INVESTIGATING DRIVERS OF GROUNDWATER-SURFACE WATER

INTERACTION IN THE LOWER FLINT RIVER BASIN,

SOUTHWESTERN GEORGIA, USA

by

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(Under the Direction of Stephen W. Golladay and C. Rhett Jackson)

ABSTRACT

Groundwater provides the majority of global water resources for domestic, agricultural, and power use while contributing surface baseflows to support healthy aquatic ecosystems. Understanding the extent and magnitude of hydrologic connectivity between groundwater and surface water components in karst watersheds is essential to the prudent management of these hydraulically-interactive systems. The objective of this research was to examine groundwater and surface water connectivity between the Upper Floridan Aquifer (UFA) and streams in the Lower Flint River Basin (LFRB) where development of agricultural irrigation intensified over the past 30 years. An analysis of USGS streamflow data for the pre- and post-irrigation period showed summer baseflows in Ichawaynochaway and Spring Creek were reduced by an order of magnitude in the post-irrigation period, indicating the strong hydraulic connection between these streams and the underlying aquifer. These data also revealed steeper annual and seasonal baseflow recession occurring within Ichawaynochaway Creek associated with periods of intensive regional groundwater pumping rather than climatic patterns. Between 2010 and 2011 physiochemical monitoring on 50 km of Ichawaynochaway Creek confirmed close hydraulic associations between this stream and the UFA. Specific conductivity was highly correlated with Ca^{2+} and indicated as much as 42% of groundwater consistently entered through five out of the 50 reaches sampled. Stable isotope values ($\delta^{18}O$ and δD) detected rapid turnovers in the quality and source of baseflow between sampling events and no significant connection between the UFA and depressional wetlands or the surficial aquifer in the study area. Finally, a large scale comparison performed to detect patterns in geomorphology at the surface, near surface and sub-surface levels, indicated a basin-wide NNW trend was shared in stream reach direction, bedrock joint azimuths and orientation of conduits in regional phreatic caves which is in agreement with tectonic fracturing. The dominant N-S trend in stream reach direction suggested regional fluvialgeomorphology is significantly influenced by neo-tectonic patterns, but partially adjusted to the tectonic template; therefore, investigating intersecting templates may warrant further investigation. The results of these hydrologic, physiochemical, and geomorphic studies provide data which are immediately useful for informing basin models and methods which are easily transferrable to other basins.

INDEX WORDS: groundwater, groundwater/surface water interaction, stream baseflow, center pivot irrigation, Upper Floridan Aquifer, karst, joint fracturing

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DEDICATION

This work is lovingly dedicated to my parents,

Buddy and Charline Rugel, who gave me wings to fly,

and to my sister Laura Rugel Glise,

who has flown before me.

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I used to pride myself on my fierce independence. While that quality has brought me far, the doctoral process has taught me that accepting help from others is equally valuable. Therefore I find myself indebted to those who have not only encouraged me to begin this journey, but tirelessly walked me through it to the end. I would like to thank first, my mentor, James Payne, who has been and continues to be my friend and guide over the past 35 years and without whose help and encouragement I would not be where I find myself today. Thanks to Nancy Moore, for giving me Reelfoot Lake as a playground to whet my appetite for water and for the friendship and insights of my friend and colleague, David Sammons, which helped me begin this journey.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Groundwater is used for drinking, agricultural, industrial and municipal purposes and currently provides over 70% of all water use in many rural, semi-arid and humid tropical communities around the world (Shah et al., 2000; Glennon, 2002; Strand, 2010). Since 1950 annual extraction of groundwater has risen from 100 km^3 to around 800 km^3 per year and is projected to increase 50% in developing countries by 2025 (Wada et al., 2010; WWAP, 2012). While removal of groundwater is essential to many economies, particularly in developing countries, impacts of intensive groundwater extraction are well documented and include lowered water tables, land subsidence, saltwater intrusion, cemetery leakage, vulnerability to nuclear, mining and septic waste, and changes to sediment and chemical loads to receiving estuarine and marine systems (Ward and Stanford, 1989; Postel, 1999; Stauffer, 1999; Chen et al., 2003; Light et al., 2005; Zektser et al., 2005; Hassan, 2006).

Groundwater contributes the baseflow for many lotic, as well as lentic, systems (Linsley et al., 1982; Gilbert et al., 1994; Winter et al., 1998); therefore, groundwater extraction can cause devastating environmental impacts to hydrologically-connected waters (Chen et al., 2003; VanLooy and Martin, 2005; Darst and Light, 2008). Altered flow regimes may affect pool and habitat complexity, temperature, waste assimilation, biological and sediment oxygen demand, hydraulic conductivities, salinity, and delivery of nutrients, as well as DOC, TOC, FPOM, CPOM, and freshwater inputs to downstream estuarine and marine ecosystems (Wallace et al., 1991; Constantz et al., 1994; Dosskey and Bertsch, 1994; Bunn and Arthington, 2002; Gillanders and Kingsford, 2002; Golladay and Battle, 2002; Mosner, 2002; Meyer et al., 2007; Opsahl et al., 2007). Flow alterations resulting from the combined effects of groundwater removal and drought have been shown to reduce species abundance and richness and increase mortality in aquatic, riparian and upland ecosystems (Stromberg et al., 1996; VanLooy and Martin, 2005; Darst and Light, 2008).

Karst aquifers are highly transmissive groundwater systems which form from the dissolution of carbonate sediments by “aggressive” water which has been acidified through soil and atmospheric processes (Jennings, 1985). These aquifers commonly form where continental rifting and paleo-oceanic recession have resulted in the deposition of deep layers of marine sediments. Karst aquifers develop hierarchical flow systems and may exhibit a high degree of connectivity with surface waters in regions in where they occur (Hicks et al., 1987; Mangin, 1994; Torak and Painter, 2006). The removal of groundwater in karst regions has been shown to negatively affect hydraulically-connected waters, making it increasingly vital to adopt water resource management which considers the interconnected nature of these systems (Winter et al., 1998; Pringle and Triska, 2000; Sophocleous, 2002; Chen et al., 2003; Shi et al., 2007). Much of the current research examining these connections is concentrated in alluvial, mountain and glacial aquatic systems leaving a paucity of information to inform management in karstic watersheds which are often highly allocated for groundwater extraction (Poole et al., 2006; Wohl, 2006; Luck et al., 2010). Flow through karst aquifers is particularly complex and exhibits fractal flow patterns that cannot accurately be predicted by Darcy’s Law, therefore, methods and results of research in other aquifer systems may not be applicable in karst domains (Jennings, 1985; Mangin, 1994).

The Lower Flint River Basin (LFRB) is an important agricultural sector in the Coastal Plain province of southwestern Georgia, USA (Couch and McDowell, 2006). Intensive groundwater and surface water removal in this basin is used to support row crop agriculture which contributes 34% of the regional economy (McKissick, 2004). Water removal permitting increased drastically in the LFRB (100%) in the 1970's when center pivot irrigation replaced less efficient cable tow systems and the basin is currently allocated for the withdrawal of more than 3.78×10^6 m^3 of groundwater per day (Pierce et al., 1984; Hook et al., 2005). Approximately 80 percent of the groundwater in the LFRB comes from the Upper Floridan Aquifer (UFA), a prolific carbonate aquifer which underlies most of the Coastal Plain of the southeastern US (Miller, 1992; Couch and McDowell, 2006). Groundwater in this aquifer is transmitted through karst dissolution pathways which have developed in underlying Tertiary marine sediments, mainly the Ocala Limestone Formation (Stringfield, 1966) and interacts heterogeneously with surface waters in this region through transmissive sediments and solution-enlarged fractures and conduits (Hicks et al., 1987). The UFA is part of the larger Floridan Aquifer system which currently supports the regional water needs of over 10 million people in the southeastern US throughout South Carolina, Georgia, Florida and Alabama (Marcella and Berndt, 2005).

Irrigation in the southern US Coastal Plains has been shown to lower regional stream flows and increase the movement and removal of water between hydraulically-connected components (Stamey, 1996; Mosner, 2002). Torak (2006) correlated changes in potentiometric head in wells in the Ochlocknee basin to increased agricultural pumping occurring in the (adjacent) LFRB indicating that potential groundwater recharge was not reaching the Ochlocknee basin. This study also documented leakage which transferred water through lateral channels in banks of Lake Seminole, in SW GA, to receiving conduits on opposing sides of the Jim Woodruff Dam. The waters of the Ochlocknee basin as well as Lake Seminole are shared with Florida and decreased inputs into Lake Seminole have been documented since the onset of intensive pumping practices (Stamey, 1996). Darst and Light (2008) also showed concurrent changes have occurred in riparian tree species and massive loss of trees (4 million Ogeechee tupelo) in the downstream Apalachicola wetlands.

A high biodiversity of aquatic fauna, including multiple species of endemic unionids (mussels), populate streams of the LFRB and are adapted to the unique physiochemical and structural habitats of this watershed. Seven species of mussels have been listed as endangered or threatened in regional waters since 1998 and the US Fish and Wildlife Service designated 1,864 stream kilometers (in Alabama, Georgia and Florida) as Critical Habitat in 2006 to reduce take under the Federal Endangered Species Act of 1973. Golladay and others (2004) showed decreases in mussel species of concern within streams in the LFRB following repeated regional drought and Albertson and Torak (2002) used modeling to identify eight regional streams which would experience drying reaches under several of eight pumping scenarios, potentially affecting these mussels.

While groundwater removal has been shown to reduce discharge and alter surface water dynamics and ecosystems in these regions there is a lack of understanding regarding where groundwater/stream exchange (gaining and losing) may be occurring within these heavily allocated watersheds. Previous research has been performed around the only major municipal area (Albany, GA), in order to determine if water withdrawals from the UFA in that region were sustainable for municipal use following overabstraction from deeper Eocene, Paleocene and Cretaceous aquifers (Hicks et al., 1987; Stewart et al., 1999). While these studies indicated that seasonal pumping would not significantly affect annual potentiometric surfaces, they were carried out in regions where the underlying UFA contains ubiquitous conduits and the highest transmissivity rates in the basin. The Ichawaynochaway and Spring Creek sub-basins of the LFRB have the largest allocations for combined groundwater and surface water in the state however information is still lacking on how and where these groundwater withdrawals may impact surface water systems (and dependent organisms) in these basins (Couch and McDowell, 2006). These data are vital to inform water resource planning and policy on regional, state and federal levels, including efforts in the larger Apalachicola-Chattahoochee-Flint (ACF) watershed currently undergoing intensive water resource restructuring (Ruhl, 2005).

The following research combined aspects of multiple disciplines including hydrologic data analysis, groundwater and surface water biogeochemistry, hydrogeology, fluvial geomorphology and remote sensing technologies, and sought to address these overarching questions: 1) how has historic removal of groundwater and surface water in the LFRB impacted the quantity and behavior of streamflow in regional tributaries; 2) where and to what extent does the UFA interact with surface water components in this basin; and 3) what geomorphological characteristics can be detected at the surface, sub-surface and groundwater level which may potentially be useful for predicting groundwater/surface water interaction in this region? We utilized long-term USGS streamflow data which is readily available for tributaries in this basin in order to compare regional pre- and post-irrigation stream behavior. Since the chemical makeup of groundwater is determined by inherent geology and residence within the aquifer we compared Ca^{2+}, Sr^{2+}, and specific conductivity along with other physiochemical parameters (temperature, pH, $\delta^{18}O$ and δD) to determine how precipitation and groundwater may be moving through these systems and contributing to the stream, shallow aquifer and wetlands in the Ichawaynochaway sub-basin (Genereux et al., 1993; Mangin, 1994; Brodie et al., 2007). Finally, we combined directional data including azimuths of regional stream bedrock fractures, cave passageways, and stream reach orientation to determine if patterns exist which might help predict the interaction of groundwater and surface water systems in this basin (Melton, 1959; Brook and Allison, 1983; Dinger et al., 2002). These methodologies are easily transferrable to other watersheds of similar geology and data will be immediately useful for informing sustainable water budgets to help protect economic and ecological health in overallocated basins.

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CHAPTER 2

EFFECTS OF IRRIGATION WITHDRAWALS ON STREAMFLOWS IN A KARST ENVIRONMENT: LOWER FLINT RIVER BASIN, GEORGIA, USA

[1] Rugel, K., Jackson, C. R., Romeis, J., Golladay, S. W., Hicks, D. W., and Dowd, J. F., 2012. Effects of center pivot irrigation on streamflows in a karst environment: lower Flint River Basin, GA, USA. *Hydrological Processes* **26**: 523-534. Reprinted here with permission of the publisher.

Abstract

Extensive implementation of center pivot irrigation systems occurred between 1970 and 1980 in the lower Flint River Basin of southwestern Georgia, USA. Groundwater within this karstic system is in direct hydraulic connection with regional streams, many of which are incised through the overburden into underlying limestone. We used long-term U.S. Geological Survey gaging station data to evaluate multiple flow metrics of two tributaries (Ichawaynochaway Creek and Spring Creek) in the lower Flint River Basin to determine the extent of changes in stream behavior since irrigation practices intensified. We compared pre-irrigation and post-irrigation flow duration curves, one-, seven-, and fourteen-day minimum flows, and eight-day (seasonal) and annual baseflow recession slopes, in addition to evaluating regional climate data to determine whether significant differences existed between the pre- and post-irrigation periods. Our results showed significant changes in low flow durations in the post-irrigation record for both gages, including a decrease by an order of magnitude for 98% exceedance flows at Spring Creek. Both gages indicated significant reductions in one-, seven-, and fourteen-day low flows. Eight-day baseflow recession curves (within early summer months) and annual baseflow recession curves became significantly steeper during the post-irrigation period for Ichawaynochaway Creek. We also found that a significant relationship existed between winter and summer minimum flows in both streams in the pre-irrigation period which was disrupted in post-irrigation years. Regional climate data for the study period revealed no significant changes in rainfall totals or frequency of drought, however there was evidence for a shift in seasonal rainfall patterns.

Introduction

The significance of hydrologic connectivity between surface water and groundwater has become an issue of increasing scientific interest and emphasis over the past two decades (Stanford and Ward, 1993; Winter et al., 1998; Boulton and Hancock, 2006). Exchange between groundwater and surface water affects both biological and hydrological regimes making the management of groundwater crucial to the protection of surface waters, particularly in regions where groundwater supports baseflow and serves as the major water resource (Shah et al., 2000; Woessner, 2000). Agricultural water use accounts for ~80% of all the fresh water used worldwide and is inherently consumptive in nature (Postel, 1997). Overextraction of groundwater has been linked to alterations in quantity and quality of surface waters, land subsidence, loss of riparian communities, and damage to the economic health of numerous regions throughout the world (Postel, 1999; Glennon, 2002; Chen et al., 2003; Zektser et al., 2005; Shi et al., 2007). Intensive groundwater removal near stream channels can cause changes in regional hydrologic gradients resulting in streamflow depletion (Sophocleous, 2002). Lowered streamflow can affect channel morphology (aggradation, pool formation, habitat complexity), lower assimilative capacity, alter stream temperature, threaten aquatic biota (Golladay et al., 2004), and reduce nutrient loading to downstream communities (Pringle and Triska, 2000; Bunn and Arthington, 2002).

Wen and Chen (2006) found that significant flow depletion in reaches within the Platte and Republican Rivers coincided with increased groundwater withdrawal sites accessing the High Plains Aquifer in western Nebraska, USA. Using 40 years of data from three Australian streams, Brodie and others (2008) revealed increased lag time between rainfall and streamflow response as well as depletions in Q90 in the post-irrigation record of the highly developed Owens River, Victoria. Zume and Tarhule (2008) modeled streamflow depletion from groundwater extraction in a semi-arid alluvial system using visual MODFLOW and showed that baseflow reductions and increased stream leakage accounted for a total of 47% of streamflow depletion within the Beaver-North Canadian River system in northwestern Oklahoma, USA.

While our understanding of the interaction between groundwater and surface water in alluvial, volcanic and glacial systems has increased, particularly in arid and semi-arid environments (Stromberg et al., 1996; VanLooy and Martin, 2005; Poole et al., 2006), the dynamics between surface water and groundwater components within karstic systems, particularly in temperate environments, merits greater investigation. Connectivity within karst catchments is dependent on the interaction of complex fractal flow development, local geohydrologic factors, regional hydraulic gradients and climate. Karst basins exist worldwide and are common where paleo-oceanic recession has occurred. Many karst areas occur in coastal regions where population growth is stressing freshwater aquifers and adjoining surface water systems.

During the past several decades, burgeoning population growth and reoccurring drought in the southeastern US have increased demand on limited water resources and generated regional and interstate conflicts. Efforts at mediation between Georgia, Alabama and Florida over the partitioning of water resources within the Apalachicola-Chattahoochee-Flint (ACF) River system have been costly, time consuming, and ultimately unsuccessful (Ruhl, 2005). Water is needed throughout this region to support

rapidly-growing urban centers, agricultural irrigation, power facilities, industrial, municipal and rural water supplies, and fresh and estuarine ecosystems.
Beginning in the 1970s center pivot irrigation systems were installed extensively throughout the lower Flint River Basin (FRB) in SW Georgia to drought-proof crops and improve quantity and quality of yields. Groundwater withdrawals for irrigation increased over 100% in Georgia between 1970 and 1976, mainly due to increased water demand when center pivot irrigation systems replaced less efficient cable tow systems in the southwestern portion of the state (Pierce *et al.*, 1984). Irrigation in this region allows for the implementation of intensive farming practices including multiple harvests per year. Approximately 80% of the water used for irrigation in the lower FRB is extracted from the Upper Floridan Aquifer, a highly productive carbonate aquifer which underlies most of the Coastal Plain province of the southeastern US (Hicks et al., 1987). Surface waters throughout the Coastal Plain are connected heterogeneously to the Upper Floridan and interchange between groundwater and surface water components can occur rapidly and frequently through sinkholes, springs and other dissolution paths (Mosner, 2002; Opsahl et al., 2007).

Long-term monitoring of stream gaging stations by the U.S. Geological Survey as well as uninterrupted climate records provide data sets of suitable length to compare stream behavior in response to changing water use patterns in the lower FRB. The inherent heterogeneities in hydraulic conductivity, hierarchical flow patterns, boundary conditions and other complex unknowns within karst systems, can be interpreted through the flow response of the unit hydrograph (Mangin, 1994). Since basin response remains relatively consistent over time these hydrographs are also informative for documenting changes in hydrologic conditions occurring within a basin due to natural or anthropogenic influences. The objectives of this study were to describe the degree to which stream flows have been altered in tributaries of the lower FRB since irrigation practices intensified and to determine how water use has affected water availability throughout this basin. We hypothesized that increased irrigation would result in alterations of low flow durations and stream flow flow metrics (one-, seven-, and fourteen-day low flows) in tributaries in the lower FRB. We further hypothesized that baseflow recession, when considered at the scale of both individual storm and annual averages, would show increasingly rapid depletion as irrigation intensified. Finally, we predicted that a relationship might exist between winter and summer streamflow minima which could be affected by increasing irrigation withdrawals. Because changes in observed flows can be the effect of differences in precipitation patterns, we evaluated the regional climate record to determine if significant shifts in rainfall or drought had occurred over the study period (~1940-2008). This information is urgently needed to update current surface water and groundwater models and to inform resource policy in this and other basins where management must strike a balance between human water supply and ecological sustainability.

Methods

Site Description

The lower Flint River Basin is located southeast of the Fall Line Hills within the Dougherty Plain district of Georgia's Coastal Plain physiographic province (Figure 2.1). The Fall Line Hills creates the western boundary of the Dougherty Plain and the peak of the Solution Escarpment separates the eastern boundary from the Tifton Upland in

Florida. Average slope within this nearly-level plain is 2.4m/km. Geology is dominated by karst, mainly limestone, formations of middle Eocene age and younger overlain by undifferentiated Oligocene and Miocene sediments. An undifferentiated overburden of Quaternary sediments is covered by slightly acidic sandy-loam soils (Hicks *et al.*, 1987). The Ocala Limestone is the main water bearing stratum within the region. This formation thins as it updips and outcrops in a northwesterly direction toward the Fall Line Hills and thickens up to 120 meters in a southeasterly direction. Percolation of regional precipitation through acidic soils has been transmitted along fractures and bedding planes into the underlying limestone formation, resulting in mature karst development and a series of unconfined, semi-confined and confined aquifers in this region. We limit our scope to the Upper Floridan Aquifer which is the source of approximately 80% of the groundwater utilized in the lower FRB (Couch and McDowell, 2006). Transmissivity rates in this aquifer are rapid and can reach approximately 1.4 x 10^4 m^2/d (Hicks *et al.*, 1987). Direction and extent of water movement depends on regional hydraulic gradients, differences in saturation of stratigraphic units, and water usage. The Upper Floridan is recharged mainly by winter precipitation (Dec.–March) when evapotranspiration rates are low (Torak and Painter, 2006). The lower confining unit of the Upper Floridan is formed by the mostly-impervious Lisbon Formation. Streams in the area begin as springs and seeps in the Fall Line Hills and flow in a southeasterly direction across the Dougherty Plain exchanging water heterogeneously with the underlying aquifer through springs, fractures and porous stream beds (Albertson and Torak, 2002; Mosner, 2002). Where the overburden has eroded, streams are incised directly into underlying limestone formations.

Climate in the lower FRB is hot and humid during summer months with temperatures ranging from 18-35 °C and winter temperatures ranging between 2-13 °C. Average annual precipitation is 1320 mm [min. 747 mm (in 1954); max. 1960 mm (in 1964)] and is distributed unevenly across the region. Rainfall is generally greatest during the winter and early spring but intense rainfall associated with thundershowers or tropical cyclones may occur during late spring, summer, and early fall (noaa.gov, Accessed February 2010). Average warm season pan evaporation rates are approximately 821 mm (Lawrimore and Peterson, 2000) or 60% of average annual precipitation.

