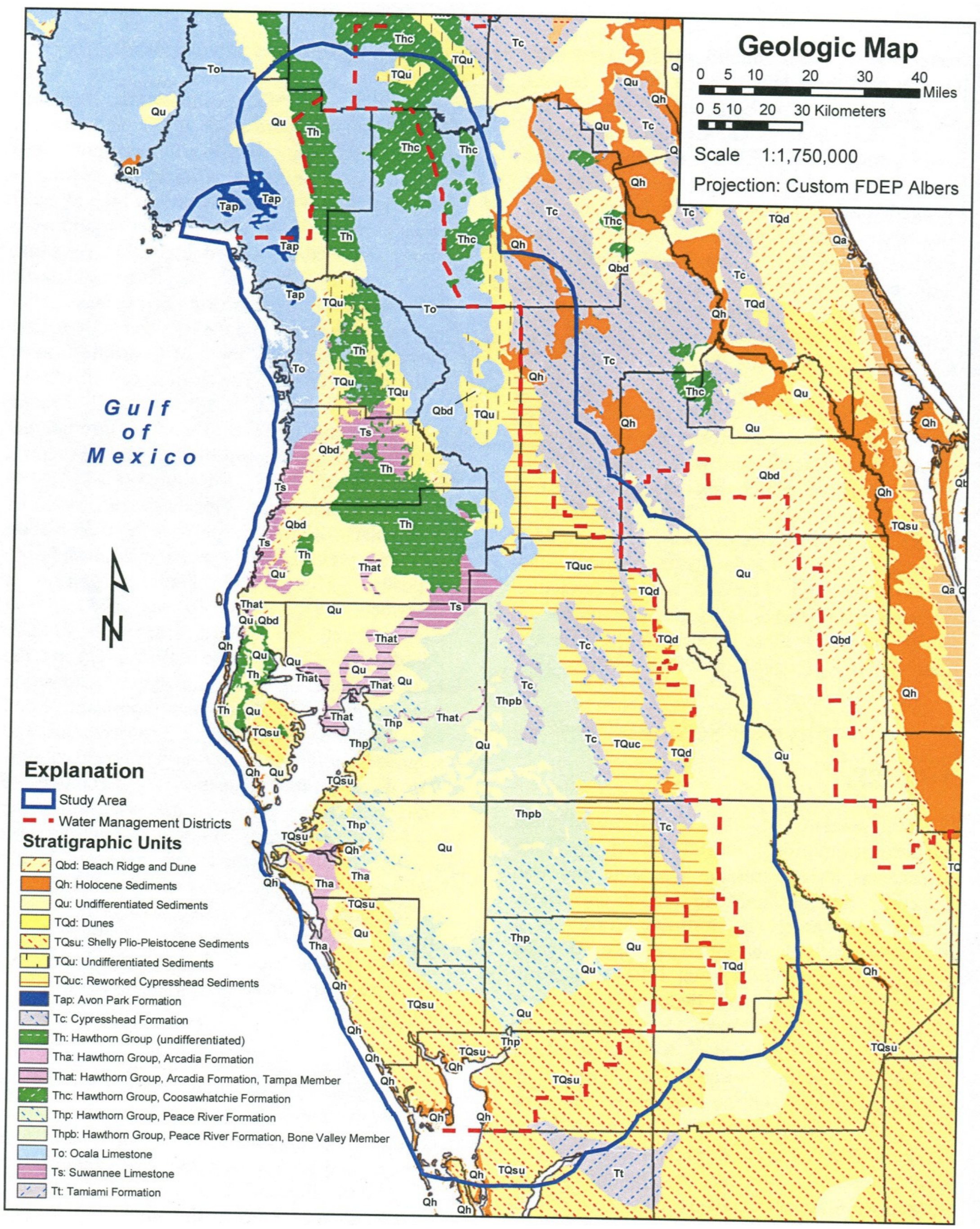


Figure 3: Geologic Map of the Southwest Florida Water Management District (Arthur et al., 2008)

CHAPTER THREE

HYDROGEOLOGY

Three aquifer systems, the surficial aquifer system (SAS), Intermediate Aquifer System/Confining Unit (IAS/ICU), and Floridan Aquifer System (FAS), exist in the area. The Floridan Aquifer System, one of the most productive aquifer systems in the world (Wilson and Beck, 1992), is composed stratigraphically of carbonate rocks, mainly limestone and dolostone. It includes the Suwannee Limestone, Ocala Limestone, and Avon Park Formations. In northern Hillsborough County, the Tampa Member is also considered to be part of the FAS (Arthur et al., 2008). In some areas of Florida, not in the study area, the FAS is an artesian aquifer and commonly discharges into springs and other surface water bodies such as wetlands and rivers (Arthur et al., 2008). Miller (1996) divided the FAS into two layers, a lower unit (LFA) and an upper unit (UFA). The latter of which is the primary groundwater source. Ryder (1985) identified the Avon Park Formation, Ocala Limestone, and Suwannee Limestone as the most productive units of the aquifer system. The potentiometric surface of the FAS is highly variable due to the inhomogeneity of lithostratigraphic units and the occurrence of sinkholes and paleosinkholes that breech underlying confining clay layers. In general within the study area, the groundwater flow is to the southwest towards the Gulf of Mexico (SWFWMD).

The intermediate aquifer system/intermediate confining unit (IAS/ICU) is composed of Hawthorn Group sediments-mainly clays, sands, and carbonates (citation Arthur et al., 2008 [pg 57]). The extent of the unit varies throughout the state, changing from a thin, discontinuous layer to a confining/semi-confining layer to an interlayered series of permeable and impermeable layers (Arthur et al., 2008). In Hillsborough County, the base of the IAS/ICU is the stratigraphic top of the Tampa Member of the Arcadia Formation. However, in other parts of the state, where more clay is present, the Tampa is considered part of the IAS/ICU. Some western counties-Sarasota, Hardee, Charlotte, Highlands, and DeSoto, withdraw between 10 and 75 percent of their groundwater from this aquifer (Marella, 2004). The thickness of the IAS/ICU varies significantly. In the northern region of the SWFWMD it is only 35 feet deep, but in the southern region it is as deep as 900 feet.

The surficial aquifer system (SAS) is composed of undifferentiated sand, shell, and clay deposits. In the central and southern Polk Upland area (Figure 4) however, the SAS is not present due to the confining nature of the Hawthorn Group sediments (Peace River Formation, Bone Valley Member) (Arthur et al., 2008). Monitor wells in northern Hillsborough County support the presence two distinct water tables, one from the SAS and another from the FAS, near Plant City. Where the SAS does occur, it ranges in thickness from 30 feet to more than 300 feet (Arthur et al., 2008). The elevation of the SAS water table mimics surface topography. According to Marella (2004), the SAS is sourced for minor groundwater withdrawals, except in Lee County where they exceed 55%. The base of the SAS is generally considered to be the top of the Peace River Formation, but it does extend into the sandy sections of this unit. It has also been observed in the uppermost Arcadia sediments. In locations where karstic features are abundant and clay and hydraulic conditions are favorable, the SAS recharges the Floridan Aquifer System locally (Arthur et al., 2008).

CHAPTER FOUR

GEOMORPHOLOGY

Geomorphology of the region has been influenced by sea level changes, karst processes, and subtle tectonic forces (in Arthur et al, 2008; Rupert and Arthur, 1990; Schmidt, 1997). Florida is a carbonate platform-deposition controlled by sea level cycles and stand durations (Arthur et al, 2008). These fluctuations in sea level created physiographic features (Healy, 1975; Randazzo, 1997). Other features such as ridges, fractures, and paleo- water bodies are also responsible for the shaping of Florida. The study area has 2 regions- the Ocala Karst District and Sarasota River District (Figure 4).

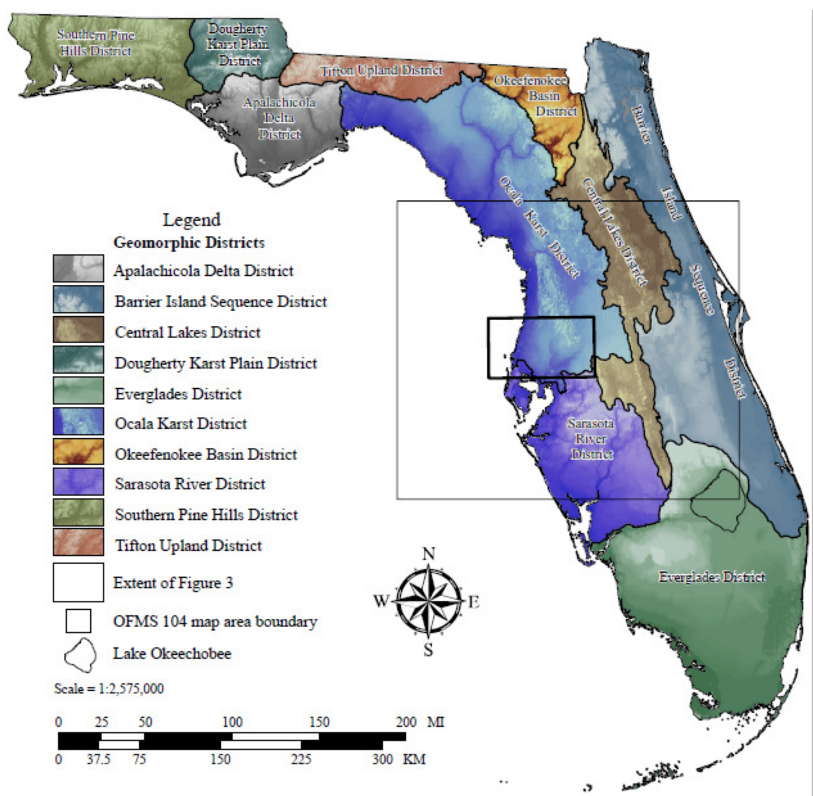


Figure 4: Geomorphic districts of Florida (Green et al., 2012)

Ocala Karst District

The Ocala Karst District, as described by Green et al. (2012), extends from Wakulla County (Florida panhandle) to Hillsborough and Pinellas Counties. The land surface of the area is predominated by carbonate sediments including: Avon Park Formation, Arcadia Formation (Tampa Member), and Hawthorn Group. The district was shaped by karst processes and includes: caves, caverns, springs, and swallets. Elevations range from 0-300 feet MSL. Rolling, minor relief is present. Many sinkholes and shallow bowl shaped depressions dominate the area. The Ocala Karst District is divided into over 7 different terranes, but only the Green Swamp Terrane is present in the study area.

Green Swamp Terrane

The Green Swamp Terrance is a poorly drained swamp region. The potentiometric surface of the Floridan Aquifer System (FAS) is high, which promotes swamp conditions. Elevations within the terrane range between 40 to 200 feet MSL. The area is characterized by karst features and exhibits a few sand dune regions and springs. Stratigraphically, the terrane is underlain by the Suwannee Limestone and some undifferentiated Hawthorn Group sediments, mostly overlain by undifferentiated siliclastic sediments of Tertiary/Quaternary age.

Sarasota River District

The Sarasota River District, as described by Green et al. (2012), encompasses most of Plant City and extends from Hillsborough County south to Lee and Glades Counties. The area is underlain by impermeable siliclastic Hawthorn Group sediments. These sediments retard the formation of karstic features. The region is dominated by streams and rivers and is flat with limited relief. Elevations range from sea level to 185 MSL. The Sarasota River District is divided into the following terranes: Coastal Lowlands, Pinellas Ridge, and Polk-Desoto Plain. Plant City is located within Polk-Desoto Plain.

Polk-Desoto Plain

The Polk-Desoto Plain is located directly south of the Green Swamp terrane. It is a flat area ranging in elevation from 5-185 feet MSL. The greatest reliefs are due to the numerous incising rivers and streams. Due to the impermeable Hawthorn Group sediments, few karst features are present. However, as seen in Figure 6 (Green et al., 2012), karst features are abundant near the study area.

