

Simulated irrigation reduction improves low flow in streams—A case study in the Lower Flint River Basin

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ABSTRACT

Study region: The Ichawaynochaway Creek watershed within the Lower Flint River Basin in the Southeast US.

Study focus: Freshwater resources are facing increasing pressure globally, even in areas not generally accustomed to water shortages. The Apalachicola-Chattahoochee-Flint River basin has experienced episodic water stress over the past three decades due to population growth, climate variability, land use change, and agricultural intensification. While precipitation in the region is relatively high, declines in streamflow suggest a growing need to develop water management options focused on reducing water consumption. Many efforts have focused on reducing water use by irrigation, the primary water consumer in the region; however, the effectiveness of irrigation reduction at restoring streamflow is uncertain.

New hydrological insights of the region: We used the Soil and Water Assessment Tool to simulate the effects of a range of irrigation reduction scenarios on streamflow during a 16-year period that included extreme drought and extremely wet conditions. Simulated irrigation reduction had a consistently positive effect on streamflow. In the absence of irrigation, annual streamflow increased 7 %, or ~6 million m³/year, compared to normal irrigation. Proportional changes in streamflow were much greater during low flow periods. Additional flow during extremely low flow periods is critically important for conserving imperiled aquatic species and maintaining healthy stream habitats. Results indicate that increased flow is achievable by broadly implementing existing water conservation technologies.

1. Introduction

Land use change, deforestation, population growth, agricultural expansion, and agricultural intensification have significantly increased pressure on global freshwater resources (Nejadhashemi et al., 2012; Woznicki et al., 2015; Rodell et al., 2018). Stress on freshwater supplies is increasingly being experienced in areas not historically accustomed to water shortages (Brantley et al., 2018; Golladay et al., 2016). In the Southeastern US, precipitation is relatively abundant (> 1000 mm/year), however projections of increasing water demands, increasing temperatures, and changing precipitation patterns will stress regional water resources (Emanuel and Rogers, 2012; Golladay et al., 2016). The region is expected to experience rapid land use changes with 12–17 million ha of new urban development by 2060 (Wear and Greis, 2013). At the same time, the regional climate is projected to be hotter, with temperature increases likely exceeding 1.5 °C by 2100 (IPCC, 2013), resulting in a greater evaporative loss. Even with abundant average annual precipitation, the Southeastern US often suffers from water scarcity due to periodic La Niña cycles, which bring warm

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and dry conditions diminishing aquifer and soil water recharge during the dormant season (Mearns et al., 2003; Singh et al., 2016).

Episodic water scarcity in the region has already caused substantial and ongoing regional conflicts over water allocation, particularly in the Apalachicola-Chattahoochee-Flint (ACF) River Basin (Ruhl, 2005) where water withdrawals in the upper basin have been blamed for negative impacts on downstream ecology and nearshore marine fisheries industry. The Flint portion of the basin is an interesting example because it has both extensive exurban development (upper basin) and intensive irrigated agriculture (lower basin). Total water withdrawal in the Flint River basin of Georgia is projected to increase further, from 3.9 million m³/day in 2020 to 4.3 million m³/day in 2050 (Lower Flint Ochlockonee Watershed Council, 2017; Upper Flint Watershed Council, 2017).

Globally, agricultural irrigation is the largest freshwater user, accounting for 70 % of water withdrawals (Fischer et al., 2007; Woznicki et al., 2015). In the Flint River basin, irrigation greatly increases crop yields and quality, and combined with other agriculture related trade sectors accounts for ~ \$6 billion, or 34 % of the regional economy (Couch and McDowell, 2006). Agricultural water consumption increased beginning in the 1970's with the adoption of center-pivot irrigation (Couch et al., 1996). Irrigated area increased from 53,000 ha in 1976 to 106,000 ha in 1977 (Pollard et al., 1978). By 1980, irrigated farmland had increased to more than 183,000 ha and presently is reported to exceed 263,000 ha [Georgia EPD, 2009 Wetted Acreage Database]. Total water withdrawal in the lower Flint River basin is dominated by agricultural irrigation, which comprises as much as 90 % of water withdrawals during the April-September growing season. These competing interests—i.e., urban, agricultural, fisheries, and ecological—suggest a growing need to develop water use and land management options focused on improving the balance between precipitation and water yield.

With extensive water use throughout the Flint River basin, stream flows have declined, particularly during extended droughts (Emanuel and Rogers, 2012; Rugel et al., 2012). Since 2000, minimum flows observed in the lower Flint River and its tributaries were substantially lower than those observed during historical droughts (Golladay and Hicks, 2015; Brantley et al., 2018). Extensive areas of losing or dry reaches have been observed regionally during the past 20 years (Gordon et al., 2012; Rugel et al., 2012). For example, Spring Creek, a tributary to the lower Flint River basin, was formerly perennial but has become intermittent since 1980 (Rugel et al., 2012). Even during winter, post-irrigation median daily flow seldom equaled or exceeded the pre-irrigation median flow value (Golladay et al., 2016). Reduced summer stream flow has negative implications for ecological communities in the river, such as freshwater mussels (Golladay et al., 2004), native crayfishes (Sargent et al., 2011), and fishes (van den Avyle and Evans, 1990; Freeman et al., 2013; Golladay et al., 2016).

Concerns about streamflow have increased interest in technologies that can improve agricultural water conservation while acknowledging that economic pressures and increasing human populations necessitate the continued use of irrigation for sustaining and improving crop yields. Thus, maximizing irrigation system efficiency—or the ratio of crop yield to water applied—is imperative. For example, application efficiency—or the ratio of water used by the crop to total water applied—has improved from < 75 % to > 85 % in center pivot irrigation systems by using low-pressure drop nozzles that reduce evaporative water loss during application [Mark Masters, personal communication 2017], and this technology has been widely adopted in the region. Other agriculture water conservation practices are being developed or employed in the region with varying degrees of effectiveness. For example, switching from standard application, where water is applied evenly across an entire field, to variable rate irrigation, where water is applied in proportion to crop needs, had a water saving of up to 15 % (Vellidis et al., 2016). And, changing from the traditional “checkbox method” to smart irrigation scheduling in combination with conservation tillage can result in water saving of 12–76 % in normal or wet years and 40 % in dry years (Vellidis et al., 2016).

For Ichawaynochaway Creek, a major tributary of the lower Flint, it has been estimated that a 20 % reduction in irrigation below 2006 levels during drought years would meet the in-stream flow criteria (Monthly 1-day Minima and Annual Low-Flow Duration) virtually all the time (Couch and McDowell, 2006). However, a more recent assessment of the broader effects of irrigation efficiency programs on streamflow is lacking. Our goal was to determine the effectiveness of irrigation water savings at restoring streamflow. We hypothesized that reduced agricultural irrigation from groundwater would result in increases in streamflow; and the impact of irrigation reduction on streamflow will be greatest during low flow periods when irrigation demand is often highest, and overall water availability is low. A hydrologic model was calibrated for the Ichawaynochaway Creek watershed, to simulate streamflow responses across a range of reductions in agricultural water use from 0 to 100 % of what is typically applied to crops based on calculated crop water demands. To accurately simulate the wide range of irrigation adjustment, we used the Soil and Water Assessment Tool (SWAT), which has the ability to represent watersheds with a wide range of land use and weather input data (Neitsch et al., 2009).

2. Methods

2.1. Study area

The Ichawaynochaway Creek watershed is a HUC-8 watershed located in the Gulf Coastal Plain of southwestern Georgia, USA, covering an area of approximately 2940 km² (Fig. 1). Ichawaynochaway Creek originates near Weston, GA, USA (31.98, −84.64) and flows in a generally southerly direction until it reaches the Flint River below Newton, GA (31.17, −84.47). For more than half of its length, Ichawaynochaway Creek flows through the Fall Line Hills physiographic district of the upper Coastal Plain region. In its southern reaches, the creek flows across the Dougherty Plain physiographic district and interacts with the Upper Floridan aquifer. The U.S. Geological Survey stream gages within the watershed have up to 75 years of flow records covering a period in which significant land use change has occurred (Pierce et al., 1984; Fanning et al., 2001). See Golladay and Battle (2002) and Golladay et al. (2004) for a more detailed description.

