Development and utilization of a river system model to integrate human and ecological water requirements in a southeastern United States river basin

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As the candidate's supervisors', I have approved this thesis/dissertation for submission

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ABSTRACT

This thesis focuses on the development and use of a river basin management model to assess water management options in the Apalachicola-Chattahoochee-Flint (ACF) catchment in the southeastern United States of America. The catchment covers three states, Georgia, Alabama and Florida with no formal agreements on basin-level water use or allocation. The ACF watershed has faced a crisis of water resource planning over the past 30 years as periodic droughts of increased intensity, duration and occurrence, increasing water consumption and the management of the Federal storage reservoirs sparked debate over the proper allocation of water resources. The fundamental research question at the core of this research project is: Can a simplified, flexible, water system model be effectively used to evaluate critical system elements within a complex, seemingly intractable water management dispute? This research effort encompassed the development and validation of a water system simulation model for the ACF catchment. This model was then used to explore drought management, agricultural water usage and reservoir release operations. This research showed that the model can produce directly comparable results to a more complex water system model used by regulatory authorities. Utilizing the model under extreme drought conditions in 2012 showed that ACF reservoirs and their subsequent management have limited capacities to increase water releases in multi-year droughts, contrary to popular beliefs. The model also showed that modifying irrigation withdrawals in a tributary stream to the Apalachicola River result in some increased downstream flows, but more surprisingly that these demand reductions often resulted in increased elevations at the upstream storage reservoirs from decreased required releases. A detailed simulation of integrated reservoir releases and the trade-off between water storage and downstream releases highlighted the relative importance of the individual causal factors that vary among drought events, implying that a one-size-fits-all approach to drought management in the ACF basin, as proposed by basin managers, is not advisable. Overall, the development of model allowed a more robust consideration of a broader array of management approaches, a means of cross-checking the modeling results with more complex models and increased access of stakeholders to simulation results.

DECLARATION 1 - PLAGIARISM

I, Steve Leitman, declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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Signed: Steve Leitman

Supervisor:

Co-supervisor

DECLARATION 2 - PUBLICATIONS

PUBLICATION 1

Leitman, S and G. Kiker. 2015. 'Development and comparison of integrated river/reservoir models in the Apalachicola-Chattahoochee-Flint basin, USA'. Environment, Systems and Decisions 35:410 - 423.

Author Contributions:

SL was the project leader, did all of the modeling work and testing of the comparisons of the model output in Fiteval program, and the lead writer in preparing the manuscript. GK contributed to the writing of the paper and provided guidance and commentary on comparing the output sets from the two models.

PUBLICATION 2

Leitman S., B. Pine and G. Kiker. 2016. 'Management options during the 2011-2012 drought on the Apalachicola River: A systems dynamic model evaluation.' Journal of Environmental Management, Vol 58 (2).

Author Contributions:

SL did all of the modeling analysis, computation work and data analyses served as project leader as well as being the principle writer of the manuscript. SL also converted graphics from publications which were prepared in R into the graphics used in this dissertation which were prepared in Excel. BP prepared all of the graphics done in R and provided conceptual insights to data and results interpretation and contributed to writing of the manuscript. GK contributed to the writing of the paper and provided guidance in how to approach comparing the output sets from the two models.

PUBLICATION 3

Leitman, S.F., G. Kiker and D. Wright. 2016, 'Simulating system-wide effects of reducing irrigation withdrawals in a disputed river basin'. Submitted to River Research and Applications, January 2017.

Author Contributions:

SL did all of the modeling analysis and computation work and data analyses served as project leader as well as being the principal writer of the manuscript. DW provided the expertise and data related to agricultural irrigation and the capacity to reduce irrigation water use, especially for sod-based rotation and contributed to the writing of the manuscript. GK contributed to the writing of the paper and provided guidance in how to approach comparing the output sets from the two models.

PUBLICATION 4

Leitman, S.F. and G. Kiker. 'Can you have your lake and drink it too? Reactive drought plans have little use with diverse climate and social dynamics'

Author Contributions:

SL did all of the modeling, computational analysis and data analysis, served as project leader and was the principle writer of the manuscript. GK contributed to the writing of the paper and interpretation of model results.

SIGNED: Steve Leitman

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This manuscript represents the culmination of over 40 years of working and researching water management issues in the Apalachicola-Chattahoochee-Flint basin. As such, there are many people who have had an influence on my understanding of this watershed, too many to give proper acknowledgement to in the beginning of this document, but there are several which I would note for their strong influence on me. First, Dr. Robert J. Livingston who is the only person I know that has spent more time than I have working in this basin and who has continued to provide me with original insights and observations on the watershed. I would also like to extend special thanks to Dr. Richard Palmer and Bill Werick for introducing me to STELLA and providing me with a tool that has expanded my capacity to understand the ACF watershed, Dr. Andy Dzurik, who as my graduate advisor when getting my Master's Degree so many years ago allowed me free reign of a University to take classes in hydrology, ecology and environmental economics rather than restricting me to the core curriculum of Urban and Regional Planning, to Jerry Ziewitz and Will Duncan of the US Fish and Wildlife Service who have allowed me to use the ACF-STELLA model on multiple projects in the watershed, to Dr. Dan Sheer and Dr. Megan Rivera for the many, many conversations on modeling and metrics, and especially to Dr. Greg Kiker for his involvement, trust, friendship and guidance in this project. I would also like to thank Randie Denker, I could not have done this without you at my side and to Elinor and Laura Phipps for believing in my work and providing support for me to continue working on the Apalachicola River at critical times in my career.

ABBREVIATIONS AND CONVERSIONS

ACF = Apalachicola-Chattahoochee-Flint

cfs = cubic feet per second

cm = centimeters

m^3/s = cubic meters per second

HEC = Hydrologic Engineering Center

JWLD = Jim Woodruff Lock and Dam

m = meters

M & I = municipal and industrial

NFREC = North Florida Research and Education Center

NIDIS = National Integrated Drought Information System

NSE = Nash-Sutcliffe coefficient of efficiency

RIOP = Revised Interim Operating Plan

RMSE = root mean square error

SBR = sod based rotation

STELLA = Systems Thinking Experimental Learning Laboratory Analysis

UIF = unimpaired flow

USACE = United States Army Corps of Engineers

USFWS = United States Fish and Wildlife Service

USGS = United States Geological Survey

VRI = variable rate irrigation

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CHAPTER 1: INTRODUCTION

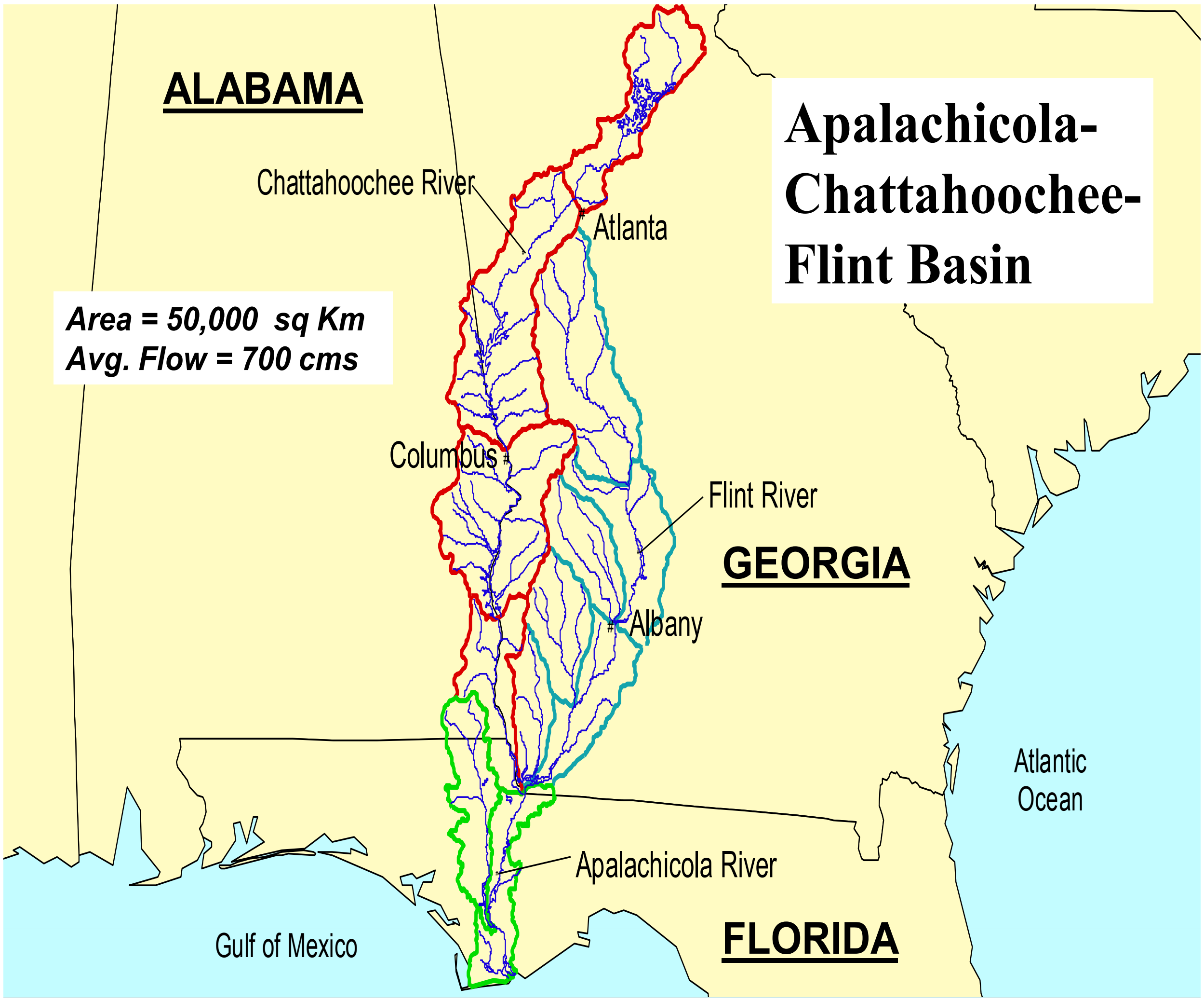
The research associated with this project focused on the development and use of a river basin management model to assess future water management options in the Apalachicola-Chattahoochee-Flint (ACF) catchment, a nearly 50 000 square kilometer basin in the southeastern United States (Figure 1.1.). This dissertation will be presented as a series of research papers that focus on addressing the objectives listed below. Accordingly, each of these papers will form chapters of the dissertation.

The ACF watershed has faced a crisis of water resource planning during the past 30 years as periodic droughts, increasing usage of water, and mismanagement of the federal storage reservoirs sparked political debate over the proper allocation of water resources (Leitman, 2005; Jordan and Wolf, 2006). The ACF water dispute has been through several iterations of study, collaboration, conflict management and litigation among multiple interest groups in Alabama, Georgia and Florida. It has long been incorrectly framed as a conflict among three States instead of a conflict among multiple interests, which reside in three States. The failure to resolve the problem has not been that the interests in the basin are facing an intractable problem, but that the process being used to resolve the problem has been inadequate (Leitman, 2005).

At the core of the ACF dispute is the challenge involved in balancing a variety of water resource needs such as: environmental interests for the riverine ecosystems of the Apalachicola, Flint and Chattahoochee Rivers; commercial fisheries of Apalachicola Bay (Florida); rural agricultural water users in Alabama and Georgia (most notably in the Flint basin in southern Georgia); hydropower production; reservoir-based interests on the Chattahoochee River; commercial navigation interests in southern portion of the basin and municipal water supply for metropolitan Atlanta and other cities in the watershed. Several recent drought periods in the southeastern US have brought renewed debate over water management, demonstrating that interim political solutions and agreements to settle flow allocations are unsustainable. Current case law and legislation in the US do not provide a clear legal precedent for the resolution of the ACF dispute. This conflict has its roots in differing political interpretations of each state's legal rights over water resources and their social needs. A resolution must be sought through either judicial interpretation or political negotiation (Ruhl, 2003; 2005, Thornley, 2006). This paucity of options suggests a need to test a new approach, such as the use of a river systems model and the development of performance metrics to develop adaptive policies for water distribution.

1.1 Description of Apalachicola-Chattahoochee-Flint Basin

The Apalachicola-Chattahoochee-Flint (ACF basin) drains nearly 50 000 square kilometers (20 000 square miles) in the States of Florida, Georgia and Alabama in the southeastern United States. Figure 1.1 shows the location of the ACF basin with about 75% of the basin in Georgia, 12.5% in Florida and 12.5% in Alabama. The basin extends from the Blue Ridge Mountains in Northern Georgia to the Gulf of Mexico near Apalachicola, Florida. The Apalachicola River begins at the confluence of the Chattahoochee and Flint Rivers at the Florida border and is the largest river in Florida in terms of flow, with an average flow at the mouth of approximately 700 cubic meters per second (m^3/s) (25 000 cfs) (USACE, 2012). Since the majority of the basin and its storage capacity lie above the Florida border, flow in the river is mostly defined by rainfall and management actions outside of the State (Leitman, 2005; Livingston, 2015). Figure 1.2 shows an annual hydrograph for a drought year; Figure 1.3 an annual hydrograph for a normal or average flow year, and Figure 1.4 the median daily flow for the period of record (1923 – 2014). From these figures, it is evident that there is great variation in flow in the Apalachicola River both within individual years and among different years. Average annual flow can vary by more than a factor of 2 and in a typical year, average daily flow in the Apalachicola River can range from far greater than 2 800 m^3/s to well below 283 m^3/s and in the extreme over 5 600 m^3/s (200 000 cfs) and less than 140 m^3/s (5 000 cfs). Flow in the basin is typically greatest in the winter months and least in the late summer months.



Scale: ⟷ = 100 Km

Figure 1.1: Map of the Apalachicola-Chattahoochee-Flint (ACF) River Basin. The basin lies in three southern US states, Georgia, Alabama and Florida.

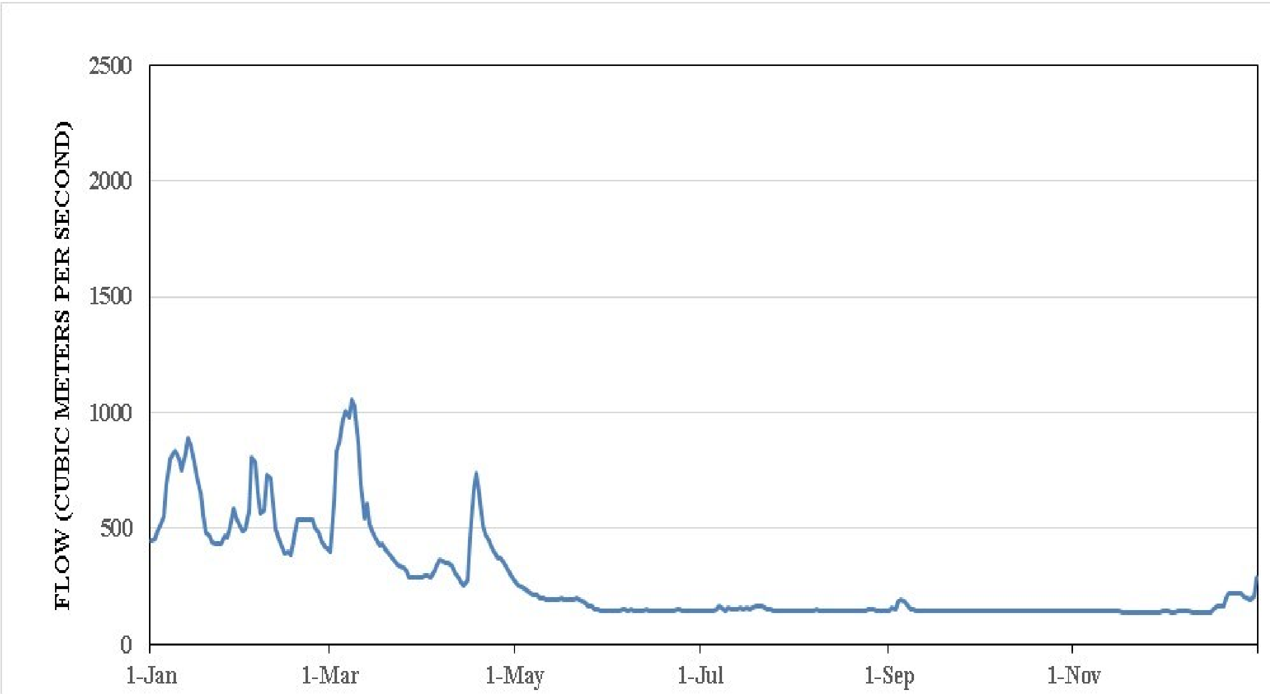


Figure 1.2: Annual hydrograph for the Apalachicola River at the Chattahoochee, Florida gauge for a drought year (2007) (data source: USGS, 2016)

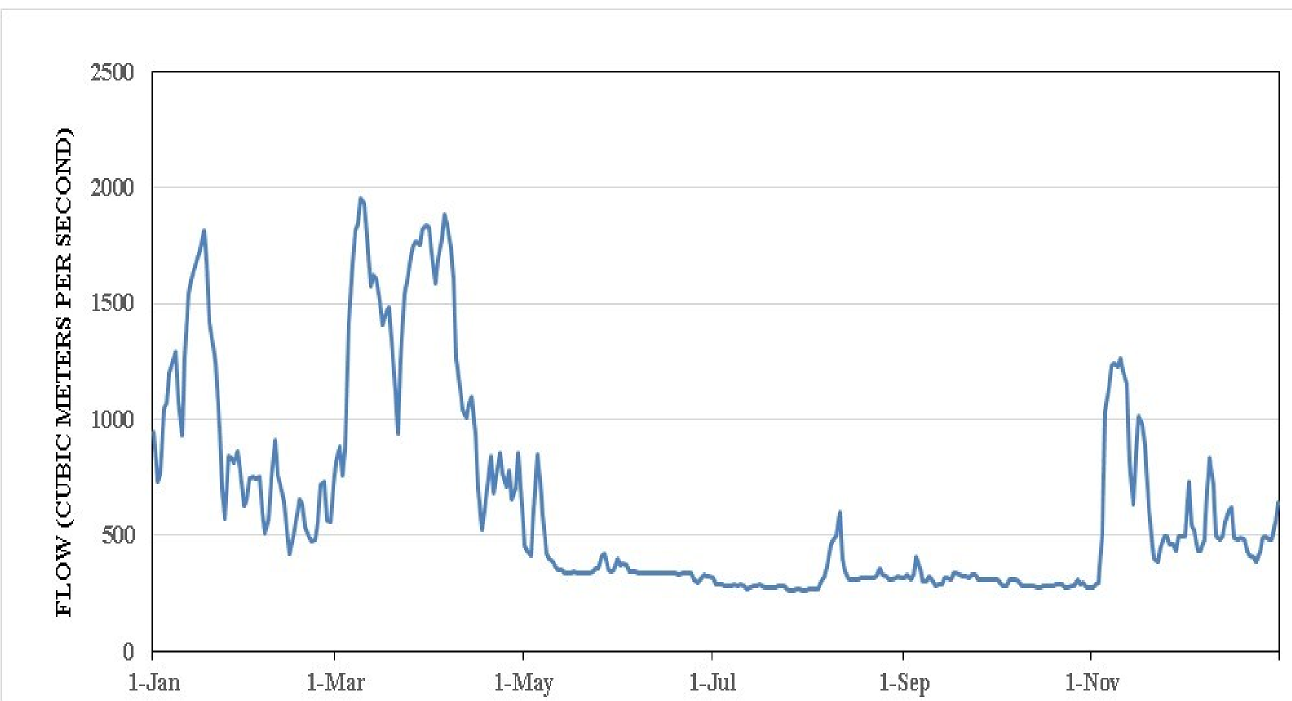


Figure 1.3: Annual hydrograph for the Apalachicola River at the Chattahoochee, Florida gauge for an average flow year (1977) (data source: USGS, 2016)

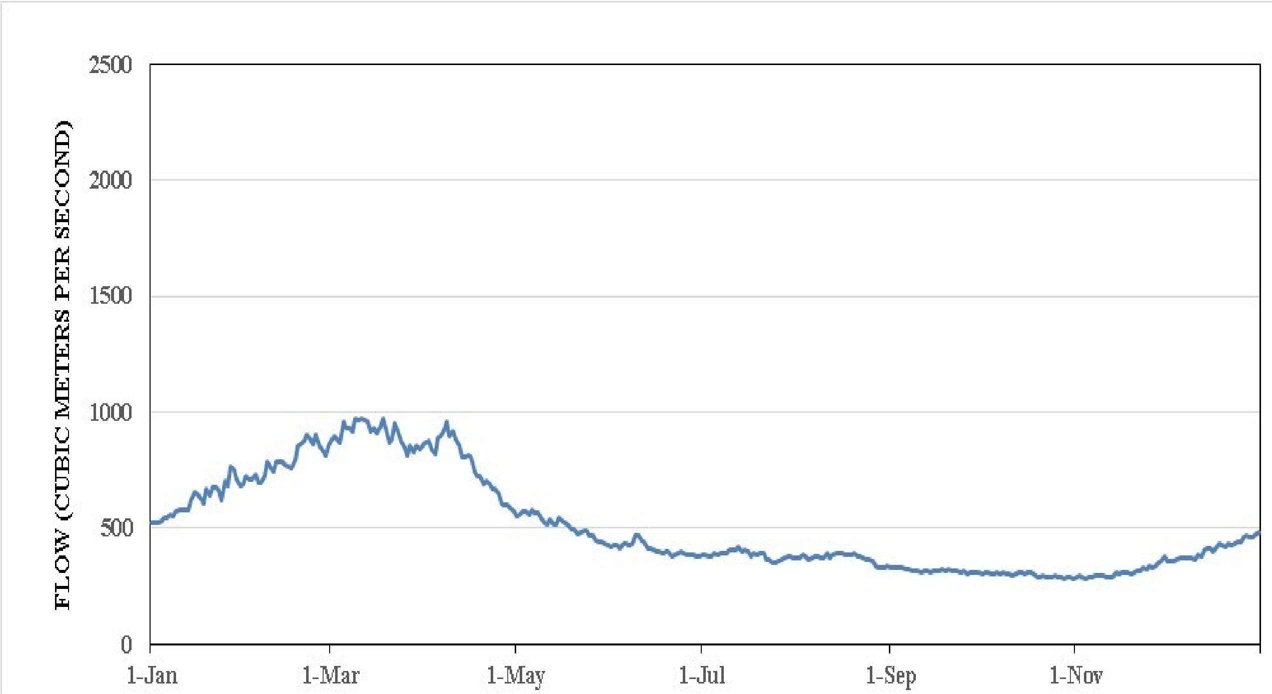


Figure 1.4: Median flow hydrograph for the Apalachicola River at the Chattahoochee, Florida gauge for 1923 - 2014 (data source: USGS, 2016)

The ACF basin is home to a multitude of biological resources ranging from endangered species such as the Atlantic sturgeon (*Acipenser oxyrinchus desoti*) and several species of mussels (fat three-ridge mussel (*Amblema neislerii),* purple bankclimber *(Elliptoideus sloatinus)*, Chipola slapshell (*Elliptio chipolaensis*)), to striped bass (*Morone saxatilis*), a robust reservoir based fisheries based on large-mouthed bass (*Micropterus salmoides*) and bream (*Lepomis sp.)*, and a seafood industry in its estuary which yields 10% of the nation's oyster (*Crassostrea virginica*) harvest*, peneaid* shrimp with the estuary also being an important nursery grounds for the Gulf of Mexico (USFWS, 2012). The expansive Apalachicola River floodplain has a large bottomland hardwood swamp with extensive areas of cypress (*Taxodium disticum*) and tupelo (*Nyssa aquatic* and *Nyssa ogeechee*) and a diverse array of bottomland hardwood species including green ash (*Fraxinus pennsylvanica*), overcup oak (*Quercus lyrata*), water oak (Quercus nigra), swamp laurel oak (*Quercus laurifolia*), water hickory (*Carya aquatic*) and sweetgum (*Liquidambar stryraciflua*) (Light *et al*., 1998). Most of the floodplain has been purchased by the State of Florida and the federal government for conservation purposes (Leitman, 2005). The Apalachicola River's floodplain forest has been shown to be integral to the riverine ecosystem

(Light *et a*l., 2006, Burgess *et al.*, 2013). The Apalachicola River drains into a highly productive estuary and the Apalachicola River dominates the associated estuary as a source of freshwater, nutrients and organic matter (Livingston, 2015). Nutrient loading from the river, in the form of inorganic nitrogen and phosphorus compounds and various forms of particulate organic matter, colloidal conglomerates and dissolved compounds are loaded into the receiving bay and the inorganic nutrients are then rapidly taken up by phytoplankton. The resulting high phytoplankton productivity and particulate organic matter form the basis for the highly productive food webs in Apalachicola Bay (Livingston, 2015).

The basin's waters are used by humans for many purposes including drinking water, hydropower generation, cooling water for coal and nuclear power plants, agricultural irrigation, and industrial activities, dilution of waste water, commercial navigation and recreational activities at both the reservoirs and in the rivers themselves (Carter, 2008; USACE, 2015). During several droughts in the past several decades, the water users of the basin have found themselves in competition for the water resources of the basin, but during periods of normal rainfall there are more than adequate water resources for all users (Leitman, 2005).

The two rivers that form the Apalachicola River, the Flint and Chattahoochee, are very different in nature and in usage. The Chattahoochee's source of flow is primarily surface water contributions, and multiple storage reservoirs allow the basin's water resources to be managed. The Flint River, on the other hand, has a large groundwater contribution and has almost no reservoir storage capacity. Therefore, flow in the Chattahoochee basin can be managed by regulating both supply and demand, whereas flow in the Flint can be managed only through demand. Management of the Flint is also complicated by the surface–groundwater interactions in the mid to lower Flint basin.

Figure 1.5 shows the location of the main stem reservoirs in the ACF basin, and Figures 1.6 and 1.7 show the relative contribution of flow in the Chattahoochee and flow in the Flint on Jim Woodruff Reservoir outflow, the dam at the confluence of the Chattahoochee and Flint rivers. These figures show that the contribution of flow from the two principal inflows differs when considering median and low flow contributions, with the Flint contributing a relatively greater share in low flow periods. In Figure 1.6 it can be seen that, over the course of the year, median flow for the Chattahoochee River at the Andrews outflow (the gage closest to Jim Woodruff outflow) is greater than the median flow for the Flint River at Bainbridge, Georgia.

Figure 1.5: Location of the major main stem reservoirs and key flow gauging stations in the ACF basin. The size of the storage reservoir icons is scaled to their full storage capacity.

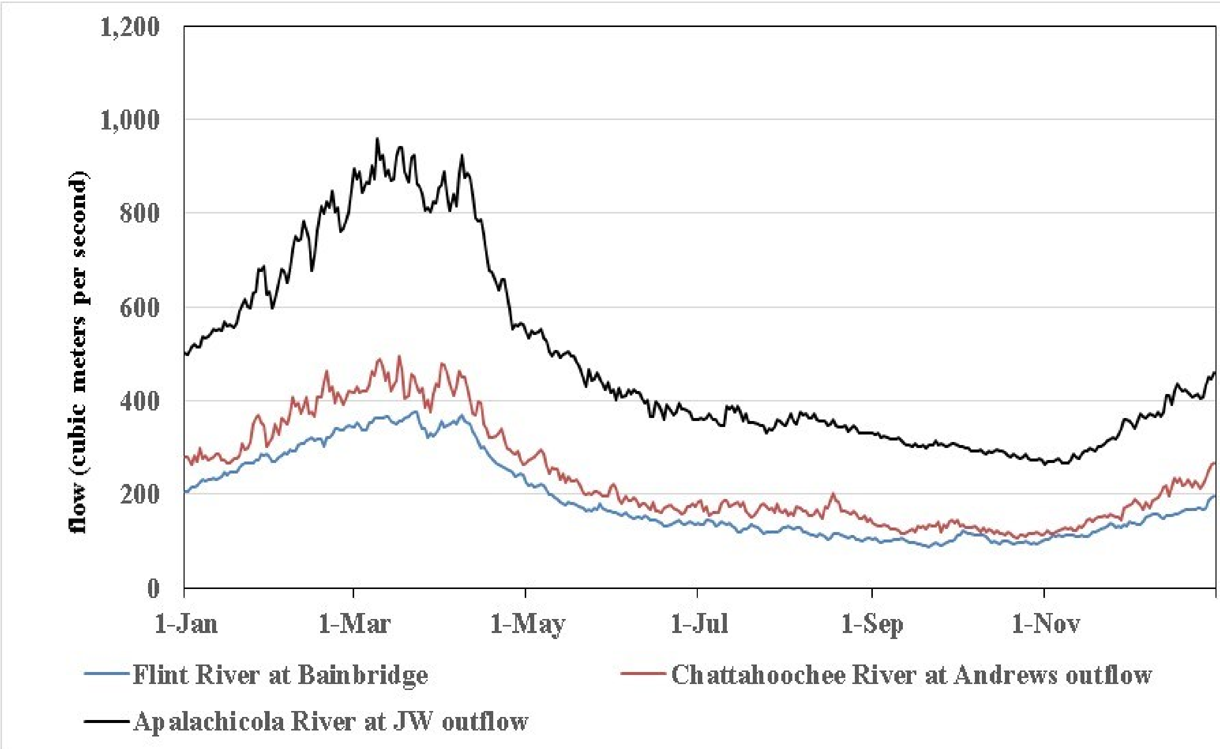


Figure 1.6: Comparison of median flows for the Jim Woodruff outflow, Bainbridge, Georgia gauge on the Flint River and Andrews outflow, Alabama on the Chattahoochee River (1939 – 2013) (USACE, 2015; USGS, 2016; 2016a). See Figure 1.5 for the location of the gauge sites included in this figure.

In contrast, Figure 1.7 shows that the 90% exceeded flows are more equitable over the year with the contribution of the Flint being greater in the late summer and early fall. This phenomenon is the result of the large spring flow contribution to the Flint River and suggests that the role of the Flint River in contributing to meeting minimum flow thresholds is important during drought events.

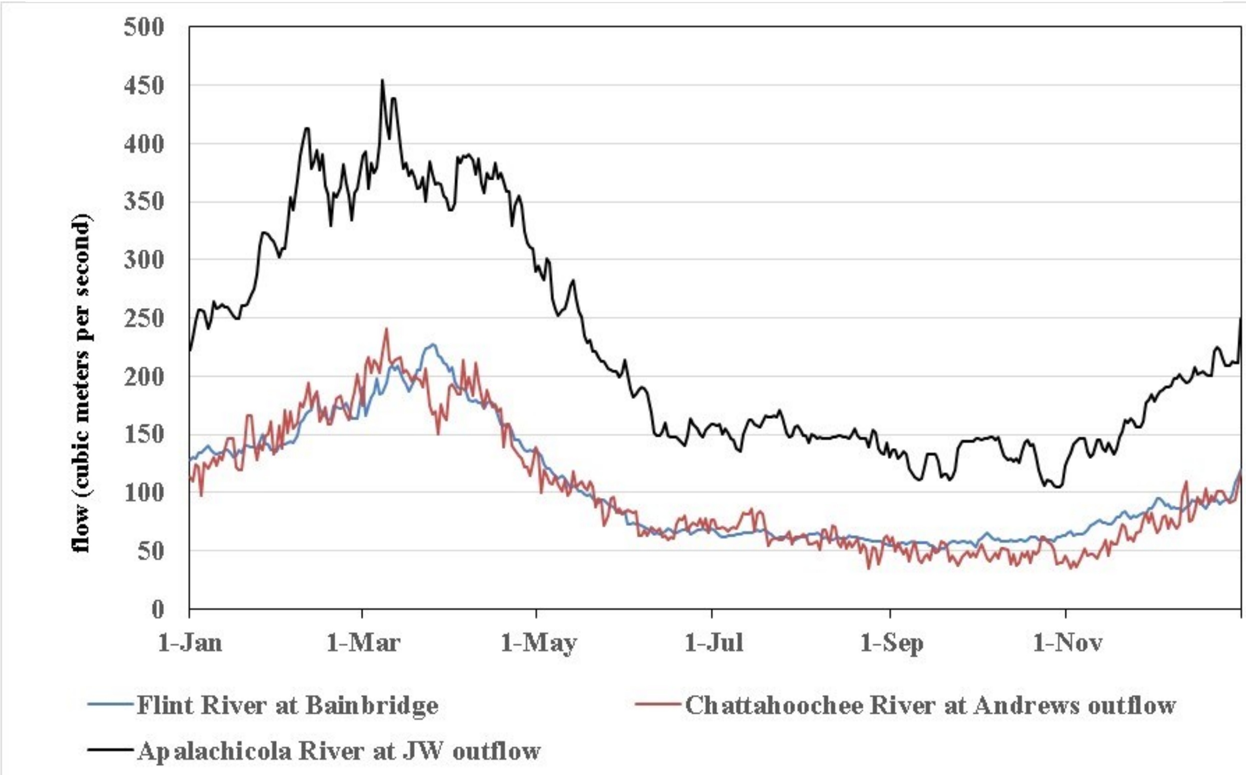


Figure 1.7: Comparison of 90% exceeded flows for the Jim Woodruff outflow, the Bainbridge, Georgia gauge on the Flint River and the Andrews outflow, Alabama on the Chattahoochee River (1939 – 2013). (USACE 2015; USGS, 2016; 2016a)

1.2 Water management in the ACF basin

In general, reservoirs are divided into three general areas or pools: the flood pool, the conservation pool and the inactive storage pool or dead zone (USACE, 2012). The flood pool is for the temporary holding of flood waters. The conservation storage pool is the active management pool. The inactive storage pool is the area below the conservation pool whose waters cannot be routinely managed due to physical constraints from the reservoir and dam design. In the ACF basin the conservation pool is further divided into four zones, called action zones (USACE, 2011). Figure 1.8 shows how one of the storage reservoirs in the ACF basin, West Point, is divided into action zones for each month. The Action Zones are used to manage the reservoirs at the highest elevation possible while balancing the needs of all authorized project purposes. In the ACF basin these zone elevations were first defined in the 1989 proposed Water Control Plan (USACE, 2011), although there is no supporting analytical documentation explaining how the exact elevations of these zones were provided. At the time of their development, the action zones were derived on the basis of the past operation of the storage projects, which considered time-of-year, historical pool level/release relationships, operational limits for conservation, and recreational impact levels (USACE, 2011).

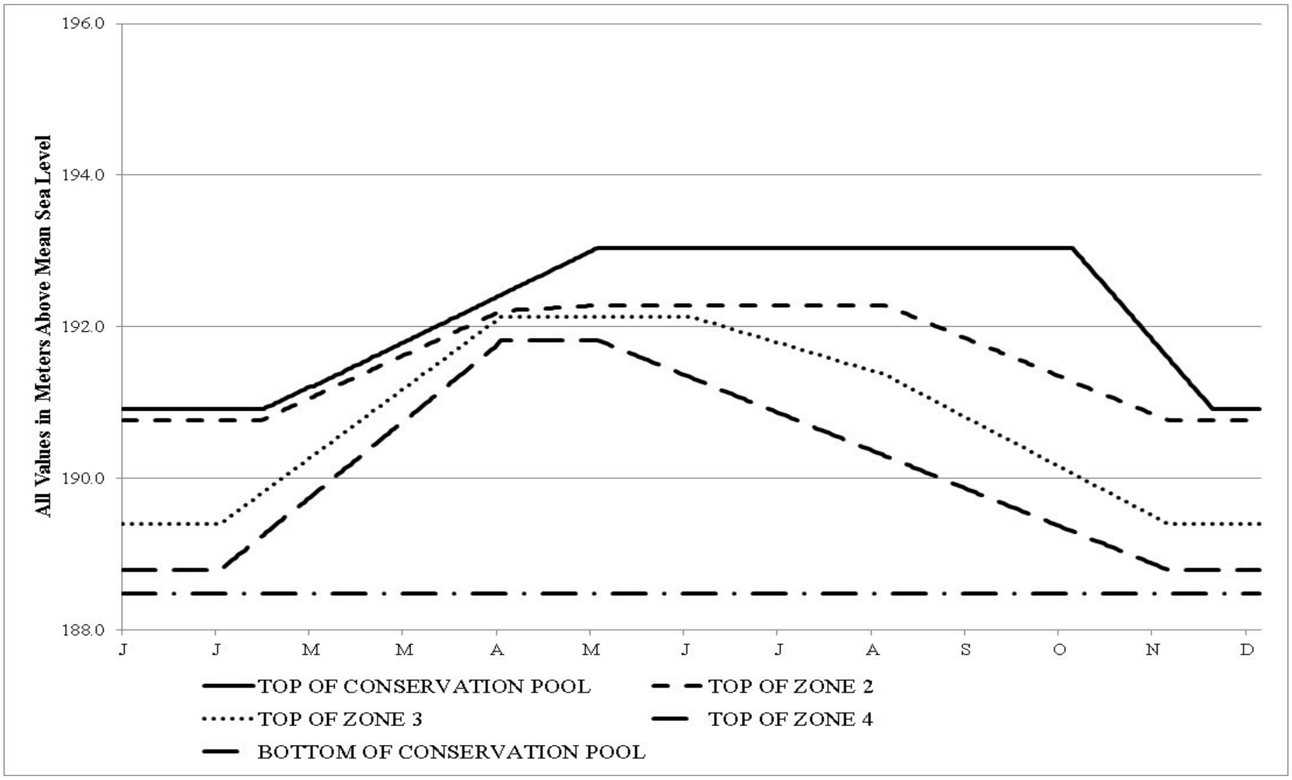


Figure 1.8: General division of the conservation pool volume into monthly action zones (USACE, 2012).

Only the conservation pools of Lake Lanier, West Point Lake and W. F. George Lake, the principal federal storage reservoirs, have been divided into action zones. The general philosophy behind the US Army Corps of Engineers' (USACE) use of the action zones is to have operational requirements more biased toward downstream augmentation when the reservoirs are full and more biased toward retaining water as they become less full (USACE, 2015). Zone 1, the highest level in each reservoir, defines a condition where all authorized purposes are met. As reservoir levels decline, Zones 2 through 4 define increasingly critical system water shortages and guide the USACE in reducing flow releases (USACE, 2011). The conservation pool at Woodruff was not divided into zones because the depth of the pool is only one-foot at Lake Seminole (USACE, 2011).

Dividing the conservation pool into action zones is necessary in the ACF basin because the majority of the basin's storage capacity (65%) is found at Lake Lanier which only impounds 6% of the basin and hence reservoir refill during drought events is a major issue at this reservoir. In considering the capacity of the reservoirs in the ACF basin to store water and augment flow, it is important that this capacity be considered in the context of the watershed. The topography of the ACF basin is relatively flat, especially in the lower half of the basin. Consequently, the reservoir system has a limited capacity to store water relative to flow in the lower river and the capacity of the overall reservoir system to retain or augment flows is limited, especially when compared to other river systems in the western US where flow is less and storage capacity greater.

Table 1.1 provides background data on these reservoirs. From Table 1.1 it can be seen that there are 13 reservoirs on the main stem of the Chattahoochee River, another two on the Flint River, and Jim Woodruff Dam is located at the confluence of the Flint and Chattahoochee Rivers. From a surface area perspective, there are over 68 000 hectares (168 000 acres) of impounded water on the main stem of the Chattahoochee and Flint Rivers when the reservoirs are at full pool. As the pool elevation in the reservoirs declines, this surface area value will also decline. Of this surface area, nearly 90% is in the federal reservoirs and 10% in the private reservoirs. Virtually all of the storage capacity is at the federal reservoirs (USACE 2015).

Table 1.1 shows that there are over 23 907 m^3-days of water in storage in the basin when all of the reservoirs are at full pool. About two-thirds of this storage is at Lake Lanier. This table also shows that although Lanier, W.F. George and Seminole have comparable surface areas at full pool, the storage volumes in the conservation pools of the reservoirs are quite different. It can also be seen that although West Point has a smaller surface area than George or Seminole, it has a greater capacity to store water. The remaining reservoirs are referred to as "run-of-the-river facilities". This term means that at these facilities, flow entering into the reservoir is essentially the same as that flowing out. This term, however, is a relative term and is dependent both on the volume of water entering the reservoir and the time scale at which the storage is managed. Although a reservoir may have some storage capacity, it can also be considered a "run-of-the-river" facility when its augmentation capacity is considered negligible over a period of time that reflects reservoir operations. For instance, Lake Seminole is essentially operated as a run-of-the-river facility by the USACE in their operations for the ACF basin because over the period of a week, total flow into Seminole will generally equal total flow out (USACE, 2015). On a daily basis, however, this may not be true and storage may be increasing or decreasing.

TABLE 1.1: An overview of the main stem reservoirs of the ACF basin. (USACE, 2015)

	Surface area at full pool		**Storage capacity**	
	(hectares)	**% of total**	**(cms-days)**	**% of total**
Chattahoochee River				
Lanier	15 571	22.9%	15 517	66.4%
Morgan Falls	234	0.3%		
West Point	10 449	15.3%	4 368	18.7%
North Highlands	53	0.1%		
Oliver	869	1.3%		
Bartletts Ferry	2 363	3.5%		
Goat Rock	424	0.6%		
Langdale	61	0.1%		
Riverview	30	0.0%		
City Mills	44	0.1%		
W.F. George	18 253	26.8%	3 506	14.9%
Flint River				
Lake Blackshear	3 444	5.1%		
Lake Worth	622	0.8%		
Flint and Chattahoochee Rivers				
Jim Woodruff	15 150	22.2%	516	2.2%

The reservoir operating plan currently being used by the USACE to manage the ACF reservoir system is the Revised Interim Operating Plan (RIOP). The RIOP operations were developed to incorporate concerns related to the federal Endangered Species Act into the management of the federal reservoirs in the ACF basin in response to litigation by the State of Florida and because revision of the basin's Water Control Manual was delayed by other litigation (USACE, 2011). Table 1.2 summarizes operations under the RIOP. Table 1.2 reveals that there are three factors that define reservoir releases from the ACF system under the RIOP: 1) month of the year, 2) composite storage zone, and 3) basin inflow. The RIOP defines releases only from Jim Woodruff Dam. The reservoir behind Jim Woodruff Dam (Lake Seminole), however, does not have ample storage capacity to support the releases called for in the RIOP. To meet the requirements of the RIOP, water must be released from the upstream major storage reservoirs

(Lake Lanier, West Point Lake, and W. F. George Lake). Therefore, the RIOP is a management plan for the entire ACF basin.

Table 1.2: Revised Interim Operating Plan (RIOP) reservoir operation criteria for the ACF basin. Note that all flows are in cubic meters per second (m^3/s) Source: (USACE, 2011)

Months	Composite storage zone	Basin inflow (BI) (cms)	Release from Woodruff (cms)	BI available for storage (cms)
March - May	1 & 2	>= 962.2	>= 707.5	up to 100% BI > 707.5
		>=452.8 & < 962.2	>= 452.8 + 50% BI > 452.8	up to 50% BI > 452.8
		>= 141.5 & < 452.8	>= BI	
		< 141.5	>= 141.5	
	3	>= 141.5	>= 707.5	up to 100% BI > 707.5
		> 311.3 & < 1 103.7	>= 311.3 + 50% BI > 311.3	up to 50% BI > 311.3
		>= 141.5 & < 311.3	>= BI	
		< 141.5	>= 141.5	
		>= 141.5		
June - Nov.	1, 2 , & 3	>= 679.2	>= 452.8	up to 100% BI > 707.5
		>= 226.4 & < 679.2	>= 226.4 + 50% BI > 226.4	up to 50% BI > 226.4
		>= 141.5 & < 226.4	>= BI	
		>= BI	>= 141.5	
Dec. - Feb.	1, 2 , & 3	>= 141.5	>= 141.5 (store BI > 141.5)	up to 100% BI > 141.5
		< 141.5	>= 141.5	
all months	4	NA	>= 141.5	up to 100% BI > 141.5
all months	drought zone	NA	>= 127.35	up to 100% BI > 127.35

The management of the ACF basin has been fraught with controversy ever since the USACE proposed to re-allocate part of the storage pool of Lake Lanier from hydropower to water supply and to update the basin's Water Control Plan (Carter, 2008). This proposal led to the federal government and the three states embarking on a Comprehensive Study of the basin, which in turn led to the first interstate Compact in the US since the adoption of the major federal environmental laws in the mid-1970s. Ultimately the Compact was terminated and a nearly 15-year period of litigation between the parties followed the termination and ultimately the settling of the lawsuits (USACE, 2015). In 2015 the USACE released a draft Environmental Impact Statement to update the management approach to the ACF reservoir system (USACE, 2015).

