An examination of extreme floods, effects on land-use change and seasonality in the Lower St. Johns River Basin, Florida using HSPF and statistical methods

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Abstract

As population growth and urbanization are steadily rising, the need for dependable flood estimation techniques is crucial. This study evaluates extreme flood events in select sub-basins of the Lower St. Johns River in Florida, USA. The study summarizes work of a recent thesis and combines that work with new research regarding the effect of urbanization on the natural hydrologic processes and flood magnitudes in the watershed. Additionally, the effects of varying seasonality into the hydrologic modeling procedure are also investigated. This research focuses on determining the 10-, 25-, 50-, and 100-year return frequency flood flows in Julington Creek, Ortega River, and Pablo Creek of the Lower St. Johns River Basin in Florida, USA. The major findings of this research indicate that by implementing a range of flood estimation methods one can better describe the inherent uncertainty with traditional estimates. Also, the research showed that varying seasonality in the hydrologic modeling procedure does not result in vast differences in the resulting flood estimates. However, various land-use scenarios may produce simulated flood flows of greater magnitude – especially when a more urbanized land-use scenario is modeled.

Introduction

Extreme flood estimation techniques are a crucial necessity for all communities. In a world where urbanization, sea-level rise, and climate change are prevalent, advancements in flood estimation techniques must occur to better protect humanity. When accurate flood estimation is implemented, economic and community wellbeing are secured. In the United States of America, flooding impacts the state of Florida most severely and it is estimated that Florida suffered \$2.5 billion in flood-related losses from 1990 to 2003 (Brody et al., 2007). Therefore, the need for accurate flood estimation techniques is evident. The research presented herein was conducted in order to better assess flood flow estimates for portions of the Lower St. Johns River in Florida, USA. Traditionally, flood estimates have relied upon one estimating methodology per study resulting in only a “best estimate” of various extreme storm events. This research intends to demonstrate that developing a wider range of estimates with multiple methods provides a more realistic approach and provides a much-needed way to assess estimate uncertainties. Much of the work presented herein is summarized from the graduate thesis of Kovalenko (2020). It is hoped that presenting the work in this venue will provide the research to a wider audience thus ensuring it helps to improve the state-of-the-art in flood estimating. A small portion of the thesis work has already been published and presented by Kovalenko et al. (2020). That effort focused upon a small subset of the total research effort and will be mentioned briefly. The work discussed herein focuses upon six sub-basins namely Julington Creek, Durbin Creek, Big Davis Creek, Black Creek, Ortega River, and Pablo Creek. Besides, summarizing the previous thesis work, this paper also introduces additional research completed this past year which has never been published anywhere. The new research extends the previous work by looking more deeply into seasonality of flow events in Northeastern Florida and by studying the effects of projected urbanization in the watershed on flood estimates. This paper presents flood estimates developed using the model code HSPF as well as multiple statistical methods suggested by the literature.

Project Background

Flood estimates for this study were developed by utilizing multiple methodologies including statistical modeling and numerical modeling. In addition, published estimates from flood insurance studies were also compared and included in the compilation. The resulting matrix of estimates provides a fairly wide range of reasonable flood flow estimates for each of the sub-basins investigated. Ultimately, the flood flow estimates themselves were combined at the different return frequencies in order to look at the underlying distribution. First, a major part of the overall effort was modification of existing numerical models. Later sections of this paper discuss the statistical estimates.

The research of Kovalenko (2020) encompasses the modification of existing hydrologic models that were initially developed by the St. Johns River Water Management District (SJRWMD). Several water management districts collaborated in 2012 to develop the St. Johns River Water Supply Impact Study (WSIS). The WSIS was developed to simulate the effects of withdrawing water from the St. Johns River and The Ocklawaha River (SJRWMD, 2012). The Hydrologic Simulation Program – FORTRAN (HSPF) and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software was used in the SJRWMD's research. These models were developed for every basin and sub-basin along the St. Johns River. Readers are referred to the SJRWMD report for further details on the massive model development effort.

Using the existing hydrologic models developed by the SJRWMD, Kovalenko (2020) developed a new methodology to utilize the models for flood estimation. The technique incorporated the consideration of land-use change, varying precipitation frequency values, antecedent moisture conditions, and two rainfall distributions in the development of the 10-, 25-, 50-, and 100-year return frequency flood estimates in Northeast Florida. Limited research was previously conducted regarding the true impacts of land-use change in the flood estimation technique. Therefore, this research extends the original work by further investigating the impacts of future land-use conditions as well as seasonality.

Study Location

This research focuses on the Black Creek, Julington Creek, Durbin Creek, Big Davis Creek, Ortega River, and Pablo Creek sub-basins of the Lower St. Johns River Basin located in Northeast Florida. The Lower St. Johns River Basin is shown in Figure 1. These sub-basins of interest are encompassed within Clay County, St. Johns County and Duval County. All the sub-basins presented in Figure 2, 3C, 3D, 3H, and 3I are pertinent to this research. These locations represent the physical boundaries of the models utilized in this research. Clay County encompasses 1,668 square kilometers, including 111 square kilometers of water (FEMA 2012). St. Johns County comprises an area of 1,577 square kilometers with approximately 109 square kilometers of Atlantic Ocean shoreline (FEMA 2011). Duval county consists of 2,378 square kilometers and includes 373 square kilometers of water area (FEMA 2013). Nearly level to gently sloping terrain with poorly drained and sandy soils can be found in all three counties (FEMA 2011, 2012, 2013).

