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Estimating a range of flow rates resulting from extreme storm events within the Wekiva River watershed through statistical testing and modeling

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ESTIMATING A RANGE OF FLOW RATES RESULTING FROM EXTREME STORM EVENTS WITHIN THE WEKIVA RIVER WATERSHED THROUGH STATISTICAL METHODS AND MODELING

by

Wesley K. Koning

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Abstract.

The middle portion of the St. Johns River is located in East-Central Florida, USA. This region of the St. Johns River is increasingly subject to urbanization and conversion of forest areas to agricultural land. Overall, these changes mean that future flood events in the area could adversely impact local citizens. Therefore, the examination of extreme flood events and resiliency to such events is critical. The purpose of this preliminary study is to explore a range of practical applications to estimate extreme flood flows at watercourses within the Middle St. Johns River Basin, focusing specifically upon the Wekiva River sub-basin. The current work illustrates the overall technical methodology and provides estimates of extreme flood flows at different return frequencies using hydrologic modeling, statistical analysis, and supporting published reports. Altogether, once fully integrated and complete, the methods will permit predictions at a range of possible flood flows as a result of an extreme storm event at any place along the watercourse.

Chapter 1. Introduction

This thesis provides an examination of the magnitude of extreme flood events in the Wekiva sub-basin, which is located in Central Florida, USA. As part of this research effort, new estimates of flood discharges were developed using multiple methods, including hydrological modeling and statistical calculations. These various estimates were compared to published estimates derived from historical Flood Insurance Studies (FIS) prepared for the Federal Emergency Management Agency (FEMA). Using both calculated estimates and gathered literature, the research team analyzed the Wekiva sub-basin to identify the benefit of statistical methods and numerical modeling estimates in developing a range of reliable flood flow results. A comparison to historical published reports provided the research team the means to decide if the implemented statistical methods could be a sufficient alternative in geographic areas where no reported historical FIS data is present. Research on the effects seen on watercourses due to urbanization, sea level rise, and climate changes is incredibly important. This research will dive directly into analyzing several methods for estimating flood flow rates based on the focus area of research, which is the Wekiva sub-basin located in the Middle St. Johns River Basin. Methods investigated include altering existing hydrologic model simulations, statistical testing, and comparison of existing flood reports. Using an existing hydrologic model provided by the St. Johns River Water Management District (SJRWMD) the team modeled the extreme storm events by altering the original rainfall datasets. The assessment of the Wekiva sub-basin in the Middle St. Johns River Basin will be broken down into three primary watercourses: the Wekiva River, Little Wekiva River, and Blackwater Creek. Storm events at the 10, 25, 50, and 100-year return frequencies are analyzed as the extreme storm events of interest. These return frequencies correlate to a 10%, 4%, 2%, and 1% annual storm occurrence probability, respectively.

This thesis is organized into nine chapters. Chapter 1 begins with an introduction to the research that will be performed within the paper. Chapter 2 takes a look back at the supporting research that has already been published within the field of flood flow estimation. Chapter 3 dives directly into the area of study and a summary of its background. Chapter 4 discusses the hydrological backbone that makes the sub-basin unique. Chapter 5 explains how the hydrologic model was modified to predict the effects of a particular extreme storm event. Chapter 6 describes the statistical procedures in deriving flood flow estimations through each method. Chapter 7 presents the results of the entire research. Chapter 8 assesses the comparison of all developed results. Chapter 9 concludes the research and identifies any recommendations for future studies.

Chapter 2. Literature Review

The following literature review took a hard look at new statistical methods, hydrologic modeling, and the reasoning behind unfavorable outcomes.

2.1 Model Simulated Estimates

Modeling an area for further investigation is a common practice seen among engineering organizations. Numerical simulations provide the capability to incorporate the characteristics of a sub-basin, including hydrology and hydraulics, in order to simulate the physical mechanism of runoff from a range of precipitation events. The benefit to the Wekiva sub-basin is that it lies within the Middle St. Johns River which is a part of the St. Johns River Water Management District (SJRWMD), an agency that runs simulations to evaluate the basin water resources. The SJRWMD was created to be one of the five water management districts in 1972 and now encompasses all nineteen of the northeast counties (Hupalo, 1994). Its goal is to maximize the environmental and economic effects through regulation and the constant study of the waterways. Through SJRWMD's ever expanding study and maintenance, they have created numerous hydrologic and hydraulic models that accurately portray the water surface elevation and flow rates that watercourses may experience. A group of data sets was derived from this environment to identify aspects of the sub-basin such as hydrology, water quality, and hydraulics through computer modeling. The model created by the United States Geologic Survey and Environmental Protection Agency (2012) suited the SJRWMD to simulate the basins through the Hydrologic Simulation Program – FORTRAN (HSPF), a plugin of Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) taken from the United States Environmental Protection Survey (2013). The HSPF plugin of BASINS is noted to be highly intelligent when predicting flows and became distinguished by the Environmental Protection Agency (EPA) for models prior. The

SJRWMD used the HSPF code to develop a series of hydrologic models of a majority of the St. Johns River Basins including the focus of this study, the Wekiva sub-basin. The SJRWMD has made the model available to the public with the results incorporated. The Wekiva sub-basin HSPF model is used in this research effort. As part of this effort, modifications are made to the original HSPF code to develop flood flow estimates in the basin. This gives an advantage to the project location as it allows for another form of support when comparing the flood flow estimates.

2.2 Statistical Flood Estimation

With an abundance of statistical methods and mathematical procedures, it is difficult to narrow the tests down to only one. This meant that multiple tests were needed to accurately discuss a range of outcomes that could better predict the flow of a watercourse. To start, it was evident that a dependable, well-known statistical test needed to be established. The Log Pearson Type III (LP3) was initially reviewed. It is commonly used within the engineering community and has been deemed as becoming America's official model since 1967 (Singh, 1998)). The model was recommended by the United States Water Resources Council in 1967, as it considers attributes such as mean, standard deviation, and skewness that would make it a top candidate for the United States base flood estimation methodology. The Water Resources Council recommended using a generalized skew coefficient; however, scientists such as Bobee and Robitaille (1975), and Tung and Mays (1981) thought otherwise. After some time, it was concluded that the best approach for the LP3 method would be to use a generalized skew coefficient based on a weighted average of the variance sample skew coefficient and the regional map skew coefficient. Thereafter, the controversy led to the number techniques in which many researchers pursued the mathematical input of modified versions (MOM), expected moments algorithm (EMA), probability weight moments (PWM), method of mixed moments (MIX), and so many more. Years after, it was

concluded by Nozdryn-Plotnicki and Watts (1979) that MOM was superior in their study, resulting in a very low standard error of the T-year flood. MOM implemented logarithms of the observed data and was more effective at estimating the flow than the original observed data. It was then described by Ashkar and Bobee (1987) that the generalized MOM might be best for estimating high and low flows. In 1980, Shen et al. investigated the end behavior in extreme events using the LP3 and Gumbel distribution, concluding that LP3 portrays a better relationship to the field data. Further trials by Loganathan et al. (1986) confirmed that the LP3 was a suitable fit when dealing with low flow waterways.

While the LP3 methodology seems well-accepted and widely used, there are a myriad of other flood estimation statistical methods available. Alternatively, the Power Law (PL) model has the potential to be advantageous, as it is known for its simplicity and having a plausible theoretical basis. The PL provides an alternative way at looking at the observed data as it implies that the discharge ratios are the same for any given return period. This labels the model "self-similar" as it does not alter at larger or smaller storm events. In this sense, it offers a realistic theoretical basis for flood frequency analysis (Kidson and Richards, 2005). Throughout the documentation published by Schertzer in 1993, a phase transition was notably concluded for the PL model. It implies that the best circumstances to use the PL model are during large events above a fairly high threshold and infers that the PL may be unreliable when a limited number of observed flow records are available. In addition, the PL was denoted to greater research and should be used with caution when flood events are near the mean flow. After a review of this research, it was deemed as another good method for flood estimation as it offers particular promise for the prediction of extreme storm events. Another benefit of the method is that literature illustrates that it can be used for both linear and non-liner model fits with equal benefit.

As part of the literature review, a third method that distinguished itself was the Theil-Sen (TS) method. Seen heavily in real estate and accounting, the TS method is very straightforward in both concept and practice. This estimator is well known for being robust in outliers within observed datasets. The TS handles heteroscedasticity directly as the scaling of observations has no effect on its calculations. This made the TS a suitable fit when defining the true mean, variance, slope, and intercept of any datasets (Ohlson, 2014). Therefore, this estimate was also used for this study.

2.3 Existing Flood Estimates

Several existing historical studies were located as part of the literature review. Both of these efforts provided flood flow estimates within the Wekiva River sub-basin.

2.3.1 Federal Emergency Management Agency (FEMA)

To analyze the risk of flooding within a given community, FEMA performs an engineering assessment called a Flood Insurance Study (FIS). The FIS is a collection of flood hazard areas along rivers, streams, and coasts. FEMA became nationally recognized, contributing to what is now known as its risk mapping, assessment, and planning. The flood maps generated by FEMA constitute an important part of the National Flood Insurance Program (NFIP) regulations and flood insurance requirements (Federal Emergency Management Agency, 2013). A FEMA flood map will inform the community about local flood risks while also issuing the minimum floodplain standards that will allow a community to build safely and resiliently (Federal Emergency Management Agency, 2013). Due to ever-changing environmental factors, population growth, and evolving engineering practices, a watershed could be reassessed and remapped if it deems necessary. For this project location, it is important that the Wekiva River, Little Wekiva River, and Black Water Creek have documented studies that pertain to its their particular flood characteristics. Further investigation establishes that the project location has a

joining county line on the Wekiva River, contributing to the assessment of two FIS reports in both Lake County (Federal Emergency Management Agency, 2013) and Seminole County (Federal Emergency Management Agency, 2014). Through the study it became apparent that neither the Wekiva River nor the Black Water Creek runs through heavily populated communities. Since these communities were not at risk, no publications were collected for either of the two mentioned watercourses to date. However, the Little Wekiva River had risk acquired for multiple communities and so an FIS was performed and published. FEMA's estimated flood discharges were taken at the Little Wekiva River on State Road 434. Figure 1 depicts its location in plan view. The acquired data provides a baseline in the team's attempt to mimic the discharge rates through statistical equations. Obtaining 10-yr, 25-yr, 50-yr, and 100-yr storm events on the Little Wekiva River is very helpful in understanding the flow that this waterway presents. Chapter 7.3 discusses the results found on the Little Wekiva River.

2.3.2 St. Johns River Water Management District (SJRWMD)

The SJRWMD is required by law to establish minimum surface water flows, flow levels, and minimum ground water levels for the Floridan aquifer system within the Wekiva Basin (Paragraph 373.415[3], Florida Statutes [FS]) (SJRWMD, 2012). HSPF a plugin of BASINS is very powerful at interpolating data among the watercourse where gages are not present. SJRWMD has input all watershed characteristics into this model, gaining a vast extent of hydrology, hydraulic and geotechnical results. Furthermore, a report was created displaying the description of flow rates and flood profiles at the 10-yr and 100-yr 24-hour storm events at the Little Wekiva River on State Road 434. As mentioned before, Figure 1 depicts its location on the map. These points of interest on the Little Wekiva River can easily be compared to FEMA. Chapter 7.3 elaborates on the discovered flows published for the Little Wekiva River.

Chapter 3. History of the Wekiva Sub-Basin

The following sections describes the history of the Wekiva sub-basin and all the characteristics that define its flow relationships. For a great visual of the Wekiva Sub-basin please refer to Appendix A.

3.1 The Wekiva Sub-Basin

Located in northeast Orlando, Florida, the Wekiva sub-basin consists of 376 square miles of the watershed (SJRWMD, 2002). The sub-basin lies in the Middle St. Johns River Basin, comprising of rivers, springs, tributaries, and preservations. SJRWMD labels the Wekiva sub-basin as Planning Unit 4E, seen in Appendix A. This entire basin has been studied to provide an accurate water improvement and management plan by the SJRWMD in January of 2002 (SJRWMD, 2002). The sub-basin consists of three major waterways, Wekiva River, Little Wekiva River, and Blackwater Creek, respectively in order of size. The sub-basin is located in portions of Orange, Seminole, Lake, and Marion counties. Local municipalities and urbanized areas within this unit include Lake Mary, Apopka, Altamonte Springs, Maitland, Eatonville, Winter Park, Orlando, Orlovista, and Mt. Plymouth (SJRWMD, 2002).

In Figure 2, a basic breakdown of the major land uses and land cover in the Middle St. Johns River Basin can be viewed. The soil characteristics of this region are very sandy, with a large portion in an area of high aquifer recharge. The Wekiva sub-basin can be classified into two major types: mixed hardwood swamp and hydric hammock communities. Hydric hammock communities exhibit a relatively constant moisture regime, while mixed hardwood swamp communities experience river overflow. Blackwater Creek has a floodplain composed of primarily mixed hardwood swamp, whereas the floodplain of the Wekiva River is composed primarily of hydric

hammock. Mixed hardwood swamp environments flood for longer durations and more frequently than hydric hammock habitats.

Additionally, private lands within the Wekiva basin include a mix of residential, commercial, and agricultural properties. The Wekiva sub-basin has multiple properties protected through public ownership; the Wekiva Basin GEOpark, Seminole State Forest, Ocala National Forest, state reserves, and the Wekiva-Ocala Greenway Conservation and Recreation Lands. Developments range from very low-density rural to high-density urban. The majority of east Lake County and northwest Orange County are low-density rural, while the greater metropolitan area of Orange and Seminole counties are high-density urban (Hupalo et al., 1994). The land encompassing the Wekiva River and everything downstream SR 434 on the Little Wekiva River is designated as "Outstanding Florida Waters" by the state under Rule 62- 302.700(9)(i), Florida Administrative Code. In 1988, the Florida Legislature passed the Wekiva River Protection Act, which preserved the land in order to maintain an environmentally friendly habitat for the local species (Wekiva Wild and Scenic River System Advisory Management Committee, 2012). Regulations prevented wetland losses and authorized local governments to create rules for runoff treatment. A defining characteristic of the Wekiva sub-basin is the high prevalence of natural springs. These springs provide a portion of the baseflow in each water course. These various spring flows are periodically monitored; however, the frequency of monitoring is typically very low. This means that during high flow flood events, the spring flow is typically unknown in this watershed.

3.2 Watercourses

The Wekiva River Planning Unit 4E is made up of three primary watercourses: Wekiva River, Little Wekiva River, and Black Water Creek. Within those watercourses it can be subdivided into the Seminole Creek Rock Springs Run, and Sulphur Run. The largest portion of the planning

unit is contributed to Blackwater Creek, draining an area of 164.8 square miles from the north, the Little Wekiva River draining an area of 55.9 square miles of the southeast, and the Wekiva River draining 78.6 square miles of the central portion (not including the Little Wekiva drainage) (SJRWMD, 2002). Approximately 76.7 square miles drain from the watershed's western edge and becomes landlocked, resulting in no contribution to surface water (SJRWMD, 2002). Documented from the Wekiva Wild and Scenic River System Advisory Management Committee (2012), Appendix A displays the location of watercourses in the Wekiva sub-basin and its relative location. The general understanding of the Wekiva River, the largest of all three watercourses, forms at the confluence of Wekiva Springs Run and Rock Springs Run approximately 14.2 miles upstream of the St. Johns River outlet point. Prior to the outfall into the St. Johns River, the Little Wekiva River merges at the Wekiva River nearly 10.5 miles before the outfall. Blackwater Creek merges only 1 mile upstream of the confluence of the Wekiva River and St. Johns River. Wetlands and undeveloped land surround the majority of the area near the Wekiva River and Blackwater Creek. The Little Wekiva River is the only watercourse that proceeds through residential and urbanized plots of land.

3.3 Springs & Tributaries

The Wekiva River and Blackwater Creek both contain their presence from spring-fed and black water streams. The Wekiva Wild and Scenic River System displays all spring flow locations as yellow dots in Appendix A, emphasized the flow from springs to be very significant in the Wekiva sub-basin. These spring fed watercourses result from the Floridan Aquifer System (Wekiva Wild and Scenic River System Advisory Management Committee, 2012). The remainder of the flow is caused by black water streams (precipitation-based) and usually has over-bank flows during the summer rainy season. Base flow and the magnitude of seasonal variation from water levels and

flows differ between black water-fed streams and spring-fed streams (Hupalo et al., 1994). A majority of these springs are home to endemic species that need to have a certain depth in the rivers. The major tributaries of the Wekiva River are the Little Wekiva River, Rock Springs Run, and Blackwater Creek. With six springs feeding into the Wekiva River, five into the Little Wekiva River, and sixteen into the Blackwater Creek, it is evident that millions of gallons of flow per day can is a result of spring flow.

Chapter 4. Hydrologic Background

The hydrological literature outlined in the following are primarily based on SJRWMD publications and the Water Supply Impact Study (WSIS) (SJRWMD, 2012). Here we will go in depth over the properties that define the Wekiva sub-basin and its major waterways.

