# SINKHOLE FORMATION AT LAKE GRADY, FLORIDA

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## ABSTRACT

Lake Grady was created by the damming of Bell Creek in 1969. In March 2000, water quality at residential drinking wells east of Lake Grady, near Riverview Florida, began to decline. Approximately 200 residential wells in the area were contaminated with coliform bacteria. The cause of the contamination was a sinkhole that was activated beneath Lake Grady approximately 200 feet from its southeast corner. Analysis of the hydrologic and hydrogeologic conditions during 1999-2001 shows that conditions were favorable for sinkhole development. Prolonged drought, early spring rainfall, and an abnormally low potentiometric surface combined to create a condition favorable for loading and flushing sinkholes beneath the lake.

## PURPOSE

Past investigations (Cardinale, 2000) determined sinkholes were the cause of well contamination in Lake Grady. None of these investigations, however, sought to determine the cause of the sinkholes. In 2000, Ann Tihansky, Dan Yobbi and Arturo Torres of the USGS proposed an investigation that would employ geophysical methods as well as other methods described in this paper to obtain a cause for the Lake Grady sinkholes (Tihansky, 2000). Unfortunately, the proposal was not funded, and the investigation never took place. In this paper we will develop a theory for the cause of the sinkholes by review and analysis of existing literature. We will summarize the investigation of the well contamination associated with the formation of the sinkholes; compile the findings of relevant investigations by several government agencies and consulting firms; characterize the area's surface-water hydrology and groundwater hydrogeology; and propose a theory for sinkhole formation in Lake Grady based on the study area's hydrologic and hydrogeologic conditions.

## HISTORY OF LAKE GRADY

Lake Grady is a 184-acre man-made lake that was created in 1969 by the impoundment of Bell Creek with an earthen and concrete dam (Figure 1). The original Lake Grady impoundment structure was constructed under a Southwest Florida Water Management District (SWFWMD) General Works of the District (W.O.D.) Permit. The purpose of the structure was to create a lake for use by residents

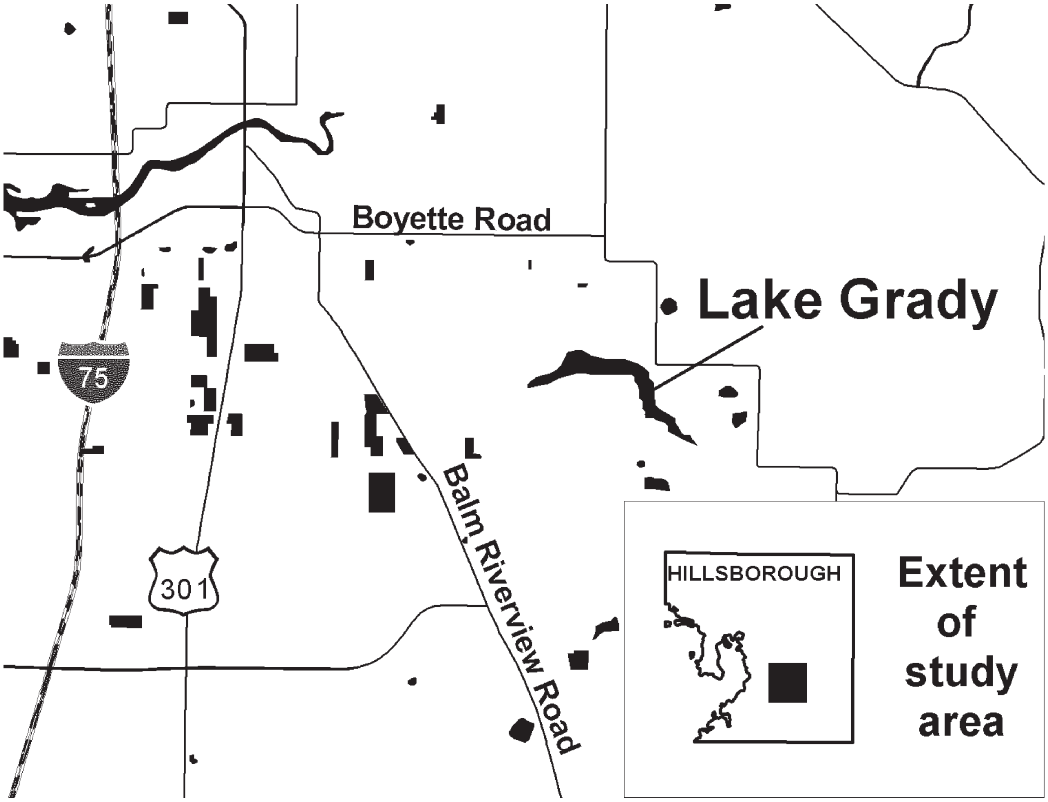


**Figure 1:** Reference map of study area.

of the nearby Shadow Run Subdivision for recreation and irrigation purposes.