The study area includes the Ichawaynochaway Creek and Spring Creek sub-basins which lie within the lower FRB (Figure 2.1). Land use is dominated by agriculture (50%) with remaining acreage in managed forestland and depressional wetlands. Row crop farming of cotton, peanuts, corn, soybeans and wheat is supported by center pivot irrigation systems using groundwater sources from the Upper Floridan Aquifer as well as surface water sources. Average irrigation depths for corn, cotton and peanuts, are ~ 358, 295 and 285 mm/yr, respectively (Harrison, 2001). Ichawaynochaway Creek is a fifth-order tributary of the Flint River. Spring Creek, a third-order stream formerly tributary of the Flint, flows directly into Lake Seminole reservoir at the Georgia-Florida border where the Flint and Chattahoochee Rivers join to form the Apalachicola River.

Low Flow Duration Curves

USGS streamflow records were screened for a minimum of 20 pre- and post-treatment years, leaving only two USGS gaging stations available for analysis: Ichawaynochaway Creek at Milford (Station 02353500), in Baker County, GA, and Spring Creek near Iron City, (Station 02357000), in Decatur County, GA (Table 2.1).

Streamflow data sets were divided into pre- and post-irrigation time periods with pre-irrigation for Ichawaynochaway Creek beginning in water year (WY) 1940 (starting October 1, 1939) through WY 1969 (ending September 30, 1969) and post- irrigation period from WY 1980 (October 1, 1979) through WY 2008 (September 30, 2008). The Spring Creek pre-irrigation period began in WY 1940 through WY 1969 and post-irrigation period was from WY 1983 through WY 2008. The following analyses did not include data from most of the 1970s due to temporary interruption of gaging site collection during that decade.

Low flow duration curves were produced from the record of pre- and post-irrigation daily flows and analyzed graphically for both Ichawaynochaway and Spring Creek (Dunne and Leopold, 1978). Flow duration curves were subsequently used to estimate differences in water yield for all flows less than the median flow between the pre- and post-irrigation periods by integrating the area between the lower end of the pre- and post-irrigation curves (below 50% exceedance flows) and converting area to a volume using methods from Davis and McCuen (2005). Deficit volume was converted to an average depth of lost annual water yield over each HUC 8 watershed.

One-, seven-, and fourteen-day average flows

Changes in average streamflow between the pre- and post-irrigation period were assessed by statistically comparing the distributions of one-, seven-, and fourteen-day minimum daily flows for Ichawaynochaway and Spring Creek and graphically evaluating differences in the seven-day low flow recurrence curves. The lowest one-, seven-, and fourteen-day average flows for each water year were calculated from the USGS daily flow records (Ichawaynochaway Creek pre-irrigation: WY 1940 - WY 1969, post-irrigation: WY 1980 - WY 2008; and Spring Creek pre-irrigation: WY 1940 - WY 1969, post-irrigation: WY 1983 - WY 2008). Differences in pre- and post-irrigation low flow metrics were tested using a one-tailed Mann-Whitney nonparametric rank sums test (α = 0.05; Null hypothesis: pre-irrigation low flow metrics were equal to post-irrigation low flow metrics) (Zar, 1984; Berryman et al., 1988). Seven-day low flow duration curves were developed using the Gringorten plot position (Stedinger *et al.*, 1993).

Baseflow recession analysis

A comparison of pre- and post-irrigation baseflow recession behavior was performed on daily flows from gage data to determine if stream depletion occurred more rapidly in the post-irrigation period (Tallaksen, 1995). Starting on the third day following peak flow, segments of uninterrupted recession which were at least eight days in length were extracted from the falling limb of all high flow events within the period of interest (Ichawaynochaway Creek pre-irrigation: WY 1940 – WY 1969; post-irrigation: WY 1980 – WY 2008; Spring Creek pre-irrigation: WY 1940 – WY 1969; post-irrigation: WY 1983 – WY 2008). From this record 269 high flow events from the Ichawaynochaway Creek gage and 228 high flow events from the Spring Creek gage fit the recession criteria (excluding extreme flood events of 1994 and 1998). The slope of each storm recession was fit to the following equation:

$$y = b_0 x^{b_1} \qquad \text{(Eq. 2.1)}$$

where y equals the estimated flow for x, x equals a given day after the start of the recession, b_0 equals the recession coefficient, and b_1 equals the exponent (slope of the recession). Recession slopes were divided into three seasons: early summer (May 1-July 15), late summer (July 16-October 31), and winter (November 1-April 30) periods and grouped into pre-irrigation and post-irrigation years. A t-test was used to compare the pre- and post-irrigation median slope for each period (α=0.05). All seasonal data for Ichawaynochaway Creek as well as winter season for Spring Creek failed normality test and data were retested using Mann-Whitney nonparametric rank sum test ($\alpha = 0.05$).

To account for delayed streamflow response due to long-term groundwater extraction, stream data were re-examined for differences in pre- and post- irrigation annual baseflow recession behavior. Baseflow recession durations of 365 days were extracted from daily streamflow data (Ichawaynochaway Creek pre-irrigation: 1940-1969, post-irrigation: 1980-2007; Spring Creek pre-irrigation: 1938-1969, post-irrigation: 1983-2007) and low points were selected on the receding limb of each annual hydrograph from approximately February to November. Calendar years were used in order to adequately capture annual recession behavior. Precipitation events within these recessions which did not result in a rise of greater than 20% over preceding flow points were deleted and recessions were smoothed by extrapolation and fit the following equation:

$$y = b_0 e^{b_1 x} \qquad \text{(Eq. 2.2)}$$

where y equals the estimated flow for x, x equals a given day after the start of the recession, b_0 equals the recession coefficient, and b_1 equals the exponent (slope of the recession). A one-tailed Mann-Whitney nonparametric rank sums test was executed on pre- and post-irrigation period median slopes ($\alpha = 0.05$).

Winter/Summer Minimum Flow Relationships

In order to determine if a relationship existed between winter and summer minimum flows in streams in the lower FRB, the lowest February daily flows (four points, where available) were selected from within each annual recession period and averaged to produce a February mean minimum flow (winter minimum) for each year (Ichawaynochaway Creek pre-irrigation: 1940-1969, post-irrigation: 1980-2007; Spring Creek pre-irrigation: 1938-1969, post-irrigation: 1983-2007). The single lowest minimum daily flow in August was selected from each year to represent the August minimum flow (summer minimum). Linear regressions were executed on February vs August minima for pre- and post-irrigation years and graphed on a semi-log scatter plot (Zar, 1984).

Climate Analysis

The distribution of seasonal climate data from the National Climate Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html, accessed August 2009) was examined over the period of study (1940-2008) in order to determine if changes had occurred in rainfall patterns between pre- and post-irrigation years (pre=1940-1974; post=1975-2008). A Mann-Whitney nonparametric rank sums test ($\alpha = 0.05$) was executed on annual, as well as seasonal, precipitation data for pre- and post-irrigation periods. The Palmer Drought Severity Index (PDSI) was used to identify and compare periods of rainfall deficit (deficits of several months or more) over the period of record to determine if changes had occurred in frequency, severity, or duration of drought since irrigation intensified in the lower FRB.

Results

Low Flow Durations

Flow duration analysis of these streams indicated substantial reductions in low flows in the post-irrigation period. For flows exceeding the median flow (50 percentile), post-irrigation flow duration curves for Ichawaynochaway Creek and Spring Creek (Figure 2.2) were very similar to the pre-irrigation record, however, flows less than the 50%

exceedance were much lower in the post-irrigation period. At the 98% exceedance flow, post-irrigation flows were 1/10th of pre-irrigation flows, and in Spring Creek flows fell to zero at the 99% exceedance level. Changes in water yield for all flows less than the median flow from Ichawaynochaway Creek and Spring Creek sub-basins were 38 and 7 mm annually.

One-, seven-, and fourteen-day low flows

One-, seven-, and fourteen-day low flows were reduced substantially in the post-irrigation period (Figure 2.3, all p values < 0.001) for both gages. During this post-irrigation period, median seven-day low flows for Spring Creek and Ichawaynochaway Creek were 51% and 61%, of their pre-irrigation values, respectively (Table 2.2). Relative deviations of the seven-day low flow recurrence curves for both Spring Creek and Ichawaynochaway Creek increased with increasing average recurrence interval, indicating effects of pumping were more severe during droughts. In the range of the 10 to 100 year recurrence interval, seven-day low flows were an order of magnitude lower in the post-irrigation period for both streams. When considering absolute changes, the seven-day low flow recurrence curve for Ichawaynochaway Creek dropped an almost uniform 3.0 to 3.5 m^3/s in the post-irrigation period. This shift is approximately equal to the 25-year seven-day low flow in the pre-irrigation period.

Baseflow recession analysis

Median eight-day baseflow recession curves were significantly steeper within the post-irrigation record during the early summer period for Ichawaynochaway Creek (Figure 2.4, $p<0.031$). No significant differences were detected for late summer or winter season median slopes on Ichawaynochaway ($p=0.992$ and 0.436, respectively). There were no significant differences between pre- and post-irrigation median eight-day recession slopes for any season on Spring Creek [p=0.366 (early summer), p=0.145 (late summer), p=0.488 (winter)] but there was a trend toward steeper recessions in the early summer and late summer seasons. Evaluation of annual baseflow recession curves revealed significant changes in annual recession slopes (steeper) in the post-irrigation period for Ichawaynochaway Creek (Figure 2.5, $p<0.001$). No significant differences between pre- and post-irrigation annual recession slopes were indicated for Spring Creek ($p= 0.174$), although the distribution moved toward steeper recession slopes.

Winter/Summer Flow Relationships

A significant positive relationship was found between winter and summer minimum flows in the pre-irrigation period for both Ichawaynochaway Creek and Spring Creek (Figure 2.6, both analyses, $p<0.001$). In the pre-irrigation period February minimum flows, which were high from recharge between late fall and early winter months, resulted in August minimum flows that were comparatively elevated. However, in the post-irrigation period, February and August minimum flows showed no significant relationship in Ichawaynochaway or Spring Creek indicating that the relationship which had existed between winter and summer minima has been disrupted and minimum winter flows no longer serves as a predictor for upcoming summer minimum flows.

Climate Analysis

No significant differences were observed between pre-irrigation (1940-1974) and post-irrigation (1975-2008) precipitation patterns (Figure 2.7, $p>0.05$). Both medians and mean values suggested annual, winter, and fall rainfall were slightly greater from 1975-2008 (Table 2.3). Spring and summer rainfall tended to be slightly lower. Spring rainfall totals did not pass the equality of variance test (Kolmogorov-Smirnov Test $p<0.05$) suggesting that the two data periods had different distributions. Summer and fall data both failed the normality test (Shapiro-Wilkoxon Test $p<0.05$) suggesting that one or both data sets were non-normal in distribution. Based on these outcomes the distribution of seasonal data was re-examined to see if subtle changes could be observed over the period of study. Spring rainfall totals showed greater kurtosis for 1975-2008 supporting the previous test indicating inequality of variance (Figure 2.7). The Palmer Drought Severity Index revealed 28 periods of rainfall deficits of several months or more, 8 of which were significant droughts (deficits persisting for greater than 1 year or exceeding a severity index of -3). These findings revealed an average inter-drought interval of 8.5 years, with 4 droughts prior to 1974 and 4 droughts after intensive pumping began (Figure 2.8), indicating no difference in frequency of drought between the pre- and post-irrigation period.

Discussion

Intensification of agricultural irrigation in the lower FRB has resulted in significant baseflow declines evident in reductions in low flow durations and one-, seven-, and fourteen-day minimum flows in the post-irrigation record for both Ichawaynochaway and Spring Creeks. These declines have been large, making the previous 25-year seven-day low flow in Ichawaynochaway Creek into the 2-year seven-day low flow. Spring Creek, a much smaller stream than Ichawaynochaway Creek, was formerly perennial but became intermittent in the post-irrigation period. Large declines in low flows have occurred while annual water budgets of these streams have changed relatively little. Water level time series in USGS long-term monitoring wells in the area show large and steep summer drops in head, but they do not show trends in winter groundwater levels. On an annual basis, recharge to the system is sufficient to maintain groundwater levels and sustain agricultural irrigation, and this likely explains the small effect of pumping on annual water budgets.

Significant changes in both eight-day early summer and annual baseflow recession curves for Ichawaynochaway Creek indicate more rapid stream depletion has occurred during post-irrigation years. Effects seen on early summer baseflow recessions in the post-irrigation period correspond to heaviest seasonal irrigation application in this region (April through June). The lack of statistical significance in the Spring Creek annual recession changes may be due to a more constrained streamflow reduction that could occur (i.e., measured flows could not go below zero).

The relatively strong linear relationship that existed between winter and summer minimum flows prior to implementation of extensive irrigation was disrupted in the post-irrigation period in both Ichawaynochaway and Spring Creek. In pre-irrigation years high February baseflows would have preceded correspondingly high August baseflows, and low February flows led to low August minima, indicating a persistent effect of winter groundwater levels on subsequent summer baseflows. The lack of correlation between winter baseflows and summer low flows in the post-pumping period indicates that agricultural groundwater pumping has significantly altered groundwater-streamflow relationships. The previous relationship between summer and winter minimum flows could have served as an indicator of impending low flow conditions and might have been a useful tool for resource managers in charge of protecting stressed water resources, but now February low flows have little value for predicting late summer drought conditions.

The Ichawaynochaway Creek and Spring Creek sub-basins are the most heavily allocated HUC 8 sub-basins for groundwater and surface water withdrawals within the state (Table 1). Presently there are more than 7,000 irrigation permits issued to users of >379 m^3/day in the lower FRB (Couch and McDowell, 2006). Approximately 35.1 m^3/s (3.03 x 10^6 m^3/day) is permitted in the Ichawaynochaway Creek sub-basin, 66% from surface withdrawals and the remainder from groundwater (Hook et al., 2005). Removal of 58.7 m^3/s (5.07 x 10^6 m^3/day) of water is permitted in the Spring Creek sub-basin with 92% coming from the Upper Floridan. Surface water removal includes direct pumping of water from regional streams as well as the diversion of runoff into holding ponds for later application. Groundwater may also be pumped and held in surface ponds for later use. Critical habitat is currently designated in streams in the lower regions of the FBR to protect seven species of mussels listed (as endangered or threatened) by the U.S. Fish and Wildlife Service (USFWS). Results of USGS hydrologic modeling of various agricultural pumping scenarios suggest that eight reaches in this area, including Spring Creek and multiple tributaries of the Flint River, are highly sensitive to drying, posing a risk to mussel populations in those reaches (Albertson and Torak, 2002). A severe drought occurring between 1999-2001 induced fish and mussel kills in this area and raised concerns over the effects of irrigation withdrawals on streams and dependent biota. The passage of the Flint River Drought Protection Act in 2000 placed a temporary moratorium on irrigation permitting and allowed the Georgia Environmental Protection Agency to buy back limited irrigation rights during drought years to reduce demand on strained regional water resources (Couch and McDowell, 2006). Declaration of drought and announcement of irrigation water buy-back must be declared by March 1, approximately five to eight months before the lowest flows may be observed in these streams. This regulatory system raised questions on whether winter baseflow conditions might be predictive of upcoming summer low flow conditions, motivating part of the analysis included in this study.

While groundwater withdrawals are estimated on an annual basis they are generally applied within only a 4-6 month period when temperatures and evapotranspiration rates are high. The differences in pre- and post-irrigation water yield for the Ichawaynochaway and Spring Creek sub-basins for all flows less than the median flow were 38 mm/year and 7 mm/year, respectively. While this amounts to only 4.5% and 0.7% of average annual yield, respectively, it belies the large effects of seasonal irrigation on growing season flows in these basins. When compared to pre-irrigation summer mean flow these losses represent 12% and 18% of average summer yields for Ichawaynochaway and Spring Creek, respectively.

Peak irrigation pumping in the lower FRB coincides with periods of generally low summer flows, exacerbating low-flow conditions such as increased stream temperatures and lowered dissolved oxygen levels (Gagnon et al., 2004). Anoxic conditions have been shown to threaten aquatic species in these and adjacent waters. Following severe drought between 1998 and 2000, Golladay et al. (2004) reported significant declines in mussel taxa richness and species abundance within mid-stream reaches of Spring Creek, >50% reduction in total mussel abundance, and lowered or absent populations of species of special concern in no-flow reaches. Mussels have been shown to provide valuable ecosystem services by significantly altering nutrient processing and biodeposition in freshwater ecosystems (Howard and Cuffey, 2006; Spooner and Vaughn, 2006). In addition to aiding in the translocation of important nutrients and water clarification within their habitat, these organisms also provide food for a variety of regional fauna including muskrat, otter, raccoons, birds and fish (Strayer, 2008). Gulf Striped Bass, an important recreational fish in the lower FRB, are also known to seek out spring conduits in regional streams during summer months, seeking relief provided by cooler groundwater inputs. Overcrowding in or lack of access to these important thermal refugia have been shown to increase stress-induced pathology and mortality of adult striped bass (Zale et al., 1990).

Although repeated droughts have occurred in the last decade, our results show there has been no significant reduction in average precipitation or increase in recurrence or severity of drought during post-irrigation years, indicating that lowered flows in this region are not a result of altered climate patterns, however, shifts in distribution of spring and summer rainfall patterns since the 1970s may have created the need for more irrigation. Rose (2009) showed no statistically significant differences in rainfall amounts from 1938 to 2005 in southeastern US, including the Coastal Plain region. Seager and others (2009) compared recent southeastern US drought years (2005-2006) with previous climatic patterns (1856- 2004). They concluded that this recent drought was typical relative to historic droughts and suggested current water shortages are due mainly to increasing water demand in this region.

Intensive groundwater removal in the lower FRB has also been shown to have out-of-basin effects. Outside of the recharge area groundwater levels are showing a permanent decline with consumptive water use. Current studies suggest that withdrawal of groundwater resources in the lower FRB has resulted in changes in the potentiometric surface of groundwater in the neighboring Ochlockonee River Basin due to removal of potential recharge (Lynn J. Torak, Hydrologist, U.S. Geological Survey, Atlanta, Georgia, personal communication, 2008). Following the implementation of intensive irrigation in the 1970's Stamey (1996) reported reduced inputs to and outputs from Lake Seminole, a man-made impoundment at the confluence of the Flint and Chattahoochee Rivers. Downstream ecosystems and fishing, shrimping and shellfish industries in the Apalachicola Bay, Florida, depend on upstream inputs of fresh water from the lower FRB in order to maintain adequate levels of nutrients and salinity as well as flushing flows vital to estuarine and marine function (Elder and Cairnes, 1982; Gillanders and Kingsford, 2002).

Current resource policy does not require reporting of water consumption by permitted agricultural irrigators, although many farmers are voluntarily submitting to monitoring programs in this region. While irrigators who applied for permits after July 1, 1988 must comply with protection of established 7Q10 for their watershed, wells which were already pumping >379 m^3/day prior to July1,1988 have been "grandfathered" into the current mandated permitting program and extraction may proceed at original pumping capacity. Groundwater removal of <379 m^3/day requires no permit or monitoring. Agricultural irrigation permits cannot be withdrawn once they have been granted (unless they have not been completed within a year); however the EPD may suspend pumping during periods of declared drought. If left unchecked, human decisions regarding crop production and extensive irrigation from groundwater resources are likely to continue to significantly affect the availability of surface water resources within the lower FRB as well as downstream.

Conclusion

Water extraction from the Upper Floridan aquifer within the Dougherty Plain of southwestern Georgia has substantially reduced stream baseflow in the lower Flint River Basin. Because the underlying karstic aquifer is shallow and streams are heterogeneously incised directly into limestone formations, there is a dynamic hydraulic connection between surface water and groundwater resources in this region. The effects of groundwater removal have intensified extreme low flow and no flow periods during the growing season in historically-perennial streams. Low flows and resulting hypoxic conditions stress important aquatic biota, including multiple threatened and endangered species. Human population in the southeastern United States is on a trajectory of rapid growth, increasing the need for reliable water resources. In addition, this region is projected to experience more extreme climatic events (including drought) under global climate change scenarios (Easterling et al., 2000). While commodity pricing and loan structuring make it necessary for farmers to use irrigation in order to compete in current markets, it is essential that future water resource policy be carefully designed in this and other regions where natural and anthropological pressures will continue to stress limited water resources which must be shared between human and ecological communities.

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Table 2.1. Summary of characteristics of selected sub-basins of lower Flint River Basin taken from summary statistics in USGS Water-Data Reports for 2008.

Stream	USGS gage	Years Before and After Pumping	Ave. Yield (mm)	Basin Area (ha)	Irrigated Area (ha)	
					Groundwater	Surface
Ichawaynochaway Creek @Milford	02353500	30/29	416	160,000	20,632	14,500
Spring Creek near Iron City	02357000	30/26	348	125,200	55,434	2,861

Table 2.2. Comparison of highest, lowest, median, mean, and standard deviation of 1-, 7-, and 14-day low flows for the pre- and post-pumping periods[a].

