

FINAL REPORT

FGS contract 243

Ground Water Flow and Interaction with Surface Water in Karst: A Hydrogeological and Modeling Investigation

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Preamble

This is a report of research and related activities conducted during the period July 2003 through June 2004 with the support of contract FGS 243, awarded by the Florida Geological Survey (FGS) to the Geophysical Fluid Dynamics Institute of Florida State University. This document serves as a final report for that contract, as well as an interim report on those projects which will be continued. The current contract is the third in a series of annual contracts awarded by the Florida Geological Survey. However, this is the first contract for which a comprehensive final report has been prepared. (In previous years, reports of individual projects were prepared and submitted separately.) The Contract manager and research collaborator is Rodney DeHan and the Principal Investigator is David Loper.

The contract consists of seven projects conducted by seven distinct teams as follows:

Project 1: Understanding the dynamics of water flow and surface water contribution to the Wakulla Springs system

David Loper, Eric Chicken and Mohamed Al-Lawati, Florida State University

Project 2: Ground Water-Tracing Experiments in the Woodville Karst Plain

Todd Kincaid, Hazlett-Kincaid Inc.

Project 3: The quantification of ground water discharge to coastal and riverine systems using Radon and Radium isotopes

William C. Burnett, Jeffrey P. Chanton and Christina Stringer, Florida State University

Project 4: Ground-truth evaluation of thermal anomalies

James R. McClean, Florida State University and Rodney DeHan of FGS.

Project 5: Development of a workshop on Aquifer Storage & Recovery (ASR) issues

Timothy Hazlett and Todd Kincaid, Hazlett-Kincaid, Inc., and the Hydrogeology Consortium.

Project 6: Development of ground water flow model and non-point source contaminant transport model in Karst: Initial Phase

Timothy Hazlett, Hazlett-Kincaid, Inc

Project 7: Continuation of the development of the Florida Maps project

James R. Anderson, Florida Resources and Environmental Analysis Center, Florida State University

This report consists of a summary, an introduction and seven sections, each focusing on one of the projects, with certain details relegated to a number of appendices. Each section begins with the scope of work for the project and a brief introduction and/or summary, then continues with a report of the work accomplished to date. In addition, several reports include a summary of current or planned activities.

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Executive Summary

This is a report of research supported by the Hydrogeology Program of the Florida Geological Survey during the 2003-04 fiscal year through Contract FGS 243, awarded to the Geophysical Fluid Dynamics Institute of Florida State University. The goal of this contract is to further the objectives of the Geological Investigations Section of the Florida Geological Survey as described in the **Introduction**. The contract consists of seven projects:

- 1: Understanding the dynamics of water flow and surface water contribution to the Wakulla Springs system
- 2: Ground Water-Tracing Experiments in the Woodville Karst Plain
- 3: The quantification of ground water discharge to coastal and riverine systems using
- 4: Ground-truth evaluation of thermal anomalies
- 5: Development of a workshop on Aquifer Storage & Recovery (ASR) issues
- 6: Development of ground water flow model and non-point source contaminant transport
- 7: Continuation of the development of the Florida Maps project

The goal of **project 1** is an improved understanding of the dynamics of water flow and surface water contribution to Wakulla Springs. This is being accomplished by correlating variations of discharge, temperature and electrical conductivity measured at the main vent with external events that cause these variations, particularly rainfall. In the past year, attention has been focused on investigation of statistical techniques suitable for quantification of the correlations Wakulla Springs, particularly storm events, during which the discharge is exceptionally large (double base flow or more) for a relatively short interval of time (on the order of one week). This project is continuing.

The goal of **project 2** is an improved understanding the interconnections between various systems in the watershed of Wakulla Springs. This is being achieved through a series of dye-tracing experiments. Two such experiments were conducted in the past year. The first quantified the rate of flow between resurgence of Black Creek and the Leon Sinks cave system, while second confirmed and quantified a hydraulic connection between the Leon Sinks Cave System and Wakulla Springs. this latter experiment is significant, in that it is the first confirmation of a hydraulic connection between these two systems. Additional tracing tests are planned both to the north (Ames Sink) and south (toward Spring Creek springs).

The goal of **project 3** is an estimation of the rate of groundwater discharge in the marine environment south of the Woodville Karst Plain. This is being accomplished by measuring and analyzing distributions and inventories of salinity and Rn and Ra isotopes. Such measurements were taken at Lanark Reef (Lanark and Sulfur Springs) and around a near-shore area just west of the FSU Marine Laboratory (FSUML). Measurements at Sulfur Spring showed essentially the same result for all parameters measured (salinity, radon, and radium), indicating that there is little mixing going on in the vent sampled, while Lanark Spring showed internal consistency in the conductivity/salinity results but a wide variation in the radon and radium results. Groundwater velocities west of FSUML range from 5-40 cm/day, with increased seepage rates at low tide.

The goal of **project 4** is to evaluate the capabilities of selected remote-sensing technologies (thermal imaging from aerial and space based platforms and marine-towed electrical resistivity) to locate and characterize groundwater and surface-water interaction zones.

The evaluation consisted of on-site surveys of places where the remote sensing indicated the existence of fresh-water discharges. Spring Creek springs show a range of water quality parameters within the basin, either the result of sea water intrusion to the deeper ground water conduits by shallow surficial conduits and/or the result of separate ground water sources. In contrast, water quality at Lanark Spring is consistent throughout a daily tidal cycle. The two springs of Lanark Reef (Lanark and Sulfur) were discharging substantial amounts of water, while discharge near FSUML was not observed. At Large Hole and Fresh Water Cave Springs (45 km SW of Stinhatchee) the temperature is lowest and salinity is highest during low tide. Fresh Water Cave appears to be an intermittent spring/seep at the base of a large sinkhole depression some 5.5 km off the Taylor County coast.

The goal of **project 5** is to facilitate exchange of information and ideas regarding a crucial issue in Florida: Aquifer Storage and Recovery. This goal was accomplished by organizing and running a two-day workshop on this topic in Tampa, FL on April 15 & 16, 2004.

The goal of **project 6** is to develop improved models of groundwater flow and transport applicable to karstic aquifers. The principal product of this project is a prototype model, dubbed KARSTMOD, that explicitly incorporates the effects of a system of caves on flow and transport. Where known, the caves are explicitly modeled; where not, they are incorporated in a stochastic manner. Current efforts are focused on applying the model to the Wakulla Springs springshed. As an alternate and comparison, a traditional finite-element model is also being run for the Wakulla Springs and Manatee Springs springsheds.

The goal of **project 7** is to develop modules for use in school curricula that integrate multidisciplinary lesson plans with the use of maps and images such as satellite and airborne imagery, aerial photography, topographic maps, and other special-purpose cartographic products (e.g., 3D anaglyph maps). The first such module, called **Explore Florida!**, contains two units : *Map Use* and *Florida Everglades*.

Introduction

By conducting, or out-sourcing, appropriate hydrologic research projects, the Hydrogeology Program within the Geological Investigations Section of the Florida Geological Survey seeks to obtain unbiased scientific knowledge of Florida's watersheds with specific emphasis on aquifer systems. The research projects summarized in this report have been supported by the Hydrogeology Program during the 2003-04 fiscal year through Contract FGS 243. Knowledge gained through this research is potentially applicable to rule making, regulatory and policy decisions that facilitate protection of the quantity and quality of Florida's water resources – a critical component of Florida's environment.

The projects described in the following sections focus on the watershed and aquifer systems in the Woodville Karst Plain (WKP) and areas immediately to the North (within Leon and Wakulla Counties), but also include the adjacent marine environment to the South of the WKP and the springshed of Manatee Spring. These projects predominantly represent advances in fundamental understanding but also include compilations, syntheses and dissemination of existing knowledge.

Four distinct types of field study have been employed in an effort to understand the flow of water and contaminants in the aquifer of the WKP, two focusing on the springshed of Wakulla Spring and two dealing with off-shore fresh-water springs. Traditional dye tracings reported in **Project 2** have clarified the flow pathways from Fisher and Black Creek sinks to Leon Sinks Cave system and from Leon Sinks Cave system to Wakulla Spring. A novel approach to the identification of flow pathways, in which water is in effect used as a tracer, is reported in **Project 1**. This approach has the potential to identify flow pathways and travel times within the entire springshed of Wakulla Spring. The approaches to the identification of fresh-water springs in the marine environment include the use of thermal imaging of spring plumes (**Project 4**) and quantification of the concentrations isotopes of Radon and Radium (**Project 3**) in the waters of Spring Creek Springs, Lanark Reef, Oyster Bar Spring, Fresh Water Cave, Steinhatchee Spring and Lamb Spring.

If the knowledge gained by the field studies is to put to best practical use, it must be incorporated into a model. The best such model incorporates the karst conduit system that conveys water and pollutants to Wakulla Springs and the Spring Creek Spring system. Such a model is described in **Project 6**. Also included in and appendix to **Project 6** is a traditional modeling study of the springshed of Manatee Spring.

In addition to the development and assimilation of fundamental scientific knowledge described in Projects 1, 2, 3, 4 and 6, the contract supported dissemination of such knowledge. A workshop on Aquifer Storage & Recovery issues is described in **Project 5**, and the continued development of the Florida Maps project is described in **Project 7**.

Project 1: Understanding the dynamics of water flow and surface water contribution to the Wakulla Springs system

*David Loper, Eric Chicken, Mohamed Al-Lawati
Florida State University*

1.1 Scope of the project

This task is a continuation of the ongoing study initiated in 2002. It is designed to study variations in discharge measured at the springs' system and cross-correlate these variations with events which affect the flow to the system.

The research project consists of two phases, each of which is divided into five tasks. The first phase, and only one covered by this Contract, focuses on the data which has been previously collected by the Northwest Florida Water Management District (NFWFMD), while in the second phase (to be completed in subsequent years and not authorized under this Contract) attention will be focused on the data to be collected by a set of newly installed meters currently under construction.

The five tasks to be accomplished in each phase are as follows:

- Statistical analyses of data (discharge, temperature and electrical conductivity) collected in Wakulla Springs.
- Identification of internal correlations among these data.
- Identification and acquisition of related data sets, particularly Doppler rainfall data for the watershed of Wakulla Springs. Other data includes water levels in wells, tide heights in Apalachicola Bay and atmospheric pressure.
- Statistical analyses of these related data and identification of correlations with the Wakulla Springs' data.
- Interpretation of the statistical correlations and the construction of a preliminary physical model of the Wakulla Springs watershed.

The data that has been produced by the single meter in the main vent contains a surprisingly rich spectrum of variations in discharge, on all timescales from hourly to (at least) annual. This variability, when properly analyzed and cross-correlated, can shed considerable light on the behavior of the Wakulla Springs flow system.

Existing data will be analyzed using standard techniques of time-series analysis (e.g., Fourier and wavelet analysis) in order to identify the principal timescales on which flows vary. The most important goal will be to correlate the features seen in the data on discharge, conductivity and temperature with specific events in the regions up-gradient from Wakulla Springs. Most likely events are rainfall, but the data described in the previous subsection covers the interval in the fall of 1999, during which Lake Jackson in northern Leon County drained. These correlations will go a long way towards determining the area of ground water contribution to the springs, the extent of the subsurface conduit system, and the relative contributions of recent surface water input versus ground water input to the springs.

In addition to rate of flow, data has been collected on the electrical conductivity and temperature of waters discharging at Wakulla Springs. Statistical analysis of these data, in coordination with the other data sets, will help to determine the source, age and path of the

waters. In particular, the remarkable constancy of the temperature of Wakulla Springs' water is a strong constraint on any model of the flow system.

The cause of variations in discharge will be identified using statistical analyses of the data sets, using two statistical approaches, *frequency-domain analysis* and *time-domain analysis*.

Deliverables: Periodic verbal reports, at a frequency agreed upon by the two project managers, on the progress of the project, quarterly invoices in conjunction with quarterly progress reports, followed by a final invoice in conjunction with a final written report detailing the findings and recommendations of the study to be submitted to the Florida Geological Survey (FGS) prior to June 10, 2004.

Most of the recent research has been focused on the first two tasks listed in the scope above; these activities are described in §1.3. Work continues on this project, as described in §1.4.

1.2 Summary

The discharge measured in the main vent of Wakulla Springs is variable on a variety of timescales, including a regular but small-amplitude signal due to the lunar tides and irregular but large-amplitude spikes, called 'storm events'. The primary focus of attention during the past year has been on these two types of signals. It was confirmed by wavelet analysis that the lunar periods (12.94 and 25.88 hours) are the only regular signals in the discharge record. Since these signals are of small amplitude, wavelet and Fourier series are not appropriate tools for analysis of the important variations that remain after the tidal signals are removed from the discharge data.

The first attempt at characterizing storm events entailed the use of Principal Component Analysis, also known as Empirical Orthogonal Analysis. While the storm events could be well characterized with relatively few basis functions, these functions have no analytic form, making it difficult to obtain a general characterization of the storm events using this approach. Also, overlapping storm events are difficult to characterize using these functions.

A more satisfactory approach is the use of an analytic form (called a scaled gamma function) which contains three parameters, two of which can be fit to the magnitude and duration of each storm event. The third parameter characterizes decay phase of the storm event, that results from the interplay between transport and storage in the aquifer. A sample set of data, including both storm events and smaller-amplitude variations of discharge, was successfully characterized by a discrete set of scaled gamma functions.

1.3 Statistical Analyses and Correlations

The statistical analysis focused on the data which has been collected in the main vent of Wakulla Spring, by the S4 meter operated by the Northwest Florida Water Management District since May 1997. The flow velocity (speed and horizontal direction), temperature and electrical conductivity have been measured every three hours with occasional breaks due to meter replacement and maintenance. The data consists of three distinct, contiguous time periods:

Set 1. 1997.05.09¹ to 1998.11.12

Consisting of 4388 data points (with a data gap of 29 points during 1997.10.20 to 1997.10.23)

¹ Here the date is designated by year.month.day

Set 2. 1999.06.18 to 2001.05.13

Consisting of 5856 data points (with a data gap of 3 points during 2000.06.10)

Set 3. 2002.04.13 to 2003.10.18

Consisting of 4421 data points (with a data gap of 2 points during 2003.01.11)

All analysis in terms of model-building, described in this sub-section has been done using the first data set only. Our intention is to use the remaining two sets to confirm the validity of the model components derived or constructed from the analysis of the first data set. It should be emphasized that, to the best of our knowledge, the statistical analysis we are conducting is novel and the correct procedure at each step is not obvious. As a consequence, we have proceeded deliberately, taking pains to ensure that we are considering all viable options for analysis at each stage.

We desire to model springs flow based on external hydrologic events. Initially, we examined only one aspect of flow, the discharge volume. The external input to be considered first is rainfall. In particular, we plan to use rainfall duration, intensity, and start time as deduced from Doppler radar data. As the model-building process progresses, other factors (such as distance of rain event from the springs and specific location of rain event) will be added. Once discharge has been modeled, we will look at other properties of the spring flow: temperature, direction of flow, conductivity, and relations of these to discharge and each other.

Initial attention was focused on the discharge data in Data Set 1, shown in Figure 1.1. Since statistical time series methods were to be employed in this analysis, the 29 missing data points have been filled in using a linear interpolation scheme, making a total of 4419 data points.

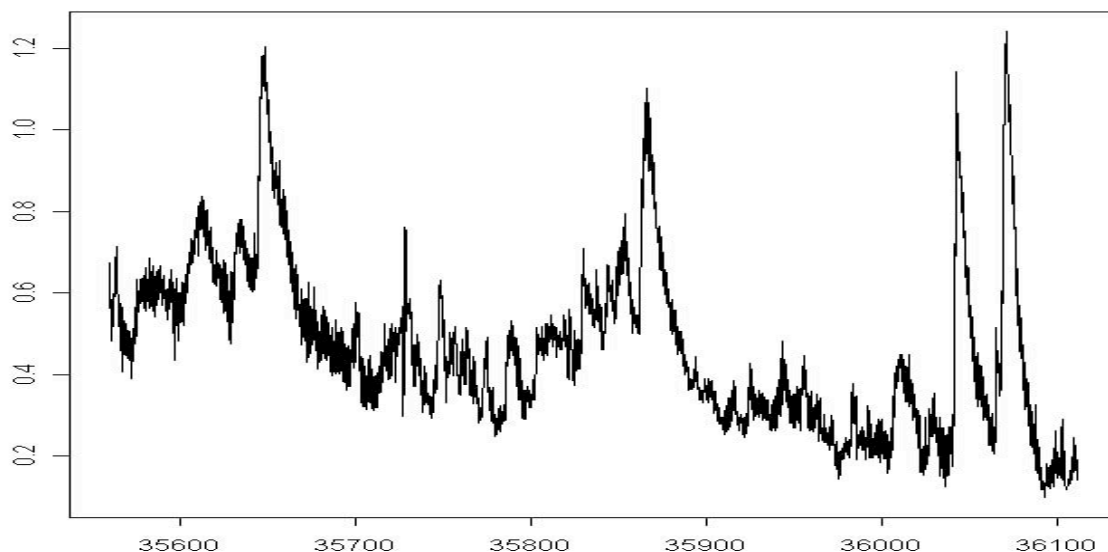


Figure 1.1. Discharge measurements from May 1997 to November 1998

The initial analysis step taken was to determine if there are any periodic events being expressed in the data. There are several methods for determining periodic events in time-series analysis, but many require assumptions on the data that we were not willing to make. For

example, the data for the time periods in question does not possess a common mean for all major subsets of the data. Additionally, the assumption of constant variance over all major subsets is not met either. Both these requirements are common assumptions for modeling periodic behavior in many time series. As an alternative, we employed continuous-wavelet spectral analysis in order to determine periodic behavior in the signal. Figure 1.2 shows the spectrum of the data in Figure 1.1. The wavelet used is a Morlet wavelet, with central frequency of 2π . The frequencies that occur regularly appear as brighter, horizontal artifacts. The frequency-scale relationship in the figure is given by $\text{frequency} = 2^{12}/\text{scale}$. The y-axis is the logarithm (base 2) of the scale. The bright vertical spikes line up with artifacts in the original data which require the use of multiple frequencies in their wavelet representation. The bright horizontal band at the top is not showing periodic behavior (the period in this case would be larger than the length of the data set), but rather shows the presence of low-frequency wavelets needed to model the long-term, smooth component of the data.

The horizontal band at about 11 reflects a periodic component with frequency $2^{12}/2^{11} = 2$ for the data set. This corresponds to the 4 large magnitude spikes in the original data. Of more interest are the two high frequency bands. This part of the spectrum is enhanced in Figure 1.3. These bands are at approximately 2 and 3, and represent frequencies of 2^{10} and 2^9 , respectively. Scaling these to the data set length gives frequencies of 4.31 and 8.63 points, or, since each point represents 3 hours, 12.94 and 25.88 hours. Thus, the only periodic behavior found relates to the daily tides.

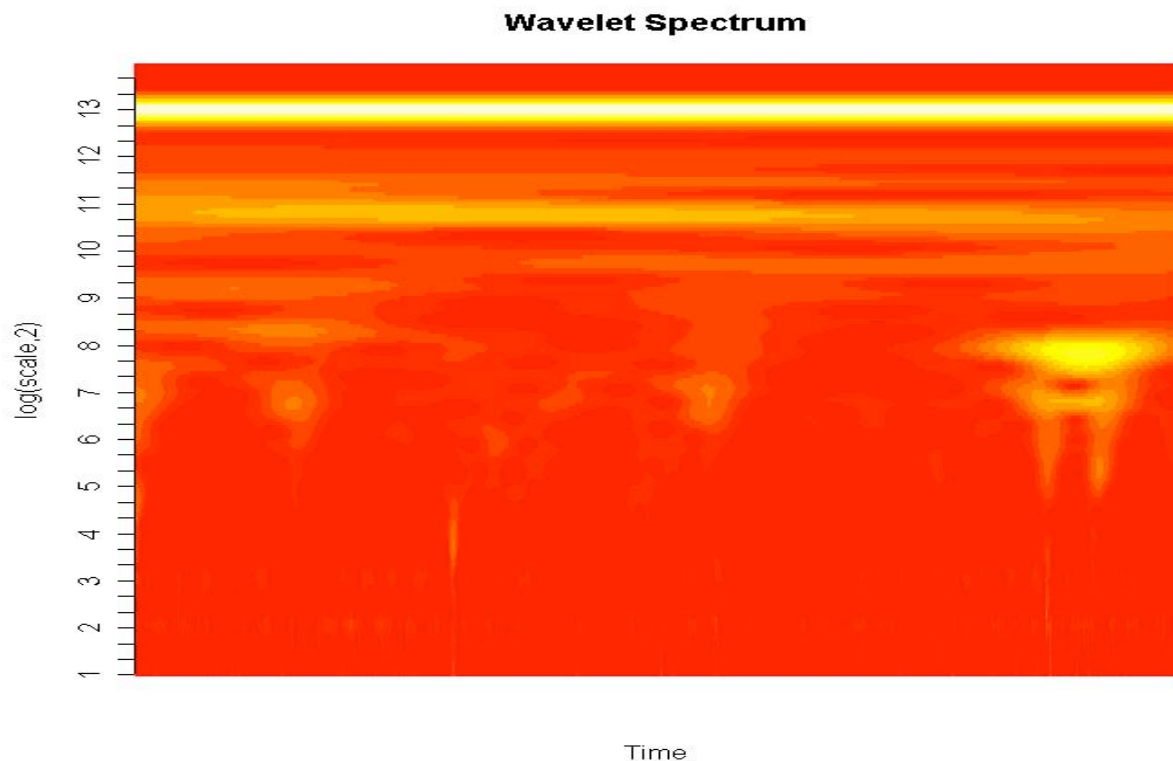


Figure 1.2. Wavelet spectrum of discharge data set 1.

These known components were removed using wavelet thresholding. Since the magnitude of the tidal effect does not appear significant in relation to the remainder of the data, it should be

effectively eliminated by this procedure. We applied various wavelet-thresholding methods, but essentially received the same results each time. The thresholded (smoothed) discharge data are shown in Figure 1.4. A second spectral analysis confirms that the periodic tidal effect has been removed. For comparison, detrending using the common local polynomial fitting failed to remove completely this daily effect, perhaps because of irregularity in the data. Note that in each of the spectrum figures, there is a bright vertical line corresponding approximately to time 1200 in Figure 1.4. This is perhaps bad data. For example, the direction of flow at this point reverses itself, something unlikely given the nature of the springs flow. It is being investigated.

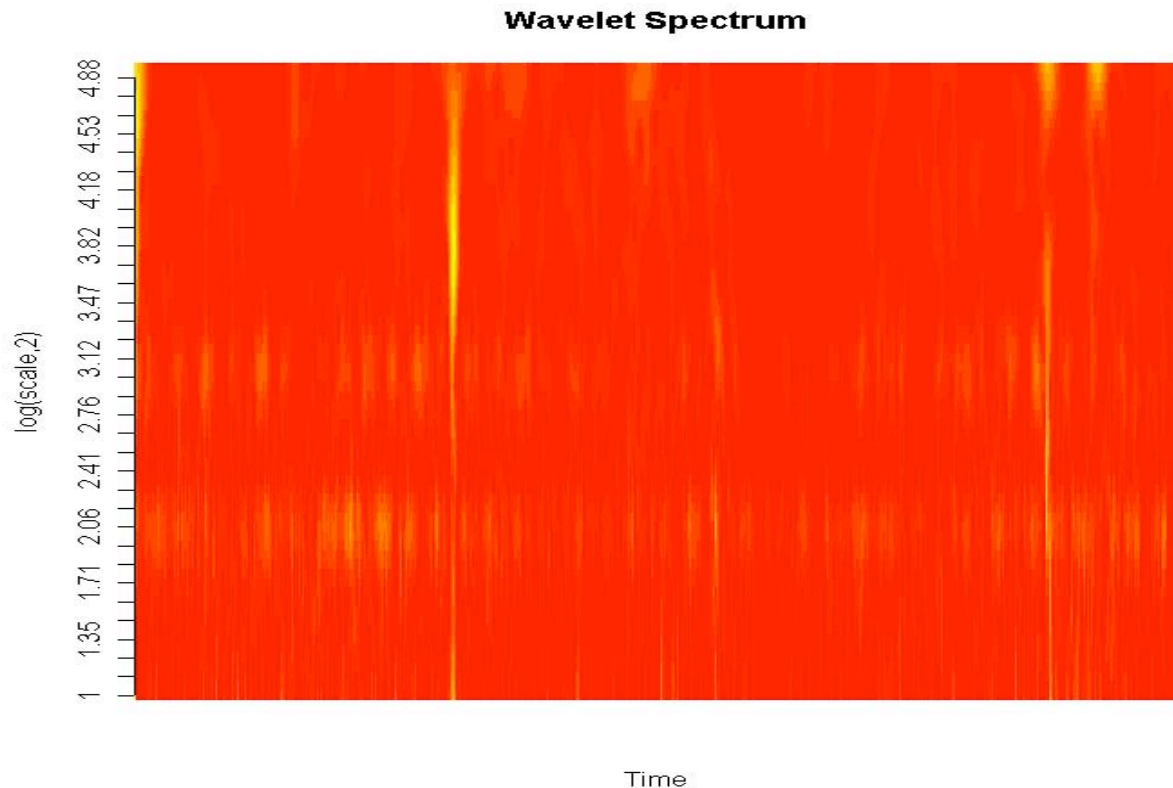


Figure 1.3. Close-up of Figure 1.2

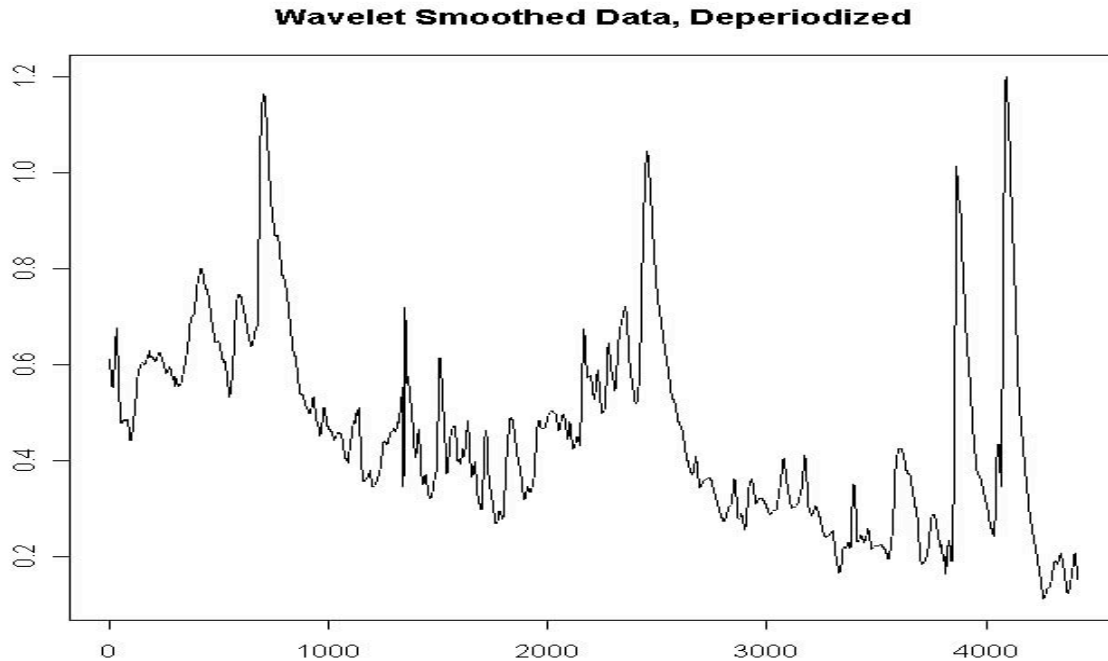


Figure 1.4. De-periodized discharge data from Set 1

Our next step was to characterize the large-magnitude events (storm events) seen as spikes in the data of Figure 1.4. The assumption for the model is that these spikes are related to rainfall in the surrounding geographic area to the spring. Since the spikes seem to possess a basic set of features (fast increase, prolonged decrease) that are merely scaled and translated throughout the x-y plane, we will have attempted to find a mathematical description of the "prototype" spike. There are two approaches to consider, one statistical, the other deterministic. First, we attempted to model a subset of these spike events with a set of orthogonal basis functions. This approach would give us a small set of functions that explain most of the variation in these spikes. Several spikes were chosen to be a training set to create the basis. Then, using Principle Component Analysis (PCA), also known as Empirical Orthogonal Analysis (EOF), a basis was chosen. What is desired is that all the spikes in the data can be represented as a scaled, translated version of some combination of these basis functions. Once this parameterization of each spike (in terms of the basis functions) is determined, we would correlate these spikes with the external events such as rainfall.

Only two basis functions were found necessary to explain over 98% of the statistical variation in the spike shapes; these are illustrated in Figure 1.5. In fact, a single one of these basis functions can explain nearly 95% of the variation.

There are a few drawbacks to this method of parameterizing the spikes, however. The basis functions have no analytic form for ease of interpretation. Additionally, they depend on the training set of spikes used in the PCA. The biggest concern is in terms of accurately modeling the underlying assumptions about rainfall and subsequent spring flow. Namely, a rainfall event should cause a quick increase in flow, followed by a long, slow decline back to the initial starting level. For the PCA method, it can be seen in Figure 1.5 that just using the first basis function is inadequate: the dropoff period ends at a much lower level than the initial point, and the dropoff

period is of a fixed duration. Adding in the second basis function will modify the first concern (note that this function is negative near 0), but does not help with the tail concern. When attempting to parameterize the spikes with a search algorithm using these basis functions, these issues led to less than favorable results.

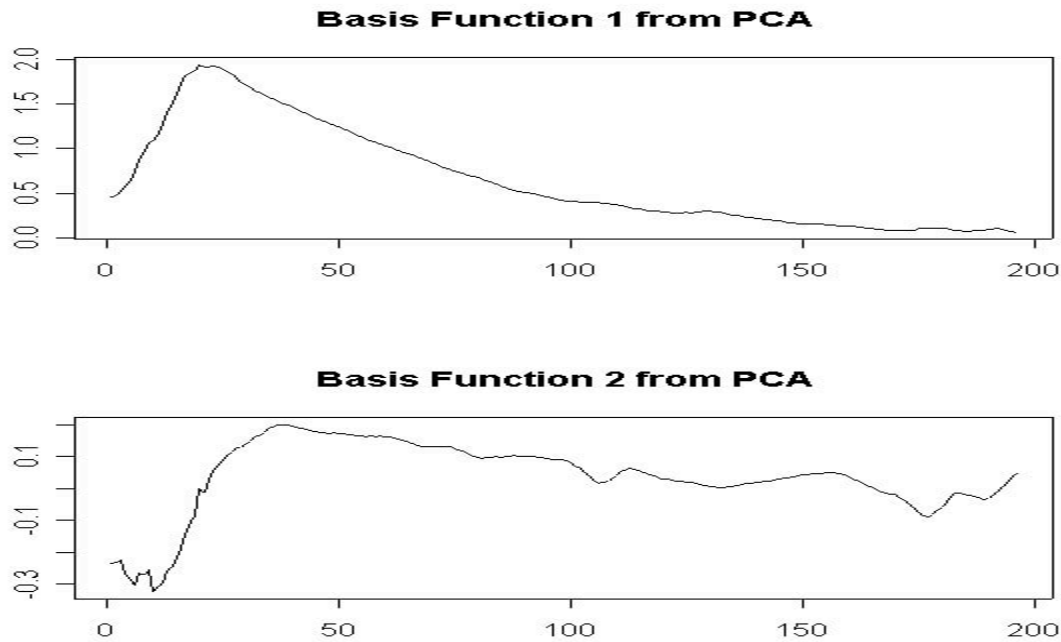


Figure 1.5. First two basis functions from principal component analysis (PCA)

The second, deterministic, approach, using a parameterized model was more successful. After some initial experimentation, we used a scaled gamma function:

$$f(x) = \gamma x^{\alpha} e^{-x/\beta},$$

where α , β , and γ take on positive values. This method proved to be much more effective for modeling the spikes. In particular, it removed the problems associated with short tail and mismatched start/end flow levels. Now, each spike is associated with a triplet of real values. Not only does this aid in data reduction, but we hope it will enable us to more easily correlate external rain data with the flow spikes. Figure 1.6 shows the results of fitting six gammas to the six largest spikes in the first 1000 points of the data. We have removed the first spike in the data since it was considered anomalous. The mixture of gamma functions is shown as a solid line, the dashed line is the original data. This method fits the data quite well.

Once the gamma curves are accounted for, the remaining signal is shown in Figure 1.7, top panel. This signal has been through three data-analysis steps. First, it was deperiodized. Next, a wavelet smoothing operation was applied to remove small-scale noise in the data. Finally, the large spike events have been identified and subtracted. At this point, a second smoothing operation is performed to remove any noise artificially incorporated into our model by the previous steps and any noise inherent in the system. This is shown as the upper curve in the bottom panel of Figure 1.7. This smoothed signal should represent the baseline flow of the springs for the period in question. Comparing baselines over multiple time periods should give

information about long term trends in area rainfall (i.e., drought periods, above average hurricane activity, etc.).

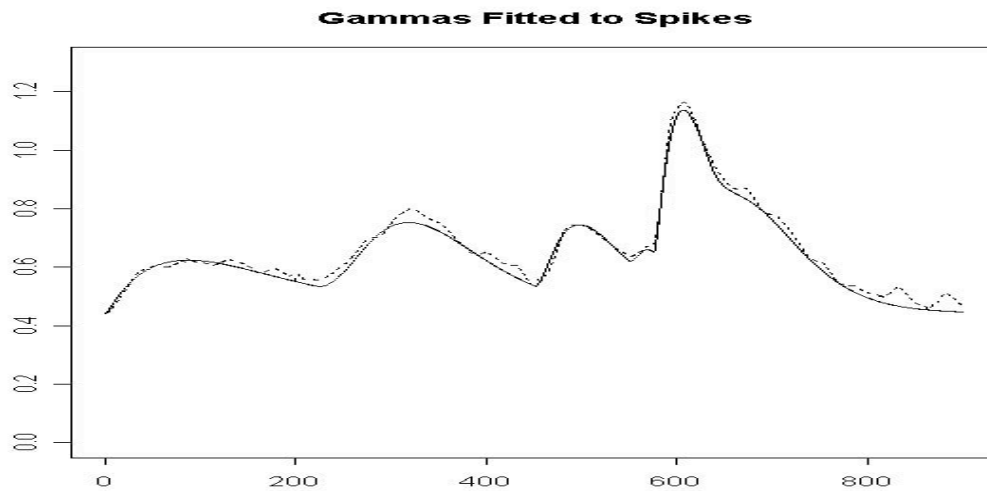


Figure 1.6. Fitted discharge data from Set 1.

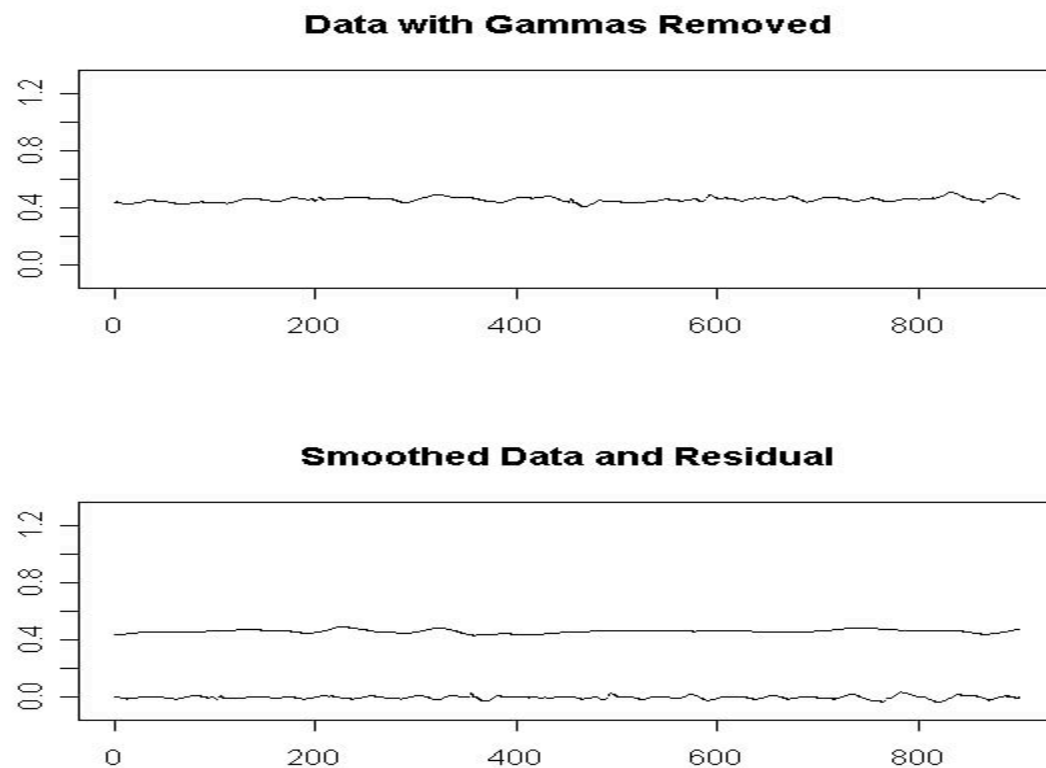


Figure 1.7. Smoothed discharge data and residuals

The residual effect after all these steps have been taken is shown as the lower curve in the bottom panel of Figure 1.7. The smoothed portion reveals that there are perhaps two more rain events between data indices 200 and 400. However, they are very small scale and may not

impact the analysis. Note that this residual amount appears to be nothing more than random oscillations in the data and can probably be ignored.

1.4 Continuing Statistical Research

There are several statistical tasks yet to be performed. First, only data set 1 has been analyzed so far. With the development of a parameterized model of storm events, we are in a position to analyze the discharge data from Sets 2 and 3 to see if the model can provide a robust representation of the behavior of the Wakulla Springs flow system. If the results with our current model do not fare well with the new data, then we will need to revisit our methods and assumptions. In addition, the discharge/speed data has so far been analyzed. The other variables (temperature and electrical conductivity) will also be examined as time permits.

Second, while we have identified much of the discharge signal with periodic behavior, system noise, and large rain events, we still need to correlate this with the external data. This will involve an extensive model building process to correlate the parameters of the gamma functions with the rain data. We have been promised access to an extensive set of rainfall data covering the Leon and Wakulla Counties for the time interval correlating to the discharge data. It will be very interesting to correlate large rainfall events with the storm events seen in the discharge data. The results of this analysis will provide significant information regarding the behavior of the Wakulla Springs flow system.

The principal task ahead is to correlate discharge with rainfall. This step has been delayed because the promised Doppler data has not yet been delivered to us. We are in the process of seeking alternate sources of this data. Once data of sufficient duration, spatial coverage and accuracy is obtained, work on this task will proceed.

Project 2: Ground Water Tracing Experiments in the Woodville Karst Plain

***Todd Kincaid
Hazlett-Kincaid Inc.***

2.1 Scope of the project

This project is also a continuation of previous studies, funded by the Hydrogeology Program, in the Woodville Karst Plain aimed at understanding the interconnections between various systems in this watershed. Hopefully, these efforts will eventually lead the development of conceptual, analytical and numerical models for depicting ground water flow and contaminant transport in karstic settings.

More specifically, the Contractor, through its subcontractor, ***Hazlett-Kincaid Inc.***, will use EPA-approved fluorescent dyes in an attempt to systematically evaluate the connection between Wakulla Spring and selected sinkholes northward of toward Ames Sink, as well as Indian and Sally Ward springs. The tracer tests will be performed such that progressively longer probable flow paths are confirmed until the final connection can be evaluated.

The Contractor will also be responsible for constructing a new database, or modifying the existing cave database, to accommodate dye tracing data from this project as well as other dye tracing data from around the State. The FGS will be responsible for populating and administering the database once it is established.

Deliverables: Periodic verbal reports on the progress of the project will be communicated with the FGS's staff. Quarterly invoices in conjunction with quarterly progress reports, followed by a final invoice and final written report on the findings will be submitted to FGS no later than June 10, 2004.

2.2 Summary

Two quantitative groundwater tracing experiments were successfully carried out in the WKP and field investigations were carried out in preparation for a future tracing experiment. The two completed traces included one between the resurgence of Black Creek and the Leon Sinks cave system, and the other between the Leon Sinks cave system and Wakulla spring. In addition, preparations were made for a future tracing experiment between the resurgence of Munson Slough (Ames Sink) and the multiple potential resurgences including the Leon Sinks cave system, Sally Ward spring, Indian spring, Mc Brides spring, the Wakulla cave system, and the St. Marks River.

All in all, the two tracer tests confirmed connects between Black Creek (surface water runoff), the Leon Sinks cave system, and Wakulla Spring; indicated a minimum transport time between surface water and conduit flow of approximately 800 m/day; indicated minimum through-conduit groundwater velocities of more than 600 m/day; provided the first definitive evidence of the suspected connection between the Leon Sinks cave system and Wakulla Springs; and demonstrated that, by and large, all the surface water flow from the region southwest of Tallahassee, and the northwestern part of Leon County flows very quickly to the Leon Sinks cave system in the Floridan aquifer and then to Wakulla Springs.

Additionally, HKI developed meta-data files for each of the GIS shape files contained in the Florida Cave Database and the files have been rendered available in both GIS and txt file formats via the project website (www.hazlett-kincaid.com/FGS).

Finally, HKI developed a template for a database for quantitative deliberate groundwater tracing results and disseminated to the FGS for internal review. The database is intended to be a central repository for all quantitative tracing work done in the State of Florida such that researchers and water resource managers will have access to important pathway and travel-time data gleaned from tracer testing but not readily accessible through the current state permitting and notification system.

The results of two tracing experiments conducted in the past year are described in §2.3, while work on the cave database is described in §2.4 and the dye tracing database is described in §2.5. All in all, this one tracer test confirmed the connection between Black Creek (surface water runoff) and the Leon Sinks cave system; indicated a minimum transport time between surface water and conduit flow of approximately 800 m/day; indicated minimum through-conduit groundwater velocities of more than 600 m/day; provided the first definitive evidence of the suspected connection between the Leon Sinks cave system and Wakulla Springs; and demonstrated that, by and large, all the surface water flow from southwestern Tallahassee, and western Leon County flows very quickly to the Leon Sinks cave system in the Floridan aquifer and very likely to Wakulla Springs.