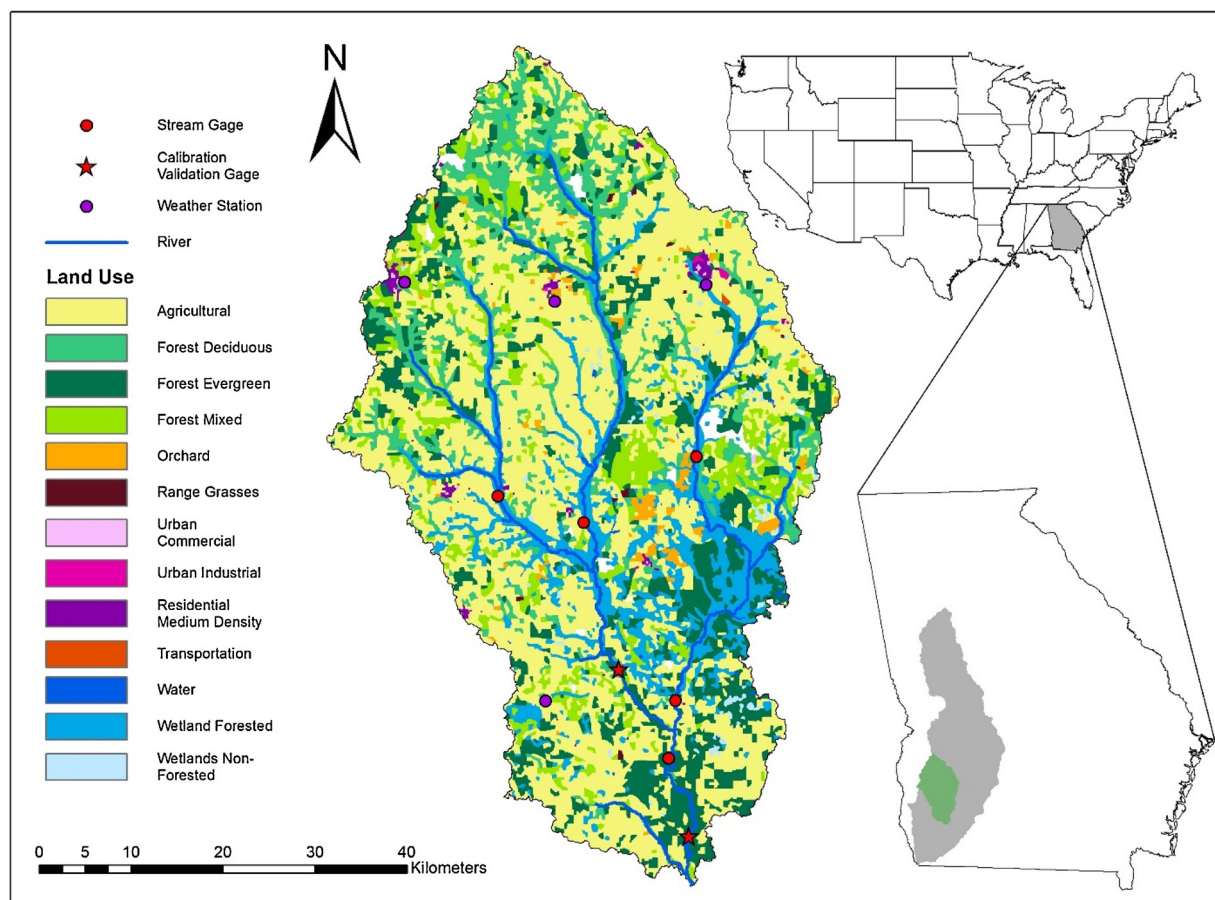


Fig. 1. The Ichawaynochaway Creek watershed is part of the Flint River watershed (gray area) in the state of Georgia. Land use of the watershed is dominated by agriculture (50 %) with remaining acreage in forestland (35 %), wetlands (14 %) and urban area (1 %) (National Land Cover Database 2011, [Homer et al., 2015](#)). Weather stations (purple circles) maintained by Georgia Automated Environmental Monitoring Network by the College of Agricultural and Environmental Sciences of the University of Georgia (www.georgiaweather.net) provided daily precipitation and maximum and minimum temperature data. Stream gages operated by U.S. Geological Survey (<https://waterdata.usgs.gov/nwis>) provided additional precipitation data (red circles and red stars). Data from two stream gages (red stars) were used for model calibration and validation.

The climate in the study area is classified as humid subtropical ([Peel et al., 2007](#)) with hot and humid summers, temperatures ranging from 18–35 °C, and mild winters, with temperatures ranging between 2–13 °C (mean annual temperature 19 °C). Mean annual precipitation is ~1300 mm and is distributed fairly evenly across the year [<http://www.ncdc.noaa.gov>, 30-year average 1987–2016]. Climatic conditions varied substantially over the modeled period from 2000 to 2016, including three multi-year droughts (1999–2001, 2006–2008, and 2010–2013) ([Fig. 2](#)). Droughts spanned both growing and dormant seasons and, because they were multi-year, sometimes extended through the dormant season (Nov–Apr) when most groundwater recharge occurs. Monthly rainfall averages about 110 mm (range 10–350 mm), but during extended droughts monthly totals were often well below this average. Periods of above-average rainfall also were common during the study period with monthly totals of 250 mm occurring during months spanning both dormant and growing seasons.

Land use in the Ichawaynochaway Creek watershed is dominated by agriculture (50 %) with remaining acreage in forestland (35 %), wetlands (14 %) and urban area (1 %) ([Fig. 1](#)), based on data obtained from National Land Cover Database 2011 ([Homer et al., 2015](#)). Streams in many areas are buffered by forests ([Houhoulis and Michener, 2000](#)) and have minimal urban impacts, good water quality, and relatively intact biotic communities ([Golladay et al., 2004](#)). Row crop farming of mainly cotton, peanuts, and corn is irrigated by center pivot systems using groundwater sources from the Upper Floridan Aquifer as well as surface water sources from Ichawaynochaway Creek, its tributaries, and multi-function ponds ([Hook et al., 2005](#)). Groundwater is the largest source for irrigation for the study region ([Fanning et al., 2001](#)). For the Flint River basin, over the year of 2001, groundwater withdrawal was ~470 million m³, surface water withdrawal was ~100 million m³, and multi-function ponds also provided ~34 million m³ of water ([Hook et al., 2005](#)). Besides runoff, multi-function ponds also collect baseflow and seepage and are often filled from nearby groundwater wells during periods without rain and runoff ([Hook et al., 2005](#)). Because of the dominance of groundwater as the irrigation source and the interconnectivity of irrigation sources, groundwater was used for the entire Ichawaynochaway Creek watershed as irrigation source for this study.

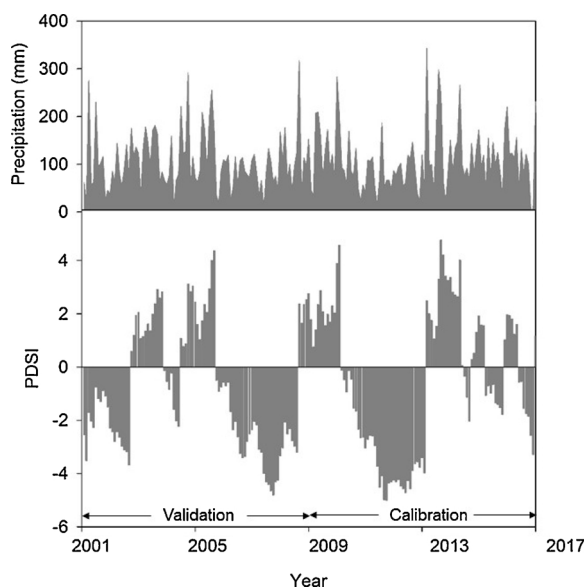


Fig. 2. Climatic conditions during the study periods of 2001–2016 in Ichawaynochaway Creek watershed. Data from NOAA NCDC for Georgia Region 7. Downloaded August 2018. (<https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmer/>).