In summation, the ACF basin (particularly the Apalachicola River and its estuary) is an environmentally significant ecological resource that has been mired in a water dispute for several decades. At present, this dispute is pending before the US Supreme Court (Supreme Court of the US, 2013). Exploration of this complex problem, along with the development of tools for systematic resolution of different concerns are addressed in a series of chapters formed as peer reviewed journal article submissions. The subsequent chapters are described as abstracts in the following sections.

1.3 Research Objectives:

The fundamental question at the core of this research project is: Can a simplified, flexible, water system model be effectively used to evaluate critical system elements within a complex, seemingly intractable water management dispute? The objectives associated with addressing this research question are the following:

Objective 1: To develop and test a planning-level river basin modeling tool (ACF-STELLA) in the ACF basin for comparison with the primary water systems modeling tool (HEC-ResSim) used by the federal agency (US Army Corps of Engineers) responsible for managing the primary reservoirs in the watershed (Chapter 2).

Objective 2: Using the river basin modeling tool (ACF-STELLA), to evaluate whether problems experienced in a recent severe drought (2011 – 2012) can be mitigated through alternative management of the existing reservoir system and/or demand management (Chapter 3).

Objective 3: Using the river basin modeling tool (ACF-STELLA) to evaluate to what degree demand management in the form of significantly reducing agricultural irrigation withdrawals will resolve downstream water flow problems (Chapter 4);

Objective 4: Using the river basin modeling tool (ACF-STELLA) to evaluate whether the rapid lowering of the largest storage reservoir in the watershed (Lake Lanier) during drought events can be mitigated through managing the storage reservoirs in a different manner (Chapter 5).

1.4 Structure of Thesis

This thesis is comprised of four separate papers relating to the development and use of a river basin management model to assess future water management options in the Apalachicola-Chattahoochee-Flint (ACF) catchment. A summary of these papers and their relation to the objectives of this research are provided below.

1.4.1. Calibration of the ACF-STELLA model with HEC-ResSim model

This paper was accepted for publication in *Environment, Systems and Decision-making* in August 2015 and satisfies Objective 1 of the Research Objectives. The content of this paper provides Chapter 2 of the thesis. The abstract follows:

This paper describes the development of a stakeholder-derived, water system model (ACF-STELLA) for the Apalachicola-Chattahoochee-Flint (ACF) basin and directly compares simulated daily outputs with a more complex model (HEC-ResSim) used by the US Army Corps of Engineers (USACE) to formally evaluate alternative basin management options. The two models were directly compared using seventy years of daily output (1939-2008; n=25,668) for eight different ACF sites: five flow stations and three reservoir elevations. The comparison between models showed a strong match (p=0.01 rejection significance) between the daily outputs for six of the eight sites, with median Nash-Sutcliffe Coefficient of Efficiency ranging from 0.732 to 0.979. In the two sites where daily comparisons were less successful, additional analysis was conducted to explore where simulated results diverged. At the Lake Lanier outflow site, a seven-day moving average comparison provided a successful match (p=0.01 rejection significance). At the Walter F. George Lake elevation site, comparisons showed a primary source of disagreement stemmed from a period where HEC-ResSim model outputs were significantly greater than historically observed reservoir elevations. Given the satisfactory model comparison as well as the significantly increased simulation speeds of ACF-STELLA, it was concluded that the ACF-STELLA model could be a useful tool in water policy planning activities to explore alternative basin management scenarios for expanded simulation by the more complex HEC-ResSim model.

1.4.2. Management options during 2011-2012 drought

This paper was published in *Environmental Management* in June 2016 and the responses to reviewer comments were submitted in April 2016. The paper addresses Objective 2 of the objectives. The content of this paper provides Chapter 3 of the thesis. The abstract follows.

In 2012, the ACF basin experienced the second year of a severe drought and its third multi-year drought in the past 15 years. During severe droughts, low reservoir and river levels can cause significant economic and ecological impacts to the reservoir, river, and estuarine ecosystems and their human users. During drought, augmenting Apalachicola River discharge through upstream reservoir releases and demand management are often-suggested solutions to minimizing downstream drought effects. In this assessment, it was examined whether the existing ACF reservoir system could be operated to minimize drought impacts on downstream water users and ecosystems through flow augmentation to the Apalachicola River. The analysis finds that in extreme drought such as observed during 2012, increases in water releases from available reservoir storage are insufficient to even increase discharge to levels observed in the 2007 drought. This suggests that there is simply not enough water available in managed storage in the basin to offset extreme drought events. Because drought frequency and intensity is predicted to increase under a variety of climate projections, the results demonstrate the need for a critical assessment of how water managers will meet increasing water demands in the ACF. Key uncertainties that should be addressed include (1) identifying the factors that led to extremely low Flint River discharge in 2012, and (2) determining how water "saved" via demand management is allocated to storage or passed to downstream ecosystem needs as part of the ongoing revisions to the ACF Water Control Manual by the US Army Corps of Engineers.

1.4.3 System-wide effects of reducing irrigation withdrawals

This paper was submitted to River Research and Applications in January 2017 and addresses Objective 3 of the objectives. The content of this paper provides Chapter 4 of the thesis. The abstract follows:

This paper tests the hypothesis that reduction in consumptive losses to streamflow through the introduction of water-saving irrigation technologies and practices will have a positive effect on Apalachicola River flows and downstream ecosystem services. Based on research on water saving agricultural irrigation devices and practices in the ACF basin, future irrigation demands could be decreased substantially while maintaining or even increasing the current levels of yield for some crops if alternative practices were to be implemented at a large scale. An integrated reservoir/reach model of the ACF basin was used to explore the effects of the following irrigation scenarios on streamflow in the lower Flint basin: 1) current irrigation withdrawal levels, 2) an expansion of irrigated agricultural area and continuation of current irrigation practices, 3) modest adoption of water conservation practices, 4) wide-spread adoption of water conservation practices and 5) rain-fed farming only. Model results were analyzed in terms of specific reach flows and reservoir elevations as well as through expert-based metrics of environmental suitability for Gulf Sturgeon habitat, mussel habitat and floodplain inundation.

Simulation results showed several, non-intuitive factors highlighting the non-linearity of this complex basin when decreasing irrigation demands. In these simulations, irrigation decreases upstream do not always translate directly to elevated flows or enhanced delivery of ecological services downstream. In higher flow years when there is less need for flow augmentation from upstream federal storage reservoirs, nearly all of the water savings from decreasing irrigation withdrawals in the Flint basin translate into slightly increased flows in the downstream Apalachicola River but with little effect on ecological services. But in drought years when there is a large need for flow augmentation from upstream federal storage reservoirs, a large percentage of the water savings are captured as higher storage elevations at these federal reservoirs as a result of reservoir managers having to provide less downstream augmentation flows under current management rules. In evaluating flow metrics used to translate flow changes to environmental effects it was found that changes to flow would occur at a time and rate which could not affect sturgeon spawning or foraging habitat for young-of-the year sturgeon nor floodplain inundation. The analysis suggests that if the intent is to protect key species or habitats then both supply and demand management are necessary since consumptive demands in the ACF basin are small relative to flow in the Apalachicola River. Given these simulation results and the increasing frequency of droughts in the basin in the past several decades, public policy decisions need to be formulated with regard to what portion of the water savings from changing irrigation practices should be allocated to the upstream storage reservoirs and what portion should be allocated to supporting downstream environmental and social needs.

1.4.4 PAPER 4: Causal factors for the lowering of Lake Lanier elevations during drought

The content of this paper provides Chapter 4 of the thesis and addresses Objective 4 of the objectives. This paper is intended to be submitted to an as yet undetermined journal in 2016. The abstract for this paper follows:

A major concern in managing the ACF basin has been the rapid lowering of Lake Lanier, the largest storage reservoir in the watershed, during drought events. To provide insight into the best

management approaches to address this rapid lowering, this paper analyzed the causal factors behind the lowering and the efficacy of the USACE's approach to refilling the reservoir pool under the provisions of the RIOP. In considering the causal factors for the lowering of Lake Lanier during droughts, it was taken into account whether or not any of the factors can be influenced by human management decisions (e.g. climate driven factors vs. consumptive demands) and whether the benefits to society from a specific factor are so great that changing them substantially would not be justified (e.g. minimum required releases from Buford Dam). Causal factors for the lowering of Lake Lanier's storage pool that relate directly to Lake Lanier include: 1) a deficit in local inflows to the reservoir from contributing rivers and streams (e.g. outflows are greater than inflows), 2) water supply withdrawals for Metro Atlanta region directly withdrawn from the reservoir, and 3) evaporative losses from the reservoir. Causal factor which relate to the release of water from Lake Lanier to the watershed below the reservoir include: 1) releases from the reservoir to meet minimum flow requirements for water quality at Peachtree Creek, 2) releases made to balance pool elevations in Lake Lanier with West Point , 3) releases to provide augmentation support to the Apalachicola River to meet minimum flow requirements of the RIOP, 4) the minimum required release from Buford Dam, and 5) hydropower releases from Buford Dam. The causal factors for the lowering of elevations at Lake Lanier were evaluated using an existing systems model of the ACF.

This analysis found that the relative importance of causal factors varies from drought event to drought event, meaning that a one-size-fits-all approach to drought management, which has been the practice to date, is not advisable. Most of the causes for rapid lowering of Lake Lanier were found to be caused by factors that cannot be controlled by management actions. It was found that increasing metro Atlanta demands to the volume requested by the State of Georgia would result in a more rapid decline in reservoir elevations at Lake Lanier, but would have a minimal effect on Jim Woodruff outflow. It was also found that reducing Jim Woodruff Dam minimum flow requirements and consequently reducing the support from Lake Lanier to meet this requirement would result in increased elevations at Lake Lanier, but would also have a negative effect on environmental resources in the Apalachicola River and Bay. Finally, it was found that changing the trigger for when normal releases under the RIOP are resumed had minimal effects on reservoir elevations at Lake Lanier, but increased the number of days that the minimum release was provided from Jim Woodruff Dam. Considering that 1) the State of Georgia anticipates a significant increase in consumptive demands for Metro Atlanta, 2) the State of Florida has filed a suit over Georgia's taking of water from the ACF basin and therefore seems unlikely to accept even less water in the future, and 3) the Corps of Engineers did not address these issues in the draft revisions of the ACF basins Water Control Manual, it seems unlikely that anything will be done about the rapid lowering of Lake Lanier during drought events.

CHAPTER 2: DEVELOPMENT AND COMPARISON OF INTEGRATED RIVER/RESERVOIR MODELS IN THE APALACHICOLA-CHATTAHOOCHEE-FLINT BASIN, USA

The primary objective of this paper is compare the output of the more simplified ACF-STELLA with the more complex HEC-ResSim model to assess the former model's skill for efficiently and independently screening potential water planning alternatives. Once the output for the two models can be shown to be comparable, this validates using the model to evaluate management questions such as those presented in Chapters 3, 4, and 5 of this thesis.

2.1 Introduction

Throughout the world, supplies of fresh water are being strained by an ever-growing human demand. The global population is increasing by nearly 100 million people annually and it is possible that two-thirds of the world's population could live in water-stressed areas by 2025 (WWAP, 2009). At the same time, societies around the world are increasingly demanding that water managers protect the freshwater ecosystems that are dependent on this same water for their health (Richter, 2014; Brisbane Declaration, 2007). Following this trend, water managers in the Apalachicola-Chattahoochee-Flint (ACF) basin in the southeast US (Figure 2.1) have struggled for over 25 years to find a compromise in managing the waters of the basin in a manner acceptable to the States of Alabama, Florida, Georgia, the federal government, and an array of disparate stakeholder interest groups (Bonney *et al*., 2013; Jordan and Wolf, 2006; Leitman, 2005). Similar to the global situation, a fundamental issue in the ACF water conflict involves providing water for human demands while reserving water for the needs of ecosystems (Tetra Tech, 2013; Leitman, 2005). In 1999, the ACF River Basin Compact was established (Leitman, 2005; Bonney *et al*., 2013). This effort was the first such compact in the US after the passage of major federal environmental laws such as the Clean Water Act (1972) and the Endangered Species Act (1973). This is notable because virtually all previous compacts in the US (e.g., Colorado River, Delaware River, Susquehanna River, Missouri River) neglected to consider ecosystem flow needs when they allocated water flows within their respective basins (Kenney, 1995; Bonney *et al*., 2013). By 2003, the ACF Compact was terminated for several reasons, including an inability to find a compromise between meeting human needs and ecosystem requirements (Leitman, 2005).

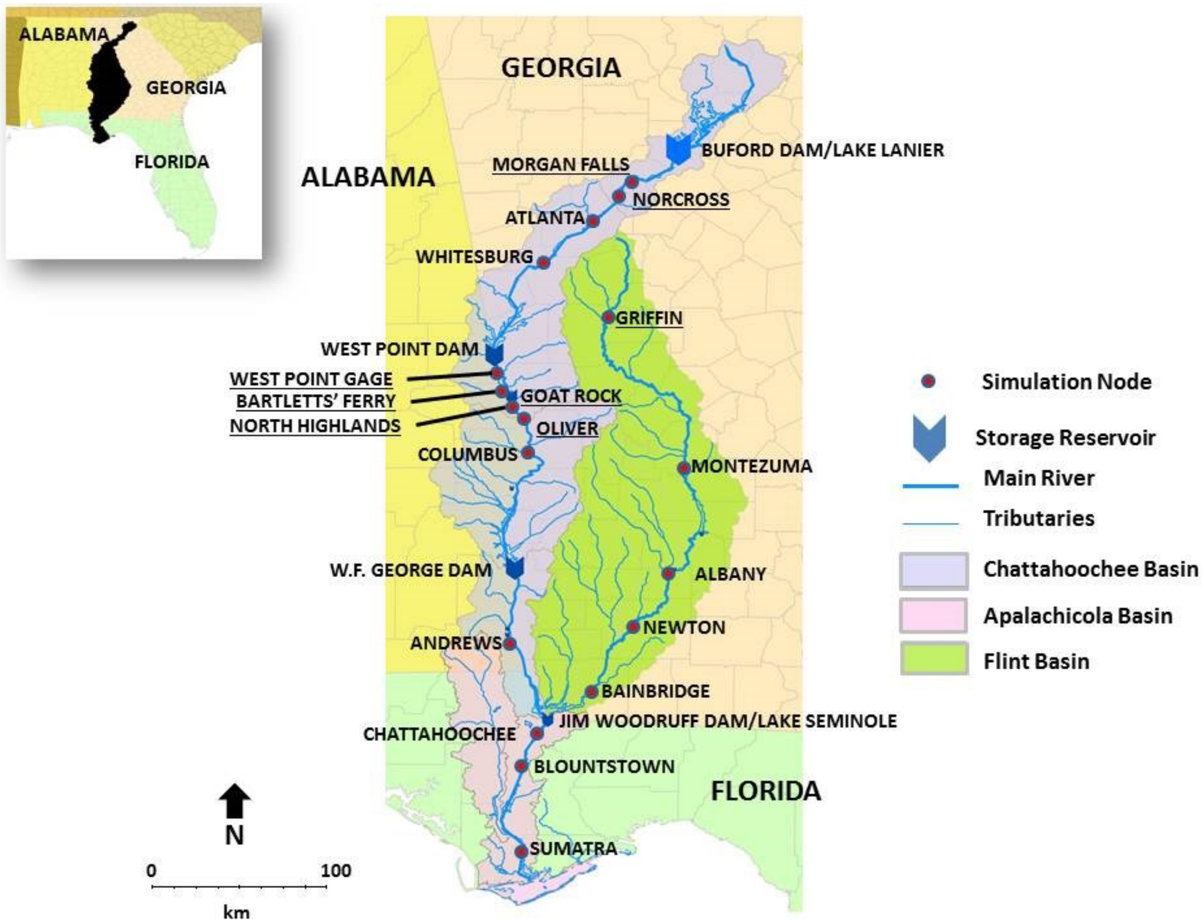


Figure 2.1: The Apalachicola-Chattahoochee-Flint (ACF) basin map with hydrological simulation nodes and storage reservoirs used in ACF-STELLA and HEC-ResSim models. The underlined titles refer to simulation nodes used only by the HEC-ResSim model. The size of the storage reservoir icons is scaled to their full storage capacity.

With the historic and continuing conflicts in the ACF basin, there is a significant requirement for system-level modeling tools to address the numerous water management challenges. The value of systems models is maximized by an appreciation of the large uncertainties involved in the simulation of interdependent hydrologic, water demand, and human decision-making processes (McMahon, 2009). The conflict over sharing the basin's waters has led to the State of Florida filing a suit in the US Supreme Court against the State of Georgia over impacts associated with the management and use of ACF water resources (Supreme Court of the US, 2013). Additionally, the US Army Corps of Engineers (USACE) has been tasked with the release of a new water management plan to define how the federal storage reservoirs in the ACF basin will be managed as a system in the future (Tetra Tech, 2013).

During the ACF Comprehensive Study and associated Interstate Water Compact negotiations, several system-wide water models of the basin were developed to aid in the development of a water allocation plan. Systems dynamic models played an integral role in water allocation negotiations among the three states and the federal government (Jordan and Wolf, 2006; Leitman, 2005; DuMars, 2004). During the ACF Comprehensive Study (Jordan and Wolf, 2006; Palmer, 1998) a decision was made to develop two distinct water management models of the basin: a daily model using the HEC-5 platform (USACE-HEC, 1998, later updated and modified into HEC-ResSim: USACE-HEC, 2014) and a monthly model using the STELLA simulation platform (ISEE Systems, 2014) as part of a stakeholder-focused Shared Vision Planning (SVP) process (Palmer, 1998). The STELLA platform was chosen for the SVP process since it was perceived to be appealing to both stakeholders and technical participants in the ACF allocation discussions (Palmer, 1998). The monthly SVP model was ultimately converted to a daily model by the Northwest Florida Water Management District (Hamlet and Leitman, 2000) to allow for more detailed management within the model at the daily or weekly time steps and to make the model's time-step consistent with the HEC-5 model.

As the USACE has operational authority over all of the reservoir storage capacity in the basin, the system modeling tools developed and used by the agency play an important role in defining present and future management (Tetra Tech, 2013; USFWS, 2012). The Reservoir System Simulation model, HEC-ResSim, was developed by the USACE to simulate reservoir operations, flood management, flow augmentation, and water supply dynamics for the ACF basin (Klipsch and Hurst, 2007; USACE-HEC, 2014) and this modeling program has been used in many other major river systems in the United States (USACE-HEC, 2014). The model utilizes a user-defined network structure with time series inputs to approximate physical infrastructure and hydrological flows. HEC-ResSim has been used in the ACF basin to formulate the current reservoir management approach as outlined in the Revised Interim Operating Plan (RIOP) (USFWS, 2012; Klipsch and Hurst, 2007) and is currently being used to develop a new basin management plan (Tetra Tech, 2013; USACE, 2015). An important limitation in using the HEC-ResSim model for broader public engagement is the significant expertise and technical understanding that are required to develop, execute, and analyze alternative basin management alternatives.

The HEC-ResSim model currently is the primary basin-level model being used to evaluate ACF flow management alternatives and potential solutions. Additional models that simulate fundamental water system characteristics in close proximity with HEC-ResSim could allow greater public involvement and interaction by generating a more diverse array of water resource alternatives. Such additional modeling tools could play a useful role in screening potential water management alternatives for expanded simulations in HEC-ResSim. Integration of multiple model results could play an important role in helping the disparate groups to explore a variety of management scenarios. This paper compares results from the stakeholder-derived ACF-STELLA model with results generated by the HEC-ResSim model to evaluate the competency of alternative modeling efforts in the ACF basin. The objectives of this paper are to:

- Provide an overview of the ACF-STELLA model structure and its assumptions towards simulating river flows in the ACF basin,
- Compare and evaluate the ACF-STELLA model results with equivalent HEC-ResSim output for the elevations and outflows at the three major federal reservoirs, as well as two other basin locations, using similar reservoir operating rules and water abstractions, and
- Draw conclusions from the comparison of models and their application for future management scenario simulations.

2.2 Methods and Materials

In this section of Chapter 2 a description of the ACF watershed, the structure and operation of the ACF-STELLA model and a comparison of the ACF-STELLA and HEC ResSim model simulations are provided.

2.2.1 Basin Description and Water Management

The ACF basin drains nearly 50 000 square kilometers in the States of Georgia, Alabama, and Florida, extending from the Blue Ridge Mountains in Northern Georgia to the Gulf of Mexico. About 75% of the basin area resides in Georgia, with approximately 12.5% of the area in both Florida and Alabama (Figure 2.1). The Apalachicola River is formed by the confluence of the Flint and the Chattahoochee Rivers. Since the majority of the basin and the reservoir storage capacity lies above the Florida border, flow in the River is mostly defined by rainfall, water extractions, and management actions outside of the State of Florida (Leitman, 2005). The waters of both the reservoirs and in the rivers, themselves are used by humans for many purposes including drinking water, hydropower generation, cooling water for coal and nuclear power plants, agricultural irrigation, industrial activities, dilution of waste water, commercial navigation, and recreational activities (Carter, 2008). During droughts in the past several decades, the water users of the basin have found themselves in competition for the water resources of the basin, but during periods of normal rainfall, there are adequate water resources for all users.

Within the ACF basin, there are 15 main-stem reservoirs. Three of these reservoirs in the Chattahoochee basin – Lake Lanier (Lanier), West Point Lake (West Point), and Walter F. George Lake (W.F. George) (also referred to as Lake Eufaula) – comprise over 95% of the basin's storage capacity (see Table 1.1, page 28) and are managed by the USACE, Mobile District (USACE, 2012). The balance of storage is in another federally managed reservoir, Lake Seminole/Jim Woodruff Lock and Dam (Seminole/JWLD), which has virtually no storage capacity in extreme low flow conditions and very limited storage as flows increase because of head limit issues (USACE, 2012; Leitman *et al*., 2012). The remaining reservoirs, including those on the Flint River, are run-of-the-river type facilities with little or no storage capacity. The ratio of reservoir storage capacity to annual flow in the lower ACF basin is small relative to other river basins in the US. Management options in this basin are consequently more limited than in other basins (Leitman *et al*., 2015). The ACF basin has the storage capacity to hold less than three months of average flow, whereas the Colorado basin has over three years of average flow in storage (Vano, 2014). While there is some capacity to augment, and retain lower volume flows, this ability of the limited storage capacity to influence flow diminishes rapidly as flows increase towards median levels (Leitman *et a*l., 2012).

The general reservoir operating rules used in the comparative simulations are patterned after the Revised Interim Operating Plan (RIOP). The RIOP was first adopted for use in managing the ACF basin's reservoir system in 2007 to provide minimum flows for endangered species until several ongoing lawsuits were settled. It has been revised several times since it was first adopted

(USFWS 2012; USFWS 2007; USFWS 2006). Releases under the RIOP are in general defined by (1) time of the year, (2) composite volume of water in the three major storage reservoirs (Lanier, West Point, W.F. George), and (3) the seven-day local inflow to the basin above Seminole/JWLD. Table 1.2 (see page 29) summarizes the major RIOP operating provisions along with basin inflow levels and releases from the Seminole/JWLD system.

Under the RIOP, reservoir storage is defined by the composite storage of the three primary reservoirs. The conservation pool of the three major storage reservoirs (Lanier, West Point, and W.F. George) is divided up into action zones (USFWS, 2012; USACE, 1989). Figure 2.2 provides an example of action zones for the W. F. George. Through the use of these action zones at the individual reservoirs water managers are able to vary hydropower generation and balance water in the conservation pool of each reservoir, whereas through the composite storage water managers are able to vary the reservoir system's support for downstream flow needs. The primary logic behind using zones in ACF reservoir management dictates that if the composite storage is within Action Zone 1 (high storage levels), the system is managed to support downstream flow needs, including flows needed for environmental purposes, hydropower releases, recreational boating, and navigation needs. Conversely, if the composite storage is within Action Zone 4 (low storage levels), then releases are defined to protect reservoir storage and downstream releases are curtailed to a minimum level. Once composite storage has reached Action Zone 4, downstream releases remain curtailed until storage levels enter Action Zone 1. Action Zones 2 and 3 are transitional operational zones between Action Zones 1 and 4 (USACE, 1989).

In periods of lower flows, supplemental releases have to be made from W.F. George to support the releases required from Seminole/JWLD. There are two primary reasons for the supplemental releases: (1) Seminole/JWLD has a small storage pool because of the local topography, and (2) the stretch of Apalachicola River below the dam has experienced over two meters of river-bed degradation since the construction of Seminole/JWLD in the mid-1950s (Light, 2006). This degradation has led to head limit issues at the dam during low periods (e.g., there is not enough difference between the reservoir pool elevation and the elevation of the tail water), forcing the lowering of the reservoir's pool during low flow events in order to meet head-limit restrictions for Jim Woodruff Dam. Table 2.1 summarizes the top of Seminole/JWLD's storage pool and the associated volume of storage available in the reservoir. From this table it can be seen that the volume of storage available to hold supplement inflows and meet RIOP requirements is extremely limited at lower flows.

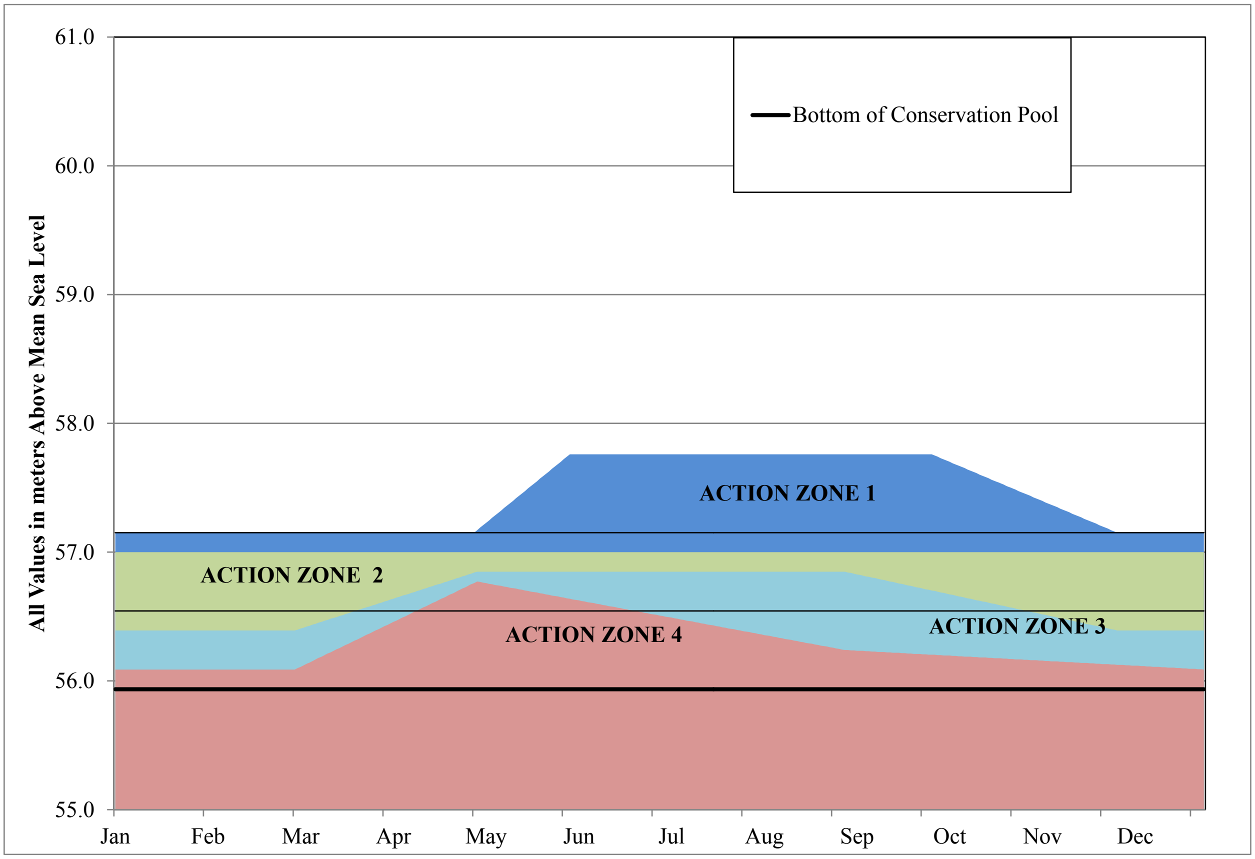


Figure 2.2: Rule curve and action zone elevations for W.F. George

Table 2.1: Elevation-storage volume relationship at Seminole/JWLD (USACE, 2015).

Release from Seminole (m3/s)	Rule curve elevation (m)	Seminole storage volume (m3/s-days)
141.50	23.10	0.0
215.08	23.18	126.5
288.66	23.26	255.5
362.24	23.33	386.9
435.82	23.41	520.7
509.40	23.48	657.0
582.98	23.56	795.7
656.56	23.64	936.8
730.14	23.71	1080.3

2.2.2 Structure and Operations of the ACF-STELLA model

Figure 2.3 provides an image of the user interface page in the ACF-STELLA model. Within each of the objects in the lower levels of the ACF-STELLA model data and equations are stored.

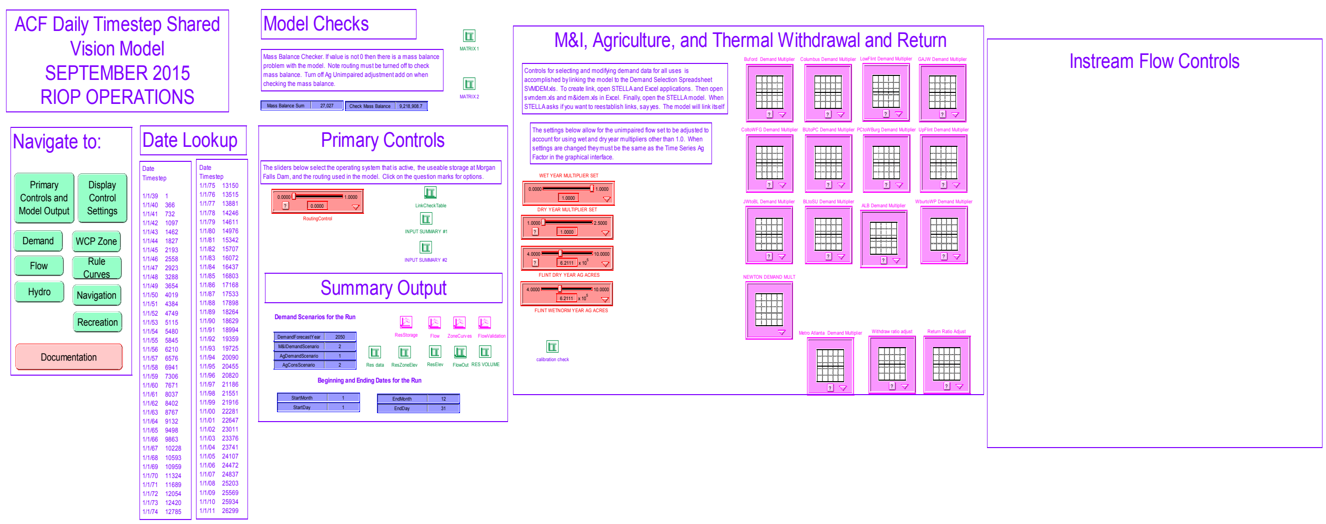


Figure 2.3: Image of the user interface for the ACF-STELLA model

From a general water-system perspective, the ACF-STELLA model simulates at a daily time-step with the ACF basin divided into 15 reaches with a node at the downstream point of each reach where input data is provided (Figure 2.1). With this configuration, the Chattahoochee basin is represented by seven nodes, the Flint basin by four nodes, with an additional node at the confluence of the Flint and Chattahoochee Rivers and three additional nodes in the Apalachicola River. Placement of simulation nodes was determined by either the existence of a storage reservoir or sites where long-term stream gauge data were available. All of the nodes in the ACF-STELLA model are also nodes in the HEC-ResSim model, although there are several additional nodes in the HEC-ResSim model which are not included within the ACF-STELLA model (underlined in Figure 2.1.). For each node, the following water balance is calculated on a daily basis:

$$\frac{dS}{dt} = Pr + I_L + I_R - O_A - O_E - O_R \qquad \text{(Equation 2.1)}$$

where:

dS/dt = the change in reach storage in one day (m^3/s/day),

Pr = direct water input to the reach from precipitation (this is only accounted for when there is a storage reservoir, elsewise precipitation gains to a reach are accounted for under I_L) (m^3/s/day),
I_L = Inflow from surface and groundwater from the reach watershed (m^3/s/day),
I_R = Inflow routed to the reach from upstream (m^3/s/day),
O_A = net outflow from net human abstractions (m^3/s/day),
O_E = net loss from evaporation/transpiration in reservoirs (m^3/s/day), and
O_R = outflow to the downstream reach (m^3/s /day).

For each reach/node combination, local inflows (I_L) are defined by an unimpaired flows (UIF) dataset (USACE, 1997; Arcadis, 2010). The UIF dataset was developed by using historical flows and then adjusting them to remove the effects of anthropogenic influences such as withdrawals, returns, and the effects of water control structures (i.e., release rules, evaporation) (USACE, 1997; Liang, 2014). Since the UIF was developed using historically observed flows, it includes both surface and groundwater sources and accounts for climatic water inputs to the basin. The UIF dataset for the ACF river basin was first developed in the 1990s by the USACE, Mobile District and the three States as part of the ACF Comprehensive Study (USACE, 1997). When first developed, the dataset extended from 1939 to 1993. Since its initial development, the UIF dataset has been extended twice and now extends through 2008 with efforts underway to further extend the dataset to include a severe two-year drought event that occurred in 2011 to 2012. While a significant source of uncertainty in the UIF dataset arises from filling missing data gaps within the historical data (Liang, 2014), it remains the standard input for federal evaluations of ACF water management plans and provides the inputs for the HEC-ResSim and ACF-STELLA comparison.

The inflows routed to the reach from upstream (I_R) are calculated using the Muskingum Method (USACE 1997). The routing equation was developed from the continuity of mass (inflow – outflow = change in storage). The storage in a reach is defined as the sum of the prism and wedge storage. The basic equation for computing the routing is:

$$S = KO + KX(I - O) \qquad \text{(Equation 2.2)}$$

where:

S = total storage in the routing reach (m^3),

O = rate of outflow from the routing reach (m^3/s),
I = rate of inflow to the routing reach (m^3/s),
K = travel time (hours), and
X = dimensionless weighting factor.

By combining the above expression for storage with the standard continuity equation and solving for the outflow over one day (Δt=24 hours), the basic routing equation is then developed:

$$O_2 = C_1 I_2 + C_2 I_1 + C_3 O_1 \qquad \text{(Equation 2.3)}$$

where:

$C_1 = (\Delta t - 2KX) / (2K(1 - X) + \Delta t)$,

$C_2 = (\Delta t + 2KX) / (2K(1 - X) + \Delta t)$, and

$C_3 = (2K(1 - X) - \Delta t) / (2K(1 - X) + \Delta t)$.

The general procedure for developing Muskingum coefficients K and X was to start with an estimate of the flood wave travel time through each river reach. Then, with an estimated K, a value of X was assumed and upstream hydrographs routed flows to the downstream gauged location and the result was compared to the observed hydrograph. The routed hydrograph should be contained within the observed downstream hydrograph and the difference between the two is the local inflow for the reach and this estimate of local inflow was used to determine the accurateness of the assumed value of X (USACE, 1997). For the ACF Basin, these values were calculated as part of the process for developing the UIF. Table 2.2 summarizes the K and X values used for routing calculations in the ACF basin.

Table 2.2: ACF Basin Routing Data used in HEC-ResSim and ACF-STELLA models (USACE, 1997).

RIVER	REACH DESCRIPTION	LENGTH (km)	travel time (h)	MUSK "K" (*=steps)	MUSK "X"
FLINT	Griffin to Montezuma	199.5	120	24 (*5)	0.0
FLINT	Montezuma to Albany	123.9	48	24(*2)	0.0
FLINT	Albany to Newton	54.7	24	24(*1)	0.0
FLINT	Newton to Bainbridge	64.4	24	24(*1)	0.0
FLINT	Bainbridge to Jim Woodruff	46.7	0	0	0.0
CHATTAHOOCHEE	Buford to Norcross	28.8	12	0	0.0
CHATTAHOOCHEE	Norcross to Morgan Falls	28.8	6	0	0.0
CHATTAHOOCHEE	Morgan Falls to Atlanta	16.1	6	0	0.0
CHATTAHOOCHEE	Atlanta to Whitesburg	69.2	24	24(*1)	0.1
CHATTAHOOCHEE	Whitesburg to West Point Res	98.1	24	24(*1)	0.1
CHATTAHOOCHEE	West Point Res to West Point gage	3.2	0	0	0.0
CHATTAHOOCHEE	West Point gage to Bartletts Ferry	33.8	6	0	0.0
CHATTAHOOCHEE	Bartletts Ferry to Goat Rock	8.0	0	0	0.0
CHATTAHOOCHEE	Goat Rock to Oliver	14.5	0	0	0.0
CHATTAHOOCHEE	Oliver to North Highlands	1.6	0	0	0.0
CHATTAHOOCHEE	North Highlands to Columbus	4.8	0	0	0.0
CHATTAHOOCHEE	Columbus to WF George	136.8	12	0	0.0
CHATTAHOOCHEE	WF George to Andrews	46.7	0	0	0.0
CHATTAHOOCHEE	Andrews to Jim Woodruff	75.6	12	0	0.0
APALACHICOLA	Jim Woodruff to Chattahoochee	1.6	0	0	0.0
APALACHICOLA	Chattahoochee to Blountstown	46.7	18	18	0.0
APALACHICOLA	Blountstown to Sumatra	93.3	Variable Muskingham method: 48 hours < 700 cms; 96 hours > 700 cms		

For each reach/node combination, the net extractions (O_A in Equation 2.1) include demands from municipal and industrial sources, agricultural sources, and thermal sources for power plants (USACE, 2014). For purposes of comparing results between ACF-STELLA and HEC-ResSim, extraction levels were set to values established by the USACE (2014). A key assumption in both models is that the volume of water used to represent withdrawals is the effect of net withdrawals on stream flow, not the total volume of water withdrawn from surface and groundwater sources. Water withdrawals in the ACF basin can come from both surface and sub-surface sources. These two sources of consumptive demands can have different impacts on river discharge. Direct surface withdrawals have a one-to-one correspondence between water used and the effect on stream flow, while groundwater withdrawals do not have such a one-to-one correspondence (USACE, 1997). Instead, the effect of groundwater withdrawals is dependent on the relationship between the streams and the aquifer where the withdrawal is occurring and the nature of the sub-surface geology. Therefore, where the average daily effect of irrigation withdrawals on stream flow during peak irrigation season (April-September) is estimated to be about 23.3 m^3/s (USACE, 2014), the average volume of irrigation water use during a 120 day irrigation season was calculated to be 78.5 m^3/s (based on usage data from Hook *et al*., 2010). The difference between these two values is that much of irrigation water in the basin is sourced from groundwater and that not all water used for irrigation from groundwater sources results in a direct reduction of stream flow.

The net evaporation/precipitation (O_e and P_r in Equation 2.1) accounts for differences in evaporation and surface runoff associated with the existence of a reservoir. Evaporation values were defined using nearby first-order pan evaporation stations (USACE, 1997). Evaporation/precipitation is calculated by multiplying the historical monthly evaporation/historical monthly precipitation rate by the surface area of the reservoir for the individual time step and then converting to volume (USACE, 1997). Precipitation gains are accounted for because any precipitation falling on the lake is a 100% gain to stream flow in the reservoir, whereas when it falls on the land of the reservoir watershed, a portion of the precipitation is assumed to be lost to groundwater infiltration and to plant transpiration.

The nodes in the ACF-STELLA model are divided into two general types, depending on whether or not the reach has the capacity to store water. At the nodes with no reach storage, outflow is defined by the sum of routed inflow from the basin above, local inflow, and net consumptive demands. Nodes with significant water storage capacity have additional parameters reflecting reservoir operating rules, including reservoir area and volume. Reservoir management parameters describe release rules that define daily water releases from storage including: (1) available water in the conservation storage pool, (2) the rule curve for the reservoir, (3) maximum release limits, (4) minimum release requirements, and (5) hydropower release requirements. Available water is defined as the volume of water accessible in the storage pool for release within a given time step. The rule curve is the elevation at the top of the conservation pool. Figure 2.2 shows an example rule curve and action zone elevations for W.F. George. Operationally, if the reservoir's water elevation is above the rule curve, water is spilled within the release limit requirements of the reservoir. Hydropower releases take into account the specific release rules for the reservoir as well as the hydropower specifications for the given reservoir (i.e., penstock capacity, releases required during peaking to meet the rated capacity of the reservoir's power unit, peaking hours per day, and minimum release requirements).

With the UIF dataset providing specific surface water and groundwater inputs at each of the simulation nodes, the ACF-STELLA model simulates the results of defined reservoir management operation rules and consumptive demands/returns to calculate reservoir elevations and flows at the nodes in the model. Within each simulated day, the release decisions within the model are defined by the following logic:

- A preliminary release from Seminole/JWLD is calculated based on the release requirements of the RIOP, whether there is ample water to make the release, and whether the Seminole/JWLD elevation is above its rule curve. The determination of whether there is ample water is based on inflow from both Flint and Chattahoochee basins as well as the total extractions and evaporative losses at Seminole/JWLD.
- If there is adequate water to make the release, the release is made. If there is not adequate water, a supplemental release is made from upstream at the W.F. George so there is adequate water to make the release. Since Seminole/JWLD has a small storage pool and because of the head limit issues mentioned earlier, the reservoir has virtually no storage during extreme low flow periods. Thus, the release called for by the RIOP often will require a supplemental release from W.F. George so that there is enough water to make the Seminole/JWLD release.
- Releases are then made upstream from West Point to support any releases from W.F. George, and then further upstream from Lanier to support the West Point releases.

An important component in computing these releases is the concept of balancing. Balancing is the act of trying to keep the volumes of the individual reservoirs comparable by keeping them in the same action zone. Therefore, if W.F. George is at a higher elevation than West Point (e.g., Zone 1 versus Zone 2), then no release is made from West Point to support the release made by W.F. George. If West Point reservoir is at a higher elevation than W.F. George, then the release made by the W.F. George is supported by an equivalent release from the West Point. If both reservoirs are in the same action zone, a prorated share of the release is supplied. This method of balancing of reservoir releases is also conducted in the HEC-ResSim model as well as in actual ACF reservoir operations (USACE, 2012).