Many hydraulic, hydrological, and geological characters affect the Wekiva sub-basin. Appendix B depicts the allocation of each St. Johns River basin through the WSIS. For this research, it has been established that the SJRWMD has done an extensive research to model the waterways and the effects they may bring to the region. This is all done through HSPF modeling, entering parameters at either physical or empirical levels. Parameters of the basins include areas, land use, precipitation, evaporation, slope, roughness, and system hydraulics (SJRWMD, 2012). An in-depth understanding can be found in Chapter 3 of the WSIS Report, Watershed Hydrology. A basic breakdown of the report will state that numerous parameters were calibrated throughout the model. The HSPF model calibrates by an iterative process of changing parameters, running simulations, checking results, and repeating until the simulated and observed data resemble each other (SJRWMD, 2012). For more information over the parameters, go to WSIS (2012) Appendix 3-B to view the HSPF Common Logic for each parameter and a relatively acceptable range with a general notes section. The model was originally calibrated to imitate the original United States Geological Survey (USGS) stream flow gages for each basin in the SJRWMD. The Long-term daily flow has been monitored by USGS and SJRWMD, as seen below in Table 1 for the Wekiva sub-basin. These same three flow gages were extensively used in this study.

Table 1. Calibrated Gages on the Wekiva Sub-basin

Water Course Name	**Gage Name**	**Gage Authority**	**Gage Number**
Wekiva River	Wekiva near Sanford	USGS	02235000
Little Wekiva River	Little Wekiva River at Springs Landing	SJRWMD	09502132
Blackwater Creek	Black Water Creek near Debary	SJRWMD	09502132

Calibration is incorporated from the original USGS observed data set, applied in the HSPF model to create a calibrated dataset. The benefit of using USGS data was to identify a longer recorded dataset compared to the HSPF calibrated dataset. This historically extended its presence into the early 1900s using the USGS data. Doing this would in fact, benefit the simulation as it was driven off long periods of record for the most accurate results. Based on the Middle St. Johns River Calibration report (SJRWMD, 2012), identifying each river's presence and the degree to which the SJRWMD has calibrated the waterways will be discussed below. The following subsections are noted to reflect the calibration effects on all three watercourses. Reference Appendix C for the calibrated SJRWMD flows compared to the observed USGS flows. It is confirmed that each of the calibrated SJRWMD peak flows is underestimated compared to the USGS observed peak flows.

4.1 Wekiva River near Sanford (USGS Gage 02235000)

The daily flow was monitored at the Wekiva River near Sanford, located at State Highway 46 bridge, approximately 6.7 miles upstream with the confluence of the St. Johns River. Figure 4 depicts the location of the Wekiva USGS gage in the center of the image. The USGS gage 02235000 began recording in October of 1935 and has been constituted as fair. The recorded data chosen to be calibrated for the SJRWMD HSPF model fell in the period of 1/1/1995 to 12/31/2006. Parameters of inflow from the Little Wekiva River, Rock Spring, Wekiva Spring, Miami Spring, and additional minor springs were implemented at appropriate locations on the Wekiva River.

Minor spring flows were captured and placed as constants throughout the model. Calibration of the Wekiva River was ultimately described as a good match to gaged flow. As seen in Appendix C, the hydrograph trend also deems the calibrated model to be a good match. The largest peak discharges were compared and seemed to be underestimated; however, the low flow conditions matched well. The low flow was approximated to be between 100 to 140 million gallons per day while an astonishing 100 to 135 million gallons per day resulted from spring flow input (SJRWMD, 2012).

4.2 Little Wekiva River at Springs Landing (SJRWMD Gage 09502132)

The daily flow obtained by the Little Wekiva River at Springs Landing is located 4.6 miles upstream of from the confluence of the Wekiva River. Figure 4 depicts its location of the USGS gage in the bottom right of the image. SJRWMD gage 09502132 was installed in June of 1995 by USGS but has since been maintained by the SJRWMD. The quality of the data was deemed as fair, and calibration period of record for the SJRWMD HSPF model fell in the period of 1/1/1995 to 12/31/2006. Parameters of inflow from the Palm Spring, Sanlando Spring, and Starbuck were implemented at appropriate locations on the Little Wekiva River. Spring flows were captured at various intervals and interpolated for daily results.

Additionally, this watercourse is connected to a complex lake system upstream that is not incorporated into the model. Calibration of the Little Wekiva River was ultimately described as a good match to gaged flow. The large peak discharges were compared and seemed to be underestimated; however, the low flow conditions are a good match (SJRWMD, 2012).

4.3 Black Water Creek near Debary (SJRWMD Gage 30143084)

The SJRWMD gage 30143084 is located 5.2 miles upstream from its confluence with the Wekiva River. Figure 4 depicts its location of the USGS gage in the top left of the image. This gage began

keeping a record in October of 1990 by the SJRWMD. The data chosen for calibration of the SJRWMD HSPF model fell in the period of 1/1/1995 to 12/31/2006 and was distinguished as being overall very good. The large peak discharges were compared and found to be underestimated; contrary, the low flow conditions are found to be a match for the first half of the recording period but tended to deviate near the end. The low flow was estimated to be between 50 to 70 cubic feet per second, while an astonishing 45 to 55 cubic feet per second resulted from spring flow (SJRWMD, 2012).

Chapter 5. Manipulating HSPF Models

5.1 Course of Action

The HSPF models created by the SJRWMD have an intercut set of calibration parameters described in the Water Supply Impact Study (WSIS). This research incorporates the base HSPF models and runs the same simulations but at larger rainfall events. Ultimately, the idea is to identify the rainfall parameters for a given storm event of interest (usually the 10, 25, 50, and 100-year storm) to produce a realistic understanding of the flood flow estimates. The process of doing this is quite simple; choose the base target dates, choose a storm event to simulate, apply the antecedent moisture condition, and identify the desired rainfall criteria. A simple diagram of the process can be seen in Figure 3 (Kovalenko, 2020). The following sections will break down this process to identify how this simulation is of value. The simulation ran on a Windows operating system and took advantage of the published models given by the SJRWMD. As previously mentioned, rainfall adjustments were incorporated by the robust Hydrological Simulation Program - FORTRAN plugin of Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) to simulate existing and future conditions.

5.2 Data Sources

The primary rainfall data sources highlighted in this section are observed and synthetic. The observed data measures the captured flow at the gage. This is the daily data captured physically at the gage. Observed streamflow data for Wekiva sub-basin was captured by United States Geological Survey (USGS, 2020) database. These data sets obtained at the USGS stream flow gages is also used in the statistical analysis portion of this research. Contrary, synthetic data is the streamflow data that is simulated. The synthetic streamflow data is what HSPF originally used in the base models (for calibration purposes) before precipitation data was adjusted as part of this

research effort. For each of the three USGS streamflow gage locations, HSPF model has created a synthetic gage. Figure 4 depicts each gage in relation to the Wekiva sub-basin.

5.3 Land-use

The HSPF model has two different characteristics when simulating the land conditions: 1995 and projected 2030. 1995 incorporates all the historical data and sub-basin characteristics for the 1995 HSPF model (United States Geologic Survey and Environmental Protection Agency, 2012). The 2030 land considers the population growth, residential growth areas, and increased area for urban land use (SJRWMD, 2012). The WSIS outlines that residential uses are expected to more than double in the Wekiva sub-basin by 2030 (SJRWMD, 2012). The differences in land-uses were assessed and further incorporated as a weighted average of the flow conditions for the year 1995 and projected 2030. Basing the effect of each land-use scenario, the HSPF models would result in varying flows.

5.4 Target Date

Determining the dates at which to alter the rainfall data, it was important to find a baseline for the calibrated dataset. The "baseline" would serve as the target dates to increase precipitation. The duration of the calibrated data, 1995 to 2006, would give a range of daily flows that could potentially be used. As described by Malamud and Turcotte (2006), the 50th percentile flood (or median flow) makes for an ideal baseline for various flood frequency analysis procedures. This was first done by acquiring the graphical outputs from the original SJRWMD HSPF model. After acquiring the graph, a flow rate could be determined in the correlation of the 50th percentile. See Figure 5 for an example of the flood frequency curve 50th percentile procedure. The process was then to distinguish ten flow dates within 15% range of accuracy to the 50th percentile flood flow

(Kovalenko, 2020). This was done by taking the calibrated dataset provided by the SJRWMD HSPF model and sorting from high to low, or vice versa, to choose ten dates that corresponded with the found 50th percentile flood flow. Extra precaution was taken when choosing the dates, as some should be omitted if the month and year were near another chosen date. This would disregard any season rainfall conditions that could play a factor when choosing a date near the 50th percentile. These ten chosen dates would serve as the baseline in adjusting the 10, 25, 50, and 100-year frequency precipitation events at the 24-hour duration for the Wekiva sub-basin.

5.5 Adjusting Rainfall

Rainfall data specified for this section is based on the National Oceanic Atmospheric Administration (NOAA) Atlas 14 (NOAA, 2017) and SJRWMD research (SJRWMD, 2012). The precipitation implemented in HSPF is calculated through the SJRWMD and is input in the model for the entire simulated period. This data can be accessed through HSPF and can be altered at the user's liking. Knowing the target dates, it is now time to review the adjustment values to incorporate a new simulate rainfall at the 10, 25, 50, and 100-year storms. Using NOAA Atlas 14, a powerful oceanic and atmospheric data collection site, locations of rainfall gages of interest is determined for the Wekiva sub-basin. Appendix E displays the NOAA rain gages known for the St. Johns River Basins. Table 2 designates the gages found within the basin and the rainfall results at the median and 90% percentile for each given storm event (NOAA, 2005).

Table 2. Precipitation Frequency Values for Gages

NOAA Atlas 14	**Recurrence Interval**	**Gage Names**					
		DeLand		**Lisbon**		**Sanford**	
		Daily (in)	Hourly (in)	Daily (in)	Hourly (in)	Daily (in)	Hourly (in)
24-hour Median Rainfall	10	6.43	0.268	6.05	0.252	6.21	0.259
	25	8.08	0.367	7.59	0.316	7.78	0.324
	50	NA.	NA.	NA.	NA.	NA.	NA.
	100	NA.	NA.	NA.	NA.	NA.	NA.
24-hour 90% Percentile Rainfall	10	7.45	0.314	7.16	0.298	7.48	0.312
	25	10.10	0.421	9.57	0.399	10.00	0.417
	50	12.10	0.504	11.40	0.475	11.90	0.496
	100	14.50	0.605	13.70	0.571	14.30	0596

*NA. identifies 50 and 100-year median rainfalls not applicable in this research effort.

The median and 90% percentile rainfall data was then incorporated for all of the ten targeted dates. Both daily and hourly precipitation are incorporated into HSPF inputs. Before running the simulations with the new rainfall data, it is important to step back and understand the real-world scenarios that follow a storm event. Antecedent moisture is the final factor for the new rainfall events. As detailed in the SJRWMD guide to SCS runoff procedures, it is important to consider the moisture conditions of the soil prior to the storm (SJRWMD, 1985). It can significantly affect the runoff volume and rate due to the soil's moisture conditions that persist the days leading to the storm event. This heavy rainfall and saturation are common and should not be overlooked. Three types of antecedent moisture conditions (AMC) exist: AMC-I for dry, AMC-II for normal, AMC-III for wet conditions (Kovalenko, 2020). For this research, it is concluded that an AMC II is best for simulating the sub-basin characteristics as it essentially enables the average conditions frequently seen for Florida's environment (SJRWMD, 1985). Table 3 identifies each type and its effect on the five days leading to the storm event. In essence, a maximum AMC type II of 2.1 inches of rainfall was incorporated the five days before each of the target dates to simulate a real-world storm event.

Table 3. Antecedent Moisture Conditions (SJRWMD, 1985)

AMC	**Total 5-Day Dormant Season**	**Total 5-Day Growing Season**
I	Less than 0.5 inches	Less than 1.4 inches
II	0.5 to 1.1 inches	1.4 to 2.1 inches
III	More than 1.1 inches	More than 2.1 inches

5.6 Output Processing

Subsequently implementing the data sources, land use, target date, adjusting the rainfall, and adding antecedent moisture, it is time to analyze the HSPF output. Doing so, it is important to compare both 1995 and 2030 land-use scenarios to understand how the basin reacts to a simulated storm event. In some, a minor difference can be seen. In this case, it is good to analyze the basin. For instance, the Wekiva sub-basin saw minimal effects when 1995 and projected 2030 land use conditions were simulated, meaning another driving flow factor could be present in the sub-basin. In this case, a heavy spring flow is identified, concluding that a simulated storm with no effect on the spring flow will inaccurately calculate a final flow estimate.

Chapter 6. Developing Statistical Tests

The following sections will support the concept of statistical methods and the step-by-step process performed for each. Here we will go through each method and how the results in Chapter 7 were produced.

6.1 Data Analysis

One of the primary aspects of doing any statistical test is to gather a solid population of data. In these two subsections, we will describe the benefit of using one data set over another.

6.1.1 Data Sets from Synthetic

As described previously, it is imperative to identify a solid population. In this case, a solid population is defined as one that has a long period of record. Because the SJRWMD has output simulated flow for the Wekiva sub-basin, it is understandable that this discharge data can be extracted and used for statistical estimation. Depicted in Table 4, the three identified locations of interest were chosen to be analyzed. As defined by the SJRWMD, each "RCH" is considered a reach. A reach symbolizes a location in the basin that has a defining characteristic and purpose (SJRWMD, 2012). Additionally, each reach produces output data that can be further assessed and extracted for statistical purposes. Furthermore, the years of record are recognized at each simulated location as this would become a controlling factor when deciding which data set to use.

Table 4. Simulated Gages in the Wekiva Sub-basin

Simulated Gage Name	**Gage Location**	**Years of Record**
RCH30	At Mouth of Wekiva River	34
USGS Gage 02234990	Little Wekiva River at State Road 434	34
RCH13	At Mouth of Blackwater Creek	34

6.1.2 Data Sets from USGS Gages

Collected flow data was additionally taken from the three USGS gages located within the Wekiva sub-basin (United States Geologic Survey, 2020). Using Figure 4 and Table 5, the gages can be identified. By reading the "Years of Record" from Table 4 and Table 5, it can be inferred that the recorded flow is substantially longer for the USGS gages rather than HSPF simulated gages. This concluded that the USGS flow dataset should be run through statistical tests.

Table 5. USGS Gages in the Wekiva Sub-basin

USGS Gage Name	USGS Gage ID	Years of Record
Wekiva River Near Sanford, FL	02235000	87
Little Wekiva River Near Altamonte Spring, FL	02234990	48
Blackwater Creek Near Cassia, FL	02235200	45

6.2 Log-Pearson Type III

Per the recommendations of the United States Water Resources Council (USWRC), it has been concluded that for annual maximum streamflow frequency studies Log Pearson Type III (LP3) is highly recommended (US Army Corps of Engineers, 1994). Noted in Chapter 2.2, the LP3 produces estimated storm peak flows based on the mean, standard deviation, and skewness of the dataset. The LP3 is performed on the USGS gage dataset as it was prominently longer in recorder years. Steps for the best approach of the LP3 method through Excel will be discussed next. A majority of the literature and support can be found in the Oregon State University's flood frequency analysis articles (Oregon State University, 2005). The LP3 equation is shown below:

$$log\,x = \overline{log\,x} + K\sigma_{log\,x} \qquad (1)$$

x : flood discharge value of some specified probability

Log (x) : discharge values

K : frequency factor (extracted from frequency factor table)

σ : standard deviation of the log x values.

Using this equation demands that we take a few steps prior. First, it is important to categorize the dataset to identify the annual peak discharges. Ranking the flow rates from largest discharge value (1) to smallest discharge value (n) will be needed. This will be required for the return period and exceedance probability function. After ranking is complete, it is necessary to take the logarithm of the annual peak flows. An average of both the annual flow and logarithm (annual flow) should be documented in the spreadsheet as it will be used within a later function. The next two columns within the spreadsheet will use Equations 2 and 3, respectively.

$$\log(Q) - average(\log(Q))^2 \qquad (2)$$

$$\log(Q) - average(\log(Q))^3 \qquad (3)$$

For Eqn. 2, the log of each discharge value (Q) subtracted by the square of averaged log (Q's) was taken. The same thing is calculated again, but this time the average log (Q's) were cubed. Then the return period was calculated using the ranking system, discussed in the beginning, to incorporate the Weibull plotting position (Malamud, B. & Turcotte D, 2006).

$$T = \frac{N_{WY}+1}{N_C} \qquad (4)$$

Nc : peak flow rank

N_{WY} : number of annual peak flows

The Weibull plotting position provided the needed variable for the exceedance probability of each flow rate seen in the following formula:

$$Exceedence\ Probability = \frac{1}{T} \qquad (5)$$

From there, the statistical estimate factors were needed. For the LP3 the variance, standard deviation, and skew coefficient were determined using the equations below:

$$\frac{\sum_i^n((logQ - avg(logQ))^2}{n-1} \quad (6)$$

$$\sigma_{\log x} = \sqrt{\frac{\sum(logx - \overline{\log x})^2}{n-1}} \quad (7)$$

$$skew\ coeff. = \frac{n * \sum_1^n(\log(Q) - average(\log(Q)))^3}{(n-1)(n-2)(\sigma \log(Q))^3} \quad (8)$$

A weighted regional and station skewness factor was incorporated to provide a realistic portrayal of the location. Doing so would lead to a weighted skew coefficient that would be transferred into k-values using the frequency factor table (Haan, 1977). A constant k-value per the desired recurrence interval (years) to the calculated weighted skewness coefficient would provide the last necessary variable to the LP3 equation (1). Calculation of each of the following major storm events was performed.

6.3 Power Law

The second method of choice was the Power Law (PL) method. As described in Chapter 2.2, the PL method is beneficial as it implies fewer analytical parameters and has a good reputation among the hydraulic community (Kidson and Richards, 2005). Like the LP3 method, observed data was tested. The following two subsections define the different routes within the PL method to accomplish comparable flood flow outputs. These two differentiated in one simple way: linear or nonlinear.

