ASSESSING THE INFLUENCE OF CLIMATE CHANGE ON FLOODING HAZARDS

FOLLOWING TROPICAL CYCLONE EVENTS IN

THE SOUTHEAST UNITED STATES

by

MONICA HELEN STONE

SAGY COHEN, COMMITTEE CHAIR
JASON C. SENKBEIL
PETER R. WAYLEN

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Geography
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2016

ABSTRACT

Recent tropical cyclones, like Hurricane Katrina, have been some of the worst the United States has experienced. Tropical cyclones are expected to intensify, bringing about 20% more precipitation, in the near future in response to global climate warming. Further, global climate warming may extend the hurricane season. This study focuses on four major river basins (Neches, Pearl, Mobile, and Roanoke) in the Southeast United States that are frequently impacted by tropical cyclones. The Soil and Water Assessment Tool (SWAT) was used to model flow along these rivers from 1998-2014 with 20% more precipitation during tropical cyclones. The results of this study show that an increase in tropical cyclone precipitation due to future climate change may increase peak flows at the mouths of these Southeast rivers by ~7-18%. Most tropical cyclones that impact these river basins occur during the low discharge season, and thus rarely produce flooding conditions at their mouths. An extension of the current hurricane season of June-November, due to global climate warming, could encroach upon the wet season in these basins and lead to increased flooding. On average, this analysis shows that an extension of the hurricane season to May-December increased flooding susceptibility by 63% for the rivers analyzed in this study. That is, 4-6 more days per year likely would have been above bankfull discharge if an average tropical cyclone had occurred any day (based on 1998-2014 data) in the months May-December than in the current hurricane season months of June-November. More research is needed on the mechanisms and processes involved in the water balance of the four rivers analyzed in this study, and others in the Southeast United States, and how this is likely to change in the near future with global climate warming.

DEDICATION

This thesis is dedicated to my dad, James Stone, for always encouraging me to pursue science and to be actively involved in research that advances human knowledge. His love for science and dedication to his research inspired me to pursue my Master's degree. I will always be grateful for his continuous support of my education.

LIST OF ABBREVIATIONS AND SYMBOLS

NSB	National Science Board
IPCC	Intergovernmental Panel on Climate Change
GFDL	Geophysical Fluid Dynamics Laboratory
SWAT	Soil and Water Assessment Tool
USGS	United States Geological Survey
DFO	Dartmouth Flood Observatory
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
GIS	Geographic Information Systems
Q	discharge
$\bar{Q}$	average of yearly discharge maxima
K	frequency factor
σ	standard deviation
σ^2	variance
Σ	sum of
n	number of years
C_s	skew coefficient

ACKNOWLEDGMENTS

I am pleased to thank my advisor, Dr. Sagy Cohen, for helping me formulate a good methodology for my research, for his continued support and help over the past 2 years, and for the generous computers and software he made available for use in my research. I would also like to thank Dr. Sarah Praskievicz for her help in teaching and helping me troubleshoot SWAT and SWATCup. Thank you to my committee members, Dr. Jason Senkbeil and Dr. Peter Waylen, for their advice and availability to answer questions. I am thankful for the help of Dr. G. Robert Brakenridge for his help in installing river gages for some of my study basins with the Dartmouth Flood Observatory. I am especially thankful for the support and encouragement of my family and friends, and their willingness to talk through aspects of my research and offer advice. And lastly, thank you to The University of Alabama for funding my trips to Boulder, CO; Orange Beach, AL; and San Francisco, CA to present my research.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

In the Southeast United States tropical cyclones are the most severe rain events (Schumacher & Johnson, 2006). While tropical cyclones occur less frequently than other rain-producing events, they cause the most damage because they cover a wide geographic area and often cause widespread flooding (Greenough *et al.*, 2001; Mousavi, Irish, Frey, Olivera, & Edge, 2011; Schumacher & Johnson, 2006). On average, tropical cyclones occurring in the Southeast bring 240.4 mm of rain in a 24-hour period (Schumacher & Johnson, 2006). The severity of flooding following tropical cyclone events is a function of tropical storm frequency, landfall location, precipitation intensity, and mean sea level (Irish & Resio, 2013). In addition to flooding, these storms cause further damage from their strong winds (Greenough *et al.*, 2001; Mousavi *et al.*, 2011), and they frequently can cause tornadoes and landslides (Greenough *et al.*, 2001; NSB, 2007).

Coastal communities in the United States, especially along the East Coast and the Gulf Coast, are most at risk to the flooding, strong winds, and heavy precipitation associated with tropical cyclones (Irish, Sleath, Cialone, Knutson, & Jenson, 2014). Unfortunately, approximately half of the United States population lives within only 50 miles of the coast (NSB, 2007), and, on average, areas that are prone to tropical cyclones are 5 times more heavily populated than the rest of the nation (Frey *et al.*, 2010). Recent increases in coastal populations and development in coastal areas is posing an increasing risk to human life and coastal infrastructure (Greenough *et al.*, 2001; Irish *et al.*, 2014). Though there has been significant growth since, in the 1990s infrastructure along the East and Gulf coasts was worth approximately $3 trillion (NSB, 2007).

Hurricanes are the most costly and cause the most damage of all weather hazards that occur in the United States (Frey *et al.*, 2010; NSB, 2007). The monetary losses from hurricanes are increasing; in 2006 dollars, average annual losses were $1.3 billion from 1949-1989, $10.1 billion from 1990-1995, and $35.8 billion from 2002-2007 (NSB, 2007). As mentioned above, tropical cyclone events often cause widespread, destructive flooding. Floods lead to more deaths in the United States than any other natural hazard (Greenough *et al.*, 2001; NSB, 2007), and half of the deaths worldwide from natural hazards are due to floods (Schumann & Di Baldassarre, 2010). About 70 million people live in hurricane-prone areas (Greenough *et al.*, 2001). Flooding from high storm surges during hurricanes has caused approximately 14,600 deaths over the last century; about 50-100 deaths occur per hurricane event (Greenough *et al.*, 2001). In addition to deaths caused by flooding, hurricanes can cause a variety of health impacts including: illnesses that result from ecological changes (changes in the abundance and distribution of disease-carrying insects and rodents, and mold and fungi), damage to healthcare infrastructure and reduced access to healthcare services, damage to water and sewage systems, overcrowded conditions in shelters, and psychological effects from the trauma faced by victims (Greenough *et al.*, 2001).

Inland areas are also impacted by tropical cyclones; several past studies have looked at the influence of tropical cyclones on inland river flooding in small catchments. Kostaschuk, Terry, & Raj (2001) investigated tropical cyclone-induced flooding in the Rewa River system in Viti Levu, Fiji. They observed that rainstorms caused a higher number of floods, but that floods caused by tropical cyclones were much larger (Kostaschuk *et al*., 2001). Waylen (1991) conducted a partial duration series flood analysis for the Santa Fe River in Florida, and found similar results. Tropical cyclone-induced floods were found to occur less often than floods from other rain-producing events, however, they tended to have larger magnitudes and longer durations (Waylen, 1991). Specifically, they found that tropical cyclone floods were ~3 times larger and ~2 times longer than other floods (Waylen, 1991). Tropical cyclones bring about 15% of the precipitation that occurs in the Southeast during the hurricane season, which is enough to end most droughts that occur in the Southeast (Maxwell, Soulé, Ortegren, & Knapp, 2012).

Numerous studies have indicated that global climate warming may intensify tropical cyclones, and is very likely to result in sea level rise (Bronstert, Niehoff, & Büger, 2002; Frey *et al*., 2010; Greenough *et al*., 2001; Irish & Resio, 2013; Irish *et al*., 2014; Kostaschuk *et al*., 2001; Mousavi *et al.*, 2011; Ouellet, Saint-Laurent, & Normand, 2012). Majors hurricanes, those that are Category 3 or higher on the Saffir-Simpson scale, for example Hurricane Katrina, are the most likely to intensify (Frey *et al.*, 2010; Mousavi *et al.*, 2011), however there is some debate about changes in tropical cyclone frequency. Some research predicts that tropical cyclone frequency will increase (e.g. Greenough *et al.*, 2001; Ouellet *et al.*, 2012). This hypothesis was refuted by Irish & Resio (2013) and Kostaschuk *et al.* (2001); both showed that tropical cyclones are likely to intensify with global climate warming, but occur less frequently.

Greenhouse gases in the atmosphere not only increase atmospheric temperature, but also can lead to increased sea-surface temperatures (Irish *et al.*, 2014). The warmer the sea surface temperature, the more intense tropical cyclones are, thus, global warming may intensify tropical cyclones, such that storms may tend to have higher storm surge levels (Frey *et al.*, 2010; Irish *et al.*, 2014; Mousavi *et al.*, 2011). Between the time periods 1850-1899 and 2001-2005 global sea-surface temperatures rose 0.55°C (Irish *et al.*, 2014). The Intergovernmental Panel on

Climate Change (IPCC) predicts that global sea-surface temperatures will increase 1.1-6.4°C over the next century (Irish & Resio, 2013; Mousavi *et al.*, 2011). Sea surface temperatures need to be at or above ~26.7°C for tropical cyclones to form (Steenhof & Gough, 2008). The current hurricane season extends from June to November, however longer seasons (i.e. storms occurring before June and/or after November) have been occurring in recent years (Dwyer *et al.*, 2015). While research on this topic is not complete, there is some indication that increased sea-surface temperatures may lead to a further extension of the Atlantic hurricane season (Dwyer *et al.*, 2015). There is an 8% increase in a tropical cyclone's pressure differential for a 1°C increase in tropical sea-surface temperature (Irish & Resio, 2013; Irish *et al.*, 2014; Mousavi *et al.*, 2011). Further, there is a 3.7% increase in a tropical cyclone's wind speed for a 1°C increase in tropical sea-surface temperature (Irish *et al.*, 2014). Climate models also suggest that precipitation rates from tropical cyclones may increase 20% by 2100 (GFDL, 2013; Knutson *et al.*, 2010).

Several studies about the effects of climate change on tropical cyclone intensity have been conducted for the Corpus Christi, TX area (Frey *et al.*, 2010; Mousavi *et al.*, 2011). Frey *et al.* (2010) conducted a study to determine how severe historical hurricanes would be if they were to occur in the current climate, and those predicted for the 2030s and 2080s. They found that, in all three climate scenarios, storm-surge flood depth, area of flood inundation, population affected, and economic damages would all increase compared to the historical levels (Frey *et al.*, 2010). In a follow-up study by Mousavi *et al.* (2011), the rise in storm-surge flood depth in response to global warming was found to be related to tropical cyclone intensification, measured in terms of central pressure. They found that sea level rise and tropical cyclone intensification contribute equally to increased flood depths (Mousavi *et al.*, 2011). This second study indicates that flooding following severe hurricane events is likely to have a detrimental impact on highly populous coastal areas (Mousavi *et al.*, 2011).

In the Eastern United States, precipitation and streamflow have been increasing over the last century (Cruise, Leyland, & Al-Hamdan, 2010). Globally, precipitation has increased 10% due to global climate warming (Bronstert *et al.*, 2002). Increased precipitation, coupled with tropical cyclone intensification and sea level rise are all increasing the risk of flooding in both inland and coastal areas, but a fourth factor with an impact on flooding is land use (Alexakis *et al.*, 2014). Flooding severity from tropical storms can be attenuated or exacerbated depending on what covers the land surface, and how it is used. Deforestation can worsen flooding following storms because runoff is increased (Shankman, 1996). In the last century, much of the agriculture that dominated the Southeast United States was moved to the West, and the Southeast transitioned to be more urban/commercial (Cruise *et al.*, 2010). The Southeast today is about 60% forest, and only 25% agricultural (Cruise *et al.*, 2010). Human activities on the land surface, like urbanization and structurally altering rivers, can lead to increased runoff and river discharge, which can worsen flooding (Bronstert *et al.*, 2002).

Urbanization, both in coastal and inland areas, has led to an increase in the number of people at risk to the effects of flooding (Greenough *et al.*, 2001). One reason for this is because the process of urbanization creates areas of land that are impermeable to precipitation (Greenough *et al.*, 2001). Overland flow occurs when the rate of precipitation exceeds the rate of infiltration (Bronstert *et al.*, 2002). Vegetation promotes infiltration of precipitation into the subsurface, and when vegetation is removed and replaced with impermeable urban surfaces, such as concrete, overland flow is increased and can cause or worsen flooding, especially in downstream areas (Alexakis *et al.*, 2014; Ouellet *et al.*, 2012; Wheater & Evans, 2009). Further, water drainage systems collect storm water in urban areas and deliver it to the nearest river much more quickly than it would naturally drain to the nearest river through the groundwater system (Wheater & Evans, 2009). Thus, by increasing overland flow, urbanization increases the amount of water delivered to rivers, and decreases the lag time between precipitation and delivery of precipitated flow to rivers (Alexakis *et al.*, 2014; Wheater & Evans, 2009; Yan & Edwards, 2013).

The second reason that urbanization has led to an increase in the number of people at risk to the effects of flooding is due to the use of floodplains for anthropogenic activities. The natural function of a floodplain is to store excess water during a flood event on a river (Wheater & Evans, 2009). Floods also serve as a source of water and nutrients for the species that inhabit the floodplain (Cruise *et al.*, 2010). However, recently, there has been an increasing use of floodplains for agriculture and increasing development on floodplains (Wheater & Evans, 2009). Of the pre-settlement floodplain forest that existed in the South, 63% was converted for agricultural purposes (Shankman, 1996). Grazing animals cause soil to become more compact and reduce soil infiltration rates, which increases runoff (Greenough *et al.*, 2001; Wheater & Evans, 2009). Also, heavy field-machinery, deep plowing, and soil tillage can reduce infiltration capabilities and lead to increased runoff (Bronstert *et al.*, 2002). Development on floodplains puts people and infrastructure at risk when the floodplain experiences a natural flood, especially when exacerbated by increased runoff from urbanization (Wheater & Evans, 2009). Detention ponds are one method that has been developed to attenuate the runoff in urban areas (Wheater & Evans, 2009). However, afforestation is the best solution, since it increases the permeability of the soil and because vegetation increases evapotranspiration (Wheater & Evans, 2009), but the larger the storm, the less effective vegetative cover becomes at attenuating runoff (Yan & Edwards, 2013).

While there has been much study of the impact of tropical cyclones on coastal flooding, there has been little research on how these high-intensity precipitation events affect the hydrology of streams just inland of coastal areas. Further, few studies have focused on how inland flooding is likely to be altered with global climate change. This study investigates the impacts of past tropical cyclones with 20% more precipitation, as is expected by 2100 (GFDL, 2013; Knutson *et al.*, 2010), and an extension of the hurricane season on flooding at the mouths of rivers in the Southeast United States. The goal of this study is to help determine how flooding patterns may change in the near future in order to elucidate the impact such changes may have on communities in the Southeast United States.

CHAPTER 2

STUDY AREAS

This study is focused in the Southeast United States, where tropical cyclone events occur more frequently, and where severe flooding following these events can have profound impacts on the prosperity of communities. Specifically, four river basins (Neches, Pearl, Mobile, and Roanoke) were selected for analysis in this study (*Figure 1*). These four study basins were chosen to be in areas that experience tropical cyclones, and a high number of severe hurricanes, but also in areas where daily discharge data since 1998 is available (*Figure 1*; *Table 1*).

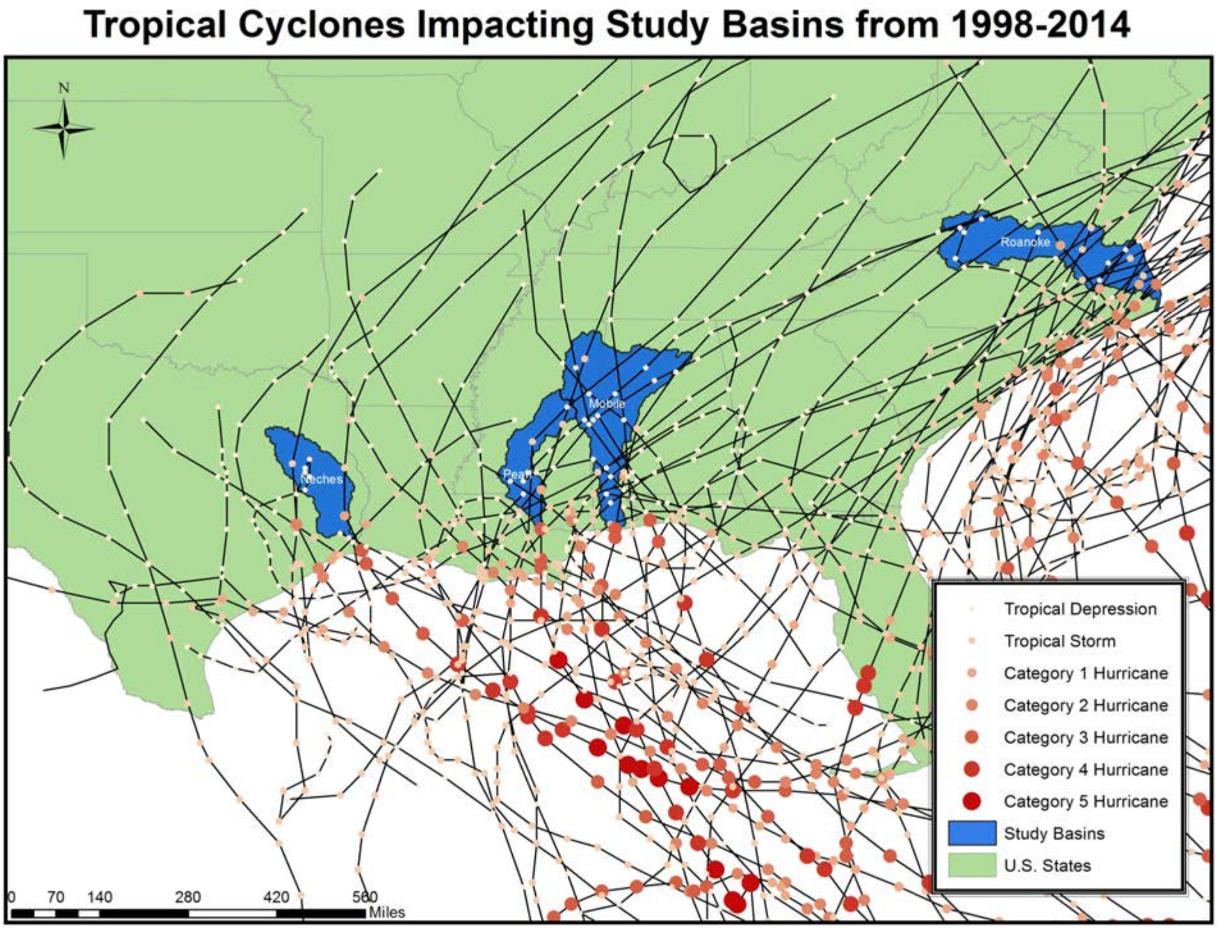

Figure 1. The location of the four study basins that are analyzed in this study (blue). Colored dots represent points along the tracks of all tropical cyclones since 1998 that impacted the study basins, where the color/size of the dot indicates the severity of the storm at that location (see legend). (HURDAT2, NHD, ESRI)

Table 1. Location of Gaging Stations in the four Study Basins

River Basin	Near	Latitude	Longitude	Basin Size
Neches	Silsbee/Evadale, TX	30.374	-94.094	25,117 km^2
Pearl	Slidell, LA	30.374	-89.774	22,894 km^2
Mobile	Mt. Vernon, AL	31.094	-87.974	110,955 km^2
Roanoke	Williamston, NC	35.864	-76.904	25,963 km^2

Gaging stations along these rivers were chosen to be inland of coastal areas so that tidal fluctuation and storm surge would not be factors when analyzing discharge, and far enough downstream to include as much of the study basins as possible. These four basins were selected to represent a range of sizes and geographic locations that exist throughout the Southeast United States. United States Geological Survey (USGS) gages were used where data was available for the period extending from 1998-2014, the time frame analyzed in this study. In many cases USGS stream gages either did not have daily discharge data or did not have a long enough history of daily discharge data, or if sufficient daily discharge data was available, the location of the gaging station was either too close to the coast where there were tidal fluctuations, or too far upstream in the catchment such that only a small fraction of the catchment was flowing to the gaging station. In these situations, Dartmouth Flood Observatory (DFO) satellite river gages where used.

