Wakulla and Sally Ward Springs:

Development of Composite Discharge Time Series

Technical Memorandum

Resource Management Division

Bureau of Water Resource Evaluation

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1 Introduction

The Northwest Florida Water Management District (NWFWMD or District) is developing minimum flows and minimum water levels (MFLs) for the Wakulla and Sally Ward Spring system located in Wakulla County, Florida. Minimum flows will address protection of water resources potentially affected by reduced spring flows due to consumptive uses, including flows in the downstream freshwater and estuarine reaches of the Wakulla River.

This technical memorandum describes methods used to develop a reference flow regime or “baseline” time series for Wakulla Spring and Sally Ward Spring. These time series (complete or a subset) will be utilized in the determination of Wakulla and Sally Ward Spring minimum flows. The development of a baseline time series of discharge for Wakulla and Sally Ward Springs is a multistep process. First, a continuous record of daily discharge estimates must be assembled. Multiple data gaps are present in the measured discharge for both springs and, if possible, these gaps are infilled using regressions developed from other data sources which are correlated with spring discharge (Figure 1). Second, climatic conditions, such as precipitation and evapotranspiration are investigated for trends which may impact spring discharge. Third, groundwater level data at Floridan Aquifer wells within the Wakulla Spring groundwater contribution area (GWCA) are investigated for long-term trends and their relation to spring discharge to help assess whether groundwater withdrawals have measurably reduced spring discharge. Changes in hydraulics along the spring run and associated stage-discharge relationships are also evaluated. Lastly, using the best available spring flow data, an appropriate reference period (hereafter referred to as “baseline”) time period was selected for use in minimum flow determination.

2 Wakulla Spring

Wakulla Spring is first-magnitude spring (median discharge >100 cubic feet per second or cfs) located within the Edward Ball Wakulla Springs State Park (Figure 1). The Wakulla Spring pool is circular with a diameter of approximately 315 ft and a maximum pool depth of 185 ft. The spring vent measures approximately 50 ft by 82 ft. The spring serves as the main source of water for the Wakulla River, which then flows approximately 9 miles to the southeast where it discharges into the St. Marks River. The St. Marks River discharges into Apalachee Bay and the Gulf of Mexico. Due to its proximity to the Gulf of Mexico, Wakulla River stage and discharge are affected by tidal variations. Multiple sources of Wakulla Spring and Wakulla River discharge data are available for developing a spring discharge time series. Methods for estimating spring discharge are discussed below.

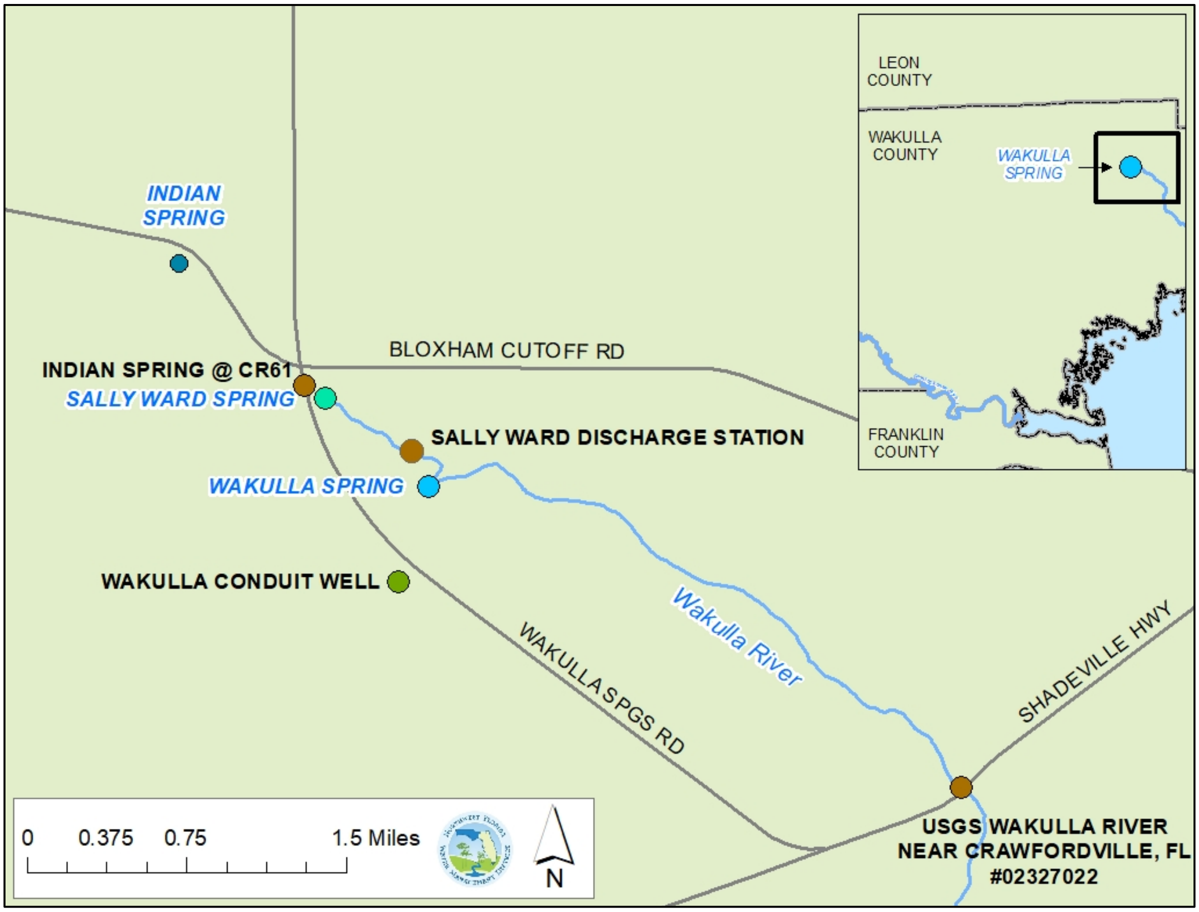


Figure 1 – Location of Sally Ward Spring and Wakulla Spring and River Discharge Monitoring Stations. The S4 and Argonaut velocity meters were/are located in the Wakulla Spring Main Vent.

2.1 Estimation of Discharge at Wakulla Spring

Wakulla Spring discharge is determined using the index velocity method. The index velocity method is used to develop a statistical relationship between water velocity measured within the Wakulla Spring main vent and manual discharge measurements taken in the spring pool just downstream of the spring vent. These relationships (more commonly referred to as 'ratings') make it possible to estimate a continuous time series of discharge values from measurements of another variable made at frequent, regular intervals such as stage or index velocity. Methods for developing these ratings, and the index velocity method are described in Levesque and Oberg (2012).

Two index velocity ratings were utilized to estimate Wakulla Spring discharge from May 9, 1997, to present. These ratings are a result of different velocity meters (S4 and Argonaut meters) being used in the spring vent. Details concerning velocity meter parameters and function, rating development, and discharge estimation are provided in Appendix A.

The record of Wakulla Spring discharge between May 10, 1997, and December 31, 2019, is depicted in Figure 2. During the period of record, water velocity data were collected at two different sampling intervals. From May 1997 through July 2006, discharge was measured every three hours. In July 2010, sampling was increased from three hours to every 15 minutes. Discharge measurements from both sets of velocity data were subsequently aggregated to daily averages. During the 1997 to 2019 period of record, Wakulla Spring discharge has displayed an increasing trend with discharges prior to approximately 2010 being substantially lower than those after 2010.

2.2 Wakulla Spring Discharge Data Gap Infilling Techniques

As is evident in Figure 2, multiple data gaps (Table 1) exist in the record of Wakulla Spring vent discharge. These data gaps range in duration from one day to four years. The NWFWMD investigated several methods for estimating spring discharges for these periods of missing data using alternative data sources which could be correlated to spring discharges. These data sources include manual (discrete) discharge measurements collected near the spring vent, Wakulla River discharges estimated by the United States Geological Survey (USGS) approximately three miles downstream from the Wakulla Spring vent, and water levels in a nearby Wakulla Spring conduit. Efforts to relate each of these data sources to Wakulla Spring discharge are described in the subsequent sections of this technical memorandum.

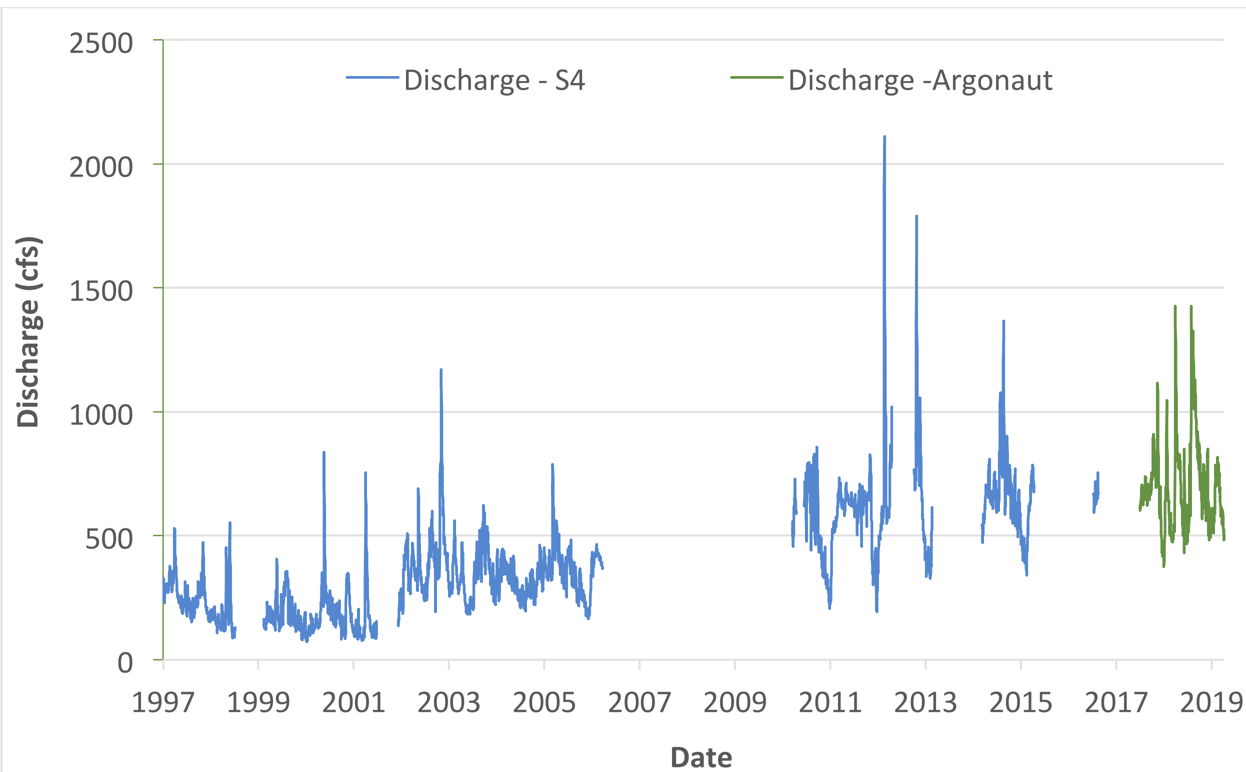


Figure 2: Daily Discharge (cfs) from Wakulla Spring as Measured by Velocity Meters Installed in the Wakulla Spring Main Vent

*Table 1- **Gaps in Continuous Wakulla Spring Discharge Time Series estimated by Index Velocity Method***

No.	Start time	End Time	Duration (Days)

1	October 20, 1997	October 24, 1997	5
2	November 12, 1998	June 18, 1999	219
3	November 3, 2001	April 13, 2002	163
4	July 31, 2006	July 21, 2010	1453
5	August 23, 2010	October 21, 2010	60
6	February 14, 2011	February 18, 2011	5
7	May 27, 2011	May 31, 2011	5
8	July 25, 2012	July 30, 2012	6
9	August 23, 2012	February 9, 2013	172
10	June 23, 2013	July 15, 2014	388
11	March 13, 2018	March 13, 2018	1
12	March 15, 2018	March 16, 2018	2

2.2.1 Manual Discharge Measurements

A total of 353 manual discharge measurements have been collected at irregular intervals near the Wakulla Spring vent between February 2, 1907, and December 31, 2019 (Figure 3). Manual discharge measurements are defined here as direct field measurements of discharge (in contrast to discharge estimates from index velocity, stage-discharge, or other types of ratings) that are made using techniques described in Turnipseed and Sauer (2010).The intervals between manual discharge measurements range from less than one day to nearly 16 years. Many of these manual discharge measurements have been used to develop the index velocity ratings. Manual discharge measurements were collected by both the USGS and NWFWMD.

During the 1907 through 2019 period of record, manual discharge measurements at Wakulla Spring averaged 443 cfs, and ranged between 25.2 cfs and 2,067 cfs (Figure 3). Manual discharge measurements are made during a relatively short period of time, typically less than one hour. The Wakulla Spring discharge values estimated using the index velocity method described above indicate that discharge can vary considerably throughout the day as a result of tidal influences (Figure 4) and, as a result, a single discharge measurement may not be representative of the daily average. In addition, the it was unable to be verified whether many manual measurements were conducted randomly or if any were targeting events (e.g. low discharges, high discharges, etc.). There are multiple large data gaps in the manual measurement discharge time series, which (when coupled with the tidal conditions and inability to infer daily mean values from the “instantaneous” manual measurements) makes it impractical to develop a long-term discharge time series for Wakulla Spring directly from these data. Due to these factors, the manual discharge measurements were not considered further for direct use in developing a long-term discharge time series for Wakulla Spring.

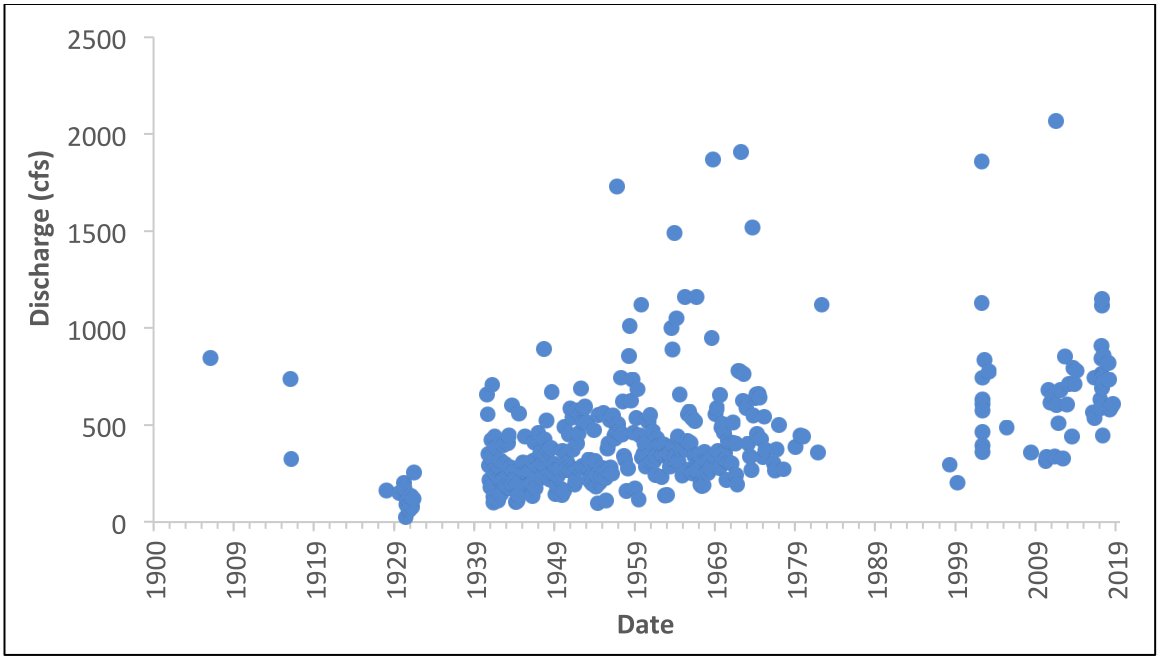


Figure 3: Manual Discharge Measurements Collected at Wakulla Spring

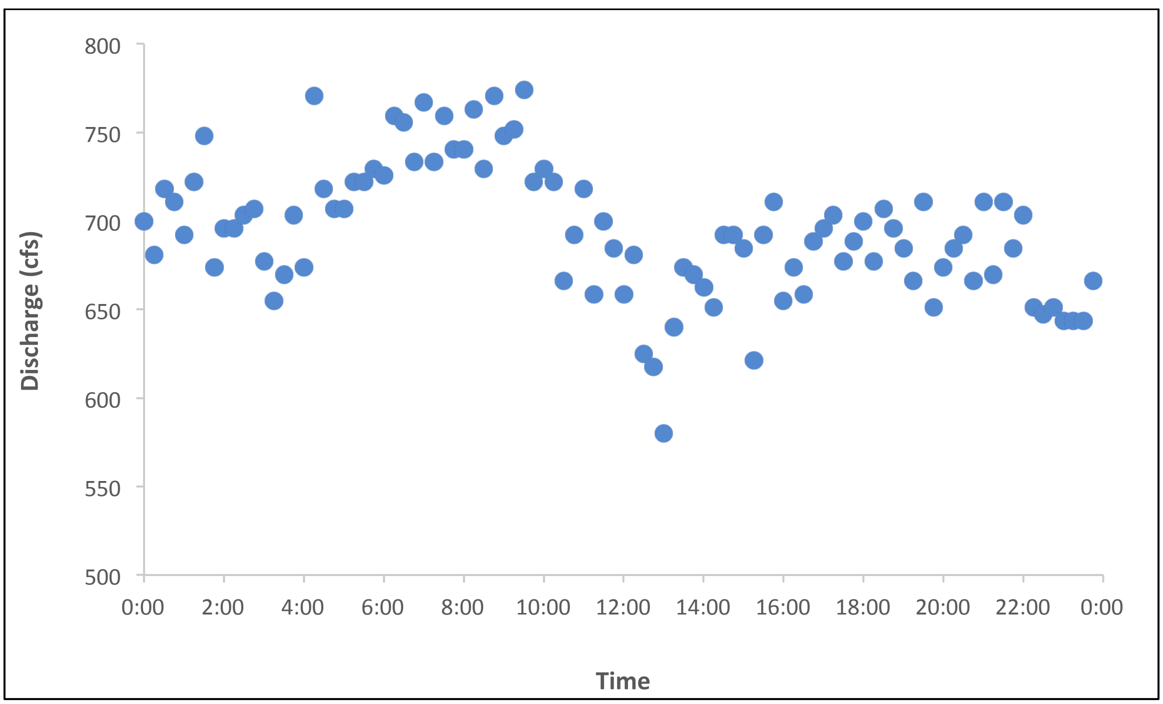


Figure 4: Tidal Variations in Index Velocity Estimated Wakulla Spring Discharge Observed on December 9, 2017

2.2.2 USGS Station 02327022, Wakulla River near Crawfordville, Florida

Approximately three miles downstream of Wakulla Spring, the USGS collects stage and discharge data at the County Road 365 (Shadeville Road) Bridge over the Wakulla River (USGS Station 02327022, Wakulla River Near Crawfordville, Florida) (Figure 1). These data are published and can be downloaded from the USGS website (https://waterdata.usgs.gov/nwis/uv?site_no=02327022). Between the spring vent and USGS Station 02327022, small quantities of inflow to the Wakulla River occur from small springs, sloughs, and diffuse groundwater inflow. These additional contributions accounted for an additional 9% of the measured Wakulla Spring discharge being added to the Wakulla River discharge between July 22, 2010, and November 7, 2019. As a result, the majority of the Wakulla River discharge at this location consists of discharge from Wakulla Spring.

The USGS began collecting Wakulla River discharge at station 02327022 on October 22, 2004, and continues through present. During this time period, discharge data from station 02327022 has a nearly continuous record that coincides with Wakulla Spring main vent discharge data collected by the District (described above). Wakulla River discharge estimates were initially computed and reported at a daily frequency by the USGS, however discharge estimates are available from the USGS National Water Information System website at a 15-minute interval beginning on October 1, 2007, and continuing to present.

In addition, station 02327022 contains discharge estimates for many of the days contained in the data gaps present in the Wakulla Spring discharge time series (Figure 5). Discharge data from station 02327022 was investigated for use as an explanatory variable for filling existing data gaps in the Wakulla Spring discharge time series using a variety of statistical methods including linear and locally-weighted (LOESS) regressions. Each of these methods for Wakulla Spring gap filling is described below.

2.2.2.1 Linear Regressions

Simple linear regressions were investigated as a means of estimating spring vent discharges from Wakulla River discharges. Two types of daily averages of Wakulla Spring and Wakulla River discharges were evaluated for this analysis: average daily data and average daily tidally filtered data.

2.2.2.1.1 Daily Average Data

Based on initial examination of scatter plots, the relationship between daily discharge at USGS station 02327022 and discharge at Wakulla Spring appeared to be linear. A simple linear regression was conducted using the period of overlapping average daily discharge data between the Wakulla Spring and Station 02327022 (Figure 6, Table 2), with the average daily discharge at station 02327022 as the explanatory variable. This regression was based on 1,891 days of concurrent discharge data between October 22, 2004, and November 8, 2018, spanning a range of discharges.

The resulting relationship between the average daily Wakulla Spring discharge and Station 02327022 is:

$$\mathbf{y=0.661x + 92.815,\ R^2 = 0.67}$$

where;

y = Wakulla Spring vent daily discharge (cfs)

x = USGS Station 02327022 average daily discharge (cfs)

The resulting regression has a mean residual of -7.83E-14 cfs, a mean absolute residual of 106.85 cfs, and a root mean square error (RMSE) of 128.3 cfs. Note that these regression analyses were based on datasets of daily values. As such, the residuals exhibit a high degree of temporal (serial) correlation. Although the presence of serial correlation doesn't affect the estimated values of the regression intercept and slope parameters, it will cause the standard error (error variance) of the regression to be underestimated and accordingly understate the true level of uncertainty in the regression relationship. Therefore, if confidence intervals or hypothesis testing is needed for this regression relationship at some point, the effect of serial correlation will need to be accounted for.

As is evident in Figures 5, 7, and 8, the relationship between discharge at the Wakulla Spring vent and Station 02327022 has changed over time, with spring discharge contributing a larger portion of the discharge at Station 023327022 in more recent years. The residuals for the regression were not evenly distributed across the entire discharge range (Figure 7) or period of record (Figure 8). Due to the changing distribution of residuals across discharges and the period of record, alternative gap filling methods were investigated.

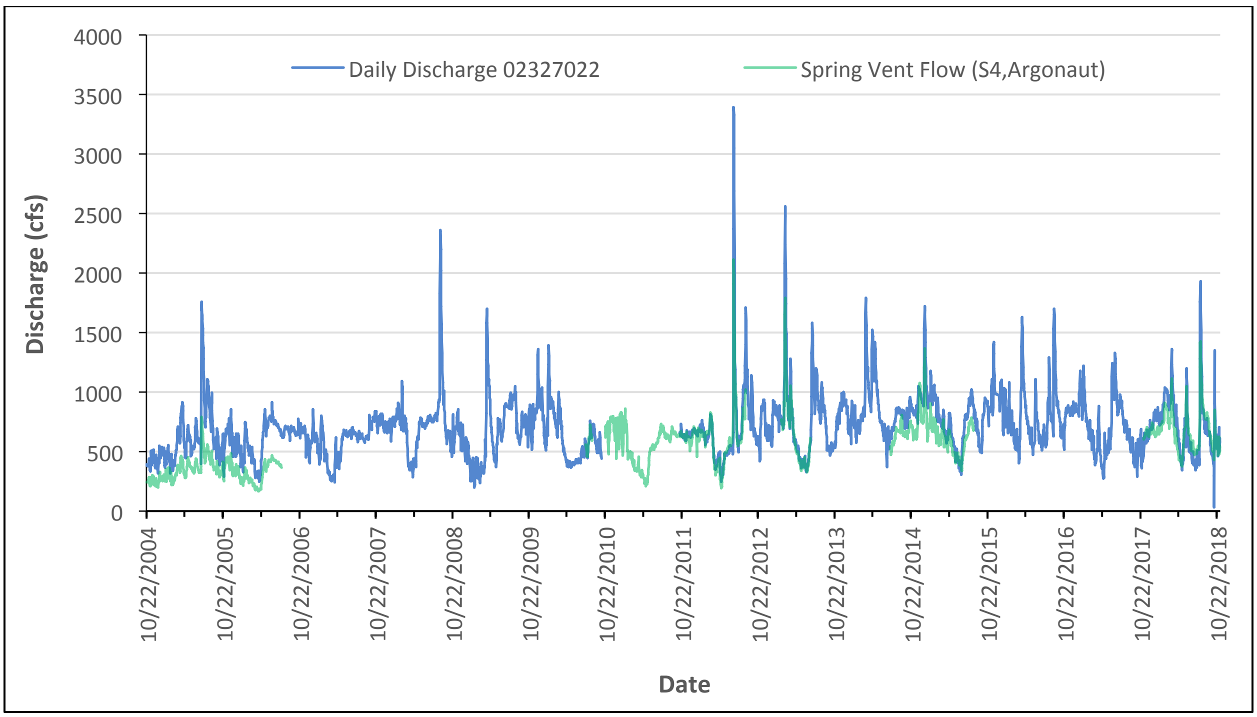


Figure 5: Average Daily Discharge at USGS Station 02327022 and Wakulla Spring Vent Between October 22, 2004, and November 18, 2018

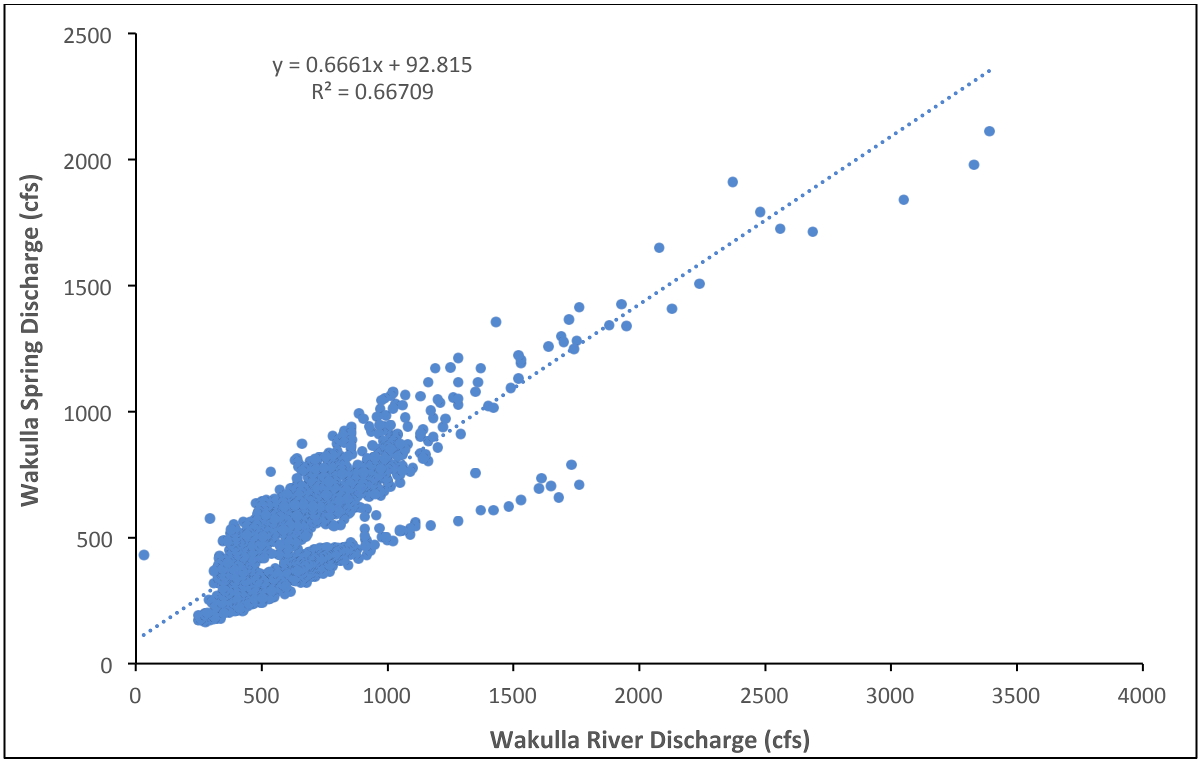


Figure 6: Linear Regression Between Daily Wakulla Spring Discharge (S4 and Argonaut) and Daily Wakulla River Discharge (USGS Station 02327022)

Table 2: Linear Regression Statistics for the Relationship Between the Wakulla Spring Vent Average Daily Discharge and Station 02327022 Average Daily Discharge

Regression Statistics	
Multiple R	0.82
R Square	0.67
Adjusted R Square	0.67
Standard Error	128.39
Observations	1891

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	62396607	62396607	3785.22	0
Residual	1889	31138795	16484.27		
Total	1890	93535403			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	92.82	7.90	11.75	8.45E-31	77.32	108.31	77.32	108.31
Daily Discharge 02327022	0.67	0.01	61.52	0	0.645	0.69	0.65	0.69

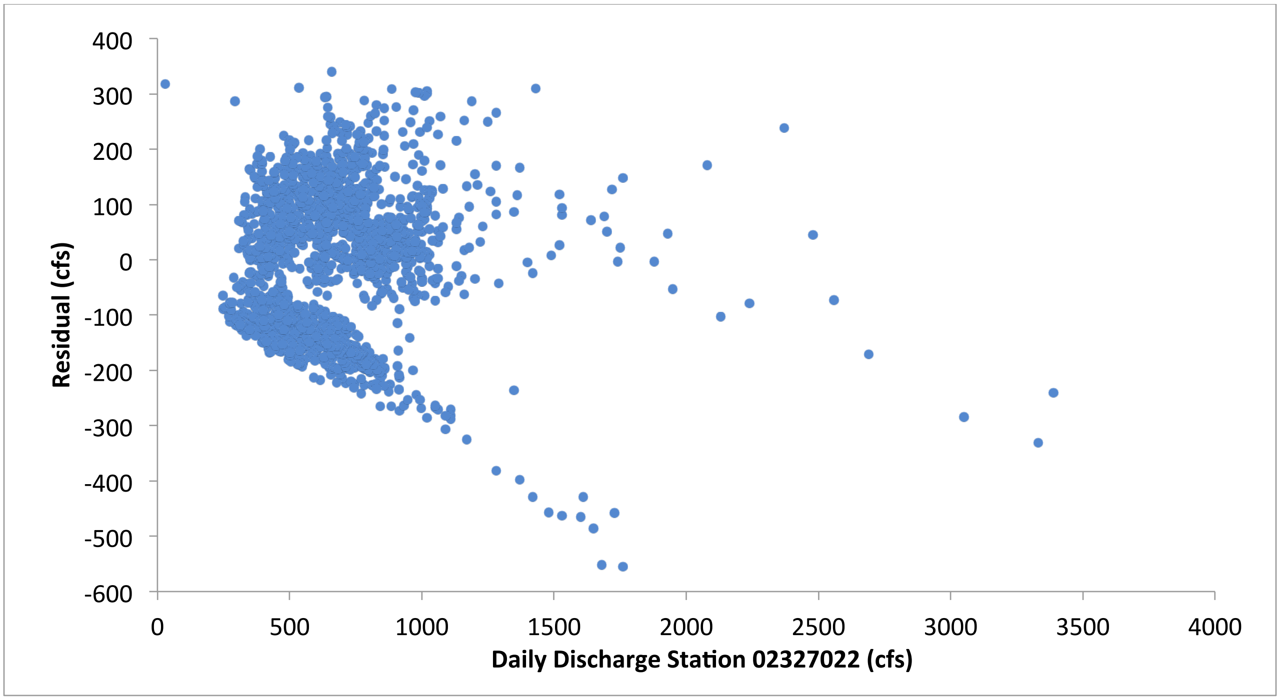


Figure 7: Residual Plot for Linear Regression Between Daily Wakulla Spring Vent and Daily Station 02327022 Discharge

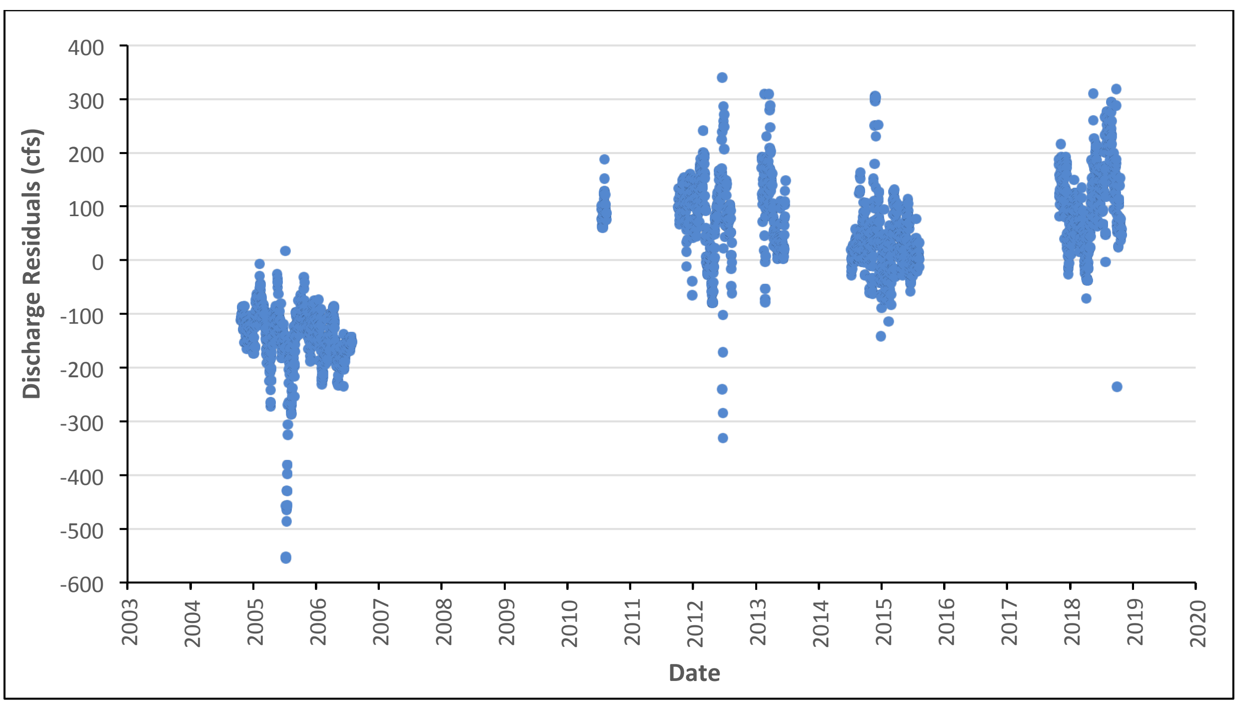


Figure 8: Residuals over Time for Linear Regression Between Daily Wakulla Spring Vent and Daily Station 02327022 Discharge

Tidally Filtered Data

As previously described, discharge along the Wakulla River is tidally influenced and displays increasing tidal variation with increasing proximity to the confluence with the St. Marks River. The availability of higher frequency, 15-minute discharge data at station 02327022 beginning on October 1, 2007, allowed for discharge data to be tidally filtered to better account for tidal influences compared to daily estimates. A tidal filter was applied to both the Wakulla Spring discharge and station 02327022 15-minute discharge data to investigate whether such a filter would improve the relationship between spring discharge and that measured at station 02327022.