In 1982, Shadow Run Boulevard was constructed along the embankment of the dam. In 1983, an engineering inspection of the dam by the SWFWMD revealed severe erosion and structural problems that led to the structure's being deemed unsafe. As a result, the sluice gate built into the structure was opened to drain the lake. In 1985, an attempt was made to rehabilitate the structure. The sluice gate was closed and the lake was again allowed to fill.

By 1987, the dam was again exhibiting severe damage caused by lateral seepage and erosion. Again the sluice gate was opened to drain the lake. The dam was essentially abandoned for a period of about 11 years.

An Environmental Resource Permit was issued by SWFWMD in 1997 to completely reconstruct the dam. The new design includes weir-crest elevations that are 1.5 ft. lower than the original structure, and the addition of a "slurry wall" under Shadow Run Boulevard to control lateral seepage through the dam. The new structure was designed to have twice the original flow capacity under Shadow Run Boulevard. The intention was to decrease the frequency and severity of floodwaters overtopping the roadway (BCI, 1997). The construction on the new structure was complete in 1999, and, on November 4, 1999, the sluice gate was closed. The lake was again allowed to fill.

## WELL CONTAMINATION

During March 2000 environmental agencies such as the Hillsborough County Health Department (HCHD), the Hillsborough County

Environmental Protection Commission (HCEPC) and the SWFWMD, which later became known as the "Lake Grady Task Force", received sporadic reports of changes in the quality of water in a neighborhood near Lake Grady (Gregos, 2000). The reported changes in water quality consisted principally of color and turbidity. The complaints led to an investigation of Lake Grady and possible sinkhole formation within the lake.

The HCHD began a study of the area to determine the extent of the water-quality problems possibly due to the entry of surface water into the drinking-water aquifer. They collected illness surveys, which included illness data on a household-by-household basis and analyzed epidemiological aspects. They also collected water quality data along with any known well construction data. Eventually, the HCHD completed a case control study to correlate the environmental sampling data and illness data to determine whether reported illnesses were likely due to the water-quality problems or were occurring at background levels (Gregos, 2000). The finding was that 76% of the residential wells were positive for total and fecal coliform. In fact, 43% of the contaminated wells tested positive for fecal coliform and the other 57% were positive for total coliform but not fecal coliform (Gregos, 2000).

The land use around Lake Grady is residential, commercial, and agricultural. When the original contamination occurred, the sources of the fecal contamination were thought to be septic tanks, cattle, and a nearby orange grove that served as a treated effluent land spread site. Investigation of the water quality of the lake, however, indicated that the coliform count was similar to background counts for nearby water bodies (Gregos, 2000).

## DYE TRACE STUDY

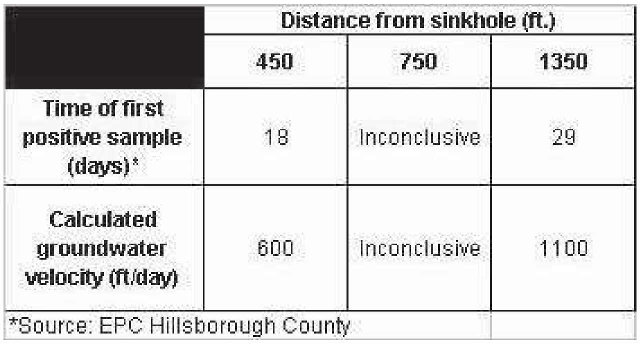
The task force determined that a dye trace study be conducted to determine if the sinkhole located nearby was indeed the source of the well contamination problems. HCEPC suggested the use of tracer dye and solicited the HCHD for monitor wells that met three criteria. The criteria desired for the monitoring wells included: 1) the wells should have a high bacterial count, 2) wells should be shallow, and 3) wells should be as close to the sinkhole as possible. Three wells were chosen according to this process, and the HCEPC proceeded with the dye test.

