DETECTION, MAPPING, AND CHARACTERIZATION OF GROUNDWATER DISCHARGES TO BISCAYNE BAY
SFWMD CONTRACT C-15870

Expanded Final Report

Atlantic Oceanographic and Meteorological Laboratory

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I. INTRODUCTION

In October 2003, the Atlantic Oceanographic and Meteorological Laboratory (AOML) entered into agreement of fourteen months duration with the South Florida Water Management District (SFWMD) to seek to locate submerged groundwater springs in Biscayne Bay and characterize the flow from one or more springs. At the time this effort was initiated, little was known about the specific locations of active springs or quantity of flow from a spring or the flow velocity to be expected from a spring. Selection of proper instrumentation was hampered by this lack of knowledge. Enough knowledge on the flow characteristics of the springs had to be gained before definite sensor selections could be made. Furthermore, it was not clear that the state of the art of sensor measurements was such that commercial instruments could be acquired to measure the (anticipated) very low flow rates and other spring characteristics for the extended deployment times desired. In due course, sensors were selected which were cheap enough to permit measurements at various prospective spring locations. After project personnel determined active spring locations, direct human contact with spring water flow suggested that sufficiently strong flow velocity existed so that an acoustic current meter would be a good choice to measure spring flow velocity. In due course sensors were identified which were cheap to purchase (within the limited budget of the project) to permit measurements at more than one site in Biscayne Bay.

There were significant concerns in undertaking this project about the ability to gather data during peak seasonal flows in springs. It was expected that there should be significant differences in flow between dry and wet-season (May-October) rainfall events. It was planned to gather spring characterization data during both seasons although this hope was tempered by the severe lack of quantitative data both on spring locations and flow strength. Arrangements were made with Dr. Hal Wanless at the University of Miami, to gather bottom and other data in conjunction with the spring study. Since operations had to be conducted from very small boats, e.g. a canoe, field measurement opportunities were limited by weather conditions.

The present expanded final report reports on data gathered by AOML since the project final report of December 2004. These data were gathered in order to permit a more complete examination of spring flow over a period of one year. It was decided to focus in depth measurement efforts on one major spring, the Ricisak spring in order to get reliable data on spring flow and other characteristics over a one year period. With this data in hand future research efforts could be designed with reliable information on major spring flow characteristics.

II. BACKGROUND

Four quarterly reports were prepared for the submerged groundwater springs project dated January 6, 2004, April6, 2004, September 3, 2004 and a final report dated December 6, 2004. Despite conclusion of the time period of the agreement between AOML and the SFWMD in December 2004, AOML personnel recognized that additional spring data was needed and that the opportunity to gather this data was available. Accordingly additional spring study deployments were made in March, June and July of 2005. A schedule of times of sensor deployments and additional data gathered is presented in Figure 1. Note that in 2005 measurements were made not only at the spring, but at two control sites as well. In the March deployment the control site was approximately 200 meters due east from the spring site, while during the July deployment control site was approximately 15 meters due east from the spring site. The data gathered during these 2005 deployments are presented in this expanded final report.

A helicopter survey in October 2003 noted the presence of 16 potential spring sites, some of which had “blurry” surface water suggesting the possibility of active flow. Difficulties were encountered in (small) boat operations so that the number of actual days gathering field data in the first half of 2004 was more limited than originally targeted. Nevertheless, several springs were identified and their coordinates determined (see quarterly reports two and three). Samples of spring water were gathered and analyzed for several chemical constituents (see quarterly report number three). Following direct human contact with major spring flows, it was estimated that flow measurement instrumentation capable of measuring flows in a range from 0.1 cm/sec to 20 cm/ sec would likely be required and that such measurements would have to be made over relatively small spatial volumes, e.g. one centimeter.

In addition to flow measurements, measurements of salinity and temperature of spring water were also required. An initial deployment of salinity and temperature sensors at spring BBS21 in October 2004 resulted in the gathering of 48 hours of temperature and salinity data. From this data which it was inferred, in agreement with earlier qualitative information, that spring flow was strongly influenced by tidal height and that flow out of spring BBS21 occurred during a time when tidal height was less than a specific value (see quarterly report number four). Also deployed in October 2004, was a new, high resolution, coherent Doppler current measurement device. This device failed due to improper placement of “O” ring seals at the factory and was returned for repair. Additionally, several Star-Oddi “Star Oddi” devices, which had been ordered to make measurements at multiple Bay sites, were found to be out of calibration and of questionable stability. In November 2004, several deployments of another system, having temperature, salinity, pressure, turbidity and chlorophyll sensors occurred. The data obtained from these deployments also indicated that tidal height was a strong influence on spring flow.

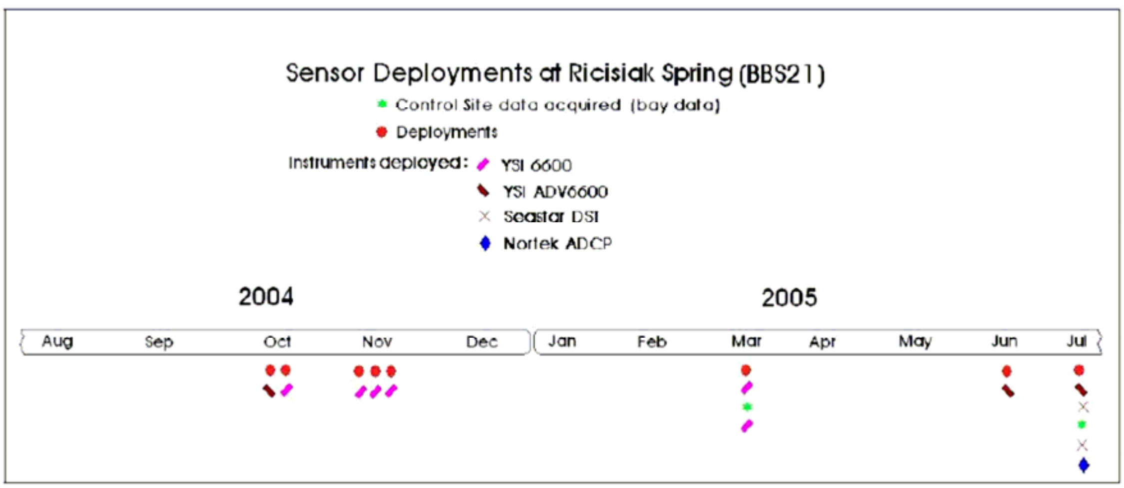
The discussion above summarizes some of the efforts described in projects reports one, two, three and four. What follows below concerns data and activities carried out by AOML since December 2004.

III. Observations

As can be seen from Figure 1, instrument deployments took place in March, June and July of 2005. In the March 2005 deployment a control site, located approximately 200 meters from spring BBS21, was established so that temperature, salinity and water height changes at the control site could be compared with temperature, salinity and water height changes at Spring BBS21 (Ricisak Spring). Later for the July deployments, the control site was moved to a distance approximately 15 meters from the spring site. Current measurements were not made in March due to continuing problems with the YSI ADV 6600 (the instrument again had to be sent back to the factory because of an electronics problem).

Figure 2 shows the locations of Spring BBS21 and control site for the July deployment. Note that the distance of separation of the two measurement sites is about 15 meters.

Figure 3 is a photograph of the BBS21 spring site including the deployed YSI ADV 6600 sensor system. The photo shows the coherent Doppler measurement probe (the probe has three prongs extending from the central support pole and is located at the left of the ADV 6600 package) over the orifice of spring BBS21. Blurry water and slight wave activity are visible in the photo. Note the quantity of vegetation present at the spring site.



10/07/2003 – spring search from helicopter over flight
02/26/2004 – spring search on UM canoe
07/08/2004 – water and sediment samples collected on UM canoe
07/12/2004 – spring search on NOAA boat
07/15/2004 – spring search on UM canoe
08/20/2004 – spring search on UM canoe
08/26/2004 – water and sediment samples collected on UM canoe
09/23/2004 – spring search on UM canoe
10/14/2004 – YSI ADV6600 deployed and retrieved. Instrument got flooded (BBS21).
10/21/2004 – spring search on UM canoe
10/28/2004 – YSI 6600 deployment and retrieval (BBS21)
11/02/2004 – YSI 6600 deployed for extended time and spring search on UM canoe
11/04/2004 – YSI retrieved
11/05/2004 – YSI 6600 deployed for extended time (BBS21)
11/10/2004 – YSI retrieved
11/18/2004 – YSI 6600 deployed for extended time (BBS21)
11/24/2004 – YSI retrieved
03/10/2005 – Two YSI 6600 instruments were deployed for the day. One on the BBS21 spring and the second one 200 meters east
06/16/2005 – YSI ADV6600 deployed on known spring. Water Samples for nutrient analysis.
07/21/2005 – A YSI ADV6600 & Star-Oddi, on the spring and the Nortek ADCP on a control site were deployed for 7 consecutive days.
07/28/2005 – Instruments retrieved.

Figure 1 – Schedule times of sensor deployments and additional data gathered

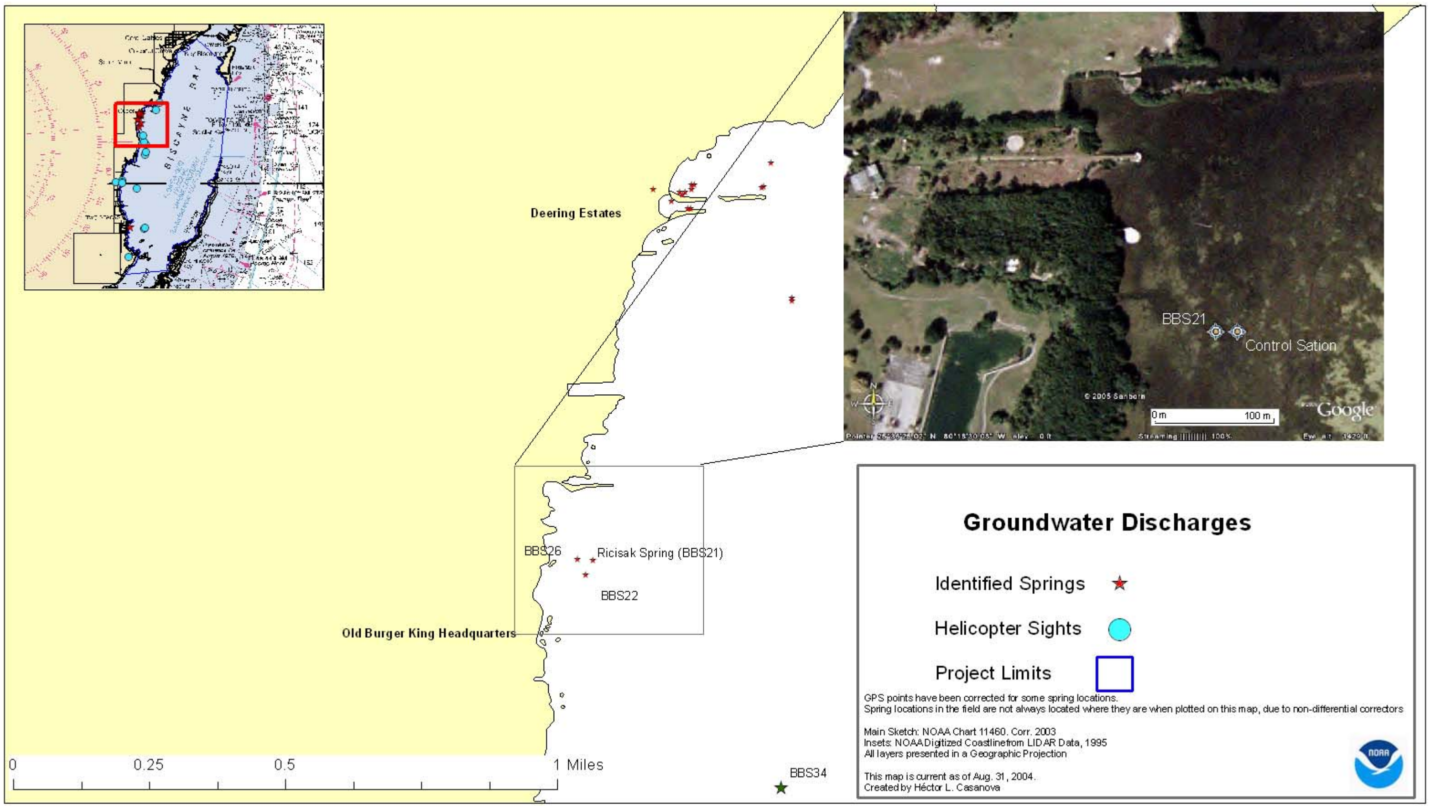


Figure 2 – Location of Spring Site and Control Site during for the July deployment

