Agricultural Groundwater Policy During Drought: A Spatially Differentiated Approach for the Flint River Basin

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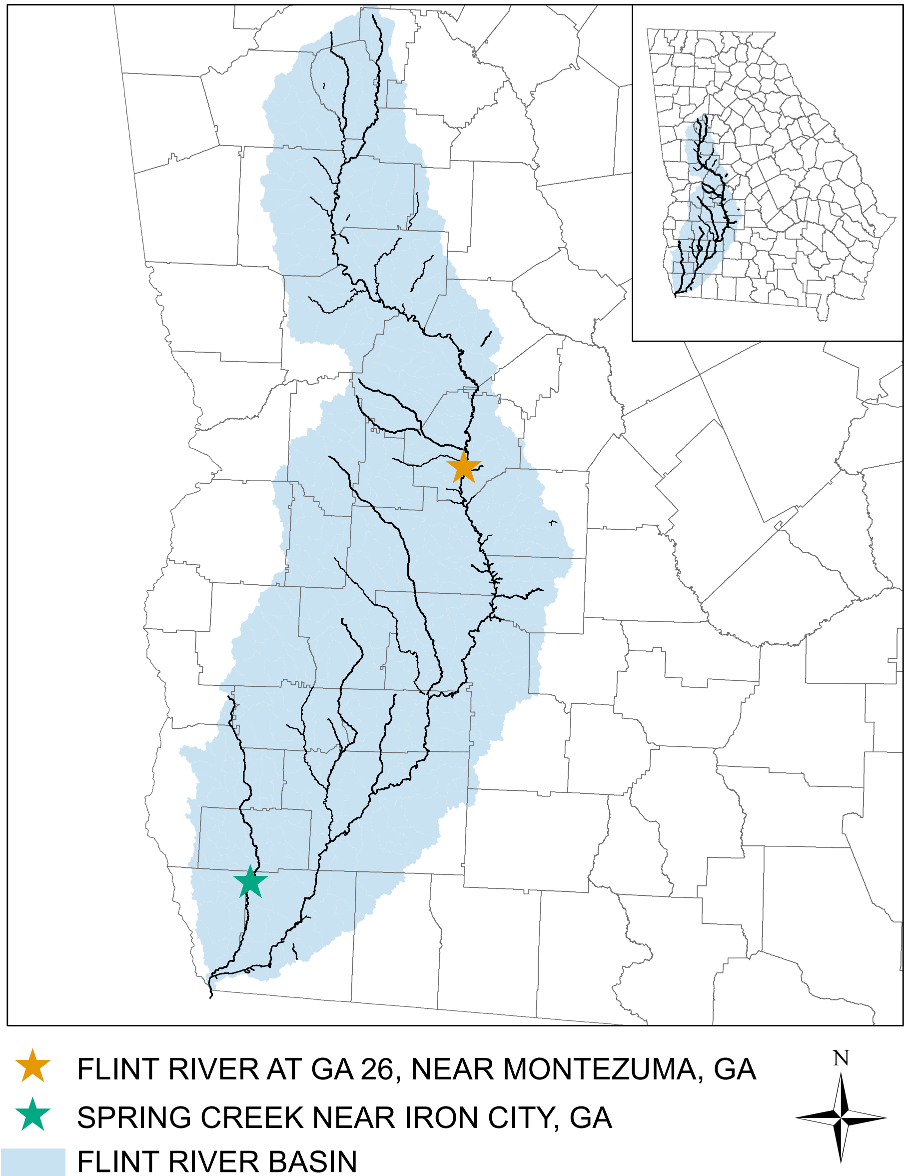
1. Introduction