2.3 Tracing Experiments

Two groundwater tracing experiments were conducted in the WKP, one in November 2003 and the other in February 2004. The purpose of the experiments was to trace the flow of water between the resurgence of Black Creek and the Leon Sinks cave system and then trace the flow of water between the Leon Sinks cave system and the Wakulla cave system. Both experiments were conducted in order to prepare for a forth-coming experiment that will trace the flow of water from Ames Sink to potential discharge points. Additional field investigations were performed to identify the most probable discharge points for the Ames Sink water and instrument some of those locations with sampling tubes in preparation for an experiment. The results of the tracer tests are presented in graphical and narrative format in §2.3.1 and 2.3.2. The material is also available via a project website at: www.hazlett-kincaid.com/FGS/Tracing.

2.3.1 Woodville Karst Plain Groundwater Tracing: Black Creek to Leon Sinks Cave

Introduction In November 2003, our group conducted a groundwater tracer test with the objective to determine the destination of water sinking from Black Creek, which drains Cow Swamp west of the Leon sinks cave system in northern Leon County.

Identifying probable connection points was a critical issue because of the proximity of Black Creek to both the Leon Sinks and Chips Hole cave systems and because very little information is available about possible dark water tunnels in the Leon sinks cave system between Emerald and Turner sinks. Sampling stations were therefore established at many accessible locations between the Black Creek sink (Black Hole) and Turner sink. Six automated water samplers, on loan to the project from the Northwest Florida Water Management District, were installed at the sampling locations to collect samples at 1-6 hour intervals.

Initial Sampling Locations

Dark water tunnel south of Emerald (~2550 m from the Black Creek sink), Fish Hole sink (~2600 m from the Black Creek sink), Upper River sink (~3500 m from the Black Creek sink), Turner sink (~4350 m from the Black Creek sink), Stafford sink (~4350 m from the Black Creek sink), and a point approximately 300 m upstream of Upper River sink accessed via tubing installed by WKPP divers.

Injection At approximately 10:00 PM on November 21, 2003, 3 kg of uranine dye were released into the flow of Black Creek 10 m upstream of the sinkhole. Our initial hypothesis was that the dye would enter the cave system somewhere between Upper River sink and Turner sink or that it might go directly to the Chip's Hole cave system. Unfortunately, we were not able to gain access to Chip's Hole from the property owner, St. Joe Paper Company, which meant that if the connection was somewhere in Chip's Hole cave, we would probably miss the dye cloud all together.

Tracer Recovery The dye entered the Leon Sinks cave approximately 60 hours after the injection at the same location that received the flow from Fisher Creek: the dark water tunnel approximately 210 m south of Emerald sink. From Emerald sink, the dye flowed south through the cave system toward each of the downstream sampling locations. In another turn of luck, the dye concentration was sufficient to provide detectable levels at each of the sampling stations except Stafford sink.

Our ambitions for the test then rapidly expanded. Sampling intervals were extended over the Thanksgiving holiday and into the next week in hopes of measuring complete breakthrough curves at each of the downstream sampling points. When the dye cloud reached Turner sink at easily detectable levels nearly 4 days after the injection, ambitions went up even further. The sampler from Upper River sink was moved to Wakulla Springs (~9300 m from the Black Creek sink) and set up to collect water samples from a tube that had been previously installed into the cave close to the entrance.

Unfortunately, we were unable to keep the experiment fully staffed for the extended period. Sampling stations were maintained for as long as possible, about 13 days for Wakulla Springs and Turner sink. Afterward, all the samples and sampling logs were collected and were shipped to Cambrian Groundwater for analysis. It wasn't until early January that we learned the good news. Nearly complete breakthrough curves were obtained for Emerald and Upper River sinks. Partial breakthrough curves were obtained for the remainder of the originally planned sampling stations except Stafford sink, and, what appears to be the leading edge of a breakthrough curve was obtained at Wakulla Springs approximately 10 days after the injection. All in all, this one tracer test confirmed the connection between Black Creek (surface water runoff) and the Leon Sinks cave system; indicated a minimum transport time between surface water and conduit flow of approximately 800 m/day; indicated minimum through-conduit groundwater velocities of more than 600 m/day; provided the first definitive evidence of the suspected connection between the Leon Sinks cave system and Wakulla Spring; and demonstrated that, by and large, all the surface water flow from southwestern Tallahassee, and western Leon County flows very quickly to the Leon Sinks cave system in the Floridan aquifer and very likely Wakulla Spring.

Figure 2.1: Map showing flow paths confirmed and inferred by the November 2003 Black Creek – Leon Sinks cave system groundwater tracing experiment. Note that the pathway established by the Fisher Creek tracing experiment is also shown and that the flows from both Fisher and Black Creeks converge and enter the Leon Sinks cave system at the same point, a dark water tunnel approximately 700 feet downstream of Emerald Sink.

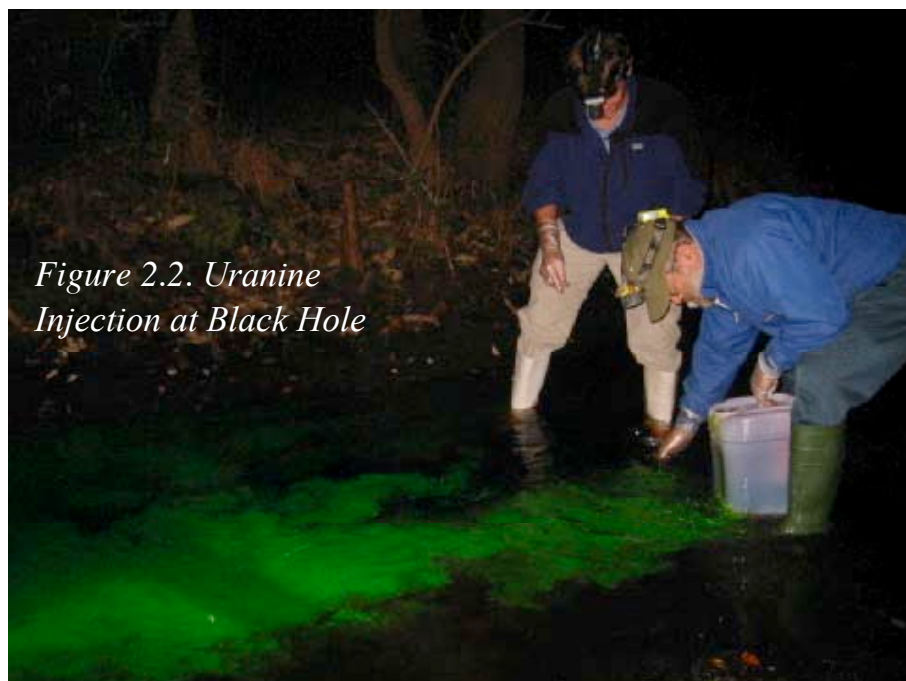
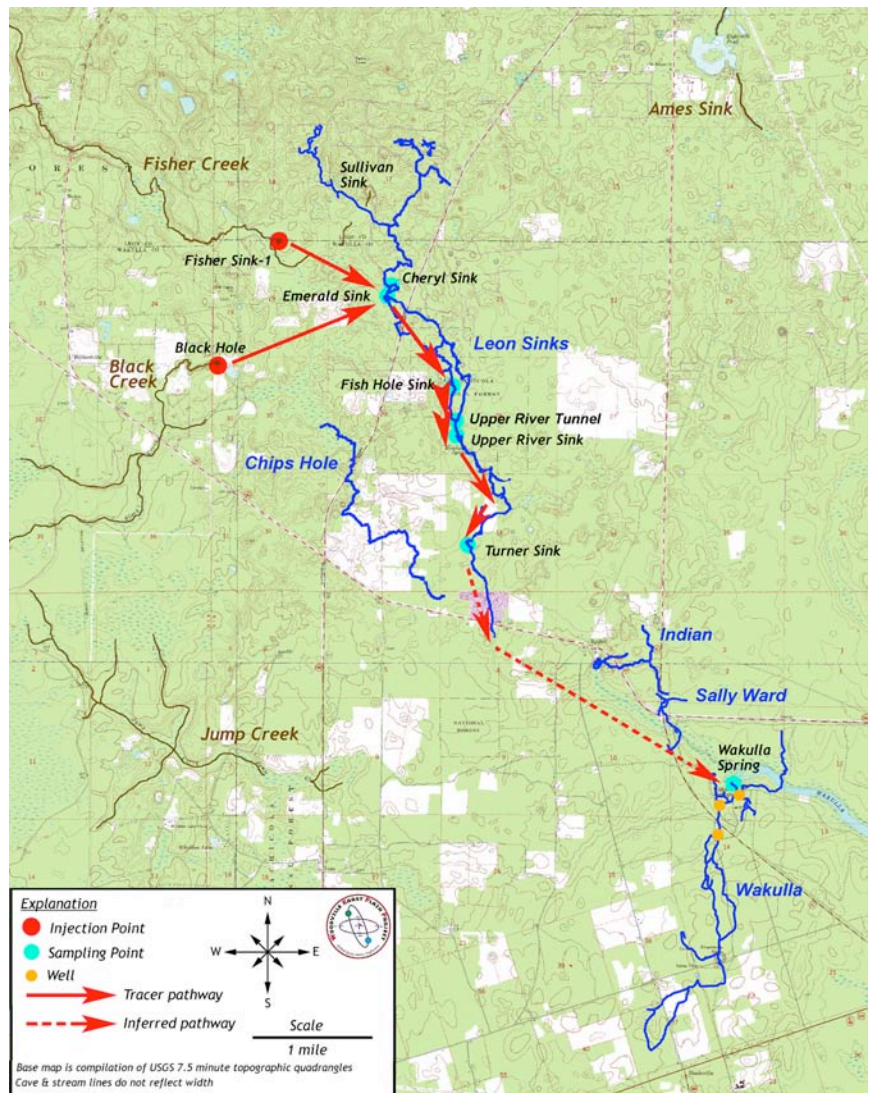


Figure 2.2. Uranine Injection at Black Hole

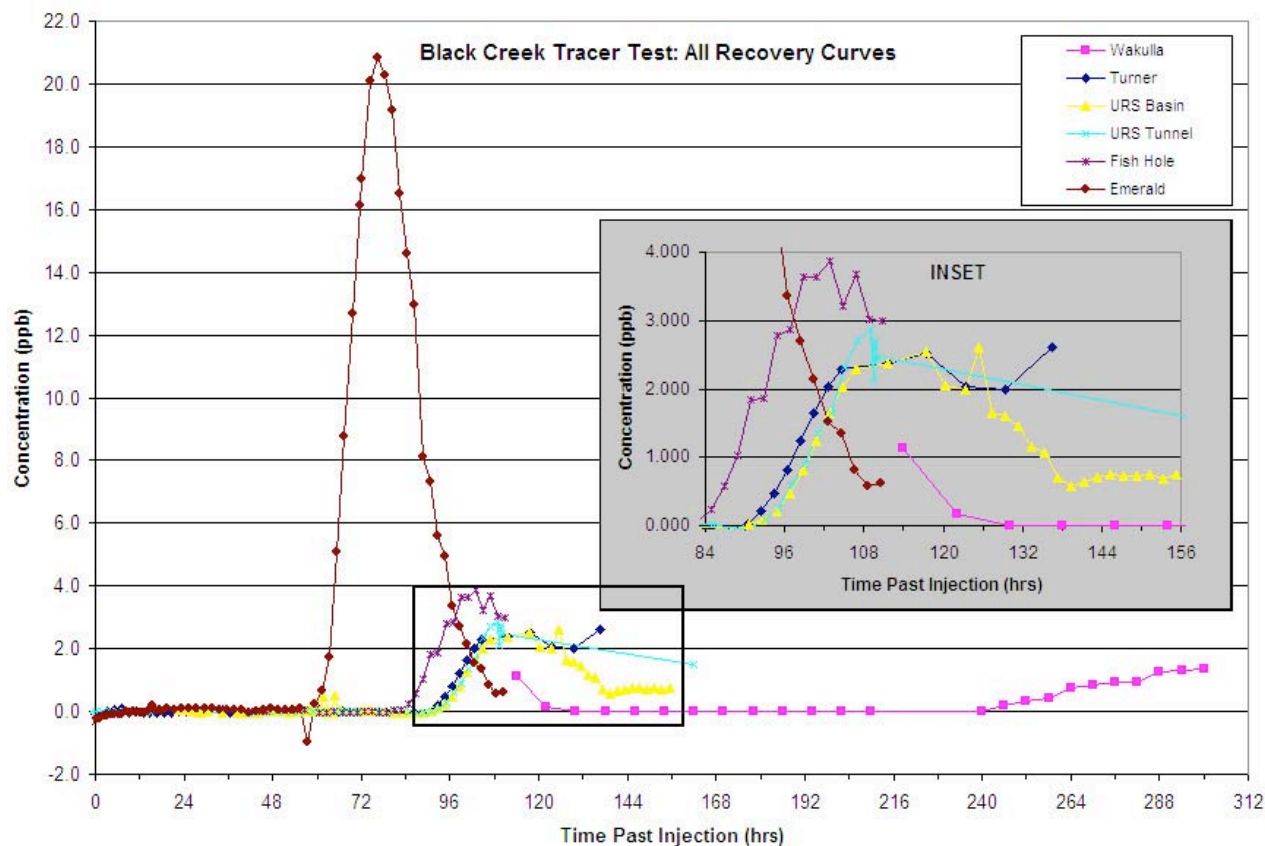


Figure 2.3 Plot showing the tracer recovery curves from all of the stations sampled for the November 2003 Black Creek – Leon Sinks cave system groundwater tracing experiment. The inset shows an expanded view of the recovery curves from the stations downstream of the initial recovery at the dark water tunnel.

2.3.2 Woodville Karst Plain Groundwater Tracing: Leon Sinks Caves to Wakulla Springs Caves

Introduction. In February 2004, our group set out to confirm the results of the November 2003 experiment, in which a groundwater tracer released into Black Creek flowed to the Leon Sinks cave system and then appeared at Wakulla Springs approximately 10 days after it sank into the Black Creek sinkhole. The objectives of the test were to confirm the connection to Wakulla Springs, identify the probable point of connection within the Wakulla Springs cave system, and obtain complete recovery curves at Upper River and Turner sinks in the Leon Sinks cave system and the sampling stations within the Wakulla Springs cave system.

Our ambitions for the test then rapidly expanded. Sampling intervals were extended over the Thanksgiving holiday and into the next week in hopes of measuring complete breakthrough curves at each of the downstream sampling points. When the dye cloud reached Turner sink at easily detectable levels nearly 4 days after the injection, ambitions went up even further. The sampler from Upper River sink was moved to Wakulla Springs (~9300 m from the Black Creek

sink) and set up to collect water samples from a tube that had been previously installed into the cave close to the entrance.

In short, the test was a complete success. The test confirmed the connections between the surface flows of Fisher and Black creeks, the Leon Sinks cave system, and Wakulla spring. Tracer detection times and locations indicate that the connection between the two caves must be somewhere south of the southern A/K tunnel junction, and complete recovery curves were measured at all sampling stations where the tracer was detected.

Injection At approximately 10:00 PM on Thursday night, February 5, 2004, we injected 3 kg of uranine dye into the western conduit of the Leon Sinks cave system 700 ft downstream of Emerald sink. The point of release is approximately 20 feet into the dark water tunnel that contributes flow from Fisher and Black creeks. The dye was injected using a pump and tubing in the same manner as was used for the Sullivan-Cheryl and Cheryl-Emerald traces. A

concentrated mixture of dye and water was mixed with approximately 4 gallons of water, which was then pumped into the cave through the tubing over the course of approximately 20 minutes. Four additional gallons of water was then pumped into the cave immediately following the dye injection to flush the tubing.

Sampling Locations and Recovery Curves

The sampling strategy called for the regular collection of water samples at

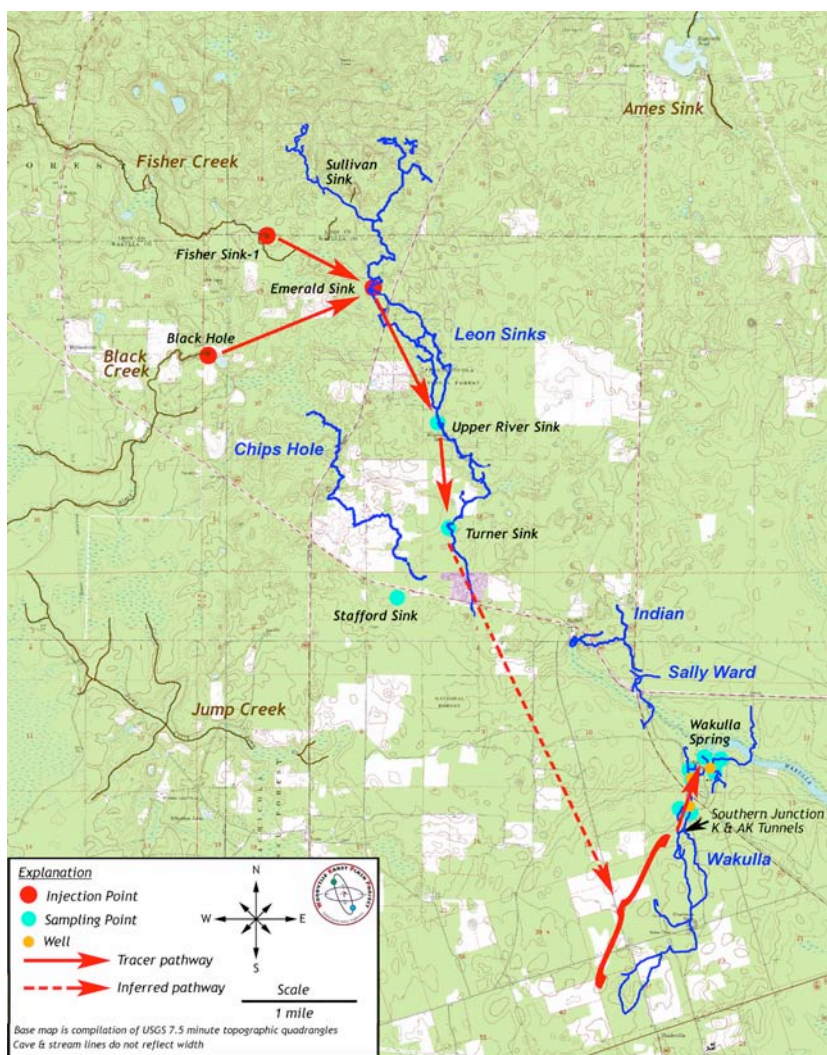


Figure 2.4: Map showing flow paths confirmed and inferred by the February 2004 Leon Sinks cave system – Wakulla Spring groundwater tracing experiment. The inferred pathway between Turner Sink and Wakulla cave follows the Leon Sinks cave for the extent of explored passage and then connects to a tunnel identified by Woodville Karst Plain Project exploration divers as the most probable connector to the Leon Sinks cave. The pathway must intersect the Wakulla cave somewhere south of the southern connection between K and AK Tunnels shown. Note that the pathways established by the Fisher Creek and Black Creek tracing experiments are also shown

nine separate locations including Upper River and Turner sinks in the Leon Sinks cave system and seven locations within the Wakulla cave system. Automated water samplers provided by the Northwest Florida Water Management District were used to collect samples at 1, 2, and 6, hour intervals at five of the sampling locations over a 10-day period after the injection. Project volunteers collected grab samples from the remaining four locations over a 7-day period after the injection. All of the samples were collected using tubing stretched from the land surface into the conduit at each location. Six of the sampling locations in Wakulla cave were accessed through wells recently drilled into the cave system. The water samples were analyzed on a field fluorometer to determine if the samples contained the tracer. A smaller number of the samples found to contain the tracer were also run on a scanning spectrofluorophotometer to verify the results. Tracer breakthrough curves were measured at six of the nine sampling locations listed below.

Figure 2.5. (at right) Gareth Davies & James McClean running the injection at Emerald Sink

Figure 2.6. (below) Gareth Davies & volunteers changing samples at the Wakulla A/K-Tunnel well



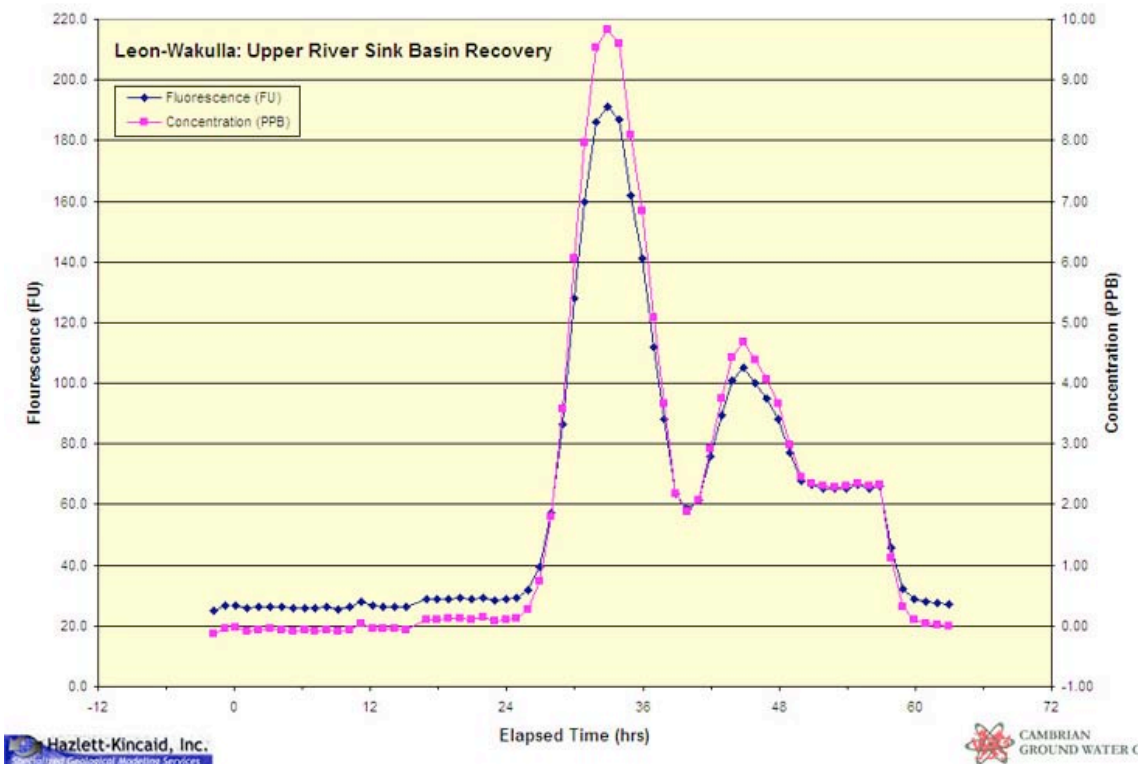


Figure 2.7 Leon: Upper River Sink (~2100 m from Emerald

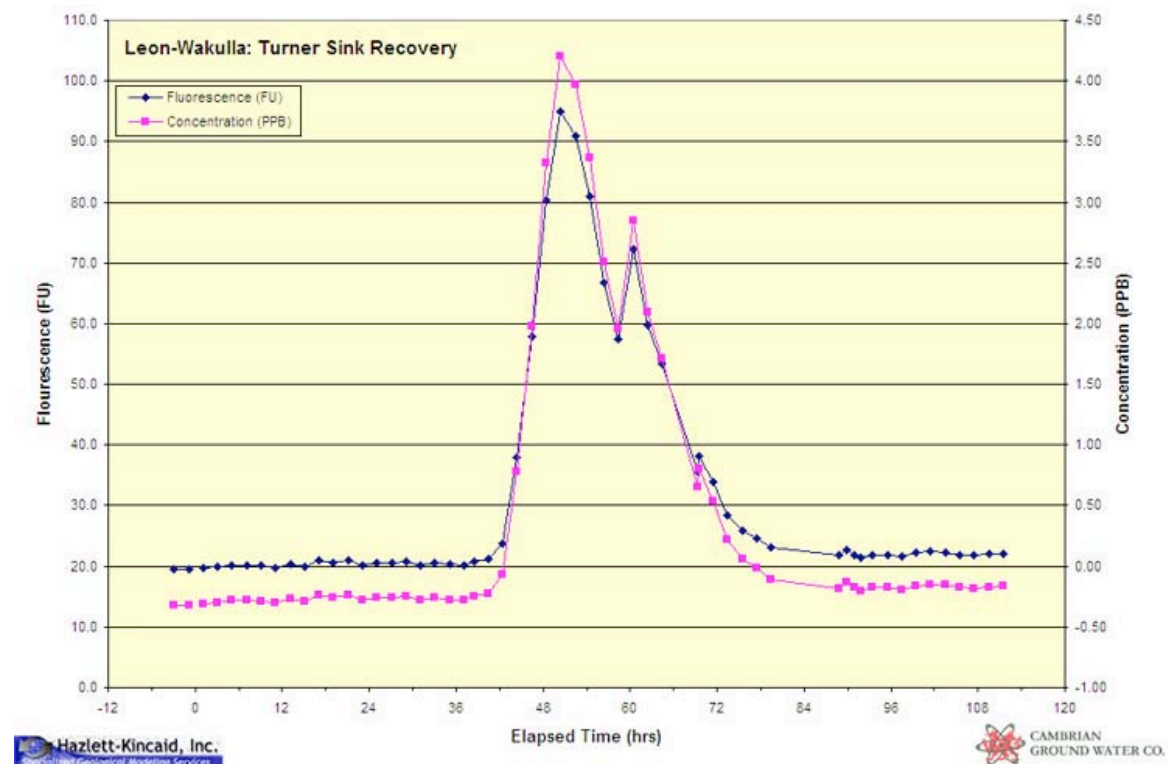


Figure 2.8. Leon: Turner Sink (~3650 m from Emerald Sink)

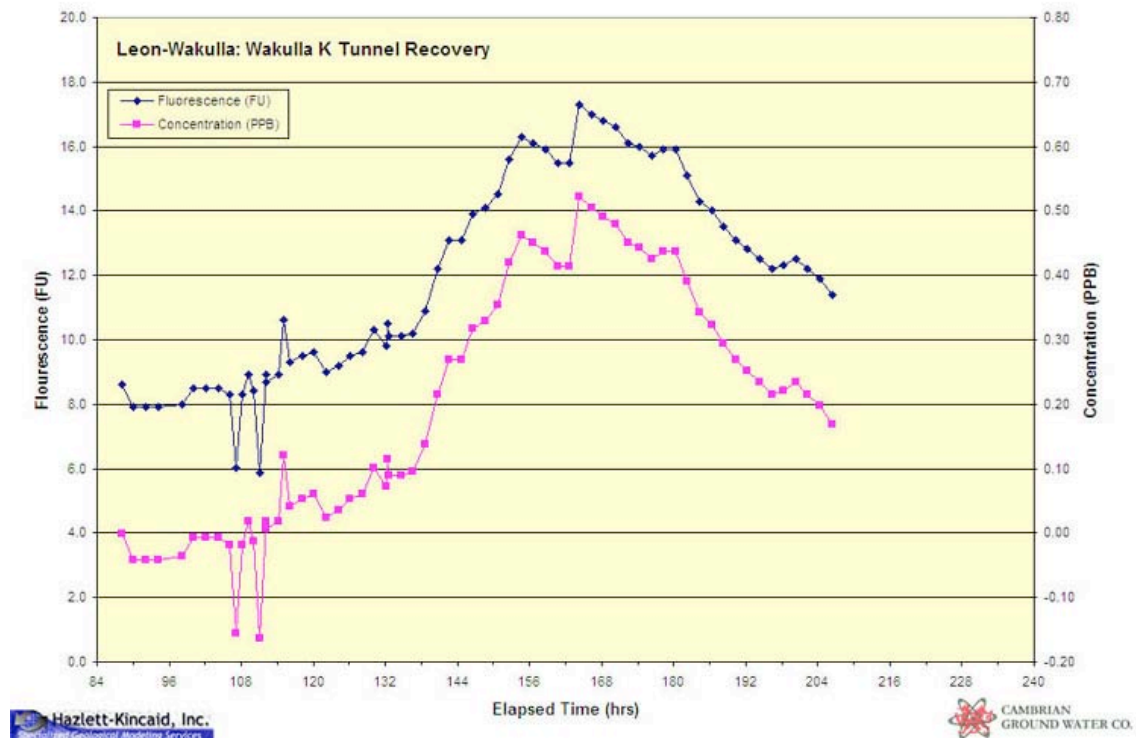


Figure 2.9. Wakulla: K-Tunnel (~14,000 m from Emerald Sink)

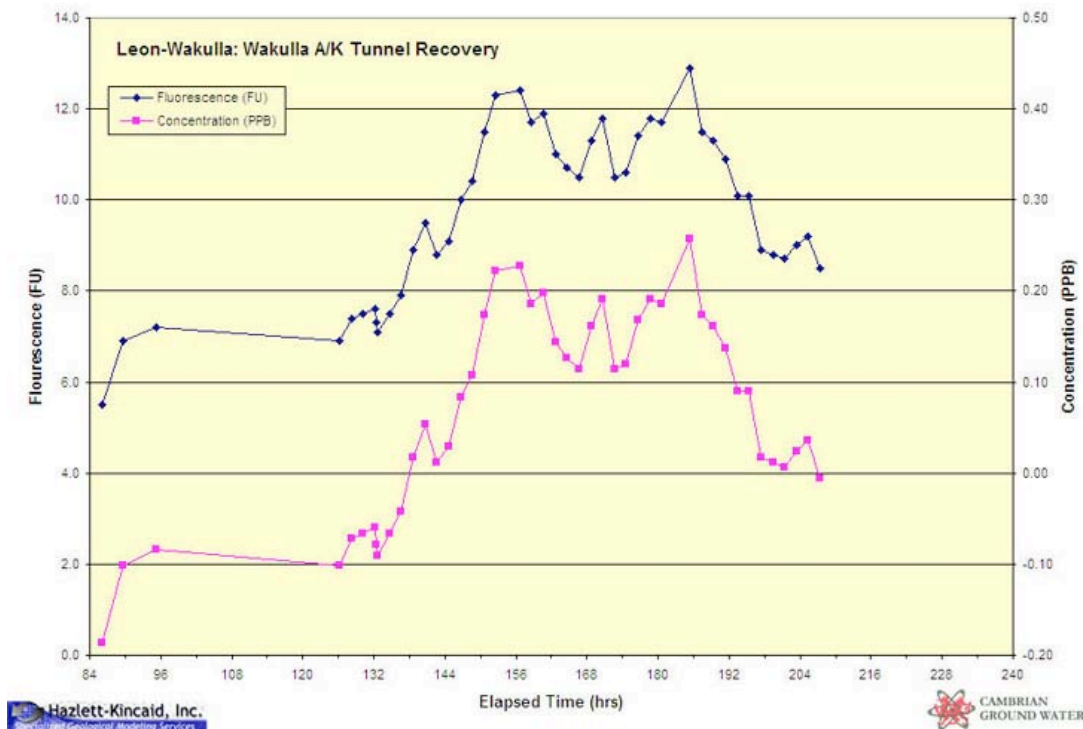


Figure 2.10. Wakulla: A/K-Tunnel (~14,000 m from Emerald Sink)

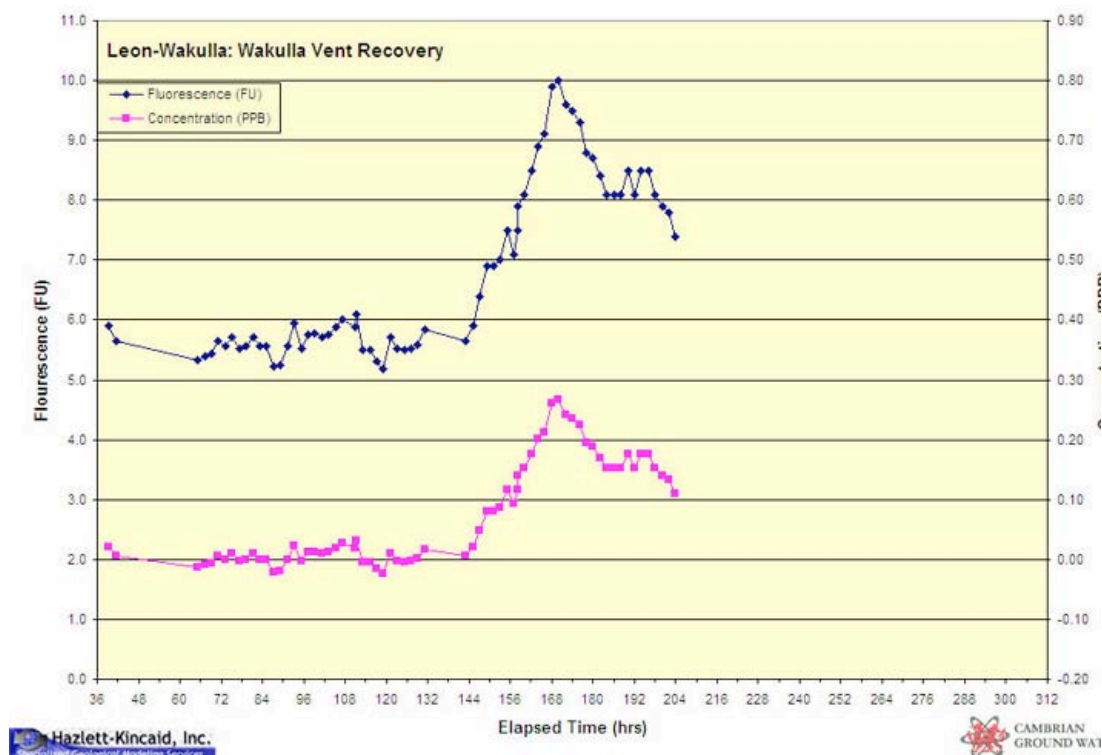


Figure 2.11. Wakulla: Spring Basin (~15,500 m from Emerald Sink)

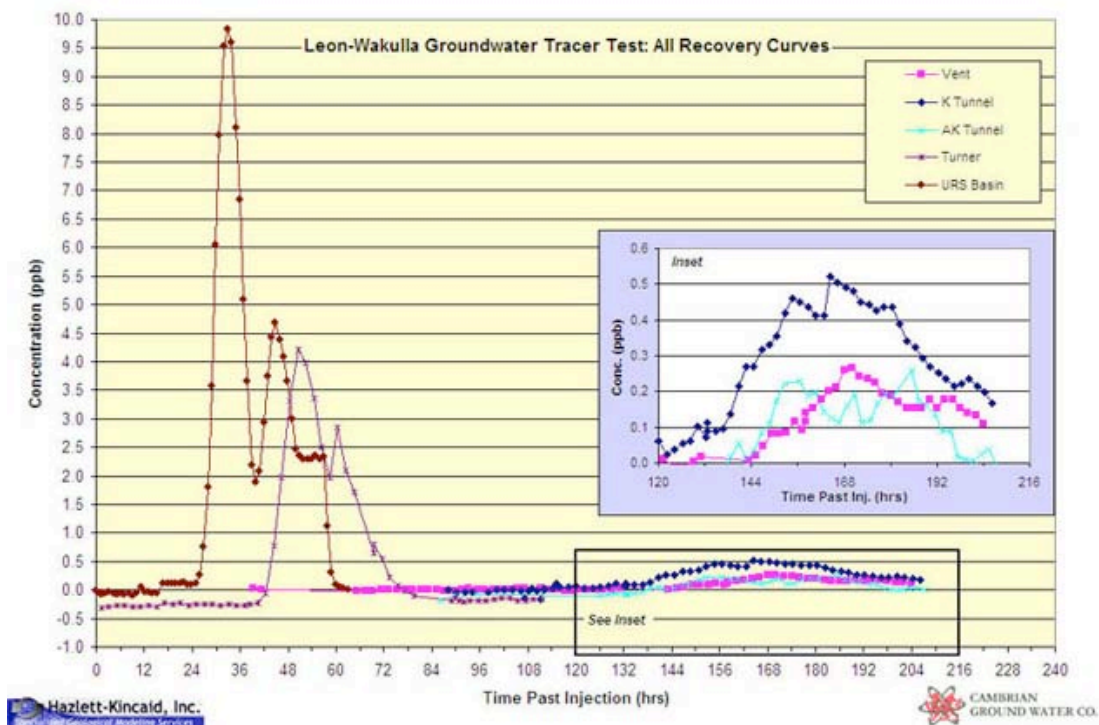


Figure 2.12. Composite of groundwater tracer breakthrough curves for each of the sampling stations at which the tracer was detected. The data from the A/D Tunnel has not yet been analyzed.

What's Next? The next phase of work will focus on Ames Sink, seeking to determine the destination of the surface waters which enter the aquifer at this point. Four possible destinations are McBrides Slough and the Leon Sinks, Indian Spring and Wakulla Springs cave systems. With the successes of the past two tracer tests, verifying a connection to Leon Sinks will be sufficient to conclusively show a connection to Wakulla Spring.

To accomplish this task, we will be launching a series of focused tracer tests between various points north of Wakulla Springs and east of the Leon Sinks cave system designed to systematically characterize the flow paths existing to the north of Wakulla Springs. The first step however will be to repeat the portion of the Black Creek test between Emerald Sink and Wakulla Springs. Sampling periods will be extended such that complete breakthrough curves are captured at all sampling locations including Wakulla Springs. This will provide the unambiguous evidence necessary to confidently demonstrate the connection between the Leon Sinks cave system and Wakulla Springs. From there, the effort will shift to Ames sink.

Global Underwater Explorers and the Woodville Karst Plain Project will again be instrumental in the success of the project through their participation in identifying and instrumenting key sinkholes and conduits adjacent to and within the Leon Sinks cave system. They are also initiating an effort to re-map the section of the Leon Sinks cave system between Turner and Emerald Sinks with focus on identifying dark water tunnels.

Ultimately, the goal of these efforts is to develop a comprehensive model of groundwater flow and groundwater/surface water interactions within the Woodville Karst Plain that will identify the key variables crucial to developing a sustainable protection plan for Wakulla Spring and groundwater resources in Leon and Wakulla Counties.

2.4 Meta Data Compilation for the Florida Cave Database

Caves are one of the most hydrologically important but least understood and documented physical features in the Floridan aquifer. Though there are currently more than 50 mapped underwater caves in Florida and perhaps as many as 4000 above water caves in Florida that have either been mapped or located, these features are rarely included in hydrogeological investigations. The primary limiting factor is access, particularly in Florida where many caves, and all of the longest caves, are fully saturated (underwater). Though very few professional hydrogeologists have actually been in an underwater cave in Florida, explorers have traditionally surveyed the trends and dimensions of the cave passages they explore and those maps now represent the most significant and extensive record of Florida's underwater caves available to the professional hydrogeologist.

As with direct observation of the underwater cave environment, the problem with using the maps has been access, because the maps do not reside in a centralized location nor are they typically in a suitable format for inclusion in a hydrogeologic investigation. The Florida Cave Database project was initiated by the Florida Geological Survey Hydrogeology Section (FGS-HS) to compile and synthesize all available cave maps and cave location data into a centralized GIS compatible database. Ultimately, the purpose is to make cave maps more accessible to professional hydrogeological investigations, and to encourage their use in such endeavors.

To date, the Florida Cave Database includes 26 of the largest underwater caves in Florida digitized from maps and survey data provided by the National Speleological Society – Cave Diving Section and the Global Underwater Explorers – Woodville Karst Plain Project. Location, conduit trend, conduit dimension, water quality, flow direction, ownership, and land use include some of the data fields underlying point and line based shape files fully documented by

metadata. The water quality component of the database will be rendered compatible with the Florida Springs database (also being developed by the FGS-HS). Though specific access issues remain to be addressed, all of the shape files are currently available to hydrogeologists via the Internet. Further information on the Florida Cave Database is available at: www.hazlett-kincaid.com/FGS/cave-db/.

As part of this contract, meta data files were prepared for each of the point and line GIS shape files describing the underwater caves in the Florida Cave Database. The metadata files are provided as GIS files (.xml format) with the corresponding shape files, which are accessible via the project website: www.hazlett-kincaid.com/FGS/cave-db/Internal_Pages/database.htm. The files are also provided as MS Word (.doc format) along with the Florida Cave Database website on a CD-ROM attached to this report as Appendix 2.1.

2.5 Preliminary Groundwater Tracing Database Design

The goal of this task is to initiate the development of a database that will contain the results and pertinent details of all deliberate groundwater tracing experiments conducted in the state of Florida. The benefit of such a database will be a broader understanding of karstic flow paths in the Floridan aquifer and thereby improved hydrogeologic characterizations and assessments in karst regions of Florida.

A draft database design outline was submitted to the FGS for internal review. The current design calls for the construction of the database as a suite of GIS shape and database files similar in concept to the existing Florida Cave Database. A copy of the draft database design outline is provided in Appendix 2.2.

Project 3: Isotopic Tracing to Provide Quantification of Groundwater Discharge to Coastal and Riverine Systems

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Florida State University*

3.1 Scope of the project

Remote sensing surveys conducted by the FGS in 2002/2003 identified “hot spots” of ground water discharge to both fresh and saline surface waters in Florida. The objective of this task is to provide tracer based estimates of the volume of ground water being discharged in these locations, under conditions of non-point source diffusive flow. This study will also evaluate the tracer approach for determination of point source or springs discharge.

To carry out this task, the researchers (Drs. Burnett and Chanton of FSU’s Department of Oceanography) will use distributions and inventories of Rn and Ra isotopes to estimate ground water discharge rates in a marine system with diffuse flow, and a freshwater riverine system with diffuse flow. They will also evaluate the effectiveness of this approach for measuring discharge in a springs system with point source flow. Ground-truthing would be performed in the diffuse systems with automated seepage meters already assembled by the research team.

Deliverables: Periodic verbal reports on the progress of the study, quarterly invoices in conjunction with quarterly progress reports, and a final invoice in conjunction with the final written and digital reports on the findings and recommendations of the study due to the Department no later than June 10, 2004.