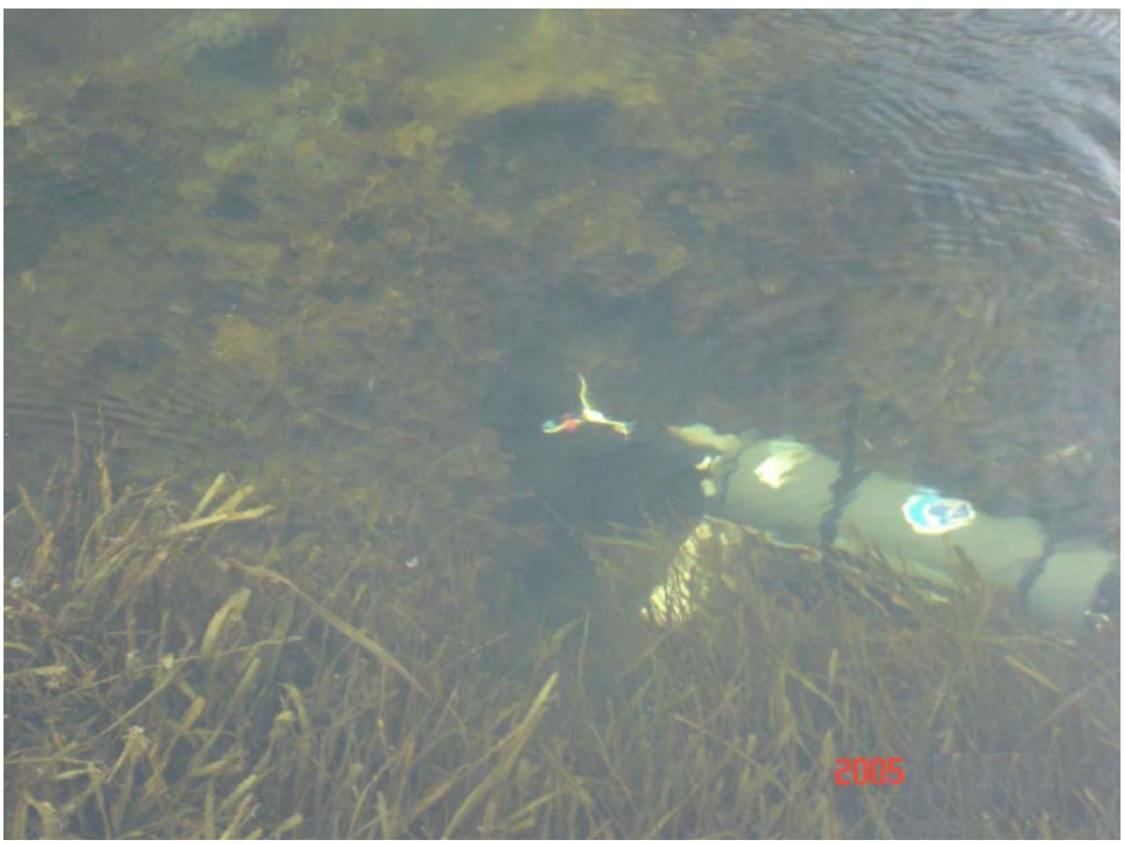
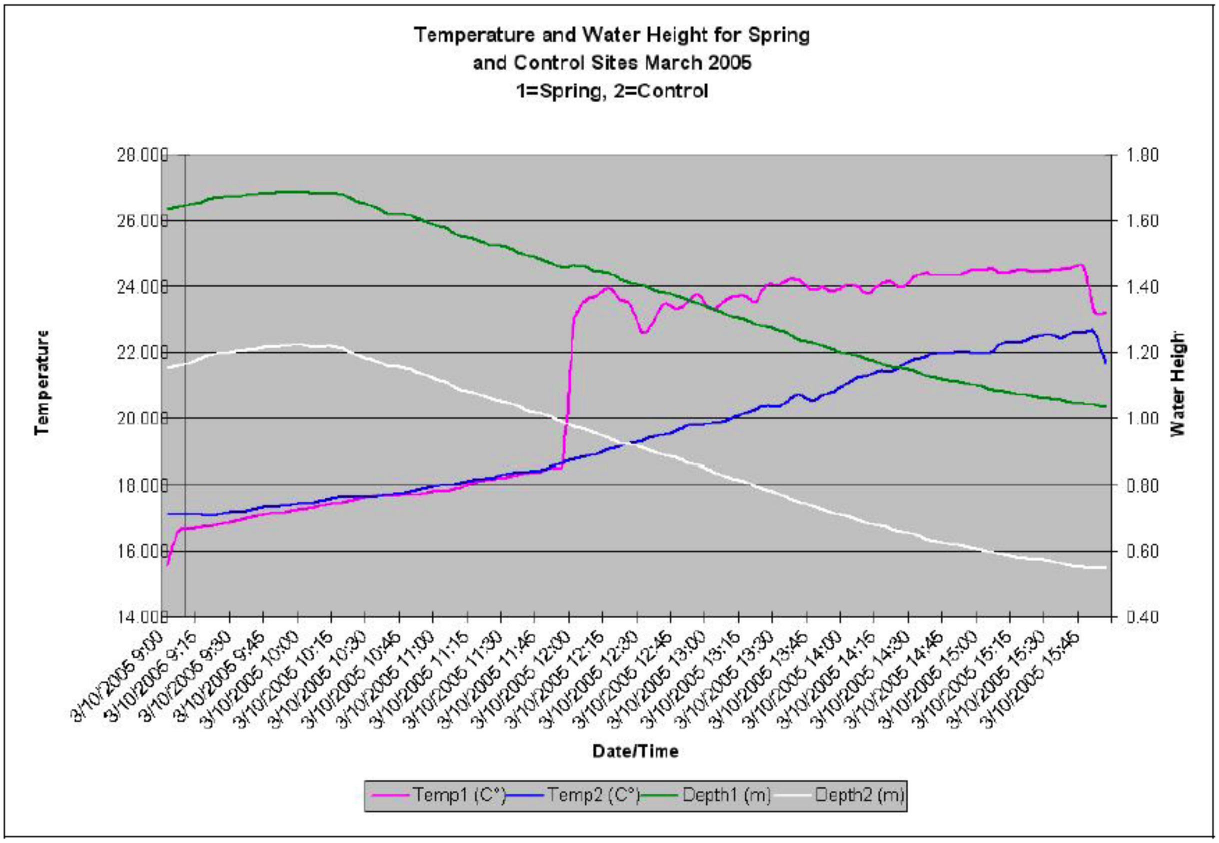


Figure 3 – Photograph of spring site and the YSI ADV6600 sensor

a. March 2005

In figures 4 are shown the temperature, salinity, and water height above the sensor data obtained at spring BBS21 and the control site on March 10, 2005. These data were gathered using two YSI instruments The YSI placed on the spring was oriented so that the measurement sensors were at the bottom of the instrument (vertical orientation). The YSI at the control site was placed with the sensors package at the side of the instrument (a horizontal orientation). The placement of the YSI ADV6600 sensor in July (shown in figure 3) is in the horizontal position. The data was gathered from 9:00 AM to 3:50 PM (0900 to 1550) on March 10, 2005. Figure 4a shows the water column height and temperatures measured at spring BBS21 and the control site. The water column height or tidal height changes above each of the sensors are very similar as is expected. The water height difference from the control site to spring BBS21 site is approximately 0.47 meters or 47 centimeters. This difference indicates that the BBS21 pressure sensor is located at a depth 47 cm greater than the pressure sensor at the control site (200 meters from the spring site). The temperature at the control site is seen to be essentially monotonically increasing from about 17 degrees centigrade at 9 AM in the Morning (0900 hours) to about 22.5 degrees at 3:50 PM (1550 hours). In contrast the temperature at BBS21 is seen to increase monotonically and in conformity with the temperature at the control site until about 12 noon. At about noontime the water temperature at the spring site increases rapidly to nearly 24 degrees and gradually increases to about 24.5 degrees at about 3:50 PM (the drop in temperature at the end of the record occurs during the recovery of the sensor package). At about noontime the water height above the BBS21 sensor has decreased to about 146 cm, a drop of approximately 22 cm from the peak tidal height of approximately 168 cm (about 125 cm above Bay bottom at the control site approximately 200 meters from the spring) occurring at about 10AM.

Figure 4b shows the salinity and temperature graphs obtained for the same time period as shown in Figure 4a at spring BBS 21 and the control site. From Figure 4b it can be seen that the salinity at the control site decreases very gradually from about 33.9 ppt at 9 AM to about 32.7 ppt at 3:50 PM. However the salinity at BBS21 undergoes a reduction from about 32 ppt to about 10 ppt in about 10 minutes at approximately noontime. This reduction of approximately 22 ppt in salinity corresponds to the increase in temperature of about 5.5 degrees in spring water seen in figure 4a.



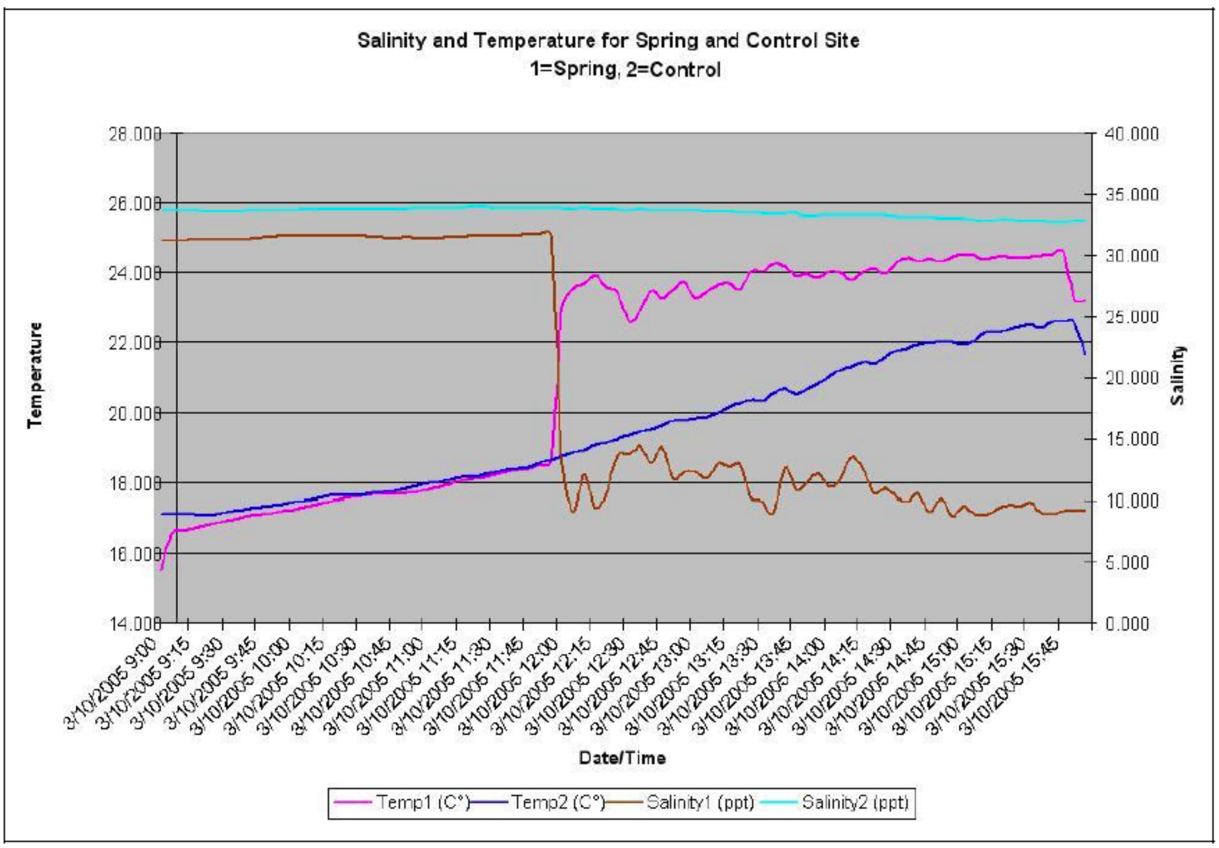


Figure 4 – Data gathered March 10, 2005 (0900-1500) **a)** Tidal Height and Temperature data from spring and control sites. **b)** Salinity and Temperature data from spring and control sites

b. June 2005

On June 16 and 17, 2005, the YSI ADV6600 was deployed (in the horizontal orientation) at the BBS21 spring. Figure 5a shows the temperature, salinity and water height above sensor data obtained between 12:26, June 16 and 11:46, June 17. The deployment time period falls between the first quarter moon phase (01:22, June 15, 2005) and the full moon phase (04:14, June 22, 2005). The June 2005 solstice occurs at 06:46 on June 21, 2005. The time period extending from 01:22, June 15 to 04:14 June 22 also correspond to the time period elapsed in going from a neap tide (June 15) to spring tide (June 22). There was significant weather activity during this measurement period, which include thunderstorm with, higher than normal winds and rain.

Figure 5b shows the vertical component of flow and the water height above sensor recorded during the time period for figure 5a

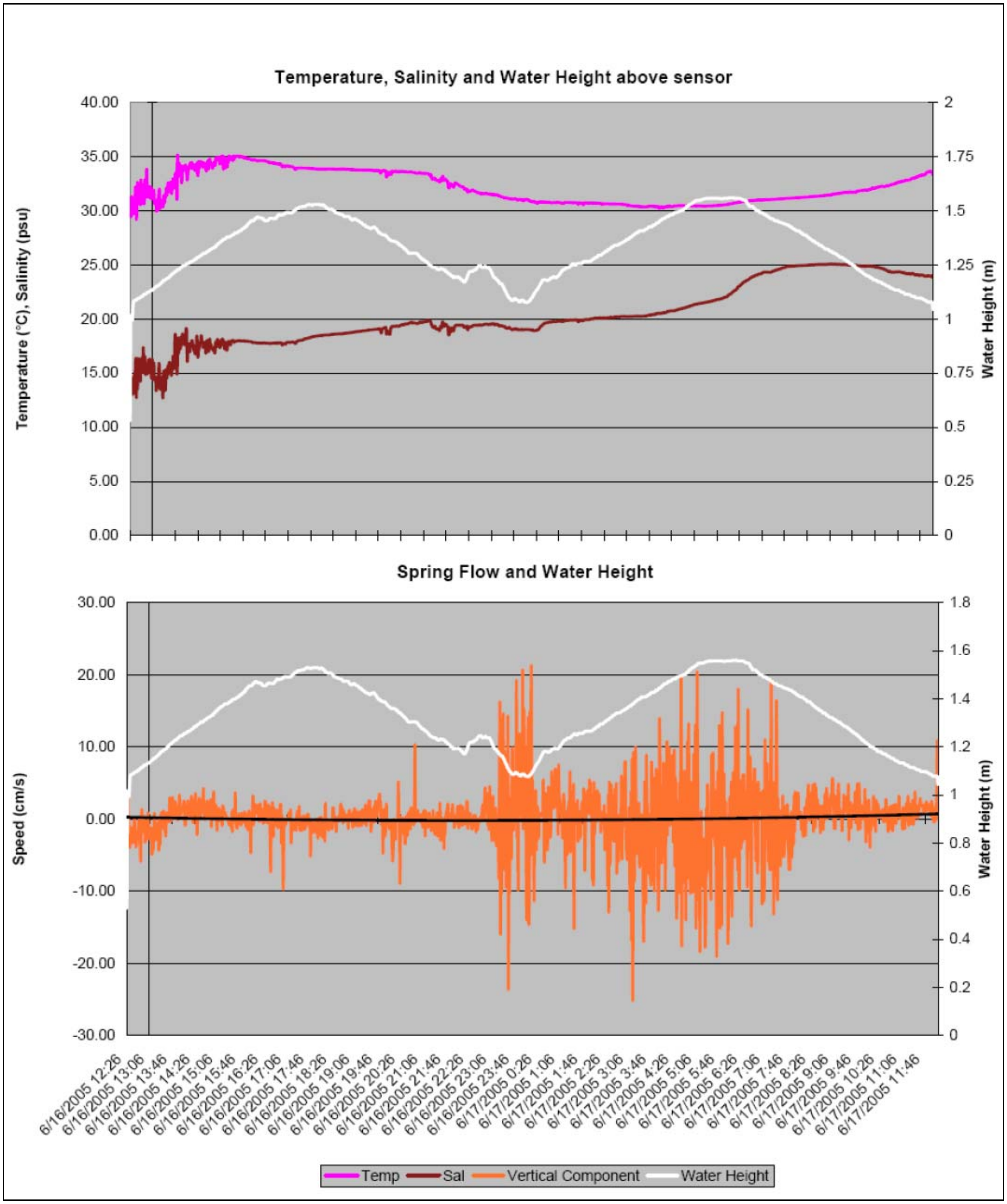


Figure 5 – a) Temperature, salinity and water height above sensor data for the time period of June 2005 b) Spring flow and water height above sensor for the same time period as **a**.

c. July 2005

The July 2005 field study had the greatest number of instruments deployed to date; A Star-Oddi sensor (#1685) was deployed at a control site located 15 meters due east of the spring. The YSI ADV6600 was deployed in a horizontal orientation as shown in Figure 3. The YSI ADV6600 was positioned at the same location and orientation as it was during the June 2005 deployment. Another Star–Oddi (#1676) was deployed in the spring 12 cm beneath the YSI.