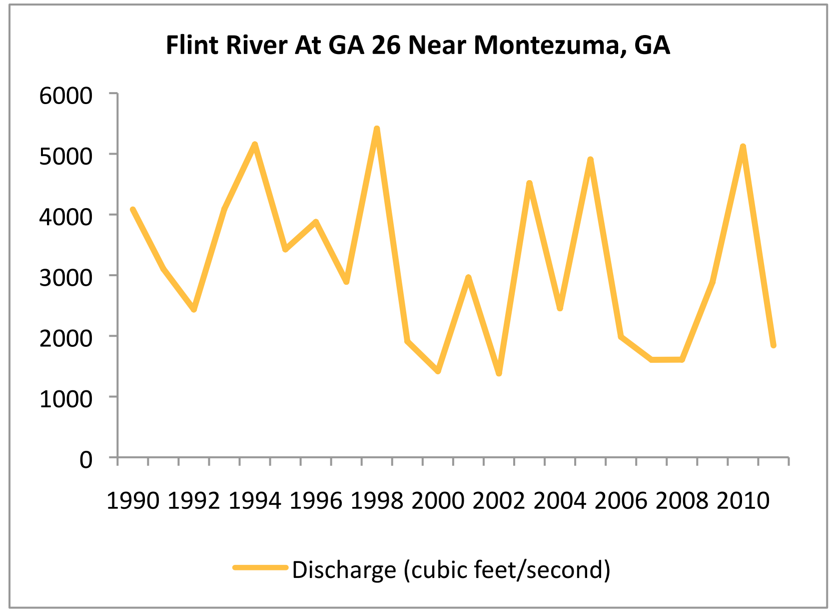
1.1. Study Area

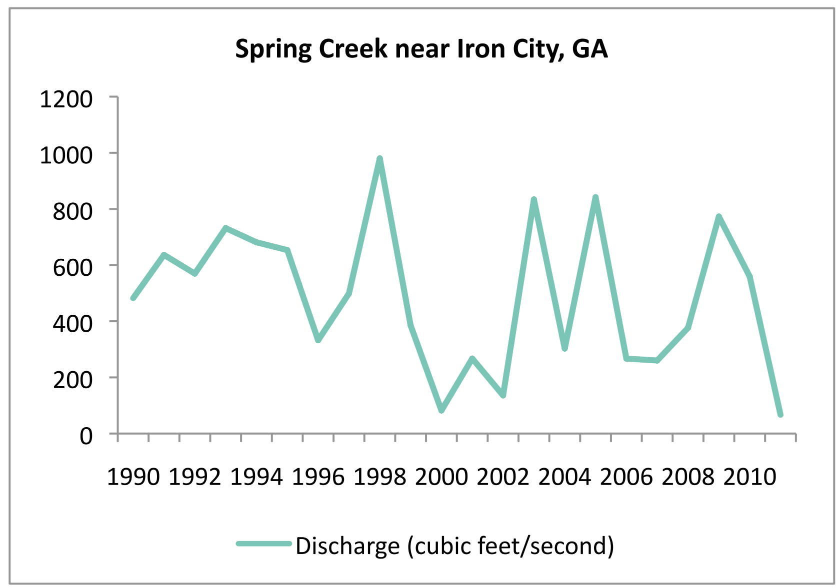
Georgia's Flint River Basin (FRB) has received particular attention regarding stream flow regulation because of its vast reaches, unique aquifer system, and varied uses. Stretching nearly 350 miles from the upper Piedmont region just south of Atlanta to the wetlands of the Coastal Plain in the southwest corner of the state, the lower FRB overlays the Upper, Lower, and middle boundary layers of the Floridan aquifer system. In its headwaters, the Flint River is a source of surface water for non-agricultural and industrial users while downstream users are largely agricultural producers of maize, cotton, peanuts, and soybeans along with supplementary horticultural products. Approximately 80% of the water used for irrigation in the lower Flint River Basin is withdrawn from the Upper Floridan aquifer, the shallowest major groundwater reservoir and one of the most productive aquifers in the country (Hicks *et al.*, 1987; Miller, 1990). The aquifer is characterized by high connectivity and permeability imparted by small, interconnected solution openings and a system of major groundwater conduits close to the Flint River (Hicks *et al.*, 1987); within the aquifer system, there is such little permeability contrast that the Floridan is effectively one continuous aquifer in parts of north Florida and southwest Georgia (Johnston & Bush, 1988). Interchange between ground and surface water in this region can occur rapidly, frequently, and unexpectedly (Rugel *et al.*, 2011). During the 1980's and 1990's, several studies suggested strong connectivity between groundwater withdrawal and reduced stream flow in southwest Georgia (Hayes *et al.*, 1983; Torak *et al.*, 1996; Torak & McDowell, 1996).

The FRB also provides critical habitat to four federally endangered (E) and two federally threatened (T) mussel species: Fat threeridge (E; *Amblema neislerii*), Shinyrayed pocketbook (E; *Lampsilis subangulata*), Gulf moccasinshell (E; *Medionidus penicillatus*), Chipola slabshell (T; *Elliptio chipolaensis*), and Purple bankclimber (T; *Elliptoideus sloatianus*) (US Fish & Wildlife Species Reports, 2012). The most commonly cited cause of mussel extinction, extirpation, or population decline is habitat degradation (Havlik, 1981; Layzer *et al.*, 1993; Palmer *et al.*, 2008); in the FRB, studies have shown low flow conditions and severe drought to adversely affect mussel distributions and assemblages (Gagnon *et al.*, 2004).

Image 1.1. Study Area & Annual-Mean Discharge for Two USGS Gage Stations







Agriculture in South Georgia was revolutionized by the implementation of center pivot irrigation systems throughout the 1970’s in an effort to combat the effects of drought on yields. Irrigation changed crop selection decisions, stabilized production and yields, and enabled the use of systems for the application of fertilizers, herbicides, and pesticides, decreasing the risk to agricultural producers (Pierce *et al.*, 1984). A burgeoning population in the northern part of the state has required more surface water withdrawals upstream; from 2000 to 2010, Georgia’s population grew by 1.5 million, a change of over 18%. The demand for water in the Southeastern United States has grown exponentially in the last four decades despite the ever-growing scarcity of water.