The distances between the wells and the sinkhole were 450 ft., 750 ft., and 1350 ft. The HCEPC asked each resident to take water samples about every three to four hours after placing dye in the sinkhole (Cardinale, 2000). The dye trace study began on Friday, August 11, 2000, and concluded when the sample bottles were picked up from the property owners on April 14, 2000 (Cardinale, 2000). The dye could not be readily viewed with the naked eye so arrangements were made with City of Tampa Bay Study Group to use their fluorometer to measure the dye concentration from the samples.

We have summarized the results of the dye test in Table 1. Two out of the three wells tested positive for the dye. The flow velocities calculated from this test, helped to validate the water quality data showing positive detections for bacteria. Given the results of both the water-quality investigation and the dye-trace test, it was deemed likely that the groundwater system was being influenced by surface water.

The use of the dye-trace test helped the task force decide to plug the sinkhole. The Hillsborough County Public Works Division led the plugging effort. An earthen dike was built

**Table 1:** Dye Trace groundwater velocity results.



| | Distance from sinkhole (ft.) | | |
|---|---|---|---|
| | 450 | 750 | 1350 |
| Time of first positive sample (days)* | 18 | Inconclusive | 29 |
| Calculated groundwater velocity (ft/day) | 600 | Inconclusive | 1100 |

*Source: EPC Hillsborough County

around the sinkhole in order to keep surface water from entering the sinkhole area. The initial phase of plugging consisted of moving filter sand via high-pressure water in hopes of filling voids at the bottom of the sink. The sink was filled to two feet above the normal water level of the lake (Cardinale, 2000). Overall, about 5000 yd$^3$ (120 truck loads) were used. The total cost incurred by the county totaled approximately $105,000 in labor and materials and another $12,300 in consultant fees.

## SINKHOLE LOCATION AND IDENTIFICATION

Our report, like many of the past investigations, concentrates on the sinkhole that opened in March 2000. This sinkhole is known as Sinkhole #2 in the literature. As the name suggests, it was not the only sinkhole to form within the lake (Fig. 2). A similar but less-documented incident occurred in April 1974, when a sinkhole (Sinkhole #1) opened and wells were contaminated. A third sinkhole (Sinkhole #3) formed within the lake in May 2001. This sinkhole was smaller and did not penetrate the underlying aquifer. Sinkhole #2 is located in Section 36, T30S, and R20E and is located approximately 400 - 500 feet to the ENE of Sinkhole #1 (Cardinale, 2000).

## HYDROGEOLOGIC FACTORS

Lake Grady is located just south of the Brandon Karst Terrain, an internally drained karst escarpment in central Hillsborough (Jones and Upchurch, 1994; PBQD, 1997). Lake Grady in particular is located in a region where cover-collapse sinkholes are common. Overburden sediments that contain clay cause these types of sinkholes (Tihansky, 1999) "The greater cohesion of the clay postpones failure, and the ultimate collapse tends to occur more abruptly" (Tihansky, 1999 p. 125). Cavities and voids covered by clayey sediment can exist concealed for long periods of time. It seems to take a "trigger event" to create the conditions necessary for the clay bridge to yield and sediments to ravel into the subsurface cavity. When this occurs, the cavity breaches the land surface. The trigger can involve a combination of factors including: changes in surface loading, excessive rainfall or drought, seasonal changes in groundwater levels, and aggressive pumping of the underlying aquifer system. More new sinkholes form during periods when groundwater levels are low than during any other time of the year (Tihansky, 1999).

**Figure 2:** Location of sinkholes in Lake Grady.

We estimate that the study area contains approximately 120 ft of clayey overburden sediments above the Floridan aquifer. The hydrogeology of Lake Grady differs from the general area, however, because of down-cutting by Bell Creek such that only 60 to 89 ft of the overburden remains (Stewart, 1984). Cavities exist underneath these sediments. During construction of test holes near the lake, vertical cavities of 1 - 5 ft were found in the surficial materials at depths of 28 - 42 feet (Stewart, 1984).

In 2002, the SWFWMD identified photolinears throughout the study area. The photolinears included closed depressions, internally drained basins, and several springs. This study placed a photolinear composed of a series of surface-closed depressions (including Sinkholes 1-3 in Lake Grady) through the southeastern section of the lake (Fig. 3).

## BELL CREEK HYDROLOGY

Bell Creek, a tributary to the Alafia River, flows from south to north and drains an area of approximately 12,600 ac at its confluence with the Alafia River (Fig. 4). Boggy Creek and Pelleham Creek are the two main tributaries to Bell Creek. Boggy Creek flows into Bell Creek upstream of Lake Grady, while Pelham Creek flows directly into the western lobe of the Lake.