CHAPTER 3

METHODOLOGY

3.1 Determining Bankfull Discharge

Daily discharge data for the outlet of each of the study basins over the period from 1998-2014 was obtained from either the USGS or the DFO's Satellite River Discharge Measurements. The DFO sites provide daily measures of discharge since January 1, 1998 (DFO, 2015). Discharge is estimated from NASA and the Japanese Space Agency TRMM microwave data (DFO, 2015). This dataset is particularly useful because it allows the user to place gaging stations at any location along world rivers. Using the daily discharge data obtained, the Log-Pearson Type III statistic was calculated for each basin. The Log-Pearson Type III statistic can be used to provide an "industry standard" of bankfull discharge for a river at a particular gaging station; times when discharge is greater than the bankfull discharge indicate the occurrence of a flood (IACWD, 1982). The bankfull discharge typically has a return period of 2.33 years (Waylen, 1991). In Kostaschuk *et al.*'s (2001) study of tropical cyclone floods in Fiji, the Log-Pearson Type III statistic was found to more accurately represent their partial duration flood series than the Pareto distribution, even though it tended to slightly underestimate the largest flows.

The Log Pearson Type III statistic was calculated using maximum yearly discharge values from 1998-2014 with the following equation:

$$\log Q = \log \bar{Q} + K\sigma \tag{1}$$

where Q is the discharge of some return period, $\log \bar{Q}$ is the average of the log Q maximum discharge values, K is the frequency factor (found using the K frequency factor table, which is based upon return period and the skew coefficient), and σ is the standard deviation of the log Q discharge values (OSU, 2005). The variance can be found using:

$$\sigma^2 = \frac{\sum_1^n (\log Q - \log \bar{Q})^2}{n-1} \tag{2}$$

where n is the number of maximum discharge values (i.e. the number of years) (OSU, 2005). The standard deviation can be found by taking the square root of the variance (OSU, 2005). The skew coefficient can be found using (OSU, 2005):

$$C_s = \frac{n \sum (\log Q - \log \bar{Q})^3}{(n-1)(n-2)(\sigma^3)} \tag{3}$$

The bankfull discharge was used to determine how many total days from 1998-2014 each river was experiencing a flood, as well as how many days from 1998-2014 during the hurricane season, June-November (Dwyer *et al.*, 2015), each river was experiencing a flood. This study focuses on discharge and flooding susceptibility at the mouths/outlets of the four study basins. It is assumed that conditions at the outlets are indicative of much of the river lengths.

3.2 Determining the Frequency and Timing of Tropical Cyclones

NOAA's HURDAT2 dataset was used to determine when tropical cyclones passed over the four study basins. For each tropical cyclone event on record, this dataset provides information on the year, month, day, time, latitude, longitude, maximum sustained wind speed (in knots), minimum pressure (in millibars), and several wind speed radii extents for points along a tropical cyclone's track (where points are spaced at 6-hour intervals). The data provided in the HURDAT2 dataset is downloadable in a text file format. A Python script was developed to extract the information provided in this database in order to create point shapefiles of tropical cyclone paths that could be analyzed in GIS (Appendix A). The paths of tropical cyclones between 1998 and 2014 were buffered to a width of 300 mi (~500 km), the average size of a tropical cyclone (Darby *et al.*, 2013). Then, a selection by location procedure was used to determine which buffered tropical cyclones passed over each of the study basins. The latitude and longitudes of the buffered points along tropical cyclone paths passing over the basins were then used to look up the corresponding dates each storm passed over each basin in the HURDAT2 dataset.

3.3 Modeling River Discharge from 1998-2014 with SWAT

The Soil and Water Assessment Tool (SWAT) was used to model discharge in each of the study basins. The model was first run using data from 1998-2014. SWAT utilizes elevation, soil type, land cover, precipitation, and weather data to model river discharge throughout a basin. Elevation and land cover data were obtained for each study basin from the USGS. Soil data was obtained for each study basin from the Web Soil Survey. Precipitation data, from two weather stations per basin, was obtained from the National Climatic Data Center. The detailed methodology on how to run SWAT is provided in Appendix B. The SWATCup model was tested as a way to calibrate the SWAT models to actual measures of discharge (from the USGS or DFO). SWATCup was able to calibrate the Pearl and Mobile basins relatively well to monthly discharge (NS=0.49 and NS=0.31 respectively), however it was not able to provide a reliable monthly calibration for the Neches or Roanoke basins (NS < 0), or reliable daily calibrations for any of the basins (NS < 0). Because tropical cyclones occur on a daily scale, SWATCup was not used for calibration of the SWAT models. The timing of the peaks and troughs of the SWAT hydrographs corresponded well with those on the USGS and DFO hydrographs (*Figures 2-5*). It was primarily the magnitude of the values of daily discharge on the hydrograph comparisons that differed; particularly, SWAT seemed to overestimate the magnitude of daily discharge. Since flow magnitude was the main difference between the modeled flow and the observed flow, adjustment equations were used based on regression analysis between modeled and observed discharge in each basin. A power-law relationship was chosen since it corrects for both high and low values, and thus could help reduce the magnitude error in the modeled daily discharge values from SWAT. Further, percent change was used when comparing discharge values for a particular day/particular tropical cyclone event in different modeling scenarios, as described below. *Figures 6-9* compare modeled daily discharge from SWAT with observed daily discharge for each of the four study basins.

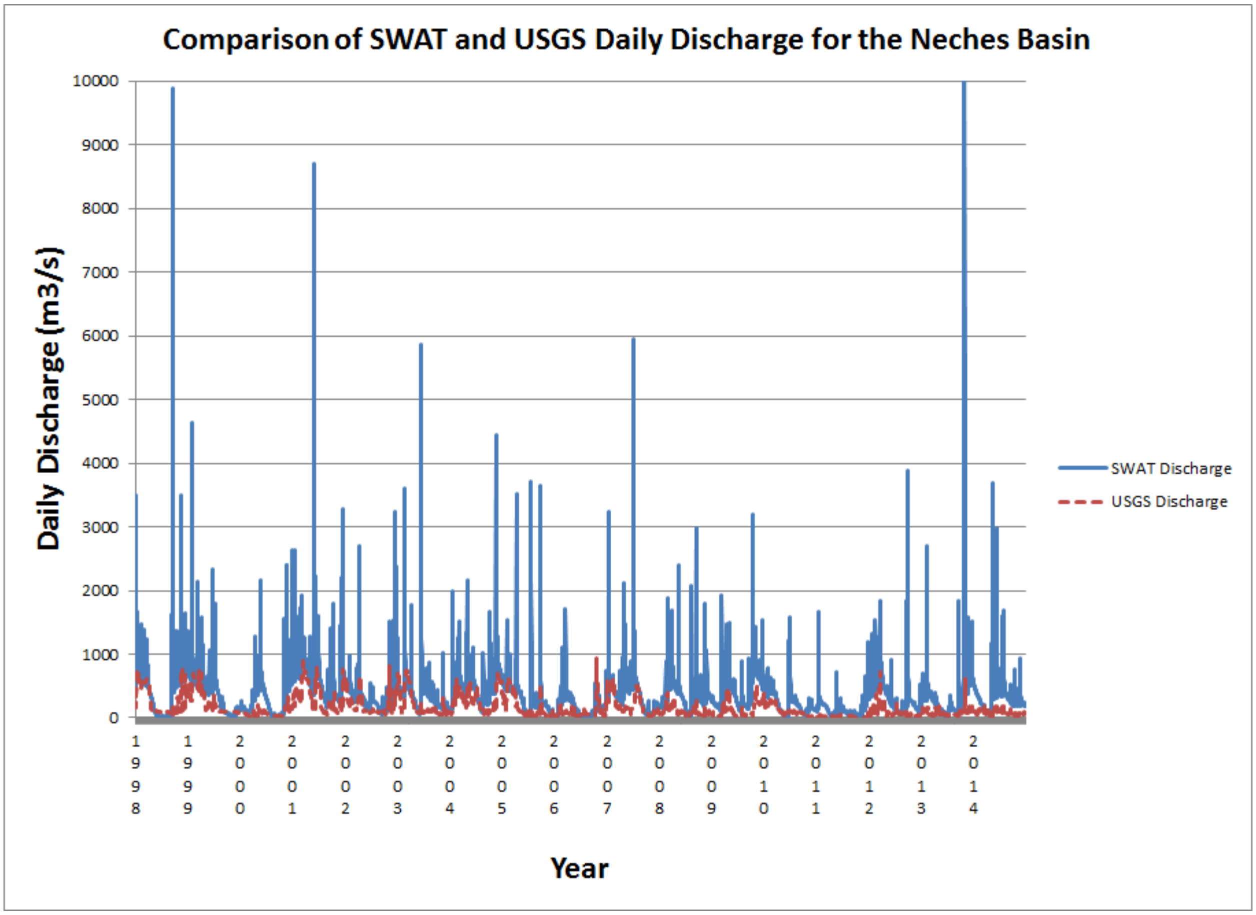

Figure 2. Comparison of SWAT Daily Discharge (blue line) to USGS Daily Discharge (red dashed line) for the Neches Basin

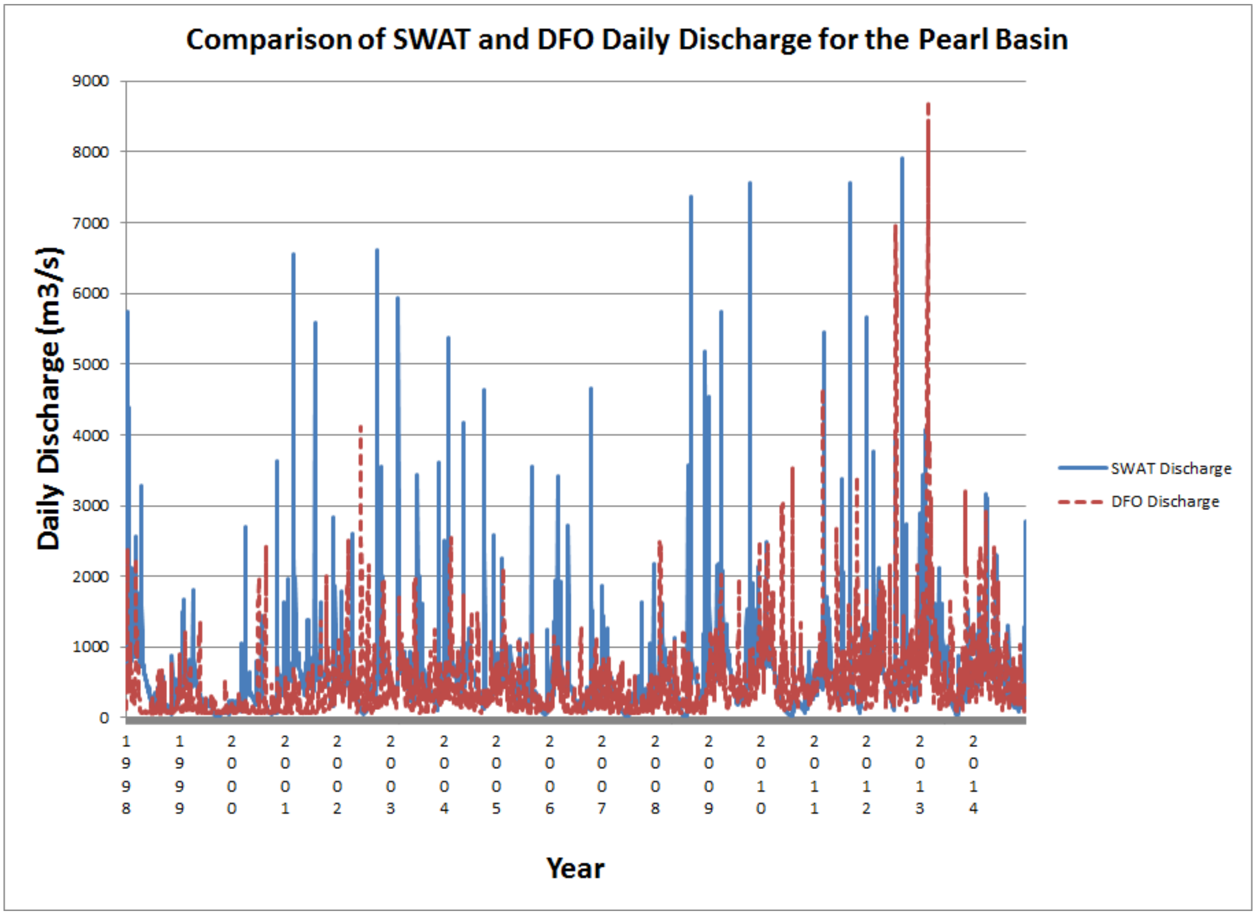

Figure 3. Comparison of SWAT Daily Discharge (blue line) to DFO Daily Discharge (red dashed line) for the Pearl Basin

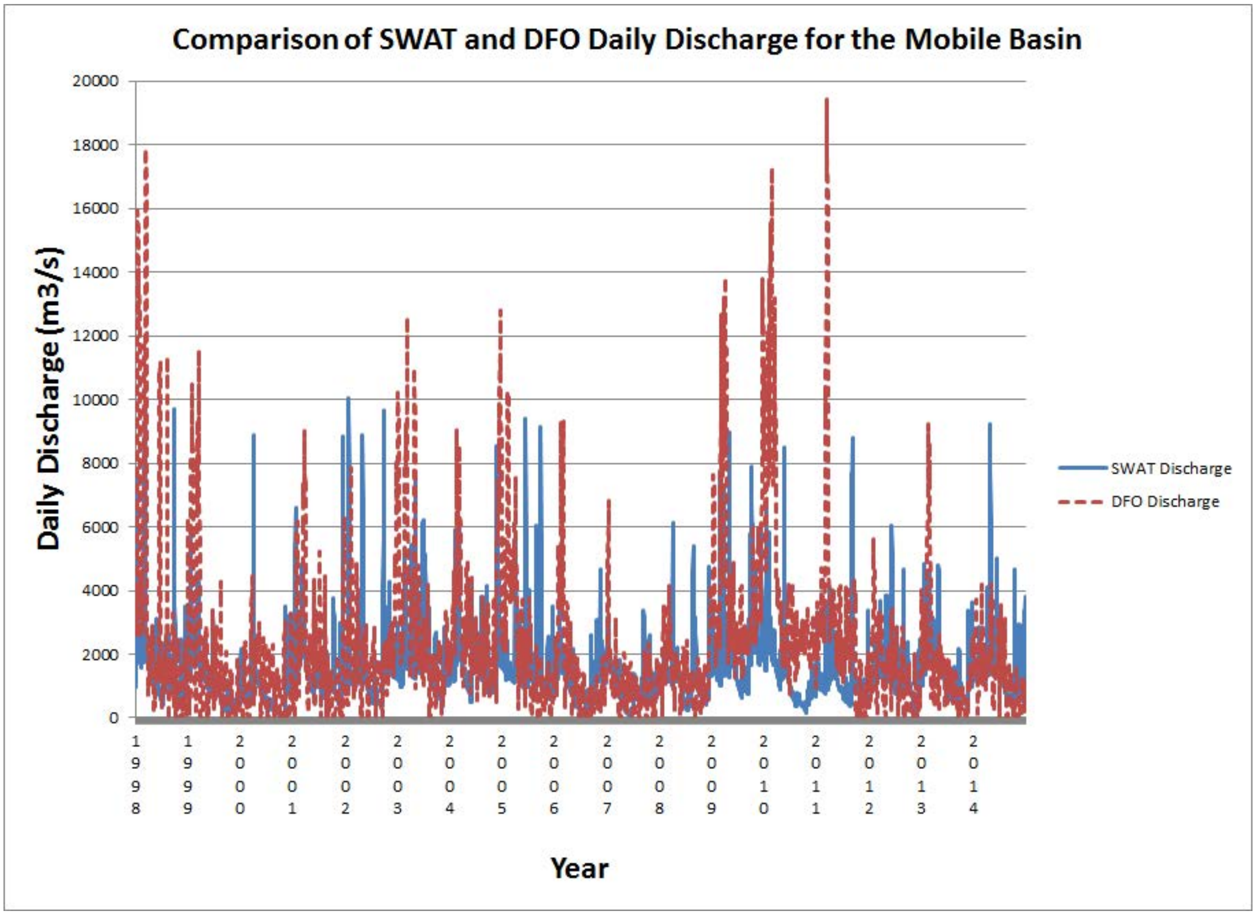

Figure 4. Comparison of SWAT Daily Discharge (blue line) to DFO Daily Discharge (red dashed line) for the Mobile Basin