A Godin filter (USGS, 2010) was applied to the 15-minute USGS Wakulla River Near Crawfordville, FL. discharge dataset (October 2, 2007 to present) and to the 15-minute Wakulla Spring discharge estimates to remove the tidal fluctuations from the discharge time series (Figure 9). The Godin low pass filter is typically recommended and applied by the USGS for such purposes (USGS, 2010). The Godin filter was not applied to the average daily data because tidal signals can't be observed at the daily time scale.

The relationship between the tidally filtered daily discharge at station 02327022 and tidally filtered discharge at Wakulla Spring appears to be linear (Figure 10, Table 3). A linear regression was developed on the period of overlapping tidally filtered average daily discharge data between Wakulla Spring and station 023270212. This regression was based on 1,217 days of concurrent discharge data between July 22, 2010, and November 7, 2018. Available data for the period after November 7, 2018, for station 02327022 was classified by the USGS as having a 'provisional' status at the time of regression analysis and therefore subject to change. Between October 2, 2007, and July 22, 2010, Wakulla Spring discharge measurements were not available.

The resulting relationship between the tidally filtered average daily Wakulla Spring discharge and USGS Station 02327022 was:

$$\mathbf{y=0.6406x + 193.09,\ R^2 = 0.80}$$

Where;

y = Wakulla Spring vent tidally filtered average daily discharge (cfs)

x = USGS Station 02327022 tidally filtered average daily discharge (cfs)

The resulting regression has a mean residual of 8.13E-15 cfs, a mean absolute residual of 62.73 cfs, and a RMSE of 77.6 cfs. Note that these regression analyses were based on datasets with long periods of consecutive daily values. As previously stated, the residuals from the datasets typically exhibit a high degree of temporal (serial) correlation so the standard error statistic will underestimate the true level of uncertainty in the regression relation.

As is evident in Figures 9, 11, and 12, the relationship between discharge from Wakulla Spring and Station 02327022 has changed over time, with spring discharge contributing a larger portion of the discharge at Station 023327022 during some periods of overlapping data than others. The residuals for the regression were evenly distributed across the entire discharge range (Figure 11), however there are extended periods of time where the regression relation consistently over- or underestimated discharge from Wakulla Spring (Figure 12). While the R^2 value (0.82) and the more consistent variability of residuals across the discharge range was an improvement over the linear regression made with nontidally filtered daily data, the linear regression between the tidally filtered average daily discharge at Wakulla Spring and station 02327022 was not considered further for use in gap filling for the Wakulla Spring daily discharge time series because of the presence of extended periods of time where the regression relationship consistently over- or underestimated discharge from Wakulla Spring.

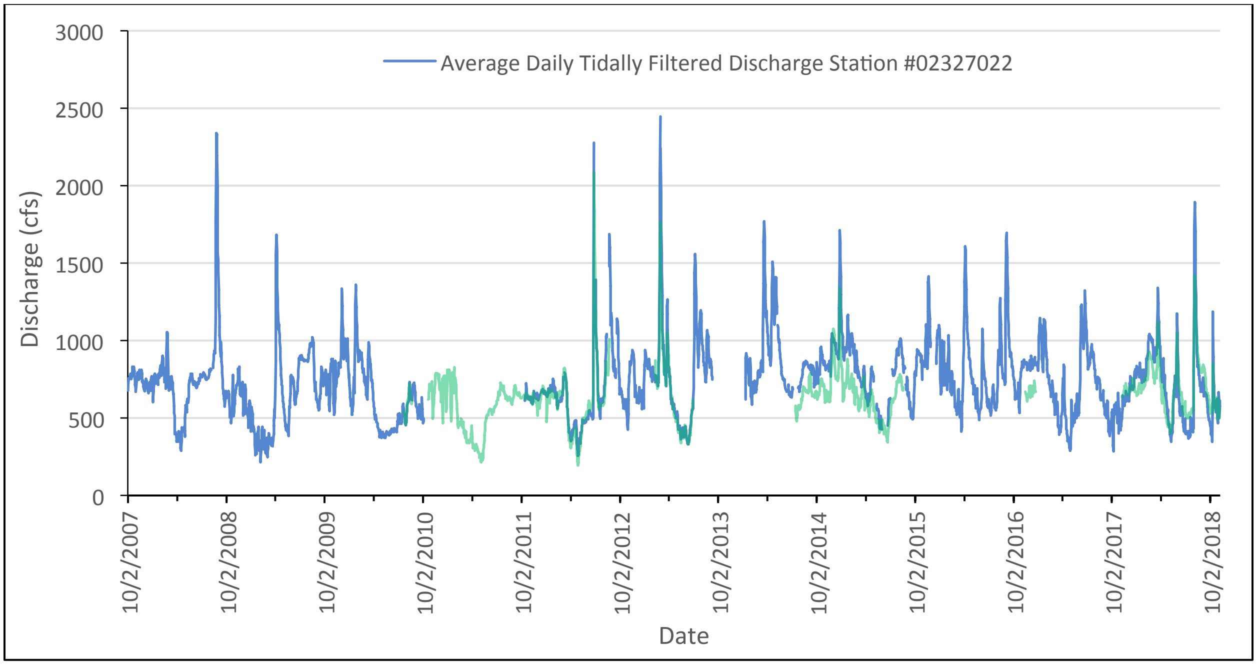


Figure 9: Average Daily Tidally Filtered Discharge at USGS Station 02327022 and Tidally Filtered Wakulla Spring Vent Between October 2, 2007, and November 18, 2018

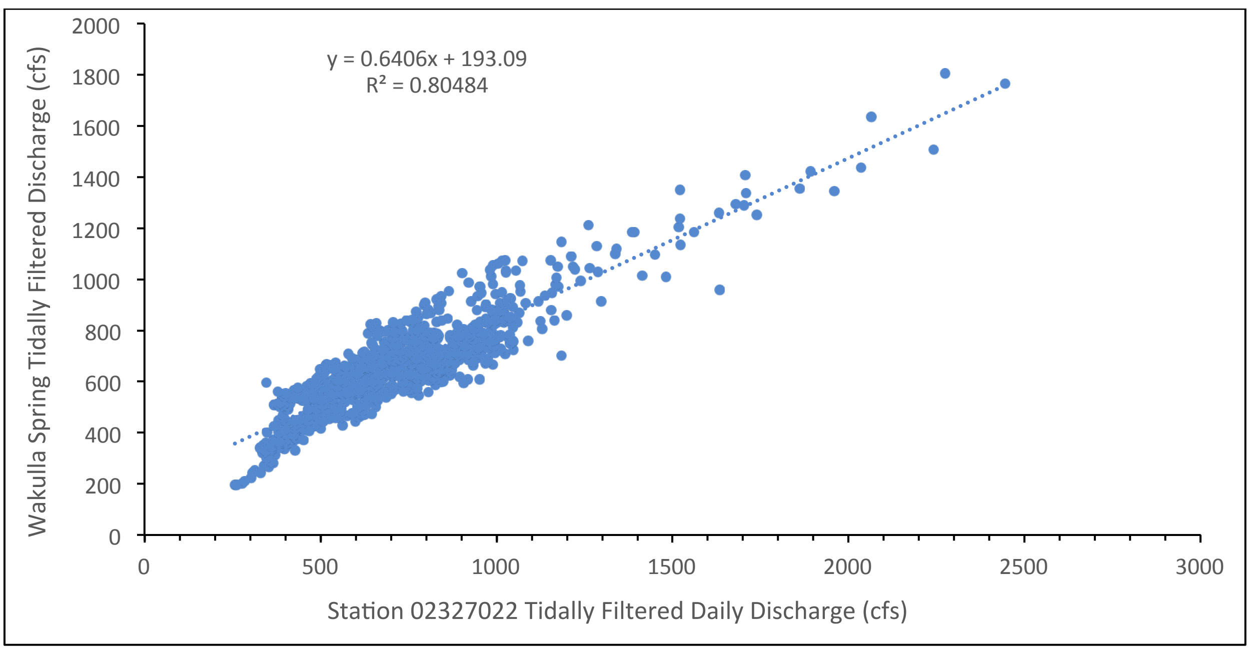


Figure 10: Linear Regression Between Tidally Filtered Wakulla Spring Discharge and Tidally Filtered Wakulla River Discharge at Station 02327022

Table 3: Linear Regression Statistics for the Relationship Between the Wakulla Spring Vent Tidally filtered Average Daily Discharge and Tidally filtered Station 02327022 Average Daily Discharge

Regression Statistics	
Multiple R	0.90
R Square	0.80
Adjusted R Square	0.80
Standard Error	77.70
Observations	1217

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	30244008	30244008	5010.57	0
Residual	1215	7333796	6036.046		
Total	1216	37577803			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	193.09	6.91	27.94	4.5E-133	179.53	206.65	179.53	206.65
X Variable 1	0.64	0.01	70.79	0	0.62	0.656	0.623	0.66

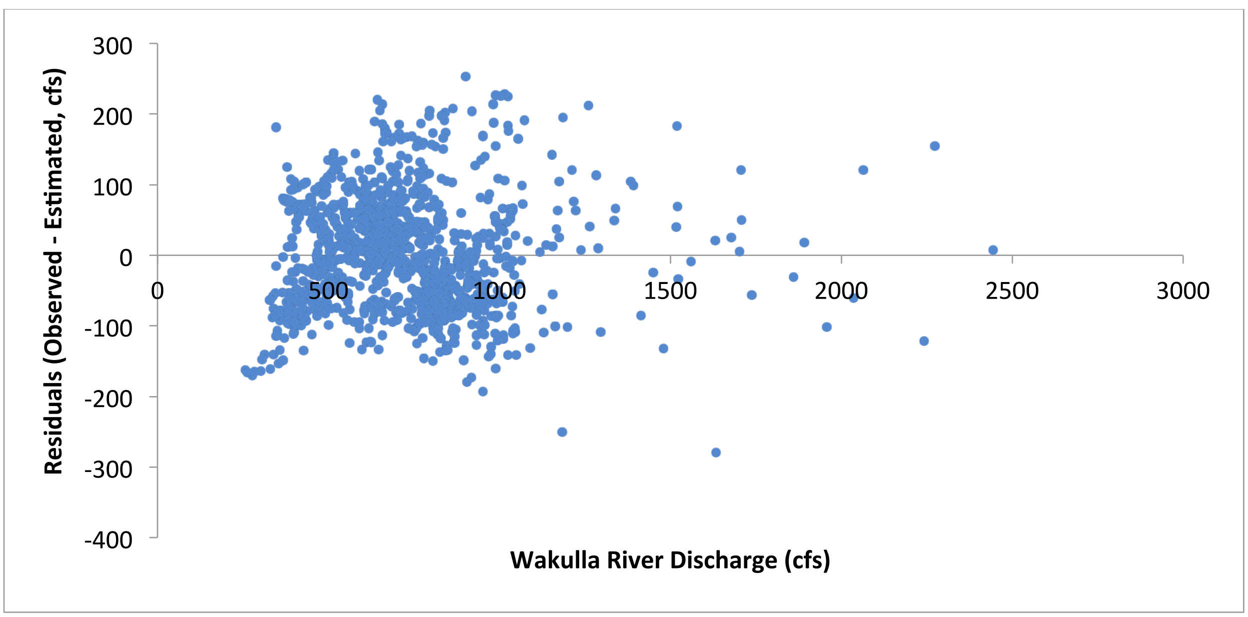


Figure 11: Residuals Across the Range of Discharges (Observed – Estimated) from the Linear Regression Using Tidally Filtered Wakulla Spring and Station 02327022 Daily Discharge Data

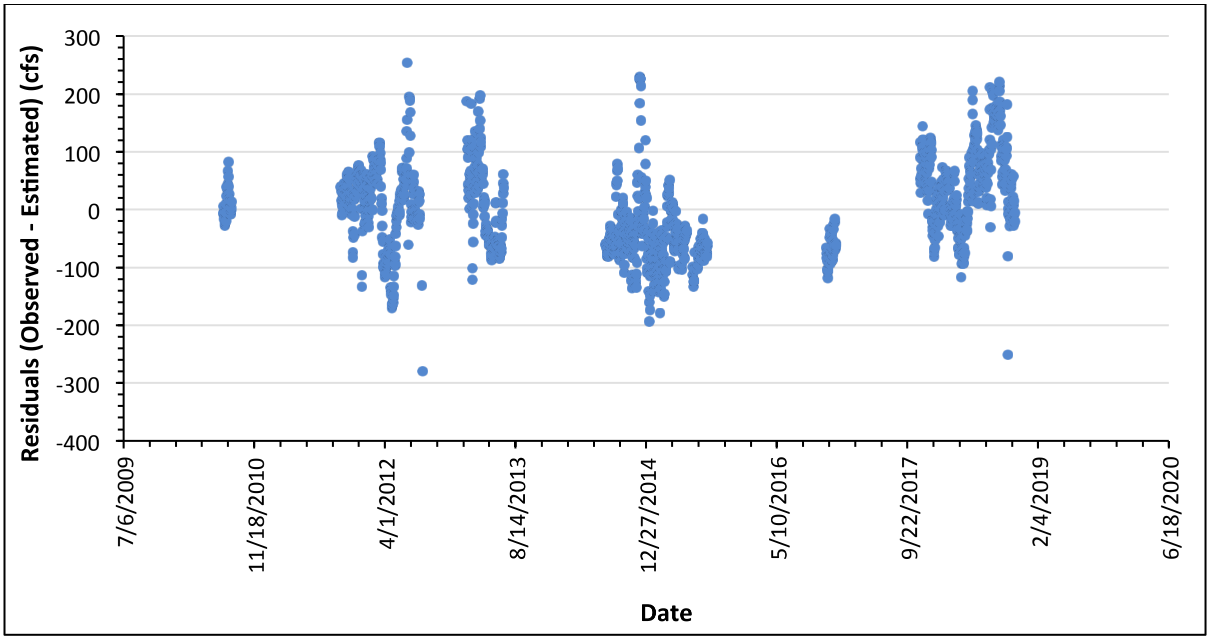


Figure 12: Residuals Over Time (Observed – Expected) for Linear Regression Using Tidally Filtered Wakulla Spring and Station 02327022 Daily Discharge Data

2.2.2.2 LOESS Regressions

Based on the analysis completed above, it is evident that the relationship between Wakulla Spring and station 02327022 has changed over time (Figure 13). As a result, a time parameter is needed to better fit the relationship between discharge at the two sites. In addition, this changing relationship has not occurred in a linear fashion with the difference between the Wakulla River and Wakulla Spring discharges generally lower for the 2010 through 2011 and the 2016 through 2018 periods than it was during the 2004 through 2006 and 2014 through 2015 periods (Figure 5). Therefore, "linear change with respect to time" parameter is not appropriate, and the changing relationship between the stations needs is better expressed using an approach that allows for nonlinear changes in this relation. A locally weighted regression (LOESS or LOWESS, Cleveland 1979) allows for such nonlinear relationship and was therefore investigated as a method for infilling missing Wakulla Spring discharge values in the time series.

The LOESS method is a locally weighted polynomial regression method that uses weighted least squares to fit linear functions of the predictors at the center of subsets of the data (Cleveland 1979). The subsets of data fitted to the regression, selected through a smoothing factor or parameter, are a specified fraction of the complete dataset. Each point within a data subset are weighted by a smooth decreasing function of their distance from the center of each subset. LOESS smoothing factors range between 0 and 1 with smaller smoothing factors using a narrower range of data predictors on either side of the estimated value to fit the regression. Large smoothing factors fluctuate the least in response to fluctuations in the data and are less likely to capture the random error associated with the data. Since the smoothing factor providing the best fit to the data was unknown, multiple smoothing factors were tested.

LOESS regressions were developed using the LOESS function in the base package of the R statistical programming language (R Core team, 2018). Multiple R software packages were also used to process the data for the regressions and evaluate their results, including the tidyverse, readx., lubridate, and dplyr packages (Grolemund and Wickham 2011, Wickham 2017, Wickham and Bryan 2019, Wickham et al. 2019). Data inputs into the model are the tidally filtered Wakulla Spring discharge data and tidally filtered Wakulla River station 02327022 discharge data using the entire period of overlapping data between October 22, 2004, and November 7, 2018 (Figure 14). Station 02327022 consisted of a combination of daily discharge data from October 22, 2004 to October 1, 2007, and tidally filtered discharge data from October 2, 2007 to November 7, 2018. Four different LOESS regressions were tested using smoothing factors (q) of 0.25, 0.5, 0.75, and 1.0 in order to help determine which factor produced the best results and ultimately should be used for discharge gap filling if that method was selected. A second-degree polynomial, Gaussian (least squares) fit was used to fit each of these LOESS regressions.

Comparisons between LOESS regressions with different smoothing parameters did not result in a significant change in the RMSE or mean residual with RMSE increasing from 52 to 70.2 cfs for smoothing parameters of 0.25 and 1.0, respectively (Table 4). Mean residual and mean absolute residual values displayed similar trends increasing from -3.1 cfs (mean absolute residual = 35.1 cfs) to 0.64 cfs (mean absolute residual = 55.7 cfs) for smoothing parameters of 0.25 and 1.0, respectively. Residuals were similarly distributed across the range of observed discharges (Figure 15) and time (Figure 16). Figures 15 and 16 indicate that the LOESS regression does a better job of mitigating against extended periods of consistently high or low residuals compared to the simple linear regressions. The measured (observed) Wakulla Spring discharge values compared with the LOESS estimated discharge values are depicted on Figure 17.

A LOESS regression with a smoothing factor of 0.5 was determined to be the most suitable for Wakulla Spring discharge gap filling. This regression was chosen based on its ability to account for a changing relationship through time between Wakulla Spring vent discharge and discharge measured downstream at USGS Station 02327022. Regression statistics showed that all smoothing factors provided a relatively good fit to the data and differences in RMSE and residuals was relatively small. A smoothing factor of 0.5 was selected based upon its ability to incorporate a relatively large amount of information around the estimated data point, without over-smoothing the time series. Increasing the smoothing factor from 0.25 to 0.5 reduced the equivalent number of parameters from 25.9 to 15.2, while further increasing in smoothing factor reduced the complexity of the regression far less. A smoothing parameter of 0.5, while using much of the data in the overlapping time period, still allows for measured discharge values closer in time to the value being predicted to provide more influence than measured values further away.

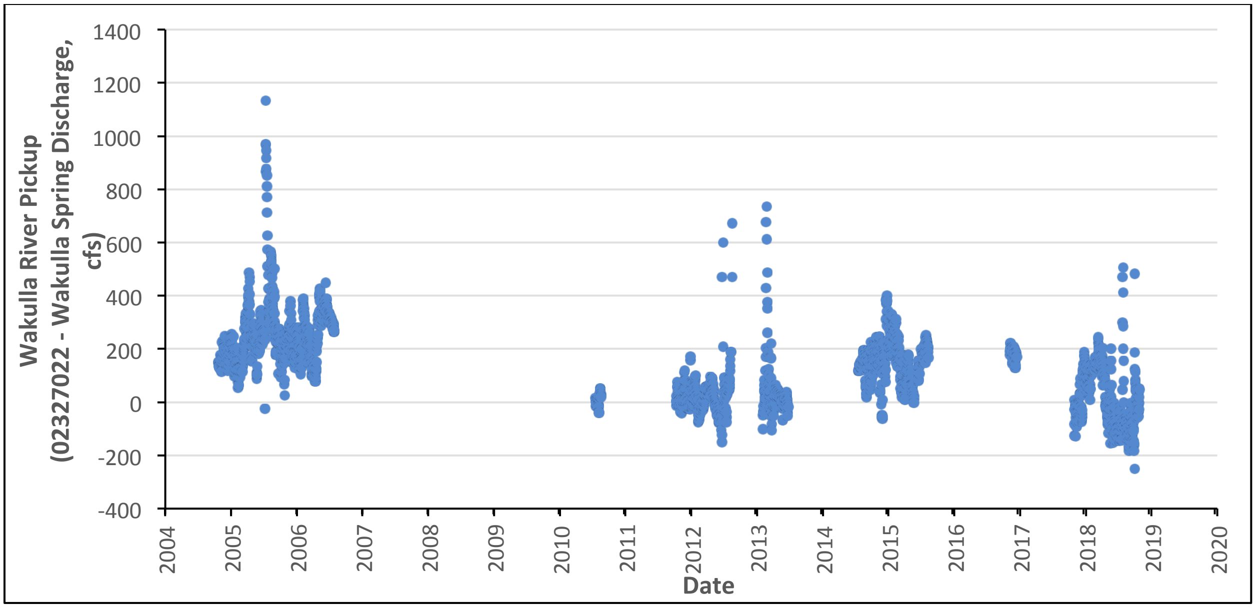


Figure 13: Change in Tidally Filtered Discharge Between the Wakulla River (Station 02327022) and Wakulla Spring Through Time

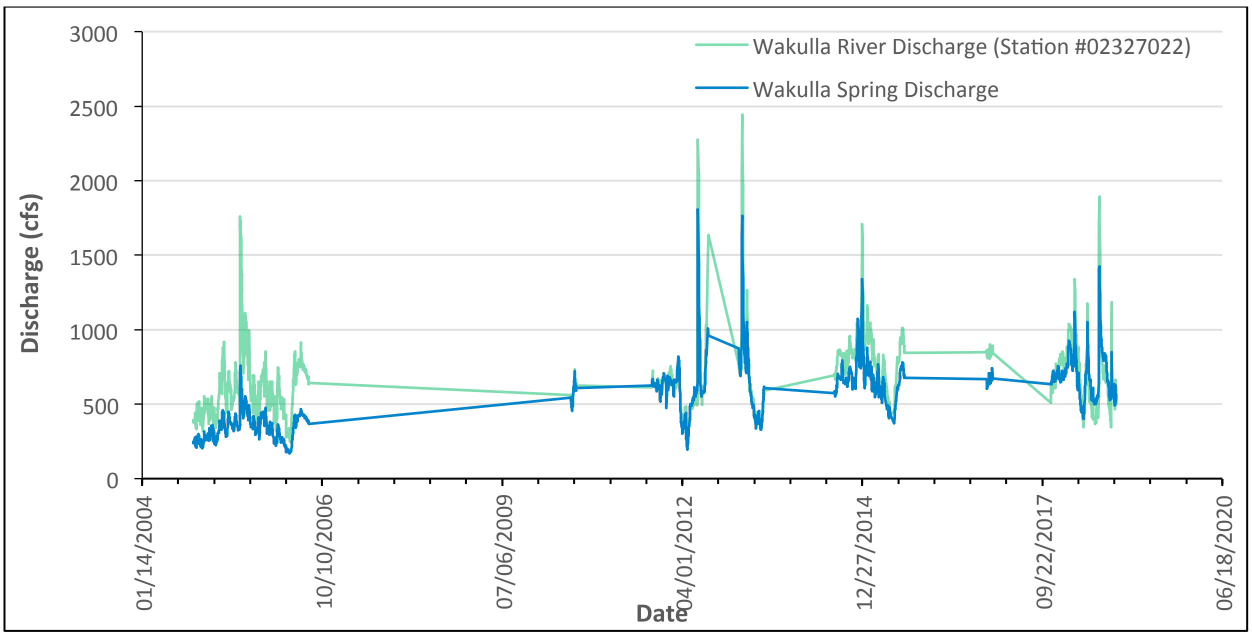


Figure 14: Overlapping Wakulla Spring and Wakulla River (Station 02327022) Discharge Data Included in the LOESS Model

Table 4: Comparison of Test Statistics for LOESS Regression Smoothing Factors Investigated

Smoothing Factor	RMSE	Mean Residual (cfs)	Mean Absolute Residual (cfs)	Equivalent # of Parameters
0.25	52.0	-3.1	35.1	25.9
0.5	56.5	-1.4	39.4	15.2
0.75	62.5	5.5	47.5	10.6
1.0	70.2	0.64	55.7	6.4

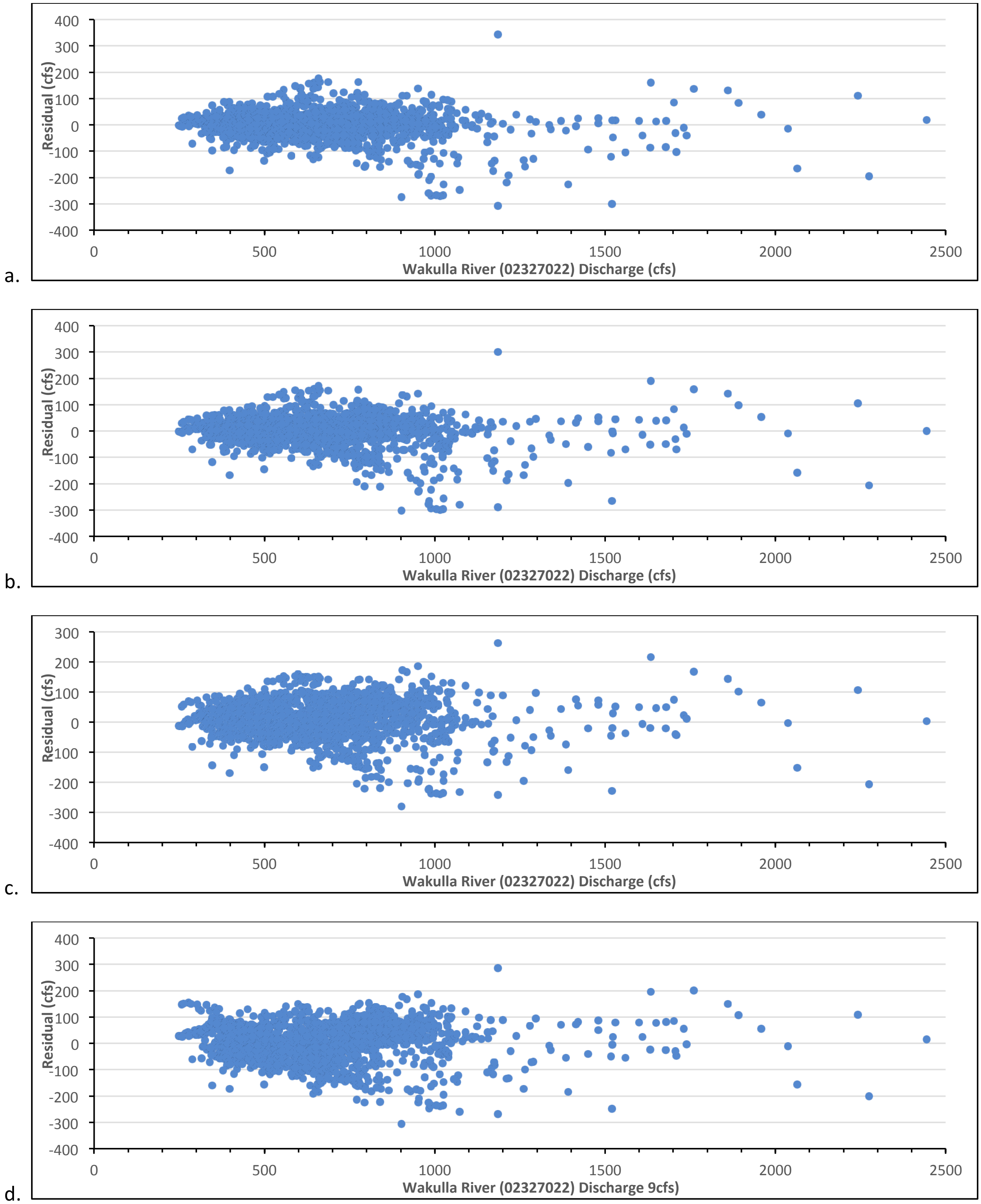


Figure 15: Residuals Across the Range of Discharges (Observed – Estimated) for LOESS Regression Using Daily and Tidally Filtered Wakulla Spring and Tidally Filtered Station 02327022 Daily Discharge Data. Smoothing Factors of 0.25 (a), 0.5 (b), 0.75 (c), and 1.0 (d) were tested.