2.2. SWAT model description

All analyses were performed using SWAT, a continuous-time, semi-distributed, process-based watershed model developed by the USDA Agricultural Research Service (Douglas-Mankin et al., 2010; Neitsch et al., 2011; Arnold et al., 2012). SWAT has been applied at scales from small watersheds to large river basins and is designed for simulating the effects of land use and land management practices on the surface- and groundwater (Neitsch et al., 2009). In this study, we used SWAT to simulate the impacts of agriculture water savings on streamflow.

2.2.1. Model inputs and set-up

Input data for SWAT included topography, soil classification, land use (including crop type), weather, and management (i.e., irrigation amount and schedule). The watershed boundary was delineated using ArcGIS 10.3 with the ArcSWAT 2012.10.19 extension (Winchell et al., 2007). Digital elevation models at the resolution of 1/3 arc-second were used as topographic input data, obtained from U.S. Geological Survey National Elevation Dataset (<https://lta.cr.usgs.gov/NED>). Based on topography, the watershed was then divided into 25 subbasins, size ranging from 10 to 190 km². The State Soil Geographic database (STATSGO, Soil Survey Staff, 2017) for Georgia was used as soil input data. The texture of soil in the watershed ranges from loam to sand, with 95 % of soil having > 50 % sand. The dominant soil hydrologic group is B, covering 70 % of the area.

The National Land Cover Database 2011 was used as land use input data (Homer et al., 2015). Where possible, land use types were further refined to better reflect actual land cover types. Parameters for mixed forest (FRST) were adjusted to better represent forest in the region (Table 1). Evergreen forest (FRSE) was split into two forest types: longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.), with loblolly pine occupying ~80 % of FRSE to represent forest composition in the region (Martin et al., 2012). Parameters associated with longleaf pine, loblolly pine, and mixed forest were obtained from field measurements conducted at the Jones Center at Ichauway (www.jonesctr.org) located within the study area (Table 1). Similarly, the agriculture (AGRL) land use classification was split into corn, cotton, and peanut, with cotton and peanut each occupying 40 % of agriculture land and corn occupying the remaining 20 % (Hook et al., 2005). Although these values change from year-to-year, these proportions reflect long-term trends in land use typical in the region. Each subbasin was further divided into hydrological response units (HRU), as each HRU was a unique combination of soil, land use, and topography class.

Daily maximum and minimum temperature and precipitation data for the model were obtained from four weather stations maintained by the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net). Seven stream gages operated by the U.S. Geological Survey within the watershed (<https://waterdata.usgs.gov/nwis>) (Fig. 1) supplied additional precipitation data. Weather data were applied to subbasins automatically by ArcSWAT based on proximity. Potential evapotranspiration was calculated by SWAT using Penman-Monteith method.

2.2.2. Model calibration and validation

Two U.S. Geological Survey streamflow gages in the Ichawaynochaway watershed were used for calibration and validation: Ichawaynochaway Creek at Milford (02353500) and Ichawaynochaway Creek below Newton (02355350) (<https://waterdata.usgs.gov/nwis>). The Milford stream gage, henceforth the upper gage, drains an area of approximately 1600 km² in the Fall Line Hills

Table 1

To represent forest in the region, several parameters of mixed forest (FRST) were adjusted, and evergreen forest (FRSE) was split into two forest types: longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.). Parameters were adjusted based on S. Brantley, unpublished data. Leaf area development parameters: maximum potential leaf area index (BLAI), fraction of growing season when leaf area begins to decline (DLAI), and the fraction of the plant growing season (FRGRW1) and the fraction of the maximum leaf area index (LAIMX1) corresponding to the first point on the optimal leaf area development curve. Stomatal conductance parameters: maximum stomatal conductance (GSI), vapor pressure deficit (VPDFR) and the fraction of maximum stomatal conductance (FRGMX) corresponding to the second point on the stomatal conductance curve. Other parameters: biomass-energy ratio (BIO_E), maximum canopy height (CHTMX), maximum root depth (RDMX).

	Parameters	Longleaf Pine	Loblolly Pine	Mixed Forest
Leaf area development	BLAI	2	6	6
	DLAI	0.99	0.99	0.8
	FRGRW1	0.1	0.1	0.1
	LAIMX1	0.7	0.7	0.3
Stomatal conductance	FRGMX	0.43	0.64	0.75
	GSI	0.002	0.002	0.002
	VPDFR	4	4	4
	BIO_E	75	75	75
	CHTMX	20	20	20
	RDMX	3.5	2	2

physiographic region of the upper coastal plain. The below-Newton stream gage, henceforth the lower gage, drains nearly the entire watershed, including a large area of the Dougherty Plain physiographic region (Fig. 1). Based on data availability, climate data from 1990 to 2016 were used for model calculation, with a model spin-up period from 1990 to 2000 to minimize the influence of initial states (Arnold et al., 2013). Stream data from 2009 to 2016 were used for model calibration because there were more climate data available for this period and the land cover input data more closely resembled current land use. Model validation utilized stream data from 2001 to 2008. Both calibration and validation periods represented a number of extremes across the longer record, including the extreme drought periods of June to November 2007, and June 2011 to July 2012 (Palmer drought severity index < -4); and the extreme wet periods of July to August 2005, January 2010, August to September 2013, and April 2014 (Palmer drought severity index > 4) (Fig. 2).

To calibrate against streamflow, relevant input parameters governing surface runoff and baseflow were selected based on initial model performance and suggestions from previous research (Arnold et al., 2012; Abbaspour et al., 2015). Parameters that govern surface runoff include: soil conservation service runoff curve number (CN2), available water capacity of the soil layer (SOL_AWC), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), surface runoff lag coefficient (SURLAG), and Manning's "n" value for overland flow (OV_N). Parameters that govern baseflow include: baseflow alpha factor (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), groundwater re-evaporation coefficient (GW_REVAP), groundwater delay time (GW_DELAY), threshold depth of water in shallow aquifer for "revap" or percolation to the deep aquifer to occur (REVAPMN), and deep aquifer percolation fraction (RCHARG_DP). Based on global and local sensitivity analyses performed by SWAT Calibration and Uncertainty Procedure (SWAT-CUP), six parameters that met sensitivity criteria (Arnold et al., 2012) were identified: ALPHA_BF, CN2, ESCO, GWQMN, GW_REVAP, and SOL_AWC (Table 2). The initial ranges of these parameters were assigned based on sensitivity analyses and knowledge of the study area.

The model was first calibrated for the upper gage, then calibrated for the lower gage including adjusted parameters for the upper watershed (Table 2). Model calibration was performed with Sequential Uncertainty Fitting (SUFI-2) algorithm using SWAT-CUP (Arnold et al., 2012). With SWAT-CUP, Latin hypercube sampling was used to generate 1000 parameter combinations within the selected minimum and maximum value range of each parameter. SWAT-CUP then ran 1000 simulations, each with a unique parameter combination. After each simulation, model simulated monthly streamflow was compared with measured streamflow. Based on

Table 2

Model parameters adjusted for calibration for the upper and lower watersheds. Parameters that govern surface runoff: soil conservation service runoff curve number (CN2), soil evaporation compensation factor (ESCO), and available water capacity of the soil layer (SOL_AWC). Parameters that govern baseflow: baseflow alpha factor (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), and groundwater re-evaporation coefficient (GW_REVAP).

Process	Parameters	Method	Upper Watershed	Lower Watershed
Surface Runoff	CN2	Relative	-0.15	-0.15
	ESCO	Replace	0.85	0.9
	SOL_AWC	Relative	0.4	0.4
Baseflow	ALPHA_BF	Replace	0.53	0.3
	GWQMN	Replace	4200	2500
	GW_REVAP	Replace	0.025	0.025

these simulations, the post processing option in SWAT-CUP suggested new parameter ranges for these parameters. The new parameter ranges were then retested using global and local sensitivity analyses. This process was repeated until no further improvement was observed (Arnold et al., 2012; Abbaspour et al., 2015).

