WOODVILLE KARST PLAIN HYDROLOGIC RESEARCH PROGRAM

REPORT ON TASKS PERFORMED IN 2009 UNDER FGS CONTRACT GW275

Prepared for:

Rodney DeHan, Ph.D.
Florida Geological Survey
Gunter Building MS #720
903 W. Tennessee St.
Tallahassee, FL 32304-7700

Prepared by:

Todd R. Kincaid, Ph.D.
H2H Associates – Specialized Geological Modeling Group
Group Leader
27 Keystone Ave.
Reno, NV 89503

Overview

H2H Associates, LLC (H2H) was contracted by the Florida Geological Survey (FGS) to coordinate and administer the FY2009 objectives of the FGS' Woodville Karst Plain (WKP) hydrologic research program and synthesize the results into this report. The FY2009 program included the five following tasks.

- Task-1: Hydraulic Instrumentation and Monitoring
- Task-2: Database & Data Portal Maintenance
- Task-3: High Water Turner Sink Trace
- Task-4: Groundwater Modeling
- Task-5: Spring Creek Radon/Methane Groundwater Tracing

The Principal Investigator for Tasks 1-3 was Dr. Todd Kincaid of the H2H Associates Specialized Geological Modeling Group (H2H). Responsibilities for Task-4 were divided between Dr. Kincaid and David Loper, Professor Emeritus at Florida State University (FSU). The Principal Investigator for Task-5 was Dr. William Burnett of the Department of Oceanography at FSU. As has been customary with this ongoing research project, specific objectives (tasks) were modified during the course of the investigations to conform to evolving goals of the overall project and logistical and weather constraints.

The contract was executed on July 21, 2008 for a period of performance of July 21, 2008 – June 30, 2009. Prolonged drought conditions stalled the execution of Task 3 until July 2009 whereupon the contract period was extended to December 31, 2009. This report provides a summary of the performance and results of each task, includes or references the specific deliverables as appendices, and constitutes the final deliverable for this project.

Task 1: Hydraulic Instrumentation and Monitoring

Objectives

The purpose of this task was to expand the data collection program; develop and maintain a set of QA/QC protocols for data collection; redeploy and confirm the Falmouth meters at existing and three new locations; deploy long-term and short-term water level meters, and transmit the data to the H2H servers for upload to the project database and the web Data Portal.

Specific objectives for the Falmouth meters included the following tasks.

1. Coordinate with the WKPP to remove the C-Tunnel meter and cable.
2. Clean up and inspect the C-Tunnel, AK-Tunnel, K-Tunnel, and Vent meters in the lab. Check these meters against a standard to determine if they are working correctly and can be redeployed.
3. Deploy one meter to the A/K Tunnel junction north of the junction such that effectively measures flow from both A-Tunnel and the K-Tunnel bypass.
4. Deploy one meter in Revel Sink outfitted with cable and surface charging/download station.
5. Deploy one meter in Turner Sink outfitted with cable and surface charging/download station.
6. Deploy one meter in Kelly Sink outfitted with cable and surface charging/download station.
7. Visit, inspect, service, and download all 8 meters once every two weeks during the entire contract period (June 2008 – June 2009).
8. Transmit the data to H2H for inclusion in the WKP database and web Data Portal immediately after every download.

Specific objectives for the water level loggers included the following tasks.

1. Deploy or confirm deployment of water level loggers from surveyed benchmarks at the following locations:
   - Spring Creek Marker #35
   - Shepard Spring
   - Revel Sink
   - Harvey's Sink
   - Wakulla K-tunnel
   - Wakulla Spring Vent
   - Turner Sink
   - McBrides Spring #4
   - Lost Creek Swallet
   - Jump Creek Swallet

2. Visit, inspect, service, and download all 10 meters once every two weeks during the entire contract period (June 2008 – June 2009).
3. Transmit the data to H2H for inclusion in the WKP database and web Data Portal immediately after every download.
4. Deploy water level loggers from non-surveyed benchmarks at six locations (to be determined) for two-month periods.
5. Rotate the water level loggers to a new set of six locations every two months for a total of six deployments during the contract period.
6. Visit, inspect, service, and download all 10 meters once every two weeks during the entire contract period (June 2008 – June 2009).
7. Transmit the data to H2H for inclusion in the WKP database and web Data Portal immediately after every download.

Results – Falmouth Meters

Water clarity conditions in the Wakulla Cave system were extremely poor throughout the contract period, which impeded all objectives that the Woodville Karst Plain Project Dive Team had defined. Though these conditions did not prevent the team from engaging in meter replacements, the poor conditions combined with higher than expected demands for the level logger installations forced us to reprioritize our objectives with respect to the Falmouth meters and ultimately reduce the effort directed toward them.

The C-Tunnel meter was not replaced and is still deployed and working. Both the K and AK Tunnel meters were successfully replaced in May 2008 immediately prior to the execution of this contract. New meters were not deployed at Revell Sink, Turner Sink or Kelly Sink due to extremely poor visibility conditions that persisted through most of 2009. New Falmouth meters were installed however at Spring Creek Vents #1 and #10 and have been working successfully since May 2009. Table 1 provides a list of all the Falmouth meters currently deployed in the WKP, the period of available data during the contract period, and the total number of records collected at each station. Plots for each data stream at each station are provided as Figures 1-6. Additional plots of Spring Creek stations #1 and #10 that correlate the parameter reading with flow direction are provided as Figures 7-9.

Table 1. Summary of Falmouth meter data collected in the WKP during the contract period.

Station	ID	Available Data Period	# Records	Flow max/min (cfs)	Temp max/min (deg C)	Cond max/min (mmho/cm)
Wakulla-AD	1665-2D	7/2/08 – 12/31/09	53,534	430/11	22/19	0.57/0.19
Wakulla-AK	1891-2D	7/2/08 – 11/19/09	47,764	595/27	22/20	0.61/0.19
Wakulla-B	1687-2D	7/2/08 – 11/30/09	50,020	116/41	21/21	0.31/0.29
Wakulla-C	1688-2D	7/2/08 – 11/30/09	50,942	63/20	21/20	0.40/0.29
Wakulla-D	1889-2D	7/2/08 – 7/8/09	36,541	46/3	21/21	0.29/0.27
Wakulla-K	1893-2D	7/2/08 – 12/21/09	53,520	270/31	22/19	0.56/0.17
Spring Creek-1	1687-2D	5/20/09 – 11/17/09	17,225	336/78	31/19	50.45/2.57
Spring Creek-10	1674-2D	5/28/09 – 11/17/09	16,492	845/2	31/20	51.11/2.24

Total number of Falmouth measurements: 326,038

Results – Level Loggers

Two types of level logger installations were engaged. Permanent stations were established by installing 1" diameter stilling wells into which transducers were inserted at measured depths and from which the top was surveyed to local bench marks. Temporary stations were established by simply placing a transducer in the water at a station in a relatively secure location and not collecting any survey information. A total of fourteen (14) water level stations have been installed in the WKP including seven (7) permanent (surveyed) stations, four (4) temporary stations, and three (3) stations that are scheduled to be converted to permanent stations once the top-of-casing elevations at the respective wells have been surveyed. Table 2 provides a list of the water level meters that have been installed in the WKP showing the installation date, type of station, and statistics on the data collected.

Table 2. Water level loggers installed and operating in the WKP during the contract period.

Station	ID	Type	Install Date	Elevation (ft NAVD-88)	# Records	Depth max/min (feet)	WT Elev. max/min (feet)	Temp max/min (deg C)
Sullivan Sink	107898	P-Insitu	3/2/09	10.01	29,568	12.7/1.3	16.1/4.6	26.3/9.4
Lost Creek	107927	P-Insitu	1/26/09	18.48	30,161	19.4/0.9	19.8/1.3	27.8/6.2
Revel Sink	107922	P-Insitu	2/26/09	8.24	27,068	5.8/1.3	8.1/3.6	25.7/18.8
Turner Sink	107893	P-Insitu	3/2/09	9.28	29,567	7.0/1.6	10.4/5.0	29.2/16.6
St. Marks Rise	107904	P-Insitu	3/4/09	13.11	24,845	5.5/2.2	8.9/5.6	21.9/16.3
Tobacco Sink	107906	P-Insitu	2/26/09	7.63	26,873	5.8/0	7.5/1.7	27.5/2.3
Wakulla Dock	107924	P-Insitu	8/14/08	10.54	54,464	5.7/1.9	9.2/4.6	27.9/19.4
Cherokee	NR	T-Global	8/11/09	NA	14,117	3.2/0.9	NA	NA
Punch Bowl	NR	T-Global	5/13/09	NA	22,268	NA	NA	NA
Smokehouse	NR	T-Global	6/10/09	NA	NE	NE	NA	NA
Spring Creek-2	107917	T-Insitu	8/27/09	NA	NE	NE	NA	NA
Wakulla-B	NR	T-Global	4/22/09	NA	NE	NE	NA	NA
Wakulla-D	NR	T-Global	7/8/09	NA	NE	NE	NA	NA
Wakulla-K	NR	T-Global	7/8/09	NA	NE	NE	NA	NA

Notes:

P-Insitu: permanent station with Insitu logger

T-Insitu: temporary station with Insitu logger

T-Global: temporary station with Global loger

NR: no record provided in the datasets

NA: measurement not available

NE: data has been collected and stored but not entered into the project database

Total number of water level measurement recorded: 258,931

Conclusions & Recommendations

The Falmouth meter data has consistently and clearly recorded three unique sources of water feeding Wakulla Spring: two northern sources that supply water to the Spring via B and D Tunnels and a southern source that supplies water to the Spring via A-Tunnel. Cave exploration conducted by the WKPP divers has revealed that the southern source also connects to the Leon Sinks Cave System.

Operation, maintenance, data processing, and data interpretation associated with the Falmouth meters require substantial personnel resources. Effort should be taken to reduce and optimize the meter placements such that the highest utility is realized with the least requirement of resource expenditure. The Wakulla Vent and Wakulla D-Tunnel Falmouth meters are currently inoperative. Both of these meters should be replaced. The C-Tunnel has been in nearly constant operation since 2003 and all analyses of the data from that meter thus far indicate that the tunnel does not connect to a substantial source of water to Wakulla Spring. Consideration should therefore be given to eliminating the C-Tunnel meter. The AD, K , and AK-Tunnel meters all record information from essentially the same tunnel where the AD meter is located in the largest south-trending conduit in the Wakulla cave system and the K and AK meters are located immediately south of a location where that tunnel splits into two separate tunnels with no side tunnels that re-connect approximately 1500 feet further south. The plots in Figure 1 and Figure 2 indicate that each of these meters is essentially recording the same water as it passes the respective locations. Consideration should therefore be given to eliminating the AD and either the K or AK meters and moving the remaining meter immediately north of the tunnel junction. Removing all the meters described above would eliminate three meters from the network that could be re-deployed at alternative locations and substantially reduce the resources required to maintain the existing data coverage.

The level logger data is providing information that is and will continue to be instrumental to the understanding of groundwater flow patterns in the WKP and the mechanisms driving groundwater / surface water exchange and saltwater intrusion to the upper Floridan aquifer via the conduits feeding the Spring Creek springs.

Consideration should be given to expanding the instrumentation network to include the wells north and northwest of the Wakulla-Leon Sinks Cave System south of L.L. Wallace Road and south of the City of Tallahassee Spray Field respectively. Additionally, the water level meters south of US 98 should be converted to permanent surveyed stations and instrumented with probes that measure both water level and conductivity. These stations will be crucial for measuring and predicting salt water intrusion via the caves trending northward from Spring Creek springs.

TASK-2: DATABASE & DATA PORTAL MAINTENANCE

Objectives

The purpose of this task was to receive all data collected from the field and ensure that it is promptly uploaded to the WKP project database, loaded onto the evolving web Data Portal, and securely backed up to redundant hard-drives for long-term storage. Specific objectives included:

1. Receive, process, upload, and confirm all data transmissions from the field to the database and Web Data Portal being maintained by H2H.
2. Confirm that all data is being regularly and correctly backed up to independent hard drives.
3. Identify and correct any database and backup problems that may arise during the contract period.

Results

Data from all of the field instruments (Falmouth meters, level loggers, and fluorometers) was received approximately monthly throughout the entire contract period. All of the Falmouth meter was data was promptly uploaded to the project database and rendered available for query and download via the Data Portal. All level logger data from the permanent surveyed stations has also uploaded to the database and is available via the Data Portal using queries that use the surveyed top-of-casing elevations to provide both the raw data and calculated water table elevations. The data from the temporary stations has been stored on the project data server but has not been rendered available via the Data Portal. It can however be provided upon request. The fluorometer data has been processed similarly in that it has been stored on the project server and consolidated into single data files but is not available via the Data Portal.

In addition to data uploads and database maintenance, the Data Portal was updated during the 2009 contract period to include a new web interface (Figures 1-4) is that an Adobe Flash graphing utility has been designed to render query results. The interface renders the query results more quickly than the original Gnuplot-based system, has sharper resolution, and features an optional cursor that enables the viewer to mouse-over the plot and dynamically view the reported values at any point within the query range. The Cursor Trace becomes available when the Cursor button is toggled. Additionally, an export feature can be executed by toggling the Export button which gives the user an option to save a snapshot of the flash query results to their local hard drive. The multiple parameters interface previously offered pre-configured comparisons of two parameters at a single meter. This has been upgraded to offer the user a choice of multiple parameters and multiple meters. This new feature can is accessible through: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

Conclusions & Recommendations

The project database and Data Portal remain extremely important to the project objectives. Approximately 1.2 million records were collected by just the water level and Falmouth devices. The database and Data Portal provide the only means of storing, protecting, and providing access to that data. It does not appear, however, that the Data Portal is very widely used. Consideration should therefore be given to the following recommendations.

- Meta Data establishing the source and Q/C records for all data streams should be included in the Data Portal interface.
- A maps feature should be added so that users can see the location of all the meter stations.
- The data download feature should be revised such that all data streams are consolidated into one file with a single consistent date field and such that the original velocity data is included with all flow exports.
- The Data Portal interface should be revised to reflect the current status and objectives of the project, to include all the project description material currently available via the root project website, and to reflect the future goals of establishing a Wakulla Springs Observatory. This should become the new home page for the project.

- Develop an interface to allow authorized users to upload data directly to the database.
- The Data Portal should be ported to the Hydrogeology Consortium website.

TASK-3: HIGH WATER TURNER SINK TRACE

Objectives

The purpose of this task was to constrain the extent to which the Wakulla and Spring Creek springsheds share water from the Leon Sinks Cave System through the use of groundwater tracing. Results of the 2007 Turner Sink trace demonstrated that, under low water level conditions, all or the vast majority of flow through the Leon Sinks cave system flows south and east to the Wakulla cave system and then north to Wakulla Spring. Observations of strong southward flow conditions in the southern part of the Wakulla cave system by the WKPP divers indicate that flow in the southern part of Wakulla cave (near the connecting tunnel to the Leon sinks cave system) can, at times, be directed south toward Spring Creek. Initially, the main objective of this task was to determine if flow from the Leon Sinks cave system is directed toward Spring Creek under high water conditions.

At the time these task objectives were defined, a tracer test initiated from the Lost Creek swallet was underway. The initial expectation was that flow from that swallet would be directly to Spring Creek. Results from that trace however revealed a significantly more complex flow pattern. Flow from Lost Creek initially traveled very rapidly to Spring Creek as expected but as the water levels declined and Lost Creek stopped flowing, groundwater flow to Spring Creek stopped, the springs reversed and groundwater from the southern part of the WKP, including the water that contained our tracer that had not completed the journey to Spring Creek, also reversed and flowed to Wakulla Spring. This pattern was recorded by the tracer detections wherein the tracer was first detected at Spring Creek, then after a long lag period, it was also detected at Revel sink and then at Wakulla Spring. These results were described in detail in the 2008 task report for Contract GW272 by H2H Associates for the FGS.

The results of the 2008 trace were exciting as they documented a significant regional reversal in groundwater flow directions associated with a cessation and reversal of flow at the Spring Creek Vents that was first documented over a prolong duration in the summer of 2006 and has occurred for several weeks in each summer since then. The significance of that trace is that it revealed probable rapid and pervasive saltwater intrusion to the upper Floridan aquifer that migrates inland along the conduits that normally convey groundwater to the Spring Creek spring vents. Because of the profound implications associated with the results of the 2008 Lost Creek trace, the objectives for the 2009 trace were changed.

The new objective was to repeat the Lost Creek trace, ideally under the same or similar hydraulic conditions as were active in 2008, which were very dry with minimal to no flow to the region’s swallets. The purpose of the redefined tracer test was to confirm the flow reversal and identify the hydraulic conditions responsible for triggering it through the expansion of the instrumentation network that was scheduled for 2009 (described in the Task-1 section of this report).

Setup

Prolonged wet conditions associated with a longer than normal rainy season in the spring of 2009 delayed an initiation of the trace. The reasoning behind the delay was that under wet conditions, when the swallets are receiving large amounts of water, the Spring Creek spring vents all discharge strongly which would likely preclude a flow reversal and therefore detection of a tracer injected at Lost Creek at Wakulla Spring. It was therefore decided to delay the tracer injection until dry conditions returned to the WKP. The target timeframe was the tail end of what would likely be the last storm of the wet season before entering the summer dry period. Injecting too early would likely result in all of the tracer traveling rapidly to Spring Creek prior to a reversal. Injecting too late would likely result in the tracer not traveling to Spring Creek at all but rather northward to Wakulla Spring. Additionally, in order to foster the best results, the ideal injection time would be immediately following a storm event such that there would be a sufficient amount of water entering the Lost creek swallet to convey the tracer into the conduits within the aquifer.

As the middle of summer 2009 approached, swallet water levels finally began to subside and the Spring Creek spring vents began to sporadically reverse. A small storm in middle July was targeted as the ideal injection time. The injection occurred on July 14, 2009 in which four (4) pales (~20 kg) of uranine dye (AY73) were injected into the Lost Creek swallet via peristaltic pump and tubing set to a depth of approximately 90 feet below the water surface. Figures 10-13 compare flow in the relevant rivers and springs and salinity measured in Spring Creek during the 2008 and 2009 tracer injections. The plots show that conditions were similar in that water levels were falling after the wet season but Spring Creek was reversing more strongly during the 2009 injection and had been doing so for a longer period prior to that injection.

Eleven primary sampling stations were established from which regular water samples were collected for tracer analysis by either automatic water sampling at 8-12 hour intervals, insitu filter fluorometers set to measure fluorescence at 15-minute intervals, or grab sampling at weekly or biweekly intervals. Sampling at these locations was conducted from approximately two (2) weeks prior to the injection through approximately the first week of October or approximately fifteen (15) weeks. In addition, four remote springs near Panacea were sampled once during the period that the tracer was being detected at the Spring Creek Vents. Table 3 descries the sampling stations and shows the number of samples collected and the number of positive detections.

Table 3. Tracer test sampling station information and record of detections.

Station	Sampling Type	# Samples	# Positives	First Detection	Last Detection	1st Detection Days after Injection
Spring Creek #1	AS, FLUOR	200	94	8/21/09	10/7/09	37
Spring Creek #2	AS, FLUOR	169	71	8/29/09	10/3/09	45
Spring Creek #10	AS, FLUOR	204	91	8/22/09	10/8/09	38
Wakulla Dock	AS	169	0	NA	NA	NA
Wakulla K-Tunnel	AS, FLUOR	186	0	NA	NA	NA
Revel Sink	AS, FLUOR	183	96	8/6/09	9/25/09	22
Shepherd Spring	AS	154	0	NA	NA	NA
Spring Creek #3	GRAB	26	26	8/27/09	10/8/09	44
Spring Creek #8	GRAB	4	NR	NA	NA	NA
Spring Creek #11	GRAB	4	NR	NA	NA	NA
Punch Bowl Sink	GRAB	55	23	8/14/09	9/25/09	30
Skipper-1	GRAB	1	0	NA	NA	NA
Skipper-2	GRAB	1	0	NA	NA	NA
Panacea-1	GRAB	1	0	NA	NA	NA
Panacea-2	GRAB	1	0	NA	NA	NA

Notes: AS – autosampler
FLUOR – fluorometer
GRAB – hand sampled
NR – not reported
NA – not applicable

Results

Table 3 summarizes the results of the tracer test. The tracer was detected first at Revel Sink 22 days after the injection, then at Punch Bowl Sink 30 days after the injection, and finally at the sampled Spring Creek spring vents approximately 40 days after the injection. Figure 14 provides a comparison of the breakthrough curves measured at each of the sampling stations where the tracer was detected. Figures 15-18 provide plots of fluorescence measured by the insitu fluorometers relative to the spectrometer results at each of the fluorometer stations where the tracer was detected. Figure 19 is a map showing the tracer pathways as they were measured by both the 2009 and the 2008 Lost Creek tracer tests.

Conclusions & Recommendations

The results of the 2008 and 2009 Lost Creek tracer tests very clearly show that the hydraulic gradient to Spring Creek reverses during summer dry periods allowing water from as far south as Lost Creek to flow northward to Wakulla Spring. Though the stage data demonstrates that even at the highest tide levels, the stage at Spring Creek is less than that at Wakulla, these two tracer tests demonstrate that the Spring Creek flow reversals are capable of driving salt water into the upper Floridan aquifer through the conduits that normally convey freshwater to Spring Creek springs. This intrusion is likely to extend as far north as US 98 and perhaps further, where the degree of intrusion is determined by the magnitude and duration of flow reversals at Spring Creek. It is likely that these reversals are being driven by depressed inland groundwater levels that have been occurring for significant periods since at least 2006. Continued drought conditions and any increases to groundwater withdrawals in the northern part of the Wakulla-Spring Creek springsheds will likely exacerbate these conditions.

In light of these results water level, flow, and salinity monitoring at Spring Creek should be continued as should water level monitoring at Lost Creek. In addition, permanent water level and salinity monitoring stations should be established at Punch Bowl and other select sinkholes and wells in the vicinity of US 98 so that the magnitude and duration of saltwater intrusion can be recorded and ultimately predicted.

Task-4: Groundwater Modeling

Objectives

The purpose of this task was two-fold: first, to develop a set of model calibration criteria or "benchmark tests" by which the evolving steady-state numerical model and statistical KARSTMOD groundwater flow models can be effectively and objectively evaluated in terms of their predictive reliability; and second, to expand both models such that they can be evaluated with those criteria or tests and such that the numerical model addresses, in principle, the concerns expressed by the NWFWMD. The calibration criteria and benchmark tests were to be developed through a statistical and hydraulic analysis of the water level, flow, and precipitation data that have been collected and/or compiled by our project over the past 5-6 years. Specific objectives included:

1. Develop appropriate benchmark tests for the evaluation of steady-state and transient groundwater models of the WKP through the statistical analysis of precipitation, discharge, and water level data previously collected.
2. Expand the steady-state numerical model to 3D as per the recommendations of the NWFWMD.
3. Develop a calibration dataset that can be used in conjunction with the benchmark test for the evaluation of steady-state numerical models of the WKP.
4. Evaluate transient data and identify what will be needed to construct an adequate calibration dataset for transient numerical models of the WKP and relate that to the benchmark test(s) developed in (1).

