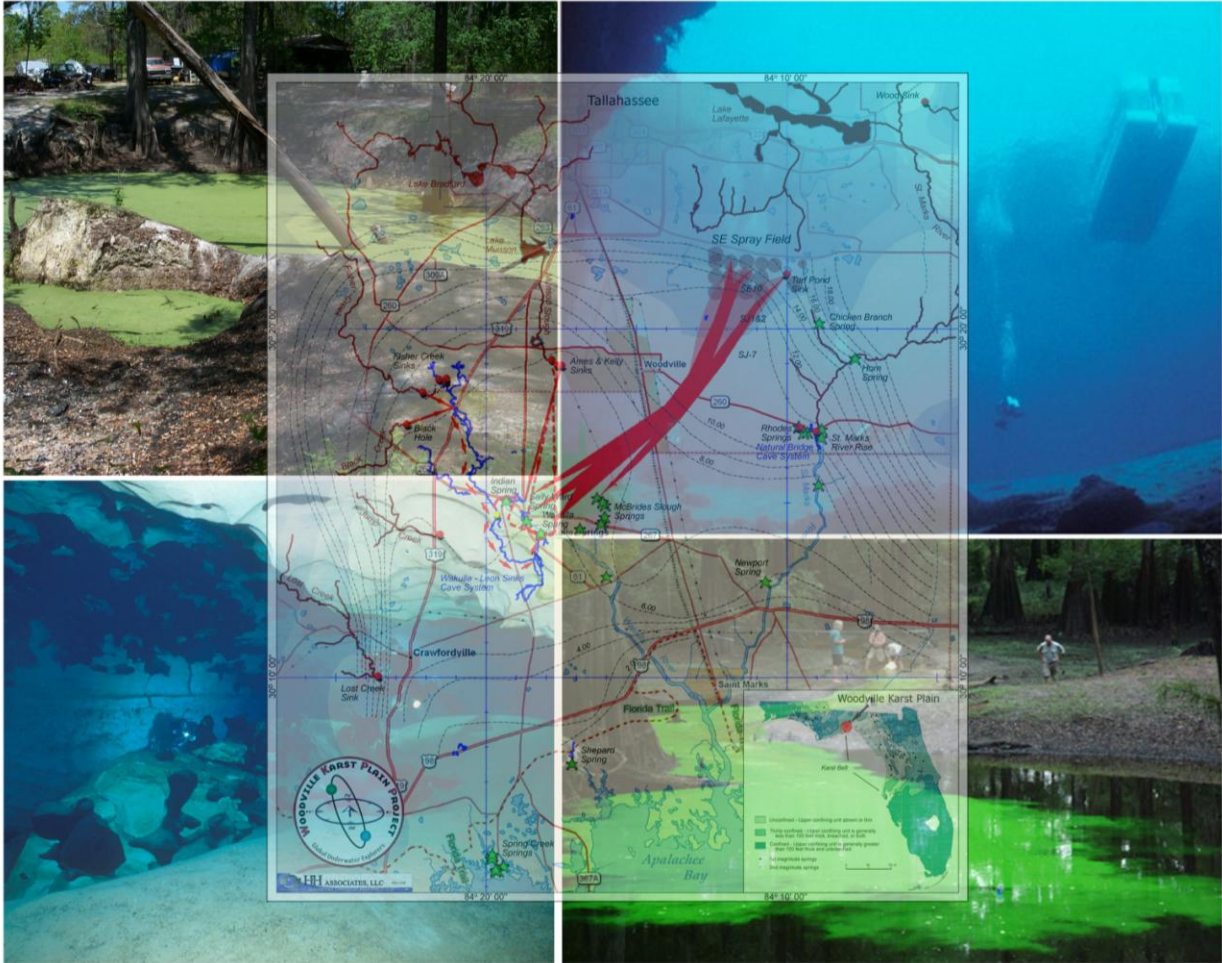


Karst Hydrogeology of the Woodville Karst Plain Florida

Field Guide for the 2008 ASCE Karst Conference Field Trip



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Date: Tuesday September 23, 2008 / 8:00 AM - 6:00 PM
 Depart: Ramada Conference Center / 2900 N. Monroe St. Tallahassee

Contributing Organizations



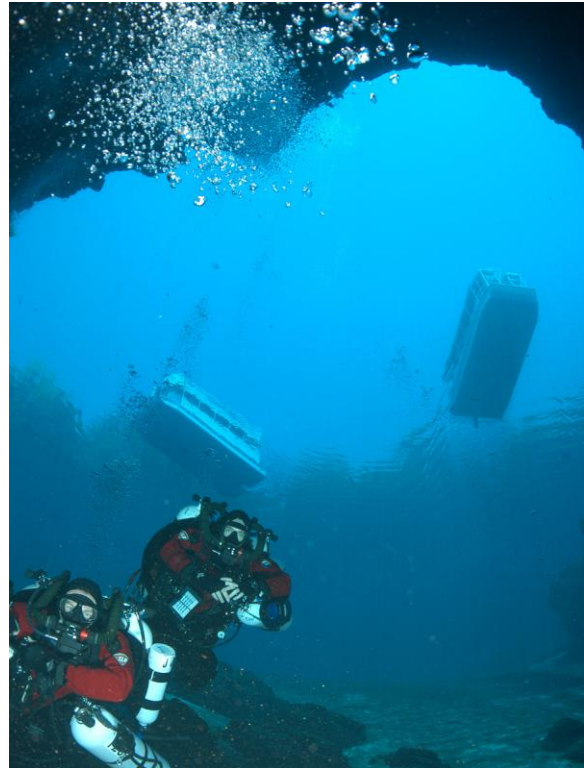
Overview

The Woodville Karst Plain (WKP) is a spectacular example of Florida karst where dissolution has created an expansive network of phreatic conduits that drain highly permeable limestones to some of the largest springs in Florida. Wakulla Spring, focal point of the Ed Ball Wakulla Springs State Park that is considered the Crown Jewel of the Florida State Parks System, is the second largest spring in the State and is the main discharge point for the world's fourth largest mapped underwater cave system - the Wakulla-Leon Sinks Cave System. Other large springs include: the Spring Creek group consisting of fourteen offshore vents south of Wakulla Spring in Apalachee Bay; the St. Marks River Rise, which is the discharge point for another expansive network of phreatic conduits draining the central part of the basin known as the Natural Bridge Cave System; and the Wacissa group consisting of sixteen individual vents that form the Wacissa River. Some believe that the WKP extends further to the east to include numerous more major springs along the Aucilla, Econfinia, Fenholloway, and Steinhatchee Rivers.

The Wakulla Spring basin is itself unique and spectacular due to its size, depth and discharge. At nearly 40m in depth and more than 90m in diameter, the Wakulla Spring basin is one of the largest spring basins in Florida. The spring vent, which forms the main entrance to the Wakulla-Leon Sinks Cave System, measures nearly 60m wide by 30m high and discharges between 3.5 and 44 m³/sec. At low flows, the water can be crystal clear allowing the State Park to run glass-bottom boats for park visitors while at high flows, the water typically becomes dark tea colored where visibility is reduced to as little as 1m.

Recharge to the aquifer in the WKP occurs as both swallet inflows and diffuse infiltration from the land surface. Groundwater tracer tests have been performed at several of the swallets, which have successfully mapped groundwater flow patterns and velocities throughout much of the region. Additionally, cave divers with the Woodville Karst Plain Project (WKPP) have been actively exploring and mapping underwater caves in the WKP for more than 25 years. For the past eight years, they have been working closely with the Florida Geological Survey (FGS) and Florida Department of Environmental Protection (FDEP) to instrument the caves with hydraulic meters and sampling tubes, increase the accuracy of the cave maps with the use of cave-radio transmitters, collect detailed measurements of conduit cross-sections, sediment accumulations, and flow rates, and record the cave passages on video. Their maps, in conjunction with the tracer-defined pathways and hydraulic data collected from the caves, make the WKP the best documented karst region in Florida and likely one of the best in the world.

This field trip for which this guide was written focuses on the western part of the WKP by tracing the flow of water from discrete and diffuse sources of recharge through mapped and traced conduits in the Wakulla-Leon Sinks Cave System to its discharge at Wakulla Spring and the exchange of water between the Wakulla, Spring Creek, and St. Marks River Rise springsheds. The purpose of this guide is to provide background for discussions that will take place at the field trip stops by describing the mechanisms controlling the rate and pattern of groundwater flow to the springs, how these mechanisms contribute to aquifer vulnerability, and the



Cave divers entering the Wakulla-Leon Sinks Cave System beneath glass-bottom boats circling the Wakulla Spring basin during a low-flow period where the water was crystal clear.

effects of various land-use practices on groundwater and spring water quality in karst regions such as the WKP. Discussions and maps presented in this guide and on the field trip capitalize on the results of an ongoing characterization study sponsored by the FGS incorporating groundwater tracing, hydraulic data collection, and groundwater modeling as well as maps, observations, and data collected from inside the underwater cave systems by the WKPP cave explorers.

Tentative Field Trip Itinerary

- 07:45 – 08:00 Ramada Conference Center Hotel (30.48088 °N, 84.30435 °W)
Meet at the Ramada Conference Center Hotel – 2900 Monroe St, Tallahassee. Please arrive before 8:00 to ensure that you are present for the introductions and that we can depart promptly at 08:00.
- 08:20 – 08:50 Lake Munson Dam (30.36488 °N, 84.30180 °W)
Lake Munson collects and stores ~ 60% of the City of Tallahassee’s storm water runoff. Our tour will follow this water on its path through the aquifer to Wakulla Spring.
Required Walking Distance: ~450m / Driving Distance to Stop: ~14 km
- 09:00 – 09:30 Ames Sink (30.31867 °N, 84.29757 °W)
Ames Sink is one of three swallets that receive the flow released from Lake Munson. From this stop we’ll discuss the results of quantitative tracer tests that have documented the paths and velocities of the water entering the swallets. This stop is on private property. Please be respectful.
Required Walking Distance: <100m / Driving Distance to Stop: ~7.5 km
- 09:40 – 11:30 Leon Sinks Geological Area (30.30523 °N, 84.34653 °W)
From here we’ll take a walking tour of several large sinkholes and karst depressions located near the margin of the confining unit where recharge is rapid but often through a relatively thick sequence of sands and an ephemeral swallet. Be prepared to walk for the majority of this time on sandy trails.
Required Walking Distance: ~4km / Driving Distance to Stop: ~7 km
- 11:30 – 12:10 LUNCH
Lunches will be waiting for us to eat on picnic tables located near the parking lot of the Leon Sinks Geological Area where we’ll be joined by a ranger from the Apalachicola National Forest who will discuss how the Forest Service manages lands to foster groundwater protection.
- 12:20 – 12:50 Cheryl & Emerald Sinks (30.30308 °N, 84.36900 °W)
These are beautiful sinkholes that are actually karst windows. They intersect the Wakulla-Leon Sinks Cave System and provide an excellent platform to describe the exploration and mapping of the cave.
Required Walking Distance: ~450m / Driving Distance to Stop: ~2 km
- 13:00 – 13:30 Wakulla Springs State Park (30.23420 °N, 84.30052 °W)
We’ll climb the high dive platform to get an aerial view of the spring and get an overview of the Florida Geological survey’s hydraulic metering program in which they’ve installed seven meters that continuously measure flow, temperature, and conductivity in six different conduits.
Required Walking Distance: ~300m / Driving Distance to Stop: ~12.5 km
- 13:40 – 14:10 YMCA Camp Indian Spring (30.25137 °N, 84.32195 °W)
From the platform overlooking the spring basin we’ll discuss the concept of overflow springs and learn more about the history of cave exploration in the WKP.
Required Walking Distance: <50m / Driving Distance to Stop: ~3.75 km
- 14:25 – 14:45 Crawfordville Wal-Mart (30.21785 °N, 84.36100 °W)
Construction of this site required a significant amount of grouting to fill near-surface voids for the foundation and it preceded the first summer drought in which the Spring Creek vents were observed to siphon strongly and for a prolonged period. Coincidence or did Wal-Mart plug up the largest spring group in Florida? We’ll discuss how rumors like this get started and how they can be dispelled.
Required Walking Distance: ~10m / Driving Distance to Stop: ~9.5 km

- 15:00 – 15:30 Harvey’s, Hatchet & Bucket Sinks (30.13090 °N, 84.35123 °W)
These sinkholes are access points into deep underwater cave systems that have not been fully explored. We’ll discuss the characteristics of the caves and probable relationship between them, Spring Creek, and the Wakulla-Leon Sinks Cave System.
Required Walking Distance: ~100m / Driving Distance to Stop: ~17.75 km
- 15:40 – 16:10 Spring Creek Springs (30.08017 °N, 84.32987 °W)
The Spring Creek Springs are a group of 14 spring vents that discharge into the mouth of Spring Creek as it empties into Oyster Bay. Our stop will take us to the largest of the spring boils which is just offshore of the Spring Creek Fish House. At its highest flow, it creates a boil of nearly ½ a meter and at its lowest, it siphons water strongly enough to create a whirlpool.
Required Walking Distance: ~50m / Driving Distance to Stop: ~11 km
- 16:45 – 17:15 Natural Bridge (30.28450 °N, 84.15150 °W)
As the name suggests, Natural Bridge provides a land bridge across the St. Marks River wherein the St. Marks Sink and River Rise are separated by approximately 920m of land. The land in between the two ends of the river is pot-marked with karst windows, each of which has been shown to connect via underwater conduits to both the Sink and the rise. Here we’ll discuss the exploration of the Natural Bridge Cave System in 2006 and how this system compares to the Wakulla-Leon sinks Cave System.
- 18:00 Ramada Conference Center and Hotel (30.48088 °N, 84.30435 °W)
End of the field trip and optional dinner with the group.

