AERIAL THERMOGRAPHY SURVEYS TO DETECT GROUNDWATER DISCHARGE IN THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT, NORTHEAST FLORIDA

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ABSTRACT

The hydrogeologic setting of the 18 counties that comprise the St. Johns River Water Management District (District) in northeast Florida provides ideal conditions to use aerial thermography surveys to detect groundwater discharge. Aerial thermography surveys were conducted on over 1,400 line kilometers of 2,800-meter swath widths. Three examples from these surveys are presented to show the thermal signatures of groundwater discharge in a variety of settings.

The sites include the second magnitude (10-100 cubic feet per second (cfs) Croaker Hole Spring located in the St. Johns River in Putnam County, the famous first magnitude (>100 cfs) Silver Springs in Marion County, and some low flow springs in the Rodman Reservoir section of the Ocklawaha River in Putnam County. The Croaker Hole site is presented to show a single spring discharging into a river dominated by surface water flow. The Silver River in Ocala, Florida includes two spring vents at the headwaters (Mammoth Springs) and 28 additional vents in the upper 1,200 meters downstream and is therefore a system where the primary river flow is comprised of groundwater discharge. Three new springs were identified and documented by divers with video and at least six other sections in the river show evidence of discharge but need to be field verified. Rodman Reservoir provided an opportunity to see discharge into a reservoir under pre- and post- drawdown conditions.

Techniques for identifying groundwater discharge from the thermography data include simple color mapping of the pixel values in a GIS and ESRI Hot Spot Analysis using the Getis-Ord GI* spatial statistic (Ord and Getis, 1995).

KEY WORDS: aerial thermography, springs, groundwater

INTRODUCTION

Aerial thermography surveys have proven to be a very useful tool to locate groundwater discharge to surface water bodies within the St. Johns River Water Management District (District) in northeast Florida (Figure 1). The source aquifer for the discharge is the Floridan Aquifer System that underlies all of Florida and is under artesian conditions in over 40 percent of the District. Discharge is generally between 21° to 25° C. Discharge may occur as spring flow from vents in limestone near the surface or diffuse flow through minute passageways in the semi-confining units that overlie the Floridan Aquifer. In many cases the discharge is easily ground-truthed in the field since it forms the headwaters of a spring run or the volume is sufficient to create visible waves (boils) on the surface of a pool or stream, or in the bottom sediment and grasses. In other cases the discharge may be obscured by water depth or clarity, vegetation, or low flow volume.

Within the District there are 91 named springs (some of which have multiple discharge points) that have been field verified. All of the known discharging springs that were surveyed resulted in identifiable thermal anomalies. These known springs also provide good reference values for interpretation of the data in other areas of a water body. Springs with discharge as low as 3rd Magnitude (1 – 10 cubic feet per second (cfs)) were detected.

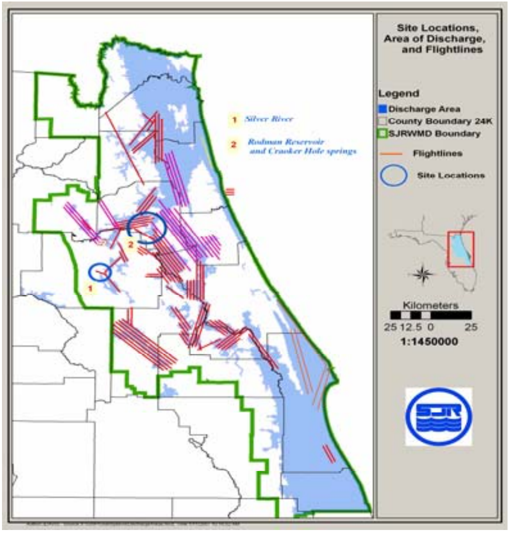

Figure 1. Location of sites, area of potential discharge, and flight lines of aerial thermography surveys. Boundary of the St. Johns River Water Management District is shown in green. Sites discussed in this report are located within the blue circles.