2.2.3. Comparison of the ACF-STELLA and HEC-ResSim Simulations

As HEC-ResSim is the primary simulation tool used by the USACE to analyze and assess the system-wide effects of potential ACF water management alternatives, it provides a useful benchmark for comparison of ACF-STELLA simulations. The latest version of the HEC-ResSim model (Version 10) was used in this direct comparison. Model output for all simulated nodes was provided by the USACE, Mobile District, Reservoir Management Section. Both models were executed using the RIOP operating rules for the reservoir system along with the same set of extractions (i.e., consumptive demands and evaporation losses) and the same set of daily UIF inputs to represent basin activity from 1939 to 2008. Output comparisons between the two models (n=25,668) in terms of daily flow (5 sites) and reservoir elevations (3 sites) were assessed at specific ACF nodes including:

- Daily flow (m^3/s) at Seminole/JWLD (lowest control point in the basin), Flint River at Bainbridge, Georgia (lowest gage site on the Flint River), Chattahoochee River at Lanier outflow, West Point outflow, and W.F. George outflow (the outflows for the three major storage reservoirs); and
- Daily reservoir elevations (m) for Lanier, West Point, and W.F. George.

As consumptive demands and reservoir management settings are fixed for the entire 70-year model run period in each simulation in both ACF-STELLA and HEC-ResSim, outputs from the models are compared directly to each other and not to any historically observed record. For both models, the historically observed flow record is integrated into the model simulations through the unimpaired data set. Thus, direct comparison of model results with historical flow and elevation data are not practical for the 1939 to 2008-time frame as different reservoirs were introduced individually over the historical period, with some not fully operational until 1975 and none before 1955. Management rules for operating the reservoirs also have changed over time once they became operational while management rules in the ACF-STELLA and HEC-ResSim models are fixed over the entire model run. In addition, consumptive water demands and reservoir operation procedures varied significantly over the historical period, with often problematic documentation until more recent years (USACE, 1997).

The goodness of fit comparison of the output between the two models over the 70 year period (1939-2008; n=25,668) is presented in several forms that include quantification of the absolute and relative error (Ritter and Muñoz-Carpena, 2012). The relative error between the outputs of the two models at each simulation node is defined by the Nash-Suttcliffe Coefficient of Efficiency (NSE) (Ritter and Muñoz-Carpena 2012). The NSE is:

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \qquad \text{(Equation 2.4)}$$

Where:

t = time (days),

Q_o^t = HEC-ResSim output for a specific day,

Q_m^t = STELLA output for a specific day, and

$\overline{Q_o}$ = the mean of HEC-ResSim output.

The range of possible NSE values span from negative infinity to 1, with 1 being a perfect fit between values. The NSE values were calculated using the FITEVAL program (Ritter and Muñoz-Carpena, 2012), which provides a systematic and robust statistical analysis including goodness of fit, outliers, and bias. As evaluating single NSE values can be misleading given the magnitude and number of data points, Ritter and Muñoz-Carpena (2012) present an objective estimation procedure of NSE using a block bootstrapping method accompanied with bias correction and 95% confidence intervals. With these modified estimates in mind, Ritter and Muñoz-Carpena (2012) justify NSE values ranging from 0.90 to 1.0 as very good, 0.80 to 0.899 as good, 0.65 to 0.799 as acceptable and less than 0.65 as unacceptable. Further expansion of these model testing concepts to cover regulatory applications are found in Harmel *et al*. (2014). In addition, the FITEVAL program provides an estimated probability (rejection significance) that the model comparison is greater than the 0.65 acceptance threshold.

The quantification of the absolute error between models was determined by the Root Mean Square Error (RMSE) which quantifies the mean differences (in output units) between outputs from the two models over n comparisons. The RMSE is defined for each comparison point by:

$RMSE = (\Sigma (X_{O,J} - X_{M,J})^2 / n)^{½}$ (Equation 2.5)

where:

$X_{o,i}$ = HEC-ResSim output for a specific day i, and

$X_{m,i}$ = ACF STELLA values for the same day i.

The model outputs being evaluated through RMSE are flow (m^3/s) and reservoir elevations (m). The range of possible values for the RMSE is 0 to infinity with lower error values desired within a comparison. The RMSE values were also calculated using the FITEVAL program using the same block bootstrapping method (Ritter and Muñoz-Carpena, 2012).

Daily model outputs over 70 years of simulations for the eight comparison sites were analyzed with FITEVAL to determine the level of agreement between ACF-STELLA and HEC-ResSim. If a daily comparison for a specific site was within the acceptable or higher ranges (NSE > 0.65 at $p<0.05$ rejection significance), no further analysis was conducted. If a comparison site did not achieve an acceptable match at the daily level, an additional FITEVAL comparison was conducted on a seven-day moving average to investigate whether daily variations were contributing to the mismatch. Analyses also were conducted to explore whether the model output mismatch was at higher or lower flows using the percent exceeded flows or elevations constructed from the daily values of the 70-year dataset. Model results were compared using the 10%, 25%, 50%, 75% and 90% exceeded values for each day of the year with selected results reported.

2.3 Results

Table 2.3 summarizes the results of median NSE and RMSE values (with 95% confidence limits) between the daily model outputs for the two models at the five flow sites and three reservoir sites using the 70-year input flow dataset. Typical simulation times were over 2 hours in HEC-ResSim and less than 5 minutes for the ACF-STELLA model. The NSE results for Seminole/JWLD outflow, Flint River flow at Bainbridge, and elevations at West Point were in the very good category (e.g., NSE >0.90 and <0.01 rejection significance). Median values of RMSE were 118.1

m^3/s for Seminole/JWLD outflow, 27.6 m^3/s for Bainbridge flow, and 0.24 m for the elevation at West Point reservoir. Results for Lanier elevation and West Point outflow were in the good category (0.899 >NSE > 0.80 and <0.01 rejection significance). Corresponding median RMSE values were 0.4 m for the elevation at Lanier and 41.3 m^3/s for the outflow from West Point. The W.F. George outflow was in the acceptable category (0.799 >NSE > 0.65 and <0.01 rejection significance). Values of RMSE ranged from median of 129.6 m^3/s with a confidence interval of 114.5 to 145.4 m^3/s.

Table 2.3: A comparison of ACF-STELLA and HEC-ResSim daily model outputs over a 70-year simulation period (n=25,668) using the Nash-Sutcliffe Coefficient of Efficiency (NSE) and the Root Mean Square of the Error (RMSE). Median values are reported with 95% confidence interval within parentheses. The rejection significance shows the probability of model comparisons being rejected as unacceptable (NSE<0.65). Units for the RMSE values are in m^3/second for outflow sites and in meters for reservoir elevation sites.

	NSE	Rejection significance	RMSE
BUFORD OUTFLOW	0.43 (0.40 - 0.47)	100%	31.4 (28.1 -34.7)
BUFORD ELEVATION	0.84 (0.77 - 0.91)	<1%	0.40 (0.37 - 0.48)
WP OUTFLOW	0.88 (0.87 - 0.90)	<1%	41.3 (38.1 - 44.7)
WP ELEVATION	0.92 (0.90 - 0.99)	<1%	0.24 (0.22 - 0.26)
WFG OUTFLOW	0.73 (0.71 - 0.76)	<1%	129.6 (114.5 - 145.4)
WFG ELEVATION	0.47 (-0.18 - 0.68)	93.7%	0.22 (0.18 - 0.27)
WOODRUFF OUTFLOW	0.94 (0.93 - 0.94)	<1%	118.1 (107.8 - 128.5)
BAINBRIDGE FLOW	0.98 (0.98 - 0.98)	<1%	27.6 (24.1 - 33.8)

Two of the eight daily comparison points were deemed unsuccessful (NSE <0.65 with a greater than 0.5 rejection significance). The outflow downstream of Lanier attained a median NSE value of 0.432 with a confidence interval of 0.398 to 0.467. The median RMSE value was 31.4 (m^3/s) with a confidence interval of 28.1 to 34.7 (m^3/s). The W.F. George reservoir elevation was also deemed unacceptable with a median NSE of 0.465 and a larger confidence interval of 0.176 to 0.675. The median RSME was 0.22 m with a confidence range of 0.18 and 0.27 m. Six of the comparison sites were in close agreement with HEC-ResSim outputs. The remainder of this section is devoted to a more detailed analysis of the two less successfully matched sites: Lanier outflow and W.F. George reservoir elevation. If the outflow comparisons for Lanier are changed from daily flows to a seven-day moving average, the median NSE value increased to 0.788 (acceptable with <1% rejection significance) and the median RMSE value decreased to 14.8 m^3/s. When using a seven-day moving average for W.F. George elevations, the median NSE value increased to 0.513 (unacceptable, with a 0.889 rejection significance) and a median RMSE value decreased to 0.19 m.

Figures 2.4 and 2.5 further evaluate the outputs from the two models for Lanier outflows in terms of percent exceedance of daily flows over the 70-year simulation. Within these figures, each day represents the percent exceedance for all 70 values of that day over the entire simulation period. For the 25% exceeded flows (Figure 2.4), the outflows from the HEC-ResSim model were much lower than those for ACF-STELLA model for April. Additionally, the hydropower peak releases in March were much greater under the HEC-ResSim model and the hydropower peaks from the two models were out of phase with each other. The 75% exceeded outflows (Figure 2.5) show that the two models are very consistent in the summer to fall period (June-November), but for the balance of the year the HEC-ResSim model shows a spiking tendency that can be attributed to hydropower release rules. As noted above, if the outflow comparisons for Lanier are changed from daily flows to a seven-day moving average the output from the NSE value from the two models increases to 0.788 (acceptable with <1% rejection significance).

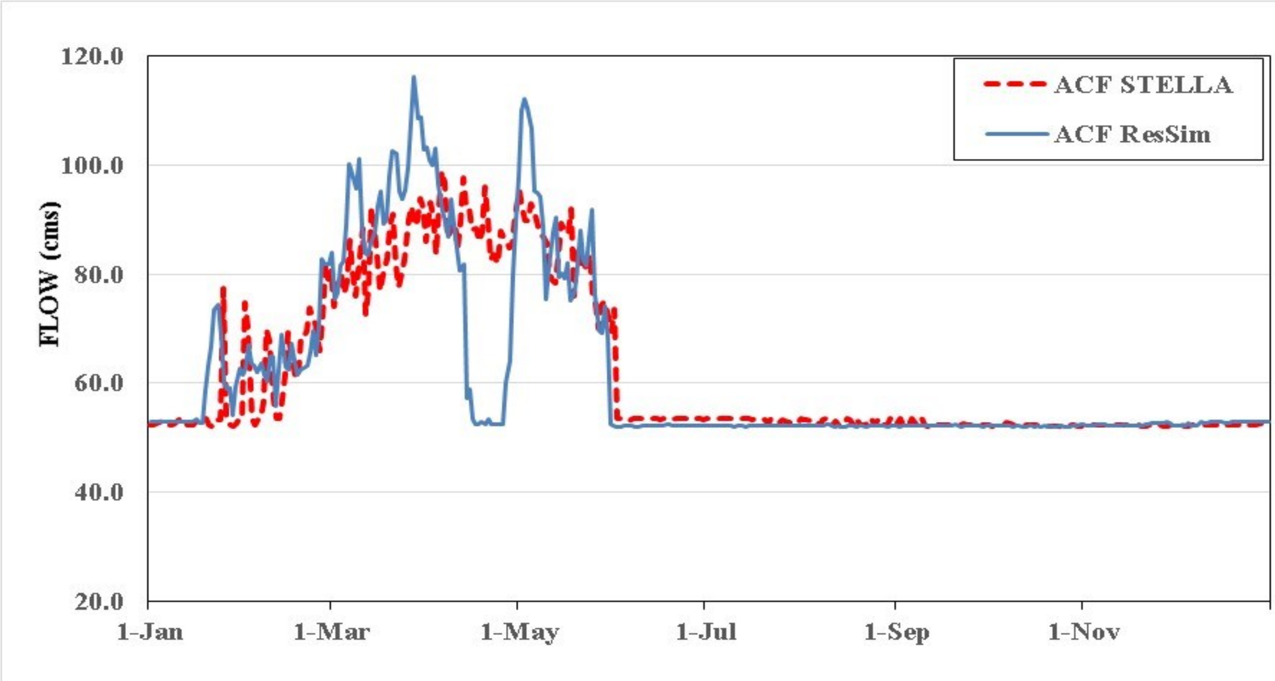


Figure 2.4: A comparison of ACF-STELLA and HEC-ResSim results of 25% exceeded outflows at Lanier (m^3/s)

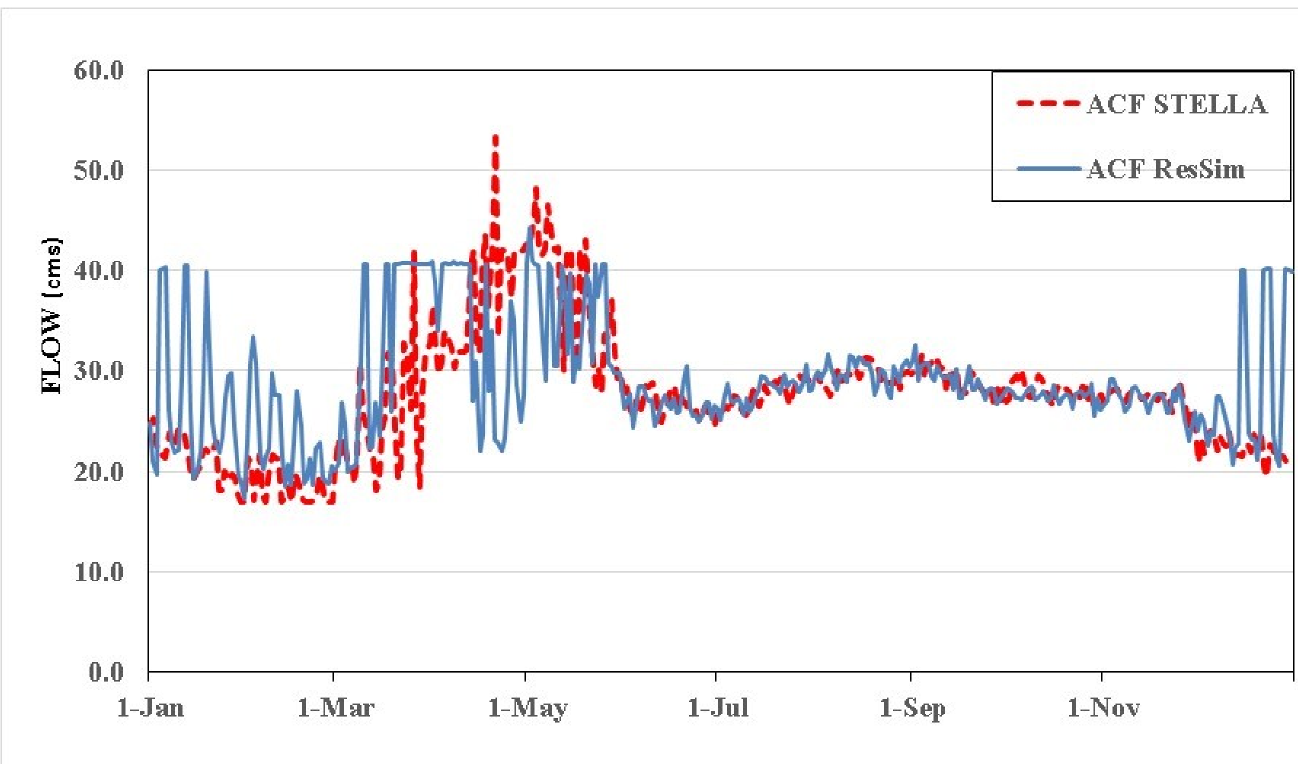


Figure 2.5: A comparison of ACF-STELLA and HEC-ResSim results of 75% exceeded outflows at Lanier (m^3/s)

Therefore, since elevations at Lanier and outflow and elevations at West Point (the next reservoir downstream from Lanier) are well correlated we decided to make no further adjustments to the release rules for Buford Dam to make the outflows correlate for one-day flows.

Figure 2.6 describes the 2.5% exceeded elevations for W.F. George and demonstrates part of the reason why the NSE values for W.F. George elevation are less successful. In the spring of the year, the HEC-ResSim model allows W.F. George to retain water in the flood storage pool far above the rule curve elevation for the reservoir. This same trend is also observed in the 5% and 10% exceeded elevations (not pictured). In the HEC-ResSim output, the maximum elevations at W.F George exceed 60.2 m NGVD (Figure 2.7). These levels are anomalous when compared with 50 years of observed W.F. George elevation data. Actual levels have not been greater than 58.7 meters NGVD except in 1990 (USACE, 2015). Figures 2.6 and 2.7 reveal a trend in the HEC-ResSim model of retaining water in the W.F. George conservation pool, whereas the ACF-STELLA model releases water to keep the conservation pool level at the rule curve as per the RIOP-defined policy. Consequently, a decision was made to program reservoir operations in the ACF-STELLA model to follow the established operating rules under the RIOP, not to try to mimic operations in HEC-ResSim which are clearly different from observed or prescribed operations. If these anomalously high elevation values (185 days of the total 25,668) at W.F. George are excluded from the dataset, the calibration between the outputs for the two model runs improves to an NSE value is 0.833 (good, with a <0.01 rejection significance) along with a median RMSE value of 0.125 meters and confidence interval of 0.111 to 0.141 meters. Therefore, the less than acceptable NSE results observed between the HEC-ResSim and ACF-STELLA results can be attributed to the inexplicable maximum elevations in the HEC-ResSim output.

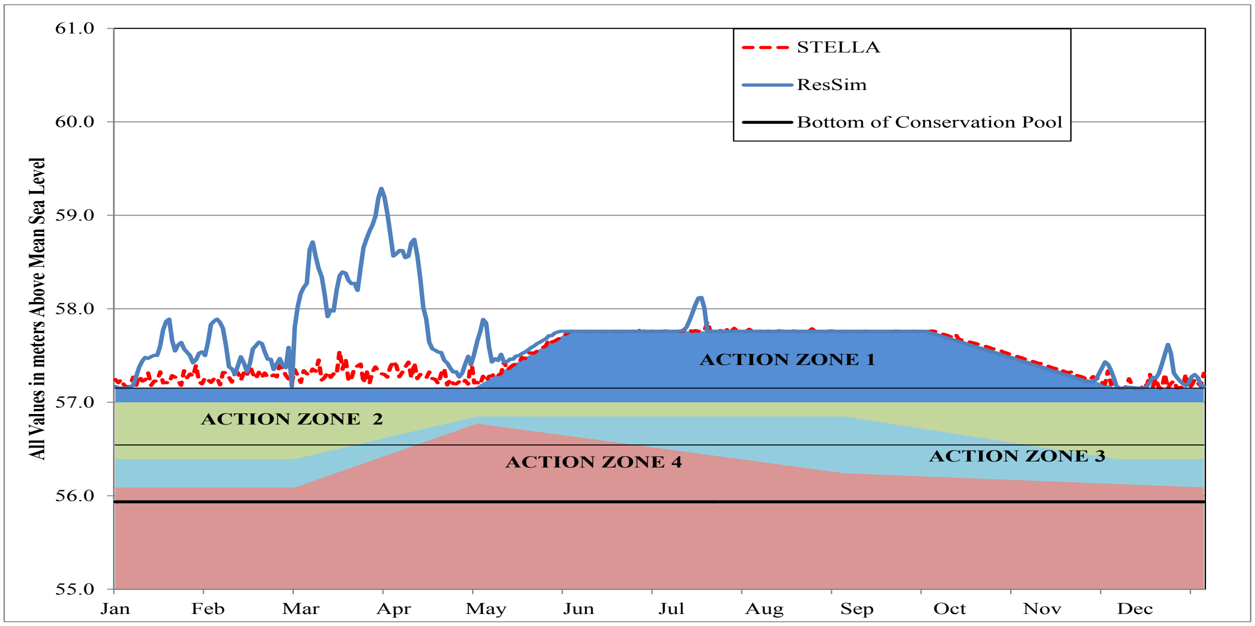


Figure 2.6: A comparison of ACF-STELLA and HEC-ResSim results of 2.5% exceeded elevations at W.F. George (meters).

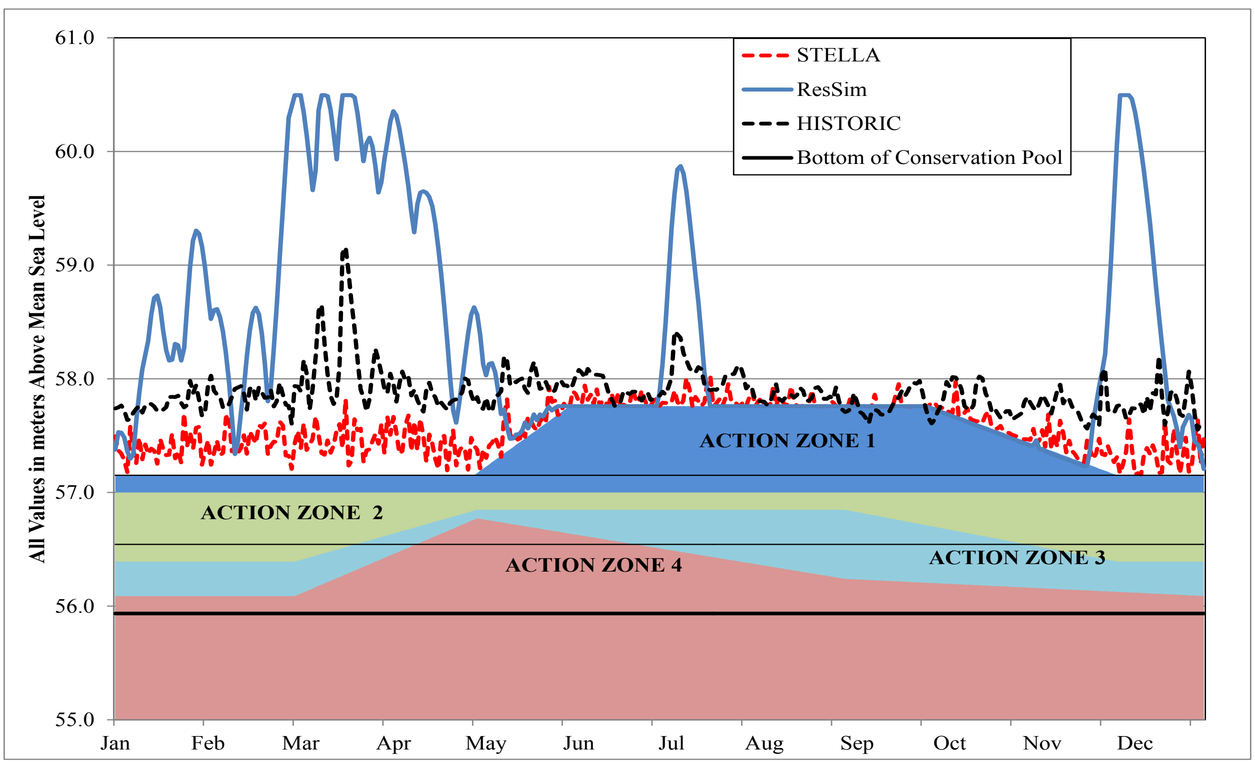


FIGURE 2.7: Maximum elevations at W.F. George for HEC-ResSim, ACF STELLA, and historical data (meters).

An additional element causing the mismatch in simulated W.F. George elevations is the fact that supplemental releases are sometimes required from the dam to support required releases downstream at Seminole/JWLD, as there is not enough water in the storage pool at Seminole/JWLD to meet the required release. As the USACE did not provide the specific release rule they used to make these supplemental releases, the authors developed a provisional release rule within ACF-STELLA. This interpreted release rule in ACF-STELLA required the RIOP release minus any upstream inflows or withdrawals to be released to Seminole/JWLD.

2.4 Conclusions

The water resources conflict in the ACF has been contentious, litigious, and prolonged. In order to allow greater exploration of water management alternatives, this paper describes and compares one water system model (ACF-STELLA) to the primary water system model used by the USACE (HEC-ResSim) to evaluate alternative management options. In comparing output from the two models for eight different sites which include flow and reservoir elevations, it was found that there was a strong fit between the daily outputs for six of the eight sites. In the two sites where the comparison was less successful, the seven-day moving average provided successful results for one of the sites (Lanier outflow). Elevation comparisons at the second site (W.F. George) showed that most of the disagreement between models was caused by HEC-ResSim output which was significantly higher than historical elevations. When this small set of anomalous, high-flow results was excluded, the site comparison was favorable. Given the generally satisfactory model comparison performance and the increased simulation speeds of ACF-STELLA (5 minutes versus 120 minutes for a 70-year simulation), using the ACF-STELLA model to screen reservoir management alternatives is an acceptable and effective means to explore certain alternative management scenarios in the ACF basin for potential simulation by larger, more complex models such as HEC-ResSim. The graphical structure of the ACF-STELLA model allows a potentially greater number of users and developers to interact with the model structure to develop novel solutions and potential water management alternatives provided they have access to the proprietary STELLA software.

This analysis helps to document the development and use of the ACF-STELLA model, which has been employed in multiple projects, including: (1) Allocation Formula negotiations between the three states and the federal government (Leitman 2005), (2) evaluation of common flow levels needed to support commercial navigation and environmental sustainability (Leitman *et al.* 2012), (3) development of resource conservation-based approach to managing the ACF water resources to update the basin's Water Control Manual (USFWS 2013a; 2013b), and (4) determination of irrigation water-saving practices to influence reservoir elevations and/or flow in the Apalachicola River. The differences in model output among different models can be used to check and verify rules/assumptions to increase confidence in various water management predictions. The use of multiple models in a river basin should not necessarily be interpreted as competitive, but instead can be seen as part of a collaborative effort to empower all stakeholders to systematically engage with their limited water resources.

CHAPTER 3: MANAGEMENT OPTIONS DURING THE 2011-2012 DROUGHT ON THE APALACHICOLA RIVER: A SYSTEMS DYNAMIC MODEL EVALUATION

In 2011 and 2012 the ACF basin experienced a severe, multi-year drought which caused significant ecological damage to the Apalachicola estuary. In this chapter the question of whether there was a possibility within the management capacity of the ACF basin to have averted the ecological damage during this drought event will be examined using the ACF-STELLA model.

3.1 Introduction and Background

The Apalachicola-Chattahoochee-Flint River basin (ACF) is one of the principal watersheds of the southeastern United States (Figure 3.1), supporting high biodiversity, large-scale agricultural and fishery operations, and one of the largest and fastest growing metropolitan areas in the country: Atlanta, Georgia. The ACF basin is also one of the more contentious river basins in the eastern US with a greater than 30-year history of "water-wars" between the basin states of Alabama, Florida, and Georgia (Ruhl, 2005) over the balance between human withdrawals, retention of water and ecological flow needs. More than 85 percent of the ACF basin is located upstream of the confluence of the Flint and Chattahoochee rivers (Figure 3.1) which form the Apalachicola River. As such, Apalachicola River discharge is more dependent on upstream conditions of climate, water management, and water use in Georgia and Alabama than on conditions in Florida (Leitman, 2005). The two river basins that feed the Apalachicola River are very different in land cover, water usage and infrastructure. Chattahoochee River discharge is primarily from surface water, and downstream discharge is regulated by three federal storage reservoirs, Lake Lanier, West Point Lake, and Walter F. George Lake (Figure 3.1). The Flint River also receives surface water and has two minor reservoirs which are run-of-the-river reservoirs and therefore essentially have no storage capacity (see table 1.1, page 28). In the middle to lower reaches of the Flint River, base flows are augmented by large groundwater contributions from the Floridan aquifer (Carter, 2007; Rugel *et al*., 2012). These groundwater resources are used to irrigate more than 2,800 km^2 of agricultural land, mostly for peanuts, corn, and cotton (Hook *et al*., 2010; Rugel *et al*., 2012). Under lower rainfall conditions, the volume of these agricultural groundwater withdrawals can decrease Flint River flow volumes (Singh *et al*., 2015; Mitra *et al*., 2015) and subsequently can influence reservoir management in the entire ACF basin (USACE, 2015). The Apalachicola River, the lowest segment of the ACF, is formed by the confluence of the Chattahoochee and Flint rivers near the Florida-Georgia border in Lake Seminole. The average annual water use in the Florida portion of the basin is about 0.8 cubic meters per second (m^3/s) (USACE, 2015) and since this water is withdrawn below Jim Woodruff Dam and is of such a relatively small volume it does not affect reservoir management in the basin. The Apalachicola River terminates in Apalachicola Bay, a large (approximately 63 000 ha) shallow (mean depth <3 m) semi-enclosed estuary that supports extensive commercial fisheries for Eastern oyster (*Crassostrea virginica)* and Penaeid shrimp as well as a recreational sportfish fishery. The fisheries in the Apalachicola area are one of the primary employment sectors for this coastal region and have historically provided about 10% of annual US Eastern oyster landings (Dugas *et al*., 1997).

Average precipitation in the ACF is generally high, about 1.40 meters annually (mostly as rain) with annual runoff ranging from 38 cm to 102 cm (USACE, 2015). Despite high average rainfall and runoff levels, during each of the three significant multi-year droughts between 2000 and 2015 in the ACF basin concern over water use and water allocation within the basin has risen (ACFS, 2015; USACE, 2015). In 2011-2012, the region experienced a severe drought leading to ecosystem and economic losses throughout the basin, including the Apalachicola Bay estuary. Stakeholders often discuss whether the management of the 15 main stem reservoirs could be altered, or consumptive demand could be reduced, to alleviate low flow conditions throughout the basin (Crane, 2013; Supreme Court of the United States, 2013; ACFS, 2015).

Water management of the federally-controlled reservoirs in the ACF basin is under the authority of the United States Army Corps of Engineers (USACE). Reservoir releases in the ACF basin currently are managed following the Revised Interim Operating Plan (RIOP). The RIOP was first adopted in 2007 as an interim (but continuing) operating approach to provide minimum flows in the Apalachicola River for species of conservation concern until ongoing lawsuits were settled and a new Water Control Plan could be adopted (USFWS, 2006; USACE, 2011). The objective of the RIOP is to support downstream flow needs when composite reservoir storage is adequate (Action Zone 1) and maintain reservoir levels with minimal downstream discharges when composite storage is low (Action Zone 4) (USACE, 1989).

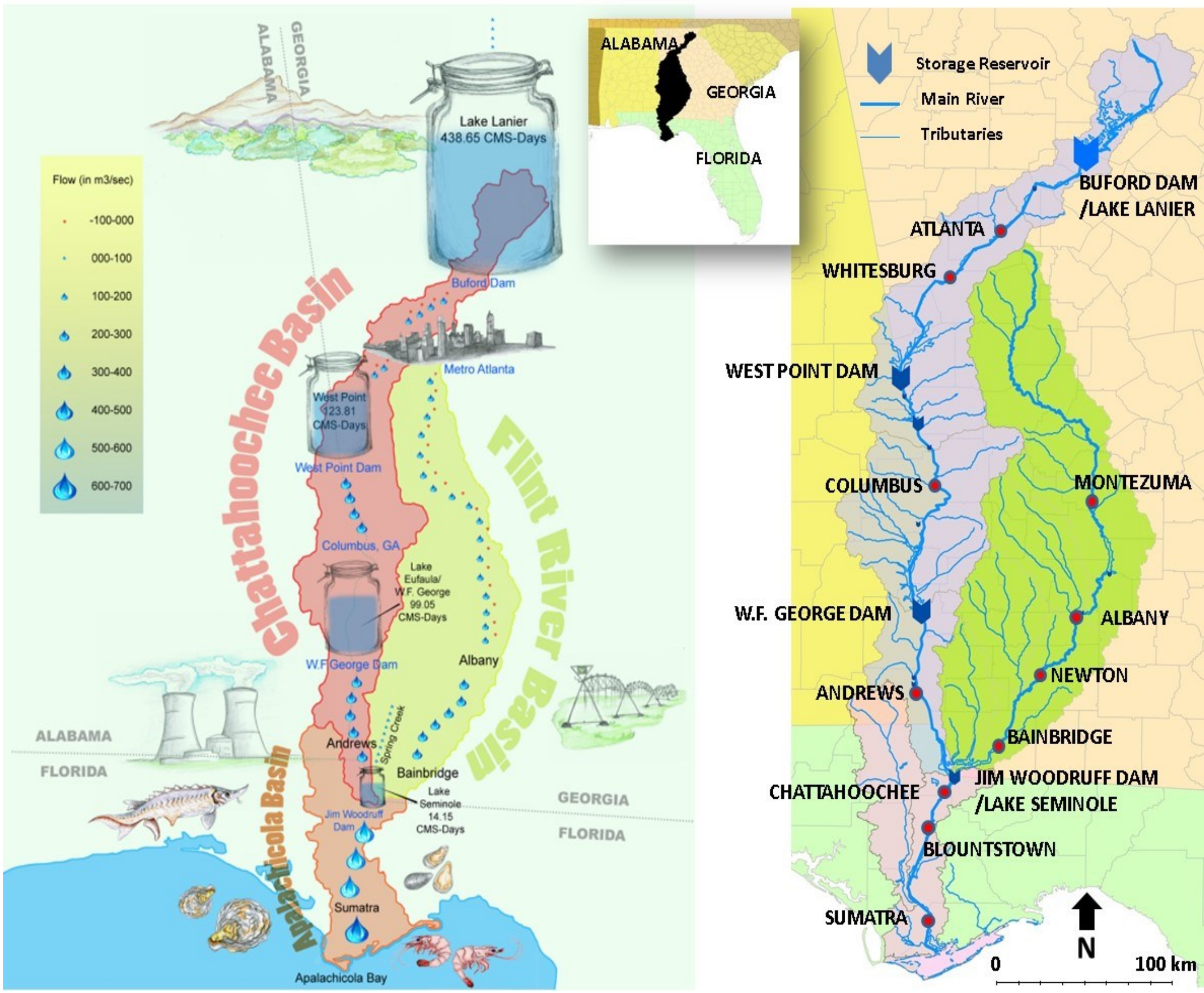


Figure 3.1. Graphic of the Apalachicola-Chattahoochee-Flint River basin adapted from the original poster work published for the Colorado River basin in High Country News (November 10, 1986). Each individual jar represents the storage (in m^3/s-days) for each storage reservoir in the basin. Each water droplet corresponds to the river discharge at that location in mean daily discharge (m^3/s). The map on the right shows the location of major storage reservoirs and gauging points in the basin.

Drought conditions in the ACF basin are defined using a variety of drought indicators including the US Drought Monitor (2015), the Palmer Drought Severity Index (Palmer, 1965) and the National Integrated Drought Information System (NIDIS, 2016), all of which inform the ACF Drought Contingency Plan (USACE, 2011). This plan then defines drought in operational terms for the ACF reservoirs in terms of drought impact on water control regulation, reservoir levels and associated conservation storage. During drought, a key parameter to determine reservoir operations is the composite storage volume of water in Lake Lanier, West Point Lake, and Walter F. George Lake (USACE, 2011; 2015). Combined, these three reservoirs contain over 95% of the storage capacity in the ACF basin. Under the RIOP, the sum of water stored in the three reservoirs is divided into five action zones. Drought operations are initiated when the composite storage enters into Action Zone 4 with normal operations resuming only when the composite storage volume enters into Action Zone 1. When drought operations are in effect, releases from the reservoirs only support the minimum release requirement from Jim Woodruff Dam (141.5 m^3/s), the most downstream reservoir in the ACF basin and the headwaters for the Apalachicola River (USACE, 2015). Emergency drought operations are triggered when the composite storage drops in Action Zone 5 and minimum releases at Jim Woodruff Dam are reduced to 127.35 m^3/s. To meet these minimum release requirements at Jim Woodruff Dam (and thus much of the Apalachicola River basin), water from the composite reservoir storage in the Chattahoochee River basin can be used to augment local inflows, including flows from the Flint River. Water from the Chattahoochee River basin is used in this augmentation because the Flint River portion of the ACF basin has no reservoir storage capacity.

In 2012, the ACF river basin experienced the second year of a severe drought with the Flint River basin classified as under "exceptional drought" conditions for much of the year (NIDIS 2014). During this period the average daily river discharge in Apalachicola River was approximately 215 m^3/s (USGS Chattahoochee gauge #02358000). This discharge was the lowest average annual daily discharge in over 90 years of record (1922-2014) and equal to about 35% of the average annual daily discharge (approximately 606 m^3/s).
Prolonged drought in the ACF basin can create significant challenges to humans and ecosystems, and the impacts are borne throughout the basin. Key concerns expressed by ACF

basin water users and resource managers related to drought include: reduced access to waterfront property and businesses due to low reservoir levels, water availability for municipalities, crop losses, increased reliance on groundwater pumping for irrigation, negative impacts to native fish and mussel species from extreme low water levels, and increased salinity in Apalachicola Bay (Carter, 2007; Havens *et al*., 2013). This region is also expected to continue to experience high levels of human population growth creating greater demand for water resources (USACE, 2015).

Existing riparian law in Alabama, Georgia, and Florida does not provide a framework for sharing common water resources or for resolving water allocation disputes. This has led to a series of "water wars" and related litigation among ACF basin states and government agencies for more than 20 years (Ruhl, 2005). This litigation includes a lawsuit filed by the State of Florida before the US Supreme Court in 2016. In this complaint, Florida states that the oyster fishery in Apalachicola Bay has:

> "…suffered declines as a result of Georgia's upstream storage and consumption of water from the Chattahoochee and Flint River Basins. Flow depletions from the Georgia portion of the ACF have already shrunk available riverine and estuarine habitats in the Apalachicola Region and precipitated a collapse of Florida's oyster fishery."

Through the appointment of a special master, the State of Florida is requesting to

> "…equitably apportion the interstate waters of the Apalachicola-Chattahoochee-Flint River basin…" (Supreme Court of the United States, 2013).

In late 2014, the Supreme Court agreed to hear this complaint.

3.2 Research Questions

During drought, low river discharge in the Apalachicola River leads to reduced freshwater inputs to Apalachicola Bay, and increases in Apalachicola Bay salinity (Livingston, 2015). During these periods, Apalachicola Bay resource users frequently advocate for augmentation of Apalachicola River flows through upstream reservoir releases and water demand management throughout the ACF basin (Supreme Court of the United States, 2013). While this approach is an intuitive solution, it is unclear whether there is sufficient water in managed ACF storage to make this is possible. Here we address a key uncertainty by seeking to determine whether low Apalachicola River discharge levels observed during severe drought conditions can be eliminated or substantially reduced by allocating water from reservoir storage to downstream river needs or by limiting consumptive extractions in the basin.

In this paper, we begin to address these issues by asking:

Q1. How severe were streamflow deficits in the 2012 drought compared to streamflow deficits in other droughts in recent decades?

Q2. To what extent could the low flow conditions observed in the Apalachicola River during 2012 have been averted or reduced through changes in reservoir management practices?

Q3. Can reductions in consumptive demands alone be used to increase Apalachicola River discharge during drought?

3.3 Methods

To address the research questions, we first examined historical measurements of available river discharge for the period of record for selected gauges in the ACF. The three gauges selected for examination were the Flint River at Bainbridge, Georgia (USGS gauge #0235600), the Apalachicola River at Chattahoochee, Florida (USGS gauge #02358000) and the Apalachicola River at Sumatra, Florida (USGS gauge # 02359170). The Flint River at Bainbridge was selected because it is the lowest gauge on the unregulated Flint River. The Apalachicola River at Chattahoochee was selected because it is the uppermost gauge on the Apalachicola River that accounts for inflow from both the Flint basin and the Chattahoochee basin. The Apalachicola River at Sumatra was selected because it the most downstream gauge on the Apalachicola River and hence the gauge closest to the Apalachicola estuary. We then compared the elevation of the three main ACF storage reservoirs (Lake Lanier, West Point Lake, and Walter F. George Lake) and the volume of composite storage of the three reservoirs in calendar years 2011 and 2012. We used this approach to determine how much storage was available in the ACF to augment Apalachicola River flows toward minimum required levels in the RIOP. We then used a river system simulation model (Leitman and Kiker, 2015) to evaluate the system-wide effects on both stream flow and reservoir elevations from changing consumptive demands in the Chattahoochee and Flint basins.

To evaluate observed Apalachicola River flows in 2012, discharge data were downloaded from the US Geological Survey (calendar year data; USGS Oct 2014; USGS Dec 2014) and data for reservoir conditions were downloaded from the USACE Mobile District, USACE (2016). To evaluate the effect of reservoir operations and consumptive demands on Apalachicola River discharge in 2012, we used ACF-STELLA, an existing model of river inflows, reservoir operations, and withdrawals (Leitman and Kiker, 2015). Other system-wide water models of the ACF have been developed to explore management alternatives for different agencies, municipalities and stakeholders (Sheer *et al*., 2013; Sauchyn *et al*., 2016; USACE-HEC, 2016; USGS, 2016; Kistenmacher and Georgakakos, 2011; 2015). The ACF-STELLA was first developed in the ACF Basin Comprehensive Study as part of a shared-vision stakeholder process (Palmer, 1998). Like most other water infrastructure models of the basin, ACF-STELLA uses a time series-dataset of estimated unimpaired flows to simulate a linked network of river and reservoir operations. Estimating unimpaired flow (UIF) data involves accounting for anthropogenic water abstractions along with evapotranspiration and simplified groundwater dynamics (USACE, 1997; Liang *et al*., 2014; Leitman and Kiker, 2015). The UIF synthesized flow data set was initially developed by the USACE and the states of Alabama, Florida, and Georgia during the ACF Comprehensive Water Resources Study (USACE, 1997) and was then extended several times by the USACE to increase the period of record (USACE, 2012; 2015). It is the accepted regulatory dataset of river discharge with consumptive demands added back into the discharge data and with any influences of reservoir operations removed (USACE, 1997;

Liang *et al*., 2014). The ACF-STELLA model was tested by comparing predictions with the HEC-ResSim model used by the USACE to formally evaluate ACF basin management alternatives. The two models were compared using 70 years of daily output (1939–2008; n = 25,668) for eight different ACF gauge sites (five flow stations and three reservoir elevations) using RIOP management inputs (Leitman and Kiker, 2015). The comparison between the two models showed a strong match ($p<0.01$ rejection significance) between the daily outputs for six of the eight sites, with median Nash–Sutcliffe coefficient of efficiencies (Ritter and Carpena, 2013) ranging from 0.732 to 0.979 (Note: a Nash-Sutcliffe value > 0.65 indicates acceptable, > 0.8 good and > 0.9 very good). The one gauge site matched 7 day moving average flows with a Nash-Sutcliffe coefficient of efficiency of 0.788 ($p<0.01$ rejection significance) and the one reservoir elevation (W.F. George) matched with a Nash-Sutcliffe coefficient of efficient of 0.833 ($p<0.01$ rejection significance) when anomalous maximum elevations were filtered from the HEC-ResSim output (Leitman and Kiker, 2015).

To establish a baseline of river flows for the model comparisons, the UIF reference data set from 1939-2008 was modified to reflect the low flows observed in the Flint basin in 2011 and 2012. We modified the dataset by replacing 2007 and 2008 data for the Flint basin with observed data from 2011 and 2012 data, because these years had the lowest flow in the Flint basin in the period of record. This was done by taking observed flows from the USGS-gauge sites and then adding or subtracting the net effects of consumptive withdrawals on a river-reach-by- river-reach basis to generate the surrogate UIF data for 2011 and 2012. As there are no storage reservoirs in the Flint River basin, no adjustments were necessary to account for reservoir management in this portion of the basin. No changes were made to the unimpaired flows for the Chattahoochee basin in the modeling for this analysis because:

- In 2007 the average annual contribution from the balance of the ACF basin other than the contribution from the Flint River at Bainbridge was about 210 m^3/s and the annual contribution from this part of the watershed in 2011 and 2012 was 206 m^3/s and 201 m^3/s;

- The USACE used the same approach for managing the ACF basin in 2007 and 2011 – 2012 (i.e., the RIOP) and the year for which comparisons in regard to management capacity of the basin is being made is 2007; and,
- Reservoir operations would also have to be accounted for in the creation of an unimpaired flow set for the Chattahoochee basin, which was beyond the scope of this project.