The timing and selection of stops is subject to change depending on weather, time, and logistics. The tentative route for the trip is shown on Map 1. Please be prepared to be outside for most of the day. Bring a hat, sunglasses, sun screen, and a rain jacket.

Hydrogeologic Setting

The WKP is an extensively karstified topographic lowland that is part of a broader karst belt that extends around Florida’s Big Bend from Ochlockonee Bay to Tampa Bay (Map 1). Within this belt, the Floridan aquifer is unconfined and is therefore more vulnerable to contamination because the clay-rich geologic formations usually overlying the limestone formations in much of the rest of Florida have eroded away. The WKP constitutes the northwestern section of this karst belt. The province is bounded on the west by the Apalachicola Coastal Lowlands, the east by the Steinhatchee River, the south by the Gulf of Mexico, and the north by the erosional margin of the lower permeability sediments comprising the Hawthorn Formation (Hendry and Sproul, 1966; Scott et al., 2001).

The geology of the WKP consists of a thin veneer of unconsolidated and undifferentiated Pleistocene – Recent quartz sand and shell beds unconformably overlying a thick sequence of relatively horizontal carbonate rocks that comprise the upper Floridan aquifer (Figure 1). Karstification in the WKP is intensified by surface water that flows onto the exposed and thinly covered limestones from the north and west where the Floridan aquifer is confined or partially confined by clay-rich sediments in the Hawthorn Formation and parts of the Tamiami, Jackson Bluff, and Micosukee Formations (Figure 1). As a result, the WKP is characterized by the presence of numerous karst features including: dolines, sinkholes, karst windows, sinking streams and springs (Lane, 1986) as well as extensive underwater cave systems.

Recharge to the Floridan aquifer in the WKP occurs by: 1) sinking streams, 2) direct infiltration of precipitation through sinkholes, 3) infiltration through the variably thick sands and soils overlying the aquifer, and 4) groundwater flow into the WKP from the north. The Florida Department of Environmental Protection (FDEP) and Florida Geological Survey (FGS) are engaged in an effort to physically document all of the sinkholes and sinking streams within the WKP. To date, more than 400 ephemeral or perennially water filled sinkholes have been mapped in the northwestern quarter of the WKP by the FDEP. This suggests the presence of more than 1000 such features across the entire WKP. Of these 1000+ sinkholes, several are known to receive water, either perennially or ephemeral, from surface streams that drain upland regions,

with flows ranging seasonally between 10^2 m³/s and 100 m³/s. The five largest such streams are, in order of relative average flow: Lost Creek, Fisher Creek, Munson Slough, Black Creek and Jump Creek in the western WKP. In the eastern WKP, the largest such sinking streams are the St. Marks River, Natural Bridge, Still Creek, Lake Drain Creek, Lloyd Creek and Burnt Mill Creek (not in order of relative average flow due to a lack of available data). Map 1 shows the locations and orientations of all these sinking streams.

Within the WKP, discharge from the Floridan aquifer occurs at springs in the southern and eastern parts of the basin and submarine springs in the Gulf of Mexico. The largest up-gradient discharges are Wakulla Spring, the St. Marks River Rise, and Wacissa Spring. All three discharges form the headwaters of the three largest rivers in the WKP, the Wakulla, Lower St. Marks, and Wacissa Rivers respectively.

Significantly more data is available for Wakulla Spring than for the other two though it is not necessarily the largest of the three discharges. The average discharge from Wakulla Spring, as determined by a multi-year period of regular measurement is 11 m³/s whereas fewer measurements collected from the other two indicate discharges of 12 m³/s for the St. Marks Rise and 11 m³/s for the Wacissa spring group (Scott et. al, 2002; 2004).

All three springs exhibit considerable fluctuations in discharge, which indicates that they are significantly influenced by local precipitation. Seasonal discharge from Wakulla Spring ranges from 0.7 m³/s to 54 m³/s (Scott et al., 2002; 2004), which is the largest reported range of discharge recorded for any spring in Florida (Rupert, 1988). Groundwater tracing to Wakulla Spring and regular flow measurements collected from numerous points within the Wakulla-Leon Sinks Cave System have revealed the large discharge fluctuations are primarily caused by local rainfall events. During these periods runoff flows into sinking streams to the west and north, which then flows rapidly to the spring through karst conduits (Kincaid et al., 2004; 2005; Loper, et. al, 2005a). During low flow periods, groundwater flowing from a 2500 km², including parts of Leon, Wakulla, and Jefferson Counties and portions of five Georgia counties as far as 80 km north of the Florida-Georgia border (Gerami, 1984; Davis, 1996) accounts for the majority of the spring flow.

The largest down-gradient springs are the Spring Creek group of springs and the resurgence of the Aucilla River at Nutall Rise. The Spring Creek group includes at least 14 underwater vents along the coast of Apalachee Bay in the Gulf of Mexico. The combined discharge from all the vents has been estimated at between 8.5 and 56 m³/s (Scott et al., 2002;2004), which, if correct, makes the Spring Creek group the largest groundwater discharge in Florida. In the past three years however, discharge from the Spring Creek vents has been observed to fluctuate greatly. The vents have even been observed to siphon significant quantities of water for prolonged periods during the past three summers. As a result, more rigorous discharge measurements are now being collected which suggest that the actual groundwater discharge from the group is significantly less than had been previously estimated. Less is known about the Nutall Rise, however the reported discharge is 10.2 m³/s (Scott et al., 2002; 2004).

Chronostratigraphic Units			Lithostratigraphic Units	Hydrostratigraphic Units	
Era	System	Series			
CENOZOIC	QUATERNARY	RECENT	Alluvium	Surficial Aquifer	
		PLEISTOCENE	Terrace Sands		
	TERTIARY	PLIOCENE	Miccosukee / Citronelle	Confining Unit / Intermediate Aquifer	
			Jackson Bluff		
			Tamiami		
		MIOCENE	Hawthorn		
			Torreya/Arcadia		
		OLIGOCENE	Chattahoochee / St. Marks		Floridan Aquifer
			Suwannee		
			EOCENE		
			Ocala		
			Avon Park		

Figure 1. Stratigraphic and hydrostratigraphic sequence of rocks in and surrounding the Woodville Karst Plain, Florida as determined by lithology and stratigraphy reported in boreholes.

Regional groundwater flow is generally from north to south toward Apalachee Bay in the Gulf of Mexico. In the western part of the WKP however, the very high permeability of the caves and conduits propagate low heads to great distances into the aquifer away from the springs to which they discharge creating troughs in the potentiometric surface that complicate groundwater flow directions even directing local groundwater flow northward against the regional gradient. The most striking of these complicated flow patterns encompasses the region between Wakulla and Spring Creek springs. Divers exploring the Wakulla-Leon Sinks Cave System have reported crossing a groundwater divide within the large south-trending conduits emanating from Wakulla Spring wherein flow is northward toward Wakulla Spring in the northern part of the cave system and southward toward Spring Creek springs in the southern part of the system (Kincaid, 1999; Werner, 1998). The presence of a divide crossing the conduits is also indicated by tracer testing results (Kincaid et al, 2008) and tide/discharge relationships (Loper et al, 2005a). Less is known about the shape of the potentiometric surface in the eastern part of the basin though it is believed that conduits in the Natural Bridge Cave System, which discharges to the St. Marks River Rise and the conduits that feed the Wacissa Spring group create similar complexities in groundwater patterns.

Significance of Caves

Cave divers of the WKPP have mapped numerous underwater caves that trend for more than 18 km across the basin from north to south at depths ranging from 15 to 85 m (Werner, 2001). The five largest mapped caves in the WKP, ordered by length of mapped conduits, are: Wakulla-Leon Sinks Cave System (>51 km), Chip’s Hole Cave (>6.7 km), Natural Bridge Cave System (>3.6 km), Indian Springs Cave (>3.6 km), and Sally Ward Cave (>2.0 km) – Map 1. Conduit diameters within these caves range from less than 2 meters to greater than 30 meters and average approximately 10-15 meters (Kincaid, 1999; Werner, 2001).

These caves are both a consequence of, and a control on groundwater flow through the WKP. The caves have formed over geologic time as a result of limestone dissolution by groundwater. Once formed, they exert significant control on groundwater flow pathways due to the fact that they are exponentially more permeable than the surrounding limestone. Cave development can therefore be described as a positive feedback wherein dissolution increases permeability, which increases the preferential convergence of groundwater flow into the high permeability features, which then fosters more rapid dissolution. In the WKP, this process has resulted in dendritic cave systems that emanate from large single conduits at springs and trend upward into the basin splitting into more numerous and smaller conduits as they get farther from the springs.

The significance of this process to groundwater flow directions and velocities cannot be understated because, in essence, the caves are the primary conveyance system for the underground flow of water through the basin. The caves provide the mechanism by which surface water flows into the aquifer and travels rapidly to springs, which has been well documented by extensive groundwater tracing (Kincaid et. al, 2004; 2005; 2006; 2008). The caves also provide the mechanism for convergence of older groundwater flowing from more distant recharge areas into spring capture zones, which is marked by well-defined troughs in the potentiometric surface around Wakulla Spring and the St. Marks River Rise (Chelette et. al, 2002). In both cases, the caves

Mapped Caves in the Woodville Karst Plain

Cave or Cave System	Length (m)
Wakulla-Leon Sinks	51,484
Chip’s Hole	6,795
Natural Bridge	3,691
Indian Spring	3,626
Sally Ward	2,090
Shepard	1,734
Bird Sink	1,475
Little Dismal	905
McBride’s	660
Church’s	642
Rat Sink	446
Hideaway	374
Hatchet	341
Spring Creek Two	247
Meetinghouse	234
Farrell Shallow	173
Ventana Azul	111

provide for very rapid flow (500m/day – >1km/day) to springs once water from either source enters the WKP (Kincaid et al., 2005; 2006; 2008).

In addition to conveyance, caves also provide a mechanism for exchange of water between neighboring spring capture zones and within the aquifer matrix driven by changing water level conditions. During floods, a cave's conveyance capacity is dominated by, and can be overwhelmed by water from sinking streams. Under these conditions, water that would normally flow to a single spring can overflow into adjacent spring basins. The resulting gradients can also drive very recent recharge from the caves into the surrounding aquifer matrix. Once the floods subside, the exchange of water between neighboring basins is reduced or stopped and water from the aquifer matrix flows back toward the nearest conduits. The situation above can be described as overlapping drainage basins wherein the degree of overlap depends on water level conditions.

