FLOW-IMPACT OFFER EVALUATION FOR INCORPORATING GROUNDWATER PERMITS INTO FUTURE IRRIGATION REDUCTION AUCTIONS IN THE FLINT RIVER BASIN

by

DAVID FLYNN

(Under the Direction of Jeff Mullen)

ABSTRACT

Severe drought conditions have been occurring more frequently over the last two decades. In 2001 and 2002, under the authority of the Flint River Drought Protection Act (FRDPA), Georgia's EPD conducted irrigation reduction auctions to buy permits from farmers for the year to conserve freshwater resources, but only targeted surface water permits. Changes to the FRDPA allow for groundwater permit holders to participate in future auctions. This paper evaluates the efficiency of the alternative mechanism, the Flow-Impact Offer (FIO), that utilizes permit-specific aquifer flux ratios to adjust bids from groundwater permits relative to surface water bids. Assessment criteria include water purchased, acres taken out of production, average price paid per acre-inch of water saved, and regional economic impacts. Results indicate using an FIO significantly increases the amount of water saved at a lower average cost per acre inch ($/ac-in), while limiting regional economic losses due to reduced agricultural activity.

INDEX WORDS: Groundwater management, water auction, drought, flux ratio, Flint River Basin, IMPLAN

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

1.1 Background:

For many years, freshwater supplies in Georgia have been considered abundant, with concerns about the impact of severe drought focused more on the western United States. With continual population growth and increased use of water for agricultural purposes, the demands upon Georgia's existing water supplies have increased considerably over the years. The Flint River Basin (FRB) has received special attention as it is where most the state's agricultural production occurs. Simultaneous pumping from numerous wells in a concentrated area near a river/stream can have a significant effect on in-stream flows. Water management issues have become more of a concern and require evaluation of the effects of intensive groundwater pumping on stream flow conditions and the effects it has on surface water sources.

The FRB covers approximately 8,460 square miles and the Flint River stretches 349 miles from the southern edge of the Atlanta metropolitan area in the upper Piedmont region to the wetlands of the Coastal Plain in the southwest corner of Georgia (Couch and McDowell, 2006). South of Dooly County, the Flint River and some of its tributaries are in hydraulic connection with the Floridan aquifer and either receive water from the aquifer or lose water to it depending on the head difference between the streams and the aquifer (Couch and McDowell, 2006). The FRB is divided into six smaller HUC8 sub-basins by the U.S. Geological Survey (USGS): Upper Flint, Middle Flint, Lower Flint, Kinchafoonee-Muckalee Creek, Ichawaynochaway Creek, and Spring Creek (Couch and McDowell, 2006).

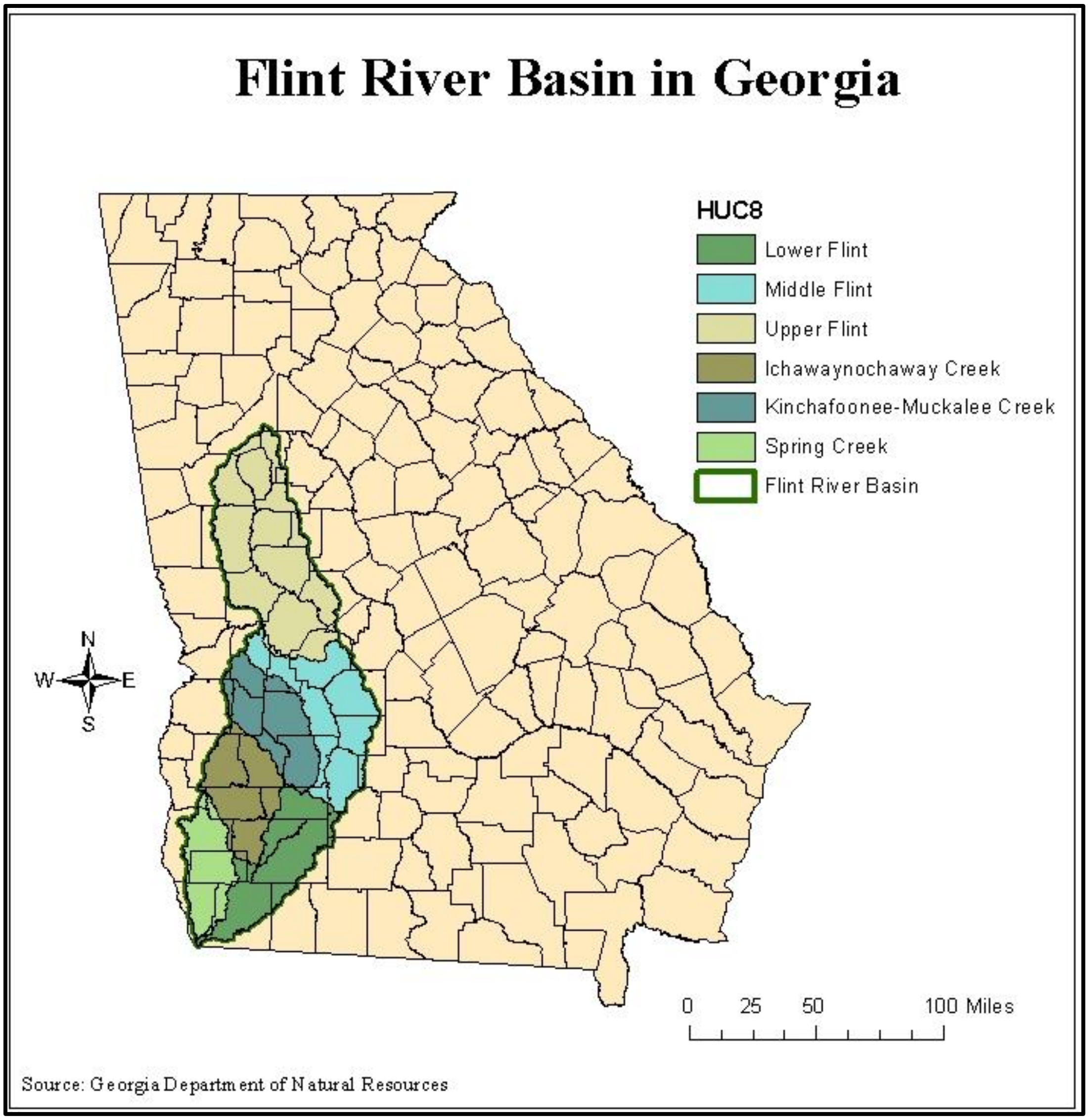


Figure 1: Map of Flint River Basin and HUC8 Watersheds

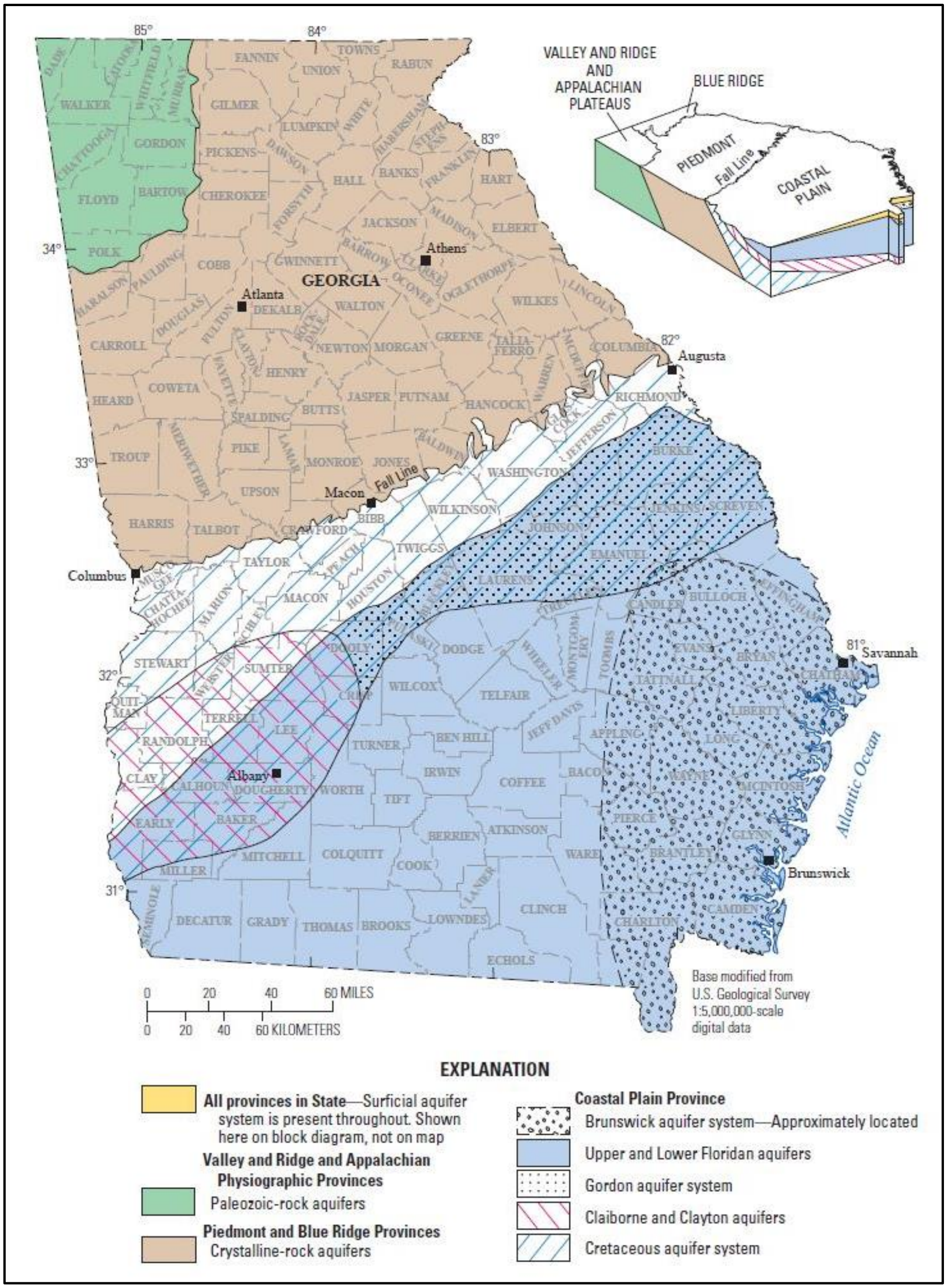


Figure 2: Areas of Major Aquifers in Georgia (Gordan and Painter, 2018)

Aquifer water levels in Georgia typically follow a cyclical pattern and fluctuate depending on the time of year. Water levels rise during the winter and spring months from increased recharge caused by precipitation and decline during the summer and fall months due to increased agricultural pumping and higher evapotranspiration rates (Gordon and Painter, 2018). The rate of groundwater pumping affects the amount of groundwater in storage and the discharge rate from an aquifer (Taylor and Alley, 2001). As groundwater storage is depleted within the radius of influence of pumping, water levels in the aquifer decline and form a cone of depression around the well. In areas having a high density of pumped wells, multiple cones of depression can form and combine to produce water-level declines across a larger area. These declines may alter groundwater-flow directions, reduce flow to streams, capture water from a stream or adjacent aquifer, or alter groundwater quality (Gordon and Painter, 2018).

There are four major aquifers that underlie the Flint River Basin: Cretaceous, Clayton, Claiborne, and Floridan (Clark and Pierce, 1985). The aquifers are separated by layers of clay or silt that impedes vertical flow of water from each other. The aquifers slope towards the southeast and overlie one another. The oldest and lowest layer is exposed farthest to the north along the Fall Line, while the youngest and shallowest layer is exposed farthest to the south (Georgia DNR, 2004). This study focuses on the Floridan, Claiborne, and Cretaceous aquifers because in 1992, the Georgia Environmental Protection Division (EPD) imposed a permanent moratorium on any new water withdrawals from the Clayton that has yet to be lifted (Peck and Gordon, 2013).

The deepest aquifer is the Cretaceous, which is composed of sand, shell, and gravel layers and some kaolin deposits (Georgia DNR, 2004). Water levels in the Cretaceous aquifer are influenced by variations in precipitation and pumping rates (Clarke and Pierce, 1985). Pumping from portions of the Cretaceous can have direct impact on stream flows in several river basins.

Counties located in the Upper Flint region just below the Fall Line such as Dooly, Lee, Macon, Marion, Stewart, Sumter, Taylor, and Webster use the aquifer as a source of groundwater for agricultural irrigation. The Cretaceous aquifer system is unconfined near the Fall Line and becomes confined where the Claiborne and Clayton aquifer systems begin. Water well depths typically range between 30 to 750 feet and yield ranges from 50 to 1,200 GPM (gallons per minute) (Gordon and Painter, 2018).

Overlying the Cretaceous is the Claiborne aquifer. The Claiborne is a sandy aquifer that contains more fine-grained sediment than the Cretaceous (Georgia DNR, 2004). The Claiborne is very productive in Sumter, Dooly, Lee, and Dougherty counties and is heavily relied upon for agricultural, industrial, and municipal water uses (Torak and McDowell, 1996). Water levels are mainly affected by precipitation and local and regional pumping activity (Hicks et al., 1981). The Claiborne has large outcrop area and will usually recharge annually if there is sufficient rainfall (Torak and McDowell, 1996). Water well depths within the aquifer system range between 20 to 450 feet. Yield ranges from 150-600 GPM, but may exceed 1,500 GPM (Gordon and Painter, 2018).

The Lower and Upper Floridan aquifers lies above the Claiborne aquifer, and is one of the most productive aquifers in the country and is the main source of groundwater in the FRB. The Upper and Lower Floridan aquifers are generally confined and consist of limestone, dolomite, and calcareous sand (Gordon and Painter, 2018). In Georgia, the Upper Floridan aquifer underlies most of the Dougherty and Coastal Plain (Miller, 1986). The aquifer is confined throughout most of its extent but is exposed throughout most of the Dougherty Plain and will usually completely recharge if there is sufficient rainfall every year (Clarke et al., 1990). In the southwestern part of Georgia, the Upper Floridan aquifer ranges in thickness from about 50 ft in the northwest to about 475 ft in the southeast (Hicks et al., 1987). The Flint River and its tributaries receive hundreds of millions of gallons of water every day from the porous limestone of the Floridan aquifer (Georgia DNR, 2004). At the surface in parts of the Floridan aquifer are directly hydraulically connected with much of the surface water drainage networks in the Lower Flint River Basin where the limestone is exposed (Georgia DNR, 2004). Water well depths will range from 40 to 900 feet, and yield ranges from 1,000 to 5,000 GPM and may exceed 11,000 GPM (Gordon and Painter, 2018).

1.2 Groundwater and Surface Water Interaction:

Understanding hydrologic connectivity between surface water and groundwater has become an issue of concern when it comes to drought management in the FRB. The management of groundwater resources is crucial to the protection of surface waters where groundwater supports baseflow and serves as the major water resource. Dense and intensive groundwater pumping near rivers and streams can cause changes in regional hydrologic gradients resulting in stream flow depletion (Sophocleous, 2002). Reduced stream flow can affect channel morphology, lower assimilative capacity, alter stream temperature, threaten aquatic biota, and reduce nutrient loading to downstream communities (Golladay et al., 2004). Groundwater and surface water are hydraulically linked in many southeastern Coastal Plain streams and should be treated as parts of the same hydrologic system when dealing with water resource management issues. Groundwater discharge from the Upper Floridan aquifer maintains baseflow and helps to sustain stream flow during drought, offers thermal refuge to aquatic life, and provides a source of high-quality water that helps mitigate the effects of wastewater discharge directly into the Flint River (Opsahl et al., 2003). A variety of approaches based on hydrograph separation, hydrologic modeling, geochemical tracing, and synoptic discharge measurements have been used to better understand groundwater and surface water interactions in the southeastern United States (Hayes et al., 1983; Hicks et al., 1987; Mosner, 2002).

An annual average of nearly 474 MGD of groundwater and 200 MGD of surface water was withdrawn from the Flint River Basin in 2010 (Lawrence, 2016). In the Upper Flint River sub-basin, 84 percent of withdrawals are from the Crystalline-rock aquifer and 16 percent from the Cretaceous aquifer. In the Middle Flint River sub-basin, 28 percent of withdrawals from the Claiborne, 26 percent from the Cretaceous, 26 percent from the Upper Floridan, and 20 percent from the Clayton. In the Kinchafoonee-Muckalee Creek sub-basin, 60 percent of the withdrawals are from the Clayton, 20 percent from the Claiborne, and 20 percent from the Cretaceous aquifer. In the Lower Flint River sub-basin, almost all groundwater withdrawals are from the Upper Floridan. In the Spring Creek sub-basin, 65 percent of groundwater are from the Upper Floridan aquifer. In the Ichawaynochaway Creek sub-basin, 40 percent of groundwater withdrawals are from the Clayton and 40 percent from the Claiborne aquifer (Lawrence, 2016).

1.3 Agricultural Water Use in the Flint River Basin:

The FRB uses more water to irrigate crops than any other area in the state. Since the introduction of center-pivot irrigation systems in the 1970s, the Upper Floridan aquifer has been used as the primary water source for irrigation in southwestern Georgia (Hicks et al., 1987). Approximately 80% of the water used for irrigation in the Lower Flint is extracted from the Upper Floridan aquifer (Hicks et al., 1987). Between 1970 and 2000, irrigated acreage in the Lower Flint increased from 146,000 to 1,500,000 acres, accounting for over half of statewide totals (Torak and Painter, 2006). The main crops grown in the FRB for agriculture are corn, cotton, peanuts, and soybeans, along with pecans and supplementary horticultural products (Wolfe and Stubbs, 2013).

According to the 2012 “USDA Agricultural Census: Total Irrigated Acres”, the 33 counties in the FRB had 1,520,252 acres of land in irrigated farms (USDA, 2013). Currently, agricultural irrigation in the FRB encompasses as much as 90% of the water used during the April-September growing season (Couch and McDowell, 2006). During these months, groundwater withdrawals for irrigation are a cause of concern for reduced stream flow throughout the FRB (Torak and McDowell, 1995; Albertson and Torak, 2002).

Except for the Upper Flint River sub-basin, groundwater is the primary source of water used in the FRB. During 2010, agricultural withdrawals averaged 501 MGD in the FRB, with 80 percent being used from groundwater sources (Lawrence, 2016). Agricultural withdrawals were greatest in the Lower Flint River (143.4 MGD), Spring Creek (118.2 MGD), and Ichawaynochaway Creek (96.59 MGD) sub-basins, which accounted for 71 percent of all agricultural withdrawals in the FRB (Lawrence 2016). The remaining 29 percent of withdrawals were from the Middle Flint River sub-basin (71.25 MGD), Kinchafoonee-Muckalee Creek (64.08 MGD), and Upper Flint River (7.9 MGD) sub-basins (Lawrence, 2016).

1.4 Endangered Species:

The Flint River has been recognized as one of the most endangered rivers in the country over the last decade. Surface water and groundwater withdrawals in the FRB can have a negative impact on stream ecology and the habitat of sensitive aquatic species. Peak irrigation pumping in the Lower Flint corresponds with periods of low summer flows. This worsens low-flow conditions such as increased stream temperatures and lowered dissolved oxygen levels (Gagnon et al., 2004). Currently, the U.S. Fish and Wildlife Service (USFWS) protects six species of freshwater mussels in the FRB (USFWS, 2019). Four species have been declared endangered and two species have been identified as threatened under the Endangered Species Act due to habitat loss and alteration. The four endangered species are the fat threeridge (Amblema neislerii), shinyrayed pocketbook (Lampsilis subangulata), Gulf moccasinshell (Medionidus penicillatus), and oval pigtoe (Pleurobema pyriforme). The two threatened species are the Chipola slabshell (Elliptio chipolaensis) and purple bankclimber (Elliptio sloatianus) (USFWS, 2019). Mussels have been shown to provide valuable ecosystem services by significantly altering nutrient processing in freshwater ecosystems (Howard and Cuffey, 2006). In 2006, low flows, extreme drought, and declining mussel populations prompted the USFWS to designate 1,158 river miles in the Lower ACF as critical habitat for federally listed mussels (Rugel et al., 2016). The Lower Flint also contains a significant population of gulf striped bass. During summer, the bass take thermal refuge in the cooler water of the blue-hole springs that are dependent on adequate ground-water discharge. Groundwater withdrawals from the Floridan aquifer may lower aquifer head, reduce spring flow, and deprive the bass of this thermal refuge. (Couch and McDowell, 2006).