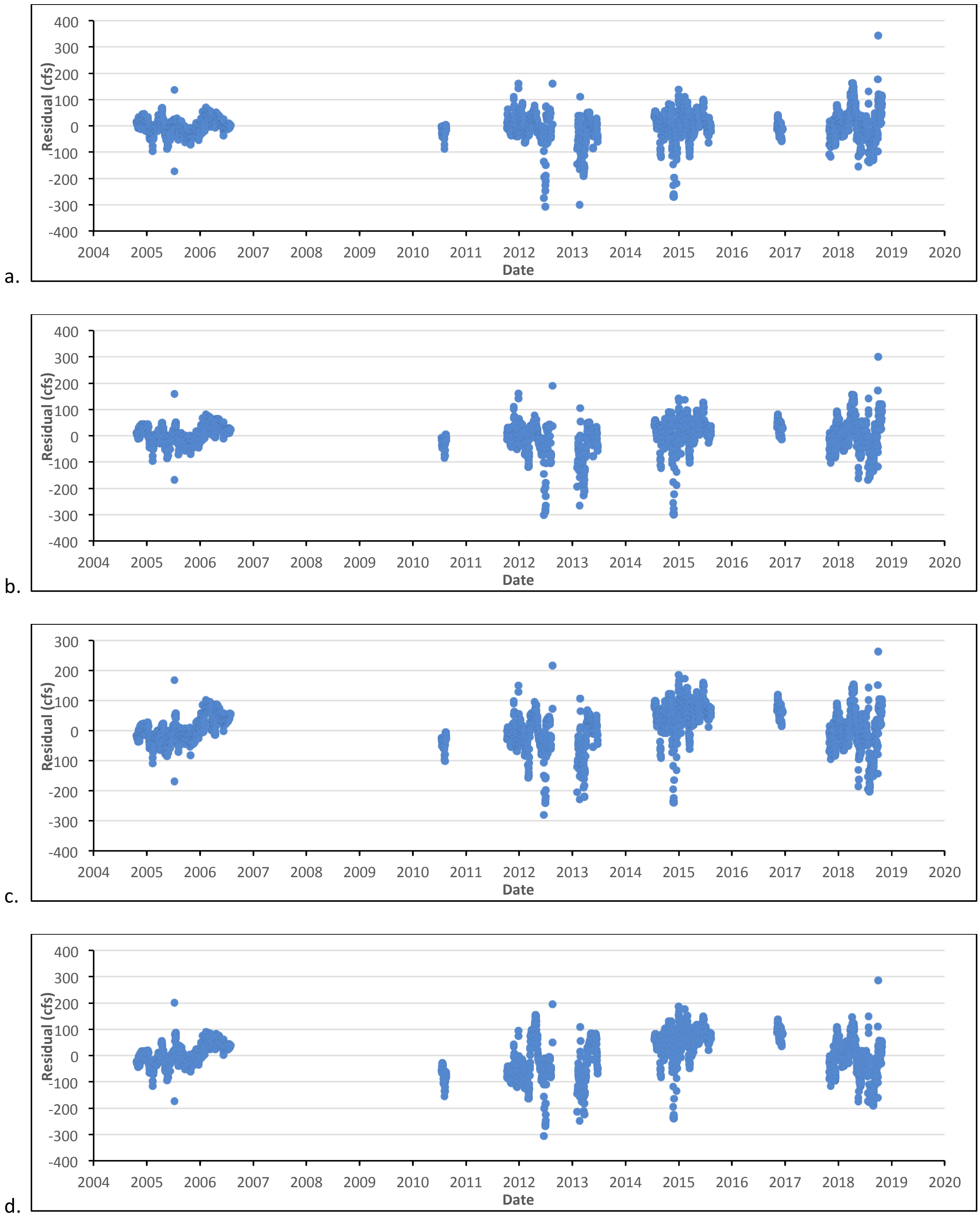


Figure 16: Residuals Over Time (Observed – Estimated) for LOESS Regression Using Daily and Tidally Filtered Wakulla Spring and Tidally Filtered Station 02327022 Daily Discharge Data. Smoothing Factors of 0.25 (a), 0.5 (b), 0.75 (c), and 1.0 (d) were tested.

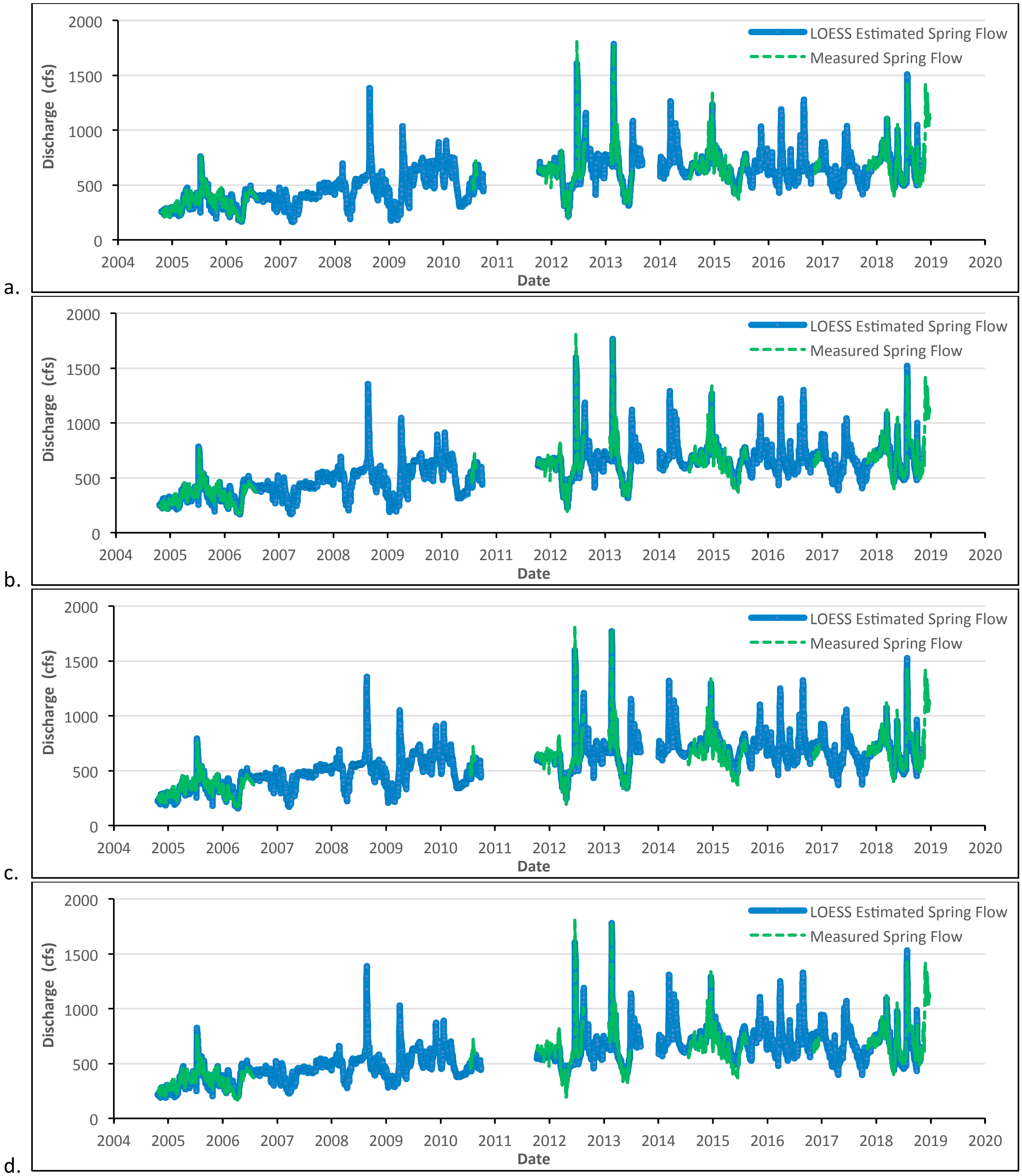


Figure 17: Measured vs. Predicted (LOESS) Wakulla Spring Daily Discharge Values for Smoothing Factors of 0.25 (a), 0.5 (b), 0.75 (c), and 1.0 (d).

2.2.3 Wakulla Conduit Well

A monitor well that is open to a conduit in the Floridan aquifer near Wakulla Spring (NWFID Station 8877, Wakulla Conduit Well @ West of HWY 61) also was evaluated as a possible explanatory variable for Wakulla Spring discharge data gap filling (Figure 1). This well (Wakulla Conduit Well @ West of HWY 61) is used to measure groundwater levels in a conduit which leads directly to Wakulla Spring. It is located approximately 0.5 miles from the vent and has a period of record which overlaps the later portion of the Wakulla Spring discharge data beginning on August 14, 2014, and extends across a considerable gap in discharge data (Figure 18). Head pressure within the Wakulla Spring conduit system would likely be highly correlated with measured Wakulla Spring discharge and therefore, was explored as an option for gap filling the Wakulla Spring discharge time series.

A linear regression was developed between the log-transformed tidally filtered daily average Wakulla Spring discharge and the log-transformed tidally filtered Wakulla conduit well daily average groundwater level. Although groundwater level fluctuation due to tidal influence was minimal, this data was filtered using a Godin Filter for consistency. Both datasets were log-transformed prior to developing the regression to reduce errors associated with differences in order of magnitude between the two variables. Concurrent tidally filtered daily averages from August 14, 2014, to January 4, 2019 were utilized to develop the regression relationship. Two outliers on October 10 and 11, 2018, were removed due to an unusually high-water level for the associated spring discharge which occurred as Hurricane Michael made landfall in northwest Florida. During this time, water levels at Wakulla Spring increased by approximately three feet and a short-term spring discharge reversal occurred (i.e. negative discharge). Figure 19 shows the relationship between Wakulla Spring tidally filtered daily average discharge and Wakulla conduit well tidally filtered daily average groundwater levels. Based on this figure, the relationship appears linear with no apparent increase in variance with higher discharges.

The resultant equation describing the relationship between Wakulla Spring tidally filtered daily average discharge and Wakulla conduit well tidally filtered daily average groundwater levels is:

$$\log(y) = 2.0082*\log(x) + 1.3641$$

Where;

x = Wakulla conduit well daily average groundwater levels

y = average daily Wakulla Spring discharge

The resulting linear regression statistics are provided in Table 5. Based on these results, Wakulla Spring daily average discharge are correlated to Wakulla conduit well daily average groundwater levels, with an R^2 value of 0.77. The mean residual value was -5.4E-15 and the mean absolute residual was 0.041 (both values are in log-transformed units). Residuals appeared to exhibit equal variance across groundwater levels (Figure 20). Serial correlation was evident in the residuals, which as previously stated is expected given the continuous, daily datasets used in this analysis. Temporally, the residuals appeared to exhibit positive and negative residual peaks that occurred approximately every three months (Figure 21). After the analysis was completed, it was determined that although the regression between the Wakulla Spring vent and Wakulla Conduit Well may be useful for infilling data, the available groundwater level data limit the use of this regression to infilling spring discharge data after August 14, 2014. However, after this time other gap filling methods (i.e. LOESS regression using station #02327022) may be better suited for Wakulla Spring discharge data gap filling.

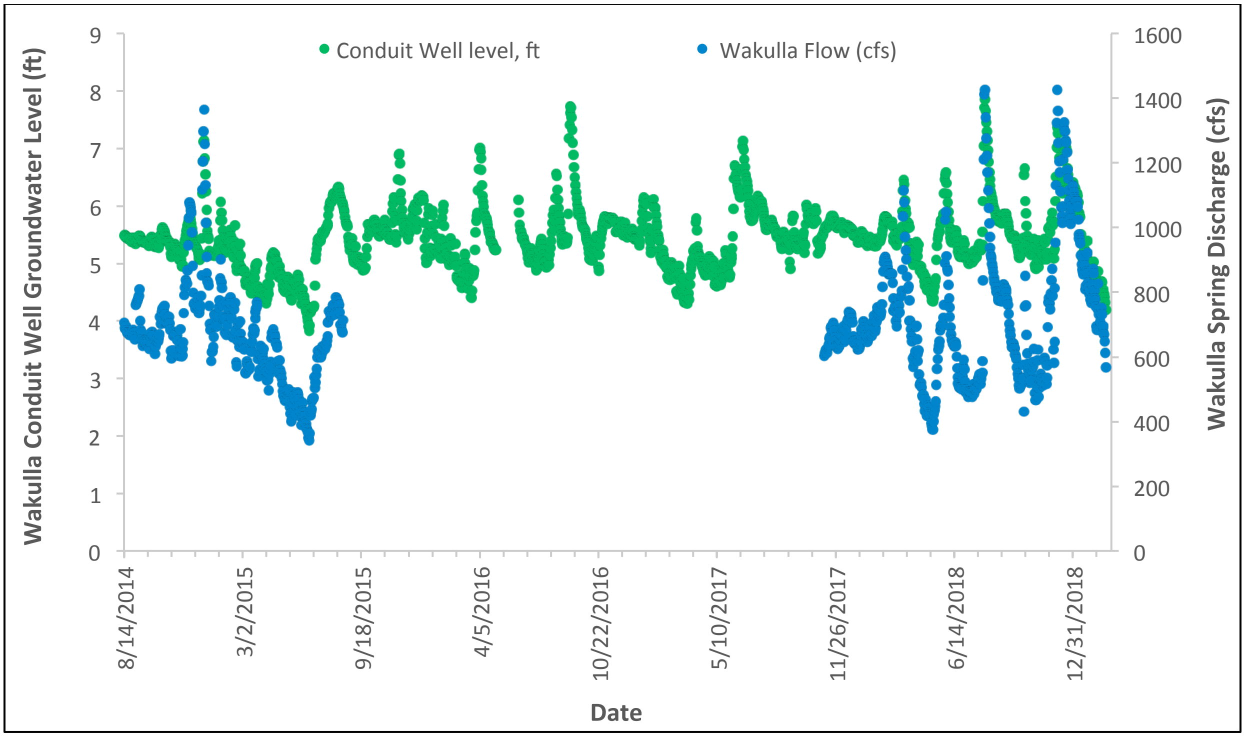


Figure 18: Period of Overlapping Data Between the Wakulla Conduit Well and Wakulla Spring Discharge.

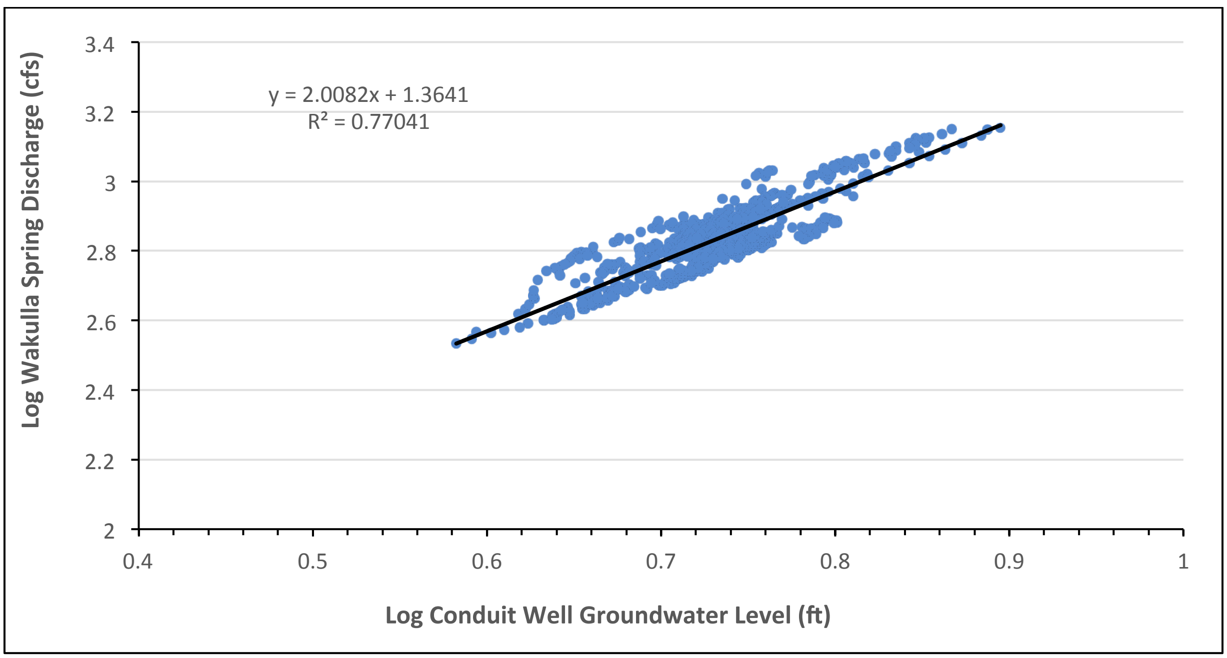


Figure 19: Linear Regression Log of Wakulla Spring tidally filtered daily average discharge vs. Log of Wakulla conduit well tidally filtered daily average groundwater levels.

Table 5: Linear Regression Statistics

Regression Statistics	
Multiple R	0.877728
R Square	0.770406
Adjusted R Square	0.770127
Standard Error	0.049572
Observations	824

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.778053	6.778053	2758.238	7.2E-265
Residual	822	2.01997	0.002457		
Total	823	8.798023			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.36409	0.027994	48.72818	1.3E-244	1.309142	1.419038	1.309142	1.419038
X Variable 1	2.008217	0.038238	52.51893	7.2E-265	1.933162	2.083273	1.933162	2.083273

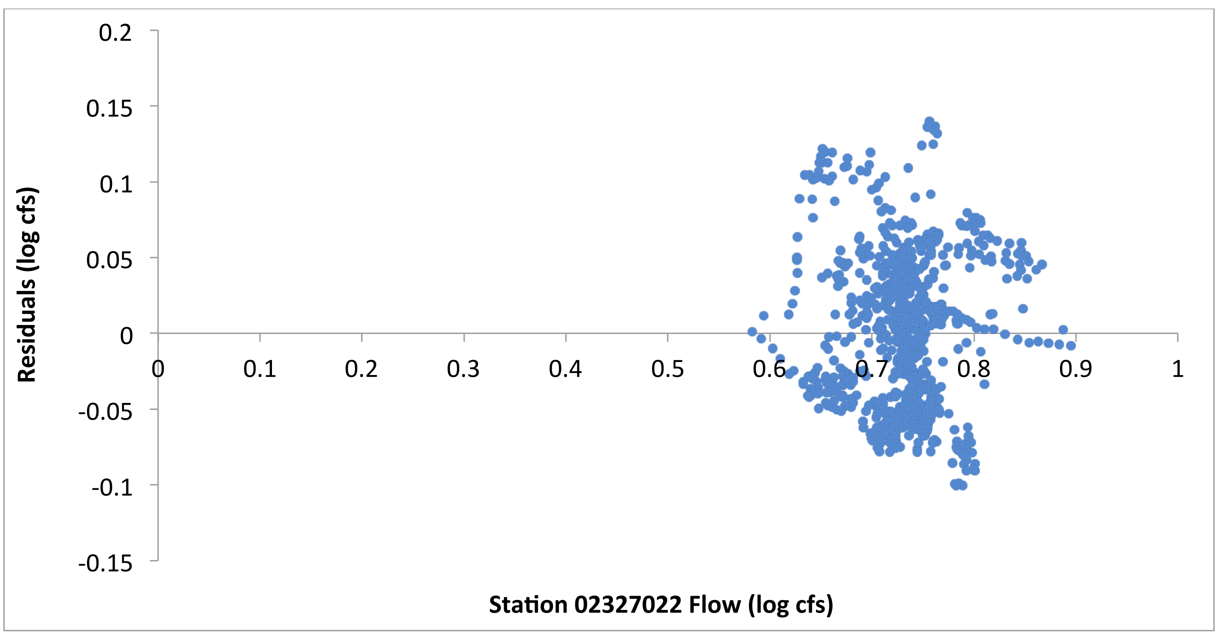


Figure 20: Residuals Across the Range of Discharges (Observed – Expected) for Regression Using Tidally Filtered Wakulla Spring Discharge and Tidally Filtered Wakulla Conduit Well Daily Groundwater Elevation Data.

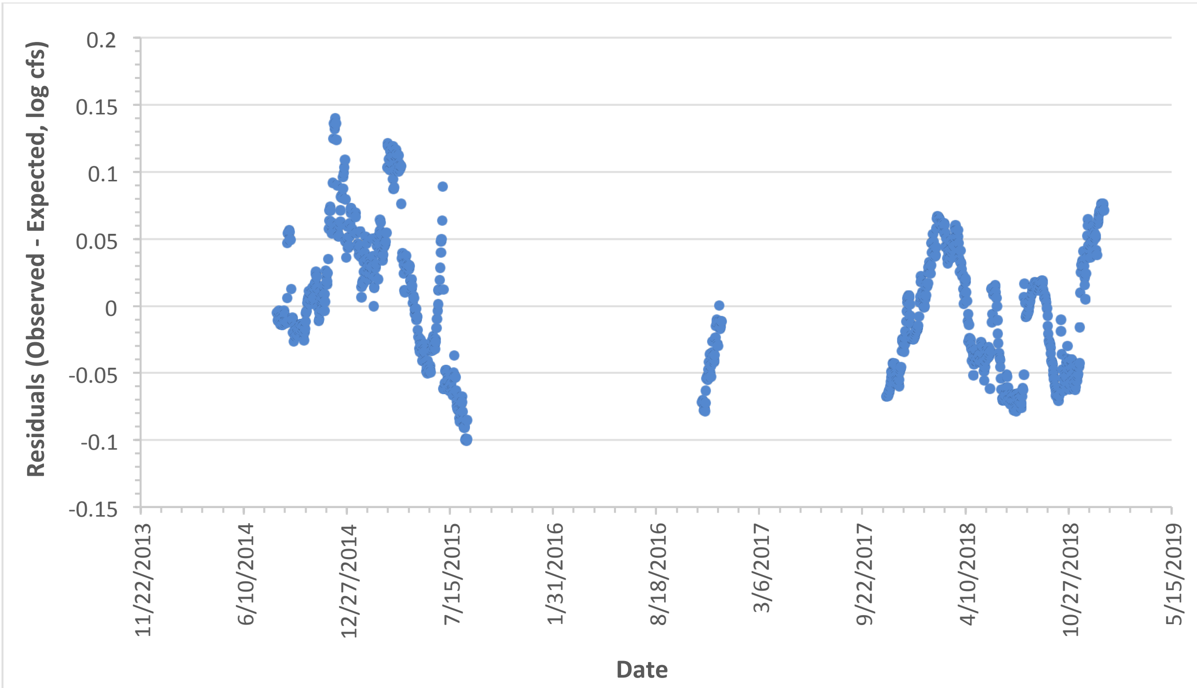


Figure 21: Residuals Over Time (Observed – Expected) for Regression Using Tidally Filtered Wakulla Spring Discharge and Tidally Filtered Wakulla Conduit Well Daily Groundwater Elevation Data.

2.3 Wakulla Spring Composite Discharge Time Series

The Wakulla Spring composite discharge daily time series is comprised of measured Wakulla Spring discharge (S4/Argonaut meters) when available and discharge estimates from the LOESS regression with a 0.5 smoothing factor. The resulting composite Wakulla Spring discharge time series extends from May 10, 1997, through December 31, 2019. A baseline period of Wakulla Spring discharge will be selected from this time period for use in minimum flow determination.

Following data gap infilling efforts using the LOESS regression, a total of 19 periods of missing data remain ranging in length from 1 day to 217 days (Table 6). In total, the number of days with no Wakulla Spring discharge data was reduced from 2,479 to 570 days between May 10, 1997, and December 31, 2018. There are limited data available to estimate Wakulla Spring daily discharge values prior to October 22, 2004.

The composite time series extends from May 10, 1997, through December 31, 2019 (Figure 22). Figure 23 depicts the effects of data gap infilling on the Wakulla Spring discharge duration curve and indicates that not addressing data gaps present in the measured Wakulla Spring discharge time series may result in an underestimation of Wakulla Spring discharge since 1997. This occurs on account of the data gaps and the ability to infill these data gaps occurs after October 22, 2004 when Wakulla Spring discharge had begun increasing. Data gap infilling increased the Wakulla Spring discharge for all but the most extreme discharge percentiles. The median discharge (50th percentile) is 358 cfs in the incomplete time series and 453 cfs following data gap filling.

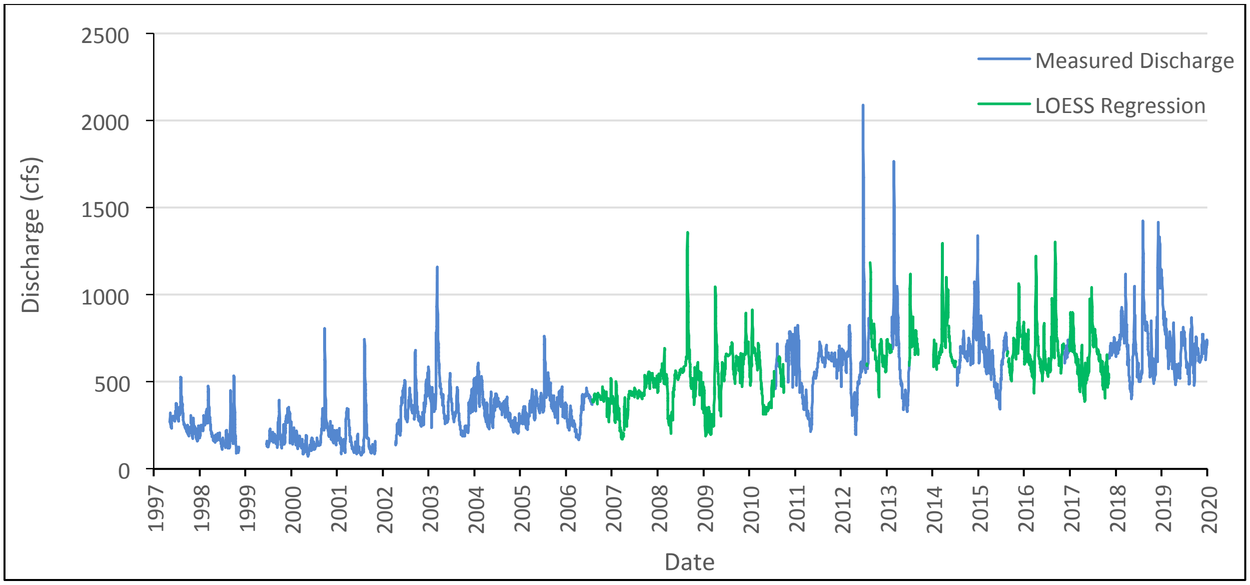


Figure 22: Full Composite Wakulla Spring Discharge Time Series from May 10, 1997, through December 31, 2019

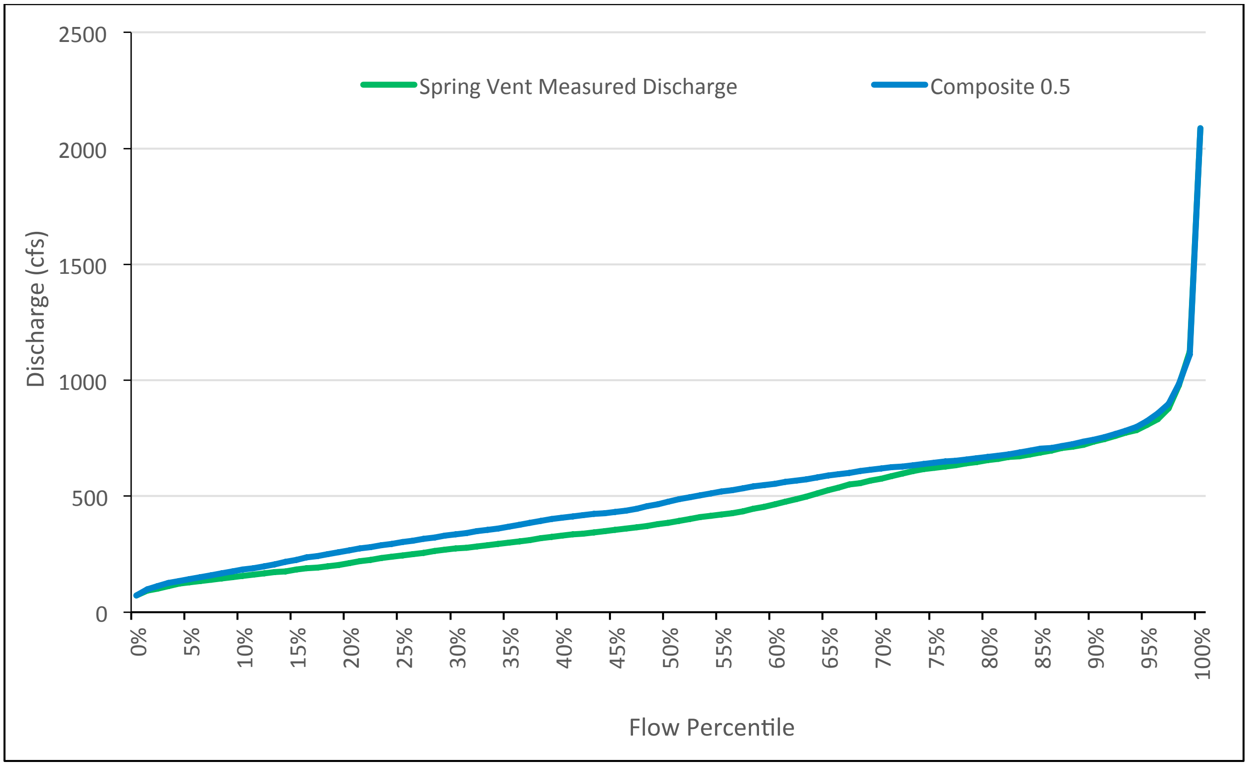


Figure 23: Discharge Percentile Curves for the Infilled Wakulla Spring Discharge Time Series from May 10, 1997, through December 31, 2019.

Table 6: Remaining Data Gaps Following LOESS Regression Infilling

Gap Start Date	Gap End Date	Number of Days
October 21, 1997	October 23, 1997	3
November 13, 1998	June 17, 1999	217
November 4, 2001	April 12, 2002	162
April 8, 2007	April 8, 2007	1
August 8, 2008	August 12, 2008	4
February 5, 2009	February 6, 2009	2
March 3, 2009	March 3, 2009	1
July 23, 2009	July 27, 2009	5
October 5, 2010	October 20, 2010	16
February 15, 2011	February 17, 2011	3
May 28, 2011	May 30, 2011	3
September 17, 2012	September 19, 2012	3
September 11, 2013	January 9, 2014	121
May 9, 2014	May 9, 2014	1
June 13, 2014	June 17, 2014	5
June 27, 2014	July 1, 2014	5
July 7, 2014	July 14, 2014	8
August 27, 2015	August 27, 2015	1
November 30, 2015	December 18, 2015	19

3 Sally Ward Spring

Sally Ward Spring is a second magnitude spring (median discharge between 10 cfs and 100 cfs) located approximately 0.7 miles to the northwest of Wakulla Spring (Figure 24). The Sally Ward Spring vent is approximately 18 ft in depth where it connects to an extensive underwater cave system. During high rainfall events, surface water can enter the Sally Ward Spring pool from a wetland slough connecting Sally Ward Spring to Indian Spring, which is located approximately one mile to the northwest. Combined discharge from both springs then flows down the Sally Ward Spring run where it connects with the Wakulla River 0.1 miles downstream from the Wakulla Spring main vent. The combined discharges from Wakulla Spring and the Sally Ward Spring run comprise the headwaters of the Wakulla River which flows more than 9 miles to the southeast into the St. Marks River and then into Apalachee Bay/Gulf of Mexico.