Thermography surveys are flown in the winter when there is maximum contrast between the surface water and groundwater temperatures. The temperature measurements derived from emittance of thermal infrared radiation from surfaces provide a more efficient and effective means to identify groundwater discharge than measurements with a standard thermometer. The Stefan-Boltzmann Law states that the emissive power, P, from a black body is directly proportional to the fourth power of its absolute temperature ($P = A\sigma\in T^4$) where σ is the Stefan-Boltzman constant (σ =5.78E-8 $W/(m^2\ K^4)$, A is the area, $\in$ is emissivity, and T is the absolute temperature (degrees Kelvin) of the source. The implication of this to our surveys is that small changes in absolute temperature can have much greater impact on emissive power. Springs may be missed by measurements with a standard thermometer because the actual temperature may vary only slightly within a short distance from the discharge whereas the aerial thermography signature will be much more pronounced. Detecting the relative changes (i.e. thermal anomaly) in thermal emittance from one point to the next is more important for our purposes than knowing the absolute temperature values.

This paper presents results from sections of the thermography surveys at three sites within the St. Johns River Water Management District. Discussion of techniques that are being used to identify groundwater discharge from thermal anomalies and verification of the interpretations is included. The three sites include Croaker Hole in the St. Johns River in Putnam County south the town of Welaka, the famous Silver Springs in Marion County, Florida, and section of the Rodman Reservoir in the Ocklawaha River in Marion County, Florida (Figure 1).

METHODOLOGY

Aerial Thermography Survey

The District has obtained aerial thermography surveys (thermography) for more than 1,400 line kilometers over lakes and rivers. All known springs that were surveyed could be identified in the resulting imagery. All of the aerial thermography data for the different sites were collected through contracts with SenSyTech, Inc. (now known as Argon ST, Inc.) based in Ann Arbor, Michigan. Silver Springs was included in a cooperative agreement with the Florida Geological Survey (FGS) in which the FGS contracted directly with SenSyTech, Inc.

The contractor was provided flight line maps and coordinates for start-of-line and end-of-line points. The location of the lines flown to date are shown in Figure 1. The Silver River line covered the entire length of the river with a 2,800-meter swath width. The known spring discharge areas in the Silver River provide some definitive control points for interpreting the temperature data. The majority of surveys were collected at two-meter pixel resolution since any significant discharge should affect the temperature of an area at least that size and a larger swath width is covered than when surveys are run at a one-meter resolution.

A dual port Airborne Multispectral Scanner (AMS) was used to collect the data. The AMS is capable of gathering 8 bands in the visible/near infrared spectrum and includes a dual element Thermal-Infrared detector. The system includes an internal blackbody (a theoretical perfect radiator with an emissivity of 1.0) calibration reference source to insure accuracy and repeatability of the data set. The Silver River and Croaker Hole surveys were flown on February 19, 2003 when the ambient air temperature was around 6° C and groundwater discharge was around 22° C. The survey was flown at an altitude of 5,200 feet above mean sea level at a ground speed of 176 knots and two-meter pixel resolution. Two surveys were flown at the Rodman Reservoirs site. The first was completed on February 19, 2003 with an air temperature of 6° C and an altitude of 5,200 feet resulting in a two-meter pixel resolution. The second survey was flown of February 12, 2005 with an air temperature of 10° C, an altitude of 2,600 feet resulting in a one-meter pixel resolution. The second survey was flown to take advantage of a controlled drawdown of the reservoir. It was anticipated that more discharge could be seen since the springs would not be submerged and the lower pressure would allow more flow.

Identification of Groundwater Discharge

Two methods are being used to identify temperature values that are potential indicators of groundwater discharge. Both methods involve the Geographical Information System (GIS) functions within ESRI ArcMap v. 9.1. The simplest method involves using the temperature values from known springs in the survey to derive a color map based on a defined temperature interval. This works best for cases where there is one spring and the discharge is significantly higher than the surrounding waters. A histogram of temperature values can be used as a start point from which to bracket the color mapping scheme (Figure 2). In the case for the Silver River data the temperature ranges between approximately 10° to 22°C is representative of the water areas and those below 10° are the land areas. The pixels with temperatures between 16° to 22°C occur much less frequently and occur at the primary site of discharge in the upper 1,200 meters of the spring run that comprises the Silver River. By creating a cold-hot color scheme that highlights the temperatures above 16° in shades of black and red, the location of the main discharge area is delineated. Further experimentation with refined temperature intervals and color choices tends to refine identification of discharge locations. Though this is somewhat subjective it provides a very quick way to narrow down areas for field verification.