The average bed slope of Bell Creek upstream of Lake Grady is over 19 ft/mi (0.0036 ft/ft), falling from an elevation of approximately 100.2 ft (relative to NGVD 1929) at its headwaters to elevation 27.7 ft at Lake Grady, 3.8 mi downstream (Parsons, 2002). Below the Lake Grady dam structure, Bell Creek flows approximately two more miles to its confluence with the Alafia River, where it has a bottom elevation of approximately –3.5 ft.

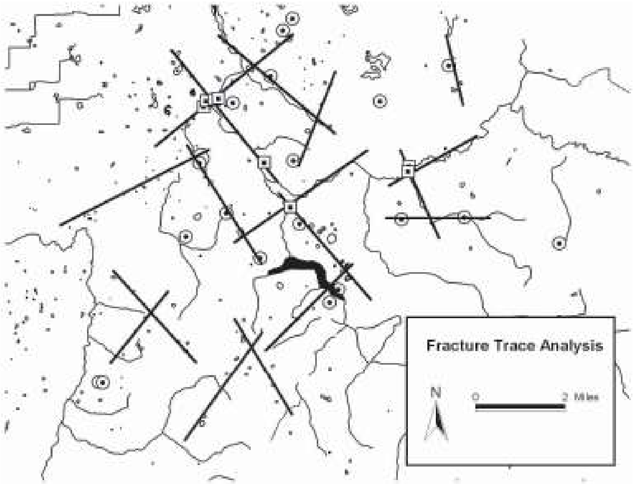


**Figure 3:** Fracture trace analysis (SWFWMD, 2002). Squares denote locations of springs. Circles denote location of sinkholes. Lines denote photolinears.

A well-defined network of surface streams drains the Bell Creek Watershed. Based on 40 years of stream-gage records from the adjacent Bullfrog Creek Watershed, Morrison (2000, p.3) estimated the annual surface-water runoff to be 19 in./yr. This represents about 42% of the average annual precipitation (44.8 in.) at the National Weather Service office in Ruskin, FL.

In addition to the surface-water streams, karst drainage features including sinkholes, underground limestone conduits and/or solution fractures may provide a flow path to drain the watershed. The direct interconnectivity of the surface and groundwater streams is evidenced by data collected by the SWFWMD from Bell Creek Spring (known locally as Boyette Spring). The spring rises approximately one mile downstream of the Lake Grady Dam within the bed of Bell Creek near the Boyette Road Bridge. Bell Creek Spring has an average discharge of approximately 22 gpm or 0.05 cfs, and it exhibits a rapid response to recharge from rainfall events

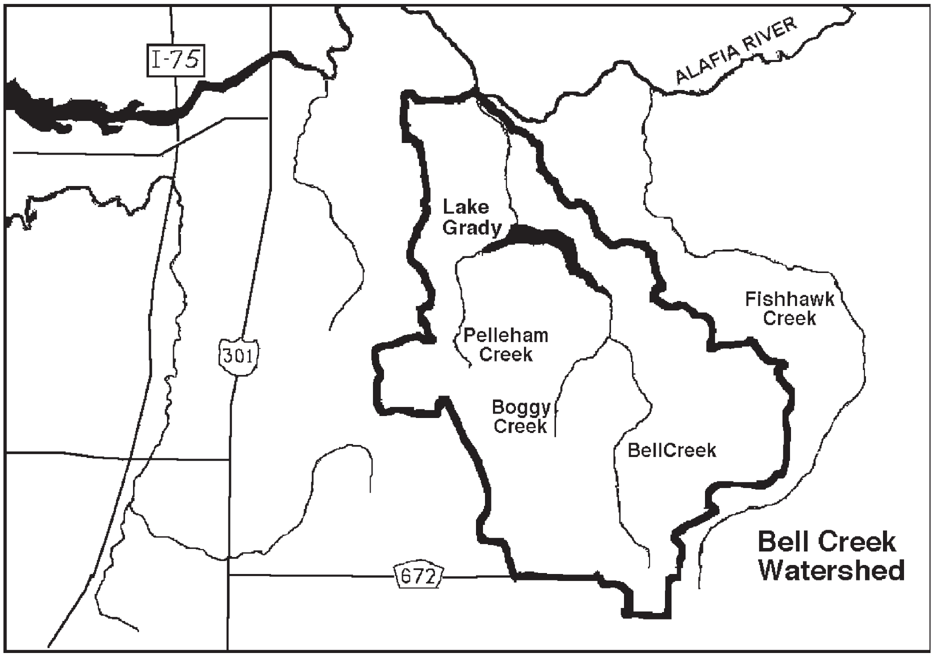


**Figure 4 :** Bell Creek Watershed (modified from Parsons, 2002).

(Morrison, 2000). In addition, the relatively low average pH value of 6.59 (Morrison, 2000) indicates that the water discharging from the spring has not had enough time to reach equilibrium with the carbonate bedrock.