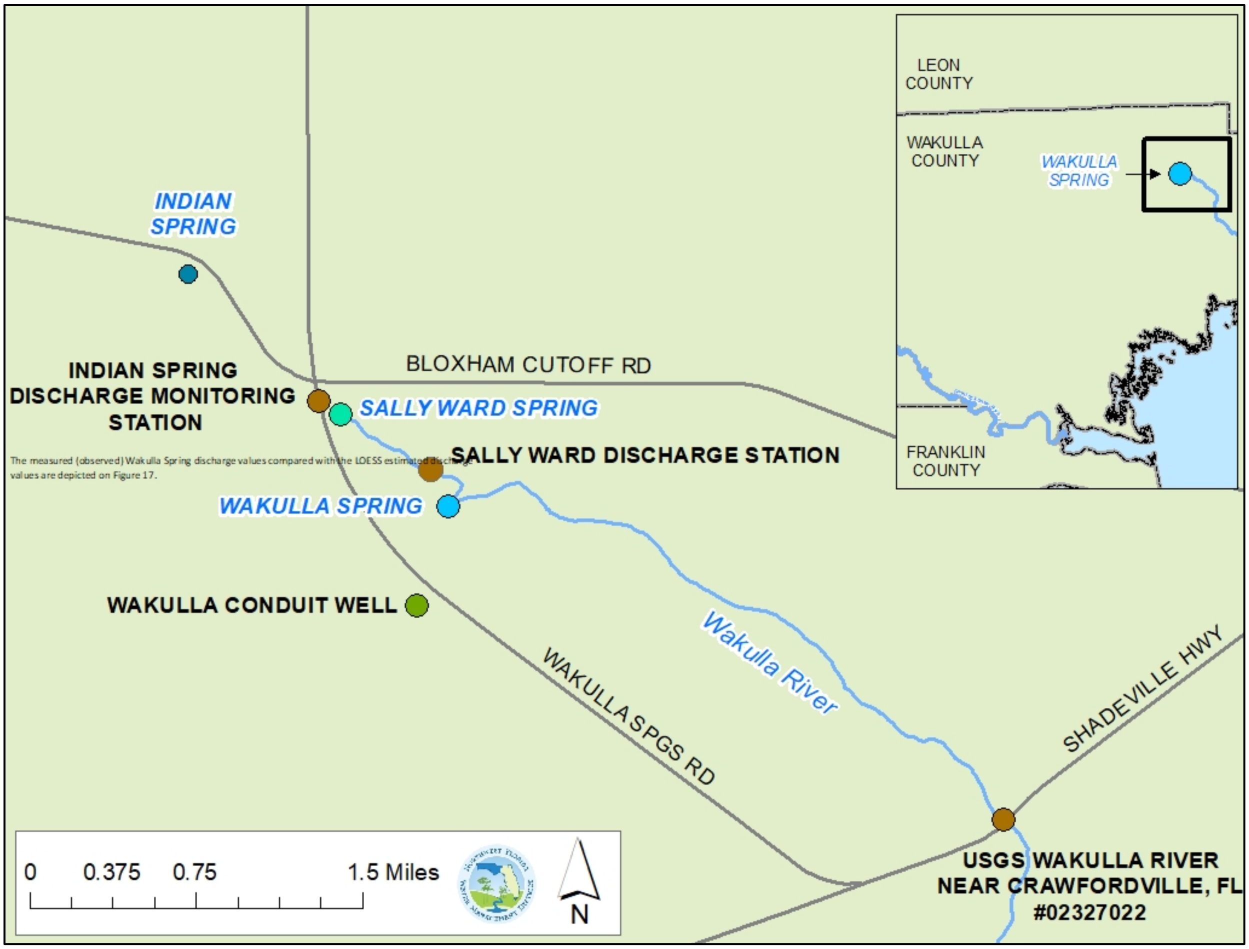


Figure 24: Sally Ward, Indian, and Wakulla Springs Locations

3.1 Estimation of Discharges at Sally Ward

Continuous stage and velocity from Sally Ward Spring is monitored at a pedestrian bridge approximately 0.5 miles downstream from the spring vent near the confluence with the Wakulla River (Figure 24). Measurements are taken at 15-minute intervals which began December 2, 2016, and continue through the time of this document's preparation (Figure 25). Continuous discharge at Sally Ward Spring is estimated using the index velocity method described by Levesque and Oberg (2012). Unlike Wakulla Spring, discharge at Sally Ward Spring is minimally tidally influenced. The Sally Ward Spring run has been hydrologically altered when it was dredged to a depth of approximately 5 ft prior to 1972. The spring run is relatively straight with spoil from the previous dredging efforts deposited on the southern bank. This spoil has since been recolonized with native vegetation. At spring run stages greater than 6.44 ft NAVD88, water may leave the channel and enter a relatively broad floodplain where it can bypass the velocity sensor and not be accounted for in spring discharge estimates. In addition, when spring run discharge leaves the channel it is unknown whether this flow returns to the Sally Ward Spring run or is discharged into the Wakulla River or spring pool. As a result, discharge measurements are not estimated when spring run stages are greater than 6.44 ft NAVD88.For the period of record where Sally Ward spring run stage data is available (January 9, 2015, through December 31, 2019), daily average spring run stages exceeded 6.44 ft NAVD88 approximately 3.7% of the time.

In addition to the continuous discharge data, a total of 96 manual discharge measurements have been taken between October 22, 1997, and October 19, 2019. Manual measurements were collected using either an acoustic doppler current profiler (ADCP) or an acoustic doppler current (ADC) meter along the Sally Ward Spring run (between the spring vent and confluence with the Wakulla River). No additional surface water inputs were present at the time of manual discharge measurements and flows were within the spring run banks.

Approximately 0.75 miles to the northwest, is Indian Spring. Discharge from Indian Spring is relatively small (<1 cfs) and is hydrologically isolated from Sally Ward Spring during normal conditions. During periods of excessive rainfall however, a wetland slough connecting the two springs becomes inundated and surface water flows drain into the Sally Water Spring pool where they combine with Sally Ward Spring discharge. Continuous monitoring of surface discharges entering the Sally Ward spring pool from the Indian Spring slough are recorded with a data logger located at the County Road 61 bridge over the slough (Figure 24). Discharge measurements are collected at hourly intervals beginning on December 18, 2014, and continue through the time of this document's preparation. Discharge measurements were estimated using the index velocity method described by Levesque and Oberg (2012).

To determine the volume of water discharging from Sally Ward Spring, discharge flowing into the Sally Ward spring pool (as measured at the CR 61 bridge) was subtracted from that measured at the Sally Ward Spring run pedestrian bridge. This provided a more accurate estimate of discharge from Sally Ward Spring (Figure 25). Between December 1, 2016, and September 10, 2019, contributions from the Indian Spring run accounted for an average of 2.7% (median 0%, range 0% to 76%) of the flow measured at the Sally Ward discharge monitoring station.

The Sally Ward Spring discharge period of record contained a total 223 days of missing values (Table 7). Multiple regression models using other data sources were investigated as potential methods for infilling data gaps in order to produce a continuous daily discharge time series for MFL determination.

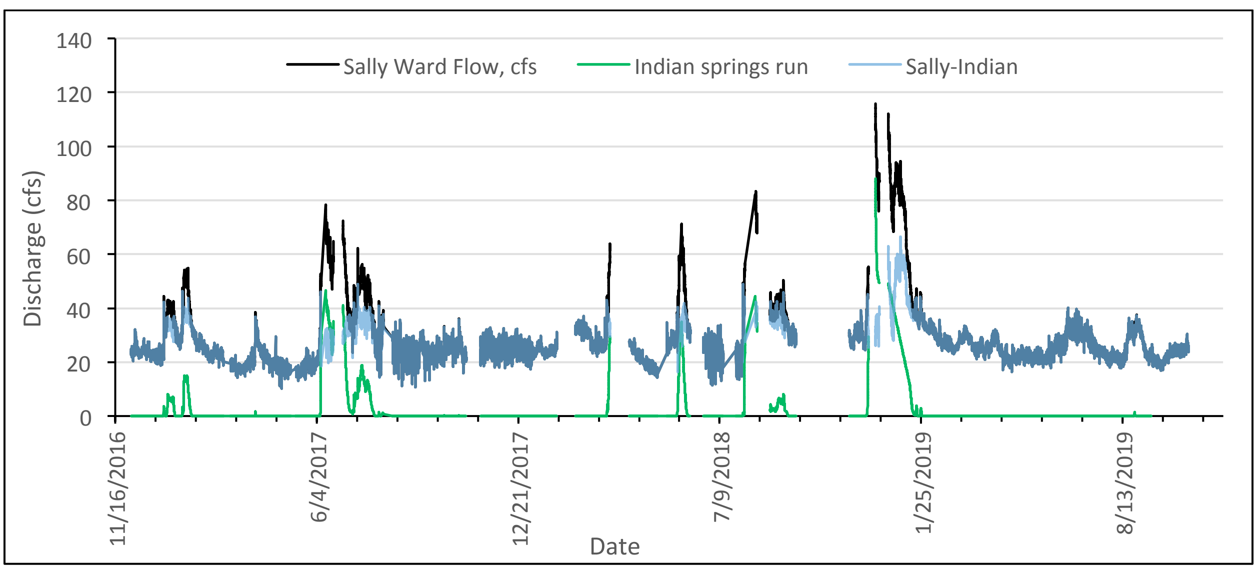


Figure 25: Measured Discharge Time series at the Sally Ward Spring Run (Sally Ward Flow), entering the Sally Ward Spring Pool from Indian Spring (Indian Springs Run), and the Difference Between Discharge Measured in the Sally Ward Spring Run and Indian Springs Run (Sally-Indian).

Table 7: Gaps in the Discharge Record of Sally Ward Spring

Gap Start Date	Gap End Date	Number of Days
3/3/2017	3/9/2017	7
5/9/2017	5/13/2017	5
6/8/2017	6/12/2017	5
6/20/2017	6/29/2017	10
8/9/2017	8/17/2017	9
10/30/2017	11/13/2017	15
1/28/2018	2/15/2018	19
3/22/2018	4/10/2018	20
5/8/2018	5/17/2018	10
5/30/2018	5/31/2018	2
6/10/2018	6/22/2018	13
7/12/2018	7/24/2018	13
8/3/2018	8/13/2018	11
8/15/2018	8/27/2018	13
9/23/2018	11/14/2018	53
12/3/2018	12/10/2018	8
12/14/2018	12/23/2018	10

3.2 Sally Ward Spring Discharge Data Gap Infilling Techniques

Figure 25 shows multiple data gaps (Table 7) that exist in the record of Sally Ward Spring discharge because of equipment failure or when spring run water levels exceeded 6.44 ft NAVD8. These data gaps range in duration from two to 53 days. A Seasonal Mann Kendall Trend Test conducted on 83 manual discharge measurements between October 22, 1997, and January 22, 2020, indicated an increasing trend (Z=4.80, P=0.00). Due to the increasing Sally Ward Spring discharges and the duration of some data gaps, several methods for estimating spring discharges for these periods of missing data which could be correlated to spring discharges were investigated. These data sources include manual (discrete) discharge measurements collected near the spring vent and Wakulla Spring discharges estimated by the NWFWMD at the Wakulla Spring vent.

3.2.1 Sally Ward Spring Manual Discharge Measurements

Manual measurements taken along the Sally Ward Spring run averaged 22 cfs and ranged from 3.25 cfs to 65.81 cfs (Figure 26). Similar to Wakulla Spring, Sally Ward discharge shows an increasing trend between 1997 and 2020. During much of this time, water entering the Sally Ward Spring pool from the Indian Spring slough were unmeasured and could not be removed from Sally Ward discharge measurements. In addition, the short-term variations in spring discharge observed in the continuous data may not be captured by manual measurements. Manual discharge measurements do however, provide insight into the long-term trends in spring flow and provide a better estimate of the low flows present prior to 2015. In addition, manual measurements are available for the same period of record as the composite Wakulla Spring daily discharge time series described above. As a result, manual measurements were determined to be useful in estimating a long-term discharge time series for Sally Ward Spring.

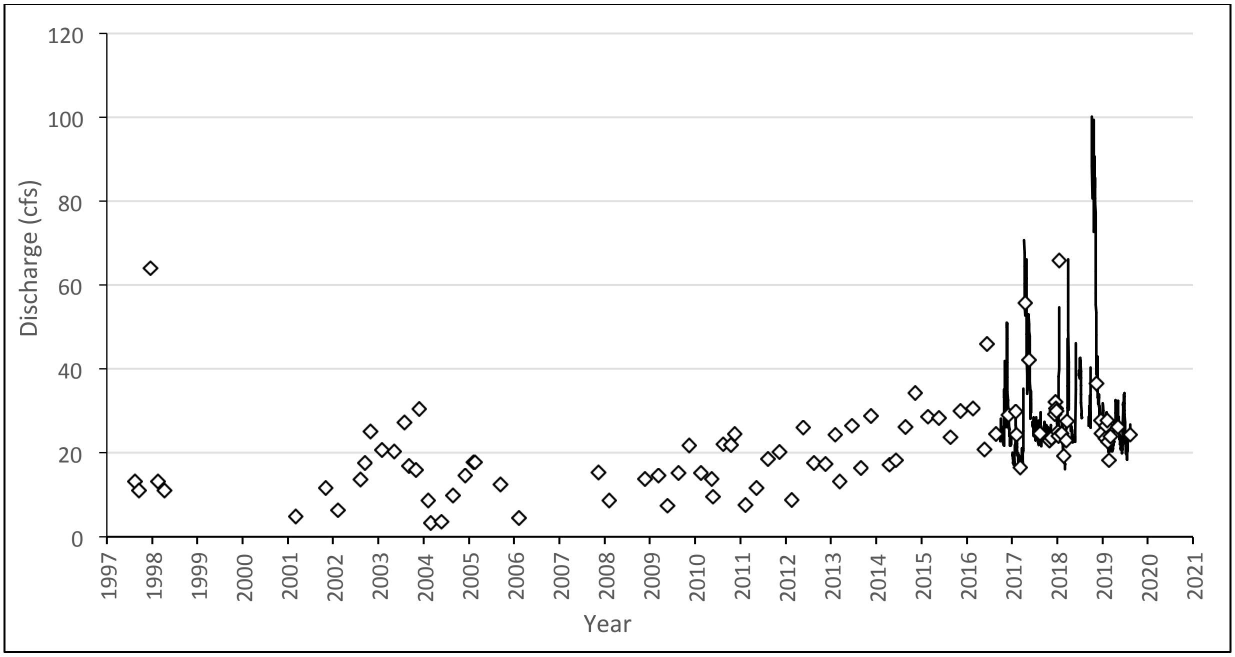


Figure 26: Manual and Continuous Discharge Data At Sally Ward Spring from 1997 through present

3.2.2 Regression Between Sally Ward and Wakulla Springs

Relationships between Sally Ward and Wakulla Spring discharges were visually assessed using a scatterplot. An exponential regression between Sally Ward and Wakulla springs was investigated as a possible source for data gap estimation (Figure 27). The resultant equation is:

$$\mathbf{y=7.332e^{0.002x}}$$

Where;

x = Wakulla spring average daily discharge

y = Sally Ward Spring average daily discharge

While this regression provided a R^2 value of 0.78 using an exponential trendline, estimates of discharge during higher discharges showed residuals up to 50% different from observed values (Figure 28). This trend increased with increasing measured Sally Ward discharge. Residuals were also not evenly distributed and estimated discharges tended to be underestimated at discharges above approximately 40 cfs (Figure 28). This is further illustrated when comparing discharge duration curves between measured Sally Ward discharge and discharge estimated with the exponential regression (Figure 29).

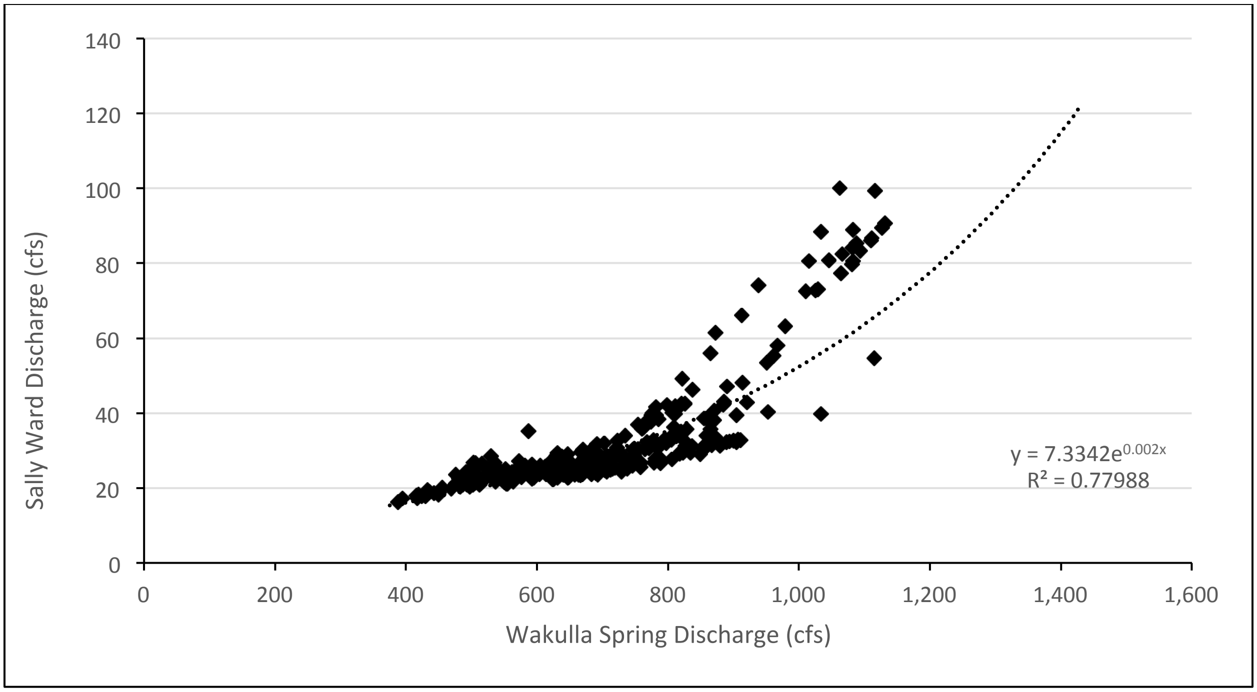


Figure 27: Exponential Regression Between Sally Ward and Wakulla Springs

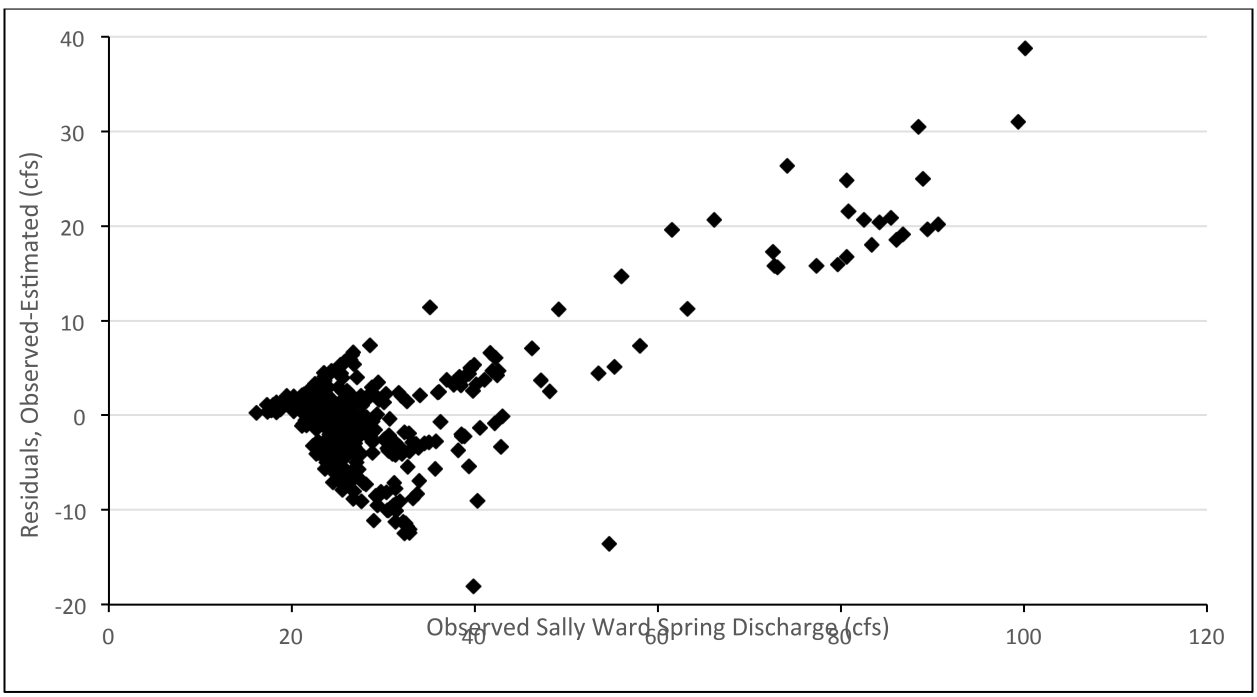


Figure 28: Residual Plot for Observed-Estimated Sally Ward Spring Discharge Using the Exponential Equation Described Above

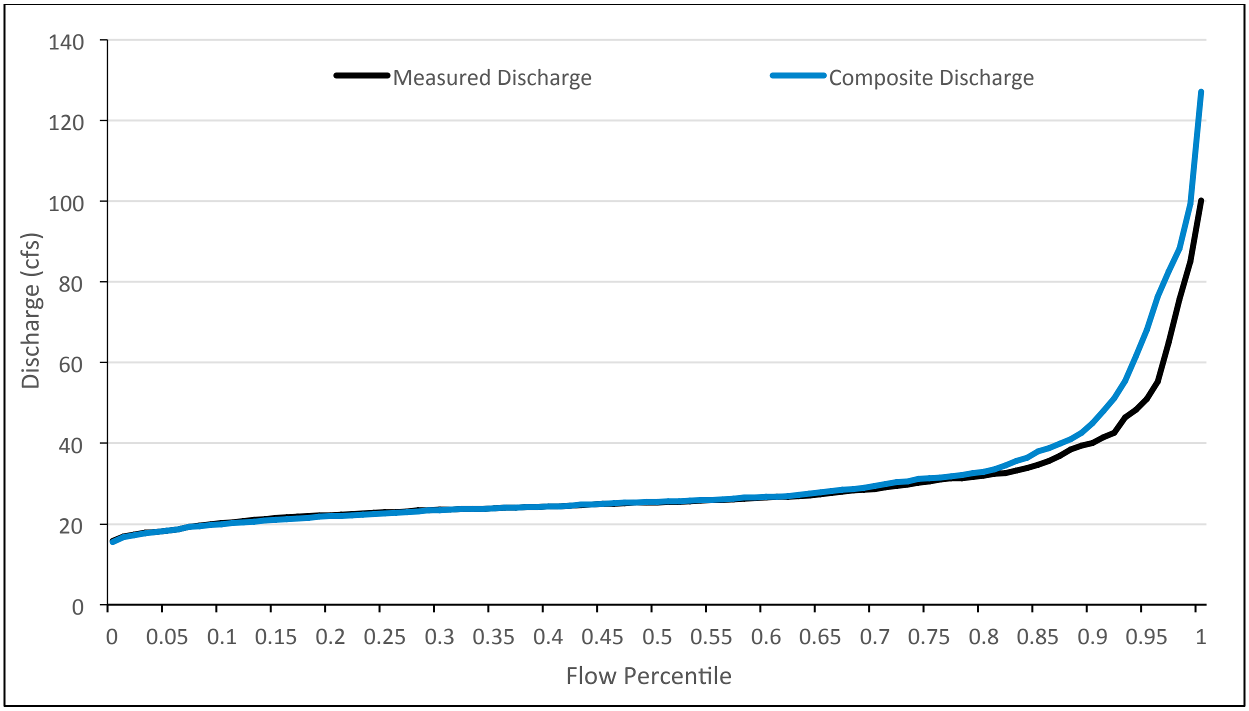


Figure 29: Discharge Duration Curves for Measured Sally Ward Discharge and Composite Sally Ward Discharge with Gap Filling Using the Regression with Wakulla Spring Discharge

3.3 Sally Ward Spring Discharge Time Series

The complete Sally Ward Spring discharge daily time series was developed using measured manual spring discharge described in Section 3.2.1. No gap filling techniques were utilized and the time series was used as measured. The time series extends from October 22, 1997, through October 17, 2019. (Figure 30). Sally Ward Spring discharge during this time period ranged between 3 cfs and 66 cfs, with an average of 22 cfs (median = 22 cfs) (Figure 31).

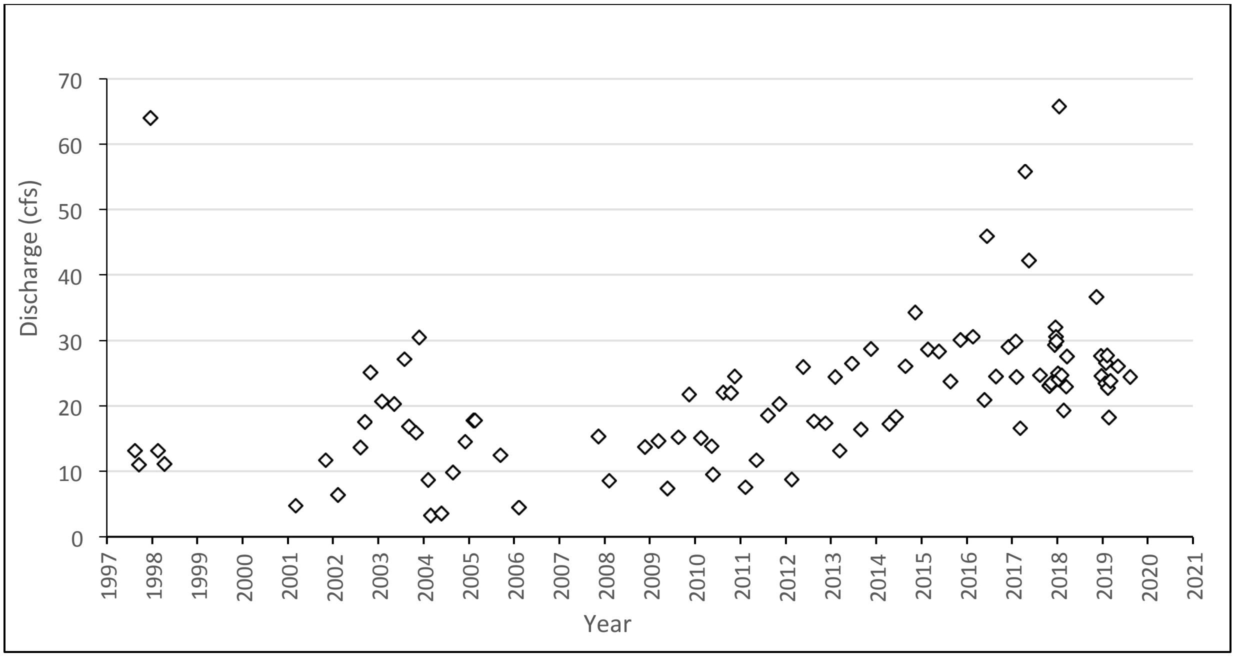


Figure 30: Daily Sally Ward Spring Discharge Time Series

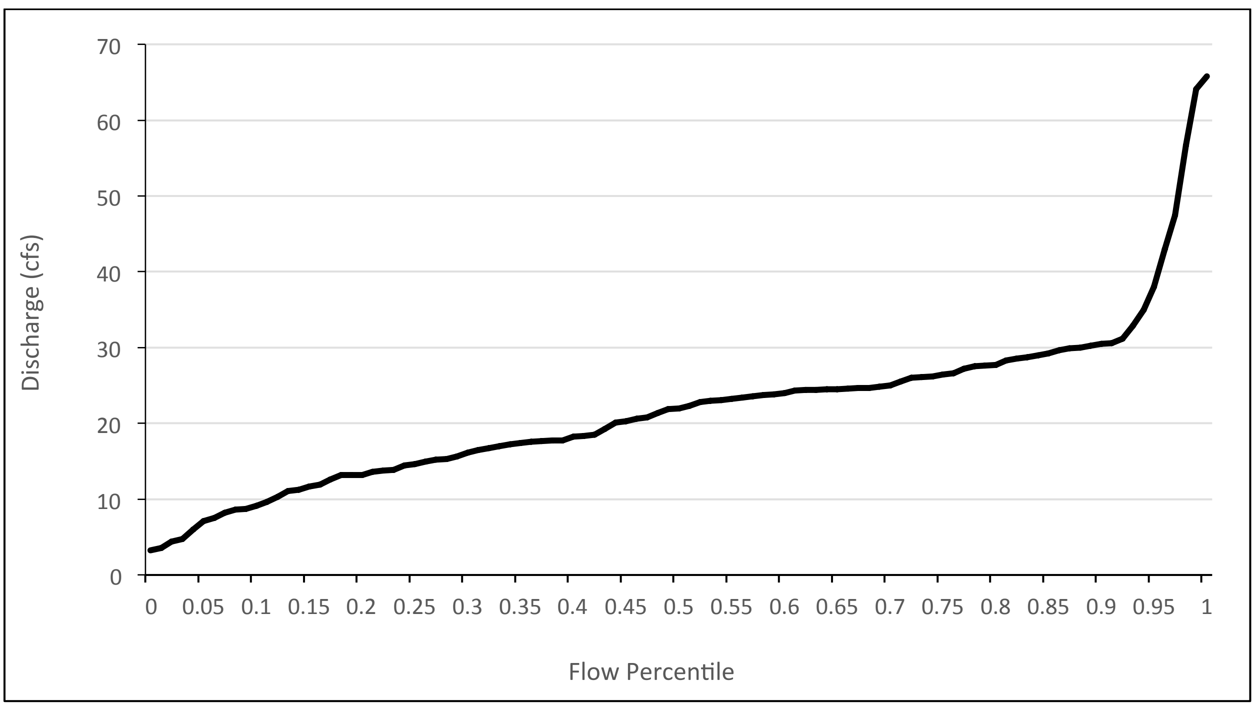


Figure 31: Discharge Duration Curve for Daily Sally Ward Spring Discharge

4 Climatic Trend Tests

As a part of the baseline time series development process, evaluations of any long-term changes in climatic conditions which may affect spring discharge were performed to assess the degree to which the baseline spring flow time series may be affected by long-term trends in climatic conditions. This section describes the available data used and subsequent analysis to assess any changes in evapotranspiration, precipitation, and groundwater levels in the vicinity of Wakulla and Sally Ward springs. The locations of climatic monitoring stations used in this analysis are depicted on Figure 32.