6.3.1 Solver

The nonlinear approach assessed the data using the ordinary least squared (OLS) method with the Solver plugin (Microsoft Excel, 2016). This procedure did incorporate the OLS process that statistical analysts highly recommend. The OLS minimized the sum of discharge modeled and

discharge documented. Minimizing the sum would be done by iterations of the α and C coefficient through the solver. A bound on α would be needed from 0.01 to 1. Modeled Q values were calculated using an arbitrary α and C coefficient with the following PL equation:

$$Q[T] = CT^{\alpha} \qquad (9)$$

The coefficients α and C is implemented for each given storm event (T) in years. The sum of squared differences is then found by the equation shown below:

$$Sum\ of\ the\ Squared\ Differences = \left(sum(Q_{Actual}) - sum(Q_{Modeled})\right)^2 \qquad (10)$$

Using equation 12 and the stand-alone variables, the Solver plugin ran to minimized the values for “Sum of Squared Differences” through the iteration process of α and C coefficients (Microsoft Excel, 2016).

6.3.2 Linear Regression

A linear model is also incorporated for the datasets as a need for additional estimates. In doing so, a linear model is taken by plotting the logarithm for probability (LogT) to the observed annual max flow (LogQ). Figure 6 represents an example of T versus Q. This again, is done for observed datasets at each desired location. Information needed is gathered prior to using the LogT equation, including; sorting the flow dataset from largest to smallest, ranking (Nc) the flows from largest being 1 to the smallest being n, finding the storm event probability (T) using Weibull plotting position, equation 9, and lastly taking the logarithm of the output.

$$T = \frac{N_{WY}+1}{N_C} \qquad (11)$$

Nc : peak flow rank

N_{WY} : number of annual peak flows

The LogQ was calculated by taking the logarithm from each annual maximum flood flow. Thereafter a scatterplot was created with log(T) the x-axis and log(Q) the y-axis. A linear

regression trendline was plotted for the points, and its equation was displayed (Microsoft Excel, 2016). The following equation identified the α and C coefficients:

$$y = Slope * (x) + y_{intercept} \quad (12)$$

Slope : α coefficient

$y_{intercept}$: logarithm of C coefficient

To convert the logarithm C coefficient to its true value, simply take the value to the power of ten. With new known variables, calculating the flow values at the 10, 25, 50, and 100-year storm events is performed through the same PL equation used for Solver:

$$Q[T] = CT^{\alpha} \quad (13)$$

C : C coefficient

T : storm event (years)

α : alpha coefficient

The linear process estimates its coefficients through a linear trendline, producing results that differ from Solver. It's noted that a large difference of these two Power Law distributions can be identified if the correlation (R^2) value is low or if outliers are present within the datasets. The assessment of two different methods in finding α and C regression coefficients of the Power Law distribution became beneficial as it provided varying flood flow estimates.

6.4 Theil-Sen

The Theil-Sen method is the third and final method selected for statistical testing. The Theil-Sen, sometimes referred to as the Kendal-Theil line, is advantageous for hydraulic estimations as it does not depend on the normality of residuals of significant test in contrast to the ordinary of least squares regression (OLS). Basically stating that the Theil-Sen line is not affected by outliers

that are commonly seen throughout hydraulic data sets. This robust estimator is for simple linear regression. It does so by the following equation:

$$y = b_o + b_1 * x \qquad (14)$$

The Theil-Sen works best by taking the Log Q and Log T, described above in Power Law and Log Pearson procedures, to define a slope between each of the points. A slope is solved for each of the points iteratively. Seen below is the equation for the slopes:

$$Slope_1 = \frac{Log_{Q1} - Log_{Q2}}{Log_{T1} - Log_{Q2}} \qquad (15)$$

$$Slope_2 = \frac{Log_{Q1} - Log_{Q3}}{Log_{T1} - Log_{Q3}} \qquad (16)$$

$$Slope_\infty = \frac{Log_{Q\infty} - Log_{Q\infty}}{Log_{T\infty} - Log_{Q\infty}} \qquad (17)$$

Using Excel 2016, the process will continue for every of the Log Q's and Log T's until an array of slopes are established. The array will then be entirely selected to calculate the total slope (b_1) of the data set by finding the median value.

$$b_1 = Median(array) \qquad (18)$$

Having the estimator continuously computing values of every data point in the set allows for the final represented data set slope to omit any radical outliers. In doing so, the Theil-Sen estimator attempts to find a value for the slope that makes Kendall's correlation tau approximately equal to zero (Wilcox, R., 2017).

Following, the Y-intercept (b_o) will be computed after we identify the median X value (Log T) and the median Y value (Log Q). Doing so will provide the last needed variable for the Y-intercept equation shown below:

$$b_o = Median(LogQ) - \ Median(LogT) \ * \ b_1 \qquad (19)$$

Then the Power Law equation shown below to find the desired discharge value for each of the desired storm events.

Chapter 7. Results

7.1 HSPF Outputs

The following subsections explain the results taken on each major watercourse in the Wekiva sub-basin. The Wekiva River, Little Wekiva River, and Blackwater Creek all display outputs for 1995 and 2030 land use conditions.

7.1.1 Wekiva River

Displayed in Tables 6, 7, and 8 are the results for the Wekiva River 1995 land use condition, 2030 land use condition, and 2021 interpolation, respectively. As described in Chapter 5.3, each land use condition will entail a different discharge output due to population growth and so forth. Pursuing the idea of determining current discharge values, Table 8 is incorporated. Discharge values (in cubic feet per second) are interpolated between 1995 and 2030 for a 2021 flow rate. Some values seen are not interpolated simply due to limited time and accessibility. Rainfall scenarios for 90% percentile, including antecedent moisture conditions (AMC), were documented for the provided locations. It was quickly deemed inaccurate to use median rainfall conditions for the HSPF simulation. For the Wekiva River, the Wekiva River near Sandford (USGS gage 02235000) and WekivaRiver_2801 from Table 8 are identified to be at the same location. Therefore these 2 gages will be used for comparison. Chapter 8 further discusses the results as a whole to identify their accuracy for the Wekiva River.

Table 6. HSPF Model Results for Wekiva River with 1995 Land Use Conditions (cfs)

HSPF Model Name	1995 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
UpWekiva_1801	124	231	365	617
RCH30_3001	471	776	1187	1965
WekivaRiver_2801	528	934	1143	2270

Table 7. HSPF Model Results for Wekiva River with 2030 Land Use Conditions (cfs)

HSPF Model Name	2030 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
UpWekiva_1801		281	434	753
RCH30_3001		844	1283	2124
WekivaRiver_2801		999	1499	2405

Table 8. Interpolated HSPF Model Results for Wekiva River in 2021(cfs)

HSPF Model Name	2021 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
UpWekiva_1801	124	268	417	718
RCH30_3001	471	826	1258	2083
WekivaRiver_2801	528	982	1477	2370

7.1.2 Little Wekiva River

The HSPF simulated the little Wekiva River as seen in Table 9, 10, and 11. For the Little Wekiva River, comparisons will be made with LittleWekiva_Computed_2401 and USGS gage 02234990. All three different land scenarios were assessed and with the tables laid out as prior. Median rainfall conditions from NOAA Atlas 14 (NOAA, 2017) were disregarded for this model as the choice to pursue 90% percentile precipitation events through the HSPF was more realistic. The differentiated results produced from the varying model scenarios provided valuable insight regarding the sensitivity of model parameter selection.

Table 9. HSPF Model Results for Little Wekiva River with 1995 Land Use Conditions (cfs)

HSPF Model Name	1995 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401	337	405	477	608

Table 10. HSPF Model Results for Little Wekiva River with 2030 Land Use Conditions (cfs)

HSPF Model Name	2030 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401		426	496	628

Table 11. Interpolated HSPF Model Results for Little Wekiva River in 2021 (cfs)

HSPF Model Name	2021 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401	337	421	491	623

7.1.3 Blackwater Creek

Exhibited in Table 12, 13, and 14 are the results for the Blackwater Creek 1995 land use condition, 2030 land use condition, and 2021 interpolation expected condition, respectively. The tables underline the 90% percentile rainfall condition being prominent throughout the research as it simulated more plausible results in correlation with reports. The Blackwater Creek watercourse BlackwaterCreek_701 and USGS gage 02235200 were concluded to be the same location. Chapter 8 will further discuss the results in detail.

Table 12. HSPF Model Results for Little Wekiva River with 1995 Land Use Conditions (cfs)

HSPF Model Name	1995 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401	258	410	493	624

Table 13. HSPF Model Results for Little Wekiva River with 2030 Land Use Conditions (cfs)

HSPF Model Name	2030 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401		488	587	782

Table 14. Interpolated HSPF Model Results for Little Wekiva River in 2021 (cfs)

HSPF Model Name	2021 Land-use, 90th Percentile Precipitation, and AMC			
	10-year	25-year	50-year	100-year
LittleWekiva_Computed_2401	258	468	563	741

7.2 Statistical Results

This section outlines the statistical approaches taken for the three main watercourses in the Wekiva sub-basin. USGS flow data recorded at the gages presented in Chapter 4 were used as the baseline for each statistical method. The results for each statistical test are defined below.

7.2.1 Log-Pearson Type III

This section presents the results of the Log-Pearson Type III (LP3) distribution statistical computations. The following information offers the results at Wekiva River near Sanford (USGS gage 02235000), Little Wekiva River near Altamonte (USGS 02234990), and Blackwater Creek near Cassia (USGS 02235200). Each location is evidently a USGS gauge and has been chosen

because it has substantial flow data needed for the LP3. Table 15 depicts the LP3 results for the desired storm events within the Wekiva sub-basin.

Table 15. Log-Pearson Type III Results (cfs)

USGS Gage	USGS Name	Log-Pearson Type III			
		10-year	25-year	50-year	100-year
02235000	Wekiva River near Sanford	1384	1693	1927	2165
02234990	Little Wekiva River near Altamonte	494	622	713	801
02235200	Blackwater Creek near Cassia	644	862	1021	1174

7.2.2 Power Law

This section presents the results of the Power Law distribution statistical computations. The results of the Power Law (PL) distribution are taken by using the calculation outlined in Chapter 6.3. After review, it is realized that two approaches would be beneficial to take, linear and nonlinear. Table 16 depicts the results using the nonlinear Microsoft Excel Solver plugin approach. Table 17 depicts the PL results using the linear regression approach. For consistency, the following USGS gages are used for the Wekiva sub-basin; Wekiva River near Sanford (USGS gage 02235000), Little Wekiva River near Altamonte (USGS 02234990), and Blackwater Creek near Cassia (USGS 02235200). The outcome for either will be discussed in Chapter 8.

Table 16. Power Law Results, Solver (Nonlinear) Approach (cfs)

USGS Gage	USGS Name	Power Law: Solver			
		10-year	25-year	50-year	100-year
02235000	Wekiva River near Sanford	1299	1767	2230	2815
02234990	Little Wekiva River near Altamonte	440	644	858	1143
02235200	Blackwater Creek near Cassia	531	821	1141	1586

Table 17. Power Law Results, Linear Regression Approach (cfs)

USGS Gage	USGS Name	Power Law: Linear Regression			
		10-year	25-year	50-year	100-year
02235000	Wekiva River near Sanford	1399	2064	2769	3714
02234990	Little Wekiva River near Altamonte	513	894	1360	2071
02235200	Blackwater Creek near Cassia	685	1500	2715	4915

7.2.3 Theil-Sen

This section presents the results of the Theil-Sen statistical estimator. The results of the Theil-Sen estimator ais outlined in Chapter 6.4. Once again for consistency, the following USGS gages are used for this study; Wekiva River near Sanford (USGS gage 02235000), Little Wekiva River near Altamonte (USGS 02234990), and Blackwater Creek near Cassia (USGS 02235200). Discussion of these results will be presented in Chapter 8.

Table 18. Theil-Sen Results (cfs)

USGS Gage	USGS Name	Theil-Sen			
		10-year	25-year	50-year	100-year
02235000	Wekiva River near Sanford	1565	2277	3026	4020
02234990	Little Wekiva River near Altamonte	840	1616	2652	4352
02235200	Blackwater Creek near Cassia	1046	2359	4363	8069

7.3 Existing Flow Reports

This section outlines the results for existing reports documented by FEMA Flood Insurance Studies (FIS) and St. John's River Water Management District's (SJRWMD). Only a few USGS locations of interest could be assessed in the Wekiva sub-basin due to limited published data.

7.3.1 Wekiva River

No results were obtained for the Wekiva River. Immediate investigation establishes that the Wekiva sub-basin has a joining county line on the Wekiva River, contributing to the assessment of two FIS reports. Both Lake County and Seminole County had reports over the Wekiva River, yet neither examined the flow rates for a storm event. The Wekiva River only reported flood elevation increase and not flow rate increase. Potentially due to the Wekiva River not displaying a heavy presence in residential areas. The majority of the watercourse led through wetlands and preserved land. The Wekiva River Protection Act, discussed in Chapter 3.1, maintained an environmentally friendly habitat that guaranteed no development for the future and also contributed to no flood endangerments due to minimal homes in this region. Since communities are not at risk, no flow rate reports were collected for the Wekiva River.

7.3.2 Little Wekiva River

The Little Wekiva River had risk acquired for multiple communities, so an FIS was performed and published (FEMA, 2014). FEMA's estimated flood discharges were taken at the Little Wekiva River on State Road 434 and detailed in Table 19. SJRWMD also developed a report for the Little Wekiva River; this is detailed for the minor 10-year and major 100-year extreme storm events highlighted in Table 20. Each table depicts the flow estimates for Little Wekiva River at SR 434, also known as Little Wekiva River near Altamonte or USGS gage 02234990. All three references describe the same location within this sub-basin. Chapter 8 will discuss the FEMA and SJRWMD published flow reports in comparison to the statistical estimates taken at this location.

Table 19. FEMA FIS Reported Estimates (cfs)

USGS Gage	Location Name	FEMA FIS Reported Estimate			
		10-year	25-year	50-year	100-year
02234990	Little Wekiva River at S.R. 434	920	1500	1800	2580

Table 20. SJRWMD Reported Estimates (cfs)

USGS Gage	Location Name	SJRWMD Reported Estimate	
		10-year	100-year
02234990	Little Wekiva River at S.R. 434	1010	2560

7.3.3 Blackwater Creek

Similar to the Wekiva River watercourse, Blackwater Creek did not receive any flow rate publications. Lake County had a reported FEMA FIS report, yet it did not justify any discharges due to storm event. Only stage elevations were assessed within this report (FEMA, 2013). Once again, potentially due to limited quantity of endangered homes near the watercourse, this contributed to no flow rates while the elevations were documented. No flow rate reports were collected for the Blackwater Creek.

Chapter 8. Comparison of Results

This section presents a detailed comparison of the results gained through various flood estimation methods. The various methods include HSPF modeling, statistical testing using the Log-Pearson Type III (LP3), Power Law (PL), Theil-Sen, and existing reports provided by FEMA Flood Insurance Studies (FIS) and St. John's River Water Management District's (SJRWMD). Results presented by the various flood estimation processes will directly examine the three USGS locations of comparison. The Wekiva River near Sanford (USGS gage 02235000), Little Wekiva River near Altamonte (USGS gage 02234990), and Blackwater Creek near Cassia (USGS gage 02235200). All identified as comparable locations for the various flood estimation methods. This discussion is based on the results presented in the previous section.

Discussion over the HSPF results is detailed first. When viewing the outputs that HSPF produced it is evident that the flow rates were incredibly low compared to any other method. After further investigation, it is concluded that two major factors are playing a part in the irrational outcomes. The first important factor is understanding HSPF. Assessing the calibration and diving deeper into the Water Supply Impact Study (WSIS) along the St. Johns River, it was evident that the model is slightly biased towards its input data. In short, HSPF has reiterated in many of the WSIS watershed hydrology reports that the low flow is a better match. The WSIS states, "The low flow conditions are matched well" (p.59) for two of the three sub-watersheds in the Wekiva sub-basin (WSIS, 2012). For more clarity over the HSPF calibration, see Chapter 4 of this report or WSIS Chapter 3, Appendix 3-J. The second factor making HSPF unreliable, specifically in the Wekiva sub-basin, is the tremendous amount of spring flow. As mentioned in Chapter 3, spring flow was encountered for each watercourse. Based on the WSIS, the Wekiva River contributed 100 to 135 million gallons of the 100 to 140 million gallons per day to spring flow. Additionally, the Little Wekiva River

estimates a discharge rate between 45 to 55 of the 50 to 70 cubic feet per second due to spring flow. Having such a heavy weight on spring flow, it is evident that simulation of extreme storm events will not accurately represent the flow rates produced without adjusting spring flow parameters. This parameter is out of the research scope but proposes as a good topic for deeper investigation.