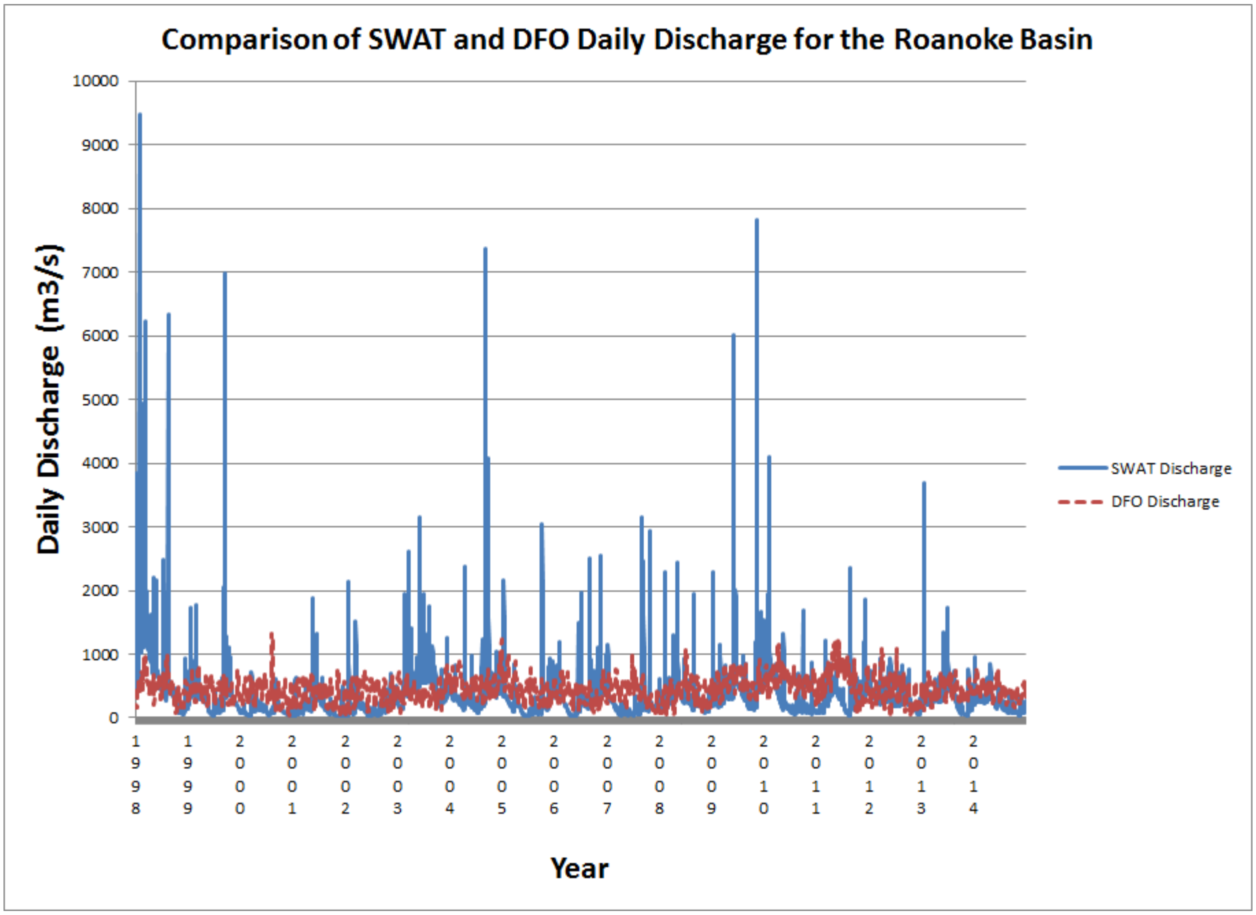

Figure 5. Comparison of SWAT Daily Discharge (blue line) to DFO Daily Discharge (red dashed line) for the Roanoke Basin

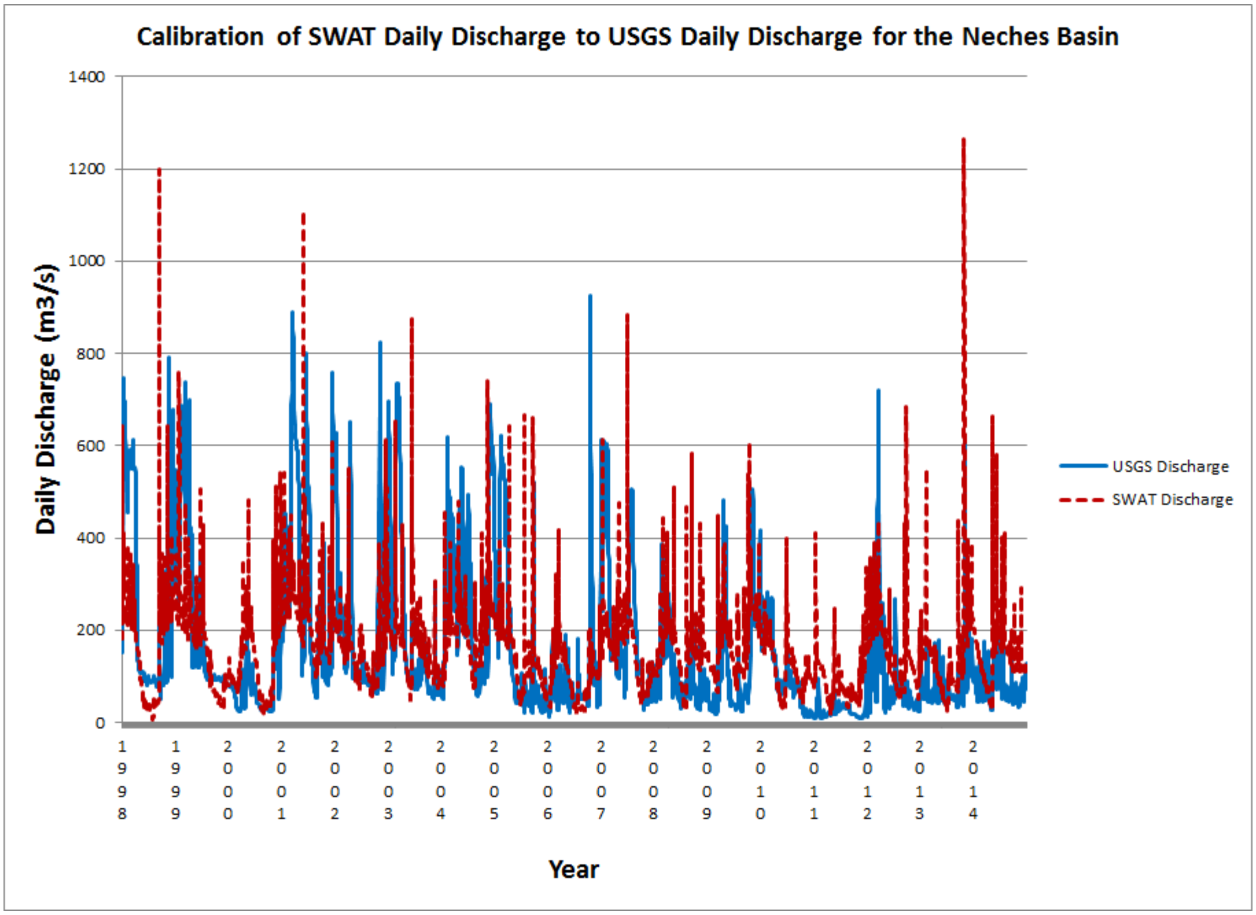

Figure 6. Calibration of SWAT Daily Discharge (red dashed line) to USGS Daily Discharge (blue line) for the Neches Basin

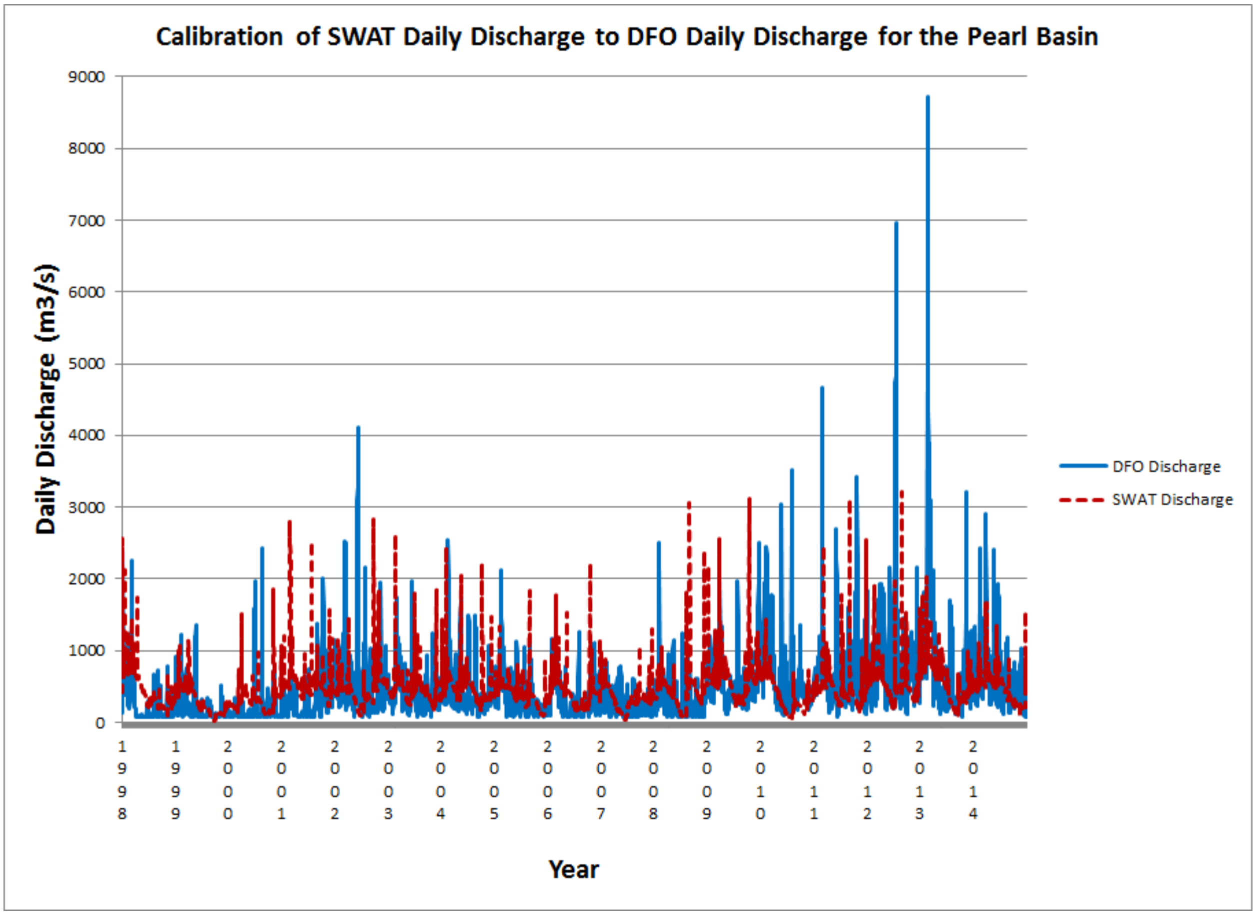

Figure 7. Calibration of SWAT Daily Discharge (red dashed line) to DFO Daily Discharge (blue line) for the Pearl Basin

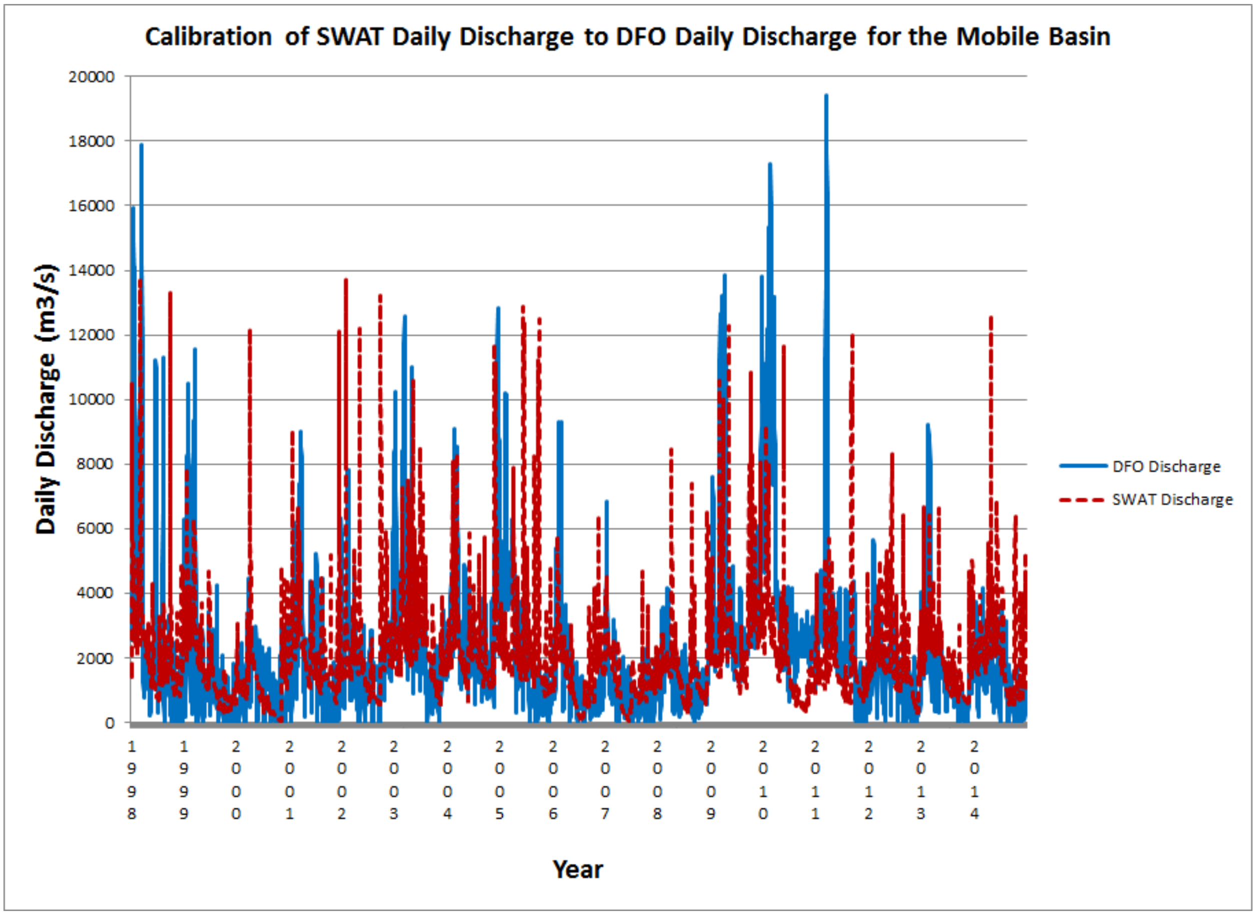

Figure 8. Calibration of SWAT Daily Discharge (red dashed line) to DFO Daily Discharge (blue line) for the Mobile Basin

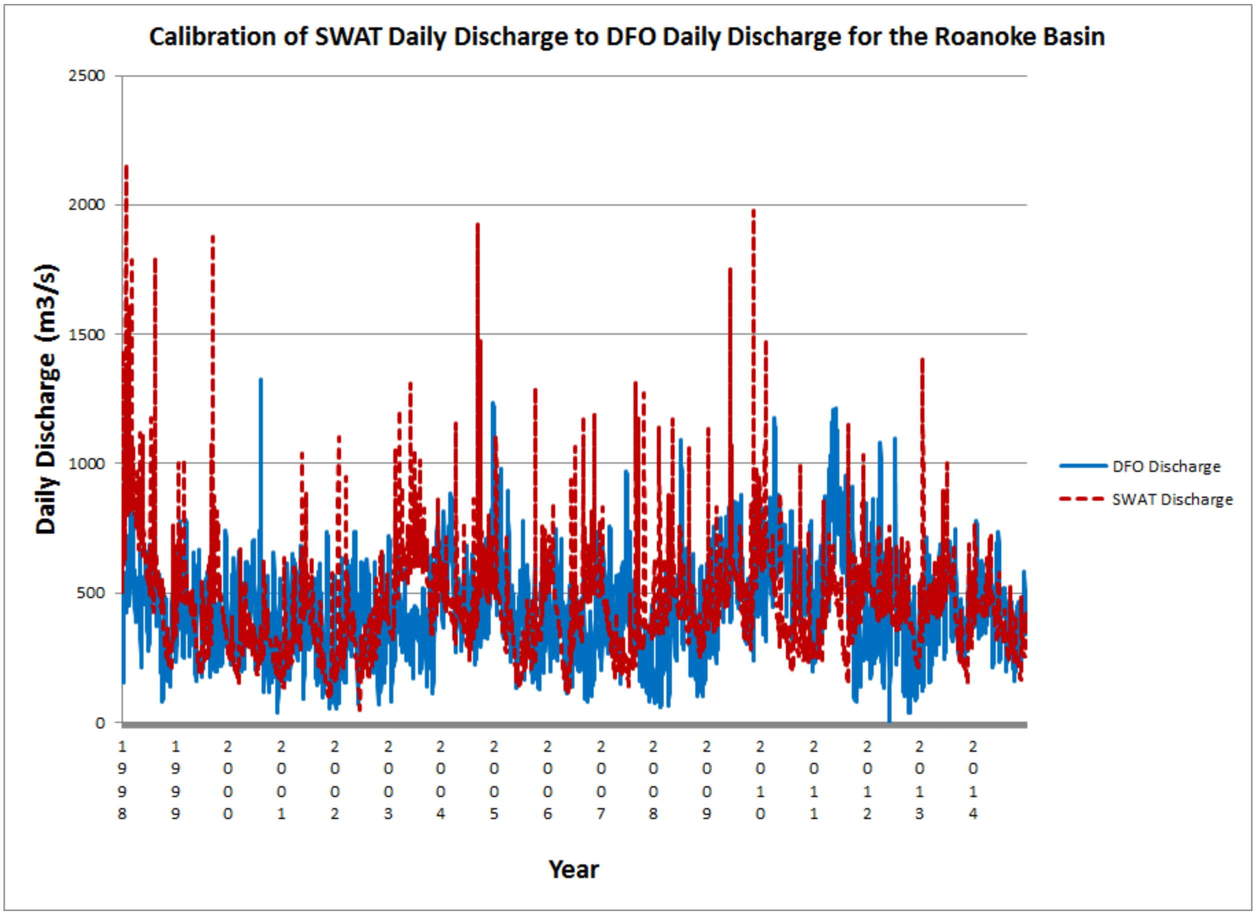

Figure 9. Calibration of SWAT Daily Discharge (red dashed line) to DFO Daily Discharge (blue line) for the Roanoke Basin

3.4 Modeling River Discharge with Tropical Cyclones Bringing 20% more Precipitation

The effects of increased precipitation from tropical cyclones on discharge in the study basins were investigated. It was estimated that tropical cyclones may bring about 20% more precipitation by the year 2100 (GFDL, 2013). SWAT was run again on each of the four study basins with precipitation increased by 20% during tropical cyclone events, and all other variables unchanged. The percent change in peak discharge following each storm in each of the four study basins was then compared to the percent of the basin area impacted by each storm and the duration (in days) of each storm over each basin. Peak discharge was considered to be the day of highest discharge, after which discharge values started decreasing, either during or just after a tropical cyclone event. To determine the area of the basin impacted by each storm, the ArcGIS tool Intersect was used to determine the overlap between the 300 mi buffered storm paths and the study basin polygons. Intersect creates an output polygon of the area of overlap that can be displayed in GIS. A field was added in the attribute tables of these overlap shapefiles and the tool Calculate Geometry was used to calculate their areas in square kilometers. To use the tool Calculate Geometry, shapefiles must be projected; UTM projections were used in this study.