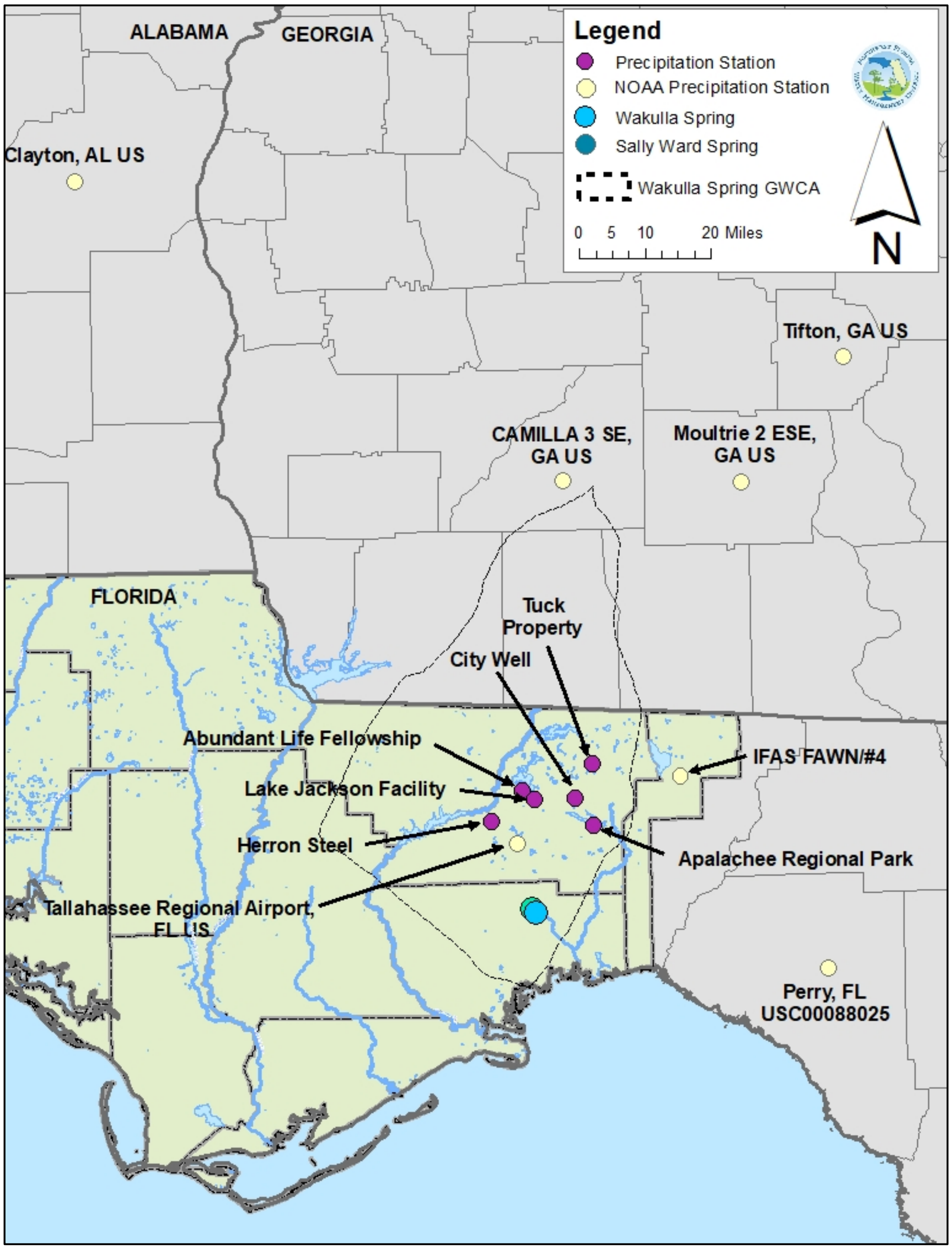


Figure 32: Location of Climatic Monitoring Stations Used for Trend Testing

4.1 Evapotranspiration

Limited long-term evapotranspiration (ET) datasets are available. Evapotranspiration data was obtained from the University of Florida Food and Agricultural Sciences (UF-IFAS) Florida Automated Weather Network (FAWN). Daily measurements of ET used for analysis were calculated from measured meteorological data at Site Number 160 (Monticello, Florida). This location has daily ET estimates beginning on April 23, 2003, daily data was available through August 18, 2019, at the time of report writing. Several data gaps exist in the period of record ranging from 1 to 374 days in length. A total of 732 days of missing ET values were present in the data set. Most gaps in ET data consisted of less than five days, however several data gaps were for more extended periods of time and are depicted in Table 8.

Daily ET rates ranged from 0.58 mm/day on January 7, 2014, to 0.23 in/day on June 14, 2011, with a mean value of 0.11 in/day (median 0.11 in/day) (Figure 33). Seasonal boxplots on monthly ET values displayed a strong seasonal pattern with maximum average and median ET occurring during the months of June (0.17 in and 0.18 in, respectively) and July (0.19 in and 0.17 mm, respectively) (Figure 34). Seasonal Kendall Test on the monthly median ET values indicated that no long-term trends in average monthly ET rates were present during the available 2003 to 2019 POR (p=0.40, Figure 35). Minimum ET occurred during January (avg.=0.05 in, med.=0.05 in) and December (avg.=0.05 in, med.=0.05 in) (Figure 36). However, due to lack of data prior to 2003, it was not possible to determine whether multidecadal trends are present that influence ET rates for the 2003 to 2019 period. Spearman Rank Correlation Coefficients between monthly ET averages and lag times ranging between 1 and 24 months indicated that ET was highly positively serially correlated with 12 and 24 month lag times (0.95 and 0.84, respectively) and highly negatively correlated with six and 18 month lag times (-0.94 and -0.91, respectively) (Figure 36).

Table 8: Data Gaps in ET Period of Record Lasting More than five consecutive days.

Beginning Date	Ending Date	Duration (Days)
7/10/2003	7/29/2003	20
12/27/2003	2/3/2004	37
2/28/2004	4/26/2004	59
5/29/2004	6/10/2005	374
3/17/2006	3/25/2006	10
11/15/2007	11/24/2007	10
12/3/2007	12/25/2007	22
6/5/2018	6/21/2018	16
12/12/2018	1/22/2019	42

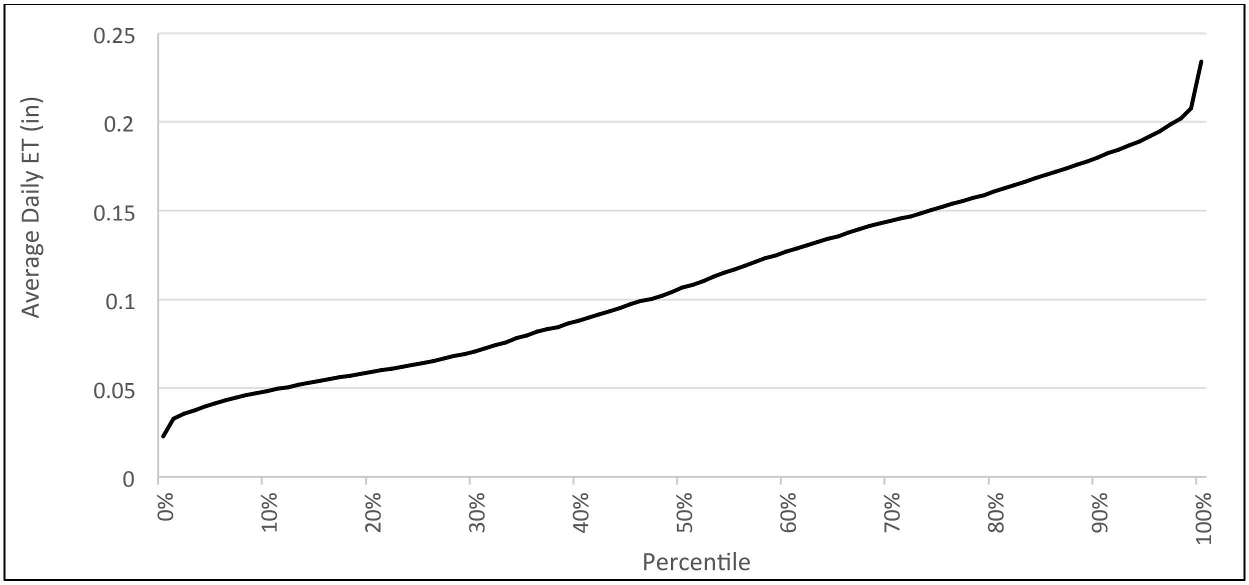


Figure 33: Distribution of Average Daily Evapotranspiration Rates(mm) at UF-IFAS FAWN Station No. 160, Monticello, Fl

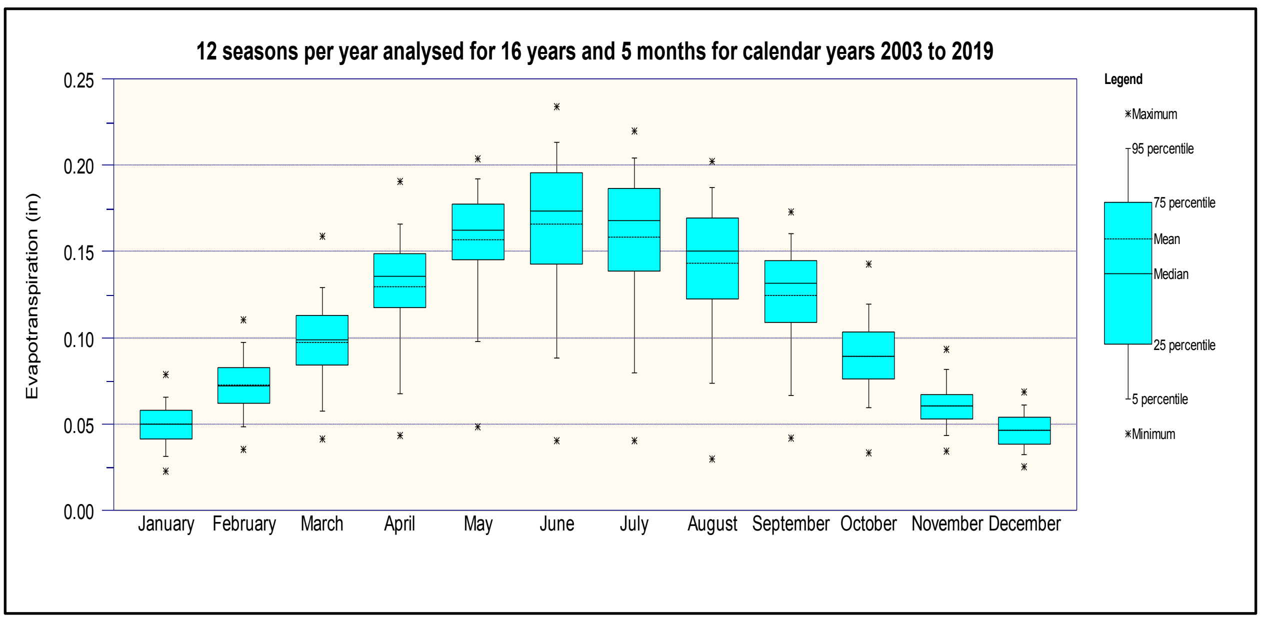


Figure 34: Seasonal Boxplots of Daily Evapotranspiration at UF-IFAS FAWN Site No. 160, Monticello, Fl.

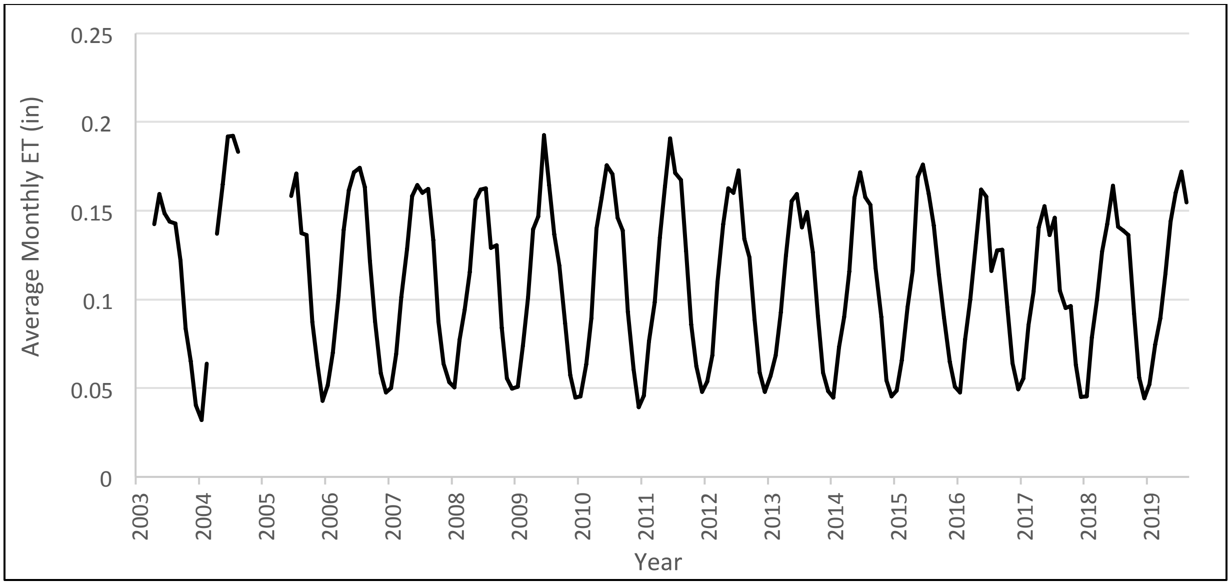


Figure 35: Average Monthly Evapotranspiration at UF-IFAS FAWN Station No. 160 from April 2003 through August 2019

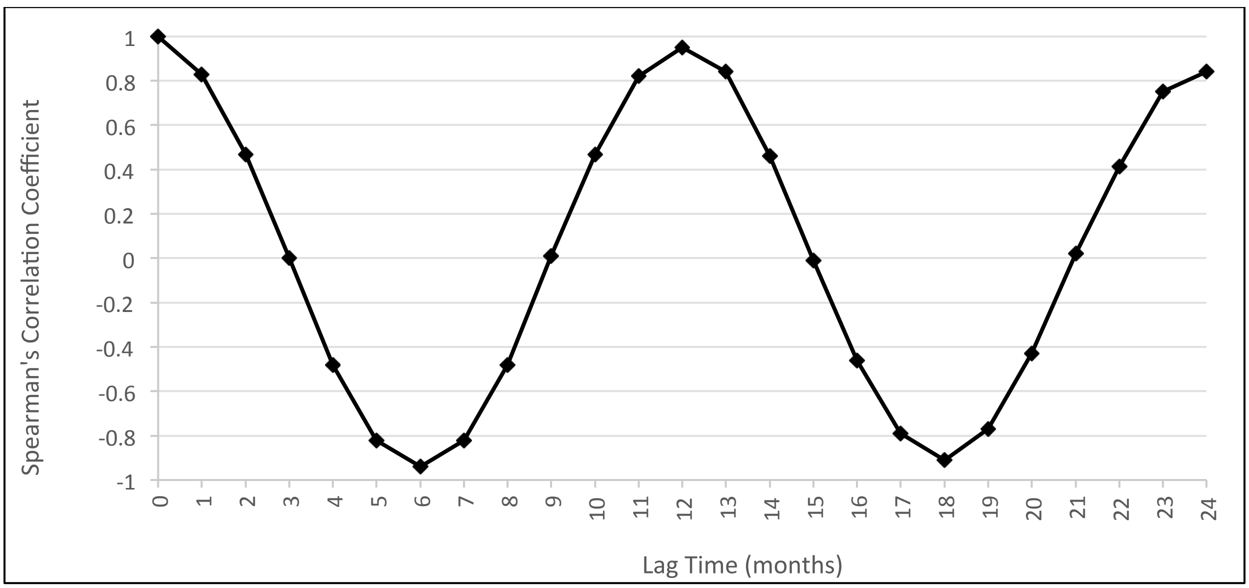


Figure 36: Correlogram of ET Values Using Different Lag Times.

4.2 Precipitation

Precipitation data was evaluated at 12 sites in the vicinity of Wakulla and Sally Ward Springs (Table 9). The sites are managed by both the NWFWMD and the National Oceanographic and Atmospheric Association (NOAA).

4.2.1 Trends in Monthly Precipitation

Trends in monthly precipitation were assessed using a Seasonal Kendal Test in Systat statistical software program. Statistical significance was determined to be for samples with p values <0.05. Because rainfall sites with short periods of record are subject to strong inter-annual variations in precipitation totals, sites with less than 20 years of data were not included in analysis. In addition, a detailed evaluation of precipitation trends at the Tallahassee Regional Airport was conducted to assess potential multidecadal rainfall patterns in the vicinity of Wakulla and Sally Ward Springs. Seasonal Mann Kendall analysis displayed no long-term trends in precipitation at any site analyzed (Figures 37, 38, 39, and 40; Table 9). It should be noted that the available period of record varied among sites.

A two-sample t test was conducted to determine if mean monthly rainfall for the proposed baseline time period from 2004-2019 differs from historical mean monthly rainfall conditions (Table 10). Mean monthly precipitation from 2004-2019 was compared to the mean monthly precipitation prior to 2004. A minimum of 15 years of pre-2004 data was required for the comparison. The length of available period of record varied among sites. The T-test analyses indicated no statistically significant differences in mean monthly rainfall between the pre- and post- 2004 periods.

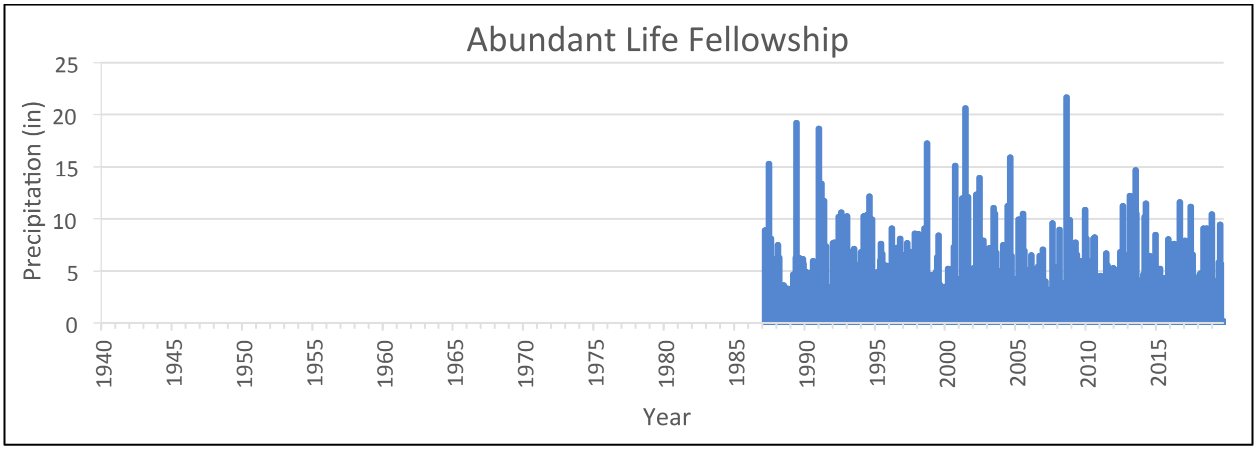
*Table 9: List of Precipitation Data Stations Evaluated for Long-Term Trends. [1]Indicates a station managed by the NWFWMD, while [2] indicates a station managed by the National Weather Service. *Indicates a statistically significant trend.*

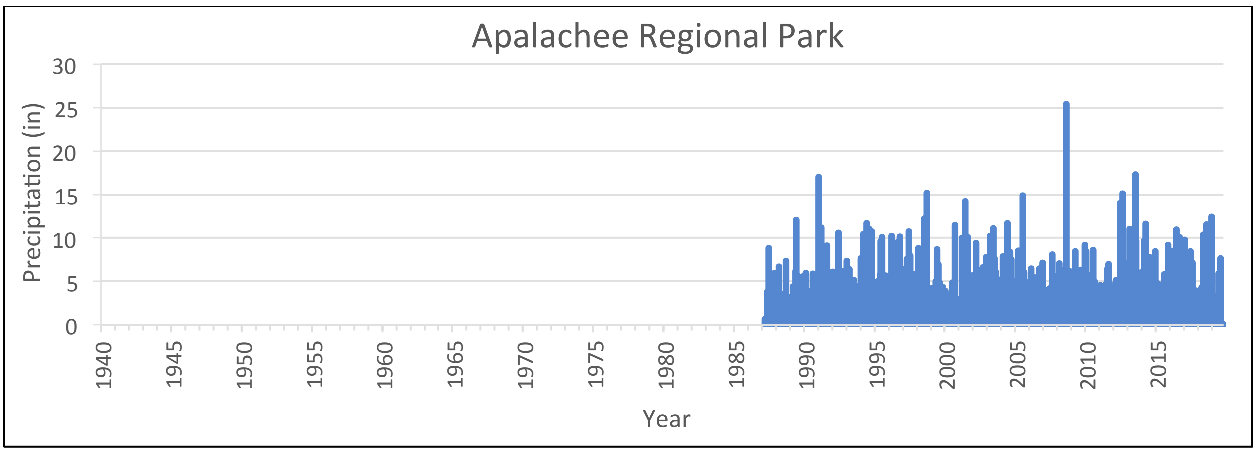
Station Name	Station Number	Period of Record		SKT p-value	Median Annual Slope
		Begin	End		
[1]Abundant Life Fellowship	011288	3/2/1987	10/10/2019	0.69	0.01
[1]Apalachee Regional Park	011299	3/1/1987	10/6/2019	0.30	0.02
[2]Camilla 3 SE. GA US	USC00096087	3/1/1940	11/15/2019	0.90	0.00
[1]City Well	011296	2/3/1987	10/10/2019	0.67	0.01
[2]Clayton, AL US	USC00011725	1/1/1940	12/6/2019	0.84	0.00
[1]Herron Steel, Silver Lake Road	011285	1/1/1987	10/9/2019	0.38	0.01
[1]Lake Jackson Facility	011289	3/1/1987	10/10/2019	0.96	0.00
[2]Moultrie 2 ESE, GA US	USC00098703	3/1/1940	11/17/2019	0.63	0.00
[2]Perry, FL US	USC00087025	3/1/1940	11/17/2019	0.62	0.00
[2]Tallahassee Regional Airport, FL US	USW00093805	3/1/1940	11/17/2019	0.66	0.00
[2]Tifton, GA US	USC00098703	3/1/1940	11/17/2019	0.99	0.00
[1]Tuck Property	011293	2/28/1997	10/10/2019	0.93	-0.00

*Table 10: Two-sample t-test evaluation of precipitation data stations comparing monthly means prior to and after year 2004. [1]Indicates a station managed by the NWFWMD, while [2] indicates a station managed by the National Weather Service. *Indicates a statistically significant trend.*

Station Name	Station Number	Period of Record		p-value	
		Begin	End		
[1]Abundant Life Fellowship	011288	3/2/1987	10/10/2019	0.63	
[1]Apalachee Regional Park	011299	3/1/1987	10/6/2019	0.58	
[2]Camilla 3 SE. GA US	USC00096087	3/1/1940	11/15/2019	0.69	
[1]City Well	011296	2/3/1987	10/10/2019	0.70	
[2]Clayton, AL US	USC00011725	1/1/1940	12/6/2019	0.55	
[1]Herron Steel, Silver Lake Road	011285	1/1/1987	10/9/2019	0.72	
[1]Lake Jackson Facility	011289	3/1/1987	10/10/2019	0.96	
[2]Moultrie 2 ESE, GA US	USC00098703	3/1/1940	11/17/2019	0.37	

[2]Perry, FL US	USC00087025	3/1/1940	11/17/2019	0.22	
[2]Tallahassee Regional Airport, FL US	USW00093805	3/1/1940	11/17/2019	0.14	
[2]Tifton, GA US	USC00098703	3/1/1940	11/17/2019	0.75	





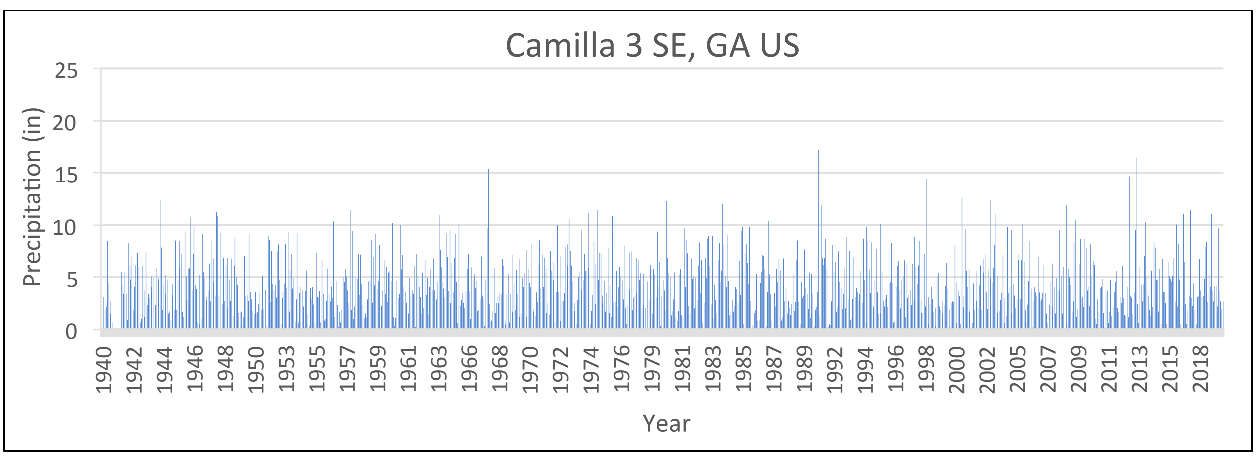
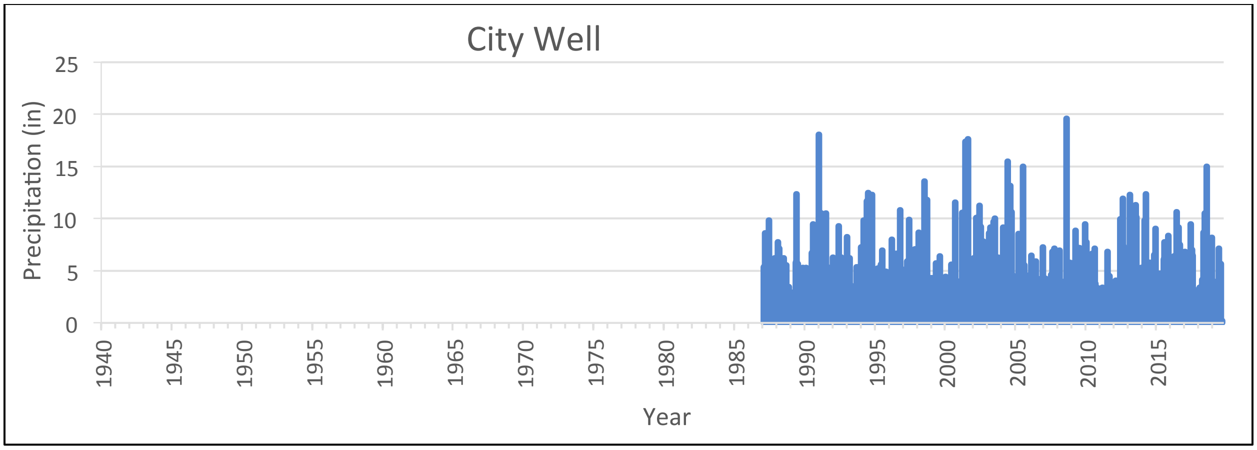
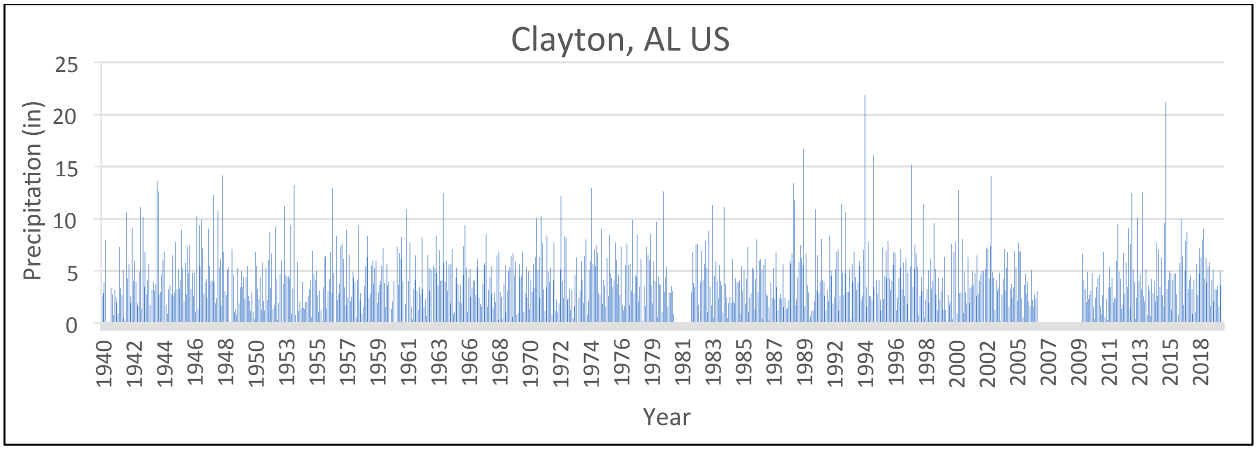


Figure 37: Monthly Total Precipitation (in) at Abundant Life Fellowship, Apalachee Regional Park and Camilla 3 SE, GA US.





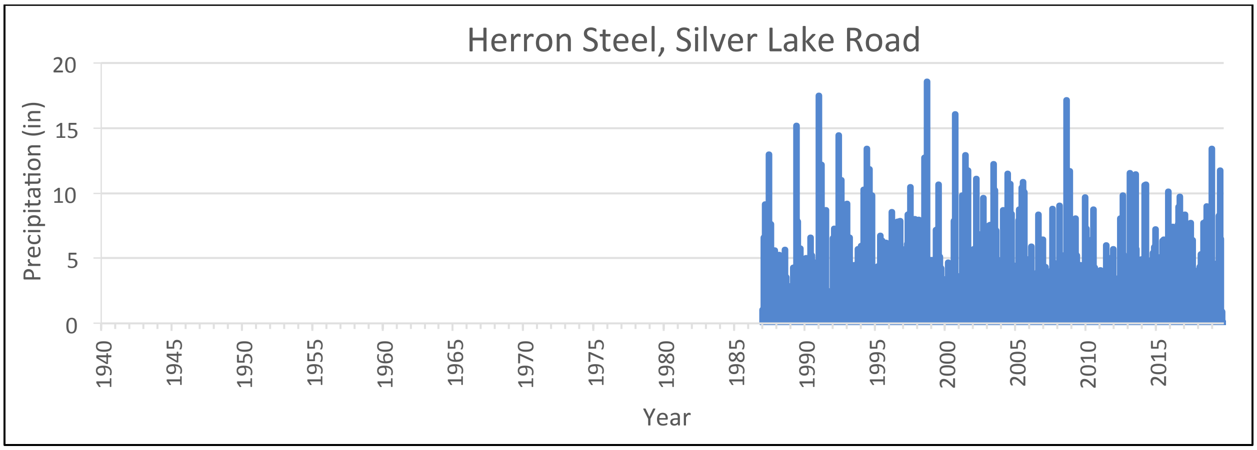


Figure 38: Monthly Total Precipitation (in) at City Well, Clayton, AL US, and Herron Steel, Silver Lake Road.