To assess the effects of consumptive extractions on reservoir elevations and Apalachicola River discharge, current upstream demands (Chattahoochee and Flint River basins combined) were multiplied by factors of 0.75, 0.5, and 0.0 (25% withdrawal reduction, 50% withdrawal reduction, and no withdrawals). These reductions are not unrealistic. For example, it has been estimated that implementing agricultural water conservation methods could reduce irrigation water use in the Flint basin by 25 to 50% while maintaining comparable yields depending on the level of implementation (Leitman *et al*., 2016). Additionally, improvements in Metro Atlanta municipal and industrial water return rates could decrease the net effects of the current volume of municipal and industrial withdrawals by Metro Atlanta (USACE, 2015). The estimates of consumptive extractions used in this model were obtained from the HEC-ResSim parameter inputs and the values represent estimated effects on stream flow, not total withdrawals (Table 3.2).

3.4 Results and Discussion

The first of the research questions to be addressed is: ***How severe were streamflow deficits in the 2012 drought compared to streamflow deficits in other droughts in recent decades?*** Figure 3.2 shows box plots of monthly river discharges from 1922-2006 for the Apalachicola River at Chattahoochee, Florida and compares these to observed monthly flows in 2007-2012. This graph demonstrates that for most months between 2007-2012, the flows in the Apalachicola River have been consistently in the lower 25% quartile of flow experienced over the period of record, with average daily winter/early spring flows (January-April) generally falling in the lower 25% quartile of measured flows for those months, and with flows during the rest of the year (May-December) mostly at the lowest levels measured for any years during the period of record. The exception to this pattern was 2009 when flows were generally normal through the winter and above normal during fall.

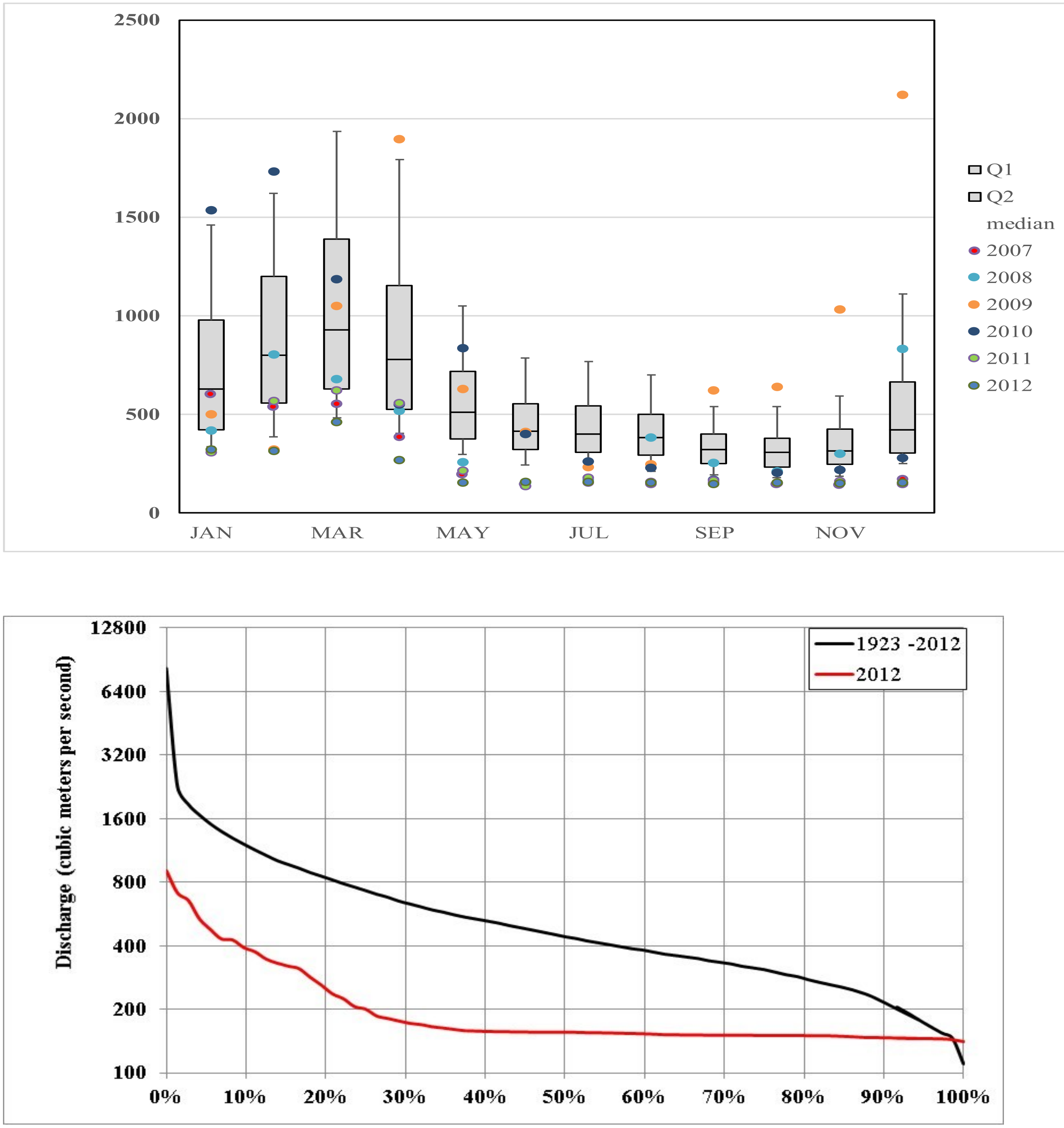
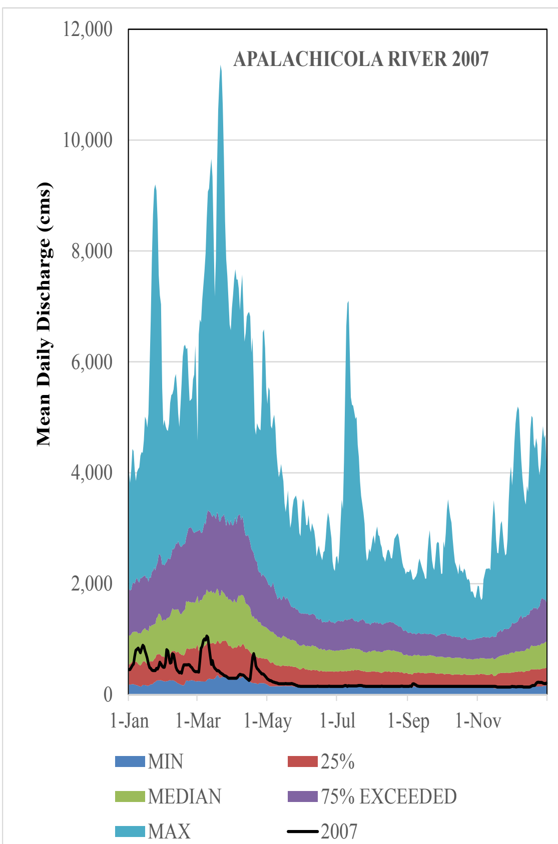
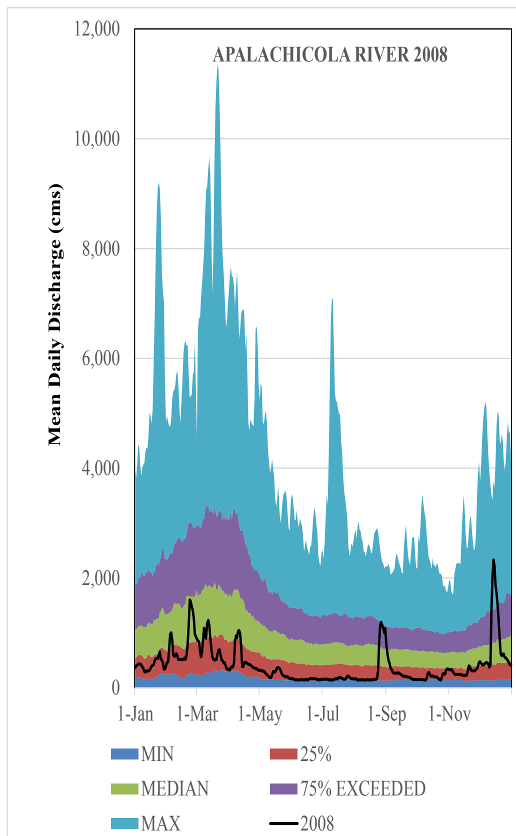


Figure 3.2. Mean daily discharge (m^3/s) by month from 1922-2006 (box plot) and from 2007-2012 (individual colored dots, see legend) for the Apalachicola River measured at the USGS Chattahoochee gauge (upper panel). Flow duration curve for the Apalachicola River measured at the USGS Chattahoochee gauge (lower panel), representing the average flow values that

were equal to or exceeded from 1922-2006 (black line) and the flows for 2012 (red line). The Q1 and Q2 boxes refer to the 25% exceeded to 50% exceeded and 50% exceeded to 75% exceeded quartiles.

Figure 3.2 also contains a stage duration curve which shows the percentage of time that the Apalachicola River flow was equal to or exceeded a given flow value in a particular year. This graph shows that in 2012 the Apalachicola River mean daily discharge was equal to or exceeded 250 m^3/s about 20% of the time, whereas during the time period 1922-2012, this same flow level was exceeded more than 80% of the time (Figure 3.2). Quartile plots of Apalachicola River discharge at the same gauge (Figure 3.3) show the high variation in discharge observed annually and seasonally in the river basin in recent years.





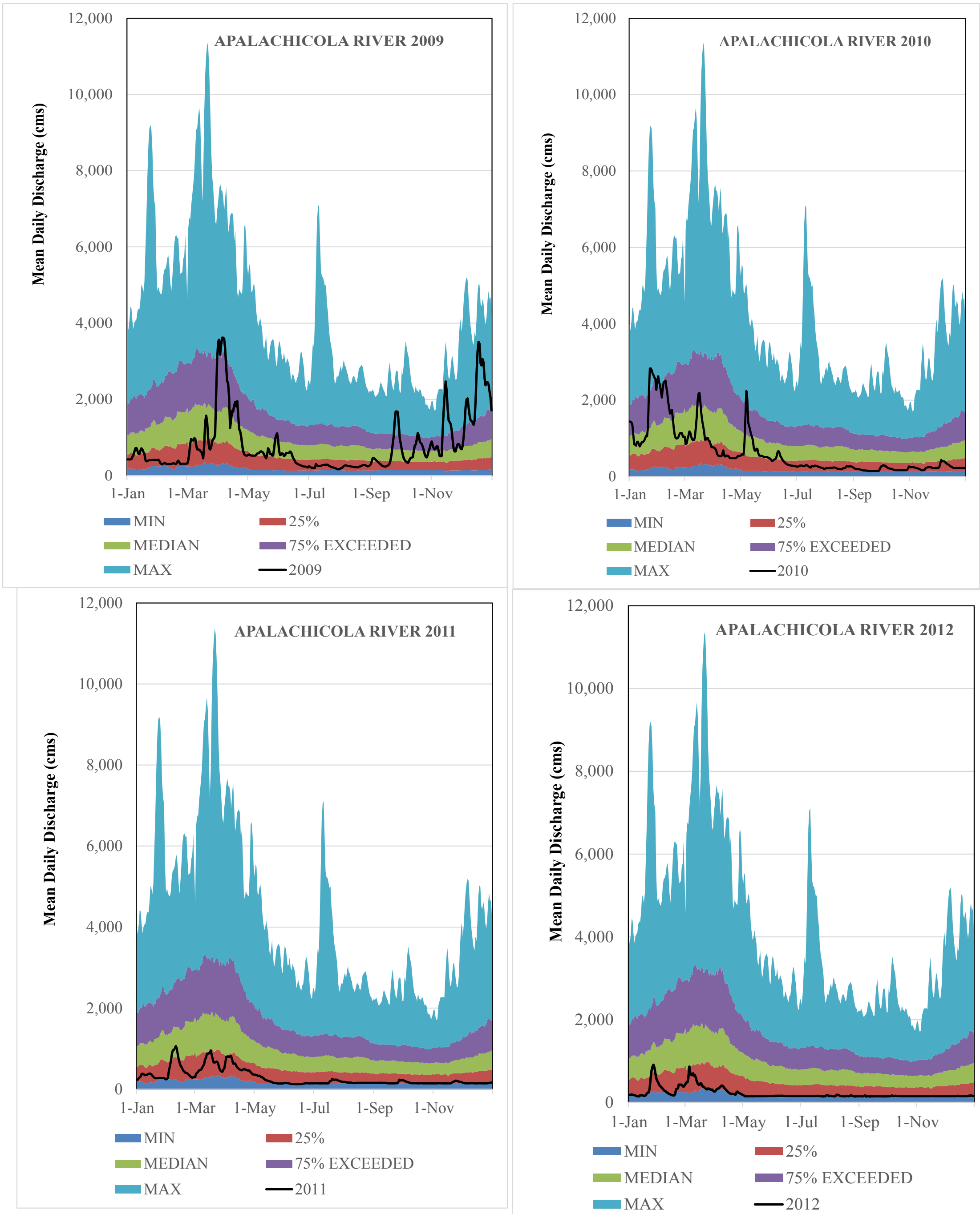
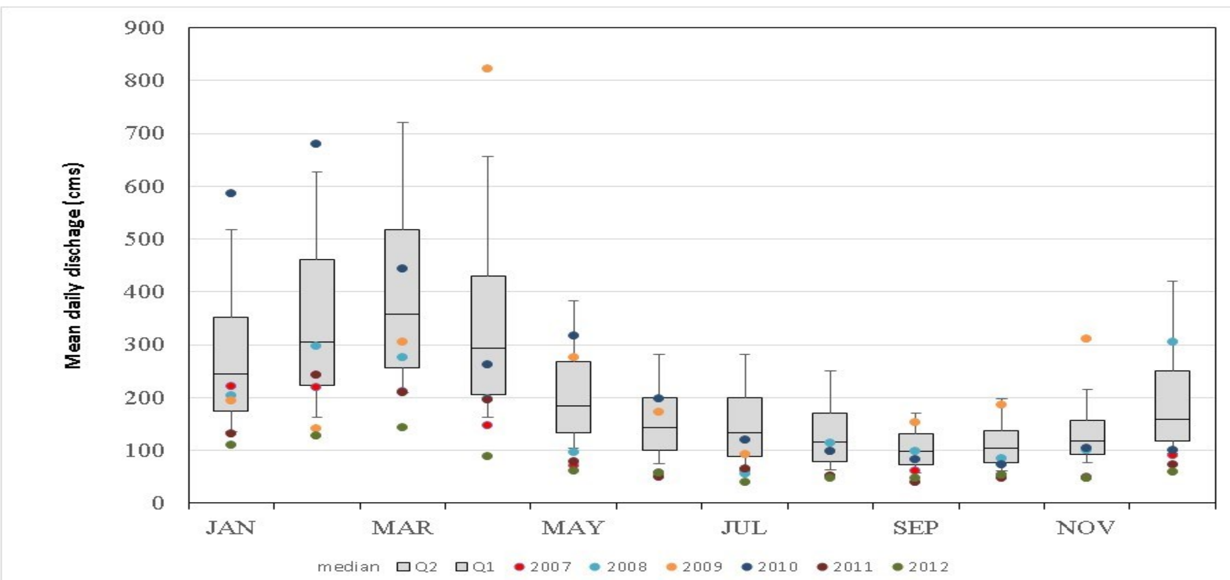


Figure 3.3. Quartile plots of mean daily discharge (m^3/s) from 1922-2006 for the USGS Chattahoochee Gauge on the Apalachicola River (colored filled areas, one color per quartile) and observed mean daily discharge by year (solid black line). As a point of reference, the green area represents the 50% quartile which is equal to the median.

For the Apalachicola River at Chattahoochee, Florida, the average annual flow for 2012 was about 36% of the average annual flow from 1939-2012 and about 78% the average annual flow for 2007, the most recent significant drought. Using data from the Apalachicola River at Sumatra, the average annual flow for 2012 was about 38% of the average annual flow for 1939 to 2012 and 86% of the average annual flow for the most recent drought of 2007. Thus the 2012 drought was the lowest in terms of annual flow in the period of record, 14% lower than the previous record drought in 2007.

A major distinguishing feature of the 2012 drought in the ACF was the extreme low discharge experienced in the Flint River. Average annual discharge at the Bainbridge gauge for 2012 was about 73.5 m^3/s, which is only 33% of the average annual flow from 1939-2012 (this time period includes both observed and synthesized flows at this gauge to fill in data gaps). This discharge rate is also lower than other recent drought years, such as 2007 when annual discharge was about 69% of annual average flow for 1939-2012. In terms of precipitation deficit, in 2011 and 2012 the Flint River basin was characterized by NIDIS as the driest area in the USA. Again, we prepared box plots of monthly river discharges for the Flint River at Bainbridge (USGS gauge #0235600, the lowest gauge on the Flint River) from 1939-2006 (Figure 3.4) and compared these to observed monthly flows in 2007-2012. Results show that for many months over the past 6 years, the flows in the Flint River were exceptionally low with average daily winter/early spring flows (January-April) generally falling in the lowest levels measured for any year during the period of record. Figure 3.4 also contains a stage duration curve which shows the percentage of time that the Bainbridge gauge flow equaled or exceeded a given flow value in a particular year. This graph shows that in 2012 the gauge for the Flint River at Bainbridge mean daily discharge equaled or exceeded 80 m^3/s about 30% of the time, whereas during the time period 1922-2012 this same flow level was exceeded 85% of the time Quartile plots of the same gauge (Figure 3.5) show that in 2012 the Flint River at Bainbridge mean daily discharge equaled or exceeded a discharge level of 100 m^3/s less than 15% of the time, whereas during the time period between 1939-2012 this same flow level was exceeded more than 80% of the time. The annual flow deficit from the Flint basin for the 2012 drought relative to the 2007 drought was about 12,169 m^3/s-days (average daily discharge deficit times the number of days in a year) and from average river discharge conditions the 2012 drought deficit was about 54,000 m^3/s-days.

The second research question to be addressed is: ***To what extent could the low flow conditions observed in the Apalachicola River during 2012 have been averted or reduced through reservoir management practices?*** The reservoirs for the ACF did not enter either 2011 or 2012 with full storage pools in terms of composite storage (Figure 3.6). The composite conservation storage in the basin could not be completely refilled in 2012 to the rule curve (the top of the storage pool) because Lake Lanier's elevation at the beginning of the year was depressed from the 2011 drought (Figure 3.6) and because the ongoing lack of rainfall did not allow for sufficient local inflow to makeup the storage deficit. Lake Lanier is found in the uppermost reaches of the Chattahoochee River, thus local inflows are small because of its headwater, piedmont location between the coastal plain and Appalachian Mountains. When combined with its relatively large storage pool (for the ACF basin), this results in long time periods required for the reservoir to refill following depletion even under normal precipitation levels (USACE, 2015).



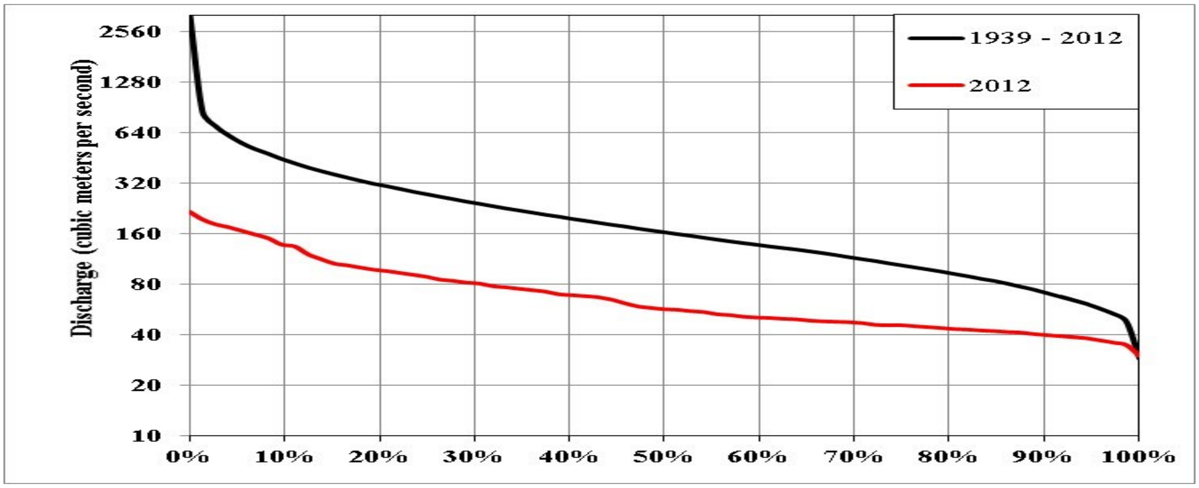
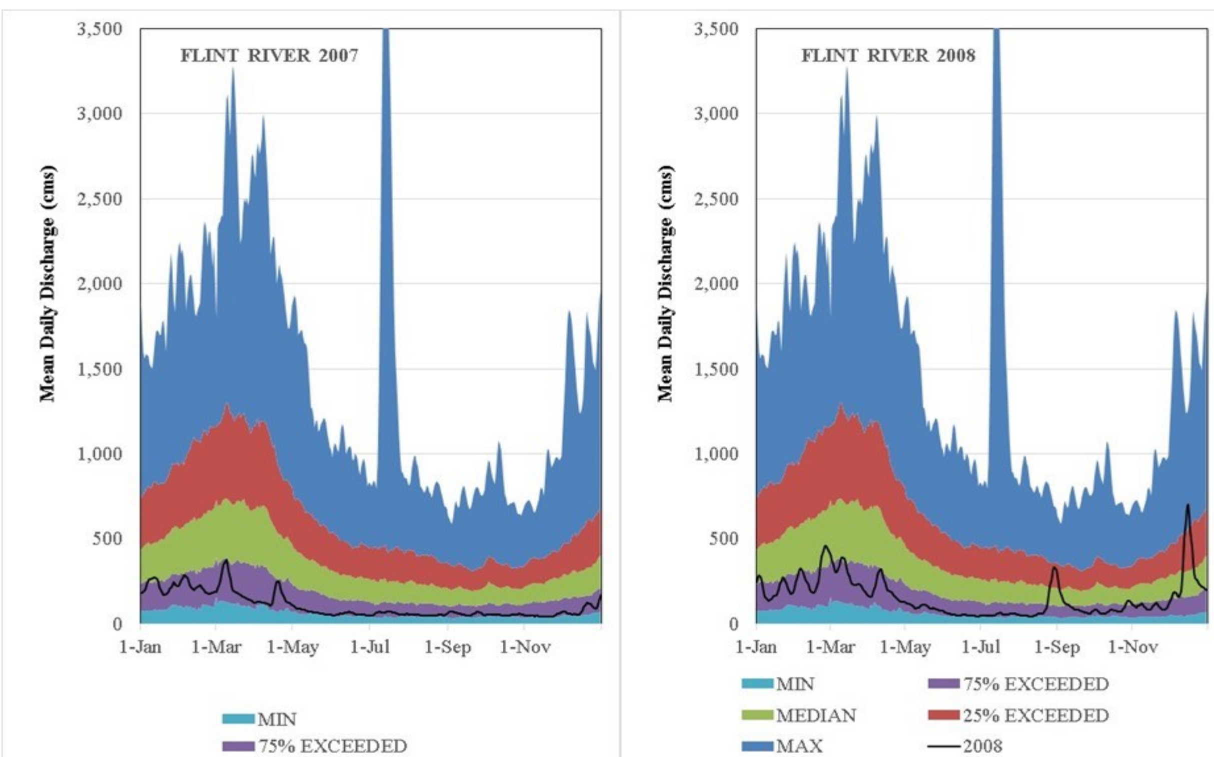


Figure 3.4. Mean daily discharge m^3/s by month from 1939-2006 (box plots) and from 2007-2012 (individual colored dots, see legend) for the Apalachicola River measured at the USGS Flint River gauge at Bainbridge, Georgia (upper panel). Flow duration curve for the Flint River (lower panel) measured at the same gauge representing the average flow values that were equal to or exceeded from 1939-2012 (black line) and the flows for 2012 (red line). The Q1 and Q2 boxes refer to the 25% exceeded to 50% exceeded and 50% exceeded to 75% exceeded quartiles.



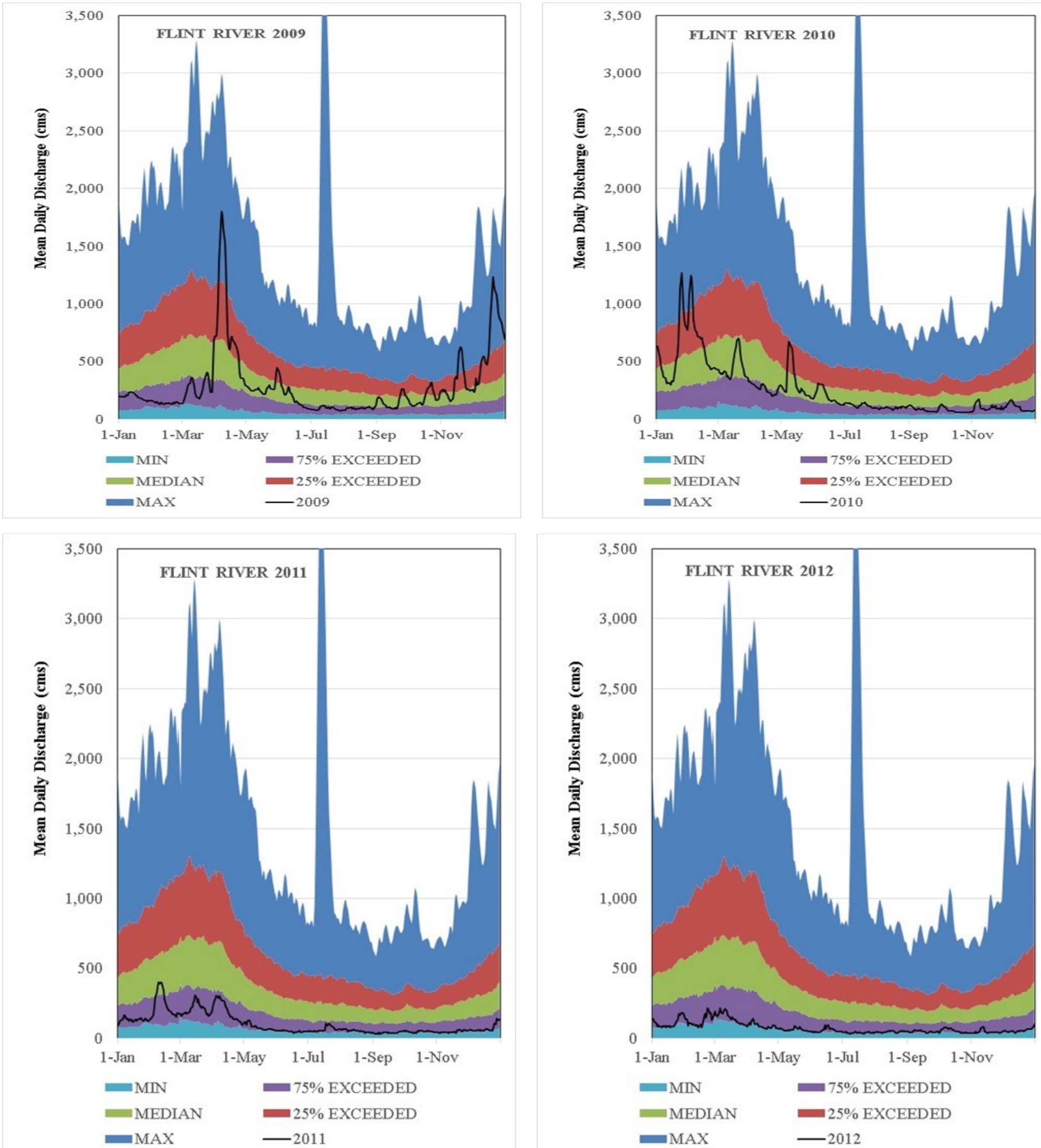
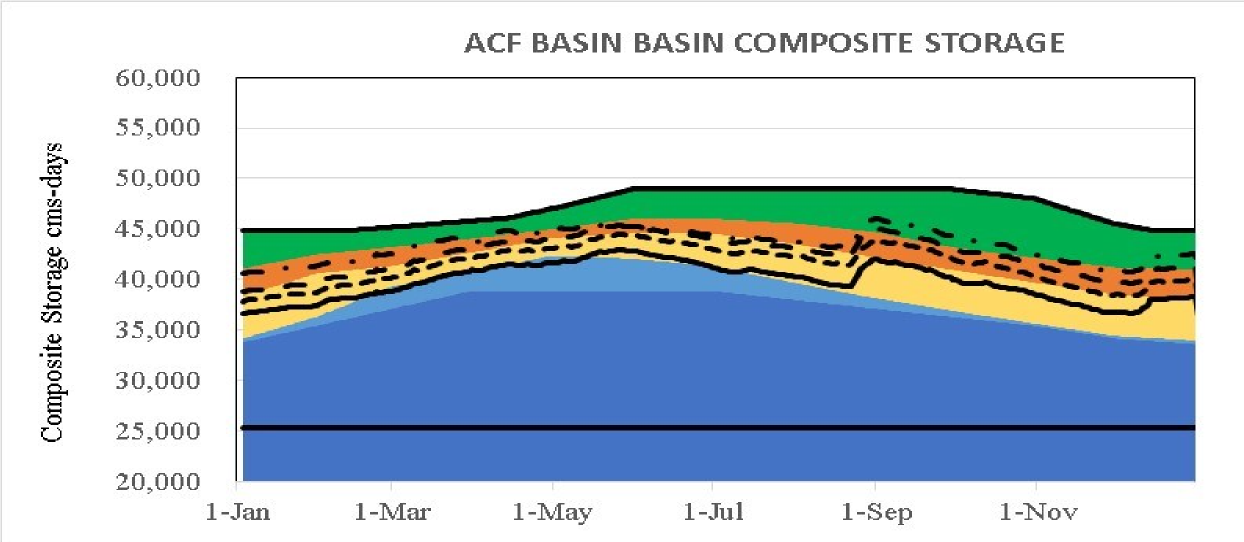
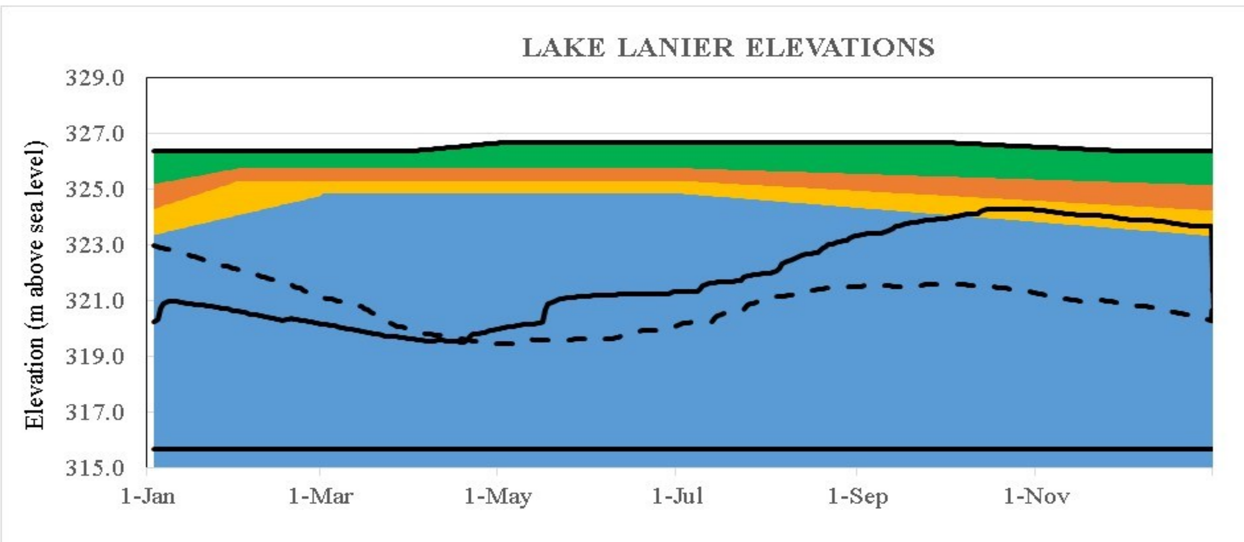
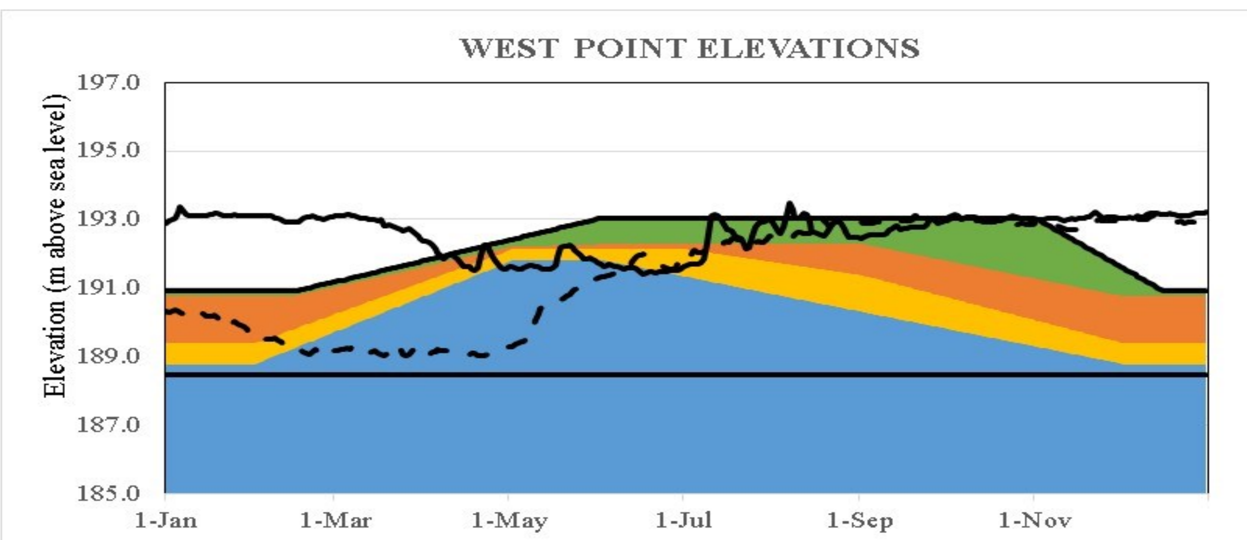


Figure 3.5. Quartile plots of mean daily discharge m^3/s from 1922-2006 for the USGS Bainbridge Gauge on the Flint River (colored filled areas, one color per quartile) and observed mean daily discharge by year (solid black line). As a point of reference, the upper bound of the green area represents the 50% quartile which is equal to the median discharge.


ACF BASIN BASIN COMPOSITE STORAGE
Composite Storage cms-days
60,000
55,000
50,000
45,000
40,000
35,000
30,000
25,000
20,000
1-Jan
1-Mar
1-May
1-Jul
1-Sep
1-Nov


LAKE LANIER ELEVATIONS
Elevation (m above sea level)
329.0
327.0
325.0
323.0
321.0
319.0
317.0
315.0
1-Jan
1-Mar
1-May
1-Jul
1-Sep
1-Nov


WEST POINT ELEVATIONS
Elevation (m above sea level)
197.0
195.0
193.0
191.0
189.0
187.0
185.0
1-Jan
1-Mar
1-May
1-Jul
1-Sep
1-Nov

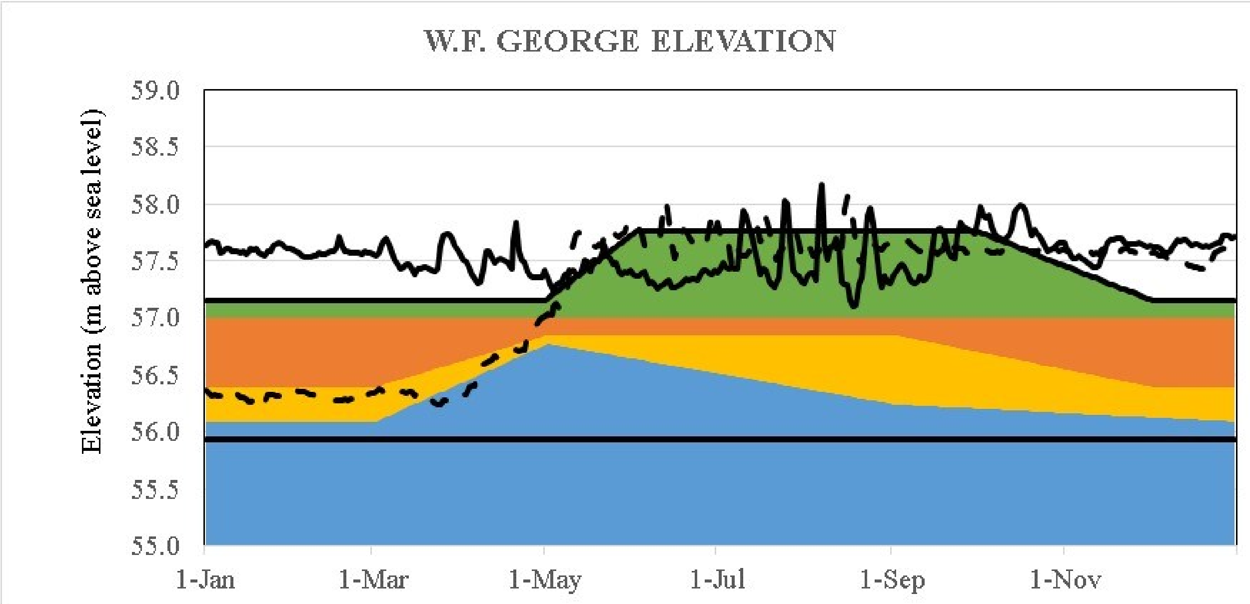


Figure 3.6: Cumulative composite reservoir storage in the ACF basin and for each of the three major reservoirs by action zone as colored polygons in m^3/s-days. Blue is action zone 4, gold is action zone 3, orange is action zone 2, and green is action zone 1. Observed reservoir elevations for Lake Lanier, West Point, and WF George reservoirs in 2011 (solid line) and 2012 (dashed line). Note that the y-axes are different on each panel. Data are from the USACE HEC-ResSim database.

Reservoir releases from Jim Woodruff Dam effectively create Apalachicola River base flow, thus the volume and timing of these releases influences downstream water availability in the Apalachicola River. Jim Woodruff Dam reservoir releases follow an annual schedule defined by the RIOP for multiple purposes, including minimum flows during spring (i.e., 141.5 m^3/s) to protect mussel species listed under the US Endangered Species Act (USFWS, 2006; 2008; 2012), and spawning habitat for the threatened Gulf sturgeon (*Acipenser oxyrinchus desotoi*; Flowers *et al*., 2009). Reservoir releases under normal operations are based on inflows from the Chattahoochee and Flint River basins, as well as the composite volume of water in the major storage reservoirs. In order to meet the 141.5 m^3/s required water releases at Jim Woodruff Dam during periods of low inflows from the Chattahoochee and Flint rivers, water must be released from storage in upstream reservoirs. Lake Seminole has very limited storage capacity (<5% ACF basin's total storage) and its pool can only be varied by < 0.6 m under normal river discharge levels. During drought, however, because of head limit considerations (i.e. the difference in elevation between the surface of the reservoir pool and the tail water; USACE, 2011; Leitman *et al*., 2012), and when minimum water releases are specified, there is essentially no storage in Lake Seminole (USACE, 2015).

This situation results in a zero-sum game between consumption in the Flint River basin and reservoir storage in the Chattahoochee River basin where any increases in consumptive demands in the Flint River basin translate into a release requirement from the Chattahoochee River basin to meet minimum flows at Jim Woodruff Dam. Increases in consumptive demands in the Chattahoochee River basin, or increased losses of water due to evaporation from existing reservoirs or the construction of new reservoirs, would also contribute to this management conundrum. Based on basin inflow data for Jim Woodruff Dam provided by the USACE (2013), for wetter years such as 2009 there were no occurrences of the zero-sum conditions where local inflow from the Flint and Chattahoochee was not adequate to meet the 141.5 m^3/s minimum flow requirement. However, in drought years such as 2007 and 2012, this situation, requiring supplemental releases from the Chattahoochee basin storage reservoirs, occurred more than 130 days in a single year.

In 2012, a major driver of the extreme low river discharge observed in the Apalachicola River was low river inputs from the Flint River (see Figures 3.4 and 3.5). For comparison, the second lowest average discharge year for the Apalachicola River Chattahoochee gauge for the period of record was 2007. Within the Chattahoochee River basin, inflows for 2007 and 2012 were comparable (about 210 m^3/s vs. 201 m^3/s respectively). Given the extremely low river discharge in the Flint River basin in 2012, the only way to compensate for the large discharge deficit from the Flint River, to even reach Apalachicola River discharge levels observed during the 2007 drought, would be to augment Chattahoochee River inputs via releases from reservoir storage. These storage releases would have had to equal about two-thirds of the maximum annual storage capacity ever released (i.e., 12,169 m^3/s-days). While theoretically possible, this assumes that reservoirs would be at full pool at the start of the drought. For example, the composite storage of the ACF storage reservoirs in early 2012 was not at full capacity (Figure 6), therefore over 90% of the available storage capacity would have had to have been released to increase the discharge for the Apalachicola River to levels comparable to the 2007 drought.

If the intent of reservoir releases was to augment Apalachicola River discharge to levels higher than 2007, then even larger water releases, and water storage, would have been required. As an example, to reach median discharge from the period of record in the Apalachicola River at the Chattahoochee gauge would require that the entire ACF basin storage capacity would have had to increase by more than threefold.

An interesting observation from our work is that reservoir storage in the ACF basin is operated conservatively, seemingly prioritizing storage over downstream releases. Total storage capacity of the reservoirs in the ACF is nearly 24,000 m^3/s-days (Table 3.1) and the majority of this storage (about 15,580 m^3/s-days, 66% of total) is in Lake Lanier. Since the completion of Lake Lanier, the maximum amount of storage actually used (water released) is about 9,548 m^3/s-days (2008) and the lowest lake elevation observed has been about 319.57 m ASL (2008) - nearly five meters higher than the bottom of the conservation storage pool (314.64 m ASL). This conservative operation is equivalent to releasing only about 60% of the conservation storage in Lake Lanier. This difference between the true storage and "effective" storage shows that about 40% of the Lake Lanier storage has never been operationally used.

If the true storage of Lake Lanier were solely used to support downstream water releases, then this amount of storage could provide the median daily Apalachicola River discharge at the Chattahoochee gauge for about for about 54 days and the effective storage could provide this same discharge level for about 40 days. This highlights that reservoir storage in the ACF basin is relatively small compared to Apalachicola River median discharge levels. By comparison, in the Colorado River basin, aggregate managed storage has a combined capacity of about 30.6 million acre-feet (over 430,000 m^3/s-days) which is equivalent to nearly three years of runoff (US Bureau of Reclamation, 2008). This higher storage capacity creates the potential to store water from high runoff years to meet flow requirements and operational needs during low runoff years. Put simply, the ACF basin has limited capacity to supplement downstream river discharge levels during drought years in the same manner as other large watersheds in the US.