1.2. The Flint River Drought Protection Act

In response to the drought conditions of 1999 and 2000, the Flint River Drought Protection Act (the Act) was enacted in 2001 as a means of maintaining acceptable stream flow in the Flint River, defined as the quantity of stream flows at one or more specific locations which provides for aquatic life protection and other needs as established by the director [of the Georgia Environmental Protection Division (GA EPD)], based on municipal, agricultural, industrial, and environmental needs (O.C.G.A. 12-5-540). The Act provides a financial incentive program to ensure certain agricultural lands throughout the lower FRB are not irrigated during times of declared drought. If the director of the EPD declares a severe drought, a “drought protection auction” could be initiated whereby eligible permitted irrigators would be paid on a per-acre basis to forgo irrigation on the permitted land. Initially, eligible auction participants were only those holding agricultural surface water withdrawal permits on perennial streams in the FRB because of the uncertainty surrounding ground and surface water interaction (Couch *et al.*, 2006).

There have been two drought protection auctions since the inception of the Act: the first in 2001 and the second in 2002. The first auction proceeded by an “iterative and interactive process,” with participants submitting blind bids for the per-acre price they wanted and the Director of the EPD either accepting or rejecting based on the total cost of all presented bids. Rejected bids could be re-submitted during subsequent rounds until enough bids were accepted to remove the targeted amount of acreage from irrigation (Couch, *et al.*, 2006). The process was inefficient and time intensive; bids submitted over five auction rounds varied wildly, from $75/acre-$800/acre. The highest bids were rejected, leaving the average accepted bid at

$135/acre. The end result presumably took more than 33,000 acres out of irrigation for a total cost of approximately $4.5 million.

The second auction in 2002 was held in response to the continued drought, and attempted to improve efficiency while maintaining the acreage removed from irrigation by instituting a cap of $150/acre on bids; all bids below this cap would be accepted “up to the point where sufficient acreage was taken out of irrigation” (Couch *et al.*, 2006). There was a single auction round with bids ranging from $74/-$145/acre and an average accepted bid of $128/acre. The 2002 drought protection auction removed more than 41,000 acres from irrigation at a cost of $5.3 million.

Though it succeeded in removing some acreage from irrigation, the Act was noticeably problematic. To be eligible in the 2001 auction, participants need only have had a surface water permit with no requirement of recent use. As a result, many participants were compensated “for very marginal or long-fallow land, or for land that is not typically irrigated (e.g. trees),” a loophole which was closed for the second auction by mandating participating permit holders to have irrigated in the previous three years (Couch *et al.*, 2006). Still, both auctions failed to remove the highest water use cropland from irrigation and excluded all holders of groundwater permits from participating; if a drought protection auction were held in 2011 under these rules, nearly 50% of permit holders and over 1,000,000 irrigated acres would be excluded from participation. In 2006, the rules were changed in order to grant eligibility to groundwater permit holders.

1.3. Previous Investigations

The issue that naturally arises from this policy change, and which has yet to be addressed in the literature, is whether groundwater permits should face the same reservation price as surface water permits.

Research into the relationship between groundwater and streams began in the 1980’s and has increased greatly ever since, due mainly to concerns about acid rain (Sophocleous, 2002). There is a significant amount of literature dealing with ground and surface water connectivity, focusing both on the Flint River Basin and other regions. Many of these studies focus on the implementation and efficacy of flow system simulators such as the U.S. Geological Survey’s three-dimensional MODFLOW-2000 model and its predecessor, the MODular Finite-Element (MODFE), while others focus on groundwater pumpage and stream flows, their temporal variation, and their impacts on the ecology of the FRB (Albertson & Torak, 2002;

Mosner, 2002; Jones & Torak, 2006; Sanz *et al.*, 2011, Rugel *et al.*, 2011). As of this study, there has been only one economic analysis of critical habitat designation for at-risk mussels in the Flint River Basin, conducted by Industrial Economics, Inc. on behalf of the U.S. Fish & Wildlife Service (2007); this study uses a low flow threshold of their designation (specifically, the 7Q10, or streamflow that occurs over 7 consecutive days and has a 1 in 10 chance of occurring in any one year) to estimate the volume of water that could potentially be restricted at a regional level due to conservation efforts. As the stream flow effects of an individual well depends on its location vis-à-vis the stream, and the timing, rate and duration of pumping, there is a real need to estimate the impacts of ground and surface water interactions and the economic effects of conservation efforts at an individual permit holder scale.

The goal of this paper is to address the gap in the literature by using a variety of modeling and simulation methods to analyze the economic effects of mussel conservation efforts on agricultural producers in the Flint River Basin. We begin by using Geographic Information Systems (GIS) pinpointed groundwater withdrawal permit locations to determine distance to the nearest reach of stream, as delineated by the U.S. Geological Survey's National Hydrography Dataset. We then use the Decision Support System for Agrotechnology Transfer (DSSAT) to simulate yields and irrigation management actions – the timing and volume of groundwater withdrawals – under varying weather conditions (drought and non-drought years) for the four main agricultural products of the FRB: maize, peanuts, soybeans, and cotton. This is done for each of the permitted groundwater withdrawal locations. Using the Stream-Aquifer Model 2 (SAM2), we estimate the effects on stream flows of the simulated irrigation management actions from each well in isolation, and for multiple wells operating simultaneously.