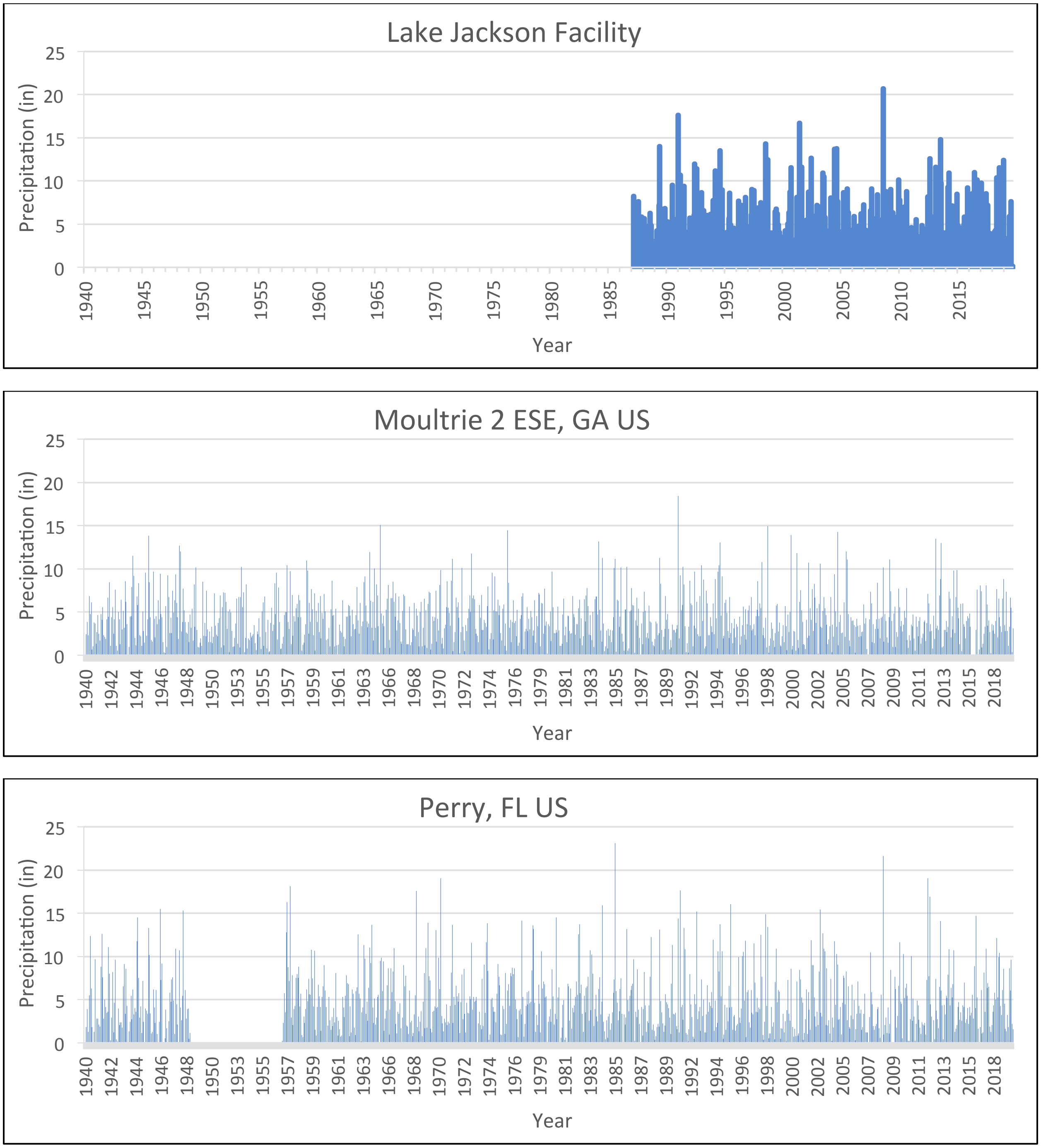


Figure 39: Monthly Total Precipitation (in) at Lake Jackson Facility, Moultrie 2 ESE, GA US, and Perry, FL US.

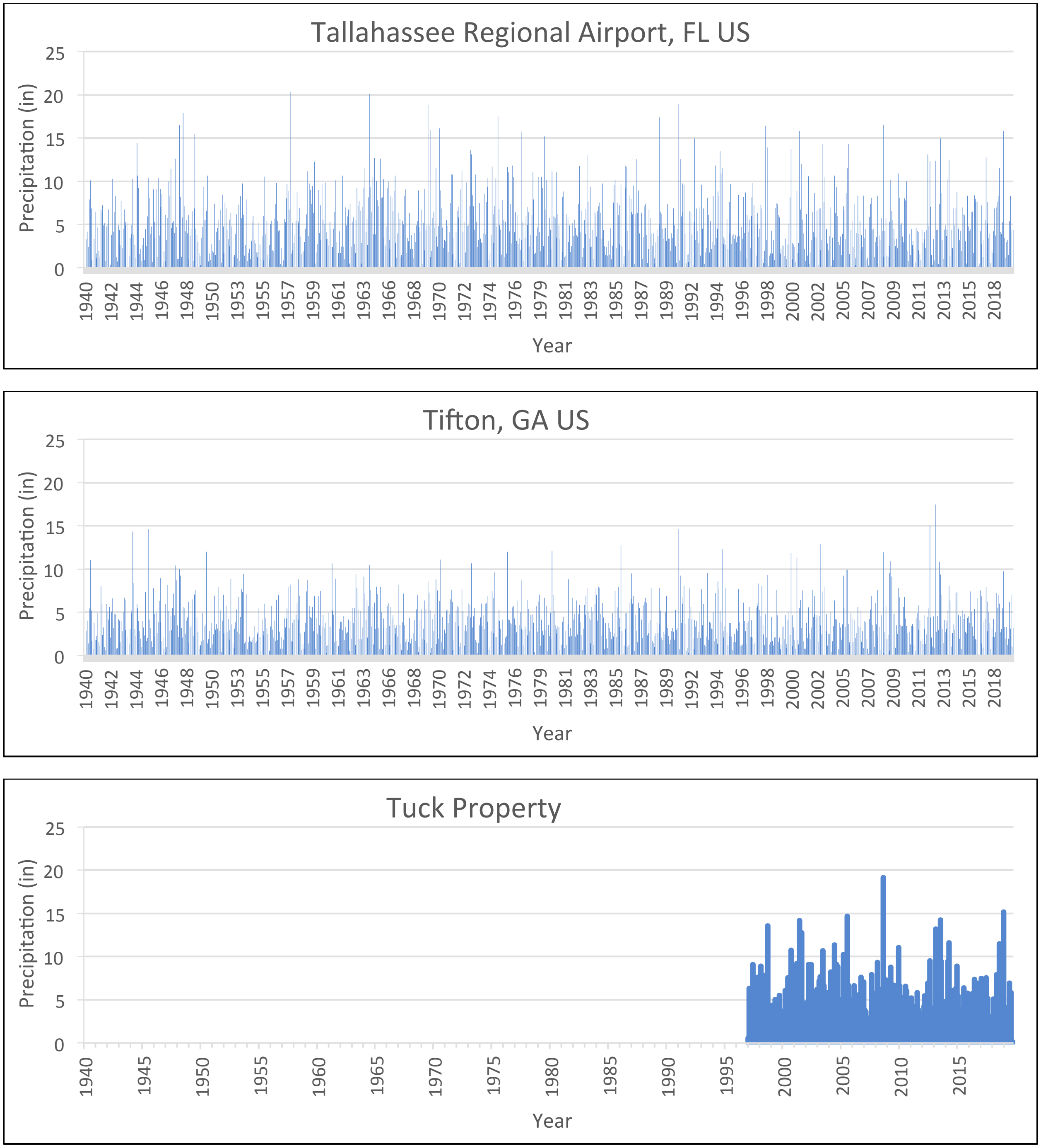


Figure 40: Monthly Total Precipitation (in) at Tallahassee Regional Airport FL, US, Tifton, GA US, and Tuck Property.

4.2.2 Precipitation Trends at Tallahassee Regional Airport

Precipitation averaged 61.7 inches annually at the Tallahassee Regional Airport between 1946 and 2019. During this period annual precipitation ranged between 31 inches (1954) and 104 inches (1964) (Figure 41). Precipitation displays bimodal seasonality with highest mean precipitation volumes occurring during the summer months of June, July, and August (7.2 inches, 8.1 inches, and 7.2 inches, respectively), along with a smaller peak during March (5.8 inches) (Figure 42). Monthly mean precipitation minimums were observed during the months of April (4.0 inches) and October /November (3.0 inches).

In addition to short-term fluctuations among and within years, the Atlantic Multidecadal Oscillation (AMO) is long-term fluctuation in sea surface temperature that has direct effects on long-term precipitation and temperature patterns in north Florida (NOAA 2020). Northwest Florida tends to receive less rainfall during warm periods and more rainfall during relatively cold periods. Since the mid-1990s the Atlantic has been in a warm period. Annual precipitation totals at the Tallahassee regional airport have shown a reduced number of years with precipitation totals exceeding the long-term average (Table 11). The period of record extending from 1996 through 2018 shows only seven years (30 percent) with precipitation totals exceeding the long-term average of 61.7 inches. The ten-year moving average annual precipitation indicates precipitation has been below the long-term average since 1999 (Figure 43). This indicates that the area has been in a precipitation deficit for an extended period, possibly associated with the AMO cycle.

To determine periods of above and below average rainfall, the 12-month standard precipitation index (SPI) was computed for the Tallahassee Regional Airport (Figure 10) using the SPI generator available from the National Drought Mitigation Center (https://drought.unl.edu/droughtmonitoring/SPI/SPIProgram.aspx). The SPI is calculated from the historical precipitation record, where precipitation accumulation over a specified period is compared to that same period of time throughout the historical record at that location. Positive SPI values represent wet conditions; the higher the SPI, the wetter the hydrologic conditions. Negative SPI values represent dry conditions; the lower the SPI, the more unusually dry a period is. A 12-month SPI was utilized to evaluate decadal climatic trends. Figure 44 illustrates a period of less precipitation from 1941 to the early 1960's coinciding with a warm AMO, followed by a period of higher precipitation to 1995 coinciding with a cool AMO and again a period of lower precipitation from 1995 to present coinciding with the recent warm AMO. Based on the 12-month SPI, recent periods of low rainfall or drought include years 2000, 2006-2007, 2011, and 2019.

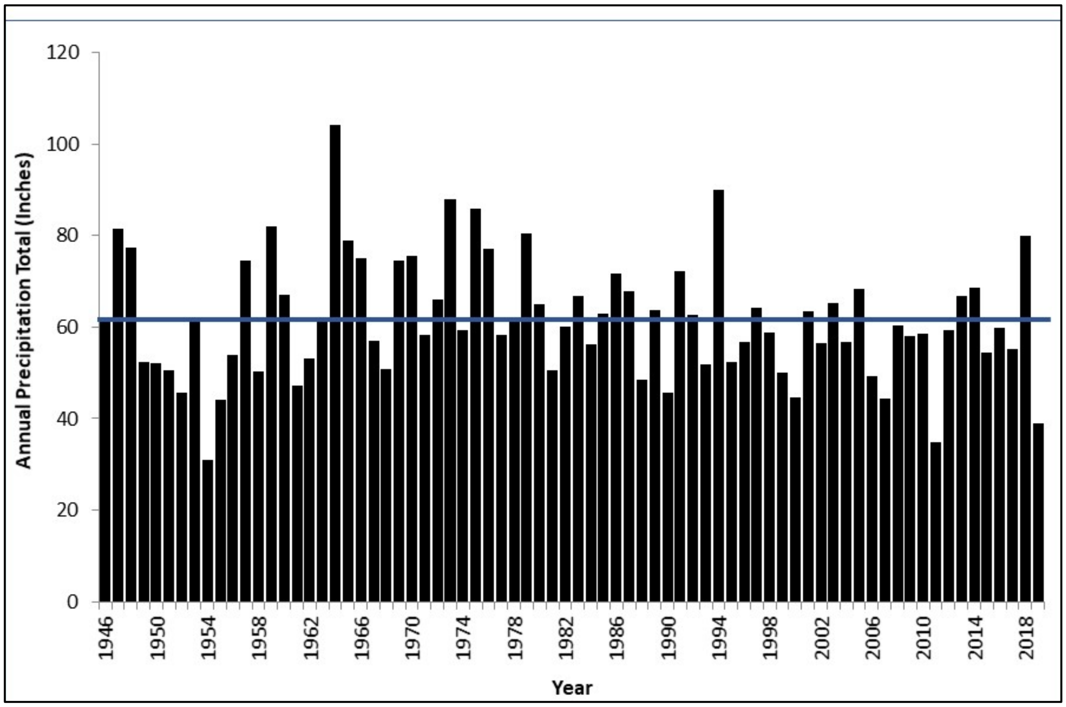


Figure 41: Annual Precipitation Totals at the Tallahassee Regional Airport (1946-2019). Blue line indicates the long-term average annual precipitation total of 61.7 inches.

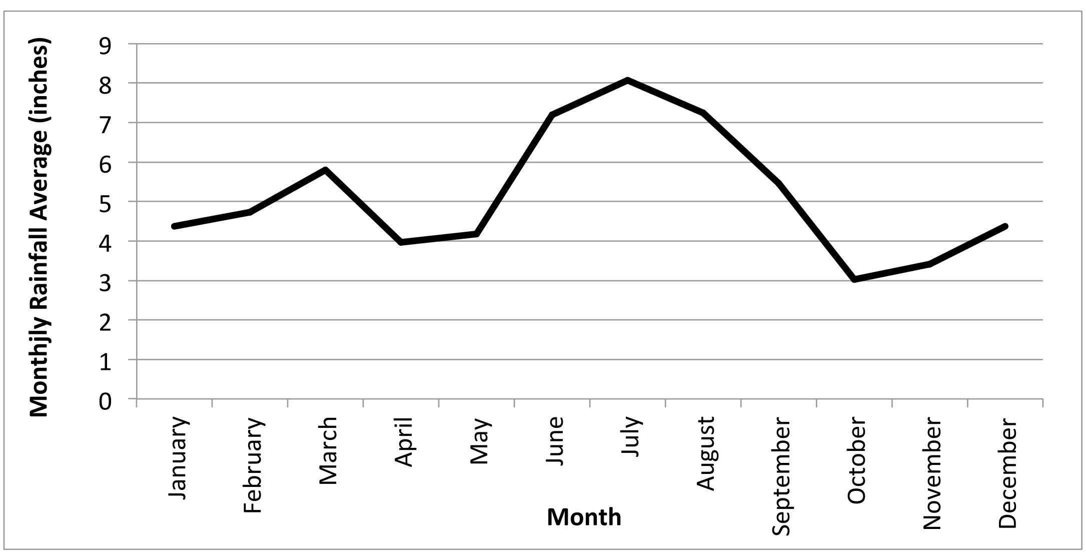


Figure 42: Monthly Precipitation Averages at the Tallahassee Regional Airport (1946-2019)

Table 11: Number of Years with Precipitation Totals Exceeding the Long-Term Average

Period of Record	Number of Years with Annual Precipitation Total Exceeding the Long-Term Average (61.7 Inches)
January 1, 1946 – December 31, 1955	2
January 1, 1956 – December 31, 1965	6
January 1, 1966 – December 31, 1975	6
January 1, 1976 – December 31, 1985	5
January 1, 1986 – December 31, 1995	6
January 1, 1996 – December 31, 2005	4
January 1, 2006 – December 31, 2018	3

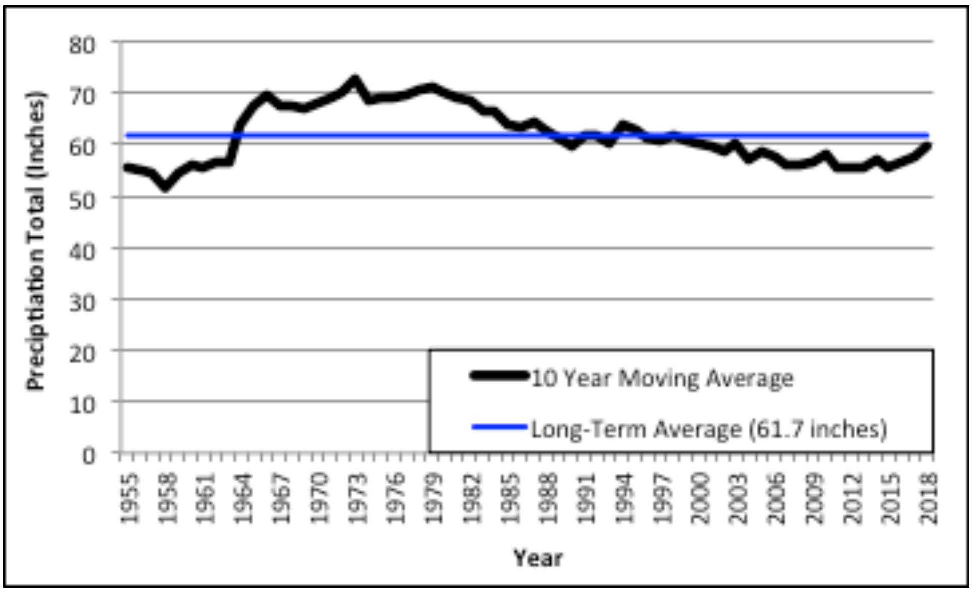


Figure 43: Average Annual Precipitation Totals for the Prior Decade

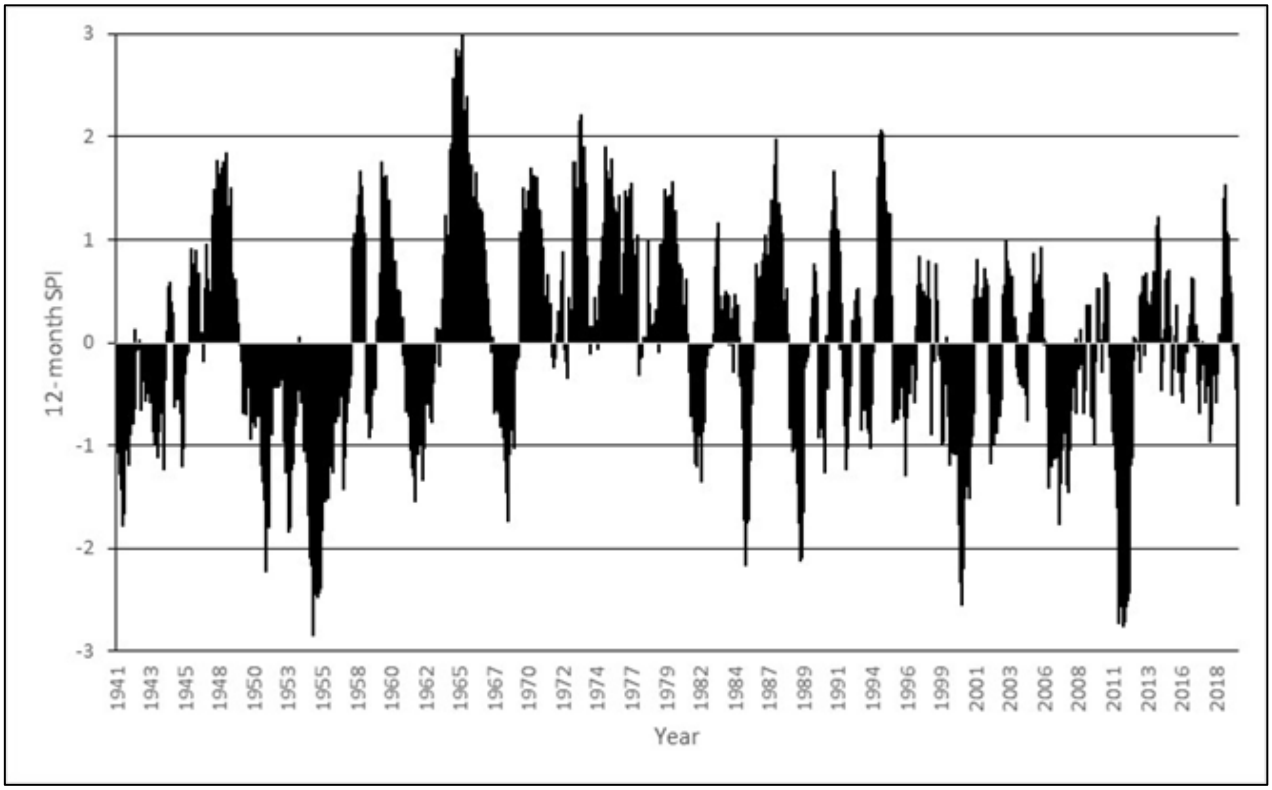


Figure 44: Twelve Month Standard Precipitation Index for the Tallahassee Regional Airport

4.3 Groundwater

Groundwater from the Floridan aquifer system discharges at Wakulla Spring and Sally Ward Spring. As such, understanding trends in groundwater levels and extraction volumes is important to understanding how groundwater extraction may impact spring discharge. The following section describes the evaluation of trends in groundwater extraction and aquifer levels.

4.3.1 Groundwater Extraction in the Wakulla Groundwater Contribution Area

Groundwater extraction data in the Florida portion of the Wakulla Spring groundwater contribution area is available from 1965 through present, while available data in the Georgia portion extends between 1985 and 2015 (Figure 45). Between 1965 and 1995, estimates of groundwater extraction in Florida increased from 13.65 mgd to 48.80 mgd, respectively. Between 1995 and 2015, the volume of groundwater extracted has remained relatively steady with an average of 52.85 mgd. The City of Tallahassee has the largest groundwater withdrawals of any permittee in the contribution area (~ 27 mgd), which have remained fairly stable since 1995 despite an increasing population. The reduction in per capita water usage by the City of Tallahassee has been attributed in part to water conservation measures and public education. Additionally, more than 50% of the water pumped by the City of Tallahassee is returned at the sprayfield where recharge rates are high due to high hydraulic loading rates, permeable sediments, and an unconfined Floridan aquifer.

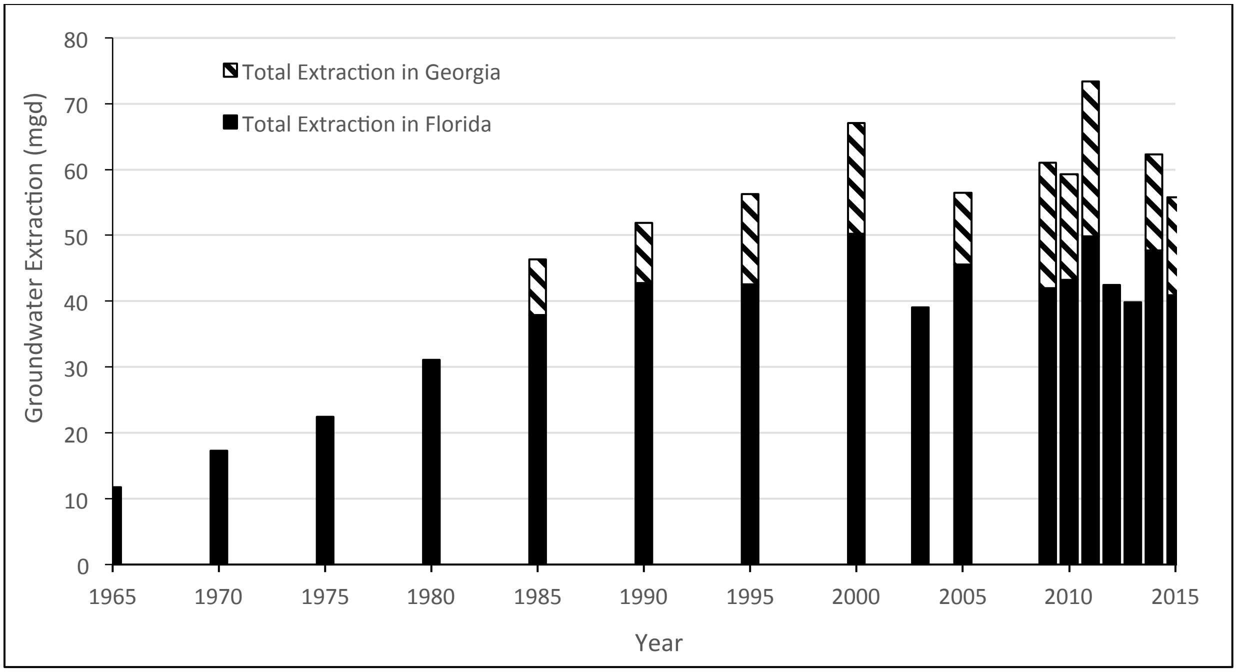


Figure 45: Estimated Groundwater Extraction Volumes in the Wakulla Spring Groundwater Contribution Area. Estimates for Georgia extraction volumes are not available for 1965, 1970, 1975, 1980, 2003, 2002, and 2003.

4.3.2 Groundwater Levels

Trends in Floridan Aquifer groundwater levels were evaluated for 16 monitor wells located in and near the Wakulla Spring and Sally Ward groundwater contribution area (Figure 46). Trends in period of record groundwater levels, except for the Lester Lewis well, were assessed using a Mann Kendall trend test. Mann Kendall trend tests were based on annual median groundwater levels to reduce the effect of serial correlation. For the Lester Lewis well, a 2-sample t-test was used due to a large data gap in the record. For this well, the difference between the mean groundwater level before and after the data gap was evaluated. Statistical significance was determined using a significance level of 0.05 (p value < 0.05). Because sites with short periods of record are subject to strong inter-annual variations in precipitation totals, sites with less than 20 years of data were not evaluated for period of record trends using the Mann Kendall test. However, groundwater levels for the two wells closest to Wakulla Spring (Nitrate #3 and Nitrate #4) were also evaluated for possible trends, although long term trends could not be formally tested due to a relatively short period of record.

Seven of the 14 groundwater monitoring wells evaluated using trend tests displayed statistically significant trends in groundwater levels over the periods of record (Table 11). No statistically significant trends were detected at seven of the 14 wells. Five monitor wells with significant trends displayed decreasing water levels and two wells exhibited increasing water levels. The majority of statistically significant trends were small in magnitude. Of the wells with statistically significant trends, three displayed water level changes of less than one foot over the entire period of record and three (Lafayette Park well site, Lake Jackson well site, and USGS #305235084125101 well site) displayed groundwater level reductions in excess of two feet (Figures 47 through 52). The Lafayette Park well is adjacent to a City of Tallahassee production well (less than 50 ft away). The Lake Jackson well site is located within 1000 feet of a Talquin Utilities public supply production well and within a mile of two additional Talquin production wells. Trends at these locations are not unexpected. The C. Donahue shallow Floridan aquifer well, located north of Wakulla Spring, exhibited no trend (POR: 1995 to present) while the C. Donahue deep Floridan aquifer well located at the same site showed a declining trend (POR: 1989 to present). Both wells monitor the Floridan aquifer but have different construction specifications and periods of record. Visual examination of the hydrographs suggests that aquifer levels at most of the 16 monitor wells appear to be slightly lower during the period of 1995 to present, which corresponds to a low rainfall period, as discussed previously.

The Otter Camp well, located northwest of Wakulla Spring within the Apalachicola National Forest, and the Wakulla Parks and Recreation well, located southwest of Wakulla Spring, exhibit slightly increases in aquifer levels. Increases in aquifer levels measured at the Wakulla Parks and Recreation well site are between one and two feet. The cause of these increases is unknown, but a drought in year 2000 occurred in the early portion of the available periods of record.

Annual median groundwater levels for the Nitrate #3 well and the Nitrate #4 well, the nearest long-term monitor wells to Wakulla Spring are shown in Figure 52. This monitor well pair is located approximately one-mile northwest of the spring. Visual inspection of these charts suggests no trends in Floridan aquifer levels at these sites. This information suggests that groundwater levels near Wakulla Spring have been relatively stable during the available period of record for these wells.

It should be noted that the sampling frequency for monitor wells varies through time from daily to months between samples and sample sizes used to determine annual medians were not equal among years. In addition, the available period of record varies among wells, making conclusions regarding regional trends difficult. In addition, as noted previously several monitoring wells are close to production wells, which can skew the interpretation of results, as trends at these sites are indicative of local conditions rather than regional trends. Groundwater withdrawals in the Wakulla GWCA have been relatively stable since 1990 (Section 4.3.1). This information and the trend analysis results suggest that groundwater withdrawals have not had a significant impact on regional groundwater levels in the Floridan aquifer. To enhance the understanding of spatial and temporal patterns in aquifer levels in the Wakulla Spring GWCA, the District installed 15 additional monitor wells during 2014-2015. While the period of record for these new wells is relatively short, as more data becomes available, groundwater level trends within the Wakulla GWCA will be re-evaluated.

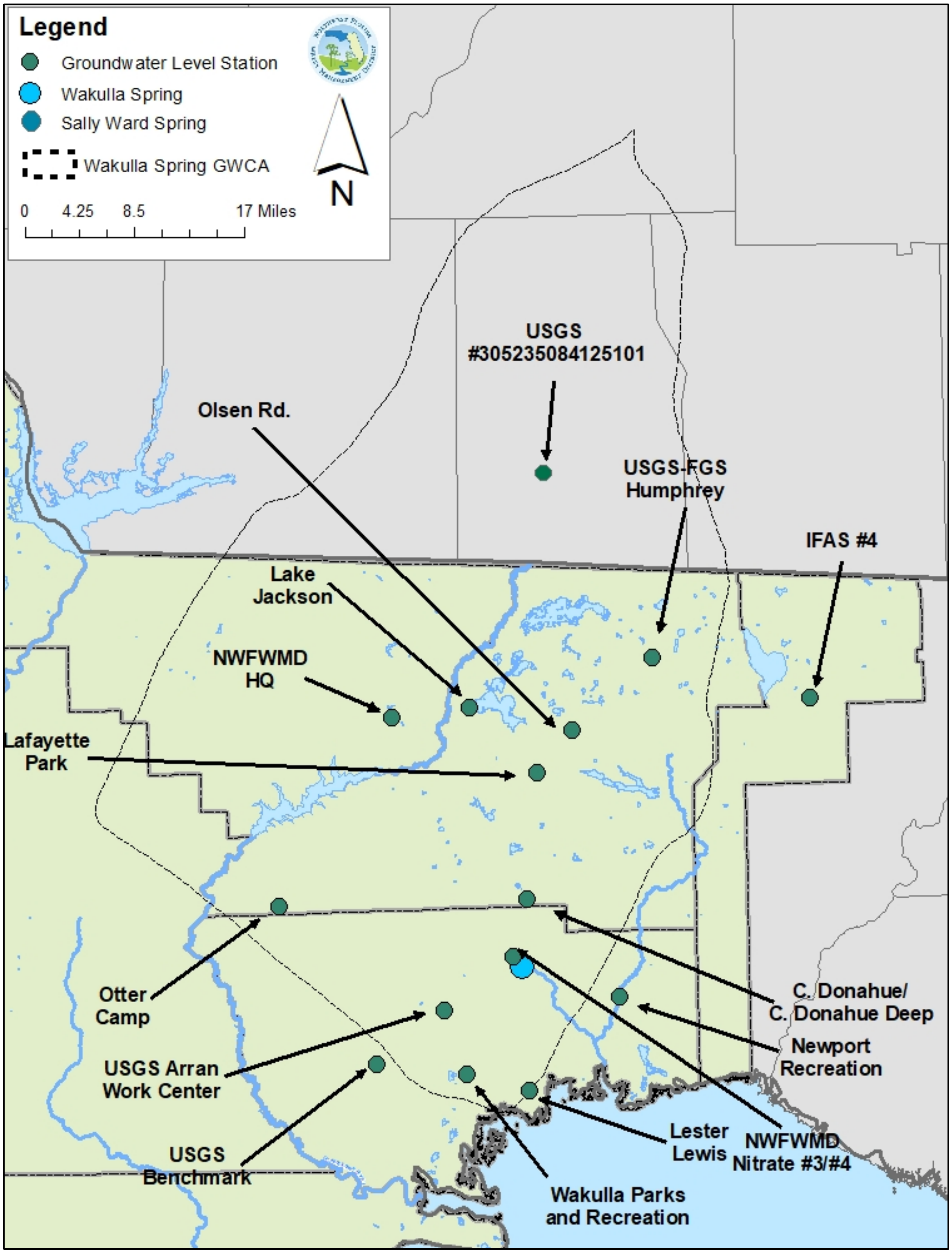


Figure 46: Location of Groundwater Wells Investigated for Long-term Trends.

Table 10: List of Groundwater Level Data Stations Evaluated for Long-Term Trends in Annual Median Aquifer Levels. All wells monitor the Floridan Aquifer.