The simulation results were evaluated based on Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), ratio of the root mean square error to the standard deviation of measured data (RSR), and R^2 (Moriassi et al., 2007). Model evaluation was based on guidelines from Moriassi et al. (2007). Model performance ratings in the range of “good” and “very good” (Moriassi et al., 2007) were accepted for further analysis. The best parameter combination was applied to model validation.

2.2.3. Agriculture irrigation scenarios

We used the calibrated SWAT model to project the potential effects of irrigation reduction on streamflow. Shallow aquifer was used as irrigation water source (IRR_SC = 3) for crops located in each corresponding subbasin. The SWAT model defines shallow aquifer as an aquifer which contributes return flow to streams within the watershed vs. deep aquifer as an aquifer which doesn't contribute return flow to streams within the watershed (Arnold et al., 1993). Because of the high connectivity between streams and groundwater in the region (Rugel et al., 2012), shallow aquifer as irrigation source was chosen for this model.

To compare water-savings scenarios, a baseline scenario was established: full irrigation withdrawal was calculated based on climate and crop type as calculated by the model auto irrigation operation (100 % irrigation; no water conservation measures in place). Modeled monthly irrigation values in the full irrigation scenario were comparable to values reported in Hook et al. (2005). Irrigation withdrawals in each HRU were then adjusted using the manual irrigation operation from 90 % of full irrigation to 0 % of irrigation (no irrigation) in 10 % increments. In total 11 scenarios covering the full range (0–100 %) of possible irrigation reduction were tested in this study to quantify the impact of irrigation on streamflow. Model-simulated streamflow (volume) was reported and later converted into water yield (depth), by dividing streamflow by watershed area, to better compare with precipitation and evapotranspiration values. To determine the effects of irrigation reduction on monthly streamflow, we used a frequency pairing analysis method where we constructed flow duration curves for each simulation from 0 to 100 % irrigation reduction. This method ranks flow periods (e.g. months) in ascending order and relies on direct comparisons of flow during relatively similar hydrologic conditions (e.g., flow at 5th, 25th, or 50th percentile) to assess change [Alila et al. 2009]. To quantify the effects of irrigation reduction during specific flow conditions, we focused on absolute and relative changes in flow during three flow conditions: median flow (50th percentile), which provides an estimate of central tendency and relates well to other metrics such as mean annual streamflow and yield; the 25th percentile, which represents a recognized state of “low flow” where “hydrologic drought” conditions start to occur; and the 5th percentile, which represents a state of “extremely low flow” where water supplies are threatened, and ecosystem function may be severely impaired.

3. Results

3.1. Calibration and validation

For the calibration period (2009–2016), model performance for the upper gage was very good regarding NSE (0.83), and RSR (0.41) and was very good in the bias between model estimation and observation for mean monthly streamflow (PBIAS = 14.4 %). For the lower gage, the NSE (0.86), RSR (0.38), and PBIAS (1.9 %) were all in the range of very good performance (Moriassi et al., 2007). During the validation period (2001–2008) the model generated good results with NSE = 0.69 for the upper gage and NSE = 0.77 for the lower gage. PBIAS was relatively small with satisfactory performance for the upper stream gage (PBIAS = 20.4 %) and good performance for the lower gage (PBIAS = 9.0 %). The root mean square error to the standard deviation of measured data (RSR) were also good for the upper (RSR = 0.56) and lower gages (RSR = 0.50) (Moriassi et al., 2007) (Table 3).

The model performed well during medium and high flow periods at both gages. Differences between model simulation and observed average monthly flow were primarily due to under-prediction of streamflow during low flow periods, especially at the upper gage (Fig. 3). This was likely the reason the model performed slightly better at the lower gage. The magnitude of differences between observed and simulated streamflow was small and monthly flow in both the simulated and actual stream never reached zero. The 95 % prediction uncertainty range covered 65 % of data for the upper gage and 59 % of data in the lower gage (Fig. 3).

Table 3

Summary of model performance for calibration and validation. Two stream gages were used: Ichawaynochaway Creek at Milford (02353500, the upper gage) and Ichawaynochaway Creek below Newton (02355350, the lower gage). The calibration results were evaluated based on Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), ratio of the root mean square error to the standard deviation of measured data (RSR), and R^2 . Calibration period: 2009–2016. Validation period: 2001–2008. Calculation and validation were performed with Sequential Uncertainty Fitting (SUFI-2) algorithm using SWAT-CUP.

	Gage Station	R^2	NSE	PBIAS (%)	RSR
Calibration	Upper gage	0.88	0.83	14.4	0.41
	Lower gage	0.86	0.86	1.9	0.38
Validation	Upper gage	0.79	0.69	20.4	0.56
	Lower gage	0.75	0.77	9.0	0.50

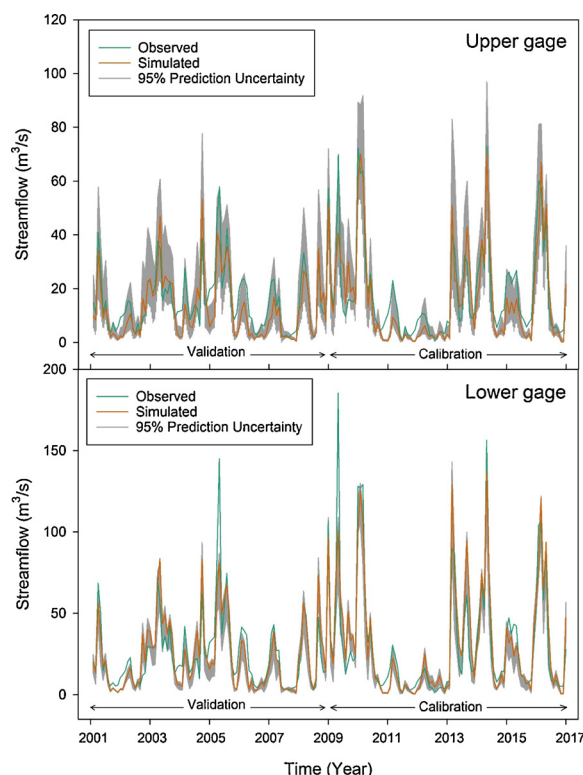


Fig. 3. Calibration and validation for monthly streamflow during the study period of 2001–2016. Calibration period: 2009–2016. Validation period: 2001–2008. Two stream gages were used: the upper gage (Ichawaynochaway Creek at Milford, top panel), and the lower gage (Ichawaynochaway Creek below Newton, bottom panel).

3.2. Annual water budget

Over the entire watershed, simulated full irrigation based on climate and crop type as calculated by the model was 38.2 ± 3.4 mm/yr, or 113.6 million m^3/yr . Eliminating irrigation reduced evapotranspiration by 14.0 ± 1.8 mm/yr and surface runoff by 3.7 ± 0.5 mm/yr, while it increased aquifer recharge by 26.6 ± 2.8 mm/yr. Annual water yield responded positively to reductions in irrigation withdrawals. Over the whole range of possible water use reduction scenarios, simulated irrigation reduction measures increased annual streamflow on average $\sim 1\%$ for each 10% reduction in irrigation. Increases in annual yield of the watershed ranged from 12.2–48.7 mm/year (20.7 ± 2.5 mm/yr) and were generally higher in years with more precipitation (Fig. 4). However, the proportional change in yield was higher in years with less precipitation and ranged from 4% to 16% increase (Fig. 4). For the upper gage, full irrigation (0% irrigation reduction) resulted in mean annual streamflow of $14.4 \text{ m}^3/\text{s}$, or 454 million m^3/yr , which translates to a mean water yield value of 235 mm/yr. When no irrigation was applied, mean streamflow was $15.6 \text{ m}^3/\text{s}$, which

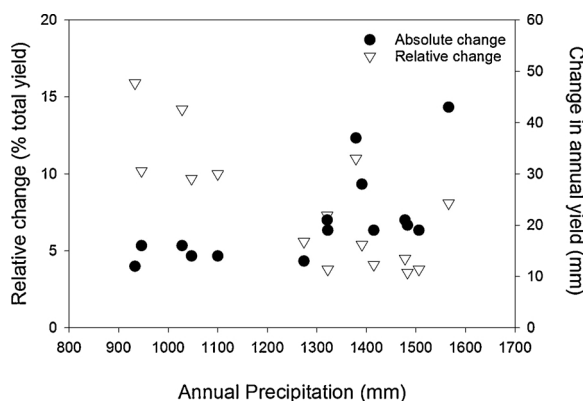


Fig. 4. Absolute and relative responses of annual yield to 100 % irrigation reduction as a function of annual precipitation from 2001 to 2016 at the lower gage (Ichawaynochaway Creek below Newton, GA, USGS 02355350).