Coupling the DSSAT simulated yields and water withdrawals with SAM2, we are able to model drought policy alternatives that include groundwater permits and examine their effects on agricultural production and revenue, in-stream flows, and state expenditures.

Ultimately, the question arising from the Flint River Drought Protection Act and the 2006 amendment to include groundwater permit holders is how to set the reservation price for a groundwater permit. It has been established in the literature that groundwater and surface water withdrawals are different enough as to warrant individual attention; it begs the question of whether reservation prices should reflect the differences inherent in the alternative permitting scenarios. More importantly, how much are these differences worth?

2. Methods

The first step in designing the GIS of this project was collecting data on permitted groundwater withdrawals, state hydrology, weather station coordinates, and U.S. Geological Survey gauge sites in the Flint River Basin and southwestern Georgia. The hydrology of the Flint River Basin was obtained from the U.S. Geological Survey's National Hydrography Dataset; weather station coordinates and the weather data for DSSAT were obtained from the Georgia Automated Environmental Monitoring Network.

To determine accurate distances from permitted groundwater withdrawal locations to nearest stream reach, it is necessary to have a basic understanding of GIS and the two types of coordinate systems, geographic and projected. Coordinate systems are arbitrary designations for spatial data and provide an easily transferable and recognizable basis for communication about a particular geographic place or area. Geographic coordinate systems use a three-dimensional spherical surface to define locations; it includes an angular unit of measure, a prime meridian, and a datum based on a spheroid and points are referenced by their longitude and latitude (Esri, 2010). Projected coordinate systems, on the other hand, are defined on a two-dimensional surface and have constant lengths, angles, and areas; they are always based on a geographic coordinate system, which is based on a sphere or spheroid (Esri, 2010). Representation of the earth's surface causes distortion of shape, distance, or direction, and different projections cause different types of distortion. There is no projected coordinate system able to preserve all three characteristics.

It is necessary to use a projected coordinate system based on the coordinate system information from the data source. The agricultural groundwater withdrawal permit holder dataset's coordinate system was unknown, and had to be identified using an iterative projection process. For logical distance measurements, it was necessary to select a projection intended to preserve distance; the Universal Transverse Mercator projection was selected for the appropriate zone containing the Flint River Basin. This projection, a specialized conformal application of the Transverse Mercator projection, has its own central meridian for each zone along which scale is constant. The Flint River Basin is contained in the Universal Transverse Mercator Zone 17N. For the purposes of this paper, Spring Creek was chosen as our initial subject area for its high sensitivity to pumpage and the presence of one federally protected mussel species, the Shinrayed pocketbook (*Lampsilis subangulata)*. Spring Creek was divided into reaches whose lengths were approximately straight in order to determine the effect of wells located on both sides of Spring Creek in a particular area; in total, 32 individual reaches were created, each with two designated sides (1 for west of Spring Creek; 2 for east of Spring Creek).

The Decision Support System for Agrotechnology (DSSAT) package was used to simulate yields and water requirements under irrigated and non-irrigated scenarios for maize, cotton, soybeans, and peanuts using historical weather data from stations within the lower FRB. The DSSAT is a collection of independent programs operating together, with crop simulation modeling at its center; databases describing weather, soil, experiment conditions and measurements, and genotype information allow for application of the models to different and customizable situations. DSSAT was first released in 1989 in an effort to integrate knowledge about the spatial and geographic variation in soil, climate, crops, and management for making better decisions about the location of production technology (Jones *et al,.* 2003; IBSNAT, 1993; Uehara & Tsjui, 1998). The heart of DSSAT is its cropping system model (DSSAT-CSM), which simulates growth, development, and yield of a crop "growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time (Jones *et al.*, 2003).

Table 2.1. Weather Data Availability by Station

Station	2000	2001	2007	2008	2011
Albany			X	X	X
Arlington	X	X	X	X	X
Attapulgus	X	X	X	X	X
Byromville			X	X	X
Cairo	X	X	X	X	X
Camilla	X	X	X	X	X
Cordele	X	X	X	X	X
Dawson	X	X	X	X	X
Donalsonville					X
Ducker					X
Georgetown			X	X	X
Howard			X	X	X
Lake Seminole	X	X	X	X	X
Moultrie			X	X	X
Newton	X	X	X	X	X
Pine Mountain	X	X	X	X	X
Plains	X	X	X	X	X
Sasser			X		X
Shellman			X	X	X
Ty Ty			X	X	X

The first step was collecting historical weather and climate data from relevant stations. For the purposes of this paper, historical weather data for 20 stations located throughout the Flint River Basin were collected and imported into DSSAT. An effort was made to collect data from all stations for the years 2000, 2001, 2007, 2008, and 2011, though not all stations had complete weather data available; a summary of station data availability is found in Table 2.1.