As the project evolved, it was decided to redirect the effort planned for the steady-state component of the modeling effort to the instrumentation and tracing tests. This allowed additional stations to be instrumented with water level meters in the southern part of the WKP and for tracer testing to be continued longer than that the 30 days that was originally planned. The KARSTMOD component of this task was however carried out as planned.

Results

Results of the modeling task were summarized in a report prepared by Dr. Loper, the principal investigator for the KARSTMOD project. His report is provided as Appendix II.

Task-5: Spring Creek Radon/Methane Groundwater Tracing

Objectives

The Spring Creek coastal region represents the southern boundary of the WKP. Characterizing its discharge and interaction with Wakulla Spring further north is essential to the development of a predictive model for the entire watershed and to calculating the WKP's water budget. Radon and methane were used last year as ground water markers to estimate contribution from coastal aquifers to saline surface waters. In order to maximize the utility of last year's findings; the following modifications will be made to the monitoring protocols: (1) a more realistic assessment of the cross-sectional area; (2) an improved representation of the geometry of the water body between the source and measurement platform; and (3) extended measurement periods to assess lunar and seasonal cycles. Our current calculations assume that the cross-section is a simple rectangle with a fixed width and variable water depth. Similarly, the current geometric depiction of the water body between the point of measurement and the source is a simple box (fixed length, variable water depth). Extended measurements would help understand this system in two important ways. First, it would allow us to examine the tidal influence over the spring-neap lunar cycle as well as the daily tidal cycle. And second, it would allow us to examine the change in flow as the spring (presumably) transitions back to "normal" (low salinity – high radon) conditions. Measurements at different times of the year would, of course, also provide useful seasonal information. We plan on conducting the following steps:

1. Quarterly surveys at Spring Creek to document the distribution of radon, methane, and salinity under different seasonal conditions. Results will be provided in graphical format with an interpretation.
2. One long deployment (at least 2-weeks) of our continuous radon monitoring equipment together with automatic logging of temperature, conductivity, and water depth. Results will again be provided in graphical format with an interpretation. The results will include discharge estimates based on a radon mass balance.

A single-test deployment of manganese “Mn fibers” for collection of radium isotopes as a possible additional tracer of groundwater discharge. These fibers would be deployed as passive collectors on buoys along transect from the source vents out towards the Gulf of Mexico for approximately 24 hours. After retrieval, samples will be processed to obtain radium isotope ratios. We would present these data in a tabular format together with an interpretation.

Results

Results of the radon tracing task were summarized in a report prepared by Dr. Burnet, the principal investigator for the radon project. His report is provided as Appendix III.

FIGURES

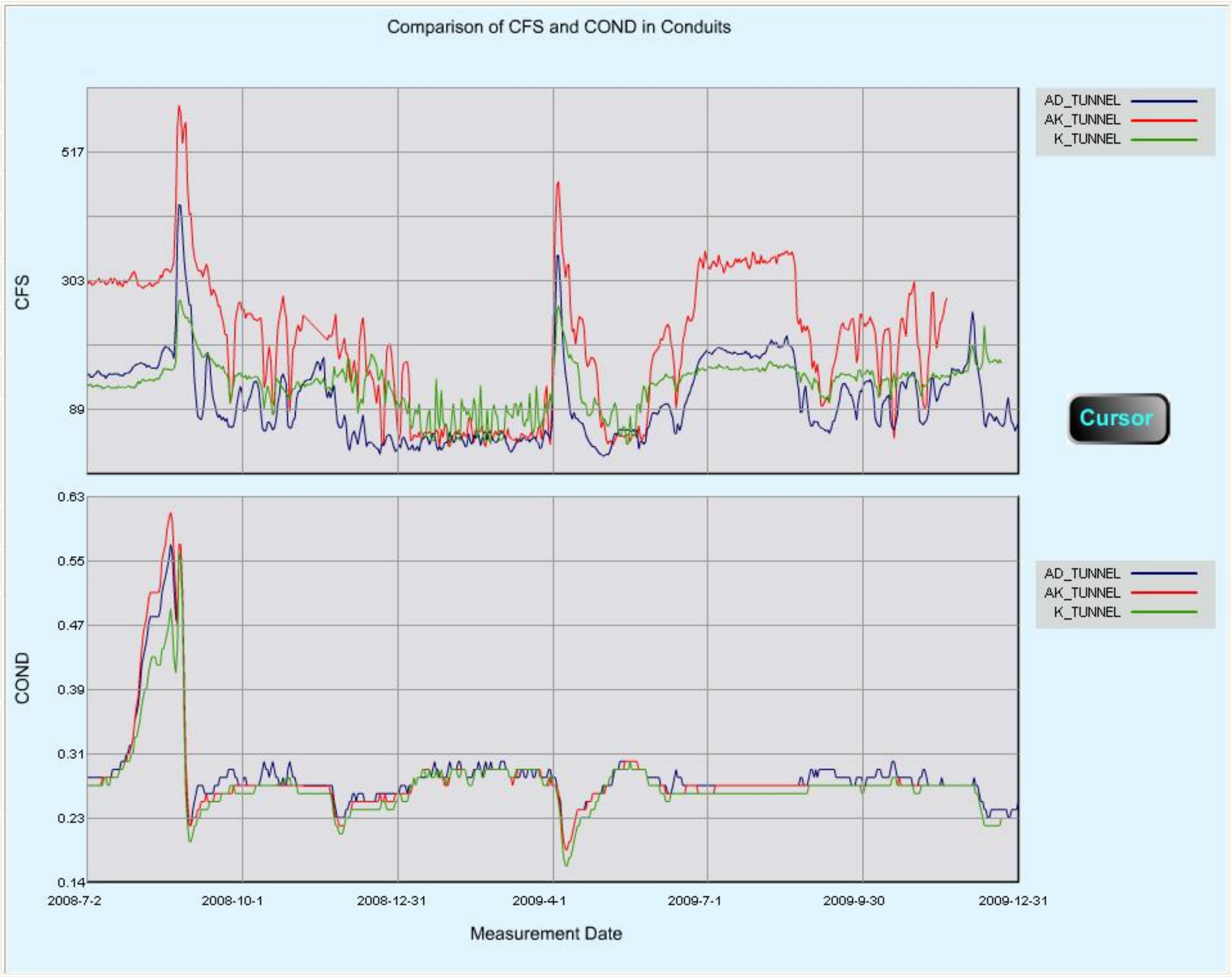


Figure 1. Plots exported from the Data Portal showing flows (top) and conductivity (bottom) measured at the AD, AK, and K-Tunnel stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

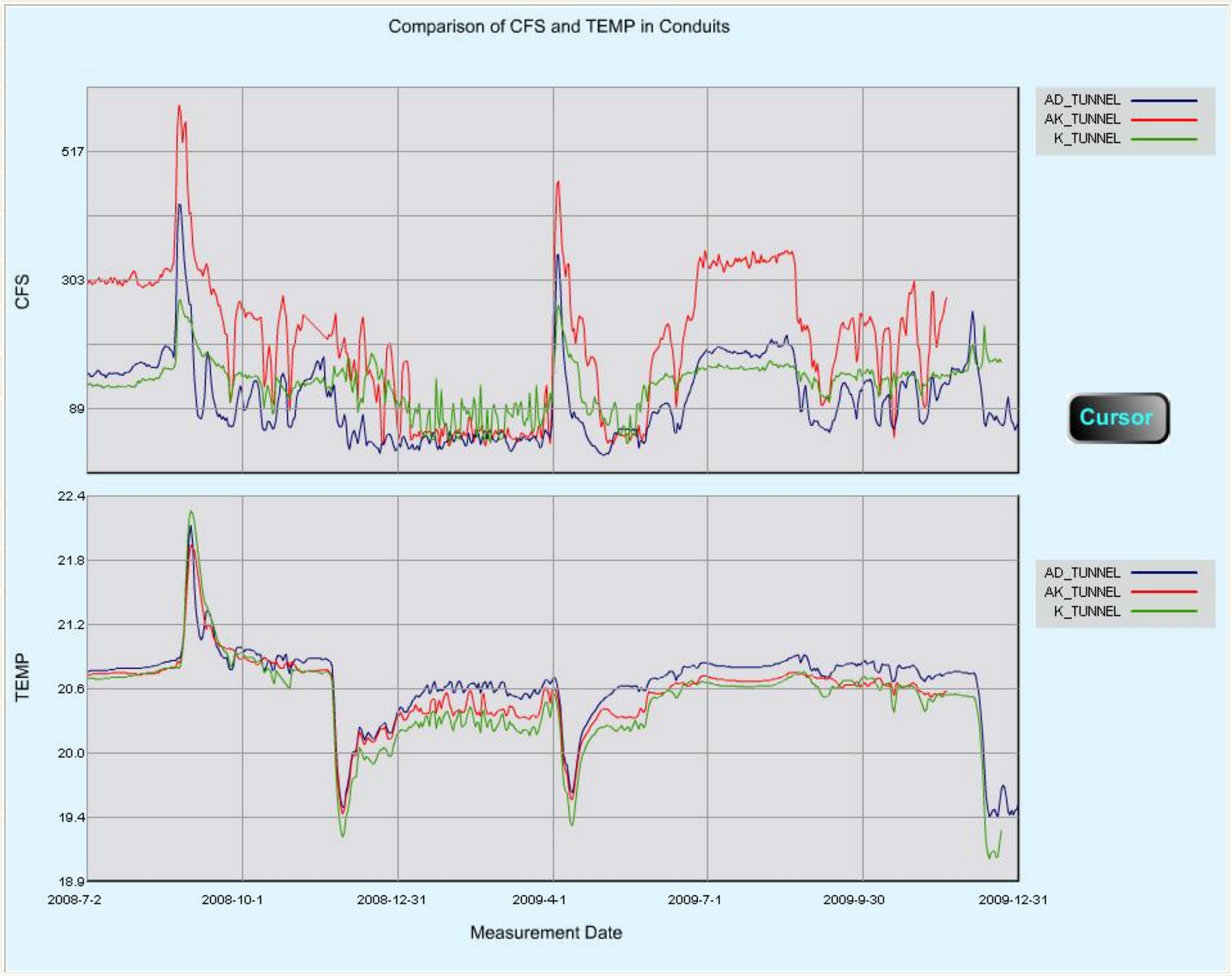


Figure 2. Plots exported from the Data Portal showing flows (top) and temperature (bottom) measured at the AD, AK, and K-Tunnel stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

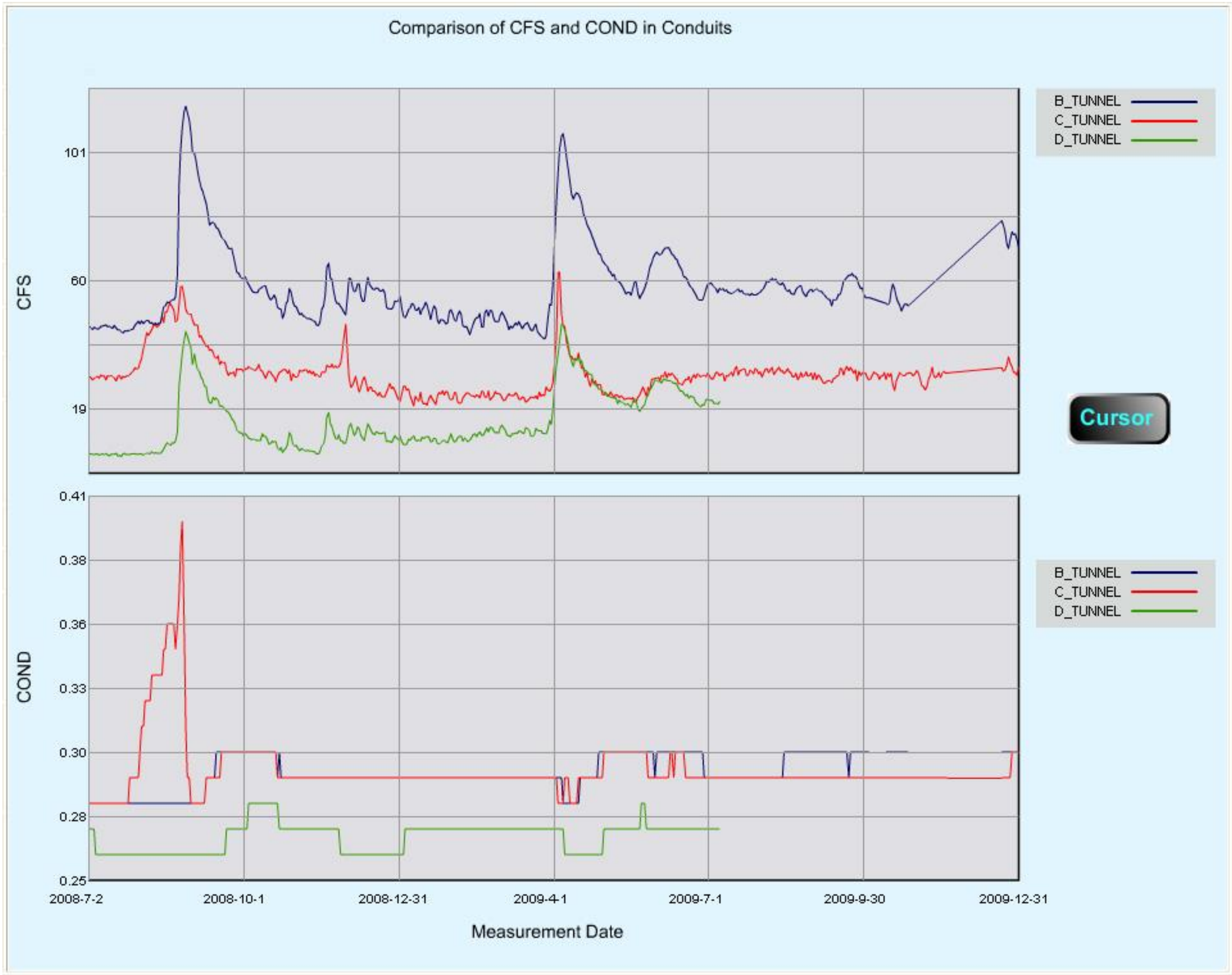


Figure 3. Plots exported from the Data Portal showing flows (top) and conductivity (bottom) measured at the B, C, and D-Tunnel stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

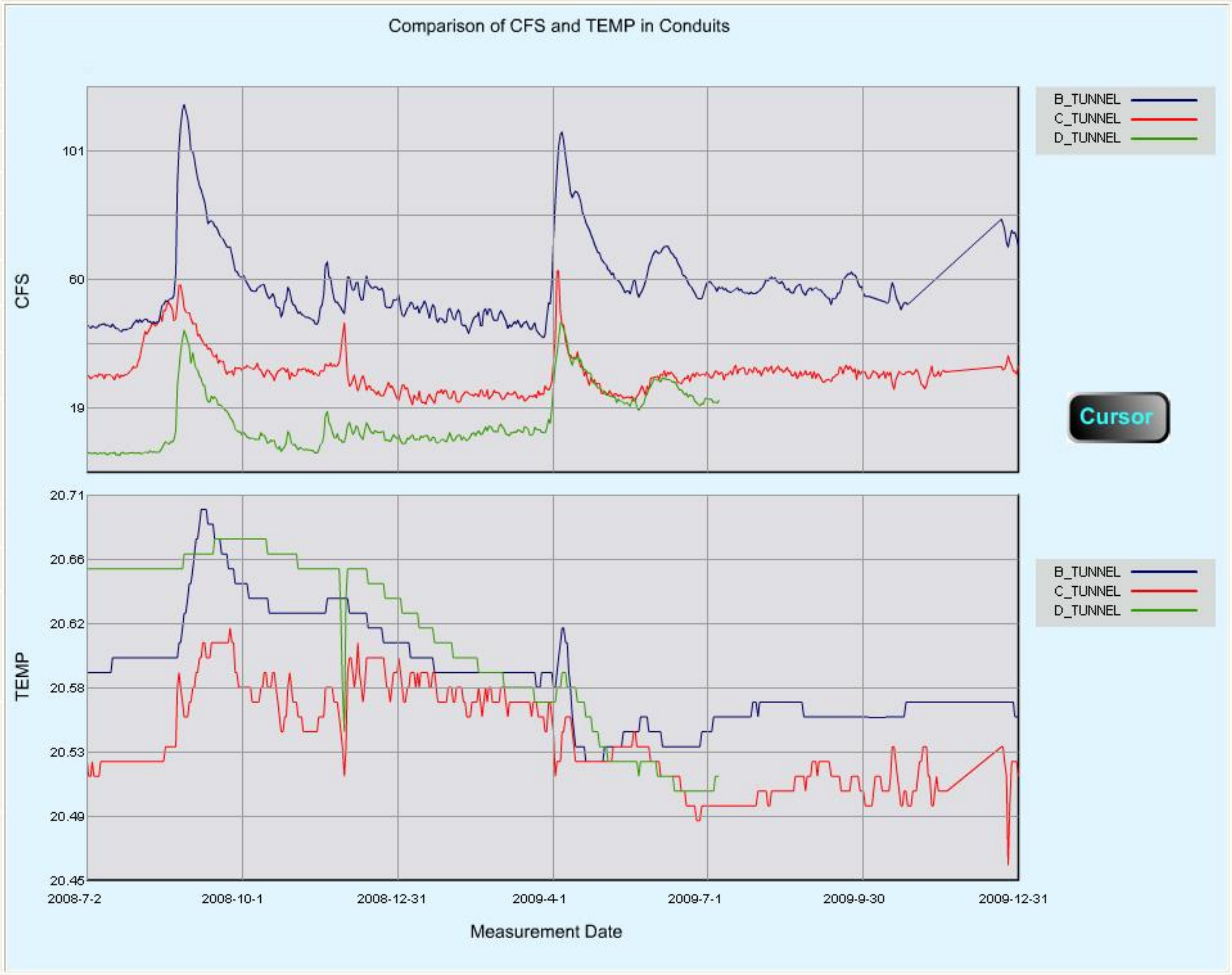


Figure 4. Plots exported from the Data Portal showing flows (top) and temperature (bottom) measured at the B, C, and D-Tunnel stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

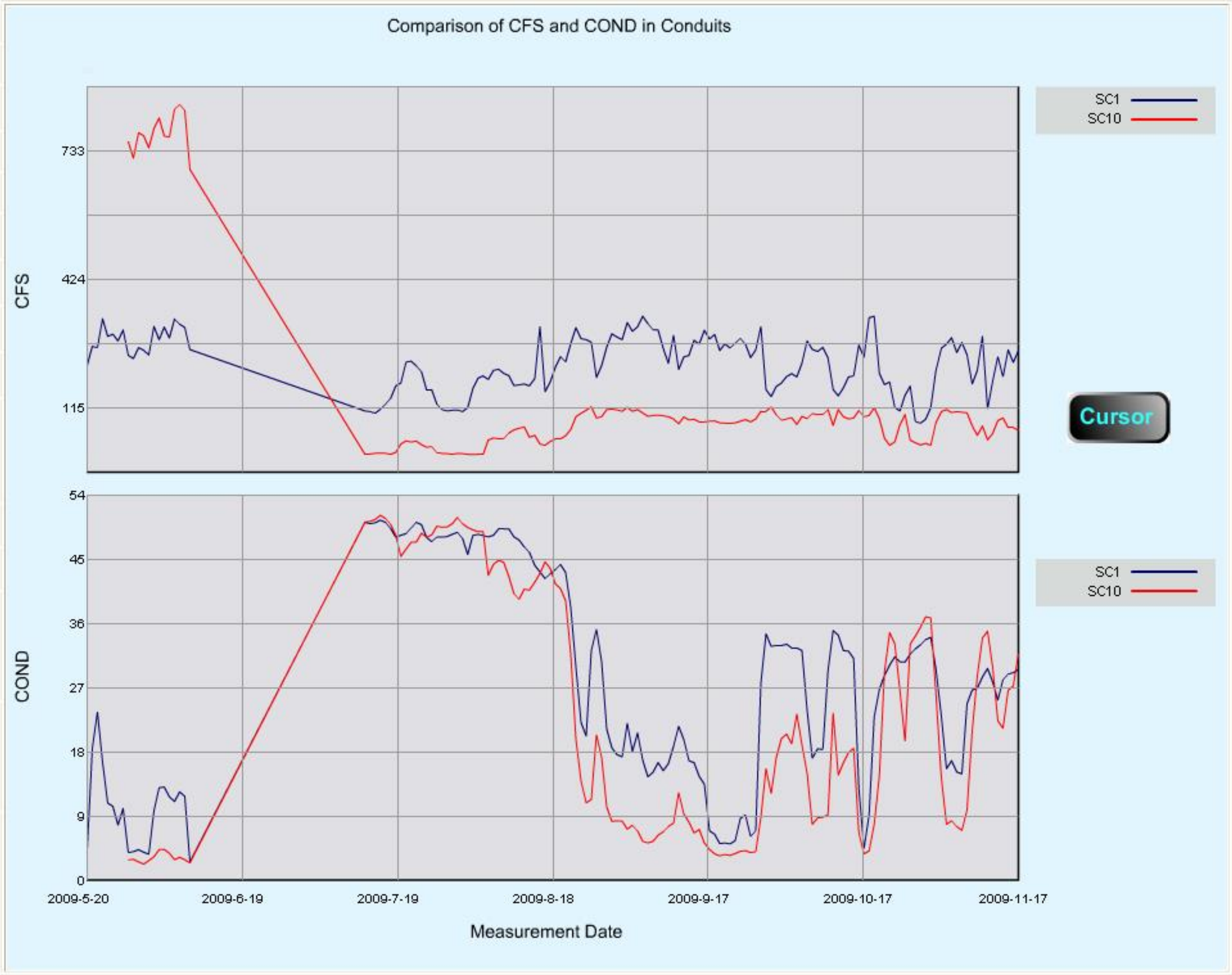


Figure 5. Plots exported from the Data Portal showing flows (top) and conductivity (bottom) measured at the SC-1 and SC-10 stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