1.5 Climate and Drought Concerns:

Average annual rainfall in the FRB ranges from 48-54 in/yr.; most of which falls between early November and mid-April (University of Georgia Weather Network, 2019). Extreme temperatures can reach as high as 110°F to as low as 10°F, but rarely last longer than a few days. In the Upper Flint, the average January temperature (min-max) is between 31-55°F. The average July temperature is between 67-96°F. In the Lower Flint, the average January temperature is between 34-62°F. The average July temperature is between 71-96°F (University of Georgia Weather Network, 2019). However, droughts are a normal aspect of Georgia’s climate and the state has experienced several periods of prolonged drought conditions from 1986-1988, 1998-2002, 2007-2009, 2011-2013, and 2016-2017 (NDMC, 2019).

The Flint River Regional Water Development and Conservation Plan was initiated by the Georgia EPD in October 1999 in response to growing concern over agricultural irrigation usage in southwest Georgia (Couch and McDowell, 2006). A moratorium was imposed on the issuance of new water-use permits in the FRB (eventually lifted in 2006). In 2000, the Georgia Legislature enacted the Flint River Drought Protection Act (Act), which has been revised on several occasions since (O.C.G.A. 12-5-540-550). The purpose of the Act was to provide the EPD with an instrument for reducing agricultural irrigation in the FRB during periods of severe drought. On March 1 of each year, the Director of the EPD is required to announce whether or not the upcoming summer will be characterized by severe drought conditions (O.C.G.A. § 12-5-546(a)). If severe drought conditions are predicted, the EPD must determine a certain number of acres within the affected areas to not be irrigated that year to maintain the acceptable stream flows (O.C.G.A. § 12-5-546(b)). The Act required that the acreage reduction target be implemented via an "irrigation reduction auction" where water permit holders in the affected areas are given the opportunity to give up irrigating their land for the year in exchange for a certain sum of money per acre (O.C.G.A. § 12-5-547). To date there have been two irrigation auctions held in 2001 and 2002, but the EPD did not reach the target acreage reduction in either one.

1.6 2001 and 2002 Irrigation Reduction Auction Background and Results:

The first irrigation reduction auction (auction) was held in March 2001 and had an available budget of $10 million and an acreage target of 100,000 acres (Petrie et al., 2004). The EPD's goal was to pay an average of $100/acre to meet the goal of 100,000 acres. Participation was limited to those with permits to irrigate from surface water sources (Petrie et al., 2004). In the 2001 auction, 576 permits covering 98,170 acres, were declared eligible to participate (Petrie et al., 2004). Of those eligible, 194 farmers registered to make offers for 347 permits, covering 61,806 acres (Petrie et al., 2004). This number was already lower than the target acreage goal set forth by the EPD.

The auction was conducted simultaneously at eight locations in the FRB. At the beginning of the auction, permit-holders were asked to submit a per-acre price at which they were willing to suspend irrigation on all acres covered by the specified permit. If the offer was accepted, the participant received the per-acre price multiplied by the number of acres covered by the permit. If another permit-holder submitted a different per-acre offer price (and the offer was accepted) they would receive their own per-acre price multiplied times the number of acres covered by their permit (Petrie et al., 2004). While irrigation was prohibited, the permit-holder was able to plant crops on the land and retained the permit for use in future years. In total, there were five rounds of this exchange with the EPD director determining which offers to accept or decline, starting with the lowest-priced offers.

Overall, 85 percent of the acreage was offered at prices between $100 and $500 (Petrie et al., 2004). In the final round, the EPD director decided to accept all offers through $200/acre. At the end of the auction, a total of 33,006 acres (34% of eligible acres or 53% of registered acres) were taken out of irrigation at a total cost of $4,478,842 with an average price of $135.70/acre (Petrie et al., 2004).

In 2002, 686 permits were declared eligible for the auction (Petrie et al., 2004). For this auction, the Georgia EPD sent letters to all eligible auction participants informing them that they would entertain all offers up to a maximum price of $150/acre, with the lowest priced offers being accepted first until the target acreage was acquired (Petrie et al., 2004). During the 2002 auction, 40,861 acres were taken out of irrigation at a total cost of $5,228,574 with an average price of $127.96/acre (Petrie et al., 2004). The average accepted offer price was lower in 2002 than in 2001 ($127.96/acre compared with $135.70/acre) and more acres were taken out of irrigation (40,861 versus 33,006). 87 percent of farmers who accepted a buyout price still planted on the land covered by their permit in 2001 and that number increased to 90 percent after the 2002 auction (Petrie et al., 2004).

Though both auctions succeeded in removing acreage from irrigation, the auctions conducted under the Act had several noticeable problems. In the 2001 auction, many participants were compensated for land that had not been recently irrigated and both auctions failed to remove the highest water-use cropland from irrigation (Couch and McDowell, 2006). Both auctions also only focused on surface water permit holders and did not allow groundwater permit holders to be declared eligible. If an irrigation reduction auction was held in 2019 under these rules for all permits that are located in the FRB, nearly 75% of permit holders and approximately 550,000 irrigated acres would be excluded from participation (Betts, 2019). However, in 2006, the rules were changed in order to grant eligibility to groundwater permit holders (Couch and McDowell, 2006).

During July 2012, the Georgia EPD implemented a moratorium on certain new permit applications for groundwater withdrawals from the Upper Floridan aquifer and on permit applications for surface water pumping from the Spring Creek, Ichawaynochaway Creek, and Muckalee Creek sub-basins (Gordon and Gonthier, 2017). The moratorium also applies to requests to modify existing permits to increase withdrawals or increase the number of irrigated acres. Aquifers such as the Claiborne and Cretaceous that underlie the Upper Floridan may be viable alternative sources of groundwater in the near future as fewer wells have been drilled in these aquifers. However, there is less information about their depths, thicknesses, water quality, and water-bearing characteristics (Gordon and Gonthier, 2017).

1.7 Problem Statement:

Surface water and groundwater permits do not have the same effect on a stream. Withdrawals from surface water have a one-to-one ratio effect—for every acre-inch of water withdrawn exactly one acre-inch of water is lost from the stream. That is not the case with groundwater withdrawals. The effects on stream flow of an individual groundwater well depends on its location near the stream, pumping rate, connectivity of the stream to the aquifer, and duration of pumping. The cone of depression within the aquifer created by the groundwater withdrawal will initially be filled by groundwater, but recharge from the stream to the aquifer may occur. This percent recharge is referred to as the stream-to-aquifer flux ratio (flux ratio). The flux ratio is the proportionate effect of the amount of water taken out of an aquifer compared to the amount that is lost in the stream. If the flux ratio of the withdrawal of an individual groundwater permit can be estimated at a specific location, this information can be used when evaluating bids from groundwater permits in future irrigation buyout auctions. Note that the flux ratio of the withdrawal from a surface water permit is equal to one.

1.8 Objectives:

There is a real need to estimate the impacts of groundwater withdrawal effects on in-stream flow at the individual permit scale within the FRB. The overall objective of this paper is to develop a methodology for comparing the economic efficiency of alternative rules for assessing bids from groundwater permit holders in future irrigation buyout auctions. To accomplish this requires us to estimate the flux ratio for each individual groundwater permit in the FRB, estimate expected water use during drought for a representative acre of irrigated land in each county within the FRB, simulate auctions under alternative rules for assessing groundwater bids, and compare performances of auction rules using a variety of auction metrics including average bids accepted, irrigated acres purchased, total expenditure, total water purchased, price per acre-inch of water saved ($/ac-in), and regional economic impacts from reduced agricultural production.

I hypothesize that auction rules that specifically take this flux ratio into account will perform better across these metrics than rules that do not. I also hypothesize that the regional economic impact will be smaller in the Upper Flint than in the Lower Flint.

1.9 Layout of Thesis:

The following is a brief overview of the subsequent chapters in this thesis, highlighting the primary objectives that will be accomplished:

- Chapter 2: Methodology: The methodological foundations are discussed in this chapter, justifying the approach and techniques used to determine the individual stream-to-withdrawal flux ratio of an agricultural groundwater well permit, development of a representative irrigated acre, the rules governing the simulated auctions, and methods used for detailing the estimation of regional economic impacts from reduced agricultural production.
- Chapter 3: Results and Discussion: This chapter introduces and explores the results from the simulated irrigation auction method used and compares the 2002 rules and FIO rules scenarios to see if there are any potential efficiency gains from using the Flow-Impact Offer method in future auctions.

- Chapter 4: Conclusion and Recommendations: In this final chapter, conclusions from the entirety of this research are presented, along with recommendations for future research.

Chapter 2: Methodology

2.1 Introduction:

In this chapter I expand upon the “Flow-Impact Offer” (FIO) proposed in Mullen (2019) as a mechanism for the prioritization of groundwater permits in future irrigation buyout auctions. Section 2.2 describes the components of the FIO developed by Mullen (2019). Sections 2.3 and 2.4 detail alternative ways to calculate the flux ratio associated with individual groundwater permits in the FRB. Section 2.5 describes the irrigation permit data for the FRB. Once a flux ratio is assigned to a permit, auctions can be simulated by randomly assigning bids to permits. The rules governing the auction determine which simulated bids are accepted. The simulation exercise and auction rules are described in Section 2.6. To estimate the impacts of a set of auction results on water use, agricultural production, and regional economic impacts requires the development of a “representative acre” of irrigated land for each county in the FRB. The development of a representative acre is described in Section 2.7. Section 2.8 explains how water use on a representative acre is estimated, and Section 2.9 details the estimation of regional economic impacts.

2.2 Flow-Impact Offer Equation:

In his 2019 paper, Mullen developed a “Flow-Impact Offer” that can be compared across groundwater and surface water bids (Mullen, 2019). The proposed flow-impact offer (FIO) is represented below:

$$\textbf{Flow-Impact Offer (\$/acre)} = \textbf{(Offer (\$/acre)/Flux Ratio)} \times \textbf{Uncertainty Ratio} \quad (2.1)$$

Here, the original offer made by a groundwater permit holder is divided by the flux ratio. If, at a particular permit location, stream flows are expected to be reduced by only half the volume of a groundwater withdrawal, then, for a given offer ($/acre), the flow you are purchasing by preventing a withdrawal is twice as expensive as the flow purchased by preventing a surface water withdrawal (Mullen, 2019). The uncertainty ratio is an additional inflationary variable that can be used to reflect the inherent uncertainty associated with the estimation of the flux ratio (Mullen, 2019). The simulation exercises in Mullen (2019) were conducted by randomly assigning a flux ratio to each groundwater permit in the FRB. In this thesis, I conduct similar simulations, but use a combination of methods to more accurately estimate the flux ratio for each permit.

2.3 Determining First Set of Flux Ratio Range:

For the simulation exercise, all surface water permits were given a flux ratio of 1. For groundwater permits, two sets of flux ratio ranges were used to determine a value range that each individual groundwater permit would realistically lie between.

The first set of flux ratios used, hereby denoted as LB Flux (Lower Bound Flux Ratio) and UB Flux (Upper Bound Flux Ratio), were calculated using the Web-Based STRMDEPL08 software found on the Michigan Water Science Center's website (available at: https://mi.water.usgs.gov/software/groundwater/CalculateWell/index.html). The software is used for calculating stream flow depletion by nearby pumping wells. It is based on STRMDEPL08 (Reeves, 2008) and STRMDEPL (Barlow, 2000). Considering the information needed to parameterize the model (see Figure 3, below), and a time constraint, the "Fully penetrating stream with no streambed resistance (Jenkins, 1968)" equation was used (MWSC, 2013).

Figure 3: Stream Flow Depletion Equation used from MWSC Website (MWSC, 2013)

The equation used to describe the analytical solution for a system with a stream that fully penetrates the aquifer with no streambed resistance between the stream and the aquifer is expressed as Equation 2.2 (Reeves, 2008; Glover and Balmer, 1954; Jenkins, 1968):

$$\mathbf{Q_s = Q_w erfc\left(\sqrt{\frac{d^2 S}{4Tt}}\right)} \qquad (2.2)$$

Where:

Q_s	is the rate of streamflow depletion (cubic length per time)
Q_w	is the pumping rate (cubic length per time)
erfc()	is the complementary error function (dimensionless)
d	is the distance from the well to the stream (length)
S	is the storativity or specific yield of the aquifer (dimensionless)
T	is the transmissivity of the aquifer (square length per time)
t	is the time

The major assumptions needed to use the equation as noted in Reeves (2008) are:

- horizontal flow dominates any potential vertical flow so that the Dupuit assumption is valid;
- the aquifer is homogeneous, isotropic, and has constant saturated thickness;

- the aquifer is either confined or changes in hydraulic head in the aquifer are minor compared to the saturated thickness, allowing the equation describing ground-water flow to be linearized;
- the stream is straight, infinitely long, and fully penetrates the aquifer;
- the pumping does not change the stage of the stream;
- the hydraulic conductivity of the streambed is similar or greater than the aquifer and does not resist groundwater flow;
- there is no stream bank storage;
- the pumping rate is constant; and
- the aquifer extends to infinity away from the stream.

This equation reveals that stream flow depletion depends on aquifer properties, distance from the well to the stream, and duration of pumping. Initially after pumping, stream flow depletion is small and the source of water to the well is from storage in the aquifer. As time approaches infinity, the volume of stream depletion approaches the volume pumped and is determined by aquifer properties and the distance from the well to the stream. Stream depletion also continues after pumping stops due to residual effects (Jenkins, 1968). The effects of intermittent pumping are approximately the same as those of continuous pumping of the same volume within large ranges of intermittency (Jenkins, 1968). Departure from these assumed conditions may cause actual flux ratios to be either greater or less than the values determined by methods used in this paper.

Values of several different independent variables that include the distance (ft.) a well is from a stream, transmissivity (ft^2/day) of the associated aquifer, storage coefficient of the aquifer, pumping rate (GPM), and days of pumping are required. Distance to stream of each groundwater permit was obtained by using ArcMap 10.5.1. Shapefiles of all the river basins in Georgia and rivers and streams in Georgia were downloaded from a .ZIP file from the Georgia Department of

Natural Resources – EPD "Geographic Information Systems GIS Databases and Documentation" webpage (GaEPD, 2019). The .xlsx file that contains data on the list of all agricultural permits within the Flint River Basin was imported and georeferenced, as each permit was provided with an X and Y coordinate associated with it. The GCS_WGS_1984 geographic coordinate system and the WGS_1984_World_Mercator projected coordinated system were used for georeferencing. The distance tool with ArcMap 10.5.1 was then used to calculate approximate distance each permit is to the nearest stream or river. The distance measurement was then converted from meters to feet using the conversion rate of 1 meter = 3.2808 feet.

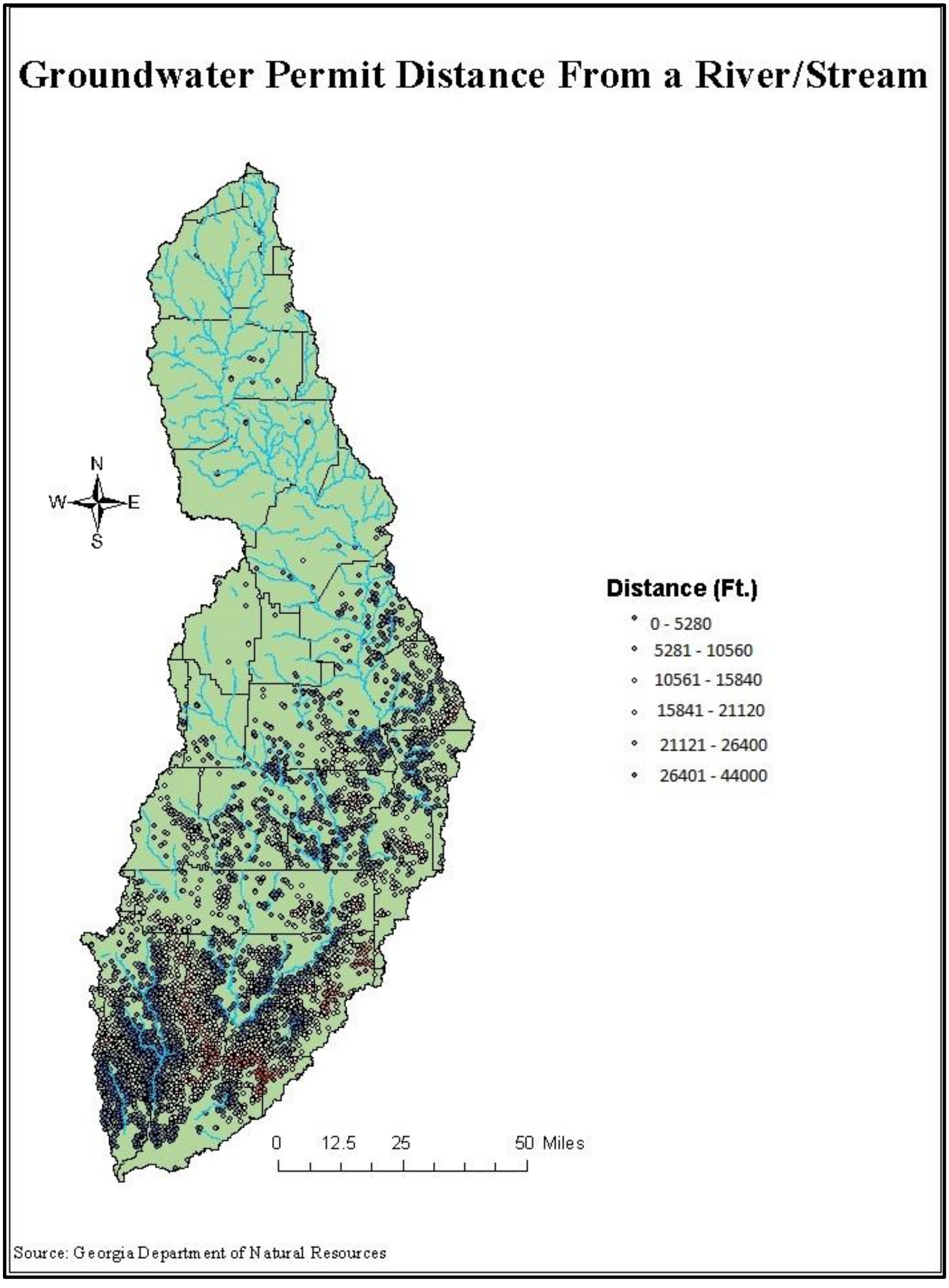


Figure 4: Groundwater Permit Distance from a River/Stream

Days of pumping was set at 160 days. This number was obtained from the UGA Extension's "Planting Guide for Row Crops in Georgia" that lists the estimated days to maturity for all crops grown in the state (Lee and Johnson, 2014). It takes corn 100-125 days to mature, cotton 140-160 days, peanuts 120-150 days, and soybeans 145-160 days (Lee and Johnson, 2014). Since the Jenkins equation assumes constant pumping and no farmer is ever pumping water constantly for such a prolonged period of time, 160 days is safe to assume to be the highest possible upper limit boundary when determining flux ratios.

Transmissivity rates were needed for the Floridan, Claiborne, and Cretaceous aquifers. Transmissivity rates for the Floridan were determined based on the transmissivity map and spatial datasets published by Kuniansky et al. (2012). The map presented (Figure 5) is based on interpolation of 1,487 values of transmissivity throughout the entire Floridan Aquifer System (FAS) (Kuniansky et al, 2012). The transmissivity values in the dataset range from 8 to 9,000,000 ft^2/day, with the majority of the values ranging from 10,000 to 100,000 ft^2/day.