The next step was designing experiments for each crop based upon user-specified planting and management conditions. Previous work using DSSAT and focusing on the FRB provided optimal planting dates, fertilizer application amounts and dates, irrigation application rates as well as planting depth, method, spacing, distribution and population for each crop and for two soils common throughout the area, Tifton and Norfolk loamy sands. Optimal irrigation application thresholds were defined as the minimum percentage of soil moisture that maximized expected utility of net returns for each crop and soil type (Alhassan, 2010). Fertilizer types for each crop followed typical production practices used in the FRB. Current limitations in DSSAT do not allow for the application of phosphorous for peanut and soybean cultivars, thus phosphorous amounts are included only for the purpose of determining fixed costs of ammonium and diammonium phosphate (two commonly used fertilizers for soybeans and peanuts, respectively) applications but do not factor into the determination of total yield. A summary of optimal growing and planting conditions for each crop is found below (Table 2.2).

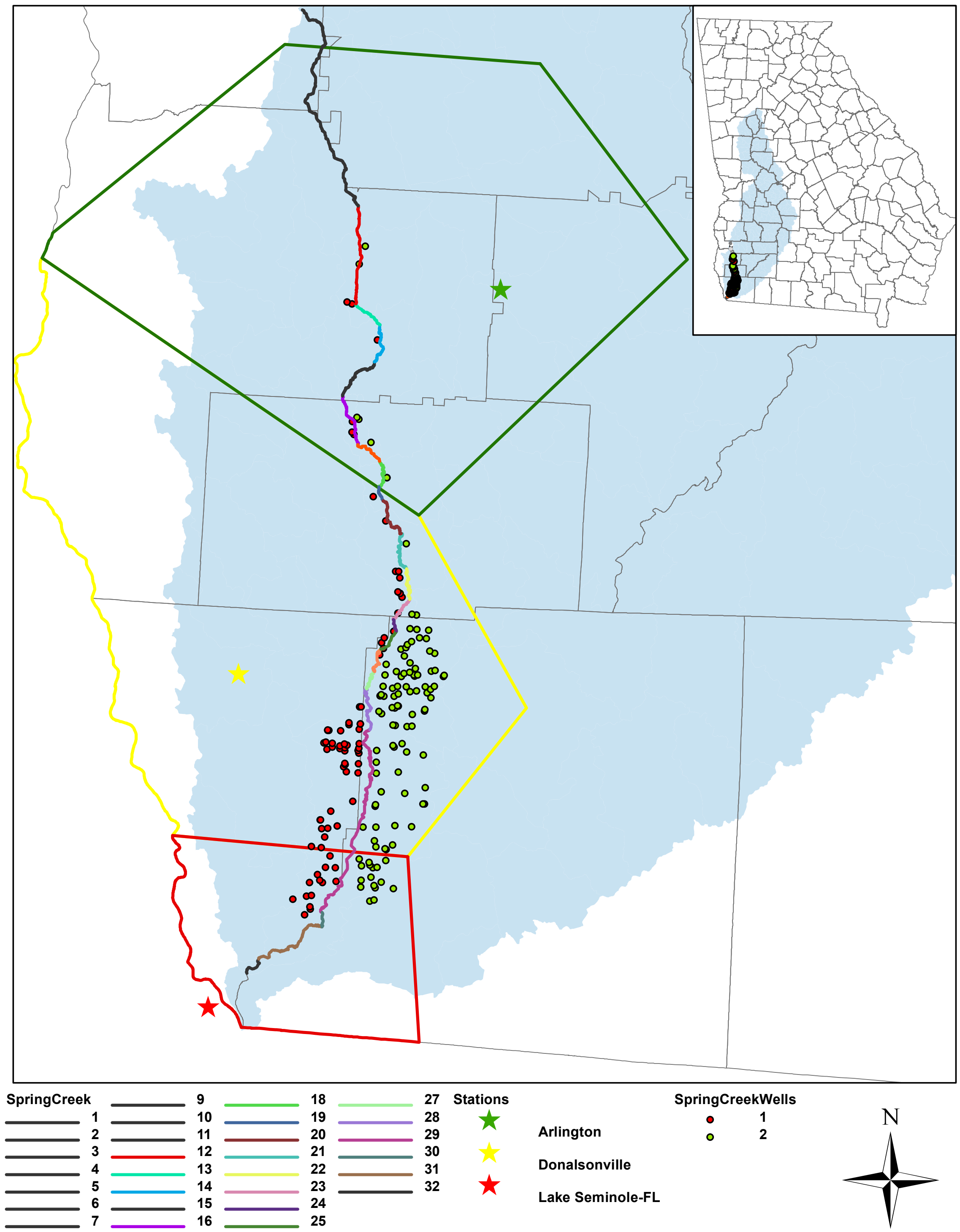
Table 2.2. Optimal Crop Management for the FRB