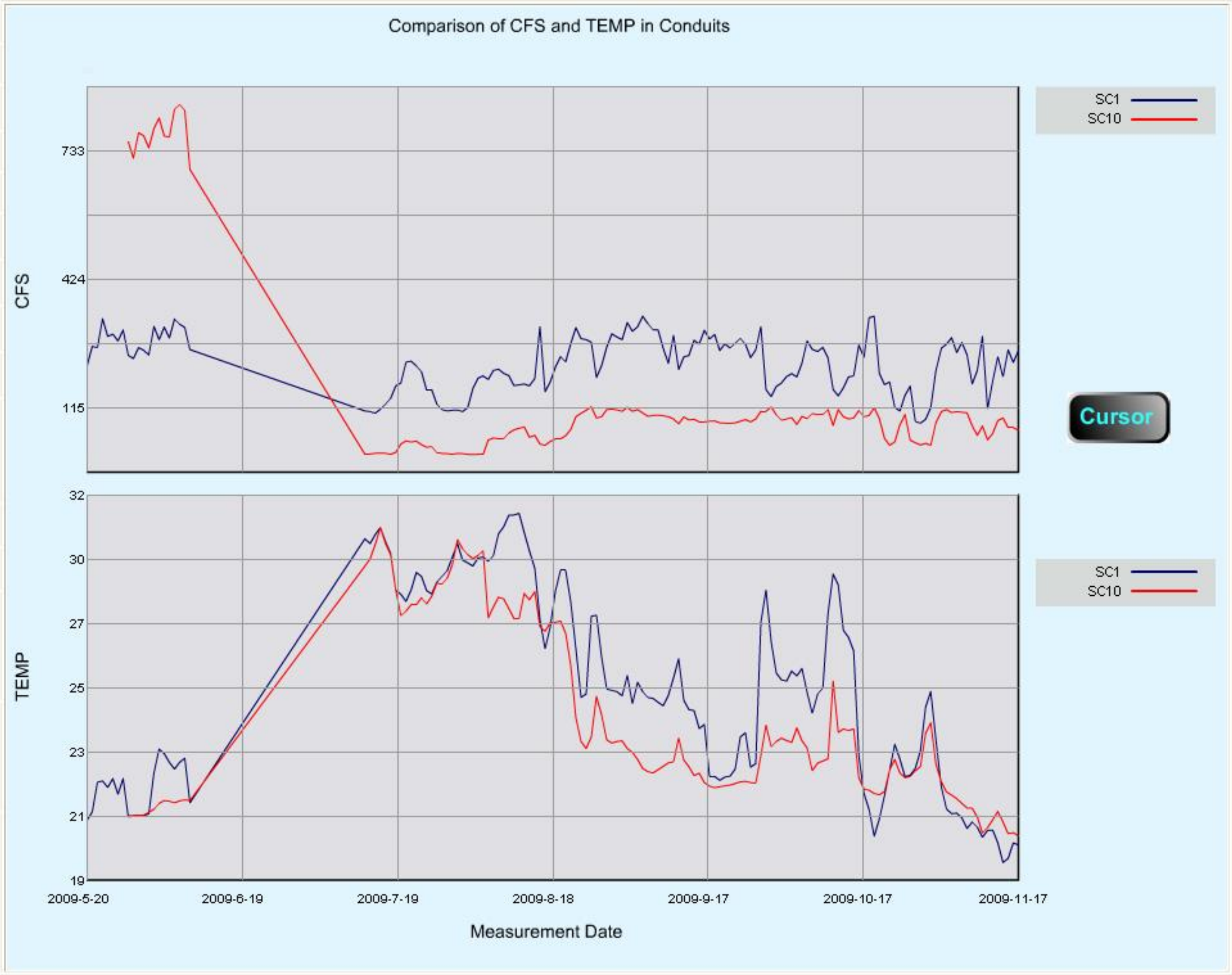
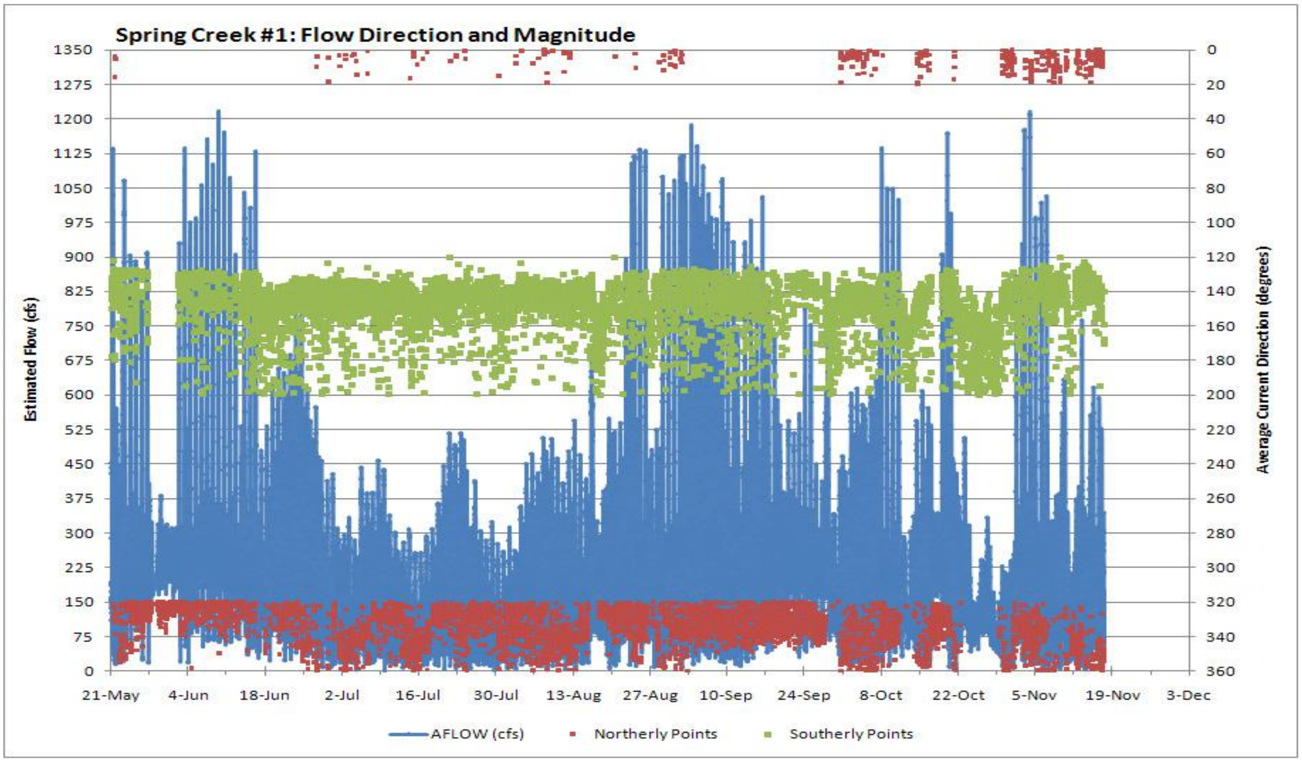


Figure 6. Plots exported from the Data Portal showing flows (top) and temperature (bottom) measured at the SC-1 and SC-10 stations. The Data Portal interface is provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.



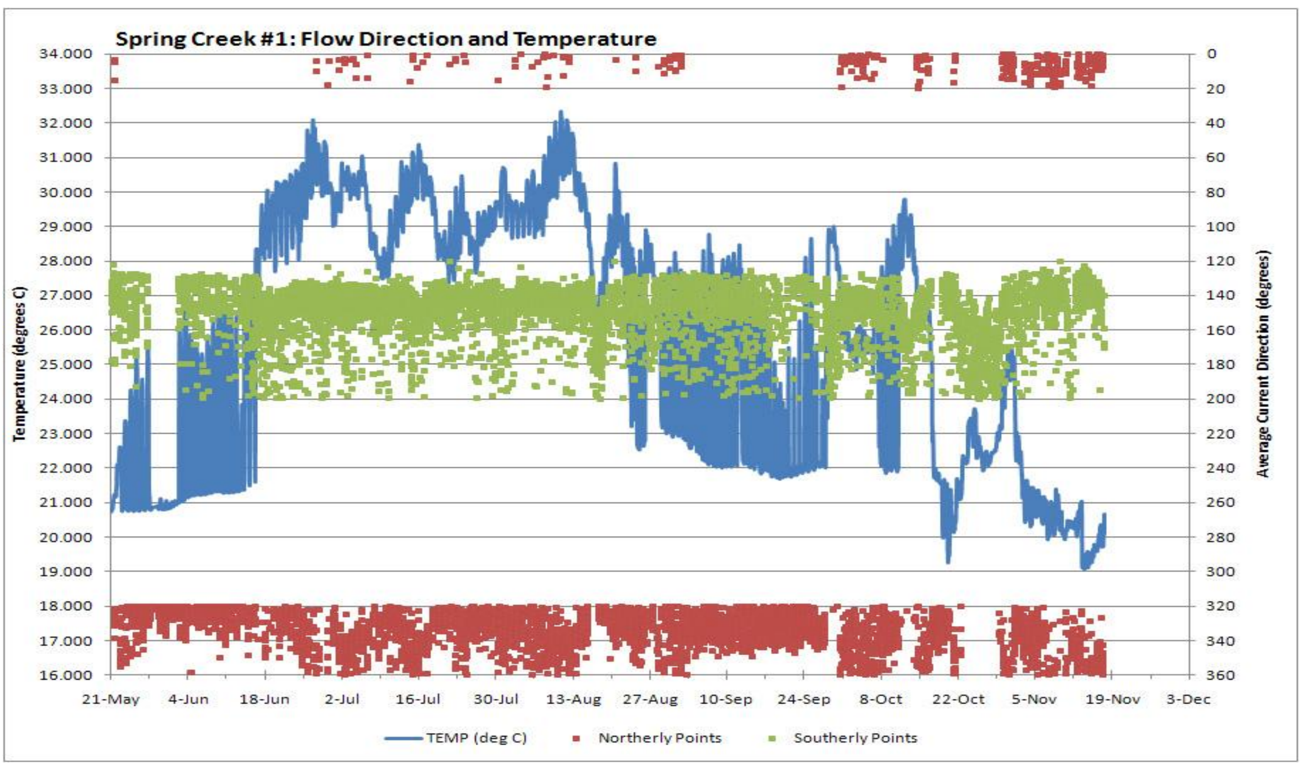
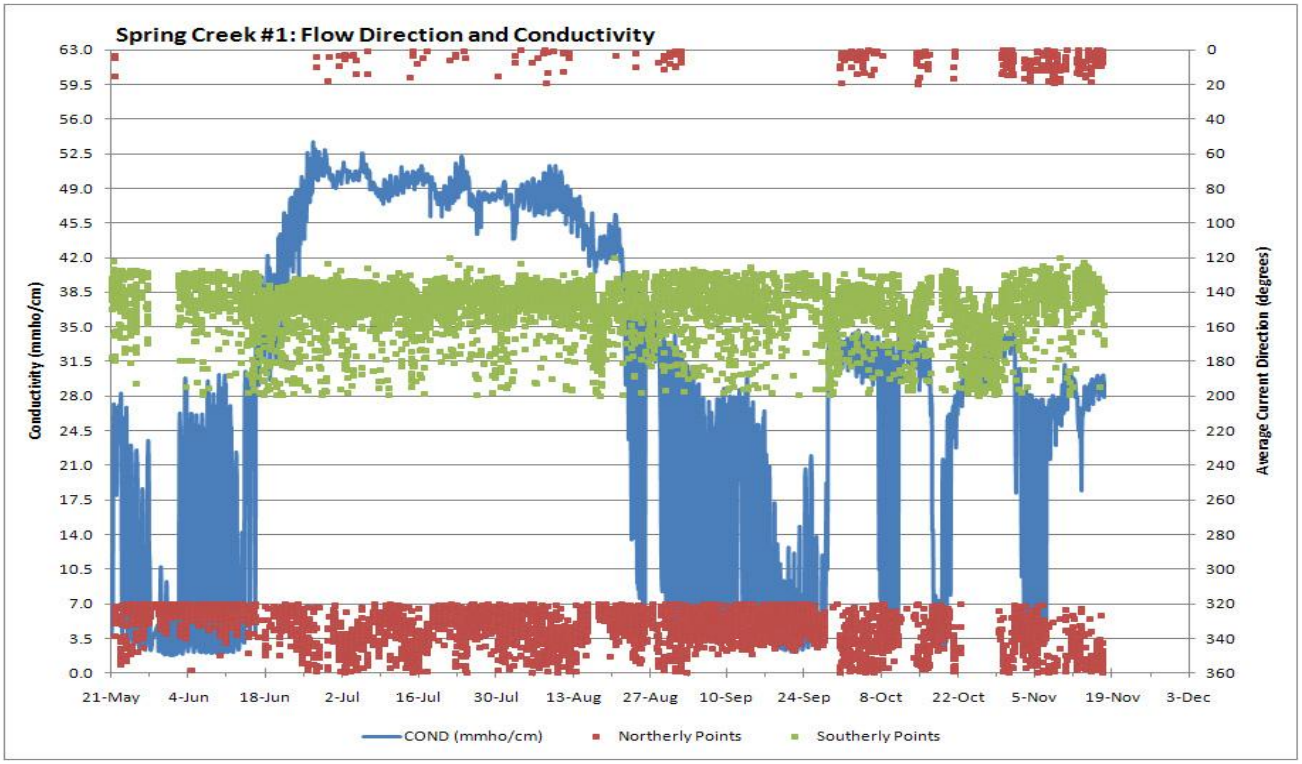


Figure 7. Plots showing flow magnitude and direction (top) and flow direction and temperature (bottom) at the SC-1 station from the date of installation in May 2009 to the last data download, which occurred in mid November 2009. The green points mark periods of southward flow indicating that the spring vent was discharging. The red points mark periods of northward flow indicating the spring vent was siphoning. These data were obtained from the Data Portal provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.



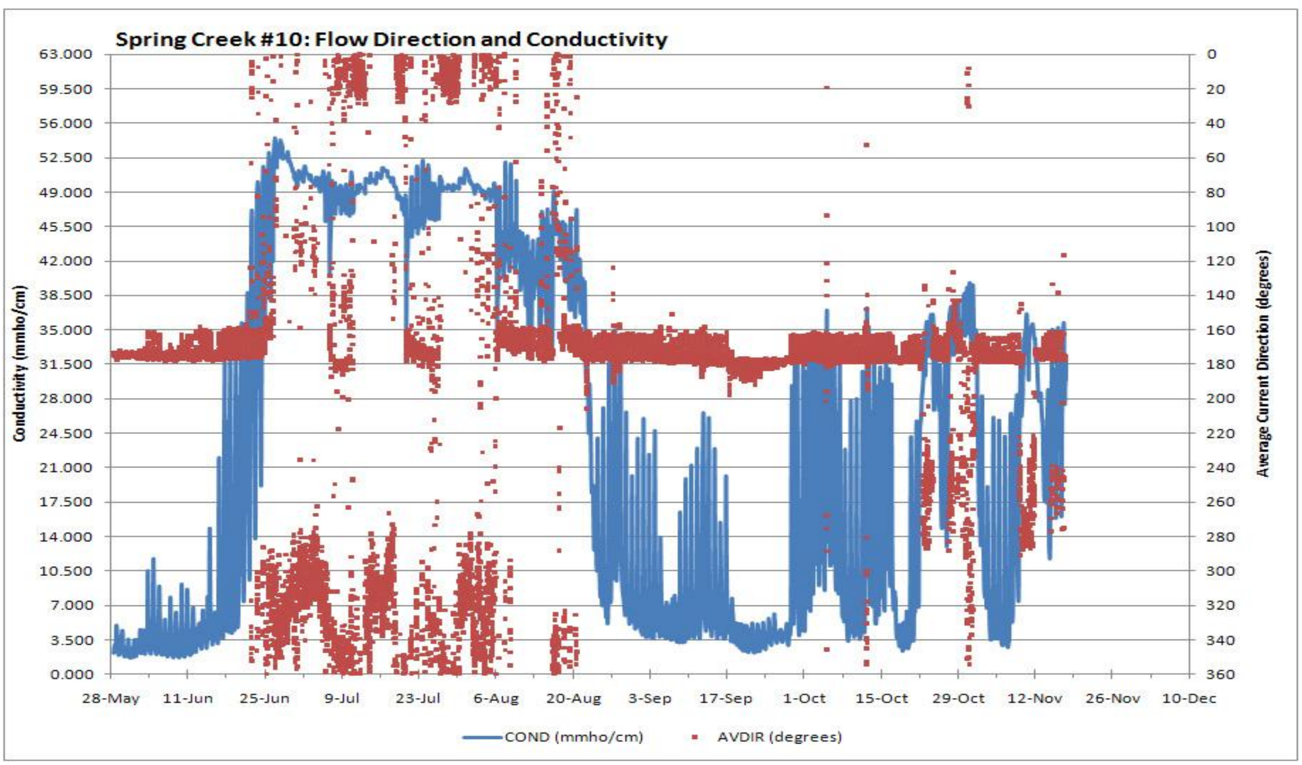
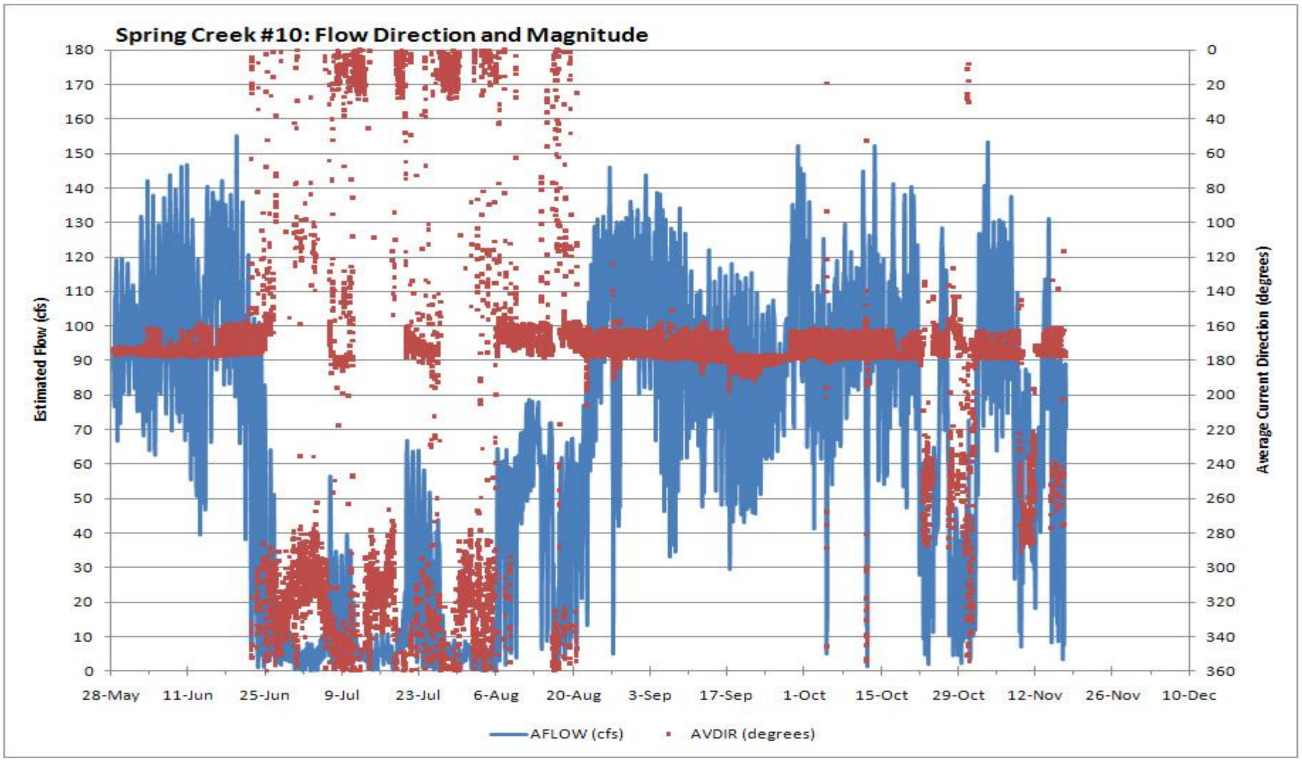


Figure 8. Plots showing flow direction and conductivity at SC-1 (top) and flow direction and conductivity at SC-10 (bottom) from the date of installation in May 2009 to the last data download, which occurred in mid November 2009. The flow direction data mark periods of both discharge and siphoning at both springs. The reversals at SC-1 appear to be strongly tidal as they occur when conductivity is high and when it is low. At SC-10, the reversals appear to be primarily related to changes in groundwater flow directions. These data were obtained from the Data Portal provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.



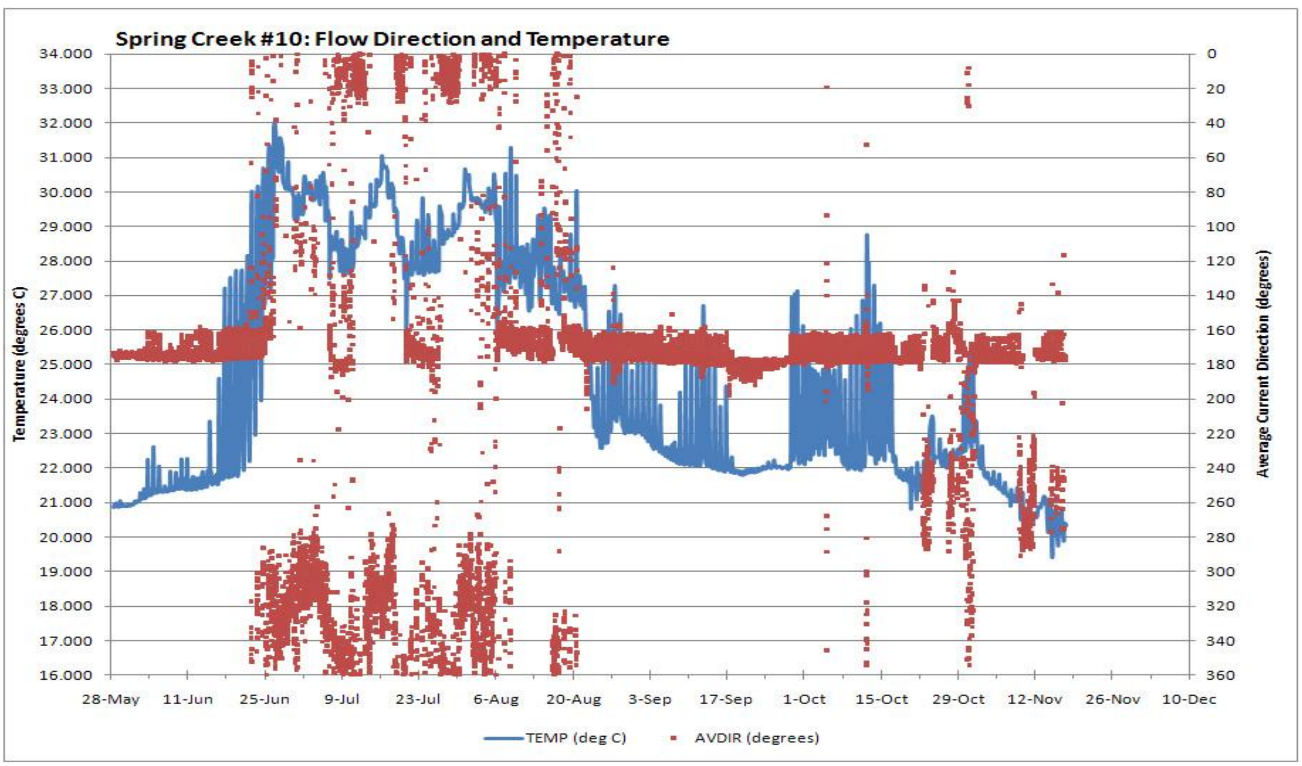


Figure 9. Plots showing flow magnitude and direction (top) and flow direction and temperature (bottom) at SC-10 from the date of installation in May 2009 to the last data download, which occurred in mid November 2009. The flow direction data mark periods of both discharge and siphoning where the reversals appear to be primarily related to changes in groundwater flow directions. These data were obtained from the Data Portal provided at: http://www.h2hmodeling.com/FGS/Meters/Query/flash/conduits_mp_flash.php.