Figure 6 shows the vertical component of flow measured by the ADV coherent Doppler sensor and the water height above the sensor for the time period extending from noontime on July 21,2005 to 2AM on July 24, 2005. Another failure of the ADV 6600 occurred at 2 AM on July 24, so that no other spring current data was obtained in the July deployment. Examination of Figure 7 shows that the vertical component of spring current ranges from approximately –2.5 cm/sec (the negative sign denotes current directed downward into the spring) to +12 cm/sec. The water height data shown in Figure 6 and 7 is the corrected Star-Oddi (see the appendix for a discussion of the term "corrected") water height data. The ADV6600 water height data is shown in Figure A5 and is seen to be 12 cm less than the corrected Star-Oddi water height. This is because the Star-Oddi pressure sensor is 12 cm further into the Spring BBS21, i.e. deeper, than the ADV6600 pressure sensor. Comparison with the tidal height data shows that spring current is directed vertically downward and into the spring for a period of three to four hours centered upon tidal peaks. Otherwise the spring current is directed generally upward out of the spring with greatest speeds occurring near times of tidal lows.

Figure 7 shows the salinity data, vertical current data and water height data for the time period from noontime July 21, 2005 to 1:41 AM July 24, 2005. From the data in this Figure it is clear that periods of reduced salinity generally coincide with periods of positive vertical spring flow (currents directed vertically upward out of the spring mouth) and that both periods are centered about times of tidal lows.

Figure 8 shows the temperature recorded at the Bay control site and the water height (corrected Star-Oddi) for the time period extending from noontime July 21, 2005 to noontime July 28, 2005 for both the control site and the spring. Note that for a time interval of three to four hours in length centered about a tidal peak that temperature values recorded at the spring are approximately equal to those recorded at the control site. Otherwise spring temperature values are lower than the control site. Water temperature values measured by the spring site temperature sensor range from as low as 28 degrees centigrade to as great as 36 degrees. The lowest spring site temperature values are recorded during periods when the tidal height is near its lowest values while temperature values as great as 36 degrees are recorded when tidal height is at or near its greatest values. All data presented in this figure were obtained using the Star-Oddi sensors. It may be also noted from the graphs in Figure 7 that a short period, e.g. two hours or less, of reduced salinity values is recorded at the control site four or so hours after initiation of upward flow out of the spring.

Figure 9 shows the salinity data recorded at the spring site and at the control site together water height at the spring site for the same time period as shown in Figure 8. The salinity data shown in figure 9 have been corrected for bias and drift of the Star-Oddi sensors. See the appendix for a discussion of these corrections. It can be seen from Figure 9, that for a time interval between 3 and 4 hours about the time of a tidal peak, that the salinity values recorded by the spring and control site sensors are approximately the same.

In Figure 10 are shown time series for water height and dissolved oxygen.

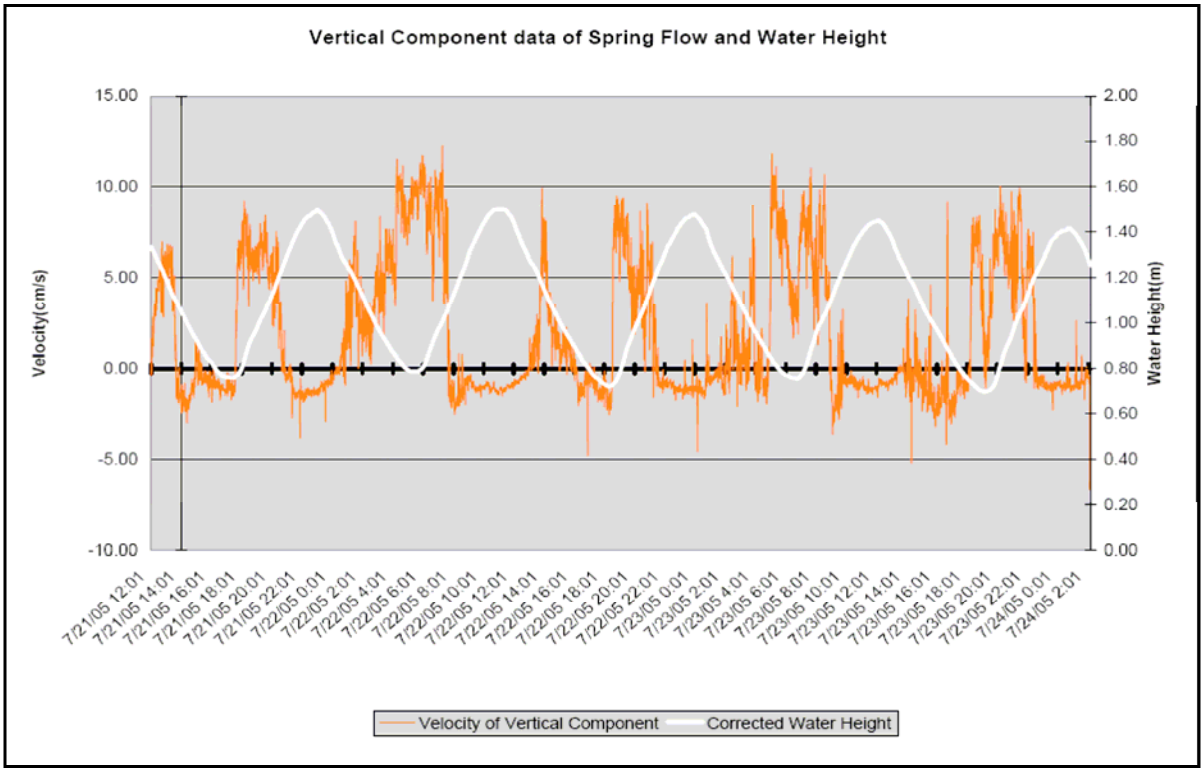


Figure 6 – Vertical component of spring flow and water height (Star-Oddi) gathered during July 21 to 24.

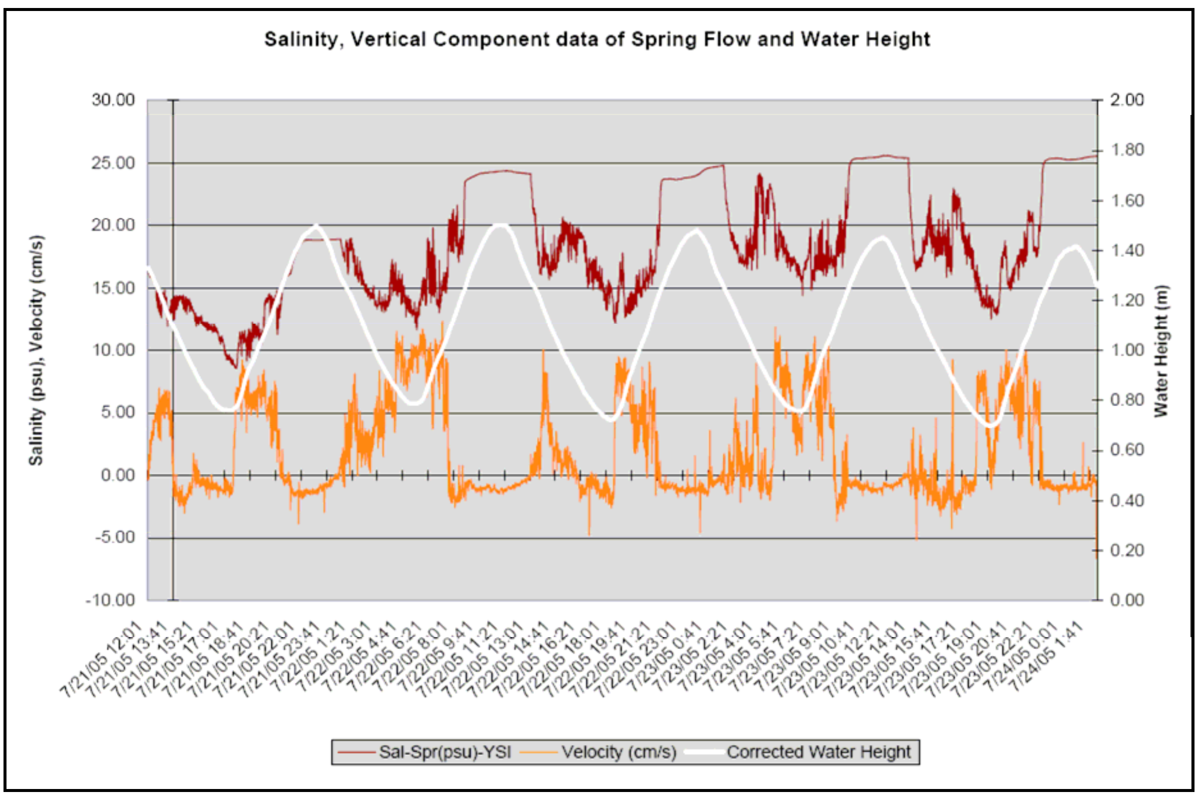


Figure 7 – Salinity, vertical component of spring flow and the water height from July 21 to July 24.

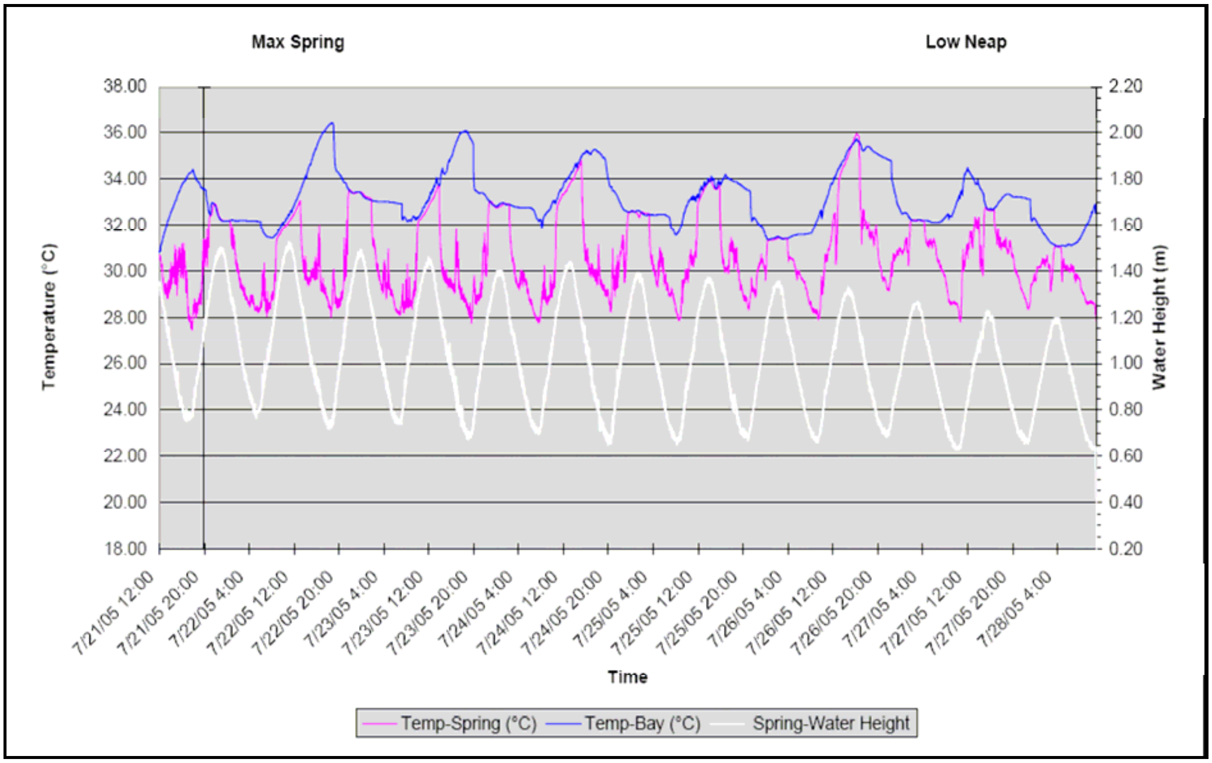


Figure 8 – Temperature data from spring and control site and the water height gathered during July 21 to July 28 (Star-Oddi water heights without their offset correctors)