Appendix F contains plots for each of the watercourses through the LP3, PL, Theil-Sen, and existing reports provided by FEMA FIS and SJRWMD. As mentioned before, existing reports are only incorporated at the Little Wekiva River. In Appendix G, the probability of a storm event to its flow rate can be viewed for each method. Included in the graphs is a goodness of fit (R^2) that associated each method to its regression line. This R^2 value is a relationship given by each curve in relation to its linear trendline. After taking a moment to understand the flow estimates based on the visuals in Appendix F and Tables 21 - 26, a few points can be made. As the observed USGS flow data "Observed" is routed as the baseline for all estimations, comparison to this gage is crucial. Correlation R coefficients seen in Tables 21 - 26 point out the relationship each method has to the observed dataset. The Log-Pearson Type III (LP3) method is repeatedly accurate when estimating the flow rates. A correlation R coefficient of 0.9640, 0.9544, and 0.9564, concludes a strong statistical method for estimating extreme storm events. The Power Law (PL) has two processes that comprise this method. The first, Solver (nonlinear), is accurate for smaller storm events but increases rapidly for larger events. It is believed that based on the correlation seen for each watercourse, it is a great process to use for smaller extreme storm events. Second, the linear regression process is noticeably unpredictable based on extrapolation between the graphed dataset. This process would not be advised if the dataset has multiple known outliers. The Theil-Sen (TS) method is found to be accurate at smaller storm events but becomes erratic when large storm events

are performed. Hesitation with using this method is advised at extreme storm events. The FEMA FIS and SJRWMD publications for the Little Wekiva River display a close relationship with one another. Based on the uncertainty of the raw flow datasets that either organization used, it can be determined that the deviation from the base observed data should be incorporated. Emphasizing this part of the research, a range should be established for the flow rates at any watercourse. After plotting the results of each method, a bounded Gumbel distribution is applied to the results. In Appendix H, the bounded Gumbel distribution is depicted of all three watercourses. The benefit to the Gumbel distribution is that it can visually portray the uncertainties of each extreme storm event. Reviewing the distribution fitting parameters for each, a location parameter and scale parameter is determined. As the extreme storm events become larger and larger, it is confirmed that the scaling parameter increases. Meaning the uncertainty will increase, more the reason a ranged analysis for flood flow estimates is considered.

Table 21. Flow Estimates: Wekiva River (cfs)

Storm Event		2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Observed		789 cfs	1075 cfs	1439 cfs	1867 cfs	2089 cfs	
Power Law	Q (Solver)	757 cfs	1030 cfs	1299 cfs	1767 cfs	2230 cfs	2815 cfs
	Q (Lin. R)	707 cfs	1043 cfs	1399 cfs	2064 cfs	2769 cfs	3714 cfs
Log Pearson Type III		798 cfs	1146 cfs	1384 cfs	1693 cfs	1927 cfs	2165 cfs
Theil-Sen		809 cfs	1178 cfs	1565 cfs	2277 cfs	3026 cfs	4020 cfs

Table 22. Correlation R Coefficients for Wekiva River (cfs)

Correlation between:			
Observed	&	Solver	0.9535
Observed	&	Linear Reg.	0.9365
Observed	&	Log Pearson	0.9640
Observed	&	Theil-Sen	0.9395

Table 23. Flow Estimates Little Wekiva River (cfs)

Storm Event		2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Observed		266 cfs	382 cfs	463 cfs	640 cfs		
Power Law	Q (Solver)	226 cfs	331 cfs	440 cfs	644 cfs	858 cfs	1143 cfs
	Q (Lin. R)	193 cfs	337 cfs	513 cfs	894 cfs	1360 cfs	2071 cfs
Log Pearson Type III		234 cfs	390 cfs	494 cfs	622 cfs	713 cfs	801 cfs
Theil-Sen		266 cfs	512 cfs	840 cfs	1616 cfs	2652 cfs	4352 cfs
FEMA FIS				920 cfs	1500 cfs	1800 cfs	2580 cfs
SJRWMD				1010 cfs			2560 cfs

Table 24. Correlation R Coefficients for Little Wekiva River (cfs)

Correlation between:			
Observed	&	Solver	0.9345
Observed	&	Linear Reg.	0.8959
Observed	&	Log Pearson	0.9544
Observed	&	Theil-Sen	0.8709

Table 25. Flow Estimates Blackwater Creek (cfs)

Storm Event		2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Observed		246 cfs	418 cfs	731 cfs	803 cfs		
Power Law	Q (Solver)	247 cfs	382 cfs	531 cfs	821 cfs	1141 cfs	1586 cfs
	Q (Lin. R)	173 cfs	378 cfs	685 cfs	1500 cfs	2715 cfs	4915 cfs
Log Pearson Type III		239 cfs	474 cfs	644 cfs	862 cfs	1021 cfs	1174 cfs
Theil-Sen		251 cfs	566 cfs	1046 cfs	2359 cfs	4363 cfs	8069 cfs

Table 26. Correlation R Coefficients for Blackwater Creek (cfs)

Correlation between:			
Observed	&	Solver	0.8970
Observed	&	Linear Reg.	0.7865
Observed	&	Log Pearson	0.9564
Observed	&	Theil-Sen	0.7767

Chapter 9. Conclusion and Recommendations

Overall, this study has provided a focused research effort to ensure the development of reliable statistical equations to approach a watercourse and estimate the discharge rates via storm events. The preliminary efforts have provided groundwork that signifies statistical methods can deem accurate results when implemented correctly. Acknowledging a range of estimated flow rates based on extreme storm events should be the preferred procedure when establishing flow rates. A single flow rate estimate should not be sufficient enough when assessing a watercourse.

This thesis presents multiple approaches to flood flow estimation. At the 10, 25, 50, and 100-year storm events, flood estimates were developed for the Wekiva sub-basin. Estimates were calculated by modifying the St. John's River Water Management District's (SJRWMD) HSPF model, conducting statistical tests with Log-Pearson Type III, Power Law, and Thiel-Sen calculations, and by analyzing the published reports provided by Federal Emergency Management Agency's (FEMA) Flood Insurance Studies (FIS) and SJRWMD. The results were compared side by side, gaining an in-depth look at the benefit of using each method. This research was meant to provide a heavy-hearted look at flood estimates. As the inevitable population growth continues and the reliance on a single flood flow estimate still remains, it is crucial that multiple methods are incorporated to discontinue the reliability of a single existing flood estimate for engineering practice.

As the hydrologic simulation program HSPF was a great approach to verifying the statistical tests, it evidently displayed some drawbacks in the Wekiva sub-basin. The HSPF model simulated flow outputs that were consecutively lower compared to the statistical approached and documented reports. A few key reasons were identified as a contribution from the start. The reality is that Wekiva sub-basin is heavily created by spring flow. Identification in Chapter 3.3 of the spring

flow parameters concluded that without any adjustment to the constant spring flow value, the outputs would not accurately represent the watercourses flow rates at extreme storm events. The Wekiva River receives nearly 96% of its volume directly from spring flow, and the Little Wekiva River receives 84% of its flow from spring flow. Thus, it can quickly be concluded that the watercourses in the Wekiva sub-basin heavily consist of spring flow. Therefore, the potential for additional research to be conducted in the HSPF spring flow parameters would be highly recommended for future research.

The statistical approaches discussed in this research led to valid answers for issues that would otherwise have simply been overlooked due to a lack of testing. The first, Log-Pearson Type III (LP3) statistical computations, is seen as the most dependable and reliable of the three methods, making the LP3 successful for the Wekiva sub-basin. As noted by the US Army Corps of Engineers in 1994, the LP3 was a highly recommended statistical analysis procedure when stream gage records were abundant. For this, the Wekiva River gage recorded 87 years, the Little Wekiva River recorded 48 years, and the Blackwater Creek recorded 45 years, making the LP3 sufficient for the Wekiva sub-basin. The LP3 method was deemed sufficient and supported its claim for being the common method for flood frequency estimation (US Army Corps of Engineers, 1994).

Additionally, the Power Law (PL) statistical method was deemed incredibly useful as it incorporated both a linear and nonlinear process to its method. The nonlinear method, Solver, was accurate at events no larger than a 50-year storm event. Similarly seen outcomes for Solver were formed in the Lower St. Johns River (Kovalenko, 2020). While the linear regression process is accurate to a degree, it is only for data sets that measure a low spread. Advising to use the PL would be recommended but with an eye on the mentioned limitations. Lastly, the Theil-Sen (TS) estimator was a useful method in determining the flood flow estimation while having no effect

from outliers. It became a great alternative to the PL linear regression process as it is not manipulated by said outliers. However, the estimator was inaccurate at events larger than a 10-year storm event. This made the Theil-Sen undesirable for most research other than supporting flow rates at small storm events.

The reports provided by FEMA FIS and SJRWMD at the Little Wekiva River proved to be a great means for supporting data derived from qualified organizations. However, due to varying methods used within each, it can be understood that estimates obtained are not always consistent. It is suggested that future extreme flood procedures could benefit from using multiple of the discussed statistical methods incorporated in the Wekiva sub-basin under certain limitations. Implementation of the bounded Gumbel distribution is deemed fit as it could accurately describe the variance of extreme storm events. Depicting larger uncertainty at extreme storm events was important.

In conclusion, this research pursued a new methodology for producing flood estimates based on current data. It is contradicting the point that a single existing flood flow estimate should be used. As typically established single value flood flow estimates are seen in FEMA Flood Insurance Studies and SJRWMD reports, growing professionals must acquire evolving techniques that will better interpret the effects on our watercourses using a range of flow estimates. This research is distinct as it assesses the Wekiva River, Little Wekiva River, and Blackwater Creek based on altering hydrologic modeling, statistical analysis, and comparing existing reports of estimated flow rates at the 10, 25, 50, and 100-year extreme storm events.

FIGURES

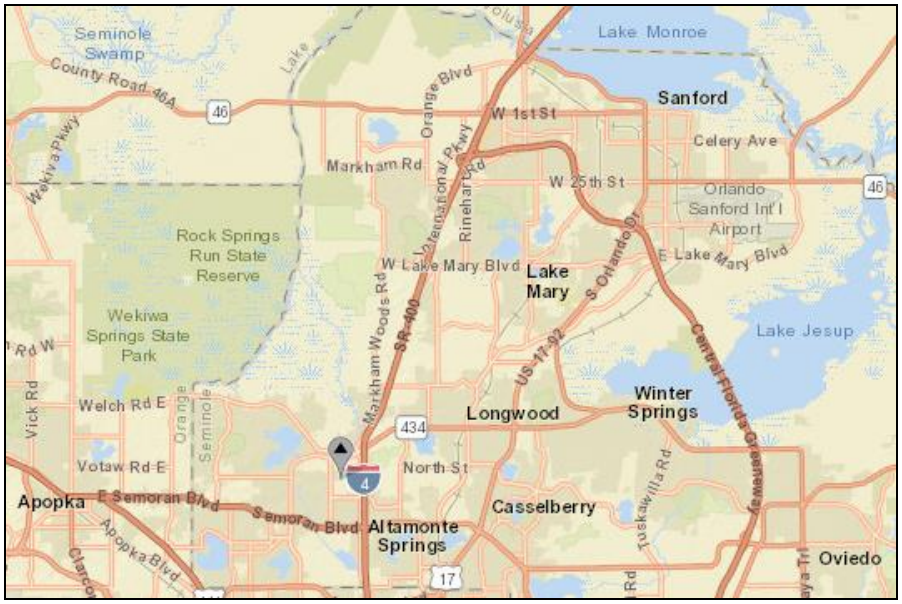


Figure 1. USGS Location of Gage on the Little Wekiva River at State Road 434

	Econlockhatchee River	Deep Creek	Lake Jesup	Lake Monroe	Wekiva River
Land Uses					
Low Density Residential	4.8%	5.5%	6.9%	7.9%	7.8%
Medium Density Residential	6.5%	0	19.8%	20.9%	11.3%
High Density Residential	6.6%	0	5.9%	1.8%	2.2%
Agricultural	12.7%	8.5%	7.4%	7.4%	15.1%
Land Cover					
Wetlands	26.0%	31.4%	18.6%	19.3%	21.2%
Upland forest	19.0%	29.6%	6.5%	14.2%	22.6%
Rangeland	10.4%	0	0	3.35	7.2%
Open Water	0	6.4%	13.8%	0	0
Other	14.0%	18.6%	21.1%	25.2%	12.6%
Totals	100%	100%	100%	100%	100%

Figure 2: Major Land Uses and Land Cover for the Middle St. Johns River Basin (SJRWMD, 2002)

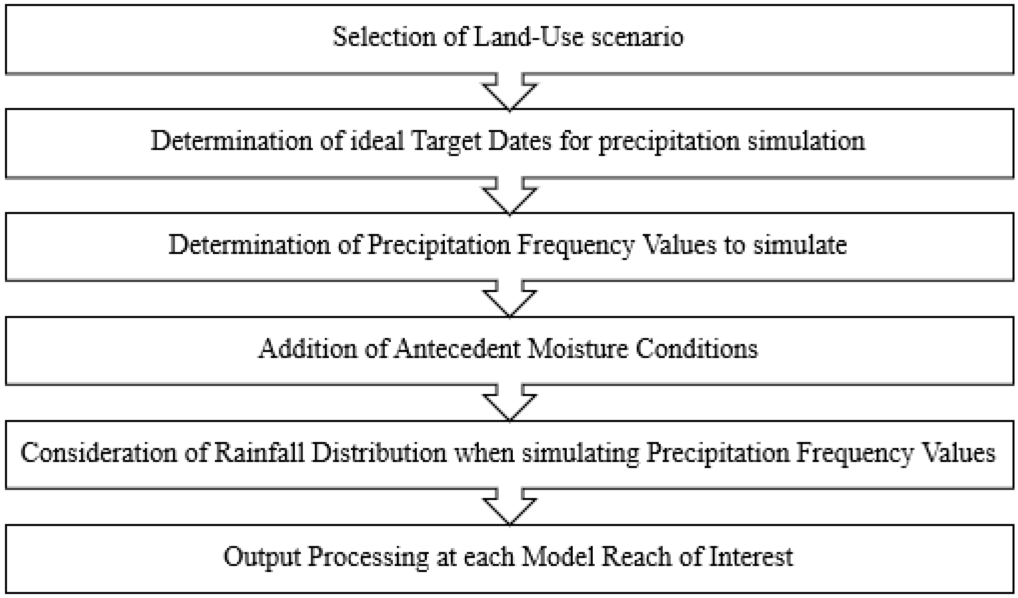


Figure 3. Procedure for Manipulating HSPF (Kovalenko, 2020)

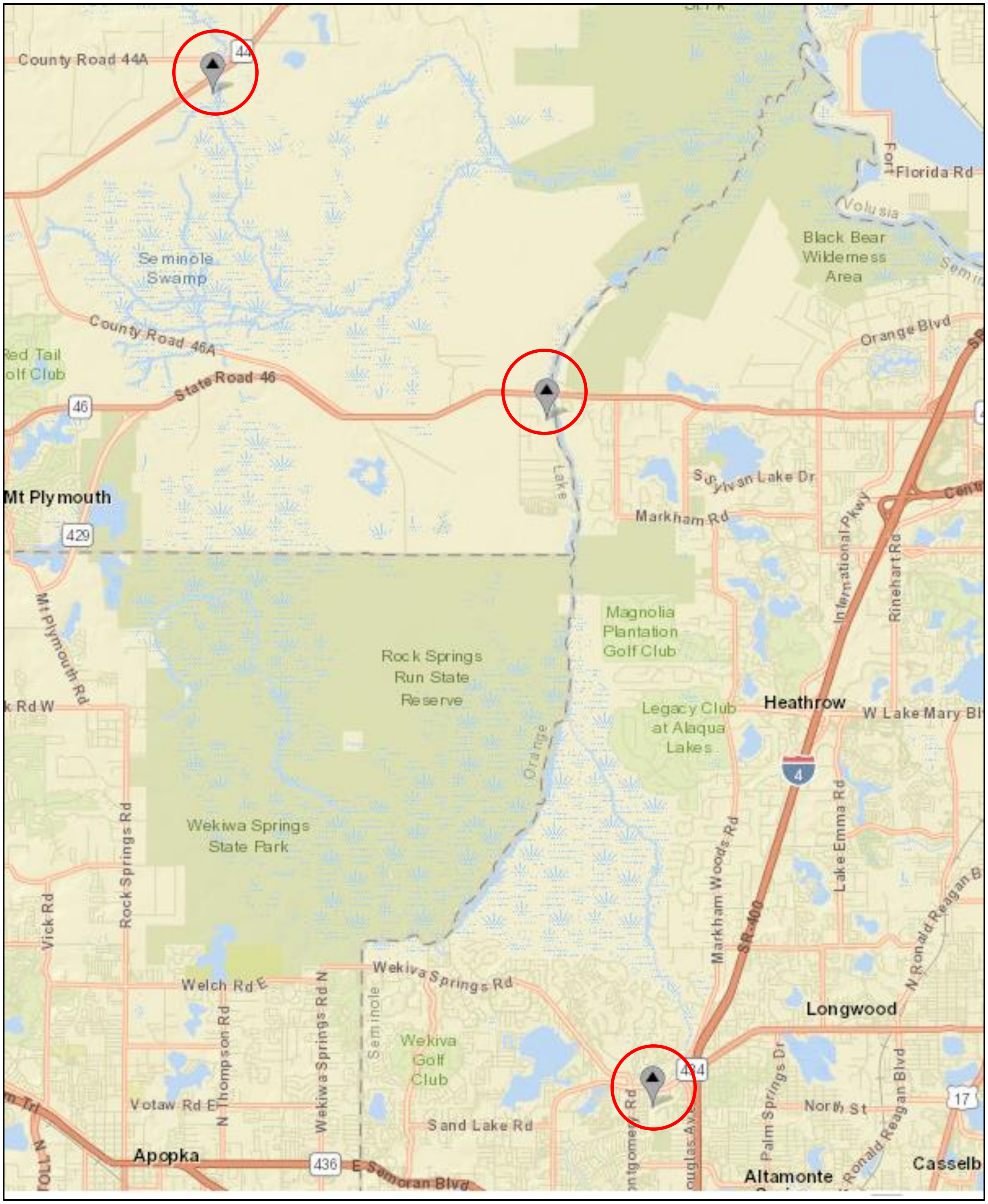


Figure 4. USGS Gage Locations (USGS, National Water Information System: Mapper, 2020)