	Ichawaynochaway Creek		Spring Creek	
	Pre-pumping N = 30	Post-pumping N = 29	Pre-pumping N = 30	Post-pumping N = 26
One-Day Low Flows				
Range (hi-lo)	12.69 – 3.32	6.96 – 0.19	4.88 – 0.26	3.60 – 0
Median	6.25	3.51	1.42	0.78
Mean	6.73	5.18	1.74	1.01
St. Dev.	2.66	2.04	1.11	1.02
Seven-Day Low Flows				
Range (hi-lo)	13.07 – 3.53	7.57 – 0.48	5.33 – 0.26	4.02 – 0
Median	6.85	4.18	1.60	0.82
Mean	7.17	5.62	1,83	1.08
St. Dev.	2.76	2.11	1.17	1.10
Fourteen-Day Low Flows				
Range (hi-lo)	14.24 – 3.62	8.28 – 0.63	5.46- 0.27	4.60 – 0
Median	7.37	5.10	1.65	0.90
Mean	7.75	6.21	1.91	1.17
St. Dev.	3.02	2.23	1.22	1.19

[a] Differences in pre- and post-pumping 1-, 7-, and 14-day low flow distributions were tested using a one-tailed Mann Whitney nonparametric rank sums test (Null hypothesis: pre-pumping low flow metrics were less than or equal to post-pumping low flow metrics). Differences were significant for all metrics for all gage records (all p values < 0.001).

Table 2.3. Regional rainfall summary for southwestern Georgia from 1940 to 2008. Data are from the National Climate Data Center drought database, accessed August 2009.

Period	Annual (cm)	Winter (cm)	Spring (cm)	Summer (cm)	Fall (cm)
Medians and inter-quartile ranges					
1940-1974	126.0 118.8-147.3	36.6 27.0-44.8	32.6 27.2-38.6	35.1 32.3-44.5	21.2 16.7-31.3
1975-2008	132.8 113.8-147.8	37.4 31.2-43.8	29.4 22.3-36.2	34.4 29.1-42.5	26.5 17.0-34.7
Means and standard deviations					
1940-1974	131.0 (23.8)	36.7 (11.1)	33.0 (7.4)	37.6 (7.8)	23.7 (10.2)
1975-2008	131.5 (22.0)	38.6 (9.4)	30.0 (10.0)	36.8 (11.4)	26.1 (10.7)

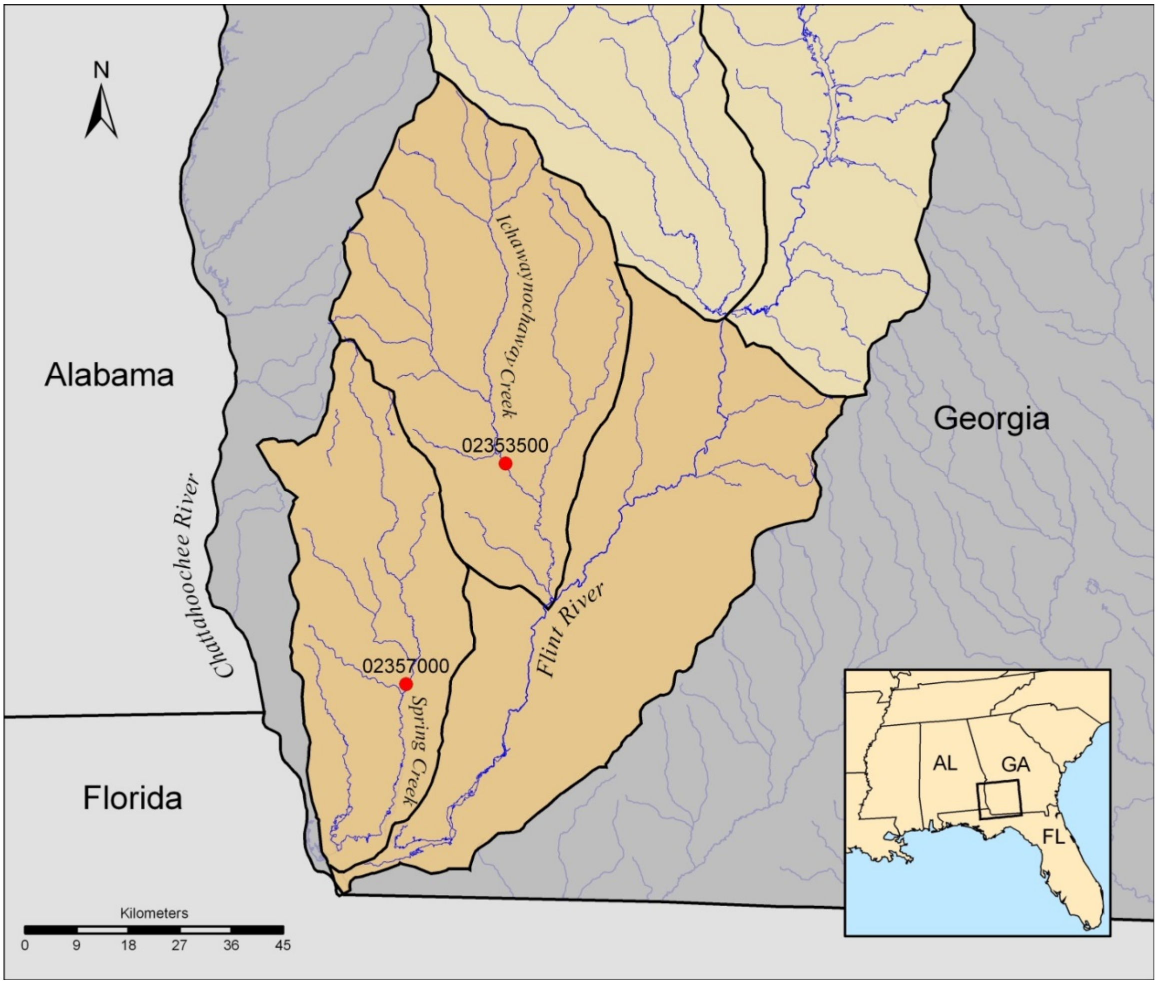

Figure 2.1.Map of study site: lower Flint River Basin and Ichawaynochaway Creek and Spring Creek sub-basins in southwest Georgia, USA.

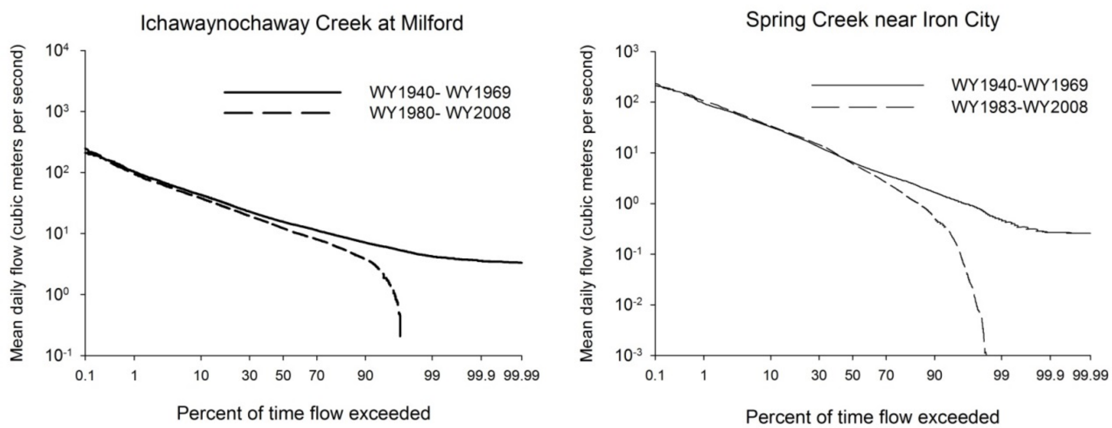

Figure 2.2. Flow duration curves for the pre- and post-pumping irrigation periods for Ichawaynochaway Creek and Spring Creek, GA.

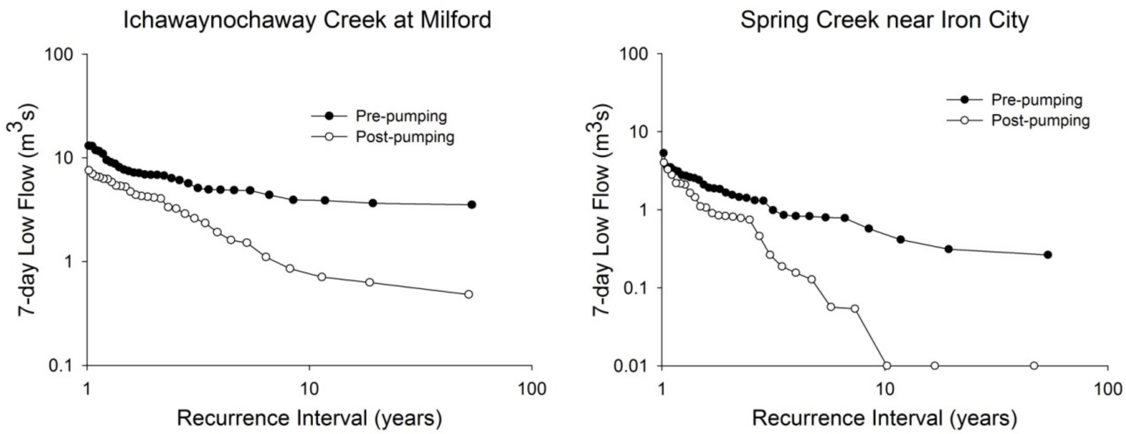

Figure 2.3. Seven-day low-flow recurrence curves in the pre- and post-pumping irrigation periods for Ichawaynochaway Creek and Spring Creek, GA.

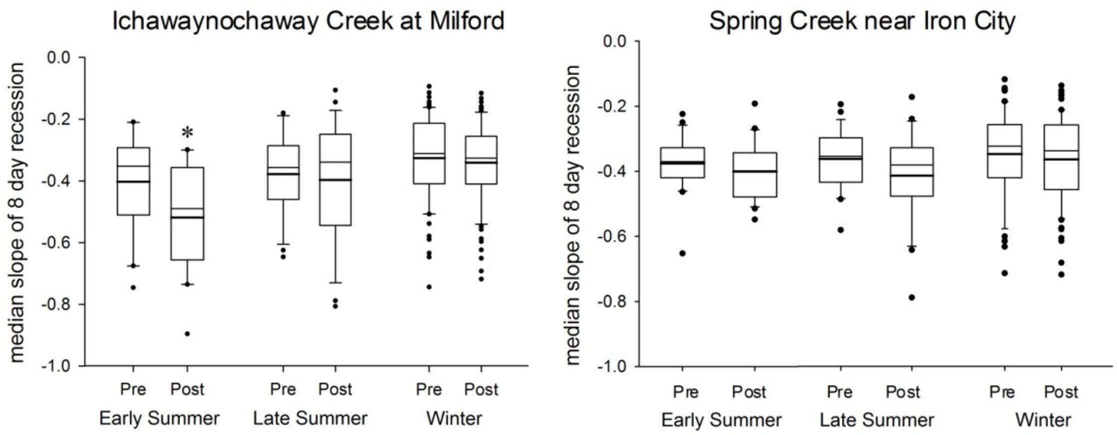

Figure 2.4. Analysis of median 8-day recession baseflow slopes for Ichawaynochaway Creek and Spring Creek, GA.

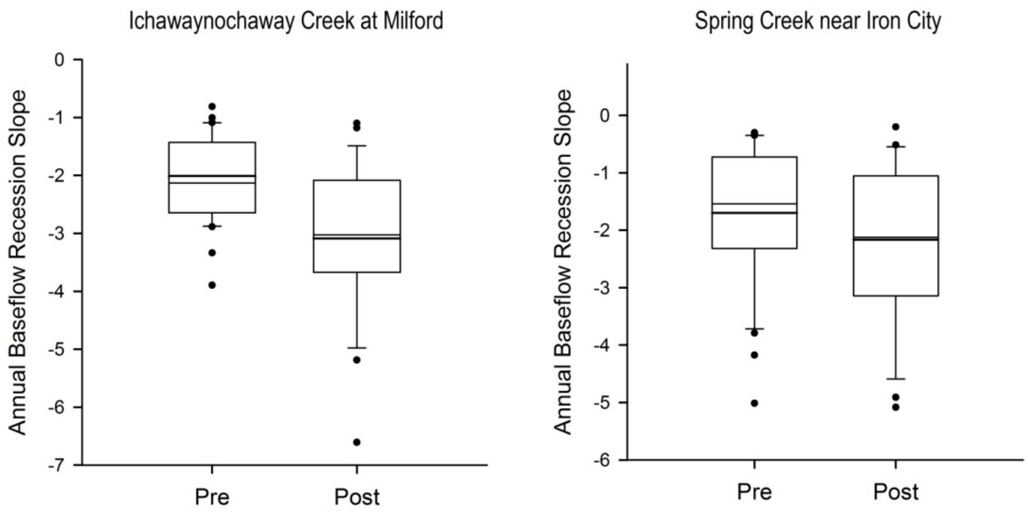

Figure 2.5. Analysis of annual recession baseflow slopes for Ichawaynochaway Creek and Spring Creek, GA.

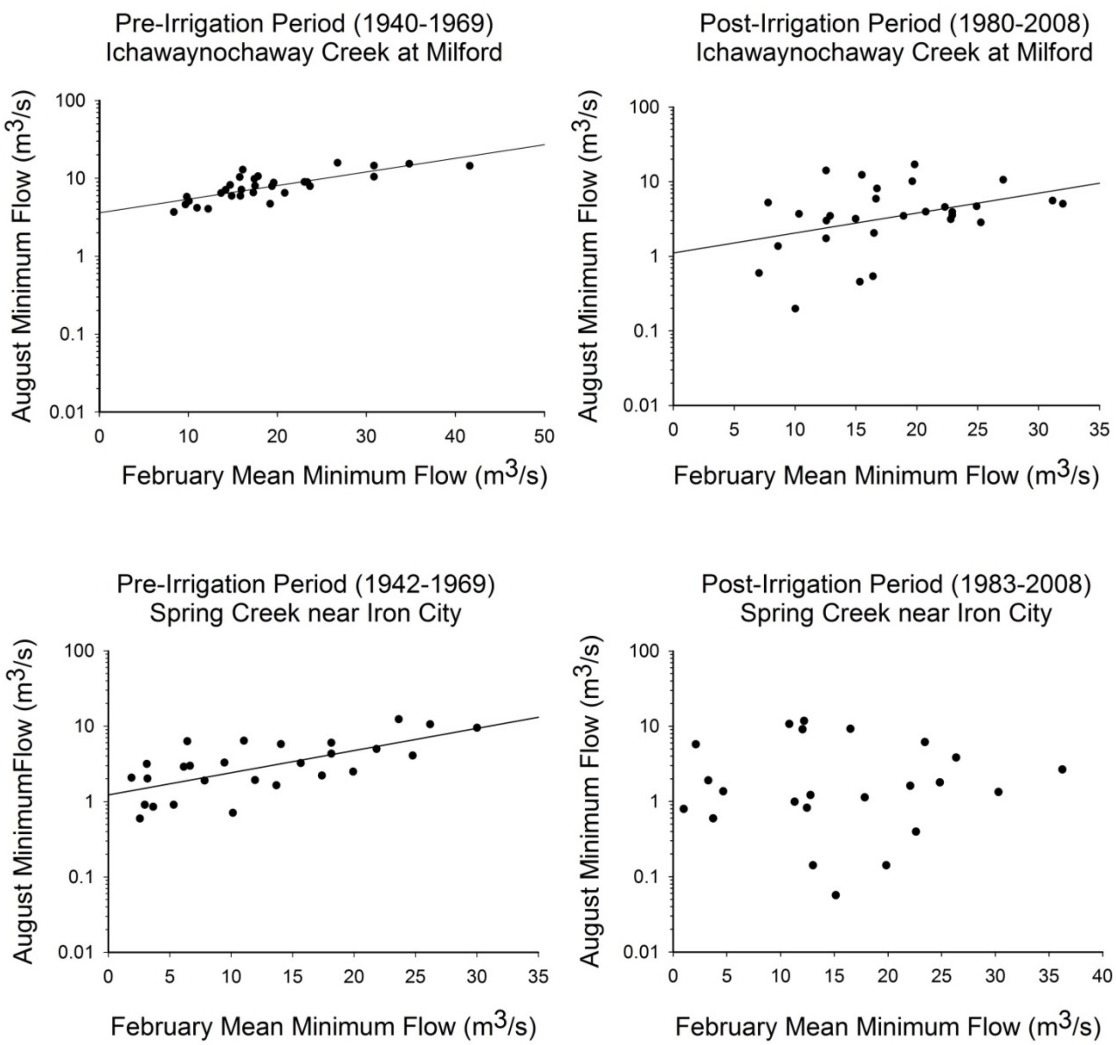

Figure 2.6. Relationship between winter–summer low flows during pre- and post-irrigation period for Ichawaynochaway Creek and Spring Creek, GA.

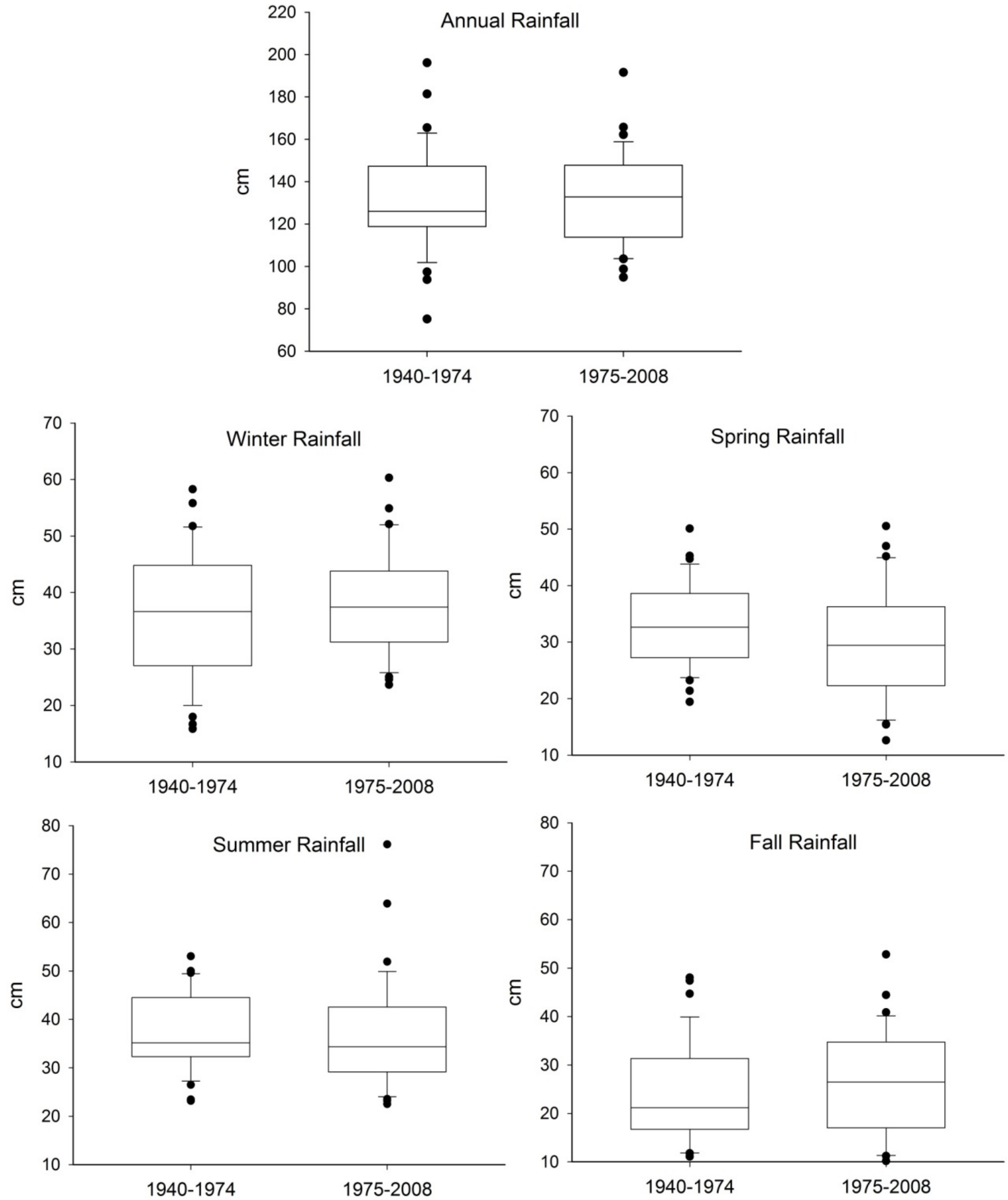

Figure 2.7. Annual and seasonal precipitation trends for lower Flint River Basin in southwest Georgia for period of record.