Crop	Cultivar	Soil	Planting Date	Soil Moisture for Irrigation Application	Fertilizer Type	Fertilizer Amount (kg/ha)	Fertilizer Application Date	Planting Method	Planting Distribution	Row Spacing (cm)	Planting Depth (cm)	Plant Population (/m^2)
Maize	PIO31G98	NLS	5/15	50%	Urea	70	5/15	Dry Seed	Row	61	7	7.2
						90	6/15					
		TLS	5/30	40%		70	5/30					
						90	6/30					
Cotton	DP 555	NLS	4/1	40%	Ammonium nitrate	20	4/01	Dry Seed	Row	90	4	14
						20	4/24					
						20	5/24					
		TLS	4/15	40%		20	4/15					
						20	5/06					
						20	6/06					
Peanut	Georgia Green	NLS	4/30	60%	Diammonium phosphate	11	4/30	Dry Seed	Row	31	4	12.9
		TLS	5/20	70%		11	5/20					
Soybean	MG VII	NLS / TLS	5/10	50%	Ammonium phosphate	15	5/10	Dry Seed	Row	60	3	20

Note: NLS and TLS are Norfolk loamy sand and Tifton loamy sand, respectively.

In total, 72 years were modeled for the 20 combined weather stations. Each simulation included two soil types and their respective planting dates and initial conditions, two irrigation treatments (rain-fed and irrigated at optimal percentage of soil moisture), and four crops and their respective management conditions; there were a resulting 1,264 individual simulations producing yields and irrigation requirements in terms of application dates and amounts in millimeters by weather station. In order to determine the permit holders that would be utilizing weather information from the stations in our study area, Thiessen polygons were overlaid on the wells previously determined to pull water exclusively from Spring Creek based on proximal Euclidean distance to nearby surface water sources. Thiessen (or Voronoi) polygons define individual areas of influence around a set of points; their boundaries define the area that is closest to each point relative to all other points, as mathematically defined by the perpendicular bisectors of the lines between all points. In the end, we were left with a study area focusing on one stream, the weather station polygons it passes through, and the corresponding permitted withdrawal locations. The length of Spring Creek passes through just three weather station polygons: Arlington, Donalsonville, and Lake Seminole. For the initial results, we chose to focus also on one year, 2011, so that all information obtained was from wells located along Spring Creek using weather information, and thus DSSAT-reported irrigation applications, from the 2011 growing season. Image 2.1, below, is a map summarizing Spring Creek, the wells known to pull water from it, and the Thiessen polygon overlay illustrating the permitted well locations that would be using weather information from the Arlington, Donalsonville, and Lake Seminole stations.

Image. 2.1. Summary Map of Study Area

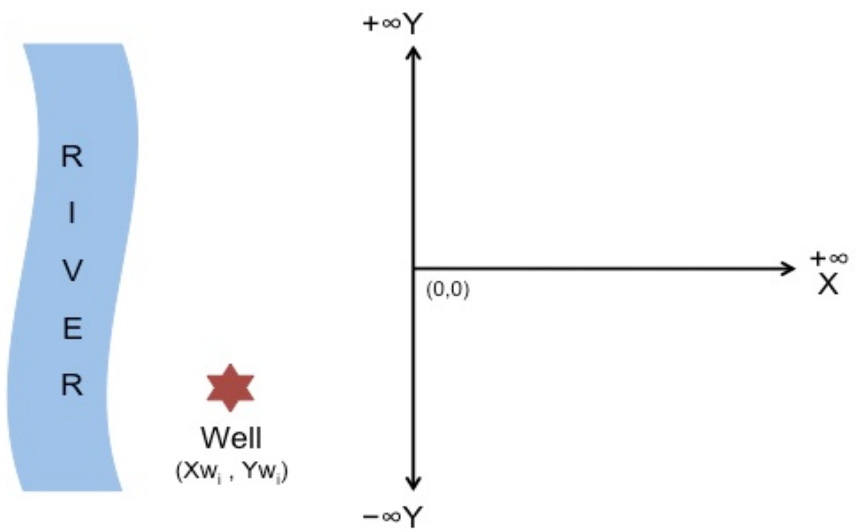


The Stream-Aquifer Model, version 2 (SAM2) is an updated two-dimensional model of an aquifer response to pumping. We used SAM2 to estimate the effect of groundwater withdrawals from one or more permitted sites within the Flint River Basin, that is, the induced recharge from the stream into the aquifer. The model's analytical solution is from Cleary & Ungs (1978), and was modified in the late 1980's to include the integration of flux from the stream for a single well. The present version can calculate the induced recharge for multiple wells, multiple time steps, and multiple pumping rates so that alternative irrigation schedules can be assessed.