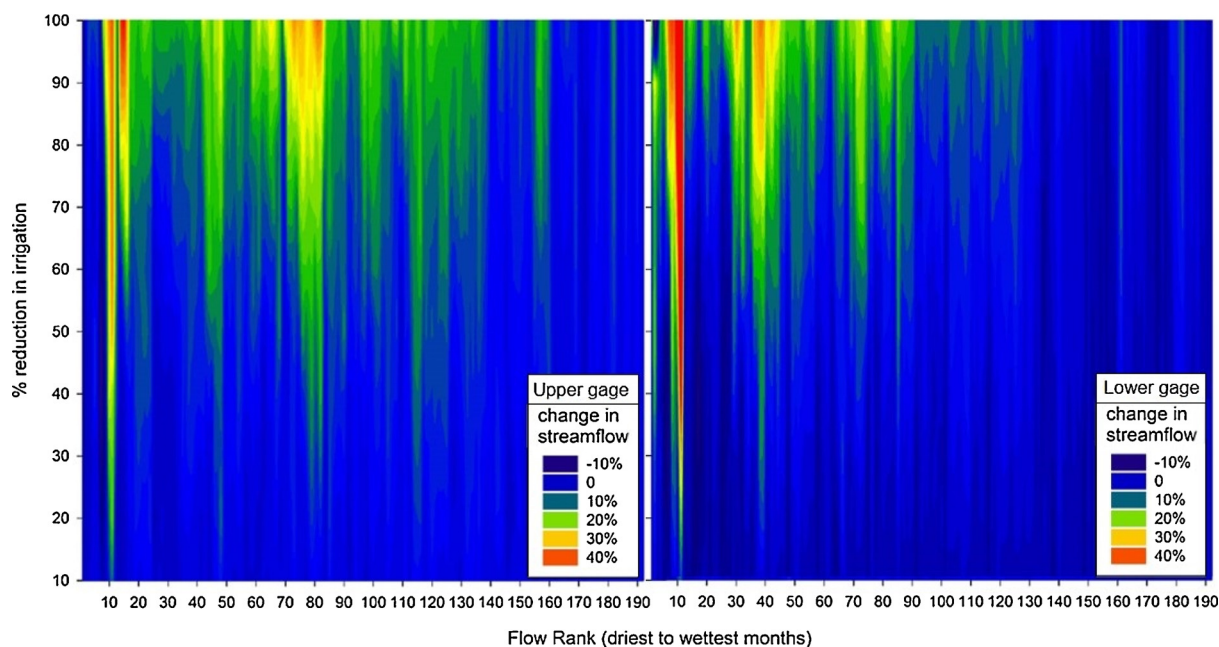


Fig. 5. Relative change in monthly streamflow in response to 10–100 % irrigation reduction in the order of ranked flow from driest to wettest month. Color represents the % change versus maximum irrigation with warmer colors indicating a greater response. Study period covered 192 months, from year 2001–2016. Two stream gages on the Ichawaynochaway creek were shown: the left panel shows the upper gage (Ichawaynochaway Creek at Milford, 02353500), and the right panel shows lower gage (Ichawaynochaway Creek below Newton, 02355350).

translates to 19 mm/year greater annual yield, or a $\sim 7\%$ increase.

3.3. Monthly streamflow effects

Simulated reductions in irrigation increased monthly streamflow over a wide range of hydrological conditions at both the upper and the lower gages (Fig. 5). Irrigation reduction has decreased the probability of extreme low flow (5th percentile). At the upper gage a mean monthly flow of $< 1 \text{ m}^3/\text{s}$ (5.5 % exceedance probability) occurred during 11 months under the normal irrigation scenario; but that number decreased to 9 months (4.5 % exceedance probability) under the no irrigation scenario (Fig. 5). At the lower gage, 100 % irrigation reduction raised 5th percentile flow from $1.4 \text{ m}^3/\text{s}$ to $2.5 \text{ m}^3/\text{s}$ (Fig. 5). Simulated irrigation reduction had a consistently positive effect on streamflow during median, low, and extremely low flow months (Figs. 5 and 6). In terms of absolute flow, median streamflow (50th percentile) increased more with irrigation reduction than low (25th percentile) or extremely low flows; however, proportional responses (% change in flow) were greatest during extremely low flows (Fig. 6). The simulated change in median monthly flow between no irrigation and normal irrigation (100 % or maximum) was $+1.73 \text{ m}^3/\text{s}$ (16 %) for the upper gage and $+0.95 \text{ m}^3/\text{s}$ (16 %) for the lower gage (Fig. 6). Monthly mean streamflow changes of extremely low flow were $+0.33 \text{ m}^3/\text{s}$ (27 %) and $+0.31 \text{ m}^3/\text{s}$ (27 %), respectively (Fig. 6). For the driest months, even small reductions in irrigation (e.g. 10–20 %) resulted in modest increases in streamflow, and a threshold of about 20–30 % irrigation reduction was necessary to achieve a $\sim 10\%$ increase in streamflow at both stream gages (Figs. 6 and 7). The upper gage appeared more sensitive to irrigation reduction than the lower gage, across a wider range of flow conditions (Fig. 7). Greater responses to irrigation reduction occurred in the drier months at both gages, with the greatest flow increase of 70–78 % at the 11th driest month of the lower gage in response to 70–100 % irrigation reduction (Fig. 7).

4. Discussion

Our simulations showed that reducing agricultural water use increased streamflow. Our modeling period covered a wide range of potential natural variability, with July 2012 representing the lowest flow since 1940. Results suggested that under these extremely low flow conditions, small irrigation reductions would trigger small, but potentially ecologically important increases in streamflow. This was evident at the upstream gage, where a 10 % reduction in irrigation resulted in a 7 % increase in streamflow. At the downstream gage, under extremely low flow conditions, streamflow was 35 % higher with no irrigation than with normal irrigation. This finding of higher sensitivity during extremely low flow conditions is consistent with several previous studies regarding land use impact on streamflow. When 16 % of the land in the Xinjiang River basin in China was changed from forest to grassland, annual basin discharge increased 1.7 % with the largest change of 4.4 % observed during the driest period (Guo et al., 2008). In the Chemoga watershed in Ethiopia, when annual rainfall decreased at a rate of 0.3 mm/year, and area of cropland and eucalypt plantations