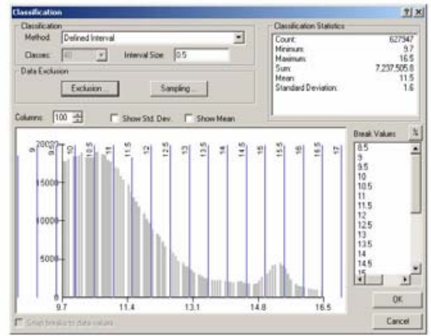

Figure 2. Histogram from Silver River thermography data showing the temperature distribution commonly associated with the primary warm groundwater discharge (>16° C), cooler spring run mixed with secondary groundwater discharge (10°-16°C), and surrounding cold land areas (< 10° C).

A limitation of this method occurs for the river sections where groundwater discharge temperatures are different than the surrounding neighbor pixels but not within the range of the maximum temperatures. The values between 10° C and 16°C may be baseflow or groundwater discharge. Temperature changes (anomalies) within a small area are the key to identification rather than the actual value. For this case a two-tiered color scheme could be used. Again, since relative changes in temperature over a discrete area is what is being sought this provides a quick way to assess the data.

Another tool to identify potential areas of discharge is to use cluster analysis to calculate the Getis-Ord Gi* (Ord and Getis, 1995) spatial statistic. This statistic identifies clusters of points with values higher in magnitude than would be expected by random chance (ESRI developer network documentation library). The Gi* statistic identifies whether high values or low values tend to cluster in a particular area. A high value of the statistic indicates areas where the temperature exceeded the mean of the values. The Hot Spot Analysis tool in ESRI ArcToolbox v. 9.1 provides a method to render a shape file that includes a field for the Gi* z score values. Though this is mostly used for point data it can also be effective for pixel data on a regular grid (Wulder and Boots, 1998). This can be useful for conditions like Silver River where the pixels from spring discharge is different from the main stream (such as in the 10° to 16°C areas in Figure 2 histogram) but less than the pixel values at the head spring area. It is also useful when a general area of scattered high values can be seen from the color mapping but a more refined location is needed such as the example presented for Rodman Reservoir. A distance threshold is required to limit how far the analysis extends beyond an individual pixel. This can include a fixed distance, Inverse Distance, Inverse Distance Squared, and a Zone of Indifference (which is a combination of fixed and inverse distance).

GROUND TRUTHING

Verification that the identified thermal anomalies are related to groundwater discharge is based on either historical site visits or recent field investigations specifically designed to document the discharge. At Silver River discharge sites were documented with underwater video by divers from Karst Environmental Services (KES, 2006) and coordinates for individual discharge points were determined with a Global Positioning System by staff of the SJRWMD and Florida Geological Survey (FGS). Verification at Croaker hole comes from historical records, visual observations of the boil on the surface of the St. Johns River, and reports from private recreational divers. Field visits to the Rodman site provided visual confirmation for Blue Springs and reports of springs in the Ocklawaha

River. Abbott (1971) provided reference to seven springs in the vicinity of Blue Springs but the exact locations where not documented sufficiently to correlate them to the observed locations of the thermal anomalies in that area. More diving reconnaissance is planned for other thermal anomalies located downstream of the site in the Silver River discussed in this paper.

THERMOGRAPHY SURVEYS

Croaker Hole Spring Thermography

Croaker Hole in the St Johns River near Welaka, Florida provides an example of a single spring vent and how simple color mapping can readily identify the spring discharge. The spring flows into a river that is predominately comprised of surface water. The discharge has ranged from a minimum of 62.0 cfs in 2001 to a maximum of 90.5 cfs in 1998 (Osburn and others, 2005). The mean discharge from the period of record is 76.2 cfs. The discharge temperature since 1995 is 22.9 degrees C. There is a single vent approximately 30 feet below the surface of the river and a visible "boil" can be seen when the river is calm. Lateral movement of the spring discharge can be seen along the west bank as the north flowing St. Johns River carries the discharge downstream. No other discharging vents are present in the area.