3.2 Summary

We surveyed near-shore areas around Lanark Reef (Franklin County), Spring Creek (Leon County), and off Taylor County for naturally occurring radon and radium isotopes as indicators of submarine groundwater discharge. In the case of Lanark reef, we also conducted detailed time-series measurements of ^{222}Rn inventories that can be related to absolute discharge estimates by a mass balance approach. Our estimates showed groundwater velocities (not necessarily fresh water but a mixture of fresh and re-circulated seawater) ranging from 5-40 cm/day with increased seepage rates at low tide. Profiles taken across Spring Creek displayed

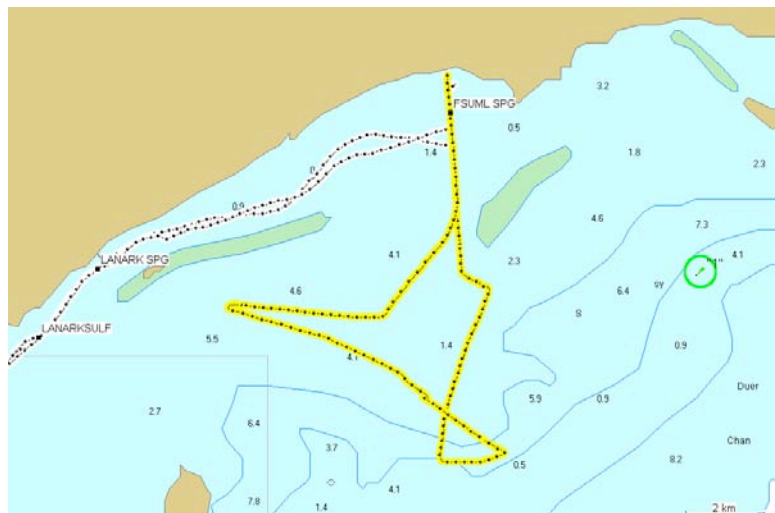


Figure 3.1 Track of radon survey around the Lanark Reef area to identify areas of enhanced seepage. The survey along the shoreline was done in a pontoon boat and the offshore work was performed from the R/V Seminole.

various degrees of mixing between spring water and ambient seawater. High and consistent radon was found south of spring numbers 8, 10, and 11 while the creek north of vent #9 displayed somewhat lower radon and higher salinities. In offshore Taylor County, radon was found to be elevated at Lamb Spring that may be connected to land via an ancient riverbed. This is a good candidate for future study.

3.3 Reports of surveys

3.3.1 Lanark Reef

During the period from March 30 to April 2 2004, investigators from FSU Department of Oceanography joined personnel from the Florida Geological Survey (FGS) to investigate the area around Lanark Reef using a continuous radon system and meter measuring conductivity, temperature and depth to search for areas of point source discharge (springs) as well as diffusive seepage. Lines were run parallel to the shore and one transect was made several kilometers out to sea (Figure 3.1). Radon inventories (^{222}Rn activity times water depth) and salinity trends clearly indicated the previously known Lanark and Sulfur springs (Figure 3.2). There is also a nearshore area just west of the FSU Marine Laboratory (FSUML) that displays lower salinity and elevated radon levels (circled region in Figure 3.2). This appears to be an area where diffusive seepage may be significant as there is no surface drainage anywhere nearby.

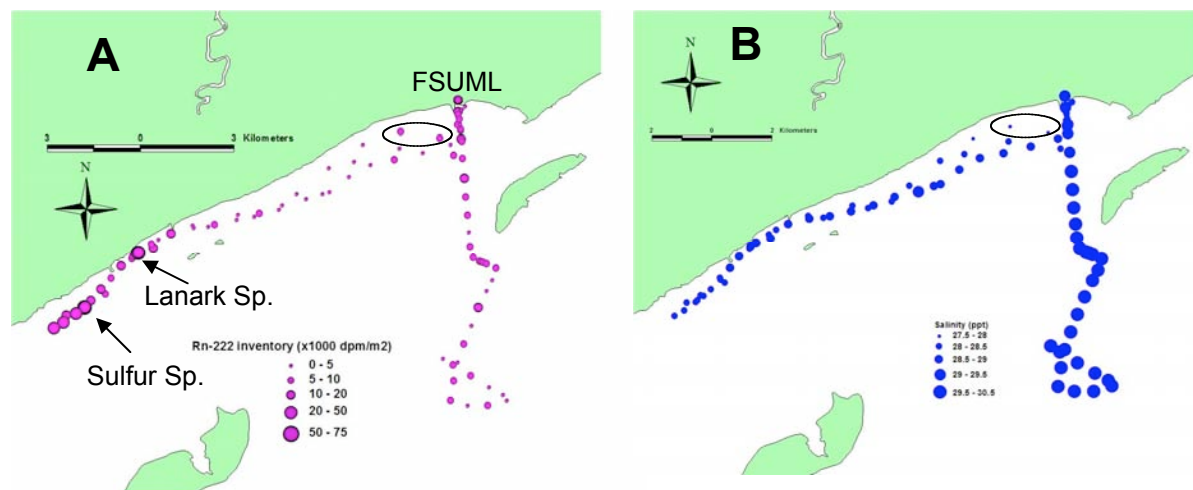


Figure 3.2. Survey results of (A) radon inventories and (B) salinity from Lanark Reef area, March/April, 2004. The sizes of the circles are proportional to the inventory of radon or salinity at each site.

During the same period that these surveys were performed, we deployed a stationary continuous radon monitor (Burnett et al., 2001) at a station about 100 meters off FSUML and collected time-series data for approximately 24 hours. These results were used to estimate diffusive seepage using the modeling approach detailed in Burnett and Dulaiova (2003). Our estimates showed groundwater velocities (not necessarily fresh water) ranging from 5-40 cm/day with increased seepage rates at low tide (Figures 3.3 and 3.4).

Such trends of enhanced seepage during lower tidal stages have now been seen in several areas including the area around FSUML (Burnett et al., 2002), and in the Florida Keys (Chanton et al., 2003). This is apparently due to a modulating effect caused by increased hydrostatic pressure at higher tides resulting in diminished groundwater discharge flow rates because the hydrostatic pressure acts in the opposite direction than the effects of the hydraulic gradient coming off the land.

During this fieldtrip to Lanark Reef, water grab samples were also taken by a DEP diver (James McClean) directly in the throat of the Lanark and Sulfur Springs and analyzed for ^{222}Rn and ^{226}Ra . These samples were collected using a new plastic sample bottle design (Stringer and Burnett, 2004) and run using a standard technique called radon emanation.

The samples were sparged on an extraction line using high-purity helium. The radon is then cryogenically trapped and transferred to an alpha scintillation cell for counting. The initial ^{222}Rn is analyzed in the first run on the extraction line and, after an in-growth period of five or more days, the samples are re-run to quantify ^{226}Ra , giving us the amount of radon supported by radium present in the water column. If the ^{226}Ra value is subtracted from the initial ^{222}Rn , the excess ^{222}Rn is determined, signifying the quantity of radon that is brought into the system from an outside source (e.g., groundwater). Table 3.1 shows the initial ^{222}Rn , ^{226}Ra , and excess ^{222}Rn for each of the six samples, along with their salinity and conductivity.

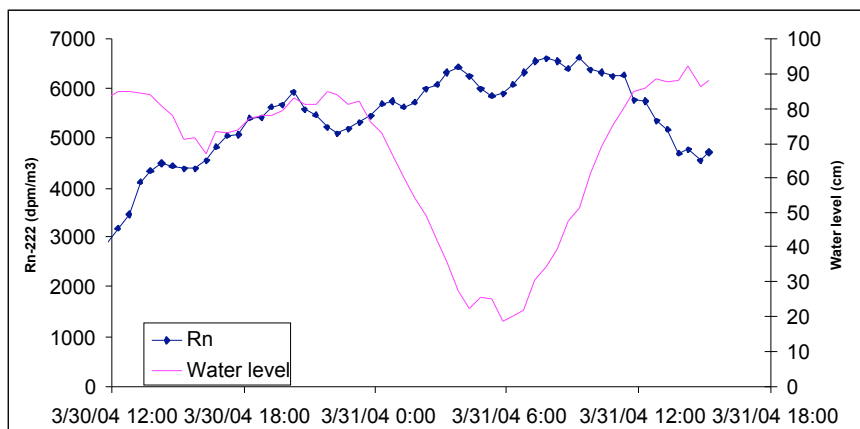


Figure 3.3 Radon concentrations and water level at the fixed station off the FSU Marine Laboratory.

	Initial ^{222}Rn Activity			^{226}Ra Activity			Excess ^{222}Rn Activity			Salinity	Conductivity
	(dpm/L)			(dpm/L)			(dpm/L)			(ppt)	(μS)
SULFUR SPRING											
Sulfur 1	777	±	27	1.10	±	0.07	917	±	32	0.16	297
Sulfur 2	724	±	25	1.00	±	0.07	855	±	30	0.13	255
Sulfur 3	653	±	24	1.08	±	0.10	783	±	28	0.16	301
Average & Standard Deviation	718	±	62	1.06	±	0.05	852	±	67	0.15	284
LANARK SPRING											
Lanark 1	806	±	27	0.80	±	0.10	938	±	32	0.14	271
Lanark 2	350	±	15	0.62	±	0.38	407	±	18	0.16	305
Lanark 3	159	±	9	0.24	±	0.13	188	±	11	0.14	259
Average & Standard Deviation	438	±	332	0.55	±	0.29	511	±	385	0.15	278

Table 3.1 ^{222}Rn and ^{226}Ra results for water grab samples collected directly from the vents of Sulfur and Lanark Springs.

The isotopic results from Sulfur Spring all show essentially the same result for all parameters measured (salinity, radon, and radium), indicating that there is little mixing occurring in the vent sampled. Lanark Spring, on the other hand, showed internal consistency in the conductivity/salinity results but a wide variation in the radon and radium results. Note that the

sample highest in radon (Lanark #1) was also the highest in radium and the other samples follow the same pattern, i.e., the lowest in radon (Lanark #3) was also lowest in radium. The most likely explanation is that there was mixing of at least two fresh groundwater end-members in the vent sampled. The high-radon sample in Lanark is fairly similar in composition to all samples in Sulfur Spring.

3.3.2 Spring Creek

The FSU team also worked together with FGS personnel on an assessment of flow rates and isotopic concentrations in waters from several vents at Spring Creek Springs on April 14, 2004. FGS researchers made measurements using continuous side scans and CTD surveys and FSU investigators collected a total of 20 samples for isotopic analysis at two transects and four individual spring vents. The first transect, T1, was across the creek northwest of spring #9. The second transect, T2, was conducted south of springs #8, 10, and 11. (See Figure 4.1 for the locations of the spring vents.) In addition to the two transects, springs numbered 1, 2, 10, and 11 were also sampled, not only by grab samples for radon emanation analysis, but also for analysis of total radon using liquid scintillation counting. Spring-water samples were obtained by dropping a sampling tube with a 25-pound weight down into each vent.

Samples at T1 had slightly lower activities of total ^{222}Rn (initial $^{222}\text{Rn} + ^{226}\text{Ra}$) than other samples taken throughout the day (Table 3.2). These lower activities correspond with slightly higher salinity measurements taken, indicating the mixing of groundwater with low-activity seawater in the system at the time of sampling.

Table 3.2 Total ^{222}Rn , salinity, and conductivity of grab samples taken across transect T1.

	Depth (m)	Average Total ^{222}Rn (dpm/L)			Salinity (ppt)	Conductivity (mS)
Center	1.5	49	±	1	11.4	18.23
West	1.0	52	±	1	11.3	18.01
East	1.5	24	±	1	17.9	27.44

Table 3.3 Total ^{222}Rn , salinity, and conductivity of grab samples taken across T2, with the numbers moving consecutively from West to East.

	Depth (m)	Average Total ^{222}Rn (dpm/L)			Salinity (ppt)	Conductivity (mS)
1	0.8	58	±	2	5.2	8.84
2	1.0	63	±	2	4.8	8.26
3	1.0	69	±	2	4.6	7.94
3	2.0	64	±	2	4.9	8.39
4	1.0	70	±	2	4.6	7.76
4	1.8	63	±	4	4.8	8.04
5	0.8	13	±	1	4.5	7.52
6	0.3	72	±	2	4.2	7.08

Spring #	Average Total ^{222}Rn (dpm/L)						Salinity (ppt)	Conductivity (mS)
	LSC			Emanation Line				
1	53	±	9	81	±	2	4.9	8.37
2	44	±	20	51	±	23	3.1	5.72
10	44	±	17	79	±	7	3.0	5.19
11	32	±	19	40	±	11	4.8	8.13

Table 3.4 Total ^{222}Rn activities determined at Spring Creek Springs by two different methods, along with salinity and conductivity measurements.

The samples taken across T2 (Table 3.3) and the individual spring vents (Table 3.4) all had similar total ^{222}Rn activities and salinities. We believe that the inability to distinguish between the isotopic signature of the surface waters and groundwater indicates that the creek in the area of T2 is saturated with spring waters.

3.3.3 Additional Offshore Samples

Five additional offshore samples were analyzed for ^{222}Rn and ^{226}Ra , after collection by FGS researchers (Table 3.5). The samples show the general decreasing trend in radon activity as you move farther offshore, away from groundwater spring inputs. Unfortunately, sample 4, taken at Spring 1-2, experienced some difficulties in either sample collection or the initial radon analysis, resulting in no radon being observed during the analysis. This is very likely an artifact and should be discounted. A slightly elevated radon activity at Lamb Spring from that seen in sample 3 (offshore open water) is very interesting. Discussion with an FGS researcher revealed that this is the location of a potential groundwater source to the offshore region. This sinkhole is believed to be possibly attached to a sunken riverbed that could serve as a conduit for groundwater travel. This site would make an excellent site for further study, possibly utilizing the continuous radon methods to look at tidal fluctuation in radon concentrations over the hole.

Sample	Initial ^{222}Rn Activity		^{226}Ra Activity		Excess ^{222}Rn Activity		Total ^{222}Rn Activity		Salinity	Conductivity
	dpm/L		dpm/L		(dpm/L)		(dpm/L)		(ppt)	(mS)
1: Steinhatchee River	103.47	± 2.79	5.91	± 0.19	187.15	± 5.37	193.06	± 5.38	0.2	0.436
2: Sea Hag Marine	37.31	± 1.02	2.99	± 0.11	65.19	± 1.95	68.18	± 1.95	12.1	18.57
3: 15 miles offshore	0.45	± 0.03	0.40	± 0.06	0.08	± 0.11	0.49	± 0.12	33.8	47.4
4: Spring 1-2	0.00	± -0.01	0.03	± 0.05	-0.06	± 0.09	-0.03	± 0.10	34.9	48.9
5: Large Hole (Lamb Spring)	0.55	± 0.03	0.30	± 0.05	0.40	± 0.10	0.71	± 0.11	34.5	48.6

Table 3.5 Radon and radium activities, as well as salinity and conductivity measurements, for offshore samples.

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Project 4: Ground Truth Evaluation of Thermal Anomalies

*James A. R. McClean
Florida State University*

4.1 Scope of the project

The focus of this project includes the continuation of remote sensing data interpretation and processing, maintenance of field instruments and equipments, and general assistance of investigators in field activities.

The duties and responsibilities of the coordinator of this project include:

- Help in finalizing the report entitled: “Evaluation of Remote Sensing Methods to Identify Areas of Interaction between Ground and Surface Waters”. This project, for which phase one is completed, was designed to evaluate three remote sensing techniques for identifying ground water discharge to surface waters on a regional basis.
- Converts raw data from remote sensing surveys into GIS-based maps for visualizing “hot spots” of areas of ground water interaction with surface water.
- Develops a plan and a schedule of activities for field verification (ground truthing) of hot spots located by remote sensing techniques.
- Implements a procedure for custodianship, usage and maintenance of instruments and equipment used in the remote sensing project including: side scan, Doppler acoustic profiler, flow meters, water quality sensors, reagents, electronic accessories, software etc.
- Participates in the effort to quantify the amount of water involved in the areas, depicted in remote sensing maps, as indicative of ground water interaction with surface water.
- Prepares “Power Point” slide shows for making presentations at conferences and other scientific gatherings of all the reports listed above.

Deliverables: Quarterly invoices in conjunction with quarterly progress reports, followed by a final invoice in conjunction with a final written report shall be submitted to the Department’s Contract Manager no later than June 10, 2004.

4.2 Introduction and Summary

This section of the report encompasses the second phase of a research project evaluating the capabilities of selected remote-sensing technologies to locate and characterize groundwater and surface-water interaction zones. The methods under evaluation include thermal imaging from aerial and space based platforms and marine-towed electrical resistivity. Initial aerial thermography was collected at 14 sites during May 2002. Also during this time electrical resistivity surveys were conducted at 16 sites, five of which overlap the thermography study areas. Additional thermography flights were conducted in February 2003, to take advantage of maximal thermal differences between ground water discharge locations and colder ambient surface water conditions. A grant from NASA’s Jet Propulsion Laboratory enabled the acquisition of Landsat 7 multi-spectral satellite imagery encompassing several winters and one summer scene of the study areas.

Ground truth verification is the primary emphasis of this second phase of the research project. Several targets identified in the remotely sensed data sets showed evidence for ground-water discharge as indicated by either a thermal signature at the water surface or as areas of higher resistance associated with electrically non-conductive fresh water within the predominantly limestone bedrock matrix associated with the Intermediate and Floridan Aquifers. The identified thermal and resistivity anomalies have been previously described by DeHan and McClean (2003). As described above, these targets are identified by either a thermal or resistivity signature characteristic of ground water flow. Field data collection surveys are planned for FY 04-05 to verify the presence or absence of ground water discharge.

The data collected for this phase of the project has covered a diverse range of water qualities from a variety of submarine springs. Spring Creek springs show a range of water quality parameters within its basin, either the result of sea water intrusion to the deeper ground water conduits by shallow surficial conduits and/or the result of separate ground water sources. The variation within this system is tidally controlled, such that springs within the system have been known to suddenly stop flowing and reverse direction throughout a single day. The tidal signature in the water velocities of Wakulla Springs' A Tunnel may indicate a pathway of connection between the Wakulla and Spring Creek systems. It is a goal of future studies to determine the extent of this connection by means of geophysical prospecting techniques and water chemistry analysis of a regional network of monitoring wells to identify a fingerprint for ground water that may be communicating between these two systems.

In contrast to Spring Creek is the consistency of water quality evident at Lanark Spring throughout a daily tidal cycle. The water samples indicate very fresh water, probably having a source within the Intermediate Aquifer. At each instance that we examined the two springs of Lanark Reef they were discharging substantial amounts of water, yet the FSU Marine Lab Spring remains elusive to this team of investigators, as does Fresh Water Cave reported to be some 5.5 km south of the mouth of the Econfinia River. A large sinkhole feature was identified in the vicinity of the previously identified thermal anomaly near the location reported for Fresh Water Cave by Rosenau et al 1977, however this sinkhole was not discharging water at the time of survey in late April of 2004. This was also true of Oyster Bar Spring, near the mouth of Big Spring Creek in Taylor County which had a strong thermal signature in February 2003, and was strongly discharging water of unknown salinity in August 2003, yet no evidence of freshwater discharge was detected during a month long instrumentation deployment during June 2003. In contrast to the much anticipated fresh water discharge, these sites were found to be discharging water typically cooler and of higher conductance than ambient sea water of the Gulf of Mexico.

The same phenomena can be said for the series of sinkholes identified some 49-52 km south and south west of Steinhatchee Florida. Sinkholes identified in the vicinity of Steinhatchee Spring were demonstrated as the source point of emanation of plumes of cooler more conductive sea water. Water quality data was collected from within the vent of the Lamb Spring Large Hole over a fortnight to test the temporal variability of the phenomena observed at Steinhatchee spring. The results from the Large Hole at Lamb Spring corroborate with those previously described above for Freshwater Cave and Oyster Bar Spring. Lowest temperatures were recorded during low tide, yet the conductivity is highest during these low tide events. Future reconnaissance missions will be planned to visit these sites if and when ground water levels increase to test the hypothesis that these systems do discharge fresh water at times of higher ground water levels. Alternatively these may be recirculation systems in which seawater is trapped in submerged karst conduits and becomes enriched with calcium ions while

simultaneously being thermally stabilized. This situation could give rise to the cooler waters, higher conductivities and increased radionuclide activities demonstrated at these sites.

4.3 Study Areas for 2004:

The study areas investigated as the topic of this report are located along the coasts of Franklin, Wakulla and Taylor counties in an area of the northern Gulf of Mexico known as Apalachee Bay. Those sites showing strong evidence of submarine ground water discharge are located near shore or within coastal estuaries, with strength of evidence diminishing with distance from the coastline.

4.3.1 Spring Creek

The Spring Creek system is located in southern Wakulla County. As many as fourteen springs have been reported within this estuary (Lane 2001 and Rosenau *et al.* 1977). Side scan sonar and bathymetric mapping performed by FGS personnel throughout 2002 were matched to thermal imagery collected May 2002 to verify the location of the fourteen springs. This is a complex system of springs exhibiting a large degree of variation in water quality from spring to spring, possibly indicating multiple sources of ground water discharge to the estuary. The system is also heavily influenced by tidal variation and springs have been reported to suddenly cease discharging and even reverse flow within a few minutes. Thermal imagery from May 2002 shows differences of several degrees in surface temperature between some of the springs; see Figure 4.1 below. This is most noticeable between spring #1, traditionally considered the main ground water source for the estuary, and spring #4. As can be seen in Figure 4.1; spring #1 is discharging warmer water than spring #4. Spring #4 also appears to be the largest contributor of ground water to the system as indicated by the central location of this spring in a large area of cooler water that presumably represents ground water. These temperature differences likely indicate different sources of ground water or infiltration by and mixing with warmer surface water. Surface water may be entering the conduits associated with springs 1, 5, 7 and 11 either from a shallow surficial aquifer, or directly from Stuart Cove via springs 12, 13 and 14, or may be Gulf of Mexico water retained during high tide and resurging at lower tidal stages.

To test the hypothesis that discharge from some of the springs is a mix of surface and ground waters, radon samples were collected by Dr. Jeffrey Chanton and Christina Stringer from FSU's Department of Oceanography at springs 1, 2, 10 and 11, as representative of the two conditions. The water chemistry results are reported in the results of Project 3. In addition, radon profiles were created at three transects across the estuary in conjunction with Acoustic Doppler Profiler measurements to determine the amount of ground water discharging from the springs. Transects were defined to isolate the springs into two groups and a control measurement upstream of the estuary. Transect 1 was made upstream of the estuary, in a tidal creek that enters the estuary from the north west. This creek is not known to have any ground water discharge and was profiled as an end member control. Transect 2 was made across the estuary at its midsection below Springs 1, 2, 3, 4, 5 and 9, while Transect 3 was made near the mouth of the estuary to capture the total discharge of the system. (Transect 3 of this project is the same as Transect 2 of Project 3; the others do not coincide.) The collective discharge of springs 6, 7, 8, 10 and 11 can be determined in theory by subtracting the midsection discharge value from the cumulative value. These radon concentration profiles were intended to quantify percent ground water contribution to the estuary in addition to modelling stratification and mixing zones within the

sampled transects. The discharge was calculated using SonTek River Surveyor v 4.20 software and is estimated at 73 m³/s on April 14, 2004. A continuous sampling regime throughout the entire tidal range would be required to accurately account for the amount of water that is moving through the estuary with the tide compared to the actual amount discharging as ground water. Future studies are planned to instrument this system to create a continuous discharge measurement station.

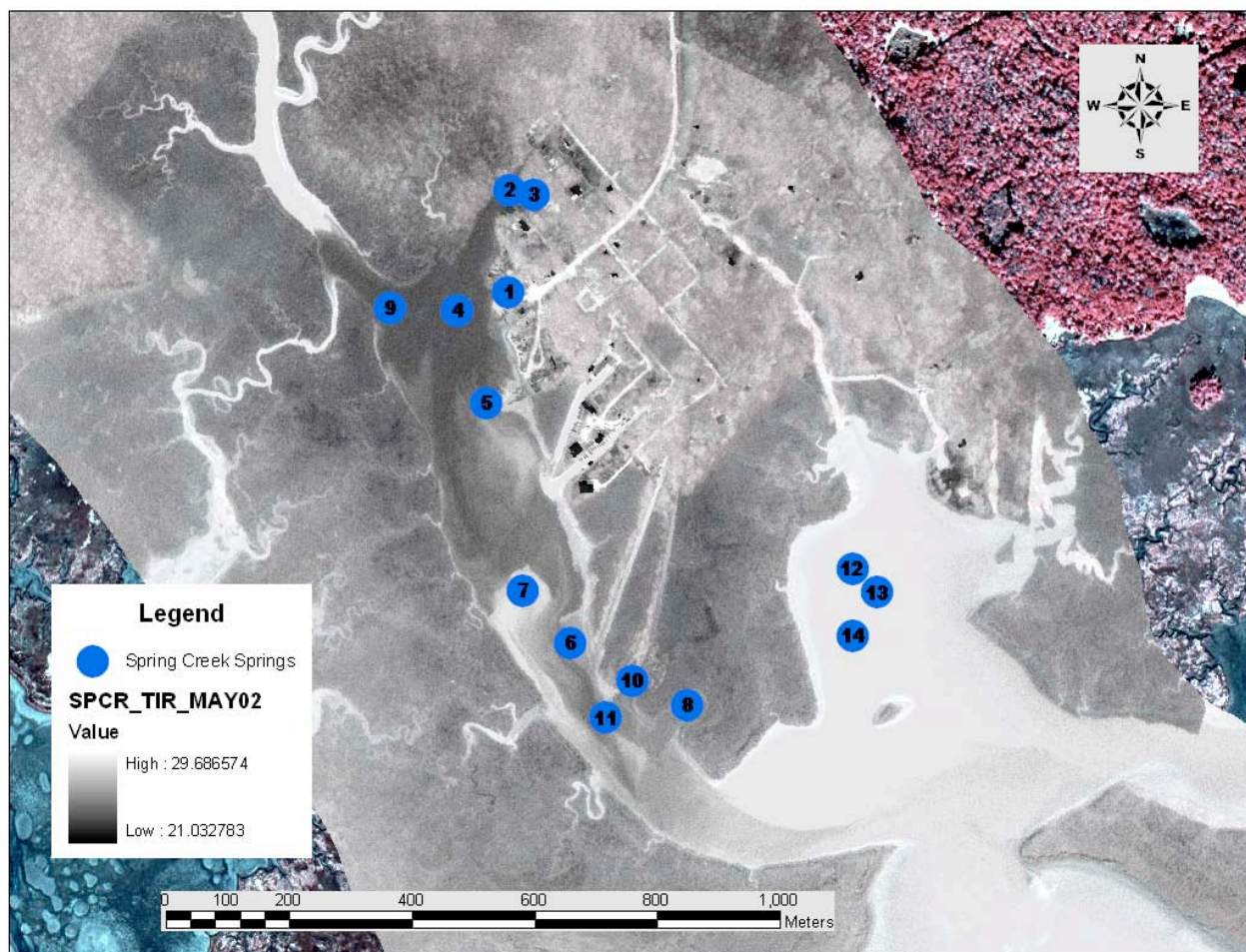


Figure 4.1. Aerial view of Spring Creek springs showing the spring locations and the result of the aerial thermography survey in May 2002.

4.3.2 Lanark Reef

Lanark Spring, Lanark Sulfur Spring and FSU Marine Lab Spring along Franklin County were visited March 30-31, 2004. The first two of these springs were identified during the resistivity surveys conducted May 31, 2002 (Figure 4.2), and again positively identified in the aerial thermography images collected February 18, 2004. The FSU Marine Lab Spring presumably flows intermittently. The FSU Marine Lab Spring is presumably an intermittent flowing spring according to local lore, although we have yet to observe any discharge at this spring neither

during the thermography survey, nor during field reconnaissance surveys on March 30-31, 2004. Both springs along Lanark Reef were visibly discharging water, as evidenced by a clearly defined surface boil when visited these same days. Water samples were collected at both these flowing spring vents from tubing placed directly into the spring vent by an FGS diver. These results are included in Appendix 4 as Tables A4.1 and A4.2. Both springs are small openings at the base of conical depressions in the sandy sea floor. The water appears to be discharging from lateral bedding planes running toward shore. Neither vent was large enough to permit entry by a diver.

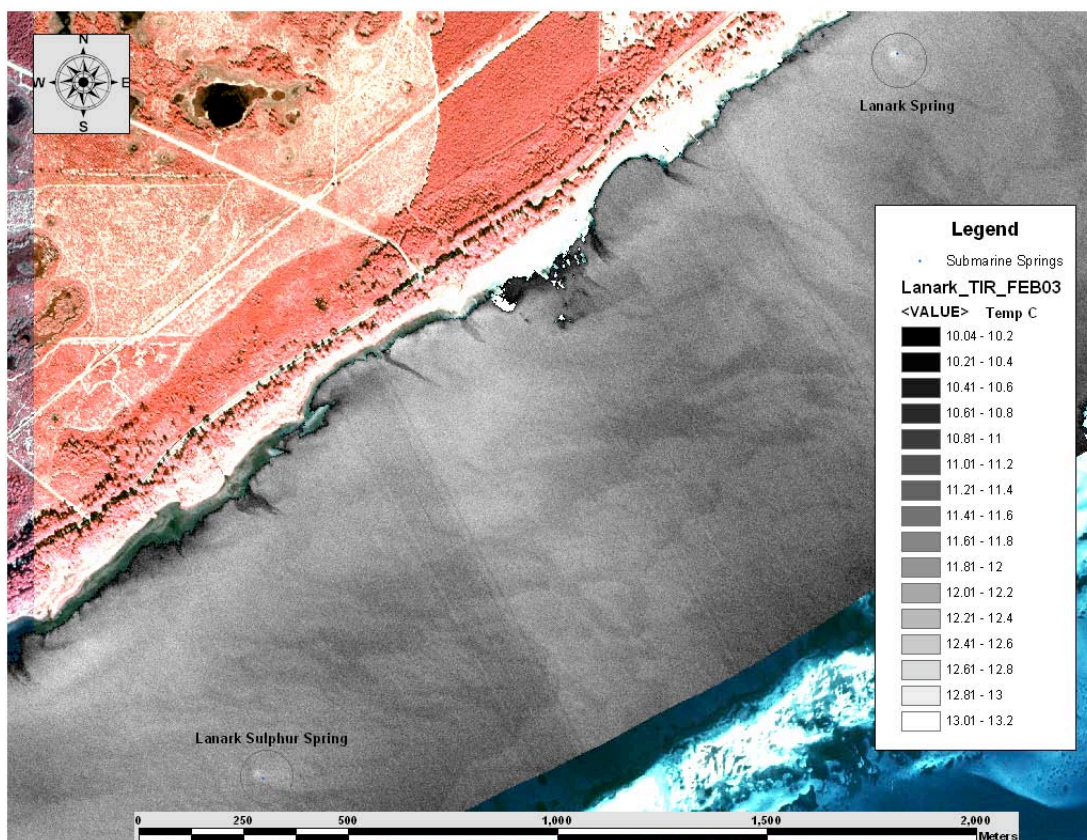


Figure 4.2. Aerial thermography survey data over Lanark Reef, 18 February 2003, 22:06. The two springs are discernible as warmer water discharging to the colder surface waters of St. George Sound just off the coast of Lanark Village, Franklin Co. Florida.

4.3.3 Submarine Springs, Taylor County, Florida

Anecdotal evidence for submarine spring locations examined during the course of this project has two sources. The Florida Geological Survey Bulletin 31, Springs of Florida has a chapter identifying sixteen submarine springs, several of which were investigated during the course of this research. A second data set was collected from local sport fishermen and divers and compiled by the Suwannee River Water Management District who made this information available to FGS personnel for research purposes. This database contains about fifty locations reported as springs, fractures or hard bottom sites within the Gulf of Mexico. Only three of these sites have been surveyed and all are presently being treated as speculative data that has yet to be verified for authenticity.

Side-scan sonar was used at a small number of targets to identify vent features on the sea floor that are associated with either a detected surface thermal signature or strong anecdotal testimony given for a spring's location. The method utilizes sound waves to create an image of the sea floor with an overhead perspective much like an aerial photograph. The FGS uses a Marine Sonic Technology 600 kHz tow fish typically configured to image 75 m wide swaths perpendicular to the track of the towing vessel. Geographic control is provided to the instrument via real time using a Garmin GPS Map168S combined depth finder and differential Geographic Positioning System (DGPS). Using the Wide Area Augmentation System differential correction signal provided free of charge by the Federal Aviation Administration the system is typically capable of horizontal spatial accuracy to within 4 m. This system is sufficient for survey purposes, while a Trimble Pro XR DGPS unit is used to collect specific vent positions with accuracy to within 1 m during sampling operations.

The side-scan sonar system is well suited to identifying sinkholes, limestone outcrops and other submerged karst features on the sea floor. Since the method uses sound energy to generate an image of the sea floor it is unaffected by turbidity and poor visibility that would otherwise prevent aerial photography using reflected sunlight. As the incident imaging energy comes in from a side looking angle, measurements of height and distance can be calculated using the sonar processing software when the altitude of the towfish is known

4.3.4 Oyster Bar Spring

Oyster Bar Spring was identified as a warm water anomaly in aerial thermography data collected along the Taylor County coast on the evening of February 18, 2003. Figure 4.3 illustrates the thermal anomaly as imaged that evening. An informal visit was made August 3, 2003, at which time the spring was discharging large quantities of water sufficient to push a swimmer out of the sinkhole depression and evident at the surface as a visible boil.

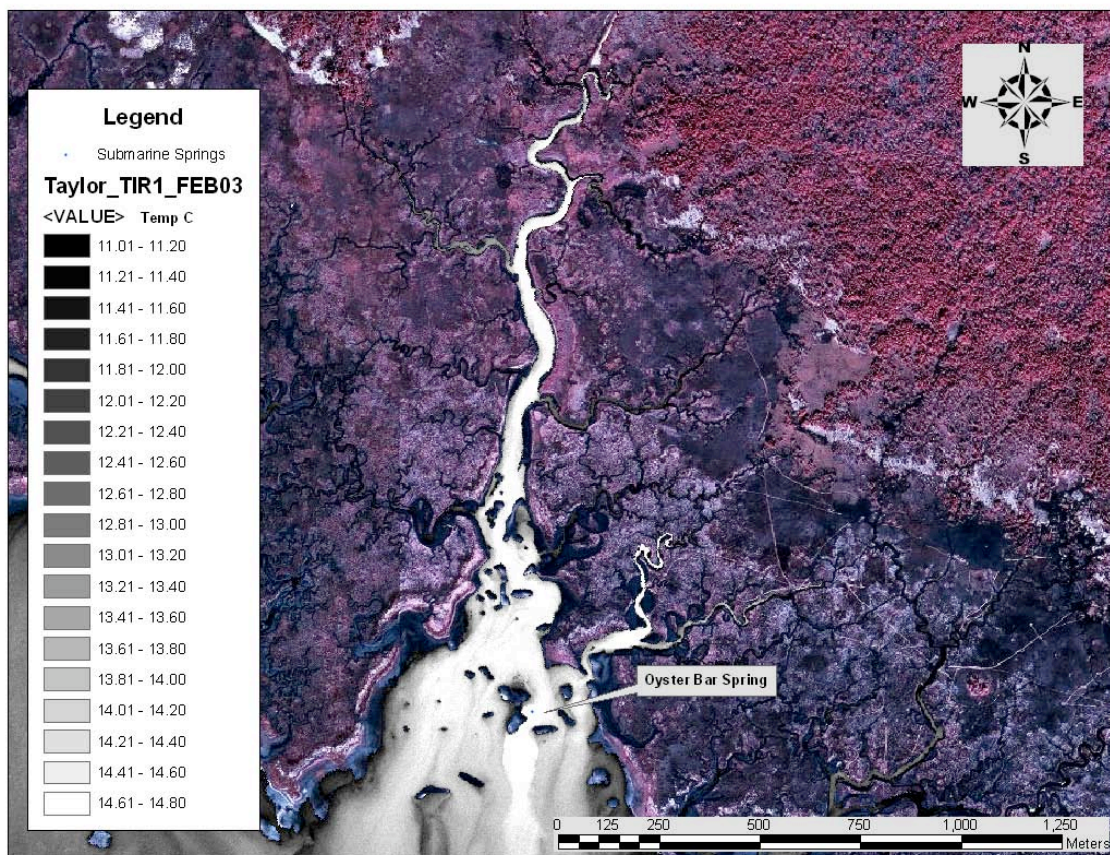


Figure 4.3. Aerial thermography data collected over Oyster Bar Spring on the evening of February 18th, 2003 at 21:28. The spring is discernible as a plume of warmer water originating within the semicircle of oyster bars as marked.

A sampling mission was organized May 16, 2004, with the intention of collecting water samples for chemical analysis, measuring flow discharge and to deploy a recording water quality data sonde within the spring vent for a month long period. Unfortunately, the spring was not discharging any water when our team arrived at low tide on May 16th. A diver was dispatched to place the water quality sonde at the base of the sinkhole. A bedding plane fracture of vertical width no greater than 30 cm was observed receding laterally back toward shore. A flashlight shone into this crack revealed that this fracture extends for some distance, but is not accessible to divers. The data sonde was deployed for a month-long period to determine the tidal influence upon this system. The summer rains had not arrived when the instrument was deployed, yet they were punctual in their arrival on June 1, 2004. It is hypothesized that the spring was dormant as a result of the continued drought conditions that have prevailed throughout the region during the recent winter months. The instrument was recovered on the June 25, 2004, at which time the spring was also not visibly flowing. Strong winds creating waves over the sinkhole may have obscured any surface boil. However, subsequent analysis of the data sonde records provide a complex and confusing record. This data is presented graphically in Figure A4.2 of Appendix 4.

The water temperature in the spring vent was coldest during low tide, which would be expected of ground water discharge; however, concurrent with these conditions the specific conductance of the water is highest. This value in terms of salinity ranges from an average low

of 22 ppt to an average high of 27 ppt. It may be the case that sea water is thermally stabilized and possibly enriched with ions during high tide and subsequently pushed out of the crack during lower tidal levels. This may be a case of an advancing salt water intrusion front moving landward as a result of depressed potentiometric surface levels. Further investigation in the form of continued data sonde monitoring and ground water levels is required to better understand the cause of this spring to cease flowing within the last year.

4.3.5 Fresh Water Cave

Another spring along the Taylor County coast that was targeted for ground truth survey this year was Fresh Water Cave. Fresh Water Cave is reported in FGS Bulletin 31 as being “in water 5 to 9 ft deep; it has a steep easterly wall and a sand bottom sloping westward. There is a white patch of sand on the SE. side of the spring that is normally visible from boat or aircraft”. Two locations are reported for this site, one as latitude and longitude and the other as bearing and range in reference to the St. Mark’s lighthouse. A thermal anomaly was identified at the bearing and range location as an irregular shaped indentation in a lobe of fresh water emanating from the mouth of the Econfinia River. The anomaly forms an obstacle around which the lobe of river water appears to wrap, see Figure 4.4. This anomaly occurs about 5.5 km offshore along a string of sinkhole feature visible in aerial photographs of the area. It is our hypothesis that this string of sinkholes is a relict of the paleo Econfinia River that would have flown along this course during lower sea level stages of the later Pleistocene (Faught and Donoghue 1997). The series of sinkholes likely formed within the river channel, or formed the controlling pathway for the river channel as a series of insurgences and resurgences as is the case for many surface water streams in Florida at present.

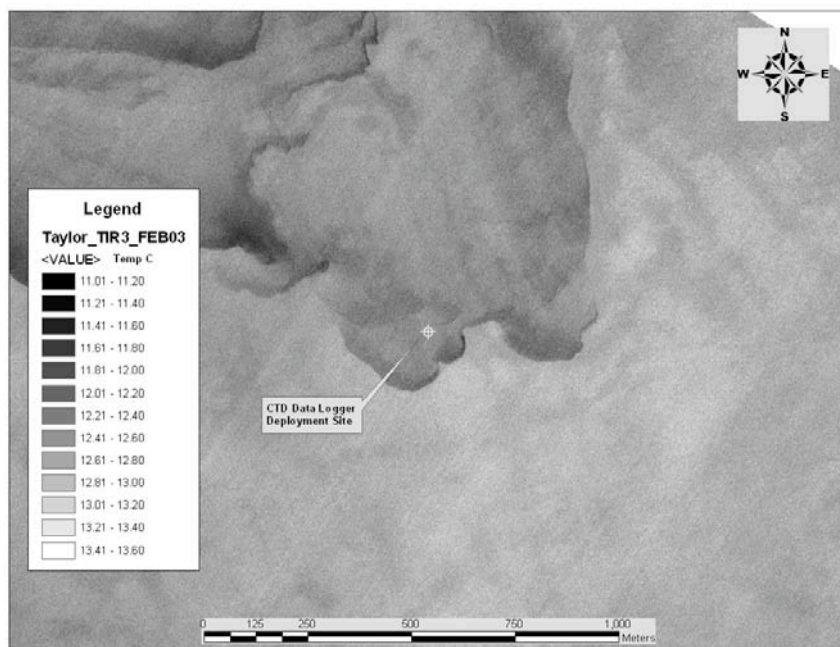


Figure 4.4. Aerial thermography image for Fresh Water Cave, February 18 2003, 21:04. The thermal anomaly appears to deform the advancing lobe of fresh water discharging from the Econfinia River (northward, out of the scene).

Side scan sonar surveys conducted in this area April 27 and 28, 2004, revealed a series of sinkhole features as indicated in Figure 4.5 below. A Hydrolab DS3R water quality data sonde was deployed within the sinkhole feature deemed most likely associated with the thermal anomaly. Time constraints limited the time of deployment to a single day. The data is presented graphically in Figures A4.3 and A4.4 of Appendix 4.