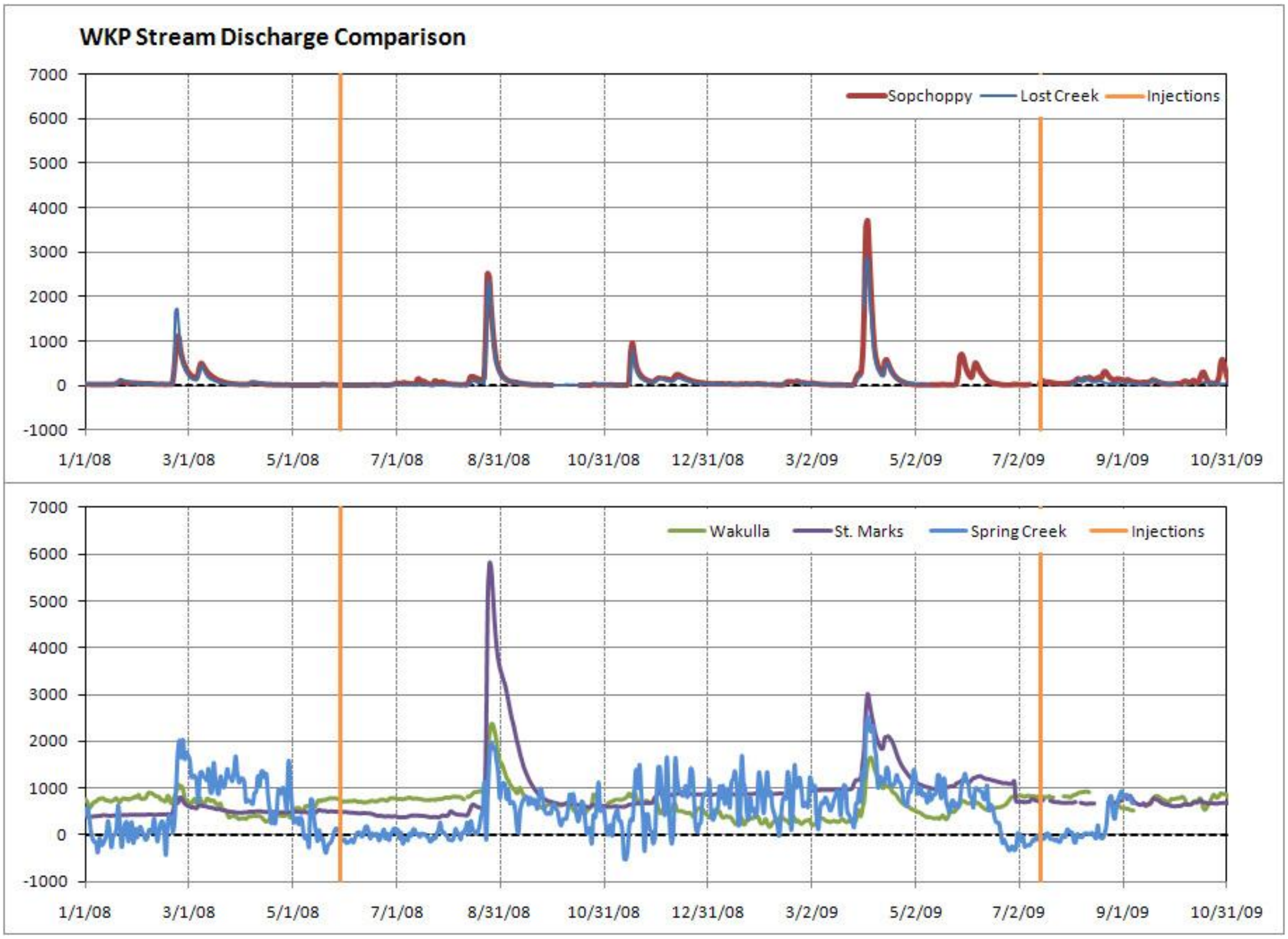


Figure 10. Comparison of discharge measured in Lost Creek, the Wakulla River, and Spring Creek in 2008 and 2009 showing that conditions were similar during both the 2008 and 2009 injections. Note that discharge in the Sopchoppy River is shown to provide a proxy for Lost Creek when that station was not operating and that discharge in the St. Marks River is plotted to show how the Wakulla River discharge rises above the St. Marks only during the summer dry periods when Spring Creek discharge is low or negative.

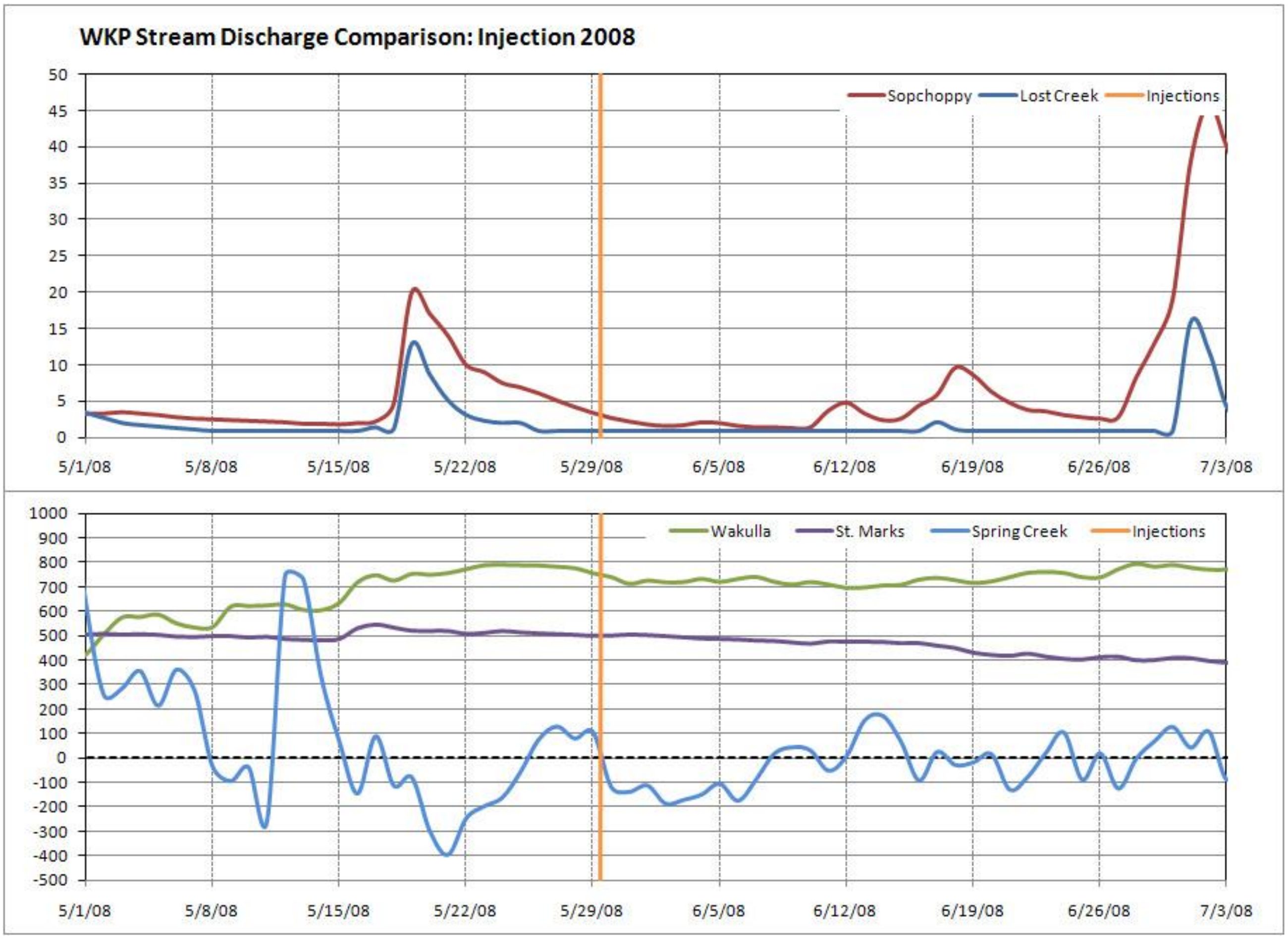


Figure 11. Closer comparison of discharge measured in Lost Creek, the Wakulla River, and Spring Creek in 2008. Note that Spring Creek oscillated between discharge and reversing conditions following the injection.

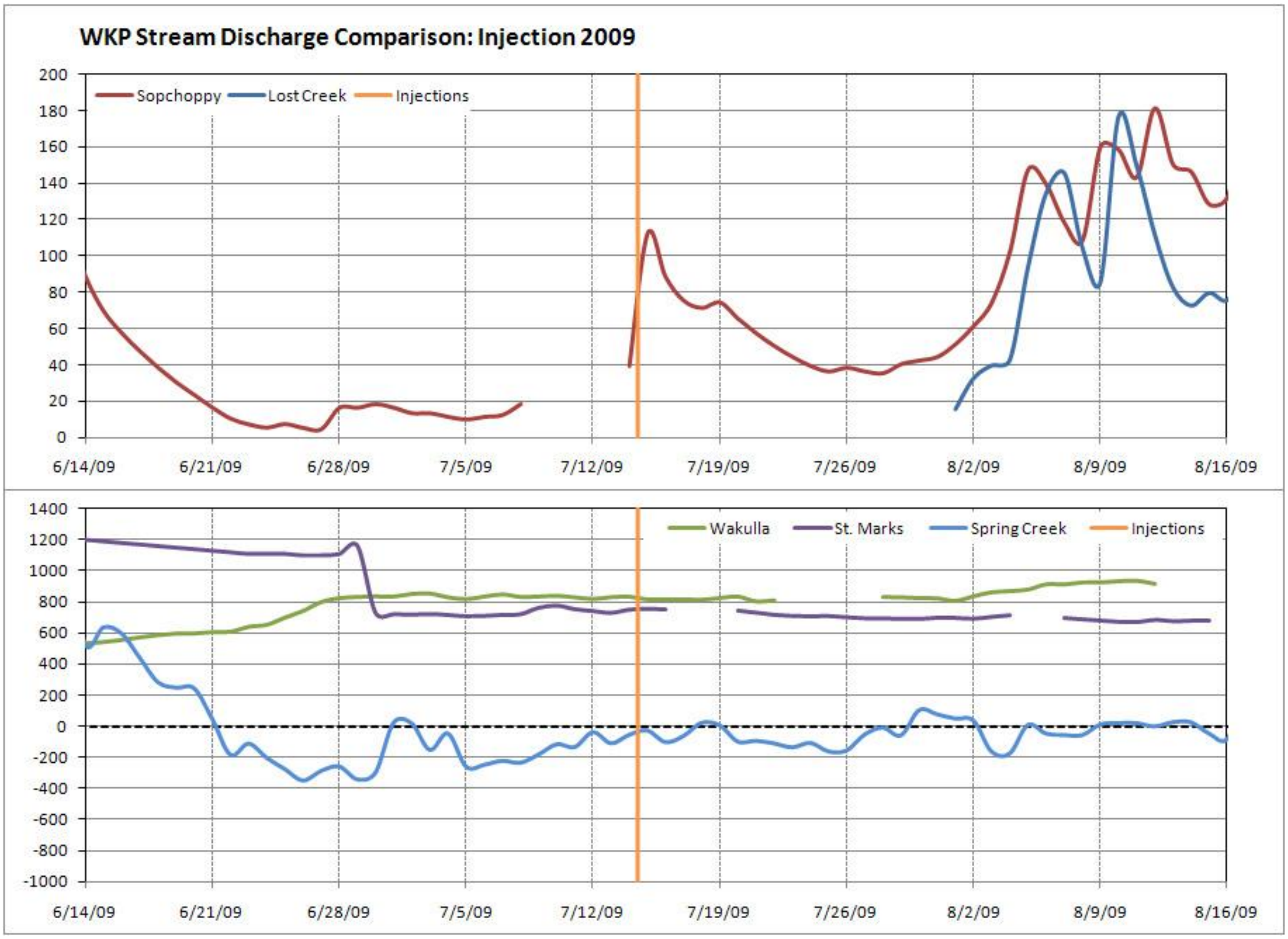


Figure 12. Closer comparison of discharge measured in Lost Creek, the Wakulla River, and Spring Creek in 2009. Note that Spring Creek was primarily reversing both before and after the injection.

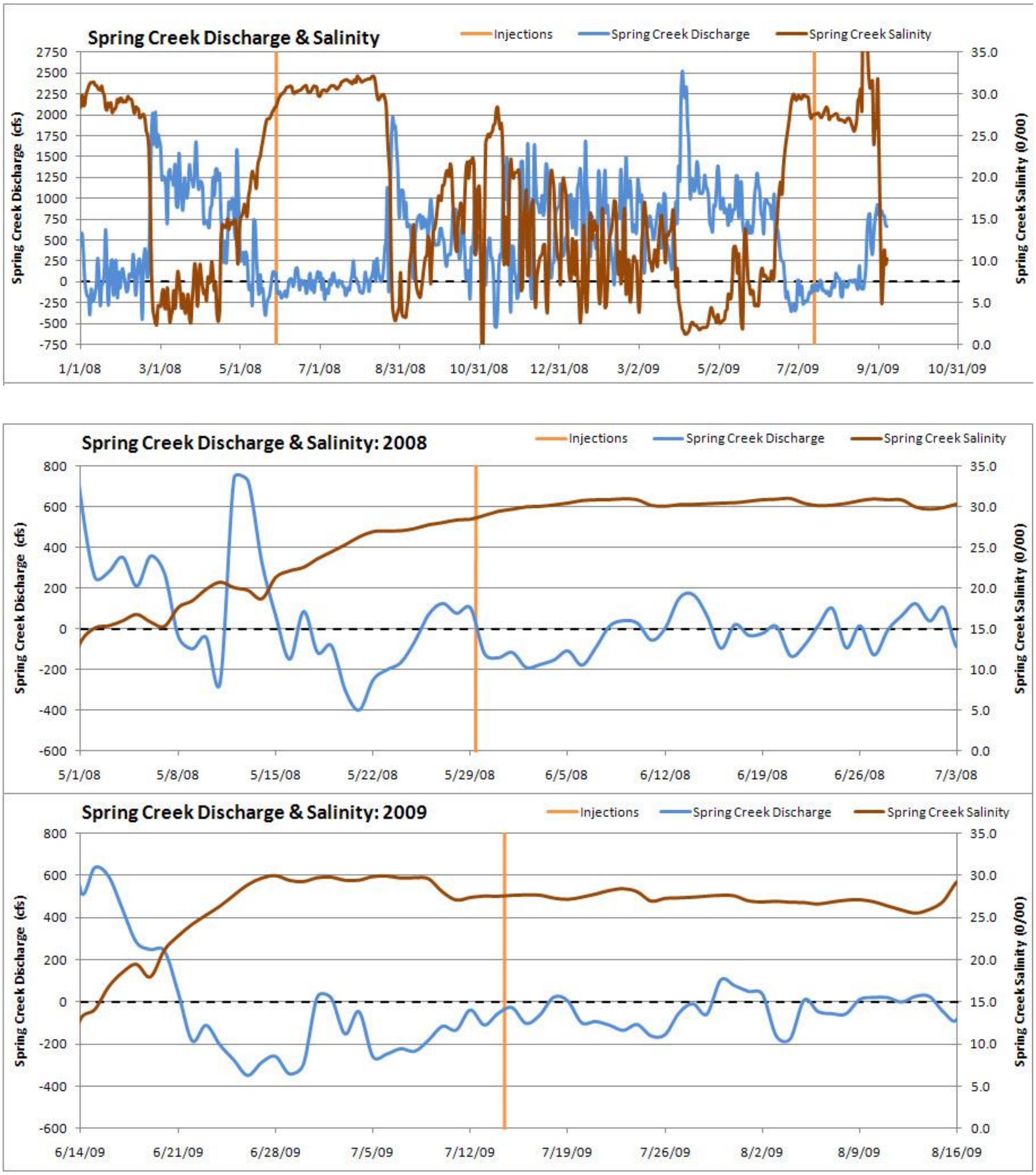


Figure 13. (Top) Comparison of discharge and salinity measured by the USGS in Spring Creek in 2008 and 2009 showing the timing of the respective injections and that Spring Creek was more strongly reversing during the 2009 the injection. (Bottom) Closer comparison of discharge and salinity in Spring Creek during the 2008 and 2009 injections.

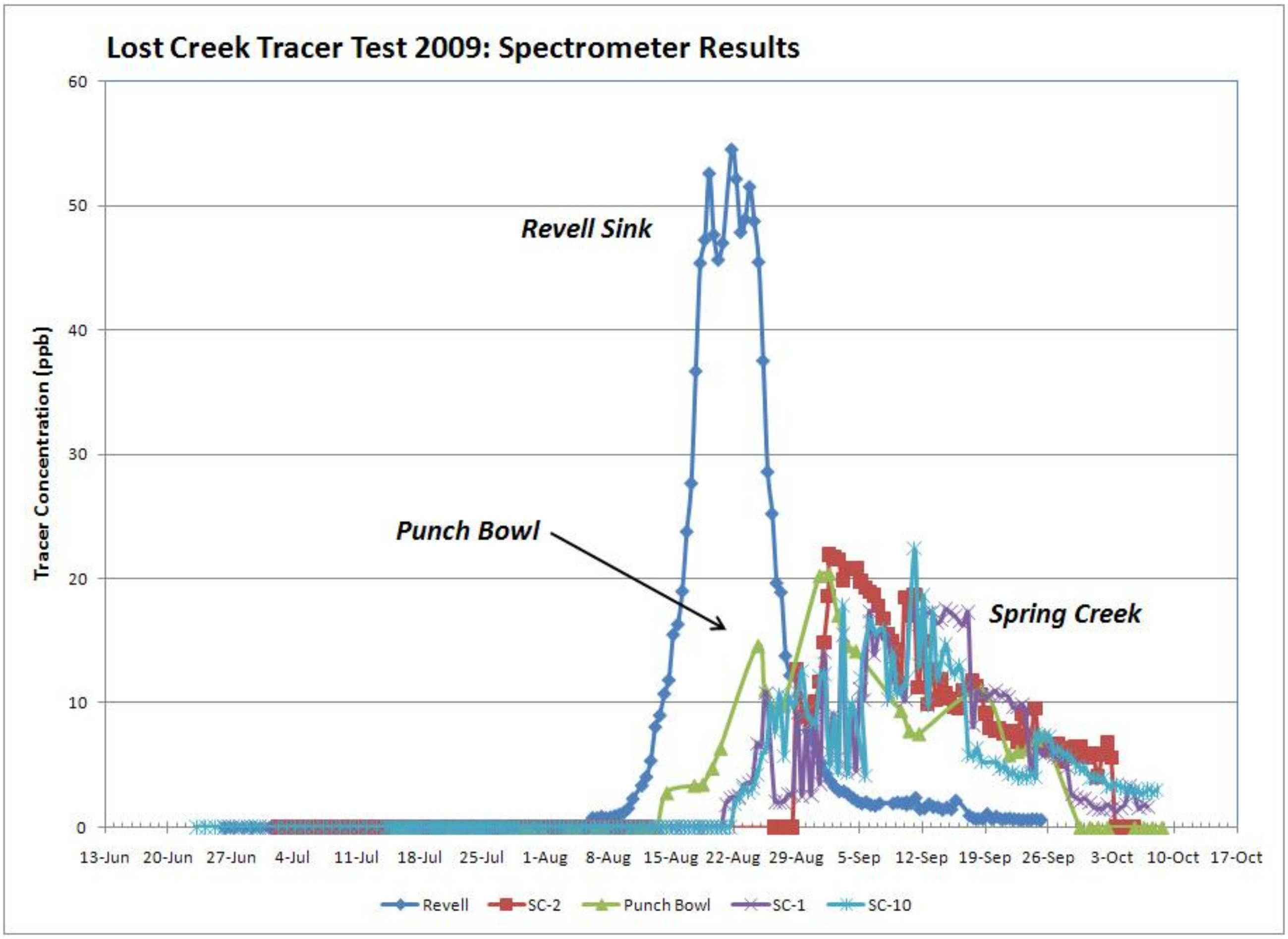


Figure 14. Compilation of tracer recovery curves showing the timing and character of tracer recoveries Tracer concentrations were measured in a laboratory by a scanning spectrofluorophotomer. The plots show that the tracer traveled first to Revel Sink and then to Punch Bowl sink and then to the spring Creek spring vents. The shape of the Revel Sink curve indicates that sampling there intercepted the tracer as it moved through a significant conduit toward Wakulla Spring. The lack of positive detections at either Wakulla K-Tunnel or Wakulla Spring indicate that the groundwater flow reversed direction after the tracer reached Revel Sink and flowed to Punch Bowl Sink and the Spring Creek spring vents. The shape of those curves indicates that the tracer passed those stations in at least two pulses, which were probably driven by changes in the local gradients.