Closed depressions and internally drained basins also indicate potential direct interconnections of surface-water and groundwater. Approximately 2-3% of the Bell Creek Watershed is drained internally, i.e., the land drains to closed depressions that have no defined surface outfall. Within West-Central Florida, these closed depressions are widely known to be the result of land subsidence consistent with karst terrain. Karst landforms such as sinkholes can provide a direct pathway for conveying surface waters into the underlying aquifers. Using Arcview mapping software, we delineated the locations of closed depressions and their contributing sub-basins within the vicinity of Lake Grady, as illustrated in Figure 5.

## LAKE GRADY WATER LEVELS

Prior to 1969, and in the intervening periods of 1983-1985 and 1988-1999, the surface water levels in Bell Creek were “uncontrolled”. Water depths within the creek were determined primarily by the rate of flow, the natural channel cross section, and the natural channel roughness.

From 1969 to 1983, the dam controlled the normal water level of the lake at an elevation of 38 ft. The rehabilitated 1985 structure included a small 4-ft-wide seasonal drawdown notch at an elevation of 37 ft, with an overflow weir crest at 38 ft. The current (1999) structure has a 4-ft-wide seasonal-drawdown notch at elevation 35.5 ft, with a 204-ft-wide overflow weir crest at 36.5 ft (BCI, 1997). The elevation of the seasonal-drawdown notch can be considered the “normal” or dry-season water level, and the elevation of the crest of the overflow weir can be considered the “seasonal high” or wet-season water level. It is important to note that these are “design” el-

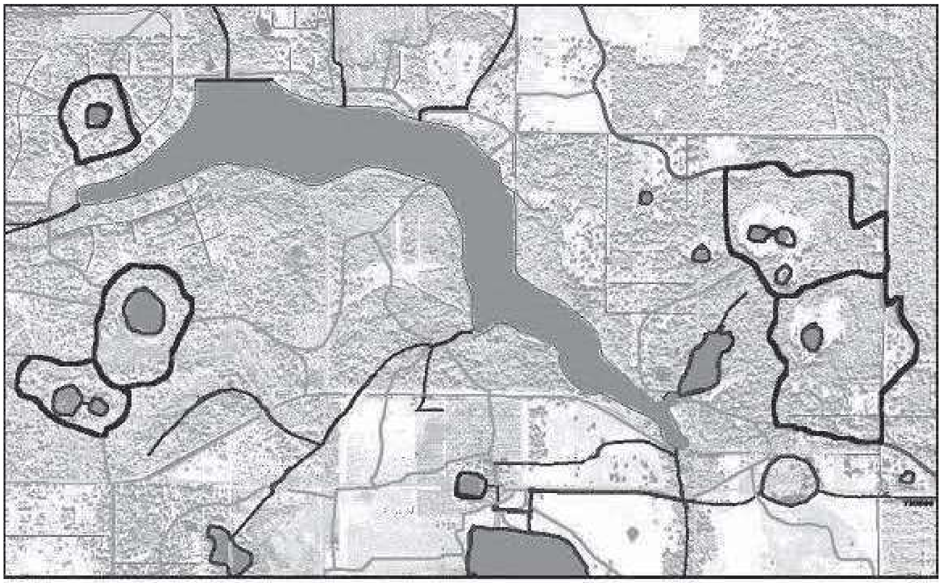


**Figure 5:** Internally drained closed basins within the vicinity of Lake Grady. Bold lines denote closed basins.

evations, and that lake levels can be expected to drop below the normal water level occasionally (i.e., in a drought), Also, the seasonal high-water level will be frequently exceeded during the rainy season. Each of the three incarnations of the structure included a sluice gate that could be manually opened in order to drain the lake for maintenance purposes or for emergencies.