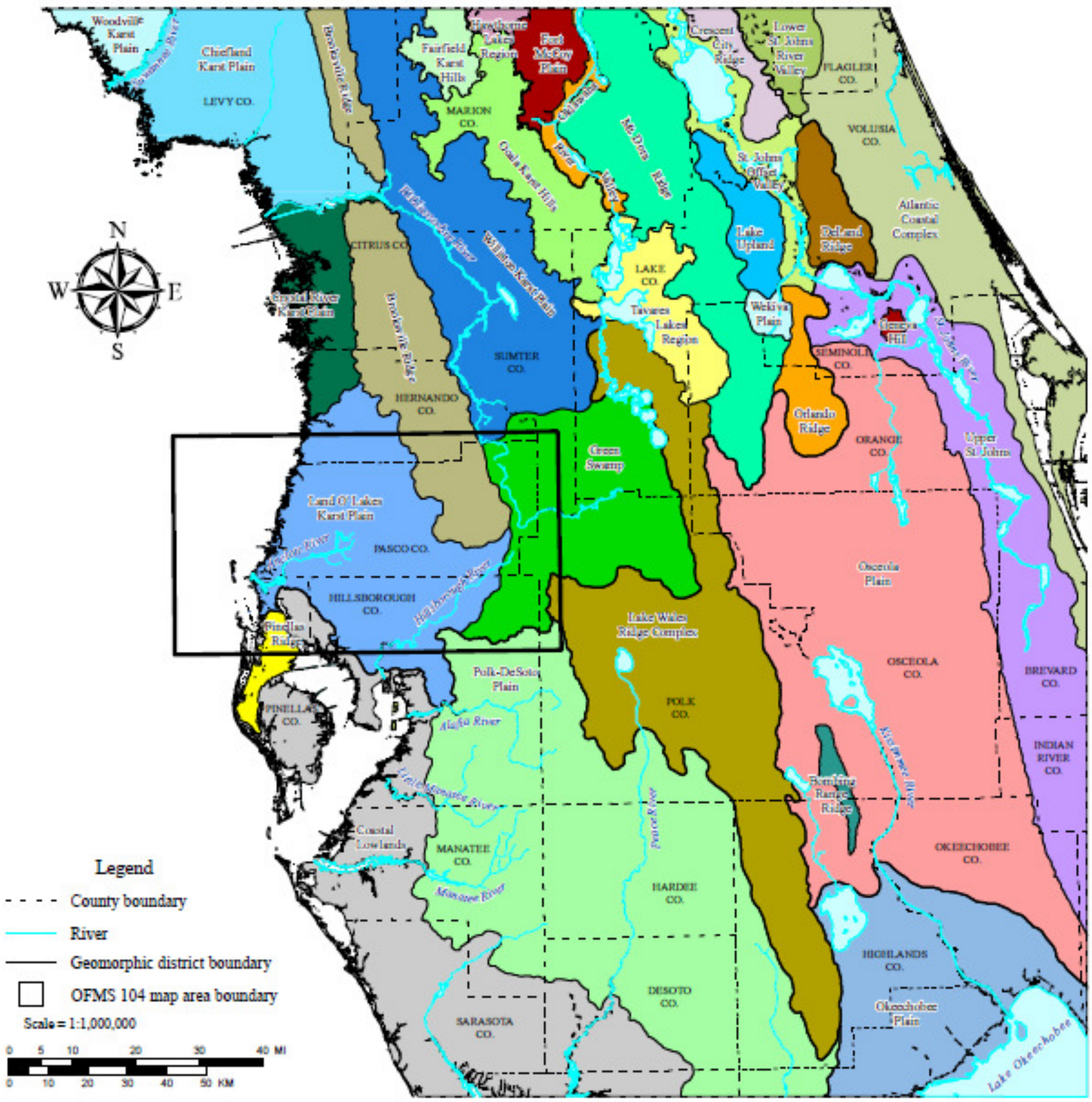


Figure 5: Geomorphic districts of the study area (Green et al., 2012)

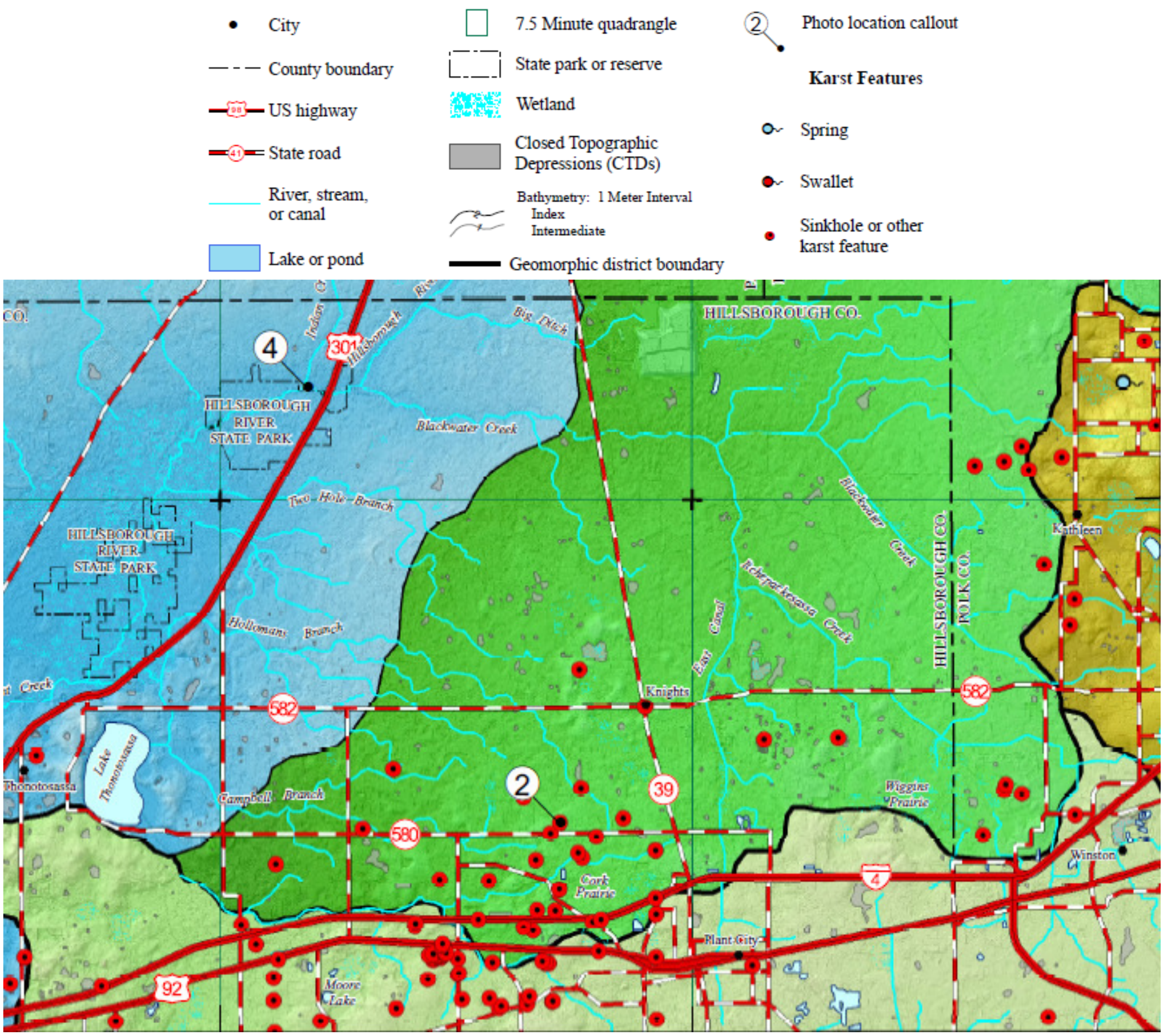


Figure 6: Location of sinkholes within Plant City, FL (Green et al., 2012)

CHAPTER FIVE

SINKHOLES

Karst Terranes

The geology of Florida is dominated by limestones and dolostones, which are susceptible to dissolution. Carbon dioxide from the atmosphere and overlying soil becomes dissolved into water and the solution becomes more acidic, forming carbonic acid. As the acidic water passes through the limestone, the rocks are chemically weathered. The resulting voids form cavities and distinctive surface features such as springs, caves, and sinkholes, known as karst (Tihansky, 1999).

Sinkhole Types

There are three main types of sinkholes, as described in Tihansky (1999). Florida sinkholes form as the result of dissolution of limestone or dolostone. Solution sinkholes cause shallow depressions in the overlying topography. As water from rainfall and surface sources infiltrate the ground surface, the carbonate rocks are dissolved and form voids. This process occurs gradually and in areas where the overlying sediments are thin. Cover-subsidence sinkholes also form gradually, but where the overburden is sandy and permeable. As cavities are formed beneath the land surface, sandy overburden slowly spalls into the opening. A depression begins to form on the land surface as the cavity grows and more sediment is infilled. Cover-collapse sinkholes are the most disastrous of the three since they form abruptly. They are dominant in areas with clay sediments. They initial formation is similar to that of cover-subsidence sinkholes in that the original cavity and spalling of sediments occurs gradually. However, because the overlying sediments are predominantly clays, the sediments form a "structural arch" due to cohesion (Tihansky, 1999). As pore pressure increases in the surrounding sediments, more clay begins to slough off the sides causing the cavity to grow larger (Tharp, 1999). Eventually, enough of the roof is eroded away causing the sediments to fail in a sudden collapse (Tihansky, 1999). A diagram showing the process of formation of the three different types of sinkholes can be found below in Figure 7.

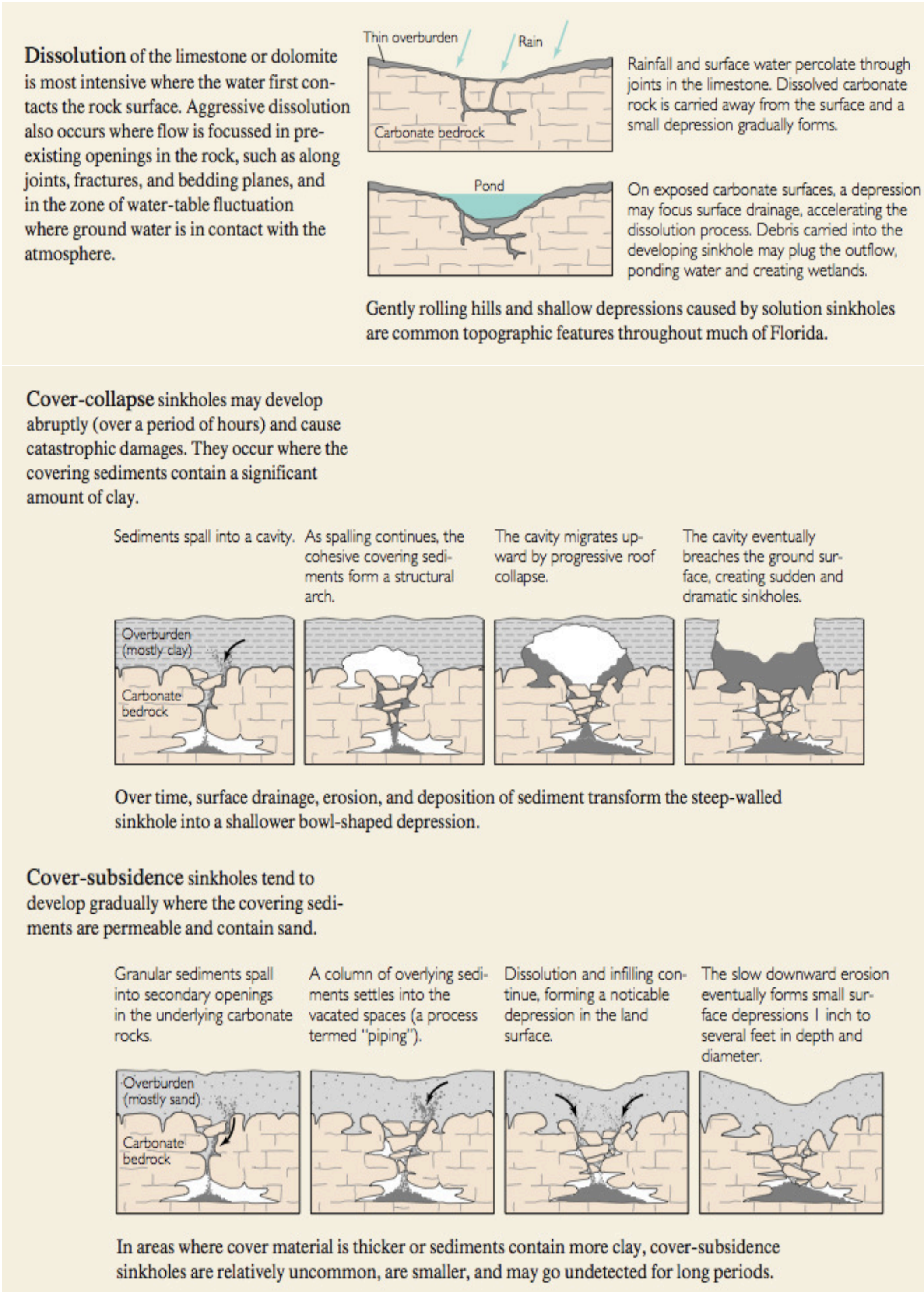


Figure 7: Types of sinkholes (Tihansky, 1999)

While Tihanksy (1999) and Wilson and Beck (1977) both relate the sinkhole formation type to overburden thickness, the composition is important as well. Overburden of 0-30 feet in thickness with high permeability tends to create more dissolution sinkholes (Tihansky, 1999). Areas with 30-200 feet thick overburden cover-subsidence and cover-collapse sinkholes are both prevalent. If the predominating sediment type is sand, cover-subsidence sinkholes are more common. If the sediments are clay, cover-collapse sinkholes are dominant. Figure 8 (from Sinclair and Stewart, 1985; Wilson and Shock, 1996) shows the type, location, and frequency of sinkholes within the SWFWMD (Tihansky, 1999). Plant City falls within the area characterized by overburden thickness of 30-200 feet and more clayey sediments.