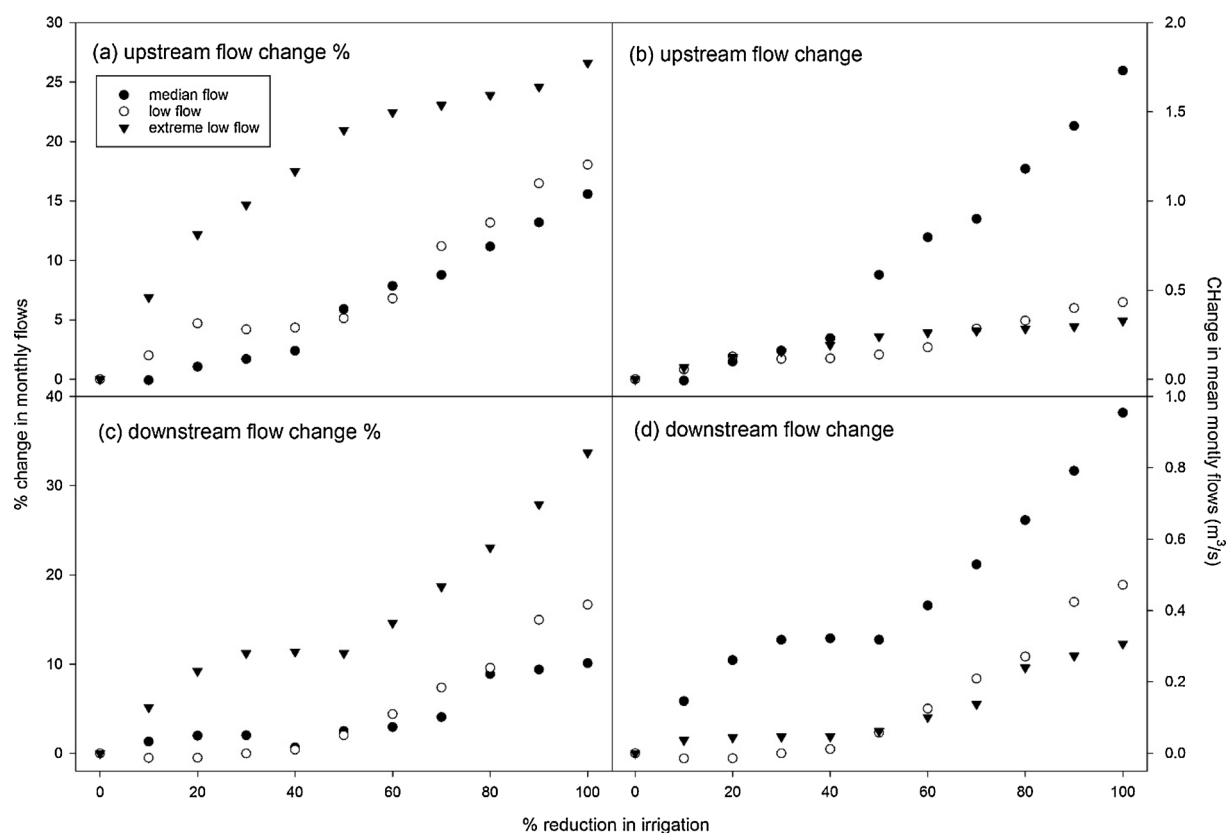


Fig. 6. Simulated responses of mean monthly streamflow to irrigation reduction at the upper gage (left) and the lower gage (right). Responses are shown at three flow levels to represent different hydrologic conditions: median flow or the 50th percentile month, “low flow” or the 25th percentile month, and “extremely low flow” or the 5th percentile month. A 0 % reduction in irrigation indicates normal irrigation amounts, or no conservation strategy employed, while a 100 % reduction indicates no irrigation withdrawal. Left panels are the proportional change in flow expressed as % change versus normal irrigation. Right panels are the simulated change in mean flow volume.

increased, annual streamflow decreased at 1.7 mm/year. The impact was most pronounced during the dry season with significant declines in monthly and daily extreme low flow, while no trend was observed during the wet season (Bewket and Sterk, 2005). These results all demonstrated that water balance during extremely dry periods is exceptionally sensitive to even small changes in water use, whether from natural ET (Oishi et al., 2010) or human consumption.

Decreased streamflows due to irrigation during periods when flows are already extremely low due to drought have substantial effects on aquatic fauna, such as fishes, mussels, and crayfishes (Golladay et al., 2004; Sargent et al., 2011; Freeman et al., 2013). Although the flow of Ichawaynochaway creek didn't reach zero during the model period or the historical record, many un-gaged tributary streams ceased to flow during extreme dry periods, and only isolated pools remained (Golladay et al., 2004; Rugel et al., 2012) indicating an increasing trend towards stream intermittency in the region (Gordon et al., 2012). A previous drought survey of mussels in the lower Flint River basin showed that flow cessation caused a decline in abundance of both federally listed and common mussel species (Golladay et al., 2004). In the upper Flint River basin, landscape-scale models showed fish species richness declined in response to drought and recovered afterward (Freeman et al., 2013). Even small quantities of additional flow may prove vitally important in maintaining in-stream habitat quality, especially during dry periods.

Under our irrigation reduction scenarios, the upper basin was more responsive than the lower basin (Fig. 7). Differences in sensitivities of the upper and lower gages may be due to differences in the land cover and/or the influence of groundwater. The upper watershed had a greater proportion of irrigated land with ~85,000 ha of agriculture, or 52 % of total area, while the lower basin had ~48,000 ha or 41 % of the total area (Fig. 1). Additionally, because the lower watershed is located in the Dougherty Plain, groundwater inputs may buffer the streamflow response to changes in surface water budgets, as reflected in the model's calibrated parameters. For example, the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) was larger in the upper watershed than the lower watershed (Table 2), and shallower GWQMN in the lower watershed allowed it to have a larger impact of groundwater on the stream. Also, the baseflow alpha factor (ALPHA_BF) was larger in the upper watershed than the lower watershed (Table 2), representing a faster groundwater flow response to changes in recharge in the upper watershed (Arnold et al., 2013). Karst systems have been known to pose unique challenges for surface and groundwater modeling (Amin et al., 2017).

Previous research has shown SWAT to be effective in modeling streamflow in karst systems on a monthly step, though less successful on finer time steps (Spruill et al., 2000). Our model performed reasonably well considering the challenge posed by the

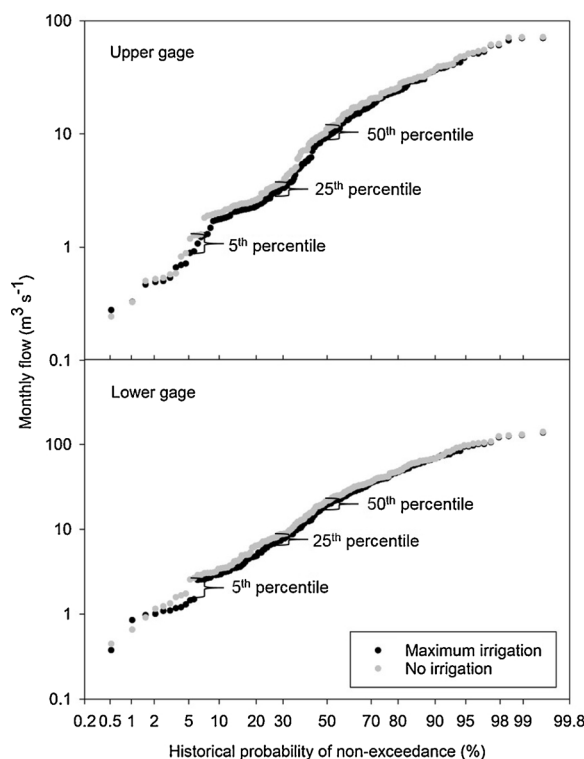


Fig. 7. Streamflow responses corresponding to historical probability of non-exceedance (%). Differences in median, low, and extremely low flows (50th, 25th, and 5th percentiles, respectively) are marked to show the differences between maximum irrigation and no irrigation scenarios. Two stream gages on the Ichawaynochaway creek: the upper gage (Ichawaynochaway Creek at Milford, 02353500) and lower gage (Ichawaynochaway Creek below Newton, 02355350).

subsurface heterogeneity and groundwater preferential flow paths characteristic of karst systems, which likely alter infiltration and surface runoff, and consequently, evapotranspiration, groundwater recharge, and streamflow (Hartmann et al., 2015; Malard et al., 2016). The modeling challenges posed by groundwater inputs were most apparent by under-prediction of streamflow during low flow periods (Fig. 3). Very low flows were relatively difficult to predict accurately, especially during extreme dry periods. Periods of very low flow also provide challenges for USGS field personnel making measurements of stream discharge. Thus, uncertainty in stage/discharge relations may also indirectly affect model predictions. The magnitude of differences between observed and simulated discharge were small, and the majority of data points were within the 95 % prediction uncertainty range (Fig. 3).