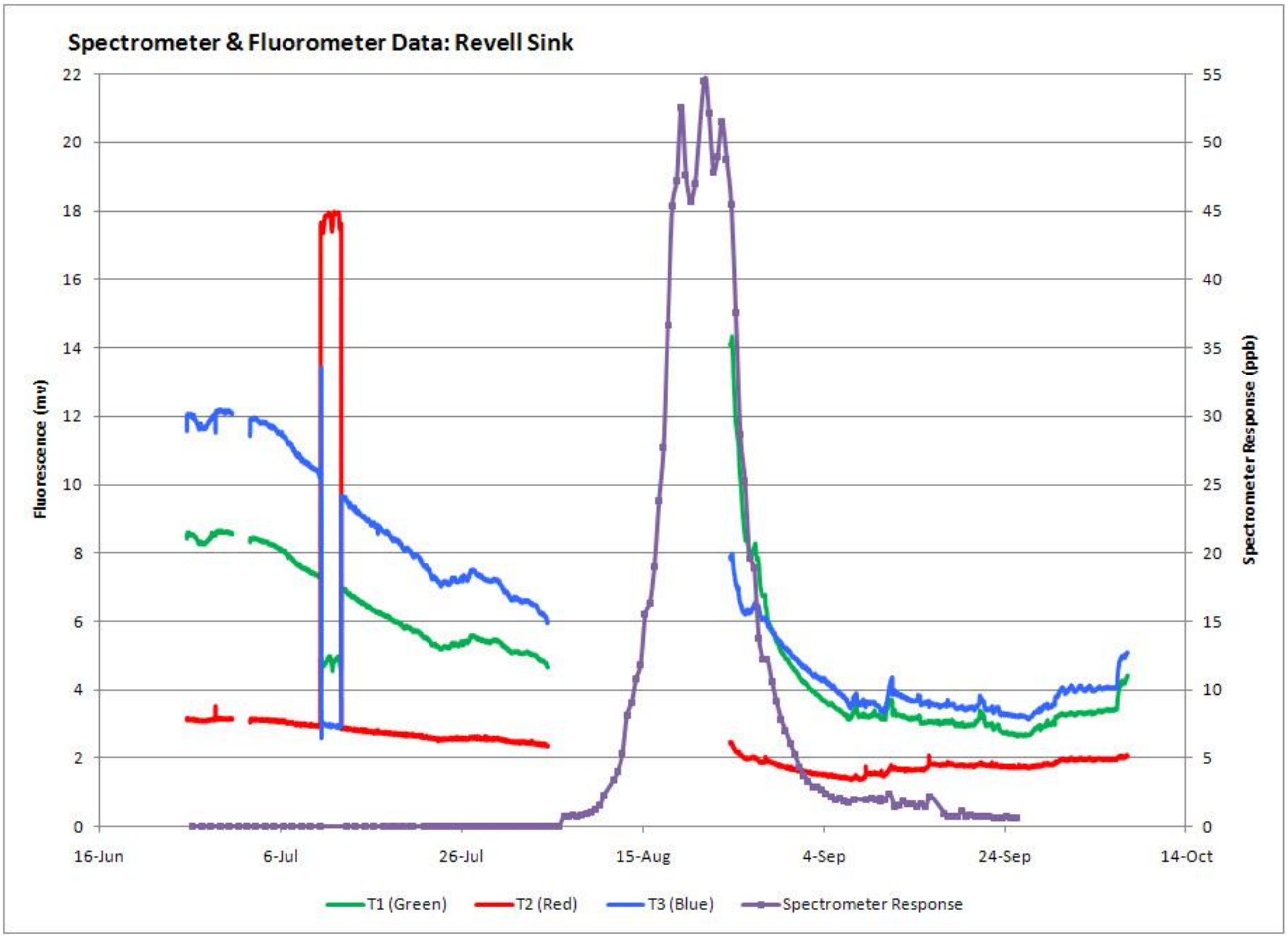


Figure 15. Comparison of fluorescence measured by the insitu fluorometers and tracer concentrations measured by a scanning spectrofluorophotomer at Revel Sink during the 2009 Lost Creek tracer test. The fluorometer malfunctioned during the critical period when the tracer was passing the sampling station however it did record the tailing edge of the tracer recovery curve (note that the green curve was higher than the blue curve during that period).

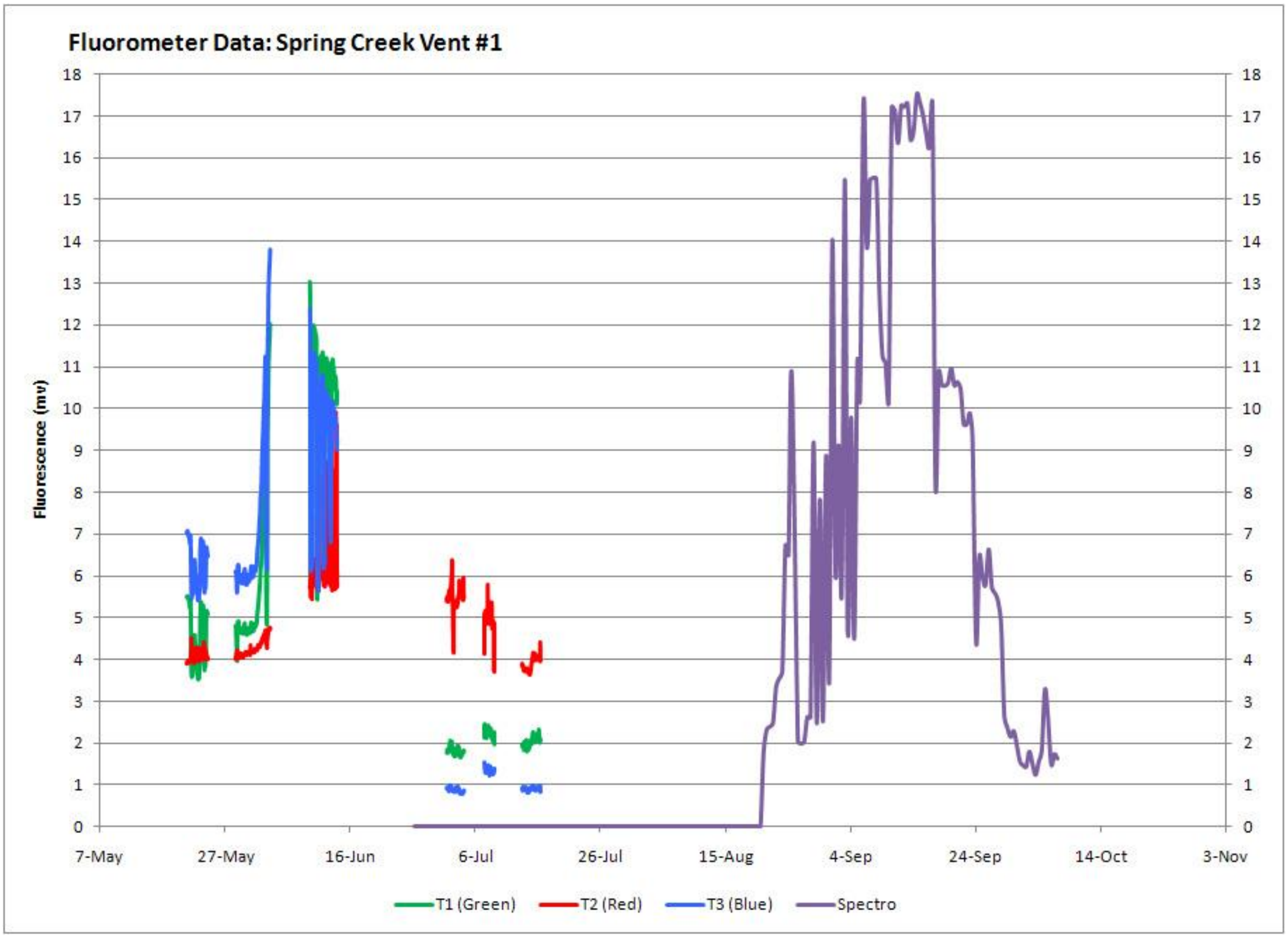


Figure 16. Comparison of fluorescence measured by the insitu fluorometers and tracer concentrations measured by a scanning spectrofluorophotomer at Spring Creek #1 during the 2009 Lost Creek tracer test. The insitu fluorometer permanently malfunctioned shortly after the injection, probably due to the high salinity and turbidity water at Spring Creek.

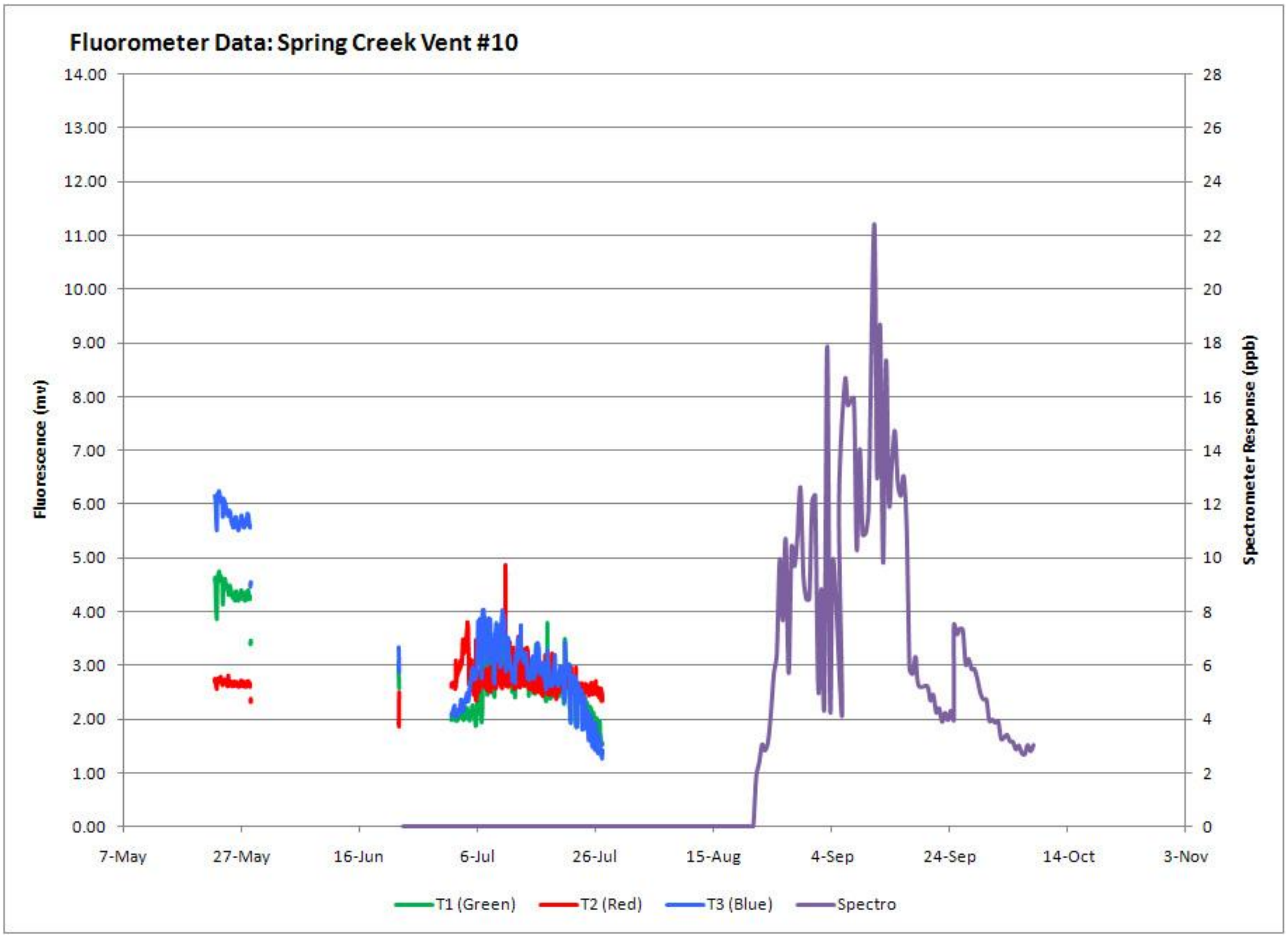


Figure 17. Comparison of fluorescence measured by the insitu fluorometers and tracer concentrations measured by a scanning spectrofluorophotomer at Spring Creek #10 during the 2009 Lost Creek tracer test. The insitu fluorometer permanently malfunctioned shortly after the injection, probably due to the high salinity and turbidity water at Spring Creek.

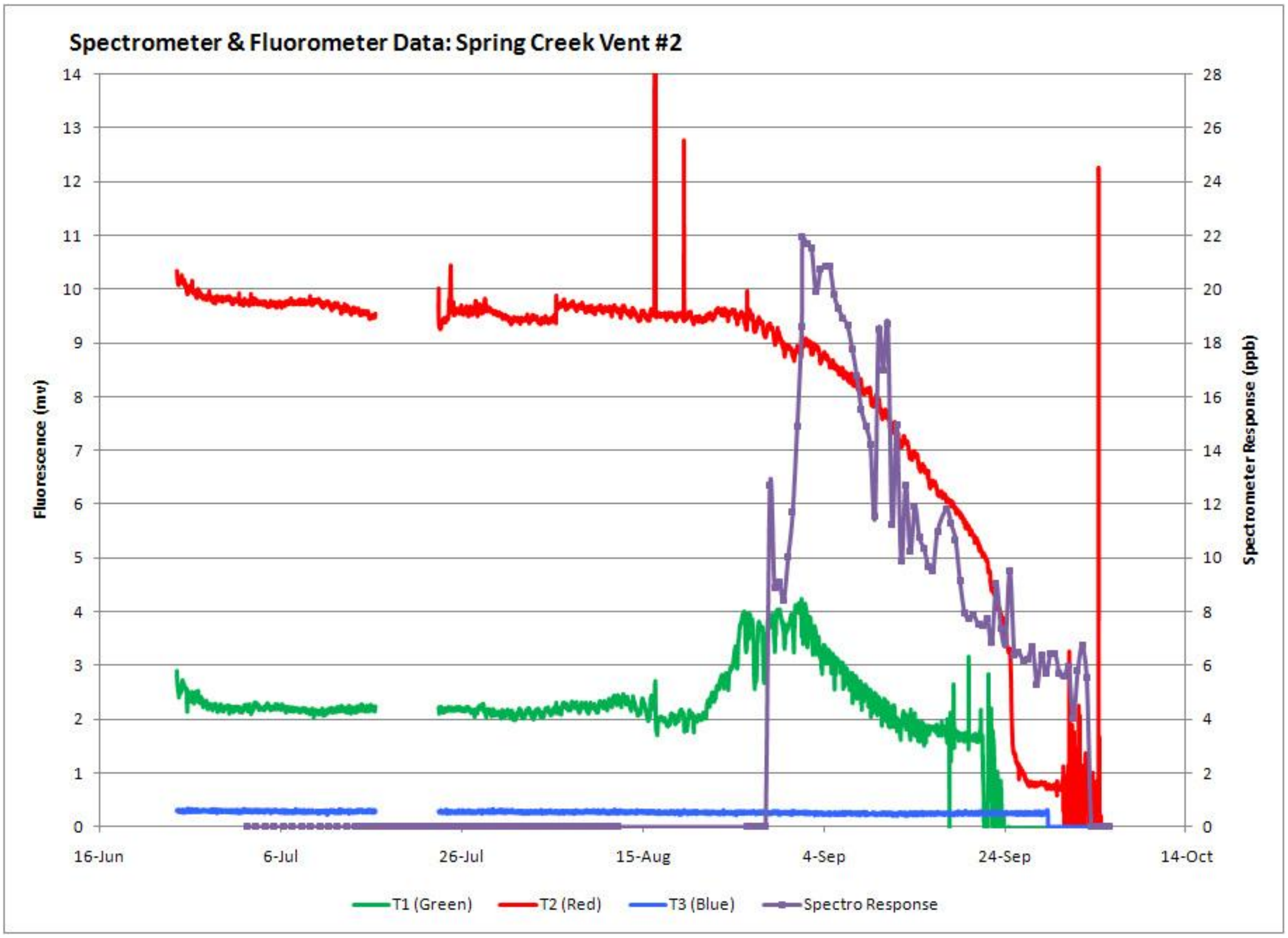


Figure 18. Comparison of fluorescence measured by the insitu fluorometers and tracer concentrations measured by a scanning spectrofluorophotomer at Spring Creek #2 during the 2009 Lost Creek tracer test. The spectrometer data recorded a sharper rising limb on the recovery curve than the fluorometer data but the tailing edge of both curves is very comparable.

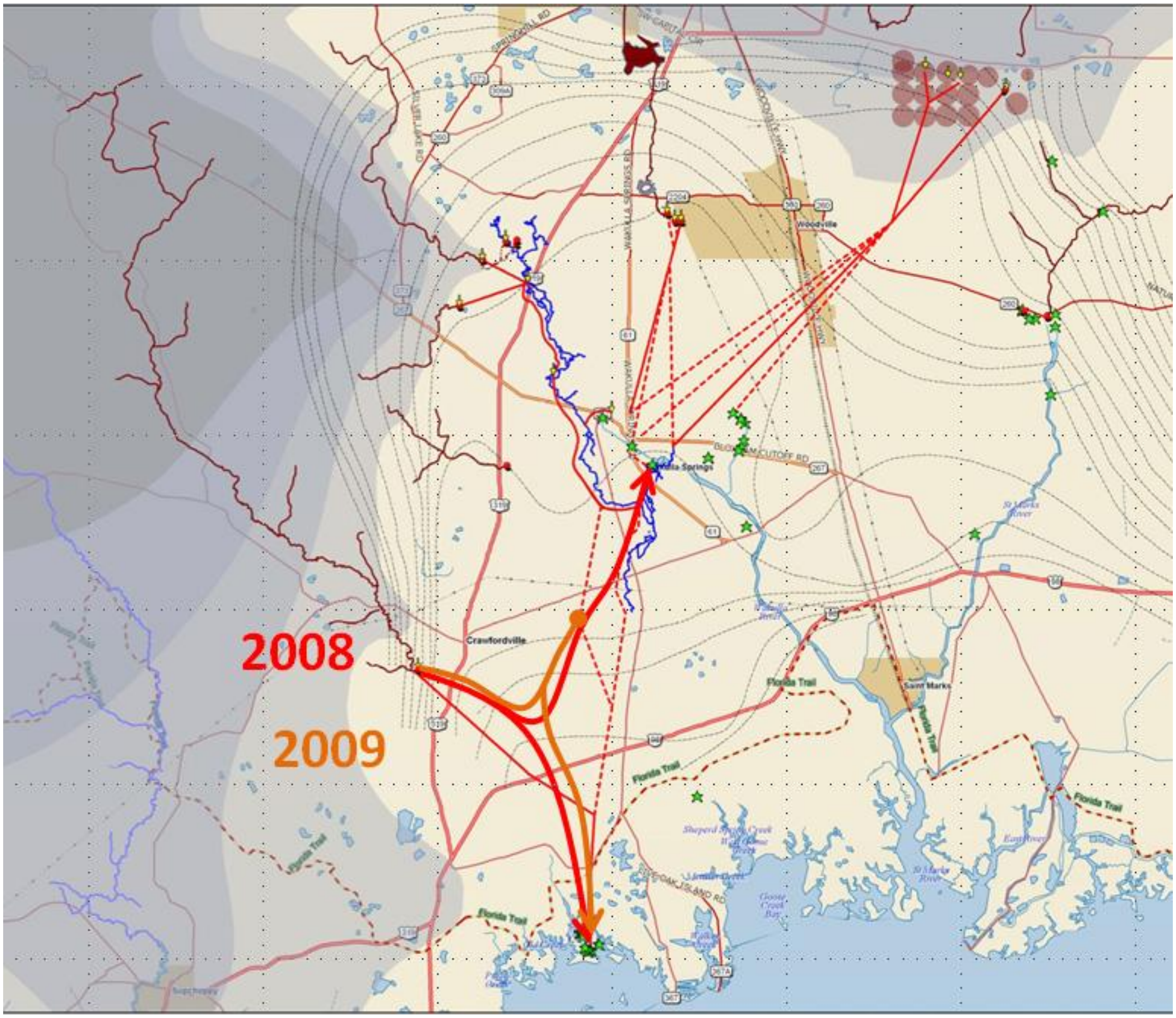


Figure 19. Map of the WKP showing the tracer pathways as indicated by the 2008 and 2009 Lost Creek tracer tests. In 2008, an initial gradient drove the tracer to Spring Creek very shortly after the injection, which reversed before the entire tracer cloud reached Spring Creek driving the remainder of the tracer cloud north to Revel Sink and Wakulla Spring. In 2009, Spring Creek was strongly reversing at the time of the injection. The initial gradient was north toward Wakulla Spring resulting in the strong detection at Revel Sink. That gradient reversed before the tracer cloud could reach Wakulla Spring driving the tracer south first to Punch bowl Sink and then to Spring Creek.

APPENDIX I: TASK-4 KARSTMOD GROUNDWATER MODELING REPORT

Final Report of GW275, Task 4 by Loper and Chicken

The following is the final report of research performed by David Loper and Eric Chicken during the period from July 21, 2008, through September 30, 2009, in support of Task 4 (Groundwater modeling) of DEP contract GW275: Characterization of the Woodville Karst Plain for the purpose of numerical modeling.

4.1. Introduction

The goal of task 4 is to develop a systematic procedure for answering this question: ***How accurately can a given model simulate flow of water and transport of pollutants within the Woodville Karst Plain?***. This question can be answered in a quantitative manner through the development and implementation of a set of benchmark tests.

A benchmark test is based on the knowledge of three components: an aquifer, a set of inputs and a set of outputs. In the simulation of flow, the inputs and outputs consist of recharge (e.g, the time history of diffuse infiltration and discrete inputs as swallets) to the aquifer and spring hydrographs, respectively. In the simulation of transport, there is an additional set of inputs and outputs: the concentrations of selected contaminants (both in the groundwater and in the input water) and breakthrough curves for those contaminants at the spring, respectively.

Ideally the aquifer employed in the test would be an actual aquifer for which suitable data is available. However, our knowledge of the aquifer (especially the number, location and sizes of karst conduits) is very limited, making the development of a reliable benchmark test based on an actual aquifer a difficult challenge. Further, as explained in §4.2.1, a karst springshed can be a dynamic, time-dependent entity, making a benchmark test based on an actual springshed all the more difficult. Alternatively, the benchmark test could be based on a simulated aquifer, with the comparison to an actual aquifer being indirect. Both approaches to the development of benchmark tests were attempted.

Task 4 consists of two sub-tasks: development and implementation. (The scope of services for this task is found in Appendix A.) Progress that has been made by Loper and Chicken on each of these two sub-tasks is summarized in subsections 4.2 and 4.3, with details found in several appendices.

In addition to the development of suitable benchmark tests, in the past year, with partial support from GW275, Loper and Chicken have developed and implemented a new model of flow in karstic aquifers, called KAM (Karst Aquifer Model).

4.2: Development of benchmark tests

As noted above, it is preferable to develop a benchmark test using an actual – as opposed to simulated – aquifer. With this in mind, we began by attempting to use the flows associated with Tropical Storm (TS) Fay in August 2008 as input and output of a benchmark test for flow. As explained in §4.2.1, this effort was subverted by the complex nature of the aquifer beneath the WKP. Following this, attention was turned to the development of a simulated aquifer together with a set of benchmark tests, as described in §4.2.2.

4.2.1. Attempt to develop benchmark tests based on the Wakulla Springshed

A good test for flow would be a large rainstorm event covering the entire springshed. It seemed that the flows induced by TS Fay would provide an ideal set of data for a flow test of the aquifer feeding water to Wakulla Spring. However, as will be explained in this subsection, Nature had a big surprise for us.

The geographic extent of the Wakulla springshed is a bit uncertain, with the best guess depicted on a map produced by the USGS shown in Figure 4.1. The rain associated with TS Fay occurred over a short span of time, so that loss due to transpiration was negligible; virtually all of the rain went to surface and ground-water flow. While detailed observations of rainfall are available throughout the springshed, it is sufficient for our purposes to use the summary graph shown in Figure 4.2. The portion of this rainwater that fell on the springshed is the input for the test, with the output being the flow at Wakulla Spring, depicted in Figure 4.3.

A basic premise of the benchmark test of flow is that the water entering the aquifer leaves at the spring. It is a simple matter to compare the volume of water that was added to the springshed depicted in Figure 4.1, due to the rainfall depicted in Figure 4.2. The total area of the Wakulla springshed is about 3000 km^2, with the rapid recharge area being about 370 km^2. Taking an average rainfall of 15 inches (= 26.7 cm), the volume of water added to the entire springshed was roughly 80×10^7 m^3, and to the rapid-recharge area, roughly 10×10^7 m^3. The discharge of 2500 ft^3/s (= 70 m^3/s) measured at Wakulla Spring on August 27, 2008, set a record. The total volume of water, above the pre-existing base level of 850 ft^3/s (= 24 m^3/s) that exited Wakulla Spring in the two-week period during and following TS Fay, coming out of Wakulla Spring is about 2.2×10^7 m^3. This volume is less than 3% of the volume of water falling on the entire springshed and less than 22% of that falling on the rapid-recharge area.