The presence and role of caves in the WKP creates a fundamental problem for groundwater sampling and groundwater modeling efforts. Because the caves have a very significant impact on groundwater flow directions and velocities, sampling strategies that fail to measure water quality fluctuations in the conduits will not adequately characterize aquifer conditions. Instead, water samples collected from the surrounding aquifer matrix are more likely to represent water within the aquifer matrix that can be stationary for long periods of time before it finally flows into a conduit and onto the springs. In the same manner, groundwater modeling strategies that do not account for conduit patterns and the resulting distribution of exponentially higher permeabilities within the aquifer framework will not be capable of adequately simulating flow patterns or contaminant transport times.

In order to be effective tools for groundwater resource management, sampling strategies must be designed such that waters from both the rapid conduit flow pathways and the aquifer matrix that can have significantly longer residence times are sampled and characterized at frequencies reflective of the travel-times between aquifer recharge and discharge. A reliance on monitoring wells for access to the aquifer is not likely to achieve this because of the statistical improbability of intersecting a conduit with a drilled well. In contrast, sampling programs that include large springs (Wakulla, St. Marks Rise, Wacissa, Nutall Rise, Spring Creek, etc) and cave systems with numerous tunnels and access points like the Wakulla-Leon Sinks and Natural Bridge Cave Systems, in addition to wells, are likely to capture and therefore measure water quality fluctuations in both the conduit and matrix components of the aquifer. To this end, the WKPP has been working with the FGS and FLDEP to instrument several of the caves in the WKP with sampling tubes that extend from points accessible from the land surface to conduit junctions whereby flowing groundwater from distinctly different parts of the WKP can be readily sampled.

Similarly, in order for groundwater models to accurately simulate flow patterns and velocities, they must incorporate an articulation of the conduit networks. Though that task is made difficult by an inability to locate and map the caves from the land surface, it is not insurmountable. Cave maps, which are available for nearly all of the identified underwater caves in Florida, document the trend, size, and depth of many known conduit systems to the extent that they're passable by humans. Tracer tests document groundwater flows indicative of conduits or conduit zones. And, much can be inferred about the presence or absence of conduits from potentiometric surface mapping and an analysis of hydrographs collected from monitoring wells where troughs in the potentiometric surface and wells with water levels that fluctuate rapidly in response to distant rainfall events are likely to be closer to active conduit networks.

Significance of the Confining Layer

The significant confining layer in the WKP consists of low permeability sediments, primarily those comprising the Hawthorn Formation, that overly the limestones comprising the Floridan aquifer. Regions where the confining unit is present and not breached by fractures or sinkholes are characterized by extensive surface water drainage and slow and diffusely distributed recharge. Active karstification is therefore inhibited by limited availability of rapid recharge from acidified surface waters. In regions where the confining unit is absent, recharge from rainfall is rapid but the rapidity of infiltration prevents the development of significant surface water drainage. Recharge waters in these regions have limited opportunity to become acidified by

contact with organic material. At the margin of the confining unit however, karstification is intensified because acidified surface waters flow off of the confining unit onto exposed limestones (Ceryak, 1981). It is therefore along the margin of the confining unit that the majority of the swallets in the region are found.

Because of its influence on karstification, an accurate delineation of the extent and thickness of the confining unit is critical to the effective mapping of both aquifer vulnerability and recharge for groundwater modeling purposes. As of 2006, no adequate map of the distribution and thickness of the confining unit was readily available. In the absence of such a map, an accepted rule of thumb was to use

the position of the Cody Scarp as the demarcation between confined and unconfined regions of the Floridan aquifer. That approach was based on the observation that, in north central Florida particularly Alachua and Columbia Counties, the position of the Cody Scarp coincides fairly well with the boundary of the Hawthorn Formation (Ceryak, 1981; Crane, 1986), which constitutes the confining unit over the Floridan aquifer. A critical examination of the basis for defining the Cody Scarp, however, reveals that, while the correlation holds in some regions of Florida, it is unlikely that it holds everywhere because the scarp was defined purely on a topographic basis rather than on geologic or hydrogeologic conditions.

The Cody Scarp was first defined by Puri and Vernon (1964) in their guidebook to classic geologic exposures in Florida and refined by White (1970) in his descriptions of the geomorphology of Florida. An excerpt from White (1970) illustrates the problematic nature of the definition. “The [Cody] scarp is the most persistent topographic break in the State. Its continuity is unbroken save by the valleys of major streams, but its definition is variable. In many places it can be delineated with unequivocal sharpness; in others it is shown only by a gradual reduction of average elevation and a general flattening of terrain as the lower elevations are reached.”

In the WKP, the correlation is particularly weak because there are numerous places north of the scarp, theoretically in the confined region of the aquifer, where rapid recharge to the Floridan aquifer occurs at swallets that receive considerable stream flow. Furthermore, field surveys in those areas confirm that the clays comprising the confining unit are not present or are very thin in many of those swallets and in some cases for some distance along the stream reaches.

As a consequence of those observations, Hazlett-Kincaid, Inc. constructed an isopach map for the thickness of the confining unit using borehole data describing the depth to the geologic units comprising the confining layer. The data for this endeavor was obtained from the FGS lithologic database for Gadsden, Leon, Jefferson, Liberty, Madison, Taylor, and Wakulla Counties (Scott et al., 2001) and the FGS Geologic Map of the Florida Panhandle (Scott et. al, 2001). The two datasets describe the depth to the top of all named geologic formations encountered in the boreholes, depth to the top of briefly described lithologic zones in the upper undifferentiated material, and the spatial orientation of geologic contacts that could be used to set a limit on the zero-thickness contour. The thickness of the confining unit was computed for each borehole by summing the thickness of all units encountered in the boreholes thought to be included in the confining layer (Figure 1), which in this region includes: all lithologic zones within the undifferentiated material described as “clay”

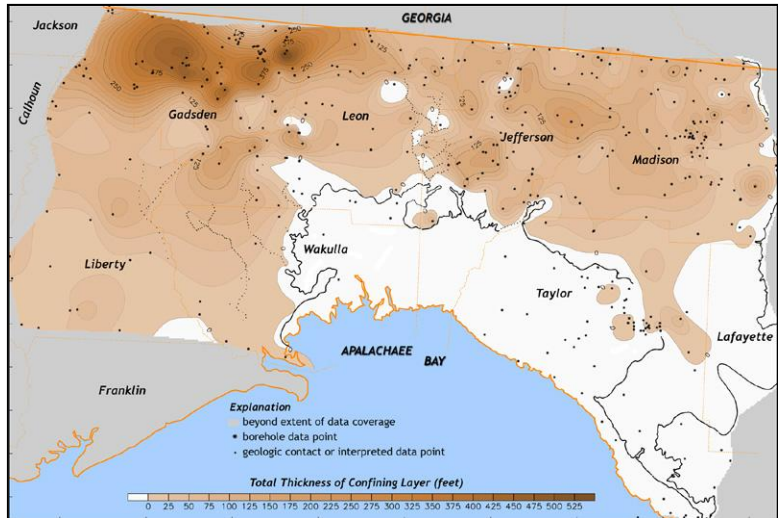


Figure 2. Map of the total thickness of the confining unit above the Floridan aquifer throughout the part of the Florida Panhandle that includes the Woodville Karst Plain.

and/or “sand in clay matrix,” Citronelle or Miccosukee Formations, Jackson Bluff Formation, Tamiami Formation, Hawthorn Group, and the Torreya or Arcadia Formations.

The borehole datasets were augmented with zero-thickness values assigned to the contacts of the relevant geologic units defined on the geologic map and at the centroid of all swallets known to intersect the Floridan aquifer. Minimum thickness values of 1-10 feet were then defined along the stream reaches immediately above the swallets and above the zero-thickness contour derived from the geologic map. The combined thickness data was gridded using the EarthVision™ geologic modeling software using a procedure that: 1) does not contour zero values explicitly but rather defines the zero-contour based on the location of the zeros and local thickness trends; and 2) accommodates minimum thicknesses at locations where the borings terminated in the confining unit (Belcher and Paradis, 1992; Paradis and Belcher, 1990). The resulting map defines the extent and thickness of the confining unit surrounding the WKP (Figure 2). Though the map will continue to be modified, particularly with limestone outcrop data, it provides a more useful delineation of aquifer vulnerability than the Cody Scarp.

Wakulla-Leon Sinks Cave System

Mapping the Cave

The Wakulla-Leon Sinks Cave System contains a total of 51,484m of mapped underwater conduits that connect to 27 named sinkholes that are actually karst windows and Wakulla Spring. It is the longest underwater cave in the United States and the fourth longest underwater cave in the world. Figure 3 and Maps 1 & 2 show the explored extent of the cave system as of September 2008.

Exploration and survey of the conduits within Wakulla Cave began in the 1950’s with the work of FSU students Gary Salsman and Wally Jenkins who made penetrations of up to 300m into the cave. The U.S. Deep Cave Diving Team conducted some additional exploration and survey dives in 1987 and published the first comprehensive map of the cave system in 1989 (Stone, 1989). Since that time, Wakulla Cave has been extensively explored and surveyed by the Woodville Karst Plain Project (WKPP) who continue to explore and survey new passages and support scientific research in the cave at the present time (WKPP, 2008). Their exploration efforts have resulted the connection of the Leon Sinks and Wakulla sections of the cave system in 2007 and continued discoveries of new conduits trending south toward Spring Creek or Shepard Springs (Figure 3 / Map 2).

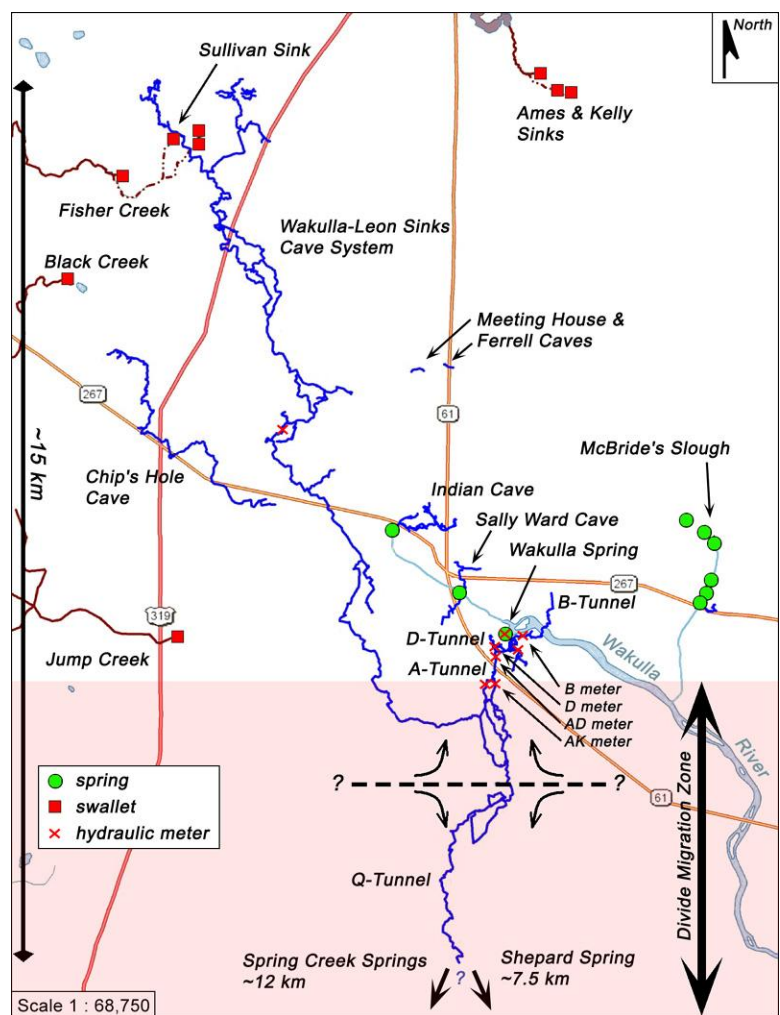


Figure 3. Generalized map of the Wakulla-Leon Sinks Cave System showing the location of the cave relative to springs, swallets, other mapped caves and the Wakulla River as well as the estimated position of the zone across which an observed groundwater divide migrates in response to changing water levels in the aquifer.