3.5 Analyzing the Effects of an Extended Hurricane Season on Flooding Susceptibility

The effects of an extended hurricane season (May-December) on flooding potential in the study basins were investigated. For each tropical cyclone in each basin from 1998-2014 the discharge the day before the event was compared to the peak discharge in order to determine the percent increases in discharge due to the tropical cyclones. For this analysis, the USGS and DFO daily discharge datasets were used. The average percent increase in discharge due to a tropical cyclone was then applied to the USGS/DFO discharge data for every day in the months June-November between 1998-2014 for each basin. The resulting increased discharge was compared with the basin's bankfull discharge to determine the number of days between June-November from 1998-2014 that would be above bankfull discharge (flooding) if the peak discharge of an average tropical cyclone were to occur on any given day during that time period. For example, an average tropical cyclone for a basin may increase river discharge by 10%. The discharge values for every day between 1998-2014 in the months of June-November would then be increased by 10%. The increased discharge values for each of these days would then be analyzed to see how many were above bankfull discharge, indicating flooding (e.g. 100 days between 1998-2014 in the months of June-November might be above bankfull discharge if the peak discharge of an average tropical cyclone were to occur on any given day during this time period). This analysis was then repeated for every day in the months May-December between 1998-2014 for each basin. The current hurricane season is June-November (Dwyer *et al.*, 2015), thus May-December was chosen to see what effect an extension of the hurricane season by one month on either side might have on flooding in these basins. A 1-month extension was considered because several May (1 month outside the current hurricane season) tropical cyclones have impacted the Roanoke Basin in recent years. NOAA's HURDAT2 dataset also indicates the occurrence of some May, as well as some December, Atlantic tropical cyclones.

CHAPTER 4

RESULTS

4.1 Bankfull Discharge and Flooding Analysis for the Study Basins

The bankfull discharge for each of the four study basins, calculated by using the Log-Pearson Type III statistic, is shown in *Table 2*. The total number of flooding days from 1998-2014 along each river, the number of flooding days from 1998-2014 during the hurricane season, and the percentage of flooding days from 1998-2014 that occurred during the hurricane season are shown in *Table 3*.

Table 2. Bankfull Discharge for the four Study Basins

Basin	**Bankfull Discharge (m^3/s)**
Neches	734
Pearl	2418
Mobile	10803
Roanoke	989

Table 3. Flooding Days from 1998-2014 for the four Study Basins

Basin	**Number of Flooding Days from 1998-2014**	**Number of Flooding Days from 1998-2014 during the Hurricane Season**	**% of Flooding Days Occurring during the Hurricane Season**
Neches	34	17	50
Pearl	81	33	41
Mobile	117	7	6
Roanoke	64	29	45
Sum	**296**	**86**	**--**
Average	**74**	**21.5**	**35.5**

4.2 Tropical Cyclone Frequency and Timing

From 1998-2014 (17 years), 15 tropical cyclones impacted the Neches Basin, 28 impacted the Pearl Basin, 30 impacted the Mobile Basin, and 36 impacted the Roanoke Basin. The number of tropical cyclones impacting each basin each year has not been constant over the period of study (*Figure 10*). The years 2004 and 2005 had high numbers of storms in every basin, and in recent years there have been very few storms. For example, in 2004 and 2005 most basins experienced 2 or more tropical cyclones, while in 2013 and 2014 only the Roanoke basin was impacted by tropical cyclones (and only 1 in each year).

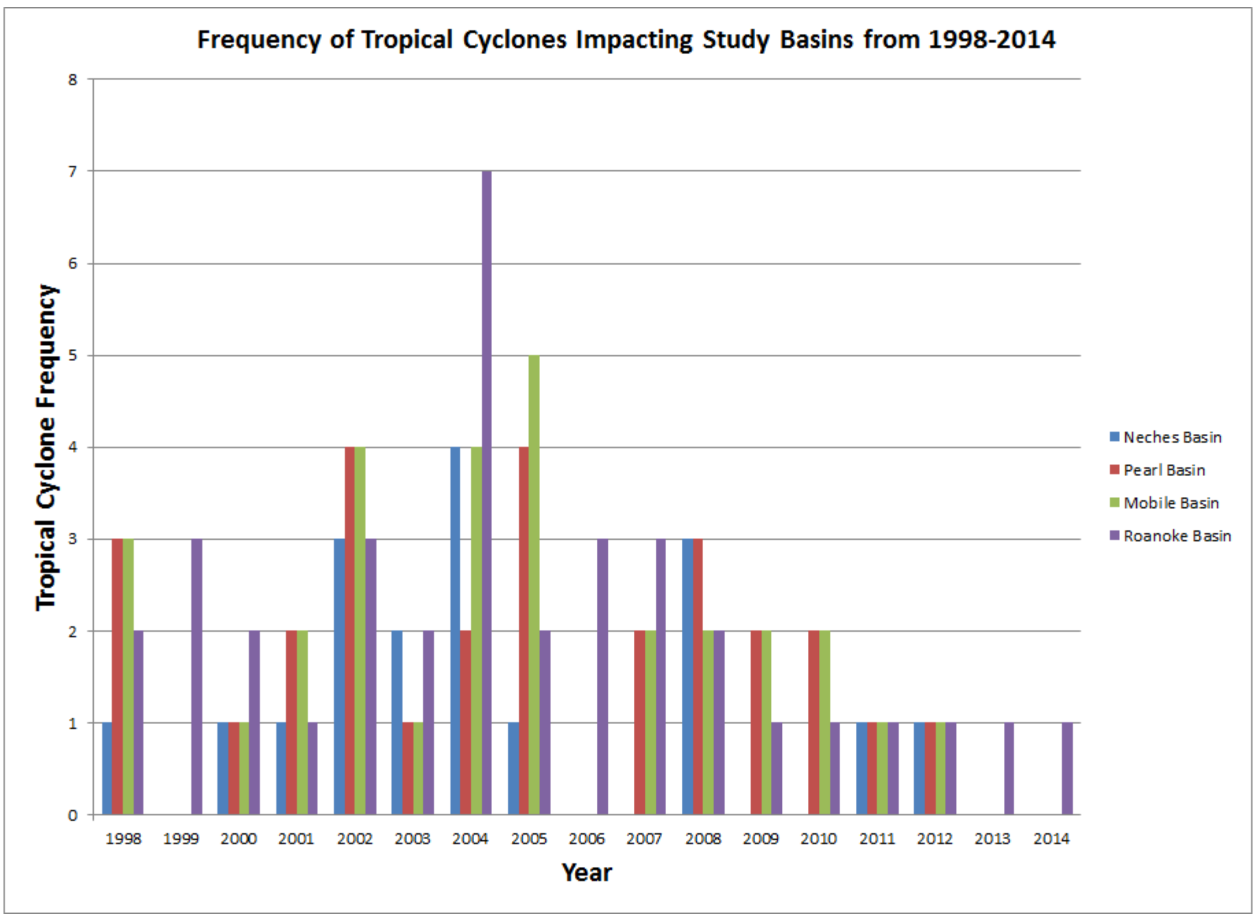

Figure 10. Frequency of Tropical Cyclones Impacting the four Study Basins from 1998-2014

Figures 11, 13, 15, and 17 show the occurrence of tropical cyclones in each of the study basins. All rivers show yearly low discharge/high discharge fluctuations, though this is less defined for the Roanoke and Pearl rivers. These hydrographs coupled with comparisons of the frequency of tropical cyclones occurring in each month for each study basin with average monthly discharge show that tropical cyclones impact these study basins primarily during low discharge seasons and rarely cause flooding (bankfull discharges are not exceeded) (*Figures 11-18*). *Figures 11-18* also show that the Neches and Mobile rivers have more pronounced dry seasons.

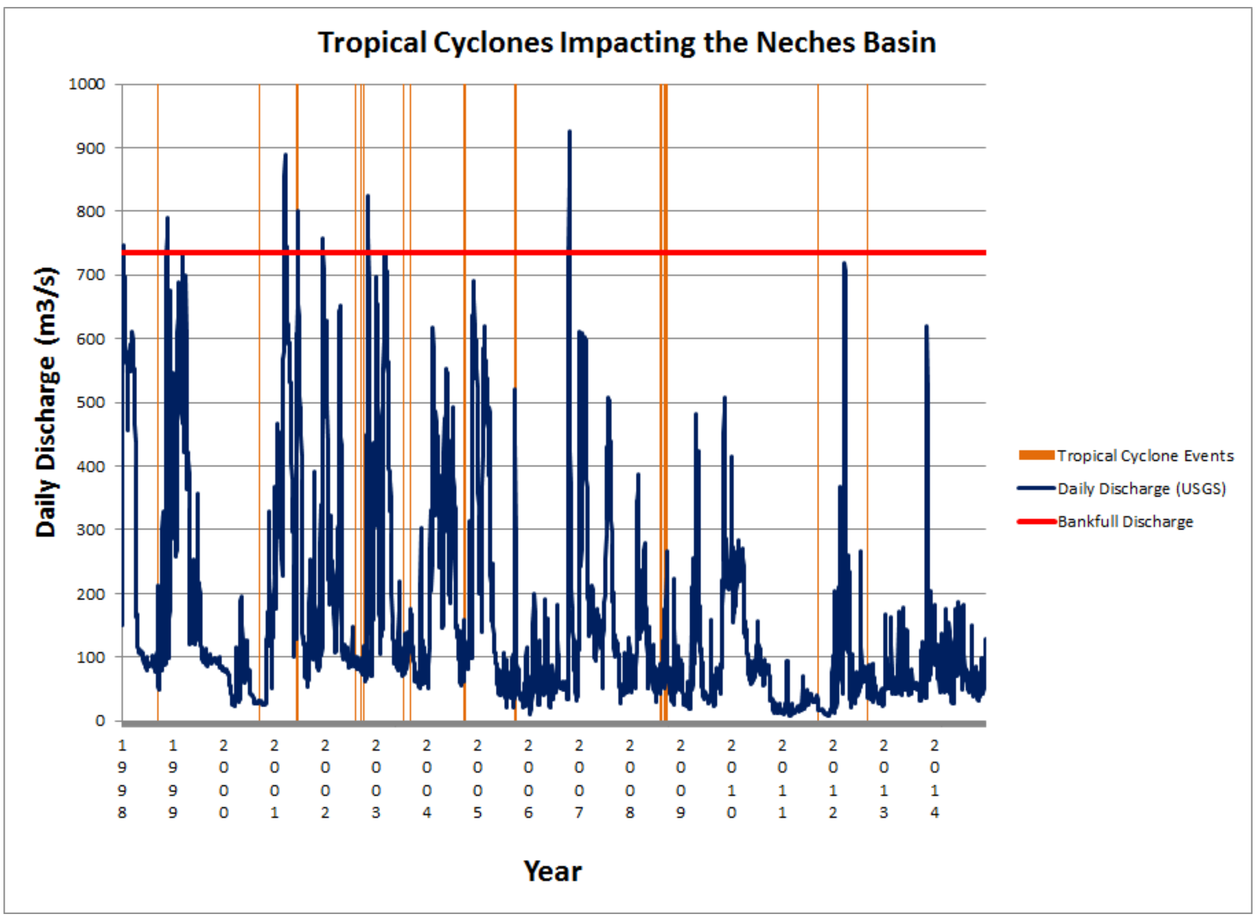

Figure 11. Tropical Cyclones Impacting the Neches Basin. Orange bars represent times when a tropical cyclone was over the basin.

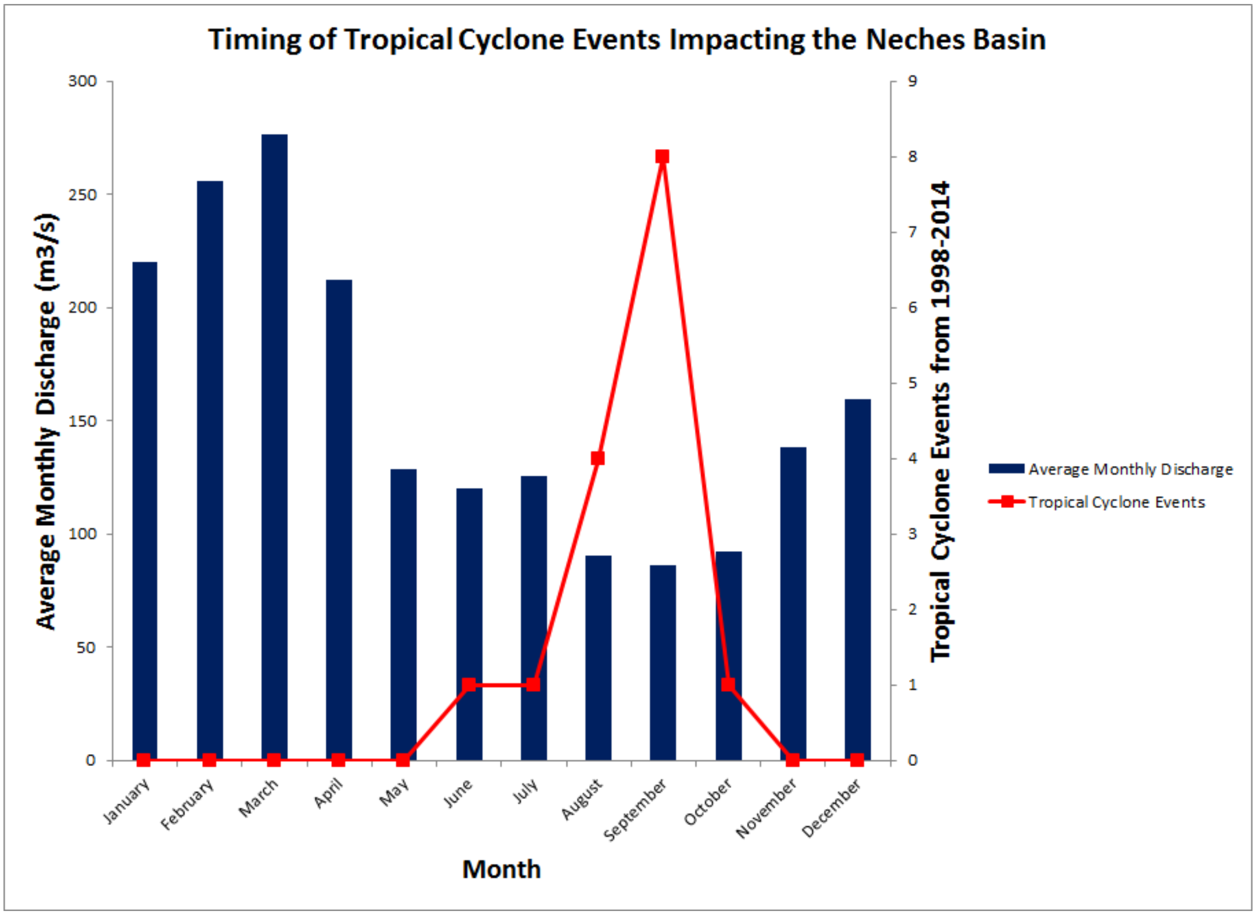

Figure 12. Comparison of Monthly Tropical Cyclone Frequency with Average Monthly Discharge for the Neches Basin

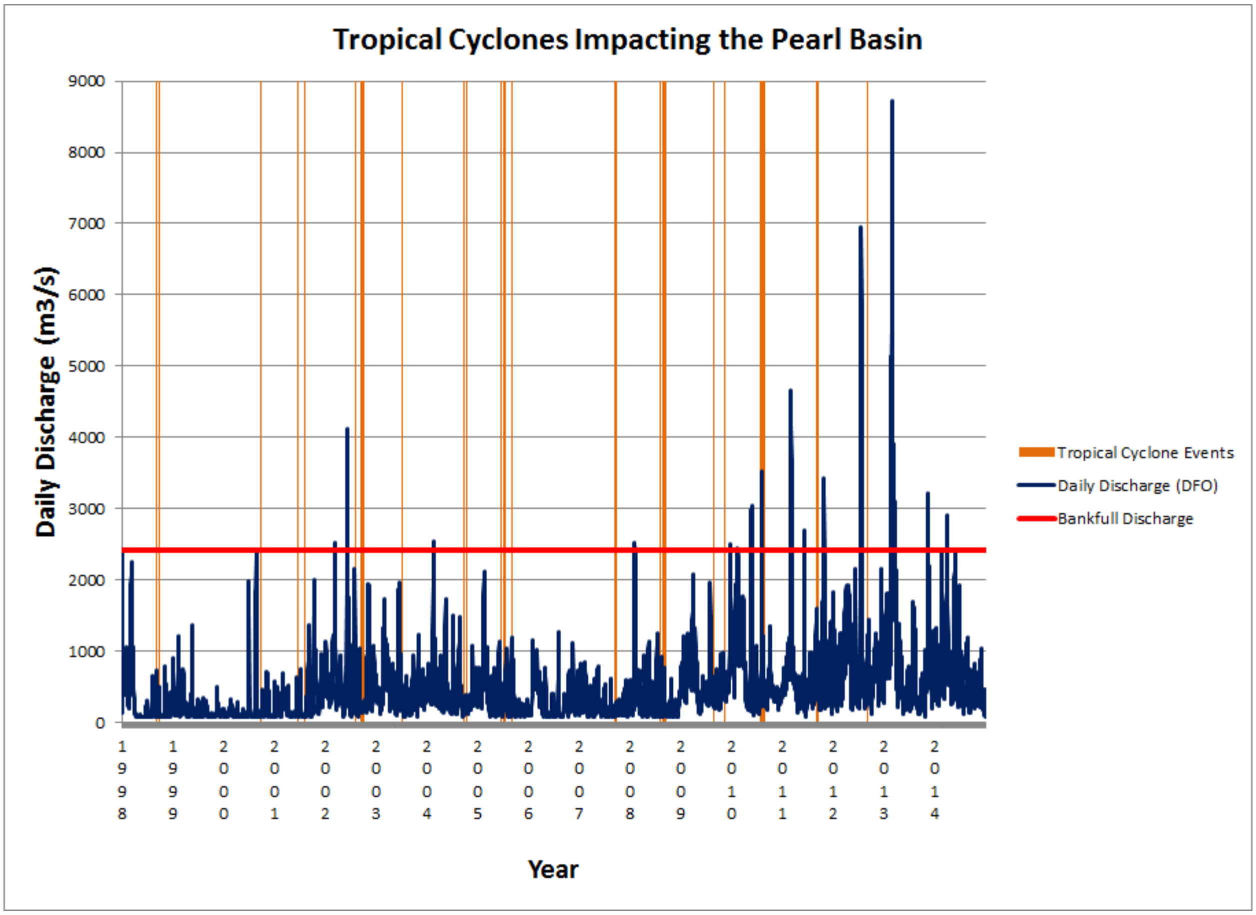

Figure 13. Tropical Cyclones Impacting the Pearl Basin. Orange bars represent times when a tropical cyclone was over the basin.