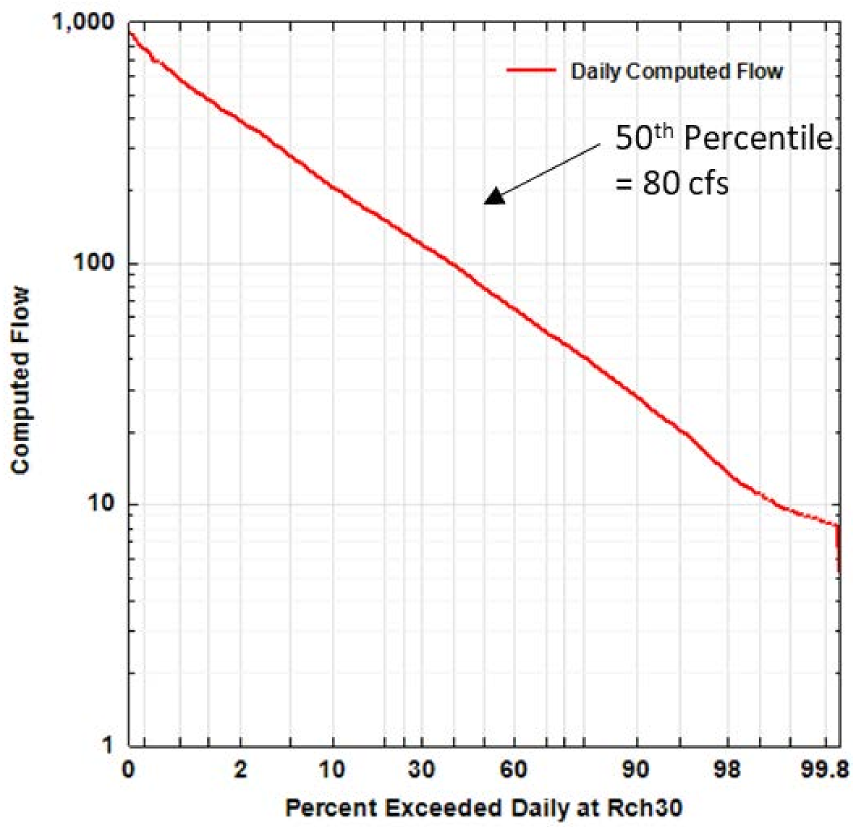


Figure 5. Determining the 50th Percentile of the HSPF Return Frequency Curve

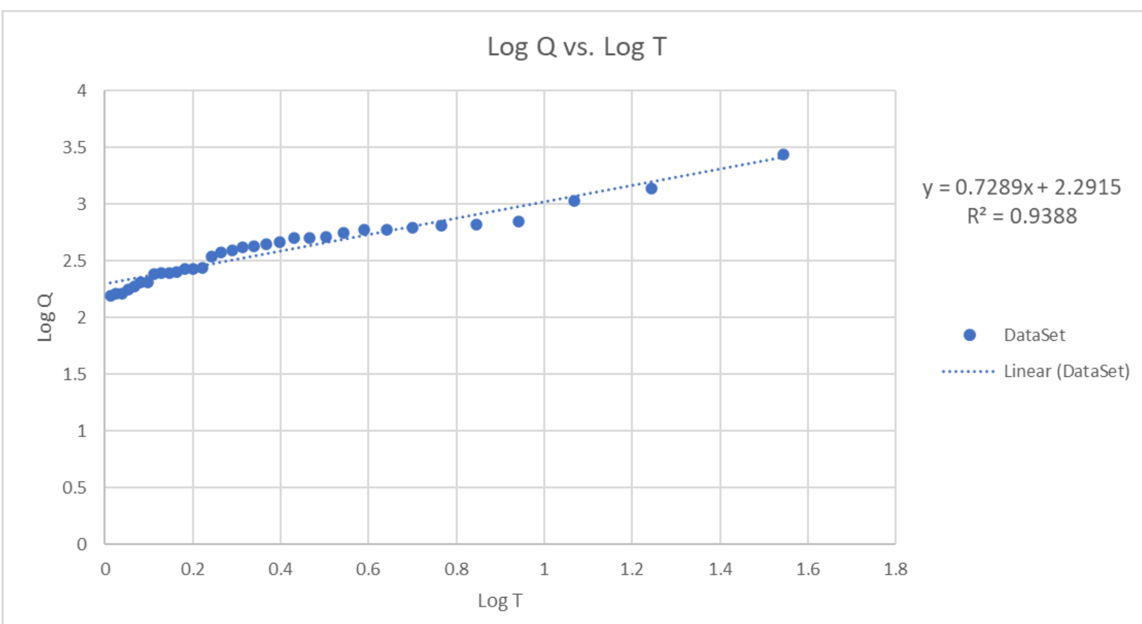
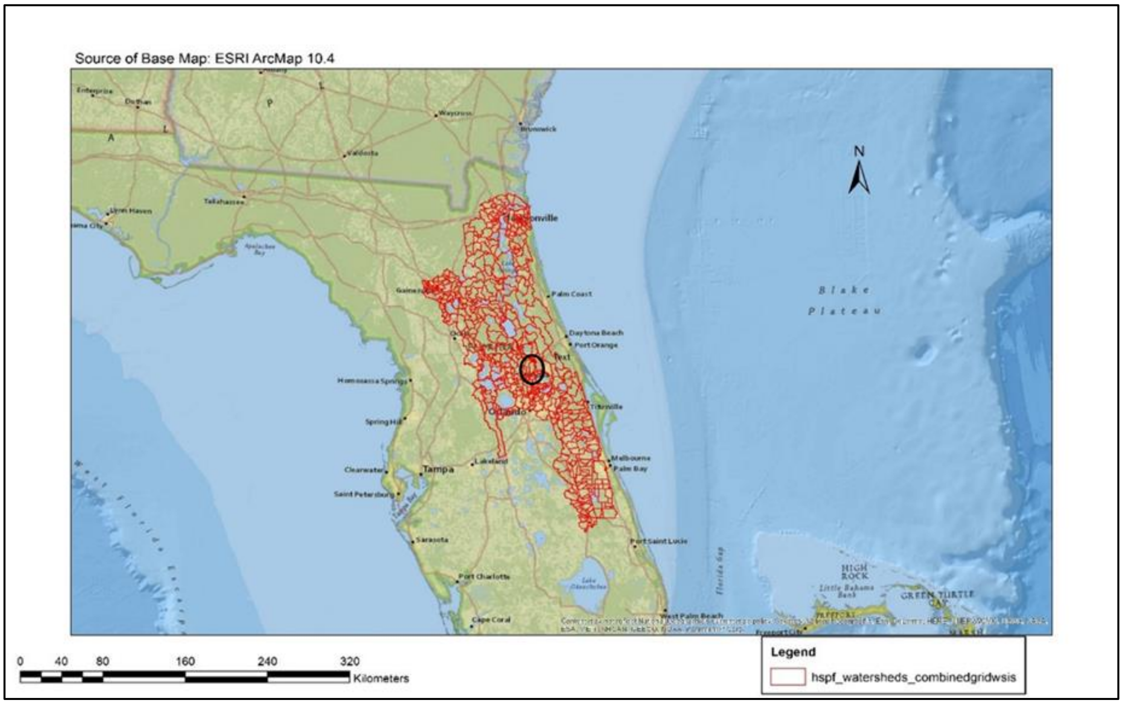
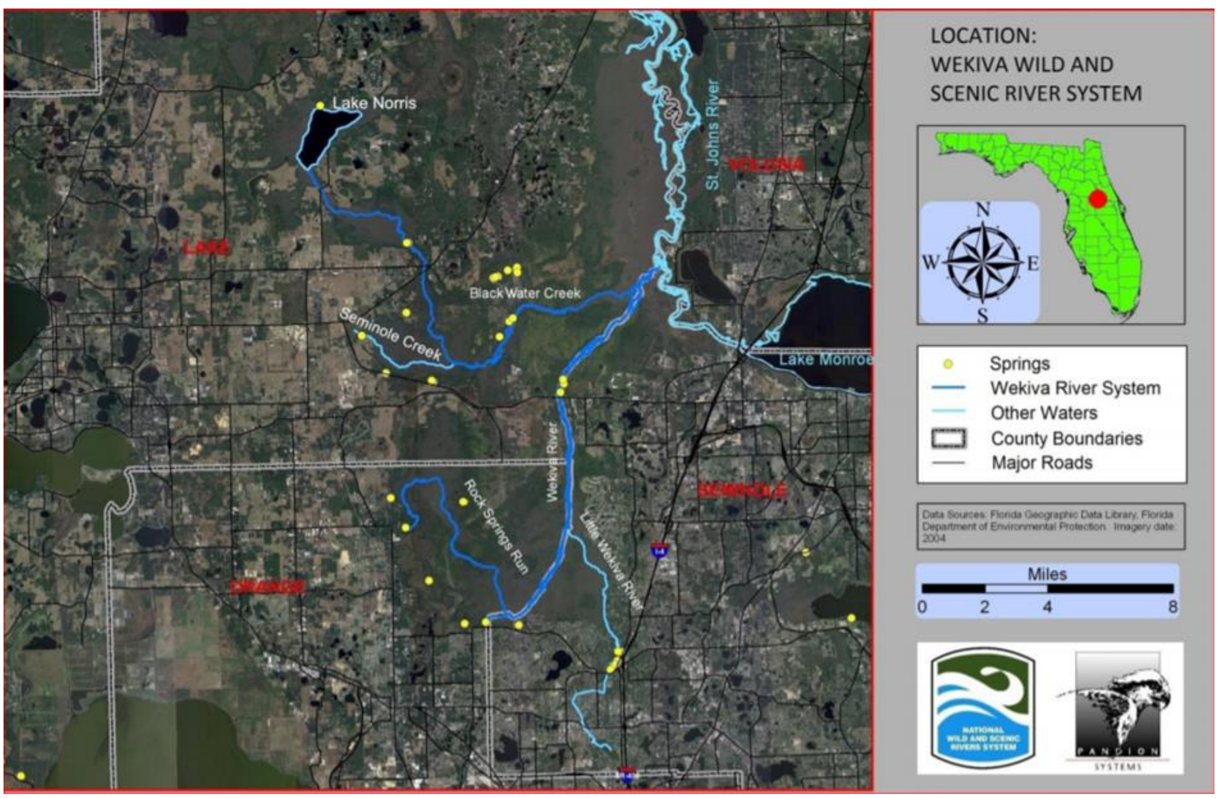


Figure 6. Determining the 50th Percentile of the HSPF Return Frequency Curve

APPENDIX A



General location of the Wekiva sub-basin (circled) in Florida.



Main Watercourses of the Wekiva Sub-basin

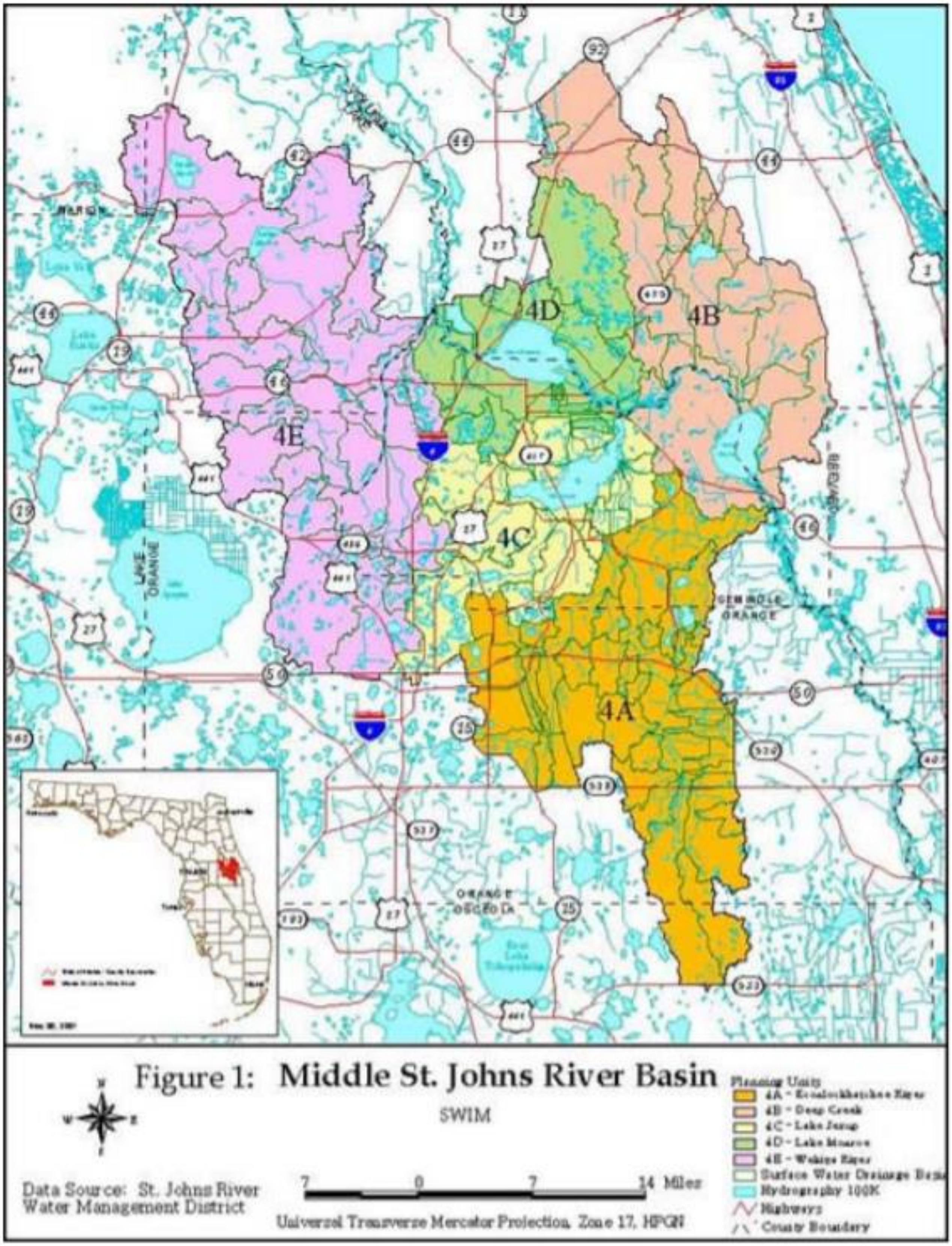
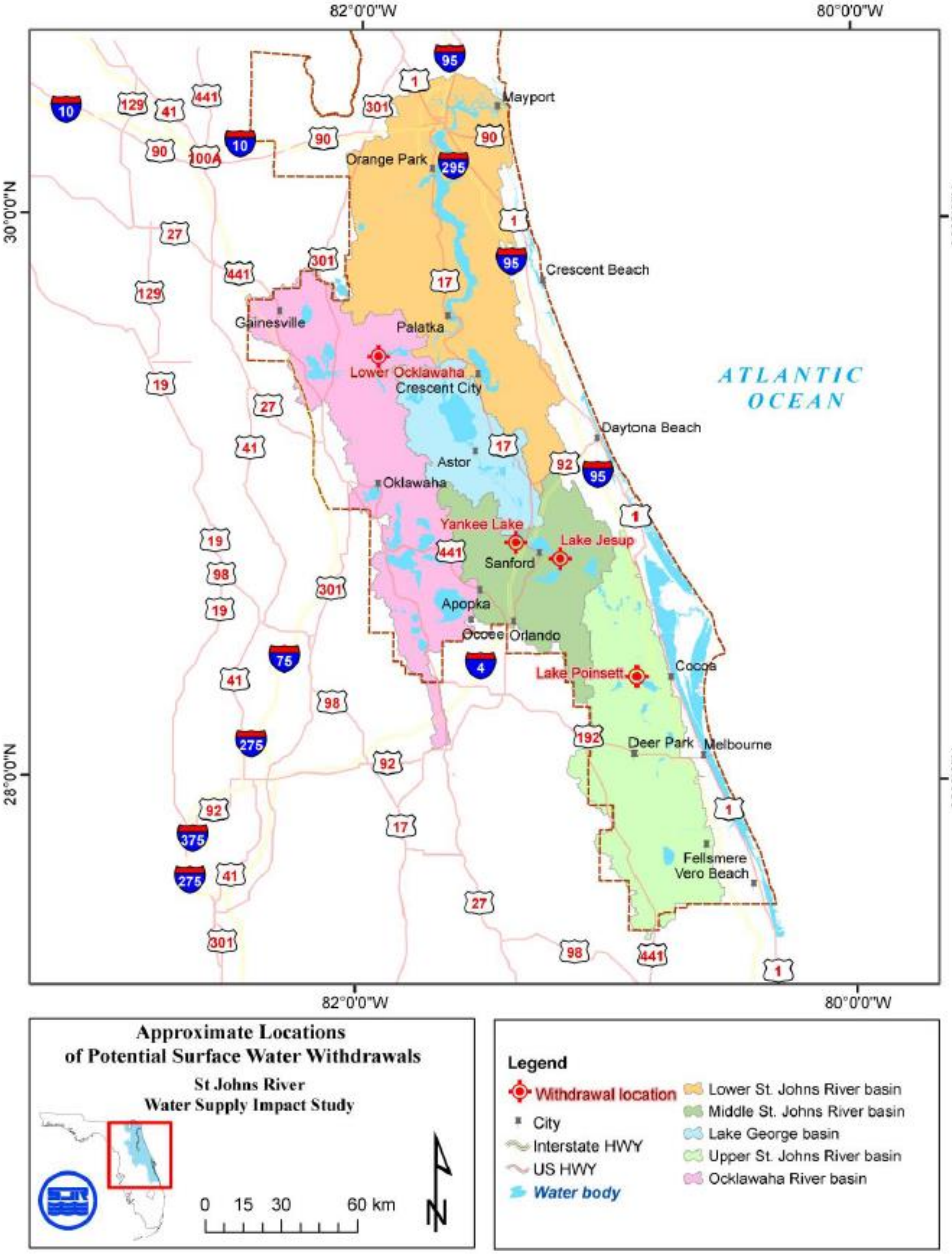