As previously mentioned, the sub-basins of interest in this research are part of the Lower St. Johns River Basin. The Lower St. Johns River basin is the northernmost basin along the St. Johns River. These sub-basins have been previously assigned a watershed unit number by the SJRWMD. The SJRWMD created model runs for each of the sub-basins. Table 1 presents all the sub-basins located in the Lower St. Johns River Basin along with the watershed unit number assigned by the SJRWMD and its model area in square kilometers. For the research program, the watershed unit numbers 3C, 3D, 3H, and 3I are of most interest and these are highlighted on Table 1 below. It is important to note the Julington Creek (watershed unit number 3H) contains two additional locations of interest that were assessed in this research – Durbin Creek and Big Davis Creek. These two additional sub-basins were modeled as individual reaches within the Julington Creek hydrologic model. Additionally, the Intracoastal Waterway model (watershed unit number 3I) contains the Pablo Creek sub-basin, which is the last location of interest for this research.

Table 1. Sub-basins belonging to the Lower St. Johns River Basin and their model area (km²).

Watershed Unit Number	Sub-basin Name	Model Area (km²)
3A	Crescent Lake	1,542
3B	Etonia Creek	924
3C	Black Creek	1,316
3D	Ortega River	271
3E	Trout River	248
3F	Deep Creek	358
3G	Sixmile Creek	331
3H	Julington Creek	252
3I	Intracoastal Waterway	268
3J	South Main Stem	997
3K	North Main Stem	630

Hydrologic Model Background

The Hydrologic Simulation Program – FORTRAN (HSPF) and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software was used in this research study. The original HSPF models incorporate either physical or empirical model input parameters (SJRWMD 2012). The physical parameters are watershed areas, land use, precipitation, evaporation, slope, roughness, infiltration, and system hydraulics (SJRWMD 2012), among others.

The models were originally calibrated by the SJRWMD using specific streamflow gages per sub-basin. Table 2 depicts which United States Geological Survey (USGS) streamflow gages were used to calibrate each sub-basin of interest. The Black Creek sub-basin was calibrated with the North Fork gage and South Fork gage. The calibration using the North Fork gage was described as overall very good and the calibration using the South Fork gage was described as overall good (SJRWMD, 2012). The 02246318 (Kirwin Rd.) Ortega River gage calibration was unsatisfactory, and 02246300 (103rd St.) Ortega River gage calibration was overall good (SJRWMD, 2012). The Big Davis Creek gage 02246150 calibration was adequate and lastly, the Pablo Creek gage 02246828 calibration was reasonable (SJRWMD, 2012). During the calibration process, the observed gage data was directly compared to “synthetic” gage data produced from the model output.

Table 2. Rainfall gages used to calibrate the original HSPF model runs (SJRWMD 2012).

Sub-Basin	Gage Name	Gage ID	Notes
Black Creek	North Fork near Middleburg	02246000	
	South Fork Penney Farms	02245500	
Julington Creek	Big Davis Creek at Bayard	02246150	
Durbin Creek	Big Davis Creek at Bayard	02246150	
Big Davis Creek	Big Davis Creek at Bayard	02246150	
Ortega River	Ortega 103rd St. Bridge	02246300	Discontinued in 2003
	Ortega at Kirwin Rd.	02246318	Replacement gage
Pablo Creek	Pablo Creek	02246828	Discontinued in 2002

One of the major requirements of the HSPF model is the incorporation of existing meteorological data. The SJRWMD maintains point rain gauge and Doppler radar rainfall datasets (SJRWMD, 2012). The Doppler radar data set provided only 13 years of rainfall data, whereas the National Weather Service (NWS) stations provided data dating back to the early 1900s. Due to the need to run long term simulations, the NWS rain gauge data was selected for the WSIS model. The model scenario simulations run from 1975 through 2008 (SJRWMD, 2012). The SJRWMD implemented a Thiessen polygon network to establish the area of influence for the NWS rain gauges. The rain gauges of interest will be discussed in further detail in the upcoming sections of this manuscript.

As previously explained, the locations of interest are modeled within four separate watersheds in HSPF. Figure 3 shows a comprehensive hierarchy of the model locations of interest. The reaches are the main points of interest and are the locations where flood estimates were developed in this research. Table 3 depicts modeled area (km²) of each location of interest.

Table 3. Model area of each reach associated with each sub-basin of interest (SJRWMD 2012).

Summary of Thesis Research

WSIS Sub-basin Name	Reach of Interest ID	Reach of Interest Name	Model Area (km ²)
Black Creek	3	South Fork	114
	6	Down North Fork	15
	12	Black Out	43
Ortega River	3	OrtegaRivDns	49
Julington Creek	1	Durbin Creek	104
	5	Julington Creek	25
	6	Big Davis Creek	4
Intracoastal Waterway	8	Pablo Creek DownS	10

As part of her thesis, Kovalenko (2020) investigated the 10-, 25-, 50-, and 100-year return frequency floods in the Black Creek, Julington Creek, Durbin Creek, Big Davis Creek, Ortega River, and Pablo Creek sub-basins. The primary methods used in the research included statistical analysis and hydrologic modeling. It was concluded by comparing the obtained flood flow estimates to existing Flood Insurance Studies (FIS) conducted by the Federal Emergency Management Agency (FEMA). The following section summarize the statistical modeling and the previous numerical modeling methodology and results.