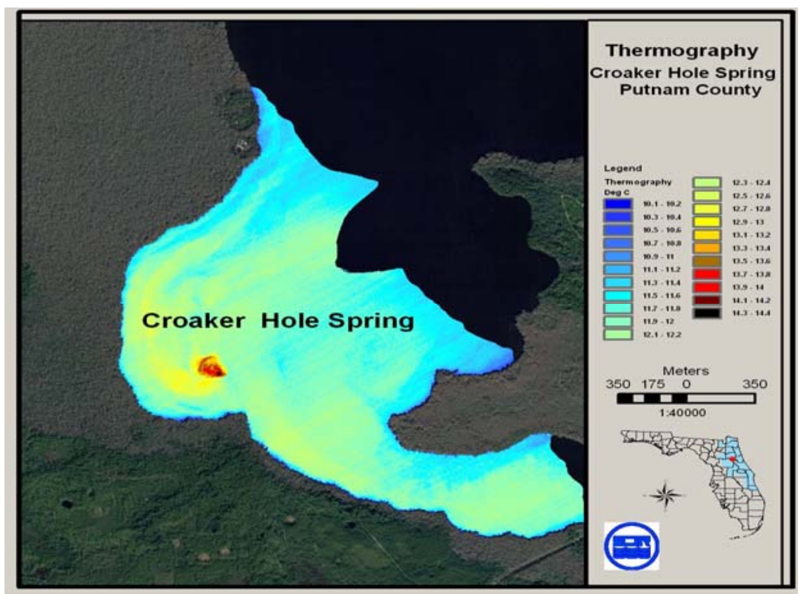

Figure 3. Thermography data for the Croaker Hole Spring in the St. Johns River, Putnam County.

Silver River Thermography

The Silver River in Marion County, Florida provides an excellent opportunity to see results of thermography in a variety of discharge settings. The rivers' headwaters includes the famous Silver Springs that discharges a mean of 761 cfs from two vents 40 feet below the surface of the spring basin (two western dots in upper panel of Figure 4) and from at least 27 other discharge points within the upper 1,200 meters of the spring run (Figure 4 – upper panel). Approximately half of the flow comes from the two main vents at the western headsprings. It has been historically thought that the discharge from the upper 1,200-meter springs comprises the majority of the flow in the Silver River. Historically, mapping of spring sites has been based on locations described from tour operations, various scientific investigations (Odum, 1957, KES, 2006, Hutchenson et al, 1993, Munch et al, 2006), and local lore. An attempt to document the location of the various vents and correlate them to historical names was done in 2005 by staff of the SJRWMD and FGS. During this process thermal anomalies identified in the thermography data were investigated. Documentation of the character of the discharge points was done using underwater video by divers of KES (2006). Flow measurements were made at some sites and water quality samples were taken (Toth, 2007). The thermography survey covered the entire run of the Silver River and results from all sections of the river along with seismic profiles showing subsurface structure below the thermal anomalies is pending (Davis, 2007).