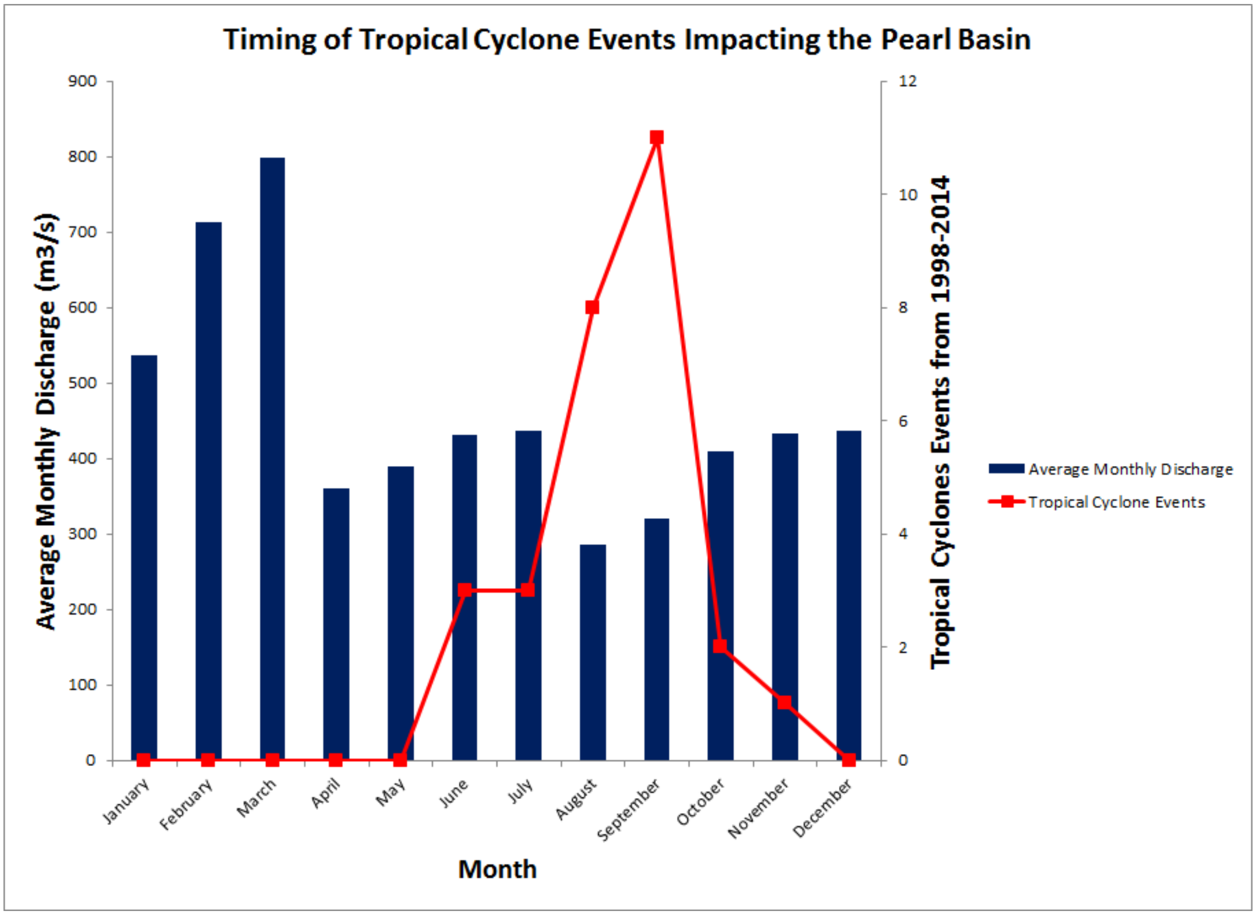

Figure 14. Comparison of Monthly Tropical Cyclone Frequency with Average Monthly Discharge for the Pearl Basin

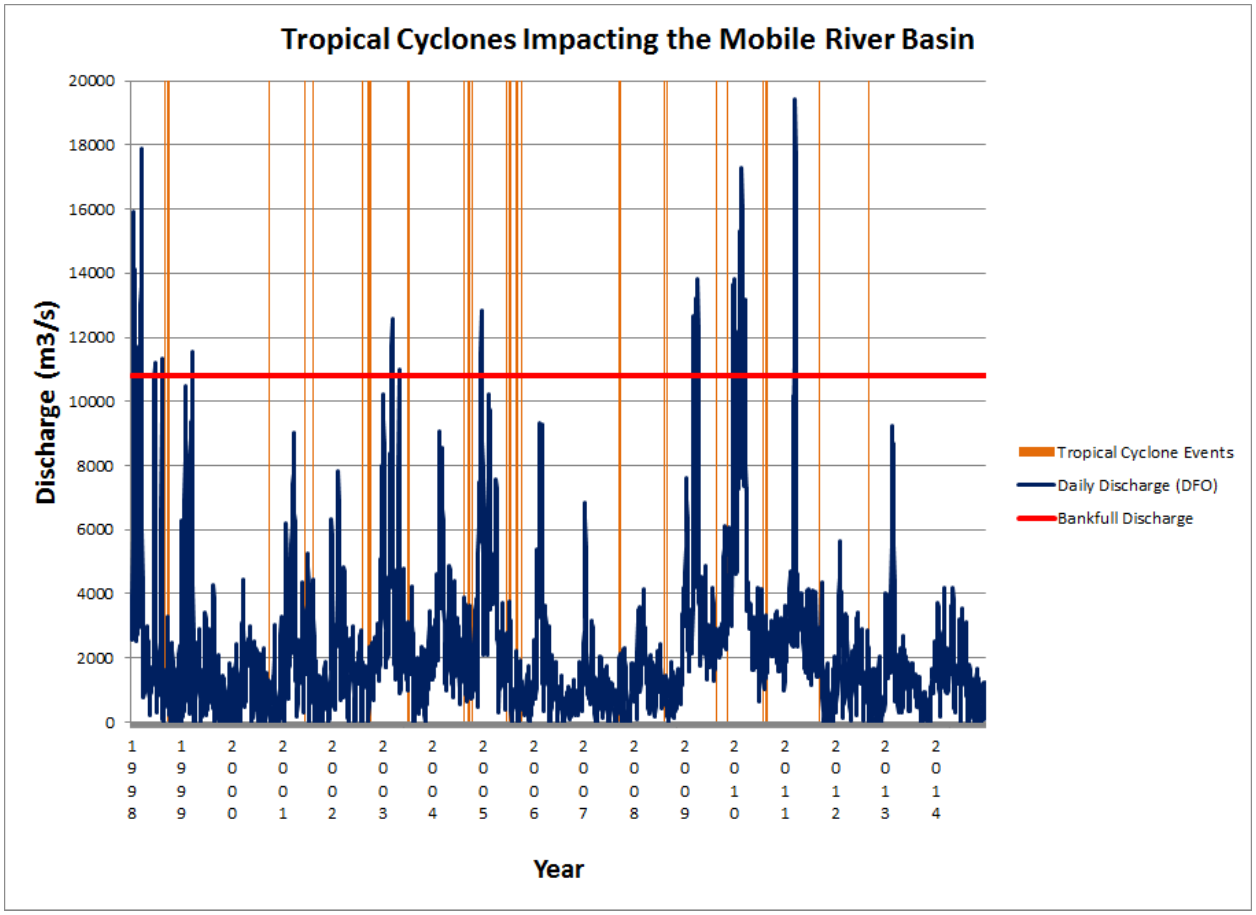

Figure 15. Tropical Cyclones Impacting the Mobile Basin. Orange bars represent times when a tropical cyclone was over the basin.

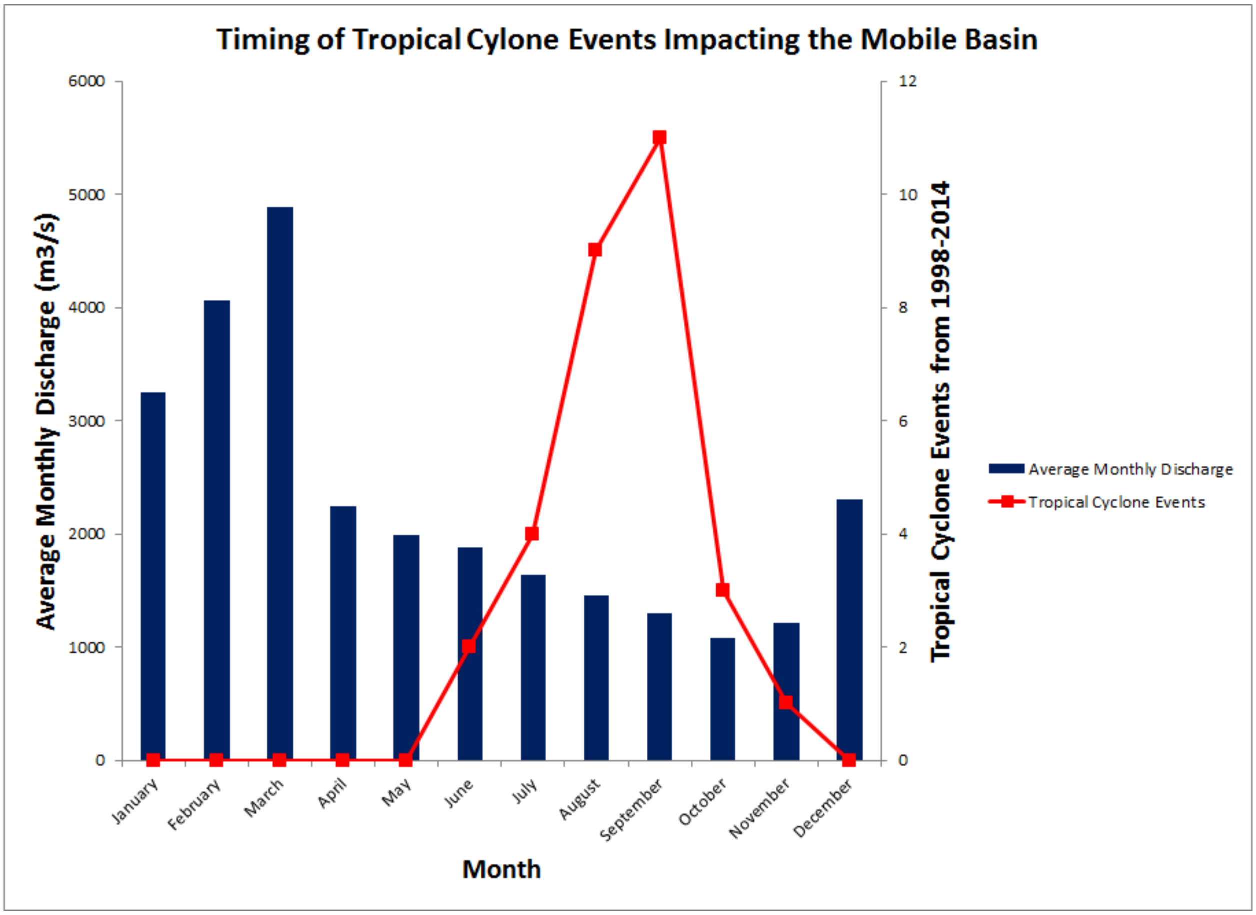

Figure 16. Comparison of Monthly Tropical Cyclone Frequency with Average Monthly Discharge for the Mobile Basin

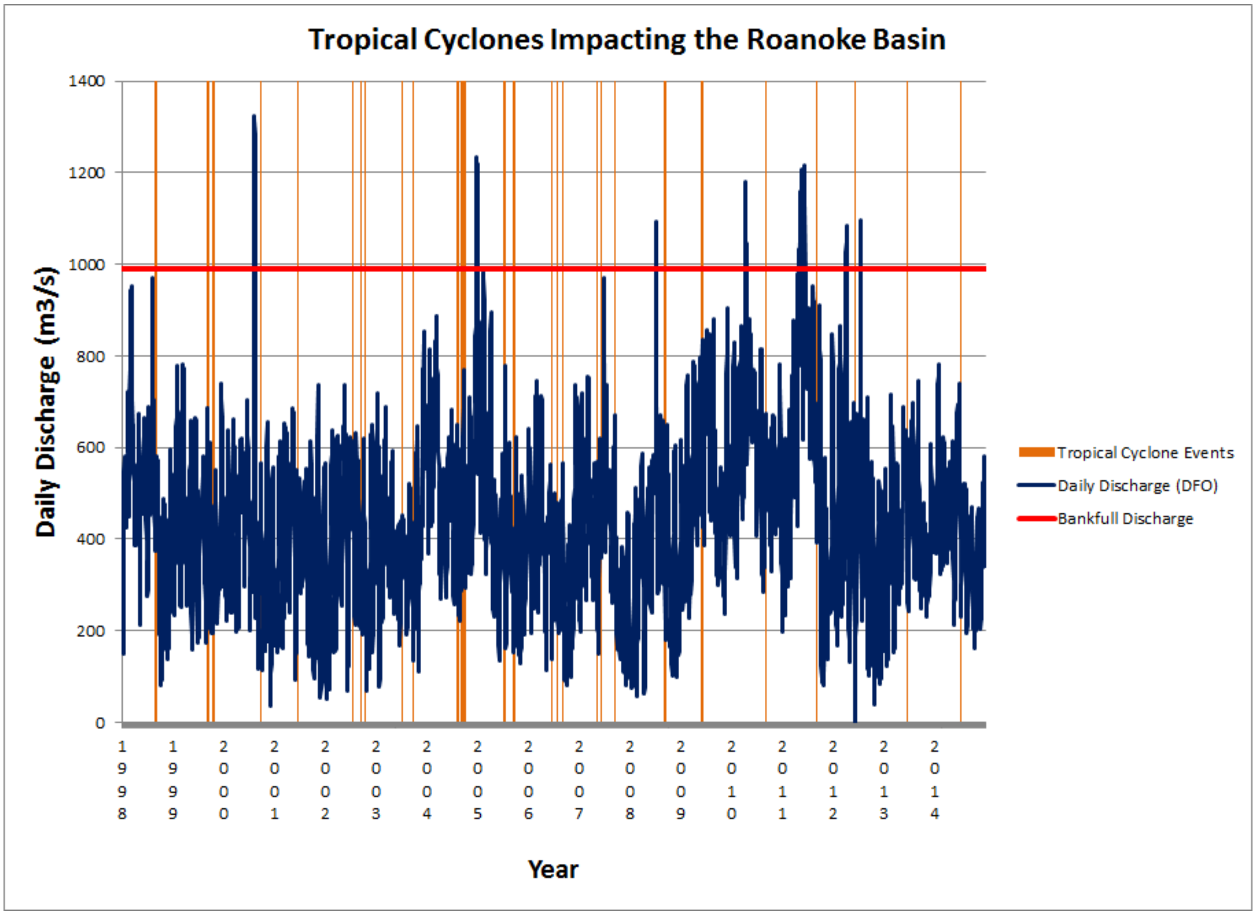

Figure 17. Tropical Cyclones Impacting the Roanoke Basin. Orange bars represent times when tropical cyclones were over the basin.

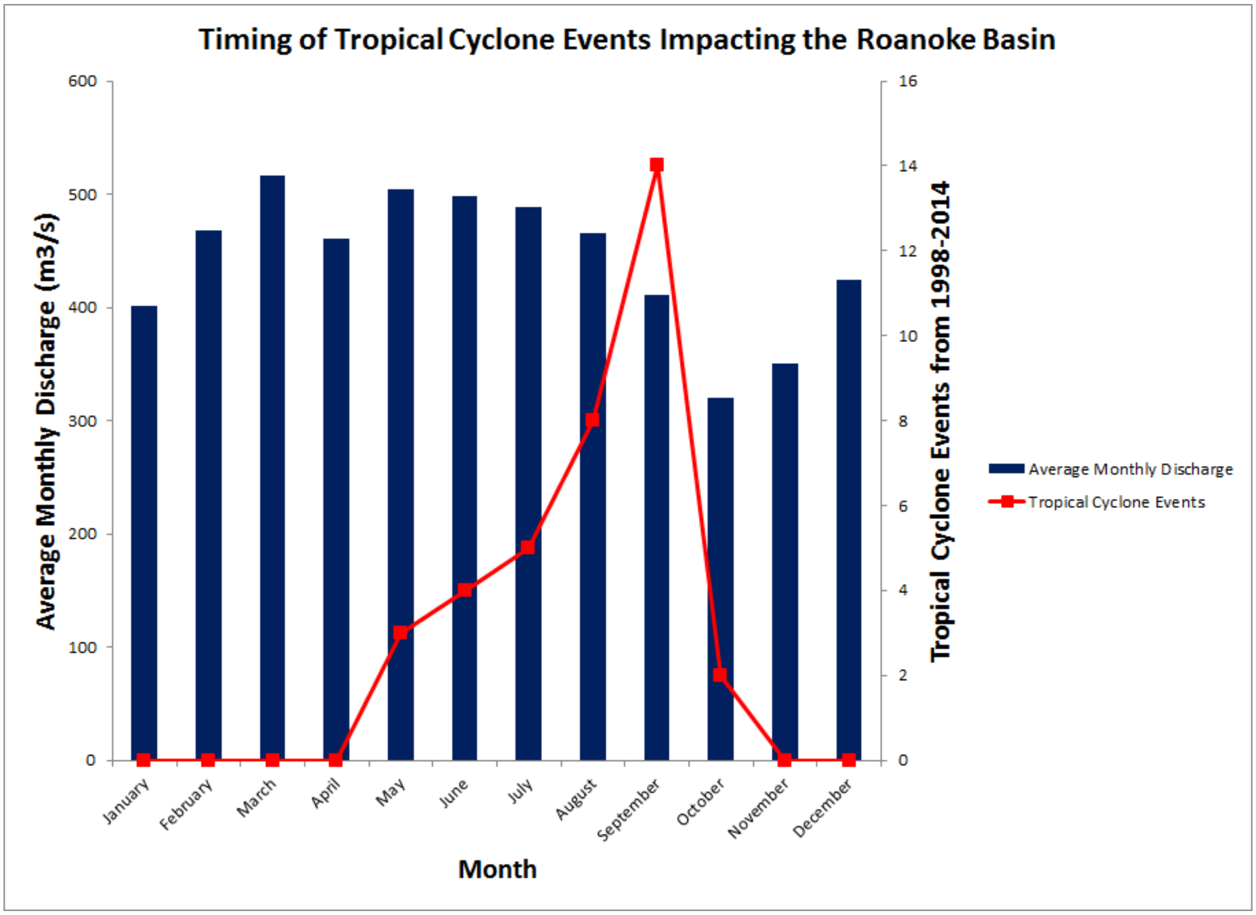

Figure 18. Comparison of Monthly Tropical Cyclone Frequency with Average Monthly Discharge for the Roanoke Basin

4.3 Modeling River Discharge from 1998-2014 with SWAT

Figures 19-22 show the delineation of the four study basins using SWAT, including subbasins and the outlets of both the subbasins and the watershed as a whole, where simulated discharge is measured by SWAT. The whole watershed outlets in these diagrams correspond with the locations of observed discharge from the USGS/DFO gages for each basin that are described in *Table 1*. The Roanoke and Mobile basins have greater changes in relief, ~1400 Δm and ~600 Δm respectively, compared to the ~200 Δm relief changes for the Neches and Pearl basins. Further, the Neches, Pearl, and Mobile rivers are oriented more or less North-South, while the Roanoke River is primarily oriented East-West.