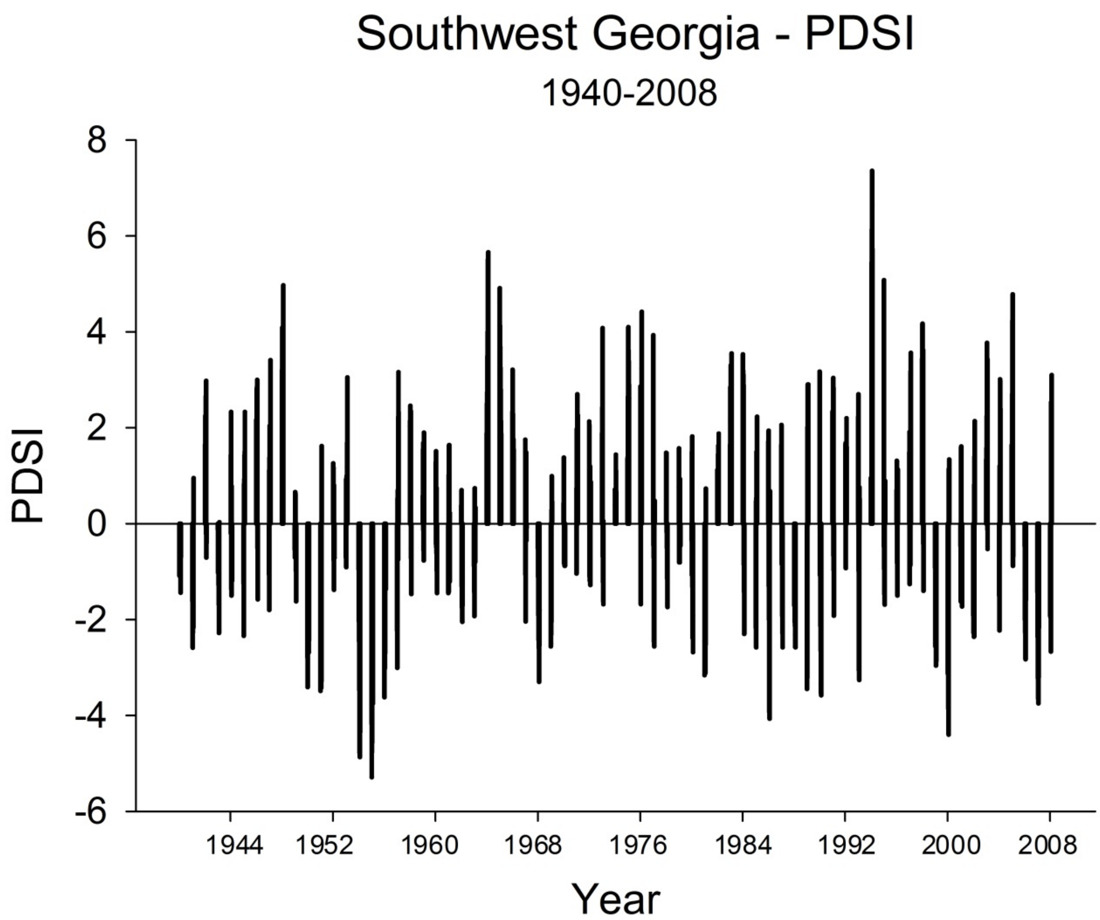

Figure 2.8. Palmer Hydrologic Drought Index time series for lower Flint River Basin in southwest Georgia for period of record.

CHAPTER 3

MULTI-SCALE ANALYSIS OF HYDROGEOCHEMICAL HETEROGENEITY WITHIN A GROUNDWATER-DEPENDENT STREAM: LOWER FLINT RIVER BASIN, SOUTHWESTERN GEORGIA, USA

Introduction

Groundwater resources are increasingly being developed to serve growing global need for freshwater (Shah et al., 2000). Intensive groundwater removal has been shown to affect regional water tables and hydraulic gradients, resulting in escalating costs to communities which must contend with land subsidence, intrusion of saline aquifers, well failures, and reduced assimilative capacity of remaining surface waters (Costanza et al., 1998; Glennon, 2002, Jones and Torak, 2006). Groundwater comprises the major component of stream baseflow between precipitations events (Freeze and Cherry, 1979) and decreased flows due to groundwater withdrawal can alter surface water temperatures, lower dissolved oxygen levels, concentrate nutrients and reduce in-stream habitat complexity, negatively impacting stream, riparian and upland biota (Bunn and Arthington, 2002; Golladay et al., 2004; Light et al., 2005; Zektser et al., 2005).

Global population increases, along with the uncertain effects of climate change, are expected to intensify pressures on limited freshwater resources. Burgeoning population trajectories for the southeastern United States project an increasing need for freshwater to support growing urban, industrial and agricultural demands. The Apalachicola-Chattahoochee-Flint (ACF) River basin is a 50,000 km^2 watershed originating in northern Georgia, occupying large portions of southwestern Georgia, parts of southeastern

Alabama, and the Florida panhandle, and terminating in the Gulf of Mexico at Apalachicola Bay. The upper ACF supports growing urban populations while water demands in the lower basin include agricultural irrigation, recreation, power generation and oyster and shrimping industries. In 2006, low flows, exceptional droughts and declining mussel populations prompted the US Fish and Wildlife Service to designate 1,863 river kilometers in the ACF as Critical Habitat in order to protect federally-listed mussels in this basin. Federal, state and regional management groups are currently developing Habitat Conservation Plans in addition to assessing the economic impact of this designation on 45 counties across Alabama, Florida and Georgia. Decades of litigation brought against Georgia by Alabama and Florida have failed to resolve conflicts over the allocation of waters within the ACF (Ruhl, 2005) and current negotiations between stakeholders, water councils and regulators have identified a lack of technical information to aid in water planning efforts in this region.

The Lower Flint River Basin (LFRB) is an economically important agricultural sector in southwestern Georgia within the larger ACF. Intensive row-crop farming in the LFRB generates 34% of local revenues (McKissick, 2004) and is supported by irrigation using groundwater from the Upper Floridan Aquifer (UFA) as well as withdrawals directly from surface waters. The UFA is a highly productive carbonate aquifer that extends under most of the Coastal Plain of the southeastern US, including portions of South Carolina, Georgia, Alabama, Louisiana, and all of Florida (Miller, 1986). Moderate karstic development of limestone formations has resulted in high secondary permeability which allows for intensive groundwater development of this highly transmissive system (Hicks et al., 1987). Between 1970 and 2000, irrigated acreage increased more than ten-fold from 59,000 to 607,000 hectares in the LFRB accounting for over half of statewide totals (Torak and Painter, 2006). Current regulations permit the removal of billions of cubic meters of water per day from the Upper Floridan as well as regional tributaries (Hook et al., 2005; Couch and McDowell, 2006). Flow duration analyses on USGS stream gage records in the LFRB showed that some streams have lost as much as 9.8×10^4 m^3d^{-1} in baseflow since pumping intensified in the last thirty years. Baseflow recession analyses during this same period showed that the highest rates of baseflow removal corresponded with periods of heaviest groundwater pumping (Rugel et al., 2012).

The Ichawaynochaway basin lies within the LFRB (Figure 3.1) and has one of the highest levels of combined groundwater and surface water removal in the state (Couch and McDowell, 2006). While this tributary is hydrologically connected to the underlying UFA, the nature of these connections and their influences on basin hydrogeochemistry and regional water budgets have not been examined. Karst systems develop complex solution paths dependent upon deposition origin, tectonic history, overlying residuum and regional precipitation. Interactions between hydrologically-connected components in these basins can be challenging to delineate, however a greater understanding of these interactions is vital to water resource planning and the protection of both surface water and groundwater systems. The objective of this study was to identify the location and extent of groundwater surface water exchange between Ichawaynochaway Creek and the Upper Floridan Aquifer and to assess the degree to which these connections affect water quantity and quality within the Ichawaynochaway basin. Movement of water in karstic systems can organize preferentially along fracture traces and conduits, dependent upon changing hydraulic gradients (Freeze and Cherry, 1979). Therefore, we hypothesized that groundwater/surface water exchange between the UFA and Ichawaynochaway Creek would exhibit both spatial and temporal heterogeneity dependent on fracture development and in response to regional hydraulic gradients created by natural and anthropogenic stressors within the basin. In order to test this hypothesis we implemented a multi-parameter approach across annual cycles to delineate the relative contribution and quality of source waters to surface waters within the Ichawaynochaway Creek basin.

Methods and Materials

Description of study site

All samples were collected within the Ichawaynochaway basin of the Lower Flint River Basin located in the Coastal Plain province of southwestern Georgia, USA. The Ichawaynochaway drainage basin (USGS HUC 8 hydrologic region 03130009) consists of approximately 2874 km^2 within Baker, Calhoun, Clay, Dougherty, Early, Miller, Randolph, Stewart, Terrell, and Webster counties. Most samples for this study were collected within Baker County with a small number in Calhoun County. All stream sampling was conducted on Ichawaynochaway Creek, a 5^{th} order tributary of the lower Flint River, which emerges from seeps and springs draining the Fall Line Hills along the northwestern boundary of the Dougherty Plain District and flows until it joins the Flint River at the southern tip of Baker County, Georgia.

Geohydrology in this region consists mainly of middle to late Eocene and early to middle Miocene sediments with an overlying mantle of undifferentiated Oligocene and Quaternary sediments (Hicks et al., 1987). The Ocala Limestone is a fossiliferous formation that makes up the main water bearing unit of the Upper Floridan Aquifer. Karstification in this limestone formation has resulted in high secondary permeability and transmissivity rates of 1.0 x 10^2 to 1.2 x 10^5 m^2/d in this aquifer which currently support extensive municipal, industrial, rural and agricultural water withdrawals (Hayes et al., 1983; Johnston and Bush, 1988; Couch and McDowell, 2006). The UFA is underlain by the mostly impervious Lisbon Formation (Claiborne Group), Clayton and Providence aquifers. These aquifers, updip and pinch out as they approach the Fall Line Hills in the northwestern portion of the Dougherty Plain and thicken downdip in a southeasterly direction towards the Gulf of Mexico. Thickness of the UFA in the study area is approximately 10-50 meters (Hicks et al., 1987). The aquifer may be unconfined, semi-confined or confined within the study area depending upon overlying residuum, regional solution features and changing hydraulic gradients (Warner, 1997).

Ichawaynochaway Creek and other tributaries of the LFRB are hydrologically connected to the UFA through springs, fractures, conduits, and streambeds. Aquifer recharge occurs mainly during winter when evapotranspiration and groundwater rates pumping are low. Annual precipitation in the Ichawaynochaway basin is 1320 mm of which approximately 790 mm are removed by evaporative processes (Lawrimore and Peterson, 2000). Land use is dominated (~50%) by row-crop farming of wheat, corn, cotton and peanuts supported by intensive agricultural irrigation (from around April to September). Remaining acreage is a mixture of deciduous hardwood and longleaf pine/wiregrass forest, isolated marshes and cypress-gum wetlands. Average regional slope within the Ichawaynochaway basin is 2.4 m/km.

End member sampling 2009-2011

We collected samples from three end members [precipitation, deep groundwater (wells) and the shallow aquifer] between October 2009 and August 2011 in order to determine the physiochemical composition of source waters within the Ichawaynochaway basin. Six rainfall samples were collected in 2009, followed by five in 2010, using an acid-washed 5x8 inch Pyrex glass pan placed 20 inches above the ground in an open area (no canopy within 20 m) proximate to the Joseph W. Jones Ecological Research Center (JERC) laboratory facilities in Baker County, Georgia. Precipitation was collected for approximately 2 hours during each rainfall event and transferred to 20 ml glass scintillation bottles for cation analysis. To measure $\delta^{18}O/\ \delta^{16}O$ and $\delta D/H$, two glass scintillation vials were filled to capacity, capped with nipple caps to remove all air and sealed with tape to prevent atmospheric contamination (Kendall and Caldwell, 1998). Samples for cation analysis were filtered through ashed 0.45µm Millipore glass filters and frozen until analysis. Navigational coordinates were taken at the precipitation collection site with a Garmin Oregon 550 hand-held GPS unit and atmospheric conditions including temperature, relative humidity, wind speed and direction were recorded for each rain event.

Groundwater samples were collected from 13 wells throughout the Ichawaynochaway basin between October and November of 2009. All wells were cased approximately 40-100 m deep and located within 2 km of either side of Ichawaynochaway Creek from Morgan, Georgia, in the upper portion of the basin, to within 2 km of the confluence of Ichawaynochaway and the Flint River (lower Baker County). Samples were taken directly from wellheads or spigots (purged for ~10 minutes to insure a representative sampling from the aquifer) and prepared as above. Navigational coordinates were collected at each wellhead. All wells were resampled in August 2011 using similar methods (2011 isotopic samples collected in 2 mL GC glass vials).

One shallow aquifer was sampled within the Ichawaynochaway basin in August 2011 to determine the extent of interaction with and physiochemical differences between the UFA and surficial groundwater in the study area. This shallow aquifer was located in the lower portion of the Ichawaynochaway sub-basin on JERC property (water level ~3 m below land surface) and represented the only surficial groundwater within range which was developed with a well for sampling. The monitoring well was purged for 10 minutes using a peristaltic pump and water was collected and prepared for all analyses as above.

Coarse scale longitudinal runs (LR) 2010

In 2010 a series of coarse longitudinal runs (LRs) were conducted on Ichawaynochaway Creek to assess large scale interactions between the Upper Floridan Aquifer and this tributary. A 50 km reach of the stream was sampled three times at baseflow between June and November 2010 commencing at the downstream confluence of Ichawaynochaway Creek and the Flint River and continuing upstream to within 7 km of the confluence of the Pachitla Creek tributary. All collections were done mid-channel at 6/10 depth at 1 km sampling intervals. Depth, pH, temperature and specific conductivity were measured during each LR using a Hydrolab Quanta®. Whole water samples were collected through Teflon® tubing with a Little Giant® Pony Pump (purged for ~30 seconds between samples) into 200 ml acid-washed Nalgene® polycarbonate bottles. Whole water samples for cation analysis were transferred into 20 ml glass scintillation vials, kept on ice, and returned to the lab within 6 hours, filtered and frozen. Stable isotope samples were collected and navigational coordinates were taken at each sampling site during each LR run. Attempts were made to replicate the position of previous sampling sites during subsequent runs; however, stream discharge and navigability determined the exact location of collection points for each collection. Minor differences in waypoint navigation did not represent a significant offset at 1 km scales.

Fine scale short runs (SR) 2011

Four 3 km reaches within Ichawaynochaway Creek were selected for resampling in 2011 in order to examine groundwater-stream interaction in these reaches at finer scales. Each 3 km SR site included a (central) kilometer where significantly greater delta (Δ) specific conductivity had been detected during 2010 LR sampling runs (> 2 μS/cm/km; *see* Results) as well as one kilometer on either side (upstream and downstream) where little or no changes had been observed (< 2 μS/cm/km). Sampling and analysis protocols followed those used in 2010 LRs, with the exception of scale and frequency. Each SR site was sampled at 200 meter intervals, two times under baseflow conditions during 2011 (SR1 and SR2 collections, respectively). Order of the four SR sites from upstream to downstream was: Milford (M), Elmodel (E), Turkey Woods (TW) and the Confluence (C). Sampling was implemented on the three upstream SR sites in May 2011 (M1, E1 and TW1) and repeated again in June (M2, E2 and TW2). Collections at the Confluence site were conducted later in the season (C1 and C2; September and November 2011, respectively). [Note: Since Milford, Elmodel and Turkey Woods sites were sampled under similar seasonal and discharge conditions, these data were analyzed collectively for some tests. The Confluence site, sampled later in the year under different conditions, was usually analyzed and reported separately; Figure 3.2].

Depressional wetlands

Two depressional wetlands were sampled in May 2008 order to assess the degree of hydrological connectivity between deep groundwater and solution features within the

Ichawaynochaway basin. Pond 68 and Pond 51, located on JERC property, were sampled using a long-handled scoop to collect whole water and isotopic samples, which were prepared for analyses as above. Navigational coordinates were recorded at both wetland sites. Exceptional drought conditions prevailed during most of the study period which prevented filling of wetlands and retesting during 2009 and 2010, however, Pond 51 was resampled in August 2011.

Baseflow analysis

Relative calcium concentration was used as an estimate of the contribution of groundwater from the Upper Floridan Aquifer to stream baseflow in Ichawaynochaway Creek during this study. The following equation (adapted from Kincaid, 1998) was used to calculate baseflow (this equation assumes minimal contribution of shallow groundwater to streamflow):

$$\% X = [(Rs - Rp) / (Raq - Rp)] * 100 \qquad (3.1)$$

where:

X = decimal fraction of groundwater in stream sample

Rs= [Ca^{2+}] in stream sample

Rp= [Ca^{2+}] in precipitation

Raq= [Ca^{2+}] in aquifer (groundwater)

Sample analysis

Increased residence time in and exposure to the underlying aquifer facilitates chemical transformations of (precipitation or stream) water traversing the carbonate system, resulting in elevated levels of calcium ions (Driscoll, 1986); therefore, end member and stream samples were analyzed for calcium concentration in order to determine the extent of interaction of samples with the groundwater system (Katz et al., 1997). Values for ^{18}O and D values were determined on 2009-2010 samples to verify reaction paths and relative exposure to the aquifer and strontium concentrations were determined on 2011 end member and surface water samples to confirm interaction of samples with deep vs. shallow groundwater systems.

Whole water samples were analyzed for calcium at the JERC using flame atomic absorption spectroscopy with addition of a lanthanum/hydrochloric acid mixture to increase sensitivity (3500-Ca B. Atomic Absorption Spectrometric Method). These analyses were performed on a Perkin Elmer 5100 (in 2010) and a Perkin Elmer AAnalyst 400 (in 2011). Strontium was analyzed at the University of Georgia (UGA) Laboratory for Environmental Analysis in Athens, Georgia, using a standard mode intermittently coupled plasma - mass spectrometer (ICP-MS) on a PerkinElmer Elan 9000. Stable isotope values ($\delta^{18}O$ and δD) were evaluated by the UGA Center for Applied Isotope Studies (CAIS) in Athens, GA, using gas chromatography (GC) methods to measure stable krypton gas in water. Isotopic values were reported in parts per thousand (reference standard, Vienna Standard Mean Ocean Water (V-SMOV); Coplen, 1996):

$$\delta_{sample}\ ({}^{0}/_{00}) = (R_{sample} - R_{standard}) / R_{standard}) * 1000 \qquad (3.2)$$

where:

δ_{sample} = isotopic ratio of sample (${}^{0}/_{00}$)

R = $^{18}O/^{16}O$ or D/H abundance ratio

Strict quality controls were maintained throughout all analyses and included calibrations using instrument blanks and standards, verified at the beginning, end and every 10-15 samples, as well as duplicates and spikes at 20 sample intervals. Upgrades to equipment occurred periodically and additional funding opportunities allowed some samples to be analyzed for parameters (i.e., strontium) which were not available at the beginning of the study. A minor number of data points were lost due to unavoidable equipment failures. All statistical analyses were performed using SigmaPlot 11.0 (http://www.sigmaplot.com).

Results

End member characteristics

The physiochemical characteristics of precipitation, groundwater and the shallow aquifer sufficiently distinguished originating end members from one another as well as from surface waters collected throughout the study (Table 3.1, Figure 3.3). Mean calcium concentration in precipitation was 0.09 (±0.07) mg/L Ca^{2+} in 2009 and 0.22 (±0.29) mg/L Ca^{2+} in 2010. Groundwater samples contained 51.14 (±9.11) and 51.30 (±8.93) mg/L Ca^{2+} in 2009 and 2011, respectively, compared with a concentration of 0.17 mg/L Ca^{2+} in the shallow aquifer (2011). Mean strontium concentration in groundwater wells sampled in 2011 was 37.61 (±31.69) μg/L Sr^{2+} while shallow aquifer samples contained 3.46 (±0.47) μg/L Sr^{2+} during the same period.

Mean values for $\delta^{18}O$ in precipitation samples during 2009 were -5.42 (±2.16) $^{0}/_{00}$ increasing only slightly to -4.11(±0.60) $^{0}/_{00}$ during 2010, while mean δD values in concurrent years were -25.02 (±9.68) $^{0}/_{00}$ and -18.10 (±7.60) $^{0}/_{00}$, respectively (Table 3.2, Figure 3.4). Mean $\delta^{18}O$ and δD in groundwater samples showed little variation between 2009 and 2011, with -3.19 (±0.70) $^{0}/_{00}$ and -3.22 (±0.27) $^{0}/_{00}$ $\delta^{18}O$, and -19.52 (±2.11) $^{0}/_{00}$ and -18.58 (±1.51) $^{0}/_{00}$ δD, respectively. Shallow aquifer samples contained 1.62 $^{0}/_{00}$ $\delta^{18}O$ and -9.18 $^{0}/_{00}$ δD in 2011.

Coarse scale longitudinal runs

Water temperature and pH increased gradually throughout the day during all 2010 LR collections on Ichawaynochaway Creek. Water temperatures ranged between 16.53 ^{o}C to 30.04 ^{o}C while pH ranged from 7.18 to 7.98. Discharge measurements from USGS stream gage 02353265 at Morgan, Georgia (used as upstream reference throughout study), showed daily stream discharge during LR1 collections averaged ~3.5 m^3s (June-July 2010; Figure 3.5). During LR2 and LR3 collections, discharge averaged ~ 2.7 m^3s and 2.6 m^3s, respectively (early and mid-October 2010).

During each of the three LR sampling events calcium concentration of stream samples increased 11.85 (±0.19) mg/L Ca^{2+} along the 50 km reach regardless of discharge or collection period. Mean calcium concentration of samples collected throughout all LRs ranged from 2.92 mg/L Ca^{2+} (average upstream minimum) to 13.68 mg/L Ca^{2+} (average downstream maximum) with an average standard deviation of only ±0.33 mg/L Ca^{2+} across LRs. Specific conductivity was positively correlated with Ca^{2+} during all three sampling runs (mean r^2=0.94, Figure 3.6 and 3.7). Median increase in specific conductivity over the entire 50 km reach was 69 µS/cm and varied only 1.73 µS/cm between the three LR sampling runs. Differences between 1km sampling sites (Δ specific conductivity/km) for all LRs averaged 1.00 ±00 µS/cm/km (increasing in the downstream direction); however, significantly greater differences in specific conductivity (per kilometer) were detected at some sites (Figure 3.8). Increases in specific conductivity at these sites, compared to preceding kilometers, ranged from 2-15 µS/cm and were detected in the vicinity of sampling sites # 2, 4, 16, 30, and 44 (Figure 3.9). Areas showing the greatest changes were generally consistent throughout the three LR sampling runs, suggesting larger volumes of groundwater were entering the stream through these reaches.