Upchurch et al (2012) argue that eastern Hillsborough County, a thickly covered karst terrane, should not be at risk to sinkhole events due to extensive clay cover. The events of January 2010 were contradictory to this and therefore require further study. It is proposed that the rapid drawdown of water levels, more than 20 feet, allow water-saturated clays to mobilize. As they become dewatered, the overlying sediments lose buoyant support and reactivate ancient sinkholes.

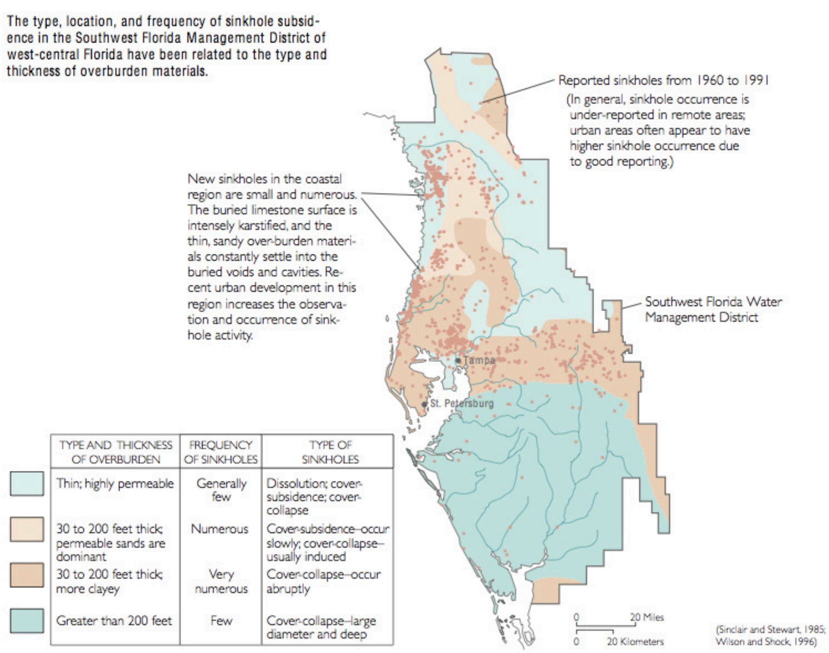


Figure 8: Thickness of overburden, frequency of sinkholes, and types of sinkholes (Sinclair and Stewart, 1985; Wilson and Shock, 1996; from Tihansky, 1999).

Augarde et al. (2003) studied idealized spherical cavity collapse to predict bounds on load parameters. The study focused on the stability of cavities during undrained conditions. A numerical modeling technique using finite-element limit analysis was used to define upper and lower bounds of the load parameters. Their study found that as soil weight increased, the zone of influence spread below the cavity axis. The spherical cavity begins to grow and vertical stresses increase which causes the movement of soils to change from strictly downward to downward with rotation. As the cavities become deeper, the failure becomes more localized.

Tharp (1999) focused his research on cover-collapse sinkholes and the mechanisms that promote their upward propagation. Most sinkholes that occur in limestone regions, such as Florida, are due to lowering of water tables below the soil-rock interface. Reasons include loss of buoyant support, increases in pore pressure gradients, and increases in water level variation amplitudes. Natural water table lowering occurs during the spring months, which can cause desiccation and promote sinkholes (Tharp 1999, Newton and Tanner, 1989; White and White, 1995). Sinkholes are also common after rain events during periods of droughts (Jeremias, 1989; Sowers, 1975). Once a cavity has formed, soil begins to move into the opening. Pore pressure increases induce further collapse with sloughing due to compressive failure. Tharp (1999) found that the rate of sloughing is linearly proportional to the diameter of the void. As time increases, the growth rate of the cavity accelerates. Such acceleration in growth can limit detection times. In instances of groundwater withdrawal, slower extraction rates may prevent sinkhole formation by lowering pore pressure gradients therefore decreasing sloughing.

CHAPTER SIX

PREVIOUS WORK

Much of the previous work conducted in the area has been by governmental agencies to propose plans to limit drawdown impacts on the Floridan Aquifer system. Hall and Metcalfe (1978) studied the freeze of January of 1977 in nearby Dover, FL. The freeze lasted three days, reached a low of 26°F, and resulted in 22 new sinkholes. Bengtsson (1987) studied the hydrogeologic effects due to groundwater pumpage in East-Central Hillsborough County. The study used data from the freeze of January 1985 and quantified the impacts using computer modeling. Of the studies done, none directly identify vulnerable areas or correlate specific drawdown amounts/ratios with the resulting sinkhole collapses.

Wilson and Beck (1992) studied sinkhole formation in the Orlando metropolitan area in order to examine the relationship between the potentiometric surface of the Floridan aquifer system and the formation of new sinkholes. A previous study by Jammal (1982) showed that for that area, May and June were the months for with the most sinkhole collapses. These times also coincide with potentiometric lows of the FAS. Much like the Plant City area, the Wilson and Beck study area is dominated by undifferentiated sands and clays that overly the underlying Hawthorn Group. Both the IAS and FAS are present in the Orlando Area. Due to the predominantly clay overlying material, this area is subject to catastrophic cover-collapse sinkholes as well. In their conclusions, Wilson and Beck (1992) identified key relationships between hydrogeologic factors and sinkhole formation. The first of which is the height of the potentiometric surface. They found that when the FAS dropped 5 or more feet, the number of new sinkholes grew exponentially (see Figure 9). The second important relationship they found was overburden thickness. The frequency of sinkholes was at its maximum when overburden thickness ranged between 120 and 150 feet. A lineament study was also conducted, but this was minor to the overall grand scheme.

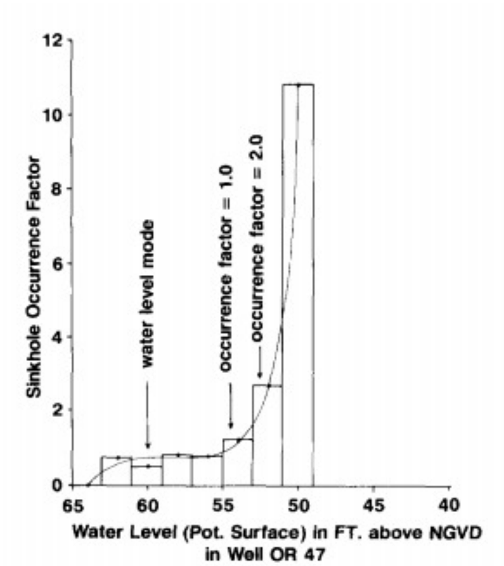


Figure 9: Sinkhole occurrence related to water levels in well OR47 (Wilson and Beck, 1992). Copyright ©, John Wiley and Sons. Used with permission.

The freeze of January 2010 was the worst experienced in the area due to its prolonged extent and devastation. Peterson and Rumbaugh (2012) studied the hydrogeologic impacts of the freeze event, which lasted a total of 11 days and resulted in 140 sinkholes. To conduct their study and evaluate the impacts, groundwater data was collected from two monitoring wells. In the two wells, Tampa 15 Deep and ROMP DV-1 (Suwannee), the lowest water elevations observed were 20.9 feet and 54.7 feet NGVD respectively. The drastic drop in water levels exposed the confining layer and left it unsupported allowing for catastrophic collapse events. The recovery period took 20 days. Rapid decline in water levels of the FAS due to intense groundwater pumping was identified as the cause of major collapse. Groundwater data was used to create a groundwater flow model so that recommendations for future prevention could be established. These recommendations included reduction in the rates or volumes of pumping within the FAS during freeze events as well establishments of the Dover/Plant City Water Use Caution Area (WUCA), Minimum Aquifer Level (MAL), and Minimum Aquifer Level Protection Zone (MALPZ). The MAL was established based on the water levels from the ROMP DV-1 (Suwannee). During the freeze, the greatest impacts occurred when this monitor well dropped below 10 feet NGVD. In order to prevent similar events in the future, the MAL was set to 10 feet NGVD. Drawdown contours produced from the groundwater flow model indicated that most of the impacts occurred within areas of 30-foot drawdowns or more. The MALPZ was set greater or equal to 30 feet. Use of irrigation and non-irrigation freeze protection alternatives has also been suggested to reduce groundwater withdraws by 20% by January 2020.

A recent study by Aurit, Peterson, and Blanford (2013) used GIS to examine the spatial and temporal relationship between sinkholes, dry wells, and groundwater pumping during freeze events. A 25 years history of data for Plant City and its surrounding area were used. Event years of 1985 and 2010 along with a non-event year of 2007 were studied. Data collected included minimum temperature data, sinkhole and dry well complaint data, water levels in three wells, and population data. The economic impacts on water authorities were also studied. For their study, they found "a strong correlation between minimum temperatures, water levels/changes in water levels" during the event of January 2010 (Aurit, Peterson, and Blandford, 2013). They also observed that the majority of sinkholes and dry wells developed within a ¼ mile of strawberry fields. Sinkholes and dry well complaints are more likely to increase when temperatures fall below 41°F and water levels experience a drop over 20 feet. Prolonged droughts will increase these odds.

CHAPTER SEVEN

DATA COLLECTION AND ANALYSIS METHODS

Data Collection

In order to establish and analyze the relationships between groundwater drawdown and sinkhole occurrence, relevant data was collected. This included groundwater levels for surrounding monitoring wells, sinkhole reports, and overburden thickness from well logs. The United States Geological Survey (USGS), Florida Department of Environmental Protection (FDEP)-Florida Geologic Survey (FGS), and Southwest Florida Water Management District (SWFWMD) provided the data.

Groundwater Data

The groundwater level data was collected for surrounding monitoring wells. Wells were selected based on the following criteria: frequency of data recording and nature of historic record. Data collected daily or faster was used. This is due to the short-term nature of drawdown events. It is noted that the averaging used for daily data may mask the severity of actual drawdown. Wells with historic data, 1980-2010, were also included to compare influences of drawdown. Water levels are reported in feet, NGVD 29. Of the data available in this area, only 15 wells were found (Figure 10). The following wells were used: ROMP 61 (17769), DV-2 FLDN AQ (L HTRN-TMPA) MONITOR (18019), TURNER FLDN (18029), MCINTOSH FLDN (18311), MORRIS BRIDGE LOWE 3-IN (18576), LHFDA 22 FLDN (18620), TAMPA 15 DEEP (18704), DV-1 U FLDN AQ (TMPA) MONITOR (18795), DV-1 U FLDN AQ (AVPK) MONITOR (18796), DV-1 U FLDN AQ (SWNN) MONITOR (18797), BLACKWATER CREEK ELAPP FLDN (19391), CONE RANCH TBW TP-2 FLDN (19456), HILLSBOROUGH RIVER STATE PARK PARKING LOT DEEP (19461), HILLSBOROUGH RIVER STATE PARK SHALLOW (19464), and HILLSBOROUGH RIVER STATE PARK DEEP (19466) (Appendix B). Water level data was not available for every well for every event.

The main data contributors were the USGS and SWFWMD.