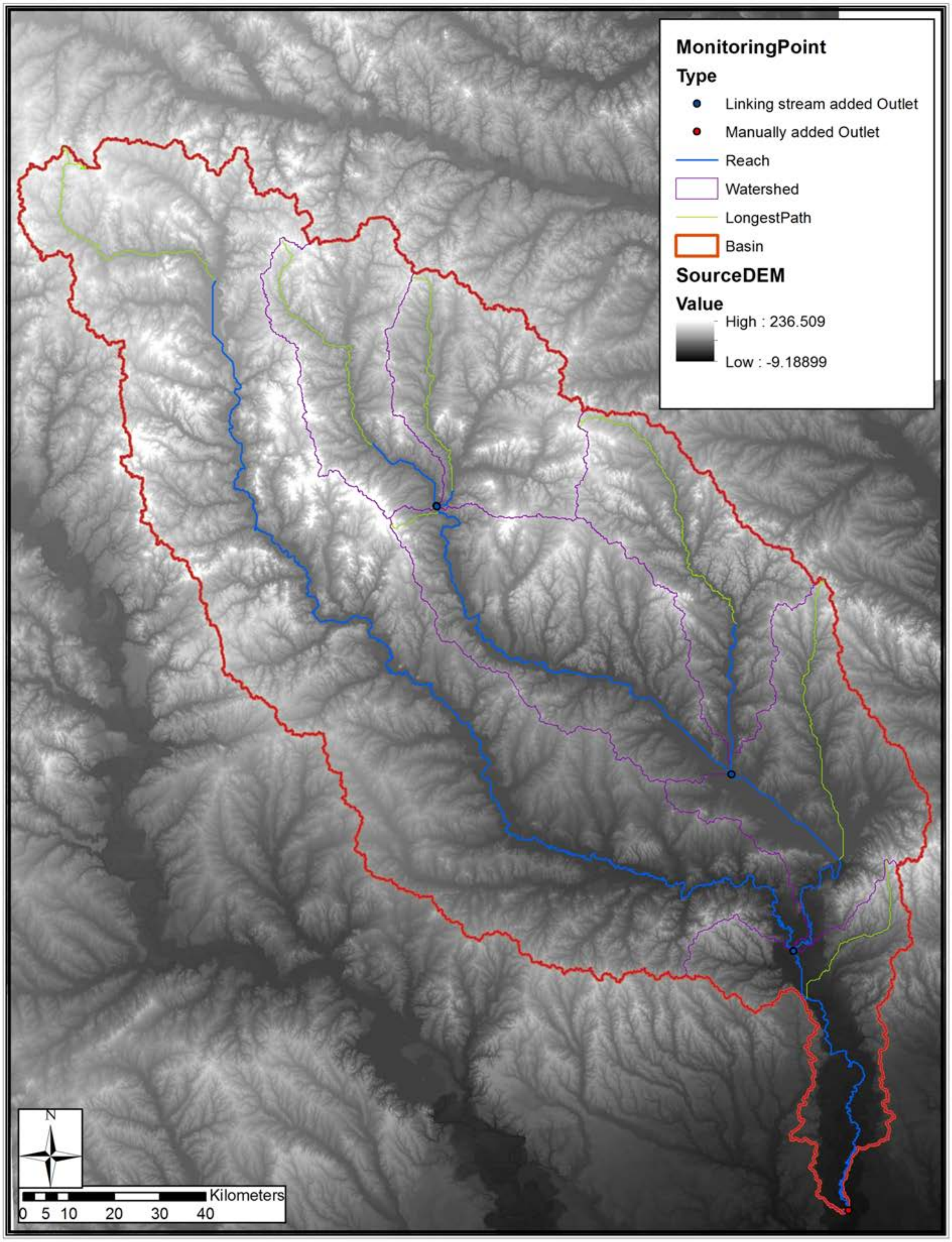

Figure 19. SWAT Delineation of the Neches Basin

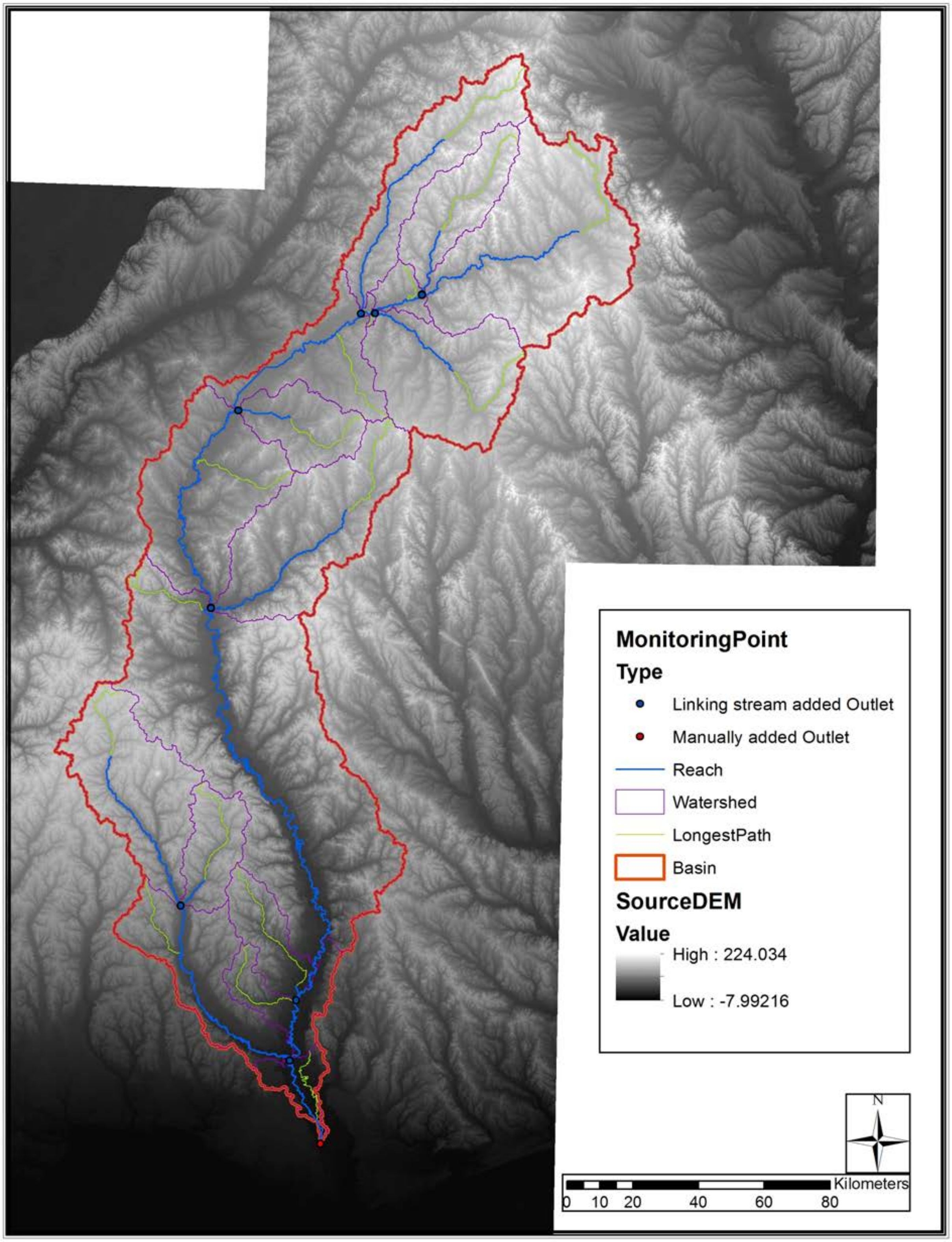

Figure 20. SWAT Delineation of the Pearl Basin

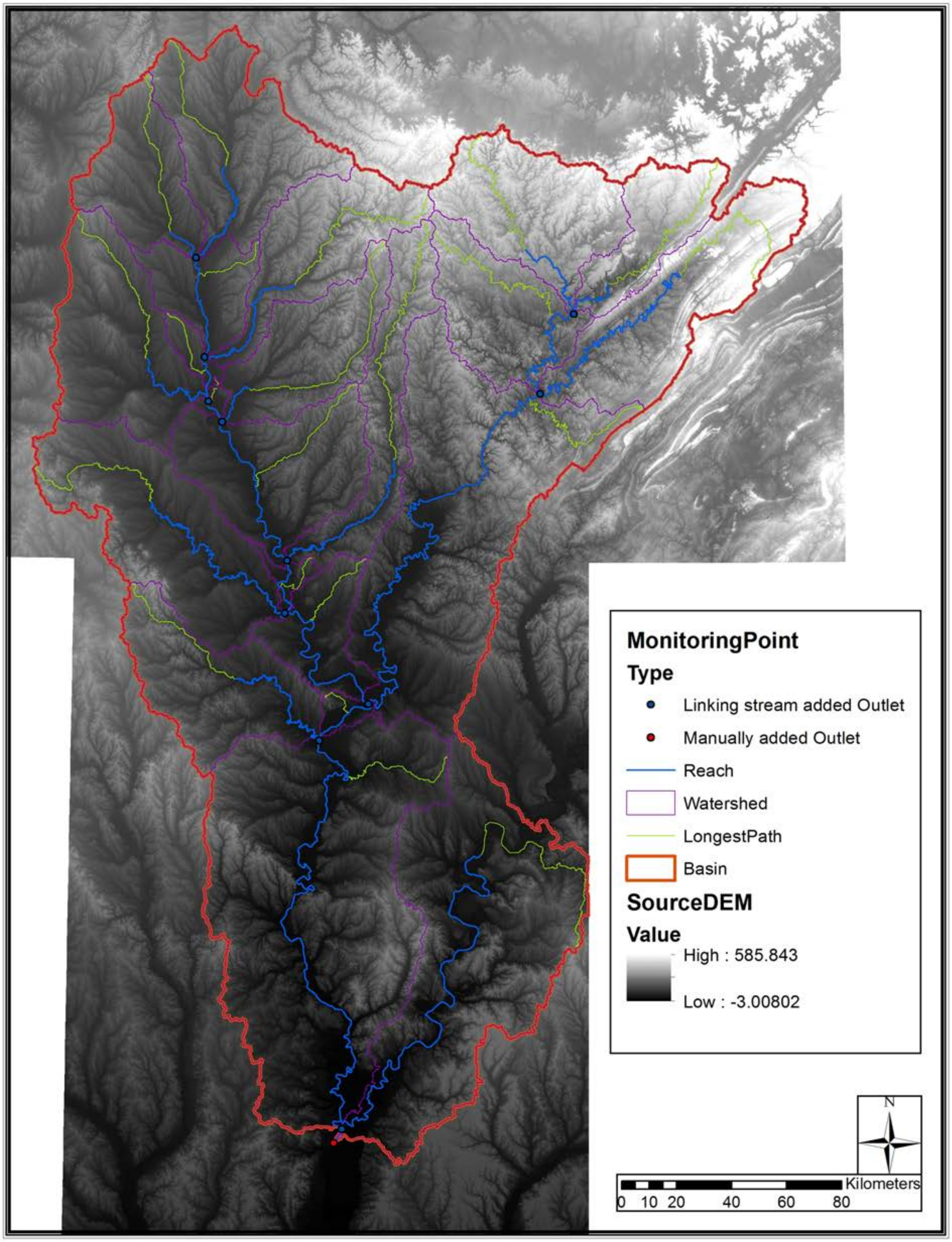

Figure 21. SWAT Delineation of the Mobile Basin

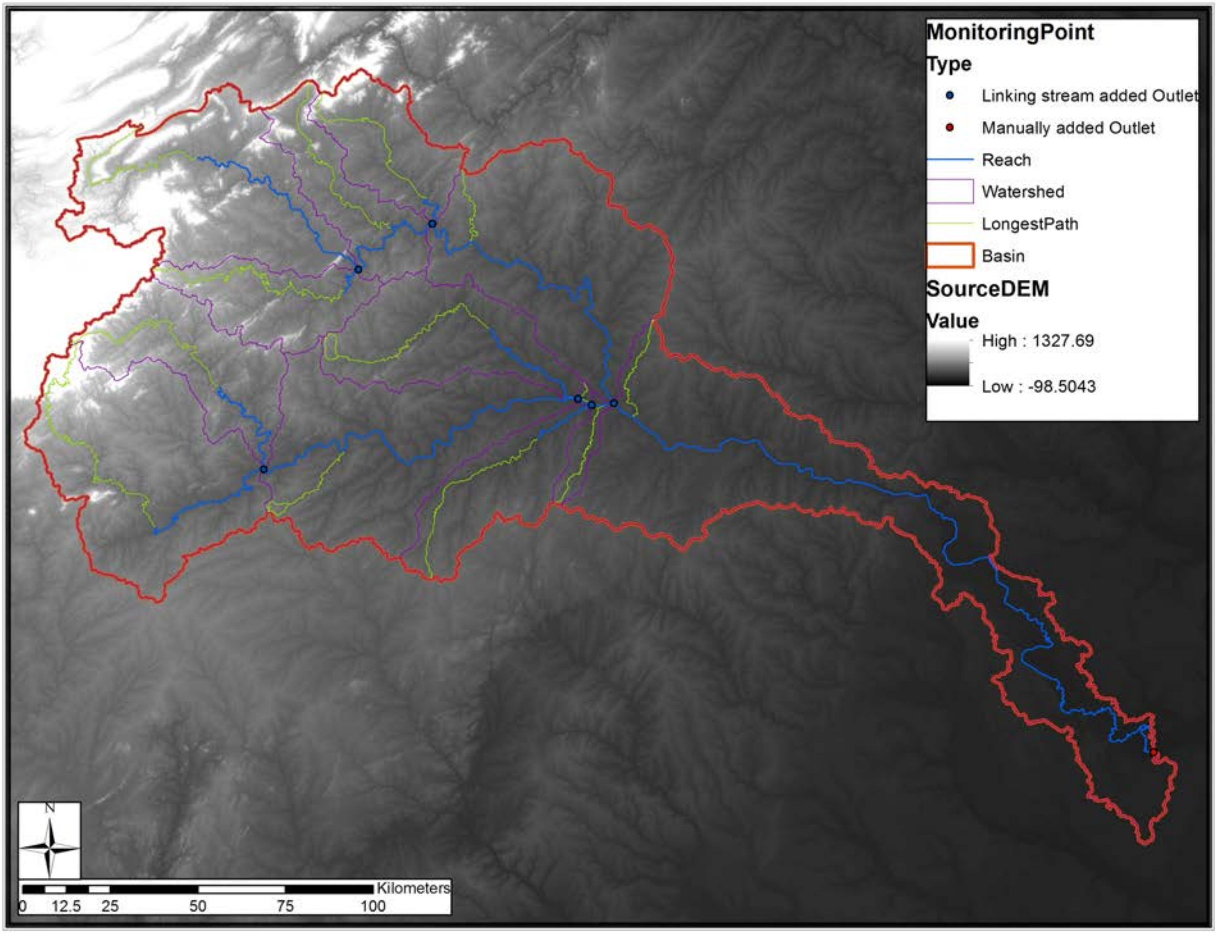

Figure 22. SWAT Delineation of the Roanoke Basin

4.4 Effects of Tropical Cyclones with 20% more Precipitation on River Discharge

With a 20% increase in precipitation during tropical cyclones, as is predicted by 2100 (GFDL, 2013; Knutson *et al.*, 2010), peak discharge is expected to increase in the rivers investigated in this study. On average, a 20% increase in precipitation during tropical cyclones caused an ~8% increase in peak discharge following tropical cyclones on the Neches River, a ~7% increase in peak discharge following tropical cyclones on the Pearl River, an ~18% increase in peak discharge following tropical cyclones on the Mobile River, and a ~10% increase in peak discharge following tropical cyclones on the Roanoke River. These results indicate that tropical cyclones are significant rain-producing events for these basins, such that a 20% increase in their precipitation alters their water balances. *Figures 23-26* show the relationships between the product of the percent of the basin area tropical cyclones passed over and their durations, and the increase in the peak discharge following the tropical cyclones. Tropical cyclones that occurred within two weeks of a previous tropical cyclone were not considered in this analysis, as discharge levels likely may not have been back to normal flow conditions. Generally, the relationship is: the larger the area of the basin that was impacted and the longer the duration of the storm, the greater the increase in the peak discharge. The R^2 values on these four graphs indicate that the percent of the basin area that is impacted by a tropical cyclone and the duration of the storm over the basin account for about 10-43% of the variability in the corresponding percent increase in peak discharge following a tropical cyclone with 20% more precipitation.