Isotopic results showed that the greatest variability in ^{18}O and D occurred during LR1. Samples during this collection period ranged from -6.21$^{0}/_{00}$ to -1.53 $^{0}/_{00}$ for δ^{18}O and -24.50 $^{0}/_{00}$ to -11.23 $^{0}/_{00}$ for δD along the 50 km reach. LR2 samples showed less isotopic variation, ranging from -4.64$^{0}/_{00}$ to -3.27 $^{0}/_{00}$ for δ^{18}O, and -32.65 $^{0}/_{00}$ to -27.21 $^{0}/_{00}$ for δD. LR3 samples contained -5.07 $^{0}/_{00}$ to -2.71$^{0}/_{00}$ δ^{18}O and -24.46 $^{0}/_{00}$ to -16.41$^{0}/_{00}$ δD (Figure 3.10). No longitudinal (upstream/downstream) trend was apparent for either isotope during the LR collections.

Fine scale short runs

Ranges and means of physiochemical parameters sampled during 2011 SRs are presented in Table 3.1. During both SR1 and SR2 collections (Figure 3.11), differences in specific conductivity (Δ specific conductivity) at 200 meter sampling intervals indicated fewer net gains in groundwater to the two downstream SR sampling sites (Turkey Woods and Confluence) and greater losses of groundwater discharge in the upstream reaches (Milford and Elmodel). Mean upstream discharge at the Morgan gage during the SR1 collection periods (M1, E1 and TW1) was ~1.07 m^3s and dropped to ~0.04 m^3s during SR2 collections (M2, E2 and TW2). Calcium remained positively correlated with specific conductivity at the three most upstream SR sites during both SR1 and SR2 collections. Calcium explained 71% of the variation in specific conductivity when M1, E1 and TW1 (SR1) data were analyzed together longitudinally ($p=<0.001$, $df=47$) and 68% of the variation during SR2 runs ($p=<0.001$, $df=47$; M2, E2 and TW2 data compiled longitudinally). Specific conductivity increased going downstream during the first 2011

SR1 collection; however, during SR2 sampling, the highest specific conductivities calcium concentrations, were detected in the most upstream reach (Milford) and decreased in a downstream direction (Figure 3.12). During C1 and C2 sampling at the Confluence, this trend reversed again, as calcium and specific conductivity both increased going downstream, similar to 2010 LR trends. Calcium was significantly related to specific conductivity during C1 sampling when discharge increased at the Morgan gage to 1.61 m^3s (r^2=0.51, p=0.002, df=15) and remained positively correlated during C2 sampling (r^2=0.62, p=<0.001, df=15, ~3.48 m^3s at Morgan). Strontium concentrations were also highest upstream, decreasing downstream during both SR1 and SR2 collections (Figure 3.13). Strontium explained 57% of the variation in specific conductivity when M1, E1 and TW1 data were analyzed together longitudinally (p=<0.001, df=47) and 52% of the variation during SR2 runs (p=<0.001, df=47; M2, E2 and TW2). Strontium was significantly related to specific conductivity during C1 (r^2=0.59, p=<0.001, df=15), and weakly correlated during C2 (r^2=0.39, p=<0.001, df=15).

Calcium was weakly related (negatively) to strontium during SR1 sampling (r^2=0.21, p=0.001, df=47; M1, E1 and TW1; ~1.07 m^3s at Morgan) but positively related during SR2 at lower discharge (r^2=0.64, p=<0.001, df=47; M2, E2, TW2, ~0.04 m^3s at Morgan; Figure 3.14). Strontium and calcium ratios in SR1 samples were 0.7:1, 0.5:1, and 0.5:1 Sr:Ca during M1, E1 and TW1, respectively, while SR2 samples had slightly lower ratios of 0.4:1, 0.5:1, and 0.3:1 (M2, E2 and TW2, respectively), all of which exceeded mean Sr:Ca ratios in groundwater (UFA) samples collected during 2011 (0.3:1). High levels of strontium were also detected in two wells during 2011 compared with other groundwater samples [Bass well (Sr:Ca 0.8:1), located on the JERC property, and Webb well (1:1) near Morgan, GA, in NW Baker County] (Figure 3.15). Ratios in stream samples remained elevated at the Confluence during late summer and fall sampling (0.6:1 and 0.7:1, for C1 and C2, respectively).

Depressional wetlands

Depressional wetlands had low calcium levels and enriched stable isotopic signatures during both sampling years. In 2008 Pond 68 contained 5.03 mg/L Ca^{2+} and $\delta^{18}O$ and δD values were 5.90 $^{0}/_{00}$ and 22.90 $^{0}/_{00}$, respectively. Pond 51 had 2.63 mg/L Ca^{2+} with 7.20 $^{0}/_{00}$ and 10.00 $^{0}/_{00}$ for $\delta^{18}O$ and δD, respectively. Retesting of Pond 51 in 2011 showed 1.25 mg/L Ca^{2+}, 1.4 $^{0}/_{00}$ $\delta^{18}O$ and 2.69 $^{0}/_{00}$ δD.

Baseflow analysis

Comparison of calcium concentration in end members and stream samples indicated substantial contributions of groundwater to discharge of Ichawaynochaway Creek during the 2010 and 2011 collection periods. Longitudinal runs (LRs) in 2010 showed groundwater contributions ranged from 5-29 % (5-28% during LR1, 8-29% during LR2 and 9-29% during LR3). During SR1 in 2011, contributions made up 29-45% of stream flows at Milford, Elmodel and Turkey Woods sites (upstream/summer) and 34-38% at the Confluence site (downstream/early fall). As discharge declined during SR2 sampling, baseflow contributions accounted for 41-72% of streamflow at Milford, Elmodel and Turkey Woods sites and 27-28% at the Confluence site (downstream/late fall).

Discussion

End member and stream physiochemistry 2009-2011

Our results supported the prediction that hydrological interactions between Ichawaynochaway Creek and the Upper Floridan aquifer would exhibit spatio-temporal heterogeneity within the basin. All LR stream samples contained high dissolved calcium compared to precipitation, implying significant groundwater/surface water interaction and substantial baseflow contributions to Ichawaynochaway Creek from the UFA. Calcium values for end member and stream samples showed that 5-29% of streamflow was generated from groundwater during the 2010 sampling period, increasing to 29-72% during 2011 sampling, as flows declined precipitously and groundwater became more concentrated in the stream. Previous hydrograph separation (HYSEP) analyses performed on USGS stream discharge data in the LFRB estimated 30-50% baseflow contributions from groundwater in this region under 1999-2000 drought conditions (Mosner, 2002).

During all 2010 LR collections, both calcium and specific conductivity increased in a downstream direction, indicating incoming groundwater from the UFA; however, these changes occurred in a stepwise fashion with specific reaches showing significantly greater gains. During LR1, LR2 and LR3, from 30-42% of the gains in specific conductivity (Δ µS/cm/km) across the entire sampling reach were explained by changes occurring within the vicinity of only 10% (5 out of fifty) of the sampling reaches, suggesting that significantly greater inputs of groundwater were entering the stream at these sites. Gaining conditions prevailed at these reaches during the 2010 sampling period when the potentiometric surface of the UFA was higher in the sampling region compared to 2011 levels (http://ga.water.usgs.gov/infodata/groundwater.html). Small scale (SR) collections were conducted in 2011 when stream discharge was exceptionally low (Morgan gage ~ 0 m^3s), concurrent with intensive groundwater and surface water pumping as well as exceptional drought. Changes in specific conductivity at that time reflected fewer gains and increased losses in some reaches where preferential groundwater inflows had previously been detected. Specific conductivity values during the SR collections indicated that the Milford site received less groundwater (particularly during SR2 sampling) while calcium results suggested that baseflow was becoming increasingly concentrated in the stream. Previous studies reported that this portion of Ichawaynochaway Creek became a losing reach (dropping from 5.97 to 0 m^3s between Morgan and Milford gages) during the 1999-2000 drought (Mosner, 2002).

While calcium concentrations increased in a downstream direction during all 2010 LR collections, these trends were not reproduced during 2011 SR sampling. Instead, both calcium and strontium were significantly elevated in upstream reaches and gradually attenuated downstream. Ratios of strontium to calcium in all 2011 SR stream samples were three times higher than those found in groundwater samples collected from this region during the same period. In general, stream ratios would be expected to be dilute compared to groundwater; however, the average ratio for UFA groundwater during the 2011 sampling period was ~0.3:1 while stream samples had ratios up to three times higher (0.3:1 to 0.9:1). The groundwater well with the highest Sr:Ca ratio (1:1) was located in the uppermost portion of the study site near Morgan, GA (Webb well). This well was cased approximately 90 meters deep (by landowner estimate) in a portion of the basin where the UFA pinches out and may only be a few meters thick. Deeper aquifers, such as the Claiborne (Tallahatta Formation), underlie the UFA and are approximately 3-80 meters thick in this region (Clarke et. al., 1984). These water-bearing units have lower transmissivity rates compared to the UFA and contain groundwater which has become highly mineralized. Strontium is known to preferentially replace by calcium, barium and/or sodium in slow moving waters resulting in greater dissolved strontium and higher

Sr:Ca ratios (Odum, 1951). Wells accessing the Claiborne between 1977 and 2008 had average Sr:Ca ratios of ~4:1 (http://nwis.waterdata.usgs.gov/ga/nwis/qwdata/). It is plausible that this aquifer may have contributed to higher Sr:Ca ratios observed in the stream during 2011 SR collections and could also explain some of the higher calcium values and specific conductivity increases observed in the upper portion of the stream during SR2 sampling. Possible mechanisms for hydraulic interaction between these formations could include encroachment from deeper aquifers as pressure was lowered on the UFA during heavy extraction of groundwater, and/or well leakage (Clarke et al., 1984). Previous studies have associated intensive pumping in the LFRB with the vertical leakage of semi-confining units as well as capture of groundwater discharge which would normally be delivered to downdip basins (Torak and Painter, 2006).

Isotope results helped to delineate the relative degree of interaction between end members and surface waters throughout the basin and provided further confirmation of groundwater-surface water interaction in this tributary. The slope of the relationship between $\delta^{18}O$ and δD in precipitation samples during the study was comparable to the Local Meteoric Water Line (LMWL) for river waters reported for this region (Kendall and Coplen, 2001; Table 2, Figure 3.4). Local meteoric water lines, which represent the relationship between $\delta^{18}O$ and δD for waters within a given region, can be generated for precipitation as well as groundwater and streams. The range of isotopic values in precipitation samples collected during the current study fell mostly along the LMWL for Georgia. Variations in $\delta^{18}O$ vs. δD values may be attributed to storm source, season and/or rainout, which collectively impact relative humidity, temperature, evaporation and enrichment or depletion in precipitation (Ingraham, 1998). Rainout is a phenomenon which occurs when lighter isotopes of oxygen and hydrogen (^{16}O and H) remain in vapor phase within storm clouds while more enriched precipitation, containing heavier isotopes (resulting in more positive δ values for ^{18}O and D), preferentially falls as condensation. As storms proceed, the reservoir of heavier isotopes remaining within the vapor cloud becomes less concentrated and subsequent precipitation downwind becomes progressively depleted in ^{18}O and D (resulting in more negative δ values and contributing to a wide range of isotopic signatures during storms of long duration).

Isotopic values in groundwater collected in 2009 and 2011 showed some slight enrichment in ^{18}O relative to ^{16}O and extremely low slopes when $\delta^{18}O$ was compared to δD (Table 3.2). Groundwater generally retains the isotopic signature of the originating waters (precipitation or stream) which compose its recharge, including the signal of effects from temperature during condensation, as well as subsequent evaporation processes which may occur during throughfall, ponding, and soil infiltration (Dawson and Ehleringer, 1998). Groundwater in karst systems can also undergo some geochemical fractionation within the carbonate system, affecting $\delta^{18}O$ values; however, more significant differences in these values are likely due to storm origin, rainout or post-rainfall evaporative effects (Gonfiantini et al., 1998; Kendall and Coplen, 2001).

Stream samples collected from Ichawaynochaway Creek during all 2010 LRs had $\delta^{18}O$ values which were comparable to the majority of precipitation samples collected during the study but displayed wider ranges in δD values. LR1 samples had the greatest isotopic variability for both ^{18}O and D when compared with subsequent LR runs (Figure 3.4). This may be attributed to inputs of heavy precipitation to the stream from a major storm which occurred during the middle of this collection period. The isotopic values of precipitation sampled throughout this 8 hr storm ranged from -6.98 $^{0}/_{00}$ to -3.50 $^{0}/_{00}$ for $\delta^{18}O$ and -35.16 $^{0}/_{00}$ to -24.50 $^{0}/_{00}$ for δD. Variability in LR1 samples may also have resulted from isotopically-enriched water entering Ichawaynochaway Creek as higher discharge reconnected tributaries and backwaters at this time. During the next collection, LR2 samples were only slightly enriched in $\delta^{18}O$ compared to precipitation; however, all samples were depleted in δD compared to the other LR runs, as well as end members, and plotted noticeably to the right of and below the LMWL for Georgia river waters (Figure 3.4). These data suggest that groundwater discharge at this time was discretely different in storm origin compared to baseflow that contributed to previous (LR1) or subsequent (LR3) runs. Isotope and calcium values implied that LR2 stream samples contained considerable amounts of groundwater which may have undergone post-rainfall evaporative effects prior to infiltration. During the final run, all LR3 samples plotted above and to the left of the LMWL (δD enriched). While these collections occurred within one week of LR2, their isotopic values indicated a distinctly different bolus of groundwater contributing to baseflow at that time. A determination of the exact source of this streamflow was outside the scope of the study; however, these data suggested that waters contributing to each LR were physiochemically heterogeneous and originated from dissimilar recharge which had been affected by unique local processes.

Samples from the shallow aquifer as well as the two depressional wetlands were highly enriched in both $\delta^{18}O$ and δD and had undoubtedly undergone considerable evaporation. Isotopic values, combined with extremely low levels of calcium, suggested that water in the surficial aquifer was more similar (almost identical) to the wetland to which it was adjacent (Pond 51) than to deeper groundwater within the basin. These results, as well as previous findings (Torak et al., 1996), supported our assumption that the surficial aquifer has little hydraulic connectivity with the underlying UFA in this region and did not contribute significantly to streamflow generation during the study.

Extreme low flows persisted throughout the summer of 2011 resulting in nearly intermittent stream conditions and stress on some aquatic populations in Ichawaynochaway Creek. Massive mussel and clam (*Corbicula*) mortality was noted at both Milford and Elmodel when discharge at the Morgan gage reported 0.4 m^3s. Thousands of stream bivalves were observed dying in shallow pools and putrefying stream conditions in the vicinity of these die-offs were intensified due to lack of flushing flows and inputs of fecal matter from opportunistic foragers. Large fish, including bass, bowfin, catfish and carp, were observed congregating in uncharacteristically large numbers in remaining deep pools within these upper reaches of the stream.

Sites of increased groundwater-surface water interaction

The distinguishing characteristics of reaches where significantly greater inputs of groundwater occurred were not consistent across all sites and groundwater-surface water exchanges in these locations were likely facilitated by a number of combined hydrogeological factors. Three out of five of these reaches (#4, #30, and #44) were directly downstream from connecting tributaries; however, only one of these streams, Chickasawhatchee Creek, was flowing during the 2010 and 2011 sampling period (determined by visual observation). Incoming water from Chickasawhatchee Creek exerted considerable influence on the stream chemistry of Ichawaynochaway Creek throughout the entire study. Samples collected directly below the Chickasawhatchee Creek confluence (around sampling site #30) showed changes of 15, 6 and 8µS/cm in

2010 sampling (LR1, LR2 and LR3, respectively) compared to the next upstream kilometer (sampling interval). Changes at this site accounted for 9-23% of the total change in specific conductivity for the entire 50 km reach during all three 50 runs. Even more significant changes were detected the following year, when specific conductivity increased 17µS/cm at this site during both SR1 and SR2 sampling (Elmodel site, Figure 3.11). Chickasawhatchee Creek drains the Chickasawhatchee Swamp, which is located in the upper northeastern portion of the Ichawaynochaway basin, in a region where upward hydrologic gradients and low-lying land surfaces facilitate the exchange of water between this swamp and the Upper Floridan Aquifer (Jones and Torak, 2006). While some of the increase in specific conductivity could be contributed to DOC enrichment from this swamp, the almost perfect correlation of specific conductivity to calcium in all LR samples suggested that most increases were accompanied by groundwater inputs entering via this tributary (Figure 3.6). A preliminary sampling of streams within the LFRB (performed at baseflow in 2007) revealed that the Little Spring Creek tributary within Chickasawhatchee Swamp had calcium concentrations of 80 mg/L Ca^{2+}, the highest of any stream tested in this basin during the 2007-2011sampling period (Rugel, unpublished data). Golladay and Battle (2002) also substantiated increased alkalinity levels which indicated greater groundwater inputs within this swamp.

In spite of the absence of surface flow, sites noted below dry tributaries may have maintained some hydrologic connection through wetted sediments and/or the bedrock matrix. Such flowpaths could deliver groundwater inputs to the main reach, possibly influencing changes in specific conductivity in streamflow below these sites. In contrast, Sites #2 and #16 were not in the direct path of tributary flow. Site #16 is located in a portion of the basin (Turkey Woods) noted for the presence of sinkholes in uplands adjacent to this reach. The development of sinkholes within the LFRB, as well as other karst basins, has been shown to follow fracturing trends which encourage dissolution of underlying carbonate formations (Freeze and Cherry, 1979; Brook and Sun, 1986, Hyatt and Jacobs 1996). Site #2 is located 2 km above the confluence of Ichawaynochaway Creek and the Flint River, where the stream has eroded overlying residuum and is deeply incised into the Ocala Limestone. During this study, a significant degree of systematic fracturing was observed within stream bedrock outcrops within this reach (also at Site #4) which may have facilitated groundwater-surface water interaction around these sites.

Hydraulic connectivity between the surface and sub-surface may also have been enhanced by multiple depressional landscape features which are found in lower portions of the Ichawaynochaway basin. These large, rhomboid-shaped depressions, which can be seen on DEMs for this region, occur alongside stream terraces of some of the lower reaches of Ichawaynochaway Creek, as well as the Flint River, near the confluence of these tributaries (Figure 3.16; enhanced with hillshade). While the geologic origins of these features were not fully investigated during this study, they may represent collapse and solutioning along existing tectonic templates (Melton, 1959; Koutepov et al., 2006) since their outlines roughly follow regional jointing trends (NW-SE and NE-SW). Vertical walls (as long as 2.9 km) flank the upland margins of these depressions dropping approximately 10 meters vertically onto relatively flat floodplains which run adjacent to the streambed. These depressions alternate and collate on either side of the stream and range in size from 1.63 to 5.5 km^2 (median area, 2.90 ±1.46 km^2. Density and intersections of lineaments such as these, which suggest underlying fracture traces, have been linked to increased groundwater productivity in regions where they occur (Brook and Sun, 1986; Jain, 1998; Dinger et al., 2002). It is likely that these geomorphological elements have influenced both past and present-day surface and underground drainage courses in this basin, and may explain some of the increases in groundwater entering the stream at Sites #2, 4, and 16.

Significance and future research

While modeling of stream-aquifer relations has been performed on portions of the larger Flint River and ACF basins (Torak et al., 1996, Jones and Torak, 2006), these studies offer little information on groundwater-surface water interaction at finer scales. The results of the current study showed that small scale interactions, which may be responding to discrete regional hydraulic gradients, can exert a profound cumulative impact on the movement of water between surface and sub-surface components and contribute substantially to basin-wide water budgets. The extent of these hydrologic exchanges results from the combined interaction of geologic setting and local anthropogenic and natural stressors, including pumping and drought.

The economic productivity of the LFRB is currently dependent upon intensive groundwater and surface water removal; however, diminishing and intermittent streamflows (in previously perennial streams), as well as threats to federally-listed species in this region, have resulted in the capping of water permits in the Ichawaynochaway and Spring Creek sub-basins (Couch and McDowell, 2006). The designation of Critical Habitat for this region may also result in further economic consequences for affected areas of Alabama, Georgia and Florida. In addition to increasing regional irrigation efficiency through conservation and equipment upgrades, propositioned solutions for mitigating declining streamflows in the LFRB include the use of aquifer storage and recovery (ASR). Testing wells are currently being proposed which will evaluate the efficacy of removing water from the UFA during periods of high groundwater potential, and storing it in an adjacent aquifer to be used to augment stream discharge during subsequent low flow periods. The current and prior analyses on groundwater-surface water interaction suggest such actions may or may not have the intended effect and could result in a further reduction of flows in some reaches, affecting both the quantity and quality of discharge (Zektser et al., 2005; Zume and Tarhule, 2008; Rugel et al., 2012).

In order for water use to be economically and environmentally sustainable in this and other basins, resource planning must be based upon an understanding of both large and fine scale exchanges between groundwater and surface water components. The methods utilized in this study were effective in establishing the general location and extent of some of the interactions occurring between the Upper Floridan Aquifer and surface waters in the Ichawaynochaway basin at various spatio-temporal scales. Future avenues of research can be launched upon these findings, including more detailed investigations of regional fracturing trends, lineaments, wetlands and other surface expressions which may be directing hydraulic connectivity in these basins. While DEMs were useful for identifying some lineament trends in this study, the acquisition of LiDAR for this region would greatly enhance detection capabilities of these features, which may otherwise be difficult to delineate. Determining the extent of active faulting as well as fracture density, intersection and the discrete locations of hydraulic connectivity could help to identify both the characteristics and specific location of groundwater surface water interaction in this region. Dahan and others (2001) demonstrated that flow through fractures in unsaturated chalk could be isolated to only 10% of the aperture along a single fracture and could increase flow in these locations by an order of magnitude. In addition to fracture density and junction, hydraulic differences were often associated with the quality of fill and remineralization along the fracture face. Combining current and future results with existing data sets for species of special regional concern, such as endangered and threatened unionids, may aid in determining potential locations for recruitment, translocation and protection of endangered species and their hosts. In addition, sampling over multiple annual cycles under differing seasonal and discharge conditions would provide vital information on the response of regional hydraulic gradients to localized stressors, both natural and anthropogenic. These data will be immediately useful in increasing our understanding of where pumping may or may not be in danger of capturing discharge in this and other basins of similar geologic origin.