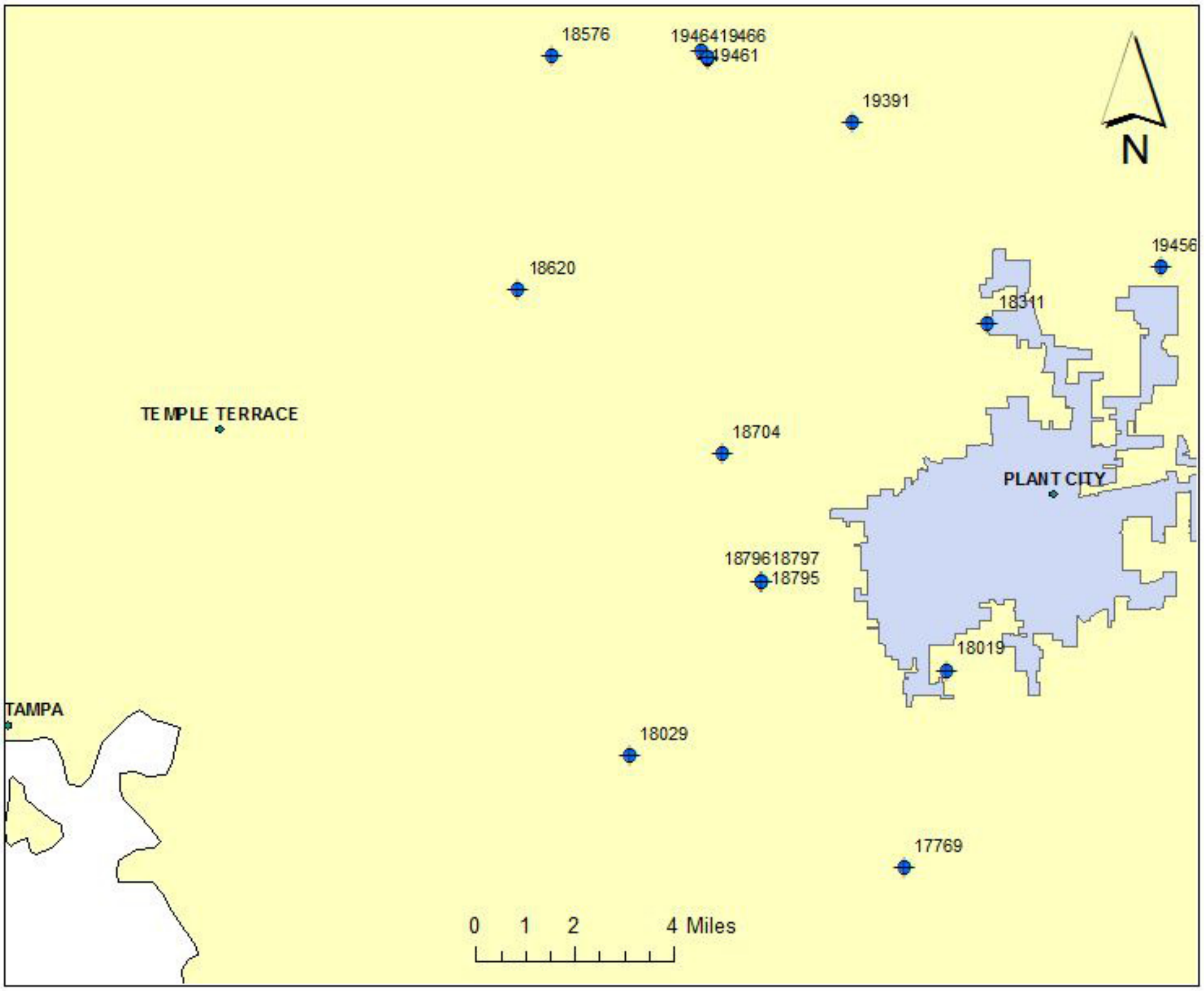


Figure 10: Well locations

Sinkhole Data

Sinkhole occurrence was determined using data provided by the FGS subsidence database, which is comprised of reported subsidence events called in by the public. The FGS does not verify the events. Therefore the validity of the dataset is questionable and comes along with disclaimers about its provisional nature and accuracy. However, no single agency exists to study sinkholes. The FGS became the primary source, but their main focus is on karst processes and groundwater systems. In 1982, an institute dedicated to sinkholes was formed, known as the Florida Sinkhole Research Institute. The institute compiled data from the FGS with its own and created a database of sinkhole instances and information. However, funding was cut in the

1990s marking the end of the institute. Although, the institute still operates in some capacity within the University of Central Florida's Department of Civil and Environmental Engineering. The responsibility of data collection and maintenance of the database was returned to the FGS. They field calls/complaints and investigate some sinkhole occurrences, but rely heavily on other state universities to aid in data collection. Due to the large nature and scope of the FGS, the quality of the data collected for such a minor portion of their research has declined (Florida Geological Society, 2005). This dataset has been used in previous studies (Tihansky, 1999; Fleury, Carson, and Brinkmann, 2008; and Aurit, Peterson, and Blanford, 2013). The data was filtered to only include subsidence events that occurred in and around Plant City within 30 days of maximum recorded drawdown.

Overburden Thickness Data

Overburden thickness (OBT) was calculated for the region using FGS Bulletin 68 (Arthur et al, 2008). This dataset includes FGS well number, county, elevation, total depth (below land surface), and depths and thickness of various geologic units and aquifer systems for the entire SWFWMD area. The geologic units in descending order, include: Hawthorn Group Undifferentiated, Peace River Formation of the Hawthorn Group, Bone Valley Member of the Peace River Formation of the Hawthorn Group, Arcadia Formation (undifferentiated) of the Hawthorn Group, Tampa Member of the Arcadia Formation of the Hawthorn Group, Nocatee Member of the Arcadia Formation of the Hawthorn Group, Arcadia Formation (undifferentiated) of the Hawthorn Group, Suwannee Limestone, Ocala Limestone, and Avon Park Formation. The aquifer systems include: surficial aquifer system, intermediate aquifer system / intermediate confining unit, Floridan aquifer system, and middle Floridan confining unit. The data was filtered to only include wells that were within the study area.

Data Analysis Methods

Data analysis was performed using R version 2.15.1. Various routines were used to calculate: drawdown curve, non-event water level surface, overburden thickness and event water level. Logistic regressions on the data were also performed to determine potential significance of hydrographic and geologic parameters to sinkhole collapse. All data was converted to UTM coordinates. A grid with separation values of 2500 meters was used to model the regional features.

Water Levels

The dataset used for analysis had the following categories: well number, location information (in UTM coordinates), non-event water levels (for 1985, 1989, 2005, and 2010), event water levels (1985, 1989, 2005, and 2010), and differences. Non-event water levels for the known wells were found by inspecting temporal trends in water level for a given year. Based on the trend, a period of "normal" water levels was chosen. For the event water levels, minimum water levels were chosen. The drawdown was calculated as the difference between "normal" and event water levels. For each event the same date was used for all the wells.

Non-Event Water Level

The potentiometric surface of the study area is not known for each specific drawdown event, so it was estimated through universal kriging using the known water levels with the R routine "geoR." The inputs include: location and regionalized variables. The location variables include the Easting and Northing UTM coordinates for the wells. However, the values are too large for the program to process so they must first be divided by 1000. The regionalized variable represents the variable you want to predict. In this case, it is the non-event water level. The R routine "eye.fit" (geoR) was used to create an appropriate semivariogram model. A directional semivariogram (with 20° increments) was generated to reveal any directional anisotropy present in the data, which can be corrected by using the "coords.aniso" routine. The semivarience plot shows the data points of known values. When fitting a semivariance model, if a smooth fit was not possible, the line was fit between the points.

Drawdown Curve

For each event a contour plot was created in R using the well locations and the drawdown values. From this plot, a center of the drawdown curve was approximated. For the remaining points, Euclidian distance from center was calculated.

Directional anisotropy was evaluated using a directional semivariogram (with 20° increments). The maximum compression direction is chosen as the azimuth associated with the smallest range, the anisotropy value is chosen based on the ratio between the largest and smallest range. These values are used in the "plotEm" program (Appendix A) to calculate the values for the gridded points. Using the input values for center, depth, R (slope of exponential surface), dir (direction of maximum continuity), and aniso (ratio of maximum to minimum range in direction, dir), a distance (from center) vs. depth diagram is produced. A best fit line and sum of square value are also plotted. The parameters can be altered until the best fit and lowest sum of square value is obtained. Using the "gridEm" program (Appendix A), values are calculated using the above parameters for the unknown values (including the added grid values). The output includes a contour plot of the estimated data.

Event Water Level

By adding the drawdown values calculated from the plotEm and gridEm programs to the non-event water levels, an estimate of the potentiometric surface in the study area during the maximum drawdown can be created.

Sinkholes

That data was filtered to only include those events in the study area that occurred during the event being studied. In order to identify the number of sinkholes per grid point, the UTMs of reported sinkholes were rounded using standard rounding practices (UTM-5000). With the ceiling function in excel, the points were then rounded to the nearest 2500 meters. Easting and Northing values were combined together, separated by a comma using the concatenate function. Each location was given a value of 1. Using the pivot table routine, the number of sinkholes per grid node was calculated.

Logistic Regression

The significance of the input parameters (overburden thickness-OBT, event water level, and drawdown) in predicting the output parameter (sinkholes) was determined using the logistic regression routine in R (Appendix C). The routine indicates significance values of each of the input parameters as p values ranging between 0 and 1, with small values being the most significant.

CHAPTER EIGHT

RESULTS

January 2010

The January 2010 event spanned a total of eleven days from January 3rd to January 13th, with nine of those nights dipping into freezing (below 32□F) temperatures (Peterson and Rumbaugh, 2011). Of the data collected, water level data was available for 12 of the 15 groundwater wells: DV-2 FLDN AQ (L HTRN-TMPA) MONITOR (18019), MCINTOSH FLDN (18311), LHFDA 22 FLDN (18620), TAMPA 15 DEEP (18704), DV-1 U FLDN AQ (TMPA) MONITOR (18795), DV-1 U FLDN AQ (AVPK) MONITOR (18796), DV-1 U FLDN AQ (SWNN) MONITOR (18797), BLACKWATER CREEK ELAPP FLDN (19391), CONE RANCH TBW TP-2 FLDN (19456), HILLSBOROUGH RIVER STATE PARK PARKING LOT DEEP (19461), HILLSBOROUGH RIVER STATE PARK SHALLOW (19464), and HILLSBOROUGH RIVER STATE PARK DEEP (19466). The lowest water levels were observed on January 12, 2010. Water surface elevations ranged from 6.78 feet to 90.03 feet (all elevations are NGVD 29). March 17, 2010 was chosen as the "normal" event. Differences between the water levels of the non-event and event ranged between -1.94 feet and -49.085 feet. The biggest drawdowns were observed in the DV-1 FLDN MONITOR and DV-2 FLDN AQ MONITOR wells. A table of all the water level data used can be found in Appendix B.

The non-event water level surface was kriged using the data from March 17, 2010. Using a exponential model, the known non-event water levels were used to estimate gridded values by universal kriging. Gridded values were then graphed using the contour plot routine in R. From the graph, the slope and character of the potentiometric surface of the area is shown. This is assumed to be the general trend of the water table. A slope to the southwest is observed (Figure 12).

The same routine as above was used to calculate the event water level, but it was determined to be unreliable due to a high degree of uncertainty. Therefore "plotEm" was used to fit an exponential curve to the drawdown values. For the January 2010 event, the center was estimated to be 384.5,3095 (NOTE: these values are UTMs divided by 1000). The routine also uses maximum depth, R (“slope” of the cone), dir (direction of maximum continuity), and aniso (ratio of how much cone is stretched in direction, dir). Different values were input to attempt to reduce the sum of squares value but it was determine that depth of -50, slope of -0.06, azimuth of 120, and anisotropy ratio of 3 had the best results. The sum of squares value was 419.402 feet^2 (Figure 13). The reported sinkholes for the month of January were plotted as points on top of a contour plot of the drawdown curve (Figure 14).

A logistic regression was run to determine the effectiveness of predicting sinkholes using overburden thickness, event water level, and drawdown (difference between event and non-event water level). Each grid node was considered a sample with the number of sinkholes (within ½ grid spacing), drawdown, overburden thickness, event water level as variables. Using a value of 1 for nodes with sinkholes and 0 for nodes with no sinkholes, it was determined that water level and drawdown were the most significant with p=0.003 and p=0.004 (99.7% and 99.6% confidence). Intercept was given a value of p=0.01 and overburden thickness was not significant at all (p=0.767, Figure 15).