Statistical Analysis

The statistical analysis conducted included multiple methods as suggested by literature including the Log-Pearson Type III (LP3) approach and two flavors of the Power Law (PL) distribution approach namely a linear fit and a non-linear fit. The LP3 distribution was selected because it is the official methodology for analyzing hydrometeorological data used by the United States Army Corps of Engineers (USACE 1994). There is also an abundance of sources providing supporting evidence that the LP3 is a reliable distribution for flood frequency analysis. Kumar (2019), Saf, Dikbas, and Yasar (2007), and Kidson and Richards (2005) all provided substantial evidence of the reliability of the LP3 distribution. The PL distribution was selected because of its increase in popularity for predicting extreme natural events (Alipour, Rezakhani, Shamsai 2016). Kidson and Richards (2005) state that it is arguably one of the simplest probability distributions. They (Kidson and Richards, 2005) demonstrated the successful implementation of the PL for flood estimation in Thailand. Alipour, Rezakhani, Shamsai (2016) demonstrated the successful use of the PL in region 3 (entire Florida, almost entire Alabama, Georgia, South Carolina, North Carolina, and part of Virginia and Mississippi) and region 8 (Mississippi, Louisiana, Arkansas, and Tennessee) of the United States.

The research team used these methods and applied them to both real and synthetic data (e.g. model-derived datasets). Real flood data was obtained from the stream flow gages that were used to calibrate the models. Synthetic gage streamflow data was obtained from the HSPF model output (if synthetic gage data was available). In addition, synthetic flow data was also obtained from the flow output of each reach of interest outlined in Table 3 thus providing a large matrix of statistical flood estimates.

Hydrologic Modeling

The original SJRWMD HSPF models were modified to produce the 10-, 25-, 50-, and 100-year flows in the sub-basins of interest. The general procedure associated with these modifications involves (1) selection

of land-use scenario, (2) determination of target date for rainfall simulation, (3) determination of precipitation frequency value for simulation, (4) addition of antecedent moisture conditions, and (5) consideration of rainfall distribution during simulation. The proposed procedure itself is novel and could be adopted in other watersheds of interest along the St. Johns River where HSPF models are already available.

The numerical model simulations investigated the following scenarios and variables:

- Rainfall amount for different frequencies and uncertainty threshold (median value and 90% confidence interval amount);
- Rainfall distribution (e.g. constant rainfall intensity or more natural distribution);
- Antecedent moisture conditions;
- Flow starting condition in each sub-basin; and,
- Land-use boundary (e.g. either 1995 or projected 2030 land-use).

To produce the 10-, 25-, 50-, and 100-year flood flows, a 10-, 25-, 50-, and 100-year frequency precipitation (24-hour duration) event was simulated. The simulated flood flows are considered to be rainfall driven. The process of simulating any given frequency precipitation event involves identifying the appropriate amount of rainfall to simulate on a specific date, referred to as a target date in this research. Before identifying the precipitation frequency values to simulate in the model, the target dates were determined.

The first step in selecting the appropriate target dates is to reference the output data generated from the original models. To do this, the original models obtained from the SJRWMD were simulated. The simulated flow data output values were obtained in graphical form. Next, the 50th percentile flood (+/- 15%) from the flood frequency curve was identified. The 50th percentile flood is a standard baseline for various flood frequency analysis procedures (Malamud and Turcotte 2006). Finally, ten (10) target dates were selected in varying months of the year to account for the varying rainfall conditions occurring throughout the seasons. This process was repeated for every sub-basin of interest. Originally, the possible seasonality of the flood flows was not investigated but the additional work completed this year rectified that oversight. The modeling of seasonality is discussed in Section 5.

Now that there is understanding on which specific dates the 10-, 25-, 50-, and 100-year rainfall events were simulated, a discussion on specifically how much rainfall to simulate is presented. Using rain gages previously used in the WSIS study, precipitation amounts were chosen using both the median values and 90% values from the National Oceanic Atmospheric Administration (NOAA) Atlas 14 (NOAA 2017).

Table 4 depicts the median and 90th percentile 24-hour 10-, 25-, 50-, and 100-year rainfall events at each sub-basins' corresponding rainfall gage.

Table 4. Rainfall frequency values (cm) applied on each target date based on appropriate rainfall gages.

Sub-basin	Rainfall Gage	24-hour 90 th Percentile Rainfall for each recurrence interval (years)				24-hour Median Rainfall for each recurrence interval (years)			
		10	25	50	100	10	25	50	100
Black Creek	Jax Airport	20.5	27.4	32.8	39.6	17.9	22.5	26.4	31.0
	Glen St. Mary	18.9	24.3	28.4	33.3	16.0	19.5	22.6	25.9
	Starke	18.1	23.2	26.9	31.8	14.8	18.1	21.0	24.2
	Federal Point	19.0	25.0	29.5	35.1	16.1	20.1	23.5	27.4
	Palatka	18.4	23.9	27.9	33.0	15.7	19.3	22.4	25.9
	Average	19.0	24.7	29.2	34.5	16.1	19.9	23.2	26.9
Julington Creek	Jax Beach	22.2	29.5	35.1	41.7	18.6	23.4	27.4	32.0
	St. Augustine	20.8	28.4	34.0	41.1	17.7	22.6	26.9	31.5
	Average	21.5	29.0	34.5	41.4	18.2	23.0	27.2	31.8
Durbin Creek	Jax Beach	22.2	29.5	35.1	41.7	18.6	23.4	27.4	32.0
	St. Augustine	20.8	28.4	34.0	41.1	17.7	22.6	26.9	31.5
	Average	21.5	29.0	34.5	41.4	18.2	23.0	27.2	31.8
Big Davis Creek	Jax Beach	22.2	29.5	35.1	41.7	18.6	23.4	27.4	32.0
	St. Augustine	20.8	28.4	34.0	41.1	17.7	22.6	26.9	31.5
	Average	21.5	29.0	34.5	41.4	18.2	23.0	27.2	31.8
Ortega River	Jax Airport	20.5	27.4	32.8	39.6	17.9	22.5	26.4	31.0
Pablo Creek	Jax Beach	22.2	29.5	35.1	41.7	18.6	23.4	27.4	32.0