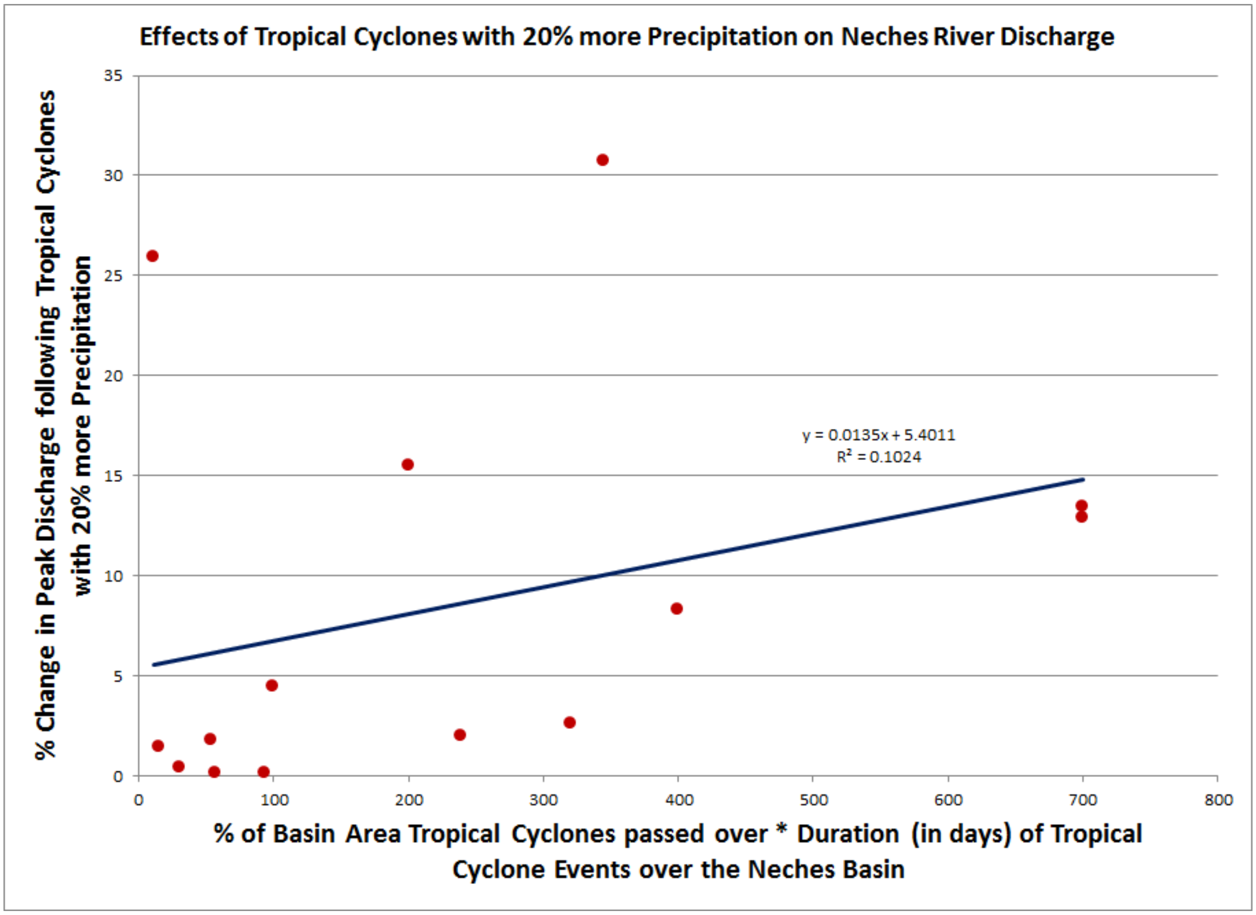

Figure 23. Relationship between the product of the % of Basin Area Impacted by Tropical Cyclones and the Duration of Tropical Cyclones to the % Increase in Peak Discharge Following Tropical Cyclones Events with 20% more Precipitation for the Neches Basin

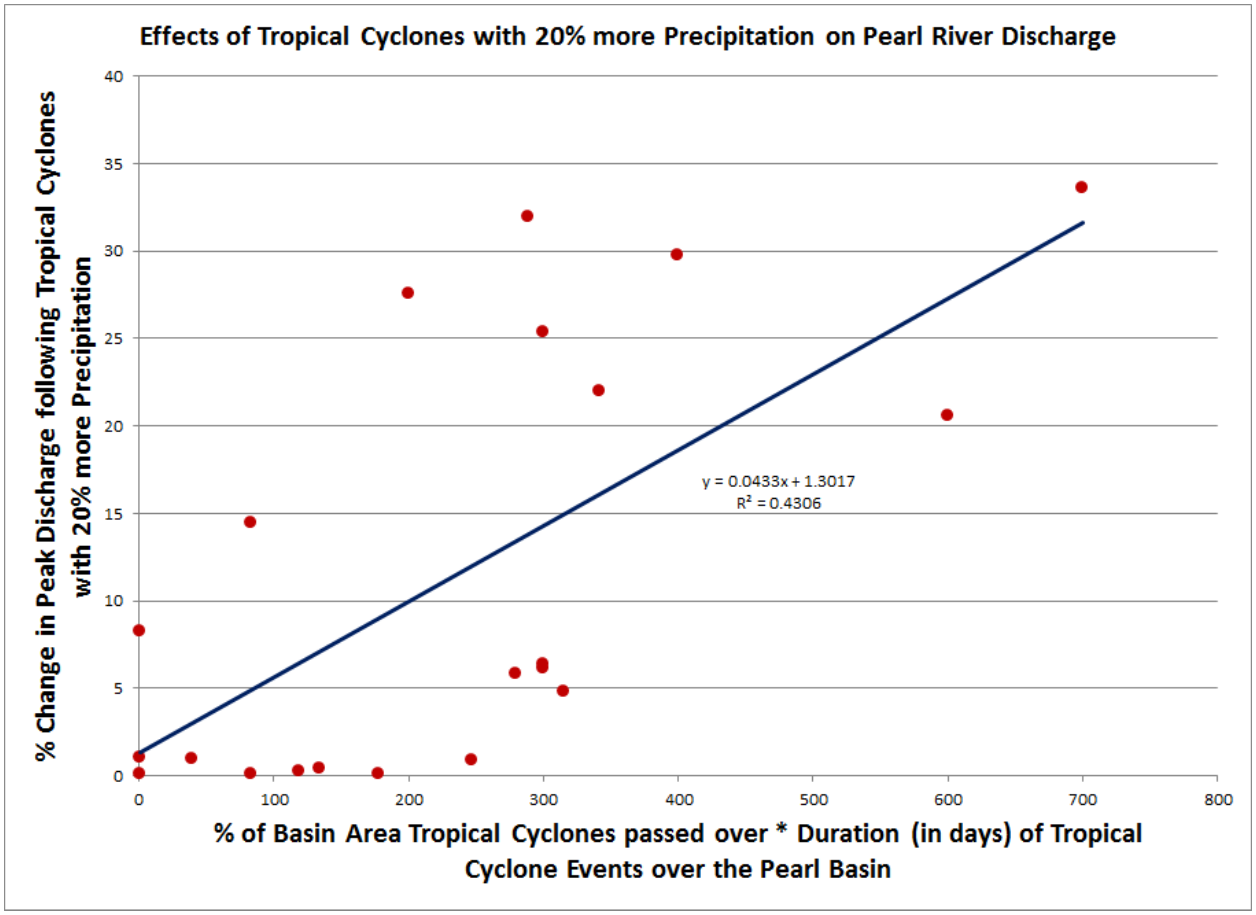

Figure 24. Relationship between the product of the % of Basin Area Impacted by Tropical Cyclones and the Duration of Tropical Cyclones to the % Increase in Peak Discharge Following Tropical Cyclones Events with 20% more Precipitation for the Pearl Basin

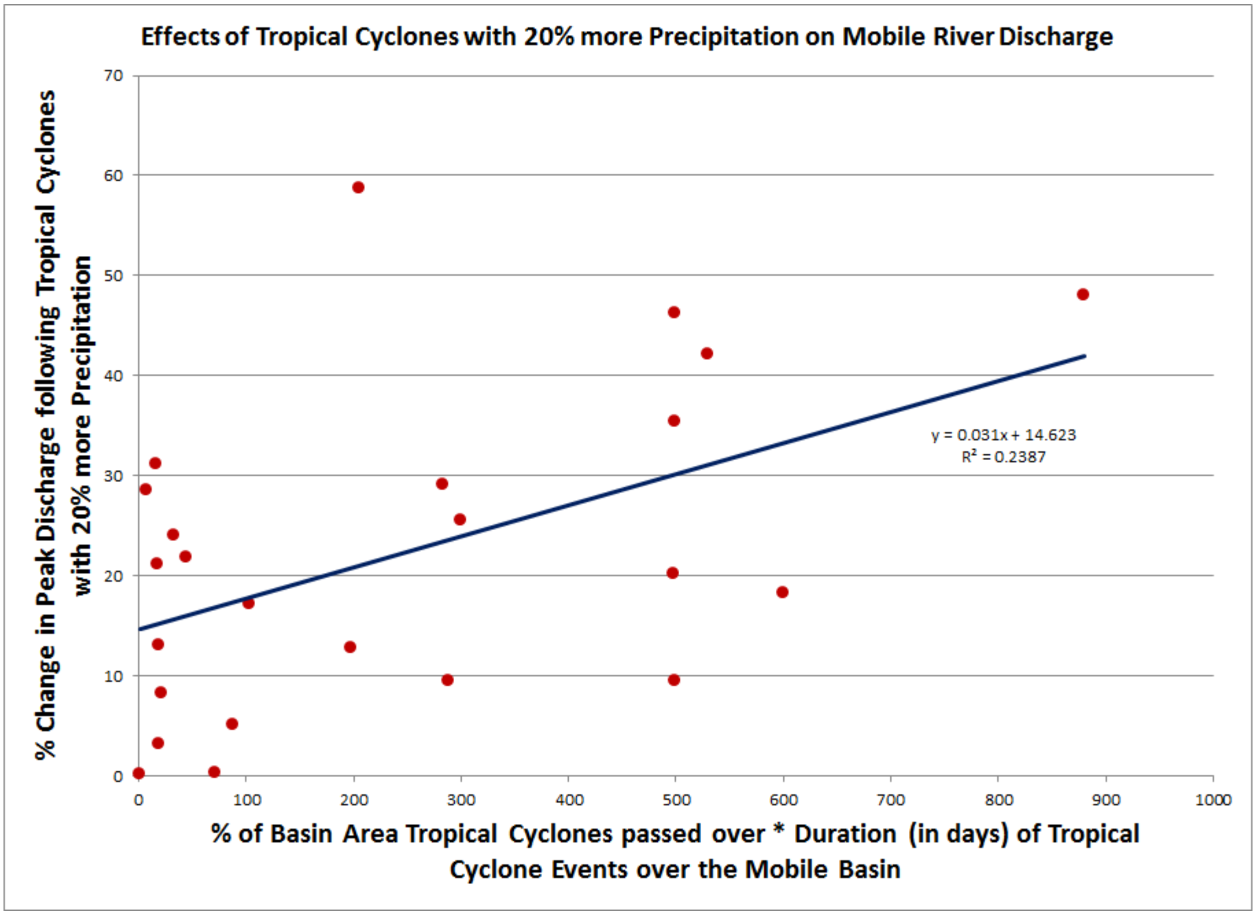

Figure 25. Relationship between the product of the % of Basin Area Impacted by Tropical Cyclones and the Duration of Tropical Cyclones to the % Increase in Peak Discharge Following Tropical Cyclones Events with 20% more Precipitation for the Mobile Basin

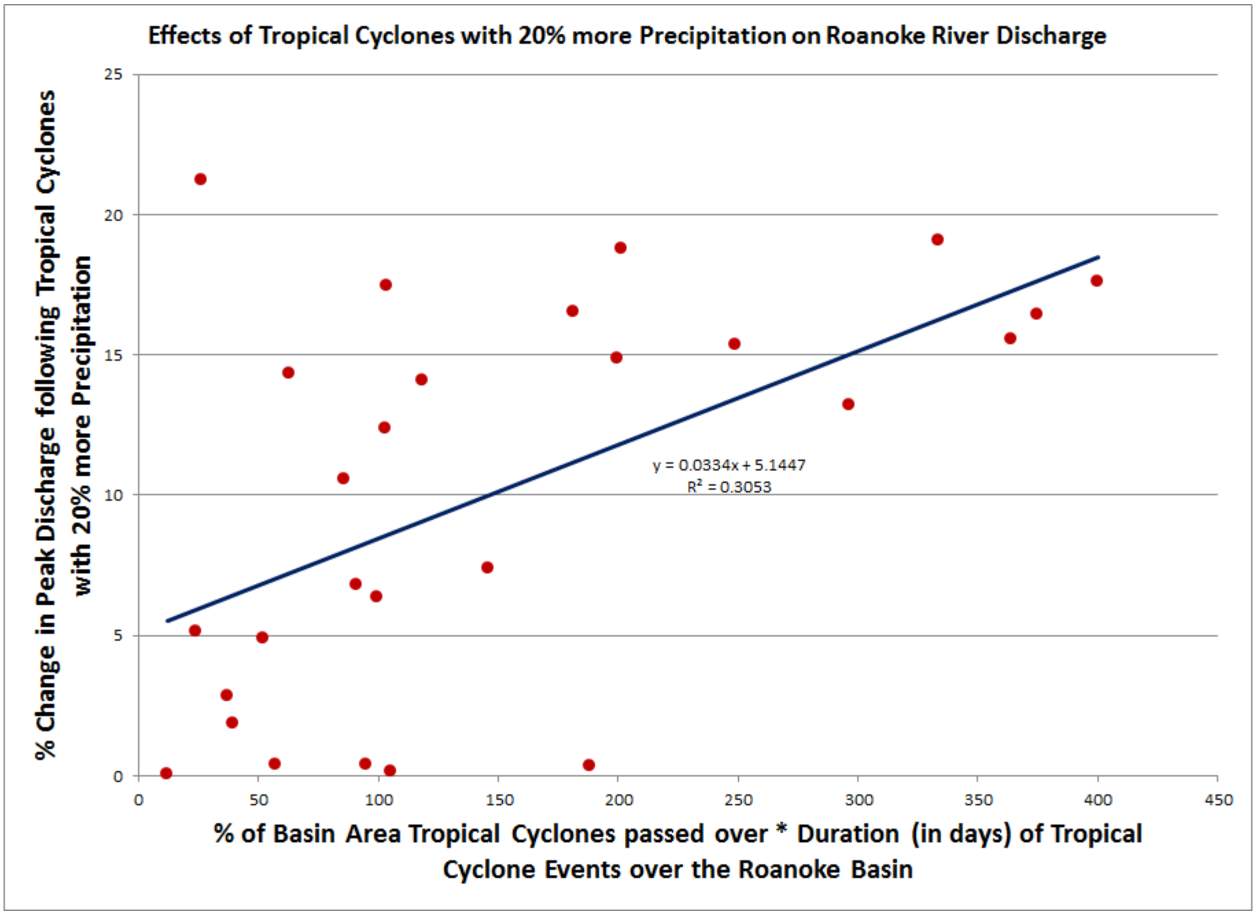

Figure 26. Relationship between the product of the % of Basin Area Impacted by Tropical Cyclones and the Duration of Tropical Cyclones to the % Increase in Peak Discharge Following Tropical Cyclones Events with 20% more Precipitation for the Roanoke Basin

4.5 Effects of an Extended Hurricane Season on Flooding Susceptibility

The current hurricane season is defined as starting in June and ending in November (Dwyer *et al.*, 2015). September has the highest frequency of tropical cyclone events for the four basins analyzed in this study (*Figures 12, 14, 16, and 18*). *Figure 27* shows the month of the first tropical cyclone for each year between 1998-2014 for each of the four study basins. More recent years (2007, 2009, 2012) have shown some tropical cyclones first occurring in May, before the "official" hurricane season, in the Roanoke Basin.

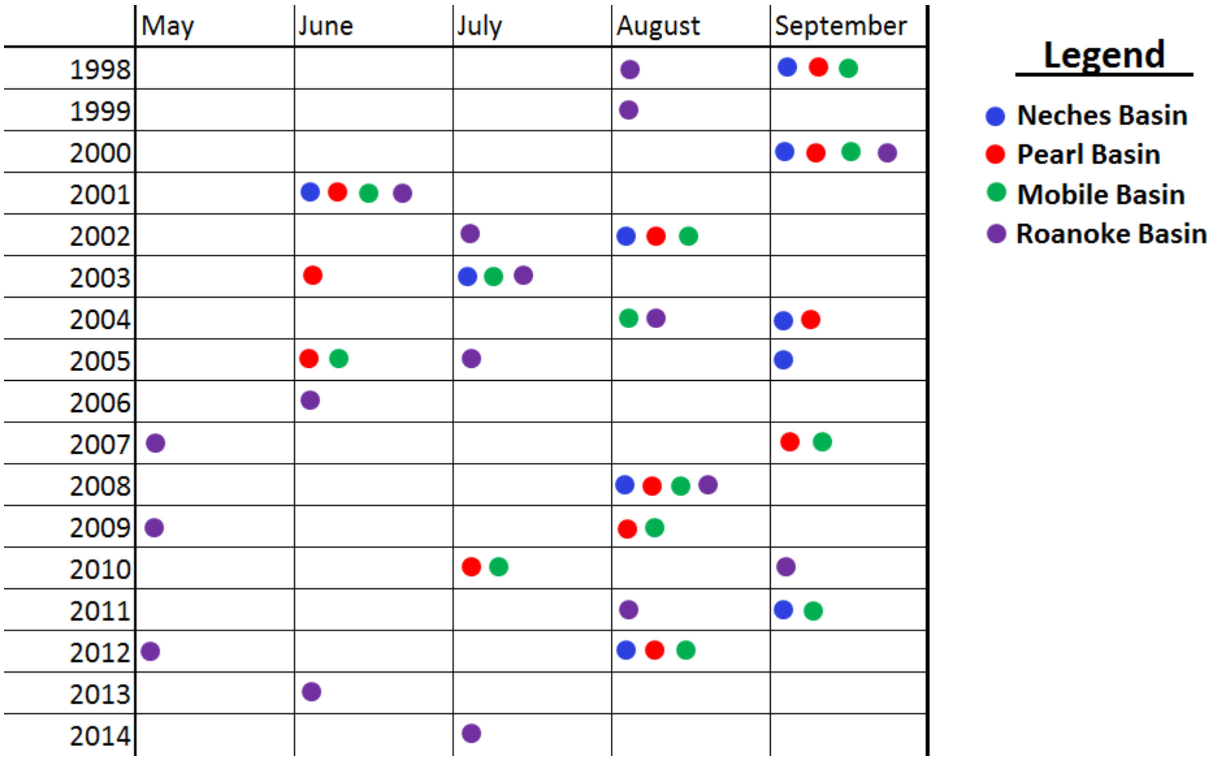

Figure 27. Month of the First Tropical Cyclone Event Occurring in each Basin from 1998-2014

A change in the hurricane season, due to global climate change, could likely impact flooding patterns in the four study basins. On average, tropical cyclones increased discharge (calculated from discharge the day before the storm to peak discharge) 107.63% on the Neches River, 136.13% on the Pearl River, 94.10% on the Mobile River, and 29.08% on the Roanoke River. Only observed USGS/DFO data was used for this analysis on the effects of an extension of the hurricane season. *Table 4* shows the number of days that would be at risk of flooding were a tropical cyclone to occur on any given day from 1998-2014 during either June-November (the current hurricane season) or May-December (an extended hurricane season). For example, if an average tropical cyclone increased discharge on the Neches River by 107.63%, 150 days (or 4.82% of the time) from 1998-2014 during the months of June-November would be at or above bankfull discharge. And, there are 256 days (or 6.15% of the time) when the Neches River would be at or above its bankfull discharge from 1998-2014 during the months May-December.

In all basins, the extended hurricane season showed a higher percentage of total days being susceptible to flooding from an average tropical cyclone. On average, 209 days per basin (or 5.02% of the time) were susceptible to flooding in the extended hurricane season scenario, while 128 days (or 4.12% of the time) were susceptible to flooding in the current hurricane season scenario. This is equivalent to a 63.28% increase in the number of days susceptible to flooding.