The cave surveys conducted by these teams represent the best available data describing the length, trend, and morphology of the cave passages. Most of these surveys focused on measuring the trend, length, and depth of the cave passages with compass, knotted line, and depth gauge. Passage morphologies, in terms of width and height were typically estimated by the divers conducting the surveys and reported as notes in the survey logs. At numerous points in the cave, more detailed measurements of location and morphology have been collected with the use of cave radio transmitters, used to locate a particular point in the cave at the land surface, and hand-held sonar depth finders used to measure the distance from a survey station to the adjacent cave walls.

The current map reflects a dendritic network of conduits that traverse more than 15 km of the WKP from north to south approximately centered on Wakulla Spring (Figure 3). All of the conduits are underwater and trend at depths of predominantly between -50 and -85m below the water table surface except where they rise to meet the land surface at the intervening karst windows and Wakulla Spring. The conduits can be roughly characterized as long tubes wherein the diameter and depth of any tube is relatively consistent though larger chambers of varying geometries sometimes divide individual or joining tubes. Conduit sizes range from less than 2 meters to greater than 30 meters in the horizontal direction and somewhat less than that in the vertical direction (Kincaid, 1999; Werner, 2001). Conduit sizes increase to the south where the largest conduits are those trending south away from Wakulla Spring (McKinlay and Jablonski, 2008).

Impacts on Groundwater Flow

Observations of groundwater flow directions and water clarity distributions throughout the cave system as well as flow, temperature, and conductivity measurements collected from eight different locations within the cave system reveal that the conduits carry a mixture of very recent recharge from swallets and older recharge from diffuse infiltration (McKinlay and Jablonski, 2008; Kincaid et al, 2006). In wet periods, all of the conduits except B-Tunnel, D-Tunnel, and the northern tunnels above Sullivan Sink carry dark tea-colored

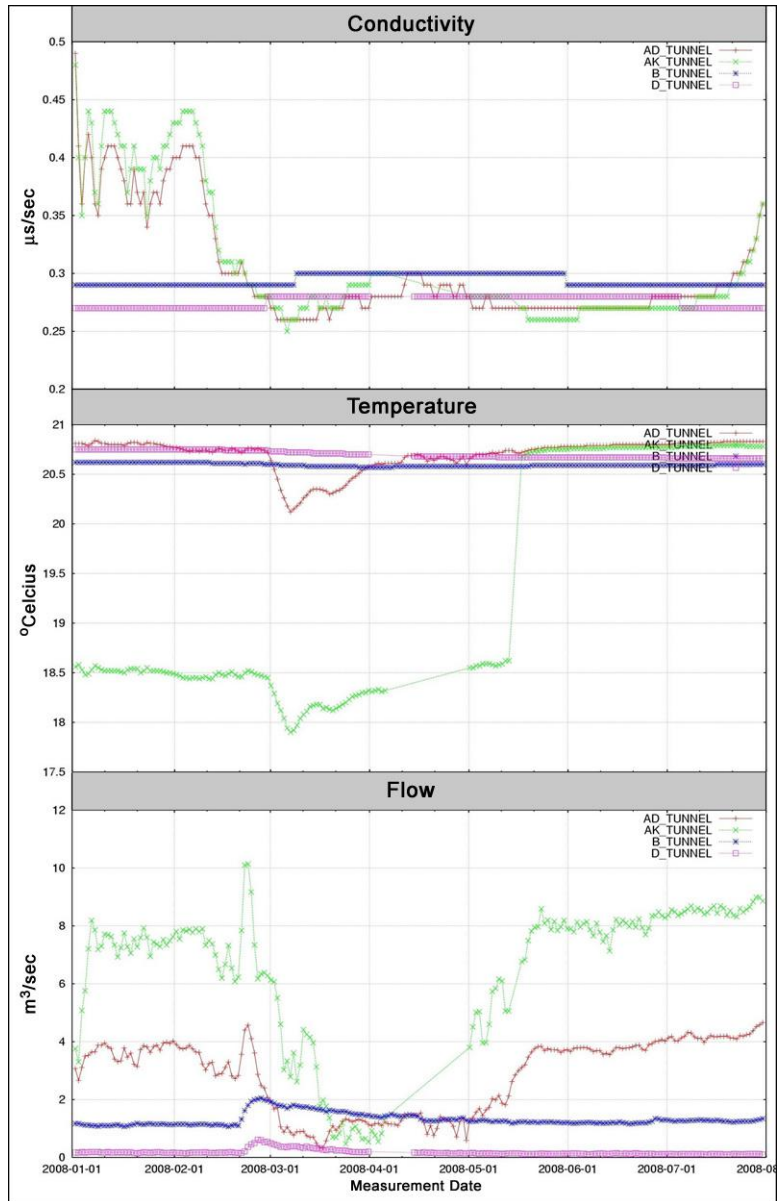


Figure 4. Flow, temperature, and conductivity measurements recorded by Falmouth hydraulic meters installed in the Wakulla-Leon Sinks Cave System at B-Tunnel, D-Tunnel, AD-Tunnel, and AK-Tunnel showing higher variability in all three parameters in the large south trending tunnels (AD & AK) than in the smaller north-trending tunnels (B and D) indicating that these tunnels are more strongly influenced by local rainfall.

water resulting in equally dark tea-colored discharge from Wakulla Spring, which prevents the operation of the Park's glass-bottom boats. Even during very wet periods when dark water is discharging from Wakulla Spring, clear water has been consistently observed discharging into conduit A from conduits B and D. In dry periods, the water in the cave system clears eventually resulting in crystal clear water in the Wakulla Spring basin and happy passengers on the Park's glass-bottom boats.

Groundwater tracing results show that swallet recharge in the northern and western parts of the western WKP (Ames Sink/Munson Slough, Fisher Creek, Black Creek, Jump Creek, and Lost Creek) flows to Wakulla Spring within 10-21 days of major rainfall events via the conduits in the Leon Sinks section of the cave system that connect to the southern conduits in

the Wakulla section of the cave (Map 1) (Kincaid et al., 2004; 2005; 2006). Recent tracer test results also show that flow bifurcates to a varying extent where part goes to Wakulla Spring and part to Spring Creek Sinks (Kincaid et al., 2008).

Flow, temperature, and conductivity gauging within the conduits confirm these results by showing significantly larger fluctuations of all three parameters in the southern tunnels connecting to Wakulla Spring than for the northern tunnels (Figure 4). The flow data also show a strong correlation between flow in the southern tunnels and tide but no such correlation in the northern tunnels (Figure 5) (Kincaid and Werner, 2007).

Finally, observations from the cave explorers reveal that water clarity in the southern tunnels (A-Tunnel, O-Tunnel, P-Tunnel, and Q-Tunnel) fluctuates from clear to very dark where the clarity is inversely related to flow but that the water clarity in the northern tunnels (B-Tunnel and D-Tunnel) remains high despite flow conditions (McKinlay and Jablonski, 2008). They have also observed that flow directions reverse as they travel south into the cave system from Wakulla Spring where the position of the reversal varies through time between approximately 2 km south of the spring and the southern extent of their current exploration.

Together, these data and observations indicate the presence of a groundwater divide that crosses the conduits in the southern part of the cave system, most likely between AK-Tunnel and the end of Q-Tunnel (Figure 3 / Map 2) and that the groundwater divide must migrate north and south, most likely depending on water levels in the aquifer (Kincaid, 1999; Werner, 1998).

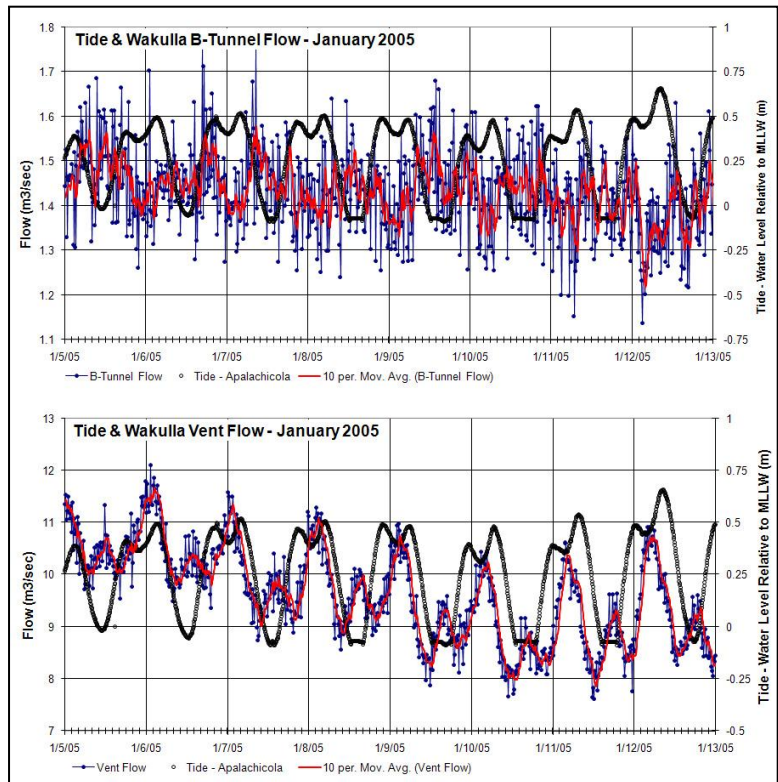


Figure 5. Plots comparing flow at the Wakulla Spring vent and B-Tunnel in the Wakulla-Leon sinks Cave system to tide measured at Apalachicola, which is approximately 65 km southwest of Spring Creek. A consistent strong correlation between flow and tide is evident in the plot for the vent flow whereas no such correlation stands out for B-tunnel.

The hydraulic meters in the cave system were operative in 2004 when two large hurricanes passed over or near the WKP. The data collected from the meters during those storms supports the existence of a migrating groundwater divide across the southern conduits and indicates that the conduit network likely extends all the way to the Gulf of Mexico connecting to coastal springs of the Spring Creek group and/or Shepard Spring (Loper et al., 2005a). Hurricane Francis, which passed directly over the WKP in September 2004, caused a precipitous drop in sea level in the Spring Creek area whereas Hurricane Ivan, which came ashore west of the WKP 10 days later, brought a storm surge that generated a precipitous increase in sea level (Figure 6). Flow data collected from the Wakulla Spring vent during both events showed a remarkable response. The drop in sea level associated with Francis correlated to a near immediate and significant decrease in flow whereas the storm surge associated with Ivan correlated to an equally immediate and significant increase in flow. And, in both cases, the spring flow returned to the pre-storm levels as sea level returned to the pre-storm tidal cycles.

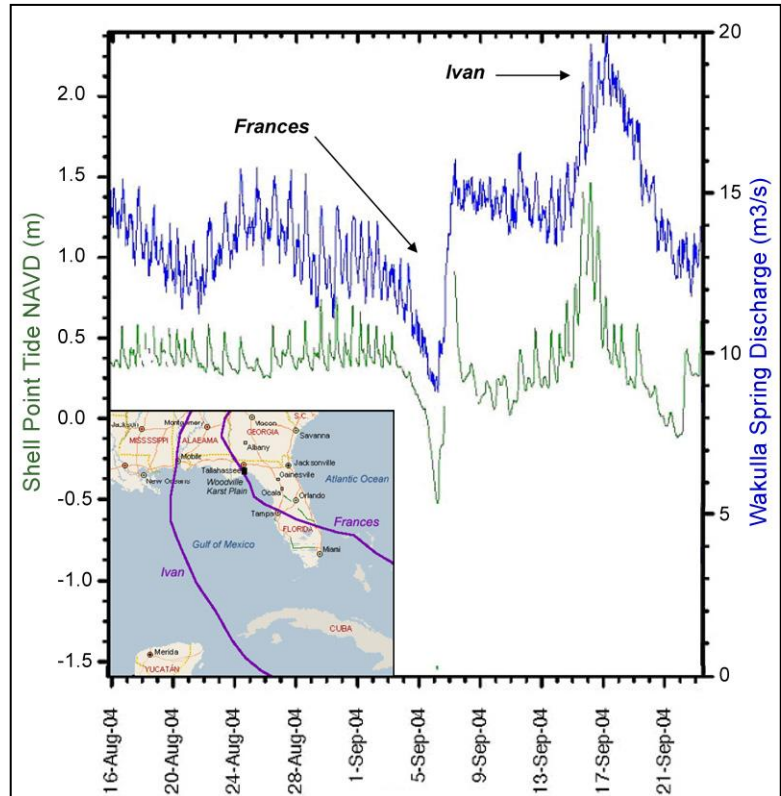


Figure 6. Plot showing the relationship between abnormally low and high tides created by Hurricanes Francis and Ivan relative to the response in discharge at Wakulla Spring with an inset showing the trajectories of the two storms. Adapted from Loper et al (2005).