Conclusion

Ichawaynochaway Creek received significant inputs from the Upper Floridan Aquifer through preferential flow paths along a 50 km reach in 2010. As much as 42% of total gains entered the stream through only 10% of the fifty reaches sampled during the three LR collections, with 9-23% of these contributions entering via the Chickasawhatchee Creek tributary. Based on comparisons of calcium concentrations in end members and stream samples, baseflow to Ichawaynochaway Creek was estimated to contribute to from 5-29% of stream discharge during 2010 sampling, increasing to as much as 72% during 2011 collections. Natural and human stressors during the 2011 sampling period resulted in nearly-intermittent stream conditions and hydrological discontinuities which threatened bivalve and fish populations in the upper reaches of the basin. Stream reaches from Elmodel to north of Milford showed the greatest losses compared to downstream reaches during this time. Agricultural water use constitutes over 70% of current global freshwater consumption (Postel, 1999). Future development of hydrologically-connected groundwater and surface water systems in this and other heavily allocated basins will require intelligent water resource planning and policies which budget for the spatio-temporal variations inherent within these watersheds and protect recharge areas which contribute substantially to water quantity and quality in these systems.

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Table 3.1. Physiochemical ranges and means for end members and surface waters (2008-2011) collected within Ichawaynochaway basin, southwestern GA, USA.

	Temp (°C) range (max-min)	pH range (max-min)	Depth at site (m) range (max-min)	Sp. Cond. (μS/cm) range (max-min)	Ca^{2+} (mg/L) range (max-min)	Sr^{2+} (μg/L) range (max-min)
Longitudinal runs (LR) 2010						
LR1 (n=51)	3.91 (30.04-26.13)	0.66 (7.84-7.18)	4.97 (5.17-0.20)	71.00 (155.00-83.00)	11.90 (14.50-2.60)	_
LR2 (n=51)	2.19 (20.22-18.03)	0.68 (7.98-7.30)	4.13 (4.25-0.12)	68.00 (122.00-54.00)	12.00 (14.90-2.90)	_
LR3 (n=51)	2.59 (19.12-16.53)	0.61 (7.92-7.31)	4.08 (4.33-0.25)	67.00 (122.00-55.00)	11.64 (14.90-3.26)	_
Short Runs (SR) 2011						
Milford 1 (M1) (n=16)	1.73 (21.45-19.72)	0.19 (7.98-7.79)	1.55 (1.75-0.20)	11.00 (142.00-131.00)	3.19 (17.87-14.67)	3.55 (25.99-22.44)
Elmodel 1 (E1) (n=16)	2.03 (26.35-24.32)	0.24 (8.10-7.86)	1.90 (2.00-0.10)	17.00 (180.00-163.00)	3.62 (21.10-17.48)	6.64 (25.19-18.55)
Turkey Woods 1 (TW1) (n=16)	1.59 (25.20-23.69)	0.64 (8.23-7.59)	2.70 (2.90-0.20)	3.00 (184.00-181.00)	5.65 (23.01-17.36)	5.05 (22.34-17.29)
Confluence 1 (C1) (n=16)	1.04 (25.08-24.04)	0.40 (7.95-7.55)	2.00 (2.33-0.33)	6.00 (125.00-119.00)	1.80 (19.47-17.67)	1.72 (23.53-21.82)
Milford 2 (M2) (n=16)	2.88 (28.18-25.30)	0.33 (7.96-7.63)	1.33 (1.50-0.17)	29.00 (267.00-238.00)	8.94 (36.66-27.72)	8.17 (30.23-22.06)
Elmodel 2 (E2) (n=16)	2.55 (29.04-26.49)	0.28 (8.10-7.86)	1.33 (1.50-0.17)	17.00 (230.00-213.00)	7.66 (28.69-21.03)	4.87 (25.53-20.67)
Turkey Woods 2 (TW2) (n=16)	2.88 (28.36-25.48)	0.30 (8.10-7.80)	2.25 (2.50-0.25)	11.00 (216.00-205.00)	4.14 (25.94-21.80)	5.00 (20.20-15.20)
Confluence 2 (C2) (n=16)	0.69 (16.57-15.88)	0.43 (7.70-7.27)	1.75 (2.00-0.25)	4.00 (109.00-105.00)	0.80 (14.53-13.73)	1.99 (23.21-21.22)
					Ca^{2+} (mg/L) mean (std.dev)	Sr^{2+} (μg/L) mean (std.dev)
Precipitation					0.09 (0.07)	
2009 (n=5)	-	-	-	-	0.22 (0.29)	-
2010 (n=6)						
Groundwater wells						
2009 (n=13)	-	-	-	-	51.14 (9.11)	-
2011 (n=13)					51.30 (8.93)	37.61 (31.69)
Shallow aquifer (n=1)	-	-	-	-	0.02	3.46
Depressional wetlands						
2008 (n=2)	_	_	_	_	5.03 (Pond 68) 2.63 (Pond 51)	_
2011 (n=1)					1.25 (Pond 51)	

Table 3.2. Isotopic comparisons of relative $^{18}O/^{16}O$ and D/H including slope/ y-intercept of local meteoric water line (LMWL) for surface waters and end members in Ichawaynochaway sub-basin (2008-2011).

	Collection dates	$\delta^{18}O$ (‰) range [max-min]	δD/H (‰) range [max-min]	Slope/y-intercept of LMWL
Longitudinal runs (LR)				
LR1 (n=51)	06/24/10-07/29/10	4.68 [-1.53 - (-6.21)]	13.27 [-11.23 - (-24.50)]	0.07/-16.51
LR2 (n=51)	10/07/10-10/13/10	1.36 [-3.27 - (-4.64)]	5.44 [-27.21 - (-32.65)]	-0.60/-32.51
LR3 (n=51)	10/18/10-10/22/10	2.36 [-2.71 - (-5.07)]	8.05 [-16.41 - (-24.46)]	-0.12/-21.09

	Collection dates	$\delta^{18}O$ (‰) mean (std.dev)	δD/H (‰) mean (std.dev)	Slope/y-intercept of LMWL
Precipitation				
2009 (n=5)	10/05/09-12/02/09	-4.11 (0.60)	-18.10 (7.60)	11.08/28.08
2010 (n=6)	06/30/10-07/12/10	-5.42 (2.16)	-25.02 (9.68)	5.72/4.37 (n=3)
Groundwater wells				
2009 (n=13)	10/09/09-12/01/09	-3.19 (0.70)	-19.52 (2.11)	-0.54/-21.67
2011 (n=13)	08/08/11-08/09/11	-3.22 (0.27)	-18.58 (1.51)	4.23/-4.95
Shallow aquifer (n=1)	08/10/11	1.62	-9.18	-
Depressional Wetlands				
2008 (n=2)	06/05/08 (Pond 68)	5.90	22.90	-
	06/06/08 (Pond 51)	7.20	10.00	-
2011 (n=1)	08/10/11(Pond 51)	1.44	2.69	-

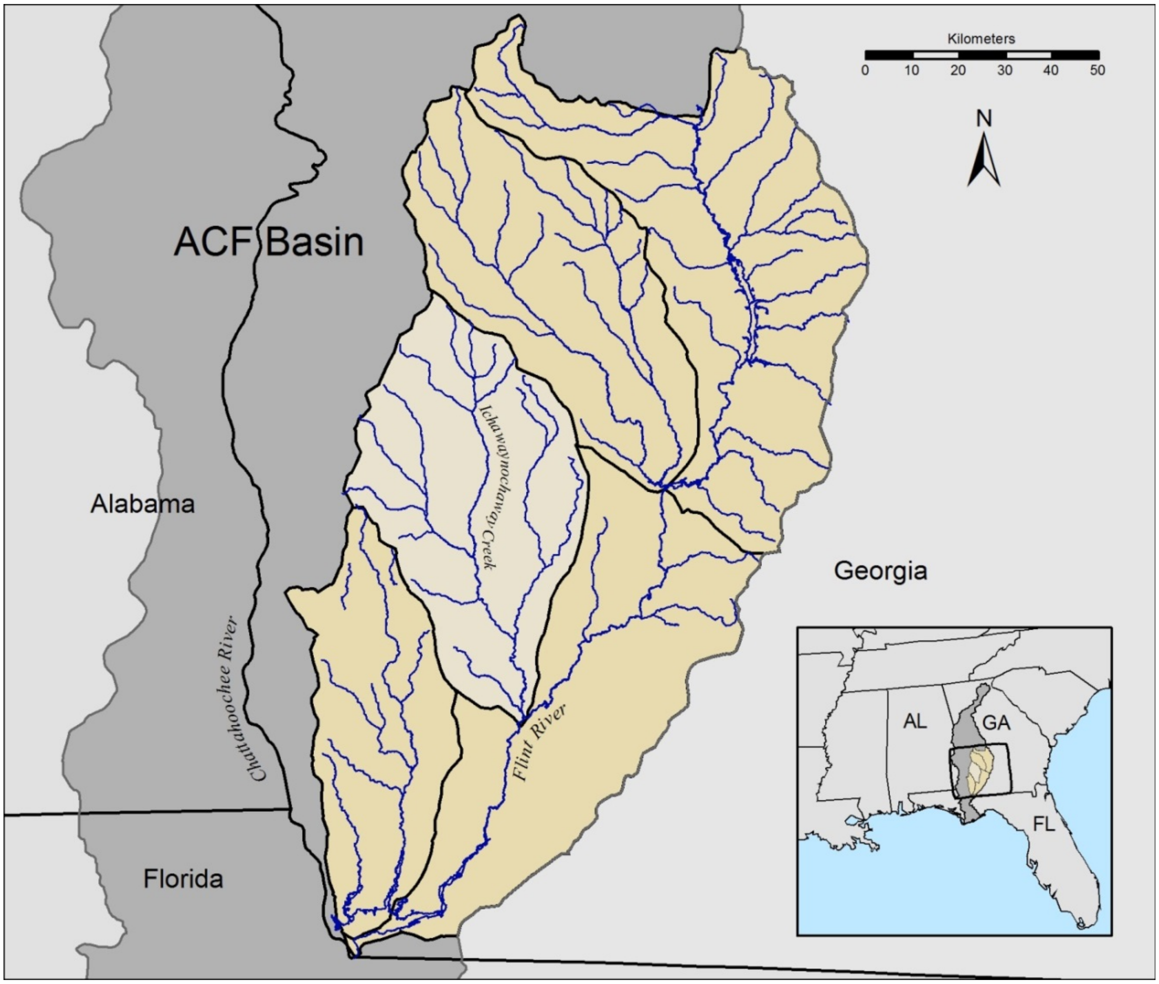

Figure 3.1. Map showing position of Ichawaynochaway sub-basin within the Lower Flint River Basin in southwestern Georgia, and the larger Apalachicola-Chattahoochee-Flint (ACF) River Basin¸ southeastern USA.

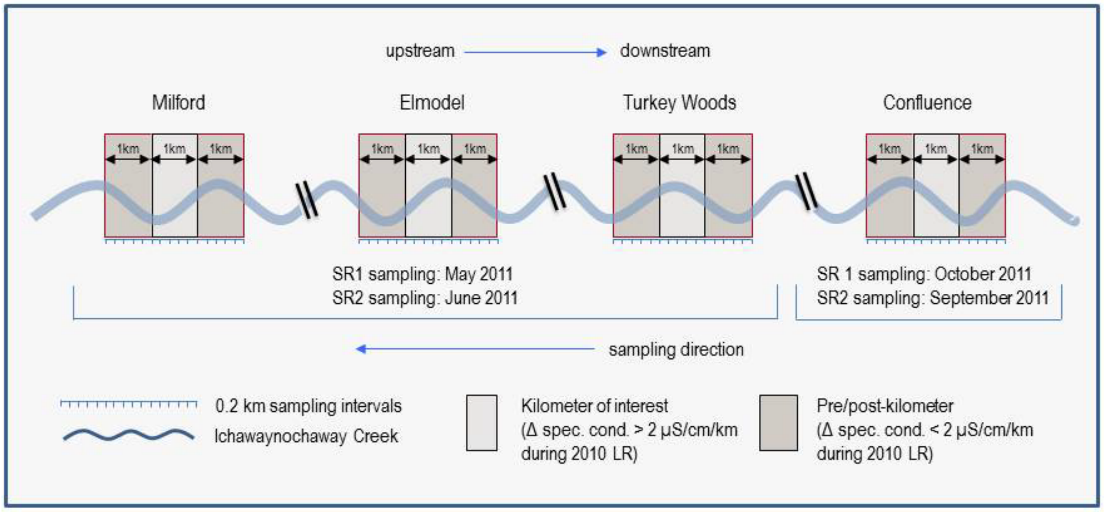

Figure 3.2. Experimental study design for fine scale sampling of short runs (2011 SRs) on Ichawaynochaway Creek at 200 meter (0.2 km) intervals.

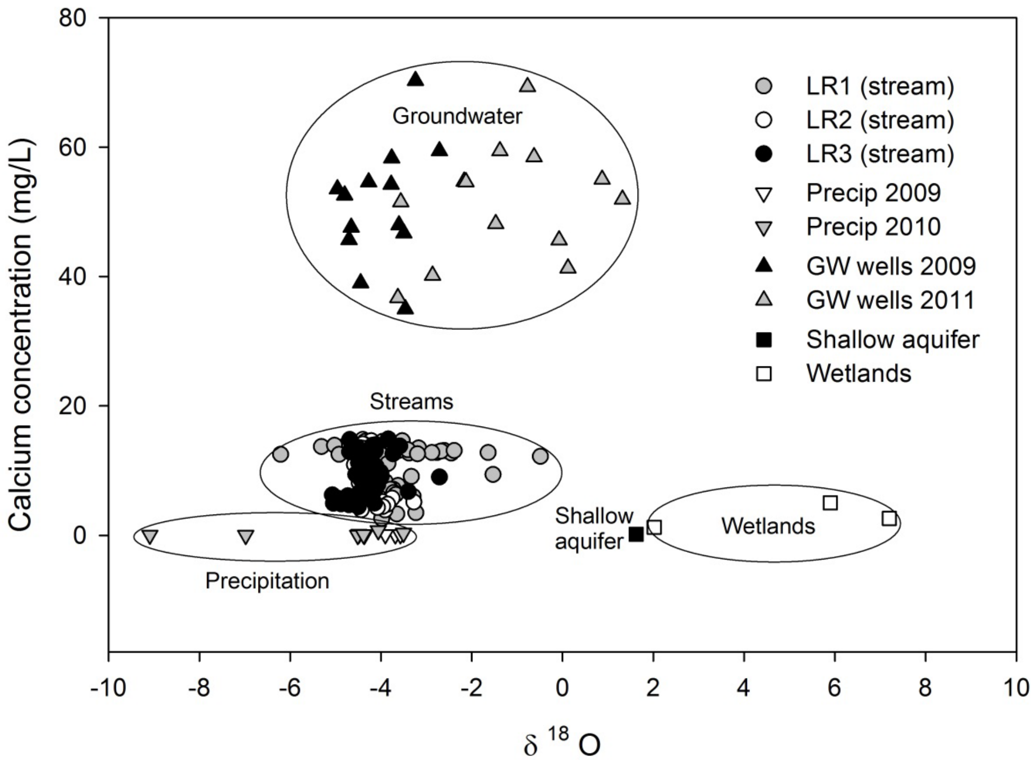

Figure 3.3. Calcium concentration versus $\delta^{18}O$ values ($^{0}/_{00}$) in meteoric and surface waters collected within the Ichawaynochaway basin in southwestern GA.

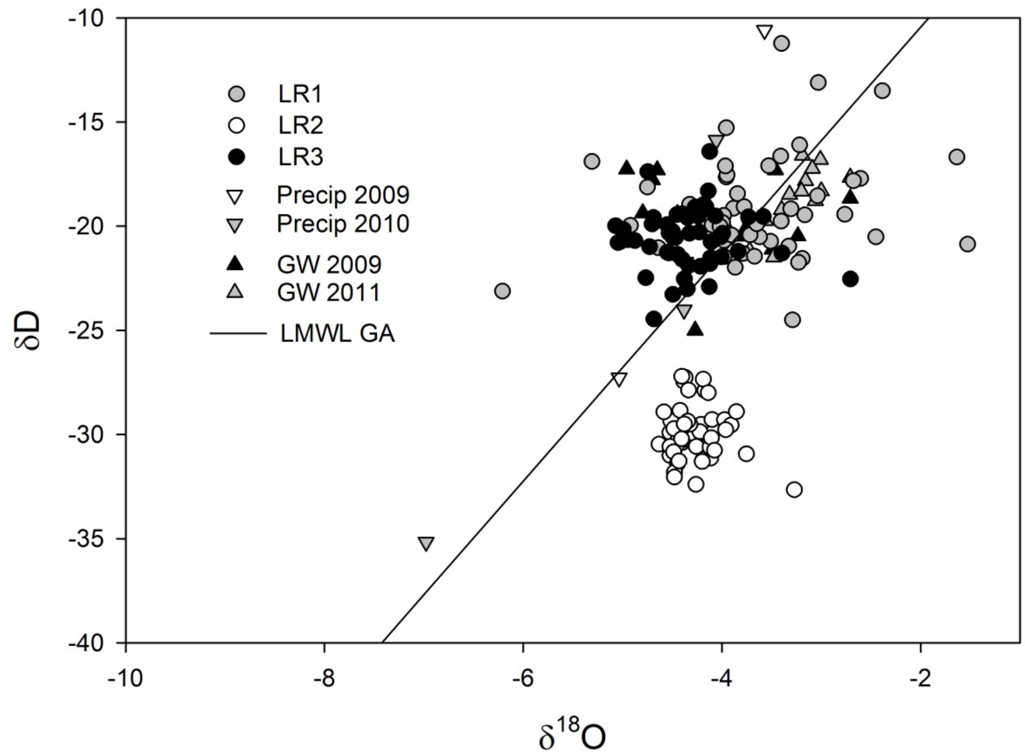

Figure 3.4. Isotopic values ($^{0}/_{00}$) for $\delta^{18}O$ and δD in meteoric and surface water samples (2011 LRs) compared to the Local Meteoric Water Line for river water in Georgia (Kendall and Coplen 2001).

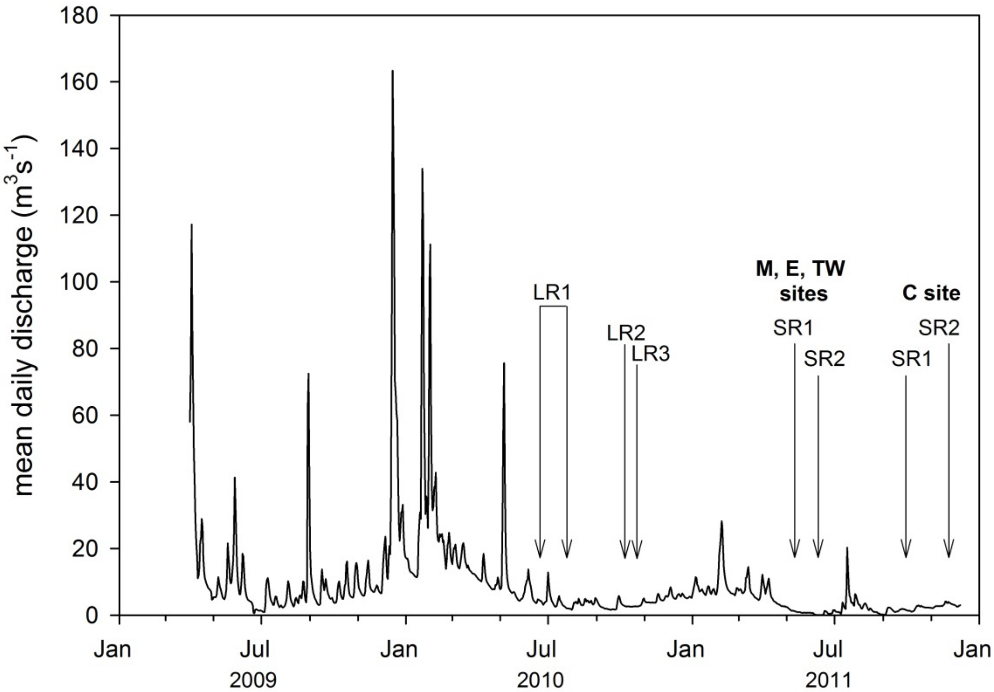

Figure 3.5. Hydrograph showing stream discharge measurements at the USGS stream gage 02353265, near Morgan, Georgia, for hydroperiod between March 2009 and December 2011including all LR and SR collection periods.