In ArcMap 10.5.1, the aquifer pumping test sites point data were overlaid with the point data of the location of agricultural permits (Figure 6). The transmissivity quantile map was then used to determine the transmissivity of each surrounding groundwater permit. Instead of using the ranges given in the Kuniansky et al. (2012) map as they varied greatly throughout southwest Georgia, each permit was given the transmissivity rate of the nearest aquifer pumping site within said quantile based on distance of the quantile shapes within the map. For instance, if a testing site had a transmissivity rate of 42,000 ft^2/day, it would lie with the quantile 25,000 to 50,000. All of the surrounding permits were assigned a transmissivity of 42,000 ft^2/day, instead being randomly assigned a value between 25,000 to 50,000.

For the Claiborne aquifer, the McFadden and Perriello (1983) transmissivity map was used (Figure 7). Transmissivity in the Claiborne aquifer is more evenly distributed than the Floridan aquifer, although slight variations have been calculated (Gordon and Gonthier, 2017). Transmissivity values throughout most of the Claiborne aquifer are between 2,000-6,000 ft^2/day ranges (McFadden and Perriello, 1983). The highest values occur east of the Flint River in Crisp and Dooly County, where transmissivity values over 10,000 ft^2/day have been recorded (McFadden and Perriello, 1983). Uniform distribution of transmissivity in the Claiborne aquifer is a result of its thickness not varying greatly over short distances. For these reasons, we assume uniformity at the county-level and use the average of the ranges in the quantile map at the county level (ex. If range was 2,000 to 5,000, then 3,500 was used). Because transmissivity rates of the Cretaceous aquifer are not well documented and hard to obtain, transmissivity rates from the Claiborne aquifer were used in place.

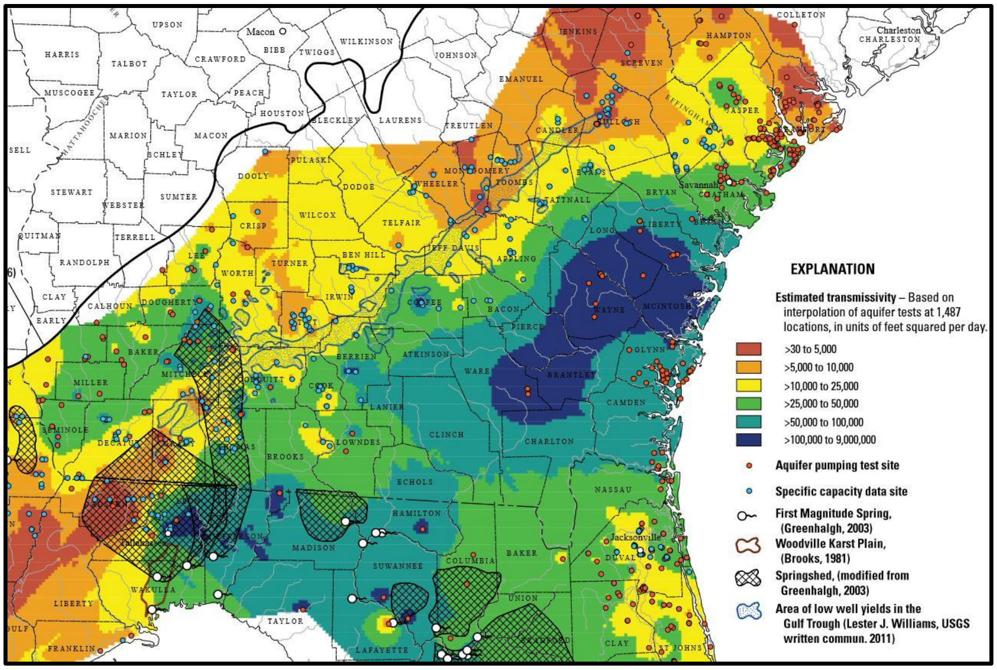


Figure 5: Transmissivity Map of Floridan Aquifer (Kuniansky et al., 2012)

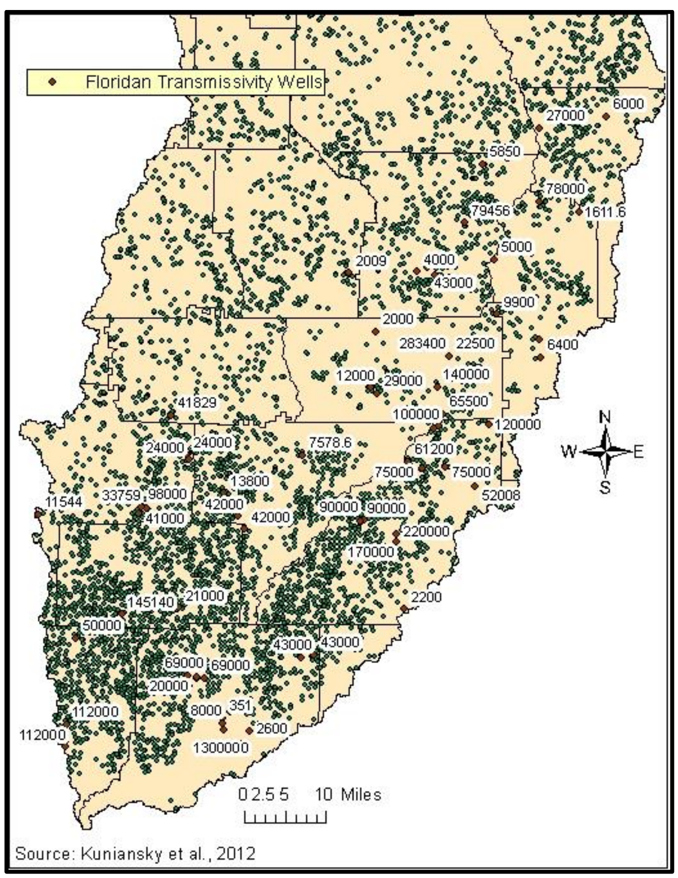


Figure 6: Floridan Transmissivity Wells with FRB Agricultural Permits

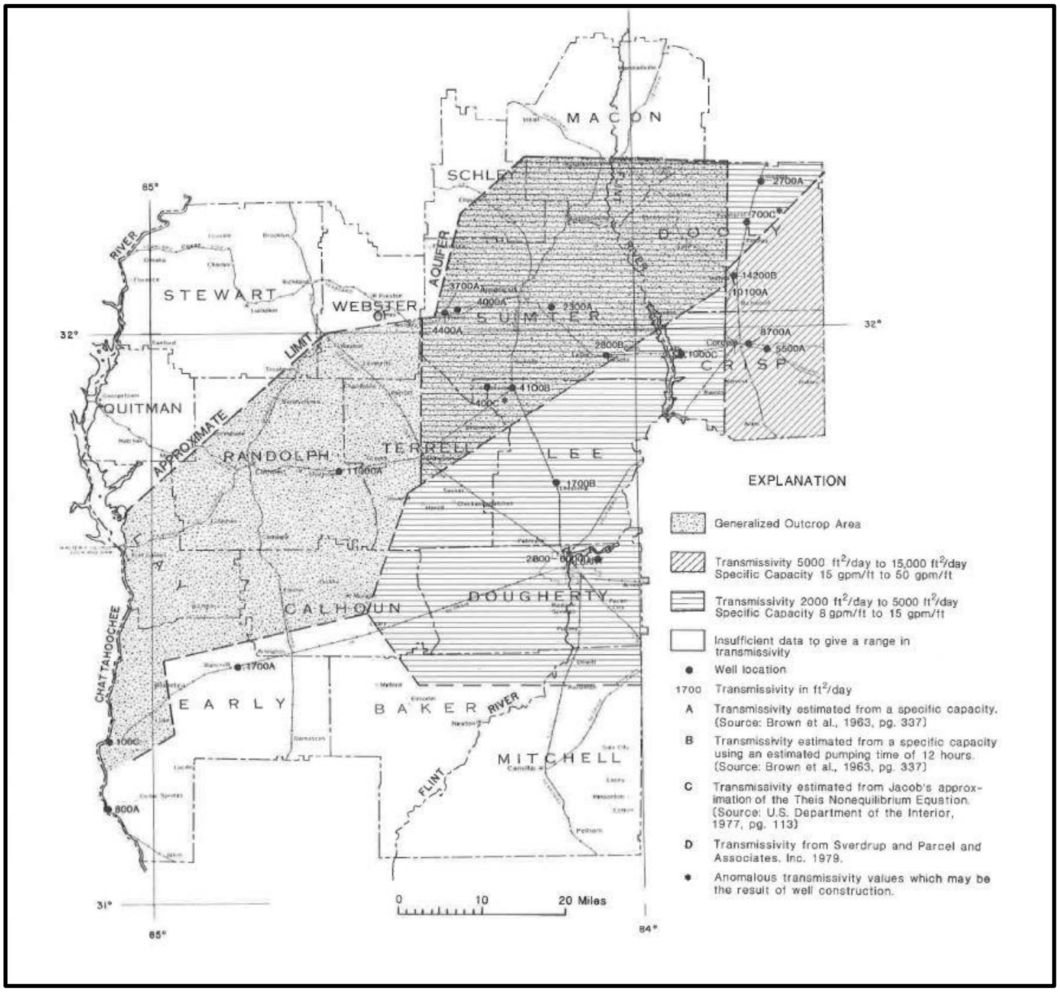
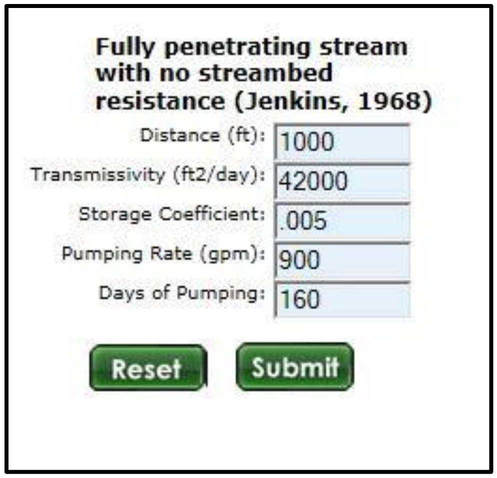


Figure 7: Transmissivity Map of the Claiborne Aquifer (McFadden and Perriello, 1983)

There is little information available on storage coefficients for the aquifers used in the study area. Storage coefficients for groundwater permits that draw from the Floridan aquifer were based off of Bush and Johnson (1988). Values between $1x10^{-2}$ to $1x10^{-3}$ are mostly recognized throughout southwest Georgia as they reflect the semi-confined nature of the system where the aquifer is very close to land surface (Bush and Johnson, 1988). The average of the range, 0.005, was used for all groundwater permits that draw from the Floridan aquifer system. For groundwater permits that draw from the Claiborne aquifer system, a value of 0.0005 was used for the storage coefficient as it is the average of the coefficients estimated in Gonthier and Gordon (2016). The values used for the Claiborne aquifer were again used for the Cretaceous aquifer from lack of data.

After all necessary input variable data were obtained, each permits variable had to be put in one at a time and interpreted. The results are given in cubic feet per second (ft^3/sec) and were converted back to gallons per minute (GPM) with the conversion rate of 1 ft^3/sec = 448.8 GPM. A denominator of the pumping rate associated with each permit was used for all groundwater permits provided in the FRB. This was done to obtain the flux ratio as a measurement of stream depletion. The LB Flux was obtained using the 1-day continuous pumping stream depletion value and the UB Flux was obtained using the 160-day continuous pumping stream depletion value.

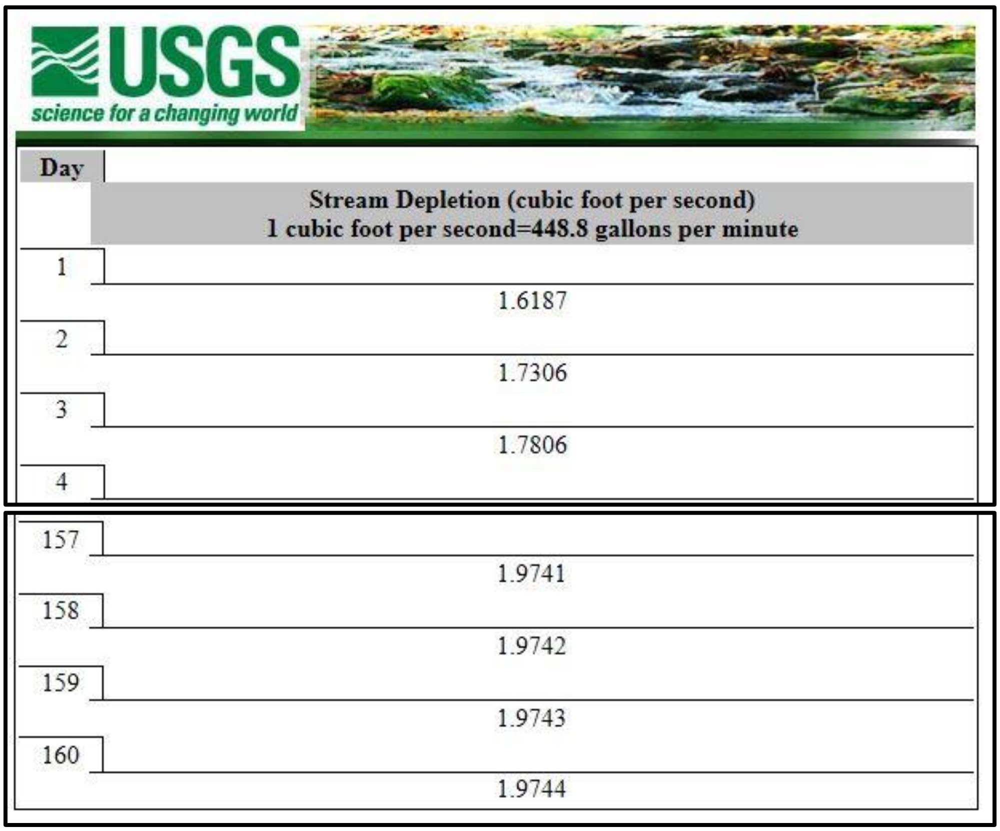
For example, a well that pumps from the Floridan aquifer with a transmissivity rate of 42,000 ft^2/day, storage coefficient of 0.005, and is 1,000 feet away from a stream has a 1-day stream depletion value of 1.6187 ft^3/sec. This is equivalent to 1.6187 x 448.8 = 726.47 GPM. The LB Flux ratio for this permit would be 726.47GPM / 900GPM = 0.807. The same permit has a 160-day stream depletion value of 1.9744 ft^3/sec, equivalent to 1.9744 x 448.8 = 886.11 GPM. The same permit's UB Flux ratio would be 886.11GPM / 900GPM = 0.985. These calculations were done for all 3,951 groundwater permits.



Fully penetrating stream with no streambed resistance (Jenkins, 1968)

Distance (ft):	1000
Transmissivity (ft2/day):	42000
Storage Coefficient:	.005
Pumping Rate (gpm):	900
Days of Pumping:	160

Reset Submit



USGS
science for a changing world

Day	Stream Depletion (cubic foot per second) 1 cubic foot per second=448.8 gallons per minute
1	1.6187
2	1.7306
3	1.7806
4	
157	1.9741
158	1.9742
159	1.9743
160	1.9744

Figure 8: Example on How to Use STRMDEPL08 Software on the MWSC Website

2.4 Determining Second Set of Flux Ratios:

The second set of flux ratios used in the simulation exercise use the LB Flux and UB Flux ratios calculated through the method above for each permit, and then multiply each one by the baseflow ratios calculated from the Baseflow Filter Program developed by the Environmental Risk Assessment Management System (eRAMS) at Colorado State University (Wible and Arabi, 2013). The Baseflow Filter Program is available on the eRAMS Flow Analysis website (https://erams.com/map/). The Baseflow Filter Program uses observed stream flow data to separate total stream flow into baseflow and storm flow and reports an average fraction of the total flow that is baseflow (Wible and Arabi, 2013).

These set of flux ratios are denoted as Flux Low and Flux High. Baseflow here is defined as the percentage of water in a river or stream that is made up of groundwater or deep subsurface flow. This could be useful to use when determining the flux ratio of an individual permit because it illustrates that the highest flux ratio a permit could have would be the baseflow percentage. For example, if a stream consists of 60% groundwater and a specific groundwater permit is determined to have the max flux ratio of 1, then it really should have a flux ratio of 0.600 (1 x 0.600 = 0.600).

The Baseflow Filter Program also estimates the average rate at which the hydrograph recedes once storm flow has ceased. The equation for this recession is an exponential decay curve, where α is the recession constant in units of inverse days (Arnold et al., 1995):

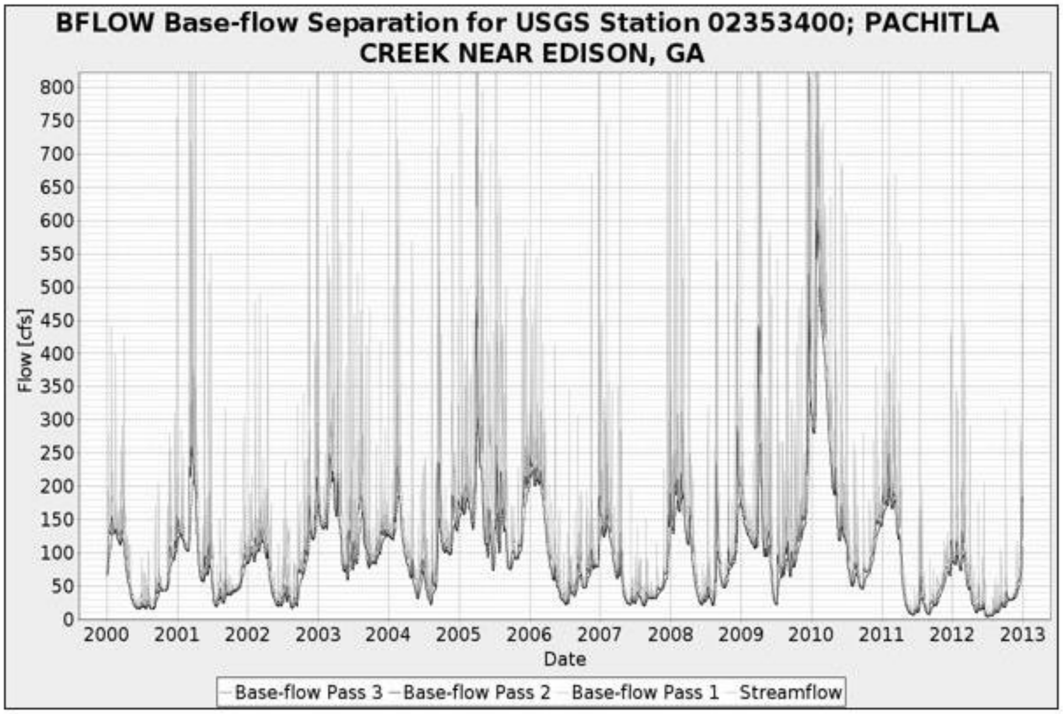
$$\mathbf{Q = Q}e^{-a}{}_{t} \qquad (2.3)$$

The baseflow recession constant is a measure of how much groundwater storage there is and transmissivity (Arnold et al., 1995). A large value indicates rapid drainage and little storage.

When using the Baseflow Filter Program, sites under the USGS database for counties that lie within the FRB were used. In total there were 42 sites that had usable data for baseflow calculations. The minimum days for the “Alpha Regression” were set to 10 and maximum days set to 300. These are the minimum and maximum number of days to use for a storm recession hydrograph (Wible and Arabi, 2013). The exact years to run are not critical, but when applicable, the end year was set at 2012-12-31, as we are using 2012 data nearly throughout the paper.

The baseflow analysis retrieves the available flow data for the specified station and analysis period. The automated baseflow filter is passed over the stream flow data three times. First forwards, then backwards, then forwards again. Each successive pass will result in less baseflow as a percentage of total flow (Arnold et. al. 1995). The value in the table indicates the average baseflow amount divided by the average flow amount to indicate a relative fraction. The average of Pass 1 and Pass 2 Baseflow Fraction is used as the representative baseflow fraction for a given permit, as Arnold et al. (1995) states the first or second pass is sufficient enough when estimating baseflow. The alpha factor is a recession coefficient derived from the properties of the aquifer in question contributing to base-flow. Large alpha factors signify steep recession indicative of rapid drainage and minimal storage (Arnold et. al. 1995). An example of what the results look like is shown in Figure 9.