Figure 1: Middle St. Johns River Basin

Wekiva River 4E Planning Unit

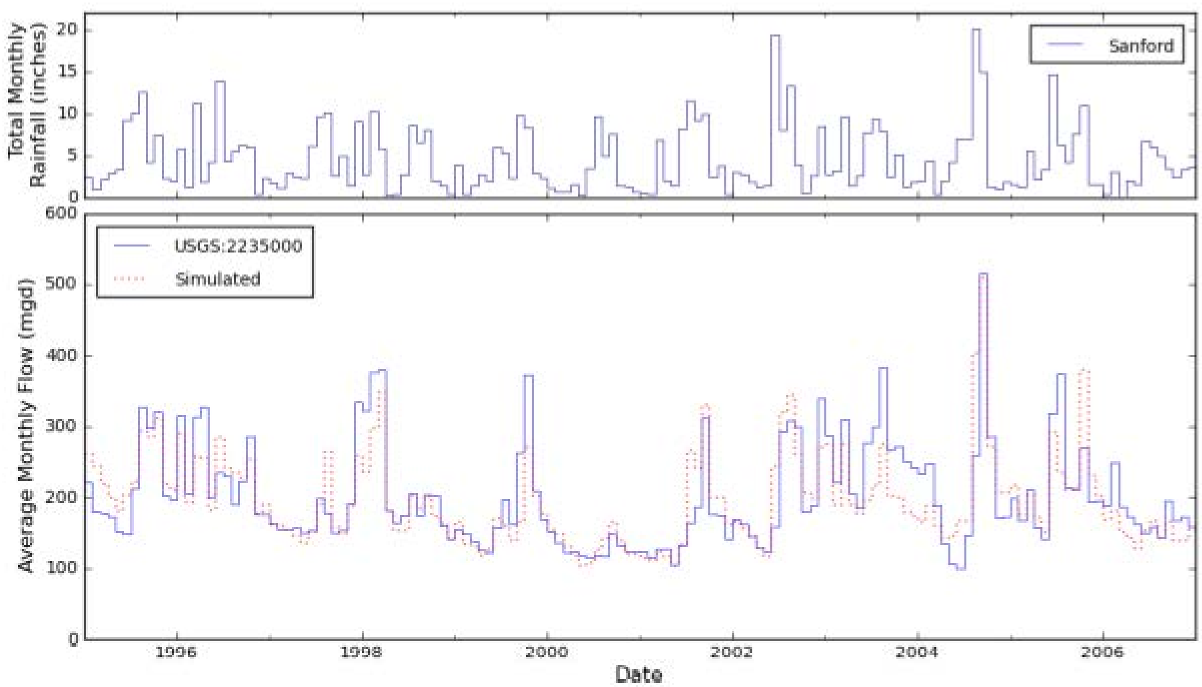
APPENDIX B



Water Supply Impact Study (2012)

Statistic (Daily Flow (mgd))	Observed (USGS:2235000)	Simulated
Average	201.01	196.26
Median	174.09	179.12
Variance	8471.20	6541.19
Standard Deviation	92.04	80.88
Skew	2.51	2.76
Kurtosis	8.72	13.62
Minimum	89.98	98.41
Maximum	911.53	1054.91
Range	821.55	956.49

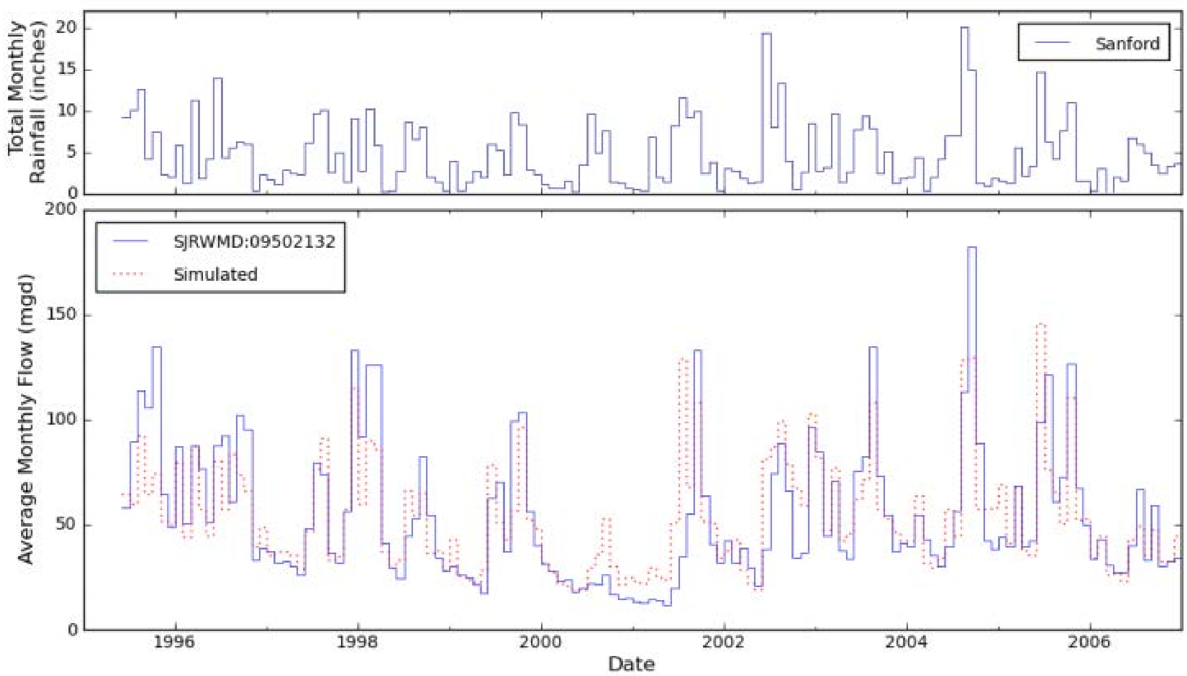
Wekiva River near Sanford calibration results



Wekiva River near Sanford monthly hydrograph

Statistic (Daily Flow (mgd))	Observed (SJRWMD:09502132)	Simulated
Average	54.39	53.54
Median	40.07	41.62
Variance	1853.70	1687.61
Standard Deviation	43.05	41.08
Skew	2.66	3.34
Kurtosis	9.92	18.69
Minimum	9.05	17.85
Maximum	418.81	510.36
Range	409.76	492.51

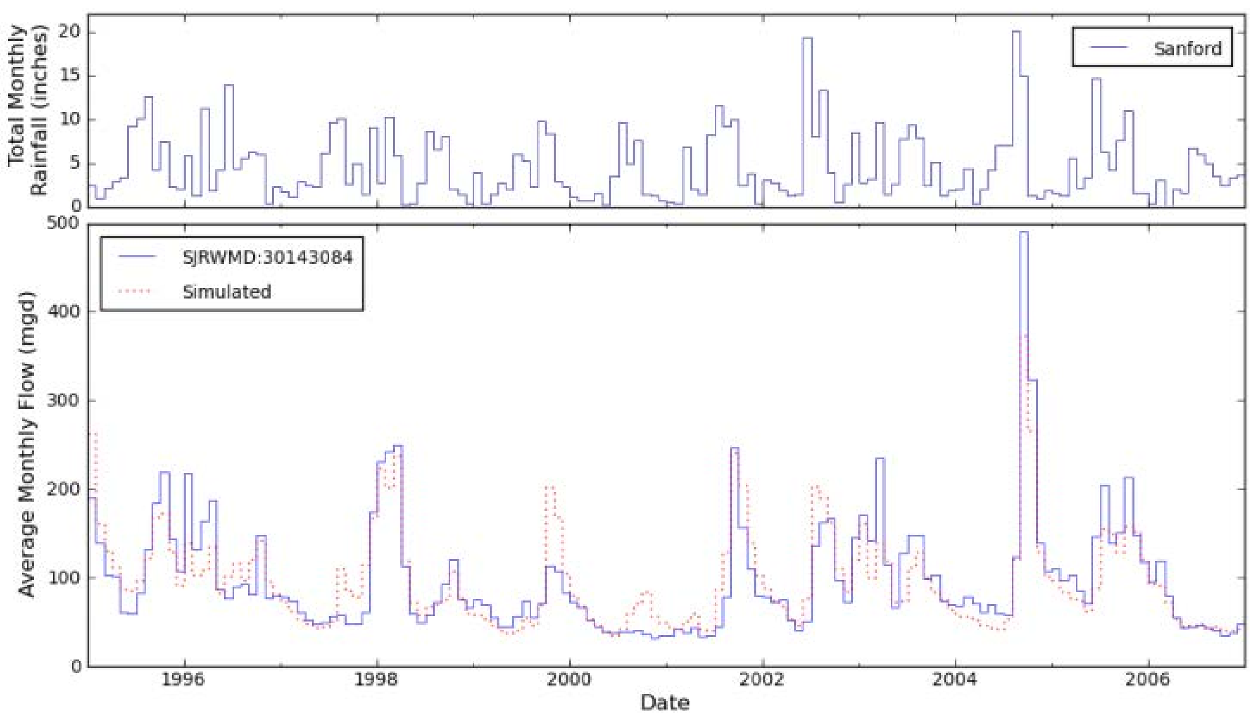
Little Wekiva River at Springs Landing calibration results



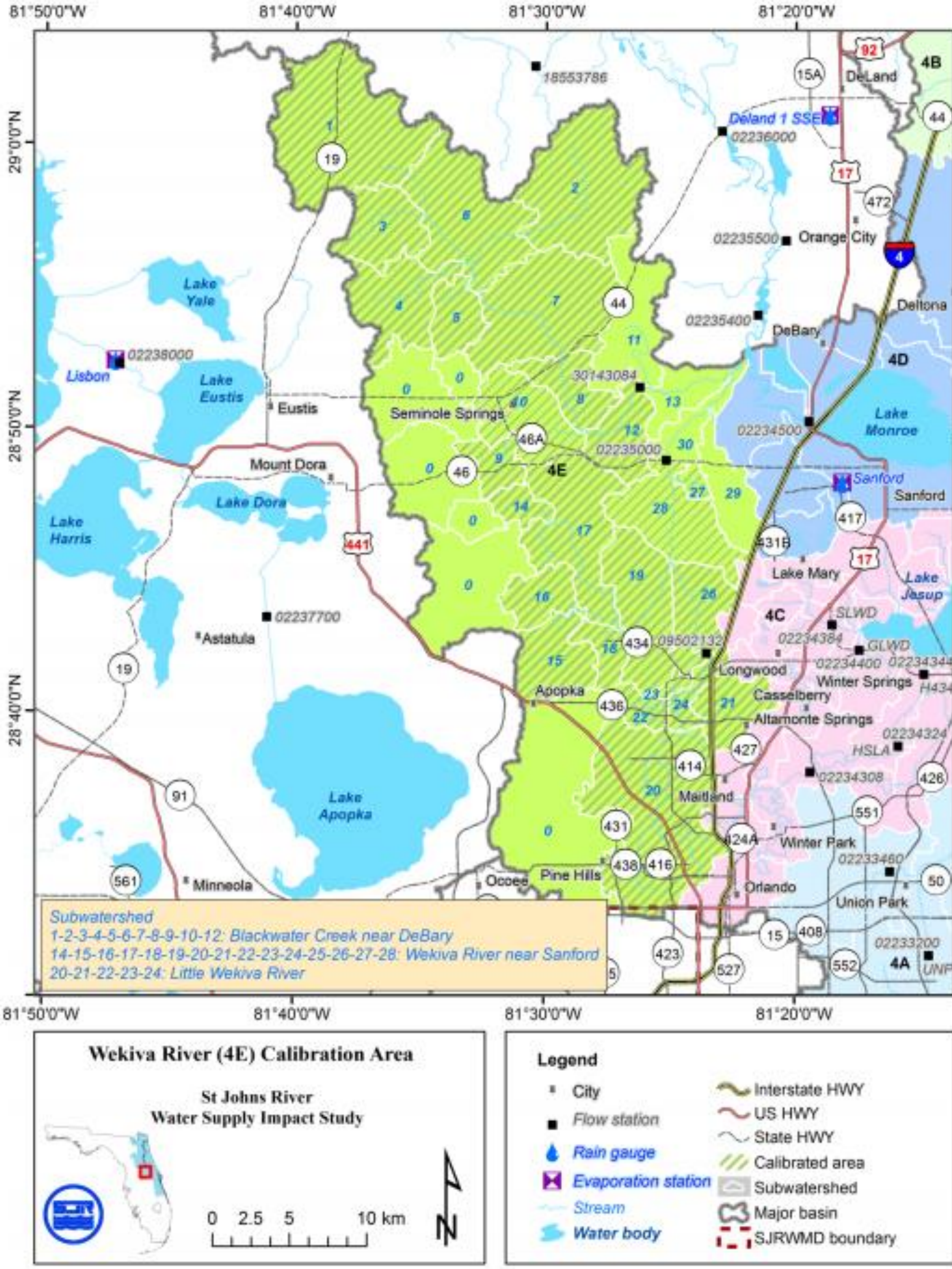
Little Wekiva River at Springs Landing monthly hydrograph

Statistic (Daily Flow (mgd))	Observed (SJRWMD:30143084)	Simulated
Average	97.90	96.58
Median	73.94	80.70
Variance	5231.40	3479.66
Standard Deviation	72.33	58.99
Skew	3.02	2.10
Kurtosis	15.02	7.03
Minimum	31.02	31.52
Maximum	789.48	512.23
Range	758.45	480.71