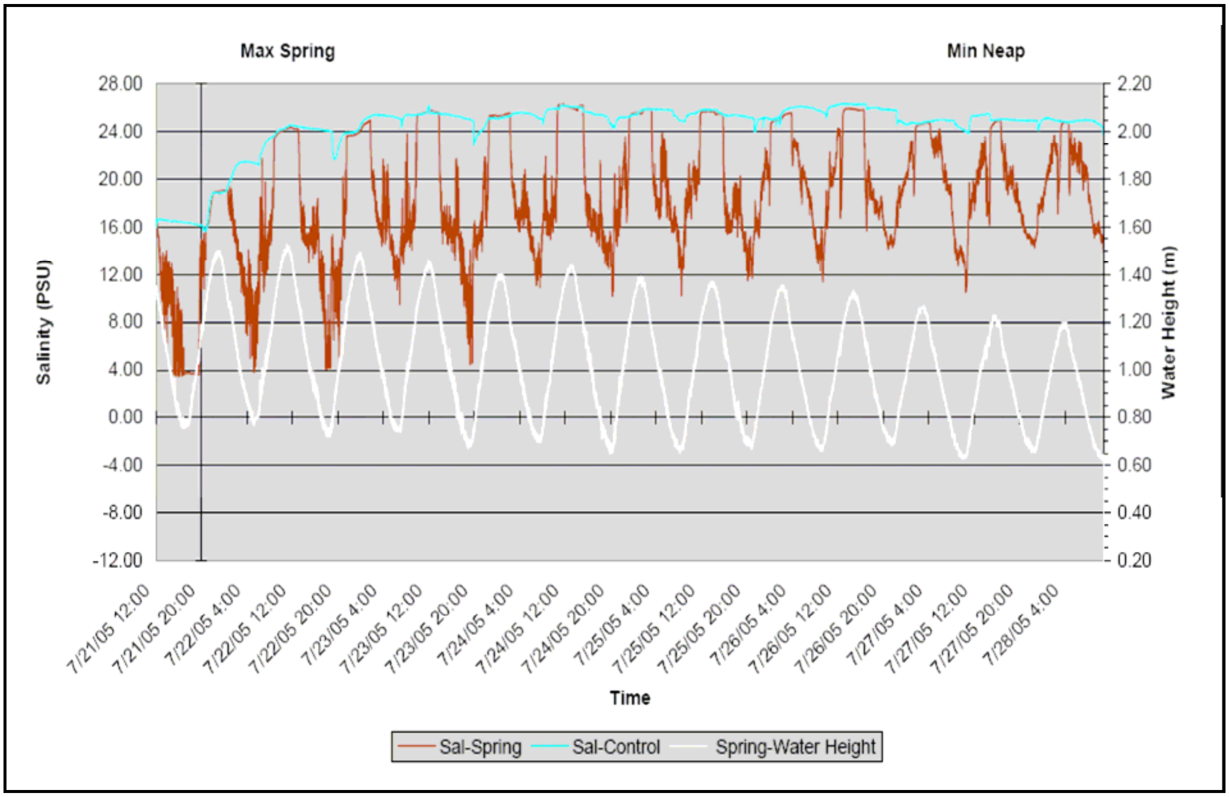


Figure 9 – Salinity data from spring and control site and water height gathered during July 21 to July 28

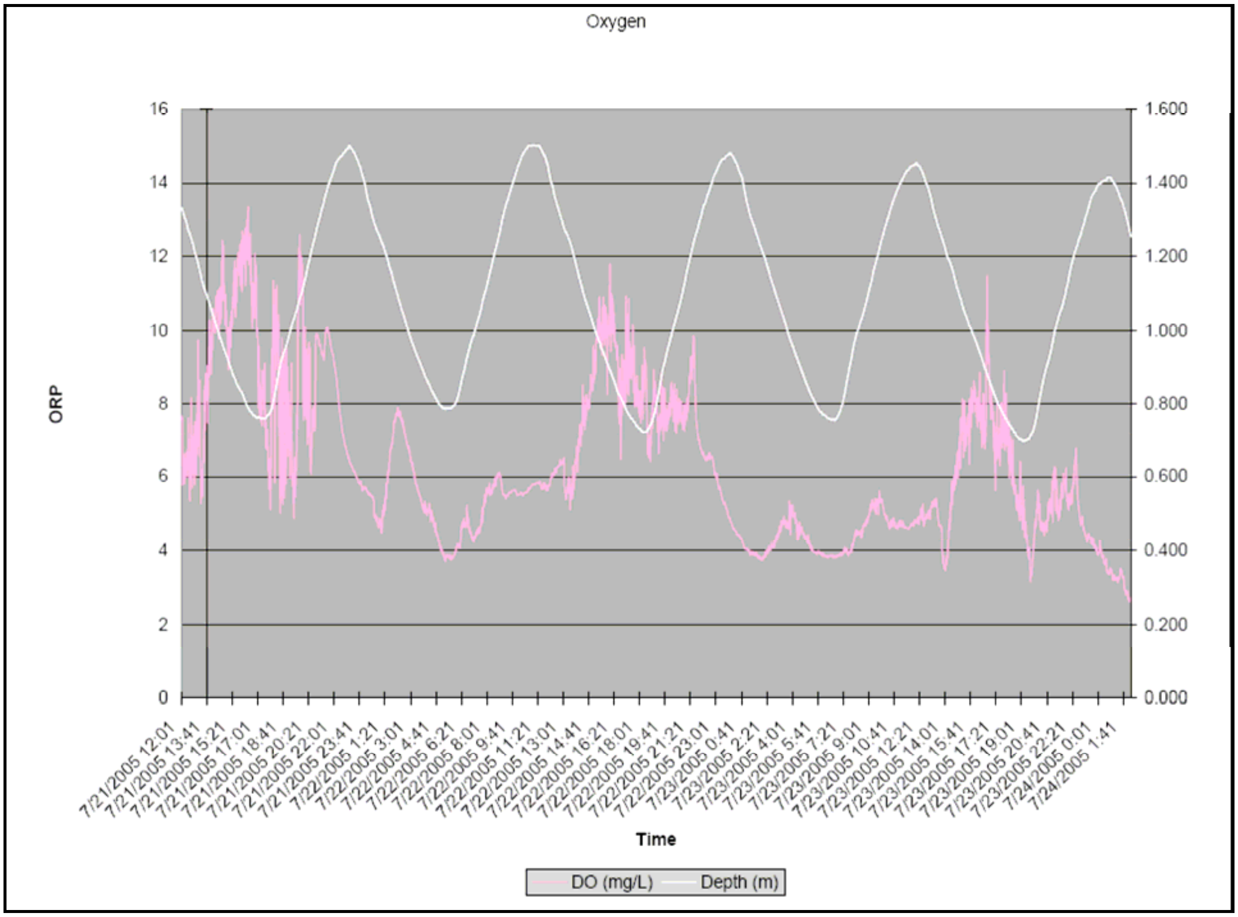


Figure 10 – Dissolved oxygen (DO), and water height for the spring site gathered during July 21 - 24

IV. Discussion

This discussion will focus upon the data gathered since December 2005 but will include discussion of selected data reported in earlier reports for this project.

Examination of Figure 9 shows that salinity values deviate from ambient Bay salinity values for periods of several hours between high tides. Further, examination of Figure 7 shows that periods of upward vertical flow, exiting the BBS21 spring, correspond, approximately, to the same time periods of reduced salinity values. For time periods on the order of three to four hours about the tidal peaks, exiting vertical flow from spring BBS21 is halted and the salinity values observed at the spring correspond to Bay water salinity values. The same is true for temperature values. It may be noted from Figures 6 and 7 that when the tidal amplitude reduces from a peak value of approximately 143 cm (average), to a value of 128 cm (average), flow out of the spring initiates and salinity begins to diminish. Flow out of the spring continues, as does salinity diminishment until the tide begins to rise again approaching another peak. When the tidal amplitude again reaches 128 cm at an average, approximately, flow out of the spring ceases and the spring salinity becomes that of the ambient Bay water (see Table 1).

The preceding observations suggest that occurrence of flow out of spring BBS21 is controlled by the height of the water column above the spring, i.e. the tidal height. The observations further suggest that salinity reduction is observed when flow exits the spring and that salinity reduction can be used as an indicator of flow exiting the spring.

From Figure 8 it can be seen that temperature recorded at the spring site reduces during the same time periods when exiting spring flow occurs and salinity diminishment occurs. In July 2005, the spring temperature is lower that that of the ambient Bay water, so that as was the case with salinity, temperature reduction can be used as an indicator of flow exiting the spring.

Examination of Figures 8, and 9 provides information on the behavior of spring flow as peak tidal heights change in accordance with the Spring-Neap tide behavior and that the tidal range diminishes between noontime on July 21 to noontime on July 28, 2005. Likewise the peak tidal amplitude diminishes from about 150 cm at 11:30 P.M. on July 21 to about 120 cm at 4PM on July 28. Examination of the temperature and salinity data in Figures 5 and 6 respectively show that the duration of the time periods occurring about each tidal peak in which the temperature of the spring water equals that of the ambient Bay water diminishes with time from July 21 to July 28, 2005. For example the duration of the ambient Bay water temperature period is about 3 hours and 38 minutes for the last tidal peak occurring on July 21 but is only about 69 minutes for the tidal peak occurring at about 4:40 AM on July 28, 2005.

The behavior described in the preceding paragraph is consistent with the idea expressed earlier that flow out of the spring is controlled by the tidal height, i.e. the height of the water column above the spring. As the height of the tidal peak reduces with time in going from a time of Spring tides to a time of Neap tides, a greater flow of spring water between tidal peaks results. As the peak tidal amplitude approaches a value of approximately 20 cm below the tidal peak height (150 cm) observed on July 21, we anticipate that almost continuous spring flow should occur. The peak tidal value observed on July 28 of approximately 120 cm is near the tidal peak height anticipated for almost continuous spring flow.

Information on the subsequent behavior of spring flow water after it exits the spring orifice is also contained in figures 8 and 9. The temperature recorded at the control site for the period July 21 through July 28, 2005 is shown in Figure 8. The daily heating of Bay water by the sun is clearly seen in the temperature trace. For example at approximately 18:00 hours (6 PM) on July 22, 2005 a peak daily Bay water temperature of about 36.2 degrees Centigrade is recorded. Thereafter, the water temperature is seen to cool to about 32.8 degrees at 08:00 hours on July 23. Shortly after 08:00 hours a dip in water temperature to about 32.1 degrees is seen to occur. Examination of the complete temperature record suggests that about every eight hours after each temperature peak a dip in water temperature is seen. When the salinity data of Figure 9 are examined it is seen that a dip in the ambient salinity recorded at the control site is registered at approximately the same after a salinity peak is seen in the spring salinity record. Further examination of the temperature record indicates that a temperature dip does in fact occur in correlation with the salinity dips following each tidal high.

The behavior described in the preceding paragraph is consistent with the hypothesis that following initiation of spring flow a “pulse” of spring water is transported to the control site and is recorded at the control site. The pulse of spring water introduces both a temperature and a salinity reduction at the control site. As time progress and tides change from Spring Tides to Neap Tides the spatial extent of the pulse increases with an even shorter time interval between pulses

A rough estimate of the dilution achieved by emitted spring water in going from the spring orifice to the control site can be made from the salinity and temperature data using the salinity deficit or temperature deficit. Results of this calculation indicate a dilution of about 4 or 5 to one.

An estimate may be made of the volumetric flux emanating from and entering into spring BBS21 for the time period July 21 through July 28, 2005. The flux estimate is made assuming pipe flow with a pipe diameter of 30cm. (Spring BBS21 is composed of a series of outlets but the outlet over which the velocity sensor was placed is estimated to be about 30cm in diameter.). Time series of salinity and volumetric flux are shown in figure 11 for the time period July 21 through July 23, 2005. Also shown are the cumulative flux of the exiting spring flow, the cumulative flux of the entering spring flow and the net cumulative flux. Flux is expressed in liters per day. In figure 12 is shown a graph of the distance traveled by a water parcel entering the spring during spring flow shut off periods. This calculation assumes straight-line flow and an open channel system. This was done because regional groundwater flow in karstified carbonate surface aquifers, like the Biscayne Aquifer; typically occur via connected system of conduits rather than a porous matrix.

In figure 13 (a) are shown plots of salinity measured at two locations within the spring and at the control site location. The vertical component of the flow exiting the spring is also shown. Also shown in figure 13 (a) are four time segments each of which extends (approximately) from a time of spring flow shut off to a time of spring flow initiation. Each time segment is comprised of two sub-segments. The leading time sub-segment of each time segment corresponds to the time period during which salinity decreases form a maximum to a minimum value while the second time sub-segment corresponds to the time period in which the salinity increases from a minimum value to a maximum. Both time sub-segments correspond to periods when flow is exiting the spring with flow generally increasing during the first time sub-segment and generally decreasing during the second time sub-segment. In figure 13 (b) are shown scatter diagrams of salinity versus temperature for the two time sub-segments for the first time period. Note that a correlation between salinity and temperature exists for each of the time sub-segments, i.e. 0.9 and 0.84 respectively.

Water samples were collected at BBSW 21 on June 16, 2005 (Table 2) and analyzed for nutrients (NO_3+NO_2, NO_2, PO_4, Si and NH_4). Nutrient concentrations in the groundwater ranged from 0.52-2.95 µM NO_3+NO_2, 0.15-0.66 µM NO_2, 0.31-2.10 µM PO_4, 28.5-39.8 µM Si and 5.8-10.0 µM NH_4 (Table 2). PO_4, Si and NH_4 values were similar to values observed near canals (B2, B3, B5, B7 and B12) during the monthly Biscayne Bay water quality-monitoring cruise conducted on June 14, 2005 for the South Florida Ecosystem Research and Monitoring Program (See Figure A8 on the Appendix for station locations).

However, NO_3+NO_2 and NO_2 values were much lower at the groundwater site when compared to the samples taken near canals (Table 3).

Valentina and Boyer (2005) found that during the wet season June-October, nutrient concentrations inshore and alongshore Biscayne Bay were elevated due to runoff via canals. These results indicate that the nutrients PO_4, Si, and NH_4 found exiting thru the groundwater springs contribute to the nutrient loading of Biscayne Bay, although since measurements have been made at only one spring the relative contribution of said nutrients remains unknown.

Date/Time	Start-End Flow	No-Flow Elapsed Time (h:mm)	Flow Elapsed Time (h:mm)	Cutt off Water Height (YSI)	Water Height (Corrected YSI)	Water Height (SeaStar)	Water Height (peak)
7/21/05 12:00	Start			1.21	1.22	1.34	
7/21/05 21:00	End		9:00	1.18	1.19	1.31	1.49
7/22/05 0:38	Start	3:38		1.17	1.18	1.3	
7/22/05 8:56	End		8:18	1.17	1.16	1.28	1.52
7/22/05 13:06	Start	4:10		1.15	1.16	1.28	
7/22/05 21:43	End		8:37	1.15	1.15	1.27	1.49
7/23/05 1:44	Start	4:01		1.13	1.12	1.24	
7/23/05 10:07	End		8:23	1.17	1.17	1.29	1.44
7/23/05 13:50	Start	3:43		1.13	1.12	1.24	
7/23/05 22:47	End		8:57	1.13	1.12	1.24	1.40
7/24/05 2:21	Start	3:34		Power Failure	1.08	1.2	
7/24/05 10:52	End		8:31		1.11	1.23	1.43
7/24/05 15:15	Start	4:23			1.06	1.18	
7/24/05 23:32	End		8:17		1.11	1.23	1.38
7/25/05 3:15	Start	3:43			1.04	1.16	
7/25/05 12:00	End		8:45		1.10	1.22	1.36
7/25/05 15:55	Start	3:55			1.00	1.12	
7/26/05 0:22	End		8:27		1.09	1.21	1.35
7/26/05 3:51	Start	3:29			1.05	1.17	
7/26/05 13:14	End		9:23		1.09	1.21	1.32
7/26/05 16:37	Start	3:23			1.05	1.17	
7/27/05 1:51	End		9:14		1.09	1.21	1.27
7/27/05 4:15	Start	2:24			1.05	1.17	
7/27/05 15:05	End		10:50		1.08	1.2	1.23
7/27/05 16:43	Start	1:38			1.03	1.15	
7/28/05 3:31	End		10:48		1.06	1.18	1.20
7/28/05 4:40	Start	1:09			1.03	1.15	
Average				**1.16**	**1.10**	**1.22**	

Table 1 – Start and End of Flows during the July 21–28 deployment.