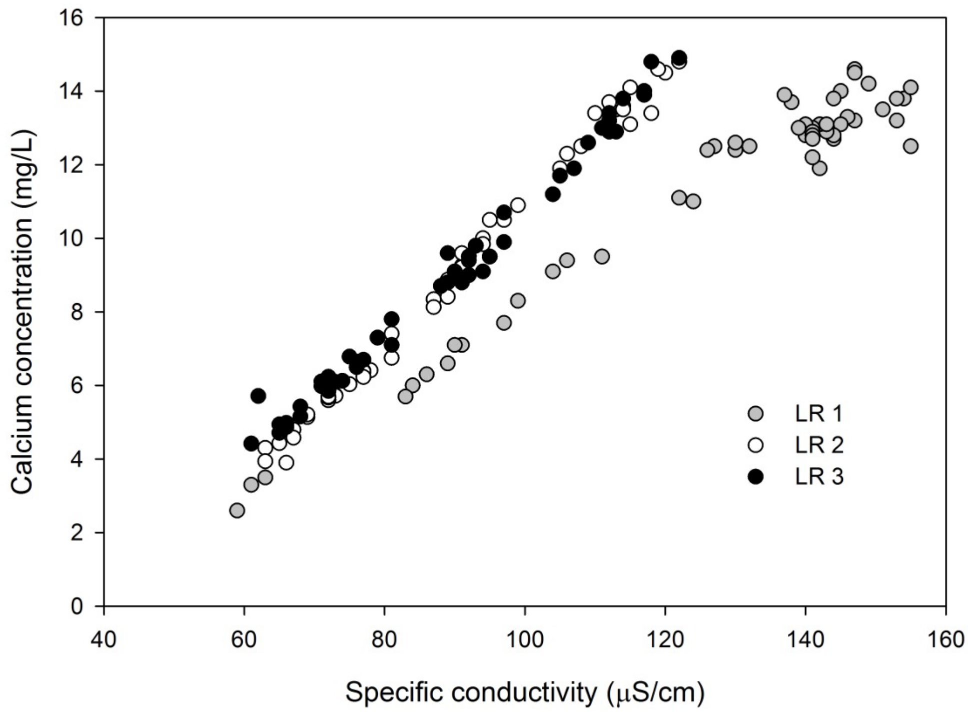

Figure 3.6. Specific conductivity versus calcium concentration detected in 2010 stream samples collected during three longitudinal sampling runs (LR) on Ichawaynochaway Creek, southwestern Georgia, USA. Results of Pearson product-moment showed a positive correlation between the two variables for all runs ($r = 0.978$, 0.996, and 0.993 for LR1, LR2 and LR3, respectively; all $df = 50$, all $p < 0.001$).

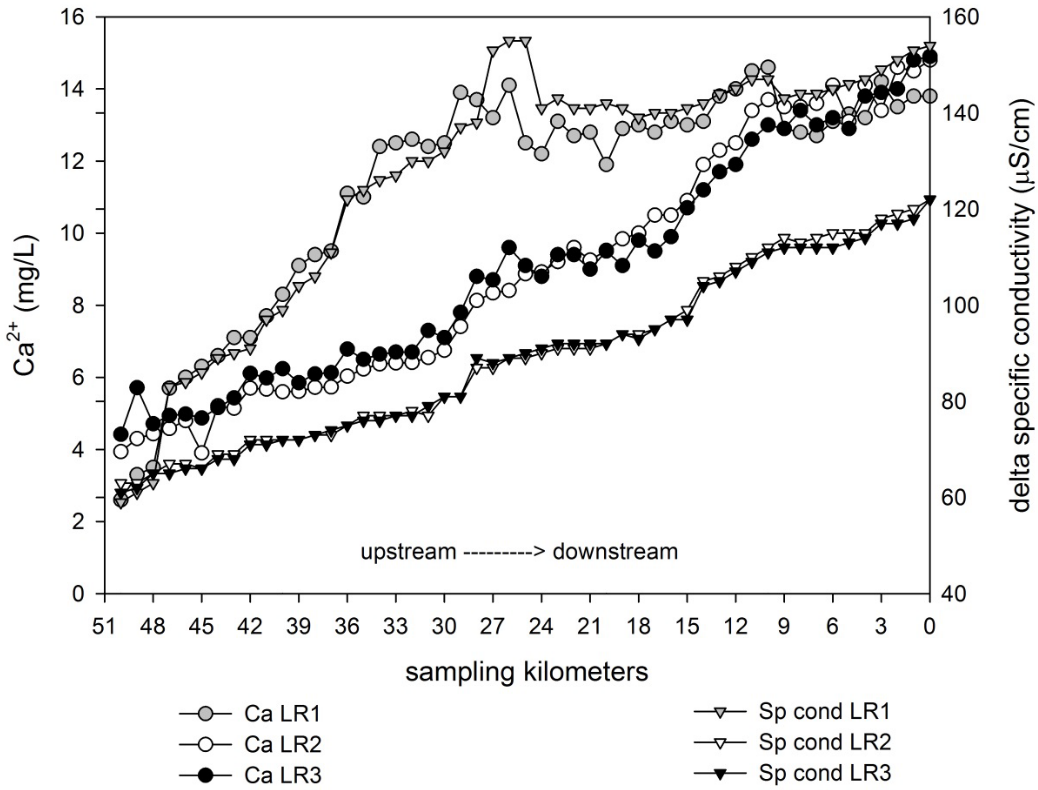

Figure 3.7. Increases in specific conductivity and calcium concentration during 2010 LR runs collected on Ichawaynochaway Creek, southwestern Georgia, US.

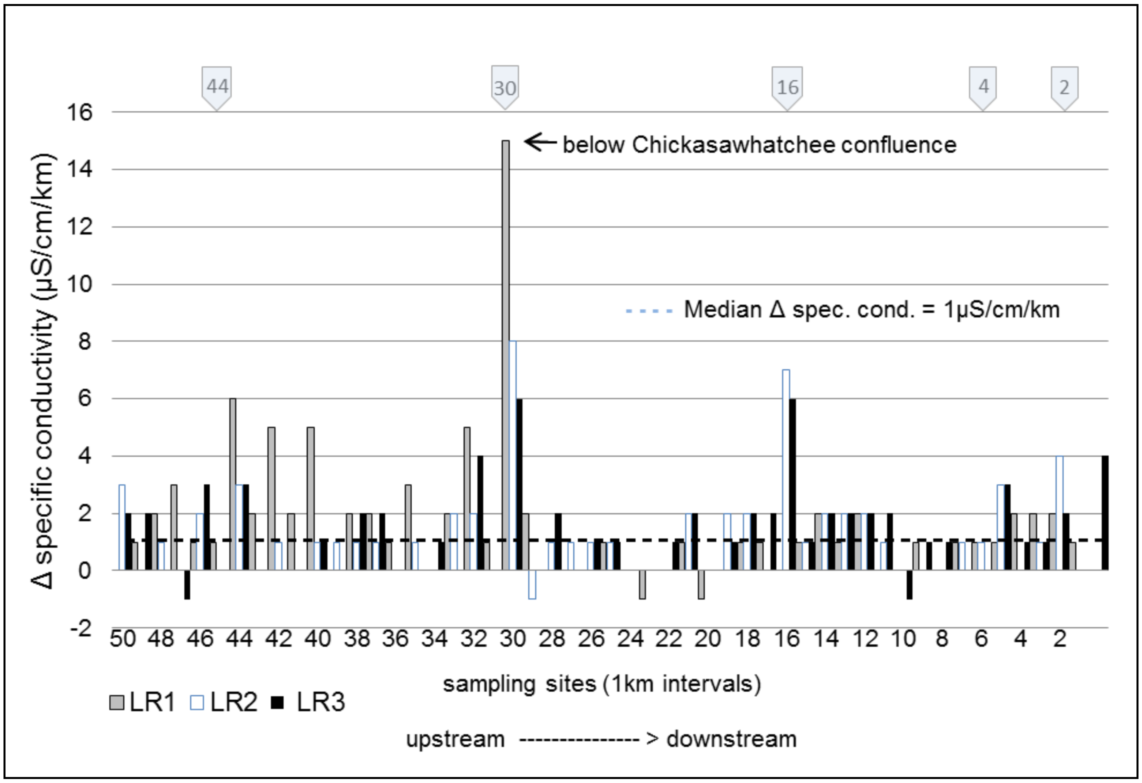

Figure 3.8. Changes in specific conductivity per sampling kilometer detected during three longitudinal assessments in 2010 (LRs) on Ichawaynochaway Creek. Arrows indicate regions of greater change in specific conductivity between sampling kilometers (suggesting increased groundwater inputs). Blank space on x-axis indicates no change in specific conductivity between sampling kilometers.

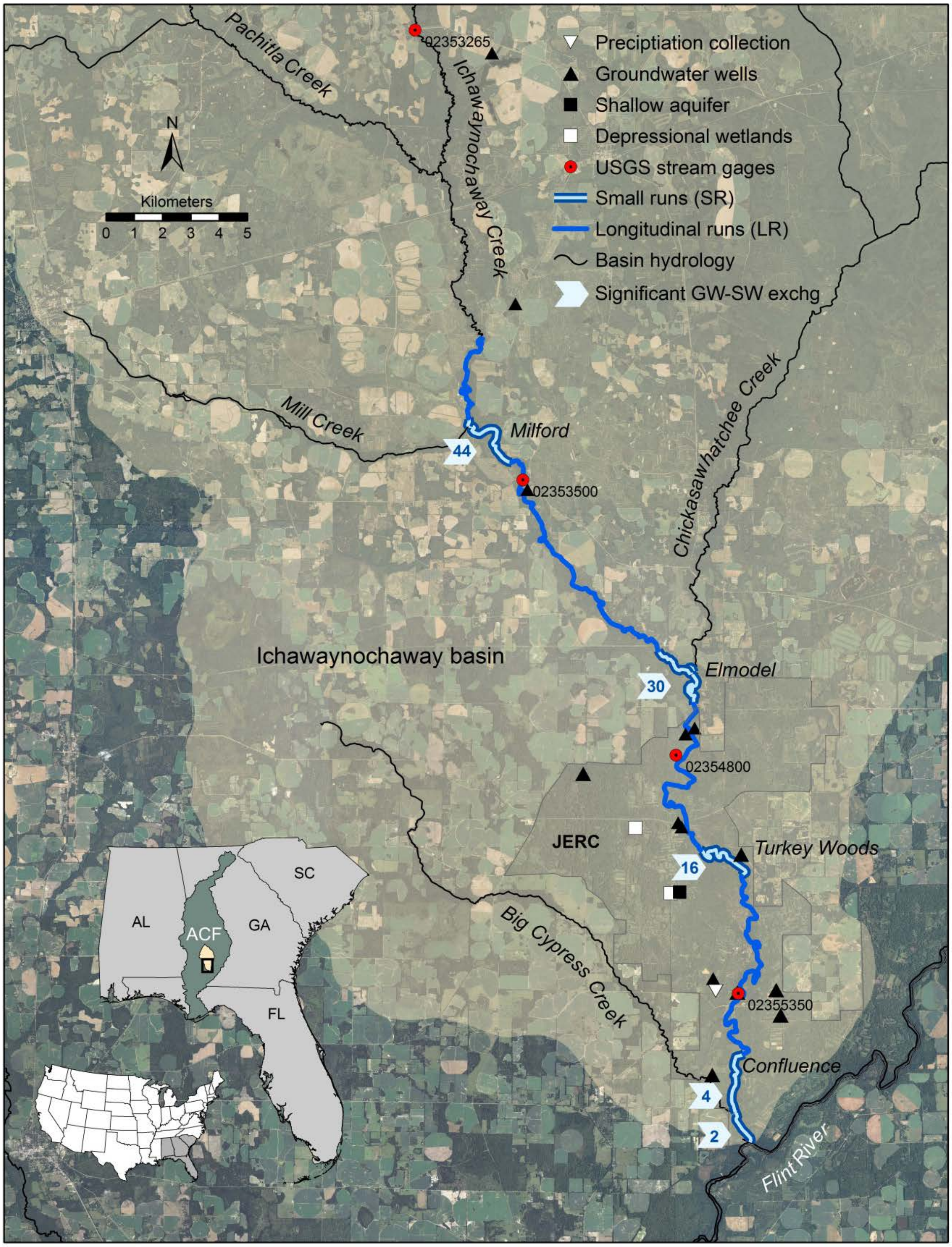

Figure 3.9. Map showing the locations of all collection sites during study within the Ichawaynochaway basin. Arrows indicate reaches of greater change in specific conductivity between sampling kilometers during LR sampling runs.

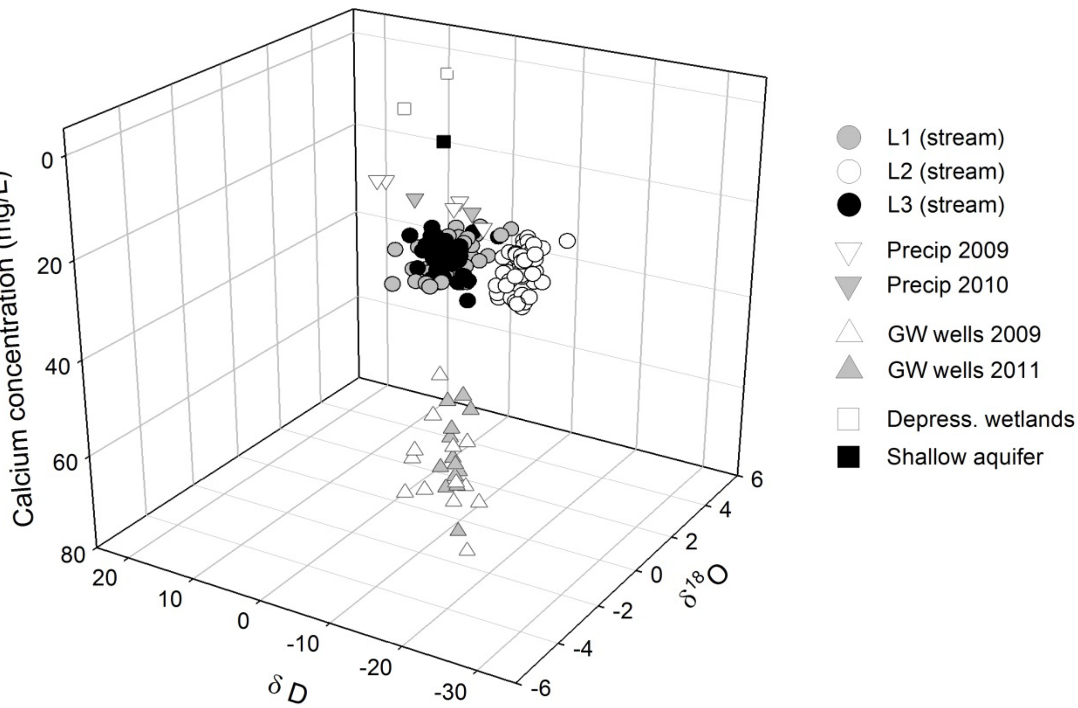

Figure 3.10. Isotopic values for $\delta^{18}O$ and δD versus calcium concentrations in meteoric and surface water samples within Ichawaynochaway basin, southwestern GA, USA.

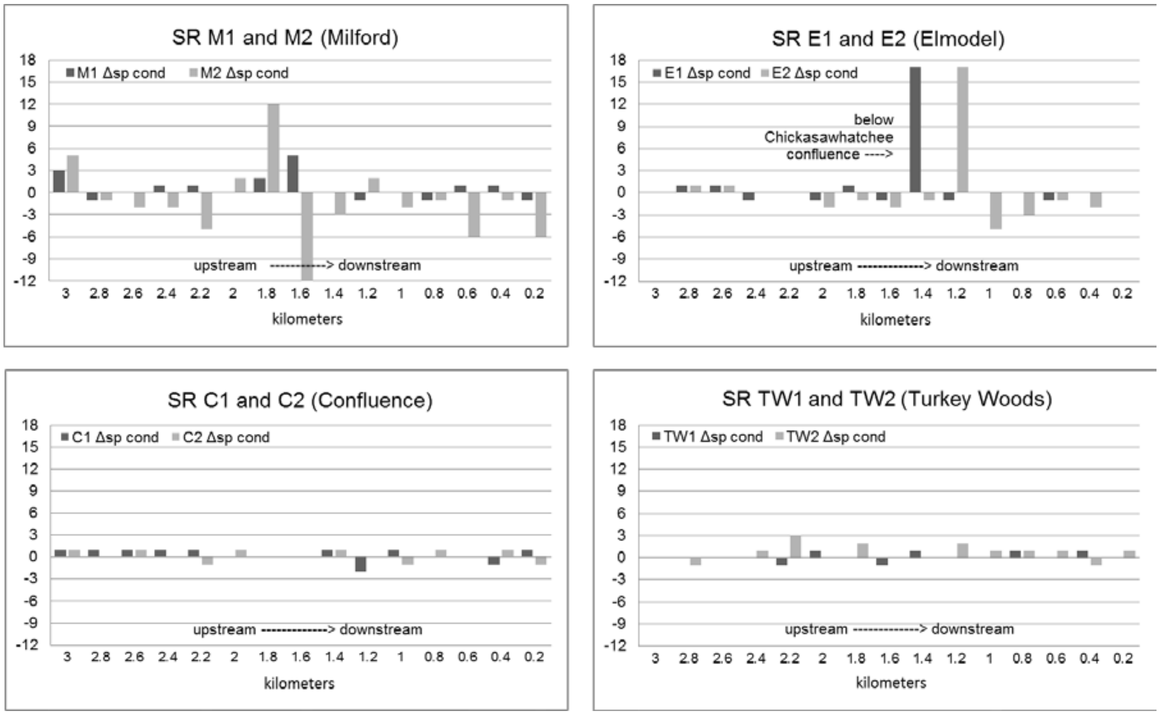

Figure 3.11. Changes in specific conductivity within Ichawaynochaway Creek at 200 meter intervals (0.2 km) indicating fewer gains downstream and more losing reaches upstream during 2011 SR collections; Order of sites (upstream to downstream, clockwise, from top left): Milford, Elmodel, Turkey Woods, and Confluence.

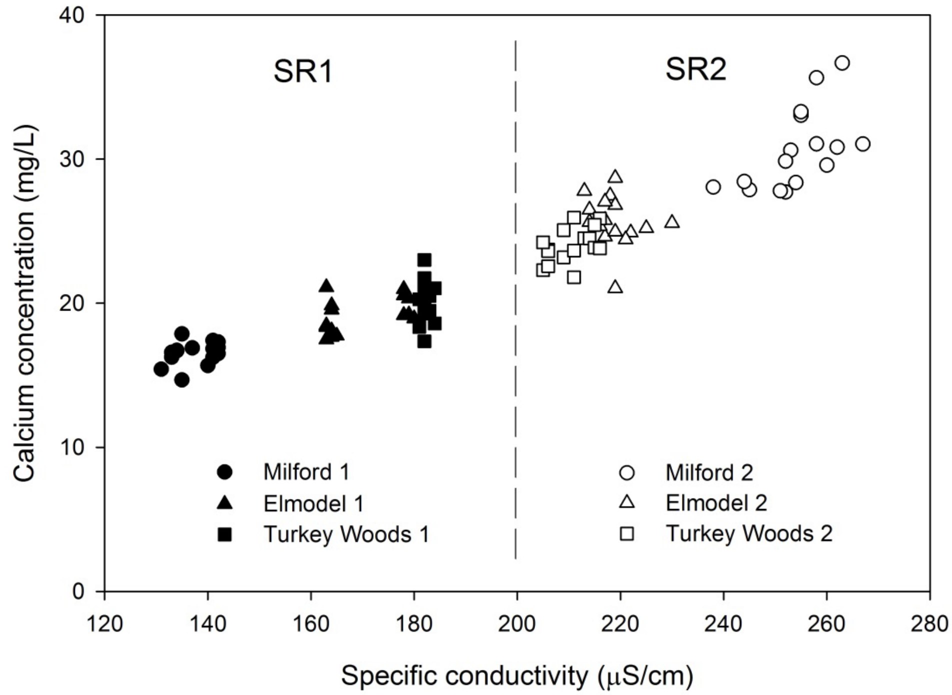

Figure 3.12. Calcium concentration versus specific conductivity in stream samples collected every 200 meters during 2011 SR collections in Ichawaynochaway Creek. Note calcium and specific conductivity were lowest upstream and increased in downstream direction during SR1; however, trend was reversed during SR2 (longitudinal compilation of data from three upstream sites: Milford, Elmodel and Turkey Woods).