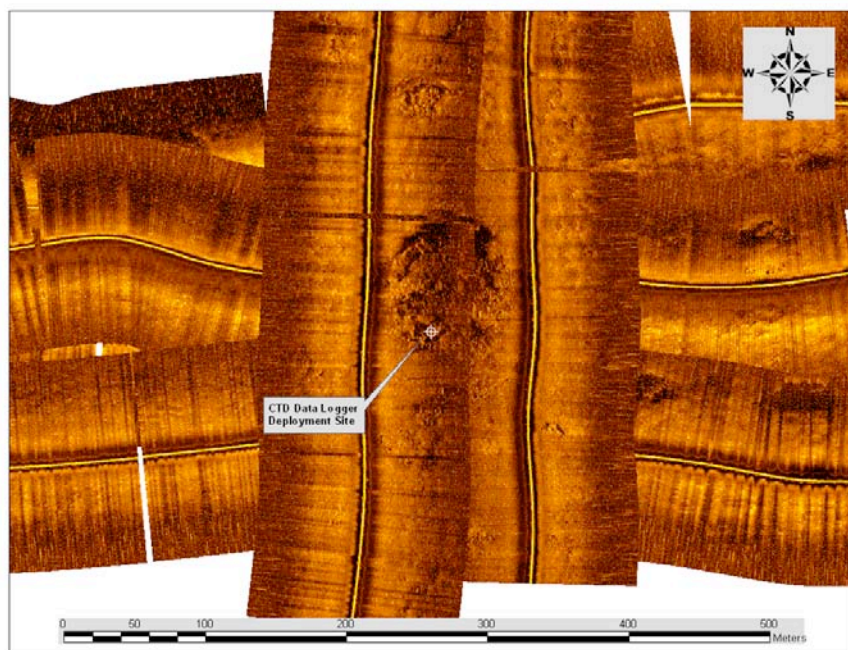


Figure 4.5. Side scan sonar record collected April 27, 2004 identifying a large submerged sinkhole in the vicinity of the previously identified thermal anomaly. Visual inspection by snorkelling revealed the presence of limestone boulders and a number of small cavities, probably solution pipes discharging at times of higher ground water levels.

4.3.6 Offshore Submarine Springs: Steinhatchee and Lamb:

Steinhatchee Spring was visited May 12, 2003. The purpose of our survey was to test the validity of rumors that fresh water is discharging at this location situated about 45 km south west of Steinhatchee Florida. Side-scan sonar data was collected with a Hydrolab Mini Sonde 4a water-quality probe in tandem with the sonar tow fish. This instrument collected parameters such as temperature, specific conductance, dissolved oxygen, and pH near the bottom while a continuously recording fathometer collected water-surface temperature and water-column depth. The water-quality data parameters were assigned a GPS coordinate by matching the instrument time stamp to the corresponding vessel position recorded in the bathymetry data file. These data points are then imported to Arc Map GIS software for spatial analysis. The data is converted to a point shape file that is then used to interpolate contour-line maps or continuous-grid coverages.

A regular grid search pattern was used that allows coverage of the target survey area by the side scan sonar with a minimum of survey lanes, while also providing a consistent sampling interval for the water quality data. These lanes are typically spaced 100 m apart as the sonar is capable of imaging a distance of 75 m to either side of the vessel in dual-channel mode. Single-channel mode is sometimes used for finer image resolution and increased data density, at the cost

of requiring additional survey lines. While single-channel mode requires more survey lines to cover an area than dual-channel mode, by switching channels with each lane a consistent beam angle results. This condition creates uniform shadow directions, which simplifies image interpretation by reducing conflicting shadow patterns.

Several limestone outcrops were identified within the survey area. Figure 4.6 illustrates the water-quality-parameter data with temperature as an interpolated grid pattern and point salinity readings over digitized polygon shapes representing the limestone outcrops. The tide during survey operations was low as interpreted from the Steinhatchee River entrance tide predictions posted for that day. There is clearly a difference in water quality as evidenced by the substantial drop in temperature from an ambient 28°C to 22°C in the vicinity of the limestone outcrop. This drop in temperature is probably the cause for sport divers giving the name “spring” to this and other similar sites. However, a distinct rise in salinity on the order of a few thousandths of μS is also recorded in conjunction with this colder water. It is premature to declare this location a “spring” based upon the evidence collected during this preliminary survey. Therefore, further surveys are planned to collect more data at similar sites to determine the quality and quantity of water possibly issuing from these submerged karst features. Our research interest is to determine if these sinkholes and fractures in the sea floor bedrock are discharging water from the Floridan Aquifer, or if sea water is being re-circulated through drowned karst passages. The increase in salinity observed at Steinhatchee Spring during our survey merits the preliminary conclusion that sea water is becoming enriched with ions as it steepes in these carbonate sediments.

On March 11, 2004 a preliminary surveying trip was conducted at Lamb Spring. The site was surveyed using the same tandem side scan sonar/ water quality sonde instrumentation as that used the previous summer at Steinhatchee Spring. A series of five sinkholes were identified at this location. Divers took water samples within the collapse features and sought to identify the occurrence of any water movement either in or out of the sinkholes. These water chemistry results are presented in Table A4.3 of Appendix 4.

A Hydrolab water quality sonde was deployed within the Large Hole at Lamb Spring for a two week period from May 7-19, 2004. The data sonde was placed at a depth of 24 m within the entrance constriction of a lateral passage to monitor differences in water quality that may be the result of ground water discharge. This instrument was configured to record temperature, conductivity, dissolved oxygen, pH and depth at thirty-minute intervals. The data is presented in graphic form in Figures A4.5 and A4.6 of Appendix 4. The depth sensor provides a local assessment of relative tide levels over the sinkhole. Both the temperature and conductivity plots show a diurnal wave form that seems to correlate well with the tidal stage. Over the two-week interval the temperature swings from a consistently average low of 20.5 °C and increases in daily high from 22.5 °C to 23.5 °C starting after noon on May 13. A corresponding increasing trend in conductivity also begins at this time, with an approximate 3% increase in conductivity values at the later period of the record compared to the initial measurements.

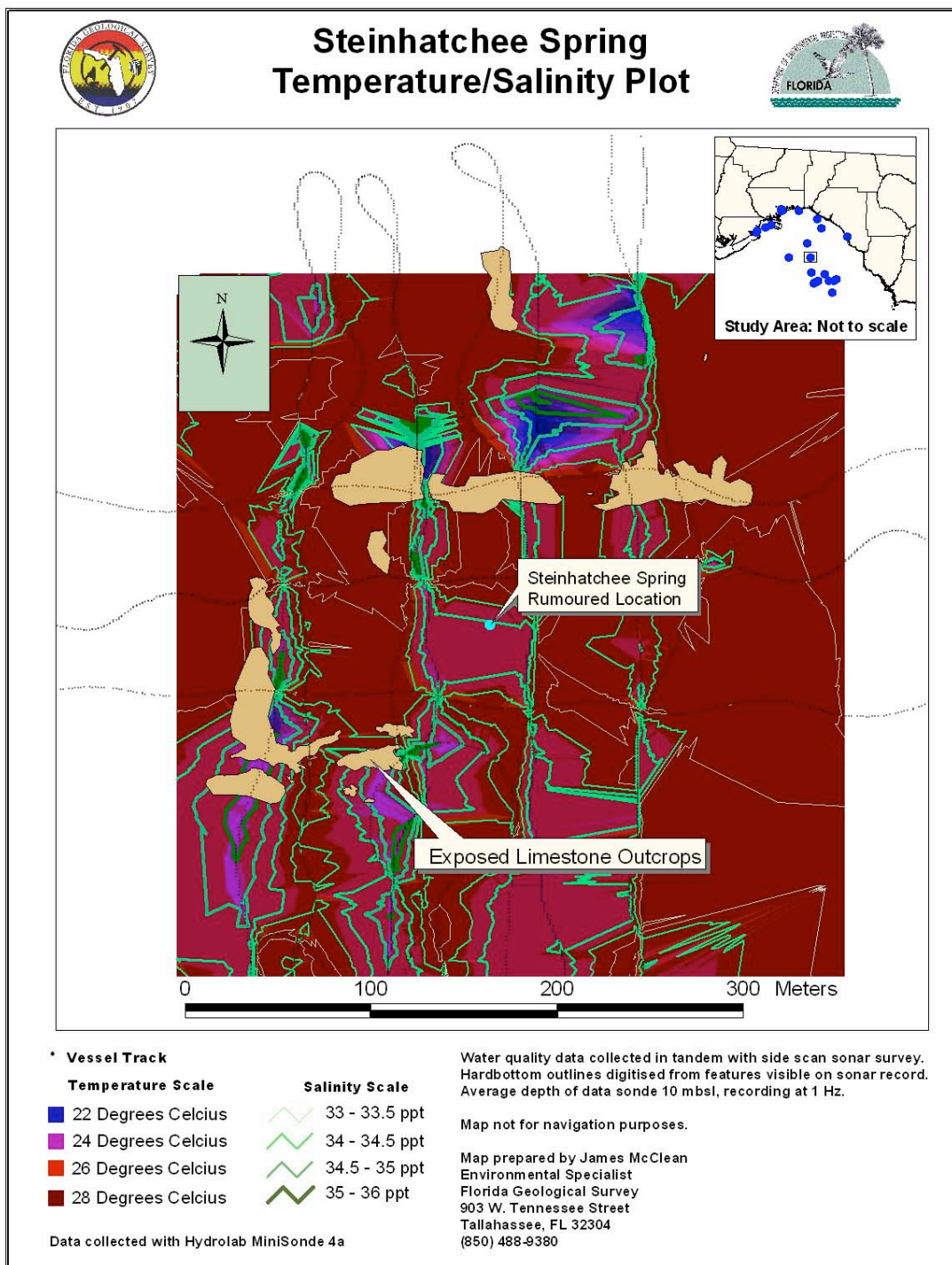


Figure 4.6: Limestone outcrops and associated water quality data collected at Steinhatchee Spring, May 12th, 2003. Note the decrease in water temperature and increase in salinity that appears to emanate from the limestone outcrops.

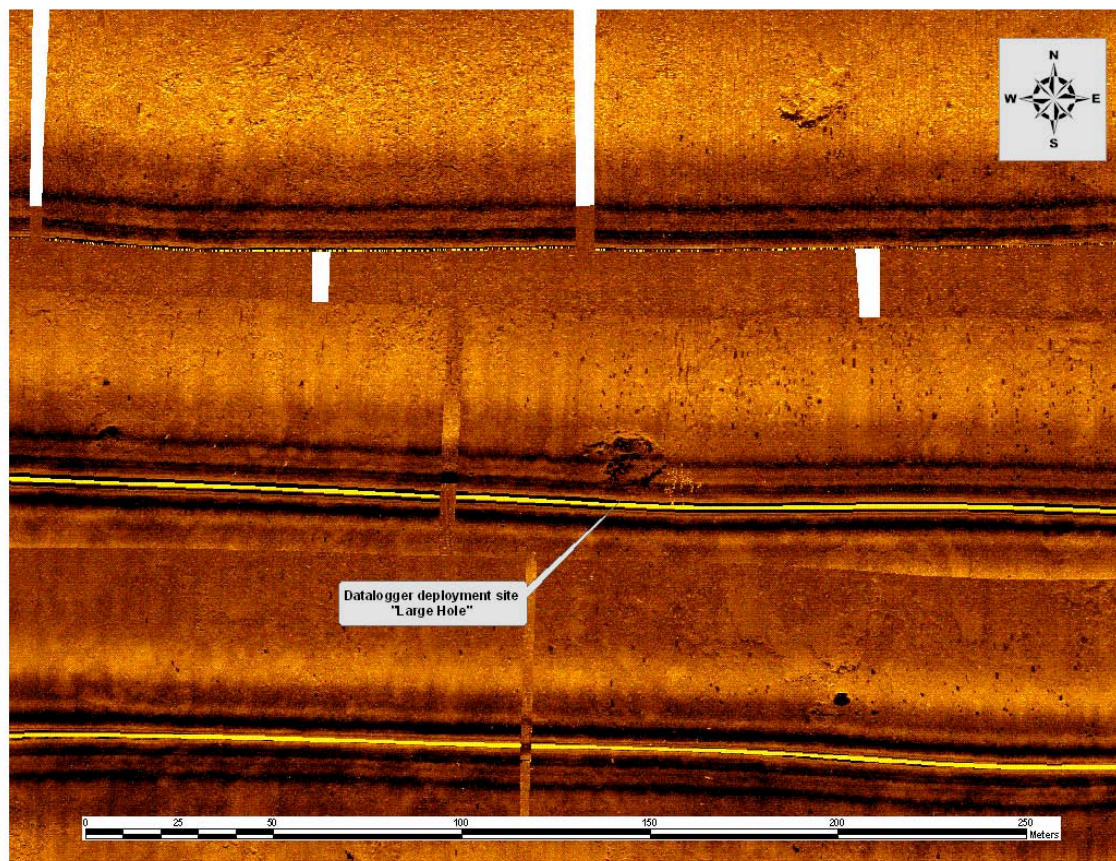


Figure 4.7 shows the five sinkhole features identified within the survey area near Lamb Spring.

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Project 5: Development of a workshop on Aquifer Storage & Recovery (ASR) issues

*Jon Arthur, Rodney DeHan of the FGS/Hydrogeology Consortium
and Timothy Hazlett, Hazlett-Kincaid Inc.*

5.1 Scope of the project

This will be a 2 day workshop organized by the **Hydrogeology Consortium and the American Ground Water Trust**; and conducted in cooperation with staff of the FGS and **Hazlett-Kincaid Inc.** The workshop will involve 100-130 people and revolve around two or three panels of invited experts in the areas of interest or concern associated with ASR systems and practices in Florida. Presentations by speakers and panelists would address the hydro-geological, ecological, environmental policy and economical implications involved in ASR projects.

Deliverables: The workshop's findings and recommendations will be developed and published within two months following the end of the workshop, which is scheduled for April 2004, but no later than June 10, 2004. The findings and recommendations will be published as Special Publication of the FGS in a CD ROM format as workshop proceedings. Copies of the CD will be distributed to registered participants and be made available to the public at the FGS library.

5.2 Summary

Staff from the FGS, and members of the Hydrogeology Consortium participated with Hazlett-Kincaid, Inc, (HKI) in the development of a workshop on Aquifer Storage and Recovery (ASR) entitled *Aquifer Storage Recovery IV: Science, Technology, Management and Policy*. The workshop was held in Tampa, FL on April 15 & 16, 2004. After the workshop, HKI collected the presentation and registration materials and compiled them into a proceedings publication that has been published as FGS Special Report 54/ 2004, and distributed to registered participants of the workshop and is now available in a CD ROM as FGS Special Publication 54/2004 at the FGS library for purchase by the public.

A short background on the issue of ASR maybe relevant at his point: the American Ground Water Trust held ASR I on September 10, 2001, in Orlando. This program provided exposure for the whole concept of Aquifer Storage Recovery and was a discussion opportunity for "environmental" and "engineering" perspectives of ASR as a water management strategy. ASR II took place on January 7, 2002 in Orlando and included sessions related to the treatment technology available for recharge water. In 2003, ASR III, also held in Orlando, served to provide a technical and policy update across the spectrum of Florida's ASR issues. This April 15-16 program in Tampa (ASR IV) is taking a different format. The Trust has teamed up with the Florida Department of Environmental Protection (Florida Geological Survey/ Hydrogeology Program) and the Hydrogeology Consortium. The two-day ASR IV program will review the status of current ASR science and technology on day one, and then relate the science to policy and management issues on day two. We hope attendees will be there for both days, but recognizing time and budget constraints, the organizers have framed each day as "stand-alone" to facilitate one day participation. ASR V will be held in Florida in 2005. Your comments on the evaluation sheets will be helpful in guiding the Trust to select content and format.

The Tampa ASR IV Forum brings scientists, planners, water-resource managers, concerned citizens, etc. together to share up-to-date information regarding challenges and successes of ASR implementation. There will be technical presentations and panel discussions. The program is designed for exchange of ideas and opinion. The critical mass of expertise focused on ASR for two days should provide an opportunity for an assessment of technology trends and research needs for future ASR-related activities. The content of the presentations and an edited transcript of the discussions have been provided to all registered participants in CD format. (see summary above for current status on this issue) ASR IV is a one-stop shop for the latest perspectives on an important emerging and ongoing issue. The program has a Florida focus but the basic science, technology, management and policy issues have direct relevance for ASR programs throughout North America and overseas.

Project 6: Development of ground water flow model and non-point source contaminant transport model in Karst: Initial Phase.

*Timothy Hazlett
Hazlett-Kincaid, Inc*

6.1 Scope of the Project

The need to develop a model for ground water movement and contaminant transport in karst has been a priority for many researchers in the field of ground water hydrogeology. *Hazlett-Kincaid, Inc.* (HKI) has cooperated with the PI; Dr. Loper of FSU; to develop such a model, and have achieved promising results with the probabilistic method and the use of FEFLOW in the Woodville karst Plain. This project, to be lead by HKI, will build upon the progress made to date by using a hydro-geo-chemical approach that evaluates both the impacts of the spring-cave systems on the groundwater flow and nitrate transport, which are both major issues in the area. This initial phase of work shall be completed by the end-of-December, 2003.

The project will be piloted in the Fanning and Manatee springsheds because:

- ◆ The Suwannee River Water Management District (SRWMD) is actively sampling water quality and collecting very accurate water level measurements from an extensive monitoring well network in the springsheds;
- ◆ The trend and extent of the cave systems for Manatee Springs are well documented on available cave maps;
- ◆ Monitoring wells have recently been installed in three conduits in the Manatee cave system and are to be instrumented with flow meters and data loggers to obtain through-conduit groundwater velocities and water quality data that, in turn, will provide important calibration points;
- ◆ A modeling study will complement other ongoing work in the area, currently being performed by FGS, SRWMD, and FSU.

This scope of work will, more specifically, involve the following primary Tasks:

1. Compilation and synthesis of all existing hydrologic data for the problem area into a database and conceptual model that will support the modeling effort, and
2. The development of a preliminary steady-state groundwater flow model of the region.

The targeted data will consist of cave maps, spring discharge data, cave through-flow velocities, and water level information from the numerous wells and sinkholes in the area as well as estimated nitrate loading rates within the presumed boundaries of the springsheds. Since such data is already in existence the project will simply compile existing data into formats suitable for inclusion in the groundwater flow model.

The groundwater model development in Task 2 will be performed by HKI using the data compiled and synthesized in Task 1 and the FEFLOW finite-element groundwater modeling software. A unique aspect of the modeling will be the inclusion of the spring-cave systems directly in the model. Hazlett-Kincaid already has the cave map data. The preliminary model will likely be an aerial, 2-D, steady state simulation of groundwater flow to the two springs and the Suwannee River. The model will eventually be hand calibrated to hydraulic heads, spring

discharges and through-conduit groundwater velocities. The purpose of the preliminary model will be to guide qualitative delineations of the two springsheds and as a guide for future data collection strategies.

Deliverables: A written report and CD containing the results of the data compilation and a basic groundwater flow model framework, which is not yet calibrated to data assembled in the data compilation. The groundwater flow model will be fully calibrated and nitrate loading scenarios may be investigated in future authorized projects.

6.2 Introduction and Summary

The goal of this project is the development and implementation of a model that can improve the accuracy of the prediction flow and transport in karstic aquifers, particularly those which have well-developed conduit systems and experience strong interactions between surface and ground waters. Conventional groundwater flow programs (i.e. – MODFLOW) do not allow for the inclusion of conduits nor consider the flow through such features. As a result in karst basins, groundwater flow velocities and transport times are generally under-predicted by these models by several orders of magnitude or more. In this work, we seek to address these inadequacies and develop a practical, simple model of flow through karstic basins, which can eventually be implemented on a desktop PC.

KARSTMOD is a numerical program (see Appendix 6.2) that implements a new mathematical model of flow and transport in a karstic aquifer (see Appendix 1). The program and model, which have been developed jointly by David Loper and Timothy Hazlett. The program and model are based on a conceptual model that incorporates the system of caves and conduits in a novel manner.

Preparatory work on this project has been in progress for several years, with the principal product being a new model of groundwater flow and transport in karstic aquifers, called KARSTMOD. The overall scope of this work is described in §6.3, while recent efforts at simulating the Woodville Karst Plain are described in §6.4.

Appendix 6.3 contains a report of the Manatee Springs modeling project. The report details a data review and preliminary development of a finite element groundwater flow model of the area along the Suwannee River including Fanning and Manatee Springs. The modeling is part of an ongoing effort which will eventually look at nitrate loading scenarios in the Manatee springshed.

6.3 KARSTMOD

The KARSTMOD (Karst Model) project is an on-going research effort aimed at developing a suite of mathematical and numerical models designed to simulate the flow of groundwater through conduit-dominated karst aquifers such as the upper Floridan aquifer in much of Florida. The project is divided into three phases: (1) conceptualization and model development, (2) calibration and refinement using site-specific high-resolution rainfall-discharge data and (3) comparison of the model and approach to established finite-element modeling techniques. This contract provided for the continuation of Phase 1, which has been supported by earlier contracts from the FGS, and the initiation of Phase 3.

During the past year both the mathematical and numerical components of KARSTMOD were refined and improved using the evolving data and understanding of groundwater flow through the Woodville Karst Plain provided for by other aspects of this work (e.g., see §2). The mathematical component is documented in Appendix 1 and the numerical program is found in Appendix 6.2. The model can currently simulate steady state flow and transient flow of recharge from anywhere in a closed spring basin to a single spring. The current goal of the modeling is to simulate rainfall-discharge relationships following large storm events for the Wakulla spring basin.

In Phase 2 data from the in-cave meters and precipitation data currently being collected at several locations throughout the basin and up-gradient in Tallahassee will be used to calibrate and further refine the model. Another goal in the modeling effort will be to incorporate multiple springs in the model and to begin to model the fate and transport of contaminants in the karst system.

6.4 WKP Finite-Element Modeling

To initiate Phase 3 of the modeling project, Hazlett-Kincaid, Inc developed an preliminary model of the Woodville Karst Plain using the FEFLOW software that incorporates data acquired from the dye tracing experiments detailed in §2.3. One of the unique characteristics of this model is that all of the known caves in the area of Wakulla Spring are explicitly included in the model along with a connection between the Leon Sinks and Wakulla cave systems identified through the dye tracing.

Two significant observations have been gleaned from the preliminary modeling: (1) the model calibrates to observed data significantly better than previously constructed groundwater flow models using finite-difference techniques such as MODFLOW, and (2) known and inferred karst conduits can be effectively included in a numerical model framework using a finite-element approach.

Two other observations from the preliminary modeling study relate specifically to the Woodville Karst Plain. The model predicts that water that enters Ames Sink probably goes to the Leon Sinks system and not to B and D tunnels (the northern tunnels) at Wakulla. In addition, preliminary sensitivity analyses indicate that groundwater may not be able to reach Wakulla quickly enough to be recharged from the upper portion of the aquifer solely. The implication of this is that Wakulla Spring receives water from a section of the aquifer that is significantly deeper than the depth of the conduits.

Though the model remains in a preliminary stage, it clearly demonstrates the feasibility of constructing “multi-porosity” numerical models of flow through karst systems that calibrate to observed data and explicitly include significant karst features that can either be delineated directly from cave map data or inferred from tracer testing. Furthermore, initial results promise to reveal significant insight into the dynamics of groundwater flow through the WKP that have not been specifically identified through the field data collection efforts.

Once KARSTMOD is refined in Phase 2 of the project and the finite-element model is refined and further calibrated, the two modeling techniques will be compared and synthesized into a comprehensive model framework with which to quantitatively evaluate scenarios within the WKP.

Project 7: Continuation of the development of the Florida Maps project

James R. Anderson

Florida Resources and Environmental Analysis Center, Florida State University

7.1 Scope of the project

The Florida Resources and Environmental Analysis Center (FREAC) in cooperation with the Florida Geological Survey (FGS) began the development of a Florida Maps school curriculum modeled after the National Science Foundation's South Eastern Maps Project (SEMAPS) project. SEMAPS was a cooperative effort with other southeastern states with Florida being represented by staff from FREAC and the FGS.

During the 2002-2003 fiscal year agreement, two units ("units" are the geographical area of the Southeast United States for which information and maps were developed in earlier phases of the Sea Map Project) developed for the SEMAPS project were adapted to a Florida Maps model. An advisory committee was also established to get input from teachers on the development of the curriculum. For the 2003-2004 agreement, FREAC will continue development of Florida Maps in cooperation with staff from the Florida Geological Survey. More specifically this task will involve:

- 1) Field testing the units developed as part of the previous contract; and,
- 2) Continuation of the enhancement of the website design that has been developed for the project

It is envisioned that the FGS would provide content material and the FREAC at Florida State University would develop the delivery products and provide editorial support for the written materials.

Deliverables:

Two additional units (topics to be decided in conjunction with FGS staff) will be produced.

- 2) A presentation of the project will be made to science teachers statewide. The format of the presentation will be determined jointly with Teachers Association and FGS staff.

7.2 Summary

Explore Florida! is a Web-based curriculum that integrates multidisciplinary lesson plans with the use of maps and images such as satellite and airborne imagery, aerial photography, topographic maps, and other special-purpose cartographic products (e.g., 3D anaglyph maps). These materials allow middle and high school students to visualize earth-system processes and human impact while relating them to disciplines beyond earth science, such as mathematics, history, social science and language arts. Student and teacher manuals contain site-specific background information and sets of "hands-on" and "minds-on" interdisciplinary activities keyed to the state science standards. All materials can be used in the classroom straight from the Web, or can be downloaded and printed in black and white, or color. A series of workshops will be held to familiarize teachers with these resources.

Explore Florida! is designed for consistent expansion and versatility. Each unit is framed around a template that includes the following components: Purpose, Student Learning Objectives, Goals, Rubrics for Assessment, Sunshine State Standards, Background Material (may be written for both student and teacher or separate material for teacher and student),

Resources such as places to visit, References, Web sites, Glossary, and Newspaper articles. Each student activity includes a materials list and worksheets. Enrichment activities and answer keys are also included.

At present, two units are available in **Explore Florida!**: Map Use and Florida Everglades; these are presented in Appendix 7.

Appendix 2.1: Florida Cave Database and Meta Data Files

This appendix consists of CD-ROM containing meta data files for each of the point and line GIS shape files describing the underwater caves in the Florida Cave Database in MS Word (.doc format). Also see www.hazlett-kincaid.com/FGS/Reporting/reporting.htm

Appendix 2.2: Florida Groundwater Tracing Database: Framework

The following outline provides a suggested structure for a tracer test database. The first outline level marks the suggested tables and indicates the referential integrity. The current structure calls for six tables, each containing numerous fields and sub-fields related to the particular table. The database could be easily constructed in MS Access but it is recommended that we obtain consensus on the structure and content before investing in actual database construction.

- Test Table
 - Test ID
 - Test Name
 - Test Type
 - Quantitative
 - Qualitative
 - Test Date Application
 - Test Date Begin
 - Test Date End
 - Test Date Results Filed
 - Number of Injections
 - Number of Sampling Stations
 - Number of Tracers
 - Tracer Name #1
 - Tracer Name #2
 - Tracer Name #3
 - Tracer Name #4
 - Testing Party (Who performed the test)
 - Test Sponsorship
 - Results published
 - yes
 - no
 - Publication Reference
 - Cost
 - Tracer Recovered
 - yes
 - no
 - Stations Table (contains all location information on injection and sampling points)
 - Station ID
 - Station name
 - Station purpose
 - Injection
 - Sampling
 - Both
 - Station Type
 - monitoring well
 - water well
 - sinkhole

- stream
 - river
 - conduit
- Station Latitude (decimal degrees)
- Station Longitude (decimal degrees)
- Geographic Projection Datum
 - WRS84
 - ...
- Position measurement method
 - GPS
 - Map
 - ...
- Position Data Source
 - direct measurement
 - published source
 - report
 - ...
- Station Easting
- Station Northing
- XY Projection
 - UTM
 - State Plane
 - Albers
 - ...
- XY Datum
 - NAD27
 - NAD83
 - ...
- XY Units
 - feet
 - meters
 - ...
- XY data source
 - direct measurement
 - published source
 - report
 - ...
- Station Elevation
 - Elevation measurement method
 - GPS
 - Altimeter
 - ...
- Elevation Datum
 - NGVD29
 - NAVD88
 - ...

- Elevation units
 - feet
 - meters
 - ...
- Elevation data source
 - direct measurement
 - published source
 - report
 - ...
- Station media
 - aquifer matrix (i.e. well)
 - conduit
 - sinkhole
 - ...
- Station Ownership
- Station Land Use
- Access Instructions
- Comments
- Sampling Stations Table (Refers to Stations & Tests)
 - Sampling Station ID
 - Test ID
 - Station ID
 - Begin Sampling Date
 - Begin Sampling Time
 - End Sampling Date
 - End Sampling Time
 - Sample media
 - water
 - charcoal
 - Sampling method
 - grab
 - automatic sampler
 - charcoal bugs
 - ...
 - Sampling Station Instrumentation
 - tubing
 - none
 - ...
 - Target Sampling frequency
 - Target Sampling frequency units
 - minutes
 - hours
 - days
 - weeks
 - months
 - ...
 - Tracer recovered

- yes
 - no
- Comments
- Injections Table (Refers to Stations & Tests)
 - Injection ID
 - Test ID
 - Station ID
 - Begin Injection Date
 - Begin Injection Time
 - End Injection Date
 - End Injection Time
 - Tracer Name
 - Injection Instrumentation
 - tubing
 - none
 - ...
 - Injection Method
 - release to stream
 - inject in well
 - inject in conduit
 - ...
 - Tracer Quantity Injected
 - Duration of injection (mins)
 - Injection Supervisor
 - Injection Supervisor Contact Information
 - Tracer Recovered
 - yes
 - no
 - Comments
- Results Table (Refers to Tests, Sampling Stations, & Injections)

Notes:

Results will be stored for each unique pathway between any two unique measurement points

Results only stored if test is successful

- Test ID
- Injection ID
- Sampling Station ID
- Path Type
 - Injection - Sampling Station
 - Sampling Station - Sampling Station
- Path Begin - Station ID
- Path End - Station ID
- Distance
- Distance Units
- Distance measurement method
 - measured
 - estimated

- Tracer Velocity
 - Tracer Velocity Units
 - Tracer Velocity Calculation Method
 - Q-Tracer Output
 - Peak-Peak Calculations
 - Estimated
 - ...
 - Results Published
 - yes
 - no
 - Publication Reference
 - Quantitative Calculations Performed
 - yes
 - no
 - Comments
 - Calculations Table (Refers to Results)
- Note the following categories are from Q-Tracer Output
- Tracer Quantity Recovered
 - % of Injection Recovered
 - Time to leading edge (hrs)
 - Time to peak concentration (hrs)
 - Peak tracer concentration
 - Peak tracer concentration units
 - Mean tracer transit time (hrs)
 - Standard deviation for tracer time (hrs)
 - Mean tracer velocity
 - Max tracer velocity
 - Standard deviation for tracer velocity
 - Tracer velocity units
 - Dispersion coefficient
 - Dispersion coefficient units
 - Longitudinal dispersivity
 - Longitudinal dispersivity units
 - Peclet number
 - Peclet number classification
 - advection > dispersion
 - dispersion > advection
 - Reynolds number
 - Reynolds number tube diameter
 - Tube units
 - Karst-conduit volume estimate
 - Karst volume units

Appendix 4: Water Quality Data

Table A4.1. Lanark Sulfur Spring Water-Quality Results from March 30, 2004

Field Measures	Result	Code	Units
Temperature	21.10		° C
DO	5.4		mg/L
pH	7.19		
Sp. Cond.	124		µS/cm
Lab Analytes			
BOD	1.0		mg/L
Turbidity	0.20		NTU
Colour	10		PCU
Alkalinity	136		mg/L
Sp. Cond.	295		µS/cm
TDS	172		mg/L
TSS	4	U	mg/L
Cl	11	A	mg/L
SO ₄	7.1	A	mg/L
F	0.070	I	mg/L
Nutrients			
TOC	2.6	I	mg/L
NO ₂ + NO ₃	0.004	U	mg/L
NH ₃ +NH ₄	0.19		mg/L
TKN	0.31	I	mg/L
P	0.15		mg/L
PO ₄	0.14		mg/L

Metals	Result	Code	Units
Al	22	I	µg/L
As	9.0	U	µg/L
B	22	I	µg/L
Ba	6.0	I	µg/L
Ca	52.8		mg/L
Cd	0.50	U	µg/L
Co	1.5	U	µg/L
Cr	3.0	U	µg/L
Cu	8.0	U	µg/L
Fe	18	I	µg/L
K	0.40		mg/L
Mg	4.1		mg/L
Mn	12.9		µg/L
Na	6.0		mg/L
Ni	4.0	U	µg/L
Pb	7.0	U	µg/L
Se	8.0	U	µg/L
Sn	23	U	µg/L
Sr	154		µg/L
Zn	7.7	I	µg/L

A=Average Value

J=Estimated value

I=Value is between laboratory method detection limit and laboratory practical quantitation limit

U,K=Compound not detected, value shown is the method detection limit

Q= Sample held beyond normal holding time

Bacteria Results (in #/100 mL)		
Analyte	Value	Code
Enterococci	1	AKQ
Fecal Coliform	1	AKQ
Total Coliform	1	AKQ

Table A4.2. Lanark Spring Water-Quality Results from March 31, 2004

Field Measures	Result	Code	Units
Temperature	20.96		° C
DO			mg/L
pH	7.20		
Sp. Cond.	98		µS/cm
Lab Analytes			
BOD	0.2	U	mg/L
Turbidity	1.20		NTU
Colour	10		PCU
Alkalinity	105		mg/L
Sp. Cond.	247		µS/cm
TDS	137		mg/L
TSS	4	U	mg/L
Cl	14		mg/L
SO ₄	7.2		mg/L
F	0.067	I	mg/L
Nutrients			
TOC	1.8	I	mg/L
NO ₂ +NO ₃	0.004	U	mg/L
NH ₃ +NH ₄	0.084		mg/L
TKN	0.18	I	mg/L
P	0.090		mg/L
PO ₄	0.08	J	mg/L

Metals	Result	Code	Units
Al	19	I	µg/L
As	9.0	U	µg/L
B	28	I	µg/L
Ba	7.0	I	µg/L
Ca	41.3		mg/L
Cd	0.50	U	µg/L
Co	1.5	U	µg/L
Cr	3.0	U	µg/L
Cu	8.0	U	µg/L
Fe	72		µg/L
K	0.53		mg/L
Mg	3.3		mg/L
Mn	11.3		µg/L
Na	7.2		mg/L
Ni	4.0	U	µg/L
Pb	7.0	U	µg/L
Se	8.0	U	µg/L
Sn	22	U	µg/L
Sr	100		µg/L
Zn	5.5	I	µg/L

U,K=Compound not detected, value shown is the method detection limit
A=Average Value
J=Estimated value
I=Value is between laboratory method detection limit and laboratory practical quantitation limit
Q= Sample held beyond normal holding time

Bacteria Results (in #/100 mL)		
Analyte	Value	Code
Enterococci	1	KQ
Fecal Coliform	1	KQ
Total Coliform	1	KQ

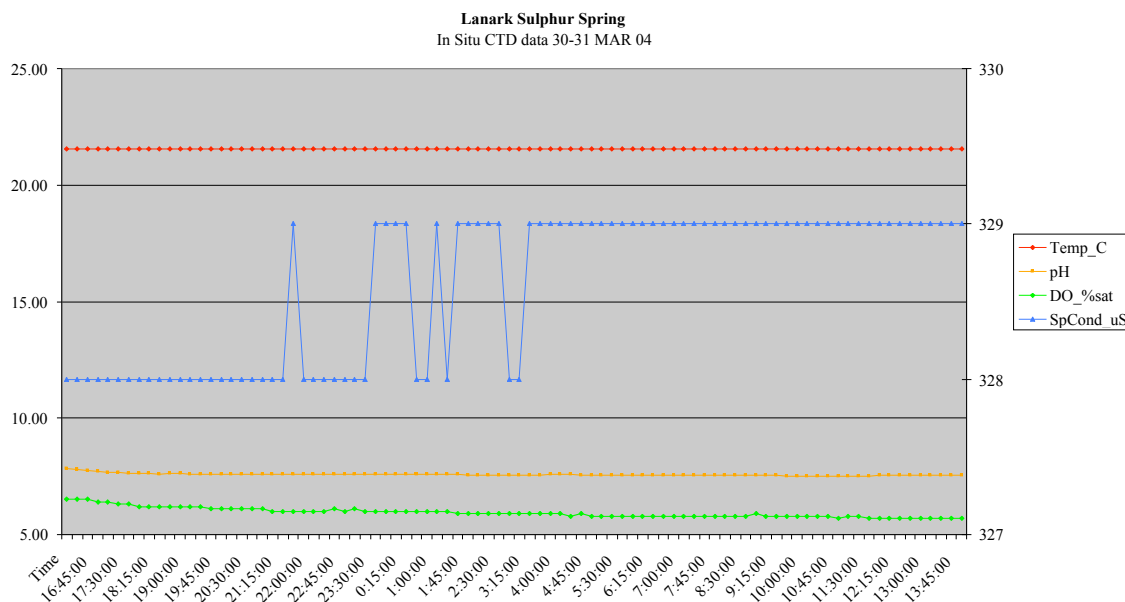


Figure A4.1: March 30-31, 2004 Hydrolab DS3 data from within the flowing vent of Lanark Sulfur Spring. This instrument is not equipped with a depth sensor; however the plot indicates consistency of parameters throughout the 22 hour sample interval. The change in conductivity of one μS is not significant as this is within the tolerance of the meter accuracy.

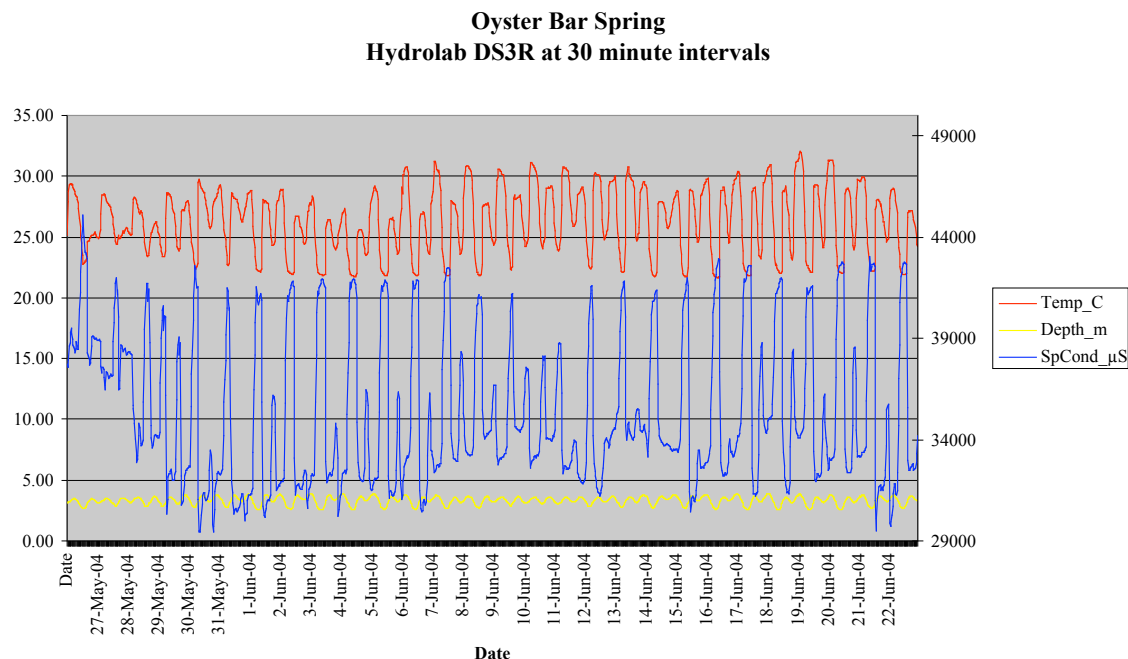


Figure A4.2. Conductivity, temperature and depth data for a one month period within the vent of Oyster Bar Spring.

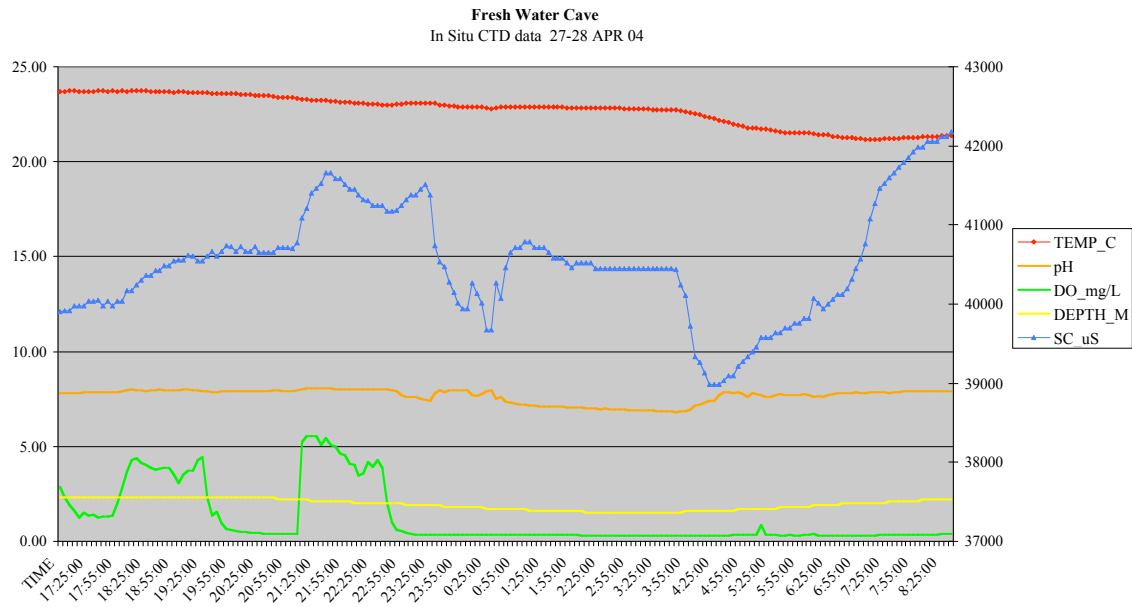


Figure A4.3. April 27-28, 2004. Hydrolab DS3R data (all parameters) from a sink hole near the location of Fresh Water Cave as reported by Rosenau *et al* 1977.