Something is clearly amiss. A large volume of rain fell on the springshed and sank into the ground, but did not come out at the spring. Where did it go? Two possibilities exist: either it remained in the aquifer and drained over a longer period of time than the two weeks or else it quickly made its way to Apalachee Bay by a different route. If the water remained in the aquifer longer than two weeks, it would have caused excess discharge at Wakulla Spring and excess flows in the St Marks and Sopchoppy Rivers. It may be seen from Figure 4.3 that the discharge from Wakulla Spring was depressed, relative to its pre-event level, starting September 6, 2008. Similarly, the elevations and flows of the St Marks and Sopchoppy Rivers, shown in Figure 4.4, are depressed beginning several weeks after TS Fay.

The only plausible explanation is that the water quickly drained from the aquifer by a route that is not normally activated: old conduits. Werner (2001) has shown that the conduits within the WKP formed in the last 500,000 years, during which time sea level was much lower than it is now. As sea level rose after the end of the last ice age, Apalachee Bay moved northward and many of these conduits were inundated with salty water and became inactive. Under normal hydrologic conditions these conduits are full of sea water, which acts as a plug, preventing fresh water to flow beyond the coast. As a result, water that used to flow in these conduits now discharges at a series of coastal springs, including the Spring-Creek group, Shepherd, Mineral, Cray's Rise and Bear Creek. The dynamics of salt-water plugs was discussed in §5.5.5 of the FY06-07 report for contract GW258.

That situation changes during a large recharge event, such as TS Fay. The due to recharge, the head in the fresh-water lens of the aquifer becomes sufficiently great that the salt water is forced from the under-sea vents, permitting a significant discharge of fresh water at various (unmapped?) off-shore vents. It is quite likely that this process caused much of the TS Fay water disappeared from the aquifer beneath the WKP – and more. Once the normally dormant conduits became active, they remained so even after water levels returned to normal.

This caused a draw-down of the aquifer to sub-normal levels. This process provides an explanation why, by mid September, discharges in the Wakulla, St Marks and Sopchoppy rivers fell to levels lower than prior to the passage of TS Fay. (This process is very similar to the flushing of a toilet, with water from the storage tank activating the trap which drains more than the added water, leaving less water in the bowl.) Eventually the flow off-shore weakened and salt water re-entered the conduits turning them off (about September 25?).

There are two lessons learned from this exercise. First, a springshed boundary is not a static feature, but can be strongly dependent on the hydrologic conditions. For Wakulla Spring, the size of the springshed varies inversely with the thickness of the fresh-water lens in the WKP. When the lens is thick, water flows preferentially to springs located to the south of Wakulla Spring. The converse is also true; when the fresh-water lens is thin, salt water invades conduits that are normally active and plugs the flow of fresh water to the south, causing flow to be diverted to Wakulla Spring. (Todd: tie this in with your idea that the extra flow to Wakulla Spring included dark water from the Apalachicola Forest which used to bypass Wakulla.)

The second lesson is that the springshed of Wakulla Spring is not a good candidate for use in a benchmark test. It is preferable to use a simpler springshed, where the discharge points are known and quantified, such as Fanning Spring, or else use a simulated aquifer. This latter possibility is discussed in the following subsection.

4.2.2. Development of benchmark tests based on a simulated aquifer

In the course of the implementation of the new karst aquifer model KAM described in §4.3, a test springshed was employed which can also be used as a simulated aquifer in a benchmark test. This test springshed, shown in Figure 4.5, consists of a set of 42 triangular elements having 27 nodes (including the spring) at their vertices and 68 straight-line connections forming their sides. 26 of the connections are locations of conduits that form a tree-like structure capable of conveying flow rapidly to the spring. The conduit sizes have been determined assuming that they convey steady-state flow to the spring from the adjacent aquifer with the regional water table having a parabolic shape. Specifically, the steady-state recharge and spring discharge have been chosen to be 4×10^{-8} /ms, and 4 m^3/s, respectively.

Five tests of time-dependent flow have been devised for this simulated aquifer. Each test runs for a year and begins with 10 days of steady state input (consisting of steady diffuse recharge, but no surface inputs), in order to verify that the model is running correctly and to provide a visual reference for the simulations. The five tests are

1. ***drought***: recharge is set equal to zero for days 11 through 365.
2. ***uniform rainstorm***: recharge equal to 30 times the steady value is applied uniformly to the entire springshed for three days (days 11, 12 and 13), then the recharge rate is returned to the steady value for the remainder of the year.
3. ***rain on a single element***: recharge equal to 100 times the steady value is applied to a selected element (in this case, element 18) for three days (days 11, 12 and 13), then the recharge rate is returned to the steady value for the remainder of the year.
4. ***surface storm water input to a single node***: a flux of surface water equal to the steady spring discharge is added to a specified node (in this case, node 11) for days 11, 12 and 13. The diffuse recharge remains equal to the steady value throughout the year.
5. ***spring-basin flooding***: the head at the spring rises steadily and uniformly for 30 days from zero at day 10 to 2 m at day 40, then falls steadily to zero over the next 30 days and remains at zero for the remainder of the year.

The spring discharge and head at selected nodes for each of these five scenarios are illustrated in Figures 4.6 – 4.10.

Task 4.3: Implementation of benchmark tests

Four of the five benchmark tests (1, 2, 3 and 5) were used to illustrate and investigate the character of the new model of flow, KAM. This new model is described briefly in §4.3.1 and the results of the benchmark tests are summarized in §4.3.2.

4.3.1 A brief description of KAM

This subsection contains a brief description of KAM, which is a new model of flow in karst aquifers that has been under sporadic development (with support from the Florida Geological Survey) for a number of years. Beginning in July 2008, Loper and Chicken made a concerted effort to make this model operational and we achieved success roughly one year later. A more complete description is given in a manuscript “A new model of flow and transport in karstic aquifers" by David E. Loper and Eric Chicken that is in preparation for submissiion to *Water Resources Research*. This manuscript is found in Appendix B. A much more detailed description of the operation of KAM is found online, in technical report M994 of the Department of Statistics ([illegible]).

KAM is based on the premise that karst spring flow is insensitive to the number and locations of conduits. Model construction begins with a springshed (having a known boundary) being seeded with nodes. Node locations can be specified or sprinkled randomly using a random-number generator. The nodes are automatically joined by connections (which are potential locations of conduits) dividing the springshed into triangular elements (which are two-dimensional representations of the Darcian porous matrix). Infiltration recharges elements, then flows to adjoining conduits with a time delay reflecting Darcian flow. Flow in conduits is quantified by Darcy-Weisbach. The model is calibrated by the known spring discharge and regional head distribution. Geometry and known recharge determine the steady fluxes in the conduits, and the known steady head distribution determines the sizes of the conduits.

The model is illustrated by running the scenarios described in §4.2.2 on the test aquifer consisting of 27 nodes, 42 elements and 68 connections. Example outputs of these runs are presented and discussed in Appendix B.

References

Werner, C. L. 2001. Preferential flow paths in soluble porous media and conduit system development in carbonates of the Woodville Karst Plain, Florida. M.S. Thesis. Tallahassee, Florida: Florida State University.

Figures

Figure 4.1. The springshed for Wakulla Spring, courtesy of the USGS. The gray region below the Cody Scarp is designated an area of rapid recharge. The total area of the springshed is about 3000 km^2, with the rapid-recharge region having an area about 370 km^2.

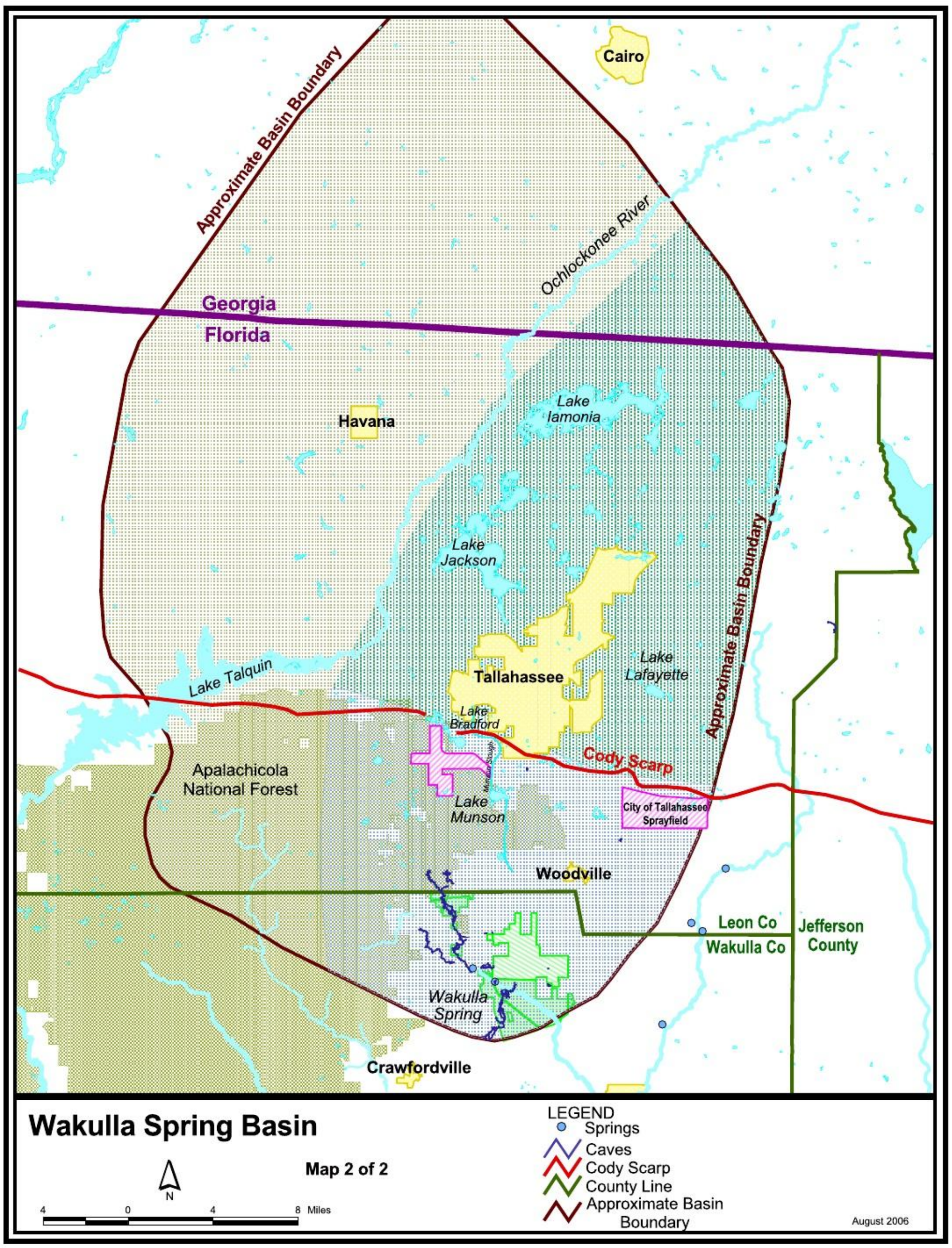


Figure 4.2. Contours of cumulative rainfall produced by Tropical Storm Fay, courtesy of the National Weather Service.

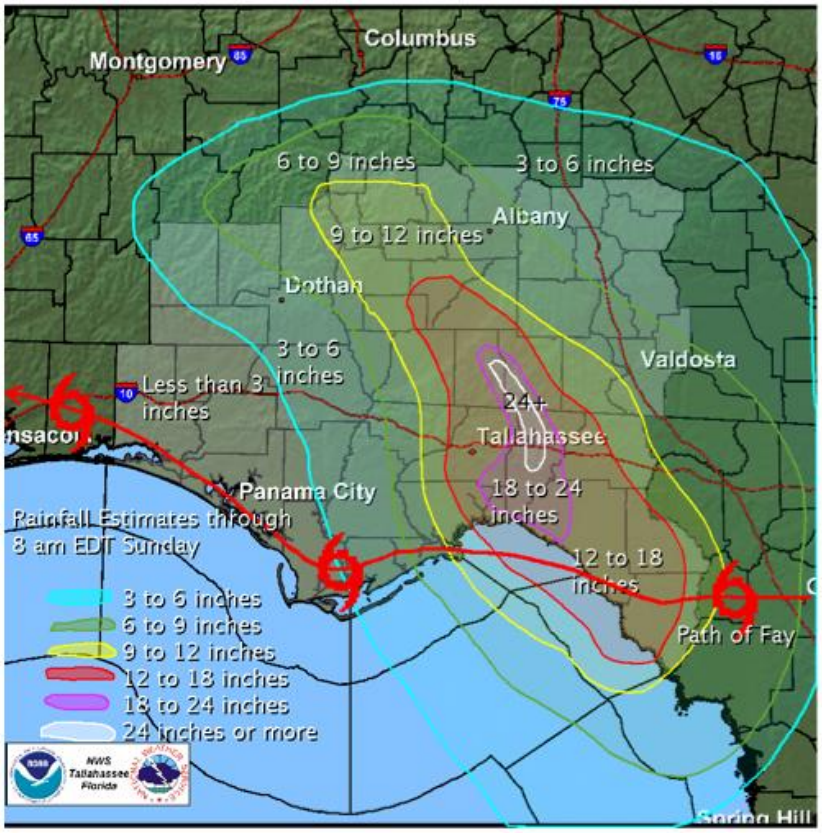


Figure 4.3. Discharge at Wakulla Spring, August and September, 2008, courtesy of the Northwest Florida Water Management District. Flow is in ft^3/s.

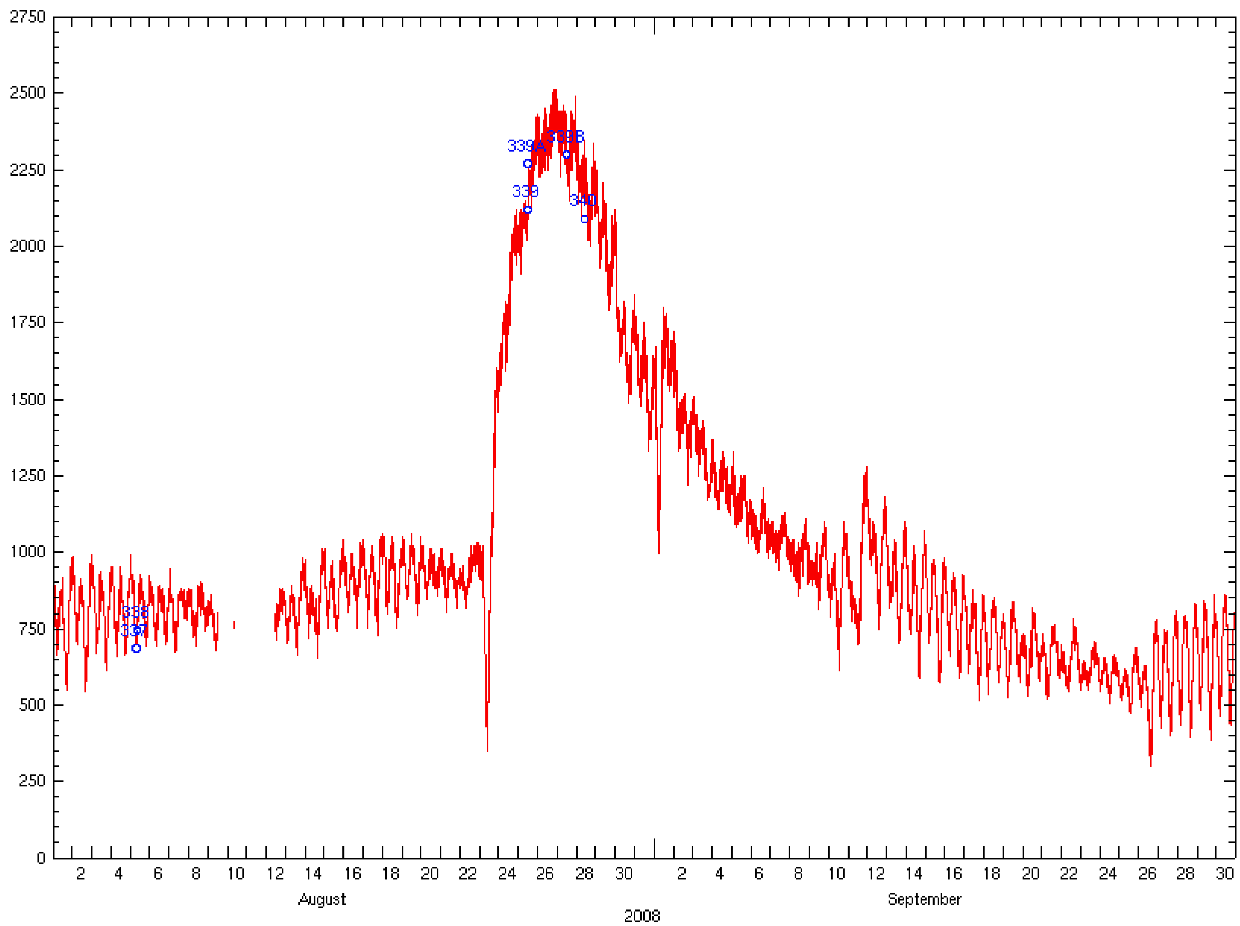
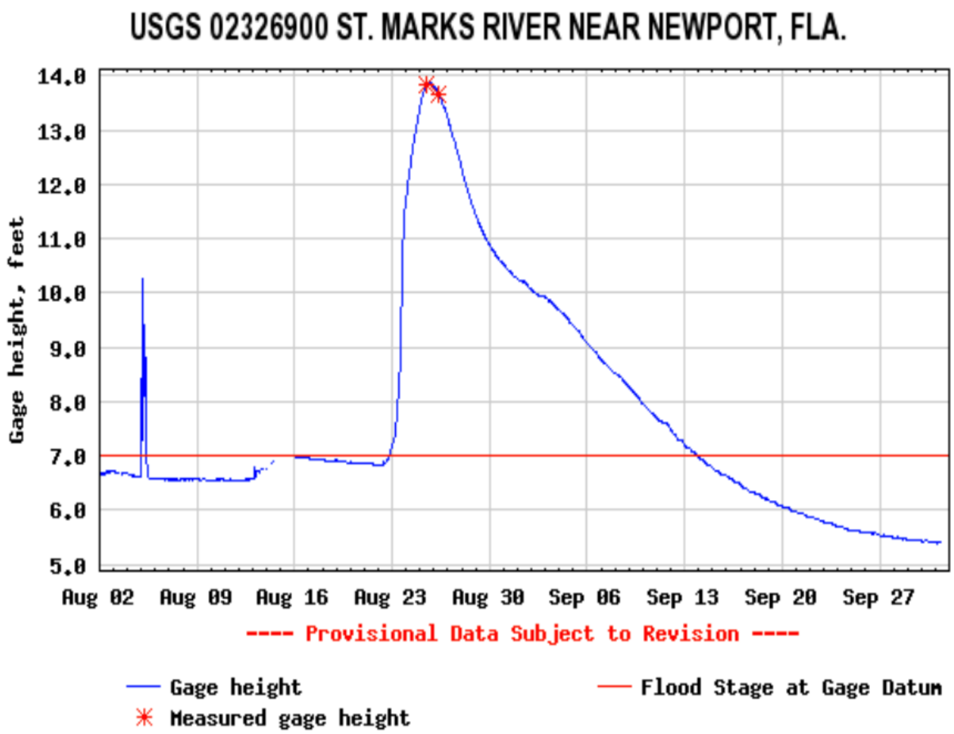


Figure 4.4. (a) Elevation of the St Marks River and (b) flow rate in the Sopchoppy River during August and September, 2008. in. Courtesy of the USGS.



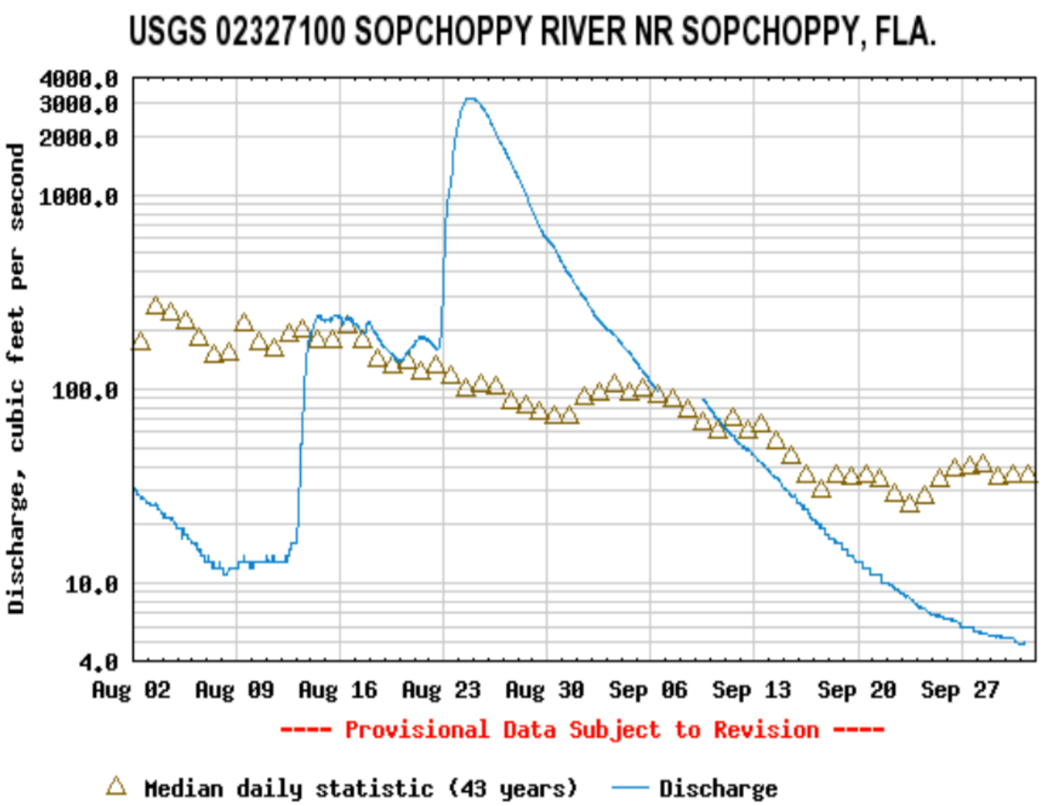
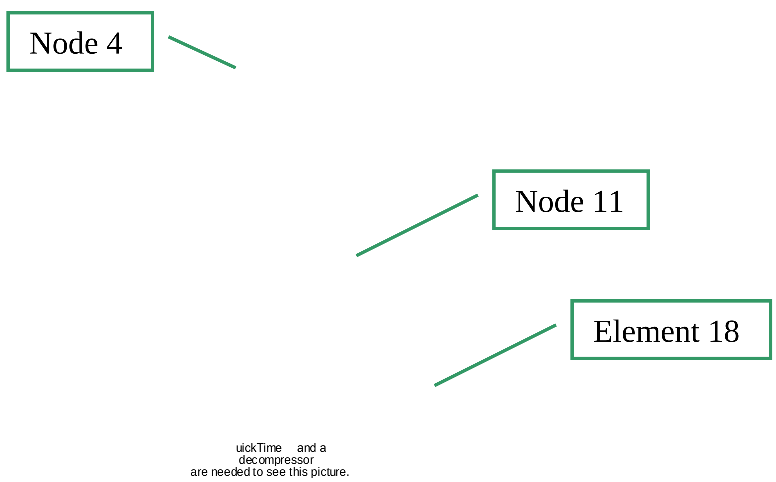


Figure 4.5. A simulated aquifer suitable for use in a benchmark test. The area of the springshed is 100 km2. The spring is located at the origin of the coordinate system. Solid lines depict conduits, which are sized to scale. Conduit sizes are determined by the condition that they convey a steady recharge from the various triangular elements to the spring with a regional water table having a parabolic shape. Nodes 4 and 11 and element 18, depicted in this figure, are singled out in the time-dependent tests



APPENDICES

Appendix A: Scope of Services for Task 4: Groundwater Modeling

The purpose of this task is two-fold. First, we will develop a set of model calibration criteria or "benchmark tests" by which our steady-state numerical model and statistical KARSTMOD groundwater flow models can be effectively and objectively evaluated in terms of their predictive reliability. Second, we will expand both models such that they can be evaluated with those criteria or tests and such that the numerical model addresses, in principle, the concerns expressed by the NWFWMD. The calibration criteria and benchmark tests will be developed through a statistical and hydraulic analysis of the water level, flow, and precipitation data that have been collected and/or compiled by our project over the past 5-6 years.