The conclusion drawn from these data is that the low tide associated with Francis increased the groundwater gradient to the coast resulting in higher than normal discharge from the coastal springs which was pirated from Wakulla whereas the high tide associated with Ivan reversed that process reducing or perhaps stopping the coastal spring discharge which was directed to Wakulla. These responses indicate that the aquifer permeability between Wakulla Spring and the Gulf of Mexico is far greater than could be reasonably expected from a porous media and therefore the conduits in the Wakulla-Leon Sinks Cave System likely connect the up-gradient and down-gradient springs.

This conclusion has significant implications for spring and aquifer protection strategies. The current strategy adopted by Wakulla County defines a protection zone around the cave system and the lands that contribute water to the cave and spring. In doing so, the goal is to define both the underground and surface drainage areas that contribute water to Wakulla Spring and consider any proposed developments in those areas more carefully and specifically in terms of their potential impacts to water quality. By connecting Wakulla with the coastal springs and sinking streams along the western margin of the WKP, the conduits greatly expand the surface water drainage areas that contribute to the spring, and allow the spring capture zones to overlap to varying but potentially large degrees.

Under one set of hydrologic conditions, the groundwater divide observed by the divers and inferred from the hydraulic data creates a flow regime wherein the northern part of the western WKP contributes flow to Wakulla and the southern part to the coastal springs. Under other hydraulic conditions however, the divide can apparently migrate far enough south such that a different flow regime is created wherein flow from much

of the southern region, including the Lost Creek drainage basin, is directed toward Wakulla. The challenge confronting us today is to identify the mechanism responsible for the migration of the divide and then to be able to predict when and for how long each of two different regimes will be operative. This information will be critical for water resource managers in their efforts to effectively develop aquifer protection zones that are appropriately weighted in terms of springs and aquifer vulnerability.

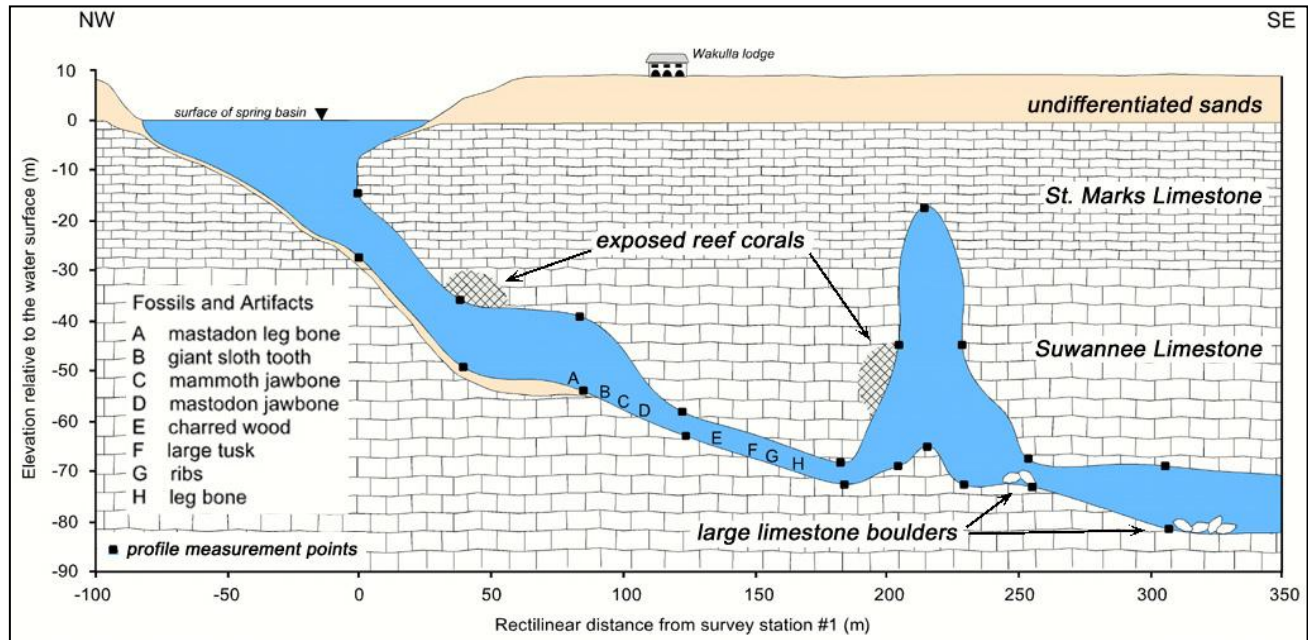


Figure 7. Location of fossil and archeological artifacts near the entrance to Wakulla cave at Wakulla Spring. Fossil and artifact locations are from Olsen (1958). Cave profile is from survey data collected by the Woodville Karst Plain Project cave divers.

History of Cave Formation

In addition to the implications for springs protection, the extent and pattern of the conduits leading south from Wakulla Spring also provides a clue to the story of how and when the cave system developed. The present-day hydraulic conditions do not favor southward development of conduits from Wakulla Spring because that is generally the down-gradient direction. When viewed in the context of other characteristics of Wakulla Spring, karstification processes in the WKP, and the recent geologic history of the WKP however, a plausible picture of how the cave system developed emerges.

Large vertebrate fossils recovered from varying distances inside the cave from the entrance at Wakulla Spring (Figure 7) reveals that the present-day spring basin may at some point in its history have functioned as a source of recharge rather than discharge because it is unlikely that such remains could have been transported into the cave against a strong discharging flow. The size and shape of the cave opening in the basin are, in fact, more consistent with large sinkholes in the WKP than with other large magnitude springs in the region. The location of such a large point of discrete recharge is however inconsistent with the present-day location of active swallets, which are situated near the margin of the confining unit. It is known though that the margin of the confining unit has been migrating northward as a consequence of several marine transgressions and regressions since the Hawthorn Formation was deposited in the Miocene. The zone of karstification has followed the landward migration of the confining unit margin leaving remnant caves and sinkholes on the evolving low carbonate land surface (Ceryak, 1981; Spangler, 1981; Scott, 1981; Lane, 1986).

The sea-level fluctuations that drove the erosion of the confining unit also repeatedly brought the Florida Platform, defined by the -80m bathymetric contour, above sea-level and thereby exposed the carbonate rocks comprising the platform to meteoric circulation. The presence of numerous karst features, some of which are reported as submarine springs, (Figure 8) indicate that karstification had established preferential flow routes

through the Floridan aquifer prior to the last sea level rise. Anecdotal descriptions of these offshore features indicate that as late as 1890 some of these features had sufficient discharge so as to be highly regarded by mariners as both sources of fresh water while at sea and places of refuge during storms due to the calming effect of the boils on the sea surface (Munroe, 1892). The most distant of these offshore features is Ray Hole Spring, which is 45 km offshore but 140 km landward of the edge of the Florida Platform (Figure 8). If the Wakulla-Leon Sinks Cave System did, at some point in the geologic past, extend out to the most distant offshore springs, it would have traversed approximately 70 km from recharge to discharge of which underwater exploration and groundwater tracing have documented over 28 km (~40%).

By tying together what is known about the fossil remains in the Wakulla Spring vent, the landward erosion of the confining unit, seal level fluctuations during the recent geologic past, and the presence and description of karst features along the coast and offshore, it becomes evident that the largest south-trending conduits developed during a period of lower sea level and more seaward extent of the confining layer. Discharge from the aquifer was likely through the present submarine springs and recharge, much as it is today, was through sinkhole-swallets that, included the Wakulla basin.

The paleo-flow system caused dissolution of rock from the aquifer that culminated in the development of a conduit network organized to deliver the swallet recharge to the down-gradient springs. Precise timing of the cave development cannot be constrained beyond any of the periods of lower sea level that post dated the deposition of the Hawthorn formation during Miocene time. Regional hydraulic gradients were reduced following the retreat of the confining layer and sea level rise. This removed the mechanism for significant offshore discharge and established a hydraulic configuration that favored more up-gradient discharge leading to the development of the current flow system.

The sinkhole that was likely a significant source of recharge evolved into Wakulla spring. New sinkholes and swallets like the Leon Sinks sinkholes, Ames Sink and Turf Pond Sink, developed farther up-gradient in the proximity of the retreating confining layer. The smaller conduits in Wakulla cave developed as a consequence of dissolution along flow paths connecting the newer sinkholes with Wakulla spring. The original conduits remained in the aquifer however, and provided preferential flow paths that connected the newly formed Wakulla Spring with the down-gradient springs that were drowned by the rise in sea level. A ground water divide has developed across the cave where flow converging on the conduit from the northern part of the Woodville Karst Plain discharges at Wakulla spring while flow from the southern part of the region enters the conduit and flows farther down-gradient to the submarine springs. The very high permeability of those original conduits allows the divide to migrate north and south to considerable distances in response to changing gradients driven by rainfall and sea level fluctuations.

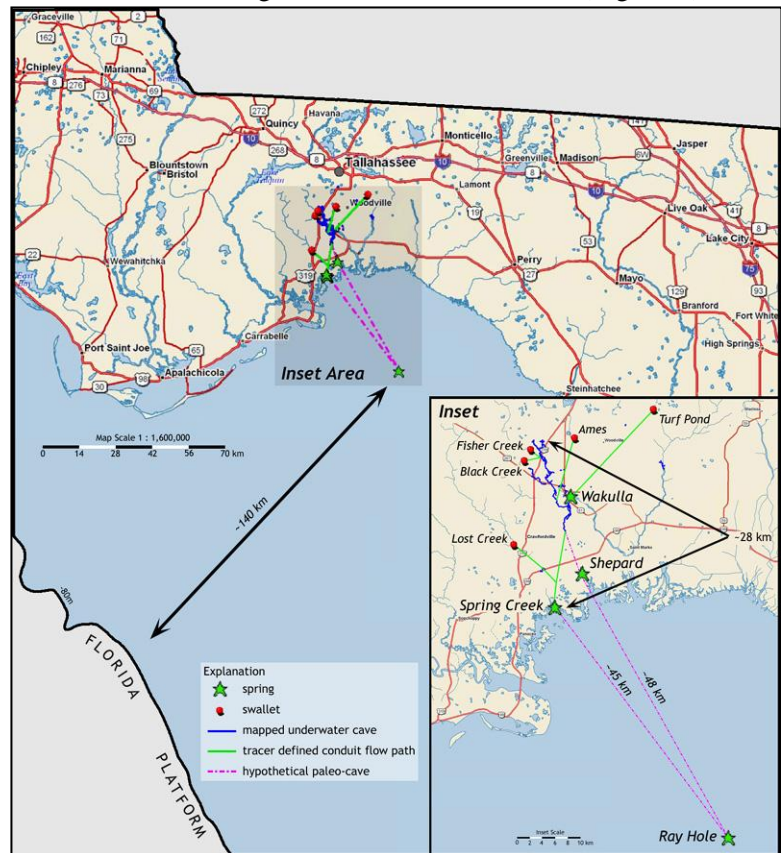


Figure 8. Mapped and traced conduits in the Wakulla-Leon Sinks Cave System relative to the location of coastal and offshore springs, and the edge of the Florida Platform in the Gulf of Mexico.