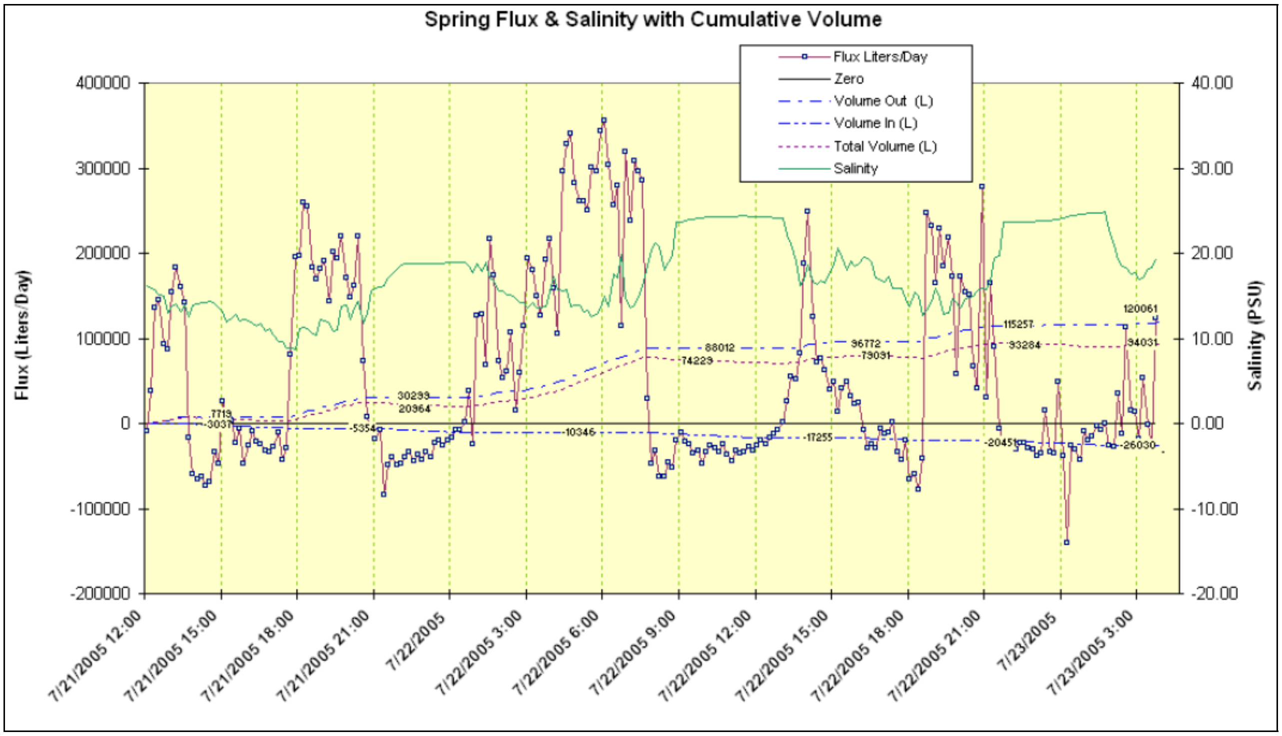


Figure 11 – Time series of flux, cumulative influx data, cumulative efflux and the cumulative net flux (calculated from velocity with a 30 cm diameter) and salinity

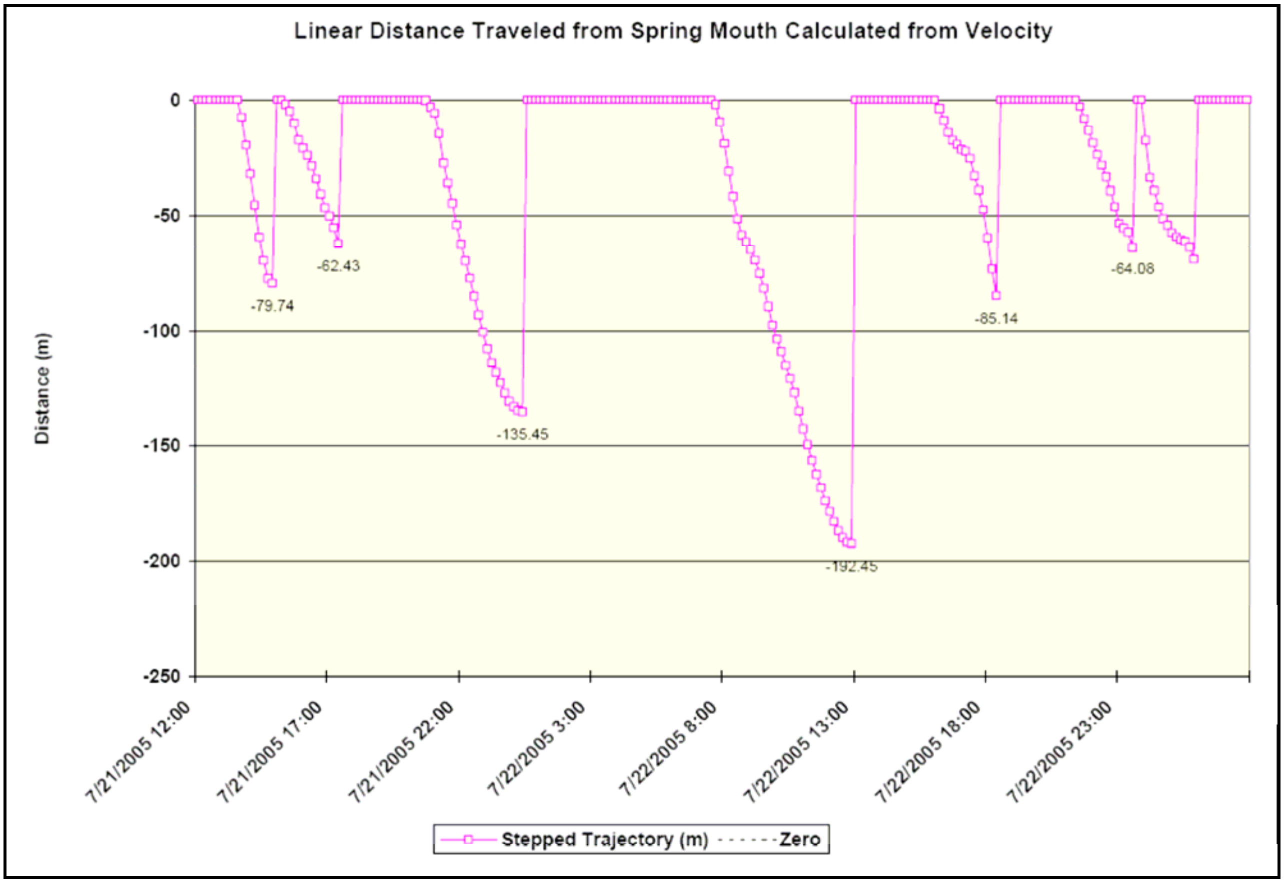


Figure 12 – Time series of distance traveled by a water parcel (Calculations assume open channel system

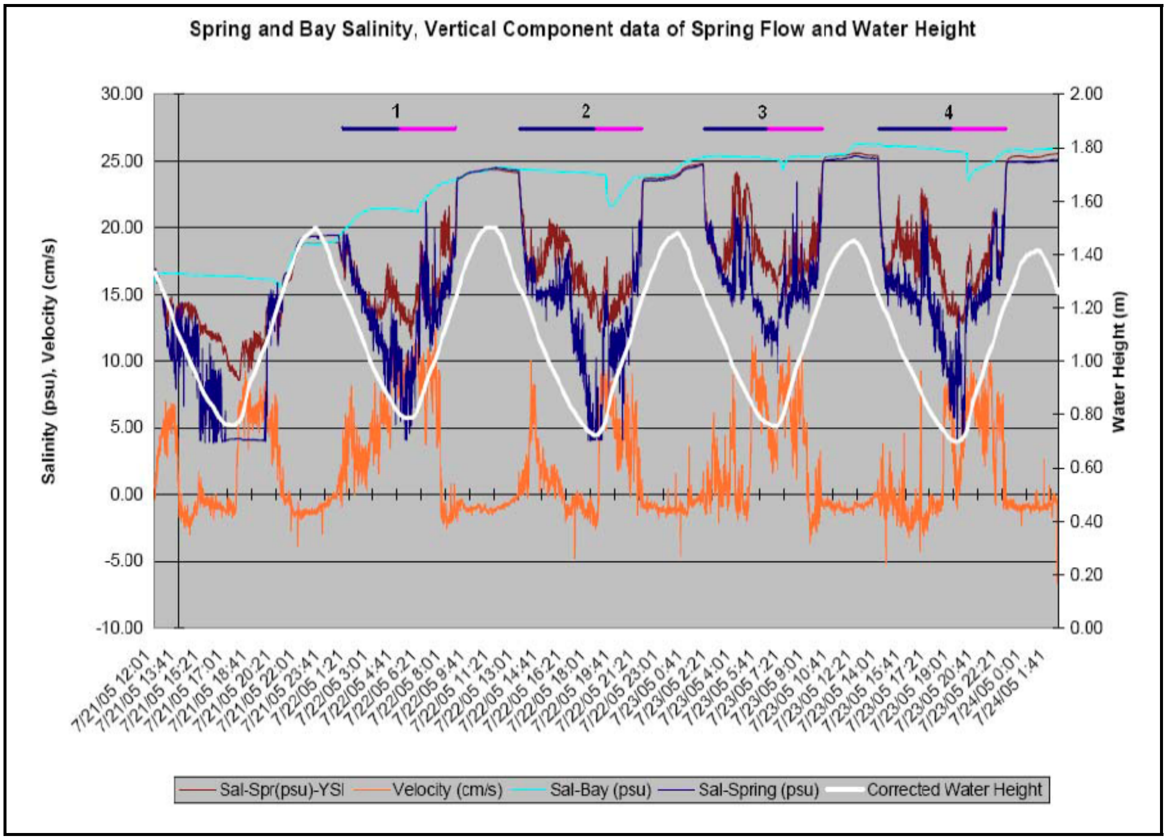


Figure 13a – Salinity from spring and control site, the vertical component of spring flow and water height

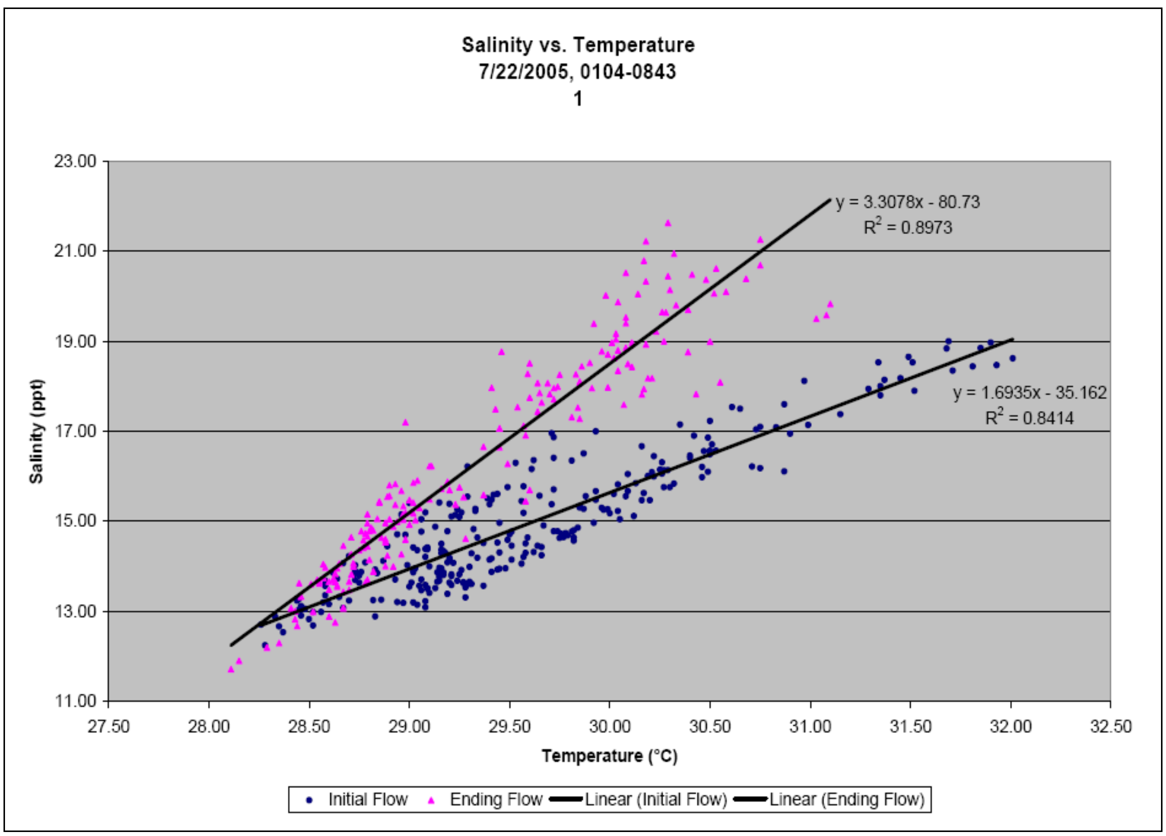


Figure 13b – Scatter diagrams of salinity and temperature for the time sub segment for the first period (for other time periods see appendix figures A5-7)

Biscayne Bay Groundwater Survey

Date Collected: 06/16/05
Date Analyzed: 06/21/05 & 07/12/05

Units in Micromoles (µM)