The third research question to be addressed is: ***Can demand management alone be used to increase Apalachicola River discharge during drought?*** We summarized the total average annual effect of consumptive demands for municipal, industrial and agricultural purposes based on the data from the HEC-ResSim database on streamflow in the ACF by evaluating estimates of current consumptive uses of water and then evaluating how changing current levels of withdrawals would affect stream flow using the ACF-STELLA model. We found that the effects of average annual consumptive demands in the Chattahoochee and Flint River basins (Table 3.1) on streamflow were about 43 m^3/s-days or about 20% of the average annual outflow from Jim Woodruff Dam measured on the Apalachicola River in 2012, or about 7% of the average annual outflow for the period of record. When we model the effects on Apalachicola River discharge and ACF basin storage from reduced consumptive demands, our model predicts changes to both Apalachicola River discharge measured at the Sumatra gauge (Figure 3.7) and to basin composite reservoir storage (Figure 3.8). Based on current operating guidelines (see Table 1.1, page 28) and composite reservoir storage, if more water is introduced to the basin via reduced consumptive demands, then less water has to be released from the storage reservoirs to meet the minimum required flow, resulting in increased reservoir elevations during extreme drought events, or as increased flows in the Apalachicola River during normal reservoir operations (USFWS, 2016). The ratio of water which goes to the reservoirs for storage, and to the Apalachicola River, varies with the volume of basin inflow and composite reservoir storage levels. For example, if Flint River discharge increases during a drought because of reduced consumptive withdrawals, then the majority of the benefits from this additional inflow to Lake Seminole would result in increased elevations at Chattahoochee River basin storage reservoirs such as Lake Lanier (due to a reduction in required releases); whereas during non-drought conditions when less flow augmentation support is provided from reservoir storage, increased Flint River discharge would translate into increased Apalachicola River discharge (Leitman *et al*., 2016). This is a key finding - this suggests that under the current operating guidelines, demand management alone is unlikely to lead to significant increases in Apalachicola River discharge during drought.

Increasing reservoir storage during drought could extend the duration of time reservoirs can make releases to support minimum downstream flow needs during a more severe drought, but this same water could also ultimately be allocated to other water users such as to support the increasing water consumption in Metro Atlanta (USACE, 2012a) instead of allocated to downstream uses. If the intent of the reservoir operational guidelines is to ensure gains in Apalachicola River discharge during drought, both the RIOP and any management actions in either the Chattahoochee or Flint River basin would have to prioritize passage of water to the Apalachicola River over storage in upstream reservoirs (see Table 1.1, page 28). The preferred alternative in the Draft Environmental Impact Statement (DEIS) for the revised Water Control Manual for the ACF basin (USACE, 2015) currently under review recommends a continuation of the RIOP, but with an even greater bias towards protecting storage in the reservoirs over the passage of water to the Apalachicola River.

Table 3.1 Agricultural (AG) and municipal and industrial demands (m^3/s-days)

	Chattahoochee basin			Flint basin		
	AG	M&I	TOTAL	AG	M&I	TOTAL
JAN	0.11	7.87	7.98	0.04	1.23	1.27
FEB	0.11	9.46	9.57	1.16	1.26	2.42
MAR	0.22	12.91	13.13	4.89	2.08	6.97
APR	0.56	16.31	16.87	10.75	3.33	14.08
MAY	1.12	23.98	25.1	29.59	4.61	34.2
JUN	1.80	25.37	27.17	39.58	5.14	44.72
JUL	2.02	23.31	25.33	44.73	6.23	50.96
AUG	2.36	28.47	30.83	48.06	6.24	54.3
SEP	1.24	24.09	25.33	35.01	5.22	40.23
OCT	0.11	15.71	15.82	13.32	3.04	16.36
NOV	0.11	14.65	14.76	10.30	2.84	13.14
DEC	0.22	12.94	13.16	8.85	2.52	11.37
ANNUAL AVE	0.83	17.92	18.75	20.52	3.65	24.17

Source: HEC ResSim data base. NOTE: The municipal and industrial (M&I) demands are net demands (consumption minus returns) and the agricultural demands represent the effects of withdrawals on stream flow, not the volume of water used for irrigation.

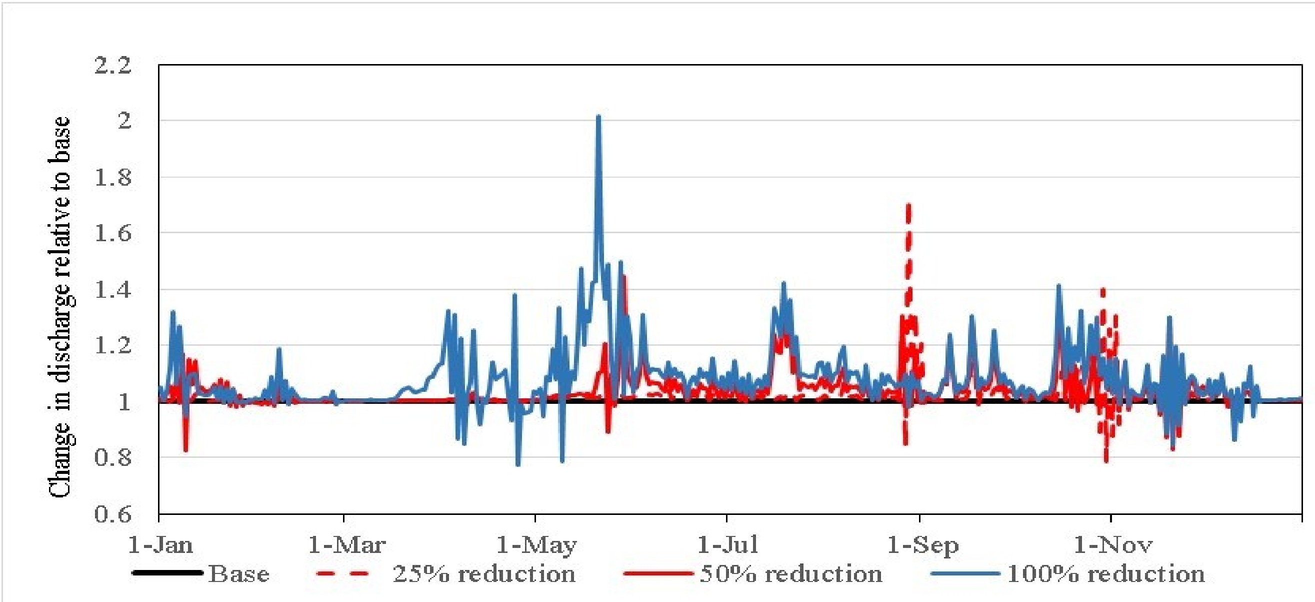


Figure 3.7. Predicted changes to Apalachicola River discharge at the USGS Sumatra gauge (m^3/s-days) relative to current level of withdrawals using the ACF-STELLA model for changing consumptive demands for each day of the year. As an example, a value of 2.0 would equal a doubling of the discharge relative to current river levels.

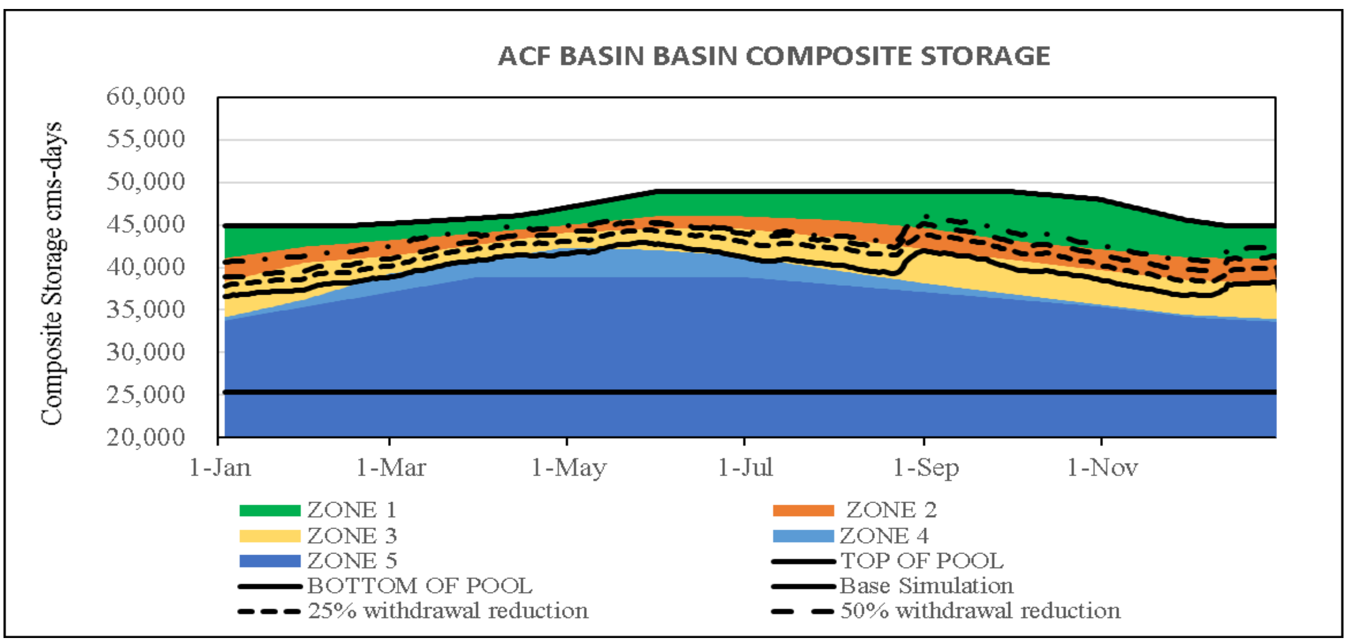


Figure 3.8: Modeled composite storage in ACF reservoirs (m^3/s-days) using the ACF-STELLA model for 2012 with changing volume of withdrawals relative to current base level withdrawals (lines) and composite action zones as colored polygons.

3.5. Conclusions

The 2012 drought in the Apalachicola-Chattahoochee-Flint River basin was not a situation where creatively managing available water in reservoir storage to minimize low flow events would have been possible or even desirable. The ACF basin has a finite, relatively small amount of water in managed storage and there are limits to its capacity to meet human and ecosystem needs. Our research also shows that the problems experienced in the 2012 drought could not simply be eliminated through demand management, especially when managers are in the middle of a drought and do not know the duration of the event. The implication of these findings suggest that managing our way out of frequent extreme drought events will be extremely challenging in the ACF.

Was the 2012 drought an anomaly or should droughts of this magnitude be expected in the future with changing climate? Long-term surrogate climate records suggest that decade-long “mega-droughts” have occurred periodically during the past 1,000 years in the southeastern US, including in the ACF (Stahle *et al*., 2007). This suggests that while the recently observed droughts in 2006-2008 and 2010-2012 were exceptional based on our <100-year period of record, they may not be exceptional compared to historic episodes (Pederson *et al*., 2012). Gibson *et al*. (2005) used multiple future climate scenarios, combined with increasing water demand from human users, to project that future river discharge conditions could include lower high discharge events and lower low flow events. From the 1940s to the 1990s (the majority of the period of record for gauges in the ACF), the southeastern US was in a persistent, unusually wet period compared to the past millennium (Seager *et al*., 2009). This is the period of time during which most of the reservoir and human development has occurred in the ACF. Thus, during the epoch when most development has occurred, and the period of record from which we derive flow assessments, the ACF probably has had fewer severe drought events potentially leading to unrealistic baselines of what can be expected. A similar situation occurred in the Colorado River basin when water allocation decisions among the basin states were made as part of the 1922 Colorado River Compact - the period of record used for determining the allocation was exceptionally wet (Woodhouse *et al*., 2006). Future growth and water management approaches in the ACF should likely not be based on expectations of perpetuation of the fortuitous wet period or a period free of severe of droughts, but should account for the likelihood of more severe and more frequent drought events.

The question looms of how to proceed in developing more informed flow operations for the ACF basin? In the absence of stated management goals for target resources or water allocation cooperation among basin states and water users, it is difficult to prioritize research efforts to experimentally manipulate or passively monitor and assess responses of species and ecosystems to various flow regimes. If resource priorities could be established, then adaptive management frameworks (Walters, 1986), which have been successfully used or proposed for a number of large regulated river systems in the US and Canada (Irwin and Freeman, 2002; Melis *et al.*, 2006; Alexander *et al*., 2006; Bradford *et al*., 2011; Failing *et al*., 2013) could be applied. As an example, while median Apalachicola River discharge could only be met for a few weeks from available ACF storage, are there benefits to downstream ecosystems such as floodplain or estuarine resources smaller discharge augmentations or pulses? Incorporating these types of questions in an adaptive management framework could provide a way to address key uncertainties related to ecosystem responses to changes in reservoir operations, demand management, and river discharge as well as uncertainties related to resource management and ongoing restoration of resources such as Eastern oysters (Camp *et al.,* 2015).

CHAPTER 4: SIMULATING SYSTEM-WIDE EFFECTS OF REDUCING IRRIGATION WITHDRAWALS IN A DISPUTED RIVER BASIN

This chapter analyzes the system-wide effects of various scales of implementation of water saving irrigation practices in the Flint watershed. The potential water savings are discussed and then current demands are modified and using the ACF-STELLA model the effects of these scenarios on both flow entering the Apalachicola River and on the storage reservoirs in the Chattahoochee basin. Changes in flow to the Apalachicola River are then compared to several ecological metrics to evaluate the significance of flow changes.

4.1 Introduction

The Apalachicola/Chattahoochee/Flint (ACF) basin is one of the principal river basins of the southeastern United States supporting high biodiversity (USFWS, 2012), large-scale agricultural operations (Hook *et al*., 2010), an estuary that is renowned for its seafood (Havens *et al*., 2013), as well as one of the largest and fastest growing metropolitan areas in the United States (Atlanta, GA). For several decades' water users and managers in the ACF basin have been locked in controversy over the use and management of the watershed. This controversy has led to: (1) the creation and subsequent termination of the first river basin compact in the US since the passage of the major environmental laws in the 1970s (Leitman, 2005; Jordan and Wolf, 2006) (2) multiple lawsuits between the three states in watershed and the federal government (see USACE, 2015 for a review of the litigation) and (3) the State of Florida filing a lawsuit with the US Supreme Court in 2013 (Supreme Court of the United States, 2013).

The Apalachicola River is formed by the confluence of the Chattahoochee and Flint rivers near the Alabama, Florida and Georgia border in what is now Lake Seminole (Figure 4.1), a reservoir that was created in 1955 with completion of the Jim Woodruff Dam. The Apalachicola River empties into Apalachicola Bay and then into the Gulf of Mexico. The two river basins that form the Apalachicola River are very different in land cover, hydrography and water use and resource management. In the Chattahoochee basin, discharge is managed through several federally operated storage reservoirs (Lake Lanier, West Point Lake, W.F. George Lake in Figure 4.1) and the major consumptive water uses are municipal and industrial consumption, whereas in the Flint basin flow is primarily altered through consumptive withdrawals of surface and groundwater for agricultural irrigation and there are no storage reservoirs in the Flint basin through which flow could be managed. Virtually all of the reservoir storage capacity in the ACF basin is managed by the US Army Corps of Engineers (USACE), Mobile District under the purview of the Revised Interim Operating Plan (RIOP) (USACE, 2012; USFWS, 2012).

The significant groundwater contribution to the Flint River complicates water management in this basin because of uncertainties in the surface-groundwater interactions in the mid to lower Flint basin as well as effects on groundwater and spring discharge from groundwater withdrawals (Jones and Torak, 2006, Rugel *et al*., 2012). Because of the large spring flow contribution to the Flint basin, the base flow of the Flint River is more stable than that of the Chattahoochee basin (Leitman, 2005). During low flow periods, the Flint basin is typically an important contributor to meeting the minimum flow needs of the Apalachicola River. It was the inability of the Flint basin to play this flow mitigation role during the 2011-2012 drought that led to the record low flows experienced in Apalachicola River in 2012 (Leitman *et al*., 2015).

Prolonged drought periods such as those which occurred in 2007-2008 and 2011-2012 can have significant economic and ecological consequences throughout the basin ranging from low reservoir water levels reducing access to lake front properties, concerns over availability of municipal water to the Atlanta metro region, dewatering of tributary stream systems and prolonged periods of high salinity in the Apalachicola estuary (Congressional Research Service, 2007; Havens *et al*., 2013). These consequences, in turn, can lead to restrictions being placed on agricultural irrigation. Long-term proxy climate records suggest that decade-long “mega-droughts” have occurred periodically during the past 1000 years (Stahle *et al.,* 2007). The 2007-2008 and 2011–2012 droughts in the southeastern US that resulted in regional water resources being precariously low are indicative of similar events that occurred in the previous 500 years (Pederson *et al*., 2012). The prospect of global climate change and more extreme weather events further exacerbates this concern. Gibson *et al*. (2005) identified that under multiple future climate scenarios combined with increasing water demand from human users could lead to more extreme low-flow events. A variety of climate models suggest that in future decades this region will see increases in temperature and greater variability in precipitation which could produce more severe and frequent droughts or floods (Wang *et al*., 2009; National Climate Assessment, 2013). Consequently, the competition between agricultural water use and non-agricultural water use (i.e. public and industrial water supply, hydropower generation, recreation) in times of limited water availability could increase the future events.

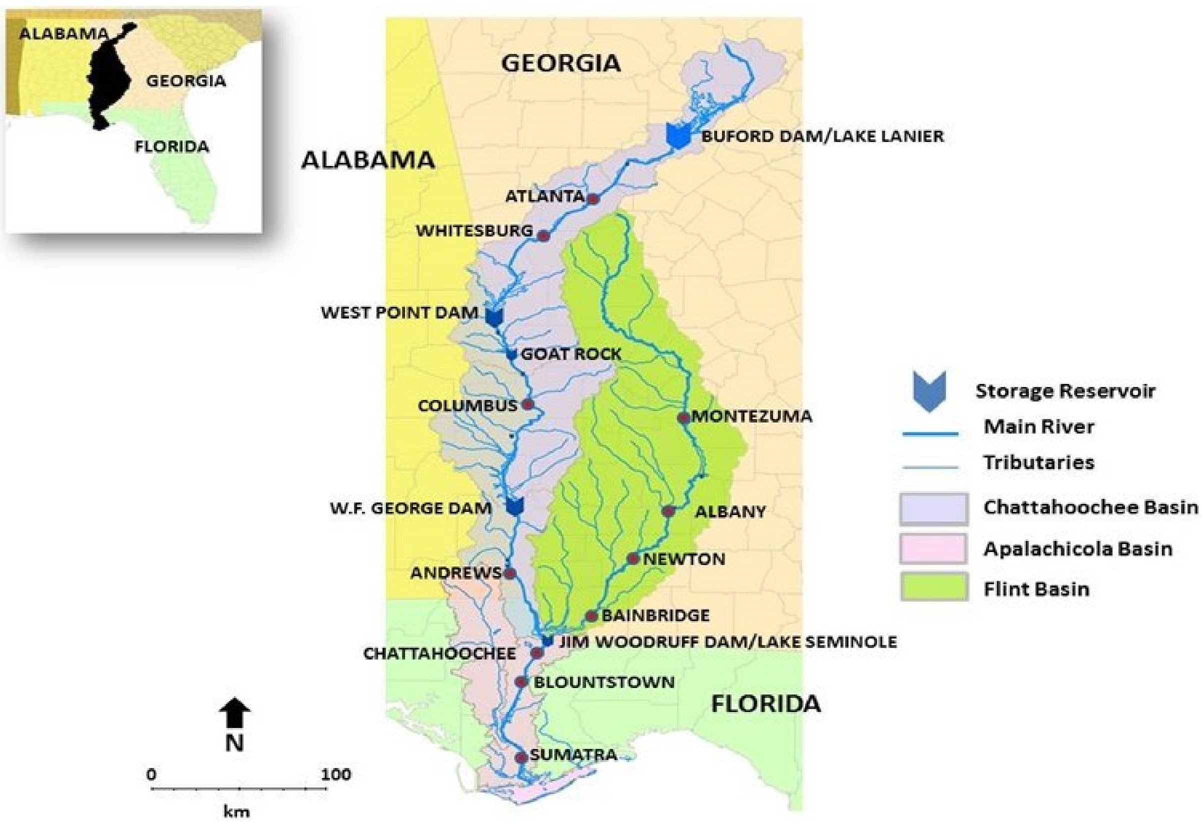


Figure 4.1: The Apalachicola-Chattahoochee-Flint River basin.

Multiple studies have established the importance of floodplain habitats to the life history of many riverine fishes, including several specific to the Apalachicola River (Walsh *et al*. 2006, 2009; Pine *et al*. 2006; Dutterer *et al.* 2011; Burgess *et al.,* 2013). Since the floodplain is not inundated to any great extent until the river tops the levees along the river (Light et al., 1998) and this does not occur until about median flow (about 450 m^3/s), then reducing agricultural irrigation demands in the Flint basin can only have minor effects on floodplain inundation.

Flow can affect Gulf sturgeon during spawning, when young of the year are in the estuary and in the provision of foraging habitat to mature and immature sturgeon (USFWS, 2016). The critical period for the inundation of Gulf sturgeon spawning habitat occurs at a time of the year when irrigation demands are lower and at a range of flow greater than median flow and therefore reducing agricultural irrigation demands is unlikely to have a significant impact Gulf sturgeon spawning. Increasing inflows to the Apalachicola estuary could have a positive impact on young-of-the-year Gulf sturgeon, but the volume of water gained by altering agricultural demands is most likely not sufficient to make a significant difference. The period January 1 to March 15 was identified as a time frame during which young of year sturgeon have been observed to access lower salinity regions of the Suwannee River estuary during winter foraging (Sulak and Clugston 1999). Discharge in the range of 16,200 cfs for the Apalachicola River at Chattahoochee has been associated with lower benthic salinity conditions (i.e., ≤10 ppt.) at the long-term monitoring station at East Bay. Sustained low flow conditions during this period would result in a reduction in low salinity foraging habitat, and therefore lower the maximum consecutive days that are associated with benefits to Gulf sturgeon (USFWS, 2016).

This paper will test the hypothesis that reductions in consumptive losses to stream flow through the introduction of water saving irrigation devices and practices could have a substantive positive effect on inflows to the Apalachicola River from the watershed above Jim Woodruff Dam. Agricultural irrigation practices which could be implemented to reduce irrigation water consumption include sod-based rotation (SBR) (Katsvairo *et al*., 2006; Wright *et al*., 2012), variable rate irrigation (VRI), and the use of high residue cover crops, conservation tillage and soil moisture sensing (Perry and Yeager, 2011). There has been research on the effects of implementing these water saving practices in the ACF basin. SBR was developed at the University of Florida's North Florida Research and Education Center in Quincy, Florida and is a conservation farming system that incorporates perennial grass (Bahiagrass)/livestock into row crop production (Katsvairo *et al*., 2006; Wright *et al*., 2012; Dourte *et al*., 2015). Research on the application of VRI, the usage of high residue crop tillage and soil moisture sensing has been conducted in the Flint River watershed for more than a decade at the University of Georgia's Stripling Irrigation Center near Camilla, Georgia (Perry and Yager, 2011). The research conducted at both of these facilities has shown that comparable or even increased yields can be attained for both cotton and peanuts while utilizing substantially less water (Wright *et al*., 2012).

To test the hypothesis, the following objectives were developed:

1. Use a water systems model to explore the potential for reductions in agricultural water consumption in the ACF basin from implementing alternative production practices, irrigation techniques and conservation measures;
2. Analyze the system-wide implications on flow in the Apalachicola River and on storage in the major federal storage reservoirs that could result from reduced agricultural withdrawals;
3. Link water resource simulation results with ecosystem indicators that may potentially respond to reduced agricultural water consumption.

4.2 MATERIALS AND METHODS

To evaluate the effects of changing agricultural irrigation demands on the ACF system, an existing water systems model developed in STELLA was used to simulate river reaches and reservoir dynamics. The ACF-STELLA model was used for this analysis because 1) the ACF-STELLA model has been shown to calibrated well with the existing Corps of Engineers HEC ResSim model (Leitman and Kiker, 2015), 2) the ACF-STELLA model has a much shorter run-time than the HEC ResSim model (< 5 minutes versus > 2 hours) (Leitman and Kiker, 2015) and 3) the modeling changes being made in this analysis are only to consumptive demands, not reservoir operations, and consequently do not require the complexity or extended run-time of the HEC ResSim model.

The ACF-STELLA model was originally developed in the ACF Basin Comprehensive Study as part of a shared-vision/stakeholder process (Palmer, 1998). Initially the model was a monthly time-step model, but it was ultimately converted by the Northwest Florida Water Management District into to a daily model for use in the Compact and allocation formula negotiations (Hamlet and Leitman, 2000). From a general water-system perspective, the ACF-STELLA model simulates a 73-year (1939 – 2011) unimpaired flow dataset at a daily time-step (n= 26,662) with the ACF basin being divided into 15 reaches with a node at the downstream point of each reach where input flow data is provided (Figure 1.1). With this configuration, the Chattahoochee basin is represented by seven nodes, the Flint basin by four nodes, with an additional node at the confluence of the Flint and Chattahoochee Rivers and three additional nodes in the Apalachicola River. The placement of nodes was determined by either the existence of a storage reservoir or sites where long-term stream gauge data was available. Water demands in the ACF-STELLA model are set on a reach-by-reach basis using values consistent with the US Army Corps of Engineers' HEC-ResSim water system model (USACE-HEC, 2014). These demands were developed by the Corps of Engineers from water use data supplied to them by the three States and represent the highest consumptive use experienced in the ACF basin to date (USACE, 2015). For each node, the following water balance is calculated on a daily basis:

$$\frac{dS}{dt} = Pr + I_L + I_R - O_A - O_E - O_R \qquad \text{(Equation 3.1)}$$

Where:

dS/dt = the change in reach storage in one day in cubic meters per second (m^3/s),

Pr = direct water input to the reach from precipitation (this is only accounted for when there is a storage reservoir, elsewise precipitation gains to a reach are accounted for under I_L) (m^3/s),

I_L = Inflow from surface and groundwater from the reach watershed (m^3/s),

I_R = Inflow routed to the reach from upstream (m^3/s),

O_A = net outflow from human abstractions, specifically agriculture (AG) and municipal/industrial (M&I) (m^3/s),

O_E = net losses from evaporation in reservoirs (m^3/s),

O_R = outflow to the downstream reach (m^3/s).

For each reach/node combination, local inflows (I_L) are defined by an unimpaired flows dataset (USACE, 1997; Arcadis, 2010). The dataset was developed by removing the human influences such as withdrawals, returns, and the effects of water control structures from historically observed flows (USACE, 1997; Liang, 2014). Since the flow set was developed using historically observed flows, it includes both surface and groundwater sources and accounts for climatic water inputs to the basin from precipitation. The dataset was first developed in the 1990's as part of the ACF Comprehensive Study. The dataset has been updated several times with the last update to support modeling efforts for the revision of the basin's Water Control Manuals (USACE, 2015). With regard to uncertainty associated with the unimpaired flow dataset, it should be understood that the purpose of the reservoir/reach model in this research is to simulate system-wide effects and not to duplicate historical conditions, but to estimate the effects of various actions on future conditions. As such, the standard to gauge the dataset is whether it provides a broad enough range of hydrologic conditions to include plausible future conditions, not whether it is a perfect representation of the past hydrology. The details of how routing, evaporation and precipitation at reservoirs and consumptive demands as accounted for in the model are explained in Chapter 2 of this document.

Reservoir operations used in the ACF-STELLA model mimic those of the Revised Interim Operating Plan (RIOP), the current reservoir system operating approach used by the USACE to manage the watershed (USACE, 2012; USFWS, 2012). As noted above, the ACF-STELLA model's representation of the RIOP has been shown to be well calibrated with the HEC ResSim model's representation of them (Leitman and Kiker, 2015) and therefore can be used reliably for an analysis such as this. The RIOP was first adopted for use in managing the ACF basin's reservoir system in 2007 to provide minimum flows for endangered species until several ongoing lawsuits were settled. It has been revised several times since it was first adopted (USFWS, 2006, 2008, 2012). The Corps of Engineers released a Draft Environmental Impact Statement for a revised Water Control Manual for the ACF basin in 2015 (USACE, 2015), and since the selected alternative closely resembles current RIOP and the timeline for completing this process is unknown at this time, the current version of the RIOP is used for this analysis. Releases under the RIOP are in general defined by (1) time of the year, (2) composite volume of water in the three major storage reservoirs (Lanier, West Point, W.F. George), and (3) the seven-day local inflow to the basin above Seminole/JWLD. Under the RIOP, reservoir storage is defined by the composite storage of the three primary reservoirs. The conservation pool of the three major storage reservoirs (Lanier, West Point, and W.F. George) is divided up into action zones (USACE, 1989; USFWS, 2012). Through use of these action zones at the individual reservoirs water managers are able to vary hydropower generation and balance water in the conservation pool of each reservoir, whereas through the composite storage water managers are able to vary the reservoir system's support for downstream flow needs.

For the purpose of this analysis only agricultural demands in the lower Flint basin (i.e. Albany to Newton reach, Newton to Bainbridge reach and Bainbridge to Jim Woodruff Dam reach in Figure 4.1) were changed by multiplying the effects of agricultural demands on streamflow by literature and expert-based factors described in further detail below. Table 4.1 summarizes the 2012 total, daily net demand for agriculture (AG) and municipal and industrial (M&I) consumers for the ACF basin above Jim Woodruff Dam. The information was provided by the three state agencies (Georgia Environmental Protection Division, Alabama Office of Water Resources, and Florida Northwest Florida Water Management District) (Hathorn, 2015)). The M&I demand in Table 4.1 are net demands (consumption minus returns) and the AG demands represent the effects of withdrawals on stream flow, not the volume of irrigation water applied to fields. A large majority of the irrigated area in the ACF basin above Jim Woodruff Dam resides in Georgia and about 77% of this total acreage in Georgia occurs in the Flint basin, 21% in the Spring Creek basin with only 2% in the Chattahoochee basin (Hook *et al*., 2010). Additionally, Table 4.1 shows the temporal nature of the irrigation demand following the primary irrigation season (April through September). To put these net demands into context, Table 4.2 shows the average and minimum monthly flow (1923-2014) for the Apalachicola River at Chattahoochee, Florida (a gauge site within one mile of where Jim Woodruff Dam was constructed). Table 4.2 shows that under average conditions the combined AG + M&I demand are relatively low when compared to average flows. Under minimal flow levels, these combined demands have more potential impact as demand levels can exceed 33% of total flows in the summer months. Thus, in years of water scarcity, decreasing the AG portion of the combined demand (especially in the Flint River Basin) may have potential system benefits. For modeling, specific reach dynamics in ACF-STELLA, the total values found in Table 4.1 are disaggregated into input parameters for the sub-reaches of the Chattahoochee and Flint Rivers (see Figure 1 for the reach and node configuration). Consequently, for each day of a specific month, the AG and M&I values are subtracted from local inflows on a reach-by-reach basis.

Table 4.1: 2012 monthly average agricultural and municipal and industrial demands effect on streamflow (m^3/s). Data in table developed by the Corps of Engineers from water use data supplied to them by the three States and represent the highest consumptive use experienced in the ACF basin to date (USACE, 2015).

	Chattahoochee basin			Flint basin		
	AG	M&I	TOTAL	AG	M&I	TOTAL
JAN	0.11	7.87	7.98	0.04	1.23	1.27
FEB	0.11	9.46	9.57	1.16	1.26	2.42
MAR	0.22	12.91	13.13	4.89	2.08	6.97
APR	0.56	16.31	16.87	10.75	3.33	14.08
MAY	1.12	23.98	25.1	29.59	4.61	34.2
JUN	1.80	25.37	27.17	39.58	5.14	44.72
JUL	2.02	23.31	25.33	44.73	6.23	50.96
AUG	2.36	28.47	30.83	48.06	6.24	54.3
SEP	1.24	24.09	25.33	35.01	5.22	40.23
OCT	0.11	15.71	15.82	13.32	3.04	16.36
NOV	0.11	14.65	14.76	10.30	2.84	13.14
DEC	0.22	12.94	13.16	8.85	2.52	11.37
ANNUAL AVE	0.83	17.92	18.75	20.52	3.65	24.17

Source: U.S Army Corps of Engineers, Mobile District, HEC ResSim data base

Table 4.2: Observed average and minimum monthly flow for the Apalachicola River at Chattahoochee, Florida (1923 – 2014) (m^3/s)

	AVG FLOW	MIN FLOW	TOTAL DEMANDS
JAN	775	206	6.42
FEB	918	295	7.87
MAR	1,101	362	13.54
APR	944	269	21.06
MAY	599	151	44.01
JUN	458	135	46.51
JUL	474	145	52.9
AUG	420	134	50.21
SEP	347	146	36.68
OCT	339	145	20.7
NOV	369	141	16.92
DEC	563	147	14.63

Source: US Geological Survey, 2014 and U.S Army Corps of Engineers, Mobile District, HEC ResSim data base

Potential water savings from implementing conservation practices (SBR, VRI, low pressure drop nozzle retrofits, high residue cover cropping, advanced irrigation scheduling) were simulated in the ACF-STELLA model by changing the agricultural demands (AG) on stream flow in the Flint River basin and lower Chattahoochee basin by factors informed by research results in the basin. These reductions reflect findings that SBR may reduce the need for irrigation by 50% to 75% on peanut and cotton as well as other crops adaptable to the system during drought events (Dourte *et al.*, 2015), low pressure drop nozzle retrofits can reduce irrigation water use on pivot or similar systems by up to 22.5%, VRI by an average of 15%, advanced irrigation scheduling by up to 15% and conservation tillage by up to 15% (Perry and Yager, 2011). After consultation with agricultural irrigation experts researching water saving conservation practices in the ACF basin, a set of scenarios was designed to modify the agricultural effects on streamflow to vary from moderate increases in agricultural production and area to significant reductions in irrigation water demand. The irrigation scenarios simulated by the ACF- STELLA model were the following: 1) Increased Demands: a 25% increase to net agriculture 2012 demands (Table 4.1) due to expansion of traditional irrigation practices and production areas, 2) Current Demands: 2012 agricultural effects on streamflow (Leitman and Kiker, 2015), 3) Moderate Decrease in 2012 demand: a 25% decrease to Table 4.1 AG values stemming from widespread adoption of SBR,VRI and related water savings technologies (Perry and Yager, 2011; Wright *et al.*, 2012; Dourte *et al*., 2015), 4*)* Large Decrease in 2012 demands: A 50% decrease to Table 4.1 AG demands effects on stream flow stemming from an even larger scale adoption of the water saving conservation practices, and 5) Rain-fed: a 100% decrease (or removal) of Table 4.1 AG demands only. In order to test the water system response to irrigation demand only, changes to agricultural withdrawals were the only parameter modifications in the ACF-STELLA model simulations. Although the selection of single-years agricultural water usage and the translation of agricultural water use data into effects on streamflow introduce uncertainty into the analysis, because this analysis is done at system-wide scale and is focused on the relative effects of different scenarios this uncertainty should not have any serious influence on the conclusions from this analysis.

Thus, for each irrigation scenario, the ACF-STELLA model was simulated for seventy-three years (1939 – 2011). Additional inter-year analysis will focus on two recent drought years (2007 and 2008) to explore temporal differences in water system response. Daily outputs for the 73-year model run period were analyzed for:

- Jim Woodruff Dam/Lake Seminole outflow (m^3/s);
- Flow for the Flint River at Bainbridge, Georgia (m^3/s); and,
- Reservoir elevations (m) for Buford Dam/Lake Lanier, West Point Lake and W.F. George Dam.

The daily Jim Woodruff Dam/Lake Seminole outflow was selected as an output site because it is the point where the Flint and Chattahoochee rivers converge and therefore aggregates all of the effects in both the Chattahoochee and Flint basins. The Flint River at Bainbridge, Georgia was selected as an output site because it is the stream gauge which is the furthest downstream in the Flint basin and therefore combines all of the irrigation changes in the Flint basin (77% of all irrigated acreage). Reservoir elevations for Buford Dam/Lake Lanier Lake Lanier, West Point Lake and WF George Dam were selected as output sites because these three reservoirs combined, account for over 95% of the conservation storage in the basin. These reservoirs are operated to supplement flow needs when minimum flow requirements in the RIOP for the Apalachicola River cannot be met by local inflow from rainfall.

The relevance of flow changes under different irrigation consumption scenarios is not necessarily that the volume of flow is changing, but on how these the changes effect the relationship between flow and the riverine ecosystem and human use changes. Three specific areas are considered with regard to ecosystem flows: 1) effects of flow changes on the Apalachicola River's floodplain inundation, 2) effects of flow changes on gulf Sturgeon (*Acipenser oxyrinchus desotoi*), a species listed as Threatened under the Endangered Species Act (ESA), and 3) effects of flow changes on several species of mussels listed under the ESA as either Endangered or Threatened under the ESA.

Since this analysis only focuses on changing one parameter, agricultural consumption in the Flint River basin, and Table 4.2 shows that the total consumptive withdrawals in the ACF basin are relatively small when compared with average flow in the Apalachicola River, then changing irrigation demands can only significantly impact relationships that occur at lower flows. To evaluate the potential effects of altering agricultural demands on the duration of higher salinity conditions that are suspected to inhibit access by juvenile Gulf sturgeon (Ages 1-5) to foraging habitat in the estuary, the maximum number of consecutive days between November 1 to March 15 (per annual cycle) when discharge at Chattahoochee, FL was ≤16,200 cfs is evaluated. Therefore, in the following section of this paper the effects of altering agricultural irrigation demands on flows < 16,000 cfs from January 1 to March 15 will be analyzed. As noted earlier, floodplain inundation occurs at a range of flows which would not be affected by changing irrigation withdrawals alone and therefore will not be evaluated in the following section.

Three species of mussels found in the Apalachicola River are federally listed under the ESA, one Endangered and two threatened. Options that reduce the occurrence and fall rates of low flow events are considered to be relatively better than options which maintain or increase the occurrence and fall rates of low flow events (USFWS 2013b). Furthermore, management actions that effect the access of fish critical to the mussel's reproductive cycle or which effect the mussel's interactions with host fish could also affect mussel populations. Consequently, increasing low flows in the Apalachicola River from reducing agricultural irrigation demands has the potential to have a positive effect on mussels in the river. The metric to be considered with regard to this analysis will be the presence of stable low flows during host infection. This metric considers both the ability of host fish to be infected as well as the ability of juvenile mussels to drop in appropriate locations to increase the likelihood of their survival. For this metric, the more days which flow is below the 7,500 cfs standard, the better it is for mussel host infection and the likelihood for juvenile mussels to drop in an appropriate location (USFWS, 2016).

4.3 RESULTS AND DISCUSSION

The objective of this research was to provide insight into the potential system-wide effects of reducing agricultural irrigation demands in the ACF basin. Through review of existing irrigation research in the basin and working with experts on water saving irrigation practices, we have defined plausible scenarios of future irrigation water use for simulation in the ACF-STELLA model to explore the impacts on stream flow and reservoir elevations. Figures 4.2 and 4.3 show the effects of different irrigation scenarios on Flint River flows at Bainbridge, GA and for the Apalachicola River at Jim Woodruff dam outflow (respectively) for the consecutive drought years of 2007 and 2008. In reviewing the results for flow changes for the Flint River at Bainbridge (Figure 4.2), the difference in flow between the increased demand scenario (X 1.25) and having the rain-fed scenario (X 0.0) is between 15 and 25 m^3/s in the peak part of the irrigation season. To put this difference into context, this difference between the two scenarios is of a magnitude that is over 50% of the river flow at the Bainbridge gauge on some days during the 2007 – 2008 drought. As expected, in months outside the growing season when irrigation demands are low, there was little difference in Bainbridge flows among irrigation scenarios. During the primary growing season, such as May, June and July, when irrigation withdrawals were greater, there was a large difference among irrigation scenarios. In comparing the effects on streamflow it needs to be understood that because the majority of the irrigation withdrawals are from groundwater sources and because of the lag-time between when irrigation water is withdrawn and when the withdrawals affect streamflow, the model results comparing the effects of different scenarios will not be synchronized with the initiation of irrigation events. The average difference in flow at the Bainbridge gauge from April 1, 2008 to August 31, 2008 between the Increased Demand and the Rain-fed scenarios was about 17.6 m^3/s. This average difference between these extreme scenarios represents about 16.8% of the average flow at the Bainbridge gauge for this time period in 2008. When comparing the Current Demands and Moderate Decrease scenarios, the average difference for the gauge was 3.5 m^3/s, or only about 2.3% of the average annual flow at the Bainbridge gauge for 2008.

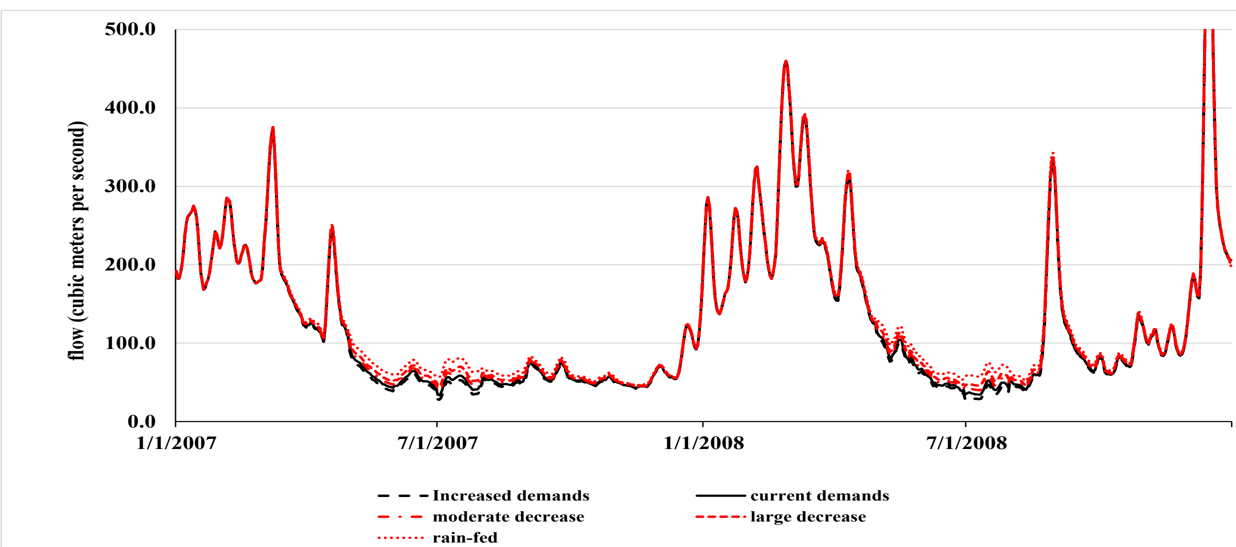


Figure 4.2: Modeled flow (cubic meters per second) for the Flint River at Bainbridge, Georgia for 2007 – 2008 with varying scenarios of agricultural irrigation abstraction: 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).