Finally, another unique feature of our study area that posed challenges for hydrologic modeling is the abundance of geographically isolated wetlands, or GIWs, in the Dougherty Plain (Martin et al., 2012). GIWs have been shown to increase landscape hydrologic capacitance by storing excess run-off during floods and slowly releasing water afterwards (Hey and Philippi, 1995; Mitsch and Gosselink, 2000; McLaughlin et al., 2014). There are ~21,000 ha (19 %) of wetlands in the lower basin (Fig. 1), most of which are GIWs. GIWs have been shown to increase baseflow contribution to streamflow via groundwater recharge during low flow periods, especially where soils have high hydraulic conductivity (Winter and LaBaugh, 2003; Evenson et al., 2015; Lee et al., 2018). However, the SWAT model represents isolated wetlands as either de-spatialized and aggregated when using the “wetland” or “pond” representation, or wetland boundaries and drainage areas are not accurately depicted when using the “pothole” representation (Douglas-Mankin et al., 2010; Evenson et al., 2015). In our model, we didn’t incorporate wetland modules due to a lack of robust corroborating data on GIW function; but we recognize that some of the error in low flow prediction might have come from this simplification of the model. Our future modeling efforts will refine or develop wetland modules to evaluate isolated wetland conservation and restoration on watershed water yields.

Overall, our model indicates that irrigation reduction is an effective way to increase streamflow. For management purposes, our model simulations are useful for evaluating the potential effectiveness of water conservation strategies and may help water managers and policymakers assess the relative value of various water conservation strategies. For example, if a goal were to increase flow by 0.2 m³/s at the downstream gage during extremely low flow periods, an irrigation reduction of 70 % from traditional application rates would be required under simulated conditions. In the upper watershed, a threshold of about 30–40 % irrigation reduction triggered a ~15 % increase in both the upper and lower gages during extreme low flow (Fig. 6), when additional streamflow would provide substantial ecological benefits (Rugel et al., 2012). Irrigation scenarios with a higher percent of water saving may not be realistic without drastic social-economical changes. However, the relatively modest reductions in agricultural water use that triggered these hydrologic responses are already within the technical capabilities of existing irrigation technologies. A study conducted within the

Ichawaynochaway Creek watershed showed lower pressure sprinkler retrofits combined with end gun controls reduced water use up to 22.5 %. Variable rate irrigation and remote soil moisture monitoring resulted in water saving of up to an additional 15 % (Stripling Irrigation Research Park, 2018). An advanced irrigation scheduling tool using in-field assessment has been demonstrated to save > 1000 m³/ha (25.7 %) of water in the Mediterranean region (Saab et al., 2019). Conservation tillage can reduce water demand up to 15 % by using a cover crop and leaving plant residue in the field (Stripling Irrigation Research Park, 2018). These practices, if widely implemented, have the potential to achieve the level of irrigation reduction that could simultaneously maintain or increase crop yield, while help restore critical flow to vulnerable aquatic ecosystems (Vellidis et al., 2016).

To ensure agriculture water conservation, water resource laws and regulations require new and existing permits to meet efficiency requirements with mandatory conservation measures [2006 Flint River Basin Water Development and Conservation Plan; 2014 Amendments to the Flint River Drought Protection Act]. Currently, in the Lower Flint River Basin, over 90 % of center pivot irrigation systems utilize low-pressure sprinkler-nozzles or low pressure drop nozzles (Lower Flint- Ochlockonee Regional Water Plan 2017). A moratorium is in place at the time of study on new agriculture surface water and groundwater withdrawal permits of the Upper Floridan Aquifer in the lower Flint River Basin to reduce future withdrawals (Lower Flint- Ochlockonee Regional Water Plan, 2017). Alternative water sources, such as the Claiborne Aquifer, are being evaluated due to their lower connectivity to regional stream flow (Rugel et al., 2016). With increasing pressure on freshwater resources from land use change, population growth, agriculture expansion and intensification, and changes in precipitation and temperature from climate change, this study provides new insight and practical applications for the development of possible thresholds for ecologically sustainable water management.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2020.100665>.

References

- Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. *J. Hydrol.* 524, 733–752.
- Amin, M.G.M., Veith, T.L., Collick, A.S., Karsten, H.D., Buda, A.R., 2017. Simulating hydrological and nonpoint source pollution processes in a karst watershed: a variable source area hydrology model evaluation. *Agric. Water Manag.* 180, 212–223.
- Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. *J. Hydrol.* 142, 47–69.
- Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2012. SWAT: model use, calibration, and validation. *Trans. ASABE* 55, 1491–1508.
- Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., Neitsch, S., 2013. SWAT 2012 Input/Output Documentation. Texas Water Resources Institute.
- Bewket, W., Sterk, G., 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. *Hydrol. Process. Int. J.* 19, 445–458.
- Brantley, S.T., Vose, J.M., Wear, D.N., Band, L., 2018. Planning for an uncertain future: restoration to mitigate water scarcity and sustain carbon sequestration. In: Kirkman, Katherine, L., Jack, S.B. (Eds.), *Ecological Restoration and Management of Longleaf Pine Forests*. CRC Press, Boca Raton, FL, pp. 291–309.
- Couch, C.A., Hopkins, E.H., Hardy, P.S., 1996. Influences of Environmental Settings on Aquatic Ecosystems in the Apalachicola-Chattahoochee-Flint River Basin. Report 95-4278.
- Couch, C.A., McDowell, R., 2006. Flint River Basin Regional Water Development and Conservation Plan.
- Douglas-Mankin, K.R., Srinivasan, R., Arnold, J.G., 2010. Soil and water assessment tool (SWAT) model: current developments and applications. *Trans. ASABE* 53, 1423–1431.
- Emanuel, B., Rogers, G., 2012. Running Dry: Challenges and Opportunities in Restoring Healthy Flows in Georgia's Upper Flint River Basin. American Rivers, Atlanta.
- Evenson, G.R., Golden, H.E., Lane, C.R., D'Amico, E., 2015. Geographically isolated wetlands and watershed hydrology: a modified model analysis. *J. Hydrol.* 529, 240–256.
- Fanning, J.L., Schwarz, G.E., Lewis, W.C., 2001. A Field and Statistical Modeling Study to Estimate Irrigation Water Use at Benchmark Farms Study Sites in Southwestern Georgia. pp. 1995–1996.
- Fischer, G., Tubiello, F.N., van Velthuisen, H., Wiberg, D.A., 2007. Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. *Technol. Forecast. Soc. Change* 74, 1083–1107.
- Freeman, M.C., Buell, G.R., Hay, L.E., Hughes, W.B., Jacobson, R.B., Jones, J.W., Jones, S.A., Lafontaine, J.H., Odom, K.R., Peterson, J.T., Riley, J.W., Schindler, J.S., Shea, C., Weaver, J.D., 2013. Linking river management to species conservation using dynamic landscape-scale models. *River Res. Appl.* 29, 906–918.
- Golladay, S.W., Battle, J., 2002. Effects of flooding and drought on water quality in gulf coastal plain streams in Georgia. *J. Environ. Qual.* 31, 1266–1272.
- Golladay, S.W., Gagnon, P., Kearns, M., Battle, J.M., Hicks, D.W., 2004. Response of freshwater mussel assemblages (Bivalvia:unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. *J. North Am. Benthol. Soc.* 23, 494–506.
- Golladay, S.W., Hicks, D.W., 2015. Using the Sustainable Boundary Approach (SBA) to assess and develop flow guidelines: the Flint River, Georgia. In: McDowell, R.J., Pruitt, C.A., Bahn, A.R. (Eds.), *Proceedings of the 2015 Georgia Water Resources Conference*. Institute of Ecology, University of Georgia, Athens, Georgia.
- Golladay, S.W., Martin, K.L., Vose, J.M., Wear, D.N., Covich, A.P., Hobbs, R.J., Klepzig, K.D., Likens, G.E., Naiman, R.J., Shearer, A.W., 2016. Achievable future