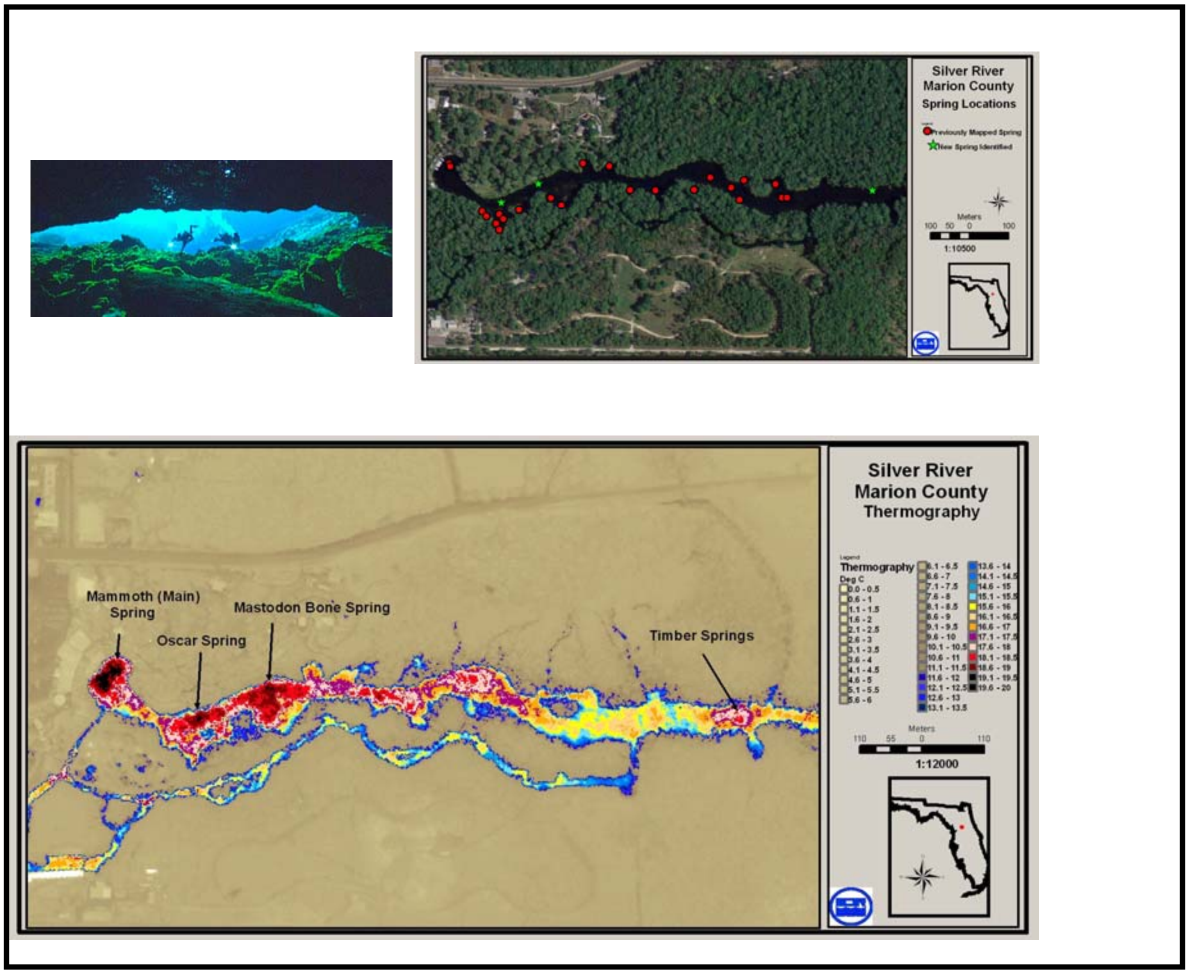

Figure 4. Location of mapped spring vents (upper right), divers in the east vent of Mammoth Spring (upper left), and thermography data from the upper 1,200 meters of the Silver River (bottom).

The Silver River thermography data presented in Figure 4 is color mapped on 0.5 degree C increments. The discharge area from the two Mammoth Spring vents is mapped in black to emphasize the maximum value encountered. Areas where there is no discharge are mapped in blue. Since nearly 50 percent of the discharge from the upper 1,200 meters of the river occur from Mammoth Springs, one would expect that the lower volume discharges downstream would be masked.

The Mammoth Spring data demonstrates the major advantage of thermography data over standard temperature measurements. It can be seen that the temperature values drop nearly three degrees within 130 meters from the source discharge. Measurements made by this author at multiple sites, inches below the water surface varied less than 0.5 degrees for over 200 meters downstream. A temperature increase occurs again where the next group of spring vents occur about 130 meters downstream near Oscar and Mastodon Bone Springs.

This group of spring vents are in water depths of about 5-30 feet. Though the discharge from Mammoth Springs did not mask the group of vents downstream, the close proximity of the numerous vents in the downstream area make it difficult to identify a thermal signature from every single vent. The discharge from the four vents west of Oscar Spring is in a deep area and moves laterally downstream before reaching the surface thereby making the hot area be offset in the thermography data. The two hot spots labeled Oscar and Mastodon Bone springs were previously unidentified. Divers from the KES team located and videoed the discharge sites. These sites were in water less than 10 feet deep but have lower flow volumes. Some of the vents downstream of Mastodon Bone Spring and upstream of Timber Springs can be associated with a thermal anomaly however the temperature of the general area is elevated relative to the base stream flow. Deep-water depths and low flow volume are probably the reason some vents are less obvious in the thermal imagery. Timber Springs represents a third newly discovered vent complex. A high temperature anomaly approximately 65 meters long is associated with several vents videoed by divers at this site. Other areas in the channel to the south of the main spring run also show sites of potential discharge but have not been verified yet. The thermal imagery in the rest of the Silver River has numerous other sites that are suggestive of discharge and preparations are being made to investigate these.