The SJRWMD defines the antecedent soil moisture conditions as an indicator of watershed wetness and soil storage availability before a storm (SJRWMD 1985). It is known that these conditions have a significant effect on runoff volume and runoff rate. Three levels of antecedent moisture conditions (AMC) exist: AMC-I for dry, AMC-II for normal, AMC-III for wet conditions (SJRWMD 1985). Table 5 depicts the seasonal rainfall limits for these three AMCs. According to Schiariti (n.d.), AMC II is considered for modeling purposes because it is essentially the average moisture condition. According to the SJRWMD's Technical Publication SJ90-3 (1990), the rainy season in northeast Florida lasts from June to October and the dry season lasts from November to May (1990). The simplest method that Kovalenko (2020) discovered to simulate antecedent moisture conditions (AMC) in the existing HSPF models was to simulate it as daily rainfall. As depicted in Table 5, the AMC was simulated over the course of five days. Therefore, to summarize the application of AMC, 5.3 centimeters of rainfall over the course of five days were simulated before each target date.

Table 5. Seasonal Rainfall Limits Antecedent Moisture Conditions (SJRWMD, 1985)

AMC	Total 5-Day Dormant Season	Total 5-Day Growing Season
I	Less than 1.3 centimeters	Less than 3.6 centimeters
II	1.3 to 2.8 centimeters	3.6 to 5.3 centimeters
III	More than 2.8 centimeters	More than 5.3 centimeters

When applied on an hourly basis, the rainfall data described in Table 5 represents a uniform distribution – each hour will receive the same amount of rainfall. However, in reality, rainfall occurs in varying temporal distributions. Therefore, an additional rainfall distribution was also applied in a separate scenario. According to Suphunvorranop (1985), the Soil Conservation Service (SCS) has developed four types of rainfall distributions – Types I, II, III (representative of different climates in the United States), and Type II Modified (representative of Florida specifically). These synthetic rainfall distributions occur over a 24-hour time period. The SCS Modified Type II rainfall distribution, obtained from the Suphunvorranop (1985), was also modeled to determine the effects on the flood magnitude predictions when different rainfall distributions are applied.

Existing Flood Insurance Studies

Existing flood estimates were obtained from the Federal Emergency Management Agency’s (FEMA) Flood Insurance Studies (FIS). The FIS contain flood-risk data that aids in the development of flood insurance rates for communities’ efforts of safe floodplain management (FEMA 2014). Between Clay County, St. Johns County, and Duval County, three different methodologies were implemented for flood risk analysis. The FEMA FIS estimates were adjusted accordingly to represent the modeled drainage basin area (Kovalenko 2020). In some cases, the HSPF modeled drainage basin area did not match the FEMA FIS drainage basin area from which the results were obtained. Therefore, a simple extrapolation was conducted to standardize the FEMA FIS estimates’ drainage basin area to match the drainage basin area of the HSPF modeled locations for more accurate comparison.

Clay County implemented the Magnitude and Frequency of Flood Discharges in Northeast Florida from the Technical Publication SJ-86-2 (Rao, 1986) to conduct their hydrologic analyses and obtain their flood estimates. The methodology involves the determination of different return periods (T). Given an annual exceedance probability of a maximum event, the return period is defined as $T = 1/P$, where P is the annual exceedance probability of a maximum event (Rao, 1986). The technique consists of applying an appropriate probability distribution and fitting it to sample data, where the sample data consists of observed annual peak flows (Rao 1986). From there, probability distributions such as the two-parameter Gumbel distribution and the five-parameter Wakeby distribution were implemented (Rao 1986). The Log-Pearson Type III distribution was also recognized and used as it was recommended by the United States Water Resource Council (Rao 1986).

St. Johns County Flood Insurance Study is a compilation of previously printed FIS reports (FEMA 2011). The 2003 countywide analyses were conducted by the United States Army Corps of Engineers using the HEC-1 computer program. The methodology was deemed appropriate for the characteristic drainage basin conditions; however, it was determined that the limited history of stream gage records prevented effective statistical analysis (FEMA 2011). The HEC-1 models incorporated the Natural Resources Conservation Service (NRCS) unit hydrograph and kinematic wave routing methods, sub-basin runoff curve numbers, lag times, stream cross sections, and Manning's "n" roughness factors (FEMA 2011). United States Geological Survey (USGS) topographic maps, field inspection, and aerial photos were utilized. Additionally, the modified SCS Type II rainfall distribution was implemented into the model. Overall, only Durbin Creek and Sixmile Creek were adequately calibrated due to a lack of sufficient stream gage data.

Duval County utilized the Environmental Protection Agency Stormwater Management Model (EPA SWMM5) versions 12 to 14 to conduct hydrologic analyses (FEMA 2013). The model applied precipitation across hydrologic units and performed hydrologic calculations, which account for hydrologic unit geometry, land use, and soil characteristics. The computed surface runoff hydrographs were routed to the dynamic hydraulic model.

These FIS reports were used as a reputable baseline for reasonable flood estimate values to expect for results obtained through the statistical analysis and hydrologic modeling approaches of Kovalenko (2020).

Initial Research Results Summarized from Kovalenko (2020)

The purpose of this section is to provide the reader with an understanding of the variety of flood estimates and scenarios that Kovalenko (2020) obtained and to compare it to the current research. Tables 6 and 7 depict 25- and 100-year return frequency flood estimates obtained from all methods conducted by Kovalenko (2020), respectively.