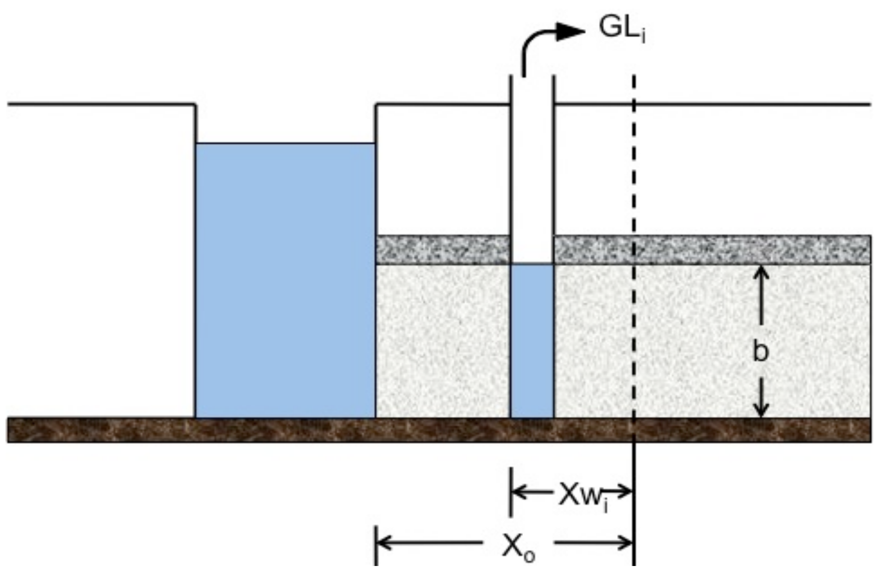
The program assumes a confined aquifer of uniform thickness with a fully penetrating stream located at $X = 0$; that is, the stream is assumed to be in contact with the confined aquifer along its entire reach, an assumption which, in the Flint River Basin, is quite possible. Figure 2.1 illustrates the model's assumptions.

Figure 2.1. Two-Dimensional Groundwater Flow at Infinite Dimensions

PLAN VIEW



CROSS-SECTIONAL



The governing equation that the program solves is

$$T_{xx}\frac{\partial^2 H}{\partial x^2}+T_{yy}\frac{\partial^2 H}{\partial y^2}+\sum_{t=1}^{n}GL_i*\delta\left(x-xw_i\right)=S\frac{\partial H}{\partial t} \qquad \text{(Equation 1)}$$

Where

T_{xx}	Transmissivity (L^2/T) in the x-direction
T_{yy}	Transmissivity (L^2/T) in the y-direction
GL_i	Pumping rate (L^3/T)for *i*th well at (xw_i, yw_i)
S	Storativity (dimensionless)

Transmissivity is the hydraulic conductivity multiplied by the thickness of the aquifer; storativity indicates the amount of water a confined aquifer releases from storage upon a unit drop of the piezometric surface.

Initial conditions are

$$H = H_0 \qquad t = 0$$

And boundary conditions are

$$\frac{\partial H}{\partial x}\rightarrow 0 \qquad x\rightarrow +\infty$$

$$\frac{\partial H}{\partial y}\rightarrow 0 \qquad y\rightarrow \pm\infty$$

$$H = H_0 \qquad x = x_0, t\geq 0$$

The analytical solution is

$$H(x,y,t)=H_0+\frac{1}{4\pi\sqrt{T_{xx}Y_{yy}}}\sum_{i=1}^{n}GL_i\left\{E_1\left(\frac{\alpha_1}{t}\right)-E_1\left(\frac{\beta_1}{t}\right)\right\} \qquad \text{(Equation 2)}$$

Where

$$\alpha_1=\left\{\frac{\left(y-yw_1\right)^2}{T_{yy}}+\frac{\left(w-xw_i\right)^2}{T_{xx}}\right\}\frac{S}{4}$$

$$\beta_1=\left\{\frac{\left(y-yw_i\right)^2}{T_{yy}}+\frac{\left(x+xw_i-2x_0\right)^2}{T_{xx}}\right\}\frac{S}{4}$$

(Equations 3 & 4)

And E_1, the exponential integral is

$$E_1(z)=\int_z^{\infty}\frac{e^{-t}}{t}dt \qquad \left|ARG(z)\right|<\pi \qquad \text{(Equation 5)}$$

In order to obtain the required inputs for SAM2, the DSSAT-reported irrigation depths (originally in millimeters) were applied to all permit holders utilizing weather information from that particular station. In other words, the values were converted to cubic meters and divided by each permit's reported acreage in hectares to obtain irrigation applications in terms of volumetric cubic meters/hectares, and then this figure was divided by the permitted hectares to get a total volume per application. Each permit holder was also issued a maximum pumping rate in gallons per minute, which was converted to cubic meters per day. By dividing the volume of irrigated water applied by the permitted pumping rate, we obtain the length of time (in days) that a permit holder must pump in order to apply the DSSAT-recommended irrigation application. This produced a theoretical pumping schedule for each well pulling water from Spring Creek, a duration in terms of days or partial days during which their pump was in operation.

3. Results

Results are pending further analysis and will be forthcoming soon.