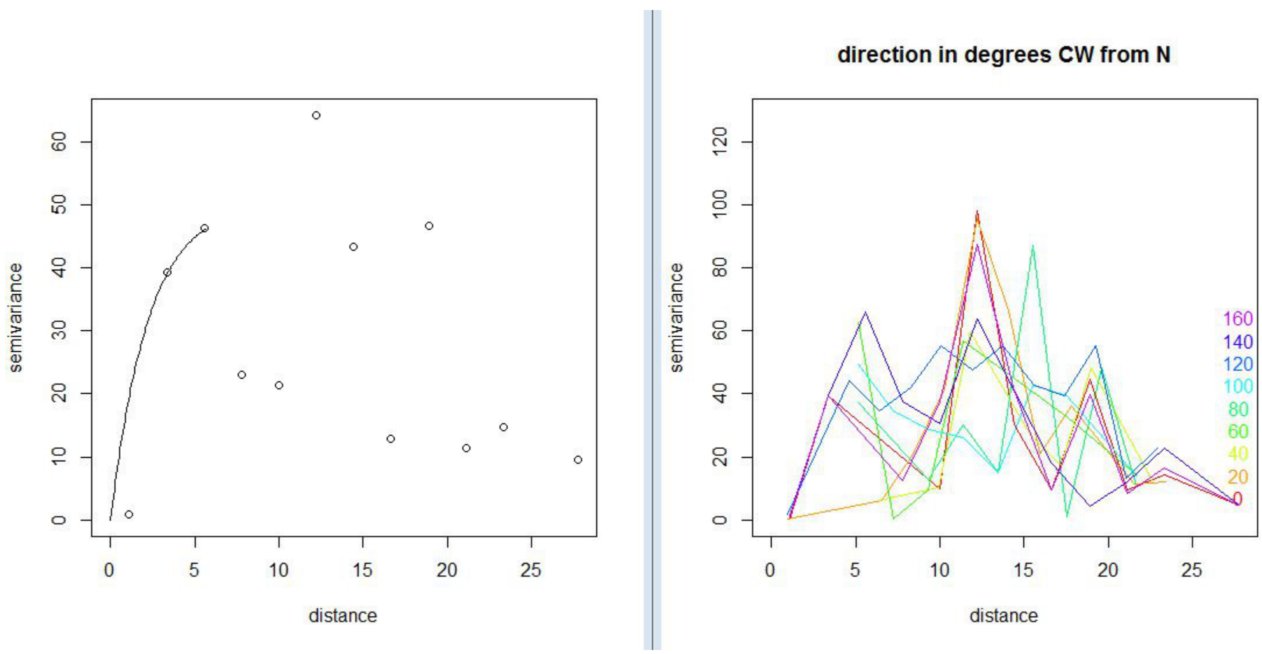


Figure 11: Directional variogram and fitted variogram for January 2010

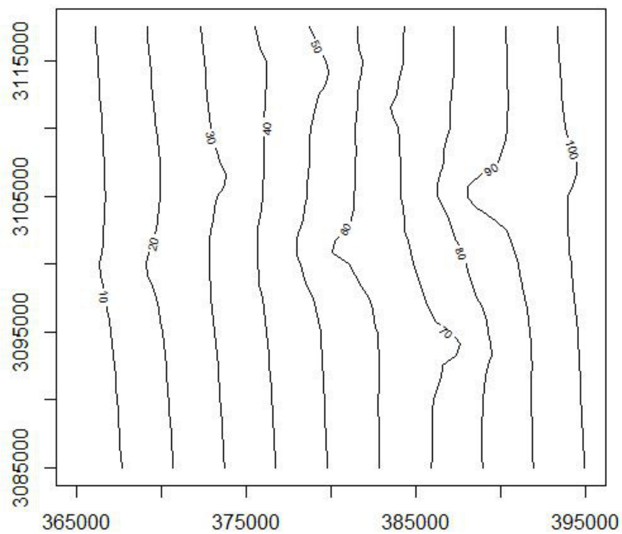


Figure 12: Non-event water level for January 2010

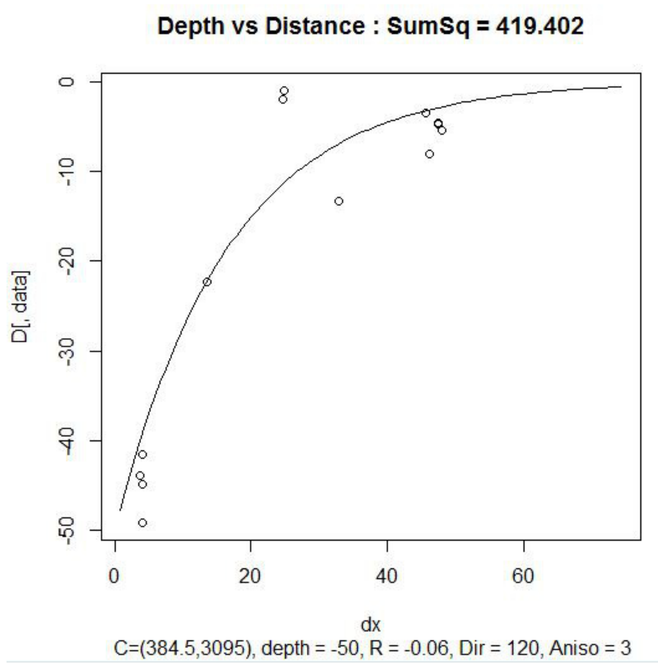


Figure 13: Sum of squares for January 2010 event using plotEm

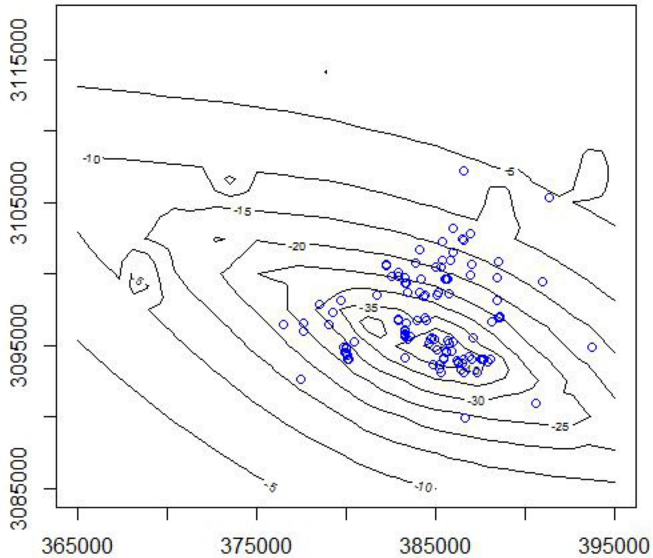


Figure 14: Calculated drawdown curve with sinkholes for January 2010

Figure 15: Logistic regression for January 2010

```
> answ <- glm(SH2~Difference+OBT+WL, data=Jan10, family=binomial())
> summary(answ)

Call:
glm(formula = SH2 ~ Difference + OBT + WL, family = binomial(),
    data = Jan10)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.0093  -0.5023  -0.2628  -0.1535   3.0057

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept) -4.91457    2.23469  -2.199  0.02786 *
Difference  -0.09953    0.03383  -2.942  0.00326 **
OBT         -0.00470    0.01587  -0.296  0.76717
WL           0.03988    0.01395   2.859  0.00425 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 117.45  on 181  degrees of freedom
Residual deviance:  97.90  on 178  degrees of freedom
  (16 observations deleted due to missingness)
AIC: 105.9

Number of Fisher Scoring iterations: 6
```

January 1985

The January 1985 event spanned a total of three days from January 21st to January 23rd, with temperatures dropping into the 20s (Bengtsson, 1987). Of the data collected, water level data was available for 7 of the 15 groundwater wells: ROMP 61 (17769), TURNER FLDN (18029), MORRIS BRIDGE LOWE 3-IN (18576), TAMPA 15 DEEP (18704), HILLSBOROUGH RIVER STATE PARK PARKING LOT DEEP (19461), HILLSBOROUGH RIVER STATE PARK SHALLOW (19464), and HILLSBOROUGH RIVER STATE PARK DEEP (19466). The lowest water levels were observed on January 23, 1985. Water surface elevations ranged from 46.9 feet to 13.75 feet (all elevations are NGVD 29). February 9, 1985 was chosen as the "normal" event. Differences between the water levels of the non-event and event ranged between -12.36 feet and +0.01 feet. The biggest drawdown was observed in the TAMPA 15 DEEP well. A table of all the water level data used can be found in Appendix B.

The non-event water level surface was kriged using data from February 9, 1985 (Figure 16). A slope of the non-event potentiometric surface shows a slope to the southwest (Figure 17). For the January 1985 event, the center was determined to be 380.5,3100 (NOTE: these values are UTMs divided by 1000). Different values were input to attempt to reduce the sum of squares value but it was determine that depth of -13, slope of -0.06, angle of 120, and ratio of 3 had the best results. The sum of squares value was 37.5658 feet^2 (Figure 18). The reported sinkholes for the month of January were plotted as points on top of a contour plot of the drawdown curve (Figure 19). After running a logistic regression, it was determined that drawdown was the most significant with p= 0.01 (99% confidence). Intercept was given p= 0.05, overburden thickness and water level were not significant (p=0.862 and p=0.430, respectively,Figure 20).