We provide a graphical comparison between the uncontrolled fluctuations of the "pre-structure" system and the design lake elevations of the current structure in Figure 6. The recorded hydrograph is from a stage recorder located on Lake Grady, immediately upstream of the dam structure. The stage and precipitation data were recorded in 15-minute intervals over a 5-mo. period by Hydrogage, Inc., as part of the data-collection effort for the Alafia River Watershed Management Plan commissioned by Hillsborough County (Parsons, 2002).

The left side of the graph shows the response of Bell Creek to a series of small rainfall events occurring in August, September, and October 1999. Based on this hydrograph, we estimate the normal water level (NWL) of Lake Grady prior to closure of the sluice gate to be 27.1 ft, and the seasonal high-water level (SHWL) to be approximately 29.5 ft. Although the rainfall amounts over the next nine weeks following closure of the sluice gate in November 1999 added up to less than 3.2 in., the response of the lake stage was a pronounced continuous upward trend corresponding to rapid filling of the lake. This would indicate a significant baseflow contribution to either the lake or to the stream network, or both. Unfortunately, the gaging station was discontinued on January 11, 2000. Nevertheless, we can use the current design NWL and SHWL of 35.5 ft and 36.5 ft, respectively (dashed in Fig. 5), to compare with the pre-structure levels. Based on a unit-weight of water equal to 62.4 lb/ft$^{3,}$ we calculate that the 8.4-ft. increase in normal water level due to the filling of Lake Grady would correspond to a hydrostatic pressure increase of approximately 3.5 psi on the lakebed.

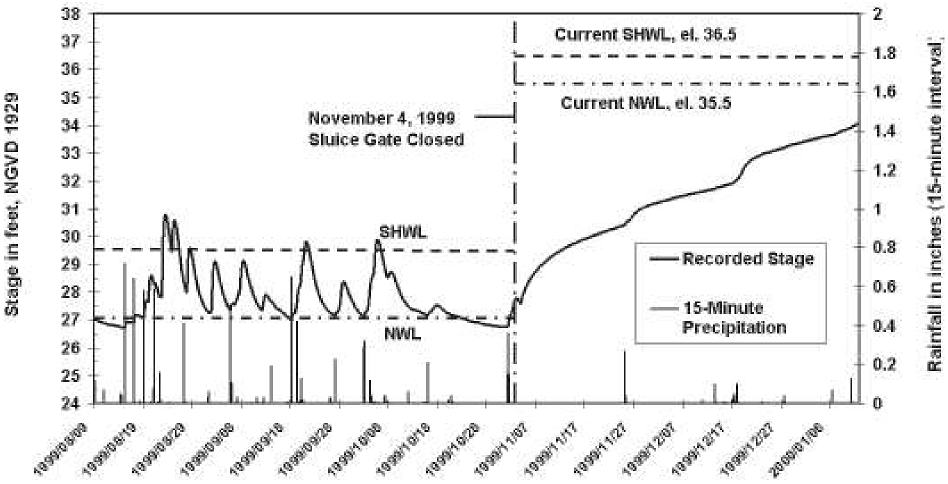


**Figure 6:** Lake Grady stage elevations and precipitation data.

## GROUNDWATER LEVELS

Increased groundwater withdrawals especially during times of seasonally low groundwater levels can induce the formation of sinkholes. "Aggressive pumping can induce sinkholes by abruptly changing groundwater levels and disturbing the equilibrium between a buried cavity and the overlying earth materials" (Newton, 1986 p. 54).

The drought of 2000 prompted an increase in groundwater withdrawals in the area from a nearby county well field approximately 4 mi east of Lake Grady and from agricultural irrigation south of Lake Grady. The potentiometric surface of the Floridan aquifer was approximately 5 ft below NAVD during the spring of 2000. Groundwater levels at monitor wells associated with the South Central Hillsborough wellfield showed Floridan aquifer levels 5–7 ft below NGVD during the spring months of 2000. The configuration of the potentiometric surface during the spring of 2000 includes a significant depression associated with this rather large area of agricultural irrigation (Fig.7). The wellfield is associated with a more localized depression away from Lake Grady.

Groundwater levels in and around the study area were at historical lows in March 2000. We use the records from SCHM 7, which is 4 mi east of Lake Grady, to estimate the potentiometric surfaces of the Intermediate Aquifer System (IAS) and Floridan Aquifer System (FAS) at the Lake. As shown in Figure 8, the water levels in the aquifers drop below the lake bottom during the dry season regularly, but, during the drought of 2000, the difference was particularly large. Figure 8 also shows that during the wet seasons the level of the IAS was above the bottom lake, meaning that there was baseflow into the lake, and this would explain why the lake filled during the drought.