Southwest Rodman Reservoir
Ocklawaha River, Marion County

The Rodman Reservoir was created when the Ocklawaha River was dammed as part of the ill-fated Cross Florida Barge Canal. Though the project was aborted in 1971 the impoundment remained and a dam provides a mechanism for periodic drawdowns. This site provided a unique opportunity to compare the ability of thermography to detect groundwater discharge when the reservoir was in a drawdown stage as well as the stage during impoundment. The impoundment causes a large area around the river to be submerged which can have a major impact on the discharge from springs.

There are two springs in the area of interest that have historical records and location coordinates in the District inventory (Osburn and others, 2005). Blue Spring – Marion is a 3^{rd} magnitude spring (1- 10 cfs) with a mean flow of 5.0 cfs based on limited measurements from October 1935 to present. Catfish Springs is located west of Blue Spring – Marion and the discharge has not been measured however a boil on the surface can be observed (Osburn and others, 2005). A total of seven springs have been referenced (Abbot, 1971) but location information is not well documented. While the simple color mapping techniques were useful for some of the springs for the surveys during submergence, further analysis using the Getis-Ord Gi* spatial statistic was helpful in some cases to pinpoint the location of discharge.

The first thermography survey was flown on February 19, 2003 in a pre-drawdown condition. The location of Blue Spring – Marion and Catfish Springs can be seen in Figure 5 and are used as reference that the spring discharge produces “hot spots” in the 15 – 18 degree C range. West of Catfish Springs an area of diffuse hot spots can be seen. The red pixels enclosed in the blue box in Figure 5 are generally in the 15 – 15.5 degree C range but are not as concentrated as they are at the two known springs. This area was chosen for a cluster analysis to calculate and map the Getis-Ord Gi* spatial statistic in an effort to identify where the warmer pixels are clustered and therefore identify the most likely location of the source of discharge. The tool in the ESRI ArcToolbox allows the user to run the analysis for different distances from a pixel and to specify a weighting method. For this analysis, distances of 8 meters, 16 meters and 30 meters were tested. Inverse distance was used for weighting since it was expected that the temperature differences would be most pronounced near the source. Clustering of high values could be identified with a larger distance band however individual springs may be missed. The 16-meter distance is presented here because it is more representative of the size of the area that the spring discharge is expected to have the most impact and could therefore resolve the individual springs.

Figure 5. Thermography of southwest section of Rodman Reservoir on February 19, 2003 before drawdown. Location of known springs is identified. Blue rectangle delineates area of hot spot analysis seen in Figure 6.

The results of analysis to calculate the Gi* statistic for the area delineated by the blue rectangle in Figure 5 is presented in Figure 6. A cold to hot color scale is applied to show areas where the clusters of pixels that indicate spatial association of high values (Gi* > 0, black/red) and low values (blue). The areas that indicate spatial association of the negative values (Gi* < 0) have been masked since they are of no concern for this application. Seven distinct areas with the highest values can be discerned and are numbered on the figure. Site number 2 with the black area has the highest values and is therefore the most likely location where a spring would be found. Sites 4, 5, 6, and 7 have the next highest values and sites 1 and 3 are the lowest but are still positive and may therefore indicate springs.

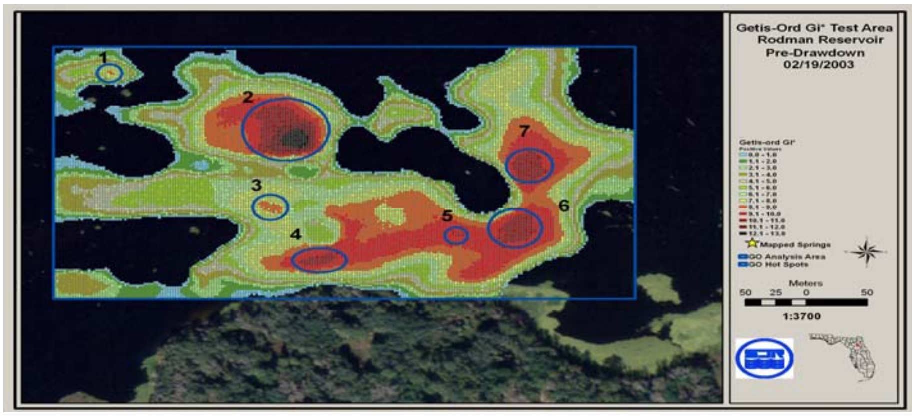

Figure 6. Map of the Getis-Ord Gi* statistic for the test area in Rodman Reservoir. The sites where groundwater discharge is most likely to be located are circled. The blue rectangle delineates the same area shown in Figure 5.