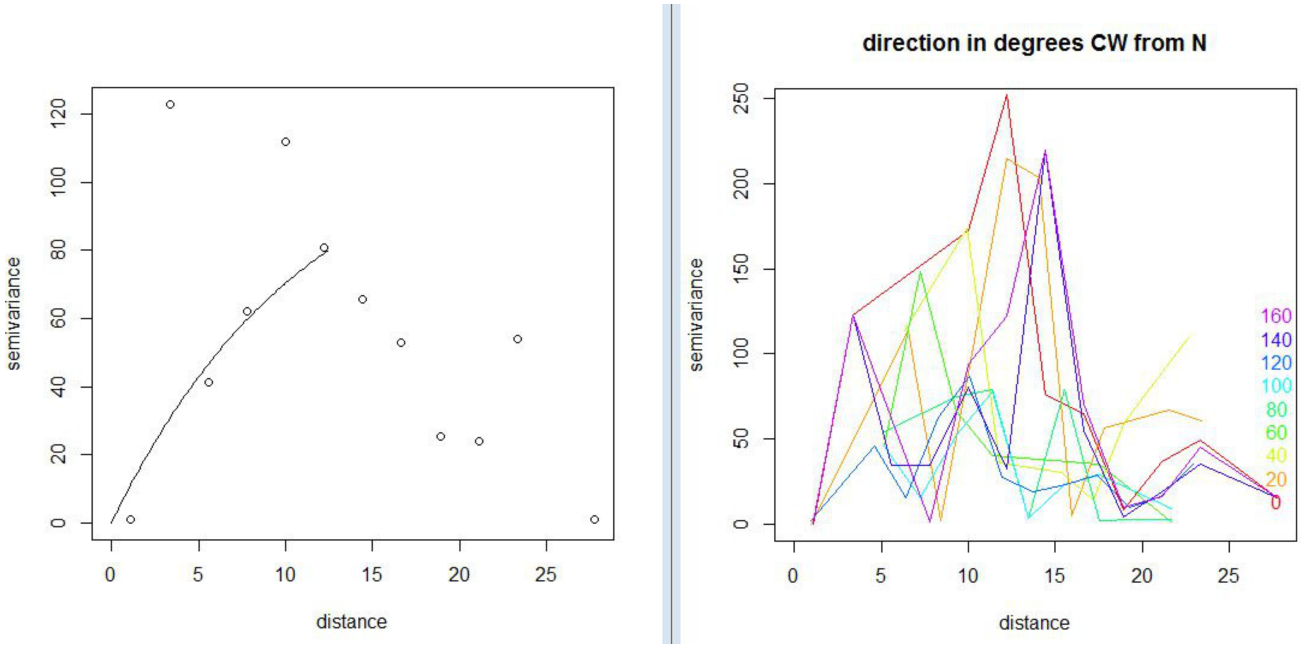


Figure 16: Directional variogram and fitted variogram fro January 1985

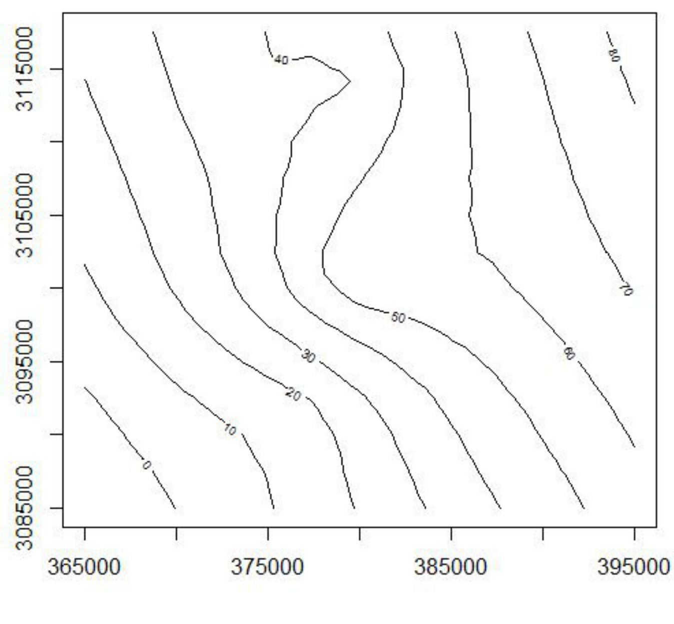


Figure 17: Non-event water level for January 1985

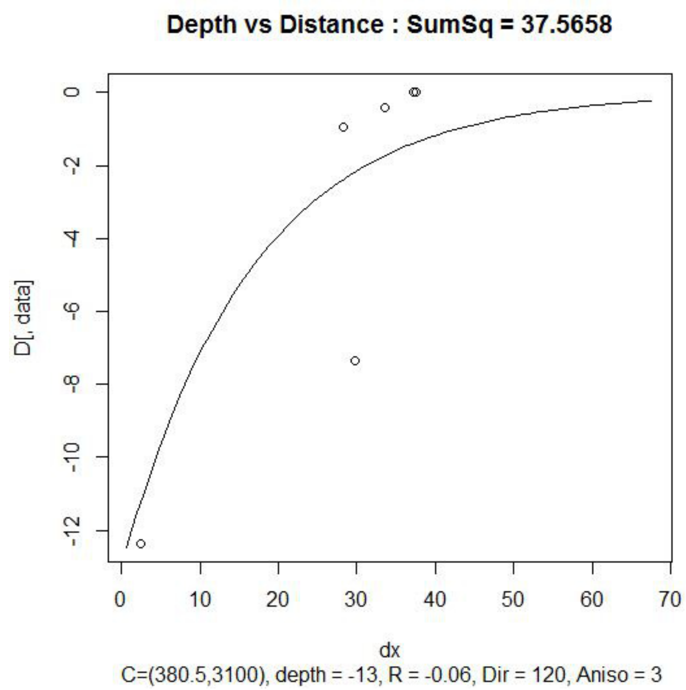


Figure 18: Sum of squares for January 1985 using plotEm

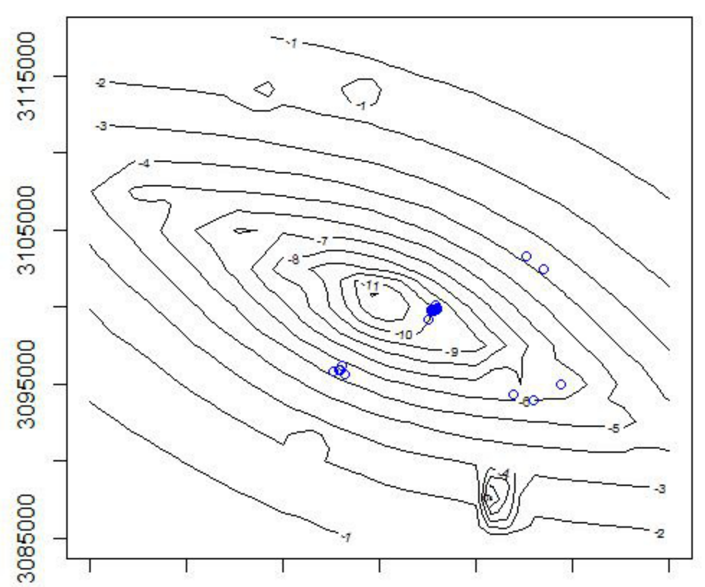


Figure 19: Calculated drawdown curve with sinkholes for January 1985

```
> answ <- glm(SH2~Difference+OBT+WL, data=Jan85, family=binomial())
> summary(answ)

Call:
glm(formula = SH2 ~ Difference + OBT + WL, family = binomial(),
    data = Jan85)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.9241  -0.2309  -0.1761  -0.1192   2.8943

Coefficients:
             Estimate Std. Error z value Pr(>|z|)
(Intercept) -3.898646   2.263917  -1.722   0.0851 .
Difference  -0.401148   0.167689  -2.392   0.0167 *
OBT         -0.002731   0.015681  -0.174   0.8617
WL          -0.028679   0.036311  -0.790   0.4296
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 45.807  on 181  degrees of freedom
Residual deviance: 39.576  on 178  degrees of freedom
  (16 observations deleted due to missingness)
AIC: 47.576

Number of Fisher Scoring iterations: 7
```

Figure 20: Logistic regression for January 1985

CHAPTER NINE

DISCUSSION

Based on the results, it is clear that a relationship exists between groundwater pumping and sinkhole occurrence. Data from both the January 1985 and January 2010 events support this. Figure 12 and Figure 16 show that the majority of the sinkholes reported develop within the calculated cone of depression. The main differences between the two events are the amount of drawdown and number of sinkholes. The drawdown in January 2010 was more than 3.5 times larger than that of January 1985 and had more than 5 times as many sinkholes. The January 2010 event had more data available in terms of the number of wells and periodicity of recording, which provided a more detailed description of conditions during the freeze event.

The logistic regression confirmed that, for those two events, drawdown was the more significant factor affecting occurrence of sinkholes in both events. Water level elevations were significant for the January 2010 event only, with p= 0.004. This could be due to a denser network of well data. In 2010, twelve of the sixteen wells had water level data while 1985 only had 7. The locations of wells with available data are spread throughout the study area and separated by large distances, although some clusters do exist. If the data were more widespread and evenly distributed throughout the affected area, the calculated drawdowns and center of drawdowns would be better constrained. Predicted potentiometric surfaces would also be more accurate, allowing for a stronger analysis/correlation.

In both events, overburden thickness (OBT) was not significant. This appears contrary to Tihanksy's (1999) study that showed cover-collapse sinkholes are characterized by overburden thicknesses of 30-200 feet. In the study area, OBT ranges between 65 and 349 feet. However, when the sinkholes of the January 1985 and January 2010 event are plotted over a contour plot of OBT, all of them plot between 100 and 200 feet of overburden thickness. Thus, the relationship to overburden thickness is never tested.

The rate of water table lowering was not analyzed during this study, but it may be a significant factor in determining sinkhole collapse. The 49 foot drawdown experienced in DV-1

U FLDN AQ (AVPK) MONITOR (18796), in January 2010, occurred over a 177 hour period. The water level started off at 54.57 feet on January 4, 2010 at 02:00 and fell to -4.6 feet on January 11, 2010 at 10:00. However multiple drawdown events exist within this period. Between each smaller drawdown event, the water level was able to recover somewhat. Using hourly DV-1 data, the average drawdown rate during the freeze event, January 4th to January 13th, was 1.46 feet/hour. The average recovery rate for the same time period was 0.86 feet/hour, less than 60% of the drawdown rate. The water level returned to an elevation of 54.56 feet on February 3, 2010. Tharp (1999) found that consolidation of soil due to loss of buoyant support causes rapid failure and sinkhole formation could be minimized by decreasing the water table lowering rate.

Surface loading may be responsible for sinkhole collapses during the January events. As water is extracted from the subsurface, it is sprayed on strawberry fields. Underlying soil loses its buoyant support at the same time it is loaded, increasing surface stress. Overburden thickness may play a role in the effect of loading on sinkhole collapse. Areas above of the 100-200 feet thickness range may have sufficient thicknesses to distribute/counter balance surface loading. This effect may also explain sinkhole collapse events tied to rainfall events. During the months of May-June, water level elevations are at a natural low and rainfall is high. The rainfall loads the surface much the same as the water sprayed on the surface during freeze events.

January was not the only month that experienced drawdown events. In 1985, other drawdown events occurred in June and December. In 2010, events occurred twice in February, once October, and twice in December. However, the reported numbers of sinkholes for the latter events were much lower than those reported in January. In some cases, specifically December 2010 and June 1985, the drawdown was equivalent to that of the January events. In June 1985, the water level dropped 10 feet, but only produced 8 sinkholes. The December 2010 events had drawdowns of 43 and 41.6 feet with only two sinkholes for the entire month. In both cases, the sinkholes did not plot near the area of maximum drawdown (Figure 21 and Figure 22). Therefore, it is possible that there is a trigger reset period. If drawdown events occur before this time, the collapse events are not as catastrophic. Both the trigger reset period and factors are unknown.

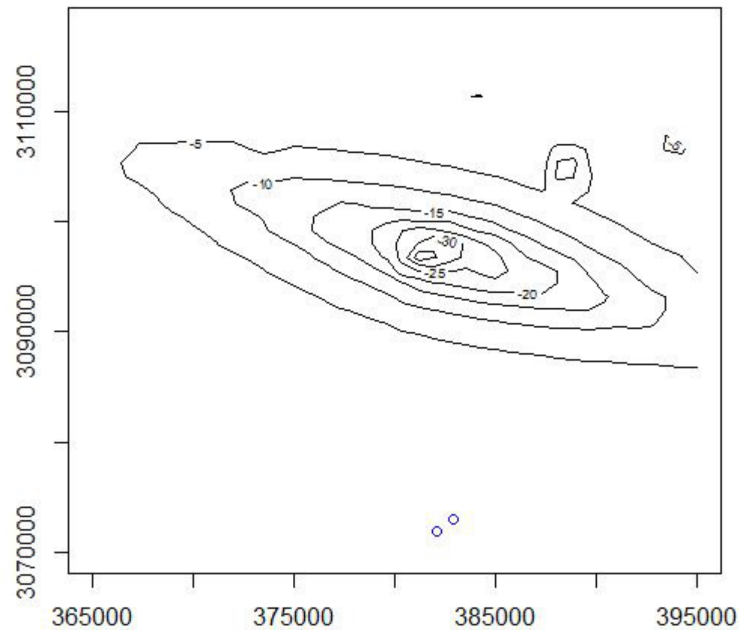


Figure 21: Location of December 2010 sinkholes

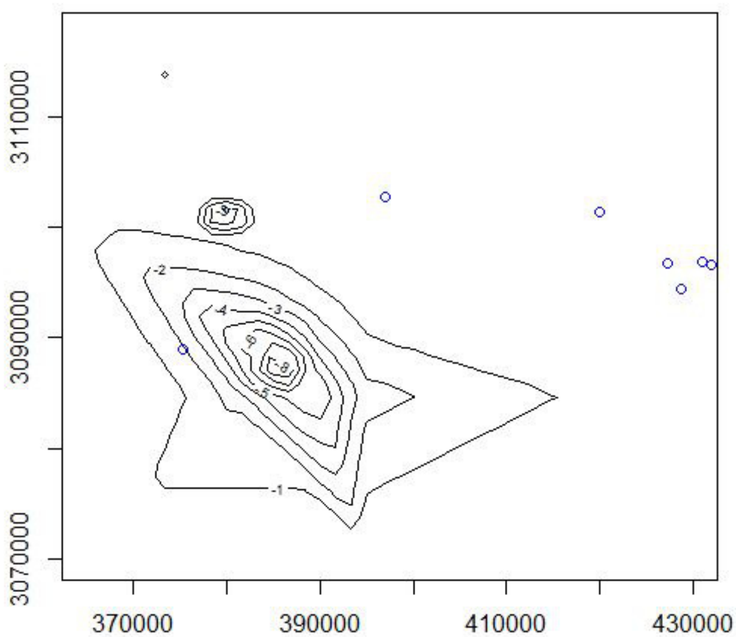


Figure 22: Location of June 1985 sinkholes

CHAPTER TEN

CONCLUSIONS

This research found a correlation between drawdown and sinkhole occurrence in January 1985 and January 2010. Other factors affecting the development of sinkholes, not studied, are present. These include: amount of surface loading, soil mechanics, and preexistence of subsurface cavities. Unlike previous studies, this research shows that drawdown amounts greater than 10 feet likely cause sinkholes to form in the study area. Aruit, Peterson, and Blanford (2013), Peterson and Rumbaugh (2010), and Upchurch et al. (2012) all suggest that drawdowns exceeding 20 feet are catastrophic. Southwest Florida Water Management District based their regulations for prevention of future events on this number. Catastrophic collapse events may occur with drawdowns lower than 20 feet. As the area experiences drought and lowering of the potentiometric surface, preexisting cavities will become exposed and unsupported leading to move cover-collapse sinkholes at lower drawdowns.