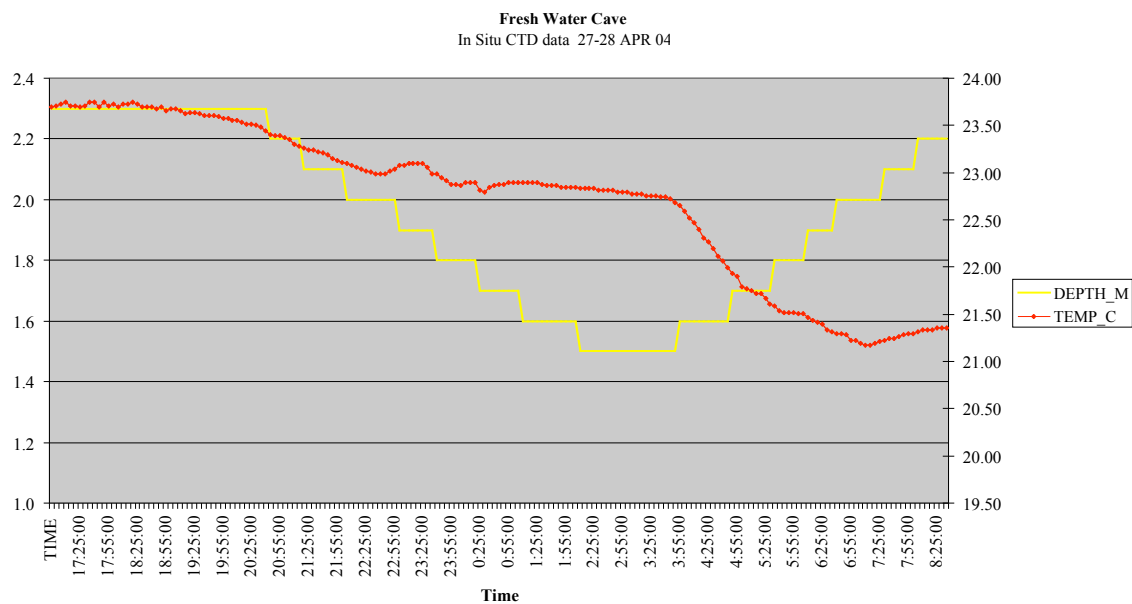


Figure A4.4. April 27-28, 2004. Hydrolab DS3R data (temperature and depth only) from a sink hole near the location of Fresh Water Cave as reported by Rosenau *et al* 1977.

Table A4.3. Water-Quality Results from Lamb Spring, March 11, 2004.

Analytical Environmental Services, Inc.

Date: 25-Mar-04

CLIENT:	Suwannee River Water Mgmt. District				Client Sample ID:	20040151	
Lab Order:	0403808				Collection Date:	3/11/2004 3:00:00 PM	
Project:	Ground Water MAR 2004						
Lab ID:	0403808-001				Matrix:	GROUNDWATER	
Analyses	Result	Qual	MDL	Rpt. Limit	Units	DF	Date Analyzed
RESIDUE, DISSOLVED (TDS)			E160.1				Analyst: ML
Residue, Dissolved (TDS)	35700		5	5	mg/L	1	3/17/2004 4:00:00 PM
TURBIDITY			E180.1				Analyst: ML
Turbidity	BRL	H	0.1	0.1	NTU	1	3/17/2004 3:00:00 PM
INORGANIC ANIONS BY IC			E300				Analyst: CMS
Chloride	24500		71.2	500	mg/L	2000	3/18/2004 4:22:55 PM
Fluoride	BRL		0.299	2.50	mg/L	10	3/18/2004 4:32:20 PM
Sulfate	2900		70.8	400	mg/L	400	3/18/2004 2:03:32 PM
ALKALINITY			E310.2				Analyst: LAV
Alkalinity, Total (As CaCO3)	26.4		1.9	3.0	mg/L	1	3/17/2004 4:16:10 PM
NITROGEN, AMMONIA (AS N)			E350.1				Analyst: LAV
Nitrogen, Ammonia (As N)	BRL		0.04	0.20	mg/L	1	3/19/2004 12:35:12 P
NITROGEN, TOTAL KJELDAHL (TKN)			E351.2				Analyst: TL
Nitrogen, total Kjeldahl (TKN)	1.0		0.1	0.5	mg/L	1	3/19/2004 2:30:52 PM
NITROGEN, NITRATE-NITRITE (AS N)			E353.2				Analyst: TL
Nitrogen, Nitrate-Nitrite (as N)	BRL		0.003	0.050	mg/L as N	1	3/18/2004 3:45:41 PM
TOTAL PHOSPHORUS			E365.1				Analyst: LAV
Phosphorus, Total (As P)	BRL		0.006	0.050	mg/L	1	3/18/2004 5:22:34 PM
TOTAL ORGANIC CARBON (TOC)			E415.1				Analyst: CMS
Organic Carbon, Total	BRL		0.6	1.0	mg/L	1	3/17/2004 6:09:25 PM
DISSOLVED ORGANIC CARBON (TOC)			E415.1				Analyst: CMS
Organic Carbon, Dissolved	4.0		0.8	1.0	mg/L	1	3/17/2004 5:47:06 PM
METALS, TOTAL			SW6010B				Analyst: CDW
Arsenic	BRL		0.0103	0.0500	mg/L	1	3/23/2004 10:46:00 A
Cadmium	BRL		0.0003	0.0050	mg/L	1	3/23/2004 10:46:00 A
Calcium	204		0.0230	0.100	mg/L	1	3/23/2004 10:46:00 A
Iron	BRL		0.0110	0.100	mg/L	1	3/23/2004 10:46:00 A
Lead	BRL		0.0028	0.0100	mg/L	1	3/23/2004 10:46:00 A
Magnesium	1200		0.400	10.0	mg/L	100	3/23/2004 3:03:00 PM
Potassium	501		4.80	50.0	mg/L	100	3/23/2004 3:03:00 PM
Sodium	12000		38.0	100	mg/L	100	3/23/2004 3:03:00 PM

Qualifiers:	*	Value exceeds Maximum Contaminant Level	B	Analyte detected in the associated Method Blank
	BRL	Below Reporting Limit	E	Value above quantitation range
	H	Holding times for preparation or analysis exceeded	J	Analyte detected below quantitation limits
	N	Analyte not NELAC certified	P	NELAC analyte certification pending
	Rpt Limit	Reporting Limit	S	Spike Recovery outside accepted recovery limits

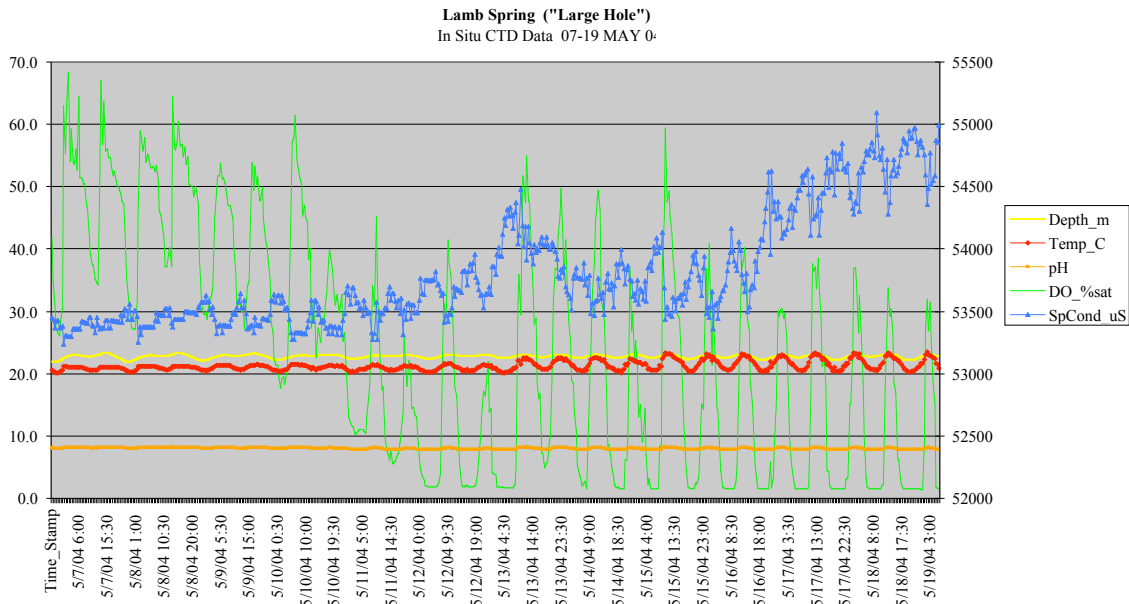


Figure A4.5. May 7-19, 2004. Hydrolab DS3R data plot for the Large Hole, all parameters.

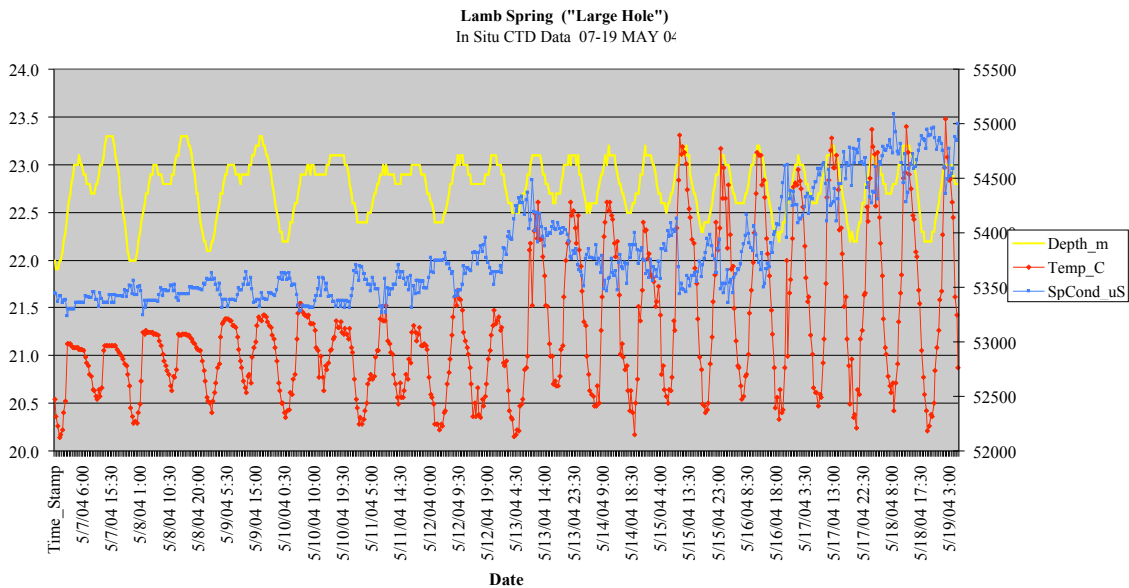


Figure A4.6. May 7-19, 2004. Hydrolab DS3R data plot for the Large Hole; conductivity, temperature and depth.

Appendix 6.1: KARSTMOD Documentation

Karst aquifer model, version 8

A6.1.1. Introduction

The purpose of this analysis is to develop a model capable of predicting the time history of discharge at a spring, $\dot{Q}(t)$, and the break-through curve for contaminants, given the upstream recharge history and the location and timing of contamination.

Begin with a drainage basin of area A which feeds a single spring. The spring may be either at a boundary of the basin or (more likely) at an interior point. Lets assume that

A1. the large-scale flow from ‘uplands’ to spring is via a system of conduits. (large-scale flow within the matrix is much smaller and will be neglected in this first-generation model).

A2. The matrix system is connected systematically via a set of ‘Y’ junctions. These are called vertices in the graph-theory literature. We will call them *nodes*.

A3. The characteristic spacing, H , of nodes and/or associated conduits is pre-determined. (e.g., 100 – 300 meters.) (It is expected that the behavior of the model will be fairly insensitive to this size.)

A4. Flow along conduits is preferentially in the direction to the spring, with no ‘backflow’, i.e., flow from a given node to a second which is farther from the spring. (The no backflow assumption makes the combinatoric problem much easier.)

A5. The basis size is constant, independent of stage.

A6. There are no sinking streams or point inputs of flow. This limitation can be relaxed fairly easily; it is made for simplicity.

A6.1.1.1 Glossary

Boundary node: A node which lies on the boundary of the drainage basin.

Connection: A directed line segment between two ‘nearest neighbor’ nodes, forming a side of an element. The connection starts at an originating node and terminates at a receiving node. Connections are candidates for conduits, or ‘virtual’ conduits.

Connection identifying number: An integer assigned to a given connection: $c = 1 \rightarrow C$. Alternately, a connection can be identified by an ordered pair of numbers: (# of originating node, # of receiving node).

Conduit: A macroscopic void roughly in the form of a cylinder.

Drainage basin: A specified land surface; all recharge to this surface flows to the spring.

Element identifying number: An integer assigned to a given element: $e = 1 \rightarrow E$.

Karst element: A triangle having three connections as its sides. The drainage basin is divided into a finite number of elements.

Nearest neighbor: One of roughly six nodes close to a given node.

Nearest neighbors: Two nodes which are relatively close together and are joined by a connection.

Node: A point in the drainage basin where (three) karst conduits might intersect. ('Might' applies when the model is run in probability mode.)

Node identifying number: An integer assigned to a given node: $n = 1 \rightarrow N$, ordered by distance from the spring, with farthest being #1 and the spring being #N.

Originating node: A node from which water is conveyed via a connection or conduit.

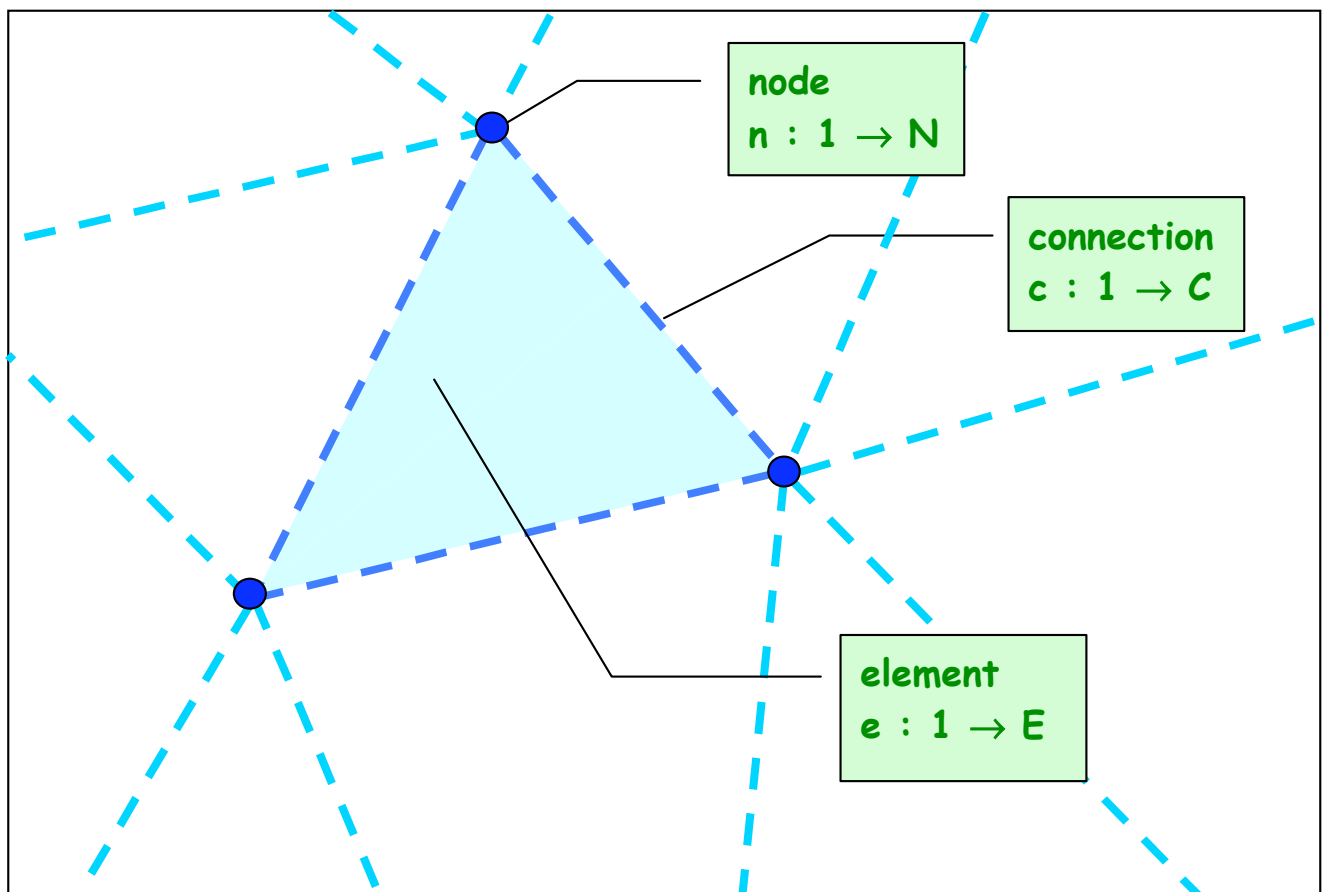
Receiving node: A node to which water is conveyed via a connection or conduit.

Recharge: Rainfall which reaches the aquifer. This may be either a rate (depth/time), denoted by $\dot{R}$, or an instantaneous amount (depth), denoted by R .

Side: A straight line forming part of the boundary of a triangle (an element).

Spring: A specific node (or set of nodes) to which all recharged water flows.

Vertex: One of three points where the sides (connections) of a triangle (an element) meet.



A6.1.1.2 Notation

A map area

A_e	area of element e ; §3.1
b	depth of aquifer (below water table); (4.4)
c	connection identifying number; §2.3
C	total number of connections; §2.3
e	element identifying number; §2.2a
E	total number of elements; §2.2a
f	friction factor; §3.3
g	magnitude of local acceleration of gravity: 9.81 m ² /s
$\mathbf{g}$	local gravity vector
h	head
H	characteristic node spacing
j	basin index; §5.3
k	permeability; units: (length) ²
l	length or distance
L	length
n	node identifying number; §2.1b
n_o	identifying number of originating node; §2.3
n_r	identifying number of receiving node; §2.3
N	total number of nodes; §2.1b
p	probability; §2.4a
p	pressure (4.6)
$\mathbf{q}$	specific discharge; units : (velocity)
$\dot{Q}$	water flux; units : (volume/time)
R	recharge; units : (depth)
$\dot{R}$	recharge rate; units : (length/time)
s	cross sectional area of a connection or conduit
t	time
t_e	equilibration time; (4.3)
$\mathbf{u}$	mean velocity of interstitial fluid
x, y	coordinates of nodes
z	elevation
a	diffusivity; (4.2)
b	recharge fraction; §3.1
G	hydraulic gradient
q	angle between connection and line to the spring; §2.4a
l	exponent in probability function; §2.4b
P	pressure divided by density; §4.1
r	density of water
n	kinematic viscosity of water; (4.6)
f	porosity

A6.1.1.3 List of Tables.

Node Location and Head Table

<i>node identifying number: §2.1b</i>	<i>x coordinate: §2.1c</i>	<i>y coordinate: §2.1c</i>	<i>sink or spring: §2.1d</i>	<i>Head: §3.4</i>
<i>1</i>				
<i>2</i>				
<i>3</i>				
<i>...</i>				
<i>N</i>			<i>spring</i>	

Element Table

<i>element identifying number: §2.2a</i>	<i>first node number: §2.2b</i>	<i>second node number: §2.2b</i>	<i>third node number: §2.2b</i>	<i>first area: §2.2c</i>	<i>first connection number: §2.3f</i>	<i>second connection number: §2.3f</i>	<i>third connection number: §2.3f</i>
<i>1</i>							
<i>2</i>							
<i>3</i>							
<i>...</i>							
<i>E</i>							

Node-connection Table

receiving node

<i>originating node</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>...</i>	<i>N</i>
<i>1</i>					
<i>2</i>		entries are the numbers of the connections; this is a sparse, upper-triangular table; §2.3d			
<i>3</i>					
<i>...</i>					
<i>N</i>					

Connection Table

<i>connection identifying number: §2.3</i>	<i>originating node identifying number: §2.3</i>	<i>receiving node identifying number: §2.3</i>	<i>connection length: §2.3e</i>	<i>angle: §2.4a</i>	<i>probability: §2.4c</i>
<i>1</i>					
<i>2</i>					
<i>3</i>					
<i>...</i>					
<i>C</i>					

Connection Flux Table

<i>connection identifying number</i>	<i>allocation of recharge: §3.2a</i>	<i>entering flux: §3.2b-f</i>	<i>leaving flux: §3.2b-f</i>	<i>mean flux: §3.2g</i>	<i>mean size: §3.3</i>
<i>1</i>					
<i>2</i>					
<i>3</i>					
<i>...</i>					
<i>C</i>					

A6.1.1.4 List of parameters and functions.

The model developed below contains a number of parameters and functions which are to be determined by matching the model output with spring head and flux data, as well as contaminant break-through data.

Parameters

Node spacing, H.

Node variability.

Probability maximum; see §6.1.2.4b.

Steady-state head gradient; see §6.1.3.3.

Permeability; see §6.1.4.1.

Functions

Probability function; §6.1.2.4.

Spring head – flux relation; (5.16).

A6.1.2. Establishment of geometry

To construct and quantify flow in a conduit network, proceed as follows.

A6.1.2.1 Location of nodes and spring.

Begin by ‘seeding’ the drainage basin with nodes, roughly A/H^2 in number, in a triangular-shaped (as opposed to square) pattern. The pattern need not be regular. (This step may be repeated in different realizations.) An additional parameter is the standard deviation of the node spacing.

2.1a. Identify (at least) one node as the spring.

2.1b. Let the number of nodes (including the spring) be N . Assign each node an **node identifying number**, n , running from 1 to N . Number the nodes according to their distance from the spring, with $n = 1$ assigned to the most distant node, and the spring being node $n = N$. If two nodes have equal distance, apply a small random perturbation to their (x, y) coordinates and re-calculate their distance.

2.1c. Record the location (x and y coordinates) of each node in the second and third columns of the **Node Location and Head Table**. The first column of this table are the node numbers, listed in counting order from 1 to N . (For numerical convenience, locate the reference coordinate system such that all nodes lie in the first quadrant so that all location entries are positive numbers.)

2.1d. A few nodes may be identified as sinks and springs; this information is recorded in the fourth column of the **Node Location and Head Table**. By construction, node N is a spring. (Initially, the model will have no sinks and one spring.)

The seeding and numbering can proceed as a single process. Start with a spring location, an approximate drainage basin boundary and a node number N . Then seed the nodes in concentric ranks, starting from the spring and working outward to the boundaries.

A6.1.2.2. Nodes and elements: Element Table.

Identify those nodes which are ‘nearest neighbors’ for each node. Each node has roughly six nearest neighbors. (This can be done within TecPlot using Delaunay triangulation.) These connections between nearest neighbors are potential conduits. The connections sub-divide the drainage basin into a set of triangles. Notes: Connections are not allowed to cross. Connections should be made between boundary nodes. (For purposes of identifying basin area.)

2.2a. Assign each triangular element an **element identifying number**, e , running from 1 to E . (How should this numbering be systematized? Perhaps by the mean distance from the spring, with the most distant element being numbered 1 and the smallest having the spring as a node being numbered E .) Construct an **Element Table** having E rows and eight columns. The first column contains the element identifying numbers in counting order, from 1 to E .

2.2b. The second, third and fourth columns of the *Element Table* contain the identifying numbers of the nodes forming the vertices of that triangular element.

These are assigned by TecPlot during the process of Delaunay Triangulation. (Note: these three entries are not ordered.)

2.2b. Using the coordinates of the nodes forming the vertices of a given element, calculate the area of the element, using the formula

$$A_e = \frac{1}{2} |x_1 y_2 + x_2 y_3 + x_3 y_1 - x_2 y_1 - x_3 y_2 - x_1 y_3|$$

and enter the result in the fifth column of the *Element Table*.

The remaining three columns contain the numbers of the connections; see §A6.1.2.2.

A6.1.2.3. Nodes, elements and connections.

A *connection* is a directed line between two nodes, running from the *originating node* (labeled n_o) to the *receiving node* (labeled n_r). These are potential locations for conduits to occur. In what follows, we will refer to these as connections, to make clear the fact that they may not be realized as conduits.

Connections may be identified from the *Element Table*. For each row in this table, the six ordered pairs of nodes $\{n_o, n_r\}$ which may be formed from the entries in the second, third and fourth columns give the locations of the endpoints of potential connections. Since the nodes are numbered such that the smaller numbers are more distant, keep only those (three in number for each element) for which $n_o < n_r$.

Assign each connection a *connection identifying number*, c , running from 1 to C . Construct a *Connection Table*, having C rows and eight columns. The first column contains the connection numbers, listed in counting order from 1 to C . The second column contains the node identifying number of the originating node and the third contains the node identifying number of the receiving node. In the process of determining head, it will be advantageous to use the following procedure in the assignment of connection identifying numbers.

2.3a. Select all connections having node $\#N$ as the receiving node. Sort these by the originating-node number, from largest to smallest. Assign these connection identifying numbers 1, 2, That is, connection 1 will be the shortest connection ending at the spring.

2.3b. Select all connections having receiving-node $\#N - 1$. Sort these by the originating-node number, from largest to smallest and continue to assign these connection identifying numbers in ascending sequence.

2.3c. Repeat step 2.3b sequentially for nodes having receiving-node $\#N - n$. When a node is reached which is not a receiving node, no connection numbers will be assigned. Exit the process after considering node $\#2$. (Node $\#1$, being the most distant, cannot be a receiving node.)

2.3d. Construct a **Node-connection Table** of size $N \times N$, with the headers for the rows and columns being the node identifying numbers. The headers for the rows represent originating nodes and for columns represent receiving nodes. Initially the table has all entries being zero. For each connection, place the connection identifying number in the table, in the row corresponding to the originating node and in the column corresponding to the receiving node. All such entries will be in the upper triangle of the Table.

2.3e. For each connection, calculate its length, using the second and third columns of the *Connection Table* to identify the originating and receiving nodes and the *Node Location and Head Table* to identify their locations. Enter this information in the sixth column of the **Connection Table**.

2.3f. For each element, use the first, fourth and fifth columns of the Connection Table to identify the connections which form its boundary. Enter the connection numbers in the appropriate rows of the sixth, seventh and eighth columns of the *Element Table*.

A6.1.2.4. Connection angles and probabilities.

For each connection, calculate the (relative) probability of it being activated as a conduit, using the following procedure.

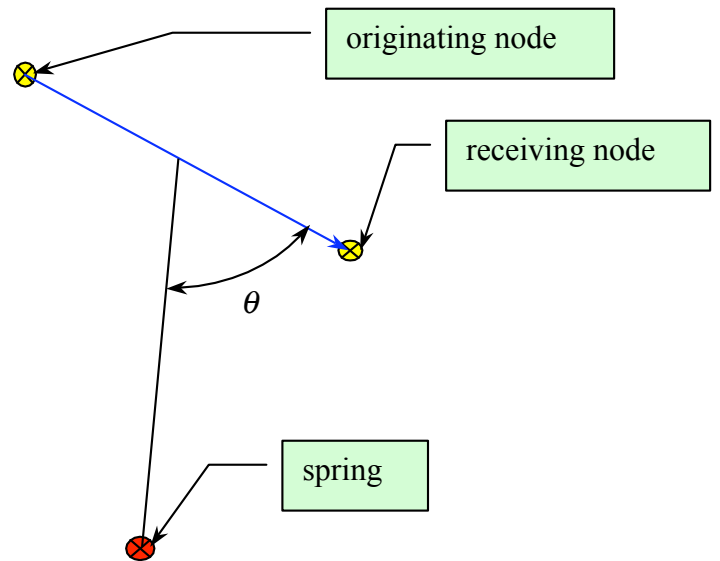
2.4a. Let the Cartesian coordinates of the nodes be represented as follows: spring (x_s, y_s) ; originating node (x_o, y_o) ; receiving node (x_r, y_r) . For each connection, calculate

$$\theta = \left| \arctan \left[\frac{(x_o - x_s)^2 + (y_o - y_s)^2 - (x_r - x_s)^2 - (y_r - y_s)^2}{2(x_r - x_s)(y_o - y_s) - 2(x_o - x_s)(y_r - y_s)} \right] \right|. \quad (2.1)$$

Enter the angle in the seventh column of the *Connection Table*.

The geometric relations are illustrated in the figure.

2.4b. Choose a probability function, $p(q)$, which dictates the probability of a given connection being “activated” as a conduit. This algorithm is a continuous, monotonic decreasing function for $0 < q < p/2$, having a maximum probability of p_0 when $q = 0$ (with $p_0 \leq 1$), reaching 0 at $p/2$, and being equal to 0 for $p/2 \leq q \leq p$. For a



random orientation of conduits $p(q) = \cos(q)$. If the conduit structure is sensitive to the regional gradient, the probability is weighted more strongly toward small values of q than is the function $\cos(q)$. A plausible form is $p(q) = 1 - (2q/p)^l$, with l being a free parameter. If $l = 1$, the function is a straight line. If $l = 2$, it approximates the cosine.

2.4c Store the probabilities in the eighth column of the *Connection Table*.

A6.1.3. Steady-State recharge and flow; Connection size

A6.1.3.1. Recharge from elements.

Recharge falls on the surface area of the drainage basin, which has been divided into a set of triangular elements by the connections. The recharge to element e is proportional to its area A_e . It is assumed that this recharge is apportioned to the three connections bordering the element. In a more realistic simulation, we could account for the probability that a given element has no activated conduits, so that a fraction of its recharge is passed to the neighboring elements. In this first-generation model, this possibility will be ignored.

Recharge is apportioned to the three connections which form the boundaries of an element as follows. Each connection receives recharge in proportion to its probability of being activated (compared with other connections which are activated simultaneously) and its associated area.

The associated area is defined as follows. For every angle, there exists a line, known as the angle bisector, which divides the angle into two equal parts. the three angle bisectors of a triangle, meet at a point called the incenter of the triangle and divide the triangle into three associated areas. Each associated area is, as the name implies, associated with the adjoining connection. The incenter is a point that is equidistant from the three sides (i.e., the three connections) of the triangle (i.e., the element), so that the sizes of the associated areas are proportional to the lengths of the connections.

Temporarily label the three connections (on the three sides of an element) 1, 2 and 3. The fraction, b , of recharge which goes to connection 1 is

$$\beta_1 = \frac{p_1}{\bar{\beta}} \left[\frac{L_1 p_2 p_3}{L_1 + L_2 + L_3} + \frac{L_1 p_2 (1 - p_3)}{L_1 + L_2} + \frac{L_1 (1 - p_2) p_3}{L_1 + L_3} + (1 - p_2)(1 - p_3) \right], \quad (3.1)$$

etc., of the recharge, where L_i is the length of connection i (which is the same as the length of side i of the element in question) and $\bar{\beta}$ is a normalizing factor for the allocation formula, which ensures that all the recharge gets allocated to some connection:

$$\beta_1 + \beta_2 + \beta_3 = 1. \quad (3.2)$$

This condition is satisfied provided

$$\begin{aligned}\bar{\beta} &= 1 - (1 - p_1)(1 - p_2)(1 - p_3) \\ &= p_1 p_2 p_3 - (p_1 p_2 + p_2 p_3 + p_3 p_1) + (p_1 + p_2 + p_3)\end{aligned}\quad (3.3)$$

Formula (3.1) may be written as

$$\beta_1 = \frac{L_1 p_1}{\bar{\beta}} \left[\frac{p_2 p_3}{L} + \frac{p_2 (1 - p_3)}{L - L_3} + \frac{(1 - p_2) p_3}{L - L_2} + \frac{(1 - p_2)(1 - p_3)}{L - L_2 - L_3} \right] \quad (3.4)$$

where L is the length of the perimeter of the element:

$$L = L_1 + L_2 + L_3. \quad (3.5)$$

The length of connections is stored in the sixth column of the *Connection Table*, and the probability information is stored in the eighth column of that table.

Given a rate of recharge (units: depth per unit time), element e receives a volume flux A_e of water (units: volume per unit time). The flux allocated to connection #1 is

$\dot{R} A_e b_1$, etc.

In this section we have been focusing on allocation of recharge from the point of view of an element; how is it passed on to the connections. In the next section we will reconsider this from the point of view of the connection: how much water does the connection convey (in steady state)?

A6.1.3.2. Recharge to connections: connection flux.

A connection conveys a flux $\dot{Q}_r$ to its receiving node. This flux is the sum of the flux $\dot{Q}_o$ entering the connection at the originating node (this may be zero), plus the flux $\dot{Q}_a$ allocated to the connection from the associated areas of the adjoining elements. An connection in the interior of the catchment basin has two adjoining elements, while connections on the boundary of the basin has only one. That is

$$\dot{Q}_r = \dot{Q}_o + \dot{Q}_a \quad (3.6)$$

where

$$\dot{Q}_a = \dot{Q}_{a1} + \dot{Q}_{a2} \quad (3.7)$$

for an interior connection.

These fluxes are to be stored in the *Connection Flux Table*, which has C rows and six columns. The first column contains the connection numbers, listed in counting order from 1 to C . The second third and fourth columns contain the allocation, entering and leaving fluxes, respectively. The fifth column contains the mean flux in the connection:

$$\bar{\dot{Q}}_c = \frac{1}{2} [\dot{Q}_o + \dot{Q}_r] = \dot{Q}_o + \frac{1}{2} [\dot{Q}_{a1} + \dot{Q}_{a2}]. \quad (3.8)$$

while the sixth column contains the mean size of the connection

To calculate the fluxes to be entered in the *Connection Flux Table*, proceed as follows

3.2a. Begin with all zeros in the second column. For each element in counting order, identify its three connections using the calculate the recharge allocated to each of its three connections, and increase the As the recharge to a given element is allocated to its three connections, three entries in this column are increased. For those connections which form the boundary of the drainage basin, a single addition will be made to the second column ($\dot{Q}_a$), while for interior connections, two additions will be made ($\dot{Q}_{a1} + \dot{Q}_{a2}$).

In addition to the local recharge quantified in §6.1.3.1, most connections also carry flux from ‘upstream’ nodes. In this section, this additional flux is quantified and the entering, leaving and mean fluxes carried by each connection are calculated and stored in the third, fourth and fifth columns of the *Connection Flux Table*.

Note that the difference $\dot{Q}_r - \dot{Q}_o$ for a given connection is given by the corresponding entry in the allocation table.

To construct the connection fluxes proceed as follows. Set the initial entries of the third column (entering flux) of the *Connection Flux Table* to zero and place in the fourth column (leaving flux) the corresponding fluxes found in the second column (allocation of recharge). These entries are increased by the following procedure. For each node in numerical order, starting with node $n = 1$, proceed as follows.

3.2b. Identify all the connections for which the node in question is a receiving node, searching the third column of the *Connection Table*. If there are none, go to step 3.2f. (There will be none for node 1.)

3.2c. Determine the flux carried by each of these connections, using the fourth column of the *Connection Flux Table*. Sum these fluxes.

3.2d. Determine all connections for which the node in question is an originating node, searching the second column of the *Connection Table*.

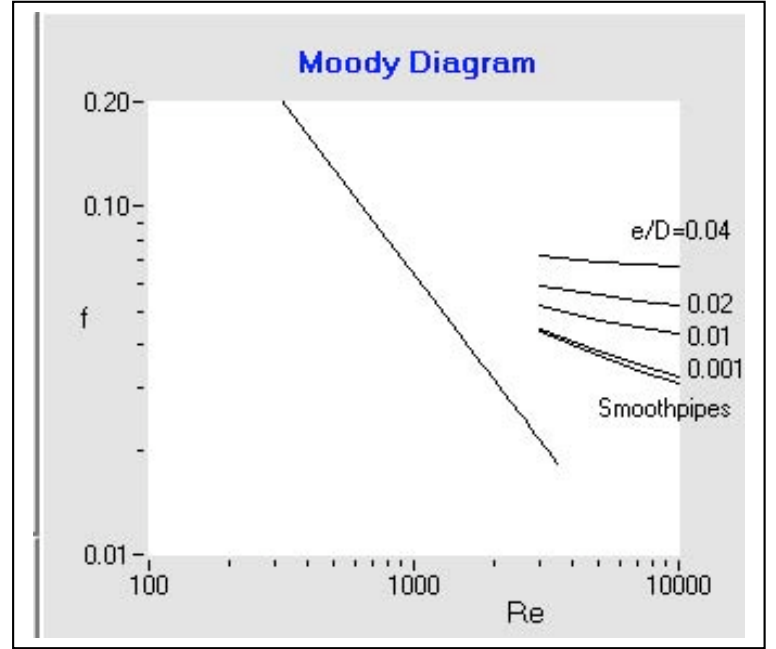
3.2e. Allocate the fluxes found in step 3.2c to the connections identified in step 3.2d according to their probabilities, using eighth column (probability) of the *Connection Table*. Note that the probabilities in that table are not normalized; they need to be normalized (so that they sum to unity) before using them in the allocation scheme. The allocations are to be inserted in both the seventh and eighth columns of the *Connection Table*, adding to the initial entries.

3.2f. Increase the node number by 1 and repeat steps 3.2b through 3.2e, beginning with node $n = 2$ and continuing through node $n = N$.

3.2g. When step 3.2f is complete, apply formula (3.8) to the third and fourth columns in each row of the *Connection Flux Table* and place the result in the fifth column.

A61.3.3. Conduit size.

Once the probable steady-state flux in each connection is known, the next step is to determine its probable size, flow speed and the travel time of water within it. We shall quantify ‘size’ by the cross-sectional area, s , of the connection. The flux of water in a given connection varies with distance from the originating node to the receiving node, because of leakage from and to the adjoining elements. Should this variation in flux be taken into account, or should a given connection be assigned a fixed amount of flux? Will the choice make any difference? Let’s make the simplest choice and assign each conduit a flux which is the mean of that entering (i.e., at the originating node) and leaving (i.e., at the receiving node). This flux is found in the fifth column of the *Connection Flux Table*.



The conduit size is related to the mean flux and gradient, Γ_c , by the Darcy-Weisbach formula

$$\bar{Q} = 2 \frac{g^{1/2} \Gamma_c^{1/2}}{\pi^{1/4} f^{1/2}} s^{5/4} \quad (3.9)$$

where g is the acceleration of gravity and f is the friction factor. We know the flux, and need to decide on the friction factor and the hydraulic gradient. The friction factor is a function of Reynolds number and wall roughness; it is usually represented in a Moody diagram. For rough-walled conduits with high Reynolds number, $f \approx 0.1$. However, Bill Wilson has reported (personal communication) that the effective friction factor for conduits in the Floridan aquifer is as high as 100!

The gradient in the connection is related to the regional gradient by

$$\Gamma_c = \Gamma \cos(\theta) \quad (3.10)$$

Now (3.9) yields

$$s = \left[\frac{\pi f^2 \bar{Q}^4}{2 g^2 \Gamma^2 \cos^2(\theta)} \right]^{1/5} \quad (3.11)$$

In this formula, f and g are the same for all connections, while $\bar{Q}$ and θ vary from connection to connection. The head gradient G is an input parameter, to be specified. In the simplest model, it is a constant; in a more sophisticated model it is a power-law function of distance, x , from the spring, i.e.

$$\Gamma = \tilde{\Gamma} x^\gamma. \quad (3.12)$$

Here $\tilde{\Gamma}$ and γ are constants to be specified.

For each connection, apply formula (3.11), with q determined by column seven of the *Connection Table* and $\bar{Q}$ determined by the fifth column of the *Connection Flux Table*. Place the result in the sixth column of the *Connection Flux Table*. Note that that these entries are constants, not varying with time.

A6.1.3.4 Head in connections

The head, h , at each node may be determined using formulas (3.10) and (3.12) together with the definition of the gradient

$$\Gamma = \frac{\Delta h}{L}, \quad (3.13)$$

where L is the length of a conduit and Δh is the head difference between the originating and receiving nodes. This head distribution is independent of the fluxes in steady state. The steady-state heads of the nodes may be calculated and stored in the fifth column of the *Node Location and Head Table*, by the following procedure. Assign (or calculate?) a spring head, h_s , and place this in the last row of this column. This head may be a function of time. For each connection in sequence (i.e., from $c = 1$ to $c = C$), proceed as follows:

3.4a. Identify the mean flux (the value found in the fifth column of the *Connection Flux Table*) and the length (using the sixth column of the *Connection Table*).

3.4b. Calculate the head difference for the connection, using formulas (3.10) and (3.13). Add this head to that of the receiving node (identified from the *Node-connection Table*). Insert this value in the fifth column of the *Node Location and Head Table* corresponding to the node number of the originating node of that connection.

Since there are multiple pathways, a node head will be calculated more than once. On the strength of formula (3.10), in steady state these values will be compatible. However, we must be careful not to make the heads too large by adding the effects of multiple pathways.

A6.1.4. Temporal variability in elements

There are many types of temporal variability in a karst conduit system. In the following two subsections we investigate two of these, related to head in elements.

A6.1.4.1 Head in elements: equilibration time

In this and the following subsection we quantify the head distribution within the elements, associated with flow of water from elements to conduits, focusing on the timescale for adjustment to uniformity. There are two factors to quantify in this process. The first is the normal, depth-averaged flux-head relationship for a 2-D aquifer studied in

this subsection. The second is the head difference needed to drive the depth averaged flow radially into the circular connection, quantified in §A6.14.2. Substituting (4.8) into (4.5) and thence into (4.4) and assuming that $|h| \ll D$, we have

$$\frac{\partial h}{\partial t} + \alpha \nabla^2 h = 0, \quad (4.1)$$

where

$$\alpha = kgb / \nu \quad (4.2)$$

is a diffusivity. Note that α is inversely proportional to ν ; as the fluid becomes less viscous, the diffusivity increases. For limestone a typical value of permeability is (Rice et al, Anisotropic Permeability in Porous Media, in Flow Through Porous Media, American Chemical Society, 1970) is $1 - 5 \times 10^{-10} \text{ m}^2$. The depth of the aquifer in Florida ranges from 100 to 1000 m. With $g = 10 \text{ m/s}^2$ and $n = 10^{-6} \text{ m}^2/\text{s}$, we have that $\alpha = 0.1 - 5 \text{ m}^2/\text{s}$. This is a fairly large diffusivity, and results in fairly small equilibration times, using the simple formula

$$t_e = l^2 / \alpha. \quad (4.3)$$

where t_e is an equilibration time and l is a typical distance. For example, with $l = 100 \text{ m}$, $t_e \leq 10^5 \text{ s} = 12 \text{ days}$. According to this estimate, flow and head in karst-matrix elements equilibrate fairly quickly. However, this calculation neglects the issue of concentration of this depth averaged flow into a relatively tiny conduit.