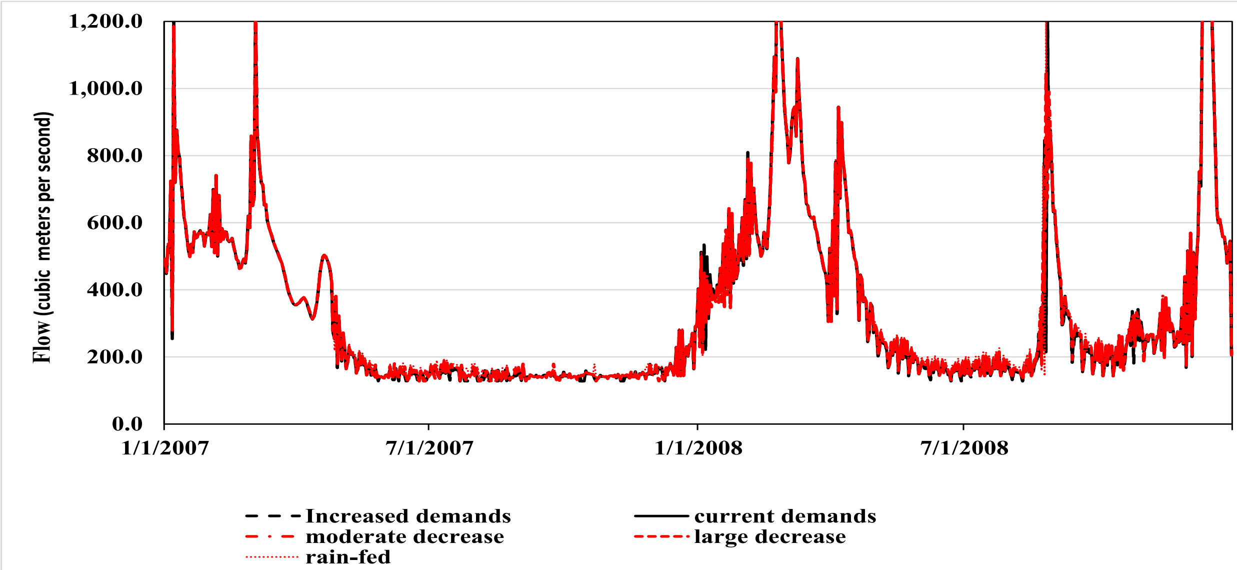


Figure 4.3: Modeled flow for the Jim Woodruff outflow to the Apalachicola River for 2007 - 2008 (cubic meters per second: 1) Increased Demands (X1.25), 2) Current Demands (x1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).

Table 4.3 shows the distribution of the effects of increasing and decreasing irrigation on Jim Woodruff Dam outflow and reservoir elevations relative to changes from the Current Demands scenario for the period of record and for two drought years, 2007 and 2008. From this table it is observed that: 1) when the entire period of record is examined, a greater percentage of the change in irrigation withdrawal's effects on streamflow occurs to flow in the Apalachicola River relative to reservoir elevations for all scenarios, and 2) for the Moderate Decrease and Large Decrease scenarios relatively more of the water savings go into the increased elevations in reservoirs than for the Increased Demand and Rain-fed scenarios. When two recent drought years (2007 and 2008) are examined, the distribution of the effects of irrigation scenarios are quite different. In 2007, a greater percentage of the water savings influence upstream reservoir elevations rather than increasing downstream Apalachicola River flows in the Increased Demands, Moderate Decrease and Large Decrease scenarios. For 2008, a greater percentage of the flow changes occur in the Apalachicola River for the Increased Demand, Large Decrease and Rain-fed scenarios than to the reservoirs and a greater percentage occurs in changes in reservoir volume for the Moderate Decrease scenario. When compared with the entire period of evaluation results, more water went to reservoir storage for the Increased Demand, Moderate Decrease and Large Decrease scenarios. To put the 2007 and 2008 droughts into context with more average flows from the Jim Woodruff Dam (593 m^3/s), the average annual outflow in 2007 was about 279 m^3/s and in 2008 was about 403 m^3/s. From these data, it appears that the more severe the drought event, the greater the relative share of water-savings from reduced irrigation withdrawals goes to reservoir storage rather than to supplementing flows in the Apalachicola River.

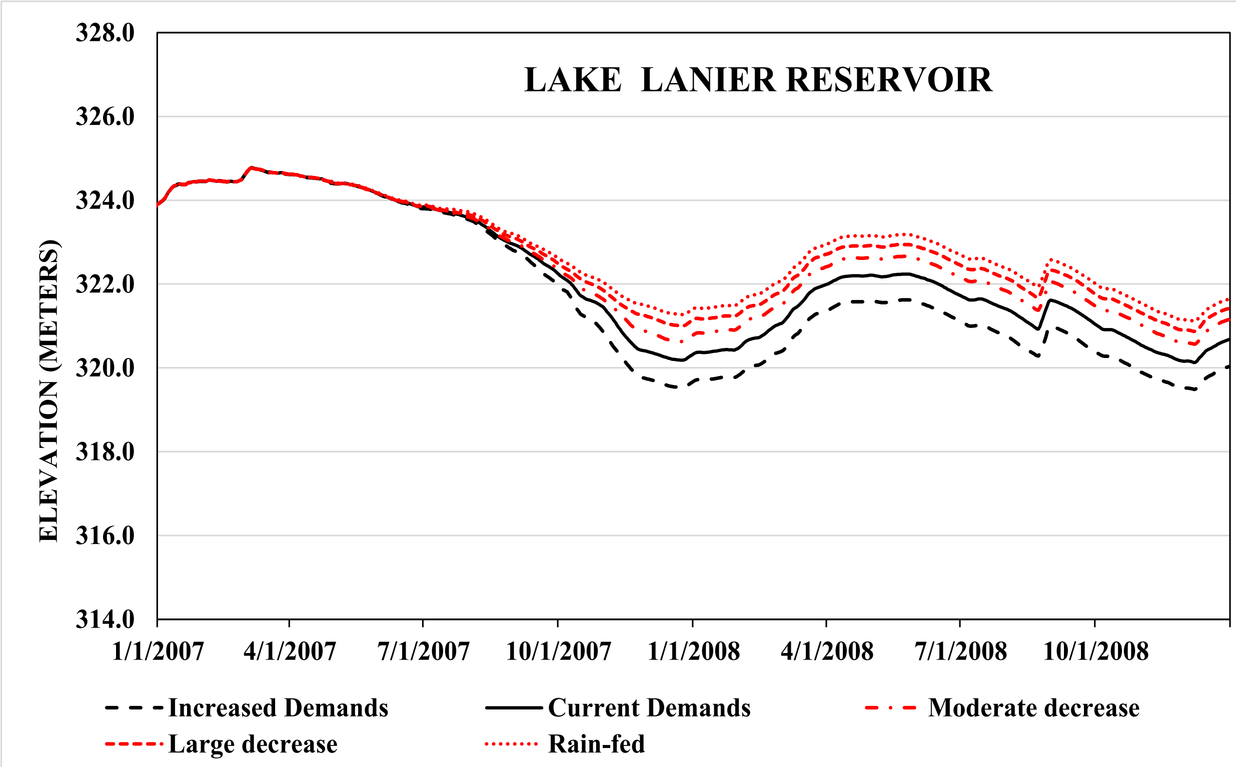
Table 4.3: Distribution of the effects from changes to irrigation withdrawals on streamflow and reservoir elevation for the period of record and for 2007 and 2008

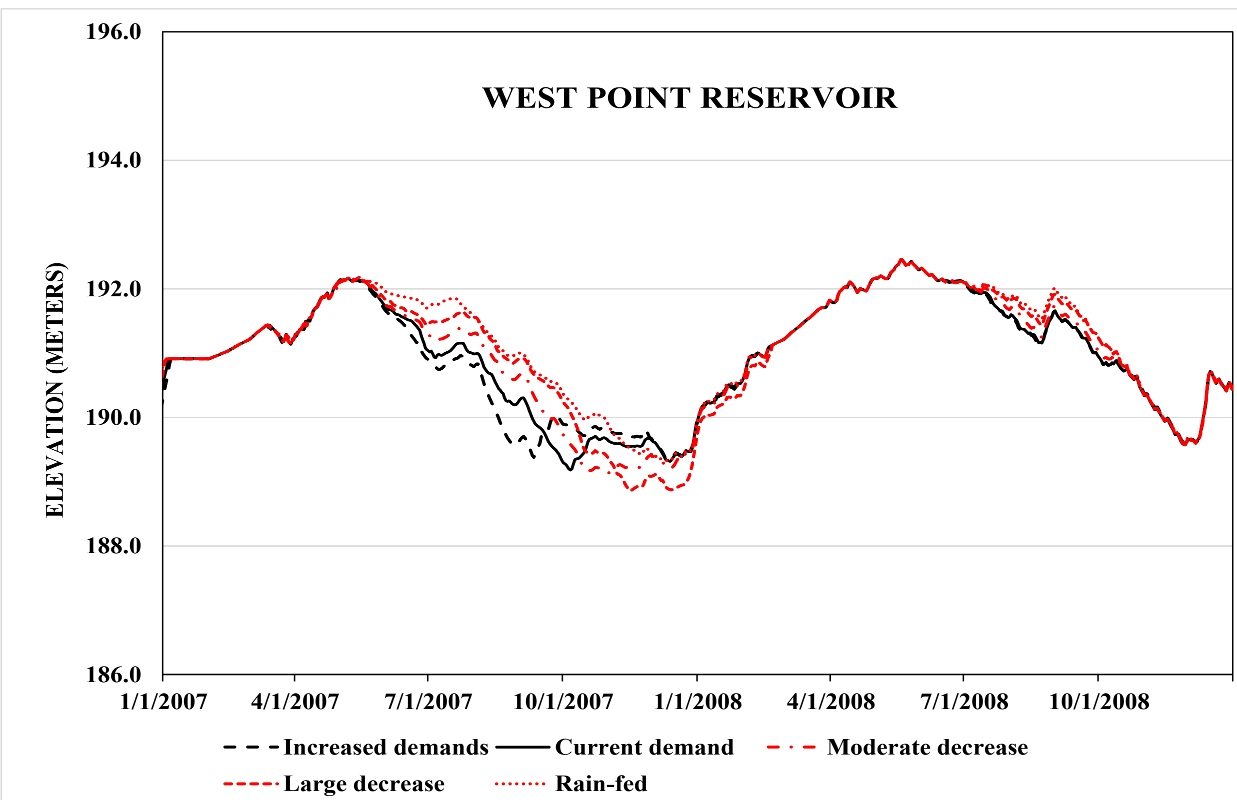
	Period of record		2007		2008	
	JW outflow	Reservoirs	JW outflow	Reservoirs	JW outflow	Reservoirs
Increase	90.4%	9.6%	36.8%	63.2%	67.4%	32.6%
Mod. decrease	63.2%	36.8%	27.5%	72.5%	44.1%	55.9%
Larger decrease	74.1%	25.9%	40.4%	59.6%	64.5%	35.5%
No irrigation	90.9%	9.1%	59.3%	40.7%	95.4%	4.6%

Output from the ACF-STELLA model for the reservoir elevations at Lake Lanier, West Point Lake and W.F. George Lake (Figure 4.4) reveal that for 2007 and 2008 the large majority of the changes in elevation and storage volume occurred at Lake Lanier. Under the different irrigation scenarios, elevations at Lake Lanier begin to diverge in the spring of 2007 and continued to show differences through the end of 2008. As the drought proceeded, the difference in elevations at Lake Lanier with the Rain-fed scenario and with the Increased Demand scenario was between 1.5 and 1.75 meters for the entire year of 2008. The difference between the large decrease scenario and the current demands scenario was 0.7 to 0.8 meters. In comparison, the changes at West Point are less pronounced and greatest in 2007, not 2008. At West Point, differences between the Rain-fed and Increased Demands scenarios differ as much as 1.3 meters for a short period of time, but are no greater than 0.5 meters in 2008. At W.F. George, the difference Rain-fed and Increased Demand scenarios is no greater than 0.2 meters in either 2007 or 2008.

In summary, the results showed that decreasing the volume of irrigation withdrawal can have non-intuitive effects on the ACF basin as a result of the rules for management of the storage reservoirs. Demand savings incurred upstream do not always directly translate to elevated flows downstream. Lake Seminole, the reservoir impounded by the Jim Woodruff Dam, has a small storage pool and virtually no storage during extreme low flow periods because of head limit issues. When large release demands are placed on this reservoir, especially during prolonged periods of low flow, there is often a requirement for supplemental releases from upstream reservoirs to meet minimum release requirements from Jim Woodruff Dam.

In situations where the local inflow from the Chattahoochee and Flint basins fall below the required minimum flow release called for by the RIOP, water releases from the Federal reservoirs in the Chattahoochee basin are made to support the required minimum flow release. This results in a zero-sum game where any increases (or decreases) in irrigation demands in the Flint basin translate into changes in the release necessary from the upstream storage reservoirs to support the release requirement. In wetter years, such as 2006, historical flow data shows that there were no occurrences where local inflow from the Flint and Chattahoochee river basins were not adequate to meet the 141.5 m^3/s minimum flow requirement. However, in drought years such as 2007 and 2008, this situation occurred more than 130 days in a single year. Consequently, in years when there is a lesser need for augmentation from the federal storage reservoirs nearly all of the water savings from decreasing irrigation demands would translate into increased flow in the Apalachicola River. But in years when there is a large need for augmentation support from the federal storage reservoirs, such as in drought years, a considerable percentage of the water savings from decreased irrigation results in higher elevations at the federal storage reservoirs. If the differences in reservoir elevations under the various irrigation scenarios found in Figure 4.4 are compared for a wetter period (2005-2006) (Figure 4.5), the differences in reservoir elevations no longer occur.


LAKE LANIER RESERVOIR
ELEVATION (METERS)
328.0
326.0
324.0
322.0
320.0
318.0
316.0
314.0
1/1/2007
4/1/2007
7/1/2007
10/1/2007
1/1/2008
4/1/2008
7/1/2008
10/1/2008
Increased Demands
Current Demands
Moderate decrease
Large decrease
Rain-fed


WEST POINT RESERVOIR
ELEVATION (METERS)
196.0
194.0
192.0
190.0
188.0
186.0
1/1/2007
4/1/2007
7/1/2007
10/1/2007
1/1/2008
4/1/2008
7/1/2008
10/1/2008
Increased demands
Current demand
Moderate decrease
Large decrease
Rain-fed

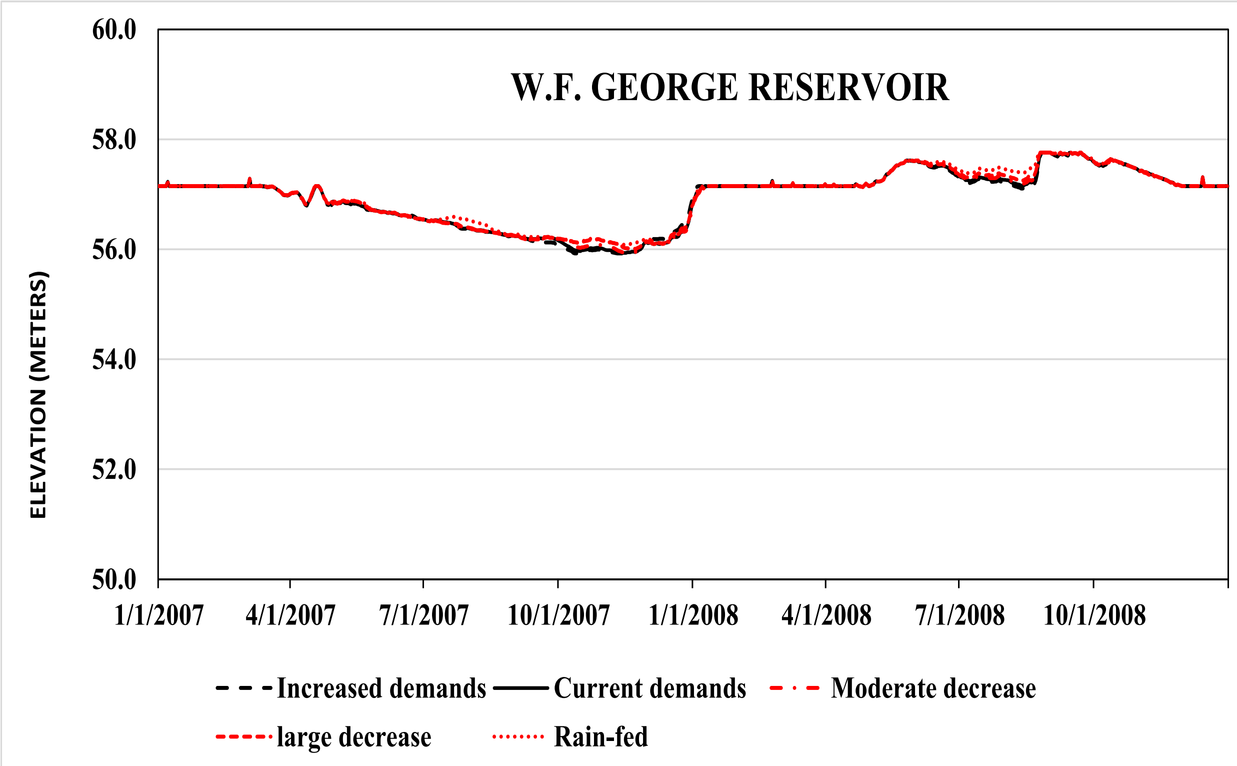
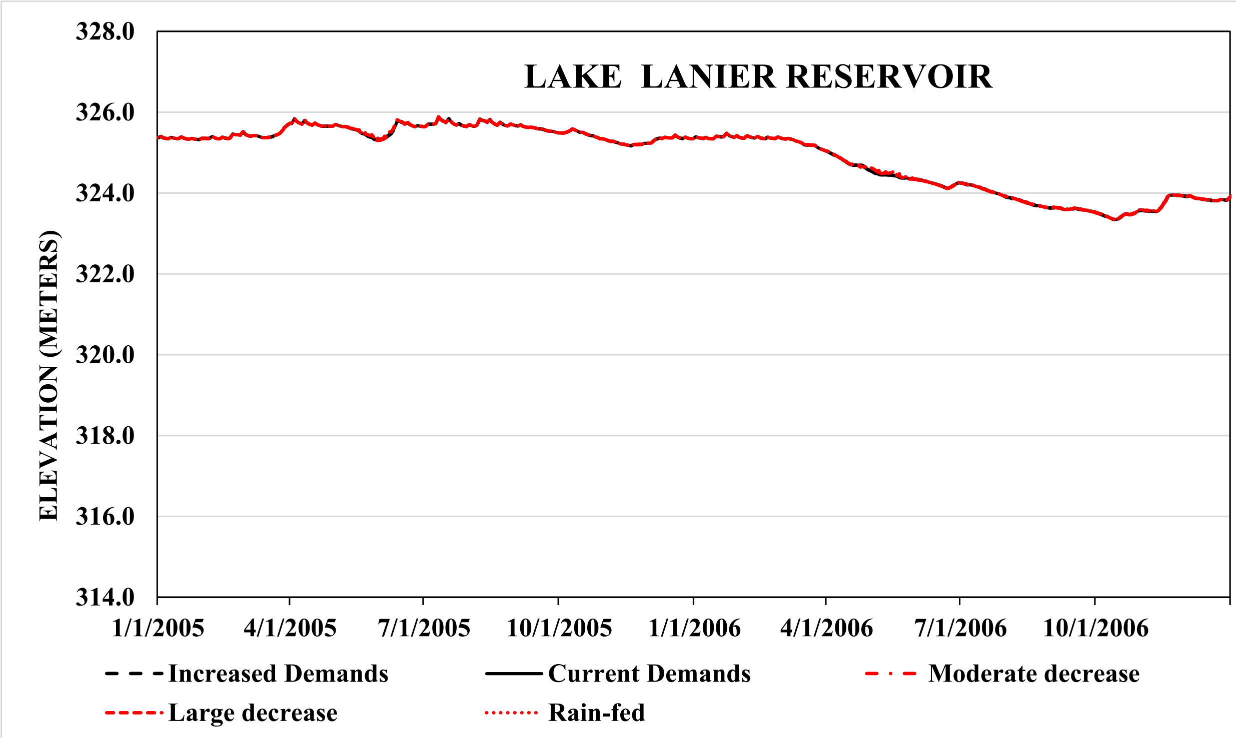
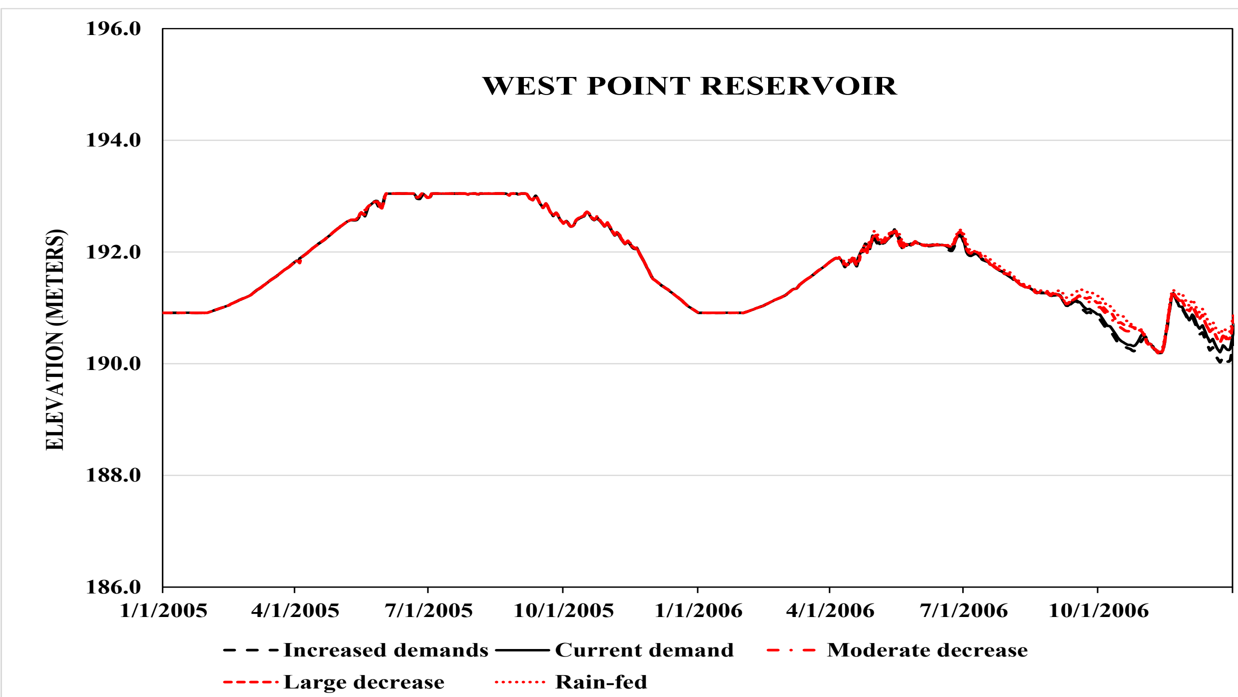


Figure 4.4: Modeled elevations at Lake Lanier, West Point and W.F. George reservoirs for 2007 and 2008 with varying levels of agricultural irrigation (meters: 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).


LAKE LANIER RESERVOIR
ELEVATION (METERS)
328.0
326.0
324.0
322.0
320.0
318.0
316.0
314.0
1/1/2005
4/1/2005
7/1/2005
10/1/2005
1/1/2006
4/1/2006
7/1/2006
10/1/2006
Increased Demands
Current Demands
Moderate decrease
Large decrease
Rain-fed


WEST POINT RESERVOIR
ELEVATION (METERS)
196.0
194.0
192.0
190.0
188.0
186.0
1/1/2005
4/1/2005
7/1/2005
10/1/2005
1/1/2006
4/1/2006
7/1/2006
10/1/2006
Increased demands
Current demand
Moderate decrease
Large decrease
Rain-fed

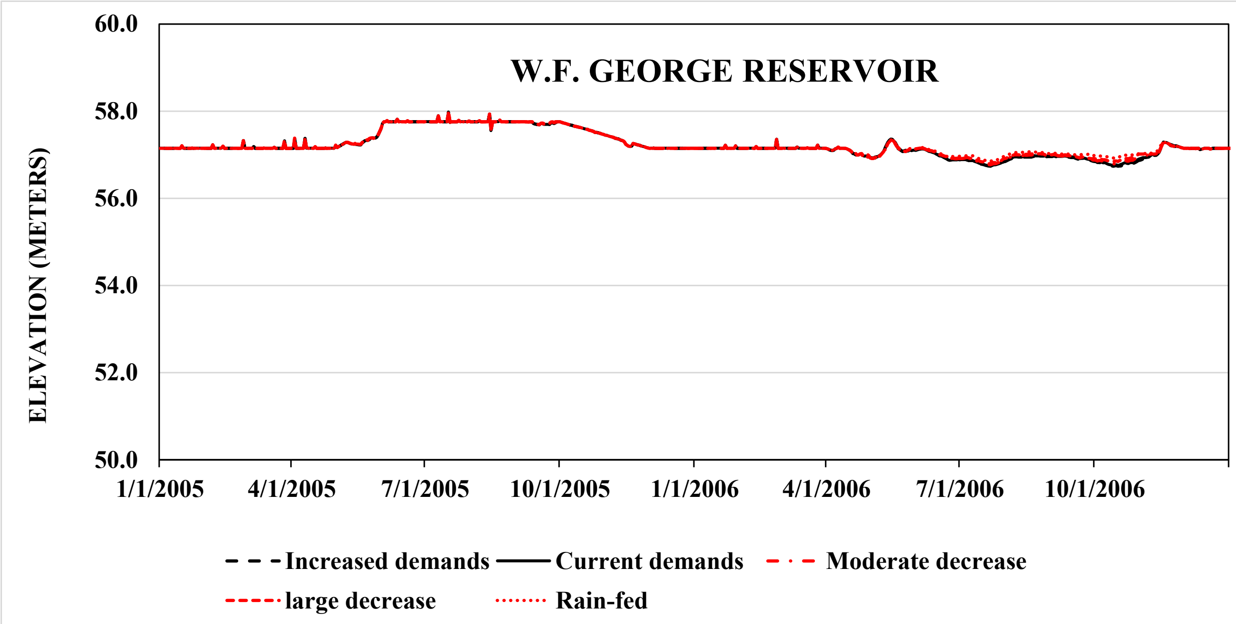


Figure 4.5: Modeled elevations at Lake Lanier, West Point and W.F. George reservoirs for 2005 and 2006 with varying levels of agricultural irrigation (meters): 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).

In reviewing the apportioning of the effects from changing the irrigation withdrawals on Jim Woodruff outflow and reservoir elevations (Table 4.3), considerable variation was found both in time period evaluated (i.e. period-of-record versus individual years) as well as with the extent of changes to irrigation scenarios (i.e. increased irrigation versus status quo versus rain-fed). When the relative changes in Jim Woodruff outflow and reservoir elevation are examined for the entire seventy-year period of record, it was found that the greatest changes in Jim Woodruff outflow occurred when irrigation demands were either increased or reduced to zero (rain-fed). When two individual low-flow years were examined (2007 and 2008) considerable variation was found between the two years. These complex responses reflect that differences in allocation support needed to meet the requirements of the RIOP. When irrigation demands are reduced a moderate amount (e.g. 25%) this results in the greatest relative contribution to reservoir elevation both for the period-of-record data and for the two drought years examined. In summary, these simulation results suggest that at present levels of withdrawal there is a delicate balance between the volume of these withdrawals and the storage capacity of the basin’s reservoirs. In light of the potential changes in the basin's hydrology suggested by both historical climate variability and the potential for climate change, more research into this relationship is certainly warranted.

As noted above, since consumptive demands are small relative to flows which affect floodplain inundation, the effects of altering irrigation demands were expected to have minimal effects on the volume of floodplain inundation. This is verified by Figure 4.6. As also noted earlier, discharge in the range of 16,200 cfs for the Apalachicola River at Chattahoochee has been associated with lower benthic salinity conditions (i.e., ≤10 ppt.) at the long-term monitoring station at East Bay. Sustained low flow conditions during this period would result in a reduction in low salinity foraging habitat, and therefore lower maximum consecutive days are associated with benefits to Gulf sturgeon (USFWS, 2016). Figure 4.7 shows the maximum number of consecutive days during the period from November 1 to March 15 for the years 1939 – 2008 under the various agricultural consumption scenarios for which flow for the Apalachicola River at Chattahoochee was less than 458.5 m^3/s. From this chart, it is evident that altering agricultural demands will have minimal impacts on Gulf sturgeon foraging.

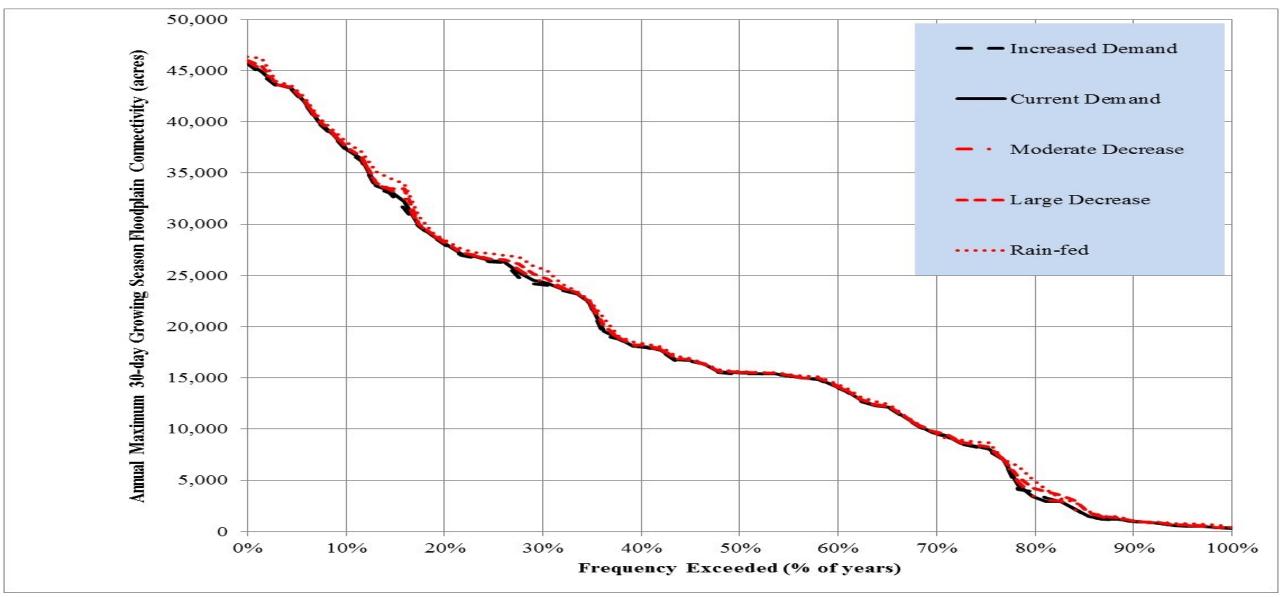


Figure 4.6: Simulated annual maximum 30-day growing season floodplain connectivity (hectares) in the Apalachicola River from varying levels of agricultural irrigation: 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).

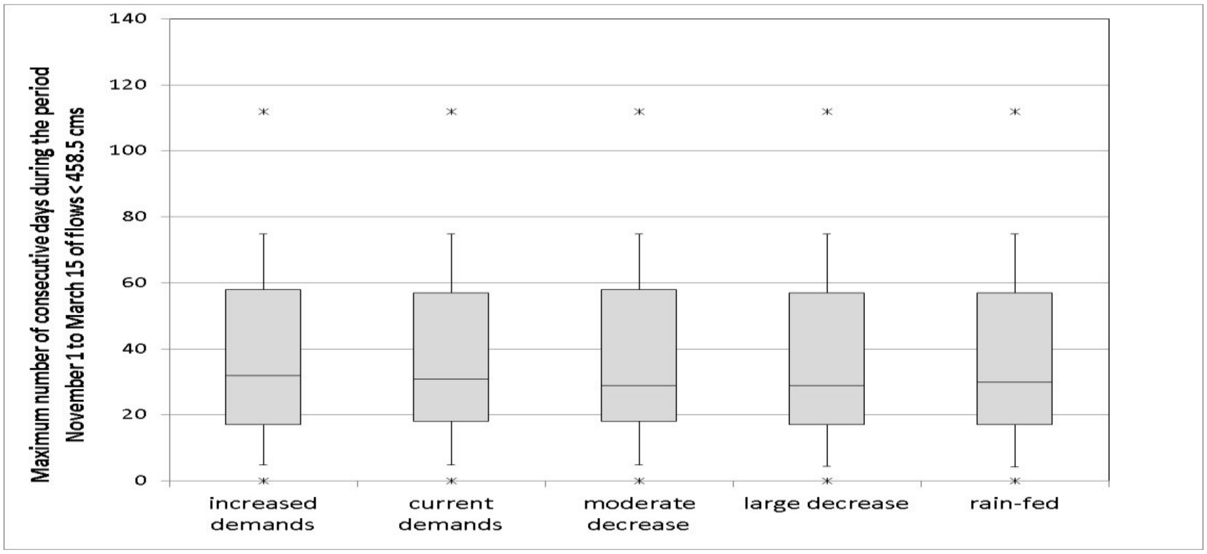


Figure 4.7: Maximum number of consecutive days during the period of November 1 to March 15 for which flows for the Apalachicola River at Chattahoochee were less than 458.5 m^3/s from varying levels of agricultural irrigation: 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X 0.0).

Figure 4.8 compares the modeling results for the presence of stable low flows during host infection for mussels under the various agricultural irrigation scenarios. This figure shows that increasing agricultural irrigation demands actually has a more beneficial effect on the ability for host fish to be infected and on the ability for juvenile mussels to drop in appropriate locations for their survival. This result is because of an earlier understanding of mussel survival was based on a paradigm of the greater the flow, the better the situation for mussel survival. Recent research, however, has shown this paradigm to not necessarily be correct all of the time (USFWS, 2016). The management approach used in the modeling of agricultural irrigation scenarios was based on the earlier paradigm and these results highlight the fact that to protect the ecosystem both supply and demand management need to be addressed.

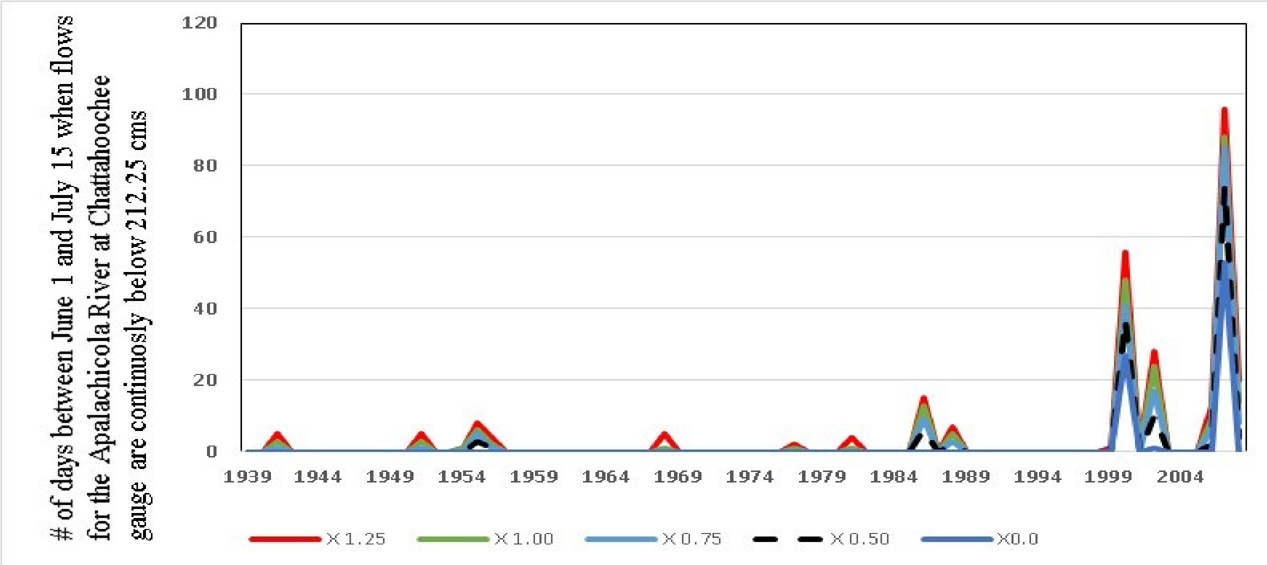


Figure 4.8: Number of days between June 1 and July 15 when flows for the Apalachicola River at Chattahoochee are continuously fellow 212.25 m^3/s from varying levels of agricultural irrigation: 1) Increased Demands (X1.25), 2) Current Demands (X1.00), 3) Moderate decrease in demands (X0.75), 4) Large decrease in demands (X0.50), and 5) Rain-fed (X0.0).

4.4 Conclusions

The results of this study show that adopting alternative agricultural practices that reduce irrigation water demands could have substantial effects in the ACF basin. Demand savings incurred upstream, however, do not always directly translate to elevated flows downstream. The differences in irrigation withdrawals' effects on streamflow manifest in both greater stream flow downstream of the agricultural irrigation (e.g. lower Flint River and the Apalachicola River) and in increased elevations at the upstream Federal storage reservoirs in the Chattahoochee basin. In years when there is a lesser need for augmentation from the federal storage reservoirs to meet minimum flow requirements from Jim Woodruff Dam, nearly all of the water savings from decreasing irrigation demands would translate into increased flow in the Apalachicola River. During drought years, under current reservoir operating rules (RIOP), it was determined that significant decreases in agricultural irrigation withdrawals had two primary results: 1) some of the supplemental releases are no longer necessary from the upstream storage reservoirs in the Chattahoochee basin which translate into higher reservoir elevations, especially at Lake Lanier and 2) a portion of the increased flows from the Flint basin reach would result in increased flows in the Apalachicola River.

The relevance of flow changes under different irrigation consumption scenarios is not necessarily that the volume of flow is changing, but on how these the changes affect the relationship between flow and the riverine ecosystem and human use changes. Since this analysis only focuses on changing one parameter, agricultural consumption in the Flint River basin, and total consumptive withdrawals in the ACF basin are relatively small when compared with average flow in the Apalachicola River, then changing irrigation demands can only significantly impact relationships that occur at lower flows and a time of the year when irrigation demands are greatest. With regard to ecological services, the relationship between flow and the ecosystem is complex and occurs at a range of flows and can be important at times of the year when irrigation demands are not large. This study suggests that to effectively develop a sustainable relationship between a river and its associated ecosystem requires both supply and demand management. It was found that under current reservoir operations increasing agricultural irrigation demands actually has a more beneficial effect on the ability for host fish to be infected and on juvenile mussels to drop in appropriate locations for their survival. This result is because reservoir management was based on an earlier paradigm regarding mussel survival and recent research, however, has shown this paradigm to not necessarily be correct all of the time.

Based on ongoing research on agricultural irrigation practices in the ACF basin at both the NFREC and the Stripling Irrigation Park, it seems plausible that irrigation demands could be decreased substantially in the future if alternative practices are implemented at a large scale. This research also suggests that a public policy decision needs to be made with regard to what portion of the water savings from changing irrigation practices should be allocated to the Federal storage reservoirs and what portion should be allocated to supporting down stream flow needs.

CHAPTER 5: AN EXAMINATION OF CAUSAL FACTORS FOR THE LOWERING OF A MAJOR RESERVOIR DURING MULTIPLE DROUGHT EVENTS

In this Chapter, the ACF-STELLA model is used to address another critical management in the ACF watershed, the rapid lowering of the largest storage reservoir in the basin during drought events. This rapid lowering has been one of the major triggers behind the interstate disputes and management decisions in the watershed. The model is used to evaluate the relative contribution of various causal effects during different drought events.

5.1 Introduction

A reservoir is a body of water where the stored water is used by man for multiple purposes and can be managed to reduce flood events and augment downstream flow needs by retaining or releasing waters. Additionally, reservoir waters are used to produce hydropower, provide a more secure water supply for municipal, industrial and thermal users, provide recreational opportunities in their storage pool and can be managed to benefit the natural ecosystem (USACE, 2015). Reservoirs can have a storage pool where the water in storage can be managed or have no storage pool and be operated as a run-of-the-river facility where flow into the reservoir is about the same as flow out of the facility, depending upon the project purposes and storage capacity for a specific facility (USACE, 2015).

Examining reservoir management approaches to drought management will be handled in this Chapter by focusing on a specific watershed in the southeast United States, the Apalachicola-Chattahoochee-Flint (ACF) basin (Figure 5.1). Reservoir management in the Apalachicola-Chattahoochee-Flint (ACF) basin has been a source of controversy among federal water managers and the three states in which the basin lies for the past 30 years (Congressional Research Service, 2007; Leitman, Pine and Kiker, 2016) and the source of multiple law suits, including a recent Supreme Court case (see USACE, 2015 for a history of recent litigation). The watershed drains nearly 50 000 square kilometers in the States of Georgia, Florida and Alabama and extends from the Blue Ridge Mountains in Northern Georgia to the Gulf of Mexico at Apalachicola Bay, Florida (figure 5.1). There are 12 main-stem reservoirs in Chattahoochee portion of the basin, two in the Flint and one at the confluence of the Flint and Chattahoochee (see table 1.1, page 28). Because the majority of the ACF basin area and virtually all of the basin's reservoir storage capacity lie above the Florida border, flow in the Apalachicola River is mostly defined by rainfall, water extractions and water management actions outside of the State of Florida (Leitman, 2005).

FIGURE 5.1: The Apalachicola-Chattahoochee-Flint basin

Managing reservoirs tends to be the most challenging at the extremes: during floods and droughts. Drought can be defined in many different ways including meteorological, hydrological, agricultural, and socio-economic. In this Chapter the focus will be on drought from a water management perspective. To define drought from the water management perspective, I rely on the definition used by the managers of the reservoirs in the ACF basin: the USACE. The definition used by the USACE in their Drought Plan for the ACF basin defines drought in terms of its impact on water control regulation, reservoir levels and associated conservation storage (USACE, 2011a). The difference between normal operations and drought operations is that when drought operations are in effect, releases from the federal storage reservoirs only support the minimum release requirement from Jim Woodruff Dam (141.5 m^3/s) (USACE, 2015). In several recent droughts, this condition has persisted for 6 months leading to ecological problems in the Apalachicola estuary (Havens *et al*., 2013).

As a result, during several severe drought events over the past several decades, water users of the basin found themselves in competition for the water resources (Congressional Research Service, 2007; USACE, 2015). However, during periods of normal rainfall there are more than adequate water resources for all users (Leitman *et al*., 2016; USACE, 2015). There have been several severe multi-year droughts since the federal reservoir system's construction (i.e. 1980 – 1981, 1986 – 1988, 1999–2001, 2007–2008, and 2011–2012) (USACE, 2015). The drought event which occurred in 2011 and 2012 is the most extreme drought in the period of record in terms of flow in the Apalachicola River (Leitman *et al*., 2016; USFWS, 2016).

Given that Lake Lanier has about 2/3 of the basin's storage capacity while only impounding about 6% of the watershed; reservoir elevations at Lake Lanier can drop rapidly during drought events, yet be slow to recover after the drought event. When the role of this reservoir to Metro Atlanta's water supply and the economic importance of recreational activities and property values around the reservoir are taken into account, it is not surprising that the elevation of the conservation pool at Lake Lanier has the distinction of being one of the major sources of contention between downstream interests which desire more water during drought and upstream interests which desire access to the reservoir and a secure water supply (Congressional Research Service, 2007). As elevations at Lake Lanier continued to decline during the 2007 drought, the USACE responded to the declining elevations by decreasing releases to Florida from the ACF reservoir system (USFWS, 2008). Subsequently, this approach has been formalized into being an important part of the USACE's management approach (USFWS, 2016). Additionally, the USACE added a further measure into their management plan of the ACF reservoir system that once drought operations are instituted, normal operations are not resumed until the storage in the federal reservoirs is nearly refilled (USACE, 2015).