Specific Tasks:

Develop appropriate benchmark tests for the evaluation of steady-state and transient groundwater models of the WKP through the statistical analysis of precipitation, discharge, and water level data previously collected.

Expand the steady-state numerical model to 3D as per the recommendations of the NWFWMD.

Develop a calibration dataset that can be used in conjunction with the benchmark test for the evaluation of steady-state numerical models of the WKP.

Evaluate transient data and identify what will be needed to construct an adequate calibration dataset for transient numerical models of the WKP and relate that to the benchmark test(s) developed in (1).

Develop and deliver a report presentation on the modeling status.

Appendix B: the manuscript submitted to Water Resources Research

This appendix is found in a separate file.

APPENDIX II: TASK-5 RADON TRACING REPORT

Final Report

To H2H and

Florida Geological Survey

Florida Department of Environmental Protection

Contract GW-275

A natural tracer investigation of the hydrological regime of Spring Creek, the largest submarine spring system in Florida

Natasha Dimova and William C. Burnett

Florida State University

Department of Oceanography

Tallahassee, FL 32306

September 16, 2009

Abstract

Florida has one of the largest network of springs not only in the US but in the world. Among the approximately 700 documented springs in the state, 33 of them are considered to be first magnitude with discharge of over $2.9x10^5$ m^3/day. With a reported average annual discharge of $4.9x10^6$ m^3/day, Spring Creek Submarine Springs in Wakulla County is the leader. During the summer of 2007 this spring was observed to have reduced significantly its flow due to extreme drought conditions. Our examination of the springs revealed that while radon-in water-concentrations were still relatively high, the salinity has increased significantly, from 4 in 2004 to 33 in July 2007. This indicates a massive saltwater intrusion into the aquifer. During a nearly two-year investigation from August 2007 to May 2009 we deployed almost on a monthly basis a continuous radon-in-water measurement system and monitored the salinity fluctuations in the spring's discharge area. As a result of a strong rain storm (total of 173 mm) at the end of February 2008, the salinity dropped from about 27 to 2 only two days after the storm. The radon-in-water concentrations dramatically increased in parallel, from about 330 Bq/m^3 to about 6,600 Bq/m^3. Our two-year observations of the springs' fresh water discharge based on both salinity and radon show that the hydrologic regime of the system is strongly correlated to local precipitation and water table fluctuations. This suggests connections between the deep and the surficial aquifers.

Keywords: *saltwater intrusion*, *submarine springs, Spring Creek Springs, salinity, radon, spring discharge*

1. **Introduction**

Submarine springs are common features on continental shelves around the world. They are often associated with offshore outcrops of carbonate rocks (Fleury et al., 2007). In Florida, springs have been influenced by sea level changes during the Pleistocene when world sea levels fluctuated between 15-20 m above present to about 120 m below present (Ferguson et al., 1947; Haq et al., 1987; Rupert and Spencer, 1988). During periods of lowered sea level, large areas of the Florida Platform were exposed to weathering and karst processes which resulted in most of today's submarine springs.

Springs are usually classified based on their discharge. Meinzner (1927) categorized them on a scale from one to eight with first magnitude being a spring with a flow rate of at least 100 ft^3/s (~$2.45x10^5$ m^3/day). Based on this classification, Rosenau et al. (1977) reported 27 first magnitude springs in Florida which was approximately one third of all known first magnitude springs in the US at that time. More recently, the Florida Geological Survey (Scott, et al., 2004) documented more than 700 springs in Florida with 33 of them being first magnitude. This ranks the State of Florida as having the largest network of springs, not only in the US but perhaps in the world. With a combined discharge of $4.9x10^6$ m^3/day, the Spring Creek Springs system in Wakulla County (NW Florida), is the leader (Rosenau et al., 1977).

Due to extreme drought conditions during the last several years in the state of Florida (**Fig. 1**) this largest spring system has significantly reduced its rate of freshwater flow.

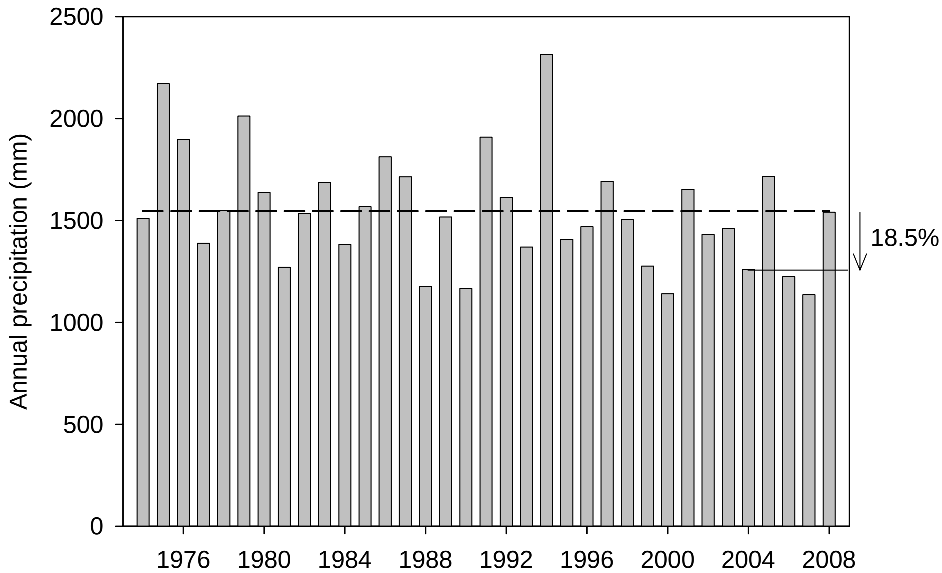


Figure 1 Historical record of annual precipitation measured in the St. Mark's watershed since 1974. The dash line refers to the average value of the record and the bold line the annual precipitation in 2004 when the dry period started. During the last several years the amount of rain was about 18-20% below average excluding 2005 and 2008 (http://www.nws.noaa.gov/).

Our inspection of the springs in the summer of 2007 revealed that the water chemistry had been altered dramatically compared to earlier observations. The salinity in the area had changed from about 4 in 2004 to a more marine-dominated environment of ~33 in 2007. Surprisingly, the high salinity we observed in 2007 was coupled with abnormally high radon-in-water concentrations for coastal seawater (up to 600 Bq/m^3). This suggests that large amounts of seawater must have intruded into the aquifer and had a residence time long enough to acquire these high concentrations.

The objective of this work was to examine the hydrologic regime of the largest submarine spring system in Florida, Spring Creek Springs, under different climatic conditions. To estimate the discharge of the springs we used measurements of salinity, current velocities and radon inventories at various times over a two-year period. We also investigated the benefits and constraints of using either salinity or radon as tracers of groundwater discharge in a tidally-influenced spring system like Spring Creek. Our long-term perspective is to combine this knowledge with climate and geologic data to reveal significant land and ocean linkages in the area.

2. Study site, methods and measurements

2.1. Study site

The Spring Creek Springs system is situated in NW Florida (**Fig. 2**) and is part of the St. Marks watershed.

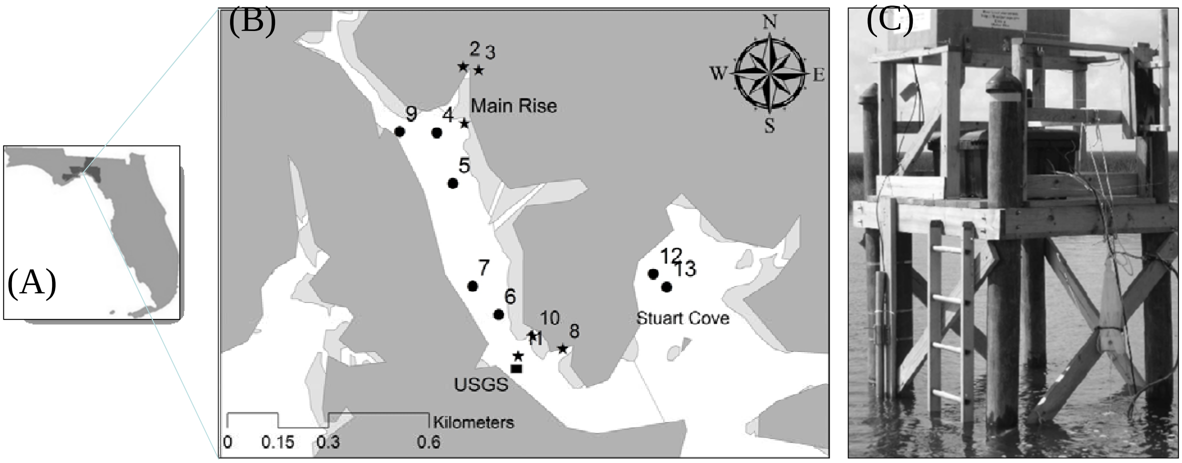


Figure 2 Maps of Florida (A) showing the location of the research area and the exact location of the springs (B). The circles and the stars with the numbers in (B) indicate the positions of each of the thirteen recognized submarine springs. The star symbols represent the springs which have installed PTF tubing for sampling. The solid square shows the position of the USGS platform presented in photo (C).

There are thirteen documented springs in the area, most of which discharge offshore (Scott et al., 2004). It is believed that the springs are part of a larger and more complicated underground cave system, including nearby Wakulla Spring, in the Woodville Karst Plain geologic unit (Davis, 2007). The west-central and north part of the Upper Floridan Aquifer in this area is just a few meters thick and it is overlain by a sequence of sand, clay, limestone, and dolomite. The overlying sand generally comprises a surficial aquifer system. Because the Upper Floridan is unconfined or semiconfined in this area (Ferguson et al., 1947; Steward, 1980), it is directly connected to the surficial aquifer and the groundwater level fluctuates seasonally in response to recharge from precipitation, evapotranspiration and periods of reduced precipitation and droughts. During the period of our study we found that the discharge of the spring system responded very quickly to changes in the water table elevation after a rainfall. This is additional evidence for direct connections between the Floridan and the surficial aquifer. We observed that it would take only one or two days for water to travel via underground conduits from an upgradient source to the coast after major rainfalls (**Fig. 3**).

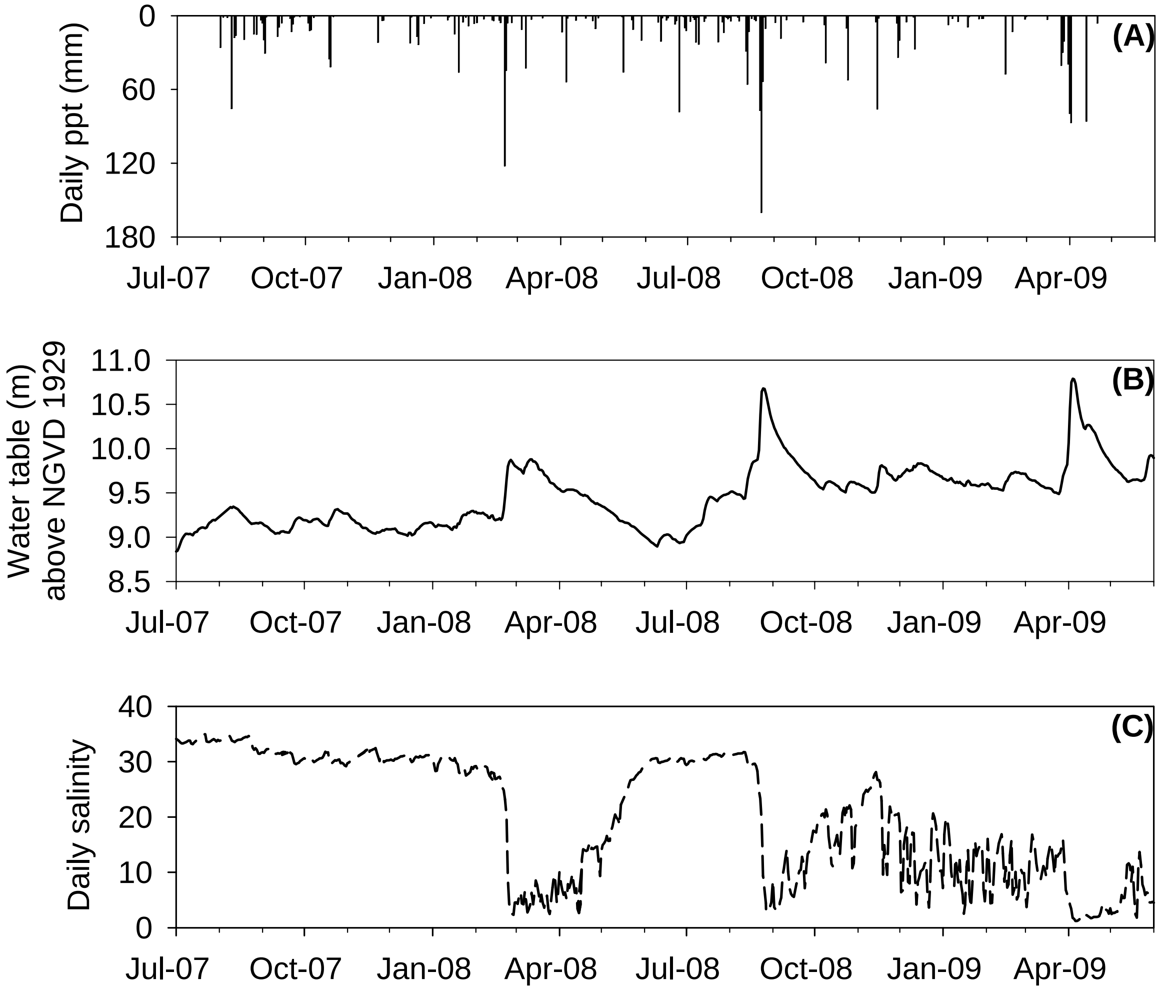


Figure 3 Time-series observation of precipitation (A), water table (B) and salinity (C) in the research area. The observation well (USGS 3007400884293001) is completed in the Upper Floridan aquifer and it is about 14.5 m (47.33 ft) above sea level (NGVD29). Salinity measurements were made at the USGS platform.

A detailed physical description of the springs was last performed by Lane (2001). Most spring vents have a conical shape and are as deep as 30 m. When there is significant discharge, many of boils can be seen at the surface. For example, the active surface of the boil of Main Rise, the largest spring in this spring network, can be as large as 9-12 m in diameter. The author was not certain about the depth of this vent because of the enormous amount of discharge during his observation "*which created so much upwelling and surface turbulence that the boat could not be held steady over the spring.*" The sources of the springs' water are still not known, but based on recent dye tracer experiments some investigators (H. Davis, USGS, pers. comm.) believe that an important contributor is from a small creek named Lost Creek, which flows as a surface water body a few kilometers northwest of the springs, disappears into a sinkhole and then is thought to flow out through Main Rise. Another very interesting phenomenon of the springs is their pulsing discharge nature. Numerous Spring Creek investigators have noticed that most of the springs flow in pulses, i.e., strong flow for some time followed by reduced or even reversed flow (Lane, 2001). This is another sign of the complicated nature of the water pathways through the underground conduits. Conclusive reports on the actual water sources and pathways are still pending.

2.2 Data collection

The radon and much of the salinity time-series measurements for this study were performed from a platform (USGS) downstream of the creek area (**Fig. 2C**). In addition to the platform deployments, salinity time-series measurements were taken in the vicinity of the Main Rise (**Fig.2B**) for several months during 2008. The platform time-series measurements were performed on an almost monthly basis between July 2007 and May 2009. In most cases the records were three or more days long with longer periods during and after major rain storms. For the radon time-series deployments we used a portable continuous radon-in-air monitor adapted for radon-in-water measurements (RAD AQUA®, Durridge Company). Information about the principle of detection of this instrumentation can be found elsewhere (Burnett and Dulaiova, 2003). Water depth was acquired by use of a HOBO® Depth Data Logger. Conductivity/salinity measurements were taken using CTD divers (Van Essen Instruments®), which were always calibrated in the lab before deployment. Stream velocity data for the time of our measurements was obtained by request from the USGS (R.J. Verdi, pers. comm.). The USGS ultrasonic current meter (USM) is set up adjacent to the same platform at the downstream end of Spring Creek where our instruments were regularly deployed. At present there are about 130 manually performed stream velocity measurements on the site used for calibration of the current meter at the platform. The USM principle of measurement and the calculations are described in detail in Ruhl and Simpson (2005) and Roberts and Roberts (1978).

Because of the position of the research platform, two of the documented springs situated in Stuart Cove, numbers 12 and 13 (Fig. 2B), are excluded from the total flow estimates. These two springs were detected during detailed radon-salinity surveys performed in July 2007, July 2008 and October 2008 with a modified version of the conventional RAD AQUA® system specifically designed to measure rapid changes in radon-in-water concentration (Dimova et al., 2009). The radon survey system was coupled with GPS navigation, depth sounding, and CTD sensors for continuous conductivity and temperature measurements during the surveys (Dulaiova et al., 2005; Stieglitz, 2005). In six of the springs, cave divers from the Florida Geological Survey have installed long PTF tubing deep into the vents with land-based outlets for sampling purposes during their dye experiments. During our study we sampled these vents a few times for radon concentrations and salinity. We also set up a continuous radon-in-water monitor to the outlet of the tubing of Main Rise using a peristaltic pump over a few-day period during the April-May 2009 deployment. These continuous measurements together with multiple individual sample evaluations from other vents were used to estimate the radon in groundwater end-member concentration used in the radon model for evaluation of the springs discharge.

2.3 Calculating spring discharge via salinity and ^{222}Rn in tidal influenced zone: stream velocity approach

We calculated the fresh water discharge in the spring area using two different geochemical tracers. In the first approach we use time-series data for salinity and stream velocity recorded downstream of the main spring area. Since the water column in some cases was stratified, especially when the springs are flowing, we defined the thickness of the fresh water layer based on salinity-depth profile measurements. To calculate the discharge one simply needs to multiply the measured cross-section of this layer by the stream velocity at that time. Because most of the time the fresh layer is brackish (salinity ~2-3) we also calculate the freshwater fraction in this layer using the highest observed value for salinity in the area (35) as a seawater end-member. With 15-min intervals for the stream velocity measurements, we take a net flow by summing all 96 cycles within a 24-hour period. Since this is a tidal region, we have reversed flow as well as positive flow out of the springs. The net water flux (sum of positive and negative flows) we report as a daily average fresh water discharge.

The main principle of using natural radon to estimate SGD is based on the assumption that groundwater is the only significant radon source to the water column (Cable et al., 1996; Cruisius et al., 2005; Burnett and Dulaiova, 2006; Swarzenski et al., 2007). Two corrections were made to the measured radon-in-water concentrations. Since our measurement system was deployed at some distance from the main spring source, to correct for the ^{222}Rn decay while the water travels downstream we calculate an average transit time for each individual positive stream discharged segment and correct for ^{222}Rn decay during transit. A second correction is made for radon evasion to the atmosphere for the same time interval is applied using data for wind speed and water temperature according to gas exchange equations presented by Macintyre et al. (2005). To convert radon fluxes into water flux we divide the estimated radon fluxes crossing the measured cross-section area by the radon concentration measured in the groundwater. For the radon-in-groundwater end-member concentration, we used an average of the radon activities recorded during the Main Rise time-series deployment during April-May 2009. During this deployment the salinities at the main spring were about 2 and the average radon concentration was 3.07×10^3 Bq/m^3. As in our salinity-stream velocity approach we sum all the positive and negative values to get a net flux to account for any re-circulated water contributions and present the result as an average daily fresh water SGD.

2.4 Calculating spring discharge using a salinity two-box model

To verify the estimates derived by the previously described approaches, we developed a simple two-box mixing model that is independent of any stream-velocity measurements. For these SGD evaluations we use concurrent salinity time-series measurements recorded near the Main Rise (S_1) and from the research platform (S_2). In this model each of these two sampling points is considered as an individual box with their respective volumes V_1 and V_2. We assume that the sum of these two volumes comprises the total volume of the rectangular prism-shaped spring area. The mixing equations for each box are:

$$V_1 \times S_1^0 + V_s \times S_s - V_s \times S_1^1 = V_1 \times S_1^1 \tag{1}$$

$$V_2 \times S_2^0 + V_s \times S_1^1 - V_s \times S_2^2 = V_2 \times S_2^2 \tag{2}$$

Where V_s is the volume discharged by the springs for each 15-minute measuring interval. We envision this model as a two-step, two-box mixing process:

1. At t_0=0 the measured salinities of boxes V_1 and V_2 are respectively S_1^0 and S_2^0
2. At time $t_1=t_0+15$ min spring water V_s with salinity $S_s = 0$ is added to the first box of the canal which induces an equal volume replacement/transfer from the first to the second box and from the second box to offshore. The transferred volume water from the first to the second box has salinity S_1^1, a resultant salinity of the mixing of the first box with spring water, while the transferred volume from the second box offshore has salinity S_2^2 which was made up from water mixing of the first and second boxes. In all cases the net transfer volume between boxes is equal to the initially discharged spring volume water V_s, which is what we what to know (equations 1 and 2).

A third equation for the total volume of the area can be written assuming it has a rectangular prism shape, i.e., vertical walls on each side:

$$V_1 + V_2 = L \times W \times d \qquad (3)$$

Where: L is the distance between the platform and the Main Rise; W is the width of the spring canal; and d is the average water depth for each 15-minute measuring cycle. After solving for V_1 and V_2 in equations (1) and (2) in terms of the other parameters and substituting into equation (3) one can evaluate the volume of the discharged volume water and the only remaining unknown V_s. We then average each set of 15-minute flux increments and express the final result as a daily average fresh water discharge.