Since there were only 42 site observations used to determine baseflow percentage and not all counties had observations, a uniform random number was generated between the lowest and highest value of whichever HUC8 watershed that a permit lied within to determine its representative baseflow percentage (Table 1). After baseflow percentages were obtained, they were multiplied by the LB Flux and UB Flux value for each permit to get the new set of lower and upper bound flux ratios.



BFLOW Separation Model Summary:

Pass 1 Baseflow Fraction	Pass 2 Baseflow Fraction	Pass 3 Baseflow Fraction	Number of Recessions	Alpha Factor	Baseflow Days
0.69	0.58	0.52	5	0.0344	66.8182

Figure 9: Baseflow Filter Program Example from eRAMs Website

Table 1: eRAMs Baseflow Filter Program Results

USGS Station	County	Water Body	HUC8	Pass 1 Fraction	Pass 2 Fraction	Average
02353500	Baker	Ichaway. Creek	Ichaway.	0.70	0.58	0.640
02354500	Baker	Chickasaw. Creek	Ichaway.	0.68	0.53	0.605
02354800	Baker	Ichaway. Creek	Ichaway.	0.72	0.59	0.655
02355000	Baker	Ichaway. Creek	Ichaway.	0.79	0.68	0.735
02355350	Baker	Ichaway. Creek	Ichaway.	0.79	0.69	0.740
02353000	Baker	Flint River	Lower Flint	0.76	0.65	0.705
02353400	Calhoun	Pachitla Creek	Ichaway.	0.66	0.54	0.600
02353265	Calhoun	Ichaway. Creek	Ichaway.	0.65	0.53	0.590
02354475	Calhoun	Spring Creek	Ichaway.	0.81	0.70	0.755
02343260	Clay	Chattahooc. River	Lower Chattahooc.	0.68	0.55	0.615
02344620	Coweta	Shoal Creek	Upper Flint	0.53	0.40	0.465
02344700	Coweta	Line Creek	Upper Flint	0.54	0.40	0.470
02350220	Crisp	Gum Creek	Middle Flint	0.70	0.60	0.650
02350300	Crisp	Cedar Creek	Middle Flint	0.66	0.54	0.600
02356000	Decatur	Flint River	Lower Flint	0.80	0.70	0.750
02357000	Decatur	Spring Creek	Spring Creek	0.68	0.53	0.605
02357150	Decatur	Spring Creek	Spring Creek	0.87	0.79	0.830
02349900	Dooly	Turkey Creek	Middle Flint	0.61	0.47	0.540
02350000	Dooly	Flint River	Middle Flint	0.72	0.61	0.665
02354350	Dougherty	Chickasaw. Creek	Ichaway.	0.69	0.55	0.620
02354440	Dougherty	Kiokee Creek	Ichaway.	0.57	0.36	0.465
02352500	Dougherty	Flint River	Lower Flint	0.71	0.59	0.650
02343801	Early	Chattahooc. River	Lower Chattahooc	0.64	0.50	0.570
02351890	Lee	Muckalee Creek	Kincha-Muckalee	0.69	0.56	0.625
02350900	Lee	Kincha. Creek	Kincha-Muckalee	0.71	0.59	0.650
02350500	Lee	Flint River	Middle Flint	0.68	0.54	0.610
02345500	Meriwether	Flint River	Upper Flint	0.61	0.48	0.545
02356638	Miller	Spring Creek	Spring Creek	0.74	0.61	0.675
02356980	Miller	Aycocks Creek	Spring Creek	0.71	0.54	0.625
02355662	Mitchell	Flint River	Lower Flint	0.78	0.68	0.730
02344872	Pike	Flint River	Upper Flint	0.58	0.44	0.510

02345000	Pike	Flint River	Upper Flint	0.65	0.52	0.585
02344478	Spalding	Shoal Creek	Upper Flint	0.58	0.46	0.520
02344500	Spalding	Flint River	Upper Flint	0.50	0.36	0.430
02346310	Spalding	Potato Creek	Upper Flint	0.51	0.38	0.445
02351500	Sumter	Muckalee Creek	Kincha-Muckalee	0.62	0.48	0.550
02348500	Taylor	Whitewat. Creek	Upper Flint	0.90	0.86	0.880
02346500	Upson	Potato Creek	Upper Flint	0.64	0.52	0.580
02346180	Upson	Flint River	Upper Flint	0.66	0.54	0.600
02347500	Upson	Flint River	Upper Flint	0.62	0.48	0.550
02350600	Webster	Kincha. Creek	Kincha-Muckalee	0.65	0.53	0.590
02350512	Worth	Flint River	Middle Flint	0.70	0.57	0.635

2.5 Agricultural Permit Data:

The simulation model was developed using parameters for the entire FRB watershed in southwest Georgia. The impact of agricultural water use on stream flow reduction was analyzed at the entire basin level and when the FRB was split into the Upper Flint and Lower Flint Basins. Agricultural water permit data for all permits that are located within the FRB were obtained from the Georgia Department of Natural Resources (DNR) website (Smith et al., 2018). Additional data that included GIS coordinate points for all individual permits, depth (ft.), casing (ft.), and diameter (in.) for all groundwater permits was provided by Edward Rooks and staff of the Georgia DNR (Georgia DNR, 2019). A total of 6,592 permits were provided and it is assumed that every permit that includes the total permitted acreage has a separate well associated with it. After removing permits that did not have permitted acres listed and groundwater permits that did not use the Floridan, Claiborne, or Cretaceous aquifers, 5,299 total permits were left; 1,348 surface water permits, and 3,951 groundwater permits (Figure 10).

In total, permits in 33 counties used the waters of the FRB for agricultural purposes. Of those 33 counties, 18 were split into the Upper Flint (Coweta, Crisp, Dooly, Houston, Lamar, Macon, Marion, Meriwether, Peach, Pike, Schley, Spalding, Stewart, Sumter, Talbot, Taylor, Upson, and Webster) with a total of 1,102 permits and 15 were split into the Lower Flint (Baker, Calhoun, Clay, Colquitt, Decatur, Dougherty, Early, Grady, Lee, Miller, Mitchell, Randolph, Seminole, Terrell, and Worth) with a total of 4,197 permits. A total of 762,958 permitted acres located within the FRB are used, with 168,130 acres and 594,828 acres located within the Upper and Lower Flint, respectively (Table 2). In total, nearly 72% of all permits received their water from groundwater sources, while only 28% were from surface water sources.

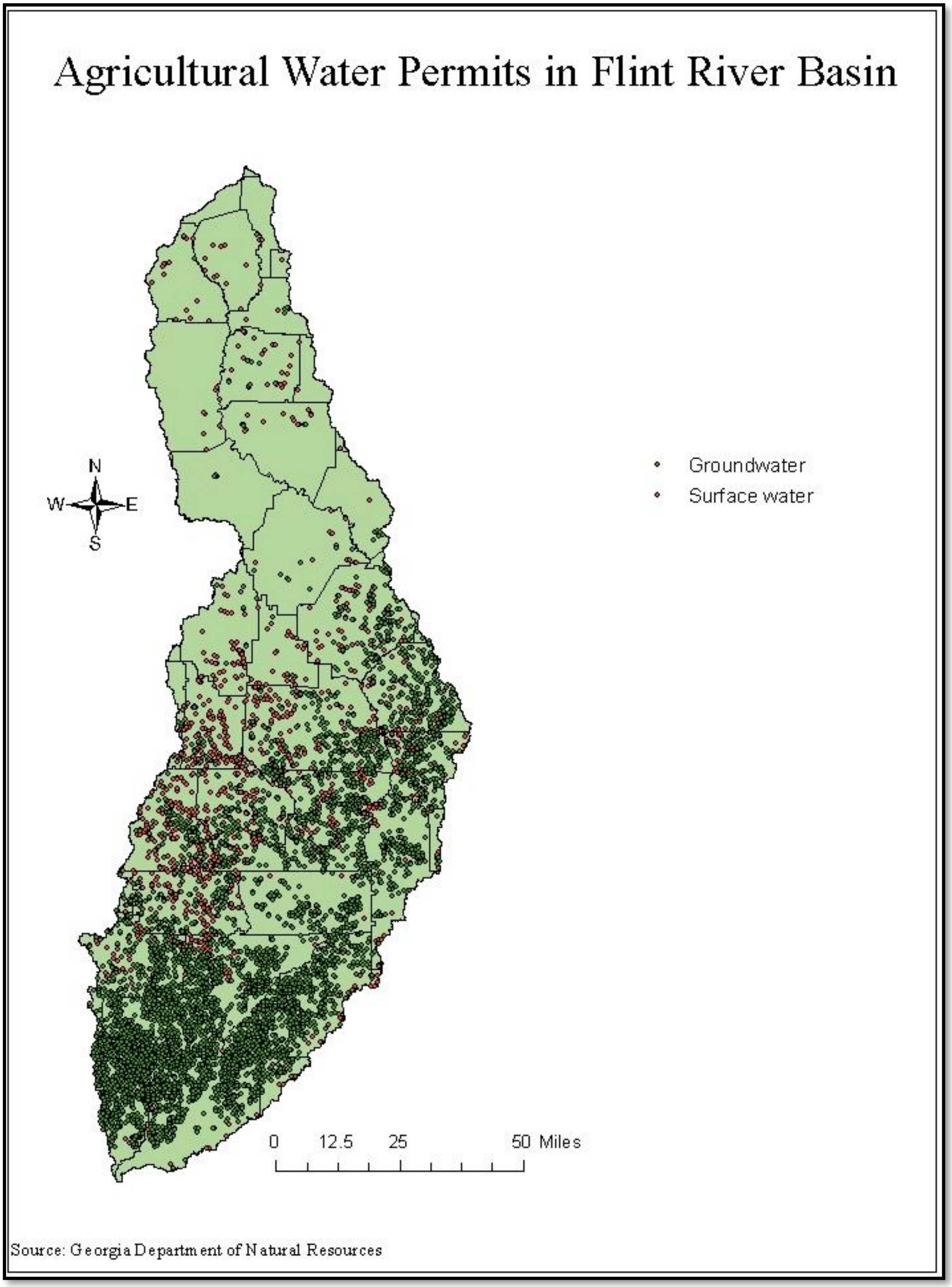


Figure 10: Agricultural Water Permits in Flint River Basin

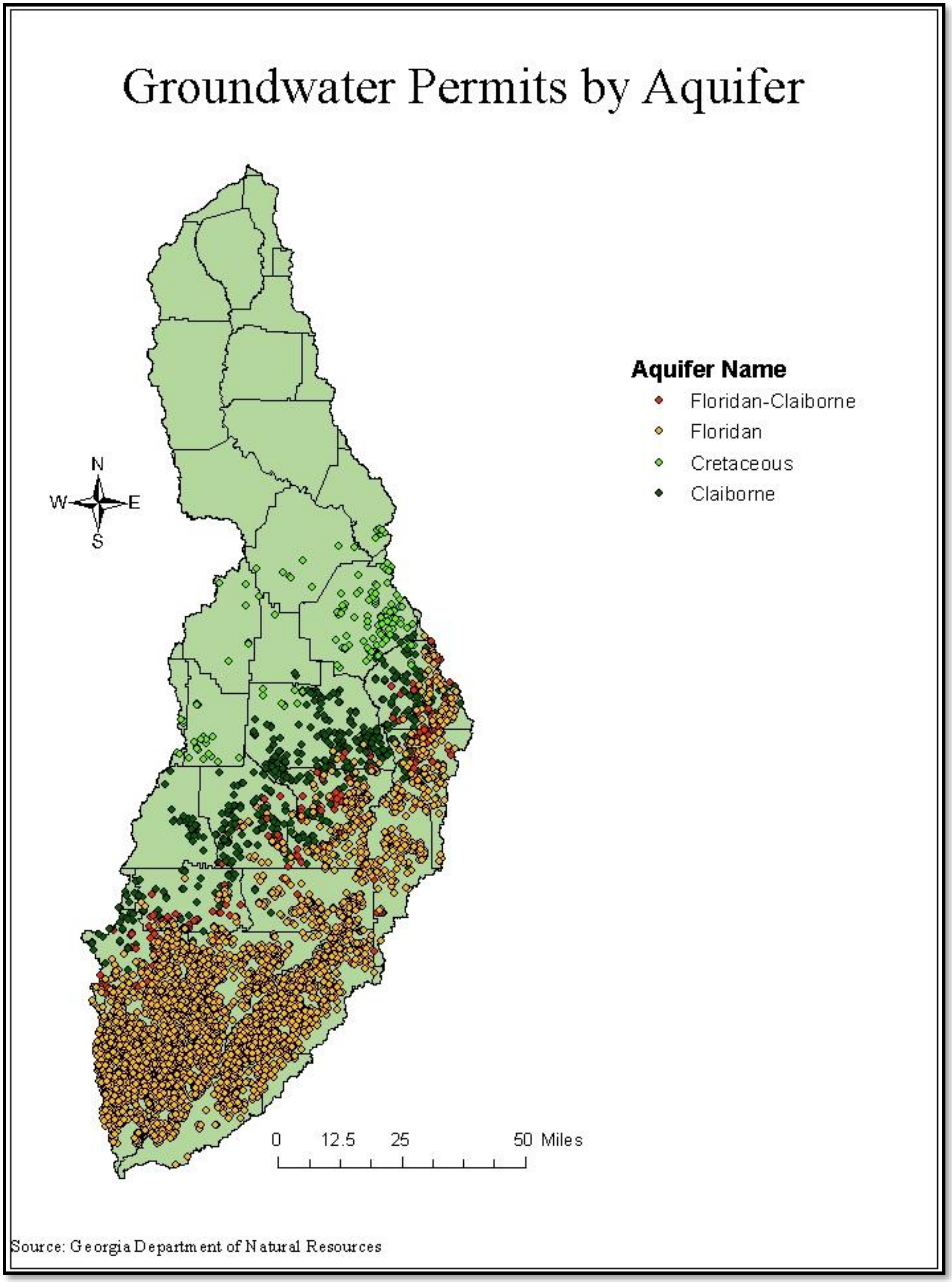


Figure 11: Groundwater Permits by Aquifer

Table 2: Total Agricultural Permits and Acreage by Source

County	GW Permits	SW Permits	Total Permits	Total GW Acres	Total SW Acres	Total Permitted Acres
Coweta	0	12	12	0	910	910
Crisp	143	64	207	18,093	11,046	29,139
Dooly	170	68	238	22,362	11,239	33,601
Houston	1	0	1	225	0	225
Lamar	0	1	1	0	100	100
Macon	8	58	66	554	9,124	9,678
Marion	0	45	45	0	7,861	7,861
Meriwether	0	7	7	0	600	600
Peach	0	0	0	0	0	0
Pike	0	27	27	0	2,110	2,110
Schley	2	28	30	260	4,169	4,429
Spalding	0	3	3	0	435	435
Stewart	0	5	5	0	498	498
Sumter	165	137	302	28,528	27,639	56,167
Talbot	0	1	1	0	40	40
Taylor	0	12	12	0	2,294	2,294
Upson	0	12	12	0	860	860
Webster	0	133	133	0	19,183	19,183
Baker	339	51	390	48,405	9,228	57,633
Calhoun	103	119	222	13,516	27,438	40,954
Clay	5	10	15	1,119	1,976	3,095
Colquitt	0	6	6	0	145	145
Decatur	486	14	500	69,323	1,640	70,963
Dougherty	159	5	164	22,762	265	23,027
Early	251	52	303	36,170	9,558	45,728
Grady	35	11	46	4,058	800	4,858
Lee	285	104	389	39,285	17,393	56,678
Miller	582	9	591	77,026	880	77,906
Mitchell	586	24	610	80,454	2,291	82,745
Randolph	27	156	183	5,058	22,592	27,650
Seminole	355	10	365	49,936	1,087	51,023
Terrell	122	127	249	15,566	17,496	33,062
Worth	127	37	164	15,224	4,137	19,361
Total	**3,951**	**1,348**	**5,299**	**547,924**	**215,034**	**762,958**

2.6 Simulated Buyout Auction Exercises:

Two simulation exercises were run that used both surface and groundwater permits to simulate a future irrigation reduction auction by the Georgia EPD. All surface water permit flux ratios were set equal to 1, as previously stated. For groundwater permits, the two set of flux ratio ranges calculated from the methods above were used (LB Flux to UB Flux, and Flux Low to Flux High). All 5,299 agricultural permits were used. For the first simulation exercise, the range of values were used based on the 2017 cash rent values for irrigated and non-irrigated cropland from the USDA, NASS Southern Region website (Ewing, 2017). Every simulation run used randomly generated buyout offers that were drawn from a uniform distribution between $80/acre and $220/acre across the entire study area (Flint River Basin). The average cash rent value of an acre of irrigated cropland in FRB counties plus one standard deviation above the mean were used when setting said range ($179.44 + $43.55 = $220.32) as the upper limit, and the average cash rent value of a non-irrigated ace of cropland plus one standard deviation above the mean was used ($59.26 + $23.54 = $82.80) to set the lower limit. The values were rounded to $80 and $220 for simplicity.

In the second simulation, every simulation run used randomly generated buyout offers that were drawn from uniform distribution at the county level based on the 2017 cash rent values for an acre of non-irrigated and irrigated cropland (Table 3) (Ewing, 2017). This is different from the first simulation where the average of all 33 counties cash rent values plus one standard deviation above the mean were used for the range of offer bid values. This was done so because in past auctions permit holders in counties that had more productive land typically put in higher bid offers compared to permit holders whose land was not as productive.

Table 3: 2017 Irrigated and Non-Irrigated Cash Rent Values by County

County	FRB	Non-Irrigated	Irrigated
Coweta	Upper	$31.50	$122.00
Crisp	Upper	$62.00	$218.00
Dooly	Upper	$78.00	$186.00
Houston	Upper	$41.50	$138.00
Lamar	Upper	$31.50	$122.00
Macon	Upper	$48.50	$126.00
Marion	Upper	$30.00	$122.00
Meriwether	Upper	$28.50	$122.00
Peach	Upper	$44.00	$169.00
Pike	Upper	$25.00	$122.00
Schley	Upper	$75.00	$213.00
Spalding	Upper	$34.00	$122.00
Stewart	Upper	$75.00	$213.00
Sumter	Upper	$49.00	$199.00
Talbot	Upper	$34.00	$122.00
Taylor	Upper	$46.00	$122.00
Upson	Upper	$21.00	$122.00
Webster	Upper	$51.00	$194.00
Baker	Lower	$77.00	$230.00
Calhoun	Lower	$70.00	$199.00
Clay	Lower	$55.00	$160.00
Colquitt	Lower	$103.00	$218.00
Decatur	Lower	$88.00	$226.00
Dougherty	Lower	$58.00	$243.00
Early	Lower	$60.00	$182.00
Grady	Lower	$78.00	$219.00
Lee	Lower	$63.50	$238.00
Miller	Lower	$78.00	$203.00
Mitchell	Lower	$97.50	$224.00
Randolph	Lower	$49.00	$183.00
Seminole	Lower	$83.00	$219.00
Terrell	Lower	$93.50	$201.00
Worth	Lower	$96.50	$216.00

As stated previously, groundwater irrigators are now allowed to participate in future auctions, unlike in the 2002. The 2002 auction rules of accepting any bid up to a reservation price of $150/acre were applied to all surface and groundwater permit bids and compared to a rule that accepts all FIOs up to the $150/acre reservation price. The effects in terms of accepted offers, total auction expenditures, acres purchased, water purchased (flow-impact avoided/water left in stream), and average water price ($/ac-in) were compared to each other, as done in Mullen (2019). A simulated auction was run 100 times using these rules.