Consider the depth-averaged flow in an element. Conservation of water is quantified by

$$\phi \frac{\partial h}{\partial t} + \nabla \cdot [(b+h)\mathbf{q}] = 0 \quad (4.4)$$

where ϕ is the porosity, h is the head (measured from some specified reference level), D is the depth of the aquifer below a reference level (such as the mean steady-state head the surrounding connections) and $\mathbf{q}$ is the specific discharge:

$$\mathbf{q} = \phi \mathbf{u}, \quad (4.5)$$

where $\mathbf{u}$ is the mean velocity of the interstitial fluid. Darcy's law states that

$$0 = \mathbf{g} - \nabla \Pi + \nu \mathbf{u} / k, \quad (4.6)$$

where Π is the pressure divided by density, ν is the kinematic viscosity and k is the permeability (length²). Assuming that flow is predominantly horizontal, we may integrate the vertical component of (4.6) to obtain

$$\Pi = \Pi_0 + g(h - z) \quad (4.7)$$

where z is elevation (positive upward). Using the gradient of (4.7), the horizontal portion of (4.6) becomes

$$\mathbf{u} = (kg/v)\nabla h, \quad (4.8)$$

A6.1.4.2 Head in elements: transfer time

Consider next the radial flow needed to get water to and from a conduit. The surface area of a conduit is equal to the perimeter of its cross-section times its (downstream) length, L . The perimeter is proportional to $\sqrt{s}$. In order for flow to seep through this surface at a rate $\dot{Q}$, a gradient G_{surf} is required, where

$$\Gamma_{\text{surf}} \approx \frac{v\dot{Q}}{kgL\sqrt{s}} \quad (4.9)$$

This gradient exists on a spatial scale comparable to the conduit radius, which is proportional to $\sqrt{s}$, so that the associated head drop is given roughly by

$$\Delta h \approx \Gamma_{\text{surf}}\sqrt{s} \approx \frac{v\dot{Q}}{kgL} \quad (4.10)$$

In this formula, L is the length of a conduit. The area of the associated element is proportional to L^2 , assuming it has a unit-order aspect ratio. The flux is related to the time-rate of change of the head:

$$\dot{Q} \approx L^2 \frac{dh}{dt}. \quad (4.11)$$

Combining (4.10) and (4.11), we have a characteristic time, t_{tr} , for transfer of water between conduits and matrix

$$t_{\text{tr}} \approx \frac{vL}{kg}. \quad (4.12)$$

Assuming that $l \approx L$, the ratio of the transfer time to the equilibration time, given by (4.3), is

$$\frac{t_{\text{tr}}}{t_e} = \frac{b}{L}. \quad (4.13)$$

This may be telling us that the effective depth of the aquifer is roughly equal to the node spacing. In any case, the head drop associated with flow into and from the conduits is at least as large as that associated with distributing flow throughout the element.

A6.1.5 Head and conduit flux in aquifer: allocation to nodes

One knotty question is whether to allocate recharge from elements to nodes or to connections. The more realistic option is allocation to connections, but as we shall see in

§6, this leads to partial differential equations. A simpler option is to allocate recharge to nodes. In this section, we develop several simple models of the behavior of head and flux in a karstic aquifer with allocation to nodes, beginning with the simplest and adding complexity systematically.

A6.1.5.1 Single basin, constant spring head.

Lets start with a model aquifer, consisting of a single basin (element) of area A , porosity f and uniform head $h(t)$ connected to a spring having head h_{s0} , via a single node and a conduit of length L . There is no leakage into the sides of the conduit; it carries a uniform flux, $\dot{Q}$, from basin to spring. The basin receives recharge $\dot{R}(t)$. Conservation of water dictates that

$$A \left[\dot{R} - \phi \frac{dh}{dt} \right] = \dot{Q} . \quad (5.1)$$

The amount of water conveyed by the conduit is controlled by the Darcy-Weisbach equation, (3.9). Noting that

$$\Gamma_c = \frac{h - h_{s0}}{L} , \quad (5.2)$$

we may write

$$\dot{Q} = \Lambda [h - h_{s0}]^{1/2} , \quad (5.3)$$

where Λ is a constant parameter incorporating the effects of conduit size and roughness.

In steady state, (5.1) and (5.3) simplify to

$$A\dot{R}_0 = \dot{Q}_0 \quad (5.4)$$

and

$$\dot{Q}_0 = \Lambda [h_0 - h_{s0}]^{1/2} , \quad (5.5)$$

where a subscript 0 denotes a constant. We may use these equations to write Λ as

$$\Lambda = \frac{A\dot{R}_0}{[h_0 - h_{s0}]^{1/2}} . \quad (5.6)$$

Now (5.3) is

$$\dot{Q} = A\dot{R}_0 \frac{[h - h_{s0}]^{1/2}}{[h_0 - h_{s0}]^{1/2}} . \quad (5.7)$$

Eliminating $\dot{Q}$ between (5.1) and (5.7), we have a predictive equation for $h(t)$:

$$\phi \frac{dh}{dt} = \dot{R} - \dot{R}_0 \frac{[h - h_{s0}]^{1/2}}{[h_0 - h_{s0}]^{1/2}}. \quad (5.8)$$

If $\dot{R}(t)$ and $h_s(t)$ are specified, it is a relatively simple matter to integrate (5.8) and determine the head in the aquifer.

Non-dimensionalize (5.8) letting

$$h = h_{s0} + [h_0 - h_{s0}] \tilde{h}, \quad (5.9)$$

$$\dot{R} = \dot{R}_0 \tilde{R} \quad (5.10)$$

and

$$\tilde{t} = t / t_{dr} \quad (5.11)$$

where

$$t_{dr} = 2\phi [h_0 - h_{s0}] / \dot{R}_0. \quad (5.12)$$

Now

$$\frac{d\tilde{h}}{d\tilde{t}} = \tilde{R} - \tilde{h}^{1/2}. \quad (5.13)$$

A simple example; suppose that $\dot{R}(t) = 0$. The solution of (5.13) is

$$\tilde{h}(t) = [1 - \tilde{t}]^2. \quad (5.14)$$

Note the appearance of a drainage timescale defined by (5.12). With reasonable values of the parameters, this is on the order of years.

A6.1.5.2 Single basin, variable spring head.

Now, allow for variation of the spring head, now denoted by h_s . With a variable spring head, (5.1) remains the same, while (5.7) becomes

$$\dot{Q} = A\dot{R}_0 \frac{[h - h_s]^{1/2}}{[h_0 - h_{s0}]^{1/2}}. \quad (5.15)$$

The relation between spring head and flux is governed by the Darcy-Weisbach equation once more, but with a significantly different interpretation from its use in the conduit. In the conduit, area is held fixed, while the head gradient varies, while in the stream or river flowing from the spring, the head gradient is fixed and the flow area is variable. The precise relation depends strongly on the shape of the river basin – how river width varies with depth. Without going into details, we have

$$h_s = F(\dot{Q}) \quad (5.16)$$

where the function F may be determined from spring head and flux data. Normally spring head varies weakly with flux:

$$\frac{d \ln(h_s)}{d \ln \dot{Q}} \ll 1. \quad (5.17)$$

Using (5.16) to eliminate h_s , (5.15) becomes

$$h = F(\dot{Q}) + \left[\frac{\dot{Q}}{A \dot{R}_0} \right]^2 [h_0 - h_{s0}]. \quad (5.18)$$

Substituting this into (5.1), we obtain a single equation for $\dot{Q}$:

$$\phi \left\{ F'(\dot{Q}) + \left[\frac{2\dot{Q}}{A^2 \dot{R}_0^2} \right] [h_0 - h_{s0}] \right\} \frac{d\dot{Q}}{dt} = \dot{R} - \frac{\dot{Q}}{A}. \quad (5.19)$$

where a prime denotes differentiation

We may non-dimensionalize the problem using (5.9) – (5.11) and

$$\dot{Q} = A \dot{R}_0 \tilde{Q}, \quad (5.20)$$

Also, the dimensionless form of (5.16) is

$$h_s = [h_0 - h_{s0}] \tilde{F}(\tilde{Q}). \quad (5.21)$$

Now (5.19) becomes

$$[\tilde{F}'(\tilde{Q}) + 2\tilde{Q}] \frac{d\tilde{Q}}{d\tilde{t}} = 2\tilde{R} - 2\tilde{Q}. \quad (5.22)$$

Special cases

A. If $\tilde{F}' = 0$, the equation simplifies to

$$\tilde{Q} \frac{d\tilde{Q}}{d\tilde{t}} = \tilde{R} - \tilde{Q}. \quad (5.23)$$

which is equivalent to (5.13).

B. The steady-state solution of (5.23) is

$$\tilde{R} = \tilde{Q} = 1. \quad (5.24)$$

C. In the case of drought, with $\tilde{R} = 0$, (5.22) simplifies to

$$\left[\tilde{F}'(\tilde{Q}) + 2\tilde{Q} \right] \frac{d\tilde{Q}}{d\tilde{t}} = -2\tilde{Q}. \quad (5.25)$$

Consider the influence of spring-head variability on the long-term behavior of the spring during a drought. We saw in the previous subsection that spring head and flux go abruptly to zero at a finite time if spring head is constant. If spring head varies quadratically (or more strongly) with flux so that $\tilde{F}'$ varies linearly with $\tilde{Q}$, this result is not changed qualitatively: the spring still goes dry abruptly. However, if the spring head varies weakly with flux, the long-term behavior of (5.25) is dominated by the structure of the flux function F . For example, suppose that

$$\tilde{F} = 1 + \varepsilon \ln(\tilde{Q}) \quad (5.26)$$

Now (5.25) becomes

$$\left[\frac{\varepsilon}{\tilde{Q}} + 2\tilde{Q} \right] \frac{d\tilde{Q}}{d\tilde{t}} = -2\tilde{Q}. \quad (5.27)$$

The solution of this which satisfies the initial condition $\tilde{Q}(0) = 1$ is

$$2\tilde{Q} - \frac{\varepsilon}{\tilde{Q}} = 2 - \varepsilon - 2\tilde{t} \quad (5.28)$$

With $\varepsilon \ll 1$, the dominant behavior is simply

$$\tilde{Q} = 1 - \tilde{t}, \quad (5.29)$$

which is equivalent to solution (5.14). However, as $\tilde{Q}$ becomes smaller than $\varepsilon^{1/2}$, the dominant behavior is given by

$$\tilde{Q} = \frac{\varepsilon}{2\tilde{t}} \quad (5.30)$$

The spring does not go dry abruptly, but has an algebraic tail of flux.

A6.1.5.3 Two basins, constant spring head.

Next, consider two spring basins with #1 feeding #2 and #2 feeding a spring. The heads and fluxes are governed by

$$A_1 \left[\dot{R}_1 - \phi \frac{dh_1}{dt} \right] = \dot{Q}_1 \quad (5.31)$$

$$A_2 \left[\dot{R}_2 - \phi \frac{dh_2}{dt} \right] = \dot{Q}_2 - \dot{Q}_1 \quad (5.32)$$

with

$$\dot{Q}_j = A_j \dot{R}_0 \left[\frac{h_j - h_{(j+1)}}{h_{j0} - h_{(j+1)0}} \right]^{1/2}, \quad (5.33)$$

for $j = 1, 2$, where $j = 3$ is the spring. The equations may be made dimensionless by setting

$$\dot{Q}_j = A_j \dot{R}_0 \tilde{Q}_j \quad (5.34)$$

$$\dot{R}_j = \dot{R}_0 \tilde{R}_j, \quad (5.35)$$

$$h_j = h_{(j+1)0} + \left[h_{j0} - h_{(j+1)0} \right] \tilde{h}_j, \quad (5.36)$$

and

$$\tilde{t} = t / t_{\text{dr}} \quad (5.37)$$

where

$$t_{\text{dr}} = 2\phi [h_{10} - h_{s0}] / \dot{R}_0. \quad (5.38)$$

Now

$$\left[\tilde{R}_1 - \frac{\beta}{2} \frac{d\tilde{h}_1}{d\tilde{t}} \right] = \tilde{Q}_1 \quad (5.39)$$

$$\left[\tilde{R}_2 - \frac{\phi}{\dot{R}_0} \frac{d\tilde{h}_2}{d\tilde{t}} \right] = \tilde{Q}_2 - \tilde{Q}_1 \quad (5.40)$$

with

$$\dot{Q}_j = A_j \dot{R}_0 \left[\frac{h_j - h_{(j+1)}}{h_{j0} - h_{(j+1)0}} \right]^{1/2}. \quad (5.41)$$

Now, eliminating $\tilde{Q}_j$ we have

$$\tilde{R}_1 - \beta \frac{d\tilde{h}_1}{d\tilde{t}} = \tilde{h}_1^{1/2} \quad (5.42)$$

and

$$\tilde{R}_2 - [1 - \beta] \frac{d\tilde{h}_2}{d\tilde{t}} = \tilde{h}_2^{1/2} - \tilde{h}_1^{1/2}, \quad (5.43)$$

where

$$\beta = [h_{10} - h_{20}] / [h_{10} - h_{s0}]. \quad (5.44)$$

A6.1.6 Head and conduit flux in aquifer: allocation to nodes

A6.1.6.1 Single conduit, constant spring head

Consider a catchment basin of length L and width $w(x)$ where $0 < x < L$. ($x = 0$ at the head of the basin and $x = L$ at the spring.) Recharge falling on the basin may vary with distance and time: $\dot{R} = \dot{R}(x, t)$ feeds water into a conduit. Also, the temporal variation of head, $h(x, t)$ in the basin can contribute flux to the conduit. The flux $\dot{Q}(x, t)$ of water through the conduit varies with downstream distance according to:

$$\frac{\partial \dot{Q}}{\partial x} = w(x) \left[\dot{R}(x, t) - \phi \frac{\partial h}{\partial t} \right]. \quad (6.1)$$

The flow in the conduit is governed by the Darcy-Weisbach equation

$$\dot{Q}(x, t) = \Lambda(x) \left[-\frac{\partial h}{\partial x} \right]^{1/2}. \quad (6.2)$$

Note that $\partial h / \partial x < 0$; head decreases with distance from head-waters. In steady state, (6.1) and (6.2) become

$$\frac{d\dot{Q}_{ss}}{dx} = w(x) \dot{R}_0 \quad (6.3)$$

and

$$\dot{Q}_{ss}(x) = \Lambda(x) \left[-\frac{dh_{ss}}{dx} \right]^{1/2}. \quad (6.4)$$

Using these to eliminate $w(x)$ from (6.1) and $\Lambda(x)$ from (6.2), we have

$$\dot{R}_0 \frac{\partial \dot{Q}}{\partial x} = \frac{d\dot{Q}_{ss}}{dx} \left[\dot{R}(x, t) - \phi \frac{\partial h}{\partial t} \right] \quad (6.5)$$

and

$$\dot{Q} = \frac{\dot{Q}_{ss}}{[-dh_{ss}/dx]^{1/2}} \left[-\frac{\partial h}{\partial x} \right]^{1/2}. \quad (6.6)$$

We need to specify an initial head distribution, $h(x, 0)$, and two boundary conditions. At the upper end of the basin, the flux is zero and at the lower end, the head is fixed by the spring value:

$$\frac{\partial \dot{Q}}{\partial x}(0, t) = 0 \quad \text{and} \quad h(L, t) = h_0 \quad (6.7), (6.8)$$

Let us non-dimensionalize the variables with

$$x = L\tilde{x}, \quad t = t_{dr}\tilde{t}, \quad \dot{R} = \dot{R}_{ss}\tilde{R} \quad (6.9), (6.10), (6.11)$$

$$\dot{Q}(x, t) = \dot{R}_0 A \tilde{Q}(\tilde{x}, \tilde{t}), \quad \dot{Q}_{ss}(x) = \dot{R}_0 A \tilde{Q}_{ss}(\tilde{x}) \quad (6.12), (6.13)$$

$$h(x, t) = h_0 + (\Delta h) \tilde{h}(\tilde{x}, \tilde{t}), \quad h_{ss}(x) = h_0 + (\Delta h) \tilde{h}_{ss}(\tilde{x}) \quad (6.14), (6.15)$$

with Δh , A and t_{dr} given by

$$\Delta h = h_{ss}(0) - h_{ss}(L), \quad (6.16)$$

$$A = \int_0^L w(x) dx \quad (6.17)$$

and

$$t_{dr} = 2\phi(\Delta h) / \dot{R}_0. \quad (6.18)$$

Now equations (6.5) and (6.6) become

$$\frac{\partial \tilde{Q}}{\partial \tilde{x}} = \frac{d\tilde{Q}_{ss}}{d\tilde{x}} \left[\tilde{R} - \frac{1}{2} \frac{\partial \tilde{h}}{\partial \tilde{t}} \right] \quad (6.19)$$

and

$$\tilde{Q} = \tilde{Q}_{ss} \left[\frac{\partial \tilde{h} / \partial x}{d\tilde{h}_{ss} / d\tilde{x}} \right]^{1/2}. \quad (6.20)$$

In steady state, $\tilde{R} = 1$, while $\tilde{Q}$ and $\tilde{h}$ are functions of x which have the following limiting values: $\tilde{Q}(0) = 0$, $\tilde{h}(0) = 1$, $\tilde{Q}(1) = 1$ and $\tilde{h}(1) = 0$. Eliminating $\tilde{Q}$ between (6.19) and (6.20), we have

$$\frac{\partial}{\partial \tilde{x}} \left\{ \tilde{Q}_{ss} \left[\frac{\partial \tilde{h} / \partial x}{d\tilde{h}_{ss} / d\tilde{x}} \right]^{1/2} \right\} = \frac{d\tilde{Q}_{ss}}{d\tilde{x}} \left[\tilde{R} - \frac{1}{2} \frac{\partial \tilde{h}}{\partial \tilde{t}} \right]. \quad (6.21)$$

Note that this equation is singular at $\tilde{x} = 0$.

Consider a perturbation away from the steady state; let

$$\tilde{R} = 1 + R' \quad (6.22)$$

$$\tilde{Q} = \tilde{Q}_{ss} + Q' \quad (6.23)$$

and

$$\tilde{h} = \tilde{h}_s + h' \quad (6.24)$$

with the primed variables having small amplitude. Now the linearized versions of (6.19), (6.20) and (6.21) are

$$\frac{\partial Q'}{\partial \tilde{x}} = \frac{d\tilde{Q}_{ss}}{d\tilde{x}} \left[R' - \frac{1}{2} \frac{\partial h'}{\partial \tilde{t}} \right] \quad (6.25)$$

$$Q' = \tilde{Q}_{ss} \frac{\partial h' / \partial \tilde{x}}{2 d\tilde{h}_{ss} / d\tilde{x}}. \quad (6.26)$$

and

$$\left[\frac{\tilde{Q}_{ss}}{d\tilde{h}_{ss} / d\tilde{x}} \right] \frac{\partial^2 h'}{\partial \tilde{x}^2} + \frac{d}{d\tilde{x}} \left[\frac{\tilde{Q}_{ss}}{d\tilde{h}_{ss} / d\tilde{x}} \right] \frac{\partial h'}{\partial \tilde{x}} = \frac{d\tilde{Q}_{ss}}{d\tilde{x}} \left[2R' - \frac{\partial h'}{\partial \tilde{t}} \right] \quad (6.27)$$

In a drought, equation (6.27) simplifies to

$$\frac{d\tilde{Q}_{ss}}{d\tilde{x}} \frac{\partial h'}{\partial \tilde{t}} - \frac{d}{d\tilde{x}} \left[\frac{\tilde{Q}_{ss}}{-d\tilde{h}_{ss} / d\tilde{x}} \right] \frac{\partial h'}{\partial \tilde{x}} = \left[\frac{\tilde{Q}_{ss}}{-d\tilde{h}_{ss} / d\tilde{x}} \right] \frac{\partial^2 h'}{\partial \tilde{x}^2}, \quad (6.28)$$

Special case: suppose that $\tilde{Q}_{ss} = \tilde{x}$ and $\tilde{h} = 1 - \tilde{x}$

$$\frac{\partial h'}{\partial \tilde{t}} - \frac{\partial h'}{\partial \tilde{x}} = \tilde{x} \frac{\partial^2 h'}{\partial \tilde{x}^2}, \quad (6.29)$$

Appendix 6.2 KARSTMOD Program

```

program karstmod
*****
*
*  VARIABLES AND ARRAYS
*
*****
real(8) :: pi,dtmp,mass,oldmass,D,N,diff,psum,oldpsum,frict,
/ p1,p2,p3,L1,L2,L3,FBAR,f1,f2,f3,P0,time,
/ perm,S,Qdot1,Qdot2,Qdot3,T11,T12,T13,T14,T15,T16,T17,
/ T18,dt,newmass,springmass,T21,T22,T23,T24,T25,T26,T27,
/ T28,T31,T32,T33,T34,T35,T36,T37,T38
real(8), allocatable :: Pconnect(:),pointxy(:,:),
/ dist(:,:),alpha(:),fract(:,:),area(:),
/ fractold(:,:),tempxy(:,:),length(:),allocation(:),
/ oldallocation(:),flux(:),oldflux(:),massin(:),
/ xarea(:),
/ centroid(:,:),diam(:),Qdot(:),Q1(:),Q2(:),Q3(:),R(:),
/ Rtrans(:),influx(:),storage(:),ssflux(:),ssallocation(:)
integer i,j,k,l,m,springpt,num,alloc_err,kfact,C,add,npts,numel
integer, allocatable :: karstel(:,:),connect(:,:),connection(:,:),
/ sides(:,:),elsides(:,:),temp(:),tmpkarstel(:,:),
/ nodes(:,:),tempconnection(:,:)
*****
*
*  MAIN PROGRAM
*
*****
c open files for writing
open(unit=11,file='fepoint_old.data');
open(unit=12,file='data.out');
open(unit=13,file='tmp.dat');
! set some constants temporarily
!
PI= 3.141592653589793238D0
read(11,*) npts, numel ! ML: Originally were assigned in code
sprintpt = 5
kfact = 2
! this is the term in the exponenet of the
! probability function that is sensitive to the angle
! of a conduiti w.r.t. a ray drawn from the spring to
! the center line of the conduit
*****
*
*  DATA INPUT SECTION
*
*****
c allocate and fill arrays with the x, y point locations and their
connections
c that form the karst elements (triangles)
allocate(pointxy(npts,3),tempxy(npts,3),centroid(numel,2),temp(3),
/ stat = alloc_err)
do i = 1, npts
do j = 1,3
pointxy(i,j) = 0.D0

```

```

end do
end do
! read in the points from unit = 11
read(11,*), ((pointxy(i,j),j=1,2),i=1,npts)
! allocate arrays to store the element info
allocate(karstel(7,numel),tmpkarstel(7,numel), stat = alloc_err)
! read in the element side connection info from unit=11
read(11,*), ((karstel(i,j),i=1,3),j=1,numel)
close(unit=11) ! close the unit since no data will be read after this
*****
*
* PRE-PROCESSING
*
*****
c calculate distances from spring to each point
print *, 'calculating distances from spring'
print *, '*****'
do i = 1, npts
do j = 1, 2
dtmp = sqrt((pointxy(springpt,1)-pointxy(i,1))**2
/ +(pointxy(springpt,2)-pointxy(i,2))**2)
pointxy(i,3) = dtmp
end do
end do
c Sort the pointxy array by distance from spring, with farthest points
first
print *, 'ranking distances from spring'
print *, '*****'
do i = 1,npts
temp = minloc(pointxy,dim=1)
tempxy(npts - (i-1),1) = pointxy(temp(3),1)
tempxy(npts - (i-1),2) = pointxy(temp(3),2)
tempxy(npts - (i-1),3) = pointxy(temp(3),3)
pointxy(temp(3),1) = 1000000
pointxy(temp(3),2) = 1000000
pointxy(temp(3),3) = 1000000
do j = 1, 3
do k = 1, numel
if (karstel(j,k).eq.temp(3)) then
tmpkarstel(j,k) = npts - (i-1)
end if
end do
end do
end do
pointxy = tempxy ! re-fill the pointxy array with sorted values
karstel = tmpkarstel ! re-fill the karstel array with sorted values
springpt = npts ! re-set the springpt
allocate(area(numel), stat=alloc_err)
print *, 'calculating element areas'
print *, '*****'
do k=1,numel
area(k)=abs(0.5*(pointxy(karstel(1,k),1)*pointxy(karstel(2,k),2)
/ - pointxy(karstel(2,k),1)*pointxy(karstel(1,k),2)
/ + pointxy(karstel(2,k),1)*pointxy(karstel(3,k),2)
/ - pointxy(karstel(3,k),1)*pointxy(karstel(2,k),2)
/ + pointxy(karstel(3,k),1)*pointxy(karstel(1,k),2)
/ - pointxy(karstel(1,k),1)*pointxy(karstel(3,k),2)))
end do

```

```

c make a ranked connection tables, where connections
c ML: made connection be of a larger size
c
allocate(connection(npts*4,2),tempconnection(npts*4,2),stat=alloc_err)
allocate(connection(numel*3,2),tempconnection(numel*3,2),
/ stat=alloc_err)
connection = 0
tempconnection = 0
num = 0
do j = numel, 1,-1 ! ML: reversed the loop to follow order in writeup
print *, ' num = ',num,' j = ',j
if(karstel(1,j).lt.karstel(2,j)) then
num = num + 1
connection(num,1) = karstel(1,j) ! originating node is 1
connection(num,2) = karstel(2,j)
else
num = num + 1
connection(num,2) = karstel(1,j) ! originating node is 2
connection(num,1) = karstel(2,j)
end if
if(karstel(1,j).lt.karstel(3,j)) then
num = num + 1
connection(num,1) = karstel(1,j) ! originating node is 1
connection(num,2) = karstel(3,j)
else
num = num + 1
connection(num,2) = karstel(1,j) ! originating node is 3
connection(num,1) = karstel(3,j)
end if
if(karstel(2,j).lt.karstel(3,j)) then
num = num + 1
connection(num,1) = karstel(2,j) ! originating node is 2
connection(num,2) = karstel(3,j)
else
num = num + 1
connection(num,2) = karstel(2,j) ! originating node is 3
connection(num,1) = karstel(3,j)
end if
end do
c count the number of connections
C = num
c sort through connections for duplicates
do i = 1, C-1
do j = i+1, C
if (( connection(i,1).eq.connection(j,1)).and.
/ ( connection(i,2).eq.connection(j,2))) then
connection(j,1) = -1
connection(j,2) = -1
end if
end do
end do
c get rid of placeholders
count = 0
do i=1,C
if(connection(i,1).ne.-1) then
count = count+1
tempconnection(count,1) = connection(i,1)
tempconnection(count,2) = connection(i,2)

```

```

end if
end do
connection = tempconnection
deallocate(tempconnection)
c Make nodes table and fill with connections
allocate(nodes(npts,npts),stat=alloc_err)
nodes = 0
C = count
do i = 1, C
nodes(connection(i,1),connection(i,2)) = i
end do
c calculate the length of each connection and put in LENGTH array
allocate(length(C), stat=alloc_err)
do i=1,C
length(i) = sqrt(
/ (pointxy(connection(i,1),1)-pointxy(connection(i,2),1))**2
/ +(pointxy(connection(i,1),2)-pointxy(connection(i,2),2))**2)
end do
c calculate angles and probabilities of connections
allocate(alpha(C),stat=alloc_err)
allocate(Pconnect(C),dist(npts,npts),stat=alloc_err)
Pconnect = 0. ! fill the porbability array with 0
! calculate distance from each poit to spring
do i = 1, C
D = (pointxy(connection(i,1),1) - pointxy(springpt,1))**2
/ +(pointxy(connection(i,1),2) - pointxy(springpt,2))**2
/ -(pointxy(connection(i,2),1) - pointxy(springpt,1))**2
/ -(pointxy(connection(i,2),2) - pointxy(springpt,2))**2
N = 2.*(pointxy(connection(i,2),1)-pointxy(springpt,1))
/ *(pointxy(connection(i,1),2)-pointxy(springpt,2))
/ -2.*(pointxy(connection(i,1),1)-pointxy(springpt,1))
/ *(pointxy(connection(i,2),2)-pointxy(springpt,2))
alpha(i) = dabs(atan(N/D)) !ML:Check that N&D should be reversed
Pconnect(i)= 1.-(2.*alpha(i)/pi)**kfact
end do
c put connection numbers in element array next to point numbers
c order them 1,2 - 2,3 - 1,3
do i = 1, numel
if (karstel(1,i).lt.karstel(2,i)) then
do j = 1,C
if ((karstel(1,i).eq.connection(j,1)).and.
/ (karstel(2,i).eq.connection(j,2))) then
karstel(4,i) = j
end if
end do
else
do j = 1,C
if ((karstel(1,i).eq.connection(j,2)).and.
/ (karstel(2,i).eq.connection(j,1))) then
karstel(4,i) = j
end if
end do
end if
if (karstel(2,i).lt.karstel(3,i)) then
do j = 1,C
if ((karstel(2,i).eq.connection(j,1)).and.
/ (karstel(3,i).eq.connection(j,2))) then
karstel(5,i) = j

```

```

end if
end do
else
do j = 1,C
if ((karstel(2,i).eq.connection(j,2)).and.
/ (karstel(3,i).eq.connection(j,1))) then
karstel(5,i) = j
end if
end do
end if
if (karstel(1,i).lt.karstel(3,i)) then
do j = 1,C
if ((karstel(1,i).eq.connection(j,1)).and.
/ (karstel(3,i).eq.connection(j,2))) then
karstel(6,i) = j
end if
end do
else
do j = 1,C
if ((karstel(1,i).eq.connection(j,2)).and.
/ (karstel(3,i).eq.connection(j,1))) then
karstel(6,i) = j
end if
end do
end if
end do
*****
*
* BEGIN STEADY STATE CALCULATIONS
*
*****
c step through elements and assign weighted fraction to sides - based
on length
c area of elements and probabilities
allocate(allocation(C),massin(C),ssallocation(C),stat=alloc_err)
allocate(oldallocation(C),stat=alloc_err)
allocate(Qdot(C),stat=alloc_err)
allocate(R(numel),stat=alloc_err)
oldallocation = 0.
allocation = 0.
R = 0.
R = 1. !assign unit recharge across all elements
P0 = 1.
do j = 1, numel
P1 = Pconnect(karstel(4,j))
P2 = Pconnect(karstel(5,j))
P3 = Pconnect(karstel(6,j))
L1 = length(karstel(4,j))
L2 = length(karstel(5,j))
L3 = length(karstel(6,j))
fbar = (P0*P0*P0) - (P0-P1)*(P0-P2)*(P0-P3)
c allocate fluxes to each conduit due to recharge
f1 = (P1/fbar)*(
/ L1*P2*P3/(L1+L2+L3)+
/ L1*P2*(P0-P3)/(L1+L2)+
/ L1*(P0-P2)*P3/(L1+L3)+
/ (P0-P2)*(P0-P3))
oldallocation(karstel(4,j)) = R(j)*area(j)*f1

```

```

allocation(karstel(4,j)) = allocation(karstel(4,j)) +
/ oldallocation(karstel(4,j))
f2 = (P2/fbar)*(
/ L2*P1*P3/(L1+L2+L3)+
/ L2*P1*(P0-P3)/(L2+L1)+
/ L2*(P0-P1)*P3/(L2+L3)+
/ (P0-P1)*(P0-P3))
oldallocation(karstel(5,j)) = R(j)*area(j)*f2
allocation(karstel(5,j)) = allocation(karstel(5,j)) +
/ oldallocation(karstel(5,j))
f3 = (P3/fbar)*(
/ L3*P1*P2/(L1+L2+L3)+
/ L3*P2*(P0-P1)/(L3+L2)+
/ L3*(P0-P2)*P1/(L3+L1)+
/ (P0-P1)*(P0-P2))
oldallocation(karstel(6,j)) = R(j)*area(j)*f3
allocation(karstel(6,j)) = allocation(karstel(6,j)) +
/ oldallocation(karstel(6,j))
end do
ssallocation = allocation
c propagate fluxes through the system to arrive at steady conditions
allocate(flux(C),oldflux(C),xarea(C),stat=alloc_err)
flux= 0
oldflux = 0
flux = allocation
do i = 1, npts
do j = 1, npts
if (nodes(i,j).ne.0) then
psum = 0.
oldpsum = 0.
do k = 1, npts
if(nodes(j,k).ne.0) then
oldpsum = Pconnect(nodes(j,k))
psum = psum + oldpsum
end if
end do
do k = 1, npts
if(nodes(j,k).ne.0) then
! flux coming in through originating node
oldflux(nodes(j,k))= flux(nodes(i,j))*
/ Pconnect(nodes(j,k))/psum
flux(nodes(j,k)) = oldflux(nodes(j,k)) +
/ flux(nodes(j,k))
end if
end do
end if
end do
end do
c compare flux discharge at spring with incoming flux
c as check of mass conservation
mass = 0.
oldmass = 0.
do i = 1, C
if (connection(i,2).eq.springpt) then
oldmass = flux(i)
mass = mass + oldmass
end if
end do

```

```

areamass = sum(area*R)
diff = areamass - mass ! This should be zero for s.s.
time = 0.
print *, 'mass = ',mass, ' area mass = ', areamass
*****
*
* TRANSIENT FLUX CALCULATIONS
*
*****
c calculation of flux from storage in aquifer
c each element will contribute to conduit flux
c perm = permeability factor
c Rtrans = recharge
c area = area of the triangle
c length = length of a side of the triangle
c pconnect= activation probability of a conduit
c time = time
allocate(Rtrans(numel),storage(numel),stat = alloc_err)
allocate(ssflux(C), stat = alloc_err)
c call the transient recharge time series integration routine
simpa = 0. ! beginning time for time series integration
simpb = 30. ! end time for time series integration
simps = 0. ! integrated recharge value over time range
call qsimp(simpa,simpb,simps)
print *, 'begin time end time integrated recharge'
print *, simpa,simpb,simps
c output data in different times for plotting purposes
dt = 1
delperm = 1
Rtrans = 1 ! set transient recharge
ssflux = flux
springmass = mass
do X = 1, 5
perm = 10*x
time = 0.
mass = springmass
write(12,*), 'Title = "Flux at spring"'
write(12,*), 'Variables = "Time", "Flux"'
write(12,238), 'ZONE T = "Transient Spring Flux (perm=',perm,')"'
write(12,*), 'I = 1000, F = Point'
write(12,*), time, mass
238 format(1X,A40,E10.2,A2)
do L = 1, 1000 ! This is to output spring fluxes at different times
! Rtrans = sin((X-1)/5)
time = time + dt
Qdot1 = 0.
Qdot2 = 0.
Qdot3 = 0.
allocation = 0.
oldallocation = 0.
237 format(2F15.3)
do j = 1, numel
P1 = Pconnect(karstel(4,j))
P2 = Pconnect(karstel(5,j))
P3 = Pconnect(karstel(6,j))
L1 = length(karstel(4,j))
L2 = length(karstel(5,j))
L3 = length(karstel(6,j))

```

```

fbar = (P0*P0*P0) - (P0-P1)*(P0-P2)*(P0-P3)
c instantaneous flux 1
T11=(perm*Rtrans(j)*L1*P1*P2*P3*(L1+L2+L3))/(4.*area(j)*fbar)
T12=exp(-1.*(time*perm*(L1+L2+L3)**2./(4.*area(j)**2.))) !new
T13=(perm*Rtrans(j)*L1*P1*P2*(1-P3)*(L1+L2))/(4.*area(j)*fbar)
T14=exp(-1.*(((L1+L2)/(L1+L2+L3)**2.)*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T15=(perm*Rtrans(j)*L1*P1*(1-P2)*P3*(L1+L3))/(4.*area(j)*fbar)
T16=exp((-1.*((L1+L3)/(L1+L2+L3)**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T17=(perm*Rtrans(j)*L1**2.*P1*(1-P2)*(1-P3))/(4.*area(j)*fbar)
T18=exp(-1.*(L1/(L1+L2+L3))**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
Qdot1 = T11*T12 + T13*T14 + T15*T16 + T17*T18
oldallocation(karstel(4,j)) = Qdot1
allocation(karstel(4,j)) = allocation(karstel(4,j)) *
/ oldallocation(karstel(4,j))
c instantaneous flux 2
T21=(perm*Rtrans(j)*L2*P1*P2*P3*(L1+L2+L3))/(4.*area(j)*fbar)
T22=exp(-1.*(time*perm*(L1+L2+L3)**2./(4.*area(j)**2.))) !new
T23=(perm*Rtrans(j)*L2*P1*P2*(1-P3)*(L2+L1))/(4.*area(j)*fbar)
T24=exp(-1.*(((L2+L1)/(L1+L2+L3)**2.)*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T25=(perm*Rtrans(j)*L2*P2*(1-P1)*P3*(L2+L3))/(4.*area(j)*fbar)
T26=exp((-1.*((L2+L3)/(L1+L2+L3)**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T27=(perm*Rtrans(j)*L2**2.*P2*(1-P1)*(1-P3))/(4.*area(j)*fbar)
T28=exp(-1.*(L2/(L1+L2+L3))**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
Qdot2 = T21*T22 + T23*T24 + T25*T26 + T27*T28
oldallocation(karstel(5,j)) = Qdot2
allocation(karstel(5,j)) = allocation(karstel(5,j)) *
/ oldallocation(karstel(5,j))
c instantaneous flux 3
T31=(perm*Rtrans(j)*L3*P1*P2*P3*(L1+L2+L3))/(4.*area(j)*fbar)
T32=exp(-1.*(time*perm*(L1+L2+L3)**2./(4.*area(j)**2.))) !new
T33=(perm*Rtrans(j)*L3*P1*P3*(1-P2)*(L3+L1))/(4.*area(j)*fbar)
T34=exp(-1.*(((L3+L1)/(L1+L2+L3)**2.)*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T35=(perm*Rtrans(j)*L3*P3*(1-P1)*P2*(L2+L3))/(4.*area(j)*fbar)
T36=exp((-1.*((L3+L2)/(L1+L2+L3)**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
T37=(perm*Rtrans(j)*L3**2.*P3*(1-P1)*(1-P2))/(4.*area(j)*fbar)
T38=exp(-1.*(L3/(L1+L2+L3))**2.*
/ (time*perm*(L1+L2+L3)**2.)/(4.*area(j)**2.)))
Qdot3 = T31*T32 + T33*T34 + T35*T36 + T37*T38
oldallocation(karstel(6,j)) = Qdot3
allocation(karstel(6,j)) = allocation(karstel(6,j)) *
/ oldallocation(karstel(6,j))
! write(13,*), qdot1, qdot2, qdot3
write(13,*), allocation(karstel(4,j)),allocation(karstel(5,j)),
/ allocation(karstel(6,j))
end do ! end of element loop for allocation to conduits
c propagate fluxes through the system to get transient flux value at
time t
flux = 0
oldflux = 0
flux = allocation + ssallocation

```

```

do i = 1, npts
do j = 1, npts
if (nodes(i,j).ne.0) then
psum = 0.
oldpsum = 0.
do k = 1, npts
if(nodes(j,k).ne.0) then
oldpsum = Pconnect(nodes(j,k))
psum = psum + oldpsum
end if
end do
do k = 1, npts
if(nodes(j,k).ne.0) then
! flux coming in through originating node
oldflux(nodes(j,k))= flux(nodes(i,j))*
/ Pconnect(nodes(j,k))/psum
flux(nodes(j,k)) = oldflux(nodes(j,k)) +
/ flux(nodes(j,k))
end if
end do
end if
end do
end do
mass =0.
c
c compare flux discharge at spring with incoming flux
c as check of mass conservation
do i = 1, C
if (connection(i,2).eq.springpt) then
oldmass = flux(i)
mass = mass + oldmass
end if
end do
write(12,237), time, mass
end do
end do
*****
**
*
* POST PROCESSING AND FILE OUTPUT
*
*****
**
c calculate the necessary size of the conduits based on fluxes
allocate(diam(C),stat=alloc_err)
fric = 0.01 ! Moody friction factor
gday = 7.323126e10 ! gravitational accel in m/day^2
gyr = 9.7696e15 ! gravitational accel in m/y^2
gsec = 9.81 ! gravitational accel in m/s^2
! diam = ((32.*fric*length*flux*flux)/(pi*pi*.1*9.81))**(1./3.)
! diam = (flux*(8.*fric*length)**(0.5)/(pi*(9.81*.1)**0.5))**(2./5.)
! diam = ((10.079*flux*0.02)/(1.*pi*(1e-5)**(0.5))**(8/3)
nu = 1e-6
diam = 0.66*((1e-3)**1.25*((length*flux**2.)/(9.81*0.0001))**4.75+
/ nu*flux**9.4*(length/(9.81*0.0001))**5.2)**(0.04)
deallocate(tempxy)
allocate(tempxy(C,10),stat=alloc_err)
***** FORMAT STATEMENTS

```

```

200 format(i6,9F10.3,E10.3)
201 format(20i4)
202 format(i4,F10.3)
203 format(2E10.3)
204 format(4F15.3)
205 format(i4,2F15.3)
end program karstmod
*****
***
*
* SUBROUTINES AND FUNCTIONS
*
*****
***
c "func" is the variable recharge function, which is fed into
c the subroutines below, for 1-D integration over the time period
desired,
c using a combination of Simpson's Rule and the Trapezoidal Rule.
real function func(X)
func = abs(20.*sin(X)/cos(X)) ! ML function discontinuous & not
integrable on [0,30]
end function
*****
* Integration routines
*****
c Simpson's Rule
subroutine qsimp(simpb,func,simps,eps)
integer jmax
real simpb,func,simps,eps
external func
parameter (EPS = 1.e-6,JMAX = 20)
c uses trapez
c returns as S the integral of the function func from a to b.
c the parameters EPS can be set to the desired fractional accuracy and
c JMAX so that 2 to the power JMAX-1 is the maximum allowed number fo
steps.
c integration is performed by Simpson's rule
integer j
real os, ost, st
ost = -1.e30
os = 1.e30
print *, 'calculating time integrated recharge'
print *, '*****'
do j = 1, jmax
call trapzd(func,simpb,func,simps,eps,j)
simps = (4.*st - ost)/3.
if (abs(simps-os).lt.EPS*abs(os)) return
os = simps
ost = st
end do
return
END
*****
c Trapezoidal Rule
subroutine trapzd(func,simpb,func,simps,n)
integer n
real simpb,func,simps
external func

```

```

c this subroutine computes the nth stage of refinement of an extended
trapezoidal rule.
c func is input as the name of the function to be integrated between
limits a and b, also input.
c when called with n=1, the routine returns as S the crudes estimate of
the integral.
c subsequent calls with n=2,3,...(in that sequential order) will
improve the accuracy of S by adding
c 2**(n-2) additional interior points. S should not be modified between
sequential calls
integer it, j
real del, sum, tnm,x
if (n.eq.1) then
sims = 0.5*(simpb-simpa)*(func(simpa)+func(simpb))
else
it = 2**(n-2)
tnm = it
del = (simpb-simpa)/tnm
x = simpa + 0.5*del
sum = 0.
do j = 1, it
sum = sum + func(x)
x = x + del
end do
sims = 0.5*(sims+(simpb-simpa)*sum/tnm)
print *, 'func = ',func(x)
print *, 'sims = ',sims
end if
return
END

```

Appendix 6.3. Data Compilation and Preliminary Hydrogeologic Modeling of the Manatee and Fanning Spring-Cave Systems

A6.3.1 Introduction

A6.3.1.1 Problem

The objectives of this project were twofold: (1) to build a hydrogeologic dataset to use for groundwater modeling of Manatee and Fanning springs and their springsheds and (2) to build the framework of a two-dimensional finite element steady-state groundwater flow model. The goal of the modeling effort will be to ultimately have the capability to evaluate nitrate loading scenarios within the springsheds and the effect of nitrate loading at the springs. One unique aspect of this project is the inclusion of the mapped Manatee cave system directly in the model.