Station	Long	Lat	Salinity	NO_3+NO_2	NO_2	PO_4	Si	NH_4
BBSW-21-1	80^{0}18'26.7"	25^{0}36'21.9"	12	0.52	0.30	0.37	39.8	8.2
BBSW-21-2	80^{0}18'26.7"	25^{0}36'21.9"	8	1.53	0.15	2.10	38.2	10.0
BBSW-21-3	80^{0}18'26.7"	25^{0}36'21.9"	12	0.89	0.21	0.61	39.1	9.4
BBSW-21-S1	80^{0}18'26.7"	25^{0}36'21.9"	15	2.87	0.66	0.25	28.8	6.2
BBSW-21-S2	80^{0}18'26.7"	25^{0}36'21.9"	15	2.89	0.65	0.28	28.5	6.3
BBSW-21-S3	80^{0}18'26.7"	25^{0}36'21.9"	14	2.96	0.61	0.31	29.4	5.8

*BDL = Below Detection Limit
*S = Sample taken at the surface above spring

Units in mg-L Nitrogen, Phosphorus & Silica (Atoms)

Station	Long	Lat	Salinity	NO_3+NO_2-N	NO_2-N	PO_4-P	Si	NH_4-N
BBSW-21-1	80^{0}18'26.7"	25^{0}36'21.9"	12	0.007	0.004	0.011	1.11	0.12
BBSW-21-2	80^{0}18'26.7"	25^{0}36'21.9"	8	0.021	0.002	0.065	1.07	0.14
BBSW-21-3	80^{0}18'26.7"	25^{0}36'21.9"	12	0.012	0.003	0.019	1.09	0.13
BBSW-21-S1	80^{0}18'26.7"	25^{0}36'21.9"	15	0.040	0.009	0.008	0.81	0.09
BBSW-21-S2	80^{0}18'26.7"	25^{0}36'21.9"	15	0.040	0.009	0.009	0.80	0.09
BBSW-21-S3	80^{0}18'26.7"	25^{0}36'21.9"	14	0.041	0.008	0.010	0.82	0.08

*BDL = Below Detection Limit
*S = Sample taken at the surface above spring

Units in mg-L Nitrate + Nitrite, Nitrite, Phosphate, Silica & Ammonium (Compounds)

Station	Long	Lat	Salinity	NO_3+NO_2	NO_2	PO_4	Si	NH_4
BBSW-21-1	80^{0}18'26.7"	25^{0}36'21.9"	12	0.06	0.013	0.035	1.11	0.15
BBSW-21-2	80^{0}18'26.7"	25^{0}36'21.9"	8	0.16	0.006	0.199	1.07	0.18
BBSW-21-3	80^{0}18'26.7"	25^{0}36'21.9"	12	0.10	0.010	0.058	1.09	0.17
BBSW-21-S1	80^{0}18'26.7"	25^{0}36'21.9"	15	0.31	0.030	0.024	0.81	0.11
BBSW-21-S2	80^{0}18'26.7"	25^{0}36'21.9"	15	0.31	0.030	0.027	0.80	0.17
BBSW-21-S3	80^{0}18'26.7"	25^{0}36'21.9"	14	0.32	0.028	0.029	0.82	0.10

*BDL = Below Detection Limit
*S = Sample taken at the surface above spring

*NO_3+NO_2, PO_4 and Si were run on the autoanalyzer
*NO_2 and NH_4 were run on the UV-VIS Spec.

Table 2 - Nutrient analysis from spring BBS21

Station	Longitude	Latitude	Salinity	NO_3+NO_2	NO_2	PO_4	Si	NH_4
B1	-80.1831	25.7405	36.672	2.45	0.78	0.055	10.25	1.82
B2	-80.24768	25.69022	23.337	3.99	1.03	0.118	10.02	0.91
B3	-80.2631	25.6544	17.635	11	1.97	0.077	62.4	5.64
B4	-80.2639	25.59126	34.719	13.1	0.57	0.002	5.1	1.82
B5	-80.31282	25.5296	5.06	65.6	2.7	0.084	82.58	14.9
B6	-80.25242	25.4915	38.335	1.71	0.16	0.002	0	2
B7	-80.3236	25.46316	19.764	76	2.43	0.058	21.43	4.7
B8	-80.2434	25.40552	35.939	2.24	0.11	0.002	0	0.19
B9	-80.32126	25.33324	37.825	1.09	0.18	0.011	0.22	0.44
B10	-80.36128	25.29704	36.736	1.12	0.36	0.02	1.62	0.43
B11	-80.376	25.23878	39.888	0.36	0.21	0.044	7.59	1.23
B12	-80.4221	25.25698	25.319	1.95	0.79	0.017	33.03	9.72
B13	-80.4228	25.17588	40.854	0.68	0.23	0.002	6.99	1.28
B14	-80.21414	25.46794	38.892	0.18	0.09	0.002	1.48	1.3
B15	-80.19906	25.5807	35.523	0.53	0.23	0.002	0	3.33
B16	-80.18688	25.6621	36.911	0.26	0.12	0.002	1.9	0.24

Table 3 - Biscayne Bay monthly water quality cruise nutrient samples collected during June 14, 2005 by the South Florida Ecosystem Research and Monitoring Program.

V. Summary and Conclusions

a. Summary

In the course of this project, aircraft, boat and human surveys were carried out to determine the locations of active submarine groundwater springs within Biscayne Bay. A number of spring locations were determined. At the time this project was initiated it was unknown what spring flow rates into Biscayne Bay water existed. Accordingly, choices for appropriate current and flow measurement sensors could not be made until some spring flow was observed. Furthermore, the availability of low cost sensors, i.e. sensors having costs compatible with the sensor purchase budget, for measurements at multiple spring sites was not established. At a few springs, direct human observations suggested that flow velocity measurement devices having a range from a fraction of a centimeter per second to several centimeters per second were appropriate. It was clear that it was not feasible to contemplate making flow velocity measurements concurrently at multiple springs due to budget limitations. The notion that salinity and or temperature measurements could be used as surrogates to identify spring exiting flows into Biscayne Bay was supported by the direct human observation of fresher water occurring when flow was present. Accordingly, some relatively low cost (but new to the market) salinity, temperature, depth measurement devices (made in Iceland) were purchased for use at multiple springs.

Numerous difficulties with both field sampling and instrumentation were encountered. In response to these multiple difficulties it was decided to focus upon a single spring having a high flow velocity. It was also decided that as complete a set of measurements as possible over the period of a year at a single high flow spring was superior to sporadic, partial measurements at multiple springs. The spring selected for in depth study was designated as Biscayne Bay Spring 21 (BBS21) and is also designated as the Ricisak spring after the discoverer of the spring, John Ricisak. Measurements of various parameters of interest were made in the time period extending from October 2004 to July 2005. In March and in July of 2005 measurements were also made at control sites located 200 meters (March 2004) and 15 meters (July 2005) respectively from spring BBS21. Examination of the measurements at these control sites clearly demonstrate that the temperature and salinity anomalies ascribed to exiting spring flow do not appear at the control sites (except after spatio-temporal dilution), thereby demonstrating that the anomalies can not be attributed to a general flow arising from land based surface sources.

A substantial correlation between the occurrence of spring flow and salinity and temperature anomalies was observed in the July 2005 deployment. Indeed, the freshness of the water measured by the spring located sensors significantly increased during periods when a collocated flow velocity sensor registered substantial vertical flow velocities of exiting spring water. During the November deployment exiting spring water was warmer than that of the receiving Bay waters while in July the reverse was true. In contrast, during periods when vertical flow velocities were negative, i.e. flow was entering the spring, both the salinity and temperature were closely equal to those of the ambient Bay water. A close correlation of flow velocity initiation and termination with salinity anomaly initiation and termination (and also with temperature anomaly initiation and termination) was observed. Based on these high correlations, the occurrences of salinity anomaly intervals were deemed to be a good indicator for the occurrence of exiting-spring-flow intervals. Thus in the conclusions below extension of flow behavior to periods when flows were not measured is based upon the use of salinity anomaly intervals as a surrogate.

The role of the tide in controlling flow exiting from spring BBS21 was clearly evident in all the flow velocity, temperature and salinity data gathered at the spring. Not only was the influence of the daily semi diurnal tide clearly evidenced, but also the influence of the Spring-Neap tides was also evident. In each of the deployments, the sensor system used to measure tidal height was placed in the same location in spring BBS21. Rather than use the term "tidal height" the more descriptive term "water height above sensor" or simply "water height" is used for both the spring site located measurement sensor and for the control site(s) located measurement sensors. The water height at the spring exceeds that at the control site(s) by the difference in depth of the sensor placements, e.g. approximately 47cm.

One of the most interesting effects of the Spring-Neap tides is the change induced in the duration and spatial configuration of the spring water "plume" in the Biscayne Bay receiving waters. The water emanating from spring BBS21 does so in "pulses" where the temporal duration of a pulse is equal to the time the tidal amplitude is below the critical value for spring flow shut off. The time between sequential pulses is equal to the time the tidal amplitude is sufficiently great so as to shut off spring flow. In the course of the Spring –Neap tidal cycle, the flow shut off time changes, increasing as time proceeds from Neap to Spring tide and decreasing as time proceeds from Spring to Neap tide. Indeed, examination of the July 2005 data suggests that an almost continuous flow from the spring occurs during the lowest Neap tide during the rainy season. In contrast examination of November 2004 data indicates that during the dry season no nearly continuous flow is seen.

Chemical samples of exiting spring BBS21 water were gathered during various deployments. The chemical samples obtained during the period covered by this report are shown in table 2.

b. Conclusions

a. Flow has been observed to emanate from spring BBS21 during each field measurement deployment. Flow occurs during both wet and dry seasons. (Salinity anomaly used as surrogate for dry season flow)
b. Spring flow into Biscayne Bay is regulated, at least in part, by the tidal amplitude during both dry and wet seasons.
c. Once the tidal amplitude exceeds a certain value, e.g. 1.22-1.28 meter, spring flow into Biscayne Bay ceases.
d. The duration of the time period during which spring flow emanating into Bay receiving waters increases as tidal amplitude decreases in time in going from Spring to Neap tide and vice versa.
e. In the time period July 21 through July 24, 2005 vertical flow velocities were observed to range from about –2.5 cm/sec to +12 cm/sec. (Positive vertical flow velocity indicates water emanating from spring BBS21 into Biscayne Bay receiving waters. Negative vertical flow velocity indicates water flow into the spring).
f. In the multiple-day time period above, salinity and temperature values approximately equal to ambient Biscayne Bay water were recorded, by sensors located at the spring site, during those multiple hour time periods when negative vertical flow velocities were observed.
g. When positive vertical velocities were recorded reduced salinities and temperatures were recorded. Salinity values as low as 5 ppt were recorded (approximately 19 ppt below the ambient Bay water salinity of 24 ppt) and temperature values
h. The flow exiting spring BBS21 does so in pulses of flow. The duration of each pulse of flow increases as the tide progresses from spring tide too neap tide. The duration of flow decreases as the tide progresses from neap to spring.
i. At a control site located 15 meters from the spring, pulses of spring water were observed to have undergone approximately a 3 to 4 fold dilution.
j. Nitrates, phosphates and ammonia were all detected in samples gathered during periods of spring flow. The magnitudes of the concentrations for PO_4, Si, and NH_4 from the groundwater spring are comparable to those made in the vicinity of canals recorded by the South Florida Ecosystem Research and Monitoring Program.

APPENDIX

I. Corrections

Corrections were required for the Star-Oddi devices. Said corrections were made during post processing of the retrieved data for drift in the salinity data, for the surface atmospheric pressure during deployment, and for bias and temperature effects in the pressure data.

a. Temperature

The temperature sensors of both Star-Oddi devices agreed well with the YSI ADV6600 both in laboratory calibration checks and during periods when Biscayne Bay water was present at the spring measurement (see figure 8 and Figure A1 (b)).

b. Salinity

A drift in salinity readings for both Star-Oddi sensors, 1676 and 1685, was observed to be present when compared with YSI ADV 6600 salinity data for the same time period. The YSI ADV6600 displayed negligible drift in calibration checks. Figure A1 (a) shows the salinity traces for the control site Star-Oddi (1685), the spring site Star-Oddi (1676) and the YSI ADV6600. In contrast to the temperature traces shown in Figure A1 (b), the three salinity traces are different from one another even during periods when Bay water encompasses all three sensors. The drift rates were determined for the Star-Oddi sensors by comparison with the YSI ADV6600 and in laboratory checks.

Corrections to the Star-Oddi salinity data were carried out by applying the drift rate to the salinity data values. In the case of the spring, a negative drift value of 3.98×10^{-4}psu/min was calculated. This value was obtained by subtracting the YSI AVD6600 water height data from the Star-Oddi during no flow conditions, when the two sensors are expected to have the same or nearly the same salinity values. These values then are divided it by the total of minutes of the no flow conditions at spring to determine a correction, which is added progressively to the value of the raw salinity values from the Star-Oddi 1676. These new values are the corrected salinity trace used in the analysis. For the control site, a drift value of 2.28×10^{-4}psu/min was calculated, so it was subtracted progressively from the original or raw values of the Star-Oddi 1685.

The drift corrected Star-Oddi salinity sensor traces and the YSI ADV6600 salinity traces are shown in Figure A2.