Spring Creek Springs

Spring Creek is a spring-fed tidal stream that flows into Oyster Bay, which is on the northwest side of Apalachee Bay. The streambed and its tributaries contain a silt and sand veneer with exposed St. Marks Limestone visible in some places (Lane, 2001). There are 14 known spring vents of the Spring Creek Springs Group (Scott et al, 2004), all discharging at the widened mouth of Spring Creek near its entrance into Oyster Bay (Figure 9). The largest discharging vents are #1, #2, #8, #10 and #11, as indicated by the observation of large surface boils. All the spring vents have been documented as being tidally influenced and have been observed to occasionally reverse flow at high tide (Lane, 2001; Scott et al., 2004). The waters discharging at Spring Creek are usually tannin stained indicating that a large portion of the discharging water is recently recharged surface water.

The FGS made several reconnaissance investigations at Spring Creek between 1995 and 1999 in which they used seismic and sonar scans to map the spring basins (Lane, 2001). From those surveys, they classified all of the vents except #8 and #10 as enlarged collapse features where vents 2, 3, 4, and 9 in particular contained large piles of St. Marks Limestone interpreted as the collapsed sides of the large circular spring pools. Vents 8 and 10 were classified as conical depressions showing no indications of collapse.

The WKPP has attempted to explore and survey the caves connecting to the spring vents several times over the past ten years. High velocity discharges that typify the vents and extensive covering of oyster shells on the substrate that extend well into the entrance of all the caves have made it nearly impossible for divers to swim into the caves safely during most of that period. They were however able to gain entrance to vents 1, 2, 8, and 10 during low-flow conditions in 2000 and 2007 during which time they were able to map several hundred meters of conduits.

The longest of the surveyed conduits was vent #2, which was mapped for over 300m to the southwest at an average depth of 45m below the water surface. Vent #10 was mapped for approximately 225m west-northwest wherein the conduit connected to vent #8 and bifurcated into at least two passages, one continuing to the west-northwest toward vent #1 and the other trending south toward vent #11. Each of those conduits averaged between 5 and 10m in diameter wherein the height was noticeably larger than the width. Vent #1 was mapped for approximately 45m to the north of the spring vent to a depth of 50m where it continued steeply downward probably exceeding 60m or more in depth. Vent #1 was the largest of the conduits explored measuring approximately 15m in diameter where the width was noticeably larger than the height.

Flows from Spring Creek have been estimated twice, once in 1974 by Rosenau and others (1977) and once in 1996 by Davis (1996). On both occasions, the flow was measured across the stream channel just downstream of vent #8 thereby measuring a composite of flow from vents 1-11. Rosenau and others measured a flow of 57

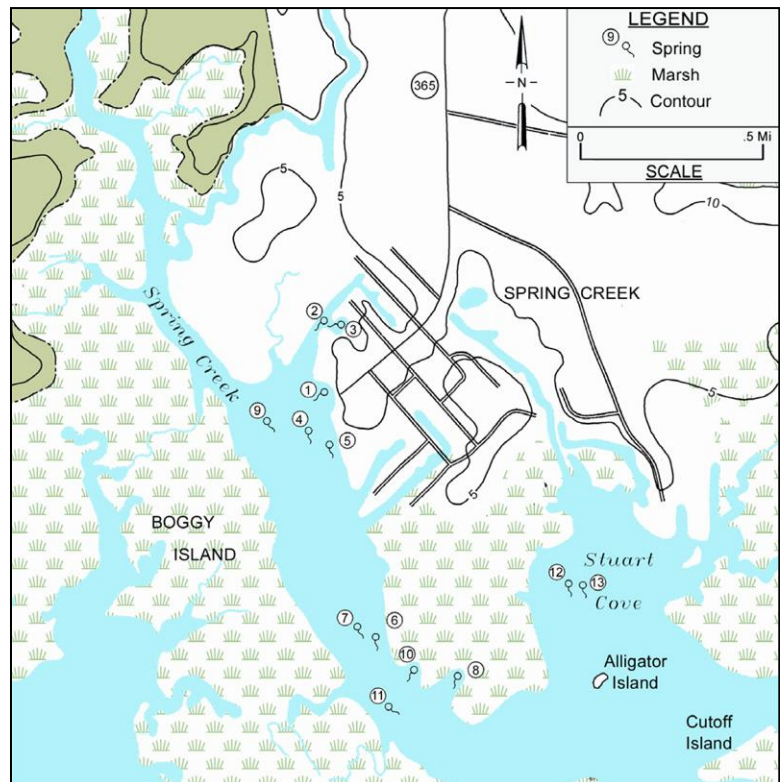


Figure 9. Map showing the locations of 13 of the 14 recognized spring vents in the Spring Creek Group that discharge into the creek just upstream of Oyster Bay. From Lane (2001).

m³/sec, which represented a high flow stage (surface streams in the WKP flowing to their swallets) that did not account for tidal exchange in and out of the channel. Davis measured a flow of 8.7 m³/sec at a low flow stage (surface streams dry and not flowing into their swallets) that did account for tidal exchange. In both cases, the flow was similar to that measured in the Wakulla River downstream of Wakulla Spring at similar flow stages. From these measurements, it is evident that, like Wakulla Spring, Spring Creek discharges a mixture of older groundwater flow (baseflow) and very recent swallet recharge. An evaluation of the position of Spring Creek and the known swallets in the WKP (Map 1) indicates that the most likely source of the swallet recharge is Lost Creek.

Beginning in the summer of 2006, the Spring Creek Vents, particularly vent #1, were observed to be strongly siphoning for longer than normal periods, even through low tide (Means, 2006). These conditions persisted through the summer and fall and only abated after the winter rains began. Since then, the same conditions have occurred during the summers of 2007 and 2008. During each period, the siphoning conditions at Spring Creek coincided with higher than normal flows at Wakulla Spring indicating that Wakulla Spring was pirating flow from Spring Creek during those periods (Kincaid and Werner, 2007; Davis, 2006).



Spring Creek vent #1 showing a large boil (top) and whirlpool (bottom) which are indicative of normal conditions and the recent summer droughts respectively. Pictures courtesy of Gareth Davies (top) and Harley Means (bottom).

Studies are currently being conducted by the USGS and the FGS to better understand and quantify flow dynamics at Spring Creek that include continuous stage and flow measurements in the Spring Creek Channel downstream of vent #8 and groundwater tracer testing. The flow measurements have not been processed yet but a tracer test conducted from Lost Creek by the FGS in 2008 has revealed that Spring Creek vent #10 must be connected via one or more conduits to both Lost Creek and Wakulla Spring (Kincaid et al., 2008).

The tracer test was performed by releasing a tracer into the flow of Lost Creek immediately after a storm had re-initiated flow into the swallet after a prolonged dry period. The tracer was detected at Spring Creek vent #10 after less than 7 days but was not detected at any of the other vents sampled (vents 1, 2, 8, and 11). Within a week of the injection, stream flow in Lost Creek subsided again such that no water was flowing into the swallet. Shortly afterward, the tracer was also detected in a karst window down-gradient of the southern extent of the Wakulla-Leon Sinks Cave System and then shortly after that in the cave system and then at Wakulla Spring. From these results, it is evident that the conduits in the Wakulla-Leon Sinks Cave System

must extend to the coast and that the southward migration of the groundwater divide between Wakulla and Spring Creek Springs must be driven, at least in part, by reduced gradients associated with recent summer droughts. Based on anecdotal accounts from local residents about salinity changes in the creek, it also appears that these reductions in gradient are probably larger than have occurred in the past century (Spears, 2007).

Natural Bridge Cave System

The WKPP was granted a rare opportunity to enter and explore the Natural Bridge Cave System in 2006. They conducted several dives between June and August that represented the first documented exploration of the cave system. Their survey data indicates that the cave system is comprised of a dendritic network of conduits that extend from the St. Marks River Rise to each of the karst windows on the Natural Bridge property and then beyond to the north, northeast, and northwest (Figure 10). They surveyed a total of 3,691m of underwater cave passages making the Natural Bridge Cave System the third-largest cave system in the WKP. They reported that the conduits trend at a depth of predominately 21 to 34m below the water table surface, flow through the conduits is generally from north to south, and that conduit diameters ranged from 6-12m on average to 25 or more meters in some large chambers.

RQ-Tunnel and NBR-Tunnel were reported to carry the clearest water. RQ-Tunnel trends to the northeast past Lahon Spring, which is presumably a secondary discharge of clear spring water. NBR-Tunnel trends to the northwest and west, where the western spur is trending directly toward the Rhodes Springs located at the corner of Natural Bridge and Old Plank Roads. Where these spring tunnels merge with the remaining passages in the cave system, the clear spring water mixes with the darker water that typifies most of the water flow through the cave.

The remaining tunnels convey water from the two sinking points of the St. Marks River through the intervening karst windows to the St. Marks River Rise. The westernmost river sink (Natural Bridge Sink) connects to the northwestern karst window via a small conduit connected to the NBR-Tunnel. The eastern river sink connects to the north-central karst window via a small connector tunnel. From that same basin, another tunnel trends northeast toward but was not physically connected to the surface water outflow of Natural Bridge Spring. The size of the conduits and magnitude of the flow encountered by the divers indicate that one of the conduits (most likely NBR-Tunnel) will continue to the north and eventually connect to the disappearing streams in the far northern reaches of the St. Marks River Basin (Map 1).

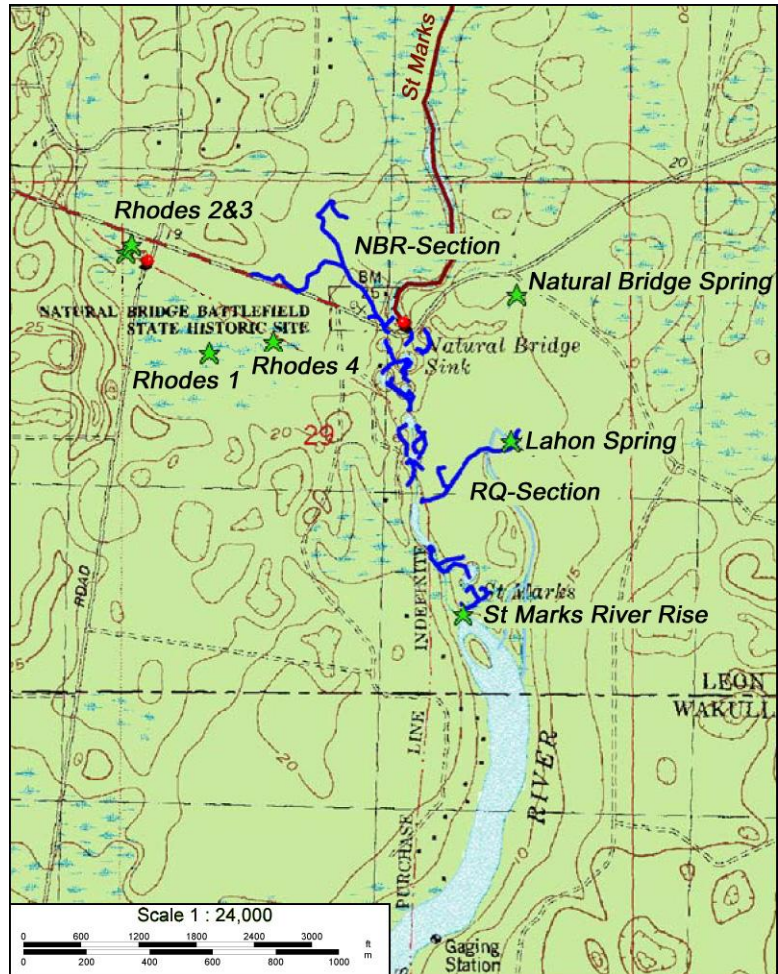


Figure 10. Map of conduits in the Natural Bridge Cave System (NBCS), Florida based on surveys conducted in the summer, 2006 by the Woodville Karst Plain Project. The basemap is part of the Woodville USGS 7.5 minute topographic quadrangle.