The sites provide a more focused point to ground truth the discharge. Several key factors should be considered when trying to locate the discharge in the field. Since the thermography data identifies radiant temperature at the waters surface, the source water may not necessarily lie directly below the high temperature values. Discharge volume, currents in the water body, and water depth may greatly impact this variance.

In 2005 an opportunity to evaluate the groundwater discharge into the reservoir during a planned drawdown occurred. The drawdown reduced the reservoir stage thereby exposing the springs and allowing more flow due to the reduced head pressure. A monitor well located approximately 2.5 kilometers southeast of Blue Springs – Marion indicated that the difference between the potentiometric surface of the Floridan Aquifer and the reservoir stage was 1.03 feet during the 2003 survey and 8.65 feet during the 2005 drawdown survey.

A thermography survey was flown on February 5, 2005 at an altitude of 2,600 feet so a one-meter pixel resolution was obtained. The upper panel in Figure 7 shows the area where the Gi* analysis was performed for the 2003 data and the lower panel shows a zoomed out view of the reservoir. As in Figure 6 the blue circles delineating the hot spot clusters identified by the Gi* analysis are included for reference. The location of Catfish Springs and Blue Springs – Marion can easily be seen in both pre and post drawdown thermography surveys. Site 1 has a Gi* value in upper range of the positive values (8-9) and an area about 15 meters to the north that has high temperature values indicative of groundwater discharge. Sites 2 and 4 have the highest temperature values and a high Gi* value suggestive of springs. Site 3 has similar Gi* values as site 1, however there is no indication of a thermal anomaly in the post-drawdown temperature values Sites 6, and 7 have high Gi* values (10-11), however there is little evidence in the post-drawdown temperature values to indicate springs at those locations. There are four high temperature areas of less than 10 meters diameter that may be discharging groundwater but are too small to effect the pre-drawdown data and were therefore not identified in the Gi* analysis.

Of the seven possible sites identified by the Gi* analysis in the 2003 pre-drawdown data sites 1, 2, and 4 are most likely a result of spring discharge. The other sites may warrant further investigation but more likely related to different hydrologic conditions between the 2003 and 2005 data, or the effects of river currents on the temperature distribution in the 2003 data. Though the two known springs could be identified in the pre-drawdown thermography data by simple color mapping the Gi* analysis provides a means to focus the sites for ground truthing for the areas where the high temperature values are more scattered. Increasing the distance threshold used to calculate the statistic resulted in fewer sites that covered a larger, but similar area. An optimum distance threshold is therefore scaled to the expected size of the area of spring discharge. The distance threshold as well as the total range of values from the cells that have been selected can affect the analysis results.

The post-drawdown thermography in the lower panel of Figure 7 emphasizes the location of the original Ocklawaha River channel, tributaries to the channel formed by spring flow, and the dredged area in the north for the barge canal. At least six other sources of discharge can be identified (yellow circles).