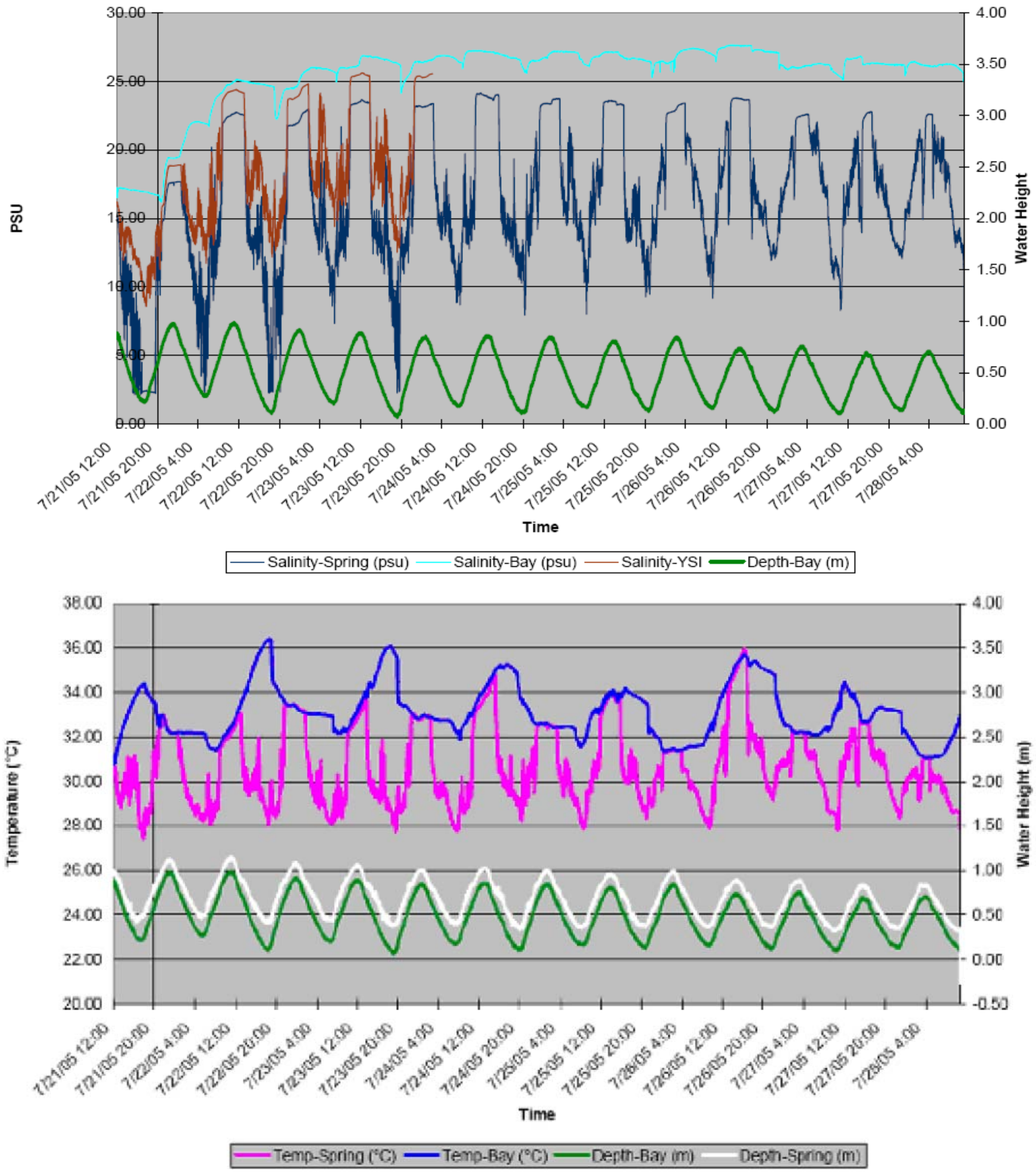


Figure A 1 - a) Raw salinity and water height measurements. b) Raw temperature and water height measurements.

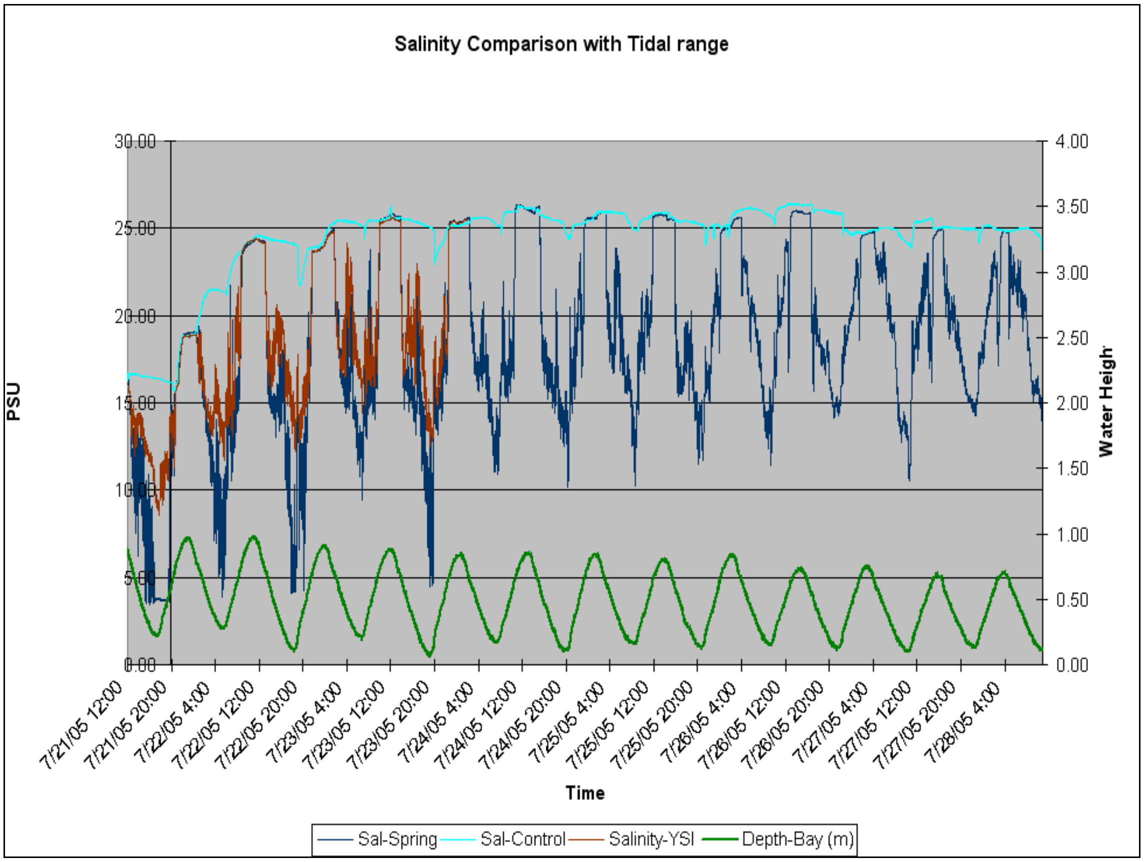


Figure A 2

c. Pressure/Depth

The pressure sensors on the Star-Oddi are provided by the manufacturer with an initial atmospheric pressure value of 1000 millibars Hg (mb). After the data were retrieved the raw data were converted to an ambient pressure of 1015mb. A value of 1015 mb was taken out of NOAA's atmospheric pressure climate database. This correction resulted in an increase of 15 cm in the water height estimate. Besides the atmospheric pressure correction, a much larger bias in the spring located Star-Oddi 1676 pressure/water height sensor was determined to be present as well.

The raw data from the Star-Oddi sensor indicated that on average, the Star-Oddi pressure sensor was 24 cm shallower than the YSI pressure sensor. In reality the Star-Oddi sensor was 12 cm deeper on the mounting frame. Besides the 15 cm atmospheric pressure correction and the 36 cm depth bias correction, yet another correction for the Star-Oddi spring located pressure sensor was required. It was found that the temperature of the water in which it was immersed affected the Star-Oddi pressure sensor reading. The upper trace in figure A3 shows a time series of the temperature recorded by the Star-Oddi device, while the lower trace in Figure A3 shows the time series of the difference of water height estimates between the YSI and the spring located Star-Oddi pressure sensors (The atmospheric correction was applied to the Star-Oddi pressure sensor before calculating the aforementioned difference). The influence of temperature on the pressure sensor data from the Star-Oddi device is clear from these two traces.

Figure A4 shows a scatterplot of the depth differences and the temperature trace from Figure A3. It was observed that the two variables were positively associated and the data could be well represented by a straight-line relationship. An over all trend line was drawn in and the line equation, $Y_T = 0.019X - 0.3537$, was used to create a corrector to match the YSI depth trace. Y_T is the depth corrector value and X the Star-Oddi temperature value at the time of measurement. This depth correction (Y_T) takes into account the -24 cm difference seen between the raw Star-Oddi water height data and the YSI data mentioned earlier. Later, this progressive correction was added to the Star-Oddi water height measurement to create a partially corrected Star-Oddi water height trace.

The final correction to the Star-Oddi 1676 pressure data is the addition of the known displacement of 12 cm. Thus 12 cm is added to adjust for the placement of the Star-Oddi 1676 in the mounting frame to fully correct the Star-Oddi pressure trace. The final equation to obtain the fully corrected Star-Oddi water height data ($<WH>_{SO}$) is:

$$<WH>_{SO} = RWH_{SO} + SAC + Y_T + DC$$

Where RWH_{SO} is the raw water height from the Star-Oddi, SAC is the surface atmospheric pressure correction, Y_T is the depth correction based upon temperature at the time of measurements (includes the 24 cm bias discussed earlier) and DC is the displacement correction.

The fully corrected Star-Oddi water height trace was used for analysis and displayed in Figures 6-10 and 13.

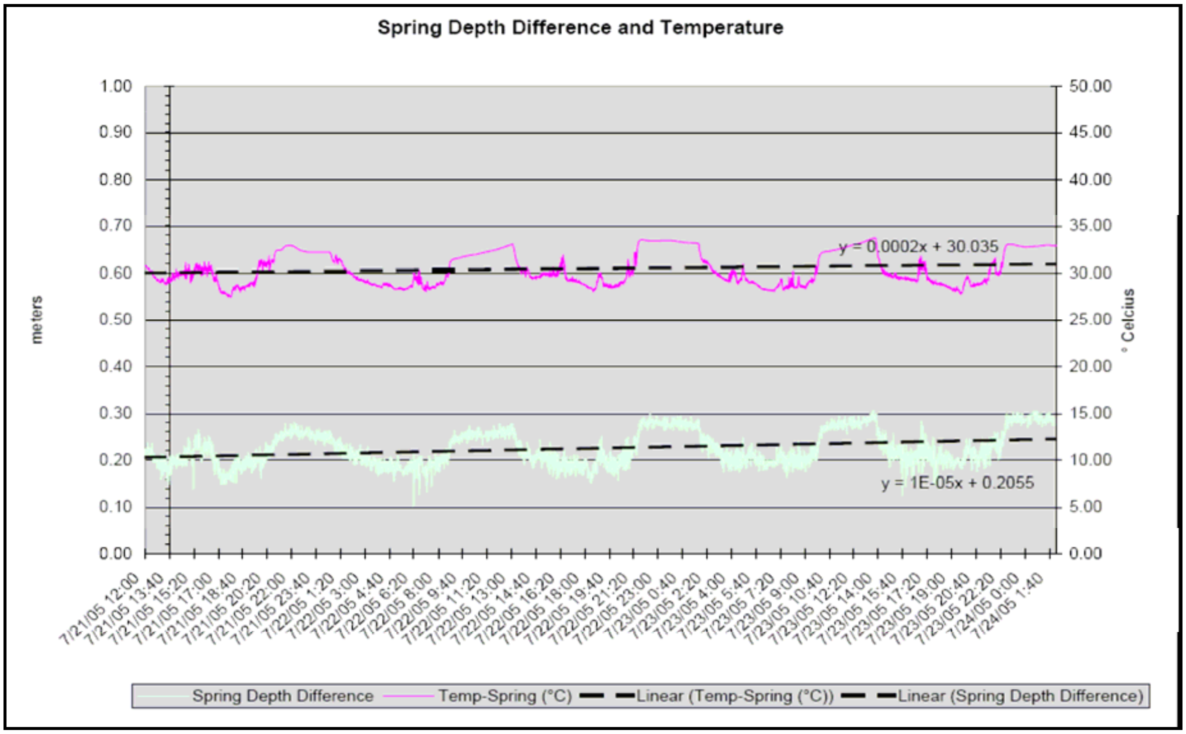


Figure A 3 – YSI and Star-Oddi depth difference plotted along with the Star-Oddi temperature sensor. Notice the same pattern between the temperature trace and the difference in depth.

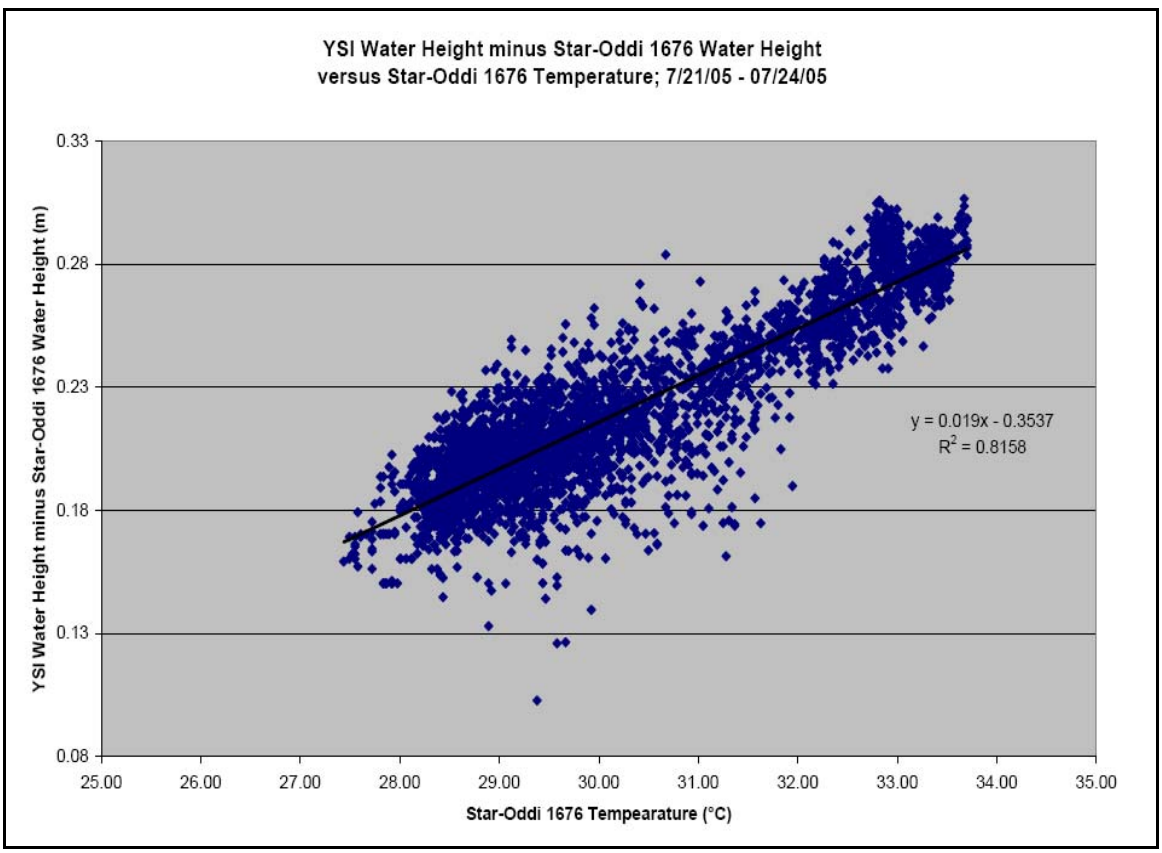


Figure A 4 – YSI and Star-Oddi water height difference versus the Star-Oddi temperature trace