From comparison of the elevations of the lake bottom and the potentiometric surface of the FAS, we conclude that the difference between the two at the time of formation of Sinkholes #2 and #3 was approximately 30-35 ft.

## THEORY OF CAUSATION

Tihansky (1999) cites several development practices that can cause sinkholes to form.

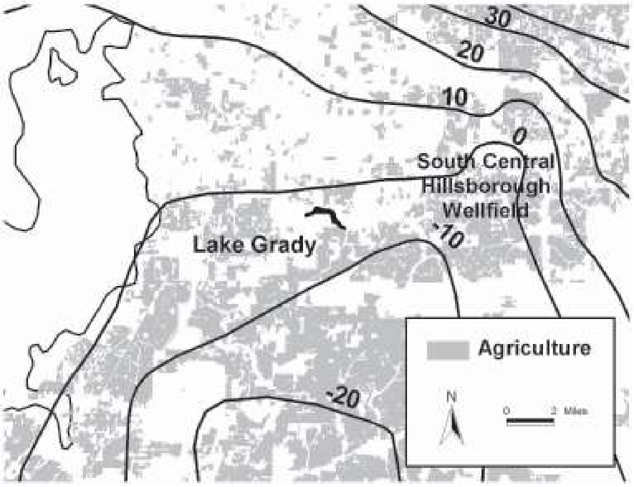


**Figure 7:** Potentiometric surface May 2000.

One of them is "manmade impoundments" of surface water that cause a "significant increase in the load bearing on the supporting geologic materials". We have attempted to use existing available data to quantify the increase in load bearing on the geologic materials underlying Sinkhole # 2, due to the filling of Lake Grady. Detailed local geotechnical evaluations are unavailable and beyond the scope of this investigation; therefore, our calculations are intended to provide only an order-of-magnitude estimate of the loadings.

Using a survey sketch of Sinkhole # 2 prepared by the Hillsborough County Survey Division, the surface area at the top of the sinkhole was measured by digital planimeter as 3,360 ft$^2$. From the survey, the average ground surface elevation adjacent to the sinkhole is approximately 34.0 ft. At this location, the lake is relatively shallow and the hydrostatic pressure on the ground surface would have fluctuated between 0.65 and 1.08 psi, as the NWL and SHWL of the newly filled lake rose 1.5 ft and 2.5 ft, respectively, above the ground surface prior to the collapse of the sinkhole. When applied over the entire area above the sinkhole, these pressure increases correspond to a total load that would have fluctuated between 157 tons and 262 tons as the lake levels rose and fell between the NWL and SHWL. However, this increase in water pressure at the ground surface would have been accompanied by a significant increase in the weight of the overburden sediments as they became saturated due to surface water inundation.

According to the Soil Survey of Hillsborough County (SCS, 1989), the soil type in the area of sinkhole # 2 is classified as Winder fine sand, frequently flooded. If we can assume that the overburden soils were at or near the wilting point prior to the filling of the lake, then the increase in soil weight can be calculated, on a unit depth basis, using typical wilting point and porosity values for fine sand. A common value for wilting point in fine sand is 10% moisture content by volume. Assuming an effective porosity of 35%, the volume of voids available for water storage, expressed as a percentage of total volume, is 35%-10%, or 25%.

It should be noted that the presence of a local water table would reduce the available water storage due to capillary effects. It is not clear, however, whether the estimated NWL and SHWL near the dam structure several hundred yards away would have translated into a local water table near the sinkhole. In fact, it is quite possible that the local system of conduits and/or caverns that preceded the sinkhole formation would have drained the excess water in the overburden soils down into the underlying intermediate and Floridan aquifers. As previously indicated, the levels in these aquifers were several feet lower than the lake bottom when the lake was filled. If, then, the 25% available water storage is a reasonable approximation, the increase in soil weight can be calculated as 0.25 x 62.4 pcf x 3,360 ft$^2$ = 52,416 lbs. or 26 tons of additional weight for each foot (depth) of overburden. However, from the available data it is not possible to determine the overburden depth over which