Table 6. All 25-year return frequency results (Kovalenko 2020) in cubic meters per second.

Sub-Basin	Method	HSPF 1995, 90 th Percentile Precip., AMC	LP3	PL Linear Regression	PL Nonlinear Regression	FEMA FIS	HSPF 1995, Median Precip., AMC
	Reach Location						
Black Creek	Reach 3	NA	234	328	272	348	251
	South Fork Gage	NA	237	364	230	NA	NA
	Reach 6	NA	328	553	344	342	265
	North Fork Gage	NA	325	581	324	NA	NA
	Reach 12	NA	405	600	481	856	573
Julington Creek	Reach 2	69	63	95	83	93	48
	Reach 5	23	27	40	31	72	15
Durbin Creek	Reach 1	44	40	69	49	109	33
Big Davis Creek	Reach 6	20	26	43	31	17	12
	Synth Gage	16	17	29	19	44	11
	Real Gage	NA	26	42	30	NA	NA
Ortega River	Reach 3	135	194	253	213	116	NA
	103 rd St. Synth Gage	88	90	126	91	70	NA
	Kirwin Real		70	86	78	119	NA
	Kirwin Rd. Synth Gage	132	101	124	110	NA	NA
Pablo Creek	Reach 8	76	75	109	94	167	NA
	Pablo Real Gage	NA	37	68	47	NA	NA

Table 7. All 100-year return frequency results (Kovalenko 2020) in cubic meters per second.

Sub-Basin	Method	HSPF 1995, 90 th Percentile Precip., AMC	LP3	PL Linear Regression	PL Nonlinear Regression	FEMA FIS	HSPF 1995, Median Precip., AMC
	Reach Location						
Black Creek	Reach 3	NA	333	718	515	531	NA
	South Fork Gage	NA	346	1,086	452	NA	NA
	Reach 6	NA	447	1,568	654	480	NA
	North Fork Gage	NA	466	1,791	652	NA	NA
	Reach 12	NA	458	1,166	787	1,268	NA
Julington Creek	Reach 2	132	87	230	180	125	82
	Reach 5	41	43	106	68	96	26
Durbin Creek	Reach 1	86	56	203	145	160	51
Big Davis Creek	Reach 6	29	37	117	62	32	23
	Synth Gage	31	24	88	40	63	20
	Real Gage	NA	39	122	65	NA	NA
Ortega River	Reach 3	212	238	446	329	175	NA
	103 rd St. Synth Gage	121	148	371	203	106	NA
	Kirwin Real	NA	90	166	144	182	NA
	Kirwin Rd. Synth Gage	189	134	245	205	NA	NA
Pablo Creek	Reach 8	98	107	150	203	249	NA
	Pablo Real Gage	NA	49	196	102	200	NA

Research Findings And Conclusions

The conclusions of Kovalenko's research (2020) are presented in this section. These findings are the inspiration for the current research conducted in this manuscript. The research of Kovalenko (2020) produced mostly reliable flood frequency estimates in the sub-basins of interest. The resulting peak flood flows in each model run typically occurred one to two days after the Target Date that was modified. However, the resulting peak flow occurred directly on the Target Date in several model runs. It is believed that when the peak flow occurred on the Target Date, the daily timestep of the model was potentially smoothing the peak to some degree. Since the original HSPF models were created by various individuals at the SJRWMD, there is a possibility that there are slight differences in modeling approaches between sub-basins. The Black Creek sub-basin naturally produces higher flow rates compared to the other basins that were studied. Because the Black Creek sub-basin contains naturally higher flow rates, the simulation

of additional precipitation frequency values resulted in the model crashing consistently. Attempts to resolve these problems in HSPF were not successful. Luckily, other watersheds did not exhibit similar issues. Like the observation made by Gebremariam et al. (2014), source-code modification for the HSPF model was challenging primarily because of lack of documentation related to code structure and subroutines. The most complete set of flood estimates obtained in the Black Creek sub-basin were the 10- to 50-year flood estimates using the 1995 land-use condition, median precipitation frequency values, uniform rainfall distribution, and antecedent moisture conditions. The HSPF model run flood estimates were generally lower than the FEMA FIS estimates.

The model runs in the Julington Creek, Durbin Creek, and Big Davis Creek sub-basins produced satisfactory results. In this area, land-use variation, variation of precipitation frequency values, and variation of rainfall distribution were assessed. Overall, the 2030 land-use paired with the 90th percentile precipitation frequency, uniform rainfall distribution, and antecedent moisture conditions produced the highest flood flows; however, these relatively high flood flow values were still lower than the adjusted FEMA FIS estimates for those locations. Although the 2030 land-use runs were successfully simulated in these basins and produced relatively high flood flows, because of the complications involved in running the 2030 land-use runs in the Black Creek sub-basin, the 1995 land-use became the default for the remainder of the sub-basins. It is also important to note that the mouth of Julington Creek is more strongly tidally influenced and could be influenced by storm surge, which makes hydrologic modeling in those locations more challenging

The Ortega River and Pablo Creek sub-basin HSPF models ran well. The 1995 land-use, 90th percentile precipitation frequency values, uniform distribution, and antecedent moisture conditions were considered in the model runs. Ortega River and Pablo Creek are also more heavily tidally influenced at the mouth and could experience a greater deal of storm surge, which poses additional challenges to the hydrologic modeling process. Additionally, it was previously observed that the FEMA FIS drainage areas were usually larger than the drainage areas in the HSPF models. A possible reason for the difference in area is the consideration of tidal influence. The hydrologic HSPF models do not consider the tidal areas of each sub-basin. The tidal areas of the project locations were instead modeled in the hydrodynamic portion of the model, which is not part of the research.