- conditions as a framework for guiding forest conservation and management. *For. Ecol. Manage.* 360, 80–96.
- Gordon, D.W., Peck, M.F., Painter, J.A., 2012. Hydrologic and Water-Quality Conditions in the Lower Apalachicola-Chattahoochee-Flint and Parts of the Aucilla-Suwannee-Ochlockonee River Basins in Georgia and Adjacent Parts of Florida and Alabama during Drought Conditions, July 2011. 2328-0328. US Geological Survey.
- Guo, H., Hu, Q., Jiang, T., 2008. Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. *J. Hydrol.* 355, 106–122.
- Hartmann, A., Gleeson, T., Rosolem, R., Pianosi, F., Wada, Y., Wagener, T., 2015. A large-scale simulation model to assess karstic groundwater recharge over Europe and the Mediterranean. *Geosci. Model. Dev.* 8, 1729–1746.
- Hey, D.L., Philippi, N.S., 1995. Flood reduction through wetland restoration: the Upper Mississippi River Basin as a case history. *Restor. Ecol.* 3, 4–17.
- Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N., Wickham, J., Megown, K., 2015. Completion of the 2011 National Land Cover Database for the conterminous United States—representing a decade of land cover change information. *Photogramm. Eng. Remote Sens.* 81, 345–354.
- Hook, J.E., Harrison, Kerry A., Hoogenboom, Gerrit, Thomas, D.L., 2005. Ag Water Pumping – Statewide Irrigation Monitoring. Final Report to Georgia Environmental Protection Division. Project Report 52. Atlanta, GA. .
- Houhoulis, P.F., Michener, W.K., 2000. Detecting wetland change: a rule-based approach using NWI and SPOT-XS data. *Photogramm. Eng. Remote Sens.* 66, 205–211.
- IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Lee, S., Yeo, I.Y., Lang, M.W., Sadeghi, A.M., McCarty, G.W., Moglen, G.E., Evenson, G.R., 2018. Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. *J. Environ. Manage.* 223, 37–48.
- Lower Flint-Ochlockonee Regional Water Plan. 2017.** <https://waterplanning.georgia.gov/>. (downloaded April 10, 2018).
- Malard, A., Sinreich, M., Jeannin, P.Y., 2016. A novel approach for estimating karst groundwater recharge in mountainous regions and its application in Switzerland. *Hydrol. Process.* 30, 2153–2166.
- Martin, G.I., Kirkman, L.K., Hepinstall-Cymerman, J., 2012. Mapping geographically isolated wetlands in the Dougherty Plain, Georgia, USA. *Wetlands* 32, 149–160.
- McLaughlin, D.L., Kaplan, D.A., Cohen, M.J., 2014. A significant nexus: geographically isolated wetlands influence landscape hydrology. *Water Resour. Res.* 50, 7153–7166.
- Mearns, L.O., Giorgi, F., McDaniel, L., Shields, C., 2003. Climate scenarios for the southeastern US based on GCM and regional model simulations. *Clim. Change* 60, 7–35.
- Mitsch, W.J., Gosselink, J.G., 2000. The value of wetlands: importance of scale and landscape setting. *Ecol. Econ.* 35, 25–33.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50, 885–900.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2009. 1.1 Overview of Soil and Water Assessment Tool (SWAT) Model. Tier B (All countries/territories Not Listed Here Are in Tier a). pp. 8.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation. Ver. 2009. USDA-ARS Grassland Soil and Water Research Laboratory and Texas A&M University, Blackland Research and Extension Center, Temple, Texas.
- Nejaddhashemi, A.P., Wardynski, B.J., Munoz, J.D., 2012. Large-scale hydrologic modeling of the Michigan and Wisconsin agricultural regions to study impacts of land use changes. *Trans. ASABE* 55, 821–838.
- Oishi, A.C., Oren, R., Novick, K.A., Palmroth, S., Katul, G.G., 2010. Interannual invariability of forest evapotranspiration and its consequence to water flow downstream. *Ecosystems* 13, 421–436.
- Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Koppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* 11, 1633–1644.
- Pierce, R.R., Barber, N.L., Stiles, H.R., 1984. Georgia Irrigation, 1970–1980: a Decade of Growth. Report 83-4177. .
- Pollard, L.D., Grantham, R.G., Blanchard, H.E., 1978. A Preliminary Appraisal of the Impact of Agriculture on Ground-Water Availability in Southwest Georgia. Report 79-7. .
- Rodell, M., Famiglietti, J., Wiese, D., Reager, J., Beaudoing, H., Landerer, F., Lo, M.-H., 2018. Emerging trends in global freshwater availability. *Nature* 1.
- Rugel, K., Jackson, C.R., Romeis, J.J., Golladay, S.W., Hicks, D.W., Dowd, J.F., 2012. Effects of irrigation withdrawals on streamflows in a karst environment: lower Flint River Basin, Georgia, USA. *Hydrol. Process.* 26, 523–534.
- Rugel, K., Golladay, S.W., Jackson, C.R., Rasmussen, T.C., 2016. Delineating groundwater/surface water interaction in a karst watershed: lower Flint River Basin, southwestern Georgia, USA. *J. Hydrol. Reg. Stud.* 5, 1–19.
- Ruhl, J., 2005. Water wars, eastern style: divvying up the Apalachicola-Chattahoochee-Flint River basin. *J. Contemp. Water Res. Educ.* 131, 47–54.
- Saab, A., Therese, M., Jomaa, I., Skaf, S., Fahed, S., Todorovic, M., 2019. Assessment of a smartphone application for real-time irrigation scheduling in Mediterranean environments. *Water* 11 (2), 252.
- Sargent, L.W., Golladay, S.W., Covich, A.P., Opsahl, S.P., 2011. Physicochemical habitat association of a native and a non-native crayfish in the lower Flint river, Georgia: implications for invasion success. *Biol. Invasions* 13, 499–511.
- Singh, S., Srivastava, P., Mitra, S., Abebe, A., 2016. Climate variability and irrigation impacts on streamflows in a Karst watershed—A systematic evaluation. *J. Hydrol. Reg. Stud.* 8, 274–286.
- Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2017. U.S. General Soil Map (STATSGO2). Available online at <https://sdmdataaccess.sc.egov.usda.gov>. (Accessed [July/2017]). .
- Spruill, C.A., Workman, S.R., Taraba, J.L., 2000. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Trans. ASAE* 43, 1431.
- Stripling Irrigation Research Park.** <https://striplingpark.org/irrigation/agricultural-water-conservation/>. (Accessed [December/2018]).
- Upper Flint Regional Water Plan. 2017.** <https://waterplanning.georgia.gov/>. (downloaded April 10, 2018).
- van den Avyle, M.J., Evans, J.W., 1990. Temperature selection by striped bass in a Gulf of Mexico coastal river system. *N. Am. J. Fish. Manag.* 10, 58–66.
- Vellidis, G., Liakos, V., Andreis, J., Perry, C., Porter, W., Barnes, E., Morgan, K., Fraise, C., Migliaccio, K., 2016. Development and assessment of a smartphone application for irrigation scheduling in cotton. *Comput. Electron. Agric.* 127, 249–259.
- Wear, D.N., Greis, J.G., 2013. The Southern Forest Futures Project: Technical Report.
- Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2007. ArcSWAT Interface for SWAT2005—User's Guide. Blackland Research Center, Texas Agricultural Experiment Station and Grassland. Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, Texas.
- Winter, T.C., LaBaugh, J.W., 2003. Hydrologic considerations in defining isolated wetlands. *Wetlands* 23, 532–540.
- Woznicki, S.A., Nejaddhashemi, A.P., Parsinejad, M., 2015. Climate change and irrigation demand: uncertainty and adaptation. *J. Hydrol. Reg. Stud.* 3, 247–264.