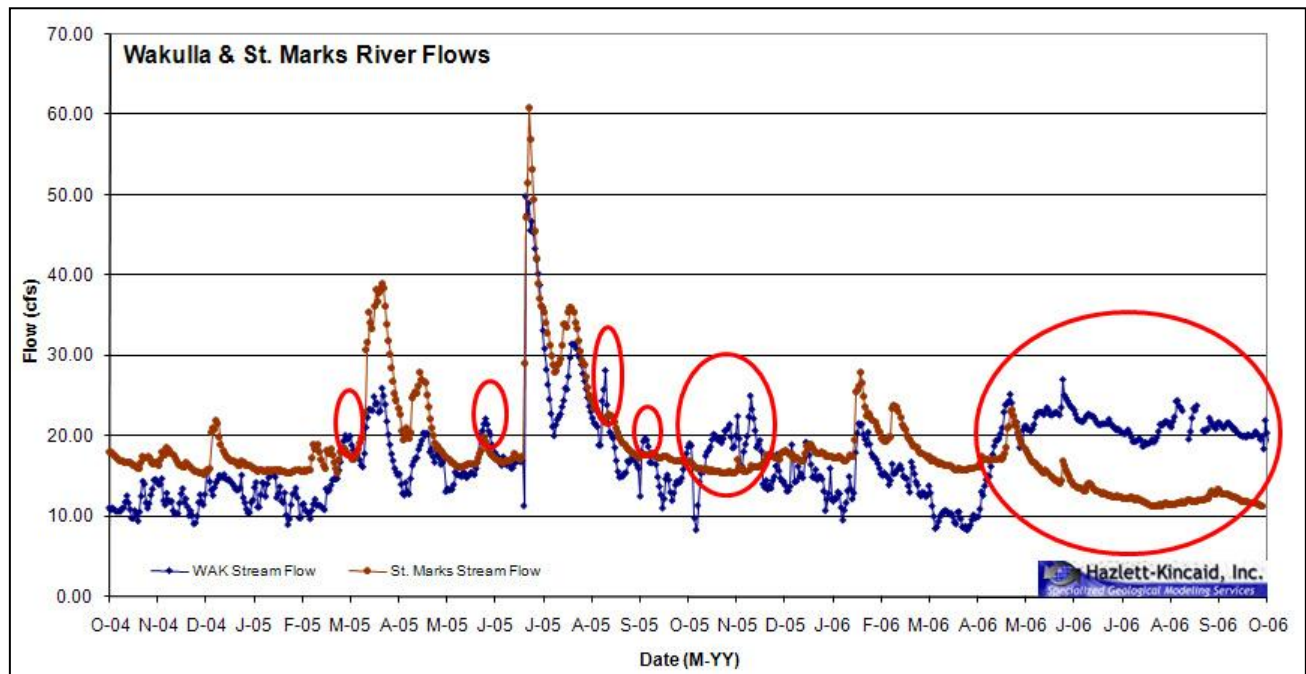


Figure 11. Comparison of Wakulla and St. Marks River flows showing that the Wakulla River flow generally tracks and is less than the St. Marks River flow except at isolated times (red circles) but that beginning in March 2006, the Wakulla River flow rose above and remained above the St. Marks flow for an abnormally long period of time. These data indicate that both the St. Marks and Wakulla River flows are significantly impacted by rainfall but that the groundwater component of the Wakulla River flow (baseflow) remained high (higher than the average flow during the preceding 1.5 year record) in the 2006 despite localized drought conditions.

The Natural Bridge Cave System is very similar to the Wakulla-Leon Sinks Cave System in that both convey a mixture of older groundwater (clear water) and sinking stream water (dark water) to a large magnitude springs (St. Marks River Rise and Wakulla Spring). Based on the conduit trends and water clarity observations, the Natural Bridge Cave System appears to be capturing water from both the Rhodes Spring and Natural Bridge springsheds, where in fact, it is likely that those springs are simply karst windows or overflows and that the St. Marks River Rise is actually the primary discharge. The flow from these sources to the River Rise is therefore analogous to the flow from the northern clear water tunnels (B-Tunnel and D-Tunnel) to Wakulla Spring. In terms of sinking stream water, the connection between the St. Marks River sinks and the River Rise has been confirmed. Additionally, there are several very large sinking streams in the Lloyd and Capitola regions of Leon and Jefferson counties (Map 1) that likely contribute flow to the Natural Bridge Cave System though the connections cannot as yet be confirmed.

In terms of discharge, the Wakulla-Leon Sinks and Natural Bridge cave systems display similar behavior though the differences between the way the two are most interesting to analyze. The USGS maintains gauging stations on both the Wakulla and St. Marks Rivers not far downstream from the spring vents. As both rivers are primarily fed by the respective spring discharges, these data can be used to compare the springs.

A comparison of Wakulla and St. Marks River flows shows that the Wakulla River flow generally tracks but is less than the St. Marks River flow except at isolated periods of time (Figure 11). Beginning in March 2006 however, the Wakulla River flow rose above and remained above the St. Marks flow for an abnormally long period. These data indicate that both the St. Marks and Wakulla River flows are significantly impacted by localized rainfall, which was low throughout Spring – Fall 2006 resulting in a drying of all the sinking streams in the Woodville Karst Plain. From March 2006 however, the groundwater component of the Wakulla River flow (baseflow) remained high (higher than the average flow during the preceding 1.5 year record) causing the Wakulla River flow to remain significantly higher than the St. Marks River flow. Therefore, either the groundwater capture zone for Wakulla Spring intercepts more regional groundwater flow than the St.

Marks springs or recharge in the Wakulla Spring capture zone was less impacted by the 2006 drought than the St. Marks River capture zone.

More detailed analyses of the stream flow and rainfall data have led us to focus on the former of those two possibilities as the mechanism responsible for the deviations in the way the two springs respond to drought. It appears that the significant difference between the two systems is the pattern of the conduit networks that deliver water to the two springs. The conduits in the Natural Bridge Cave System all essentially trend to the north thereby intercepting southward groundwater flow and delivering it to the St. Marks River Rise. The conduits feeding Wakulla Spring, on the other hand, trend both north and south from the spring and are now known to connect, in some capacity, to the coastal Spring Creek Springs. We believe that it is these southern tunnels that provided the increased groundwater baseflow to Wakulla Spring during the 2006 drought period by pirating flow that would have otherwise gone to Spring Creek.

The pirating appears to have recurred in both the 2007 and 2008 summer droughts and during all three periods, the abnormally high flows at Wakulla Spring were associated with siphoning conditions at the Spring Creek vents, unusually high water levels in sinkholes near the coast, and increased conductivity levels in the water filling those sinkholes. These conditions have significant implications for protecting water quality at Wakulla Spring because prolonged and significant quantities of pirating appear to facilitate saltwater intrusion into the Floridan aquifer along the conduits connecting to Spring Creek. As a consequence, multiple gauging stations have been installed, or soon will be installed, at Spring Creek to quantify the exchange of water between the two springsheds and multiple groundwater tracing experiments have been carried out and planned to attempt to constrain their boundaries.

Water Quality Concerns

Springs discharge groundwater from a broad region of the surrounding aquifer. Within that region, recharge, from often multiple sources, merges together within the aquifer and flows to the spring. The spring discharge is a composite of the waters from these sources. The quality of the spring water should thus be considered as a proxy for the water quality within the spring's capture zone in the aquifer. Understanding and mitigating the mechanisms for spring water quality degradation will therefore contribute greatly to protecting the broader groundwater resource.

A ten-year decline in water quality at Wakulla Spring and the ecological health of the spring basin (Chelette et al., 2002) has focused considerable public and government attention and effort on protecting Wakulla Spring from further degradation. Part of this attention has focused on revising zoning ordinances, regulations on development and best management practices in an effort to minimize the potential impacts of development on the quality of water at Wakulla Spring. It is becoming recognized that the most important aspects of protecting the spring center on a determination of where and how water is recharged within the springshed and how a given development will likely impact the quality and mechanism of that recharge.

The decline of water quality at Wakulla Spring can be separated into two basic categories: 1) increasing dark water resulting in decreased water clarity, and 2) increasing nitrate loading resulting in the explosive growth of algae in the basin and possibly exacerbating problems with hydrilla (Loper et al., 2005b). Groundwater tracing demonstrates that the sinking streams along the western and northern margins of the WKP are the sources of dark tannin-rich waters in the spring discharge (Kincaid et al., 2005). It follows therefore, that developmental actions that create a change in the rate or quantity of runoff to these sinking streams will impact the quantity and timing of dark tannin-rich water flow to the spring, and thus the water clarity.

Determining the source of the increased nitrate to Wakulla Spring has been a far more contentious issue than the water clarity concerns. The consensus of scientific opinion at present has identified septic systems and the City of Tallahassee's wastewater spray field as the two predominant sources of nitrate in the spring discharge (Chelette et al., 2002; Loper et al., 2005b). Of those two sources, the City's wastewater spray field has been identified as the primary source, though septic systems are considered a potentially more chronic problem (Loper et al., 2005b).

The most rigorous effort aimed at establishing guidelines for protecting water quality at Wakulla Spring was convened as a public workshop in 2005 entitled “Solving Water Pollution Problems in the Wakulla Springshed of North Florida.” This workshop convened scientists, engineers, regulators, and other interested parties to present the most recent data describing the problems, debate the implications of those data for protection efforts, and to develop specific recommendations on how the government and public can most effectively endeavor to protect and restore water quality at Wakulla Spring (Hydrogeology Consortium, 2005; Loper et al., 2005b). Of those recommendations, the following recommendations from the workshop were directed primarily at private parties and intended to serve as guidelines for voluntary measures that should be considered for future and existing developments in the Wakulla Springs capture zone.

- Delineate zones of aquifer vulnerability as defined by rapid recharge at sinking streams or sinkholes connected to the Floridan aquifer by conduits (via active sinkholes) and minimize surface water runoff into such features.
- Minimize the use of onsite waste disposal systems (septic systems) by using some form of centralized waste management system for all new developments whenever possible.
- Use only EPA rated Level 4 or Level 5 onsite disposal systems that can achieve at least 70% nitrogen reduction, 95% reduction in BOD and TSS, and 98% reduction of fecal coliforms when centralized waste management systems cannot be used.
- Protect high aquifer vulnerability zones through the use of conservation easements.
- Reduce development density to 5 acres or more when centralized waste water systems cannot be used.
- Make it a primary goal of all wastewater disposal activities in Leon and Wakulla Counties to reduce nutrient loading (nitrogen and phosphorus) to the aquifer.
- Reduce and eliminate, if possible, the use of fertilizers within the Wakulla Springshed.
- Engage in public education on the above recommendations for the long-term health of Wakulla Springs and its ecosystems.

Water Quantity Concerns

In addition to the water quality and clarity problems, there is growing concern over potentially diminishing groundwater supplies and availability. The concept most central to this issue is that of the groundwater budget, which identifies the amount of groundwater available for use as the amount left in storage after outputs are subtracted from inputs. It is most often expressed by the following equation: $Inputs = Outputs + Change\ in\ Storage$. The inputs are defined as all sources of recharge. Outputs are defined as all forms of discharge, and the change in storage can be thought of as the amount of groundwater available for use. If usage increases such that the total outputs exceed the total inputs, the change in storage will be negative, which means that the aquifer will be depleted. By contrast, as long as the total inputs equal or exceed the total outputs, there will be groundwater available for users.

In the WKP, there are three inputs: 1) water flow into the aquifer through sinkholes at the terminus of sinking streams; 2) infiltration from rainfall in the WKP; and 3) groundwater inflow to the WKP from northern regions. The main forms of discharge are: 1) natural discharge to springs, of which Wakulla, the St. Marks Rive Rise, and Spring Creek are the largest; 2) groundwater withdrawals from wells; and 3) small spring discharge and seepage into the Gulf of Mexico. The relative magnitude of spring water discharge compared to seepage into the sea is currently a debated topic. However, regardless of the final determination on that subject and as the water budget equation demonstrates, groundwater pumping necessarily diminishes spring water discharge, seepage, or both.