The modeling effort utilizes the finite element method (FEM) and the FEFLOW software (<http://www.wasy.de>). The FEM is an advanced numerical modeling approach which affords the user the ability to model complex problem geometry and generally is more flexible than finite difference methods (i.e. MODFLOW). The cave systems can actually be incorporated directly into the model, as important features that channel flow. Most other models do not and can not include the cave systems explicitly, which we see as a failing, particularly when these other models are used to attempt fate and transport predictions in karst systems. The FEM approach we have used here proves superior in this respect.

A6.3.1.2 Geologic setting

The problem area (Figure 1) is located within the Suwannee River Water Management District in north Florida. The geology consists generally of thin clay and sand sediments overlying the upper Floridan aquifer. The sediments thin from east to west and are completely absent in places along the river and in the floodplain. Both the sediments and the upper Floridan limestone have relatively high hydraulic conductivities: the former due to its unconsolidated nature and the latter due to karst features.

The surficial aquifer and the upper Floridan aquifer are both productive, although the upper Floridan provides the primary drinking water supplies in the region. Groundwater in both units drains towards the potentiometric lows along the Suwannee River, where a combination of spring flow and diffuse flow provide the majority of flow to the river. It is the spring discharge at Fanning and Manatee springs and their influence on the regional groundwater flow system that are of greatest interest in this investigation.

A6.3.2 Approach

A6.3.2.1 Data compilation

GIS Files

Numerous GIS files were compiled, each containing a spatial data component to ultimately be included in the model. The GIS files were mostly obtained from the Florida Geological Survey (FGS) and can be located on the compact disc (CD) included with this report. Files included electronic 1:24,000 scale topographic quadrangles files overlapping the entire model area: the Trenton, Wane, Vista, Suwannee River, Manatee Spring, Chiefland SW, Fourmile Lake, and Chiefland quads. A partial listing of other GIS files includes: geology and stratigraphy, Manatee cave, sinkhole locations, park and recreation areas, first magnitude springs, topographic digital elevation model, elevation of the top of the Floridan aquifer, county boundaries, SRWMD boundary, major rivers, and potentiometric surfaces in the upper Floridan at various times through 2002. Data not available in GIS format were compiled into a spreadsheet presented on the CD (Project_data.xls). These included data and some plots of yearly rainfall, water chemistry in the Manatee cave, discharge measurements for Fanning and Manatee, and nutrient loading at Fanning spring.

Hydraulic Data

Average discharges for Fanning and Manatee Springs were calculated from data provided by the FGS. Hydraulic conductivities (K's) were estimated from the literature (Freeze and Cherry, 1979) for the construction of the preliminary model, as regionally extensive K's were not available. Regional head elevations were compiled from SRWMD publications with the data covering a time period of 1973 to 2002. Data were compiled in the form of heads at wells and contour maps as GIS shape files. Mapped cave data were not available for the Fanning system but were available for Manatee (Figure 2). The data were acquired from the Florida Cave Database (<http://hazlett-kincaid.com/FGS/cavedb/index.htm>), a project currently underway at the FGS.

Groundwater Contamination

Nutrient data collected from the individual tunnels at Manatee were acquired from the FGS (Table 1). In addition, similar water quality data was obtained from the SRWMD web site (Tables 2 and 3). Preliminary analyses of these data has shown that there is a direct, positive correlation between discharge at each spring and the nitrate concentration in the water.

A6.3.2.2 preliminary model development

A preliminary groundwater flow model was developed. All of the elements of the model were established: two layers, Fanning and Manatee springs, the Suwannee River, and the Manatee cave system. Initial heads were set using data from SRWMD from May 2002 and boundary conditions were also set using the same data, but the model has yet to be calibrated.

Model Area

The model area (Figure 3) extends from the highlands east of Fanning and Manatee to the Suwannee River on the western boundary and encompasses 564 km² (~218 mi²). To the north and south, the boundaries were chosen so as to be far enough away from the two springs that they were not likely to have a direct influence on those boundaries. The area encompasses portions of both Levy and Gilchrist Counties and includes several small

towns, such as Chiefland, as well as several large agricultural operations, which may be evaluated as possible nitrate sources in the future modeling effort.

The shape of the model area emphasizes the flexibility of the finite element modeling approach. The twists and turns of the Suwannee River boundary are exactly matched and the mesh is fined in the area near Manatee Spring.

Springs and Caves

Manatee and Fanning Springs are both included in the model, as is the Manatee cave system, since it is partially mapped (Figure 2). The Manatee cave is included as a discrete feature located in the model at the top of the Floridan aquifer layer. The cave conduits are modeled using a Darcian representation of pipe flow.

The modeled parameters include for the cave:

1. cross-sectional area of the cave (m^2),
2. conductivity (10^{-4} m/s),
3. compressibility of the water ($1/\text{m}$),
4. source/sink of groundwater into or out of the cave (10^{-4} 1/d),
5. density ratio (1) of the fluid(s) (in case of saltwater intrusion), and
6. the transfer rate into or out of the cave (10^{-4} 1/d).

Note that the transfer rate (5) and the source sink (3) are both for representing water into or out of the cave, but different mechanisms for this flux are represented by each, respectively. The springs are currently represented in the model as points of fixed discharge from the upper Floridan aquifer.

Hydraulic Boundary Conditions

The river boundary is set as a linearly decreasing head along the river from north to south. The remaining boundary conditions are set as constant head. The constant heads along the remaining boundaries were interpolated from a set of head data representing the maximum water elevation conditions (<http://www.srwmd.state.fl.us/resources/resource4.pdf>) across the area in 2002. Data for a minimum potentiometric surface (<http://www.srwmd.state.fl.us/resources/resource5.pdf>) also exist and will be used in the same fashion to construct a second, comparative model.

Both Manatee and Fanning Springs are included in the model, but only Manatee has a mapped cave system. Because of this, the Fanning system is represented by a point discharge from the model of $1.11 \text{ m}^3/\text{s}$, which is the mean of discharge data collected from May 2001 to September 2003. The Manatee system is represented in the model as both a cave network and a spring, discharging at a mean rate of about $5.05 \text{ m}^3/\text{s}$ (after Scott, et. al., 2002), based on data from March 1932 to October 2001.

Layer Top Elevations

The preliminary model consists of two layers (3-D). The original intent was for the model to be two-dimensional (one layer), but in discussions with the FGS, it became clear that the surficial materials may play an important role in the springshed flow systems. In the next phase of work, the model can easily be converted to 2-D if necessary.

As such, the top layer starts at the land surface and extends down to the top of the upper Floridan aquifer. The land surface is represented by a high resolution digital elevation model (DEM). The elevation of the top of the Floridan aquifer is represented by

elevations provided by the FGS. An arbitrary bottom for the model was chosen as being at an elevation of 200 m below sea level.

Head Calibration Targets

The conceptual groundwater flow model is for water to flow through the upper Floridan aquifer from east to west, discharging at the Suwannee River diffusely (Figure 3) and at Manatee and Fanning Springs, as point discharges. We chose historical maximum (Figure 4) and minimum (not shown) potentiometric surfaces against which to calibrate.

Note that in the historical maximum potentiometric surface (Figure 4), most all of the modeled area falls within the 10 ft NGVD (~3 m) contour, with only the northeast corner of the model area having historically higher heads. In addition, the groundwater gradient is very flat over most of the model area, with the exception of the northeast corner. These observations reflect the fact that the upper Floridan is covered by increasingly thicker sediments to the northeast.

A6.3.3 Further work

A6.3.3.1 steady state model refinements

During the next phase of this project, the steady state model be refined and calibrated. In order to be able to investigate the behavior of the flow system under a wide range of conditions, the historical maximum and minimum potentiometric surfaces will both be used for calibration of comparative scenarios. Examining the flow system under these different In addition, further existing data on the spatial variability of the hydraulic properties of both the surficial material and the upper Florida aquifer system will be collected and applied.

We will attempt to represent the springs, which currently are represented as constant discharge features, more realistically. In order to do this, we ultimately would like to include them in the model as head dependent discharge features. This means that if heads are low, the spring flow decreases and under high head conditions, the discharge increases. This refinement would only become meaningful under transient flow analysis, which would possibly be performed after the model is calibrated to steady state conditions.

A6.3.3.2 loading scenarios and transient modeling

During the data collection phase, data on the concentration of nitrates in groundwater discharging at the springs was assembled. During the next phase of work, contaminant loading scenarios will be established such that the model can be used to evaluate their feasibility. An example of this would be to assign a concentration of nitrate as occurring in the area of an agricultural operation, to represent nutrient loading. Next, transient fate and transport scenarios could be evaluated, where the model might be used to answer questions such as: how long does it take for nitrates to travel from the farm to Manatee spring or from which farm is the contamination at the spring most likely coming?

A6.3.3.3 spring and cave impacts

Although the Manatee cave system is partially mapped, it is thought by some, based on the highly variable composition of waters coming from different tunnels, that the cave

system may be much more extensive and may draw waters from quite distant regions. In particular, cave passages are thought to extend away from the spring to the northeast. The flexibility of the finite element modeling environment allows us to explore hypothetical scenarios where additional cave reaches can be inserted into the model, as actual hydraulic features, and the impacts to the groundwater model flow field may be quantitatively assessed.

Another type of scenario to be assessed would be to try and evaluate the travel time of contaminants from source to spring with respect to the cave systems. An example of this would be to quantify, through a transport analysis, the time of travel from the nutrient source to the cave system (whether real or hypothetical) and then the ensuing and relatively much shorter time of travel through the cave system to the spring. Since we have amassed nutrient concentration versus discharge data for the springs, we could compare our modeled discharge versus concentration against the real data and could perform sensitivity analyses in regard to loading, discharge, and cave hydraulic parameters.

A6.3.4 References

Freeze, R. A. and Cherry, J. A., Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979.

Scott, et. al., First Magnitude Springs of Florida, Florida Geological Survey Open File Report No. 85, Tallahassee, FL 2002.

A6.3.5 Figures and tables

Figure 1. Location Map. The study area is designated by green diagonal lines. It is bordered on the west by the Suwannee River and contains both Manatee and Fanning (“Fannin”) Spring.

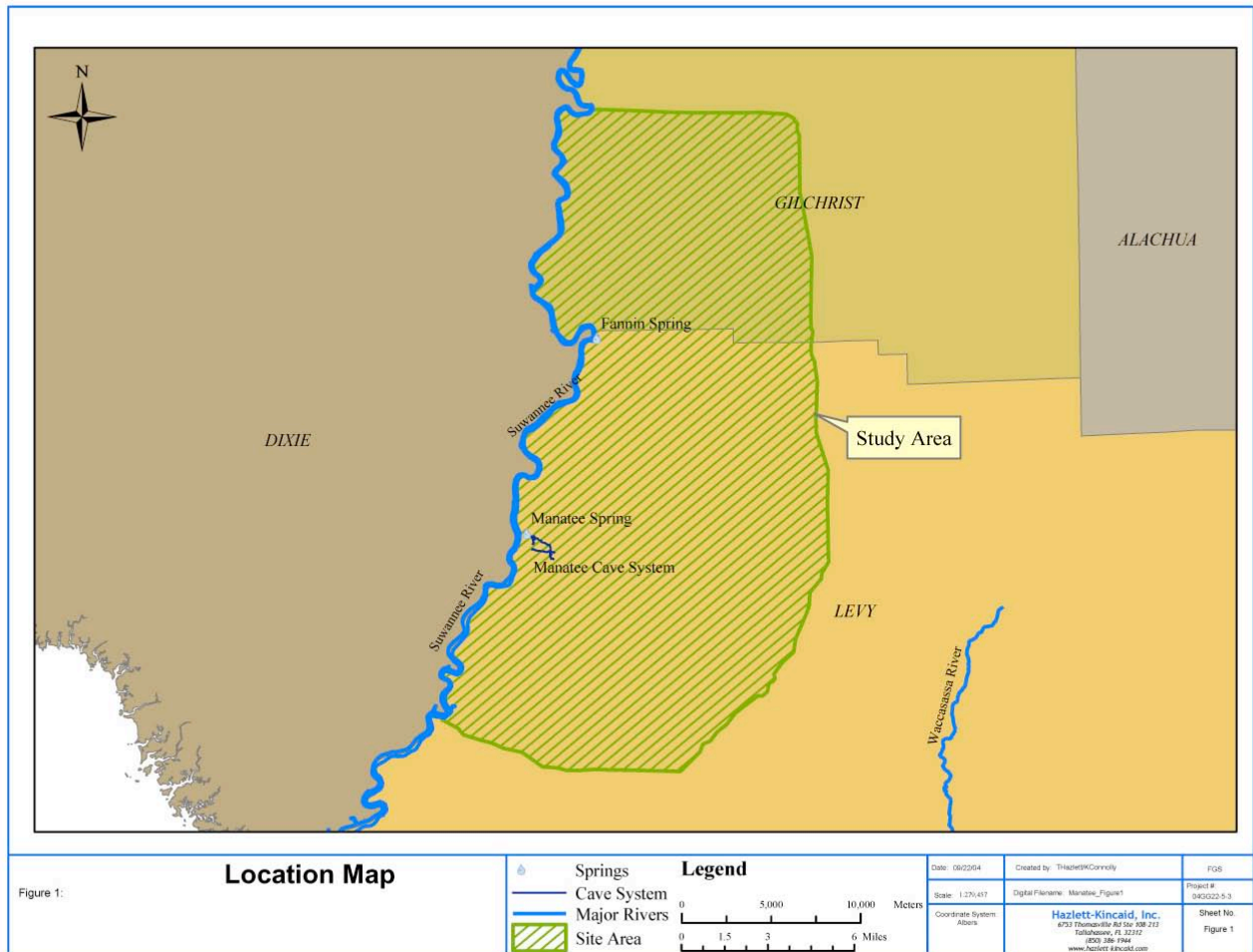


Figure 2. Manatee Cave. The study area is shown with an expanded view in the top left of the Manatee Cave System.

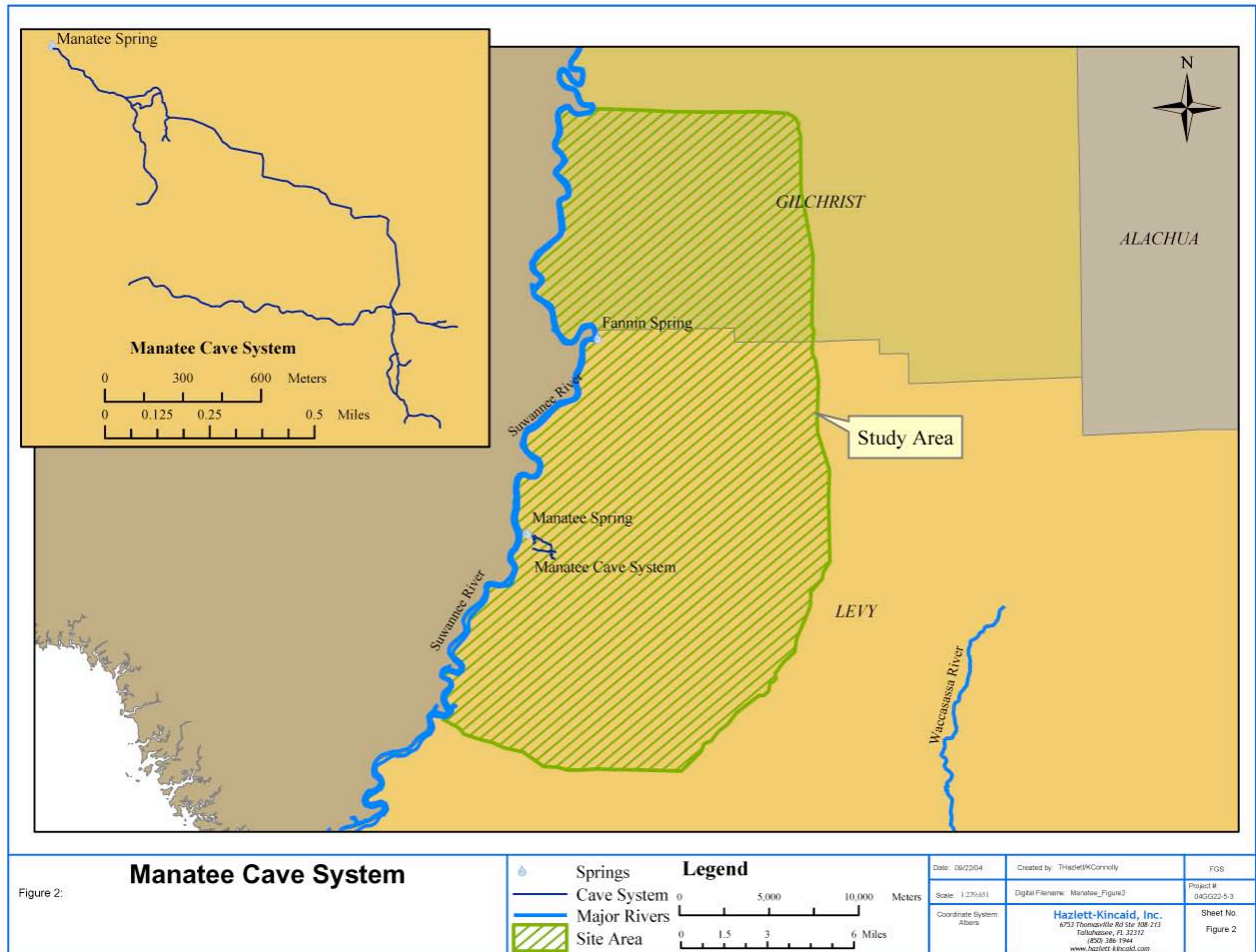


Figure 3. Model Mesh and Boundaries. The triangular finite element mesh is shown over the model area. The Manatee Cave System is included in the mesh as discrete elements. In the preliminary model framework, the river is represented by a linear decreasing head, from north to south, and a constant head on the remaining boundaries.

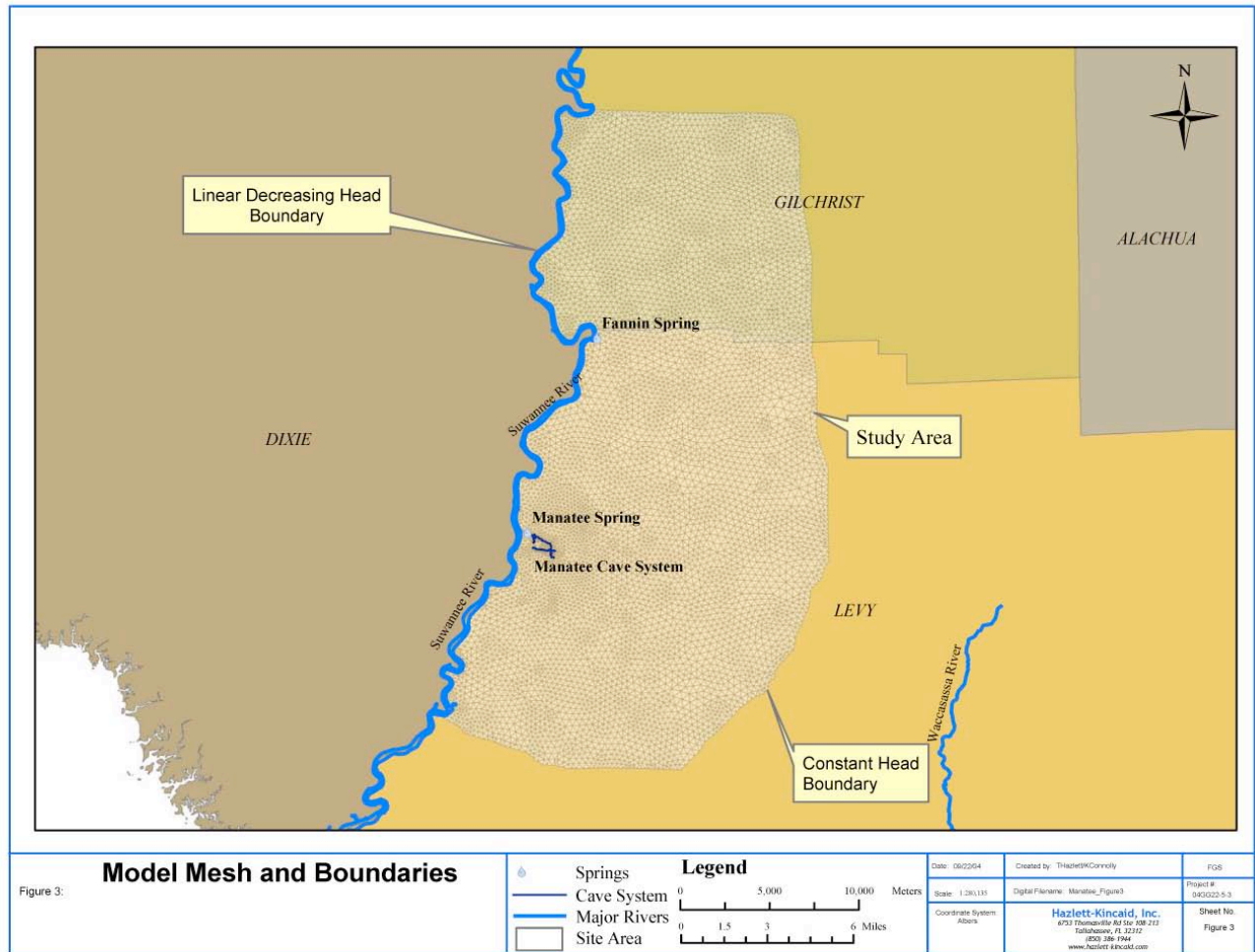


Figure 4. Maximum Water Levels . The map shows contours (ft NGVD) of the historical maximum water levels at wells throughout the District, including in the modeled area. Note the extremely flat gradient across most of the model area as well as the fact that most of the model falls within 10 ft (~3 m) or less of sea level.

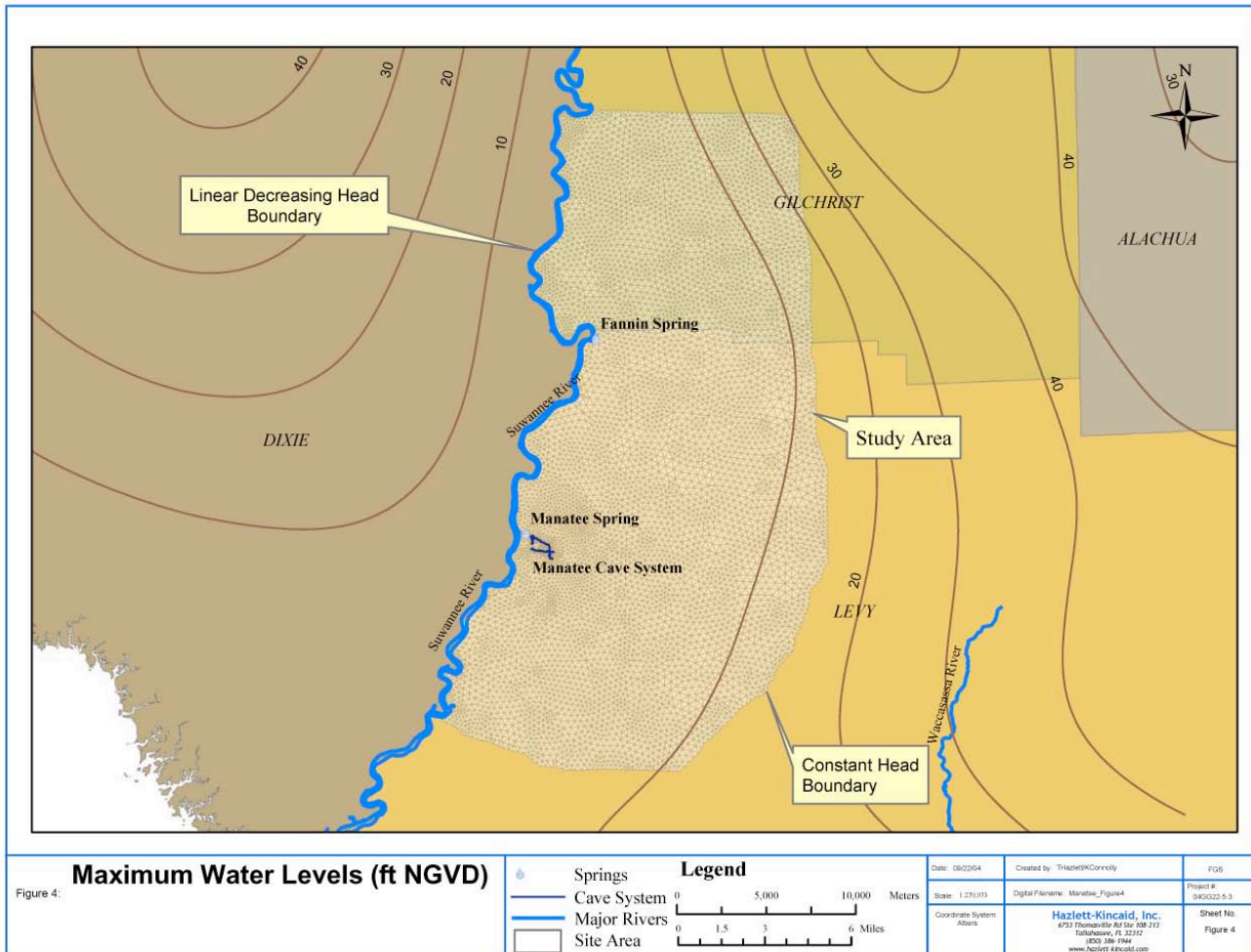


Table 1 - NO2NO3-N and Turbidity in Manatee Cave Tunnels

Field ID	Date Sampled	Reference Method	Analysis	Component	Result	Units	
#1 HEADSPRING	8/12/2001 14:20	EPA 180.1	TURBIDITY	Turbidity	0.55	NTU	
	W-	mg					
#1 HEADSPRING	8/12/2001 14:20	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.7	N/L	
#2 SEWER TUNNEL	8/12/2001 14:12	EPA 180.1	TURBIDITY	Turbidity	3.8	NTU	
	W-	mg					
#2 SEWER TUNNEL	8/12/2001 14:12	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.3	N/L	
#3 MILK TUNNEL	8/12/2001 15:05	EPA 180.1	TURBIDITY	Turbidity	0.5	NTU	
	W-	mg					
#3 MILK TUNNEL	8/12/2001 15:05	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.4	N/L	
#4 BLUE WATER TUNNEL	8/12/2001 14:10	EPA 180.1	TURBIDITY	Turbidity	0.1	NTU	
	W-	mg					
#4 BLUE WATER TUNNEL	8/12/2001 14:10	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	4.5	N/L	
#5 UPSTREAM MAIN TUNNEL	8/12/2001 14:00	EPA 180.1	TURBIDITY	Turbidity	0.2	NTU	
	W-	mg					
#5 UPSTREAM MAIN TUNNEL	8/12/2001 14:00	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.4	N/L	
#6 SNACK BAR TUNNEL	8/12/2001 14:20	EPA 180.1	TURBIDITY	Turbidity	0.25	NTU	
	W-	mg					
#6 SNACK BAR TUNNEL	8/12/2001 14:20	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.7	N/L	
#7 SUE SINK	8/12/2001 14:17	EPA 180.1	TURBIDITY	Turbidity	0.5	NTU	
	W-	mg					
#7 SUE SINK	8/12/2001 14:17	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.5	N/L	
#8 CCC TUNNEL	8/12/2001 14:50	EPA 180.1	TURBIDITY	Turbidity	0.5	NTU	
	W-	mg					
#8 CCC TUNNEL	8/12/2001 14:50	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	1.2	N/L	
	W-	mg					
#9 GEOTHERMAL VENTS	8/12/2001 14:10	EPA 353.2 (March 1983)	WNO2NO3	NO2NO3-N	0.86	N/L	

Table 2 – FANNING SPRING WATER QUALITY DATAData sourced from <http://www.srwmd.state.fl.us>.

Sample date	Field conductivity	pH (field)	Dissolved Oxygen concentration	Apparent color	Nitrate plus Nitrite Nitrogen	Total Phosphorus
5/10/2004	456	6.92	2.6	5	4.44	0.086
4/19/2004	449	7.19	2.0	5	4.9	0.097
2/11/2004	455	7.19	1.9	5	5.08	0.106
1/13/2004	452	7.24	1.9	5	1.22	0.096
11/10/2003	453	7.21	1.9	5	5.3	0.08
10/13/2003	464	7.21	2.1	5	5.59	0.092
9/8/2003	450	7.21	1.8	5	5.55	0.09
8/4/2003	453	7.23	2.0	5	5.72	0.079
7/7/2003	469	7.15	1.8	5	5.2	0.08
6/2/2003	459	7.26	1.6	5	4.96	0.1
5/12/2003	446	7.13	1.2	5	3.92	0.11
2/17/2003	64	6.05	7.3	450	0	0.2
2/6/2003	455	7.31	1.8	5	4.4	0.08
12/2/2002	438	7.13	3.8	5	4.8	0.06
11/11/2002	443	7.19	1.8	5	4.6	0.13
10/28/2002	449	7.13	3.8	5	4.8	0.08
9/9/2002	436	7.01	1.8	5	5.25	0.06
8/26/2002	433	7.18	1.8	5	5.25	0.069
7/11/2002	436	7.19	2.1		5.1	
7/11/2002	436	7.19	2.1		4.94	
7/11/2002	436	7.19	2.1	5	5	0.065
6/20/2002	426	7.22	1.8	5	4.62	0.063
6/20/2002	426	7.22	1.8	5	4.68	0.056
5/9/2002	425	7.11	1.7	5	4.19	0.057
5/9/2002	425	7.11	1.7	5	4.19	0.067
4/3/2002	434	7.18	1.7	5	4.14	0.082
3/12/2002	437	7.22	1.7	5	4.06	0.066
2/7/2002	434	7.25	1.7	5	3.97	0.069
1/15/2002	439	7.29	1.7	5	3.9	0.066
1/15/2002	439	7.29	1.7		3.9	
12/6/2001	440	7.17	1.8	5	4.15	0.068
11/8/2001	441	7.2	1.7	10	3.78	0.04
10/15/2001	439	7.3	1.6	5	4	0.1
9/6/2001	436	7.19	1.7	5	4	0.054
8/13/2001	432	7.27	1.6	5	3.45	0.059
7/16/2001	441	7.19	1.5	5	4.2	0.066
6/19/2001	445	7.21	1.5	5	3.9	0.072
6/19/2001	445	7.21	1.5		3.55	
6/19/2001	445	7.21	1.5		3.85	
5/10/2001	435	7.07	1.8	5	4	0.071
3/8/2001	432	7	1.6	5	4	0.073
2/15/2001	438	7.16	1.7	5	3.6	0.067
1/8/2001	438	7.03	1.5	5	3.95	0.088
12/13/2000	439	7.16	1.6	5	4.1	0.071
11/6/2000	438	7.15	1.8	5	4.2	0.061
10/16/2000	439	7.31	1.6	5	4.1	0.061
9/11/2000	431	7.15	1.7	5	4.2	0.064
9/11/2000	431	7.15	1.7	5	4	0.064
8/14/2000	432	7.27	1.9	5	3.7	0.075
7/18/2000	431	7.14	2	5	3.4	0.065
7/18/2000	431	7.14	2	5	3.35	0.062
6/19/2000	428	7.31	2	5	2.8	0.069
6/19/2000	428	7.31	2		2.8	
6/19/2000	428	7.31	2		2.7	
5/10/2000	429	7.27	1.9	5	3.35	0.061
5/10/2000	429	7.27	1.9	5	3.4	0.061
4/13/2000	429	7.14	1.9	5	3.05	0.064
3/9/2000	429	7.12	2.2	5	3.45	0.061
3/9/2000	429	7.12	2.2	5	3.5	0.065
2/10/2000	429	7.32	2.2	5	3.25	0.082
1/5/2000	415	7.19	1.8	5	3.5	0.067
12/20/1999	430	7.35	1.7	5	3.5	0.066

11/9/1999	427	7.32	1.8	5	3.65	0.06
10/19/1999	421	7.29	2		3.78	0.057
10/19/1999	421	7.29	2		3.74	0.061
9/27/1999	438	7.13	1.8	5	3.51	0.063
8/3/1999	429	7	1.9	5	4.1	0.062
6/17/1999	421	7.15	2.1	5	3.97	0.061
4/15/1999	427	7.24	2.1	5	4.27	0.065
3/16/1999	425	7.25	2.2	5	3.79	0.069
12/9/1998	431	7.12	2	5	4.49	0.067
8/17/1998	435	7.23	2.1	5	4.44	0.163
7/14/1998	430	7.09	2.4	5	4.02	0.08
6/9/1998	412	7.16	2.5	5	3.89	0.051
8/18/1997	415	7.01	2.4	5	3.69	0.079
7/24/1997	418	7.16	2.3	5	3.3	0.074
6/16/1997	419	7.09	2.3	5	2.35	0.08
8/15/1996	419	7.43	2.4	1	3.44	0.057
7/23/1996	415	7.06	2.5	5	3.59	0.054
6/11/1996	412	7	2.6	1	3.28	0.069
9/11/1995	420	7.26	2.2	1	3.94	0.087
8/14/1995	420	7.39	2.3	1	3.67	0.05
7/13/1995	415	6.98	2.2	1	3.52	0.069
6/8/1995	410	7.25	2.3	1	3.47	0.061

Table 3 – MANATEE SPRING WATER QUALITY DATA

Data sourced from <http://www.srwmd.state.fl.us>

Sample Date	Field Conductivity	pH (Field)	Dissolved Oxygen Concentration	Apparent Color	Nitrate plus Nitrate Nitrogen	Total Phosphorus
5/10/2004	457	6.98	1.9	5	1.58	0.058
5/10/2004	457	6.98	1.9	5	1.58	0.052
4/8/2004	457	7.22	1.6	5	1.7	0.045
3/10/2004	458	7.22	1.8	5	1.57	0.053
2/19/2004	450	7.36	2.3	5	1.74	0.068
1/14/2004	442	7.3	1.8	5	1.84	0.065
1/14/2004	442	7.3	1.8	5	1.86	0.064
12/1/2003	455	7.28	1.8	5	1.8	0.065
11/10/2003	448	7.31	1.8	5	1.84	0.046
10/13/2003	459	7.25	2	5	1.98	0.069
9/10/2003	449	7.27	2.2	5	1.64	0.045
8/4/2003	448	7.28	1.9	5	1.88	0.051
7/8/2003	465	7.25	1.8	5	1.6	0.04
6/2/2003	464	7.35	1.7	5	1.67	0.06
5/12/2003	475	7.22	2	5	1.46	0.06
3/13/2003	453	7.21	2	5	1.62	0.06
2/13/2003	468	7.13	1.5	5	1.8	0.06
1/14/2003	452	7.28	1.4	5	1.62	0.05
12/2/2002	459	7.17	2.4	5	1.52	0.04
11/11/2002	437	7.26	1.4	5	1.7	0.06
10/28/2002	459	7.24	1.3	5	1.78	0.05
9/9/2002	437	7.26	1.5	5	1.7	0.022
8/12/2002	447	7.25	1.1	5	1.97	0.017
7/15/2002	455	7.05	1.1	5	1.58	0.032
7/15/2002	455	7.05	1.1	5	1.54	0.026
6/20/2002	416	7.26	1.3	5	1.47	0.031
5/9/2002	426	7.14	1.5	5	1.44	0.029
4/11/2002	450	7.22	1.3	5	1.3	0.038

3/11/2002	456	7.23	1.3	5	1.54	0.023
2/11/2002	448	7.27	1.2	5	1.58	0.027
1/16/2002	446	7.38	1.2	5	1.58	0.026
1/16/2002	446	7.38	1.2	5	1.6	0.015
12/6/2001	449	7.21	1.3	5	1.63	0.026
11/8/2001	445	7.41	1.4	5	1.78	0.06
10/25/2001	449	7.42	1.4	5	1.82	0.06
9/10/2002	460	7.25	1.1	5	1.99	0.02
9/10/2001	460	7.25	1.1	5	2.12	0.02
8/14/2001	471	7.2	0.9		1.85	
8/14/2001	471	7.2	0.9		1.85	
8/14/2001	471	7.2	0.9	5	1.82	0.021
7/17/2001	467	7.27	1.1	5	1.56	0.027
6/19/2001	427	7.29	1.3	5	1.18	0.034
6/19/2001	427	7.29	1.3	5	1.2	0.027
5/10/2001	442	7.15	1.5	5	1.24	0.037
5/10/2001	442	7.15	1.5	5	1.24	0.037
4/11/2001	433	7.47	1.4	5	1.46	0.075
4/11/2001	433	7.47	1.4	5	.14	0.075
3/15/2001	439	7.07	1.4	5	1.53	0.046
3/15/2001	439	7.07	1.4	5	1.54	0.046
2/21/2001	437	7.05	1.6	5	1.36	0.031
2/21/2001	437	7.05	1.6		1.42	
2/21/2001	437	7.05	1.6		1.44	
1/11/2001	435	7.45	1.7	5	1.4	0.029
1/11/2001	435	7.45	1.7	5	1.38	0.029
12/19/2000	445	7.09	1.3		1.6	
12/19/2000	445	7.09	1.3		1.58	
12/19/2000	445	7.09	1.3	5	1.62	0.025
12/19/2000	445	7.09	1.3	5	1.63	0.025
11/6/2000	442	7.23	1.7	5	1.73	0.025
10/16/2000	445	7.32	1.6	5	1.6	0.022
10/16/2000	445	7.32	1.6	5	1.65	0.025
9/11/2000	409	7.33	1.3	5	1.63	0.026
8/17/2000	458	7.3	1.4	5	1.62	0.026
8/17/2000	458	7.3	1.4		1.66	
8/17/2000	458	7.3	1.4		1.62	
7/18/2000	442	7.17	1.6	5	1.61	0.027
6/7/2000	437	7.25	1.6	5	1.31	0.042
5/10/2000	432	7.26	1.8	5	1.38	0.031
4/13/2000	439	7.3	1.7	5	1.38	0.03
3/9/2000	439	7.18	2.2	5	1.38	0.031
2/15/2000	440	7.27	2.3	5	1.41	0.027
2/15/2000	440	7.27	2.3		1.45	
2/15/2000	440	7.27	2.3		1.47	
1/12/2000	430	7.31	1.5	5	1.5	0.032
12/20/1999	438	7.21	1.4	5	1.51	0.027
11/16/1999	432	7.29	1.6	5	1.49	0.03
10/19/1999	439	7.3	1.6		1.56	0.027
6/17/1999	432	7.24	1.5	5	1.62	0.044
6/17/1999	432	7.24	1.5	5	1.59	0.061
4/15/1999	429	7.28	1.2	5	1.26	0.032
3/16/1999	439	7.17	1.4	5	1.48	0.024

3/16/1999	439	7.17	1.4	5	1.53	0.024
12/17/1998	450	6.77	1.2	5	1.56	0.024
8/13/1998	441	7.23	1.1		1.61	
7/28/1998	430	7.22	1.3	5	1.58	0.02
6/11/1998	432	7.16	1.2	5	1.48	0.03
6/25/1997	436	7.14	1.5		1.35	0.04
6/25/1997	436	7.14	1.5		1.35	0.036
8/15/1996	439	7.65	1.6		1.48	0.024
7/23/1996	440	7.14	1.4		1.45	0.022
6/12/1996	435	7	1.8		1.36	0.027
9/11/1995	422	7.27	1.5	1	1.64	0.057
8/14/1995	448	7.41	1.4	1	1.37	0.021

Appendix 7. Units produced for Explore Florida!

A7.1 Map use

PURPOSE

The most fundamental geographic concept is location. Maps are the tools that are needed to accomplish this task. Places have physical and human characteristics. Many of these can be portrayed through the use of maps. All places on Earth have distinctive characteristics that help to identify them. Students need to understand what a map is and what the basic processes are that are common to all maps. What are the elements that make up a map. It is not possible to identify everything about a place on a single map. Different types of maps are used. They are designed to meet a certain need and supply information on a variety of subjects.