In a case study conducted by Ninov et al. (2008), the results of their HSPF modeling for flood assessment yielded flood flows that were 130% higher than the historical flood flows, while the modeled annual, seasonal, and low flows were approximately 25% to 33% less than the observed respectively. This case study provides a perspective on the variety of results that can be obtained with the use of the HSPF model. This is a valuable perspective to consider when developing a flood estimation methodology. The research of Ninov et al. (2008) produced flood flows that were too high while the results of the HSPF flood modeling presented in Kovalenko (2020) appeared lower compared to FEMA FIS estimates. The results and certainty of the HSPF model simulations cannot be concretely proven and serve only as estimates.

Overall, the Log-Pearson Type III (LP3) statistical computations were successful. The trends found in the data were conclusive and expected. This was the expected outcome of the LP3 results as it is a common method for flood frequency estimation. The Power Law (PL) statistical computations were mostly successful. The PL derived flood estimates were typically much higher than the LP3 results and the HSPF modeled results. The PL derived flood estimates were even higher than the adjusted FEMA FIS estimates at times. The PL distributions produced more reasonable estimates for the 10- and 25-year flood estimates. The PL distribution seemed to massively overestimate the 50- and 100-year flood flows. The PL was selected because of the praise it received in various research studies for being a simple and effective method. However, there was certainly a caveat that the PL performs best with a larger data set (Kidson and Richards, 2005). The difference in computing the PL distribution regression coefficients using the Linear Regression model and Nonlinear Regression model also produced varying results. It was evident that the data sets were better suited for one method over the other in certain cases.

The use of the FEMA FIS estimates proved to be an asset as the estimates were derived by qualified professionals. There is more certainty in comparing the estimated developed herein to the FEMA FIS estimates. However, it has also been established that the FEMA FIS estimates were all obtained using varying methods. This raises a question regarding the consistency of the FEMA FIS estimates. It was evident that different methodologies can at times produce widely varying flood flows. As previously established, the FEMA FIS estimates are either based on hydrologic modeling or statistical estimates. Research conducted by Okoli et al. (2019), compared statistical and hydrological methods for the estimation of design floods based on 10,000 years of synthetically generated weather and discharge data. Although their hydrologic modeling did not reflect any real applications and was intended as a baseline for discussion for comparison of results, their ultimate findings suggest that more than one flood estimate should be obtained and the maximum value (within reason) should be selected to minimize the likelihood of underestimating the design flood (Okoli, 2019). As part of the research conducted, the various flood estimates were compiled together irrespective of method used to develop them. The estimates at a particular return frequency were then evaluated to discern their underlying statistical distribution. First, a normal distribution was assumed. This worked well in Ortega River Reach 3 and Julington Creek Reach 2 and 5 for the 10-year through 50-year flood events, but overall was not satisfactory since the lower tail of the distribution can lead to negative flow rate estimates for floods which is physically impossible. Alternatively, it was assumed that the underlying distribution of the flood estimates was log-normal, but this led to a narrow band that did not fit the outliers well. Ultimately, a bounded normal distribution assumption worked well as a first iteration to more realistically portray the range of values. For example, for the Durbin Creek Reach 1, 100-year flood estimates shown in Table 7, a mean of 116.83 cms and a sample standard deviation of 61.75 were calculated and the estimate range was bounded by 51 cms as a minimum and 203 cms as a maximum. Using a Monte-Carlo approach, this distribution was simulated 10,000 times and the 90% value (~178 cms) was selected as an improved “best estimate” but with a better understanding of the considerable uncertainty. It should be noted that this improved best estimate exceeded the recommended flood insurance value.

Therefore, this work has demonstrated the possibility for obtaining a wide range of flood estimates depending on the estimation method selected. Kovalenko (2020) concluded that the establishment of extreme flood estimates based on one methodology is outdated and involves higher risk in the development of planning measures for flood protection. Therefore, this work advocates for consideration of various techniques when developing flood estimates. As presented in Kovalenko (2020), consideration of seasonality was not incorporated when developing the HSPF model runs and the final results of all methods assessed indicated that considering the 2030 land-use condition could increase the magnitude of the simulated flood flows and perhaps provide better numerical estimates in each sub-basin.

New Research Evaluation of Land-use Change

This past year, follow on work was completed regarding model simulations using HSPF building upon work completed in 2020. The hydrologic modeling technique implemented in this research is in accordance with the original hydrologic modeling technique discussed in previous portions of this paper. Table 8 provides an overview of the parameters included in the hydrologic models developed in new effort. The 2030 land-use condition was used for all model runs in this research. The 90th percentile confidence interval precipitation point value was simulated at each sub-basin of interest. The precipitation frequency values were obtained using the methodology described in Kovalenko (2020) and summarized earlier in this manuscript. The Type II Antecedent Moisture Condition (AMC) was incorporated into model runs. Lastly, the uniform rainfall distribution was applied when incorporating the precipitation frequency values and the AMC. According to prior research conducted by Kovalenko (2020), modeling a uniform rainfall distribution versus varying temporal distributions does not have a significant effect on the resulting flood flows in the locations of interest.

Table 8. Parameters incorporated in this research's model run modification procedure.

Parameter	Type
Land-Use Condition	SJRWMD 2030
Precipitation Frequency	90 th Percentile
Antecedent Moisture Conditions	Type II (5.3 centimeters over 5 days)
Rainfall Distribution	Uniform

Contrary to the earlier research, this research considers the effects of seasonality when simulating flood flows. For this set of simulations, the team chose to simulate ten (10) Target Dates from varying months and developed an average flood flow magnitude from all ten (10) estimates. This research considers five (5) Target Dates from the rainy season and five (5) Target Dates from the dry season in each sub-basin. The flood flows obtained from simulating rainfall in the wet season are compared to the flood flows obtained from simulating rainfall in the dry season in this research.