Blackwater Creek at DeBary calibration results

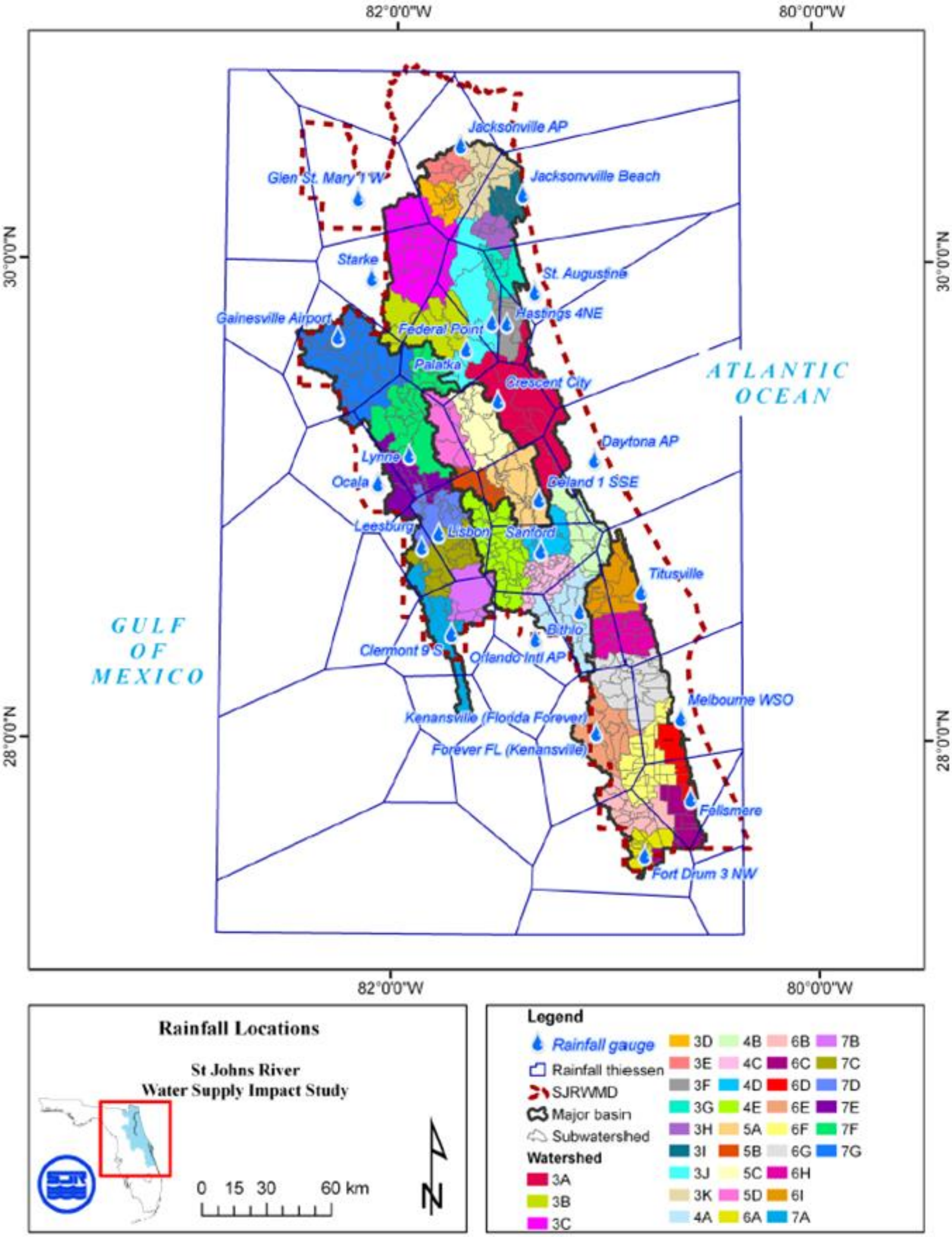


Blackwater Creek at DeBary monthly hydrograph

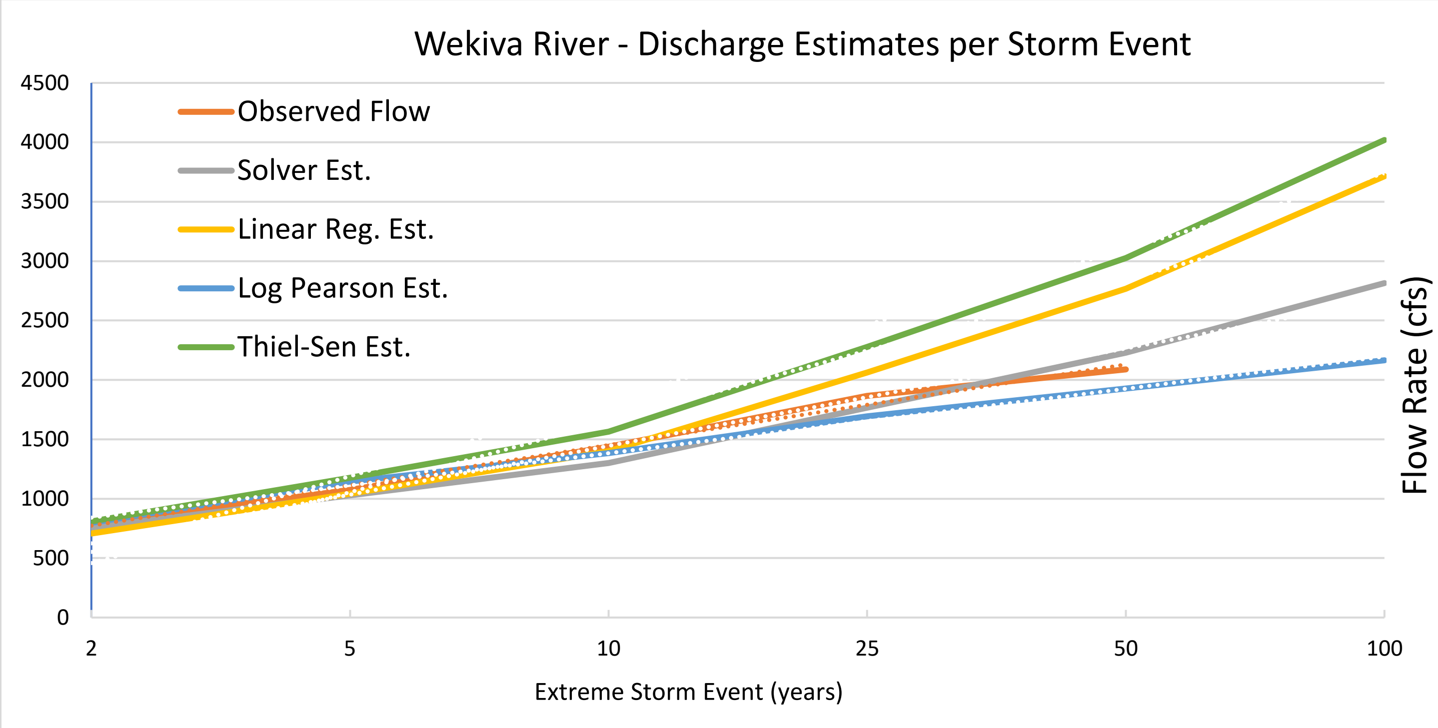


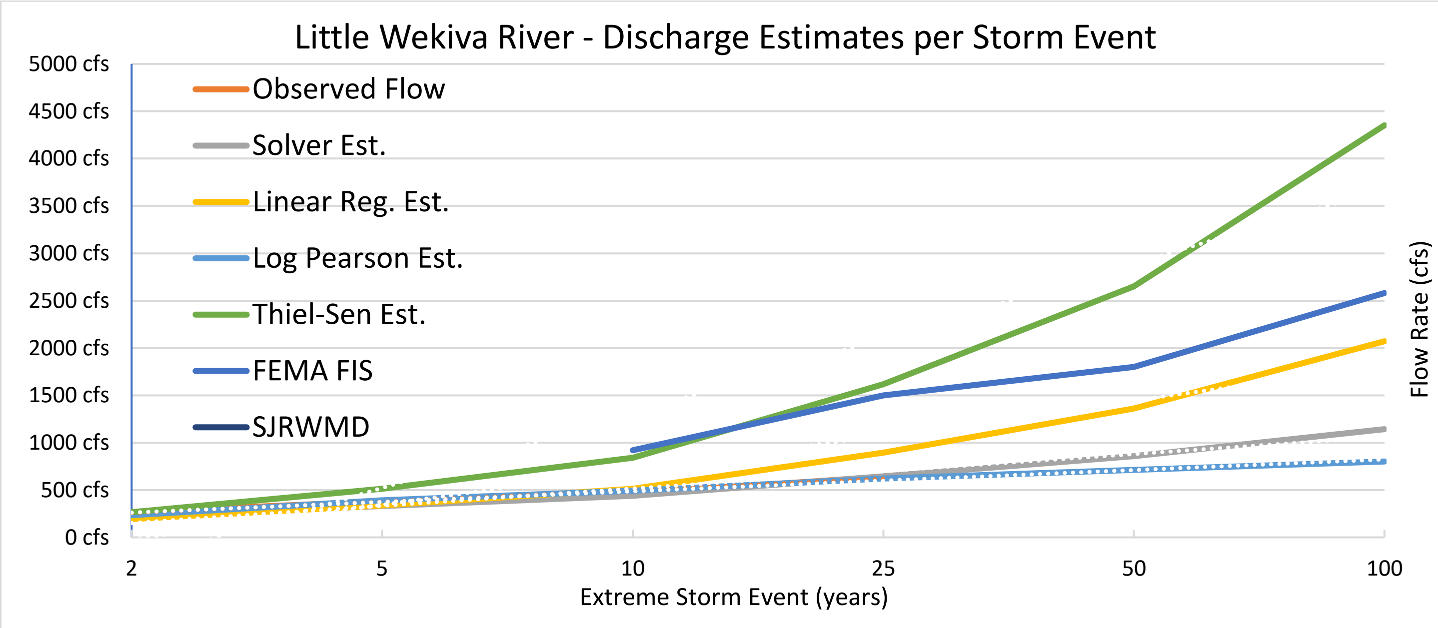
Water Supply Impact Study (2012)

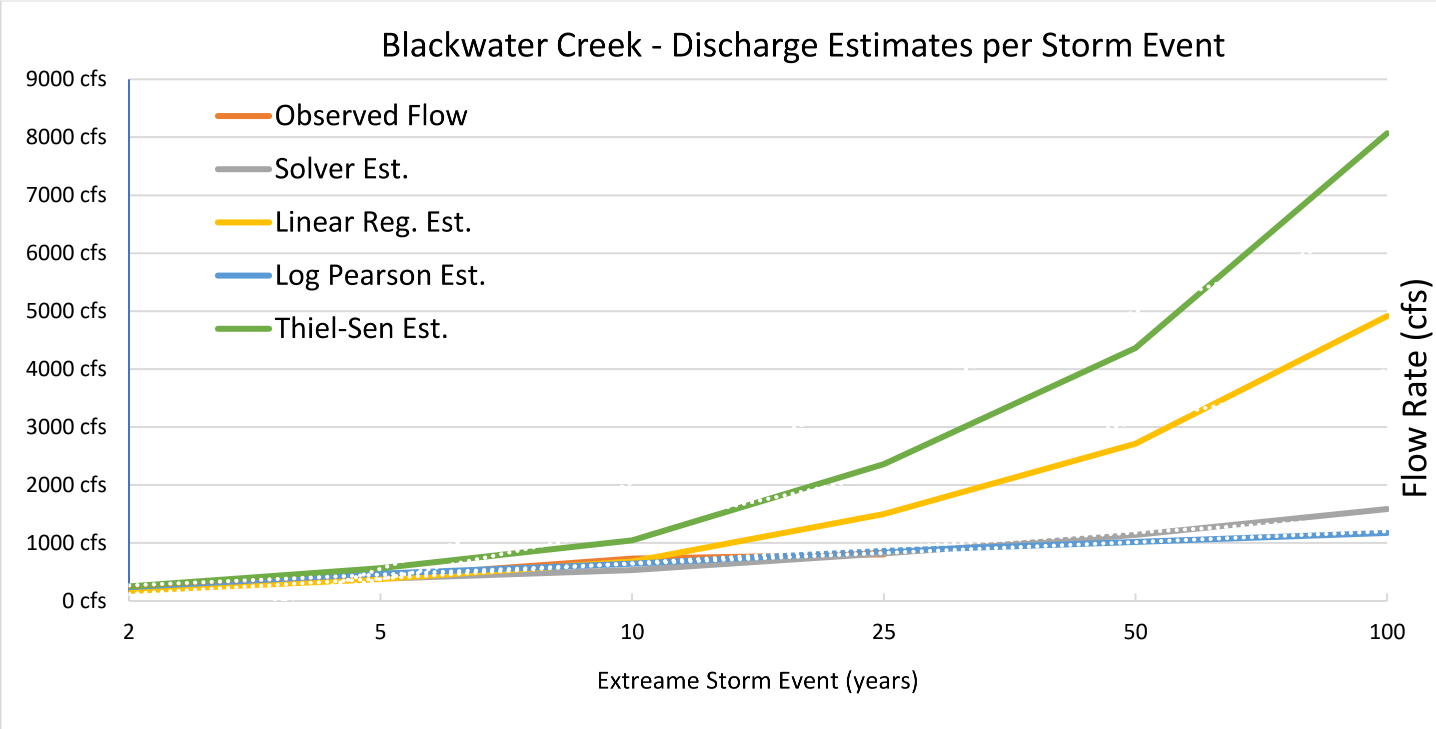
APPENDIX E

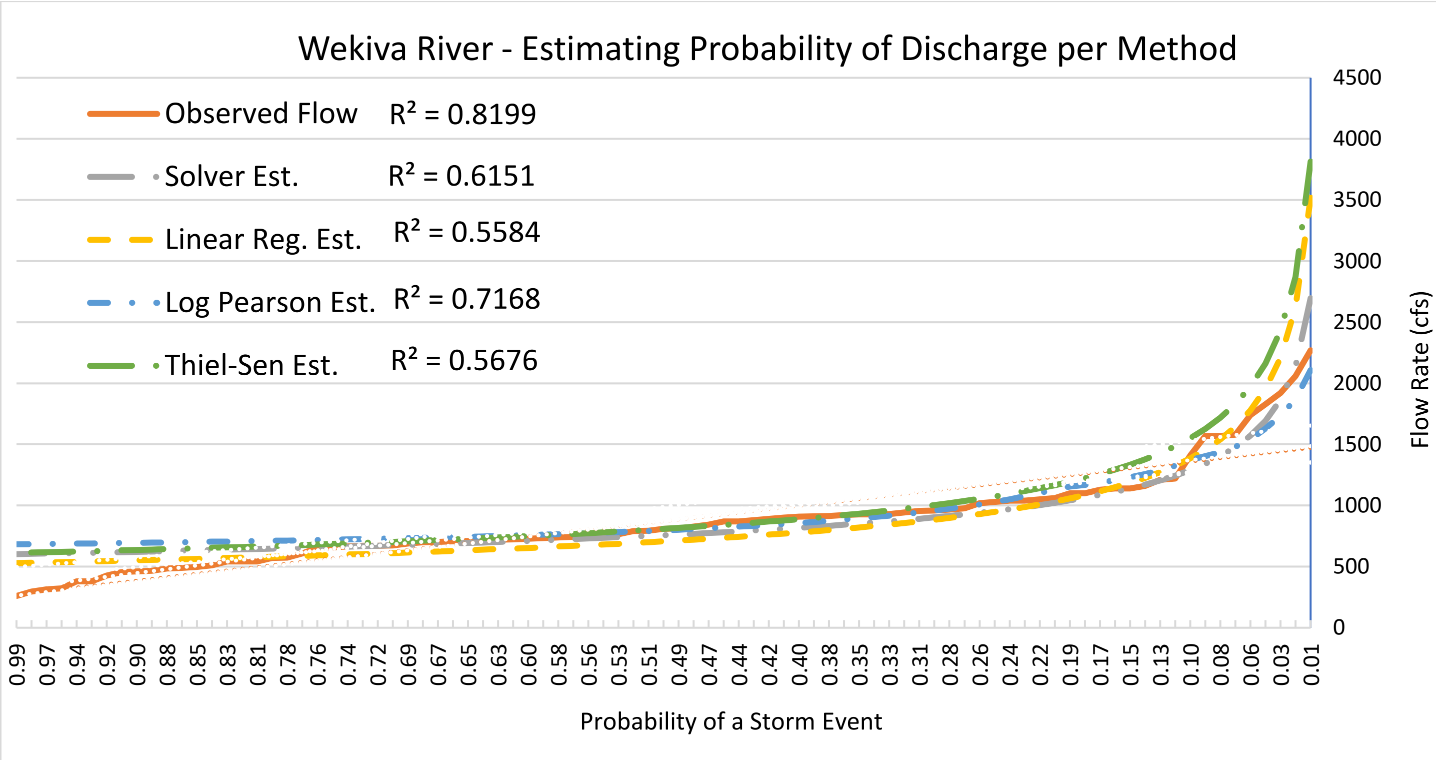


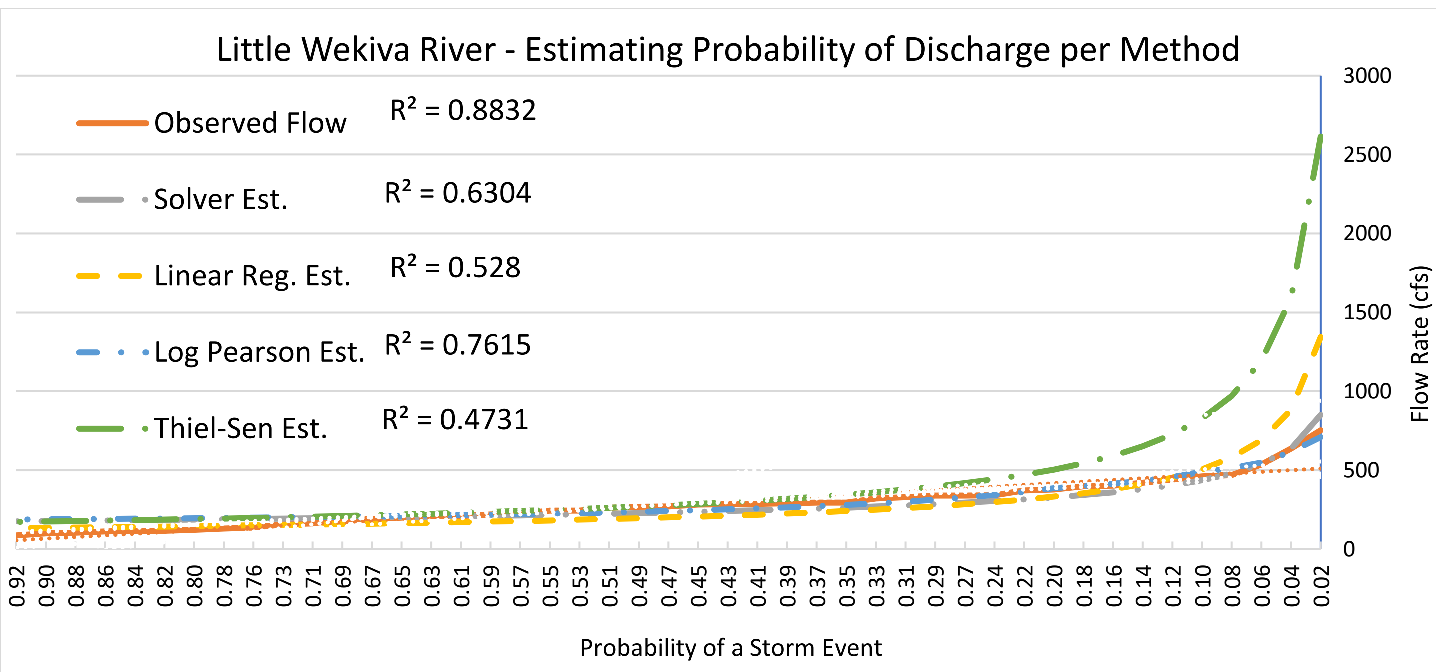
Source: Water Supply Impact Study (2012)