This Chapter will analyze the causal factors behind the rapid lowering of the elevation of Lake Lanier during multiple drought events and the efficacy of the USACE's approach to refilling the reservoir pool before ending drought operations. Drought, in essence, is a specific term for a variable concept (i.e., each drought is a unique event). In the ACF basin droughts can vary in many ways including: 1) the intensity and duration of the event, 2) whether the drought is severe in the Flint basin, in the Chattahoochee basin or in both basins, 3) whether the drought occurs in the upper, mid or lower basin or in some combination of these, and 4) in what season the year the drought initiates and ends. Consequently, it is my hypothesis that a one-size fits-all approach to drought management may not be the optimal approach to reservoir management in the ACF basin.

To test this hypothesis, this Chapter will first provide an overview of the current operational management plan for the ACF reservoirs. Next, the causal factors for the lowering of elevations at Lake Lanier during five separate drought events will be evaluated using an existing systems model of the ACF basin and then the causal factors will be parsed into those which could be managed by humans and those which are beyond our capacity to manage. Finally, the factors which caused the lowering during the distinct drought events will be compared and analyzed. At last, I will provide some guidance towards designing a better approach for managing reservoirs in the ACF basin in drought and hopefully making a contribution towards disentangling the ACF basin from its long-term legal quagmire.

5.2. Methods and materials

In this section of Chapter 5, an overview of the management of the federal reservoirs in the ACF basin, a discussion of analysis methods and a discussion of factors which cause the lowering of reservoir elevations at Lake Lanier during drought events are provided.

5.2.1 Federal Reservoir Management in the ACF Basin

The reservoir storage capacity in the ACF basin is managed by the USACE under the Revised Interim Operating Plan (RIOP) (see Table 2.1, page 29), although in 2015 the Corps proposed minor revisions to the RIOP under a revised Water Control Manual (WCM) (USACE, 2015). The RIOP was first adopted in 2007 as the Interim Operating Plan, an operating approach designed to provide minimum flows for endangered species until several ongoing lawsuits were settled (USFWS, 2016) and it has been revised several times since it was first adopted (USACE, 2015; USFWS, 2016). The alternatives in the DEIS for WCM essentially kept the same management logic used in the RIOP made minor revisions to the operational guidelines. Releases under the RIOP are defined by 1) time of the year, 2) composite volume of water in the three major storage reservoirs (Lake Lanier, WP and WFG) and 3) the seven-day local inflow into the basin above Jim Woodruff Dam.

In the ACF basin, the conservation pool of the three major storage reservoirs (Lanier, WP and WFG) is divided up into a set of action zones (USACE, 2015). Under the RIOP, reservoir storage is defined by the composite storage of the three major storage reservoirs and this action zone approach is extended into the composite storage management approach by simply summing the volume of water in the action zones for each individual reservoir (USACE, 2015). Through use of action zones, the USACE is able to vary the reservoir system's support for downstream flow needs based on the volume of water in storage. If the composite storage is in Action Zone 1, the system is managed to support downstream flow needs. But if the composite storage is in Action Zone 4, releases are defined to protect reservoir storage and provide minimum releases downstream. Action Zones 2 and 3 can be thought of as transitional operational requirements between those two states. An Emergency Drought Zone is also provided for to deal with persistent drought conditions that drain the conservation storage in the basin and the minimum release is subsequently reduced when Emergency Drought Operations are in effect.

5.2.2 Analysis Methods

At the foundation of this analysis is a system-wide water balance model of the ACF watershed (ACF-STELLA) developed at a daily time-step and rigorously tested against model results simulated by the primary river-basin management model in the watershed, HEC-ResSim (Leitman and Kiker, 2015). This analysis is based on modeled data rather than historical data so that multiple drought events could be evaluated with consumptive demands and reservoir operations consistent during all events examined. If historical data were used, both reservoir operations and the volume of consumptive demands would vary from drought event to drought event, introducing more uncertainty into the comparison of the causal factors. Using the model also allows for the ready disaggregation of all of the driving factors in defining releases from

Lake Lanier. The ACF STELLA model was run with the RIOP rules for operating the reservoir system and 2007 consumptive demands.

The period of analysis of the drought events extends from January 1, 1939 to December 31, 2008. Based on historically observed elevations at Lake Lanier (see Figure 5.2), four time periods were selected within this time frame to be used in this analysis. The first period extends from 1980 to 1984, the second from 1985 to 1988, the third from 1999 to 2003, and the last from 2007 - 2008. For purposes of analyzing the causal factors for the lowering of Lake Lanier during droughts, these four time periods were then reduced so that the analysis focused only on the period of time during which the elevations at Lake Lanier were rapidly declining, the focus of this paper. For purposes of this analysis, rapid decline was defined as a decline greater than 0.75 centimeters/day for at least 100 days. The specific dates for each of the five events where declining elevations at Lake Lanier will be analyzed are:

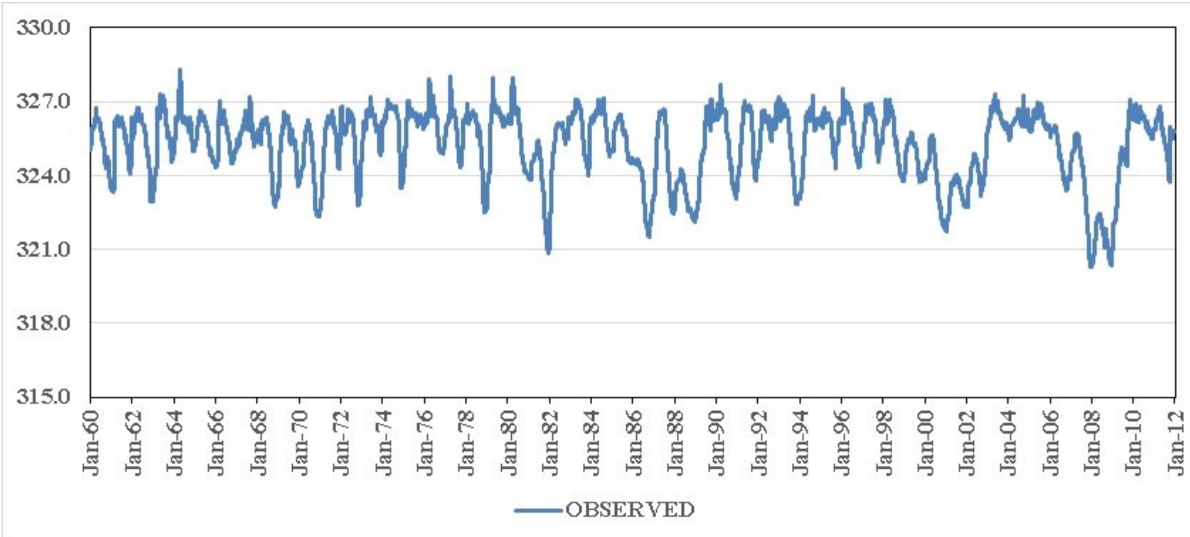
Declining Event #1: July 1, 1980 to December 18, 1981

Declining Event #2: August 29, 1985 to October 21, 1986

Declining Event #3: June 1, 1987 to December 27, 1988

Declining Event #4: May 8, 2000 to January 5, 2001

Declining Event #5: May 4, 2007 to December 6, 2007



SOURCE: USACE, 2017.

FIGURE 5.2: Historically observed reservoir elevations (m) at Lake Lanier for 1960 - 2012

In the balance of this paper when the term "period" is referring to the four extended time periods (four years for the first three and two years for the fourth) and the term "event" refers to the five time periods when the elevation was in decline. The length, extent of decline and rate of decline for each of these events is summarized in Table 5.1. The amount of time which Lake Lanier was in Zone 4 varies among these five events. During declining event #1 Lake Lanier was in Action Zone 4 about 1.1% of the time, during event #2 about 60.6% of the time, during event #3 about 35.2% of the time, during event #4 about 18.5% of the time and during event #5 about 76.3% of the time.

Table 5.1: Rate of decline, decline and duration of lowering events at Lake Lanier

	DURATION (days)	DECLINE (meters)	RATE OF DECLINE (meters/day)
EVENT 1	171	4.33	0.0253
EVENT 2	338	4.11	0.0122
EVENT 3	539	4.60	0.0085
EVENT 4	242	3.84	0.0159
EVENT 5	216	5.12	0.0237

An analysis was made of the hydrologic conditions in the ACF basin during the five declining events using the local inflow data from the Corps of Engineers unimpaired flow set (USACE, 1997) to characterize each of the declining events. In this analysis, the local inflow data for each of the unimpaired flow nodes were analyzed for the percentile exceedance over the period of the unimpaired flow set (e.g. 1939 – 2011, n=73) to gauge the severity of the drought relative to the entire period of record. The analysis included the 30 days preceding the initiation of the declining event. Table 5.2 shows the results of this analysis, with the value in this table being the average value over the period of the decline. From these data, the nature of each of the declining events can be summarized as:

- <u>Declining event #1:</u> Flow deficits were most severe in the upper watersheds of both the Flint and Chattahoochee basins and in the West Point and W.F. George reaches of the Chattahoochee basin. The severity of flow deficit was roughly comparable in both basins. In both watersheds, average inflows were in the 75 to 80% exceeded range.
- <u>Declining event #2:</u> Flow deficits were most severe in the upper reaches of both basins and in the lower reaches of the Chattahoochee basin. The flow deficit was more severe in the Chattahoochee basin. In the Flint basin, average inflows were in the 75 to 80% exceeded range whereas in the Chattahoochee basin average inflows were in the 80 to 85% exceeded range.
- <u>Declining event #3:</u> Flow deficits were most severe in the upper reaches of the basin and the flow deficits were far more severe in the Chattahoochee basin. In the Flint basin, average inflows were in the 75 to 80% exceeded range whereas in the Chattahoochee basin average inflows were in the 80 to 85% exceeded range.
- <u>Declining event #4:</u> Flow deficits were most severe in the upper Chattahoochee and mid Chattahoochee and Flint basins and far more severe in the Chattahoochee basin. In the Flint basin, average inflows were in the 80 to 85% exceeded range and in the Chattahoochee basin average inflows were in the 85 to 90% exceeded range.
- <u>Declining Event #5:</u> Flow deficits extended over both basins comparably with the deficits at the Atlanta gage being the only one which were not severe. On both basins, average inflows were in the 85 to 90% exceeded range.

Table 5.2: Characterization of local inflow during declining events. A value less than 0 represents flows greater than median flow, a value of 0 to 1 represents flows in the range of 50 - 75% exceeded flows, a value of 1 to 2 represents the range of 75 - 80% exceeded flow, a value of 2 to 3 represents the range of 80 - 85% exceeded flows, a value of 3 to 4 represents the range of 85 - 90% exceeded flows, a value of 4 to 5 represents a range of 90 - 95% exceeded flows and a value of 5 to 6 represents a range of 95 - 97.5% exceeded flows and a value greater than 6 represents greater than 97.5% exceeded flows.

	EVENT 1	EVENT 2	EVENT 3	EVENT 4	EVENT 5
FLINT BASIN	2.20	1.92	1.70	2.80	3.79
GRIFFIN	2.13	2.88	3.06	2.90	4.53
MONTEZUMA	3.81	3.38	3.31	4.36	5.04
ALBANY	2.42	1.86	1.79	2.55	2.58
NEWTON	2.00	1.54	0.72	1.83	3.86
BAINBRIDGE	1.19	0.90	0.91	1.00	3.51
WOODRUFF	1.64	0.94	0.44	4.18	3.24
CHATTAHOOCHEE BASIN	2.39	2.57	2.57	3.50	3.83
LANIER	4.45	4.24	4.23	3.74	4.38
ATLANTA	1.74	2.45	2.91	1.38	1.27
WHITESBURG	1.12	1.76	1.84	3.14	4.77
WEST POINT	3.09	2.48	2.49	3.76	3.43
COLUMBUS	0.93	1.99	1.83	5.60	4.41
WF GEORGE	3.51	2.26	2.35	2.81	3.78
ANDREWS	1.87	2.78	2.33	4.08	4.74

Although the lowering of Lake Lanier is obviously caused by the fact that more water is leaving the reservoir than is entering the reservoir, management requires a much deeper understanding of the problem. In this analysis, the lowering of Lake Lanier will be examined in two parts: (1) factors at and above Lake Lanier and (2) factors that define the release of water from the reservoir to the watershed below Buford Dam. Causal factors for the lowering of Lake Lanier's storage pool which relate directly to Lake Lanier include: 1) a relative deficit in local inflows to the reservoir from contributing rivers and streams (i.e., outflows are greater than inflows), 2) water supply withdrawals for Metro Atlanta region directly withdrawn from the reservoir, and 3) evaporative losses from the reservoir. Causal factors which relate to the release of water from Lake Lanier to the watershed below the reservoir include: 1) releases from the reservoir to meet minimum flow requirements for water quality at Peachtree Creek, 2) releases made to balance pool elevations in Lake Lanier with West Point , 3) releases to provide augmentation support to the Apalachicola River to meet minimum flow requirements of the RIOP, 4) the minimum required release from Buford Dam, and 5) hydropower releases from Buford Dam.

The first factor to be considered at Lake Lanier is inflow deficits at the reservoir. Inflow deficits are defined in equation 5.1:

Lake Lanier Inflow deficit (m^3/s-days) = $LI_{LL} - O_{LL} - E_{LL} - Cons_{LL}$, (Equation 5.1)

where:

LI_{LL}= local inflow into Lake Lanier from the Chattahoochee basin above Buford Dam

O_{LL} = outflow from Buford Dam

E_{LL} = evaporation from Lake Lanier

$Cons_{LL}$= consumptive withdrawals from Lake Lanier.

The local inflow into Lake Lanier (LI_{LL}) is defined by daily values in the unimpaired flow set. The outflow from Buford Dam (O_{LL}) in m^3/s-days is defined by equation 5.2:

O_{LL} (m^3/s-days) = $Buf_{min} + Buf_{hydro} + Buf_{PTCmin} + WP_{bal} + JW_{min}$ (Equation 5.2)

where:

Buf_{min} = minimum required release from Buford Dam,

Buf_{hydro} = hydropower releases from Buford Dam,

$Buf_{PTC\ min}$ = release from Buford for meeting the meeting the Peachtree Creek minimum water quality target,

WP_{bal} = releases from Buford Dam for balancing the volume of storage in Lake Lanier and West Point Lake storage pools,

JW_{min} = direct releases from Buford Dam to support meeting Jim Woodruff minimum releases under the RIOP.

Apportioning outflow from Buford dam is complicated as releases from the reservoir are made conjunctively, that is, the same water is used to meet multiple project purposes. Consequently, the approach taken to quantify or project releases was to first account for the most upstream releases, those releases made directly from the Dam either for hydropower or to meet the project's required minimum required release of 16.98 m^3/s (USACE 2012). Minimum releases from Buford Dam (Buf_{min}) are made so that there will be sufficient water in the Chattahoochee River below the dam (USACE 2015). Normally the Buford project is operated as a peaking plant for the production of hydroelectric power and during off-peak periods, it maintains a continuous flow (USACE 2015). Releases from Buford are re-regulated by Georgia Power Company's Morgan Falls Reservoir to ensure the City of Atlanta has sufficient flow for water supply and wastewater assimilation (USACE 2015). The rules for hydropower releases used in the ACF STELLA model are those defined by the RIOP (Leitman and Kiker 2015).

Next, we quantified the releases made to meet the Peachtree Creek water quality target ($Buf_{PTC\ min}$), the release requirement which is the next most downstream release. The minimum water quality flow requirement for Peachtree Creek is 21.225 m^3/s (USACE, 2015). In meeting the minimum flow requirement for Peachtree Creek, it must be also determined whether there is a deficit between local inflows and consumptive withdrawals between the Buford outflow and Peachtree Creek location. If there is a deficit, a supplemental release must be made to offset the deficit and ensure that the minimum flow requirement is met. After determining the release necessary to meet the Peachtree Creek water quality target, any water released either for the minimum flow requirement or for hydropower was subtracted from the release necessary to meet the Peachtree Creek minimum since that water was already being released for another project purpose and was therefore already going downstream whether or not there was a required minimum flow for Peachtree Creek.

Once the volume of water needed for Peachtree Creek minimum flow requirement was met, the volume of water needed to meet the next project purpose (e.g. balancing the reservoir pools for Lanier and West Point) was determined and any water whose release was already accounted for to meet 1) the Peachtree Creek target, 2) the minimum release requirement and 3) hydropower releases was then subtracted from the computed volume. This same conjunctive use process is used when computing the release to meet Jim Woodruff outflow minimum required release, only releases for balancing were also subtracted. Augmenting flows to balance reservoir conservation storage refers to releases made from Lake Lanier's conservation pool in order to have the storage pools of Lake Lanier and West Point in the same Action Zone. In computing the release from Lake Lanier to balance the conservation pools it must be recognized that water is not released directly from Lake Lanier to support releases from Jim Woodruff Dam. Instead, water is released from W.F. George to support releases from Jim Woodruff Dam and then water is released from West Point reservoir to balance the release from W.F. George and finally water is released from Lake Lanier to balance the releases from West Point (see Figure 1 for the location of these reservoirs).

In considering the volume of water released to support the RIOP requirement from Lake Lanier, both the release to balance the reservoirs and any release made directly to support the minimum flow requirement in the situation where there is not adequate water storage in the basin to support required release will be considered as being released to support the RIOP flow. However, probably not all of the water released to balance Lanier and West Point reservoirs is for meeting the minimum flow requirement.

The final factor that needed to be considered in evaluating the outflow from Lake Lanier is the release necessary to assure that Lake Seminole has adequate water to meet the requirements of the RIOP. This was calculated by the equation 5.3:

$$\boldsymbol{JW_{MINREL}}\ (\mathrm{m^3/s\text{-}days}) = JW_{RIOP} - LI_{Flint} - LI_{Chatt} + Con + Evap, \qquad \text{(Equation 5.3)}$$

where:

JW_{RIOP} = RIOP required release from Jim Woodruff Dam,

LI_{Flint} = local inflow to Lake Seminole from the lowest nodal point in the model on the Flint River (Bainbridge flow),

LI_{Chatt} = local inflow to the Chattahoochee basin below Buford Dam,

Con = net consumptive extractions from the Chattahoochee basin below Buford Dam,

$Evap$ = evaporation/precipitation losses/gains from West Point, W.F. George and Lake Seminole.

From this calculated value, releases apportioned to meeting the Peachtree Creek required minimum flow and for balancing the conservation pools of West Point and Lake Lanier must be accounted for by subtracting them from the Buford outflow value. Then the lesser value of Buford outflow and the preliminary calculation is the value that is attributed to the release and releases made from West Point and W.F. George are filtered out. The fact that some of the release made to meet the required minimum flow may have been provided by West Point and/or W.F. George releases also needs to be accounted for. This was done by assuring that the sum of releases provided from Lanier for meeting the Peachtree Creek minimum, balancing Lanier and West Point and meeting Jim Woodruff minimum required release never exceed the volume of the release from Buford Dam for that day.

To evaluate alternative management approaches to addressing the lowering of Lake Lanier, three distinct tests were made: 1) decreasing irrigation demands in the Flint basin, 2) revising the consumptive withdrawals at Lake Lanier, and 3) revising the minimum release required from Jim Woodruff Dam. It has been shown that if agricultural consumptive withdrawals effects on streamflow in the Flint basin are drastically reduced by introducing alternative farming practices that during drought events the most of the water savings result in higher elevations in the Flint basin, not increased flows in the Apalachicola River (see Chapter 4). This is because under the RIOP a minimum release is required from Jim Woodruff Dam (e.g. 141.5 m^3/s), therefore if inflow from the Flint basin is increased through the implementation of these water savings, then less water has to be released from the storage reservoirs to meet the required minimum flow. At times when the reservoirs do not need to make supplemental releases, all of the increases in flow from reducing agricultural water demands would translate into increased flow in the Apalachicola River. Hence, the widespread introduction of water-saving agricultural practices actually increases pool elevations at the reservoirs and has the potential to contribute to an answer that allows residents of the basin to have their lake and drink it to.

To examine the effects of changing consumptive extractions on the lowering of Lake Lanier in more depth, the ACF-STELLA model was employed and two identical model runs were made with 1) the current volume of withdrawals and 2) with the increased withdrawals requested by the State of Georgia. In May, 2000, the Governor of the State of Georgia submitted a formal request to the Assistant Secretary of the Army (Civil Works) to adjust the operation of Lake Lanier, and to enter into contracts with the State of Georgia or water supply providers in Georgia, to accommodate increases in water supply withdrawals from Lake Lanier and downstream at Atlanta over the next thirty years, culminating in total, gross withdrawals of 297 MGD from Lake Lanier and 408 MGD downstream by the year 2030 (USACE, 2012, USACE, 2015). Georgia's request included a projected increase in the proportion of withdrawals returned by water supply providers to Lake Lanier, in the form of treated wastewater, from a rate of 7 percent in 1999 to a rate of 36 percent in 2030, or 107 MGD to Lake Lanier, so that the maximum net withdrawals from Lake Lanier would be 190 MGD in 2030. These changes would translate into a 37.85% increase in demands for the Buford reach and a 47.48% increase in demands for the Atlanta/Peachtree Creek reach.

To test the sensitivity of changing the releases from Buford Dam to balance the conservation pools at West Point and Lake Lanier, the minimum release from Jim Woodruff Dam was reduced from 141.5 m^3/s to 127.35 m^3/s (the release permitted during critical drought periods under the RIOP). Again, the results were evaluated for two of the periods where Lanier elevations dropped precipitously: January 1, 2000 to December 31, 2002 and January 1, 2007 to December 31, 2008.

To evaluate the recovery of the storage pool at Lake Lanier after emergency drought operations are put into effect, the first task is to define the time frame of when emergency drought operations were in effect in the model output. Under the RIOP drought operations are initiated when the composite storage of the basin enters Zone 4 and are in effect until the Composite storage reenters Zone 1. In the preferred alternative in the WCM (USACE, 2015) this provision was altered so that drought provisions would go into place when composite storage enters Zone 3. In the model runs with the return to normal operations zone set at Zone 1, from 1939 to 2008 drought operations were only put into effect twice: 1) from July 10, 2000 to July 9, 2001 and 2) from October 3, 2007 until December 31, 2008. In total, drought operations were in effect 822 days in the 70-year time frame, or about 3.2% of the time

To test the efficacy of waiting to resume normal operations until the composite storage volume is in Zone 1 the RIOP operations were modeled with drought operations being terminated once the composite storage reaches Composite Zone 1, Composite Zone 2 and Composite Zone 3 and to graphically compare the elevations at Lake Lanier and the outflows from Jim Woodruff Dam.

5.3 Results

The inflow deficits (inflow - outflow) at Lake Lanier during the five declining events noted above are summarized in Table 5.3. This table shows that there is considerable variation in average daily deficit (the deficit ranges from 7.76 m^3/s/day to 19.25 m^3/s/day) and the duration of the events (the duration ranges from 216 days to 574 days) as well as the total inflow deficit during the events. It can also be seen that in the five events evaluated, the timing of the higher rates of decline and longer duration of the events observed between 1939 and 2008 never coincided.

Table 5.3: Summary of flow deficits (inflow - outflow) at Lake Lanier during the five events which the elevation at Lake Lanier was lowered rapidly (cubic meters per second – days)

	TOTAL DEFICIT (m3/s - days)	AVERAGE DEFICIT (m3/s - days)	LENGTH OF EVENT (days)
DROUGHT EVENT 1	-6010.74	-11.24	535
DROUGHT EVENT 2	-4356.03	-10.42	418
DROUGHT EVENT 3	-4870.46	-7.76	574
DROUGHT EVENT 4	-4657.89	-19.25	242
DROUGHT EVENT 5	-6255.30	-10.32	216

Table 5.4 summarizes the average volume of contribution to the lowering of Lake Lanier from inflow deficits, consumptive demands from Lake Lanier, evaporation from Lake Lanier, minimum flow releases from Buford Dam, hydropower releases from Buford Dam releases to meet the Peachtree Creek water quality minimum flow, releases to balance Lanier and West Point reservoirs, and releases to support the Jim Woodruff minimum flow requirement. Table 5.5 summarizes the relative contribution of each factor in terms of percentages during the five declining events. From these tables, it can be seen that the range of effects of the different causal factors range from less than 1.0 m^3/s for releases for meeting the Peachtree Creek minimum flow and direct releases from Lake Lanier to meet the Jim Woodruff minimum release to over 10 m^3/s for hydropower releases and the required minimum release from Buford Dam. It can also be seen that several of the factors varied minimally among the declining events (e.g. the minimum required release from Buford Dam and withdrawals from Lake Lanier) while others varied

considerably from drought event to drought event. Table 5.5 also shows that over 60% of the lowering in the five events was caused by the combination of the minimum required release from Buford Dam and peaking hydropower releases.

Table 5.4: Average volume of deficits for five drought events (m^3/s-days)

	DROUGHT EVENT					
	1	**2**	**3**	**4**	**5**	**AVE**
PTC RELEASE	0.7	0.2	0.6	1.0	1.2	0.7
BALANCING	0.5	0.0	0.0	6.6	12.5	3.9
JW RELEASE	0.0	0.0	0.0	0.0	0.0	0.0
HYDROPOWER	13.6	8.2	8.6	9.3	11.4	10.2
BUF MIN RELEASE	17.0	17.0	17.0	17.0	17.0	17.0
INFLOW DEFICIT	3.6	2.7	0.5	11.4	2.4	4.1
WITHDRAWALS	5.6	5.6	5.3	5.8	5.7	5.6
EVAPORATION	2.0	2.2	2.0	5.7	2.2	2.8
TOTAL	42.9	35.8	33.9	56.9	52.4	44.4

Table 5.5: Relative contribution of various factors to the lowering of Lake Lanier during five separate drought events (percent).

	DROUGHT EVENT					
	1	**2**	**3**	**4**	**5**	**AVE**
PTC RELEASE	1.6%	0.5%	1.7%	1.9%	2.4%	1.6%
BALANCING	1.1%	0.0%	0.0%	12.4%	23.8%	7.5%
JW RELEASE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYDROPOWER	31.6%	23.0%	25.4%	17.6%	21.7%	23.8%
BUF MIN RELEASE	39.5%	47.5%	50.0%	32.0%	32.4%	40.3%
INFLOW DEFICIT	8.4%	7.5%	1.4%	21.5%	4.6%	8.7%
WITHDRAWALS	13.0%	15.5%	15.7%	11.0%	10.9%	13.2%
EVAPORATION	4.7%	6.1%	5.8%	3.7%	4.2%	4.9%

Table 5.6 summarizes the average inflow into Lake Lanier and into Lake Seminole from the Flint basin (e.g., flow for the Flint River at Bainbridge, Georgia) during the five events. From this table, it can be seen that there is a large variation in the average flow for the Flint River at Bainbridge over the five events ranging from 82.5 to 147.5 m^3/s and a lesser variation in the average inflow into Lake Lanier over the five events ranging from 22.0 to 28.1 m^3/s. To put these

two values into context, the average local inflow into Lake Lanier from 1939 to 2008 was 57.4 m^3/s and the average flow for the Flint River at Bainbridge from 1939 to 2008 was 223.9 m^3/s.

TABLE 5.6: Average local inflow into Lake Lanier and flow for the Flint River at Bainbridge, Georgia for the five drought events (cubic meters per second-days)

	Local Inflow to Lake Lanier	Flint River at Bainbridge
DROUGHT EVENT 1	28.1	122.1
DROUGHT EVENT 2	22.8	147.5
DROUGHT EVENT 3	24.1	134.3
DROUGHT EVENT 4	22.0	82.5
DROUGHT EVENT 5	27.4	109.0
AVERAGE	24.9	119.1

As was noted earlier, emergency drought operations were in effect about 3.2% of the time (822 days) in the 70-year time period of the model runs (i.e., Jan 1, 1939 to Dec 31, 2008) when the trigger to resume normal operations was set for Zone 1 as required under the RIOP. In changing this trigger, it was found that drought operations were in effect for 2.3% of the time (598 days) when the trigger was in Zone 2 and 1.0% of the time (263 days) when the trigger was in Zone 3. Figure 5.3 shows the outflow from Jim Woodruff Dam from July 1, 2000 to December 31, 2008 when the trigger to resume normal RIOP operations is set for when the composite storage of the reservoirs' is modified and Figure 5.4 shows the same data for elevations at Lake Lanier. In comparing outflow from Jim Woodruff Dam for 2000 - 2001 (Figure 5.3), it is evident that the daily differences can be rather large (e.g. > 100 m^3/s), but the average differences over the entire time period is essentially the same for all three options. In comparing the elevation at Lake Lanier under the three options for 2000 – 2001 (Figure 5.4), any differences in elevation are very minor (e.g. > 0.1 meters). When the differences for the Jim Woodruff outflow and Lanier elevations for the October 1, 2007 to December 31, 2008-time period are compared, the data in figures 5.3 and 5.4 obtains similar results as those noted for the earlier time period.

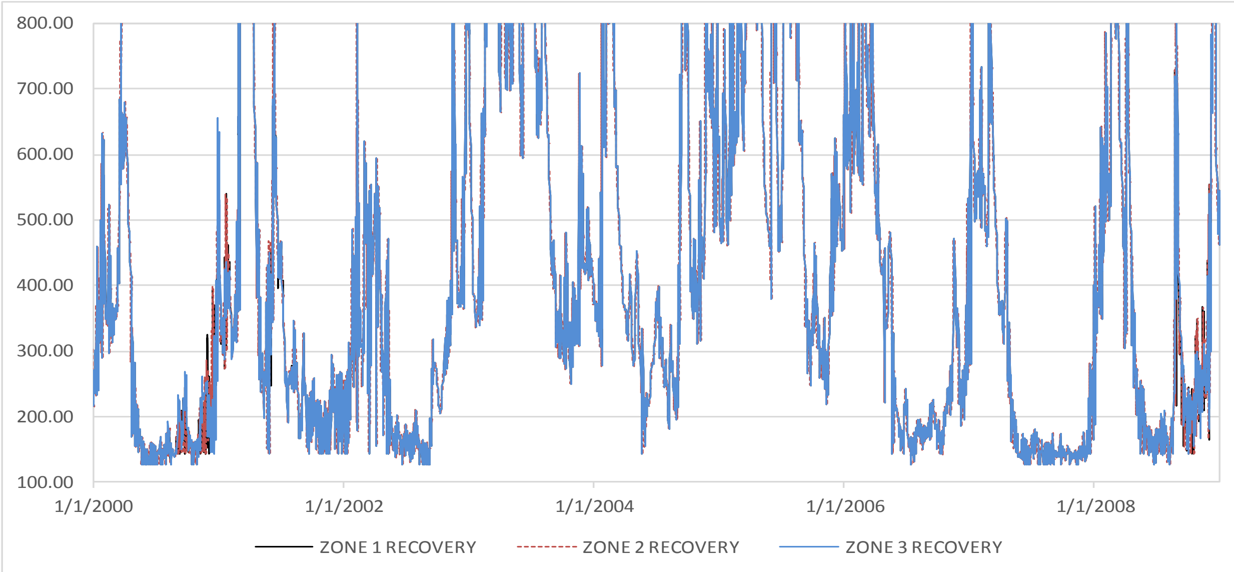


Figure 5.3: Outflow from Jim Woodruff Dam for Jan 2000 to Dec 2008 with trigger to resume normal drought operations set at composite storage zones 1, 2, and 3 (m^3/s)

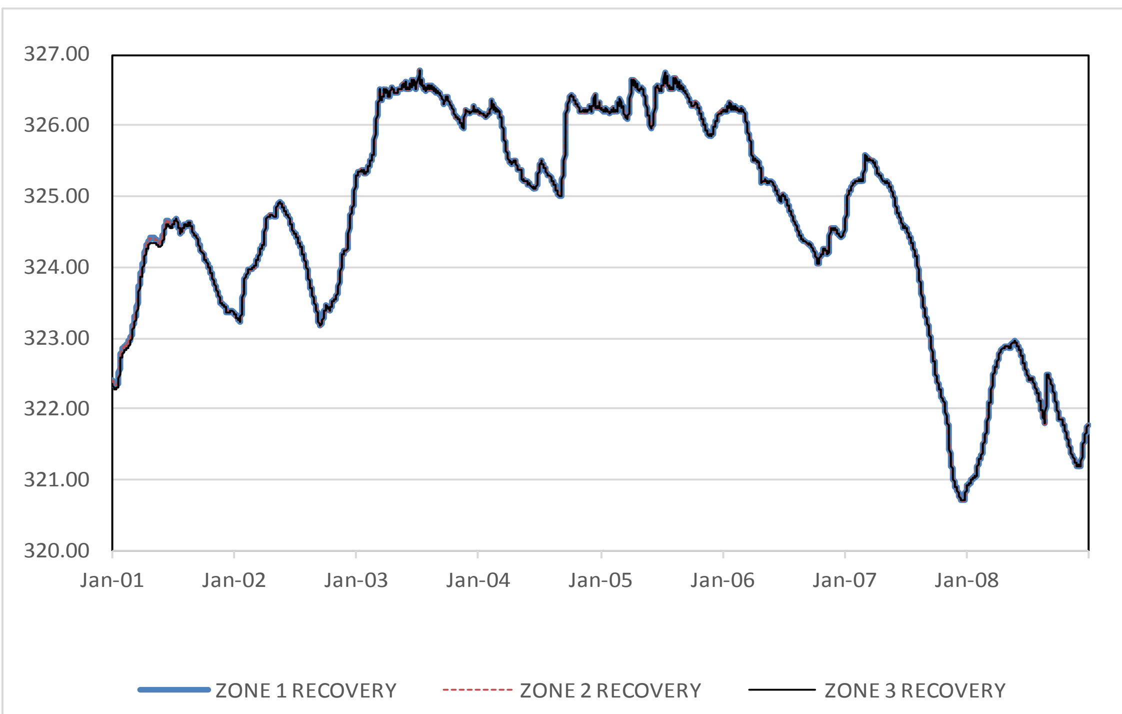


Figure 5.4: Elevations at Lake Lanier for Jan 2000 to Dec 2008 with trigger to resume normal operations set at composite storage zones 1, 2, and 3 (m^3/s)

Analyses of reducing Flint River irrigation demands by 25% and 50% found that for the performance metrics associated with Lake Lanier that there were minimal to no changes in the metrics associated with rate of decline and extent of decline for events 1, 2 and 3, but significant differences in events 4 and 5. In event 4 the extent of the drop off during the decline decreased 0.25 meters and in event 5 the extent of the decline decreased by 1.5 m. Similar results were noted for the recreation access metrics. The metrics associated with Jim Woodruff outflow showed a decrease in the amount of time Jim Woodruff outflow was below low flow thresholds for all of the events and minor increases in the amount of time flow exceeded bank full flow for three of the drought events, but a minor decrease for one of the drought events. All of the drought events showed an increase in the volume of Jim Woodruff outflow during the drought events.

The results from modifying the volume of consumptive demands from the Metro Atlanta consumptive from the current level to those requested by the State of Georgia (USACE, 2012) were evaluated for two of the periods where Lake Lanier elevations dropped rapidly: January 1, 2000 to December 31, 2002 and January 1, 2007 to December 31, 2008. Figure 5.5 shows the elevations at Lake Lanier during these time periods and Figure 6 shows Jim Woodruff outflow for these two periods. Figure 5.6 shows the effects on Jim Woodruff outflow from these changes in consumptive demands would have been minimal. Table 5.7a shows the rate of decline and the magnitude of the decline for all four drought periods, Table 5.7b the percent of time reservoir impact thresholds were exceeded, Table 5.7c the amount of time Jim Woodruff outflow was below the low flow thresholds and Table 5.7d the amount of time Jim Woodruff outflow exceeded the threshold for topping the river levees.

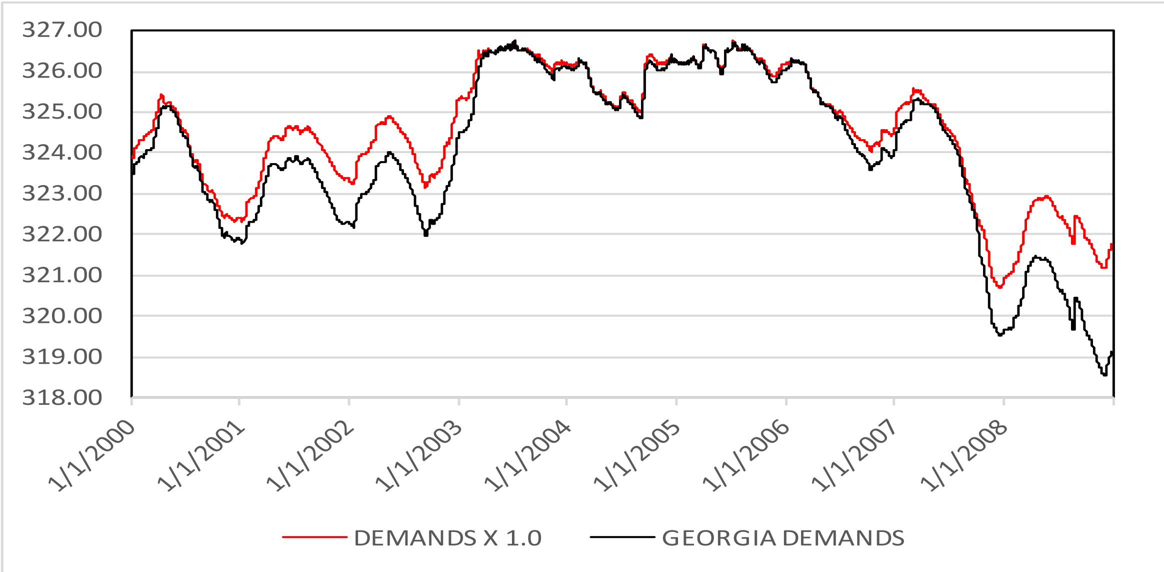


FIGURE 5.5: Effects on elevations at Lake Lanier with consumptive demands for Metro Atlanta increased to levels requested by the State of Georgia (meters)

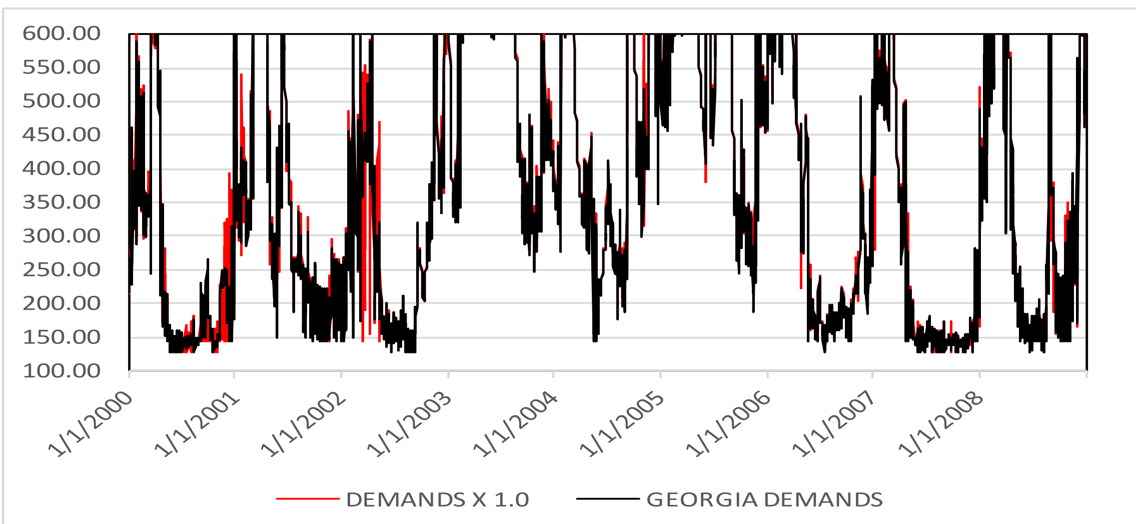


FIGURE 5.6: Effects on Jim Woodruff outflow with consumptive demands for Metro Atlanta increased to levels requested by the State of Georgia (m^3/s)

TABLE 5.7a: Performance metrics for comparing the increase of Metro Atlanta consumptive demands: rate and magnitude of decline of elevations at Lake Lanier.

	CURRENT DEMANDS	
	RATE OF DECLINE (m/day)	**MAGNITUDE OF DECLINE (m/day)**
EVENT 1	0.013	2.26
EVENT 2	0.008	2.72
EVENT 3	0.005	2.92
EVENT 4	0.012	2.88
EVENT 5	0.020	4.36
	GEORGIA DEMANDS	
	RATE OF DECLINE (m/day)	**MAGNITUDE OF DECLINE (m/day)**
EVENT 1	0.016	2.69
EVENT 2	0.011	3.86
EVENT 3	0.007	3.92
EVENT 4	0.014	3.33
EVENT 5	0.025	5.48

TABLE 5.7b: Performance metrics for comparing the increase of Metro Atlanta consumptive demands: Percent of time recreation threshold levels were exceeded.

	PERIOD 1	**PERIOD 2**	**PERIOD 3**	**PERIOD 4**
INITIAL IMPACT LEVEL				
CURRENT DEMANDS	65.6%	33.0%	34.6%	19.7%
GEORGIA DEMANDS	58.9%	25.3%	28.5%	12.2%
RESTRICTED ACCESS				
CURRENT DEMANDS	92.3%	61.3%	70.8%	30.4%
GEORGIA DEMANDS	87.6%	41.3%	43.0%	29.0%
WATER ACCESS LIMITED				
CURRENT DEMANDS	96.5%	85.0%	91.1%	35.1%
GEORGIA DEMANDS	94.5%	68.9%	74.9%	33.3%

TABLE 5.7c: Performance metrics for comparing the increase of Metro Atlanta consumptive demands: Percent of time below minimum flow thresholds (flow thresholds in cubic feet per second)

	< 142.915	<155.65	<169.8	<198.1	<226.4	<254.7	<283
PERIOD 1							
142.5 min	0.3%	0.9%	1.8%	5.0%	10.7%	16.2%	24.9%
127.35 min	0.4%	1.0%	2.1%	5.7%	11.3%	17.1%	25.1%
PERIOD 2							
142.5 min	1.0%	2.7%	5.3%	9.4%	15.5%	26.6%	35.1%
127.35 min	1.2%	2.8%	5.4%	9.6%	16.1%	27.9%	36.8%
PERIOD 3							
142.5 min	5.1%	11.7%	18.3%	26.6%	32.9%	40.4%	46.3%
127.35 min	5.4%	12.6%	18.8%	26.7%	34.0%	42.2%	47.7%
PERIOD 4							
142.5 min	15.0%	30.0%	36.7%	46.4%	50.1%	56.1%	59.4%
127.35 min	16.0%	30.4%	37.9%	47.2%	50.9%	56.4%	59.8%

TABLE 5.7d: Performance metrics for comparing the increase of Metro Atlanta consumptive demands: Percent of time above threshold for exceeding floodplain levee (396.4 m^3/s)

	CURRENT DEMANDS	GEORGIA DEMANDS
PERIOD 1	53.8%	52.6%
PERIOD 2	43.9%	42.8%
PERIOD 3	35.0%	33.6%
PERIOD 4	30.9%	31.2%

The results from modifying the minimum required releases from Jim Woodruff Dam in order to lessen the volume of water which had to be released from Lake Lanier to balance its conservation pool with West Point's conservation pool are shown in Figures 5.7 and 5.8. Figure 5.7 shows the elevations at Lake Lanier during these two time periods and Figure 5.8 shows Jim Woodruff outflow for these two periods. Figure 5.7 shows that elevations at Lake Lanier would increase with the lowering of the Jim Woodruff target flow. Figure 5.8 shows limited effects on Jim Woodruff outflow in general. However, a more detailed examination of the data shows that from January 1, 2007 until the end of 2008 there would have been 142 days when outflow from Jim Woodruff Dam was below the current minimum flow of 141.5 m^3/s, compared to 0 days when the minimum target was 141.5 m^3/s. In analyzing the performance metrics for lowering the minimum required flow for Jim Woodruff outflow the slope of the decline during the four drought events was comparable for the first four drought events showing a slight decrease in the minimum elevation except for drought event 5 in which there was a significant decrease and a nearly 3.0-foot increase in the minimum elevation. In reviewing the recreation levels, there again was a slight increase in the amount of time each of the recreation levels was exceeded, except again for event 5 where there was a significant increase. In analyzing the performance metrics Jim Woodruff outflow there was minor differences in event 1, a more substantial difference for drought events 2, 3, 4 and 5 for the extreme lowest flows. For the first three drought periods the average flows from Jim Woodruff during the four-year periods were comparable, however the average outflow from Jim Woodruff during the two years from 2007 – 2008 were about 2.83 m^3/s different.