References

Albertson, P.N. and L.J. Torak. 2002. *Simulated Effects of Ground-Water Pumpage on Stream Aquifer Flow in the Vicinity of Federally Protected Species of Freshwater Mussels in the Lower Apalachicola-Chattahoochee-Flint River Basin (Subarea 4), Southeastern Alabama, Northwestern Florida, and Southwestern Georgia*. U.S. Dept. of the Interior, U.S. Geological Survey.

Alhassan, M. 2010. "Valuing Irrigation Information in Irrigated Agriculture," *Department of Agricultural & Applied Economics*: University of Georgia, 78 p.

Bush, P. and R. Johnston. 1988. "Ground-Water Hydraulics, Regional Flow, and Ground-Water Development of the Floridan Aquifer System in Florida and in Parts of Georgia, South Carolina, and Alabama," U.S. Geological Survey, 80 p.

Cleary, R. and M. Ungs. 1978. "Groundwater Pollution and Hydrology: Mathematical Models and Computer Programs," Department of Civil Engineering, Princeton University Report 78-WR-15.

Couch, C.A. and R.D. McDowell. 2006. "Flint River Basin Regional Water Development and Conservation Plan." *Atlanta, GA. Georgia Department of Natural Resources Environmental Protection Division*.

Gagnon, P., S. Golladay, W. Michener and M. Freeman. 2004. "Drought Responses of Freshwater Mussels (Unionidae) in Coastal Plain Tributaries of the Flint River Basin, Georgia." *Journal of Freshwater Ecology*, 19, 667-79.

Havlik, M.E. and L.L. Marking. 1987. "Effects of Contaminants on Naiad Mollusks (Unionidae): A Review," Resource publication; U.S. Department of the Interior, Fish & Wildlife Service: 164 p.

Hicks, D.W., H.E. Gill and S.A. Longsworth. 1987. "Hydrogeology, Chemical Quality, and Availability of Ground-Water in the Upper Floridan Aquifer, Albany Area, Georgia." Available from Books and Open File Report Section, USGS Box 25425, Denver, CO 80225. USGS Water Resources Investigations Report 87-4145.

Layzer, J.B. and L.M. Madison. 1995. "Microhabitat Use by Freshwater Mussels and Recommendations for Determining Their Instream Flow Needs." *Regulated Rivers: Research & Management*, 10(2,4), 329-45.

Miller, J. 1990. "Ground Water Atlas of the United States: Alabama, Florida, Georgia, & South Carolina," U.S. Geological Survey, HA 730-G.

Mosner, M.S. 2002. *Stream-Aquifer Relations and the Potentiometric Surface of the Upper Floridan Aquifer in the Lower Apalachicola-Chattahoochee-Flint River Basin in Parts of Georgia, Florida, and Alabama, 1999-2000*. U.S. Dept. of the Interior, U.S. Geological Survey: Water-Resources Investigations Report 02-4244.

Palmer, M.A., C.A. Reidy Liermann, C. Nilsson, M. Florke, J. Alcamo, P.S. Lake and N. Bond. 2008. "Climate Change and the World's River Basins: Anticipating Management Options." *Frontiers in Ecology and the Environment*, 6(2), 81-89.

Peterson, J.T., J.M. Wisniewski, C.P. Shea and C. Rhett Jackson. 2011. "Estimation of Mussel Population Response to Hydrologic Alteration in a Southeastern US Stream." *Environmental Management*, 1-14.

Pierce, R., N. Barber and H. Stiles. 1984. "Georgia Irrigation 1970-1980: A Decade of Growth," U.S. Geological Survey, Atlanta, GA: 180 p.

Rugel, K., C.R. Jackson, J.J. Romeis, S. Golladay, D. Hicks and J. Dowd. 2012. "Effects of Irrigation Withdrawals on Streamflows in a Karst Environment: Lower Flint River Basin, Georgia, USA." *Hydrological Processes*, 26, 523-34.

Sanz, D., S. Castano, E. Cassiraga, A. Sahuquillo, J.J. Gomez-Alday, S. Pena and A. Calera. 2011. "Modeling Aquifer-River Interactions under the Influence of Groundwater Abstraction in the Mancha Oriental System (SE Spain)." *Hydrogeology Journal*, 19(2), 475-87.

Sophocleous, M. 2002. "Interactions between Groundwater and Surface Water: The State of the Science." *Hydrogeology Journal*, 10(1), 52-67.

Torak, L.J. and R.J. McDowell. 1996. "Ground-Water Resources of the Lower Apalachicola, Chattahoochee, Flint River Basin in Parts of Alabama." U.S. Geological Survey: OFPR 95-321. 145 p.

Torak, L.J., J.A. Painter and Reston Geological Survey, VA. 2006. "Geohydrology of the Lower Apalachicola-Chattahoochee-Flint River Basin, Southwestern Georgia, Northwestern Florida, and Southeastern Alabama," U.S. Geological Survey: Water-Supply Paper 2460.

U.S. Fish & Wildlife Service. 2012. "Species Reports," Environmental Conservation Online System. http://ecos.fws.gov/