Discussion

Tables 9 through 11 show the 25-year and 100-year flood estimates at Ortega River and Pablo Creek. Figures 4 through 8 represent a comparison of the 1995 land-use HSPF model runs, 2030 land-use HSPF model runs, and the adjusted FEMA FIS estimates. A graphical representation of the flood estimates at Black Creek was not created because of the lack of data. As discussed previously, the modeling capabilities in the Black Creek sub-basin were limited due problems encountered modifying the source code to produce the flood estimates desired. Therefore, only the 10-year flood estimates (2030 land-use and seasonality included) were obtained at Black Creek. The adjusted FEMA FIS estimates discussed previously were included in the tables and graphs for the reader for comparison purposes. After all, the FEMA FIS estimates are highly revered and professionally derived estimates. The comparison graphs shown in Figures 4 through 8, depict that the 2030 land-use condition paired with the 90th percentile precipitation values, and antecedent moisture conditions produce higher flood flows than the 1995-land use condition and the FEMA FIS estimates in Julington Creek Reach 2 and Ortega River Reach 3; while all other locations depict that the FEMA FIS estimates produce higher flows than the other approaches. Generally, the flood estimates increased in magnitude from the FEMA FIS estimate, to the 1995 land-use HSPF model derived estimates, to the 2030 land-use scenario model derived estimates. However, in the sub-basins where the highest flood flow estimate was that of the FEMA FIS estimate, there are indications that that sub-basin is likely more tidally influenced. Therefore, the HSPF models may not be the most suitable route for flood estimation in those locations since the hydrodynamic portion of the model is not represented.

Table 9. Ortega River 25-year Return Frequency Flood Estimates (cms).

Data Analysis	103rd St. Synth Gage	Kirwin Rd. Synth Gage	Reach 3
2030 Average Wet Season	96	142	144
2030 Median Wet Season	96	142	145
2030 Average Dry Season	98	146	157
2030 Median Dry Season	98	146	152
2030 Total Median	97	144	149
2030 Total Average	97	144	151
1995 Total Average	88	132	135
Total Average Difference	9	13	16
FEMA	70	120	117

Table 10. Ortega River 100-year Return Frequency Flood Estimates (cms).

Data Analysis	103rd St. Synth Gage	Kirwin Rd. Synth Gage	Reach 3
2030 Average Wet Season	129	200	219
2030 Median Wet Season	129	200	220
2030 Average Dry Season	132	204	232
2030 Median Dry Season	132	204	228
2030 Total Median	131	202	225
2030 Total Average	130	202	226
1995 Total Average	121	190	212
Total Average Difference	9	13	14
FEMA	106	182	175

Table 11. Pablo Creek Results Flood Estimates (cms).

Data Analysis	25-year	100-year
	Reach 8	Reach 8
2030 Average Wet Season	77	99
2030 Median Wet Season	77	100
2030 Average Dry Season	77	100
2030 Median Dry Season	77	100
2030 Total Median	77	100
2030 Total Average	77	99
1995 Total Average	76	99
Total Average Difference	1	1
FEMA	167	249

Overall, the results of this research point towards a noticeable difference between consideration of the 1995 land-use condition and the 2030 land-use condition when implementing Kovalenko's (2020) flood estimation technique using the SJRWMD hydrologic models. Consideration of seasonality in selecting Target Dates for precipitation simulation in the hydrologic models also resulted in various flood flows. It was observed that simulating the 2030 land-use condition 10-, 25-, 50-, and 100-year return frequency floods in the dry season produced lower flood flows than simulating in the wet season which was expected.

Besides the more in-depth evaluation of the effect of urbanization and land-use change, this additional work compares the effects of wet and dry seasonal precipitation frequency induced rainfall events to obtain flood estimates. All remaining sub-basins that were examined (Black Creek, Ortega River, and Pablo Creek) exhibited an increase in flood flows when the precipitation frequency events were modeled during the wet season.

Sahu et al. (2016) deduced that the most accurate forecast of flood prediction should incorporate seasonal streamflow predictions utilizing hydrologic models which are calibrated for individual river basins. In the case of the methodology discussed in this paper, the pre-existing SJRWMD HSPF models of the St. Johns River Basins have been calibrated sufficiently such that their use should be valid. With

the incorporation of seasonality and assurance of sufficient calibrations per each sub-basin, individuals who chose to implement the flood estimation technique presented herein should be producing reasonable flood estimates for most sub-basins. Additionally, Alipour, Rezakhani, and Shamsai (2016) determined that incorporating seasonality into the hydrologic modeling procedure can improve the magnitude of flood estimates. This is especially true in the results obtained in this research. The hydrologic models which were simulated during the wet season produced higher flood flows. Although the wet season scenario produced higher simulated flood flows, the consideration of seasonality did not truly yield dramatic differences. However, according to others, the incorporation of seasonality into hydrologic flood modeling is a widely recommended. Although the result of these sub-basins may have not indicated the greatest variability between wet and dry season derived flood estimates, the inclusion of seasonality in flood estimation is encouraged based on other relevant sources.