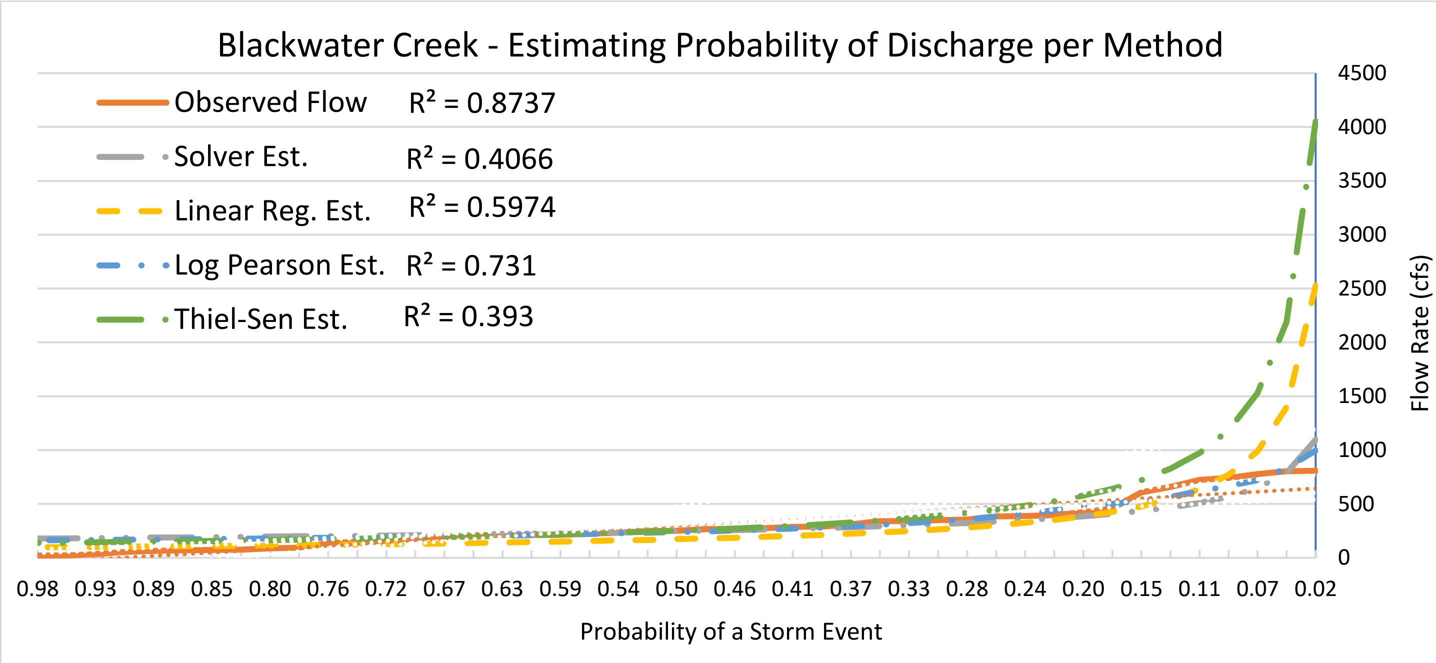

Wekiva River - Discharge Estimates per Storm Event
Observed Flow
Solver Est.
Linear Reg. Est.
Log Pearson Est.
Thiel-Sen Est.
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2
5
10
25
50
100
Extreme Storm Event (years)
Flow Rate (cfs)


Little Wekiva River - Discharge Estimates per Storm Event
Observed Flow
Solver Est.
Linear Reg. Est.
Log Pearson Est.
Thiel-Sen Est.
FEMA FIS
SJRWMD
5000 cfs
4500 cfs
4000 cfs
3500 cfs
3000 cfs
2500 cfs
2000 cfs
1500 cfs
1000 cfs
500 cfs
0 cfs
2
5
10
25
50
100
Extreme Storm Event (years)
Flow Rate (cfs)

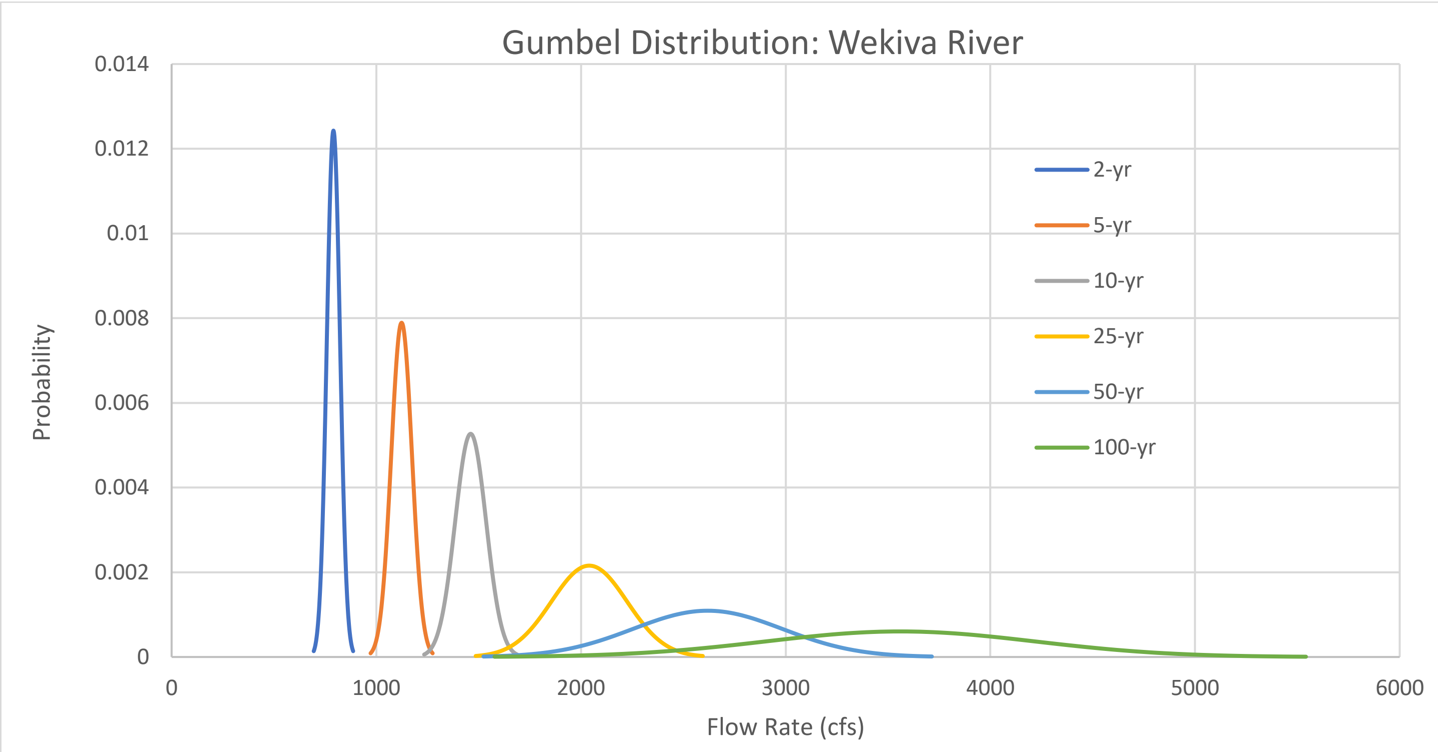

Blackwater Creek - Discharge Estimates per Storm Event
9000 cfs
8000 cfs
7000 cfs
6000 cfs
5000 cfs
4000 cfs
3000 cfs
2000 cfs
1000 cfs
0 cfs
Observed Flow
Solver Est.
Linear Reg. Est.
Log Pearson Est.
Thiel-Sen Est.
2
5
10
25
50
100
Extreame Storm Event (years)
Flow Rate (cfs)


Wekiva River - Estimating Probability of Discharge per Method
Observed Flow R² = 0.8199
Solver Est. R² = 0.6151
Linear Reg. Est. R² = 0.5584
Log Pearson Est. R² = 0.7168
Thiel-Sen Est. R² = 0.5676
Flow Rate (cfs)
Probability of a Storm Event

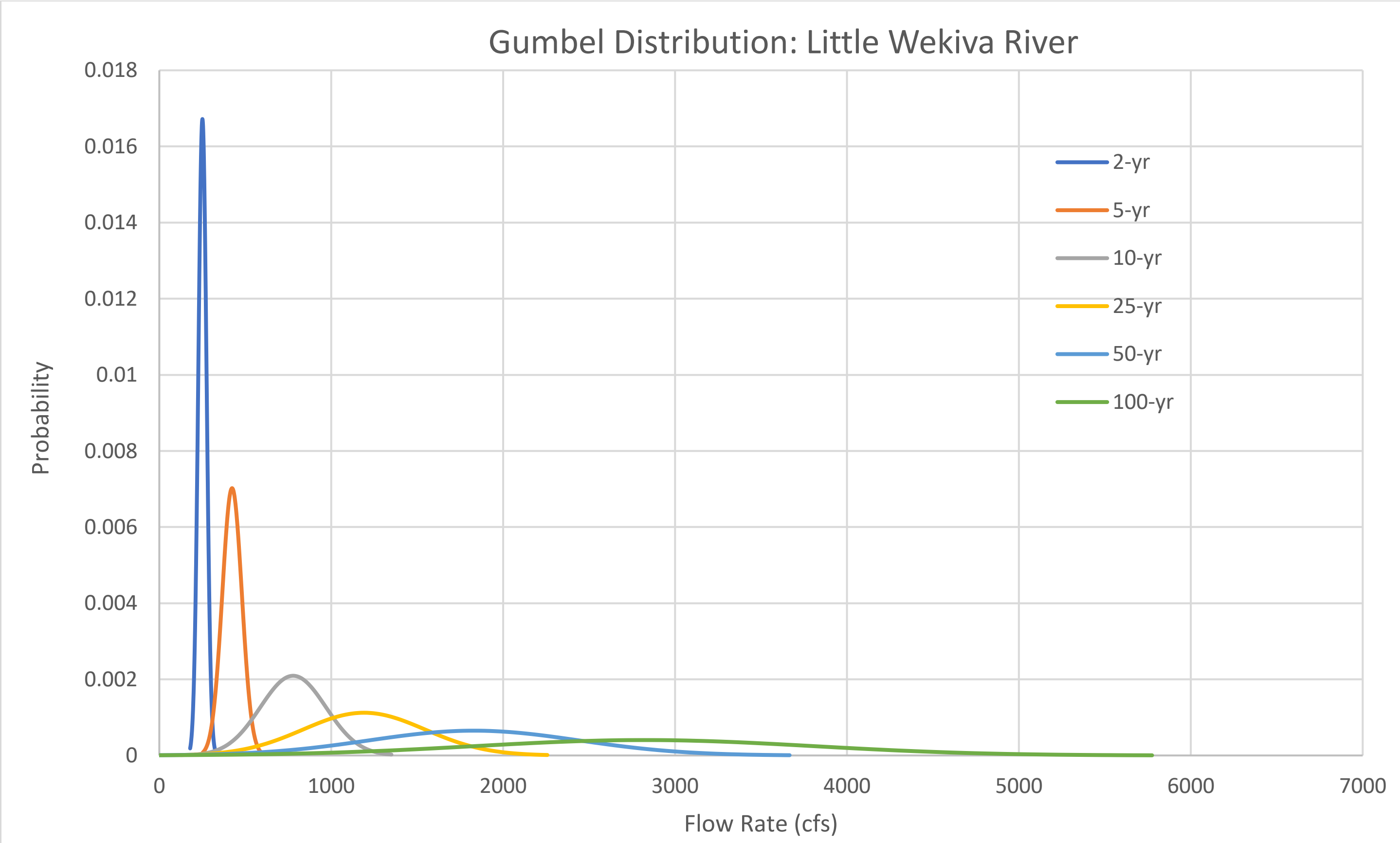

Little Wekiva River - Estimating Probability of Discharge per Method
Observed Flow R² = 0.8832
Solver Est. R² = 0.6304
Linear Reg. Est. R² = 0.528
Log Pearson Est. R² = 0.7615
Thiel-Sen Est. R² = 0.4731
Flow Rate (cfs)
Probability of a Storm Event


Blackwater Creek - Estimating Probability of Discharge per Method
Observed Flow R² = 0.8737
Solver Est. R² = 0.4066
Linear Reg. Est. R² = 0.5974
Log Pearson Est. R² = 0.731
Thiel-Sen Est. R² = 0.393
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Flow Rate (cfs)
0.98 0.93 0.89 0.85 0.80 0.76 0.72 0.67 0.63 0.59 0.54 0.50 0.46 0.41 0.37 0.33 0.28 0.24 0.20 0.15 0.11 0.07 0.02
Probability of a Storm Event

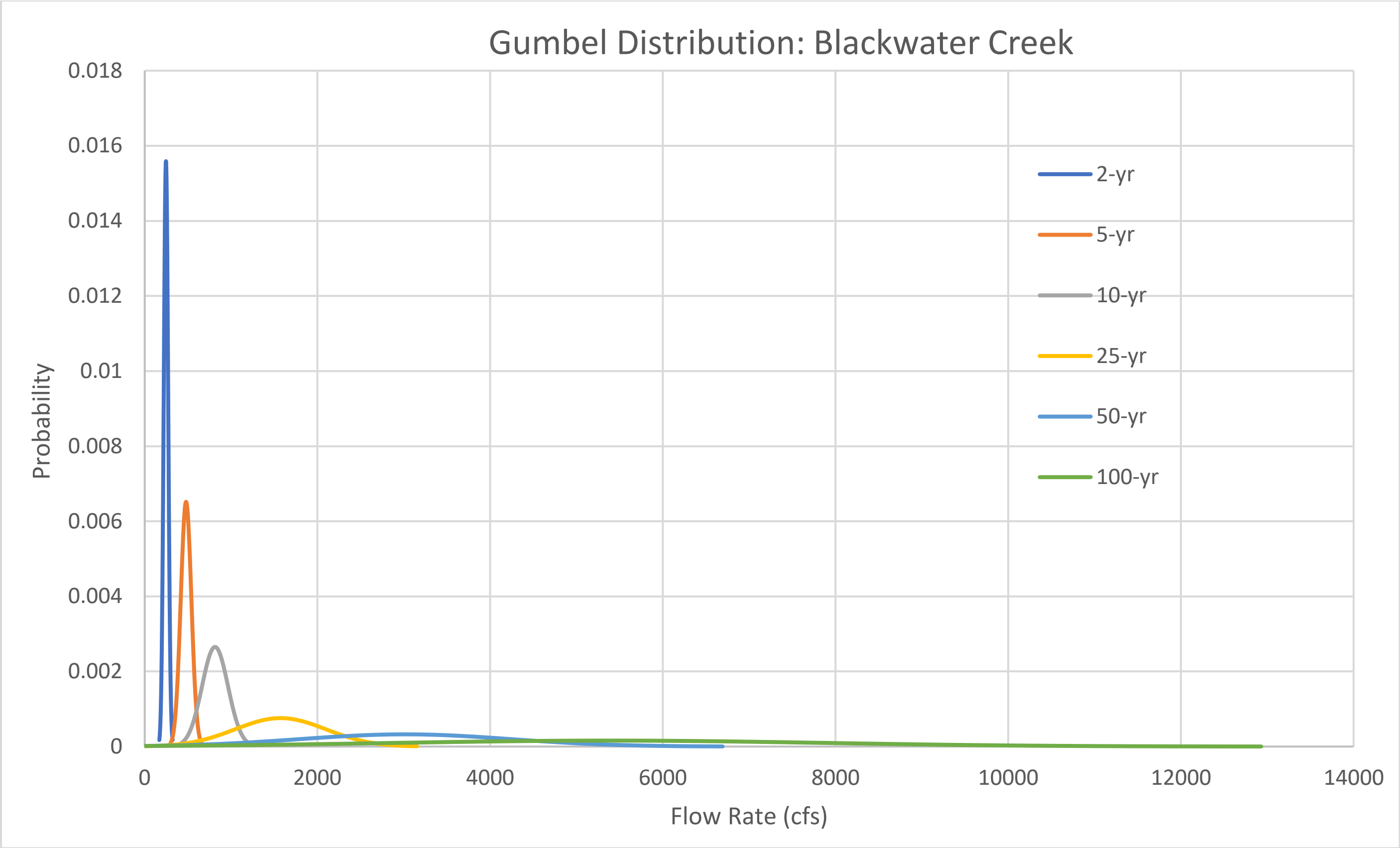
APPENDIX H



Gumbel Distribution: Wekiva River
Probability
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
1000
2000
3000
4000
5000
6000
Flow Rate (cfs)
2-yr
5-yr
10-yr
25-yr
50-yr
100-yr



Gumbel Distribution: Little Wekiva River
Probability
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
1000
2000
3000
4000
5000
6000
7000
Flow Rate (cfs)
2-yr
5-yr
10-yr
25-yr
50-yr
100-yr


Gumbel Distribution: Blackwater Creek
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Probability
0
2000
4000
6000
8000
10000
12000
14000
Flow Rate (cfs)
2-yr
5-yr
10-yr
25-yr
50-yr
100-yr

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VITA

Wesley Koning, the author, was raised in Sebring Florida where he received his Associates of Arts Degree at South Florida State College. Thereafter, he transferred to the University of North Florida in January of 2017 and began studying Civil Engineering. Receiving his Bachelor of Science in Civil Engineering in 2019. Wesley was devoted to many engineering organizations during his undergraduate degree while also completing his business minor. Directly after completion of his undergraduate career, Wesley decided to pursue a Master of Science at the University of North Florida. Doing so led him to complete many internships to gain experience while further expanding his knowledge in the classroom setting. He anticipates graduating from the University of North Florida with a Master of Science in April 2021.