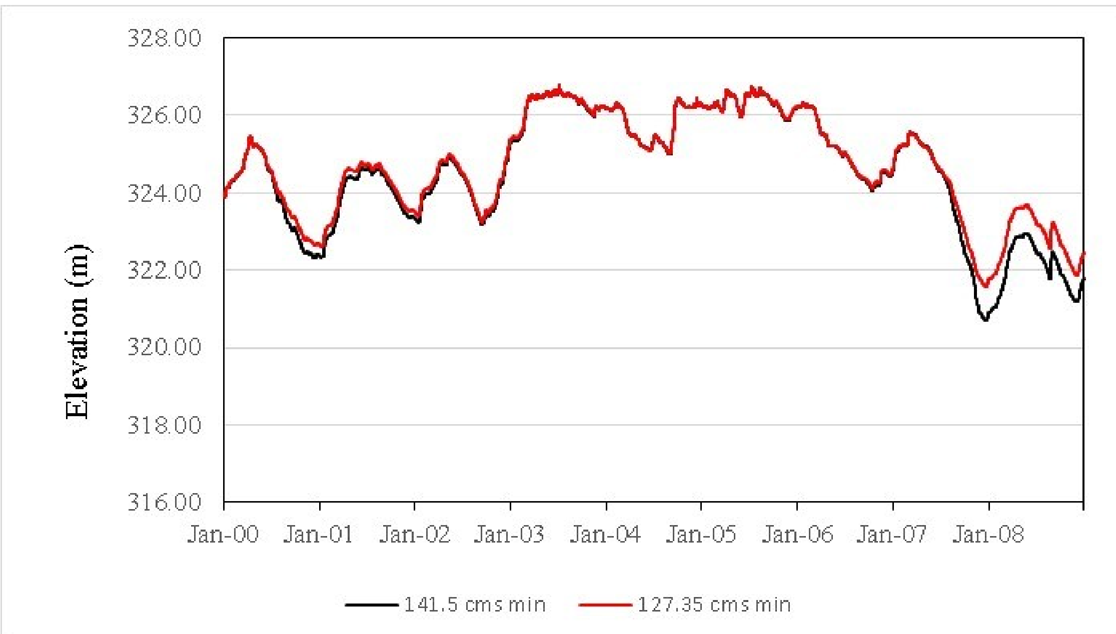


FIGURE 5.7: Effects on elevations at Lake Lanier from lowering the minimum release from Jim Woodruff Dam from 141.5 m^3/s to 127.35 m^3/s (meters)

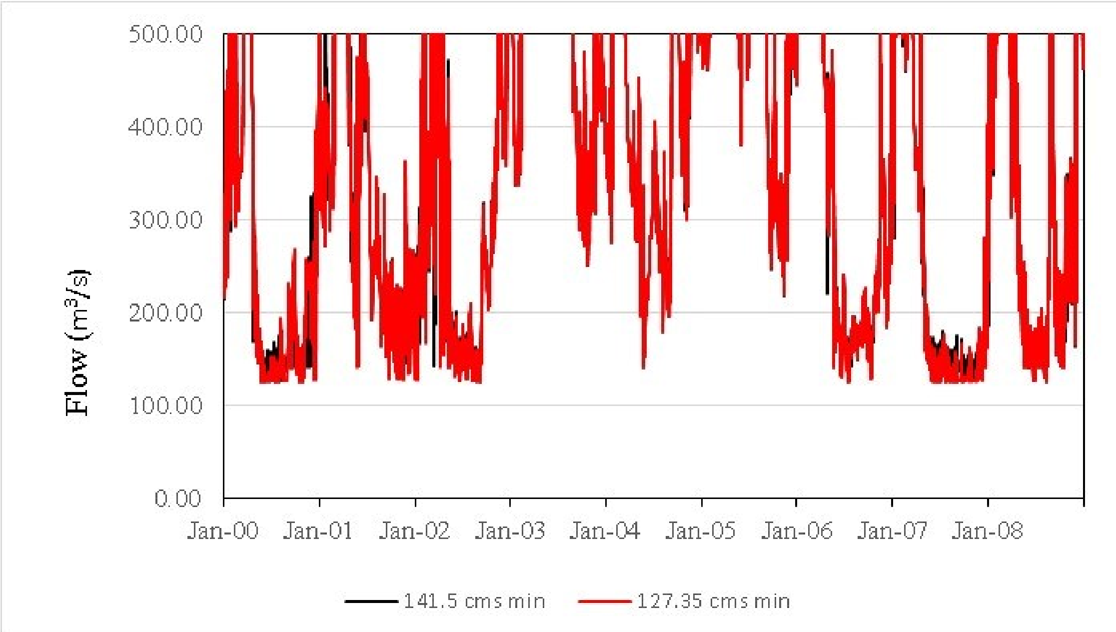


FIGURE 5.8: Effects on Jim Woodruff outflow from lowering the minimum release from Jim Woodruff Dam from 141.5 m^3/s TO 127.35 m^3/s

5.4 Discussion

In considering management actions to address the causal factors for the lowering of the reservoir's elevation, causal factors need to be parsed into two groups: 1) factors which can be influenced by human management decisions and 2) factors which either cannot be influenced by management decisions or whose benefits to society are so great that changing them substantially would not be justified (e.g. hydropower benefits). Over 60% of the lowering in the five events analyzed was caused by the combination of the minimum required release from Buford Dam and peaking hydropower releases. Eliminating the required minimum release would mean there would be little to no water in the reach of the Chattahoochee River below Buford Dam to Atlanta, a situation which would be unacceptable and unrealistic because of the economic and ecologic impacts associated with having this dry or minimally wet stretch of river. Furthermore, some of the releases made to meet the required minimum release from Buford Dam, 16.98 m^3/s (USACE, 2015), would still have to be released so that there is ample water in the river to meet the required Peachtree Creek minimum flow if the required minimum release was lowered. For some of this release, this would ultimately just be a reassigning of the purpose a release was made, not changing the volume of the release.

Peaking hydropower releases could be curtailed earlier in time (i.e., when the pool enters into Zone 3) to reduce their role in lowering the elevation during drought events, but this curtailing would come at a high cost in terms of foregone power benefits. Because of the hydropower release rules for the management of Buford Dam (USACE, 2016), peaking releases are not made during the entire declining event. During two of the declining events, peaking hydropower releases were only made fewer than 30% of the time while reservoir elevations were declining: 29.6% of the time in event 5 and 27.9% of the time in event 2. In the other events, peaking hydropower releases were made 70.7% of the time (event 1), 46.2% of the time (event 3) and 58.4% of the time (event 4). Pre-emptively eliminating peaking releases before a drought event would also inevitably lead to some false readings of drought and loss of societal benefits from hydropower peaking releases when the elevations at Lake Lanier were not going to rapidly decline.

Local inflow and evaporation from the reservoir are defined by climate and therefore not a factor which can be readily managed to mitigate the lowering of the reservoir. Consequently, in the end there are only four factors that can practically be addressed to mitigate the effects of the rapid lowering events: 1) direct consumptive withdrawals from Lake Lanier and from the reaches above Peachtree Creek, 2) releases made directly to Lake Seminole from Lake Lanier in order to meet Jim Woodruff minimum flows, 3) releases made to West Point reservoir that ultimately are used to help meet the Jim Woodruff minimum release requirements or 4) releases made to support meeting the Peachtree Creek minimum flow. The earlier analysis (Tables 5.2 and 5.3) shows that the effects of direct releases to Jim Woodruff Dam and releases to support the Peachtree Creek minimum flow requirement on the lowering of Lake Lanier elevations during drought events are minimal. Consequently, management actions to revise them would have little to no effect in mitigating the lowering of Lake Lanier. This leaves only two factors where such releases could be managed to substantively mitigate the precipitous lowering: consumptive extractions and releases to West Point to balance the two reservoirs.

Analyses showed that increasing the demands to the volume of consumptive demands for Metro Atlanta requested by Georgia in their 2000 request to the USACE would have exacerbated the lowering of Lake Lanier (Figure 5.5), but would have a minimal effect on Jim Woodruff outflow (Figure 5.6) with the current management operations. In comparing increasing the consumptive demands with current demands for Metro Atlanta with the four sets of performance metrics it was found that the rate of decline, the magnitude of decline increased as consumptive demands increase (table 9a) with the greatest difference occurring in the most severe drought (period 4) and the amount of time Lake Lanier elevations exceeded recreation threshold values decreased (Table 5.9b). It was also found the amount of time Jim Woodruff outflow was below the low flow thresholds increased (Table 5.9c) and the amount of time Jim Woodruff outflow exceeded the threshold for topping the river levees decreased (Table 5.9d). Average Jim Woodruff outflow declined during all of the events. In total, there is a cost associated with increasing consumptive demands to the level requested by Georgia in terms of both decreased reservoir elevations at Lake Lanier and decreased performance in terms of Jim Woodruff outflow for the metrics evaluated. If consumptive demands are increased for Metro Atlanta there needs to be a decision balancing what level of negative effects are acceptable and what volume of increase is acceptable.

Preliminary analyses also showed that elevations at Lake Lanier would increase with the lowering of the Jim Woodruff target flow, but limited effects on Jim Woodruff outflow. However, a more detailed evaluation of Jim Woodruff outflow shows that there would be a 142 day increase in the number of days which flow was below 141.5 m^3/s from January 1, 2007 until the end of 2008 if the Jim Woodruff minimum release target was changed. This increase in the number of days which flow would be below 141.5 m^3/s would have a negative impact on several species of endangered mussels (USFWS 2012) and salinity associated impacts to the Apalachicola estuary (USFWS 2012). In analyzing the set of four performance metrics used in this analysis it was found that for the rate and magnitude of decline during the five events that both declined (Table 5.8a) with the largest decline happening during event 5. For the metric evaluating the amount of time recreational access thresholds were exceeded it was found that they were exceeded more often (Table 5.8b) with the largest improvement again found during event 5. For the metric regarding exceedance of low flow thresholds (Table 5.8c), it was found that the lower thresholds tended to be exceeded more frequently, but some of the lesser thresholds less frequently. And, for the metric which considers the inundation of the Apalachicola River floodplain (table 5.8d), it was found that in some cases the floodplain was inundated more frequently with the lowering of the required minimum and some cases less frequently, but in all cases the differences were minor. In sum, again there are tradeoffs associated with lowering the required minimum flow and the major question regarding this change is the effect of increased severe low flows on the Apalachicola River and Bay ecosystems.

TABLE 5.8a: Performance metrics for comparing the lower of the minimum required release for Jim Woodruff Dam: Rate and magnitude of decline of elevations at Lake Lanier (percent of time flow was below the threshold)

	141.5 cms mininum	
	RATE OF DECLINE	**MAGNITUDE OF DECLINE**
EVENT	**(m/day)**	**(m)**
1	0.013	2.259
2	0.008	2.719
3	0.005	2.920
4	0.012	2.880
5	0.020	4.365
	127.35 cms minimum	
	RATE OF DECLINE	**MAGNITUDE OF DECLINE**
EVENT	**(m/day)**	**(m)**
1	0.013	2.192
2	0.008	2.697
3	0.005	2.859
4	0.011	2.588
5	0.016	3.475

TABLE 5.8b: Performance metrics for comparing the lower of the minimum required release for Jim Woodruff Dam: Percent of time recreation threshold levels were exceeded.

	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4
INITIAL IMPACT LEVEL				
CURRENT DEMANDS	79.7%	41.6%	40.7%	20.1%
.5 X CURRENT DEMANDS	80.2%	41.6%	42.1%	20.5%
RESTRICTED ACCESS				
CURRENT DEMANDS	95.0%	73.4%	78.0%	29.9%
.5 X CURRENT DEMANDS	95.0%	73.4%	79.7%	31.0%
WATER ACCESS LIMITED				
CURRENT DEMANDS	100.0%	96.4%	90.4%	33.7%
.5 X CURRENT DEMANDS	100.0%	96.2%	94.4%	46.7%

TABLE 5.8c: Performance metrics for comparing the lower of the minimum required release for Jim Woodruff Dam: Percent of time below minimum flow thresholds (percent of time flow was below the threshold)

	< 142.915	<155.65	<169.8	<198.1	<226.4	<254.7	<283
PERIOD 1							
142.5 min	0.3%	0.9%	1.8%	5.0%	10.7%	16.2%	24.9%
127.35 min	0.4%	1.0%	1.8%	4.9%	10.3%	16.3%	25.1%
PERIOD 2							
142.5 min	1.0%	2.7%	5.3%	9.4%	15.5%	26.6%	35.1%
127.35 min	1.8%	3.1%	5.7%	9.2%	15.1%	26.6%	35.5%
PERIOD 3							
142.5 min	5.1%	11.7%	18.3%	26.6%	32.9%	40.4%	46.3%
127.35 min	7.8%	12.4%	18.1%	25.4%	32.2%	40.6%	46.2%
PERIOD 4							
142.5 min	15.0%	30.0%	36.7%	46.4%	50.1%	56.1%	59.4%
127.35 min	22.0%	29.1%	37.8%	46.1%	49.7%	55.8%	59.2%

TABLE 5.8d: Performance metrics for comparing the lower of the minimum required release for Jim Woodruff Dam: Percent of time above threshold for exceeding floodplain levee (396.2 m^3/s)

	141.5 cms minimum	127.35 cms minimum
PERIOD 1	53.8%	53.9%
PERIOD 2	43.9%	43.8%
PERIOD 3	35.0%	35.4%
PERIOD 4	30.9%	31.6%

In analyzing the effects of changing the volume of composite storage for which reservoir operations revert from drought operations to normal management operations, it was found that changing the trigger from Action Zone 1 to Action Zones 2 and 3 had minimal effects on either the elevations at Lake Lanier or the average outflow from Jim Woodruff Dam (Figures 5.4 and 5.5). Changing the trigger however had an impact on the number of days in which only the minimum outflow from Jim Woodruff Dam would be provided. When the trigger is set for Composite Zone 1, the number of days in which only the minimum release is supported by the federal storage reservoirs increases by 559 days over the 70 year modeling time period when compared with a Composite Zone 3 setting.

It should be understood that just because emergency drought operations are in effect, it does not necessarily mean that Jim Woodruff outflow is at its minimum level. If local inflow from the Flint and Chattahoochee basins is greater than the RIOP minimum outflow of 141.5 m^3/s, this water will be passed through Jim Woodruff Dam because there is not sufficient storage capacity in Lake Seminole to store this water. Of the 822 days when emergency drought operations were in effect and when the trigger to resume normal operations was set for Action Zone 1, Jim Woodruff outflow was less than 142.9 m^3/s (this provides a slight buffer over the actual minimum value of 141.5 m^3/s) only 61 days. Similarly, of the 598 days that emergency operations were in effect and the trigger was set for resumption of normal operations when composite storage was in Action Zone 2, Jim Woodruff outflow was less than 142.9 m^3/s only 62 days. When the trigger was set for Action Zone 3, emergency operations were in effect 263 days, but flow was less than 142.9 for only 39 days. Figure 5.9 shows the local inflow for the ACF basin on days when the drought trigger was in effect and when the recovery zone was set for

Composite Zone 1. This figure shows that the majority of the time that the drought trigger was in effect, local inflow for the basin was above the minimum release and about half the time local inflow was more than twice the minimum flow. Because the design of the drought trigger operations was to allow the recovery of the reservoir storage, in addition to protecting the existing storage, some disconnect between local inflow and the occurrence of emergency drought operations should be expected.

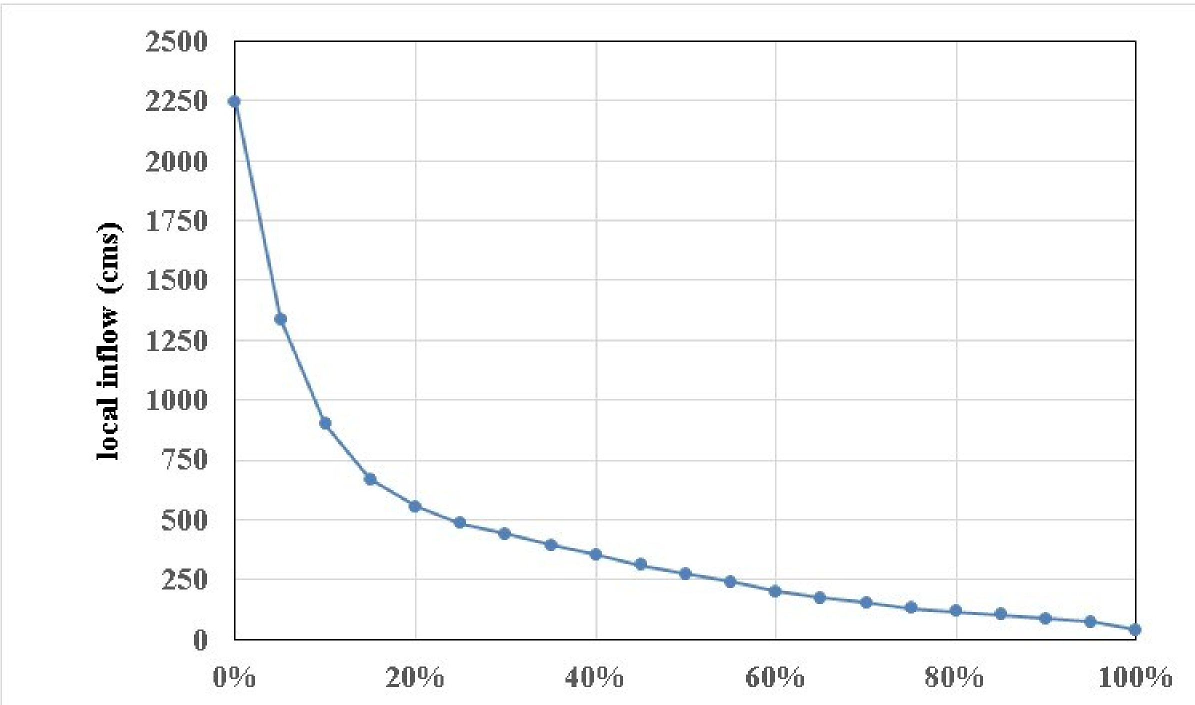


FIGURE 5.9: Frequency of exceedance of modeled local inflow for the ACF basin above Jim Woodruff Dam when the drought trigger was set for Action Zone 1 and the drought trigger was in effect (Jan 1939 to Dec 2008)

Another reason for the disconnect between the timing of drought operations releases and the release from Jim Woodruff Dam is that composite storage plays an important role in defining reservoir system support of the Woodruff release. Because Lake Lanier has 65% of the storage in the watershed, this reservoir plays a larger role in defining composite storage then either West Point or W.F. George. Since the watershed for Lake Lanier drains only about 6% of the basin, the reservoir is very slow to refill after being drawn down. Hence a situation occurs where Lake Lanier elevation is forcing the drought trigger to remain in drought relief operation mode, but local inflow below Lake Lanier is of such a magnitude that Jim Woodruff outflow is far greater than the minimum required release. The prolonged period of being in drought relief is apparently having a minimal, if any, effect on Lanier elevation.

Introducing irrigation practices which use less water in the Flint basin and therefore decreasing the volume of releases necessary to meet minimum flow requirements during drought events was analyzed. Table 5.9 shows that as the volume of water consumed by agriculture decreases, the average outflow from Jim Woodruff Dam during the four drought periods increases. It should be noted, however, because some of the water gained is diverted to increasing the storage at the reservoirs. In comparing the volume of increase is smaller during the more severe drought periods (e.g. 1999-2003 and 2007 – 2008) changes in both Lanier elevations and Jim Woodruff outflow against the performance metrics it was droughts in events 4 and 5 and negligible in the other events (Table 5.10a). In reviewing the amount of time recreation access thresholds were exceeded (Table 5.10b) similar results were found. In reviewing the metric for exceeding low flow thresholds for Jim Woodruff outflow (Table 5.10c) it was found that the greatest improvements occurred in the higher flow thresholds and during the less severe droughts. This is because at those times there was less of a need for augmentation support from the Chattahoochee basin storage reservoirs and consequently most of the water savings from decreased agricultural consumption went to increased flows in the Apalachicola River. In reviewing the amount of time flow exceeded the threshold for topping the levees it (Table 5.10d) it can be seen that the differences are minor.

TABLE 5.9: Average outflow from Jim Woodruff Dam with decreased agricultural irrigation during the four drought periods (m^3/s)

	CURRENT DEMANDS	.75 X	.5 X
PERIOD 1	640	642	644
PERIOD 2	464	466	468
PERIOD 3	425	427	429
PERIOD 4	347	348	349

TABLE 5.10a: Performance metrics for comparing the decrease of irrigation withdrawals in the low Flint watershed: Rate of decline of elevations at Lake Lanier (percent of time flow was below the threshold

	current irrigation demands	
	RATE OF DECLINE	**MAGNITUDE OF DECLINE**
EVENT	**(m/day)**	**(m)**
1	0.010	1.695
2	0.008	2.603
3	0.005	2.448
4	0.011	2.774
5	0.025	5.407
	0.5 X current irrigation demands	
	RATE OF DECLINE	**MAGNITUDE OF DECLINE**
EVENT	**(m/day)**	**(m)**
1	0.010	1.692
2	0.008	2.603
3	0.005	2.463
4	0.010	2.527
5	0.018	3.944

TABLE 5.10b: Performance metrics for comparing the decrease of irrigation withdrawals in the low Flint watershed: Percent of time recreation threshold levels were exceeded

	PERIOD 1	**PERIOD 2**	**PERIOD 3**	**PERIOD 4**
INITIAL IMPACT LEVEL				
CURRENT DEMANDS	79.7%	41.6%	40.7%	20.1%
.5 X CURRENT DEMANDS	80.2%	41.6%	42.1%	20.5%
RESTRICTED ACCESS				
CURRENT DEMANDS	95.0%	73.4%	78.0%	29.9%
.5 X CURRENT DEMANDS	95.0%	73.4%	79.7%	31.0%
WATER ACCESS LIMITED				
CURRENT DEMANDS	100.0%	96.4%	90.4%	33.7%
.5 X CURRENT DEMANDS	100.0%	96.2%	94.4%	46.7%

TABLE 5.10c: Performance metrics for comparing the decrease of irrigation withdrawals in the low Flint watershed: Percent of time below minimum flow thresholds (percent of time flow was below the threshold)

	< 142.915	<155.65	<169.8	<198.1	<226.4	<254.7	<283
PERIOD 1							
142.5 min	99.6%	99.2%	98.3%	94.8%	89.1%	84.0%	76.6%
127.35 min	99.6%	99.2%	98.6%	95.4%	89.7%	84.4%	77.3%
PERIOD 2							
142.5 min	1.1%	2.5%	4.7%	9.1%	14.5%	25.9%	34.9%
127.35 min	0.9%	2.2%	4.2%	8.8%	14.3%	24.8%	34.0%
PERIOD 3							
142.5 min	4.6%	10.6%	16.5%	25.5%	32.2%	40.1%	46.2%
127.35 min	4.2%	9.3%	15.8%	24.3%	31.7%	39.8%	45.5%
PERIOD 4							
142.5 min	14.0%	28.2%	35.7%	44.9%	49.4%	55.1%	59.0%
127.35 min	14.0%	26.1%	34.1%	44.5%	48.7%	54.6%	59.2%

TABLE 5.10d: Performance metrics for comparing the decrease of irrigation withdrawals in the low Flint watershed: Percent of time above threshold for exceeding floodplain levee (396 m^3/s)

	CURRENT DEMANDS	.75 X	.5 X
drought 1	53.1%	53.4%	53.6%
drought 2	43.6%	44.1%	44.4%
drought 3	35.7%	35.5%	35.9%
drought 4	31.7%	31.3%	31.2%

5.5 Conclusion

In evaluating the causal factors for the rapid lowering of Lake Lanier during drought events it was found that the relative importance of the individual causal factors varies from drought event to drought event implying that a one-size-fits-all approach to drought management in the ACF basin, which has been the practice to date, is not advisable. Many of the causes for rapid lowering of the elevation Lake Lanier during various drought events were found to be caused by factors which cannot be controlled by reservoir or demand management actions including: 1) climatically driven factors such as evaporation or severely reduced inflow into Lake Lanier, 2) factors which provide substantial benefits in non-drought times (hydropower releases), or 3) factors which cannot be readily abandoned (minimum release from Buford Dam).

There were four factors identified and then evaluated which could implemented in an effort to reduce the rapid lowering of Lake Lanier elevations: 1) direct consumptive withdrawals from Lake Lanier, 2) releases directly to Lake Seminole from Lake Lanier in order to meet Jim Woodruff minimum flows, 3) releases made to West Point reservoir which ultimately are used to help meet the Jim Woodruff minimum release requirements or 4) releases made to support meeting the Peachtree Creek minimum flow. Of these four, two of them had a very minor role in the precipitous lowering of Lake during the drought events investigated and consequently management actions to revise them would only have little to no effect in mitigating the lowering of Lake Lanier.

In further investigating the remaining two factors it was found that increasing Metro Atlanta demands to the volume requested by the State of Georgia with current reservoir management practices would result in a more rapid decline in reservoir elevations at Lake Lanier, but would have a minimal effect on Jim Woodruff outflow. It was also found that reducing Jim Woodruff Dam minimum flow requirements and consequently reducing the necessary support from Lake Lanier to meet this requirement via balancing with West Point reservoir would result in increased elevations at Lake Lanier, but would also have a negative effect on environmental resources in the Apalachicola River and Bay.

The effectiveness of the approach used by the USACE in terminating drought operations in the ACF basin was also evaluated. It was found that changing the trigger from when drought operations are initiated and terminated under the RIOP had minimal effects on reservoir elevations at Lake Lanier, but increased the number of days that the minimum release was provided from Jim Woodruff Dam.

Considering that 1) the State of Georgia anticipates a significant increase in consumptive demands for Metro Atlanta, 2) the State of Florida has filed a suit over Georgia’s taking of water from the ACF basin and therefore seems unlikely to accept even less water in the future, and 3) the draft WCM proposed by the USACE (USACE, 2015) essentially proposes a continuation of the current approach to reservoir management with only minor changes to certain operational parameters, it seems unlikely that anything will be done about the rapid lowering of Lake Lanier during drought events in the near term.

On a more optimistic side, a stakeholder group in a recent report noted that varying reservoir releases based on predictive drought indicators would be beneficial (ACFS, 2015) and made the following recommendations with regard to drought management: 1) the states of Alabama, Florida and Georgia should collaborate in the development of a drought management plan, perhaps in the context of a regional MOU that includes defining drought conditions, using NOAA as a resource, identifying triggers for actions, delineating responses by water use sector, and documenting changes in operational strategies; 2) urges USACE to utilize predictive drought indicators in the revised Water Control Manual; 3) various combinations of predictive drought indicators can be used that allow operation decisions to be made in drought years that enhance system flows while still preserving adequate reservoir storage during the drought; and 4) urges the USACE to utilize real time drought management.

In addition, this paper illustrates that a win-win solution can be found by increasing the implementation of agricultural water saving practices and revising reservoir management practices to 1) provide releases that inundate floodplains more often, remove restriction of returning to normal releases once composite storage leaves Action Zone 4, defining limit to Metro Atlanta's consumptive allowance from the ACF basin.

CHAPTER 6: CONCLUSIONS

The Apalachicola-Chattahoochee-Flint (ACF) river basin is a large, complex watershed in the southeastern United States with ongoing legal and regulatory conflict. The basin is home to a rich array of biological resources ranging from multiple endangered species to a robust reservoir-based fishery to an economically significant seafood industry in its estuary to being an important nursery grounds within the Gulf of Mexico. The ACF watershed has faced a crisis of water resource planning during the last 30 years with increasing occurrence and intensity of periodic droughts, increasing usage of water, and conflict over the management of the federal storage reservoirs have sparked political debate over the proper allocation of water resources and ultimately a lawsuit in the US Supreme Court. Complex water resources challenges require systematic tools and analysis to deconstruct and assess the various drivers of basin flows and analyze potential management alternatives. ***The fundamental question at the core of this research project is: Can a simplified, flexible, water system model be effectively used to evaluate critical system elements within a complex, seemingly intractable water management dispute?*** The objectives associated with addressing this research question are the following:

<u>Objective 1:</u> To develop and test a planning-level river basin modeling tool (ACF-STELLA) in the ACF basin for comparison with the primary water systems modeling tool (HEC-ResSim) used by the federal agency (US Army Corps of Engineers) responsible for managing the primary reservoirs in the watershed (Chapter 2).

<u>Objective 2:</u> Using the river basin modeling tool (ACF-STELLA), to evaluate whether problems experienced in a recent severe drought (2011 – 2012) can be mitigated through alternative management of the existing reservoir system and/or demand management (Chapter 3).

<u>Objective 3:</u> Using the river basin modeling tool (ACF-STELLA) to evaluate to what degree demand management in the form of significantly reducing agricultural irrigation withdrawals will resolve downstream water flow problems (Chapter 4);

Objective 4: Using the river basin modeling tool (ACF-STELLA) to evaluate whether the rapid lowering of the largest storage reservoir in the watershed (Lake Lanier) during drought events can be mitigated through managing the storage reservoirs in a different manner (Chapter 5).

The first paper of this thesis (Chapter 2) was dedicated to validating that the ACF-STELLA model produced comparable results to the USACE's HEC-ResSim model with regard to the operation of the federal storage reservoirs in the watershed. A decision to use an alternative modeling tool to the USACE's model was based on the fact that the ACF-STELLA model is a more flexible tool which allows for the ready analysis of a broader array of alternative management approaches and that the ACF-STELLA model has a much faster run time (i.e., 5-6 minutes versus over 2 hours) and therefore allows for the running and testing of more alternative scenarios. In Chapter 2 it is shown that the two models produce similar results and from Chapter 2 the following conclusions can be made:

- It is beneficial to have a screening model (e.g. ACF-STELLA) as well as a more detailed operations model (e.g. HEC ResSim) in analyzing the management of a river basin. This allows a more robust consideration of a broader array of alternative management scenarios and a means to cross-check the results of both modeling tools. This also prevents a situation where the capacity of the modeling tool limits the range of alternatives considered. In the Corps of Engineers' update of the Water Control Manual (USACE 2015) all of the alternatives were essentially current operations with minor adjustments. It is probable that the narrow array of options was due to the difficulty and expense of representing a broad array of alternative approaches in HEC-ResSim.
- The use of multiple modeling tools is not necessarily a competitive exercise, but can also be a collaborative exercise. It depends on how the models are utilized as to whether the use of multiple modeling tools is collaborative or competitive. In this case, the ACF-STELLA model could be used to screen a broad array of alternatives and then only the most promising of these alternatives would have to run in the HEC-ResSim model.
- The use of a screening tool can enhance the involvement of stakeholders in the process of selecting management alternatives. Allowing stakeholders to be involved in the development of performance metrics is a meaningful role which should be within the technical capacity of many stakeholders. By having access to such technology, the

stakeholders might be better able to define the metrics, which in turn might result in them being more accepting of the modeling process and its conclusions. For example, within inter-agency discussions concerning the Water Control Manual, further consultative research to develop the water management alternatives suggested by the US Fish and Wildlife Service (USFWS), used the ACF-STELLA model to evaluate management scenarios where staff of the USFWS developed performance metrics against which alternatives would be measured (USFWS, 2013a; USFWS, 2013b). This modeling approach with ACF-STELLA placed the USFWS in a proactive role in developing the Water Control Manual in contrast to the typical reactive role.

- There are multiple uses of simplified models including 1) validation of more complex models, 2) screening of alternatives to be run in more complex models, and 3) use in focusing on specific questions (e.g., tradeoffs from reductions in agricultural irrigation withdrawals on basin management, causal factors for the lowering of Lake Lanier during drought events or management responses to the 2012 drought).

It should be noted that when the USACE updated the HEC-ResSim model for use in the update of the Water Control Manual (USACE, 2015), the maximum elevation problems at W.F. George reservoir within the HEC-ResSim model (as noted in Chapter 2) was fixed and the output for the two models calibrated better (NSE = 0.848, $p < 0.01$) than was reported in the published paper in Chapter 2.

The next chapter of this dissertation (Chapter 3) was dedicated to using the river basin modeling tool to evaluate whether problems experienced in a drought which occurred in 2011-2012 could be mitigated through alternative management of the existing reservoir system and/or demand management. This analysis concluded that the 2012 drought in the ACF basin could not have been avoided through creative management of available water in reservoir storage to minimize low flow events. Not only would this not have been possible, it would not even have been desirable. The ACF basin has a finite amount of water in managed storage and there are limits to its capacity to meet both human and ecosystem needs. The implication of these findings suggests that managing our way out of frequent extreme drought events will not always be possible. Droughts will continue to be extremely challenging in the ACF Basin. This finding is especially topical because the State of Florida has filed a lawsuit against the State of Georgia in the US Supreme Court over impacts to the Apalachicola estuary associated with the 2011 – 2012 drought alleging that Georgia is responsible for the impacts (Supreme Court of the United States. 2013).

The public's perception of reservoirs appears to be similar to the public's perception of drinking water: i.e. people do not recognize that there is a limited resource and instead think that managers can simply release or provide more water to solve the problem. In reality, reservoirs have finite capacities and cannot always solve drought or flooding problems simply by releasing or retaining more water. Put simply, it should not be assumed that there is enough water storage to meet expectations from all ACF water users under severe drought conditions. It is possible to have problems beyond the management capacity of a watershed. Given the high uncertainty in how ecosystems and species may or may not respond to changes in flow, much more work is needed to determine how to best respond to drought events within the water management capacity of the ACF basin. For instance, if the intent is to ensure discharge gains in the Apalachicola River during drought, both the RIOP and any management actions in either the Chattahoochee or Flint River basin would have to prioritize water allocation between the Apalachicola River and upstream storage reservoirs.

The next chapter of this dissertation (Chapter 4) was dedicated to using the river basin modeling tool to evaluate to what degree demand management in the form of significantly reducing agricultural irrigation withdrawals could contribute to resolving current problems of downstream flow levels. In this chapter an analysis was done on the effects of modifying agricultural irrigation demands in the Flint basin on both flows in the Apalachicola River and on reservoir elevations in the Chattahoochee basin. The results of this study show that adoption of alternative agricultural practices that reduce irrigation water demands could have substantial effects in the ACF basin. Demand savings incurred upstream, however, do not always directly translate to elevated flows downstream. The differences in irrigation withdrawal effects on stream flow manifest in both greater stream flow downstream of the agricultural irrigation (e.g. lower Flint River and the Apalachicola River) and in increased elevations at the upstream Federal storage reservoirs in the Chattahoochee basin. In years when there is a lesser need for augmentation from the federal storage reservoirs to meet minimum flow requirements from Jim Woodruff Dam, nearly all of the water savings from decreasing irrigation demands would translate into increased flow in the Apalachicola River. The significance of these findings is that governmental interests in Florida suggest in their Supreme Court lawsuit that reducing agricultural demands in the Flint basin would help mitigate the low flows experienced during extreme drought events (Supreme Court of the United States, 2013), but the results of this research suggest that this is not necessarily the case. To achieve this result, reservoir operations would also have to be altered. Based on ongoing research on agricultural irrigation practices in the ACF basin, it is plausible that irrigation demands could be decreased substantially in the future if alternative practices are implemented on a large scale. This research also suggests that public policy decisions need to be made concerning how the water saved, as a result of changed irrigation practices, should be allocated between the federal storage reservoirs and the downstream flow needs.

Additionally, evaluation of performance metrics used to translate flow changes to environmental service metrics found that changes to flow would occur at a time and rate which could affect federally listed mussel species and habitat for young-of-the-year sturgeon, but not sturgeon spawning nor floodplain inundation. For a change in management to be beneficial to a given species, the change must occur at a time of year and within a range of flows that are related to the ecological needs of the species. Thus, it is useful to consider that different ecological services in a river system have differing spatial and temporal requirements. Cognizance of these spatial and temporal requirements will help stakeholders and basin managers to construct realistic expectations of ecological effects stemming from reductions in anthropological water abstractions.

The next chapter of this dissertation (Chapter 5) was dedicated to using the river basin modeling tool to evaluate whether the rapid lowering of the largest storage reservoir in the watershed (Lake Lanier) during drought events can be mitigated through managing all the storage reservoirs in a different manner. In this application, an analysis was done on the causal factors for lowering of Lake Lanier during multiple drought events. In evaluating the causal factors, it was found that the relative importance of the individual causal factors will vary from drought event to drought event. This implies that a one-size-fits-all approach to drought management in the ACF basin, which has been the practice to date, is not advisable. Many of the causes for rapid lowering of the elevation of Lake Lanier during various drought events were found to be caused by factors which cannot be controlled by reservoir or demand management actions including: 1) climatically driven factors such as evaporation or severely reduced inflow into Lake Lanier, 2) factors which provide substantial benefits in non-drought times (hydropower releases), or 3) factors that cannot be readily abandoned (minimum release from Buford Dam).

Four factors were identified which could be implemented in an effort to reduce the rapid lowering of Lake Lanier elevations: 1) direct consumptive withdrawals from Lake Lanier, 2) releases directly to Lake Seminole from Lake Lanier in order to meet Jim Woodruff minimum flows, 3) releases made to West Point reservoir that ultimately are used to augment Jim Woodruff minimum release requirements or 4) releases made towards meeting the Peachtree Creek minimum flow. Of these four, two of them had only a very minor role in the precipitous lowering of Lake Lanier during the drought events investigated and therefore could not be expected to have a major effect on the lowering of Lake Lanier elevations.

Further investigation of the remaining two factors concluded that increasing Metro Atlanta demands to the volume requested by the State of Georgia under current reservoir management operations would result in a more rapid decline in reservoir elevations at Lake Lanier, but would have a minimal effect on Jim Woodruff outflow. It was also found that reducing Jim Woodruff Dam minimum flow requirements and consequently reducing the necessary support from Lake Lanier to meet this requirement via balancing with West Point reservoir would result in increased elevations at Lake Lanier, but would also have a negative effect on environmental resources in the Apalachicola River and Bay. The effectiveness of the approach used by the USACE in terminating drought operations in the ACF basin was also evaluated. It was found that changing the trigger from when drought operations are initiated and terminated under the RIOP had minimal effects on reservoir elevations at Lake Lanier, but increased the number of days that the minimum release was provided from Jim Woodruff Dam. Considering that 1) the State of Georgia anticipates a significant increase in consumptive demands for Metro Atlanta, 2) the State of Florida has filed a suit over Georgia's taking of water from the ACF basin and therefore seems unlikely to accept even less water in the future, and 3) the draft WCM proposed by the USACE (USACE 2015) essentially proposes a continuation of the current approach to reservoir management with only minor changes to certain operational parameters, it seems unlikely that anything will be done about the rapid lowering of Lake Lanier during drought events in the near term.

On a more optimistic side, a stakeholder group in a recent report noted that varying reservoir releases based on predictive drought indicators would be beneficial (ACFS, 2015) and made the following recommendations with regard to drought management: 1) the states of Alabama, Florida and Georgia should collaborate in the development of a drought management plan, perhaps in the context of a regional Memorandum of Understanding, that includes defining drought conditions, identifying triggers for actions, delineating responses by water use sectors, and documenting changes in operational strategies; 2) the USACE should utilize predictive drought indicators in the revised Water Control Manual; 3) various combinations of predictive drought indicators can be used that allow operation decisions to be made in drought years that enhance system flows while still preserving adequate reservoir storage during the drought; and 4) the USACE should utilize real-time, adaptive drought management.

As was noted in several of the references included in the previous chapters of this dissertation, the period-of-record for which flow data is available for the ACF basin is the most drought free period in the last 600 years (Stahle *et al.*, 2007; Seager *et al.*, 2009; Wang *et al.*, 2009; Pederson *et al.,* 2012) and the recent major droughts experienced in 2000 – 2001, 2007 – 2008 and 2011 – 2012 may be more representative of the long-term climate in the basin than the relatively drought free period experienced in the period-of-record before 2000.

The way that future water management options have been addressed in the ACF Basin is problematic. There is a need to use modeling tools to ask germane questions regarding the management of the watershed before making critical management decisions. For example, modeling tools could provide valuable information about the influence of the rapid lowering of Lake Lanier on the management of the watershed as was done in Chapter 5. Before a remedy to this lowering can be identified (if one is available) and integrated into the reservoir management approach to the watershed, the cause of the lowering needs to be well understood. An engineering-oriented problem cannot be solved without understanding what caused the problem.

Likewise, in the draft Environmental Impact Statement (DEIS) for the Water Control Manual (USACE 2015), the answer that the USACE proposed was to expand the amount of time that the emergency drought relief trigger was in effect. As was made clear in Chapter 5, however, there is not a direct correlation between how often the drought relief trigger is in effect and outflow from Jim Woodruff Dam or the elevation of Lake Lanier. The USACE's answer does not really address the root of the actual problem or the variability of drought events. This situation could have been avoided by first identifying metrics which would evaluate how well the problem is being addressed and then evaluating alternative approaches using a planning-level river basin modeling tool.

One of the clear lessons of this research is that it takes more than effective modeling tools to address long-standing water disputes. Models can certainly support the resolution of research questions by providing a means for testing alternative approaches to addressing the management of the watershed. But it also takes a process that translates the output of these model runs into societal values and metrics related to the sustainability of ecosystems. When the three states and the Federal government were unable to agree on an Allocation Formula as part of the ACF Compact negotiations, one of the major reasons was that the parties were never able to mutually agree upon a set of criteria or metrics which had to be met for the agreement to be successful (Leitman, 2005). And more recently, during the update of the USACE Water Control Manual for the ACF basin (USACE, 2015), the metrics used to select the preferred alternative in the draft Environmental Impact Statement (DEIS) appeared to have little to do with the sustainable management of the watershed. In reaction, a broad, diverse array of stakeholders including Metropolitan Atlanta (King and Spalding, 2016), navigation interests (B. Houston, Tri-Rivers Waterway Development Association, personal communication), environmental groups (National Wildlife Federation et al., 2016), Federal agencies (US Department of Interior, 2015) and others (Battelle Memorial Institute, 2015; Georgia Water Resources Institute, 2016) criticized the metrics and selection approach used by the USACE. This lack of consensus on such basic performance metrics could presage significant challenges for the USACE when they attempt to have the Final Environmental Impact Statement approved by various stakeholders and state agencies.

In looking towards the future there are several areas which require more attention and research if the ACF basin is to be managed in a sustainable manner. These include: 1) climate change effects on current approaches to water management, 2) improvements of decision analytics to transparently rank alternatives and 3) a process to deal with the uncertainties faced in both current parameters and future conditions. Climate analyses should focus on both projected changes in the volume of precipitation and anticipated changes in timing of rainfall events, including the possibility of fewer rainfall events, but of greater intensity. Improvements of decision analytics would include improving the set of metrics used to determine the acceptability of alternative approaches and using these metrics to determine the course of action, not to justify the course of action. Finally, the uncertainties to be faced in the future can only be addressed through an effective adaptive management program and a regular review and, if necessary, modification of the approach to managing the watershed.

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