The question then becomes: to what degree can the springs and seepage be diminished without causing irreparable harm or undesirable changes in the natural systems that are dependent on spring discharge or seepage? Answering this question is one purpose of the State’s Minimum Flows and Levels (MFL) program,

which is intended to establish the minimum amount of flow to key natural systems, such as Wakulla Spring and the Wakulla River, necessary to sustain a natural and healthy ecological system. In the ideal case, once the MFLs are established for the key natural discharges, the remaining groundwater can be safely used for human consumption and fairly divided amongst the various users.

At present, the MFLs for Wakulla, Spring Creek, or the remaining springs in the WKP have not been established. However, in keeping with the MFL concept and in order to evaluate the impacts of groundwater withdrawal on Wakulla Spring, proposed groundwater withdrawals must be viewed in the context of all users in the spring catchment. Minimizing one use while disregarding others is not likely to have the desired protective effect on the quantity of spring water discharge. In addition, the fate of the water once it leaves the ground must also be considered in order to effectively evaluate the impacts to the water budget and thus flows to the springs. Groundwater that is pumped, used, cleaned, and then returned to the aquifer will have less impact on spring flows than uses that transfer the water out of the basin.

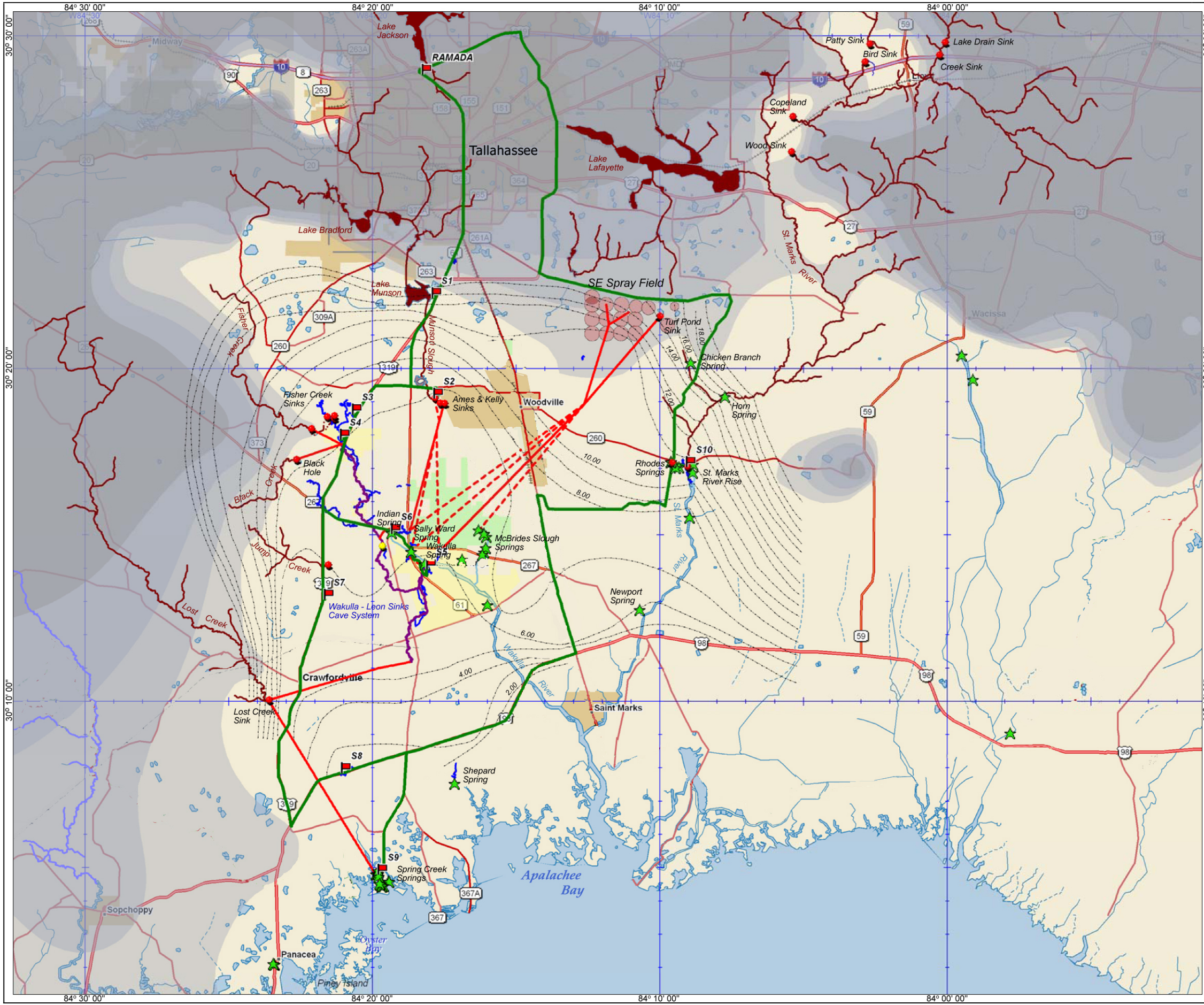
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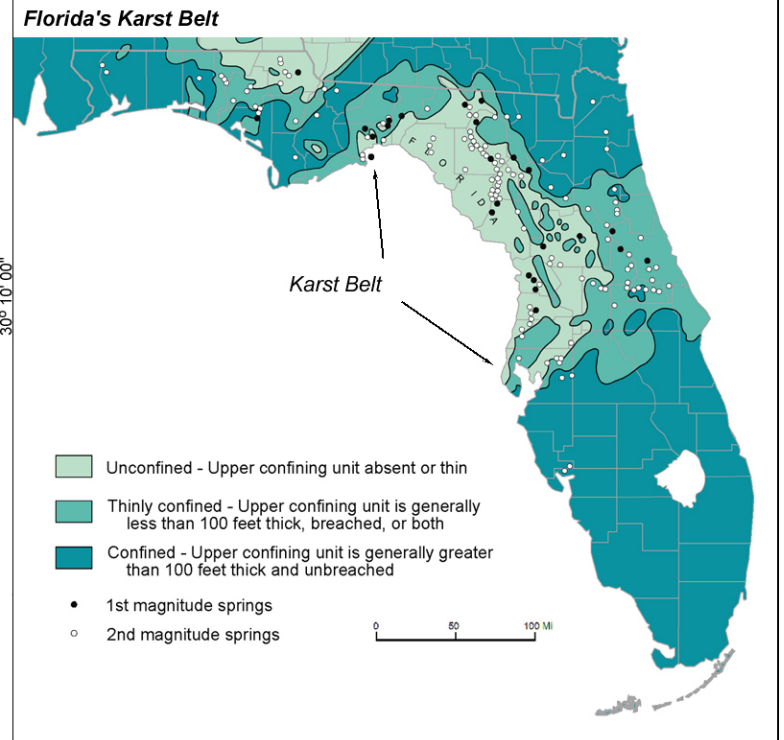
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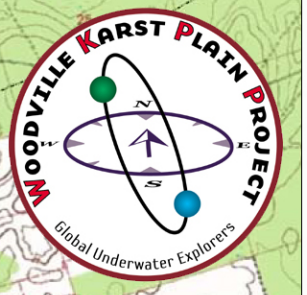
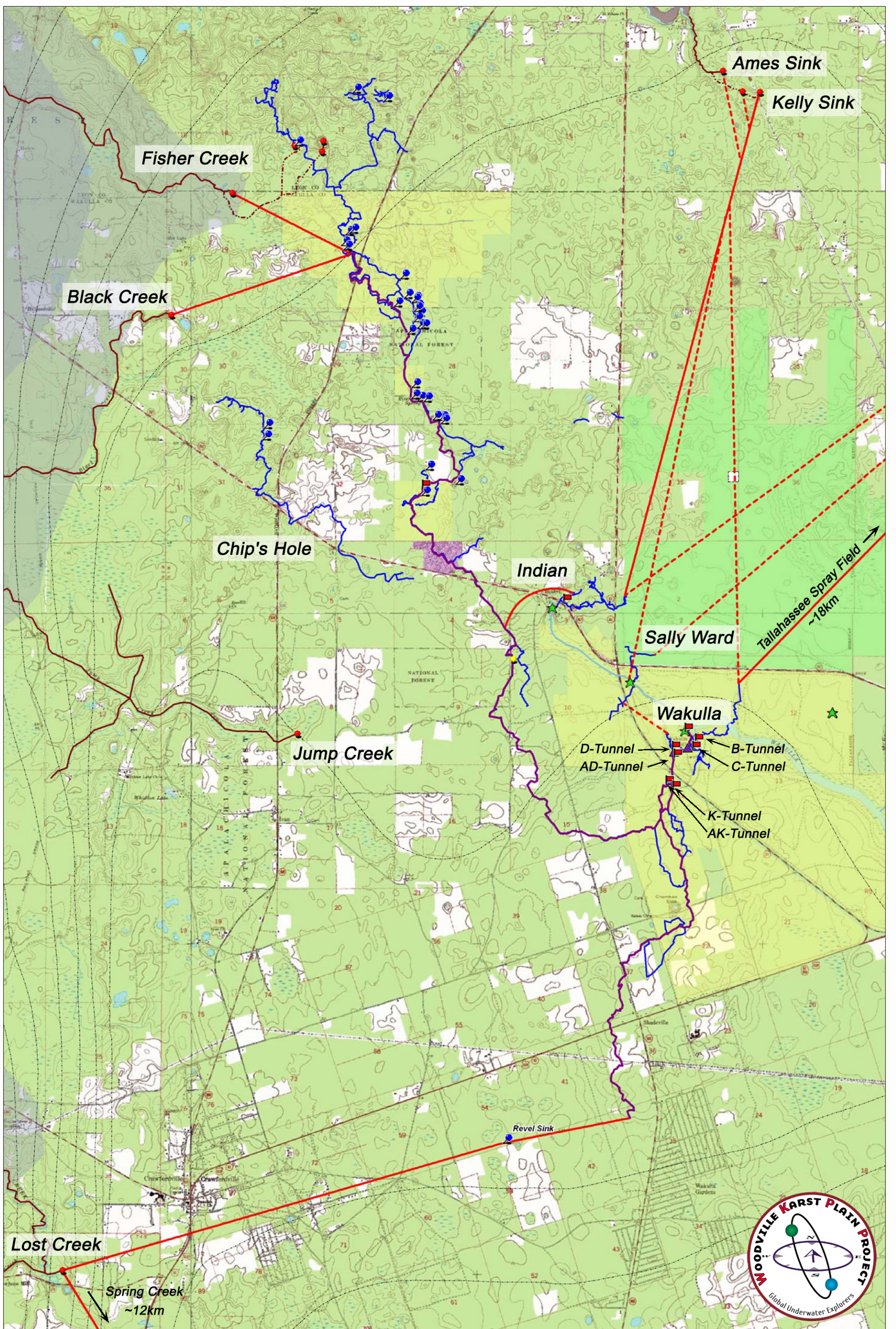
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Woodville Karst Plain North Florida



- Explanation**
- tentative field trip stop
 - tentative field trip route
 - swallet: sinkhole at terminus of a sinking stream
 - ★ spring discharge
 - poorly confined region: clay formations 0 - 25 feet thick
 - moderately confined region: clay formations 25 - 50 feet thick
 - more confined region: clay formations > 50 feet thick
 - Wakulla Springs State Park boundaries
 - Wakulla State Forest boundaries
 - primary groundwater flow pathway defined by tracing
 - - - secondary groundwater flow pathway defined by tracing
 - mapped and surveyed underwater cave passage
 - surface water drainage upstream of known swallet
 - surface water drainage downstream of any known swallets
 - - - potentiometric surface of the Floridan aquifer





Explanation	
Connection Point	Connected karst window
Spring	Hydraulic Meter
Swallet	Well Penetrating Cave
Connection Point	Wakulla Springs State Park
Connected karst window	Wakulla State Forest
mapped cave passage	traced flow path secondary
traced flow path - primary	confining unit 0 - 8m thick
traced pathway through mapped conduit	confining unit 8 - 16m thick