Table 4. Flooding Susceptibility of the four Study Basins

Basin	**Increase in Discharge due to Average Tropical Cyclone**	**Susceptibility with June-Nov. Hurricane Season**	**Susceptibility with May-Dec. Hurricane Season**	**Increase in Susceptibility with Extended Season**
Neches	107.63%	150 days (4.82%)	256 days (6.15%)	+106 days (+1.33%)
Pearl	136.13%	214 days (6.88%)	293 days (7.03%)	+76 days (+0.15%)
Mobile	94.10%	26 days (0.84%)	93 days (2.23%)	+67 days (+1.39%)
Roanoke	29.08%	122 days (3.92%)	195 days (4.68%)	+73 days (+0.76%)
Average	**91.74%**	**128 days (4.12%)**	**209 days (5.02%)**	**+80.5 days (+0.91%)**

CHAPTER 5

DISCUSSION

This study reveals many factors that contribute to flooding along the Neches, Pearl, Mobile, and Roanoke rivers following tropical cyclone events. The yearly frequency, or number of tropical cyclones that occur per year, is one such factor. A higher yearly frequency of tropical cyclones likely will bring more precipitation to the basin, enhancing the risk of flooding. Tropical cyclone frequency was found to be highly variable in the four river basins analyzed in this study over the period 1998-2014. The period 2002-2005 had the highest yearly frequencies, while there were hardly any tropical cyclones from 2010-2014 (*Figure 10*). The Roanoke Basin was the only basin to have been impacted by tropical cyclones in 2013 and 2014, and with only 1 in each year. Most tropical cyclones impacting these four basins occur during September, or the middle of the low discharge season (*Figures 12, 14, 16, and 18*). Tropical cyclones seem to rarely cause flood events on these rivers, even though they bring high amounts of precipitation, because they occur primarily during the low discharge season when discharge is relatively low.

Besides how often and when tropical cyclones occur, how much precipitation they bring is another factor that impacts flooding potential on the four rivers analyzed in this study. Precipitation during tropical cyclone events is expected to increase by 20% by the year 2100 (GFDL, 2013; Knutson *et al.*, 2010). The results of this study indicate that a 20% increase in tropical cyclone precipitation is likely to cause, on average, an ~8% increase in peak discharge following storms impacting the Neches Basin, a ~7% increase for the Pearl Basin, an ~18% increase for the Mobile Basin, and a ~10% increase for the Roanoke Basin. Were a tropical cyclone to occur during a time when these rivers are relatively full, these increases in peak discharge likely could cause flooding. The differences between average increases in peak discharge between these four basins could potentially be due to differences in their size. The largest basin, the Mobile Basin (110,955 km^2), had the largest increase (~18%). The Roanoke, Neches, and Pearl basins were relatively similar in size (25, 963 km^2, 25,117 km^2, and 22,894 km^2 respectively), and showed similar increases (~10%, ~8%, and ~7% respectively), with the slightly smaller Neches and Pearl basins having a slightly smaller increase in peak discharge than that of the Roanoke Basin.

Generally speaking, the greater percentage of basin area impacted by a tropical cyclone with 20% more precipitation and the longer the storm is over the basin, the greater the percent increase in peak discharge (*Figures 23-26*). However, the rate of change of percent increase in discharge with area of the basin impacted by a storm and the duration of a storm over the basin differs between basins. This is likely due to differences in land cover, soil types, and land slope across the four different study basins. *Figures 23-26* show the relationships between the product of the percent of basin area impacted by tropical cyclones and the duration of the tropical cyclones over the basin, and the resulting percent increase in peak discharge along the rivers. Common outliers on these graphs are storms that cover relatively small portions of the total basin areas and/or have short durations over the basins, but that cause large increases in peak discharge along the rivers. These are likely cases where a front, or some sort of rain-producing event, passed over the basins shortly before, at the same time, or soon after these tropical cyclones. Thus, the increases in discharge would be reflecting not only the precipitation from the tropical cyclones, but the other rain-producing events as well. Also, this could likely be due to the storm passing more directly over the outlets of the basins. None of the four study basins showed a strong relationship between the product of the percent of the basin impacted by a tropical cyclone and the duration of the storm over the basin, and the percent increase in peak discharge (*Figures 23-26*). The percent of the basin area a tropical cyclone passes over and the duration of a tropical cyclone over the basin together can only explain 10-43% of the variability in the percent increase in peak discharge following tropical cyclones with 20% more precipitation. The lack of a strong correlation on any of the four rivers indicates that more storm characteristics (e.g. location of storm within the basin, timing of storm in relation to other non-tropical rain events, moisture content of storm, etc.) are important and should be investigated in future research.

A further consideration is the length of the hurricane season. The current hurricane season is defined as beginning in June and lasting through November (Dwyer *et al*., 2015), which as described above coincides primarily with the low discharge seasons of the four basins analyzed in this study. However, some May tropical cyclones have already occurred in the Roanoke Basin during 2007, 2009, and 2012 (*Figure 27*). More recent storms impacting these four basins thus not only seem to be fewer in number, but seem to be starting earlier as well. A scan through NOAA's HURDAT2 dataset also shows the occurrence of several May and even some December tropical cyclones. As shown in *Table 3*, the Mobile and Pearl rivers flooded more frequently (1.88% and 1.30% of the time respectively) than the Roanoke and Neches rivers (1.03% and 0.55% of the time respectively) over the period from 1998-2014. Further, the Mobile and the Neches rivers flooded less frequently during the June-November hurricane season (0.23% and 0.55% of the time respectively) than the Roanoke and Pearl rivers (0.93% and 1.06% of the time respectively). While they showed less flooding during the June-November hurricane season, the Mobile and Neches rivers showed more susceptibility to potential flooding following an average tropical cyclone with an extended hurricane season of May-December (*Table 4*). For the Mobile River, 0.84% of days from 1998-2014 in the months June-November (the current hurricane season) had the potential of flooding due to an average tropical cyclone, while 2.23% of days from 1998-2014 in the months May-December (an extended hurricane season) had the potential of flooding due to an average tropical cyclone. This is a percent increase of 165.48% in the number of days susceptible to potential flooding were an average tropical cyclone to occur, with just 2 additional months added to the hurricane season. For the Neches River, 4.82% of days from 1998-2014 in the months June-November (the current hurricane season) had the potential of flooding due to an average tropical cyclone, while 6.15% of days from 1998-2014 in the months May-December (an extended hurricane season) had the potential of flooding due to an average tropical cyclone. This is a percent increase of 27.59% in the number of days susceptible to potential flooding were an average tropical cyclone to occur, again with only 2 additional months added to the hurricane season. On the other hand, the Roanoke River and Pearl River showed 19.39 and 2.18 percent increases, respectively, in the number of days susceptible to potential flooding were an average tropical cyclone to occur. On average, an extended hurricane season will likely cause a 63.28% increase in the number of days susceptible to flooding were an average tropical cyclone to impact these Southeast rivers. The Neches and Mobile rivers likely show greater susceptibility to increased flooding due to an extended hurricane season because they have more pronounced low discharge seasons (i.e. May discharges are more drastically greater than June discharges and/or December discharges are more drastically greater than November discharges) (*Figures 12 & 16*). Thus, an extension of the current hurricane season, such that it encroaches upon the high discharge seasons of these four basins, is likely to lead to an increase in the frequency of floods following tropical cyclone events if these events start occurring more frequently in May and December, especially for the Mobile and Neches rivers.

This study has two main limitations. First, the SWAT daily discharge data could not be perfectly calibrated to match observed USGS/DFO daily discharge data. One potential reason for this could be the existence of small dams and man-made reservoirs on the rivers or tributaries to the four rivers studied. Future research on this topic could attempt to incorporate information about dams and man-made reservoirs into SWAT to improve the daily discharge data produced by the model. Second, analysis of the precipitation data used in this study indicated that many tropical cyclones occurred shortly after other rain-producing events, making it challenging to isolate the influence of just the tropical cyclones on changes in river discharge. Extending this study to other basins along the East and Gulf coasts would also be useful in determining regional trends. For example, peak discharge on the Roanoke River was considerably less affected by tropical cyclones than the other three rivers along the Gulf Coast. Further, a key focus of this study was on the timing of the hurricane season. More explicit modeling of future tropical cyclone dynamics using a stochastic approach, rather than average statistics, could potentially produce a more robust understanding of the effects of future climate dynamics on flood susceptibility. Most past research on how global climate change is likely to alter tropical cyclones has focused on changes in their magnitude and frequency. More research is needed on the effects of a shifted, or extended, hurricane season, and the effects of this coupled with changes in magnitude and frequency on water balances in river basins along the East and Gulf coasts.

CHAPTER 6

CONCLUSIONS

Most tropical cyclones impacting the Neches, Pearl, Mobile, and Roanoke river basins from 1998-2014 occurred during the low discharge season, and caused little flooding along these rivers. SWAT was used to model daily discharge along these rivers with 20% more precipitation during tropical cyclone events, as is expected by the year 2100 (GFDL, 2013; Knutson *et al.*, 2010). A 20% increase in tropical cyclone precipitation caused, on average, an ~8% increase in peak discharge following tropical cyclones impacting the Neches Basin, a ~7% increase in the Pearl Basin, an ~18% increase in the Mobile Basin, and a ~10% increase in the Roanoke Basin. The influence of tropical cyclones with 20% more precipitation on increasing peak discharge is likely due in part to basin size. Although the current hurricane season is June-November, some May and December tropical cyclones have occurred in recent years. An extension of the hurricane season to May-December would likely increase flooding susceptibility on the four rivers analyzed in this study. On the Neches River, 106 more days (+1.33% of the time) from 1998-2014 in the months May-December likely would have been above bankfull discharge if an average tropical cyclone had occurred than during the current hurricane season months of June-November. The Pearl, Mobile, and Roanoke basins had similar increases of 76 more days (+0.15%), 67 more days (+1.39%), and 73 more days (+0.76%). The results presented in this study propose that predicted increases in tropical cyclone precipitation and extension of the hurricane season due to global climate change will lead to increased susceptibility of Southeast rivers to inland flooding. Future research should focus on the mechanisms and processes involved in the alteration of the water balance on rivers in the Southeast United States due to global climate change, such that we may be better prepared for the likely changes in flooding potential following tropical cyclones in the near future.

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APPENDIX A

Script for Converting HURDAT2 Tropical Cyclone Data into Point Shapefiles

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"""

Hurricane Track Model

This model takes the National Hurricane Center (NHC) HURDAT2 dataset and plots the tracks
of all hurricanes from 1851-2013.

Requirements:
NHC HURDAT2 Dataset (in textfile format) ("Hurricane_Dataset.txt")
WGS spatial reference file ("sample_wgs_projection.shp")
Empty output folder called "Hurricanes"
Before executing this script file, the user must manually change the Workspace Path (line 27),
the Hurricane Dataset File Path (line 34), and the Sample WGS Projection File Path (line 68 and
line 89).

Products:
For each hurricane event, a point shapefile of its track is produced.  Each point includes the
windspeed at that location as an attribute.
A single polyline shapefile ("hurricane_tracks.shp") that includes the tracks of all hurricanes
from 1851-2013, each represented by a line segement.

Author: Monica Stone (mhstone@crimson.ua.edu)

Created: November 23, 2014

"""
#Import Arcpy Module
import arcpy

#Define Workspace
workspace_path =
r"C:\Users\SDML\Desktop\Frequency_Analysis\Hurricane_Track_Model\Hurricanes"
arcpy.env.workspace = workspace_path

#Turn-om Overwrite
arcpy.env.overwriteOutput = True
```

```
#Open Hurricane Dataset File
h = open(r"C:\Users\SDML\Desktop\Frequency_Analysis\Hurricane_Dataset.txt", "r")

#Create Lists
xy_list = []#This list temporarily stores the XY coordinates for a hurricane event.
points_list = []#This list contains the lists of XY coordinates for all hurricane events.
windspeed_list = []#This list temporarily stores the windspeeds for a hurricane event.
cum_windspeed_list = []#This list contains the lists of windspeeds for all hurricane events.
numbers_list = ["AL011998"]#This list contains the unique identification numbers for all
hurricane events.

#Extract XY Coordinates and Windspeed for all Hurricane Events
h.readline()
for line in h:
    if "AL" not in line:
        line_list = line.split(",")
        latitude = line_list[4].replace("N", "")
        longitude_west = line_list[5].replace("W", "")
        longitude_east = longitude_west.replace("E", "")
        point = [longitude_east, latitude]
        xy_list.append(point)
        windspeed = float(line_list[6])
        windspeed_list.append(windspeed)
    else:
        points_list.append(xy_list)
        xy_list = []
        cum_windspeed_list.append(windspeed_list)
        windspeed_list = []
        header_list = line.split(",")
        number = header_list[0]
        numbers_list.append(number)

#Create a Point Shapefile for each Hurricane Event that Includes Windspeed as an Attribute
i = 0
for item in points_list:
    points_shapefile_name = str(numbers_list[i])
    points_file = arcpy.CreateFeatureclass_management(workspace_path, points_shapefile_name,
geometry_type = "POINT", spatial_reference =
r"C:\Users\SDML\Desktop\Frequency_Analysis\sample_wgs_projection.shp")
    cursor = arcpy.da.InsertCursor(points_file, ["SHAPE@"])
    for coordpair in item:
        coordpair[0] = -1 * float(coordpair[0])
        coordpair[1] = float(coordpair[1])
        point = arcpy.Point(coordpair[0], coordpair[1])
        cursor.insertRow([point])
    del cursor
```

```
    arcpy.AddField_management(points_file, "WINDSPEED", "FLOAT")
    cursor = arcpy.da.UpdateCursor(points_file, ["WINDSPEED"])
    wind_numbers = cum_windspeed_list[i]
    j = 0
    for row in cursor:
        row[0] = wind_numbers[j]
        cursor.updateRow(row)
        j = j + 1
    del cursor
    i = i + 1

#Create Polyline Shapefile with all Hurricane Tracks
polyline_shapefile_name = "hurricane_tracks.shp"
arcpy.CreateFeatureclass_management(workspace_path, polyline_shapefile_name,
geometry_type = "POLYLINE", spatial_reference =
r"C:\Users\SDML\Desktop\Frequency_Analysis\sample_wgs_projection.shp")
cursor = arcpy.da.InsertCursor(polyline_shapefile_name, ["SHAPE@"])
for item in points_list:
    line_array = arcpy.Array()
    for coordpair in item:
        coordpair[0] = float(coordpair[0])
        coordpair[1] = float(coordpair[1])
        point = arcpy.Point(coordpair[0], coordpair[1])
        line_array.add(point)
    track = arcpy.Polyline(line_array)
    cursor.insertRow([track])
del cursor

#Close Hurricane Dataset File
h.close()
```

APPENDIX B

Instructions for Running SWAT

SWAT Project Setup Menu

- New SWAT Project: set the Project Directory to your project folder, then click OK.

Watershed Delineator Menu

- Automatic Watershed Delineation:
  - Download 1-arc second DEM data for the watershed from the National Map (http://viewer.nationalmap.gov/basic/).
  - In a separate map, use the tool Mosaic in ArcGIS to patch the DEMs into one large DEM for the study area. Then, use the tool Project Raster in ArcGIS to give the mosaicked DEM a projection.
  - In the Watershed Delineation GUI click "Open DEM Raster." Then select "Load from Disk" and the say OK. Navigate to the mosaicked, projected DEM for the watershed, and then say "Add."
  - Click "DEM projection setup," and input "meter" for the "Z Unit."
  - Click "Flow direction and accumulation." This process will take a little time.
  - Click "Create streams and outlets."
  - In a separate map, create a new point shapefile for the outlet for which you want discharge measurements from. Then add the outlet shapefile to the SWAT map document. Zoom into the point once you have added it to the map.
  - Under the Outlet and Inlet Definition submenu, click the "Add" button next to "Edit manually." Use this function to place a point on the stream network near your outlet point created in the step above. Then remove the outlet shapefile that was created in the step above from the SWAT map.
  - Click the "Whole watershed outlet(s)" button and then select the point that you just created in the step above.
  - Click "Delineate watershed."
  - Click the "Calculate subbasin parameters." This process will take a long time.

HRU Analysis Menu

- Land Use/Soils/Slope Definition:
  - Download the 2011 NLCD from USGS (http://www.mrlc.gov/nlcd11_data.php).
  - In a separate map, use the tool Clip to trip the 2011 NLCD file to the extent of your soil file. Then, use the tool Project Raster to give your clipped land cover file the same projection as your DEM.
  - Click the "Land Use Data" tab. Click the folder icon below "Land Use Grid," select "Load Land Use dataset(s) from disk" and then "Open." Navigate to your clipped and projected land use file.

- Under “Choose Grid Field,” select “VALUE” from the drop down menu, and then hit OK.
- Hit the “LookUp Table” button and select “NLCD 2001/2006 Table,” and then say OK.
- Click the “Reclassify” button.
- Download STATSGO2 soil data for your basin from the Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).
- In a separate map, use the tool Merge in ArcGIS to combine your soil shapefiles if your basin covers more than one state. Then, use the tool Project in ArcGIS to give the soil file the same projection as your DEM.
- Click the “Soil Data” tab. Click on the folder icon under “Soils Grid,” and select “Load Soils dataset(s) from disk” and then “Open.” Navigate to your projected soil file.
- Select “MUKEY” from the drop down menu under “Pick field grid code values:” and then say OK.
- Under “Choose Grid Field” select “VALUE” from the drop down menu and then say OK.
- Under “Soil Database Options” select “ArcSWAT SSURGO.”
- Click the “Reclassify” button.
- Click the “Slope” tab. Select “Multiple Slope” under “Slope Discretization.”
- Under “Number of Slope Classes,” choose 5 from the drop down menu. Use the “Current Slope Class” and “Class Upper Limit (%)” options to choose each class and set the upper limit. Split the classes equally to fit the range of your slope data.
- Click the “Reclassify” button.
- Click the “Overlay” button at the bottom.

- HRU Definition:
  - Under the “HRU Thresholds” tab, use the slider bars to indicate what land use, soil class, and slope class subbasin coverage percentage must be reached to designate each to a subbasin. 5% is a good number for each.

Write Input Tables Menu

- Weather Stations:
  - Under the “Weather Generator Data” tab, select “WGEN_US_COOP_1980_2010” from the drop down menu.
  - Under the “Rainfall Data” tab, select “Raingages.” Set the “Precip Timestep” to “Daily.”
  - Use the folder icon next to “Locations Table” to navigate to your locations table file. (Make sure your precipitation location table is in the correct format and that you have the precipitation files for each gage saved in the same folder. You can use the ArcSWAT help to find examples of what each of these files should look like.)
- Write SWAT Database Tables:
  - Hit “Select All,” and then “Create Tables.” Say Yes to any messages that pop-up about weather.

SWAT Simulation Menu

- Run SWAT:
  - Enter the starting and ending dates of the period you want to simulate.
  - Under “Printout Settings,” select “Daily.” If you want to run some “warm up” years through SWAT before collecting discharge outputs, indicate the number of years of “warm up” in “NYSKIP.” (Note: SWAT will start the “warm up” years from the starting date indicated in the Setup SWAT window. For example, if you indicated to run the model from 1/1/1996 to 12/31/2014 with NYSKIP=2, then 1996 and 1997 will be run as “warm up” years, and data outputs will begin on 1/1/1998.)
  - Leave all else as is, and hit the “Setup SWAT Run” button.
  - Hit the “Run SWAT” button.