To calculate total expenditure for all accepted bids under auction institution i, the offer, not the FIO, for permit j was multiplied by the permit holder's listed permitted acres. The total expenditure for an auction was calculated as the sum of expenditures over all accepted bids, along with total acres purchased as in the equation below:

$$\textbf{Expenditures}_{\mathbf{i}} = \sum \textbf{Offer}_{\mathbf{i,\,j}} \textbf{ x Permitted Acres}_{\mathbf{i,\,j}} \tag{2.4}$$

To calculate the total amount of flow impact avoided, i.e. water purchased from an accepted offer in the auction, the total water per permit accepted (representative acre water demand times permitted acres) times the respective flux ratio (f) (where f = LB, UB, FL, or FH) is summed across all accepted offers (j) in a given simulated auction institution (i):

$$\textbf{Water Purchased}_{\mathbf{i,\,f}} = \sum \textbf{Offer}_{\mathbf{j}} \textbf{ x (Total Water}_{\mathbf{j}} \textbf{ (ac-in) x Flux Ratio}_{\mathbf{f,\,j}}\textbf{)} \tag{2.5}$$

To calculate the average water price total expenditure is divided by total water purchased:

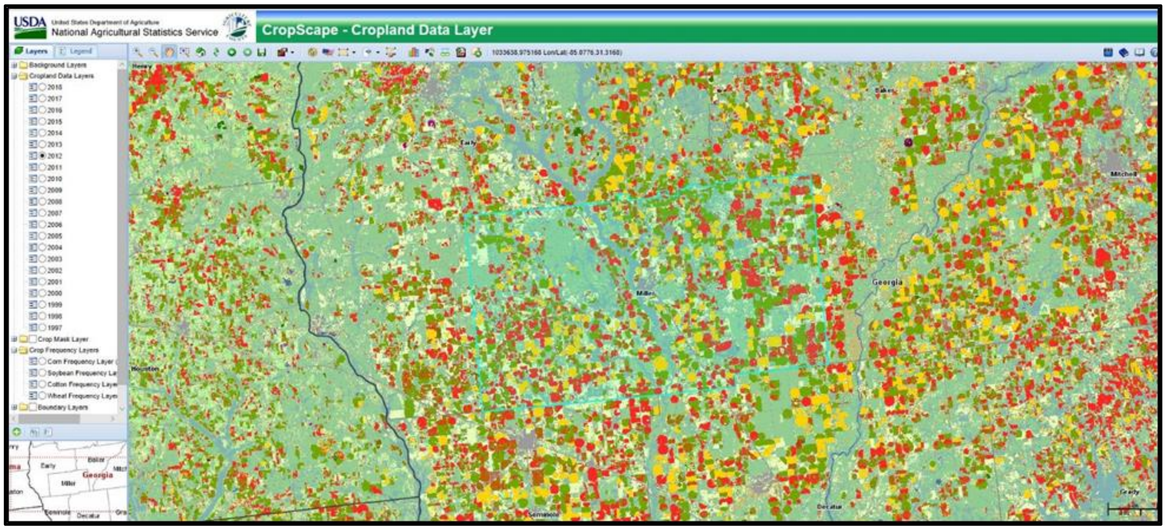
$$\textbf{Average Water Price}_{\mathbf{i,\,f}} \textbf{ (ac-in) = Total Expenditure}_{\mathbf{i,\,f}} \textbf{ / Total Water Purchased}_{\mathbf{i,\,f}} \tag{2.6}$$

<u>2.7 Creating a Representative Irrigated Acre:</u>

From 2007-2012, agriculture in the FRB mainly consisted of corn, cotton, peanuts, soybeans, and pecans (USDA, 2014). Using the U.S. Department of Agriculture (USDA) and

National Agricultural Statistics Service (NASS) CropScape—Cropland Data Layer, a "representative irrigated acre" could be used to establish the share of irrigated acres in the FRB for each of the major crops. This would create a simplified schedule of irrigation withdrawals. A "representative irrigated acre" was created to use as a baseline to estimate how much water a given permit would use in a growing season based on the share of irrigated acres in the FRB for four of the five major crops (corn, cotton, peanuts, and soybeans) (USDA, NASS CropScape website, 2019). Pecans were not used to form this representative acre because pecans are perennials that take several years to mature. A pecan orchard represents a long-term investment, as opposed to a field of corn that can be replaced the following year. Not watering a pecan tree during a severe drought would cause considerable damage, possibly killing the tree. It is, therefore, very unlikely a pecan grower would participate in an irrigation reduction auction. CropScape—Cropland Data Layer can be accessed here: https://nassgeodata.gmu.edu/CropScape/.

The Cropland Data Layer (CDL) contains crop and other specific land cover classifications obtained using remote sensing for the conterminous United States. This agricultural geospatial data is a crop and other specific land cover classification encompassing the entire contiguous United States. It provides geo-referenced, high accuracy, 30 or 56 m resolution, crop specific cropland land cover information (Han et al., 2012). This raster-formatted and geo-referenced product has been widely used in such applications as disaster assessments, land cover and land use research, agricultural sustainability studies, and agricultural production decision-making (Han et al., 2012).



2012 Cropland Data Layer Statistics for Miller, Georgia

Display Crop Categories Only

Value	Category	Pixel Counts	Acreage
1	Corn	43555	9686.4
2	Cotton	115080	25593.2
4	Sorghum	257	57.2
5	Soybeans	573	127.4
10	Peanuts	151670	33730.6

Figure 12: Miller County CropScape – Cropland Data Layer Example

Table 4: 2012 Cropland Data Layer Crop Total Acreage by County

County	Corn	Cotton	Peanuts	Soybeans	Total Acres
Coweta	38	13	0	162	213
Crisp	1,697	33,669	15,714	247	51,327
Dooly	2,901	62,537	17,540	719	83,697
Houston	2,076	11,419	2,557	437	16,489
Lamar	16	196	0	92	304
Macon	7,253	16,906	5,275	1,940	31,374
Marion	975	1,151	2,000	673	4,799
Meriwether	92	3	0	12	107
Peach	1,828	2,257	725	375	5,185
Pike	16	3	0	5	24
Schley	464	1,494	729	198	2,885
Spalding	5	107	0	133	245
Stewart	267	2,706	4,020	250	7,243
Sumter	8,040	24,319	15,402	664	48,425
Talbot	24	5	6	11	46
Taylor	217	1,918	612	3,172	5,919
Upson	33	12	0	3	48
Webster	278	7,458	7,638	49	15,423
Baker	9,452	16,785	24,623	32	50,892
Calhoun	9,567	9,513	20,425	81	39,586
Clay	1,523	5,291	10,036	15	16,865
Colquitt	2,873	57,746	27,101	322	88,042
Decatur	8,644	25,170	35,842	391	70,047
Dougherty	3,728	4,564	3,729	193	12,214
Early	8,245	24,895	39,777	466	73,383
Grady	6,312	28,774	12,012	456	47,554
Lee	11,127	14,577	17,078	800	43,582
Miller	9,686	25,593	33,731	127	69,137
Mitchell	17,168	43,952	38,601	304	100,025
Randolph	8,250	8,745	15,440	353	32,788
Seminole	8,583	21,469	25,108	153	55,313
Terrell	9,854	16,689	19,137	225	45,905
Worth	6,145	52,084	37,573	338	96,140
Total	**147,377**	**522,020**	**432,431**	**13,398**	**1,115,226**

Table 5: 2012 Cropland Data Layer Crop Percentage by County for Representative Acre

County	Corn %	Cotton %	Peanuts %	Soybean %
Coweta	17.84%	6.10%	0.00%	76.06%
Crisp	3.31%	65.60%	30.62%	0.48%
Dooly	3.47%	74.72%	20.96%	0.86%
Houston	12.59%	69.25%	15.51%	2.65%
Lamar	5.26%	64.47%	0.00%	30.26%
Macon	23.12%	53.89%	16.81%	6.18%
Marion	20.32%	23.98%	41.68%	14.02%
Meriwether	85.98%	2.80%	0.00%	11.21%
Peach	35.26%	43.53%	13.98%	7.23%
Pike	66.67%	12.50%	0.00%	20.83%
Schley	16.08%	51.79%	25.27%	6.86%
Spalding	2.04%	43.67%	0.00%	54.29%
Stewart	3.69%	37.36%	55.50%	3.45%
Sumter	16.60%	50.22%	31.81%	1.37%
Talbot	52.17%	10.87%	13.04%	23.91%
Taylor	3.67%	32.40%	10.34%	53.59%
Upson	68.75%	25.00%	0.00%	6.25%
Webster	1.80%	48.36%	49.52%	0.32%
Baker	18.57%	32.98%	48.38%	0.06%
Calhoun	24.17%	24.03%	51.60%	0.20%
Clay	9.03%	31.37%	59.51%	0.09%
Colquitt	3.26%	65.59%	30.78%	0.37%
Decatur	12.34%	35.93%	51.17%	0.56%
Dougherty	30.52%	37.37%	30.53%	1.58%
Early	11.24%	33.92%	54.20%	0.64%
Grady	13.27%	60.51%	25.26%	0.96%
Lee	25.53%	33.45%	39.19%	1.84%
Miller	14.01%	37.02%	48.79%	0.18%
Mitchell	17.16%	43.94%	38.59%	0.30%
Randolph	25.16%	26.67%	47.09%	1.08%
Seminole	15.52%	38.81%	45.39%	0.28%
Terrell	21.47%	36.36%	41.69%	0.49%
Worth	6.39%	54.18%	39.08%	0.35%
Average	**13.21%**	**46.81%**	**38.78%**	**1.20%**

To create this acre, the 2012 Cropland Data Layer dataset was used because the 2012 "USDA Agricultural Census: Total Irrigated Acres" dataset was used to calculate the total amount of acres irrigated as the 2017 USDA Agricultural Census was not released at the time, and because the U.S. 536 Sectors—2010-2012 dataset was the most recent one provided by IMPLAN for economic analysis. This way the data compared is more consistent throughout to provide more accurate results and interpretations. Acreage totals for the four main crops used in the region were obtained in CropScape by selecting each county individually and looking at the county level crop acreage statistics. A thing to note is CropScape does not have separate categories for irrigated and non-irrigated cropland. Because of this, we will assume that irrigated and non-irrigated cropland grow these crops uniformly at the same percentages throughout. To find what percentage of each crop per acre in each county, we divide the crop total acreage by the total acreage of all four crops:

Corn Percentage (%) = (Corn Acreage) / (Corn + Cotton + Peanut + Soybean Acreage) (2.7)

For example, in Miller County, there were 9,686 acres of corn and a total of 69,137 acres between all four crops. This would imply that 14.01% of all permitted acreage irrigation (9,686 / 69,137 = 0.1401) in Miller County grew corn that year (USDA, NASS CropScape Website). This was done for all 33 counties used.

2.8 Water Use for Representative Acres:

Simulated water use for each representative acre of cropland was determined by using DSSAT model projections for each crop in each county (Hook et al., 2010). DSSAT values were derived for major crops based on models using 58-year meteorological record (1958-2007) for each county or its nearest NOAA cooperating weather station and planted at median date recommended for each county by Cooperative Extension Service and runs averaged for three common soils of each county's primary soil associations (Hook et al., 2010). The irrigation management strategy utilized in the DSSAT models was to apply 25 mm of water whenever the soil moisture content within the root zone dropped below 50% over the course of a growing season (Hook et al., 2010). Because the buyout auctions were only implemented by the EPD director under extreme drought conditions, the 90th percentile of the cumulative distribution functions of the irrigation application distributions were used for the simulation exercise for determining water use, just like in Mullen (2019).

The 90th percentile of water application depth in the months given per crop were totaled and then multiplied by the percentage each crop represented in an acre. For counties that were not within the water use projections provided (Upper: Coweta, Henry, Houston, Lamar, Peach, Stewart; Lower: Clay, Randolph), as they are considered to be within the Middle Flint River Basin. I used the average water application depths and crop percentages of all counties in the basin they were split into previously (see above). The sum of all four crops and percentages was used as the average application depth per acre uniformly in their respective counties for each permit that lies within its boundaries:

90%tile Total (ac-in) = (Corn % x (90%tile Corn Water Applied (ac-in)) + (Cotton % x 90%tile Cotton Water Applied (ac-in)) + (Peanut % x 90%tile Peanut Water Applied (ac-in)) + (Soybean % x (90%tile Soybean Water Applied (ac-in)) (2.8)

Total water use for each permit was then calculate by multiplying the permitted acreage by the water application per acre:

Total Water (ac-in) = (Permitted Acres) x (90%tile Total (ac-in)) (2.9)

2.9 Regional Economic Impact Analysis using IMPLAN Online:

Regional economic impact analysis was ran using IMPLAN Online to see what the effect of reducing a certain acre amount of cropland would have on the local economy. IMPLAN data is compiled from an assortment of disclosed government sources including the U.S. Department of Commerce, Bureau of Economic Analysis (BEA), U.S. Bureau of Labor Statistics (BLS), U.S. Census Bureau, and others (IMPLAN Group, 2016). IMPLAN's regional economic research data for the United States, is available at every regional level, spans multiple data years, and offers up to 536 sectors for analysis. The IMPLAN model accounts for industrial and commodity production, employment, labor income, household and institutional consumption and domestic and international trade. Economic multipliers are calculated for each industry to estimate the secondary effects of economic activity. Indirect effects multipliers represent the economic activity generated in the supply chain through the purchase of intermediate inputs from vendor firms, while induced effects multipliers represent the impacts of spending by industry employee households and governments. The total economic impacts are calculated as the sum of direct, indirect, and induced effects (IMPLAN Group, 2016).

The U.S. 2010-2012 IMPLAN dataset for the state of Georgia was provided by Dana Shifley, who is the Director of Business Development at IMPLAN. The U.S. 2012 dataset was used as it was the most recent provided, along with it being a prolonged drought year. This is useful it that our economic data analysis as the results should reflect similar to how they would if an auction was implemented, as they only would be if the EPD Director considers it to be an extreme drought year. Three different study areas were defined (Flint River Basin, Upper Flint, and Lower Flint) to see which area would be affected the most, or if the FRB is affected uniformly, if all irrigated acres were taken out of a specific region. The "Total Impact Summary" (employment, labor income, value added, and output) and “State/Local Tax Revenues” sections were analyzed.

Since we are assuming that only four crops will be taken out of harvest (corn, cotton, peanuts, and soybeans), several assumptions of the data are needed. The only crop that IMPLAN Online has as its own industry sector is cotton. Because of this, “Oilseed farming” was used to represent soybeans, “Grain faming” was used for corn, and “All other crop farming” was used for peanuts. IMPLAN Online has separate industry sectors for fruit, vegetable, tree nut, and tobacco farming. Total output ($) was manipulated to show the industry change effects when a certain number of cropland acres are reduced. Famers are still allowed to plant on their land if they choose to accept the buyout offer as long as they do not irrigate (i.e. watered from rainwater), but in this scenario we assume that no faming is done on the cropland for the full year.

To get a better representation on the economic losses of total output associated with the reduction in cropland acreage, the 2012 Farm Gate Value Report published annually by The Center for Agribusiness and Economic Development at the University of Georgia’s College of Agricultural and Environmental Science was used for each crop (Table 9) (Wolfe and Stubbs, 2013). The Total Farm Gate Value for each crop in all counties associated with each region were summed together respectively. These values were used as the baseline for what dollar amount was subtracted from each IMPLAN category for economic analysis. The percentage of each crop grown used as a part of a representative acre was used to determine the percentage of the crop grown in the three defined study regions. These were then used for how much total input of each category to subtract based on how many acres were reduced. The “2012 Irrigated Acres” report from the USDA’s 2012 Agricultural Census were used as the baseline for what percentage of total irrigated land would be taken out for regional economic analysis (Table 10) (USDA, 2014). In

2012, the FRB had a total of 625,035 out of 1,520,252 acres (41.11%) were irrigated with 159,884 acres located in the Upper Flint and 465,151 acres in the Lower Flint (USDA, 2014).

Table 6: Crop Percentage by Region for Representative Acre

Study Region	Corn %	Cotton %	Peanut %	Soybean %
Flint River Basin	13.21%	46.81%	38.78%	1.20%
Upper Flint	9.58%	60.70%	26.38%	3.34%
Lower Flint	14.40%	42.29%	42.81%	0.51%

Table 7: Farm Gate Crop Total Value by Region

Crop	Flint River Basin	Upper Flint	Lower Flint
Corn	$274,389,597	$36,318,249	$238,071,348
Cotton	$592,825,741	$153,197,618	$439,628,123
Peanuts	$454,883,451	$74,697,573	$380,185,878
Soybeans	$35,383,313	$20,909,559	$14,473,754
Total	$1,357,482,102	$285,122,999	$1,072,359,103

Table 8: IMPLAN Online Total Output by Region ($)

Crop	Flint River Basin	Upper Flint	Lower Flint
Corn	$116,243,353	$16,838,481	$99,404,872
Cotton	$256,382,302	$67,852,000	$188,530,302
Peanuts	$193,101,964	$31,339,180	$161,762,784
Soybeans	$13,602,633	$8,274,789	$5,327,843
Total	$579,330,252	$124,304,450	$455,025,801

Table 9: 2012 Farm Gate Values by County

County	FRB	Corn	Cotton	Peanuts	Soybeans
Coweta	Upper	$4,050	$0	$0	$151,109
Crisp	Upper	$1,053,445	$31,523,149	$17,800,146	$795,226
Dooly	Upper	$4,014,562	$65,065,000	$20,801,462	$3,789,345
Houston	Upper	$3,369,600	$0	$0	$954,322
Lamar	Upper	$384,562	$295,324	$0	$811,466
Macon	Upper	$6,938,055	$16,247,125	$7,008,365	$5,569,974
Marion	Upper	$1,575,000	$409,176	$1,591,000	$920,550
Meriwether	Upper	$546,750	$0	$0	$281,250
Peach	Upper	$3,091,500	$1,790,379	$998,800	$1,795,998
Pike	Upper	$0	$0	$0	$3,690
Schley	Upper	$0	$962,325	$412,800	$156,009
Spalding	Upper	$0	$0	$0	$940,500
Stewart	Upper	$345,600	$2,593,545	$3,167,000	$126,825
Sumter	Upper	$14,325,000	$26,371,800	$15,540,000	$2,056,275
Talbot	Upper	$31,125	$0	$0	$0
Taylor	Upper	$112,500	$1,371,415	$823,000	$2,298,240
Upson	Upper	$112,500	$0	$0	$130,815
Webster	Upper	$414,000	$6,568,380	$6,555,000	$127,965
Baker	Lower	$19,425,000	$17,017,000	$22,325,000	$498,750
Calhoun	Lower	$18,111,000	$13,987,885	$27,719,796	$278,623
Clay	Lower	$2,232,487	$6,355,849	$10,526,880	$225,720
Colquitt	Lower	$3,712,500	$65,108,680	$27,348,750	$359,100
Decatur	Lower	$22,652,500	$34,235,246	$37,756,040	$1,075,500
Dougherty	Lower	$33,450,000	$5,005,000	$2,535,000	$0
Early	Lower	$13,531,500	$36,148,203	$45,595,875	$1,334,580
Grady	Lower	$11,048,212	$31,731,700	$7,132,250	$1,961,950
Lee	Lower	$14,272,237	$13,404,209	$22,307,962	$1,691,839
Miller	Lower	$17,941,087	$34,536,752	$37,444,950	$1,301,096
Mitchell	Lower	$25,358,175	$64,546,004	$41,591,850	$448,162
Randolph	Lower	$12,607,500	$12,230,400	$15,860,000	$3,847,500
Seminole	Lower	$19,516,000	$27,428,525	$26,846,400	$156,009
Terrell	Lower	$12,935,700	$23,790,413	$18,443,425	$1,036,046
Worth	Lower	$11,277,450	$54,102,257	$36,751,700	$258,879
Total		$274,389,597	$592,825,741	$454,883,451	$35,383,313