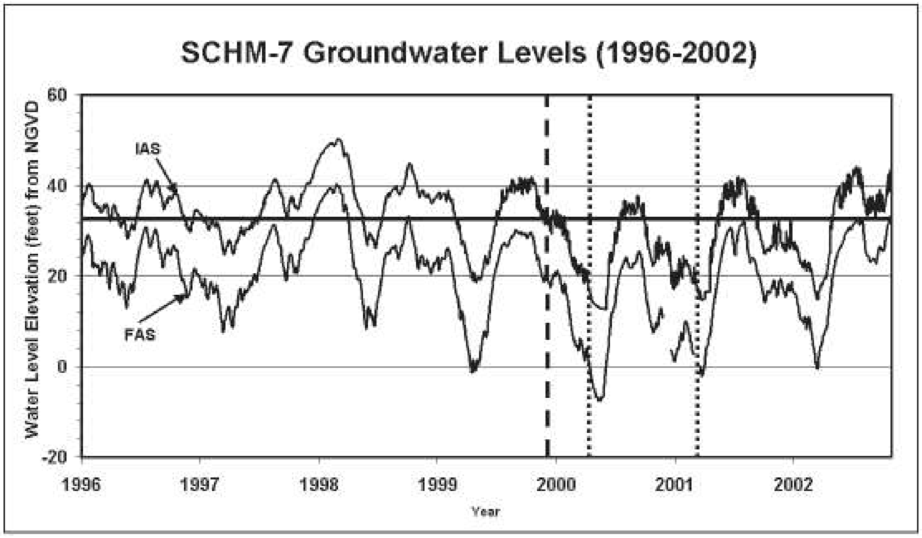


**Figure 8:** Groundwater levels in SCHM-7. FAS denotes potentiometric surface in Floridan Aquifer. IAS denotes Intermediate Aquifer water levels. Solid horizontal line denotes elevation of lake bottom at Sinkhole #2. First dashed vertical line denotes closure of sluice gate on November 4, 1999. Second and third lines denote development of Sinkhole #2 and #3, respectively.

this value would apply. Among other factors, the applicable depth would depend on the size, geometry, and crown elevation of any cavern that may have existed prior to the collapse.

It should also be noted that the timing of the lake level rise coincided with a sharp decline in the groundwater levels of the underlying aquifers. This head difference between the Floridan aquifer and the surficial sediments caused by the surface water load appears to have reached a critical level. We have estimated the difference at approximately 30-35 ft from the SCHM-7 groundwater-level data. As the difference is head increases, water from the surficial sediments moves downward and increases raveling of overburden sediments into cavities. Once the overburden bridge can no longer support the weight of the impounded water, the bridge collapses yielding a pathway for surface water to infiltrate directly into the Upper Floridan aquifer. This seems to have been the cause for the formation of sinkholes and the subsequent surface-water contamination of residential wells surrounding Lake Grady.

## CONCLUSIONS AND RECOMMENDATIONS

1) The sinkhole collapse was likely triggered by a combination of factors that resulted in historical low groundwater levels coinciding with a rapid rise in surface water levels. The combination of causes is: appropriate lithology; prolonged drought during the study period; historically low groundwater levels in the Floridan Aquifer system; early spring rainfall; contribution of baseflow to Bell Creek and Lake Grady; and the damming of a natural drainage system. The potential for sinkhole development may have existed prior to the damming of Lake Grady.

2) A more rigorous investigation of the local hydrology and hydrogeology could have provided the original design engineers and permitting agencies some clues regarding the karst terrain and the potential for sinkhole development stemming from the impoundment of Lake Grady. Future permitting for impoundments of natural drainage systems

within karst terrain should include a complete subsurface investigation in addition to the surface impact studies already done. Unfortunately, the lowering of the potentiometric surface of the Floridan Aquifer to create a head difference of this magnitude was not necessarily predictable in 1969.

3) Additional sinkhole development is likely as long as the lake control structure stays closed and the groundwater levels remain low.

This area is karst-prone and will most likely develop into a surface system that regularly drains surface water into the subsurface via sinkholes. These types of surface water/groundwater systems are common throughout Florida's active karst regions. Continued adverse effects on domestic wells will likely continue and may migrate away from the local area that have been affected so far, depending on the size of the next sinkhole and its location.

Future studies of this area should include a geophysical investigation of the formations under the lakebed such studies might reveal additional subsidence features, caverns or other voids that could develop into active sinkholes in the future. The surveys should be followed up with an engineering investigation to identify structural and management alternatives that could be implemented to reduce the risk of more sinkholes. The alternatives might include: draining the lake and stabilizing any additional karst features discovered during the geophysical investigations; reducing groundwater pumpage; lining the lakebed with clay to reduce downward seepage; and/or removing the structure. This engineering investigation would include evaluations of the effectiveness, capital costs, and environmental impacts associated with each of these alternatives.

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