Station Name	Station Number	Period of Record		Well Depth (ft)	Well Casing Depth (ft)
		Begin	End		
C. Donahue	997	12/18/1995	9/17/2018	200	105
C. Donahue Deep	978	5/16/1989	9/17/2018	157	113
IFAS #4	3413	5/28/1996	9/18/2018	256	166
Lafayette park	2691	6/13/1945	9/19/2018	300	159
Lake Jackson	3402	9/30/1966	8/6/2019	225	100
Lester Lewis	342	6/3/1961	7/9/2019	83	35
Newport Recreation	671	6/30/1961	9/17/2018	69	12
Nitrate #3	7494	1/12/2000	10/8/2019	270	250
Nitrate #4	7495	11/22/1999	10/8/2019	70	50
NWFWMD HQ	3340	10/31/1981	4/30/2019	356	232
Olson Rd.	3156	10/1/1977	8/8/2019	444	289
Otter Camp	965	6/24/1996	7/15/2019	255	218
USGS #305235084125101	n/a	8/21/1964	1/16/2020	971	467
USGS Arran Work Center/Nitrate Pot	635	12/11/1996	9/17/2018	129	75
USGS Benchmark	392	1/5/1967	12/11/2019	127	121
Wakulla Parks and Recreation	372	2/24/1986	3/22/2019	120	35

*Table 11: Results of Seasonal Kendall Trend Test on Monitor Wells within the Wakulla Spring GWCA. *Indicates a statistically significant trend..*

Station Name	p-value	Slope
C. Donahue	0.297	-0.014
C. Donahue Deep	0.036*	-0.027
IFAS #4	0.369	-0.075
Lafayette park	0.027*	-0.057
Lake Jackson	0.016*	-0.090
Lester Lewis	0.222	n/a
Newport Recreation	0.003*	-0.010
Nitrate #3	n/a	n/a
Nitrate #4	n/a	n/a
NWFWMD HQ	0.514	0.044
Olson Rd.	0.095	-0.078
Otter Camp	0.035*	0.039
USGS #305235084125101	0.020*	-0.118
USGS Arran Work Center/Nitrate Pot	0.597	0.027
USGS Benchmark	0.096	-0.007
Wakulla Parks and Recreation	0.009*	0.078

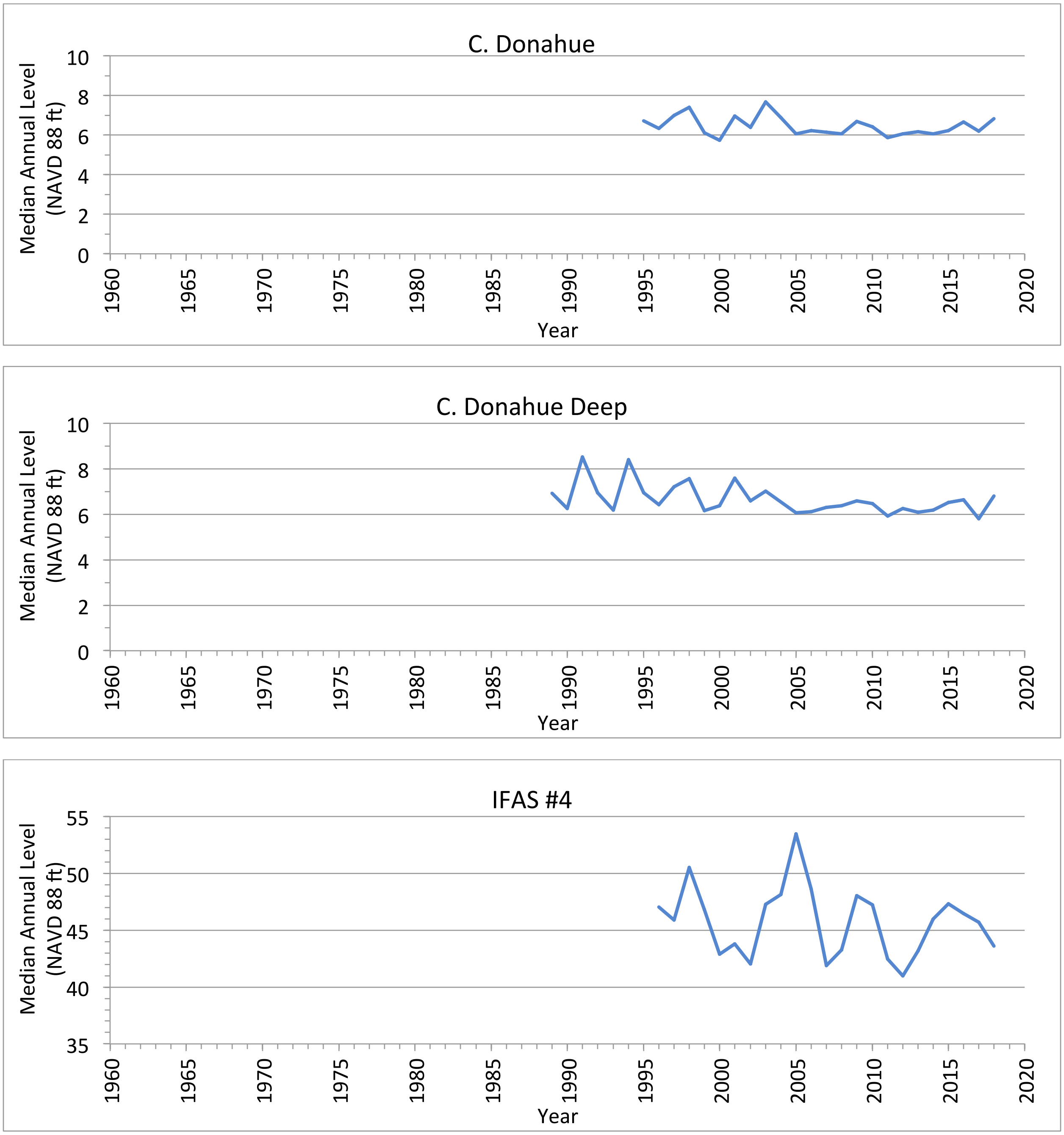
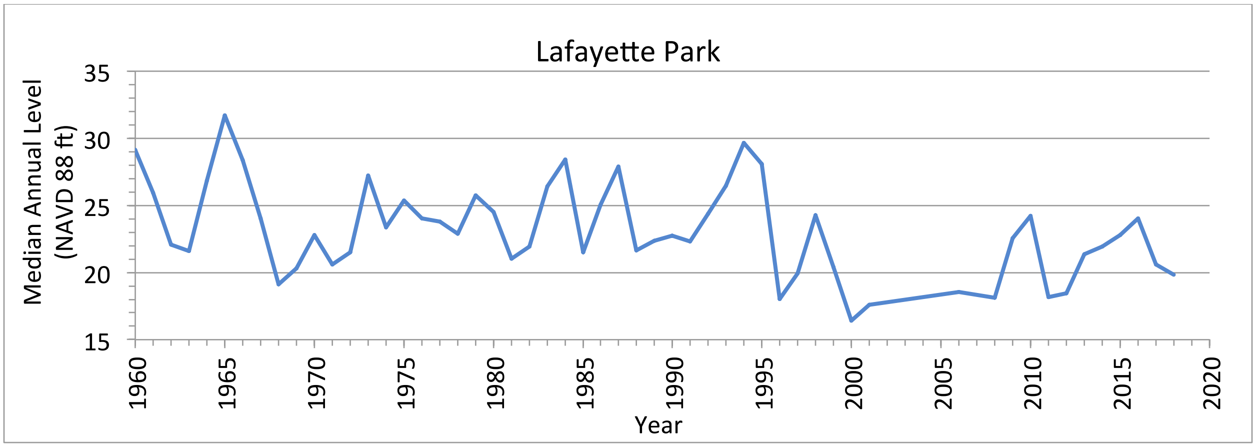
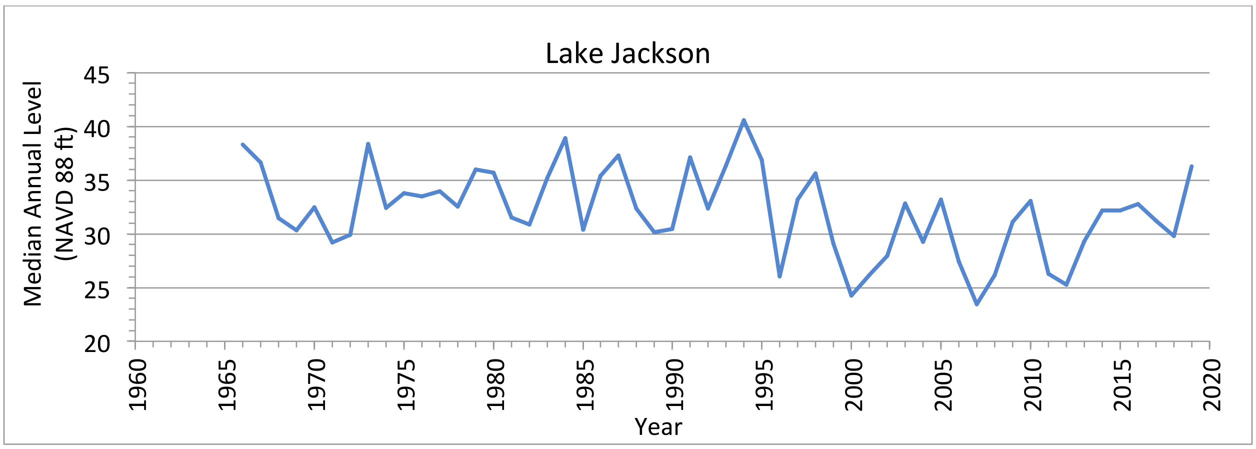


Figure 47: Median Annual Groundwater Levels for Groundwater Wells: C. Donahue, C. Donahue Deep, and IFAS #4.





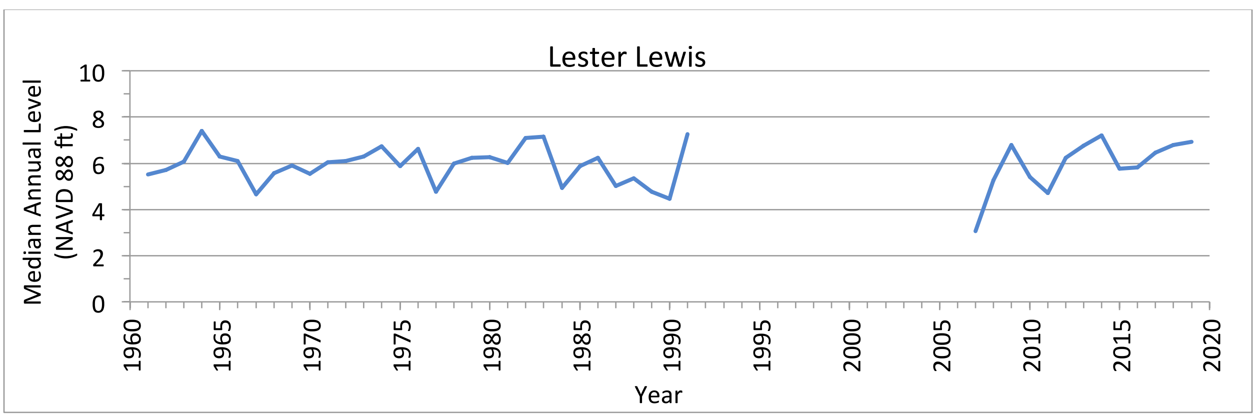
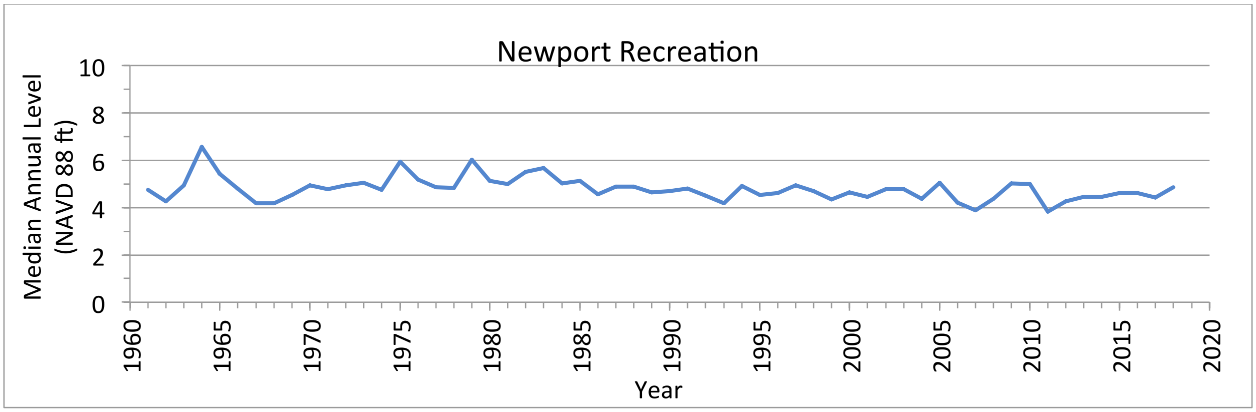
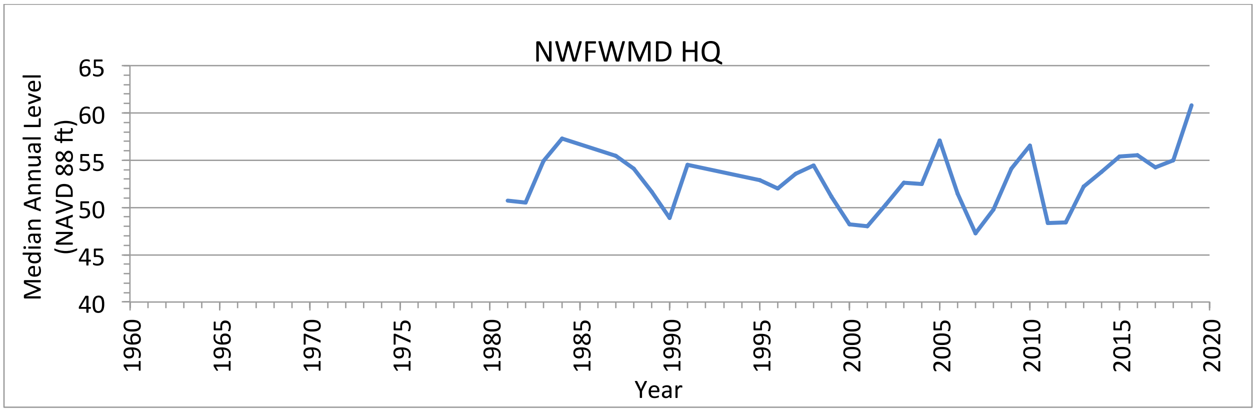


Figure 48: Median Annual Groundwater Levels for Groundwater Wells: Lafayette Park, Lake Jackson, and Lester Lewis.





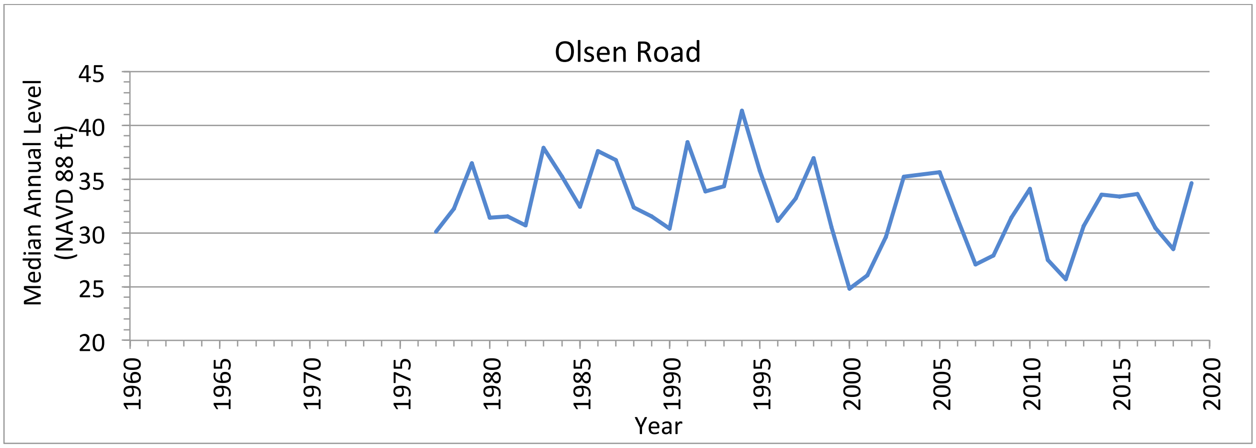
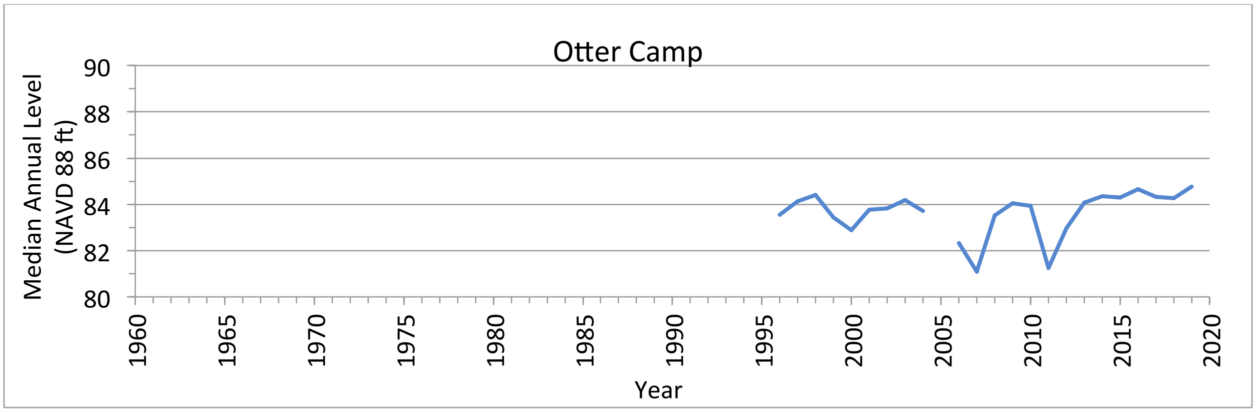
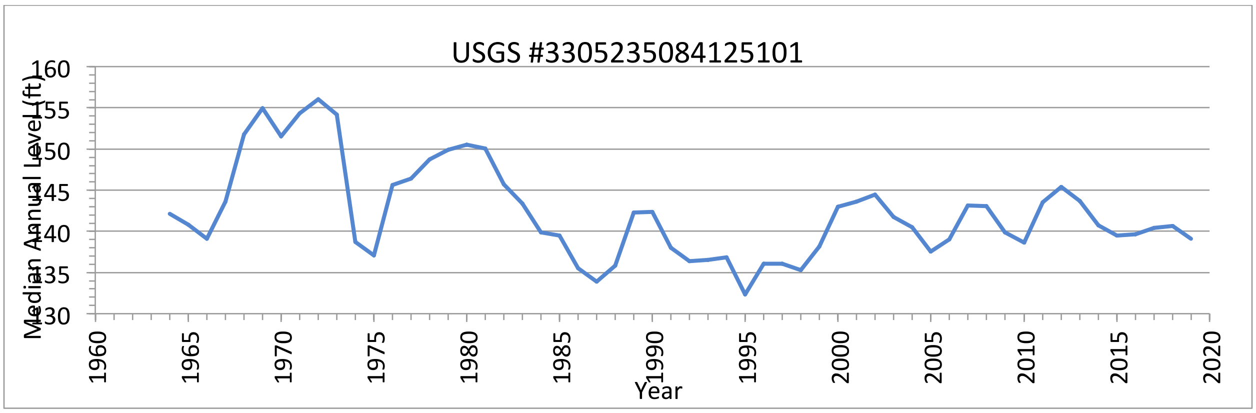


Figure 49: Median Annual Groundwater Levels for Groundwater Wells: Newport Recreation, NWFWMD HQ, and Olson Road





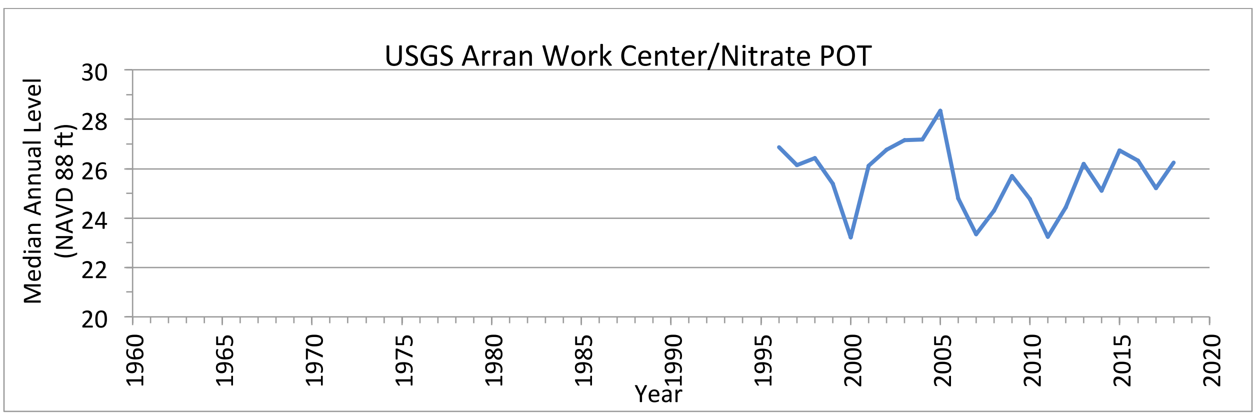
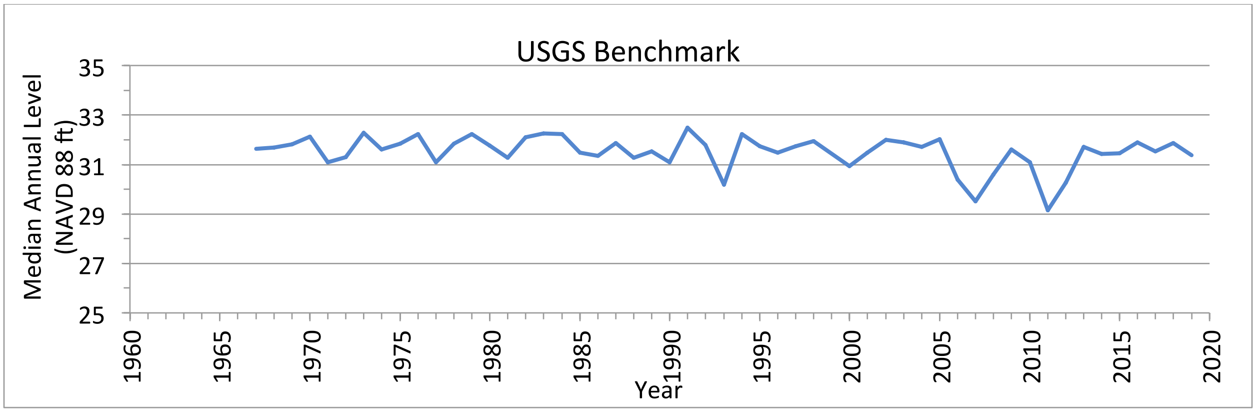


Figure 50: Median Annual Groundwater Levels for Groundwater Wells: Otter Camp, USGS #305235084125101, and USGS Arran Work Center/Nitrate Pot



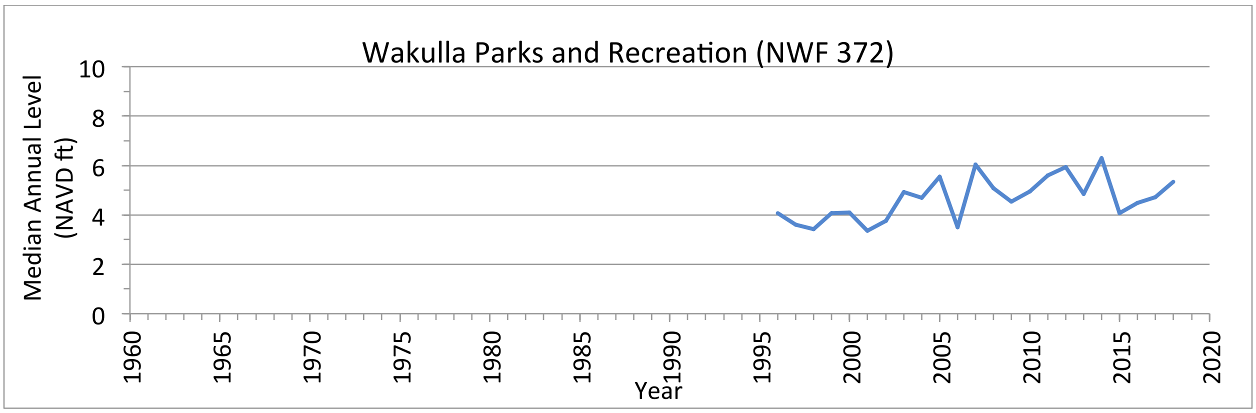


Figure 51: Median Annual Groundwater Levels for Groundwater Wells: USGS Benchmark and Wakulla Parks and Recreation.

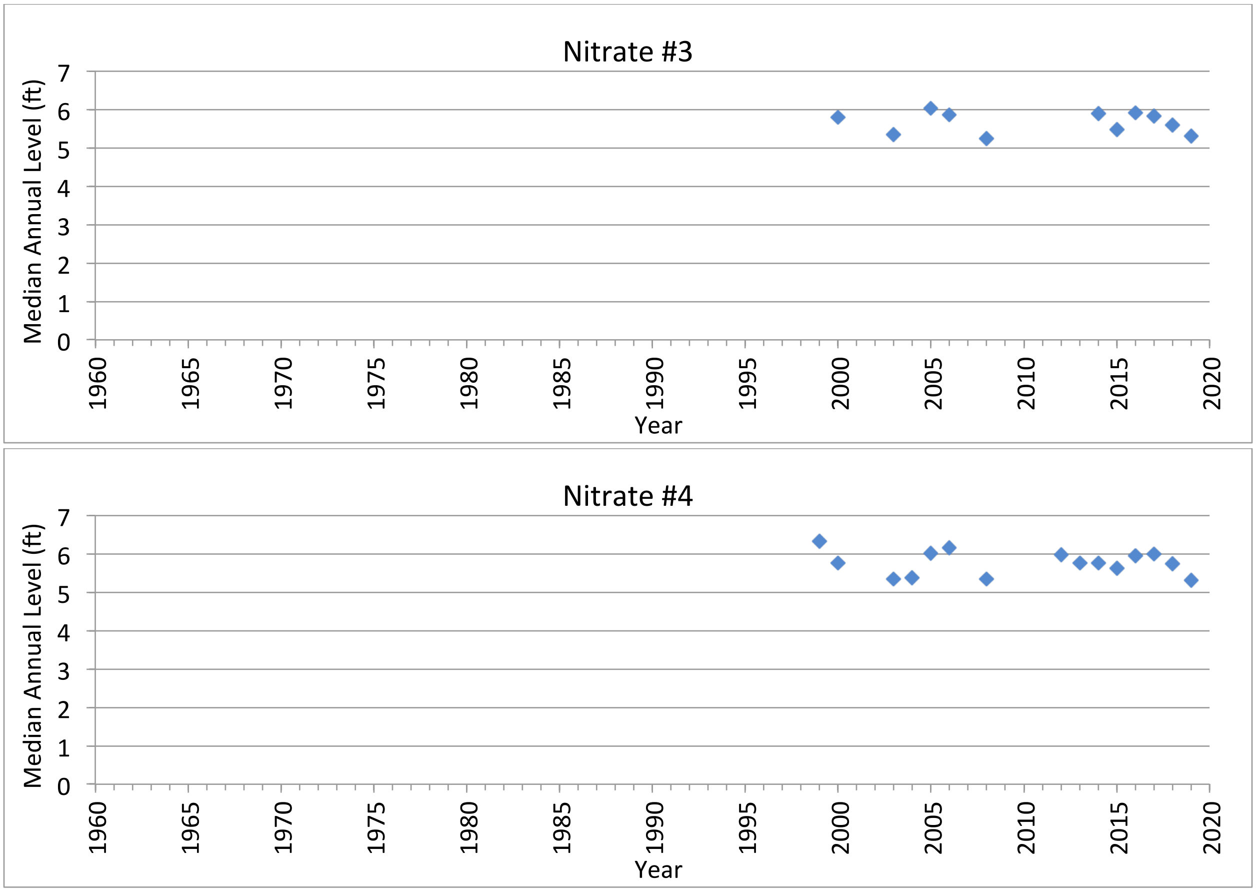


Figure 52: Median Annual Groundwater Levels for Groundwater Wells: Nitrate #3 and Nitrate #4.

5 Wakulla and Sally Ward Spring Baseline Discharge Timeseries

Previous sections in this document described the compilation of discharge time series for both Wakulla and Sally Ward Springs, in addition to analysis of trends in rainfall, evapotranspiration, and groundwater levels in the Wakulla Springs basin.

After review of the previously presented data, it was determined that groundwater extraction within the contribution area was a relatively small portion of the volume of water flowing through the system and not have resulted in a measurable decrease in Wakulla and Sally Ward Spring discharge. This determination was based upon the following observations:

1- Both Wakulla and Sally Ward Springs have displayed a large increase in discharge between 1997 and 2019.

2- Groundwater extraction volumes are relatively stable between 1995 and 2019.

3- Groundwater levels in wells closest to Wakulla and Sally Ward Springs have shown either no significant trends or a slight increase/decrease compared to wells farther away.

Based upon the observations listed above, it was determined that reductions in spring flow associated with consumptive use not measurably reducing spring discharge and adding additional springflow to compensate for extraction to an already increasing flow trend would be inappropriate. As a result, the daily Wakulla and Sally Ward Spring flows for the period of 2004 to 2019, as described in Sections 2.3 and 3.3, were considered the best estimates of spring flows and were used as the baseline time series for minimum flow determination.

To summarize, the period of record between May 10, 1997, and December 31, 2019, was available for consideration as a baseline time series of continuous data for Wakulla Spring discharge. Manual discharge measurements dating back to year 1907 were not considered for baseline flows since their collection dates could not be verified as being collected randomly and the extensive data gaps are present, which in some cases extend nearly 20 years. As previously described, the period immediately prior to hydrilla removal (1997 to 2002) was an altered system and was not representative of general conditions in the Wakulla River, particularly in relation to the stage-discharge relationship. As a result, the Wakulla River stage and discharge data observed between 1997 and 2002 was determined to not be representative of natural or typical conditions. Furthermore, discharge estimates from the USGS Station 02327022 are required for input into the HEC-RAS model and these flows could not be reliably estimated prior to October 22, 2004, due to changes in the inflows to the Wakulla River between the spring vent and Shadeville Road. Accordingly, Wakulla River, Wakulla Spring, and Sally Ward Spring flows prior to October 22, 2004, were not considered further for use in MFL determination.

The period of baseline flows identified for use in the Wakulla Spring minimum flow determination extends from October 22, 2004, through December 31, 2019 (Figure 45 and Figure 46). During this time, Wakulla Spring flows averaged 575 cfs and ranged between 168 cfs and 2,086 cfs. The period of baseline flows identified for Sally Ward Spring similarly extends from October 22, 2004, through December 31, 2019. During this time period, Sally Ward Spring flow averaged 23 cfs and ranged between 4 cfs and 66 cfs.

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7 Appendix A-Wakulla Spring Index Velocity Development

An index velocity method is usually composed of two ratings: a stage-area rating and an index velocity rating. A stage-area rating defines a relation between water-surface elevation and the submerged cross-sectional area through which discharge occurs. An index velocity rating defines a relation between the velocity at a point or subsection of the cross-sectional area of flow and the mean flow velocity for the cross section. Because the cross section where flow velocity was measured was inside the underwater conduit, the area remains constant regardless of spring pool stage, making a stage-area rating component of the index velocity method unnecessary. Therefore, the index velocity was directly correlated with discharge in this application of the index velocity method.

The meters installed in the spring conduit measure flow velocity at a single point in the conduit and as a result, cannot be used to directly calculate discharge using the cross-sectional area. The point velocity is an indicator, or index, which is highly correlated with the measured discharges and thus can be used to develop a rating.

To develop the rating, manual discharge measurements were made in the spring pool during the high frequency, continuous recording of velocities by a meter in the conduit. The discharge measurement transect location is approximately 200 ft downstream of the spring vent. Velocities recorded by the velocity meter during the time of each manual discharge are averaged to create a single velocity for each manual discharge measurement. A linear regression is developed using this average velocity and the manual discharge data. The average velocity is then used as an index from which the spring discharge can be calculated. The best-fit linear regression between discharge and the averaged velocity is represented by the equation:

$$Q = m * Vi + b$$

Where;

Q= calculated discharge (cubic feet per second, ft^3/s, cfs)

m= slope (ft^2)

Vi= velocity measured by the velocity meter (ft/s)

b= y-intercept (cfs)

The rating equation is used to estimate discharge from the continuous record of velocity measurements from the velocity meter in the conduit. All calculated discharges within a 24-hour period were averaged to compute a daily mean discharge. Alternatively, the 15-minute data was tidally filtered using a Godin filter, then averaged within a day to generate tidally filtered daily discharge.