Table 10: 2012 Farm Gate Value for Irrigated Acres

County	FRB	Irr. %	Irr. Corn	Irr. Cotton	Irr. Peanuts	Irr. Soybeans
Coweta	Upper	18.99%	$769	$0	$0	$28,695
Crisp	Upper	32.03%	$337,470	$10,098,403	$5,702,256	$254,750
Dooly	Upper	46.90%	$1,882,803	$30,515,052	$9,755,747	$1,777,178
Houston	Upper	35.98%	$1,212,295	$0	$0	$343,340
Lamar	Upper	37.10%	$142,669	$109,563	$0	$301,047
Macon	Upper	51.01%	$3,538,815	$8,286,986	$3,574,677	$2,841,013
Marion	Upper	17.29%	$272,317	$70,746	$275,084	$159,163
Meriwether	Upper	12.67%	$69,258	$0	$0	$35,626
Peach	Upper	21.63%	$668,730	$387,281	$216,053	$388,497
Pike	Upper	17.78%	$0	$0	$0	$656
Schley	Upper	17.06%	$0	$164,159	$70,418	$26,613
Spalding	Upper	4.88%	$0	$0	$0	$45,878
Stewart	Upper	22.85%	$78,978	$592,691	$723,740	$28,983
Sumter	Upper	59.24%	$8,486,010	$15,622,433	$9,205,765	$1,218,120
Talbot	Upper	0.00%	$0	$0	$0	$0
Taylor	Upper	33.94%	$38,178	$465,402	$279,292	$779,928
Upson	Upper	11.71%	$13,170	$0	$0	$15,314
Webster	Upper	23.43%	$97,020	$1,539,284	$1,536,148	$29,988
Baker	Lower	53.06%	$10,306,488	$9,028,855	$11,845,165	$264,626
Calhoun	Lower	30.20%	$5,469,932	$4,224,658	$8,372,007	$84,150
Clay	Lower	34.92%	$779,691	$2,219,766	$3,676,489	$78,832
Colquitt	Lower	45.90%	$1,704,037	$29,884,878	$12,553,074	$164,827
Decatur	Lower	46.32%	$10,491,886	$15,856,629	$17,487,344	$498,136
Dougherty	Lower	32.36%	$10,823,998	$1,619,555	$820,294	$0
Early	Lower	32.11%	$4,345,325	$11,608,149	$14,642,048	$428,569
Grady	Lower	24.88%	$2,748,874	$7,895,075	$1,774,555	$488,147
Lee	Lower	32.11%	$4,582,549	$4,303,842	$7,162,671	$543,218
Miller	Lower	48.58%	$8,716,236	$16,778,832	$18,191,709	$632,106
Mitchell	Lower	54.12%	$13,724,144	$34,933,061	$22,510,001	$242,551
Randolph	Lower	33.91%	$4,275,475	$4,147,592	$5,378,468	$1,304,770
Seminole	Lower	63.12%	$12,319,184	$17,313,848	$16,946,390	$98,478
Terrell	Lower	39.26%	$5,078,140	$9,339,351	$7,240,295	$406,718
Worth	Lower	35.81%	$4,038,912	$19,376,211	$13,162,273	$92,715
Total		41.11%	$116,243,353	$256,382,302	$193,101,964	$13,602,633

Table 11: 2012 Farm Gate Values $/Acre by County

County	FRB	Corn	Cotton	Peanuts	Soybeans
Coweta	Upper	$1,350	$0	$0	$527
Crisp	Upper	$1,368	$976	$1,170	$598
Dooly	Upper	$1,462	$1,001	$1,137	$527
Houston	Upper	$1,350	$0	$0	$527
Lamar	Upper	$1,312	$935	$0	$499
Macon	Upper	$1,350	$935	$1,138	$527
Marion	Upper	$1,125	$924	$1,075	$485
Meriwether	Upper	$1,350	$0	$0	$625
Peach	Upper	$1,500	$864	$1,100	$499
Pike	Upper	$0	$0	$0	$527
Schley	Upper	$0	$819	$1,075	$485
Spalding	Upper	$0	$0	$0	$855
Stewart	Upper	$900	$773	$1,000	$285
Sumter	Upper	$1,433	$956	$1,050	$527
Talbot	Upper	$249	$0	$0	$0
Taylor	Upper	$177	$935	$1,138	$527
Upson	Upper	$1,125	$0	$0	$428
Webster	Upper	$900	$1,001	$1,175	$713
Baker	Lower	$1,388	$942	$1,560	$641
Calhoun	Lower	$1,500	$773	$1,365	$428
Clay	Lower	$1,387	$1,050	$1,169	$399
Colquitt	Lower	$1,238	$1,069	$1,316	$207
Decatur	Lower	$1,743	$1,001	$1,300	$0
Dougherty	Lower	$1,500	$1,047	$1,493	$590
Early	Lower	$1,500	$1,001	$1,175	$706
Grady	Lower	$1,297	$910	$1,175	$527
Lee	Lower	$1,612	$1,169	$1,350	$641
Miller	Lower	$1,537	$1,228	$1,500	$149
Mitchell	Lower	$1,660	$1,092	$1,269	$641
Randolph	Lower	$1,538	$1,047	$1,316	$52
Seminole	Lower	$1,743	$773	$1,000	$428
Terrell	Lower	$1,350	$819	$1,000	$285
Worth	Lower	$1,425	$935	$1,150	$527

IMPLAN industry change activities were run for all budget constrained simulation results (2002 and FIO rules) as being taken out of the FRB as a whole, just in Upper Flint counties, and just out of Lower Flint counties. The values for the average acre reduction under the $5 million budget constraint scenario simulation of each flux ratio were used. Because the FIO rules acres purchased for LB Flux ratio, Flux Low ratio, and Flux High ratio were within 200 acres and 0.1% of each other for all defined study regions, the average of all three were used in IMPLAN for simplification as these had nearly the same economic effect as each other. Only the Flux High ratio was significantly different enough to warrant its own. Local purchasing power (LPP) was set at 100% and Output and GDP deflators were set at 1.000. This is because setting the LLP to the SAM value may cause direct effects to be further reduced as an unintended consequence, and we want to keep in 2012 values for accuracy.

For the 2002 rules, as noted in Table 13, if 58,782 acres are bought out, that would represent 9.40% of total irrigated acreage in the FRB, 36.74% in the Upper Flint, or 12.64% in the Lower Flint. For the FIO rules for LB, FL, and FH flux ratios, if 51,733 acres are bought out, that would represent 8.28% of total irrigated acreage in the FRB, 32.34% in the Upper Flint, or 11.12% in the Lower Flint. For the FIO rules for UB flux ratio, if 55,889 acres are bought out, that would represent 8.94% of total irrigated acreage in the FRB, 34.93% in the Upper Flint, or 12.02% in the Lower Flint.

An example of the IMPLAN industry change analysis is that with the 2002 rules and a $5 million budget constraint, 58,782 acres would be bought out. If we were to run the analysis for the FRB as a whole, this is equal to 58,782 / 625, 035 = 0.094, or 9.40% of the total acreage. Based on the CropScape data used to create a representative acre, 13.21% of all crops grown in the FRB are corn, 46.81% cotton, 38.78% peanuts, and 1.20% are soybeans (Table 5). Total Farm Gate

Value in the FRB counties of the four crops equals $1,357,482,102. However, in 2012, only 41.11% of all land in irrigated farms was actually irrigated (USDA, 2014). So, Total Farm Gate Value for all irrigated acreage in the FRB is equal $579,330,252 for IMPLAN analysis (Table 7). 9.40% of that total is equal to $54,457,044. This $54,457,044 is how much total output will be reduced from the FRB if all 58,782 acres bought out and farmers choose not to plant any crops for the entire year. Based on percentages in this example, $7,196,493 will be subtracted from the "Grain farming" (Corn) sector, $25,490,498 from the "Cotton farming" (Cotton) sector, $21,115,822 from "All other crop farming" (Peanuts) sector, and $654,231 from "Oilseed farming" (Soybeans) sector.

Table 12: IMPLAN Upper Flint Inputs (2012 FGV)

	Total Output ($)	1% Reduc. (1,600 Acres)	36.74% Reduc. (2002) (58,782 Acres)	34.93% Reduc. (UB Flux) (55,889 Acres)	32.34% Reduc. (FIOs) (51,738 Acres)
Grain (Corn)	$16,838,481	$119,059	$4,374,210	$4,158,714	$3,850,353
Cotton	$67,852,000	$754,550	$27,722,182	$26,356,445	$24,402,160
All Other (Peanuts)	$31,339,180	$327,924	$12,047,929	$11,454,387	$10,605,063
Oilseed (Soybeans)	$8,274,789	$41,512	$1,525,135	$1,449,999	$1,342,484
Total	$124,304,451	$1,243,045	$45,669,455	$43,419,545	$40,200,059

Table 13: IMPLAN Lower Flint Inputs (2012 FGV)

	Total Output ($)	1% Reduc. (1,600 Acres)	12.64% Reduc. (2002) (58,782 Acres)	12.02% Reduc. (UB Flux) (55,889 Acres)	11.12% Reduc. (FIOs) (51,738 Acres)
Grain (Corn)	$99,404,872	$655,155	$8,281,165	$7,874,968	$7,285,328
Cotton	$188,530,302	$1,924,240	$24,322,388	$23,129,360	$21,397,544
All Other (Peanuts)	$161,762,784	$1,947,849	$24,620,808	$23,413,141	$21,660,078
Oilseed (Soybeans)	$5,327,844	$23,014	$290,901	$276,632	$255,919
Total	$455,025,801	$4,550,258	$57,515,261	$54,694,101	$50,598,869

Table 14: IMPLAN Flint River Basin Inputs (2012 FGV)

	Total Output ($)	1% Reduc. (1,600 Acres)	9.40% Reduc. (2002) (58,782 Acres)	8.94% Reduc. (UB Flux) (55,889 Acres)	8.28% Reduc. (FIOs) (51,738 Acres)
Grain (Corn)	$116,243,353	$765,584	$7,196,493	$6,844,324	$6,339,038
Cotton	$256,382,302	$2,711,755	$25,490,498	$24,243,091	$22,453,332
All Other (Peanuts)	$193,101,964	$2,246,364	$21,115,822	$20,082,495	$18,599,894
Oilseed (Soybeans)	$13,602,633	$69,599	$654,231	$622,215	$576,280
Total	$579,330,252	$5,793,303	$54,457,044	$51,792,125	$47,968,545

Chapter 3: Results and Discussion

3.1 Introduction:

The results of the simulated auction exercises are presented and discussed below. Sections 3.2 to 3.6 discuss the potential efficiency gains from incorporating the FIO into future auctions. Section 3.7 talks about the results from IMPLAN for regional economic analysis and its effects. Section 3.8 discusses the histograms created to show the distribution of groundwater permit flux ranges and section 3.9 discusses the potential of source switching groundwater wells in the FRB.

3.2 Simulated Auction Results:

The average results for the two institutions—2002 rules versus FIO rules—across the 100 simulated auction exercises are presented below, with standard deviations in parentheses for both auctions. Two budget scenarios are explored for each institution: 1) an unlimited budget where all offers (2002 rules) or FIOs (FIO rules) at or below the reservation price are accepted; 2) a $5 million budget where offers/FIOs are accepted sequentially from low to high until either $5 million is spent or the final offer/FIO below the reservation price is accepted. The cap of $5 million was chosen because the 2001 and 2002 irrigation buyout auctions spent $4.5 million and $5.3 million, respectively.

The results of both simulation exercises reinforce the potential efficiency gains from using the Flow-Impact Offer (FIO) developed by Mullen (2019) compared to treating groundwater bids the same as surface water bids in future auctions. Quantile maps were created using ArcMap 10.5.1 based on the flux ratios calculated for each surface and groundwater permit (Figures 13 and 14).

The quantile maps show that the closer to a river or stream, the higher the flux ratio. Distance to a stream or river appears to be a powerful proxy for the flux ratio and should be considered by state and local authorities in future irrigation buyout auctions.

For each county, the number of acres bought out was calculated for each simulation run. Averaged across all 100 auction runs, the 10 counties that had the most acres associated with accepted bids during the first $5 million budget constrained simulation were Mitchell, Miller, Decatur, Sumter, Seminole, Baker, Lee, Calhoun, Early, and Dooly (Table 15). Eight of the ten counties in the top 10 are located in the Lower FRB. For the second $5 million budget constrained simulation, the top 10 counties were Early, Randolph, Lee, Calhoun, Macon, Webster, Crisp, Miller, Marion, and Sumter (Table 16). The top four counties are still located in the Lower FRB, but only five out of ten are located in the Lower FRB. This is because the 2017 cash rental rates for irrigated and non-irrigated land for counties in the Upper FRB are on average lower than counties in the Lower FRB due to productivity rates. Under the agricultural production and auction parameters considered, we examine these potential efficiency gains for the two sets of flux ratio ranges used in the simulations.

Table 15: Budget Constraint First Simulation Average Acre Reduction by County

County	FRB	Total Acres	Avg. Acre Reduction
Mitchell	Lower	82,745	6,068.38 (949.18)
Miller	Lower	77,906	5,308.98 (668.55)
Decatur	Lower	70,963	5,077.46 (891.18)
Sumter	Upper	56,167	4,351.79 (989.29)
Seminole	Lower	51,023	3,792.88 (1,068.14)
Baker	Lower	57,633	3,785.27 (559.04)
Lee	Lower	56,678	3,586.98 (584.53)
Calhoun	Lower	40,954	3,488.44 (942.91)
Early	Lower	45,728	2,736.40 (767.75)
Dooly	Upper	33,601	2,486.00 (919.91)
Crisp	Upper	29,139	2,306.56 (539.83)
Randolph	Lower	27,650	2,006.75 (833.28)
Dougherty	Lower	23,027	1,968.25 (502.79)
Terrell	Lower	33,062	1,900.90 (301.76)
Webster	Upper	19,183	1,336.35 (494.61)
Macon	Upper	9,678	1,071.60 (397.83)
Worth	Lower	19,361	1,012.81 (379.70)
Marion	Upper	7,861	686.46 (228.90)
Grady	Lower	4,858	405.17 (248.07)
Schley	Upper	4,429	252.98 (186.33)
Meriwether	Upper	600	245.79 (174.14)
Stewart	Upper	498	232.73 (155.57)
Taylor	Upper	2,294	202.31 (179.44)
Spalding	Upper	435	196.83 (147.46)
Clay	Lower	3,095	172.13 (109.41)
Pike	Upper	2,110	150.06 (92.45)
Upson	Upper	860	139.17 (141.51)
Coweta	Upper	910	100.29 (65.65)
Houston	Upper	225	38.29 (45.53)
Colquitt	Lower	145	26.73 (21.45)
Lamar	Upper	100	20.27 (26.47)
Talbot	Upper	40	15.21 (12.59)
Peach	Upper	0	0.00 (0.00)

Table 16: Budget Constraint Second Simulation Average Acre Reduction by County

County	FRB	Total Acres	Avg. Acre Reduction
Early	Lower	45,728	9,938.70 (587.73)
Randolph	Lower	27,650	8,221.74 (507.96)
Lee	Lower	56,678	7,004.11 (561.35)
Calhoun	Lower	40,954	5,797.85 (656.07)
Macon	Upper	9,678	4,858.37 (760.71)
Webster	Upper	19,183	4,463.41 (339.17)
Crisp	Upper	29,139	4,353.30 (363.37)
Miller	Lower	77,906	4,197.81 (562.04)
Marion	Upper	7,861	3,817.52 (557.26)
Sumter	Upper	56,167	3,640.33 (715.96)
Dougherty	Lower	23,027	3,388.22 (371.64)
Baker	Lower	57,633	3,176.11 (591.84)
Dooly	Upper	33,601	2,032.70 (480.45)
Taylor	Upper	2,294	1,327.63 (288.00)
Pike	Upper	2,110	1,189.33 (86.80)
Clay	Lower	3,095	1,110.74 (237.27)
Seminole	Lower	51,023	539.67 (280.56)
Upson	Upper	860	431.52 (96.10)
Meriwether	Upper	600	386.33 (117.41)
Schley	Upper	4,429	342.22 (121.38)
Coweta	Upper	910	315.15 (105.40)
Mitchell	Lower	82,745	262.52 (212.95)
Grady	Lower	4,858	218.07 (47.80)
Decatur	Lower	70,963	161.70 (130.53)
Worth	Lower	19,361	146.04 (102.31)
Spalding	Upper	435	89.41 (60.74)
Stewart	Upper	498	71.04 (41.30)
Terrell	Lower	33,062	39.26 (24.65)
Talbot	Upper	40	22.07 (12.45)
Colquitt	Lower	145	20.32 (12.06)
Houston	Upper	225	0.00 (0.00)
Lamar	Upper	100	0.00 (0.00)
Peach	Upper	0	0.00 (0.00)

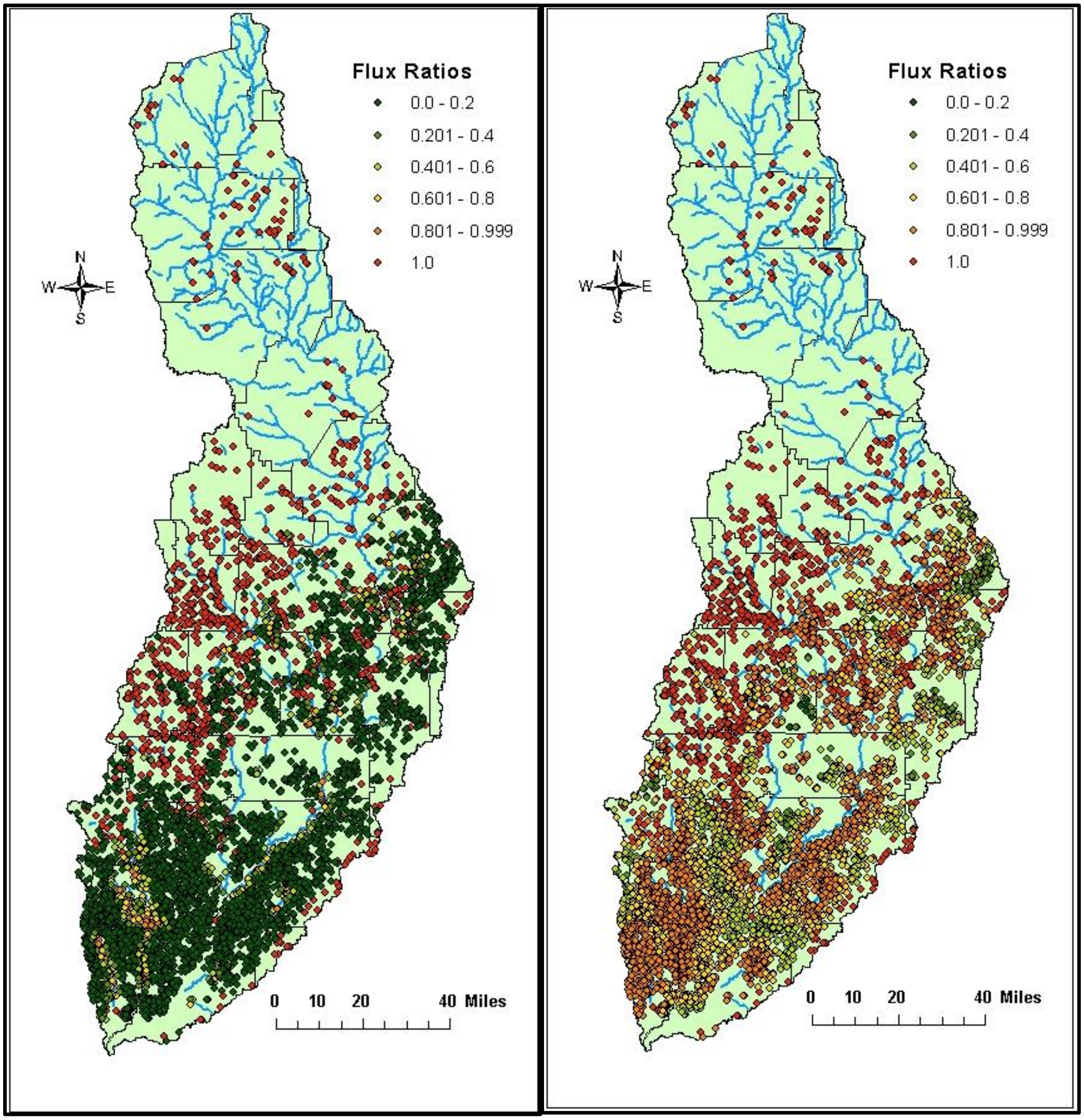


Figure 13: Quantile Map of Flux Ratios for LB Flux (left) to UB Flux (right)