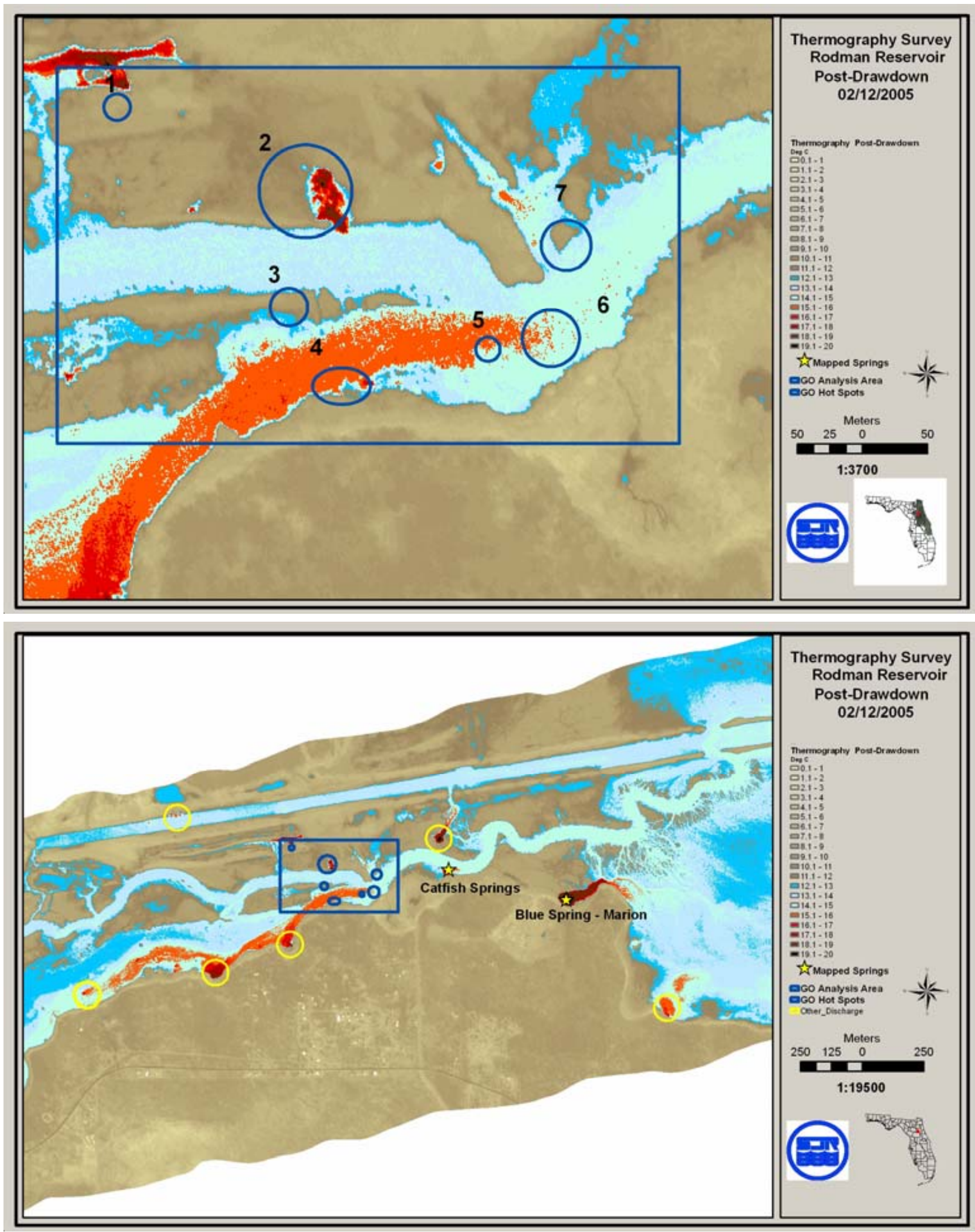

Figure 7. Post-drawdown thermography survey of Rodman Reservoir. A detail of the area where the Gi* analysis was run on the pre-drawdown data is shown in the upper panel and a zoomed out view of the entire area where most of the springs occur is shown in the lower panel.

CONCLUSIONS

Aerial thermography is a very effective tool to identify groundwater discharge in northeast Florida sites during the winter cold periods. Thermal anomalies were identified at all sites surveyed where discharge was occurring at the time of the survey. Previously undocumented discharge was identified at the location of thermal anomalies in the Silver River and the associated spring vents were field verified. Simple color mapping of the pixels based on radiant temperature value provides a quick and effective way to highlight many areas of discharge especially for a case like the Croaker Hole Spring. The major changes in temperature within a short distance of the discharge greatly enhances the ability to narrow down the location of the source spring. Color mapping may require a two tiered color ramp for such cases as when multiple discharge sites occur downstream of a high volume primary spring, spring flow volumes are low, water depths are variable, or multiple vents are present in a close area. In some cases cluster analysis using the Getis-Ord Gi* statistic is helpful to refine the location of discharge for future ground truthing. In the Rodman Reservoir, seven sites were identified with significant clustering of high positive values during a period when the springs were submerged. A survey during a drawdown confirmed the location of discharge at three of those sites. Sites 5 and 6 occur within a warm plume that originates from upstream springs (three yellow circles to the southwest in Figure 7). The clustering indicated by the high positive values offset from the source spring may be a result of currents moving more warm water to those sites before the water reached the surface.

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