How are things located on a map and how are symbols used to identify features. Since the Earth is not perfectly flat, how is relief shown on a flat map? Maps are used to display information other than the physical location of places. Examples are Census data and other information related to the environment in which we live. How do aerial photographs or scanned images relate to maps, what do they show, and how are they used.

BACKGROUND MATERIAL

1) Intro

Five geographic concepts have been developed by the Joint Committee on Geographic Education of the National Council for Geographic Education and the Association American Geographers. The five concepts represent the types of questions that are used to help understand and define the Earth.

The first concept is location. Every place on the earth has a unique location. Maps are used to show these locations using a set of imaginary lines that run north-south and east-west locations. The intersection of these lines defines a location. The most common of these coordinate systems is latitude-longitude. Lines of longitude measure distance east and west and lines of latitude measure distance measure distance north and south. Locations are expressed in degrees. For example, St. Louis, Missouri is located approximately at 39° (degrees) north latitude and 90° (degrees) west longitude.

The second concept is place. Every location has unique characteristics. Places can differ in climate, soil type, land use, population density, and numerous other physical and cultural characteristics. How do these characteristics affect the way people live? What is the history of the place and how has it affected it evolution?

The third concept is relationships with places and how humans have adjusted to their environments. Environments differ according to climate, physical characteristics, and political boundaries. Geographers look at where people live and why they settled there. What changes have been made to enable the residents to live in that environment? Were changes made to the environment or did the environment shape settlement decisions?

The fourth concept is movement. How do people move from place to another to settle or interact with other people. Everyone relies on others for goods and services. Are there patterns to the movement of people, goods, services, and information?

The final concept is one of regions. Are there ways to classify areas based on physical or cultural characteristics? Regions can be classified as physical or cultural. Once regions are defined, they can be compared with other areas.

2. What is a Map and What are the processes that are common to all maps

Maps can be defined in several ways. Some definitions include:

“A map is a reduced, simplified, categorized/classified, symbolized, and annotated representation of the earth’s surface which has been projected on a plane or flat surface.”

“A picture or drawing that shows an area or place in different ways.”

“A useful guide to direct me to places.”

“A visual description of a surface.”

All maps have certain basic processes in common. First, all maps are reductions. It is not possible to make a map that is the same physical size as the area being represented on the map. Cartographers (people who make maps) must choose a scale that sets limits on the amount of information that can be shown.

Since the earth is spherical in shape, a transformation must be made to a flat or two-dimensional surface. This transformation is called a map projection.

All maps must be generalized. It is not possible to show every detail about a place when the scale is reduced.

Graphic representations or symbols must be designed to represent places or features on a map.

3. Principal Roles of Maps

Maps are used in several ways.

They are an instrument of communication. Many times a picture or drawing can show things that words cannot adequately describe.

Maps are efficient for spatial searches. It is much easier to move your eyes over a map to see relationships between places and things.

Maps have become the infrastructure of society. There are so many things that we do that have become dependent on the use of maps. For example, they are used to locate streets, identify routes between places, find locations of features, provide a means to locate utilities, real estate boundaries, and to provide addresses for emergency vehicles.

Maps can be used as research tools by enabling the study of patterns and distributions of certain phenomena. For examples, crime locations can be plotted on maps to see if there is a relationship between the scene of the crime and any characteristics of the population or location of businesses.

4. Elements of a Map

Maps have three main elements: scale, projection, and symbols.

Scale is the ratio between map distance and earth distance. Since a map cannot show the same detail for an area or place because of size limitations, the cartographer must make a decision as to what the appropriate scale should be. Scale is expressed in one of three ways:

Word statement: example: one inch equals one mile

Arithmetic ratio (sometimes called RF or representative fraction): example: 1:24,000

Graphic symbol

Because maps must be generalized to accomplish scale changes, several techniques have been developed. The amount of area shown on a map will dictate the amount of generalization that must occur. Four techniques are frequently used:

Selection: Retain more important features in an area and delete lesser features.

Simplification: Shapes that are retained are simplified.

Combination: Two or more similar features are combined into one area.

Locational shift and size exaggeration: Adjacent features are moved to show distinction. For example, a railroad that runs along a road might be shifted slightly to show the distinction between the two features because the scale of the map might place them right on top of each other.

A projection is a systematic transformation of the latitudes and longitudes of locations on the surface of the earth into locations on a flat surface. If you are using a globe to show the earth, you can assume for simplicity that areas are correctly represented, that distances are correct, that angles between places are correct, and that the shape of areas are correct.

When the sphere or globe is projected onto a flat surface, the map will no longer contain all of these properties. The cartographer will select a projection that tries to maintain one of these properties at the expense of the others. Perhaps, the most famous projection is the Mercator projection which was designed for navigation purposes during the time that Europeans were sailing back and forth to the New World.

When mapping small areas like a city, the projection used may not even be noticeable. When constructing a world map, the projection used is quite noticeable.

The final element that is contained on all maps are symbols. Symbols have been created to show features that must be scaled to be represented. There are three main types of symbols: photographic symbols, pictographic symbols, and geometric symbols. Photographic symbols are rarely used, but they would be an actual picture of a feature that is then placed on the map at a reduced size. Pictographic symbols are sometimes used if a picture can be designed that accurately represents what the feature is that is being represented. A good example is a square with a cross on top, which represents a church. Geometric symbols are the most commonly used and they often require a legend or explanation to be placed on the map to identify what they represent. Three types of features are shown with geometric symbols: lines, points, and areas. Lines can be varied using width, color or pattern to describe linear features like railroads and roads. Points are used to locate features that reside at a certain location. For example, cities on a state map may be represented by different size dots depending on the population of the place. Areas are defined by lines around a feature that may be filled in with a pattern or color. Examples would be lakes or political boundaries.

5. Types of Maps

Three major types of maps exist. The type of map selected will determine what its primary use will be. The most basic type of map is called a planimetric map. They are sometimes referred to as outline or base maps. The most distinguishing feature of a planimetric map is that they do not attempt to show relief in measurable form. Examples of these maps would be a road map or a real estate map that shows property boundaries. All maps begin with a planimetric map, but they may be classified differently depending on what is added to them.

The second major type of map is called a topographic map. Topographic maps use different methods to show the shape and elevation of the terrain. There are several types of topographic maps. The most common is a map which uses contour lines to show relief. Other methods include shading, photographic maps which use a photo image to demonstrate relief, computer generated graphics which give the appearance of relief or raised relief maps which are expensive to make but give a good visual picture of an area's terrain.

The third type of map is called a thematic map. The word thematic is based on the word “theme” and this type of map can show information on any number of special topics. To construct a thematic map a planimetric or base map is selected and additional information is added to it. Thematic maps can be used to show land use types, soils, school zones, population distributions based on income or age, the location of features or any number of human activities.

6. The use of contours to show relief

The most common method to show relief that is portrayed in a measurable form on a map is the use of contours. A contour is an imaginary line that joins point of equal elevation above or below a specified datum (usually sea level). An infinite number of contour lines could be drawn on a map but an interval is selected by the cartographer that allows for the adequate representation of the relief in the mapped area. In an area where there is very little difference between the highest and lowest point on a map a small interval such as 5 feet might be selected. In an area containing a large number of hills or mountains a much larger interval would be used.

There are several types of contours. Index contours are usually shown with a heavier line weight and on U.S. Government maps are used for every fifth contour line. The actual elevation value for the line is printed on the map. Lines in between index contours are called intermediate contours. These are usually in a smaller lineweight and are not numbered. The user determines the value of the line by adding or subtracting the contour interval from the nearest index contour. Depression contours are used to depict features such as sinkholes. A line is drawn around the feature and hachure marks (tick marks inside the feature) are added to show that there is a hole or depression. There is no way to accurately measure how deep the depression is.

There are some characteristics of contour lines that are useful to understand. First, all contour lines will close by returning to the point from which they started. This may not occur on the same map sheet. Second, contours that close on the same map sheet or in a relatively small area usually represent a hills or depressions of limited size. Third, the horizontal spacing of contour line reveals the nature of the slope. The closer the lines are together the steeper the hill.

7. Aerial Photographs and Scanned Imagery

Cartographers often use aerial photographs or scanned images for the preparation of maps. They can also be used by themselves to identify features on the ground. There are three types of photographs: horizontal, oblique, or vertical. A horizontal photograph is taken by pointing the camera straight at the subject. The feature being photographed will be represented but it is not possible to determine what features are behind the image or to measure distance. Oblique photos are shot at an angle above or below the subject. Depending on the angle, it is possible to record other features that might be in front of or behind the primary feature. However, it is not possible to measure distance between features. Vertical photographs are taken looking straight down at the target area. They are usually taken from cameras or scanners mounted underneath an airplane. These are most useful to cartographers because they determine the distances between features, the area of features, and the type of feature.

The difference between aerial photographs and scanned images is primarily the type of media that is used to record the image. Photographs are taken with a camera which requires film that must be developed. Scanned images are computer recorded digital files and can be viewed immediately without processing. Early scanning devices did not offer the same resolution as cameras, but today anyone has access to high resolution digital cameras. Digital files can be edited and enhanced using commercially available software packages.

Both types of imagery can be produced in black and white or color. With photography, color is more expensive because of the processing cost, but with digital color the only constraint is the larger file size that is produced.

One of the most common types of imagery used for mapping applications is called color-infrared. Color-infrared uses invisible portions (to the human eye) of the electromagnetic spectrum. Using film or scanners that can detect this near-infrared allows users to “see” the surface of the earth in other than natural colors. The result of this combination wavelengths produces images that:

Show healthy vegetation in a red color

Unhealthy or dormant vegetation appears light-red or a light shade of blue-green

Water absorbs near-infrared wavelengths and appears black

Water that contains varying amounts of sediment will show up in shades of blue

Color infrared photography was originally developed World War II and provided the military a method of detecting camouflaged enemy tanks because they were dead vegetation which showed up as different color on the photographs.

Uses today include crop inspections, tree-growth inventories, damage assessment of diseased vegetation, geologic investigations, and urban mapping applications because a sharp boundary exists between vegetation and buildings. It will also penetrate smog and show sharp distinctions be seen between land and water.

RESOURCES

Links

www.usgs.gov

www.labins.org

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GLOSSARY

Contour

Latitude

Longitude

Map

Planimetric Map

Projection

Scale

Symbol

Thematic Map

Topographic Map

ACTIVITIES

1. Introduction to Maps. Find different types of maps. Classify them by type: planimetric, topographic, or thematic. What does each map show?
2. Construct an index grid for a map. Construct and label a grid showing latitude/longitude.
3. Topographic Map Exercise
4. Scale, measuring distance, and identifying symbols.
5. Use a vertical air photo to identify features on the ground.

ENRICHMENT

1. You are asked to construct a map whose purpose is to highlight a certain theme. For each of the following, what information would need to be contained on your map in order to fulfill the purpose of the map. Include information for the map and the legend.

How states voted in the last presidential election

School bus routes

Ski areas in Colorado

Weather map

2. Draw a detailed map of where you live from memory. The area covered by the map should include your home and the school you attend. Fill in as much detail as you can including all major roads. Locate churches, schools, grocery stores, and other major buildings. Label major streets.

3. Go to www.labins.org. Find the DRG (Digital Raster Graphic) and the DOQQ (Digital Orthophoto Quarter Quad) for the area where you live. See if you can find your house.

A7.2 South Florida/Everglades area

PURPOSE

1. The Kissimmee-Lake Okeechobee-Everglades (KOE) ecosystem is made up of canals, land, and water and managed by the South Florida Water Management District, (SFWMD) one of five regional water districts in the state. The KOE ecosystem is a vast and interconnected system of water and land, plants and animals.
2. Hurricanes between 1920s and 1940s began a U.S. Army Corps of Engineers project to construct miles and miles of canals to drain the floodwaters and control the waters during drought.
3. In 1968 the Dade County Port Authority began construction of an international jetport in the Big Cypress Swamp. Beginning 1970, a study was made of the effects of major construction on the South Florida water supply.
4. Many laws have been passed over the last century to protect South Florida's water supply including the Water Resources Act, passed in 1970s; Save Our Rivers or Preservation 2000; Everglades Forever Act; and the Comprehensive Everglades Restoration Project (CERP).
5. There are more than 68 threatened or endangered species living in the Everglades-Lake Okeechobee region. There are increasing numbers of invasive (non-native) species in the ecosystem.
6. Population growth in the south Florida region poses a threat not only to the ecosystem but to the "people system" by depleting water resources and increasing pollution of air and land. Approximately 800 people move into Florida every day.

7. Geological formations include limestone which underlie the peat soil and form the base of the Everglades National Park. It is called *Miami Oolite*. A wide variety of soil types such as Histosols, Spodosols, and sandy areas make up the southern peninsula.
8. Lake Okeechobee is the second largest freshwater lake in the continental United States. It plays a major role in the water resources of the south Florida area.
9. Florida is rich in history with different people who have lived here from the Seminole and Miccosukee Indians to the Florida Crackers to the "transplants." Five different flags representing five separate governing bodies have flown over Florida.

STUDENT LEARNING OBJECTIVES

- * Compare the length, width, and formation of the bodies of water which make up the KOE ecosystem.
- * Determine a safe location to go in the event of a hurricane warning and plan evacuation routes from coastal and low-lying areas.
- * Identify the characteristics of estuaries of Florida Bay.
- * Compare the historical uses of rivers and wetlands to current uses and analyze the economic and environmental impacts of these uses.
- * Compare the environmental impacts and regulatory requirements of the U.S. Army Corps of Engineers actions.
- * Describe the topography of the south Florida KOE ecosystem.
- * Describe the role of the Floridan and Biscayne aquifers.
- * Identify the geologic processes that created the KOE ecosystem.
- * Identify some of the endangered and threatened species which live in the area.
- * Compare the population numbers over a period of time and make predictions for future growth.
- * Identify the various ecosystems which comprise the south Florida region.
- * Identify the geologic characteristics which make south Florida a unique area.

RUBRICS FOR ASSESSMENT, based on FCAT short- or extended-response questions

3 points	The response indicates that the student has a complete understanding of the reading concept embodied in the question. The student has provided a response that is accurate, complete, and fulfills all the requirements of the question. Necessary support and/or examples are included, and the information given is clearly text-based.
2 points	The response indicates that the student has an understanding of the concept embodied in the question. The student has provided a response that is accurate and fulfills all of the question, but the required support and/or details are not complete or clear.
1 point	The response indicates the student has a very limited understanding of the concept embodied in the question. The response is incomplete, may exhibit flaws, and may not address all requirements of the question.
0 points	The response is inaccurate, confused, and/or irrelevant or the student has failed to respond to the question.

BACKGROUND MATERIALS

Historical aspect of the Everglades

Pahayokey, "the grassy waters," was the name given the Everglades by the Native Americans living in and around the river. When Englishmen visited the area, they saw vast expanses of green, wet prairie and named it for their homeland countryside, calling the extensive grasslands "Everglades." Today, Everglades National Park is made up of 1.5 million acres of marshes, mangrove thickets, hardwood forests, estuaries, swamps, rivers, and bays.

"There are no other Everglades in the world. They have always been one of the unique regions of the earth, remote, never wholly known. Nothing anywhere else is like them: their vast glittering

openness, wider than the enormous visible round of the horizon, the razing free saltiness and sweetness of their massive winds, under the dazzling blue heights of space. They are unique also in simplicity, the diversity, the related harmony of the forms of life they enclose.

“The miracle of the light pours over the green and brown expanse of sawgrass and of water—shining and slow moving below, the grass and water that is the meaning and central fact of the Everglades of Florida.

“It is a river of grass.

Marjorie Stoneman Douglas in *Everglades: The River of Grass*

Water resources are a major factor defining the face of South Florida. The region's water resources include natural waterways, such as the Kissimmee-Lake Okeechobee- Everglades (KOE) system, the Big Cypress Basin, and the watersheds of the Caloosahatchee River and the Indian River Lagoon. It also includes one of the largest manmade drainage systems in the nation, the Central and Southern Florida Flood Control Project (C&SF), as well as the water surrounding the only coral reef in the continental U.S. In addition to these surface waters, the region's groundwater resources include one of the most prolific aquifers in the world, the Biscayne aquifer.

Lakes, canals, and other water bodies

The Kissimmee chain of lakes is the most northern part of the KOE system. Imagine yourself a drop of water traveling this system. Your journey begins in Turkey Lake, travels through a chain of several bodies of water with such names as East and West Lake Tohopekaliga, Lake Cypress and Lake Hatchineka and ends up in Lake Kissimmee. This totals over 245.5 km² (94.8 mi² or 60,750 acres) of water! Eventually, you would end up in Lake Okeechobee before you entered the Everglades.

Lake Okeechobee covers 730 square miles, and is a relatively shallow lake with an average depth of 2.7 m (9 ft). It is considered the "liquid heart" of South Florida and is the second-largest freshwater lake in the continental United States. Lake Okeechobee's drainage basin covers more than 11,913 km² (2 4,600 square miles).

The Everglades systems stores and filters water until it reaches Florida Bay. It is called a **watershed** because it is a land area that delivers runoff water, sediment, and dissolved substances to a major rivers system. This watershed is 80 km (50 miles) wide in some places, 0.3 to 0.9 meters (one to three feet) deep in the slough's center but only 15 cm (6 inches) deep elsewhere. It flows south 30 meters (100 feet) per day across Everglades sawgrass toward mangrove estuaries of the Gulf of Mexico. The Everglades is a unique system because it is a shallow river of grass with a sheet flow.

A **system** is anything which functions as a whole by the interaction of organized parts. In the Everglades system, the canals control the ebb and flow of water. The once abundant wildlife is on the decrease. This unique ecological system not only contributes to South Florida's water supply, flood control, and recreation, it serves as the habitat for a wide diversity of wildlife and plant life. The Everglades system is one of the most unique in the world and is endangered as a result of adverse changes in water quality, and in the quantity, distribution, and timing of flows through canals and other alterations.

An **ecosystem** can be predicted from the underlying geology forces. Under the Everglades lies the Biscayne aquifer which is **porous** and **permeable**. It is very shallow (only 76.6 m or 250 feet deep) and acts as the recharge area from rainfall producing a large amount of fresh water. Water that percolates through the **Biscayne aquifer** flows into a confining layer of clay and silt, which does not produce fresh water. Rainfall which does not collect on the surface or flow into rivers moves quickly into the **Floridan aquifer** which is brackish to salty water.

One of the most productive aquifers in the world, the Floridan aquifer system underlies a total area of about 259,000 km² (100,000 mi²) in Alabama, Georgia, South Carolina, and all of Florida. It has been called "Florida's rain barrel" because it provides water for many cities throughout the state. The Floridan aquifer is defined on the basis of **permeability**--not uniform in the number and spacing of openings and at least 10 times more permeable than its upper and lower confining units.

The Biscayne aquifer underlies a large area of south Florida and is a carbonate-rock aquifer, very close to the land surface. This aquifer is the source of drinking water for more than 3 million people. The aquifer consists of highly **permeable** interbedded limestone and sandstone. These highly **permeable** rocks are covered by a thin veneer of porous soil. The high permeability of the Biscayne aquifer is created largely by extensive dissolution of the carbonate minerals that comprise the limestone units. Large solution openings are produced when part of the rock is dissolved by ground water and common in carbonate rocks. These openings store and diffuse large quantities of water. Most carbonate rocks originated as sedimentary deposits under water. This is further evidence that Florida was underwater during various times in history. The carbonate-rock aquifers of Florida are called platform carbonates and have intergranular porosity in addition to large solution openings.

South Florida is underlain with limestone. Solution holes and limestone outcropping are a result of the natural weathering process in this ecosystem. Karst topography occurs when carbonate rocks are exposed at the land surface, evidenced by sinkholes, blind valleys, and sinking or disappearing streams. Because water enters the carbonate rocks rapidly through sinkholes and other large openings, contaminants in the water can enter and spread through the aquifers.

An **estuary** is where the rivers and other fresh waters meet the sea. As a result, the water in an estuary is usually brackish, or slightly saline and slightly fresh. Florida's estuaries suffer from an overabundance of fresh water. Although there is not an abundance of rainfall, 100-165 cm (40-65 inches) per year, the canals which channel the flowing water into the estuaries cause severe problems. Estuaries are necessary for the survival of many species of animals including birds, fish, and shellfish which depend on the area for spawning and protection. Estuaries also provide an area for **ecotourism**, where humans can fish, recreate, boat, and enjoy viewing wildlife.

Historical peoples of Florida

Seminole Indians settled throughout Florida before the first Spanish explored the peninsula. They came from Georgia and north Florida and made their homes along the winding Kissimmee River and on thousands of small islands in the area now called the Everglades. Big Cypress yielded the big trees which the Seminoles used for boats and homes. Cypress log walls and palmetto frond roofs built homes called **chickees**. Canoes called dugouts were carved from the abundant cypress trees. Seminoles lived off the land and were careful not to damage their lively hood. They fished, hunted and gardened and used natural resources to their advantage. The challenge of maintaining their unique Seminole culture while living in the mainstream economy is the priority for today's Seminole Tribe of Florida.

Miccosukee Indians were originally part of the Creek Nation, part of Georgia and Alabama. They settled in south Florida in the 1700's when some were encouraged by the Spanish explorers to relocate into "Spanish Florida" in the panhandle. As they hunted, Miccosukee traveled further into south Florida and ended up in the Everglades region. They, too built homes called **chickees** and lived off the land, hunting and fishing. Today, Miccosukee strive to maintain their native heritage as well as "live in" the modern society.

"Florida cracker" is a name given to early Florida settlers or to the folk of the backwoods. There are many theories as to the origin of the name, but one popular belief is it originated with the sound made of the whip as it cracked over the oxen or mule or cattle. "Crackers" are people who live in rural areas, in small cabins usually with porches, and are self sufficient, growing their own food sources. Today, it can be a derogatory or insulting comment. There are certain words or phrases associated with "Crackers". Examples like cooter (a freshwater turtle), curlew (pink spoonbills hunted for their plumes and as food) or grits (coarsely ground dried corn) are terms coined by crackers.

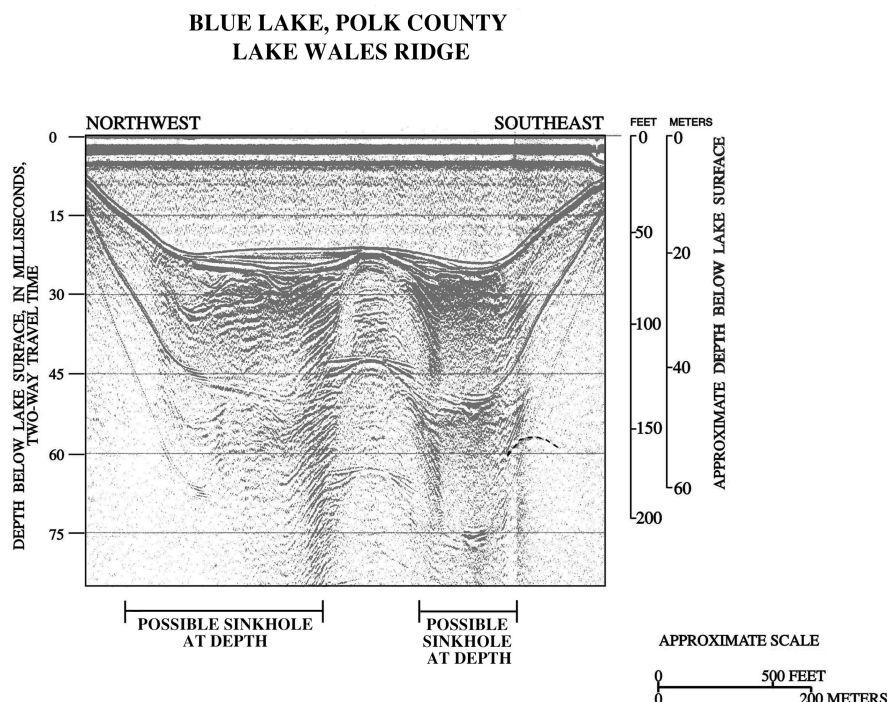
Florida's heritage is enriched by many cultures. Five national flags have flown over Florida including Spanish, French, British, United States and the Confederate States of America. Today, more than 700 people a day move into the Sunshine state, bringing more diversity.

Ridges and landscapes

A "ridge" is the result of high fluctuations of sea levels and contain both upland and wetland ecosystems. There are several ridges in Florida. The Atlantic Coastal Ridge is the highest and oldest land

in southern Florida. The slight elevation assists water flow from the Everglades into the Florida Bay. This ridge's base is Miami Oolite.

Another ridge is called the Lake Wales Ridge and connects the central Florida area to the South Florida waters. The Lake Wales Ridge is a series of sand dunes, formed some 2 million years ago as a shoreline ridge during the pre-Pleistocene era. The ridge contains many sinkhole lakes and cavities, caused in the limestone as the naturally acidic rains **percolate** through the sands into the limestone.



This image is a seismic profile taken in a lake on the Lake Wales Ridge. The flat surface of the scan is the water surface, and the lakebed is seen at about 20m below the surface. The image is made possible by reflectors of the dipping beds beneath the bottom of the lake... works kind of like a sonogram, except the oil industry developed the technology long before they thought to use sonograms on pregnant women.

In the image, the downward dipping reflectors between 20 and 40m depth are interpreted as relict sinkholes that have been filled in with sediments. These reflectors are an indication that the origin of the lake is related to karst activity. One possibly cool way to think about it: If the lake is about 800 m (0.5 mile) across (east-west) and has a perimeter of ~3350m (2 miles) and was formed by collapsed cavities in the limestone that lies ~80m (87 yds) below the bottom of the lake, was the cavity bigger than a football stadium?

Current problems

There are a variety of "identified problems" with the South Florida system. Nutrient runoff due to agriculture which surrounds the river system as well as the Everglades has changed the water quality. Fertilizers, containing phosphates and nitrates, are used on gardens, golf courses, fields and yards. When it rains, these nutrients flow into the canals and eventually end up in Florida Bay, the Everglades filtering system or accumulate in the muck surrounding the bodies of water. Often, this is called **non-point pollution** since specific sources cannot be identified.

Other pollutants of concern are carbon dioxide (CO₂), a result of incomplete burning of fossil fuels; carbon monoxide (CO) which accumulates when there are huge populations of cars, boats, airplanes, and lawn mowers; Mercury (Hg) levels are very high in many animals making them unsafe for human consumption and may cause the death of mammals that live in the region. Cattle waste also washes an abundance of pollutants into the system. Sulfur dioxide (SO₂) and nitrogen oxides (NO_x) are the primary causes of acid rain. These pollutants come from electric power generation that relies on burning fossil fuels like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. Sunlight increases the rate of most of these reactions. The result is a mild solution of sulfuric acid and nitric acid.

There are more than ____ miles of canals in the KOE system. The first ones were built by the Swamp Land Act of 1850 to drain the land for farming purposes. Winter vegetables, sugarcane and citrus were among the agriculture that benefited from this act. The idea of drainage received political support from Napoleon Broward in his campaign for governor in 1904. Canals were dug to shunt surplus Lake Okeechobee water directly to the Atlantic. The hurricanes of 1926 caused floodwaters to rise and severe damage in the Miami area and Lake Okeechobee. In 1928, another hurricane caused heavy property damage in the Lake Okeechobee area when the levees broke. As a result, additional canals were built. *(this is where I see the animation or however we are going to present the expansion.... P. 106 in the Atlas of Florida)*

The natural flow of water diverted with dams, canals, and dikes has presented problems for the KOE system. Agricultural additions through the ages have diverted the water for growing sugarcane. By 1920 four massive canals had been carved from the Okeechobee to the Atlantic Ocean, draining the swamp creating fertile farmland.

Laws

	date	summary
Water Resources Act	1972	Creates Florida's five water management districts which are principally responsible for planning and managing water resources within the state.
Save Our Rivers or Preservation 2000	1981	Water districts purchase land surrounding rivers and lakes for water managements, supply, conservation and protection.
Everglades Forever Act		to restore and improve the south Florida water supply through the Everglades
the Comprehensive Everglades Restoration Project (CERP)--		a framework and guide to restore, protect, and preserve the water resources of central and southern Florida
Environmental Land and Water Management Act	1972	The Areas of Critical State Concern program focuses public attention on geographic areas whose environmental or historical uniqueness is important to protect.

5. Future of So FL

Between 1900 and 2000, southeastern Florida's coastal population changed from just ____ to _____, an increase of _%!!

****growth of cities, impact on water supplies**

6. water cycle

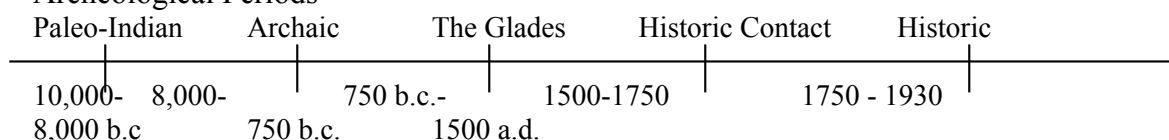
****pollution of water**

****sources—aquifers, locations and names**

****treatment of water—desalination?**

****amount of water used—in 1995 South Florida used 3,750 million gallons of clean water daily. By 2020, predicted to need 4,652 million gallons of clean water daily.**

Archeological Periods



During the Paleo-Indian period, Native Americans are thought to have lived with mammoths, bison and other large fauna in arid conditions. Climates changed and wetlands emerged and with it came deer, rabbits and marine life.

The Archaic period (post glacial) saw the seas rise and Florida's land base decrease. Cypress swamps and hardwood forests developed. Inhabitants relied on shellfish as well as expand their hunting ranges. As this period came to an end, tools began to emerge.

Pottery marks the Glades period and hunting improved.

Europeans explorers arrived during the Historic contact period. Five separate tribes were thriving. As this period came to an end, many of the Native Americans had migrated to Cuba.

The Historic period saw "white settlement" and migration of Native Americans into South Florida. Separate bands of Indians settled into the Everglades area in order to prevent being moved out of Florida. It was also during this period that canals were being built to drain South Florida's waters.

The Everglades region composed more than nine million acres when the Spanish explorers came onshore. Today, the region comprises only 1.5 million acres.

Geological formations and ages

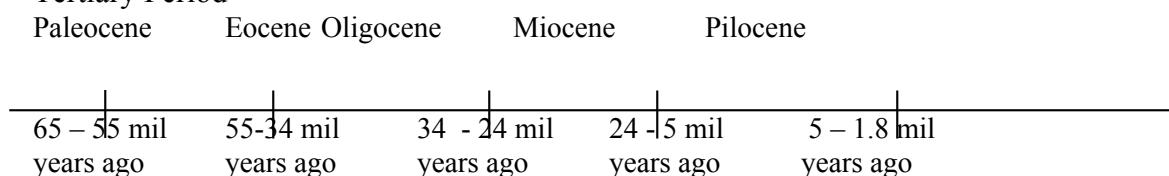
Geology, the rock beneath the soil, is important because geology controls the development of vegetation and animals (flora and fauna). Geology also controls the movement of water underground, how and where it is stored, and how it is delivered for use. Geology controls the environment.

Cenozoic Era (age of mammals) divided into Tertiary and Quaternary

Quaternary Period



Tertiary Period



South Florida is relatively young terrain, its basement rock made up of the carbonate remains of marine algae and shells deposited in an ancient sea. Evidence indicates earliest geologic formations began during the Tertiary Eocene era. Those shallow sediments are called Suwannee Limestone. Over the tertiary and quaternary periods, the sea rose as the polar ice caps melted and ebbed as the water evaporated. *This is where the cross section of South Florida should be a hot link.*

Approximately 20,000 years ago, during the Pleistocene period, the last glacial stage occurred which allowed the Florida peninsula to almost double in size. Florida was connected to the American southwest and narrowed the Gulf of Mexico.

The rocks of the Big Cypress Swamp were formed during the Miocene period, 6 million years ago when a shallow sea covered this area. Sediments of silt and sand contained calcium particles which cemented into limestone. Siliciclastic-bearing carbonates indicate formation during the Miocene period.

Between thirty and fifty thousand years ago, South Florida was a shallow submarine bank. Sediments of silt and sand containing particles of calcium deposited by glaciers make up the limestone. Much of the Everglades National Park is floored by this recent limestone which geologists call **Miami Oolite**. Oolite comes from a Greek term meaning "egg." Oolite is made up of egg-shaped particles which solidify into rock. Like a pearl forms in an oyster, oolite begins as a particle of sand or shell and as calcium carbonate precipitates, the oolite forms. Miami Oolite also covers most of the area east of the Everglades National Park and most of Florida Bay.

Although no glaciers ever formed in Florida, effects were seen with water levels lowered to more than 91 meters (300 feet) below today's levels. The oolitic sediments were formed as the ocean water rose and fell.

Because there is "limited elevation" in the South Florida region, fresh water flows very slowly through the lakes and canals into the Everglades and on into the salty Florida Bay. Mangrove forests filter this water which teems with life. Florida Bay is the home of an ancient coral reef.

Ecosystems of South Florida

Ecosystems of the South Florida vary greatly. Pine flatlands, cypress hammocks, saw grass Everglades, tree swamps, solution basin prairies, saw palmettos, groves of cabbage palms, mangroves and a variety of temperate and tropical hardwoods all define the unique landscapes. In each ecosystem, life varies as well. Panthers, bears, alligators, rattlesnakes, Florida sandhill cranes, caracara and the burrowing owl are just a few of the species which inhabit the ecosystems. The South Florida flora and fauna are the most unique for a single area in the northern hemisphere.

Pine flatlands are characterized by relatively open lands covered with pines, low shrubs and other plants. In South Florida, these pine forests are found on the high ground of the Atlantic Coastal Ridge. Saw palmetto, gallberry or wax myrtle is some of the plant species. The soils are usually loose and sandy with low organic matter. There is a variety of bird life small mammals, different amphibians and reptiles and white-tailed deer.

The saw-grass Everglades are one of the most unique in the world. Saw-grass gets its name for the spiny, serrated leaf blades. Because the waters are very shallow, the Everglades was named "The River of Grass" as the waters flow slowly over the grasses.

Cypress hammocks are differentiated by the amount of water standing in the area. Water fluctuates with seasons allowing for the soils to be exposed to the air and water alternately. Sediments form **peat**, a particularly carbonized vegetable matter which is considered to be rich in nutrients.

Mangroves are waterlogged trees which grow in brackish water and sediment deposited by freshwater runoff and tides. They grow in low-lying intertidal zones and provide habitat to a wide range of invertebrates and vertebrates including fish, birds, Florida manatee, crocodiles or alligators.

One specific type of **muck**, rich for growing vegetables is called Custard Apple Muck, considered to be one of the finest growing soils in the world. The area once was a natural levee on the southern shores of Lake Okeechobee. Waters that flowed over the levee into the Everglades during rainy season carried the rich, dark granular muck with it enriching the brown-grey peat in the poorly decomposed Everglades saw grass. Unfortunately, exposure to air (oxidation) has depleted the region's soil nutrients.

Other soils types found in south Florida include **shelly sand** which is found mostly on beaches, dunes, tidal marshes and tidal swamps. Dominated by nearly level to sloping sandy beaches and adjacent sand dunes or level, these areas are very poorly drained coastal marshes and swamps of variable textured mineral and organic soils subject to frequent tidal flooding. **Histosols** are dominated by level, very poorly drained organic soils underlain by marl and/or limestone and are primarily used for sugar cane, vegetables, pastures, and sod. This "soil" is what makes up the bulk of the area south of Lake Okeechobee throughout the Everglades. **Entisols** are dominated by level, very poorly drained marly and very thin sandy soils underlain by limestone. These areas are used for winter vegetables in localized

areas about the soil is very poor and do not encourage homesites and urban development. This type of soil dominates much of the very southern portion of Florida's peninsula.

Endangered species

The Everglades, Biscayne National Park, and Big Cypress are home to more than 60 endangered or threatened species. Among the larger species on this list are wood storks, American crocodile, West Indian manatee, and Florida panther. Along the beaches Atlantic Ridley turtle, Atlantic hawksbill, and Atlantic leatherback sea turtles nest. The Key Largo woodrat and Key Largo cotton mouse are listed as endangered. Insects include the Schaus Swallowtail butterfly. Endangered birds like the Red-cockaded woodpecker and the Cape Sable seaside sparrow, an "indicator species" reside. The sparrow's population numbers have dwindled steadily as has the population of wood storks. Other birds are the Snail (Everglade) Kite and the Southern Bald eagle. There are also several species of orchids which thrive in the South Florida climate and are threatened by loss of habitat.

Alligators, called *halp_te* by the Seminole Indians, were once hunted to near extinction for their hides and food. These reptiles are an important animal in the Everglades since they dig holes that collect water for their dens. Other animals and plants share these 'gator holes during times of drought. Plans for their protection prevented the demise of this reptile.

Other "hard to find" species include the tropical heart-shaped fruit of the custard apple tree. Native Americans used the fruit for eating and for ceremonies. The leaves were used for dyes and dried, the fruit is used for medicinal purposes.

Loss of habitat with draining of wetlands and alteration of water flow are just two reasons a species becomes endangered or threatened. History shows that over-hunting, often for just the hide or feathers, contributes as does pollution. The Endangered Species Act of 1973 affords some protection to wildlife. Listing a species as endangered or threatened allows for environmental protection.

Invasive species

Cattails, which grow so thickly that wading birds cannot find food or land, cause a "ripple effect" through the Everglades. Although they were considered a "good plant" by Native Americans, the cattail is taking over the space of such native plants as bulrush.

An exotic or invasive species introduced was Melaleuca (bottle brush or punk trees) to help "dry up" the region for planting. It invades natural areas of pine or cypress and needs less water. It provides poor habitat for native wildlife. Brazilian Pepper is another invasive species which is spread by birds. Its brilliant red seeds are widespread throughout South Florida. Dense stands of pepper do not provide suitable habitat for native species.

Australian pine or ironwood is an exotic plant brought to the United States from Australia and the East Indies in the 1800s. It too was introduced to "dry up the swamps". As is the case with many exotic plants, the Australian pine is spreading quickly across the southeast United States. Dense stands of these 30 m trees invade beaches where its dense root system prevents endangered sea turtles from digging their nests. The wood is brittle and does not make good lumber.

There are more than 100 documented invasive species in the Everglades and south Florida region. They are a threat to the natural environment because they replace native vegetation and therefore displace native animal species.

Florida Bay and Coral Reefs

Florida Bay is an **estuary** within the Everglades National Park. The bay is shallow, approximately one meter (about 3 yards) deep and 2,200 km² (849.4 mi²) in size. Water flows into the Florida Bay from the Everglades and surrounding creeks. Seagrass meadows distinguish the bay from the Everglades. Mangrove isles make up less than 2% of the area, but provide habitat for fish and birds.

Beneath the seagrass beds, calcium carbonate rock allows the water to percolate through the carbonate sediments into the aquifer. Sponges, juvenile fish, and other invertebrates thrive in this habitat.

Coral reefs are also prominent in the South Florida waters. In fact, Florida is the only state in the continental United States to have shallow water coral reef formations near the coast. Florida's coastal reefs were formed during the Holocene period, 5,000 to 7,000 years ago following the Wisconsin Ice Age.

Coral reefs provide shelter, food and breeding sites for numerous plants and animals. Reefs provide a breakwater for storms coming on shore.

To form, there must be a solid base, warm waters, specific salinity, clear and clean water free of phosphates and nitrogen, and moderate wave action which brings oxygen and plankton to the reef area. Florida Bay waters are threatened with fertilizer pollutants as well as large quantities of fresh water.

Visitors to the coral reefs pose additional problems. Boaters damage the reefs when they run aground. Swimmers who touch the coral cause it to die because of the oil and other "chemicals" on their hands. It is illegal to take coral from the reef.

Big Cypress National Preserve

Big Cypress National Preserve, located on the northern boundary of the Everglades, was the first National Preserve set aside in the National Park System. Boasting more than 2.95 km² (729,000 acres), Big Cypress is a mixture of pines, hardwood prairies, mangrove forests, cypress stands and knees. Cypress trees are unique in that they have "knees" or domes extending from the ground near the roots of the tree. As they spread, these knees provide additional stability to the tree as well as habitat for water-intolerant plants or birds to roost.

Big Cypress is the "home" to white-tailed deer, bear and the Florida panther. Rare orchids, tree snails and the royal palm also can be found here. This area serves as the fresh water retention needed for the estuaries of the thousand islands area. Purchase of the land prevented the construction of an airport, planned in the 1970s.

The Big Cypress Preserve is one of the few areas in Florida where oil has been found and drilled. The bedrock is the same limestone as the Everglades and oil has been extracted since the early 1970s. Nearly 65,000 barrels of oil are removed each month. Oil occurs in the porous limestone about 3.35 m (11,000 ft) below the surface.

Conclusion

South Florida is a unique

RESOURCES

Links

www.evergladesplan.org/education/teacing_resources.cfm

www.nps.gov/ever

www.florida-everglades.com/

www.everglades.org-- Friends of the Everglades strives to protect and restore the Greater Kissimmee-Okeechobee-Everglades Ecosystem. "Our primary tools are legal advocacy and education. In this site, you will find information on the Florida Everglades and on how you can help us all win the fight to protect one of the world's unique natural treasures."

everglades.fiu.edu/ Everglades's information network

www.evergladesplan.org/ Information about CERP

www.nps.gov/bicy/ Big Cypress National Preserve information

www.npca.org/across_the_nation/ten_most_endangered/florida.asp information about both Big Cypress National Preserve and the Everglades

visibleearth.nasa.gov/ a searchable directory if images, visualization, and animations of the Earth

www.everglades.national-park.com/info.htm#geo

www.dep.state.fl.us/lands/invaspec/

www.aoml.noaa.gov/general/flbay_aoml.html

www.firn.edu/flbaydude/

www.seminoletribe.com/

www.miccosukeeresort.com/mivillage.html

www.dep.state.fl.us/coastal/habitats/coral.htm

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PLACES TO VISIT

Everglades National Park
www.nps.gov/ever
 (305) 242-7700
 Florida Bay
 Big Cypress National Preserve
 HCR61, Box 110
 Ochopee, FL 33943

GLOSSARY