Water velocity data for Wakulla Spring are available using two different sensors: an InterOcean System S4 Current Meter (S4 meter) and a Sontek Argonaut-ADV meter (Argonaut meter). While these two meters are located in approximately the same location in the main spring vent and collect water velocity data, they measure velocity differently and cover two separate time periods (Figure 2). Each of these meters and the resultant spring discharge data are discussed separately below.

7.1 Wakulla Spring S4 Meter

From May 9, 1997, through August 19, 2015, velocity inside the main discharging conduit was measured using an InterOcean System S4 Current Meter (S4). The S4 is a 10-inch diameter sphere with four electromagnetic sensors located symmetrically around its central axis. The meter creates an electromagnetic field that produces a voltage as the water flows through the field. The sensors then measure the voltage which is proportional to the water's velocity. The S4 contains a compass to provide directional information with the velocity data.

The S4 was installed approximately 500 feet inside the main conduit at a depth of approximately 180 ft from the water surface (Figure 23). The planar cross-section of the conduit at the meter location is 741 ft^2 (Figure 24). The S4 was mounted at the midline of conduit and the supporting structure did not interfere with the water velocities collected. The S4 was retrieved by a diver every six to nine months, data was downloaded and the meter returned to the manufacturer for maintenance and calibration. A second calibrated S4 was installed in its place on the same day, allowing for a continuous rotation of calibrated meters.

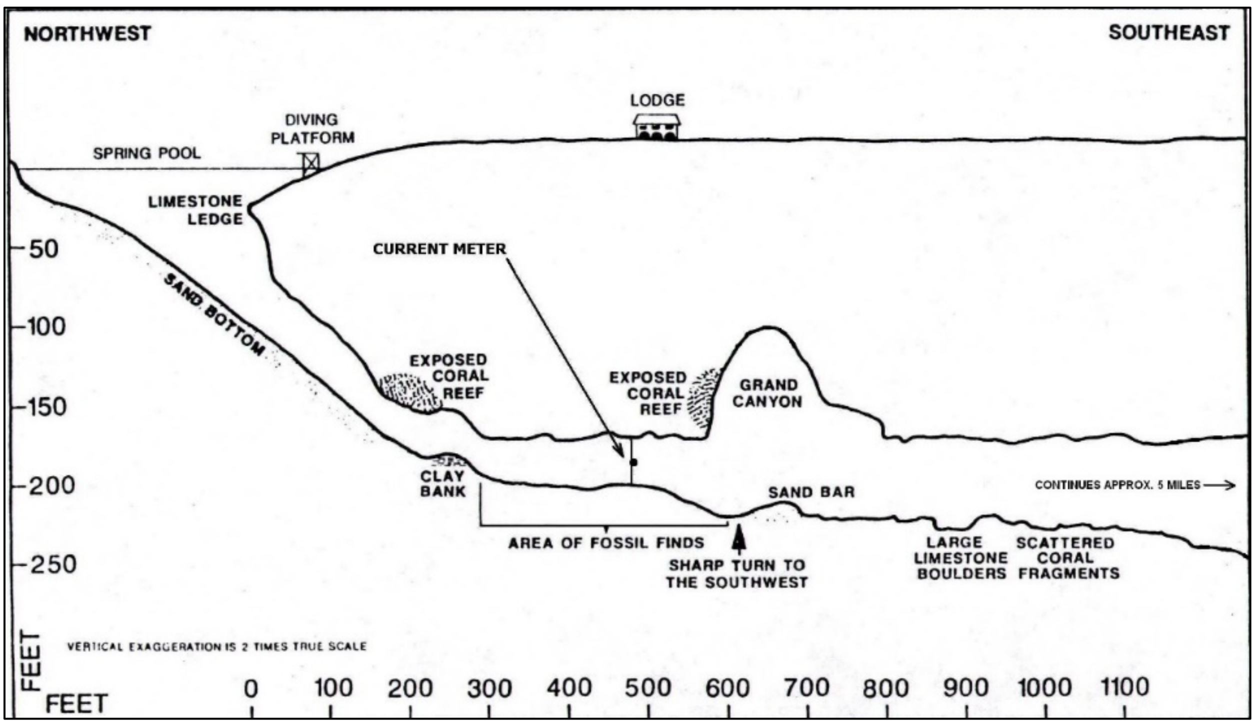

*Figure 41: **Cross-Sectional** Diagram of Wakulla Spring Main Vent and Location of Velocity Meters. Figure Adapted from: Olsen 1958.*

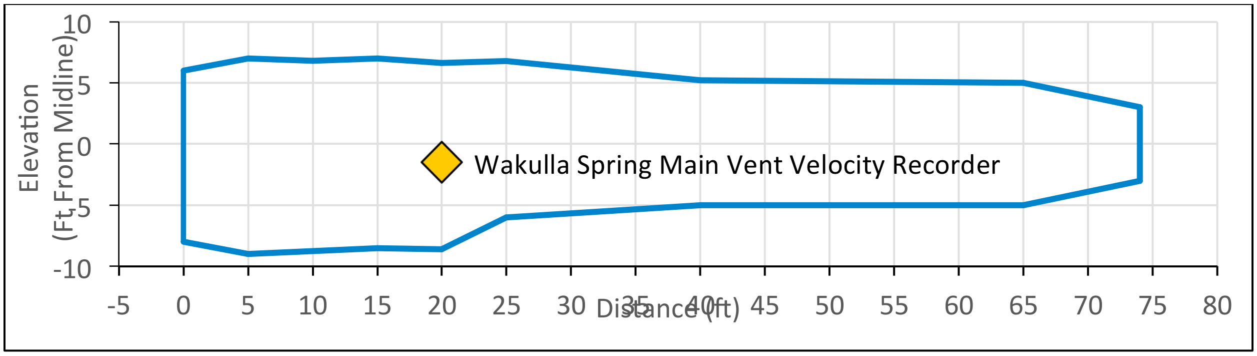

Figure 42 Wakulla Conduit Standard Cross-Sectional Area

During the period of record for the S4, water velocity data were collected at two different sampling intervals. From May 1997 through July 2006, the S4 sampled the index velocity for 2 minutes every 3 hours. In July 2010, sampling was increased from 3 hours to every 15 minutes.

Until 2011, access to the spring pool for discharge measurements was not permitted by the Edward Ball Wakulla Springs State Park. During this time period, discharge measurements were taken downstream from the main spring vent at the County Road 365/Shadeville Road bridge. These downstream manual measurements were not used in the linear regression because of the distance from the main spring vent. Eleven manual discharge measurements using an acoustic doppler current profiler (ADCP) were collected between March 2011 and January 2015 (Table 7). Concurrent manual discharge measurements and average velocity (Vi) measurements from the S4 are listed in Table 7 (Figure 25).

Table 12: Date, Wakulla Spring Discharge, and Water Velocity Collected During Manual Discharge Measurements

S4 Meter		
Discharge Date	**Manual Measured Discharge (ft3/s)**	**Average Vi (ft/s) during Manual Discharge**
May 3, 2011	315	0.71
April 20, 2011	334	0.72
July 14, 2011	680	1.47
October 17, 2011	616	1.42
April 23, 2012	337	0.69
June 28, 2012	2,067	4.81
July 24, 2012	602	1.35

Argonaut Meter		
Discharge Date	**Manual Measured Discharge (ft3/s)**	**Average Vi (ft/s) during Manual Discharge**
January 3, 2018	630.53	1.54
January 18, 2018	587.53	1.58
February 16, 2018	843.96	2.29
February 23, 2018	907.36	2.22
February 23, 2018	853.79	2.20
March 2, 2018	764.98	2.05
March 15, 2018	744.38	1.82

May 16, 2013	328	0.73
August 13, 2014	792.95	1.73
October 28, 2014	712.3	1.61
January 14, 2015	779.34	1.54

March 15, 2018	692.42	1.82
March 22, 2018	1,117.66	2.85
March 22, 2018	1,149.74	2.84
April 10, 2018	742.09	1.72
April 26, 2018	446.64	1.01
January 19, 2019	819.96	2.13
February 21, 2019	732.8	1.75
February 26, 2019	577.75	1.43

When manual discharge measurements were plotted with the corresponding spring vent velocity measurements (Figure 24), the following linear regression was developed:

Q= 424.77*(Vi)x+38.898

Where;

Q = calculated discharge (cfs)

(Vi)x = velocity measured by the velocity meter (ft/s)

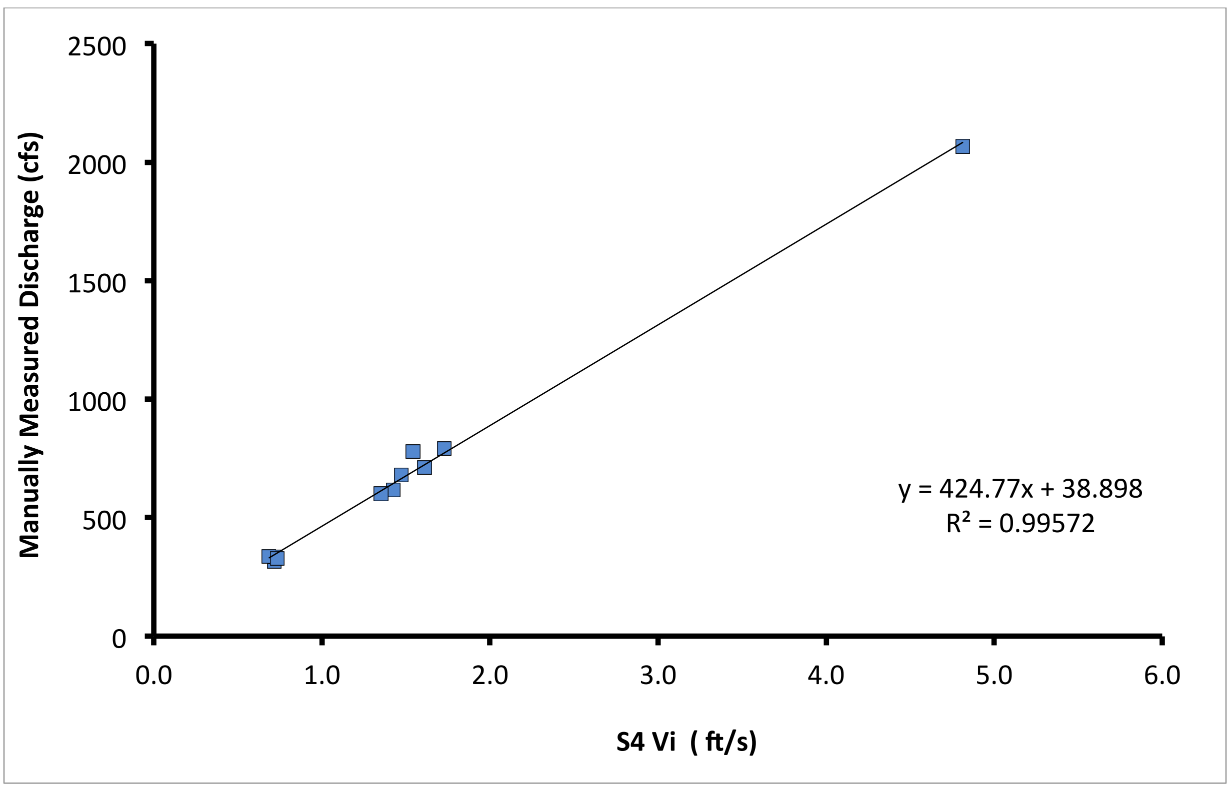

Figure 43: Relationship Between Wakulla Spring Vent Water Velocity Using the S4 Meter and Manually Measured Spring Discharge

The linear regression for the S4 and Wakulla discharge manual measurements indicated that these data were highly correlated (Table 8). There were no obvious signs of nonconstant variance in plots of residuals from the linear regression results, although one of the residuals was noticeably larger than the others (Figures 26 and 27).

Table 13- Linear Regression, Graphs and Statistics Using InterOcean Systems S4 Velocity Data

Regression Statistics	
Multiple R	0.998
R Square	0.996
Adjusted R Square	0.995
Standard Error	34.160
Observations	11

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	38.8982	17.529	2.219	0.054	-0.755	78.550
Avg Vi	424.768	9.287	45.737	5.71E-12	403.759	445.778

RESIDUAL OUTPUT

Observation	*Predicted Discharge (ft3/s)*	*Residuals*	*Standard Residuals*
1	342.304	-27.304	-0.843
2	346.147	-12.147	-0.375
3	664.794	15.206	0.469
4	643.131	-27.131	-0.837
5	330.572	6.428	0.198
6	2083.095	-16.095	-0.4973
7	612.942	-10.942	-0.338
8	350.394	-22.394	-0.691
9	772.331	20.619	0.636
10	723.247	-10.947	-0.338
11	694.634	84.706	2.614

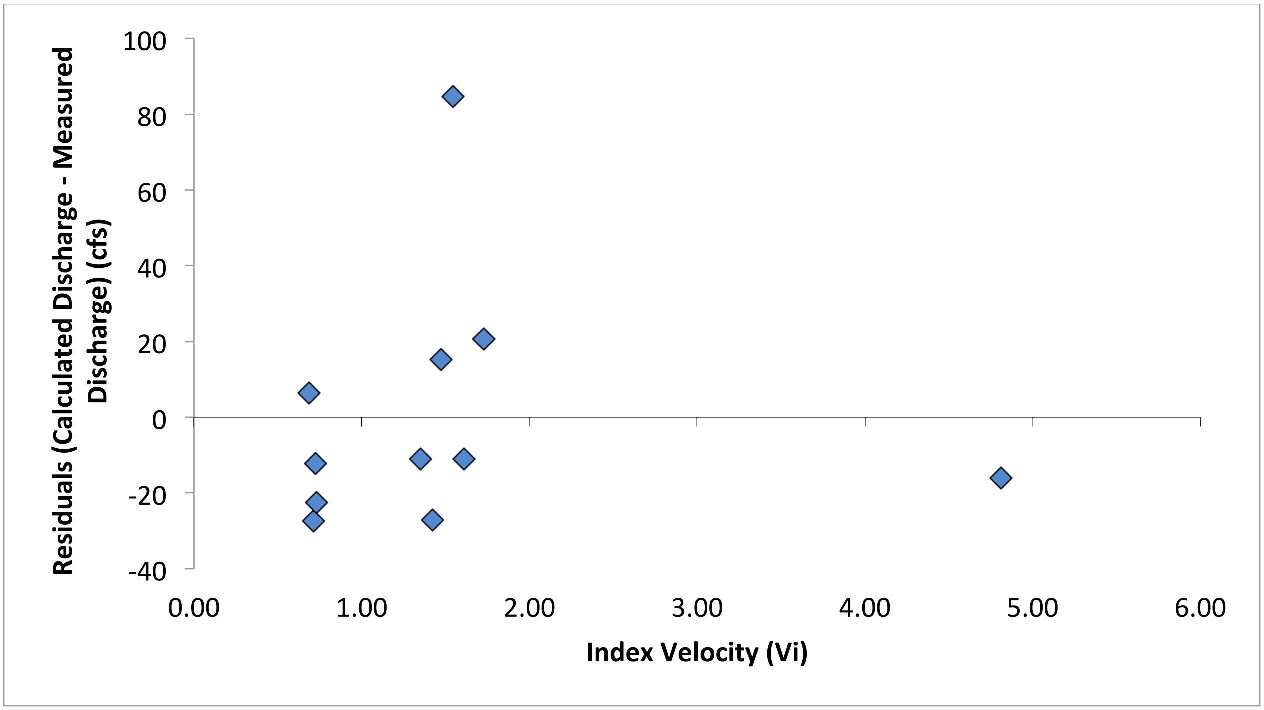

Figure 44: S4 Residuals (Wakulla Spring Discharge Calculated by Index Velocity – Wakulla Spring Discharge Manually Measured) and Wakulla Spring Water Velocity

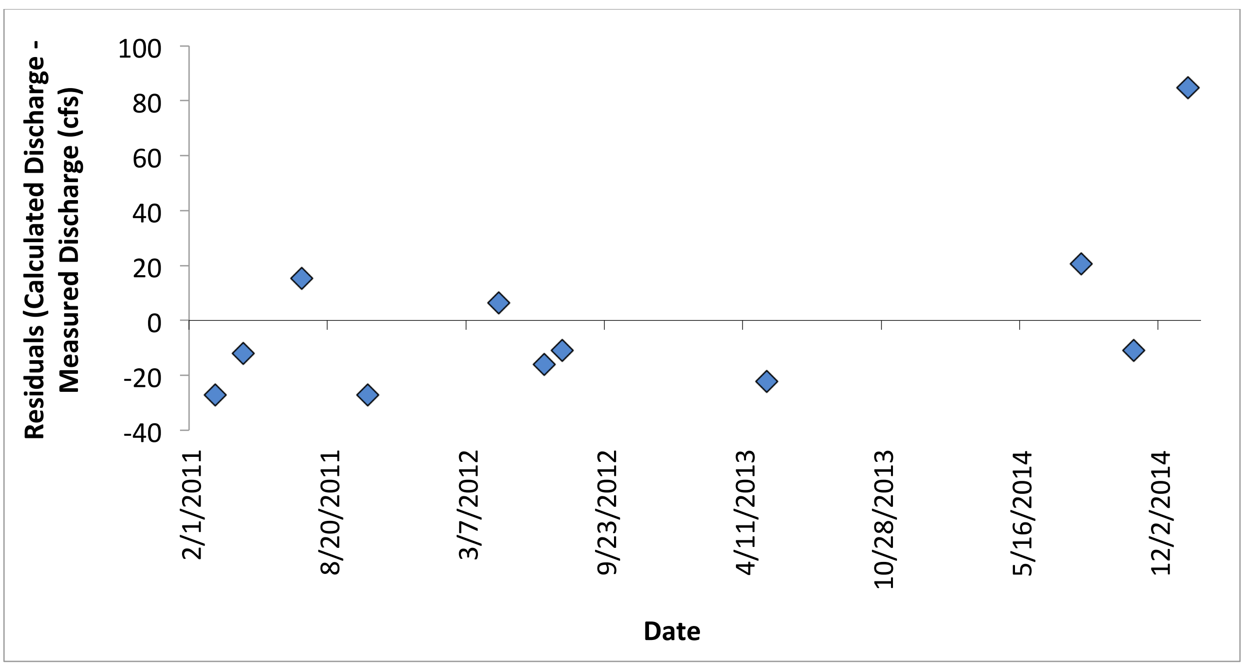

Figure 45: S4 Residuals (Wakulla Spring Discharge Calculated by Index Velocity – Wakulla Spring Discharge Manually Measured) Throughout the S4 Period of Record

7.2 Wakulla Spring Argonaut Meter

On November 6, 2017, cave divers installed a Sontek Argonaut ADV (Argonaut) in the same location as the previous S4 current meter (Figure 23 and Figure 24). Similar to the S4, the Argonaut measures velocity at a single point in the water column. To collect comparable velocities to historical values, the same mounting structure inside the cave was used with minor alterations for the installment of the Argonaut.

The Argonaut uses acoustical signals (SONAR) to measure water velocity. The Argonaut consists of a three-pronged probe, with one acoustic transmitter and three acoustic receivers. The meter also has a compass and tilt sensor to provide directional information. The velocity measurements are based on the Doppler effect. There is an internally mounted temperature sensor to calculate the speed of sound in the water column, which varies with temperature. Acoustic waves are reflected by particles in the water and water is assumed to be moving at the same velocity as the particles, therefore water velocity can be estimated from the shift in the frequency of reflected waves returning to the meter. Low concentrations of particles in the water can result in low SNR (signal to noise ratio) and can result in less accurate velocity measurements. Specifications of the meter's accuracy and precision are provided in Table 5. The Argonaut comes factory calibrated and does not need to be retrieved for periodic maintenance and calibration. The Argonaut index velocity measurements are averages of individual velocity measurements that are made a frequency of 10 measurements per second for a 5-minute period, every 15 minutes.

Fifteen manual discharge measurements near the spring pool were collected from January 2018-February 2019 using an ADCP Acoustic Doppler Current Profiler (Table 7). During manual discharge measurements, the frequency with which the Argonaut's velocity measurements were increased from 5-minute averages every 15 minutes to one-minute averages every minute. This allowed the discharge measurement to be precisely matched to the velocities recorded during the measurement.

A scatterplot of the relation between concurrent manual discharge measurements and spring vent velocity measurements is shown in Figure 28. A linear regression analysis of this relation resulted in the following equation:

$$Q = 372.9848 * Vi + 46.7856$$

Where;

Q= calculated discharge (cfs)

Vi= velocity measured by the velocity meter (ft/s)

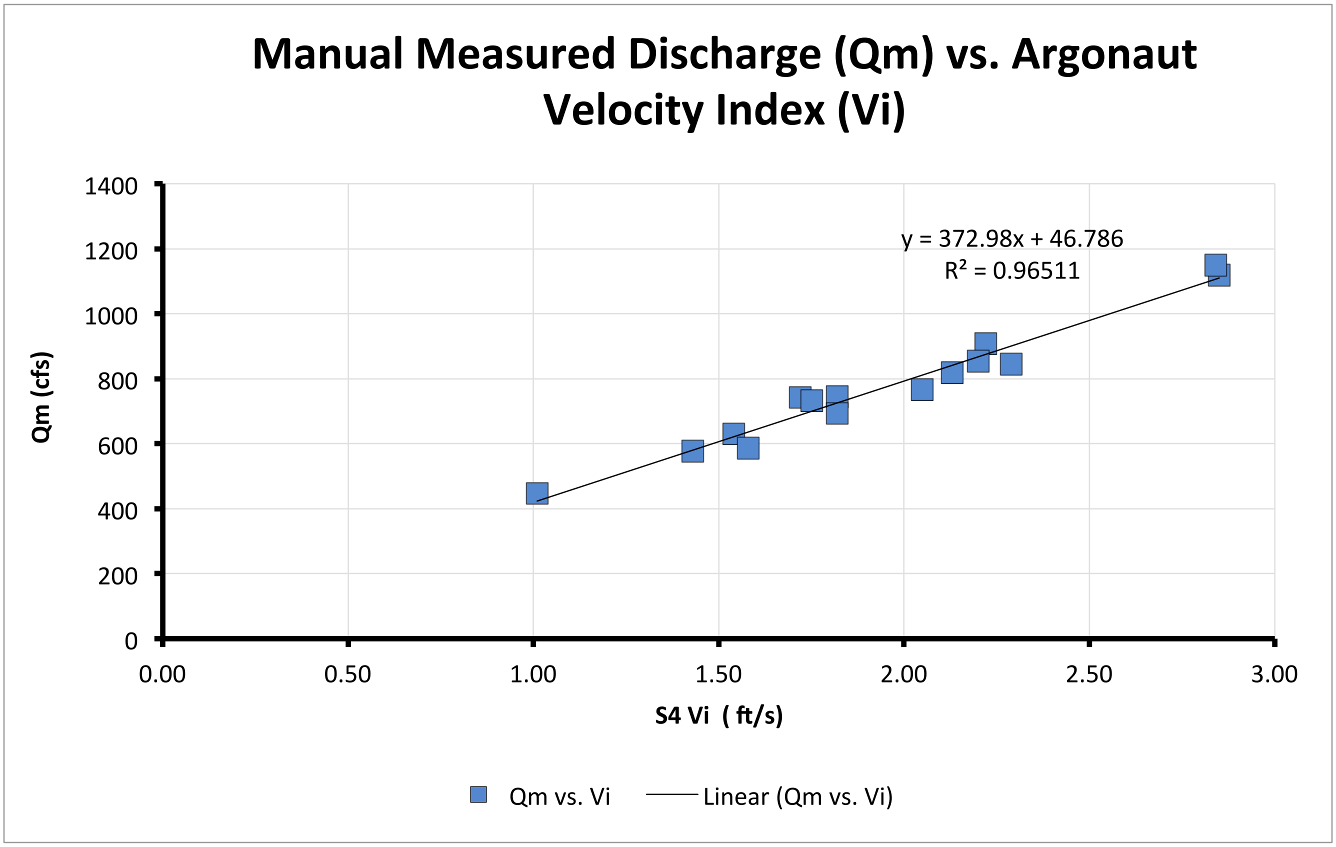

Figure 46: Index Velocity Equation for the Argonaut

The linear regression for the Argonaut and Wakulla Discharge manual measurements indicated a high correlation (Figure 28, Table 9). There were no obvious signs of nonconstant variance in plots of residuals from the linear regression results (Figures 29 and 30). Please note that these statistics and plots should be interpreted with caution, given the limited sample size.

Table 14: Linear regression, graphs and statistics using Sontek Argonaut ADV S4 velocity data

Regression Statistics	
Multiple R	0.982
R Square	0.965
Adjusted R Square	0.962
Standard Error	36.697
Observations	15

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	46.786	39.507	1.184	0.258	-38.564	132.134
Average Vi (ft/s)	372.985	19.669	18.964	7.43E-11	330.494	415.476

RESIDUAL OUTPUT

Observation	*Predicted Manual Measured Discharge (ft3/s)*	*Residuals*
1	621.182	9.348
2	636.102	-48.572
3	900.921	-56.961
4	874.812	32.548
5	867.352	-13.562
6	811.405	-46.425
7	725.618	18.762
8	725.618	-33.198
9	1109.792	7.868
10	1106.063	43.678
11	688.320	53.771
12	423.500	23.140
13	841.243	-21.283
14	699.509	33.291
15	580.154	-2.404

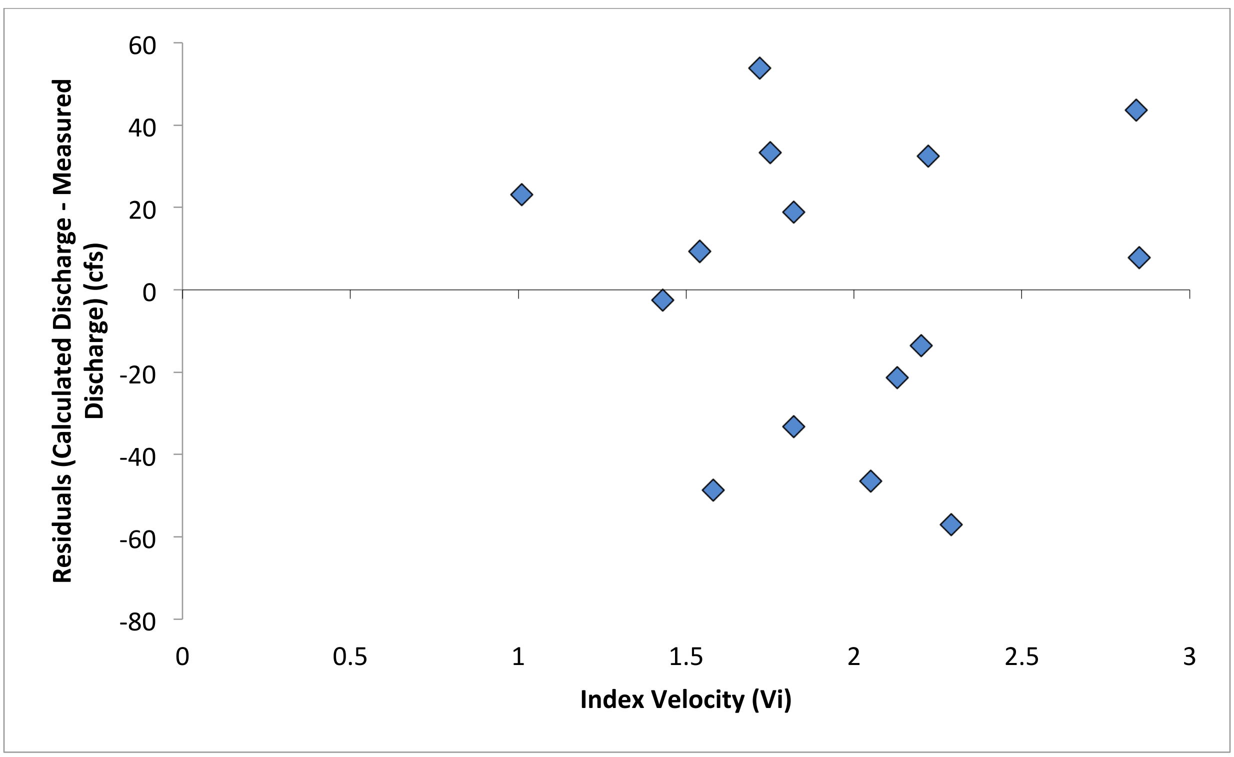

Figure 47: Argonaut Residuals (Wakulla Spring Discharge Calculated by Index Velocity – Wakulla Spring Discharge Manually Measured) and Wakulla Spring Water Velocity

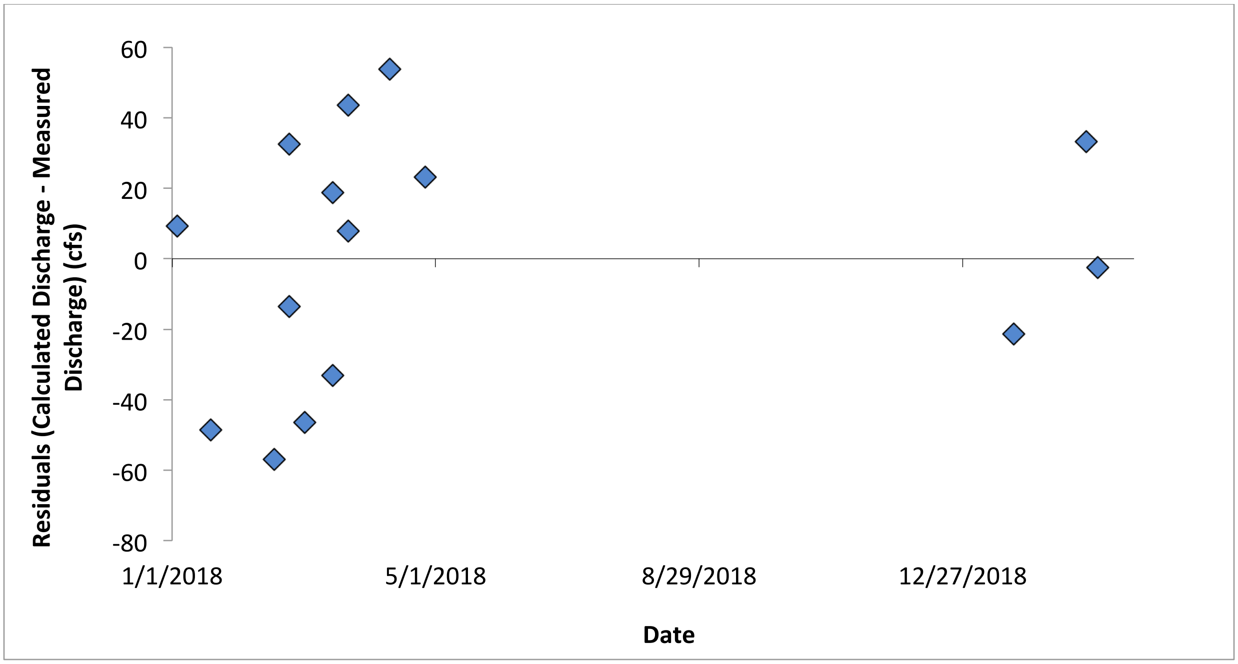

Figure 48: Argonaut Residuals (Wakulla Spring Discharge Calculated by Index Velocity – Wakulla Spring Discharge Manually Measured) Throughout the S4 Period of Record

7.3 Literature Cited

Olsen, S.J. 1958. The Wakulla Cave. Natural History. 67 (7): 396-403.