As urban expansion increases with the growth of the human population, land-use change is inevitable in humanity's future. The results of this research indicate that the consideration of a more urbanized land-use has the potential to produce higher flood flows. This research demonstrates the 1995 land-use condition in comparison to the 2030 land-use condition. Black Creek, Julington Creek, and Durbin Creek experienced a difference of up to the second order of magnitude between the flood estimates derived from the 1995 land-use and the 2030 land-use scenario models. Choi and Deal (2008), confirmed in their research that land-use change involved with urban growth can result in higher surface flows and that low flows tend to decrease. Baloch, Ames, and Tanik (2014) not only considered land-use change but also climate change in their predictive hydrologic modeling efforts. Although climate change was not considered in this research, it is important to note that not only did Baloch, Ames, and Tanik (2014) observe an increase in flood flows when climate change was considered, but they also confirmed that the effects of land-use change resulted in a compounding effect on flood flows. Their research confirmed that the magnitude, frequency, and duration of flood flows are significantly modified as urbanization increases. Therefore, it is further evident that land use is a crucial component of accurate extreme flood estimation for the future.

As was mentioned earlier in this paper, the underlying distribution for each range of flood flow estimates was of great interest in this research effort. Using the *NIST/SEMATECH e-Handbook of Statistical Methods* (2012), the Shapiro-Wilk test was conducted on all results obtained by all methods from this research regarding Reach 3 of the Ortega River sub-basin. The Shapiro-Wilks test revealed that the 10-year, 25-year, and 50-year flood frequency estimates were normally distributed because the determined P-values were greater than alpha (0.05). However, the Shapiro-Wilks test did not indicate a normal distribution of the 100-year flood estimates of all methods applied at Ortega Reach 3 because the P-values were less than alpha (0.05). For the best understanding of the results at all sub-basins, testing for normality should be conducted. Although only Reach 3 at Ortega River was tested for normality, it is evident that these results indicate variance between testing methods and between flood magnitude. In the case of Ortega River Reach 3, the 100-year flood estimate was not normally distributed and that is expected because there is greater uncertainty involved in flood estimates of larger magnitude. As was determined previously and confirmed with the normality tests utilized, a truncated or bounded normal

distribution appears to be a reasonable underlying distribution to use when evaluating and using a range of flood flow estimates instead of just the one, best estimate. It was suggested earlier that using this approach combined with a Monte Carlo simulation, it is possible to perhaps derive a superior “best estimate”. For this work, the team adopted the 90% from the Monte Carlo simulation which is consistent with many engineering reliability studies.

Conclusions

This research assessed the significance of seasonality and land-use change when developing hydrologic flood estimating models in HSPF for the 10-, 25-, 50-, and 100-year flood frequency estimates at Black Creek, Julington Creek, Durbin Creek, Big Davis Creek, Ortega River, and Pablo Creek. Although the model runs developed in the wet season versus the dry season did not vary significantly in the sub-basins involved in this research, consideration of seasonality is still recommended based on other available literature (Alipour, Rezakhani, and Shamsai 2016). The 2030 land-use scenario models resulted in higher flood flows than the 1995 land-use scenario models. Each sub-basin varied in regard to the significance that land-use variation played in the model runs. The 2030 land-use scenario produced higher flood flows than the 1995 land-use scenario in all locations except for Pablo Creek, where the two produced almost identical results. In all locations except for Ortega Reach 3 and Julington Creek Reach 2, the adjusted FEMA FIS estimate produced the greatest flood estimate. The methodology originally developed by Kovalenko (2020) has its limitations. The locations of the flood estimates developed in this research are closely tied to the tidal regions of the St. Johns River. Since the HSPF model does not directly consider the impacts of tidal behavior, a level of uncertainty is present regarding the 10-, 25-, 50-, and 100-year flood flows developed using this methodology. Since this research only assessed sub-basins in the Lower St. Johns River Basin, there is much opportunity remaining to assess the remaining in-land sub-basins of the St. Johns River that are not heavily influenced by the tides. Another opportunity for further research involves the assessment of the hydrodynamic activity impacts to flood estimation in the tidal regions of the Lower St. Johns River Basin. Overall, the HSPF models developed by the SJRWMD serve as a valuable tool for developing flood estimates in precise locations along the various sub-basins of the St. Johns River and it is recommended to incorporate seasonality and land-use change for most accurate development of flood estimates. To better account for the uncertainties associated with traditional methods of flood estimation, this research demonstrates that the superior flood estimate may possibly be obtained through the implementation of multiple estimation methods paired with a Monte Carlo simulation.

Declarations

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Conflicts of interest/Competing interests – There are no known conflicts of interest.

Availability of data and material – Supplementary data has been uploaded.

Code availability – The HSPF code for each sub-basin is available from the St. Johns River Water Management District (SJRWMD).

Authors' Contributions – Samantha Kovalenko completed the data analysis, writing, and revisions. Dr. Brown assisted with data analysis, review, and editing. Drs. Akan and Schonning assisted with editing and review.

Ethics approval – All work presented herein was completed by the research team listed. Portions of the work was published in the Master's Thesis of Kovalenko (2020) and in Kovalenko et al. (2020) and have been cited in the paper as such. The Master's Thesis work is summarized and discussed thoroughly herein.

Consent to participate – Consent is granted to share this research with the journal audience.

Consent for publication – All necessary approvals are granted for manuscript publication.

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Figures

Figure 1

Major Basins of the Water Supply Impact Study (SJRWMD 2012)

Figure 2

Sub-basins of the Lower St. Johns River Basin (SJRWMD 2012)

Figure 3

Hierarchy of HSPF model run structure

Figure 4

Comparison of Results at Ortega River Reach 3

Figure 5

Comparison of Results at Pablo Creek Reach 8

Figure 6

Comparison of Results at Durbin Creek Reach 1

Figure 7

Comparison of Results at Julington Creek Reach 2 and Reach 5

Figure 8

Comparison of Results at Big Davis Creek Reach 6

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