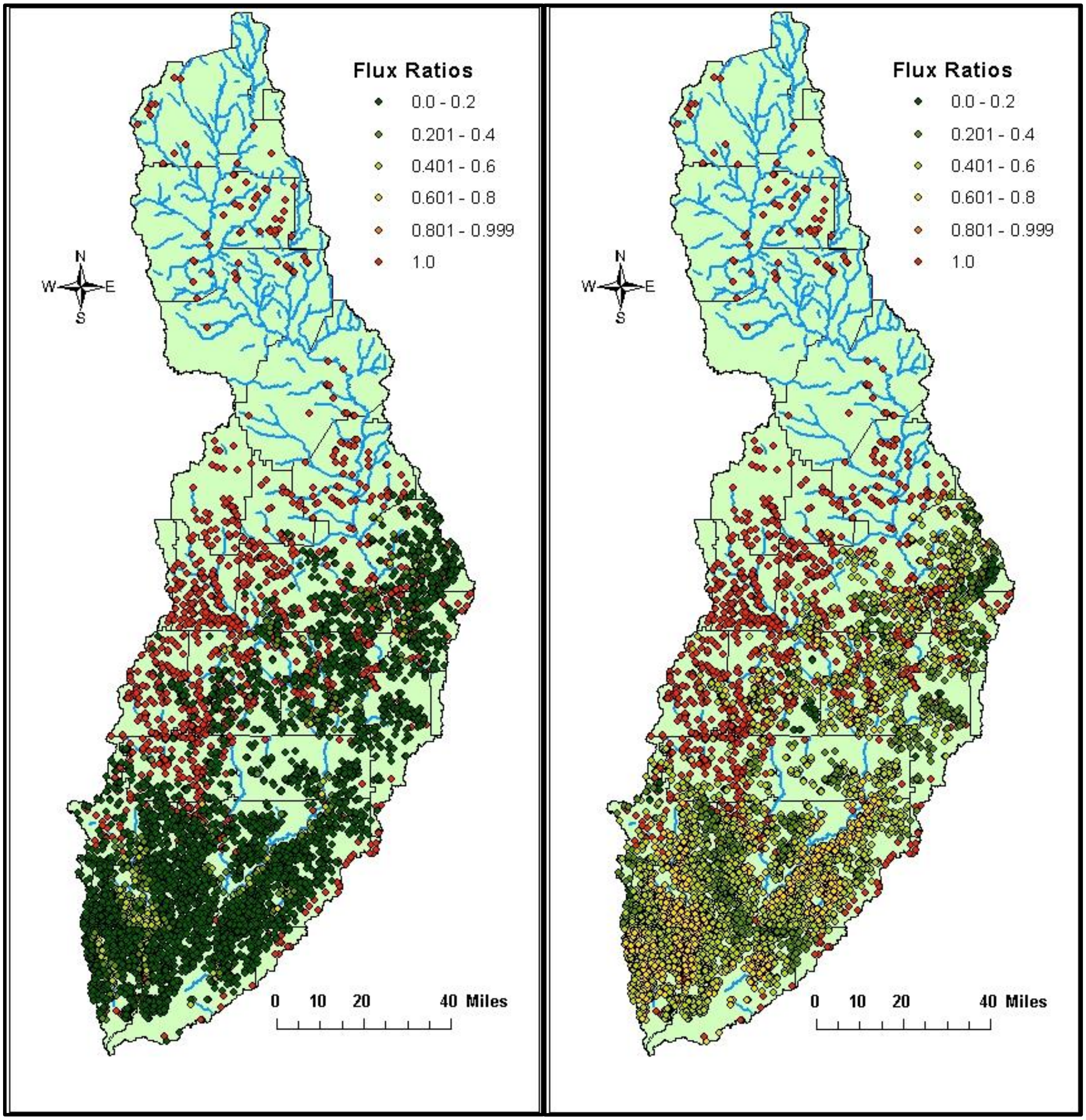


Figure 14: Quantile Map of Flux Ratios for Flux Low (left) to Flux High (right)

3.3 First Simulation Lower Bound (LB) Flux to Upper Bound (UB) Flux Ratio Range Results:

Here the results of using the parameters of the 2002 rules versus the FIO rules for the first set of flux ratios calculated using the STRMDEPL08 software are presented. When the state is faced with an unconstrained budget, it would accept an average of 2,672 offers using the 2002 rules and take 384,200 acres out of irrigation (Table 17). If the FIO rules are used, the state would accept 718 to 1,649 offers and take 113,149 to 244,208 acres out of irrigation (Table 17). To accomplish that, however, the state would spend 1.66 to 3.41 times as much money in absolute terms compared to the LB to UB Flux ratio range (Table 19). When looking at total water purchased (ac-in), if the 2002 rules were used, the state would prevent 1,746,951 to 4,116,402 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 1,470,533 to 2,930,947 ac-in of water (Table 17). With regards to average water price (\$/ac-in), the state would spend 1.18 to 2.87 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules (\$10.72-\$25.28/ac-in compared to \$8.80-\$9.05/ac-in) (Table 17 and 19).

In the \$5 million budget constraint simulation exercise with the FIO rules, fewer bids are accepted, slightly less acreage is purchased, but more water is purchased and at a lower average price compared to the 2002 rules. When faced with a \$5 million budget constraint, the state would accept an average of 407 offers using the 2002 rules and take 58,782 acres out of irrigation (Table 18). Using the FIO rules, the state would accept 329 to 370 offers and take 51,754 to 55,889 acres out of irrigation (Table 18). With regards to total water purchased (ac-in), if the 2002 rules were used, the state would prevent 273,371 to 631,228 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 677,765 to 708,570 ac-in of water (Table 18). With regards to average water price (\$/ac-in), the state would spend 1.12 to 2.49 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($7.91-$18.35/ac-in compared to $7.04-$7.36/ac-in) (Table 18 and 19).

3.4 First Simulation Flux Low to Flux High Ratio Range Results:

Recall that these second set of flux ratios used in the simulation exercise use the LB Flux and UB Flux ratios calculated multiplied by the baseflow ratios calculated from the Baseflow Filter Program. When the FIO rules are used, the state would accept 687 to 835 offers and take 109,692 to 129,573 acres out of irrigation (Table 17). If the 2002 rules are used instead of the FIO rules, the state would spend 3.09 to 3.50 times as much money in absolute terms when compared to the Flux Low to Flux High ratio range (Table 19). When looking at total water purchased (ac-in), if the 2002 rules were used, the state would prevent 1,638,554 to 3,242,480 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 1,439,274 to 1,603,185 ac-in of water (Table 17). With regards to average water price ($/ac-in), the state would spend 1.53 to 3.08 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($13.61-$26.96/ac-in compared to $8.76-$8.92/ac-in) (Table 17 and 19).

In the $5 million budget constraint simulation exercise and the FIO rules are used, fewer bids are still accepted, slightly less acreage is purchased, but more water is purchased and at a lower average price compared to the 2002 rules, just like when using the first flux ratio range. When faced with a $5 million budget constraint, the state would accept an average of 407 offers using the 2002 rules and take 58,782 acres out of irrigation (Table 18). Using the FIO rules, the state would accept 323 to 324 offers and take 51,622 to 51,822 acres out of irrigation (Table 18). With regards to total water purchased (ac-in), if the 2002 rules were used, the state would prevent 256,677 to 498,829 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 677,363 to 679,391 ac-in of water (Table 18). With regards to average water price ($/ac-in), the state would spend 1.37 to 2.66 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($10.01-$19.57/ac-in compared to $7.33-$7.35/ac-in) (Table 18 and 19).

Table 17: Results for Unconstrained Auction Budget Simulations

Simulation Results with Unconstrained Auction Budget (LB Flux to UB Flux Ratio Range)				
	2002 LB Flux	**2002 UB Flux**	**FIO LB Flux**	**FIO UB Flux**
Accepted Offers	2,672.11 (39.06)	2,672.11 (39.06)	718.47 (17.90)	1,649.05 (32.06)
Acres Purchased	384,200 (7,031)	384,200 (7,031)	113,149 (4,150)	244,208 (5,608)
Total Expenditure	$44,132,178 ($804,616)	$44,132,178 ($804,616)	$12,938,030 ($480,002)	$26,531,629 ($606,764)
Water Purchased (ac-in)	1,746,951 (60,815)	4,116,402 (77,280)	1,470,533 (55,143)	2,930,947 (68,241)
Average Water Price ($/ac-in)	$25.28 ($0.65)	$10.72 ($0.07)	$8.80 ($0.09)	$9.05 ($0.05)

Simulation Results with Unconstrained Auction Budget (Flux Low to Flux High Ratio Range)				
	2002 Flux Low	**2002 Flux High**	**FIO Flux Low**	**FIO Flux High**
Accepted Offers	2,672.11 (39.06)	2,672.11 (39.06)	686.77 (17.51)	834.91 (24.11)
Acres Purchased	384,200 (7,031)	384,200 (7,031)	109,692 (4,416)	129,573 (4,669)
Total Expenditure	$44,132,179 ($804,617)	$44,132,179 ($804,617)	$12,606,414 ($507,434)	$14,299,774 ($502,771)
Water Purchased (ac-in)	1,638,554 (59,933)	3,242,480 (68,161)	1,439,274 (58,266)	1,603,185 (58,451)
Average Water Price ($/ac-in)	$26.96 ($0.74)	$13.61 ($0.12)	$8.76 ($0.09)	$8.92 ($0.08)

Table 18: Results for $5 Million Constrained Auction Budget Simulations

Simulation Results with $5 Million Constrained Auction Budget (LB Flux to UB Flux Ratio Range)				
	2002 LB Flux	**2002 UB Flux**	**FIO LB Flux**	**FIO UB Flux**
Accepted Offers	407.40 (15.17)	407.40 (15.17)	329.14 (14.28)	370.26 (13.13)
Acres Purchased	58,782 (254)	58,782 (254)	51,754 (696)	55,889 (360)
Total Expenditure	$4,988,587 ($14,183)	$4,988,587 ($14,183)	$4,984,627 ($19,449)	$4,987,010 ($12,559)
Water Purchased (ac-in)	273,371 (20,774)	631,228 (11,196)	677,765 (10,371)	708,570 (6,799)
Average Water Price ($/ac-in)	$18.35 ($1.36)	$7.91 ($0.14)	$7.36 ($0.11)	$7.04 ($0.07)

Simulation Results with $5 Million Constrained Auction Budget (Flux Low - Flux High Ratio Range)				
	2002 Flux Low	**2002 Flux High**	**FIO Flux Low**	**FIO Flux High**
Accepted Offers	407.40 (15.17)	407.40 (15.17)	324.01 (14.25)	323.13 (11.34)
Acres Purchased	58,782 (254)	58,782 (254)	51,622 (713)	51,822 (866)
Total Expenditure	$4,988,587 ($14,183)	$4,988,587 ($14,183)	$4,976,457 ($39,810)	$4,975,716 ($34,901)
Water Purchased (ac-in)	256,677 (21,815)	498,829 (14,924)	677,363 (10,398)	679,391 (10,902)
Average Water Price ($/ac-in)	$19.57 ($1.60)	$10.01 ($0.29)	$7.35 ($0.11)	$7.33 ($0.11)

Table 19: Simulation Auction Budget Efficiency Comparison Results

Unconstrained Auction Simulation Budget Efficiency Comparison (2002 Rules / FIO Rules)				
	LB Flux Ratio	**UB Flux Ratio**	**Flux Low Ratio**	**Flux High Ratio**
Accepted Offers	3.72	1.62	3.89	3.20
Acres Purchased	3.40	1.57	3.50	2.97
Total Expenditure	3.41	1.66	3.50	3.09
Water Purchased (ac-in)	1.19	1.40	1.14	2.02
Avg. Water Price ($/ac-in)	2.87	1.18	3.08	1.53

$5 Million Auction Simulation Budget Constraint Efficiency Comparison (2002 Rules / FIO Rules)				
	LB Flux Ratio	**UB Flux Ratio**	**Flux Low Ratio**	**Flux High Ratio**
Accepted Offers	1.24	1.10	1.26	1.26
Acres Purchased	1.14	1.05	1.14	1.13
Total Expenditure	1.00	1.00	1.00	1.00
Water Purchased (ac-in)	0.40	0.89	0.38	0.73
Avg. Water Price ($/ac-in)	2.49	1.12	2.66	1.37

3.5 Second Simulation Lower Bound (LB) Flux to Upper Bound (UB) Flux Ratio Range Results:

Here the results of using the parameters of the 2002 rules versus the FIO rules for the first set of flux ratios calculated using the STRMDEPL08 software are presented. When the state is faced with an unconstrained budget, it would accept an average of 2,944 offers using the 2002 rules and take 427,458 acres out of irrigation (Table 20). If the FIO rules are used, the state would accept 947 to 1,896 offers and take 148,074 to 284,160 acres out of irrigation (Table 20). To accomplish that, however, the state would spend 1.62 to 3.07 times as much money in absolute terms compared to the LB to UB Flux ratio range (Table 22). When looking at total water purchased (ac-in), if the 2002 rules were used, the state would prevent 2,174,101 to 4,624,183 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 1,917,373 to 3,434,649 ac-in of water (Table 20). With regards to average water price ($/ac-in), the state would spend 1.21 to 2.71 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($10.22-$21.73/ac-in compared to $8.03-$8.48/ac-in) (Table 20 and 22).

In the $5 million budget constraint simulation exercise with the FIO rules, fewer bids are accepted, slightly less acreage is purchased, but more water is purchased and at a lower average price compared to the 2002 rules. When faced with a $5 million budget constraint, the state would accept an average of 478 offers using the 2002 rules and take 69,900 acres out of irrigation (Table 21). Using the FIO rules, the state would accept 393 to 445 offers and take 63,075 to 67,150 acres out of irrigation (Table 21). With regards to total water purchased (ac-in), if the 2002 rules were used, the state would prevent 520,208 to 794,073 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 829,975 to 852,089 ac-in of water (Table 21). With regards to average water price ($/ac-in), the state would spend 1.09 to 1.60 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($6.28-$9.61/ac-in compared to $5.78-$6.01/ac-in) (Table 21 and 22).

3.6 Second Simulation Flux Low to Flux High Ratio Range Results:

Recall that these second set of flux ratios used in the simulation exercise use the LB Flux and UB Flux ratios calculated multiplied by the baseflow ratios calculated from the Baseflow Filter Program. When the FIO rules are used, the state would accept 901 to 1,070 offers and take 148,074 to 284,160 acres out of irrigation (Table 20). If the 2002 rules are used instead of the FIO rules, the state would spend 2.75 to 3.27 times as much money in absolute terms when compared to the Flux Low to Flux High ratio range (Table 22). When looking at total water purchased (ac-in), if the 2002 rules were used, the state would prevent 2,058,907 to 3,706,958 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 1,855,203 to 2,085,912 ac-in of water (Table 20). With regards to average water price ($/ac-in), the state would spend 1.57 to 2.87 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($12.74-$22.95/ac-in compared to $8.01-$8.14/ac-in) (Table 20 and 22).

In the $5 million budget constraint simulation exercise and the FIO rules are used, fewer bids are still accepted, slightly less acreage is purchased, but more water is purchased and at a lower average price compared to the 2002 rules, just like when using the first flux ratio range. When faced with a $5 million budget constraint, the state would accept an average of 478 offers using the 2002 rules and take 69,900 acres out of irrigation (Table 21). Using the FIO rules, the state would accept 405 to 420 offers and take 62,570 to 62,904 acres out of irrigation (Table 21). With regards to total water purchased (ac-in), if the 2002 rules were used, the state would prevent 507,655 to 684,737 ac-in of water from being used for irrigation. When the FIO rules are applied, the state prevents 812,958 to 820,223 ac-in of water (Table 21). With regards to average water price ($/ac-in), the state would spend 1.22 to 1.64 times more for an ac-in of water if it were to use the 2002 rules instead of incorporating the FIO rules ($7.29-$9.86/ac-in compared to $5.98-$6.02/ac-in) (Table 21 and 22).

Table 20: Results for Second Unconstrained Auction Budget Simulations

Second Simulation Results with Unconstrained Auction Budget (LB Flux to UB Flux Ratio Range)				
	2002 LB Flux	**2002 UB Flux**	**FIO LB Flux**	**FIO UB Flux**
Accepted Offers	2,944.38 (25.73)	2,944.38 (25.73)	947.21 (20.56)	1,896.32 (24.12)
Acres Purchased	427,458 (6,275)	427,458 (6,275)	148,074 (1,925)	284,160 (4,498)
Total Expenditure	$47,237,363 ($802,375)	$47,237,363 ($802,375)	$15,386,421 ($272,986)	$29,121,609 ($646,220)
Water Purchased (ac-in)	2,174,101 (54,958)	4,624,183 (74,692)	1,917,373 (28,973)	3,434,649 (48,603)
Average Water Price ($/ac-in)	$21.73 ($0.38)	$10.22 ($0.04)	$8.03 ($0.10)	$8.48 ($0.08)

Second Simulation Results with Unconstrained Auction Budget (Flux Low to Flux High Ratio Range)				
	2002 Flux Low	**2002 Flux High**	**FIO Flux Low**	**FIO Flux High**
Accepted Offers	2,944.38 (25.73)	2,944.38 (25.73)	901.45 (20.41)	1,069.71 (18.36)
Acres Purchased	427,458 (6,275)	427,458 (6,275)	141,210 (2,676)	167,576 (4,158)
Total Expenditure	$47,237,363 ($802,375)	$47,237,363 ($802,375)	$14,864,162 ($448,695)	$16,964,869 ($532,174)
Water Purchased (ac-in)	2,058,907 (54,264)	3,706,958 (66,996)	1,855,203 (32,784)	2,085,912 (54,834)
Average Water Price ($/ac-in)	$22.95 ($0.43)	$12.74 ($0.09)	$8.01 ($0.09)	$8.14 ($0.09)

Table 21: Results for Second $5 Million Constrained Auction Budget Simulations

Second Simulation Results with $5 Million Constrained Auction Budget (LB Flux to UB Flux Ratio Range)				
	2002 LB Flux	**2002 UB Flux**	**FIO LB Flux**	**FIO UB Flux**
Accepted Offers	477.81 (11.45)	477.81 (11.45)	393.21 (10.32)	445.48 (9.21)
Acres Purchased	69,900 (674)	69,900 (674)	63,075 (600)	67,150 (565)
Total Expenditure	$4,986,379 ($15,092)	$4,986,379 ($15,092)	$4,985,375 ($16,656)	$4,926,592 ($63,256)
Water Purchased (ac-in)	520,208 (29,794)	794,073 (15,841)	829,975 (5,491)	852,089 (10,367)
Average Water Price ($/ac-in)	$9.61 ($0.55)	$6.28 ($0.12)	$6.01 ($0.04)	$5.78 ($0.10)

Second Simulation Results with $5 Million Constrained Auction Budget (Flux Low - Flux High Ratio Range)				
	2002 Flux Low	**2002 Flux High**	**FIO Flux Low**	**FIO Flux High**
Accepted Offers	477.81 (11.51)	477.81 (11.51)	420.02 (13.55)	405.26 (10.19)
Acres Purchased	69,900 (674)	69,900 (674)	62,904 (535)	62,570 (872)
Total Expenditure	$4,986,379 ($15,092)	$4,986,379 ($15,092)	$4,935,251 ($47,160)	$4,985,269 ($12,964)
Water Purchased (ac-in)	507,655 (30,891)	684,737 (21,164)	820,223 (6,729)	812,958 (8,568)
Average Water Price ($/ac-in)	$9.86 ($0.60)	$7.29 ($0.22)	$6.02 ($0.09)	$5.98 ($0.07)

Table 22: Second Simulation Auction Budget Efficiency Comparison Results

Unconstrained Auction Simulation Budget Efficiency Comparison (2002 Rules / FIO Rules)				
	LB Flux Ratio	**UB Flux Ratio**	**Flux Low Ratio**	**Flux High Ratio**
Accepted Offers	3.11	1.55	3.27	2.75
Acres Purchased	2.89	1.50	3.03	2.55
Total Expenditure	3.07	1.62	3.18	2.78
Water Purchased (ac-in)	1.13	1.35	1.11	1.78
Avg. Water Price ($/ac-in)	2.71	1.21	2.87	1.57

$5 Million Auction Simulation Budget Constraint Efficiency Comparison (2002 Rules / FIO Rules)				
	LB Flux Ratio	**UB Flux Ratio**	**Flux Low Ratio**	**Flux High Ratio**
Accepted Offers	1.22	1.07	1.14	1.18
Acres Purchased	1.11	1.04	1.11	1.12
Total Expenditure	1.00	1.00	1.00	1.00
Water Purchased (ac-in)	0.63	0.93	0.62	0.84
Avg. Water Price ($/ac-in)	1.60	1.09	1.64	1.22

3.7 Regional Economic Impact Analysis:

From an economic standpoint, all FIO rule scenarios reduce the economic loss for each region (FRB, Upper Flint, and Lower Flint) when compared to using the 2002 rules as measure by total impact ($) and state and local tax revenues. Flux ratios LB Flux, Flux Low, and Flux High were associated with the least loss in each region. In all three economic region scenarios, the UB Flux ratio reduces losses across all economic categories by 4.9% compared to 2002 rules. The other flux ratios reduce total impact loss across all categories by 12% (Tables 23 to 27). One reason for why the UB Flux ratio was considerably lower than the other flux ratios is because the continuous days of pumping were set to 160. Based on the Jenkins equation, as time approaches infinity, the volume of stream depletion approaches the volume pumped. As stated earlier, this number was used to safely assume the highest possible upper limit boundary when determining a permits flux ratio. Using the baseflow ratios of the streams to determine the second set of flux ratios (Flux Low and Flux High) seems to more accurately assess a realistic lower and upper limit boundary of a permit's flux ratio.