II. Additional Figures

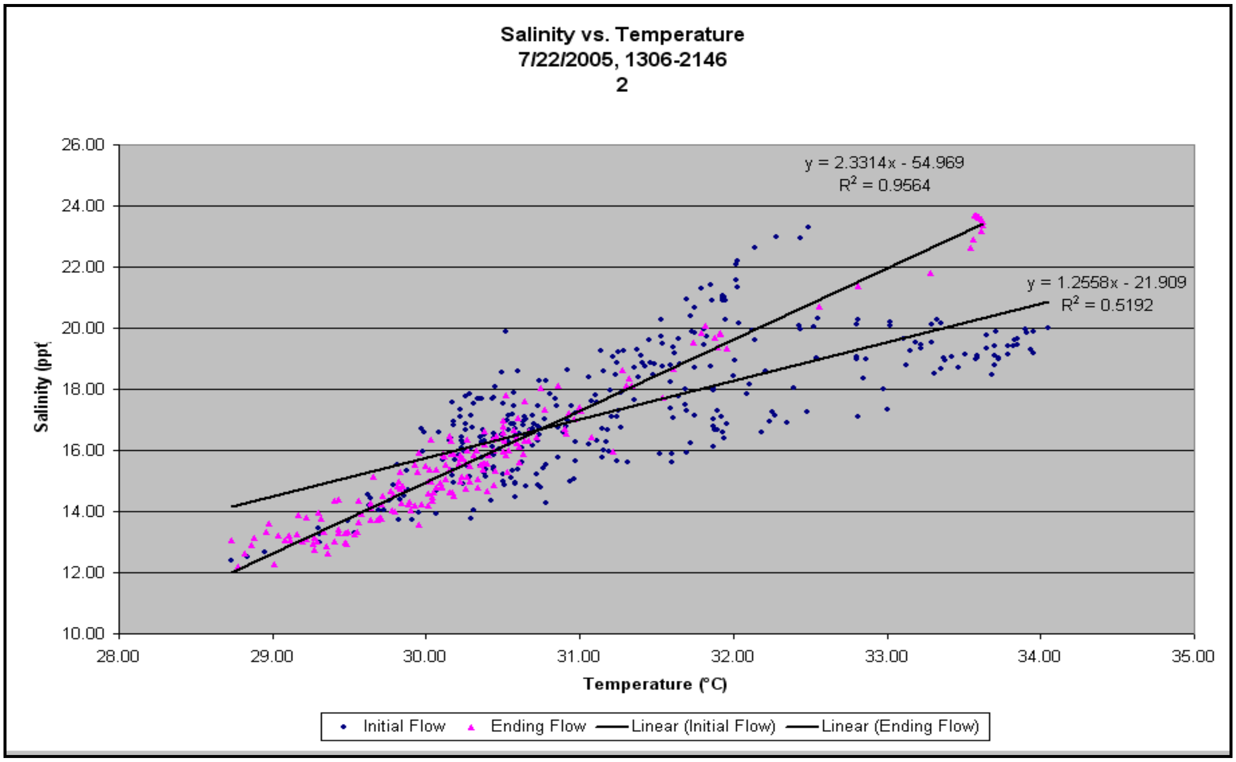


Figure A 5 - Scatter diagrams of salinity and temperature for the time sub segment for the second period

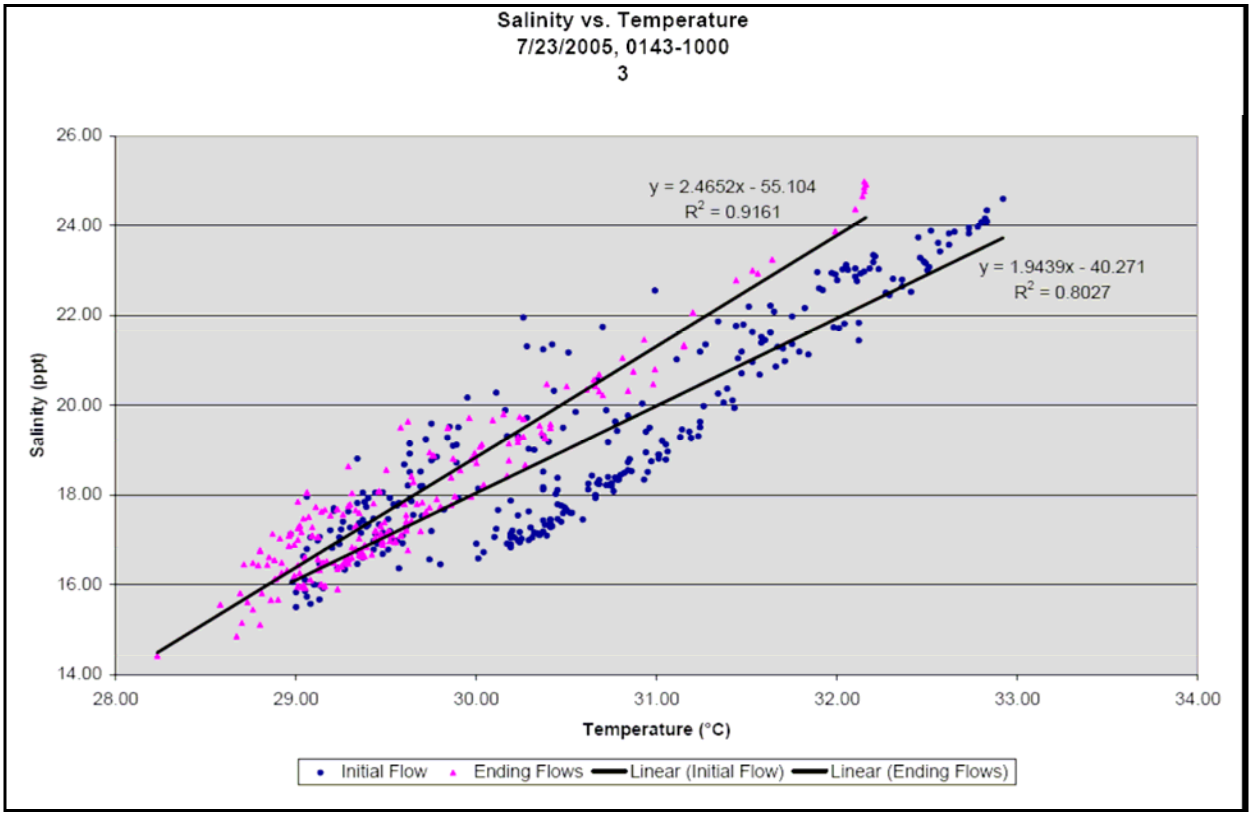


Figure A 6 - Scatter diagrams of salinity and temperature for the time sub segment for the third period

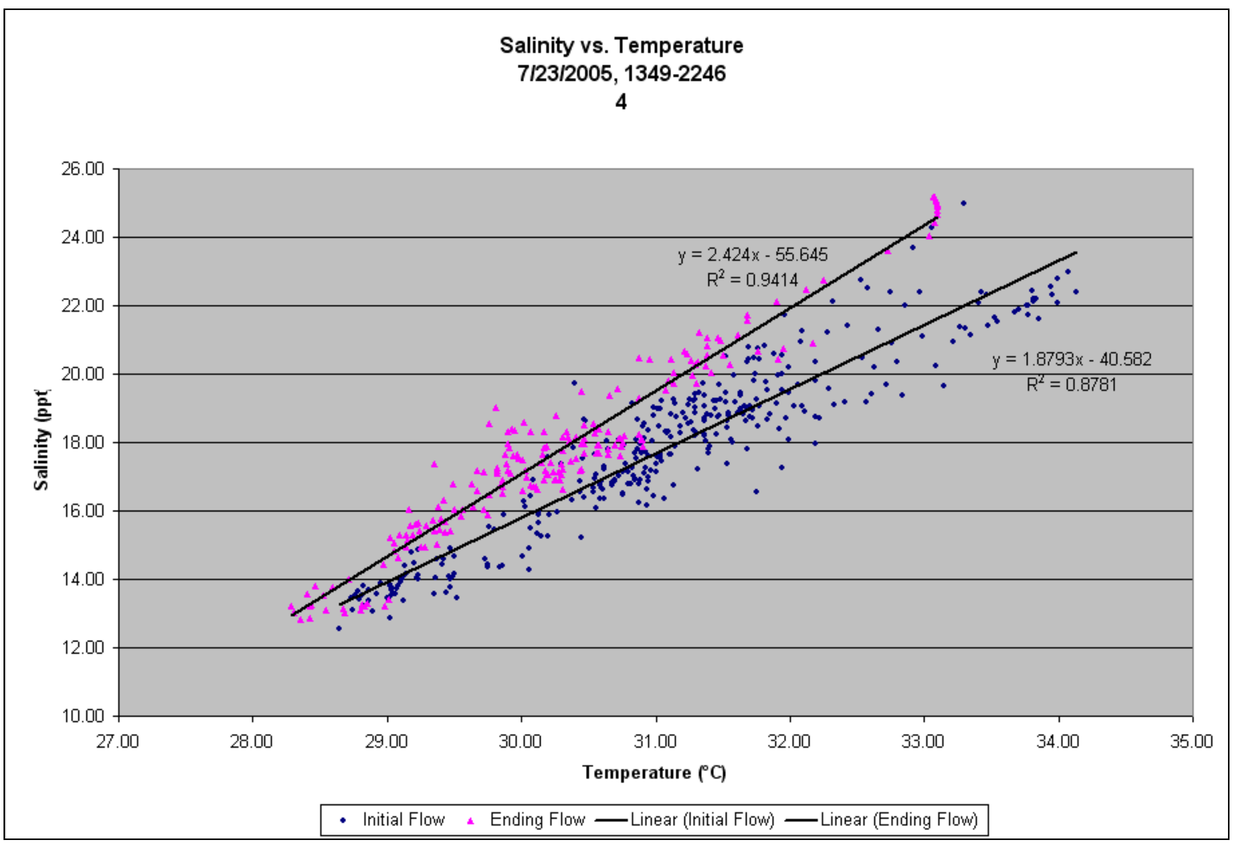


Figure A 7 - Scatter diagrams of salinity and temperature for the time sub segment for the fourth period

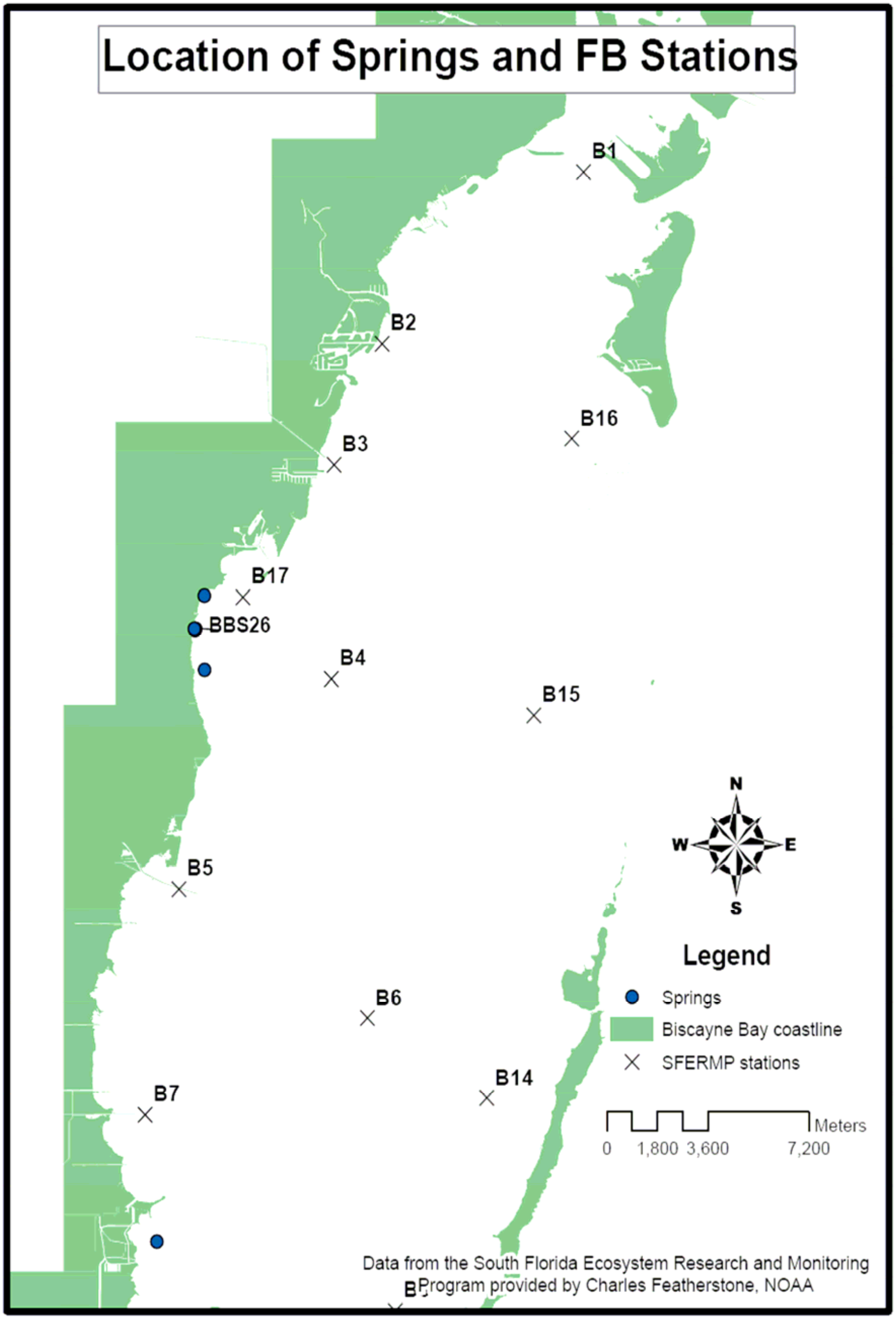

Location of Springs and FB Stations
B1
B2
B16
B3
B17
BBS26
B4
B15
N
W
E
S
B5
Legend
Springs
Biscayne Bay coastline
SFERMP stations
B6
B14
B7
Meters
0 1,800 3,600 7,200
Data from the South Florida Ecosystem Research and Monitoring Program provided by Charles Featherstone, NOAA

Figure A 8