In order to better understand the relationship between groundwater pumping and sinkhole occurrence during freeze events, more research is necessary. Data coverage for the study area is incomplete, both geographically and temporally. A denser network of continuously monitoring groundwater wells is needed, although due to recent budget cuts this may be difficult. It is also important to closely monitor the extraction at agricultural wells of groundwater during the freeze events. Alternative freeze protection methods may help reduce loss of crops as well as reduce amounts of groundwater extracted.

Freeze events will continue to plaque the Plant City area and its strawberry crops. Sinkholes will also be a problem due to the geologic setting. Therefore, no direct solution is available. Prevention is the key to minimizing impacts. This is possible with increased monitoring networks, data collection, alternative protection methods, and communication with famers and the community.

APPENDIX A

R CODE

newCone:

```
plotEm <- function(D,east=1,north=2,data=3, center=c(0,0), depth=0, R=-.1, dir=0, aniso=1){
```

Where:

- D is the name of the data file
- 1,2, 3 refer to the column numbers in the data set ‘D’ in which values for Easting (east), Northing (north), and data are found
- center ‘c’ is easting and northing coordinates, chosen from contour plot of drawdown values (default is the cords of the lowest measured point)
- depth is maximum drawdown (default is minimum observed value)
- R is “slope” of exponential drawdown cone, value less than 0
- dir is azimuth of maximum continuity chosen from directional variogram
- aniso is amount of semivarience anisotropy as a ratio of $h_{max\ range}/h_{min\ range}$ (always > 1), based on directional variogram

```
require("circular")
```

- Tells the program to use the “circular” package

```
d=dir*pi/180
```

- Converts direction, dir, into radians

```
if(depth==0) depth=min(na.omit(D[,data]))
```

- If no depth is specified, sets depth to minimum value in data file ‘D’

```
if(center[1]==0) {
	for(i in 1:nrow(D)) {
		if(!is.na(D[i,data])){
			if(D[i,data] <= depth) {
			depth=D[i,data]
			center = c(D[i,east],D[i,north])
			}
		}
```

```
        }
}
```

- If no center values are entered, uses minimum depth location data and sets as center

```
dx <- vector(length=nrow(D))
```

- Creates a vector with the same number of rows as data file 'D'

```
sumsq=0
for(i in 1:length(dx)){
        dx[i]=sqrt((D[i,east]-center[1])^2+(D[i,north]-center[2])^2)*(1+abs(sin(abs(-d-(coord2rad(D[i,east]-center[1],D[i,north]-center[2])+pi/2))))*(aniso-1))
```

- Uses Pythagorean theorem to calculate distance from center of each data point and normalizes the distance based on dir and anios

```
        if(!is.na(D[i,data])) sumsq=sumsq+(D[i,data]-depth*(exp(R*dx[i])))^2
```

- For observed data, calculates and sums squared differences between observed and predicted values

```
}

plot(dx,D[,data],main=paste("Depth vs Distance : SumSq = ",format(sumsq,dig=6),sep=""), sub=paste(" C=(",format(center[1],dig=5),",",format(center[2],dig=6),"), depth = ",depth,", R = ",R,", Dir = ",dir,", Aniso = " ,aniso,sep=""))
```

- Plots depth versus normalized distance from center

```
G <- matrix(nr=100,nc=2)
for(i in 1:100){
        G[i,1]=max(dx)*i/100
        G[i,2]=depth*(exp(R*G[i,1]))
}
```

- Generates an 'ideal' exponential curve to fit the data points

```
lines(G)
}
```

- Plots line G on plot above

```
gridEm <- function(G,east=1,north=2,data=3, center=c(0,0), depth=0, R=-.1, dir=0, aniso=1) {
```

Where:

- G is the name of the data set
- 1,2, 3 refer to the column numbers in the data set ‘D’ in which values for Easting (east), Northing (north), and data are found
- center ‘c’ is easting and northing coordinates, chosen from contour plot of drawdown values
- depth is maximum drawdown
- R is “slope” of drawdown cone, value less than 1
- dir is azimuth of maximum continuity chosen from directional variogram
- aniso is amount of semivariance anisotropy as a ratio of $h_{\text{max range}}/h_{\text{min range}}$ (always > 1), based on directional variogram

```
require("car")
require("akima")
require("circular")
```

- Loads the packages: “car”, “akima”, and “circular”

```
D=dir*pi/180
```

- Converts direction, dir, to radians

```
if(depth==0) depth=min(na.omit(G[,data]))
```

- If no depth is specified, sets depth to minimum value in data file ‘G’

```
if(center[1]==0) {
    for(i in 1:nrow(G)) {
        if(!is.na(G[i,data])) {
            if(G[i,data]<= depth) {
            depth=G[i,data]
            center = c(G[i,east],G[i,north])
            }
        }
    }
}
```

- If no center values are entered, uses minimum depth location data and sets as center

for(i in 1:nrow(G)) if(is.na(G[i,data])) G[i,data]=depth*(exp(R*sqrt((G[i,east]-center[1])^2+(G[i,north]-center[2])^2)*(1+abs(cos(abs(-D-(coord2rad(G[i,east]-center[1],G[i,north]-center[2])))))*(aniso-1))))

- Exponential function for calculating depth from distance from center, normalized by directional anisotropy.

plot(G[,east],G[,north], type="n”)

- Plots frame for contour of data

contour(interp(G[,east],G[,north],G[,data]))

- Contours data in the plot frame

text(10+min(G[,east]),max(G[,north]),labels=paste("Gridded Contour: C=(",center[1],",",center[2],"), Dir=", dir,", Aniso=",aniso,", R=",R,sep=""))

return(G)

- Prints headings on top of graph plotted above

}

APPENDIX B

DATA

Table 3: Well locations

Well Number	Well Name	Easting	Northing	Datum
17769	ROMP 61	385727	3087609	NGVD29
18019	DV-2 U FLDN AQ (L HTRN-TMPA) MONITOR	387075.85	3094040.54	NGVD29
18029	TURNER FLDN	376788	3091276	NGVD29
18311	MCINTOSH FLDN	388413.49	3105341.66	NGVD29
18576	MORRIS BRIDGE LOWE 3-INTER	374221.81	3114083.32	NGVD29
18620	LHFDA 22 FLDN	373139.62	3106460.31	NGVD29
18704	TAMPA 15 DEEP	379768.55	3101101.06	NGVD29
18795	DV-1 U FLDN AQ (TMPA) MONITOR	381060.04	3096945.47	NGVD29
18796	DV-1 U FLDN AQ (AVPK) MONITOR	381060.13	3096954.66	NGVD29
18797	DV-1 U FLDN AQ (SWNN) MONITOR	381062.76	3096942.34	NGVD29
19391	BLACKWATER CREEK ELAPP FLDN	384008.12	3111905.38	NGVD29
19456	CONE RANCH TBW TP-2 FLDN	394099.99	3107198.1	NGVD29
19461	HILLSBOROUGH RIVER STATE PARK PARKING LOT DEEP	379090.5	3114250.25	NGVD29
19464	HILLSBOROUGH RIVER STATE PARK SHALLOW	379328.11	3114007.78	NGVD29
19466	HILLSBOROUGH RIVER STATE PARK DEEP	379336.45	3114020.06	NGVD29

Table 4: Freeze event data

Well	Easting	Northing	EventDate_1	Waterlevel_1	Non-eventDa	NDWaterlevel_1	Difference_1	EventDate_2	Waterlevel_2	Difference_2
19466	379336.5	3114020	01/12/10	42.09	3/17/10	46.74	-4.65	02/14/10	NA	NA
19464	379328.1	3114008	01/12/10	42.15	3/17/10	46.89	-4.74	02/14/10	NA	NA
19461	379090.5	3114250	01/12/10	38.391	3/17/10	43.789	-5.398	02/14/10	41.289	-2.5
19456	394100	3107198	01/12/10	90.03	3/17/10	98.12	-8.09	02/14/10	95.75	-2.37
19391	384008.1	3111905	01/12/10	69.51	3/17/10	73.02	-3.51	02/14/10	72.25	-0.77
18797	381062.8	3096942	01/12/10	10.34	3/17/10	55.235	-44.895	02/14/10	43.95	-11.285
18796	381060.1	3096955	01/12/10	6.78	3/17/10	55.865	-49.085	02/14/10	43.96	-11.905
18795	381060	3096945	01/12/10	13.66	3/17/10	55.18	-41.52	02/14/10	45	-10.18
18704	379768.6	3101101	01/12/10	37.9	3/17/10	60.16	-22.26	02/14/10	56.59	-3.57
18620	373139.6	3106460	01/12/10	24.75	3/17/10	26.69	-1.94	02/14/10	26.18	-0.51
18576	374221.8	3114083	NA	NA	NA	NA	NA	NA	NA	NA
18311	388413.5	3105342	01/12/10	79.88	3/17/10	93.24	-13.36	02/14/10	88.75	-4.49
18029	376788	3091276	NA	NA	NA	NA	NA	NA	NA	NA
18019	387075.9	3094041	01/12/10	23.12	3/17/10	67.05	-43.93	02/14/10	56.2	-10.85
17769	385727	3087609	NA	NA	NA	NA	NA	NA	NA	NA

Table 4: continued

EventDate_3	Waterlevel_3	Difference_3	EventDate_4	Waterlevel_4	Difference_4	EventDate_5	Waterlevel_5	Difference_5	EventDate_6	EventDate_3
02/26/10	NA	NA	10/18/10	NA	NA	12/15/10	NA	NA	12/29/10	02/26/10
02/26/10	NA	NA	10/18/10	NA	NA	12/15/10	NA	NA	12/29/10	02/26/10
02/26/10	40.41	-3.379	10/18/10	37.529	-6.26	12/15/10	36.529	-7.26	12/29/10	02/26/10
02/26/10	95.92	-2.2	10/18/10	94.41	-3.71	12/15/10	90.46	-7.66	12/29/10	02/26/10
02/26/10	71.81	-1.21	10/18/10	68.14	-4.88	12/15/10	66.47	-6.55	12/29/10	02/26/10
02/26/10	43.505	-11.73	10/18/10	30.92	-24.315	12/15/10	14.545	-40.69	12/29/10	02/26/10
02/26/10	43.33	-12.535	10/18/10	29.71	-26.155	12/15/10	12.56	-43.305	12/29/10	02/26/10
02/26/10	44.836	-10.344	10/18/10	32.805	-22.375	12/15/10	18.48	-36.7	12/29/10	02/26/10
02/26/10	57.08	-3.08	10/18/10	49.29	-10.87	12/15/10	47.25	-12.91	12/29/10	02/26/10
02/26/10	26.06	-0.63	10/18/10	26.22	-0.47	12/15/10	23.25	-3.44	12/29/10	02/26/10
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
02/26/10	88.18	-5.06	10/18/10	NA	NA	12/15/10	78.12	-15.12	12/29/10	02/26/10
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
02/26/10	56.03	-11.02	10/18/10	40.12	-26.93	12/15/10	NA	NA	12/29/10	02/26/10
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 4: continued

Waterlevel_3	Difference_3	EventDate_4	Waterlevel_4	Difference_4	EventDate_5	Waterlevel_5	Difference_5	EventDate_6	Waterlevel_6	Difference_6
NA	NA	10/18/10	NA	NA	12/15/10	NA	NA	12/29/10	NA	NA
NA	NA	10/18/10	NA	NA	12/15/10	NA	NA	12/29/10	NA	NA
40.41	-3.379	10/18/10	37.529	-6.26	12/15/10	36.529	-7.26	12/29/10	36.43	-7.359
95.92	-2.2	10/18/10	94.41	-3.71	12/15/10	90.46	-7.66	12/29/10	89.83	-8.29
71.81	-1.21	10/18/10	68.14	-4.88	12/15/10	66.47	-6.55	12/29/10	66.21	-6.81
43.505	-11.73	10/18/10	30.92	-24.315	12/15/10	14.545	-40.69	12/29/10	15.9	-39.335
43.33	-12.535	10/18/10	29.71	-26.155	12/15/10	12.56	-43.305	12/29/10	14.26	-41.605
44.836	-10.344	10/18/10	32.805	-22.375	12/15/10	18.48	-36.7	12/29/10	19.69	-35.49
57.08	-3.08	10/18/10	49.29	-10.87	12/15/10	47.25	-12.91	12/29/10	46.47	-13.69
26.06	-0.63	10/18/10	26.22	-0.47	12/15/10	23.25	-3.44	12/29/10	22.8	-3.89
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
88.18	-5.06	10/18/10	NA	NA	12/15/10	78.12	-15.12	12/29/10	77.97	-15.27
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
56.03	-11.02	10/18/10	40.12	-26.93	12/15/10	NA	NA	12/29/10	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 4: continued