Table 23: Upper Flint River Basin Total Impact Summary Results

2002 Rules				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-571.13	-$20,898,079.68	-$24,391,429.19	-$45,669,456.00
Indirect Effect	-119.59	-$2,854,074.73	-$4,688,959.11	-$8,500,825.29
Induced Effect	-79.73	-$(2,192,011.33	-$4,969,456.87	-$8,843,442.41
Total Effect	-770.45	-$25,944,166.00	-$34,049,845.00	-$63,013,724.00

FIO Rules (UB Flux Ratio)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-543.00	-$19,868,533.40	-$23,189,782.67	-$43,419,545.00
Indirect Effect	-113.70	-$2,713,468.40	-$4,457,956.99	-$8,082,031.14
Induced Effect	-75.80	-$2,084,021.64	-$4,724,636.01	-$8,407,769.21
Total Effect	-732.49	-$24,666,023.00	-$32,372,376.00	-$59,909,345.00

FIO Rules (LB Flux, Flux Low & Flux High Ratios)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-502.73	-$18,395,315.43	-$21,470,299.64	-$40,200,060.00
Indirect Effect	-105.27	-$2,512,269.39	-$4,127,407.16	-$7,482,762.45
Induced Effect	-70.18	-$1,929,494.99	-$4,374,312.30	-$7,784,347.44
Total Effect	-678.18	-$22,837,080.00	-$29,972,019.00	-$55,467,170.00

Table 24: Lower Flint River Basin Total Impact Summary Results

2002 Rules				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-474.61	-$29,992,202.82	-$29,486,214.50	-$57,515,261.12
Indirect Effect	-136.06	-$5,092,631.10	-$8,034,216.40	-$13,551,527.81
Induced Effect	-164.08	-$5,026,215.14	-$10,163,893.98	-$17,982,105.94
Total Effect	-774.71	-$40,111,042.88	-$47,684,324.16	-$89,048,901.12

FIO Rules (UB Flux Ratio)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-451.33	-$28,521,066.29	-$28,039,897.02	-$54,694,101.16
Indirect Effect	-129.39	-$4,842,834.33	-$7,640,133.00	-$12,886,816.79
Induced Effect	-156.04	-$4,779,676.11	-$9,665,348.55	-$17,100,072.26
Total Effect	-736.71	-$38,143,570.84	-$45,345,377.88	-$84,680,996.16

FIO Rules (LB Flux, Flux Low & Flux High Ratios)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-417.54	-$26,385,545.52	-$25,940,403.89	-$50,598,868.96
Indirect Effect	-119.70	-$4,480,226.10	-$7,068,076.46	-$11,921,913.71
Induced Effect	-144.35	-$4,421,796.87	-$8,941,653.56	-$15,819,700.80
Total Effect	-681.54	-$35,287,563.04	-$41,950,133.28	-$78,340,488.96

Table 25: Flint River Basin Total Impact Summary Results

2002 Rules				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-527.05	-$27,509,872.25	-$28,204,671.09	-$54,457,038.80
Indirect Effect	-131.83	-$4,302,135.48	-$6,873,976.39	-$11,827,378.75
Induced Effect	-124.91	-$3,634,034.95	-$7,748,133.73	-$13,781,651.44
Total Effect	-783.77	-$35,446,046.40	-$42,826,785.40	-$80,066,069.80

FIO Rules (UB Flux Ratio)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-501.25	-$26,163,644.46	-$26,824,442.50	-$51,792,119.88
Indirect Effect	-125.38	-$4,091,605.45	-$6,537,590.32	-$11,248,592.13
Induced Effect	-118.80	-$3,456,199.20	-$7,368,969.74	-$13,107,230.20
Total Effect	-745.42	-$33,711,452.64	-$40,731,006.54	-$76,147,942.98

FIO Rules (LB Flux, Flux Low & Flux High Ratios)				
Impact Type	**Employment**	**Labor Income ($)**	**Value Added ($)**	**Output ($)**
Direct Effect	-464.25	-$24,232,100.23	-$24,844,114.53	-$47,968,540.56
Indirect Effect	-116.13	-$3,789,540.61	-$6,054,949.42	-$10,418,159.16
Induced Effect	-110.03	-$3,201,043.55	-$6,824,951.84	-$12,139,582.34
Total Effect	-690.39	-$31,222,687.68	-$37,724,019.48	-$70,526,282.76

Table 26: Upper Flint River Basin State & Local Tax Total Results

2002 Rules					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$16,044	$0	-$966,292	-$664,728	-$33,903
FIO Rules (UB Flux Ratio)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$15,253	$0	-$918,687	-$631,980	-$32,233
FIO Rules (LB Flux, Flux Low & Flux High Ratios)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$14,122	$0	-$850,568	-$585,120	-$29,843

Table 27: Lower Flint River Basin State & Local Tax Total Results

2002 Rules					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$29,552.32	$0	-$1,490,850.08	-$1,019,428.64	-$28,338.88
FIO Rules (UB Flux Ratio)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$28,102.76	$0	-$1,417,722.94	-$969,425.02	-$26,948.84
FIO Rules (LB Flux, Flux Low & Flux High Ratios)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$25,998.56	$0	-$1,311,570.64	-$896,839.12	-$24,931.04

Table 28: Flint River Basin State & Local Tax Total Results

2002 Rules					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$23,368.40	$0	-$1,242,040.80	-$905,586.60	-$28,876.80
FIO Rules (UB Flux Ratio)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$22,224.84	$0	-$1,181,260.08	-$861,270.66	-$27,463.68
FIO Rules (LB Flux, Flux Low & Flux High Ratios)					
	Emp. Comp.	**Propr. Inc.**	**Prod. and Imp. Tax**	**Household**	**Corporations**
Total	-$20,584.08	$0	-$1,094,052.96	-$797,686.92	-$25,436.16

3.8 Histograms of Groundwater Permit Flux Ratios:

Histograms of all groundwater permits were made to evaluate if flux ratios were significantly different based on if they were located in the Upper Flint Basin or the Lower Flint Basin (Figure 15). Intervals were set at ratios of 0.1 from 0 to 1. The Lower Flint first has a far larger number of groundwater permits in the region compared to the Upper Flint (3,462 to 489). The counties with the largest number of groundwater permits were Mitchell, Miller, Decatur, Seminole, Baker, Lee, Early, Dooly, Sumter, and Dougherty. Regardless of a permit's geographic location, the state should use the FIO to buyout a permit. However, if the state had to choose between the Lower Flint and the Upper Flint, whichever region has a higher distribution of flux ratios should be where the state should focus on buying out permits first. The histograms show that distributions are not different across the sub-basins.

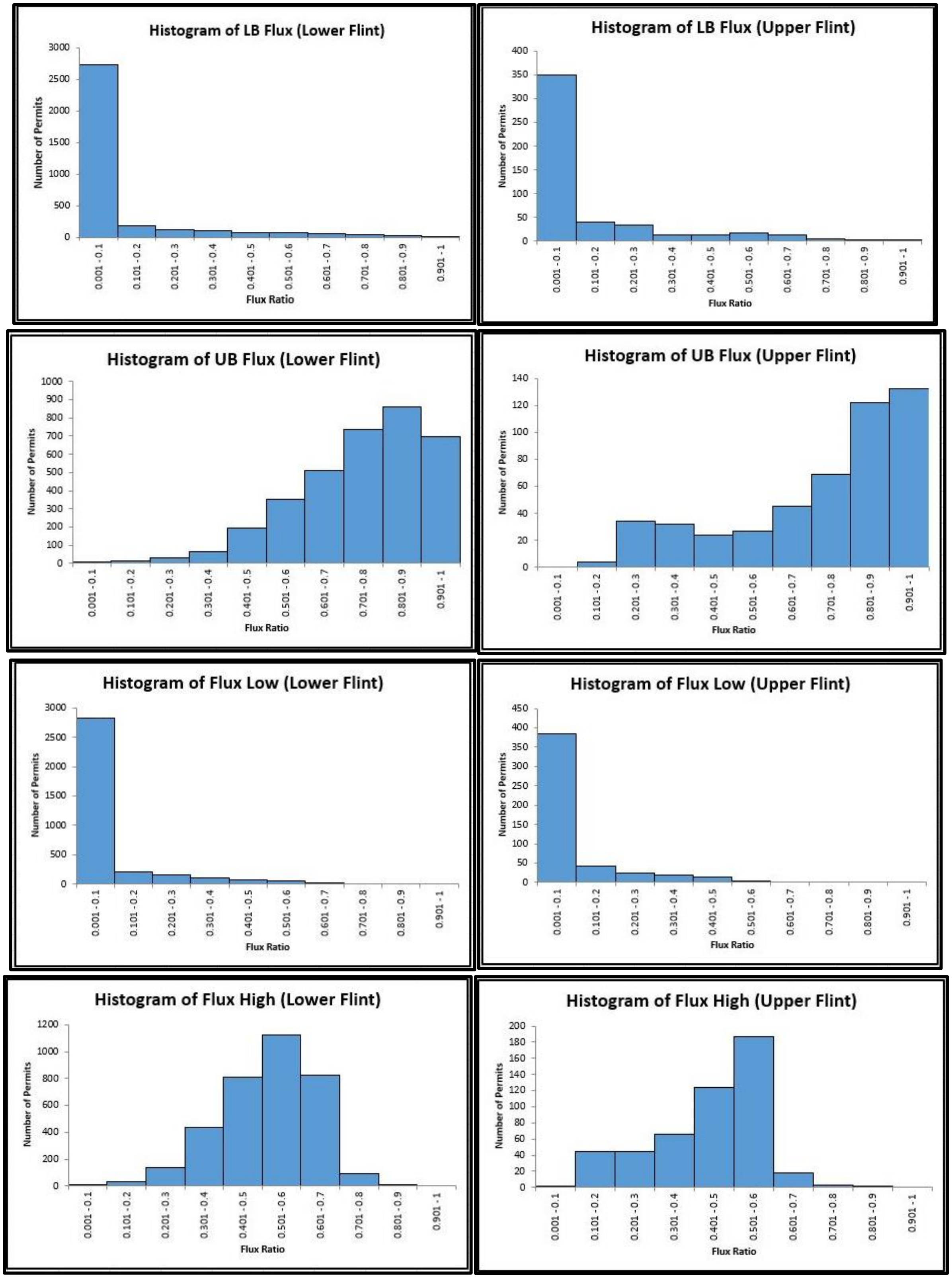


Figure 15: Histograms of Groundwater Permits

3.9 Potential of Drilling Deeper Wells:

Between 2010 and 2015, all across Georgia, irrigators are switching from surface water sources to groundwater sources (Manganiello, 2017). This trend of switching from surface to groundwater across Georgia was due to a moratorium on new surface water withdrawals in the Flint River Basin. This led irrigators to drill new groundwater wells in other parts of the state, as many producers believe groundwater is a more reliable source that can ensure consistent crop yields and eliminate the risk of declining surface flows. As an alternative to buying out permit holders on a yearly basis in time of severe drought in Georgia, the EPD could look into compensating farmers to source switch from surface water to groundwater or to dig deeper wells from the Floridan to the Claiborne aquifer when applicable. This could lead to better long-term water conservation measures with respect to stream flow in the FRB as compared to a water permit auction that is more of a short-term solution. The solution to switch from the Floridan to Claiborne aquifers would be reasonable in counties that lie above both aquifers and already have permit holders extracting from either aquifer. Baker, Calhoun, Clay, Crisp, Dooly, Dougherty, Early, Lee, Macon, Randolph, Schley, Sumter, and Terrell County would be the target areas as they fall under this category. Whatever budget the EPD has put towards a water permit auction, they could instead pay farmers to switch from surface to groundwater or from the Floridan to the Claiborne aquifer.

Construction of a Claiborne aquifer well is a little more complex than a Floridan well because the loose sands of the aquifer normally must be screened to prevent collapse of the well. A typical Claiborne aquifer well is first drilled to the top of the aquifer and casing is installed and grouted. A hole is then drilled into the aquifer and screens are installed opposite water-producing sands, which are best determined from geophysical logs. The screened interval may or may not be gravel packed depending on the intended use of the well. Yields generally will be higher in gravel packed wells. After drilling is completed the well is developed to remove drilling fluids from the well and aquifer (McFadden and Perriello, 1983).

To find out what the price of drilling a new and/or deeper well, I contacted multiple well drillers working in the Flint River Basin area via email and phone call from the "Georgia Licensed Water Well Contractor" list. I heard back from four different well drilling companies in the area that provided me with information on the costs associated with drilling small and large agricultural wells. Based on all the information provided to me, for each gallon per minute (GPM) of water that the water well is pumping it costs between $120-$130 considering all costs associated with the drilling process (pump/end, drilling per foot, pipe diameter, electricity, miscellaneous parts, labor costs, etc.). For instance, if a water well is designed to pump 250 GPM, the cost of building said well would usually be between $30,000 and $32,500 and a 1000 GPM water well would be between $120,000 and $130,000 on average. However, the cost of building a new well can often be two or three times this amount if drilling conditions are harder than expected due to rockiness of the underground soil. Table 29 illustrates some of the costs that go into drilling a new agricultural well estimated on a cost per foot and GPM basis.

Unfortunately, all four local well drilling companies that reached back to me informed me that you cannot just dig a deeper hole for the current well. Instead, you would essentially need to build a whole new water well along with drilling a deeper hole to reach the new aquifer. The cost and time associated with digging a new well will most likely vary by county as aquifer depths vary throughout the region. The cost of source switching in Sumter County will not be the same as source switching in Calhoun County. Source switching within counties may not even be uniform as different permit holders have different permitted acres, GPM of a well, and could lie on different soil type.

Table 29: Costs Associated with Well Drilling

Labor/Parts	Costs
Submersible pump and motor	$10,000-$30,000
Miscellaneous Parts	$5,000-$20,000
Piping and power	$2,000-$10,000
Water and Electrical Service Line	$11.50 per/L. ft
Just Drilling Rate per foot	$35-$55
Pump and Related Equipment	$120-$130
Each GPM	$120-$130
Drilling per foot (all costs)	$125/V. ft

Chapter 4: Conclusion and Recommendations

4.1 Conclusion:

With severe droughts becoming a more common aspect of the Georgia climate, there is a real need to estimate the impacts of groundwater withdrawal effects on in-stream flow at the individual permit scale within the Flint River Basin. One way to do this is by developing a methodology for comparing the economic efficiency of alternative rules for assessing bids from groundwater permit holders for future irrigation buyout auctions. To accomplish this we needed to estimate the flux ratio for each individual groundwater permit in the FRB, estimate expected water use during severe drought conditions for a representative acre of irrigated land in each county within the FRB, simulate auctions under alternative rules for assessing groundwater bids, and compare performances of auction rules using a variety of auction metrics. Under the agricultural production and auction parameters considered, all buyout auctions simulated with the administration of the FIO rules reduced flow impact by a substantial amount for a lesser price when compared to the 2002 rule run simulations. These results imply that under the FIO rules, the agricultural production impacts of the buyout are significantly reduced, as is the state's financial expenditure, but the reduction in flow impacts is also considerably lower when there is no budget constraint. From the perspective of $/ac-in of flow impact saved, the FIO rule outperforms the 2002 rule significantly. When a budget constraint is in place, as would be in the real world, for the same amount of money, the state could significantly reduce flow impacts while minimizing agricultural production effects by adopting the FIO rule through purchasing less total irrigated acreage but allowing more water to stay in-stream. In all three economic region scenarios, incorporating the flux ratios calculated into the FIO rules contributed to less economic loss than using the 2002 rules.

Continued population growth, increasing demand of water for agriculture, and climate change bringing with its prolonged periods of extreme drought has put a major challenge ahead for water resource management practices in the near future. A future irrigation buyout auction that is administered under any of these FIO rules can serve as an efficient short-term water management solution to help mitigate the effects of agricultural water use on stream flow volume in not only the Flint River Basin, but other vulnerable watersheds across the country.

4.2 Recommendations:

The FIO examined in this paper can serve as a starting point to efficiently manage low flows in vulnerable watershed that is the Flint River Basin and others across the world. In any future irrigation buyout auction administered in Georgia, informing a permit holder of what the flux ratio of their individual permits are will allow for a more efficient auction. With this information, a permit holder will be able to better assess a more reasonable offer to bid. This could lead to more permits being bought out as there is less of an information gap on the actual value of the permit from an environmental standpoint. This can be relayed to the permit holders through a topographic map of all permits showing the flux ratio range their permit lies within.

Some limitations in this paper regarding determination of a permit's flux ratio can be minimized with more information on aquifer and stream characteristics in the basin. The flux ratio ranges provided in this paper give a realistic lower and upper boundary. More research is needed to be done on aquifer characteristics of the Floridan, Claiborne, and Cretaceous aquifer such as transmissivity, storage coefficient, and streambed leakance, along with determining which streams are fully/partially penetrating with or without streambed resistance can help narrow down the flux ratio ranges. Regarding the uncertainty ratio, the GaEPD can determine what value should be used when assessing an offer based on the amount of information on where a permit is located. For example, if there is more information on the characteristics of Spring Creek sub-basin than the Ichawaynochaway sub-basin or Floridan aquifer compared to the Cretaceous aquifer, than permits associated with these would have a value closer to 1.

A more in-depth look into the cost and benefits of source switching compared to holding a future irrigation auction using the new FIO rules outlined could help the state and EPD in determining which method is more cost-effective. Research on the environmental effects of adding additional wells to deeper aquifers and more information on the economic costs associated with paying for permit holders to dig deeper wells to permanently withdraw from a groundwater source, instead of buying them out on a year-to-year basis when extreme drought is declared.

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