A basic assumption in our model is that the distance between our measuring unit and the source (L) and width of the canal (W) are constant. While the assumption for the first parameter is always valid, we deployed our instrumentation at the same distance from the main spring source every time, one could argue that the cross-sectional area in terms not only of water depth (d) but also as width of the canal (W) varies with the tidal stage. We measure the depth continuously during our field deployments so that parameter is adjusted as needed. Field measurements of the canal width performed on a regular basis by USGS personnel show that the deviation from the average value we used in our calculations could be as large as 10-15% (R.J. Verdi, pers. comm.). We feel that such an uncertainty of this parameter is acceptable for SGD evaluations of these orders of magnitude.

3. Results and discussion

3.1 Horizontal and vertical surface ^{222}Rn and salinity distribution

In October 2007 under a moderate spring flow regime, a survey revealed strong salinity and radon gradients (**Fig.4**).

The salinity within the spring canal area, where most of the springs are situated, was between 6 and 13 and the radon inventories were up to 133-218 Bq/m^2. In contrast we observed high salinities (up to 32) coupled with low radon (2-20 Bq/m^2) in nearby offshore areas.

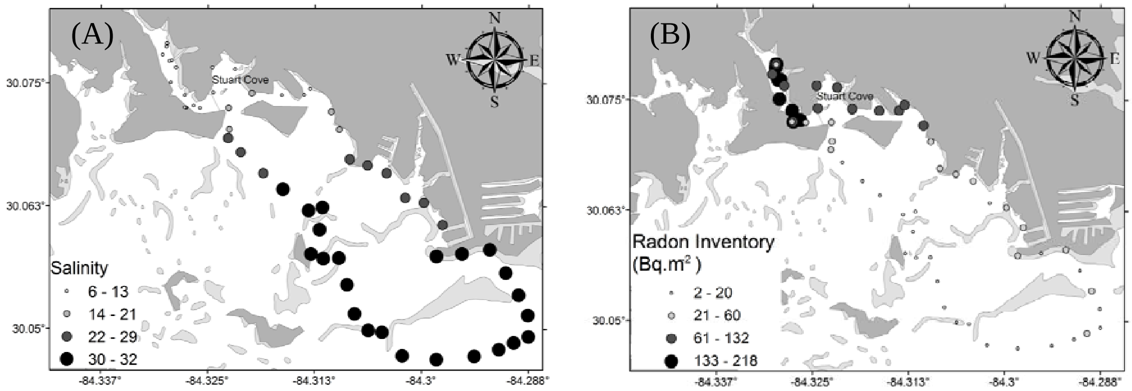


Figure 4 Salinity (A) and radon inventory (B) distributions throughout the area during a survey in October, 2008.

The strong reverse correlation (R^2=0.87) observed on a large horizontal scale through the area (**Fig. 5**) suggests that fresh water from the springs is the major source for radon in the water column.

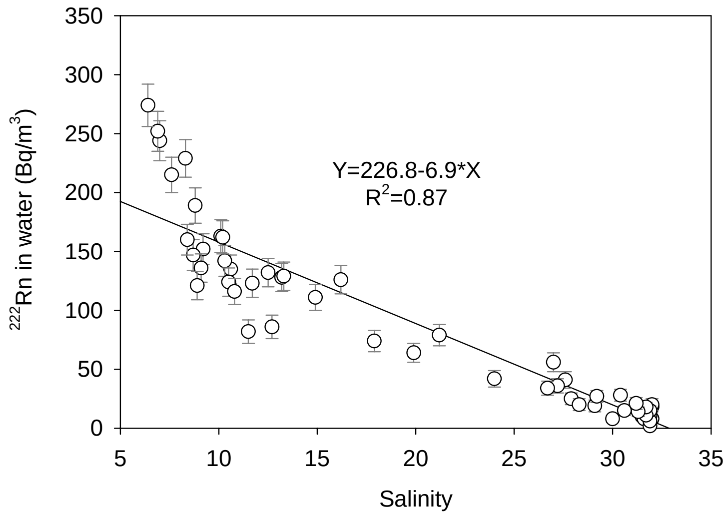


Figure 5 Radon vs. salinity correlation during a survey in October, 2008 (**Fig. 4**).

A reverse correlation between salinity and radon was also evident during the outgoing tide in most cases in our time-series observations (**Fig. 6**).

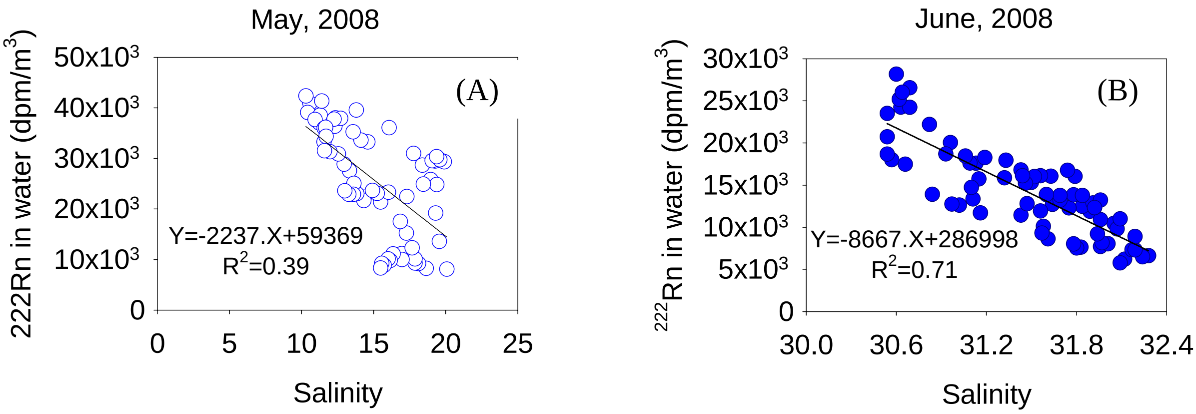


Figure 6 Radon vs. salinity relationships under (A) low salinity; and (B) high salinity conditions. The presented data is selected from the outgoing tide intervals from deployments in (A) May 2008 and (B) June 2008.

Our time-series deployments from the platform between August 2007 and May 2009 also revealed some interesting fluctuations of salinity and radon-in-water concentration in the surface water. We observed some extreme salinity and radon variations during this period. For example, as a result of a very strong rain (total of 173 mm) at the end of February 2008, the salinity dropped from about 27 to 2 only two days after the storm. The radon-in-water concentrations dramatically increased in parallel by about two orders of magnitude, from about 300 Bq/m^3 to about 7200 Bq/m^3 (**Fig. 7**).

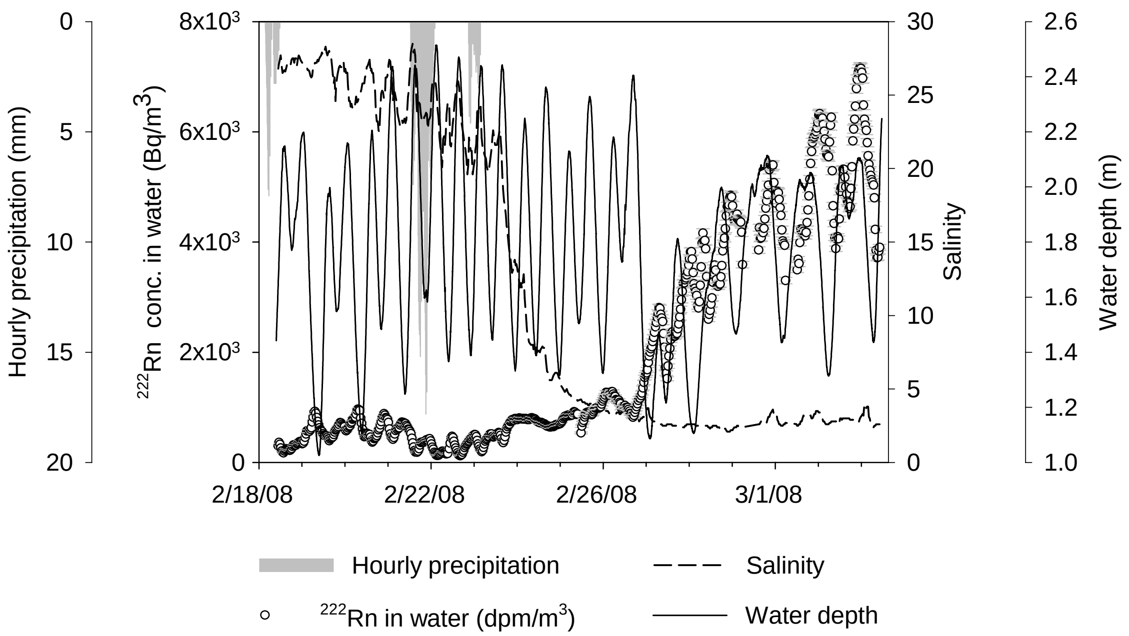


Figure 7 Radon-in-water time-series measurements during a February 2008 fresh water breakthrough event.

The results from a five-point salinity depth profile deployment in April-May 2009 from the platform confirmed previous measurements that the water column in the area is only slightly stratified during spring flowing conditions (**Fig. 8**).

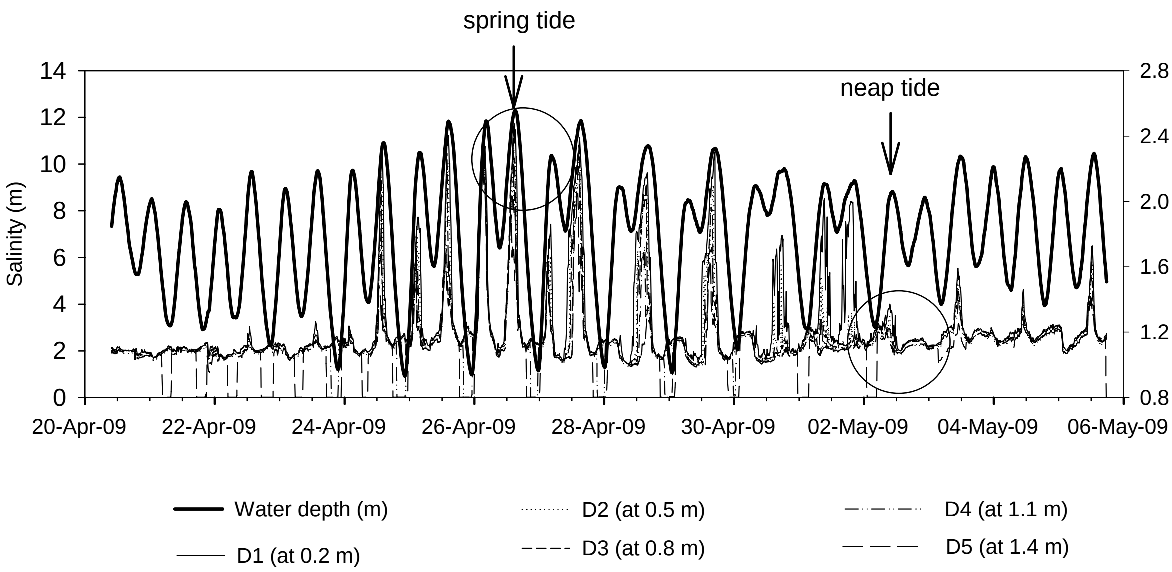


Figure 8 Salinity depth profiles during deployment April-May 2009. Five CTD divers were deployed at different constant distances from the bottom: D1 at 0.2 m, D2 at 0.5 m, D3 at 0.8 m, D4 at 1.1 m, and D5 at 1.4 m. In places where salinity drops to zero, the respective CTD diver was exposed out of water because of very low water level. During the deployment we observed pronounced spring and neap tide water column stratification.

As one could expect, larger differences in the salinities were observed during spring tide stage compared to neap tide. An example of the spring tide depth profile (**Fig. 9**) shows that there is really only a significant halocline during the highest tide and, at that time, it lies between 1.5 and 2.5 m water depth.

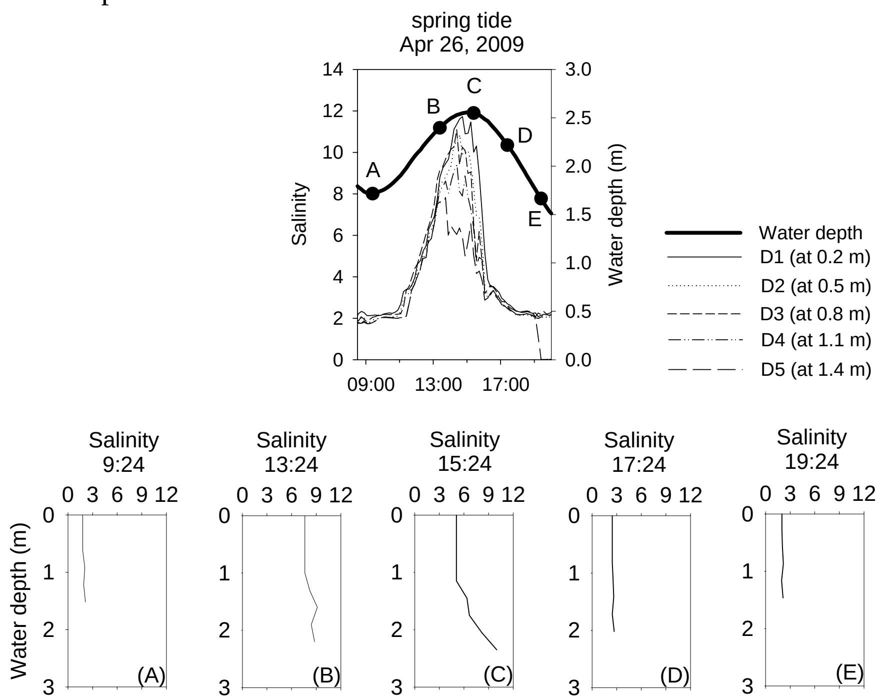


Figure 9 Salinity depth profiles at several points during the spring tide of April 26, 2009.

The largest difference in this specific case was ~6 parts per thousands. We thus think that even in spring flowing conditions stratification is not very significant. An illustration is given by the salinity profile during neap tide (**Fig. 10**) where the differences between the surface and bottom salinities were very small.

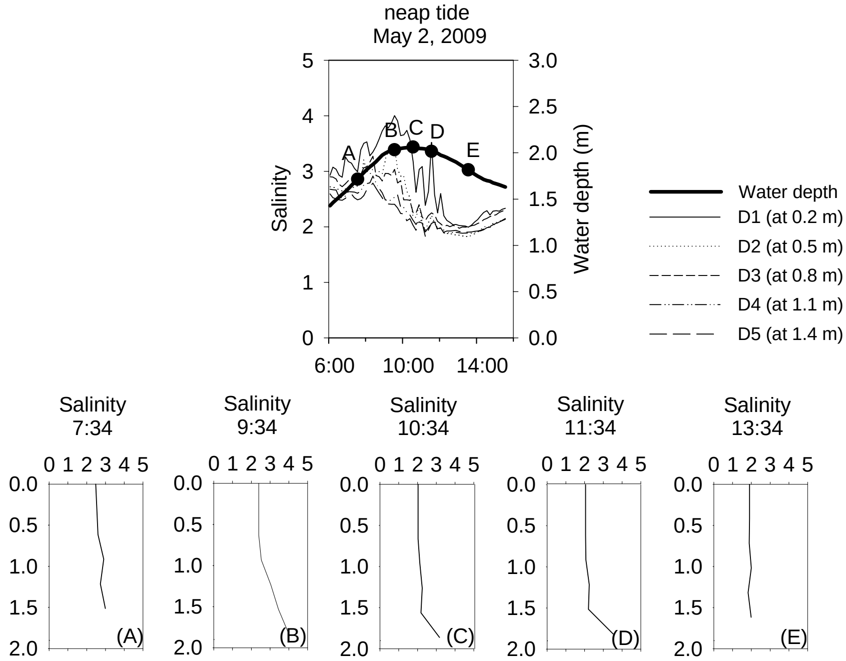


Figure 10 Salinity depth profiles at several points during the neap tide of May 2, 2009.

Thus for our salinity-stream velocity SGD estimations we used a stratified water depth (1.5 m) only for spring tide stages and during spring flowing conditions. In cases where there was very low or no spring flow at all, we assume that there is a vertically well-mixed water column.

3.2 Comparison of spring discharge estimates

The results from the three previously described methods applied to evaluate the spring flow during the study period are displayed in **Table 1**. These results are compared to independent estimates provided by the USGS (Verdi, 2008) which are based on the methodology of Ruhl and Simpson (2005) and use only gauge height and stream velocity measurements. All four methods show similar flow fluctuation pattern (**Fig. 11**) and very good agreement in estimating the spring water flux through the study period.

The highest discharge (~3.0 x10^6 m^3/day) was recorded during March 2008. These high flow conditions were preceded by local strong rain from the end of the previous month (**Fig.7**). The high flood conditions during hurricane Fay in August 2008 resulted in discharge which was estimated by all four methods as around two thirds of the one in March 2008. All calculations, except the two-box model, resulted in "negative" water fluxes during the summer of 2007 and June-July 2008. These negative fluxes are recorded after long periods of drought which has resulted in a low water table and high salinity in the Spring Creek area (Fig. 3). These observations suggest that significant salt water intrusion occurs during periods of drought, even in an area characterized by the very large springs. Abnormally high radon concentrations coupled with high salinity during these periods support this hypothesis.

Table 1 Numerical data of the springs' discharge presented in **Fig.11**.

	USGS	Sal-SV	Rn-SV	Box Model
Jul-07	-2.72E+05			
Aug-07	-1.37E+05	-9.52E+03	-3.19E+04	
Sep-07	-2.91E+05	4.24E+04	7.12E+04	
Oct-07	-1.68E+05			
Nov-07	-5.65E+04			
Dec-07	-5.65E+04			
Jan-08	9.17E+04			
Feb-08	1.15E+06	1.50E+06	1.58E+06	
Mar-08	2.96E+06	2.59E+06	2.86E+06	2.62E+06
Apr-08	2.17E+06			2.51E+06
May-08	1.82E+05	-1.27E+04	1.44E+04	1.26E+05
Jun-08	-6.26E+04	-8.72E+04	-6.59E+04	8.77E+04
Jul-08	-3.23E+04	-6.14E+04	-4.50E+04	
Aug-08	1.15E+06	9.91E+05	1.10E+06	1.13E+06
Sep-08	1.64E+06	1.71E+06	1.48E+06	1.58E+06
Oct-08		9.03E+05	1.56E+05	1.70E+06
Nov-08		9.85E+05	6.68E+05	6.45E+05
Dec-08				1.34E+06
Feb-09				1.54E+06
Apr-09		8.76E+05	1.93E+06	
May-09		1.14E+06	8.51E+05	

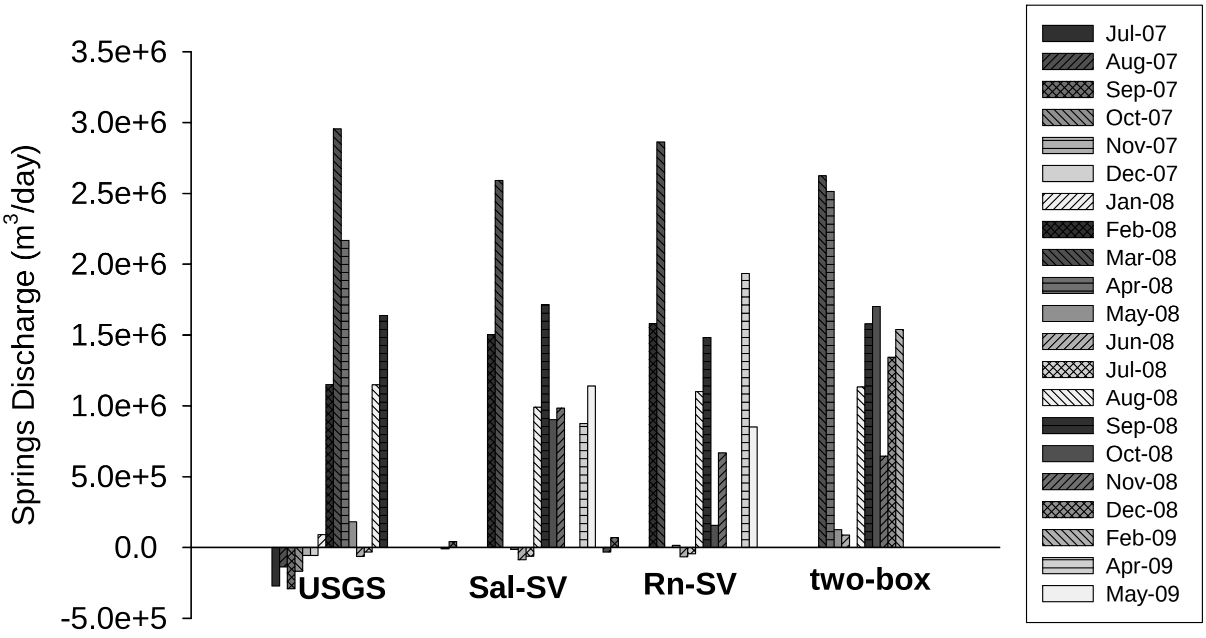


Figure 11 Comparison results of four different methods for estimation the springs' discharge during 2007-2009: "USGS" are the estimates based on Ruhl and Simpson (2005), "Sal-SV" and "Rn-SV" are the estimates based on <u>sal</u>inity and <u>s</u>tream <u>v</u>elocity, <u>Rn</u>-in-water concentration and <u>s</u>tream <u>v</u>elocity measurements, and the "box-model" evaluations, respectively.

4. Conclusions and implications

The hydrological regime of one of the largest submarine spring systems in the world was monitored during and after a period of prolonged drought using salinity and radon-in-water measurements. We observed a wide range in salinity and radon during periods of drought alternating with large local rain storms. The rapid response in the coatal waters suggest that the surficial aquifer is one of the major contributors for SGD in the area. Substantial saltwater intrusion, negative net water discharge, was evident during both 2007 and 2008 summers in the research area, while high flow spring conditions were observed twice a year during spring (March-April) and mid-late summer (August-September in 2008). The spring flow during our research period never reached that reported by Rosenau et al. (1977). The maximum flow recorded in March 2008 (~$3x10^6$ m^3/day) was only about two thirds of that reported a few decades ago. This may be a concern of the water management in the state.

Acknowledgments

The authors would like to thank the graduate students from the Department of Oceanography at Florida State University who helped during our multiple deployments at the Spring Creek Springs area. Special thanks to R.J. Verdi and Sandra Holt (USGS, Tallahassee) for providing the data for stream velocity and their spring discharge evaluations for years 2007 and 2008. Scott Barrett Dyer (Florida Geological Survey) helped sampling during different periods of this research. Financial support was provided by the Florida Geological Survey, Department of Environmental Protection contract #GW-275.

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