EventDate_7	Waterlevel_7	Non-eventDa	NDWaterlevel_7	Difference_7	EventDate_8	Waterlevel_8	Difference_8	EventDate_9	Waterlevel_9	Difference_9
1/23/85	39.52	2/9/85	39.52	0	6/6/85	38.09	-1.43	12/28/85	42.72	3.2
1/23/85	39.49	2/9/85	39.49	0	6/6/85	38.04	-1.45	12/28/85	42.8	3.31
1/23/85	36.86	22/9/85	36.85	0.01	6/6/85	35.69	-1.16	12/28/85	38.72	1.87
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/23/85	46.9	2/9/85	59.26	-12.36	6/6/85	52.07	-7.19	12/28/85	54.36	-4.9
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/23/85	39.68	2/9/85	40.11	-0.43	6/6/85	37.65	-2.46	12/28/85	43.94	3.83
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/23/85	13.75	2/9/85	14.69	-0.94	6/6/85	11.01	-3.68	12/28/85	15.04	0.35
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/23/85	31.14	2/9/85	38.49	-7.35	6/6/85	27.68	-10.81	12/28/85	36.85	-1.64

Table 5: Overburden thickness data

REFNUM	EASTING	NORTHING	E	N	ELEV	TD	FASBLS	OBT
30	389648.2	3099864.4	389.6	3099.9	130.00	367.00	NA	NA
267	387123.1	3086900.0	387.1	3086.9	84.00	570.00	NA	NA
1448	389973.4	3083929.6	390.0	3083.9	57.00	820.00	-80	137
2158	377161.6	3104725.7	377.2	3104.7	55.00	111.00	NA	NA
2382	378293.7	3105674.4	378.3	3105.7	64.00	144.00	-15	79
2493	373379.9	3101527.2	373.4	3101.5	57.00	110.00	NA	NA
2677	370342.3	3087622.7	370.3	3087.6	37.00	443.00	-70	107
3113	362960.7	3082841.2	363.0	3082.8	7.00	45.00	-45	52
3970	364251.3	3100279.0	364.3	3100.3	42.00	465.00	NA	NA
4181	360214.5	3110113.6	360.2	3110.1	63.00	285.00	NA	NA
4614	363571.8	3102964.6	363.6	3103.0	80.00	510.00	NA	NA
4802	369562.2	3081825.0	369.6	3081.8	49.00	0.00	NA	NA
4802	369352.1	3082032.0	369.4	3082.0	49.00	337.00	NA	NA
5099	378661.2	3099139.6	378.7	3099.1	126.00	700.00	NA	NA
7032	387916.5	3116161.7	387.9	3116.2	84.00	20.00	-20	104
7032	387916.8	3116161.7	387.9	3116.2	84.00	400.00	NA	NA
7572	362936.0	3083118.8	362.9	3083.1	16.00	1075.00	NA	NA
9022	384275.4	3080771.7	384.3	3080.8	109.00	740.00	NA	NA
9029	383768.4	3084931.5	383.8	3084.9	78.00	482.00	NA	NA
9039	380692.1	3083576.5	380.7	3083.6	64.00	480.00	NA	NA
9043	392056.0	3085131.4	392.1	3085.1	83.00	560.00	NA	NA
10253	399338.3	3098178.1	399.3	3098.2	135.00	1842.00	NA	NA
10577	395403.7	3093163.6	395.4	3093.2	111.00	650.00	-80	191
10621	367638.8	3080450.1	367.6	3080.5	33.00	294.00	NA	NA
11337	368073.1	3100082.4	368.1	3100.1	29.00	307.00	NA	NA
11338	368094.9	3097096.6	368.1	3097.1	20.00	332.00	NA	NA
11531	373428.3	3089868.1	373.4	3089.9	40.00	160.00	-57	97
13100	375266.4	3085382.4	375.3	3085.4	52.00	70.00	-70	122
13491	387980.9	3093878.4	388.0	3093.9	155.00	49.00	NA	NA
13519	393130.1	3097040.2	393.1	3097.0	38.00	250.00	NA	NA
13637	388664.8	3104600.9	388.7	3104.6	142.00	20.00	NA	NA
13717	385726.9	3087610.6	385.7	3087.6	104.00	68.00	-50	154
13838	371179.2	3109600.6	371.2	3109.6	72.00	1000.00	-96	168
13944	380836.9	3098133.5	380.8	3098.1	32.00	35.00	-35	67
14016	379650.8	3111493.5	379.7	3111.5	132.00	150.00	NA	NA
14168	374323.8	3094964.6	374.3	3095.0	53.00	50.00	-50	103
14663	365231.3	3092609.9	365.2	3092.6	119.00	760.00	-250	369
14668	367943.1	3104161.2	367.9	3104.2	14.00	22.00	-22	36
14883	377814.4	3107150.6	377.8	3107.2	128.00	635.00	-166	294

Table 5: continued

REFNUM	EASTING	NORTHING	E	N	ELEV	TD	FASBLS	OBT
15280	382492.3	3102966.8	382.5	3103.0	23.00	220.00	-220	243
15321	380521.3	3094500.0	380.5	3094.5	90.00	305.00	-120	210
15328	395842.1	3100042.3	395.8	3100.0	80.00	648.00	NA	NA
15342	377310.1	3100808.3	377.3	3100.8	143.00	680.00	-115	258
15347	379268.5	3099779.9	379.3	3099.8	130.00	1998.00	NA	NA
15378	379631.5	3089627.2	379.6	3089.6	63.00	715.00	NA	NA
15379	386202.5	3090786.3	386.2	3090.8	90.00	820.00	-110	200
15938	380336.2	3081611.5	380.3	3081.6	82.00	444.00	NA	NA
16575	381044.5	3096949.3	381.0	3096.9	21.00	115.00	-115	136
16576	387053.1	3094010.2	387.1	3094.0	113.00	850.00	-90	203
16618	360152.1	3100363.3	360.2	3100.4	10.00	119.00	-119	129
50006	364764.8	3087653.5	364.8	3087.7	50.00	620.00	NA	NA
50142	367421.4	3115202.1	367.4	3115.2	187.00	1167.00	NA	NA
50148	371592.7	3112416.2	371.6	3112.4	50.00	9.00	-9	59
50149	364643.0	3103318.1	364.6	3103.3	40.00	0.00	NA	NA
51898	390203.5	3104598.6	390.2	3104.6	95.00	0.00	NA	NA

Table 6: January 2010 reported sinkholes

Reference Number	Easting	Northing
10-1000	382888	3099826
10-1001	382888	3099826
10-1002	386929	3102870
10-1003	385251	3093141
10-1004	356498	3063265
10-1005	384186	3099647
10-1006	384692	3095436
10-1007	384692	3095436
10-1008	384692	3095436
10-1009	378503	3097883
10-1010	373912	3072015
10-1011	373926	3072012
10-1012	390569	3090975
10-1013	390569	3090975
10-1014	377412	3092597
10-1015	386534	3107187
10-1016	384755	3095572
10-1017	384732	3095551
10-1018	362230	3104326

Table 6: continued

Reference Number	Easting	Northing
10-1019	363192	3109445
10-1020	385450	3094094
10-1021	386582	3094078
10-1022	387680	3094069
10-1023	387527	3094073
10-1024	387309	3093128
10-1025	383242	3094116
10-1026	383270	3095685
10-1027	382886	3096872
10-1028	383282	3096120
10-1029	383295	3099329
10-1030	385751	3098630
10-1031	385739	3098608
10-1032	385140	3098745
10-1033	386575	3094071
10-1034	385764	3095188
10-1035	385347	3102270
10-1036	386158	3093902
10-1037	388466	3100836
10-1038	385911	3094636
10-1039	385579	3099618
10-1040	387058	3095529
10-1041	385950	3095272
10-1042	385593	3094541
10-1043	385560	3094589
10-1044	386965	3099910
10-1045	386972	3094075
10-1046	388135	3096661
10-1047	388446	3098119
10-1048	384885	3095427
10-1049	385639	3095310
10-1050	388458	3099733
10-1051	383282	3095961
10-1052	383256	3095771
10-1053	385430	3094087
10-1054	385017	3100534
10-1055	379708	3098167
10-1056	379252	3097311
10-1057	388072	3094019

Table 6: continued

Reference Number	Easting	Northing
10-1058	388596	3096935
10-1059	390958	3099490
10-1060	375770	3095363
10-1061	385971	3093804
10-1062	350348	3107216
10-1063	387965	3099185
10-1064	353368	3109922
10-1065	362330	3104995
10-1066	351708	3101893
10-1067	382046	3071891
10-1068	382913	3072990
10-911	379973	3094386
10-912	382885	3096876
10-913	383271	3095716
10-914	382193	3100597
10-915	382203	3100662
10-916	387921	3093893
10-917	385497	3099655
10-918	384121	3101751
10-919	386555	3102326
10-920	381680	3098484
10-921	386872	3094268
10-922	386248	3093886
10-923	382906	3100123
10-924	385249	3100455
10-925	387023	3100720
10-926	377629	3096608
10-927	385834	3100970
10-928	362064	3090206
10-929	383295	3099742
10-930	385372	3100985
10-931	382873	3096788
10-932	384456	3096729
10-933	382883	3096844
10-934	380142	3094078
10-935	380142	3094078
10-936	380142	3094078
10-937	380142	3094078
10-938	383964	3096730

Table 6: continued

Reference Number	Easting	Northing
10-939	384456	3096729
10-940	388530	3096956
10-941	386576	3093107
10-942	386381	3093264
10-943	386267	3093764
10-944	387608	3094062
10-945	383372	3096529
10-946	383394	3098700
10-947	385083	3098562
10-948	388569	3096922
10-949	380458	3095283
10-950	385056	3094706
10-951	383391	3095465
10-952	386644	3089949
10-953	383846	3100756
10-954	385983	3103240
10-955	377629	3096597
10-956	377573	3096010
10-957	376507	3096464
10-958	380001	3094778
10-959	380001	3094778
10-960	380035	3094312
10-961	380082	3094046
10-962	380092	3094035
10-963	380111	3094034
10-964	384407	3096941
10-965	388550	3096967
10-966	388569	3096989
10-967	388578	3096922
10-968	385654	3099620
10-969	385585	3099632
10-970	385634	3099620
10-971	384638	3095209
10-972	391320	3105340
10-973	384820	3093656
10-974	379815	3094924
10-975	379998	3094838
10-976	384348	3098474
10-977	379993	3094486

Table 6: continued

Reference Number	Easting	Northing
10-978	385955	3101506
10-979	385955	3101506
10-980	385955	3101506
10-981	384405	3098511
10-982	379882	3094533
10-983	386455	3102453
10-984	385238	3093662
10-985	384113	3098717
10-986	383313	3099357
10-987	383313	3099357
10-988	379040	3096462
10-989	385206	3093360
10-990	382550	3099842
10-991	382550	3099842
10-992	382888	3099826
10-993	383566	3095626
10-994	383280	3095675
10-995	386452	3093726
10-996	393711	3094846
10-997	359345	3094452
10-998	353926	3097335
10-999	382888	3099826
16-851	442299	3069669
16-852	442279	3079927
16-853	464881	3074490
16-854	442013	3081944
16-855	442370	3080447
16-856	444360	3069870
16-857	448211	3069465
16-858	437602	3112967
16-859	434161	3121326

Table 7: January 1985 reported sinkholes

Reference Number	Easting	Northing
10-584	382877	3100083
10-585	382957	3099866
10-586	382957	3099866
10-587	382655	3099777

Table 7: continued

Reference Number	Easting	Northing
10-588	382656	3099869
10-589	382711	3099838
10-590	382738	3099838
10-591	382765	3099807
10-592	382820	3099806
10-593	382792	3099776
10-594	382847	3099775
10-595	382655	3099715
10-596	382902	3099836
10-597	382984	3099897
10-598	387954	3093971
10-599	377633	3095798
10-600	377919	3095946
10-601	378189	3095636
10-602	377973	3095946
10-603	378054	3096200
10-604	382957	3099897
10-605	382877	3100083
10-606	382877	3100083
10-607	388471	3102491
10-608	387632	3103330
10-609	389357	3094943
10-610	382504	3099226
10-611	386892	3094350
10-613	355547	3103336
10-628	388471	3102491
16-540	428697	3094553

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