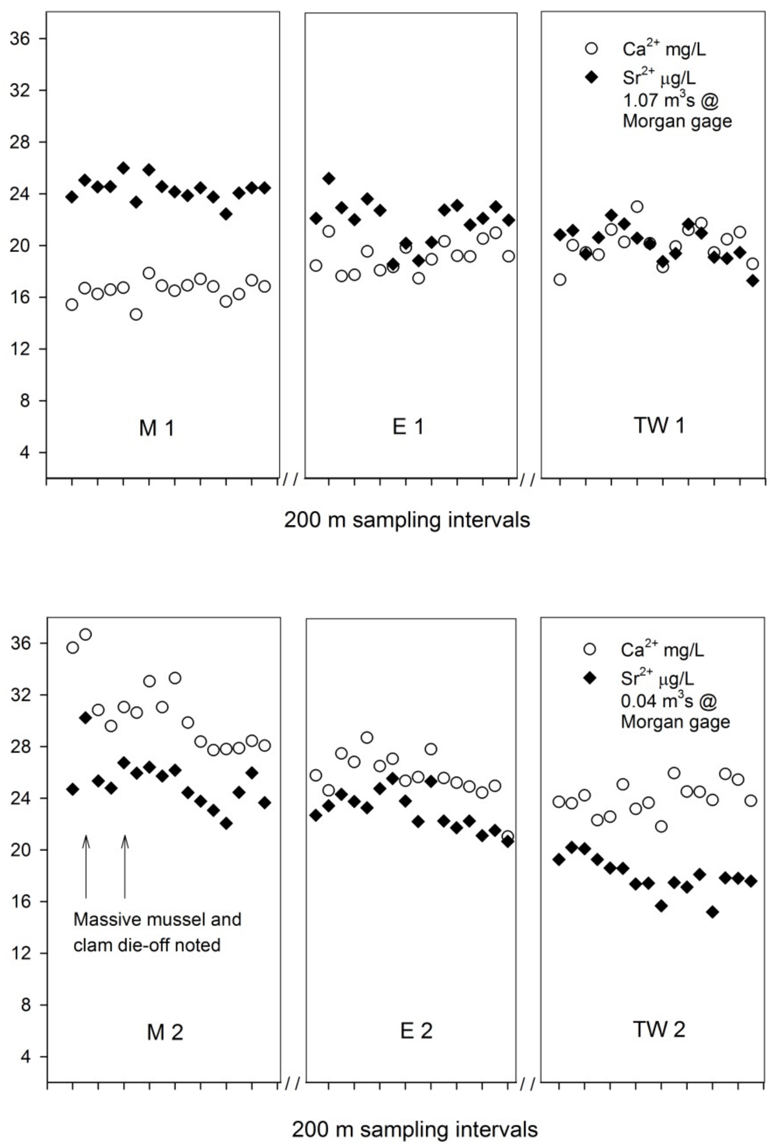

Figure 3.13. Calcium and strontium concentrations at 200 meter sampling intervals during 2011 SR1 and SR2 sampling runs on Ichawaynochaway Creek, southwestern GA, USA.

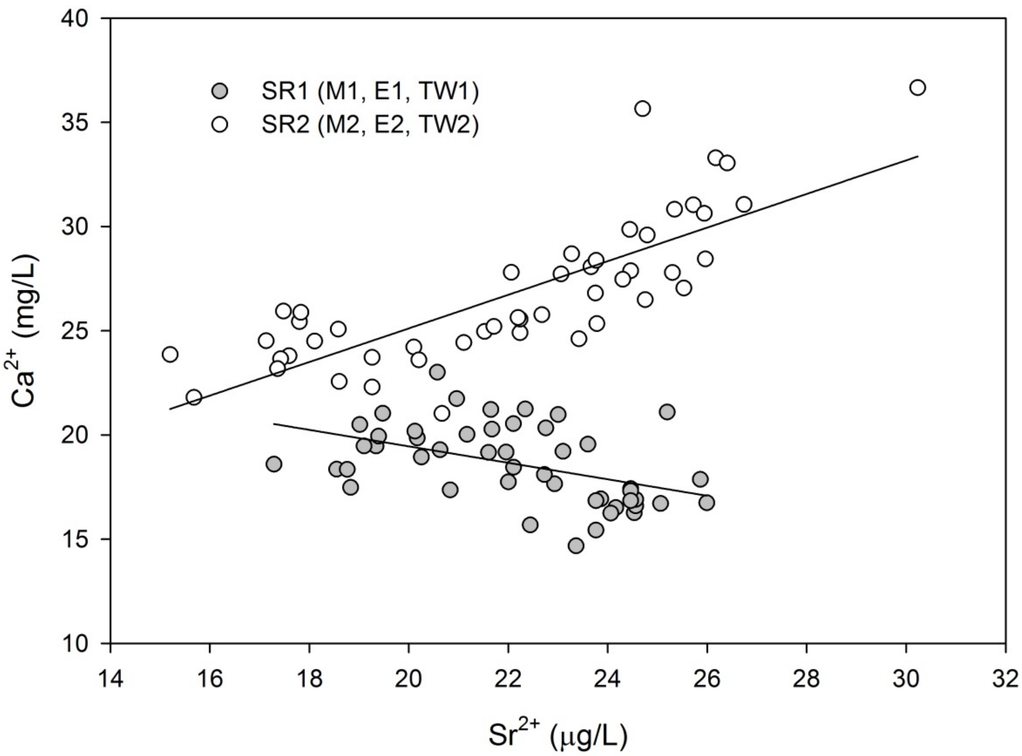

Figure 3.14. Relationship between calcium and strontium concentrations in stream samples from Ichawaynochaway Creek under differing discharge conditions (SR1~1.07 m^3s, SR2~0.04 m^3s, M, E and TW sites combined).

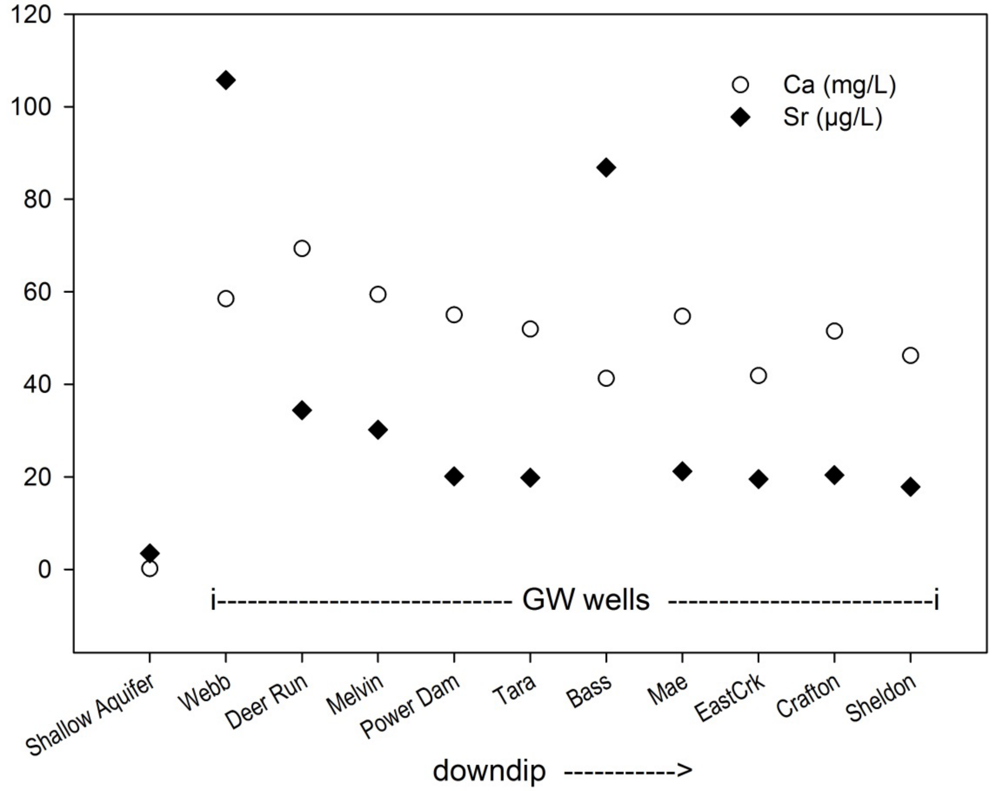

Figure 3.15. Calcium and strontium values in shallow aquifer and deep groundwater samples collected in 2011 within the Ichawaynochaway sub-basin, southwestern GA.

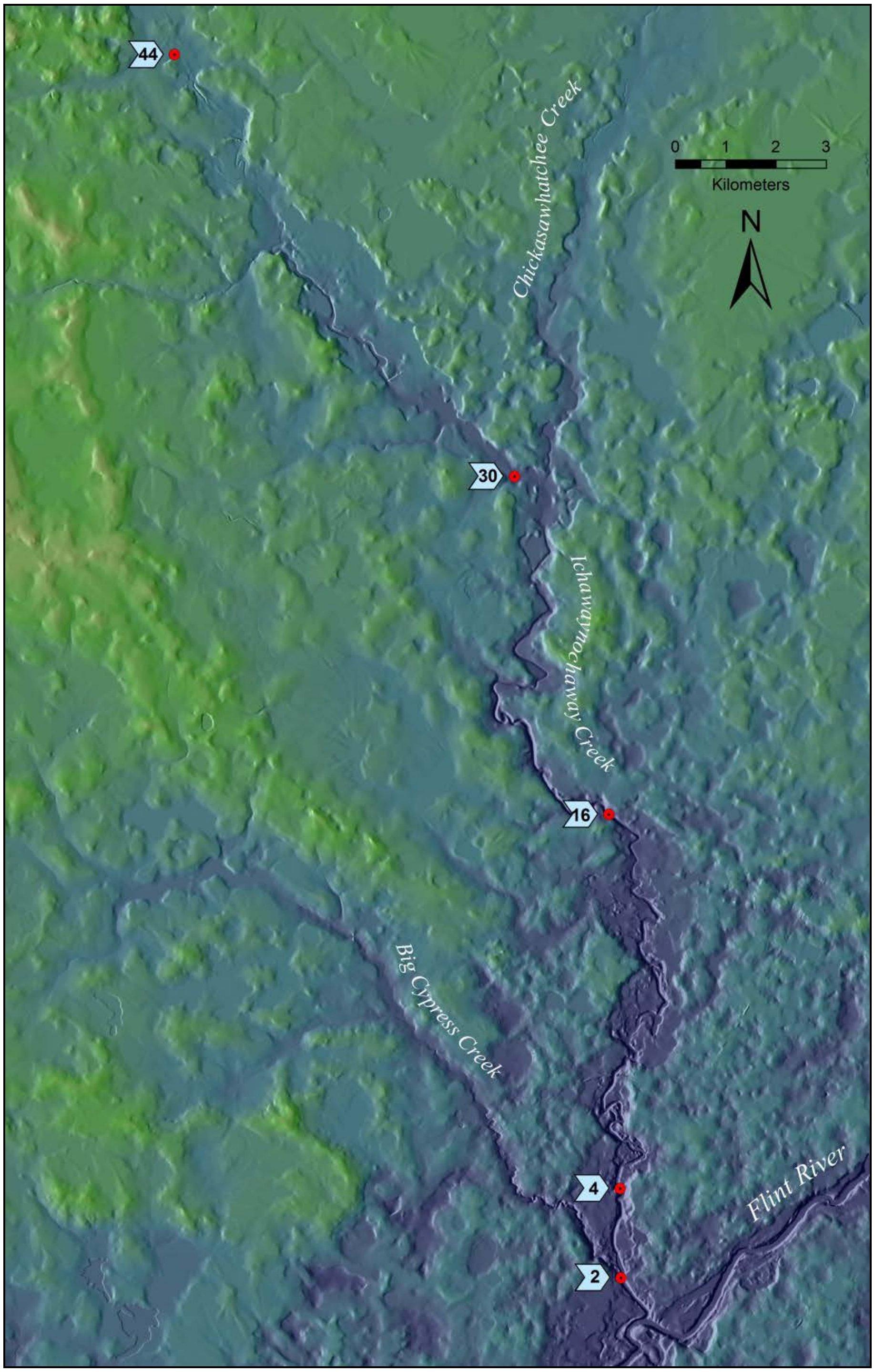

Figure 3.16. Digital elevation map (enhanced with hillshade) of lower portion of Ichawaynochaway Creek and sites of significant groundwater input. Enhancements highlight large floodplain elements which follow regional fracturing trends (NW-SE and NE-SW), particularly from Site #16 downstream.

CHAPTER 4

HYDROGEOMORPHOLOGICAL TRENDS WITHIN THE LOWER FLINT RIVER BASIN, SOUTHWESTERN GEORGIA, USA

Introduction

There is a growing need for research to understand how the intensive development of both groundwater and surface water resources may be affecting aquatic systems in overallocated basins. The Upper Floridan Aquifer (UFA) which underlies the southeastern Coastal Plain of the United States is part of one of the most prolific aquifers in the world (Miller, 1986). This aquifer has developed secondary permeability as a result of karstification processes occurring in carbonate sediments within the Ocala Limestone Formation (Stringfield, 1966). Lateral and vertical drainage patterns throughout this formation have organized into a binary karst system which is heterogeneously connected to surface drainage and streams throughout the region (Stringfield, 1966; Mosner, 2002).

Use of water from the Floridan Aquifer system increased 500% between 1950 and 2000 (Johnston and Bush, 1988; Marcella and Berndt, 2005) and currently provides over 15 million cubic meters of groundwater per day for agriculture, municipal, industrial and domestic use throughout portions of Alabama, Georgia, South Carolina and all of Florida. The Lower Flint River Basin (LFRB) lies within the Dougherty Plain District of southwestern Georgia in the southeastern US and is a vital sector of the regional economy (Couch and McDowell, 2006). This region underwent extensive agricultural development in the 1970s following the implementation of center pivot irrigation (Pierce et al., 1984) and is currently in a period of intensive regional water resource restructuring. Since a close hydraulic connection exists between the UFA and streams in this karst region, the withdrawal of millions of cubic meters of groundwater and surface water for seasonal irrigation has significantly reduced summer baseflows in regional tributaries (Couch and McDowell, 2006; Rugel et al., 2012). Loss of streamflow in this watershed has also been associated with reduced flows in downstream groundwater, estuarine and marine basins with deleterious effects on these ecosystems (Elder and Cairnes, 1982; Stamey, 1996; Jones and Torak, 2006; Darst and Light, 2008)

Remote sensing data sets are currently being exploited to evaluate basin-scale trends in near surface processes and improve predictive capabilities in climate, hydrology, soil moisture, subsidence, biogeochemical processing and habitat complexity (Dinger et al., 2002; Robinson et al., 2008; Galve et al., 2008; Luck et al., 2010; Noilhan and Planton, 1989). An emerging body of research is employing these tools to understand how hydrogeomorphological templates influence and predict the interaction of groundwater and surface water in groundwater-dependent systems (Loague et al., 2006; Cardenas, 2008; Poole, 2010; Whited et al., 2011). These interactions affect a myriad of physical factors including residence time, hyporheic exchange, bed transport, sorting, nutrient loading and retention, and ultimately habitat and biological complexity, productivity and community structure in aquatic systems (Freeman et al., 2007; Bunn and Arthington, 2002; Doyle et al., 2003; Valett et al., 1996). Gathering information on geomorphic attributes that influence hydraulic connectivity in karst systems may help to predict groundwater and surface water quantity and quality, vulnerability to contaminant and nutrient loading, and potential changes in biogeochemical processing in these streams which can result from both natural and anthropogenic pressures.

Understanding geomorphologic patterns and their effect on regional hydrology is vital to the sustainable management of karst systems where groundwater and surface water systems are highly interactive and development of water resources is often extensive. Jointing and fracturing trends have been used to understand the movement of water, gases, nutrients and contaminants between groundwater and surface water components in many hydrologic systems (Brodie et al., 2007; Condon, 2003; Bailly-Comte et al., 2009; Elhatip, 1997); however, these relationships have not been fully explored in karst basins, such as the Lower Flint River Basin, where pumping of millions of cubic meters of groundwater and surface water threaten streamflows and endangered aquatic biota (Hook, et al., 2005; Couch and McDowell, 2006). Applin and Applin (1944) gathered information on geological bedding and regional dissolution patterns throughout the southeastern Coastal Plain region at the height of World War II in order to inform geological exploration for expanding energy requirements. Studies in the LFRB have since used aerial photography to examine relationships between regional jointing and well productivity as well as solutioning along lineament trends. Brook and Sun (1986) showed that 89% of variability in specific capacity of wells in the Albany, Georgia area could be explained by proximity to the nearest fracture trace (identified in aerial photographs) and that density and intersection of these fractures were positively correlated with well capacity. Hyatt and Jacobs (1996) found that the formation and morphology of 312 sinkholes in the Albany, GA area, which collapsed following Tropical Storm Alberto (1994), also followed joint-controlled linear trends. Other investigations in the LFRB have analyzed and modeled stream discharge and hydrogeochemistry to understand hydraulic relationships between groundwater and surface water components which drive aquatic ecosystem function (Hicks et al., 1987; Plummer et al., 1998; Jones and Torak, 2006; Rugel et al., 2012).

Regional hydraulic conductivity and porosity are affected by inherent properties of the limestone matrix as well as the presence of solution-enlarged joints and conduits which generally follow regional fracture trends (Freeze and Cherry, 1979; Worthington, 1999). As a result of these solution features, local transmissivity rates in the LFRB have been shown to differ by orders of magnitude, reaching up to 1.0×10^5 m^2/d (Hicks et al., 1987). Interpreting geologic templates that influence these regional hydraulic patterns at surface and sub-surface levels should increase our ability to predict hydrologic connectivity, which ultimately affects discharge-related processes in these aquatic systems. The objective of this study was to examine large and small scale hydrogeomorphic patterns at both the near surface and sub-surface levels in the LFRB. To this end we performed a basin-wide analysis to assess directional trends in regional fluvial geomorphology of stream reaches in the LFRB and compared these findings with azimuth orientations of jointing found in stream bedrock outcrops in this region. Finally, we examined phreatic cave maps to determine the major trends in solution conduit and cave passageway formation in this region.

Site Description and Methods

Study site and hydrogeological setting

The study site lies mostly within the Dougherty Plain Province of southwestern Georgia, USA (Figure 4.1). The LFRB consists of approximately 15,100 km^2 of gently rolling, well-drained Coastal Plain with a slope around 2 m/km. Average annual temperature is 16^oC and rainfall totals are approximately 1320 mm per year with regional evapotranspiration rates around 60% (Lawrimore and Peterson, 2000). Row crop agricultural farming and pasture lands account for over 50% of land use, with remaining acreage in managed pine plantation, deciduous forest, and some depressional wetlands. The region is heavily developed for groundwater and surface water extraction with more than 6,000 irrigation systems permitted to extract approximately 5 x 10^6 m^3 of water per day from regional groundwater and surface water sources (Hook et al., 2005).

The LFRB is underlain by a series of carbonate formations from the Tertiary period which overlie deeper clastic rocks of the Cretaceous system (Applin and Applin, 1944). Together these sediments form a wedge-shaped series of hydrogeologic units which underlie much of the Coastal Plain region of Alabama, Georgia and South Carolina and all of Florida. Carbonate formations in this region consist of uncemented marine sediments deposited during transgressive and regressive sea levels which correspond to glacio-eustatic conditions during the Tertiary period (Stringfield, 1966; Florea et al., 2007). These formations updip in a northwesterly direction where they interfinger and outcrop along the inside margin of the Fall Line Hills and collectively thicken downdip in a southeasterly direction towards the Gulf of Mexico and the Atlantic Ocean, where they can reach a thickness of up to 7,600 m.

The Ocala Limestone Formation makes up the main water-bearing unit of the Upper Floridan Aquifer and consists of two major lithological units of fossiliferous limestone which are (mostly) hydrologically continuous but may be stratigraphically distinguished by the presence of key fossil types (Applin and Applin, 1944). In general, fragments of larger foraminiferal species occur within the upper unit which consists of interbedded porous, fine grained, chalky, white coquina sediments. The lower unit contains smaller species of foraminifera and is more highly calcitic, light cream, limestone with some grey to dark brown glauconitic limestone and dolomitization (Applin and Applin, 1944; Miller, 1992). Where present a middle confining unit consists of more impermeable clayey, chalky limestone interbedded with non-calcareous clay and silt. The Ocala Formation is underlain by the mostly imperious Lisbon Formation and overlain unconformably by undifferentiated sediments of Oligocene limestone, clays and sands, mantled by an unconsolidated overburden of Quaternary sediments. The UFA is mostly confined in the study area depending upon dissolution of the overburden. Thickness of the aquifer in the study region ranges from a few meters in northwestern portions of the Dougherty Plain (updip extent) to over 150 m in the southeasterly direction as it approaches the Pelham Escarpment, which borders the Tifton Upland (Hicks et al., 1987).

Alternating primary stress fields occurring during the Tertiary period have produced folding, normal listric faulting and jointing in this region (Zoback and Zoback, 1980) followed by solutioning in limestone formations during the Pleistocene time, which enlarged joints and conduit passageways corresponding to Quaternary sea levels for this region (Stringfield, 1966; Florea et al., 2007). Transmissivity in the UFA can range from 1.9×10^2 to more than 1.2×10^5 m^2/d in the LFRB and generally increases in a southeasterly direction (Torak and McDowell, 1996). Tributaries in this region, including the Kinchafoonee, Muckalee, Ichawaynochaway and Spring Creeks, begin as seeps and springs inside the Fall Line Hills and organize into a rectangular drainage pattern which flows across the Dougherty Plain Province into the lower Flint River. Moderate to mature karstification of underlying limestone and erosion of overburden has directed much of the surface drainage below ground and established a close hydraulic connection between surface water and groundwater in this region (Mosner, 2002; Torak and Painter, 2006; Rugel et al., 2012).

Methods

Stream reach orientation analysis

The U.S. EPA Reach File 1 (RF1) for the Conterminous United States was used to determine orientation trends of stream reaches within the LFRB. A VB script was generated (Jenness, 2007) to segment the original line file in an ArcView v.3 extension adapted for ArcGIS v.9. This code (pathfind.avx) was used to dissect the continuous reach line data at stream turns (vertices) and create stream segments (reaches) and associated segment length and azimuth attributes. Polygon data that represented lakes, wetlands or reservoirs in the original RF1 were manually excluded for the analysis. All other segments were chosen and attribute tables for azimuth and length (.dbf) were exported into Microsoft Excel® and loaded into a Boreland C++ program (http://www.borland.com/) to generate rose diagrams [Fracture Rose v.1.0.3.1, jdowd@uga.edu; additional tools used to enhance rose diagram program included: Steema Tee Chart (www.steema.com), Dew Research MtxVec (www.dewresearch.com), LMD Tools (www.lmdinnovative.com), and Axolot XLSReadWrite (www.axolot.com)]. Rose diagrams were produced using 36 bin divisions of 5^{o} arcs with mirrored sets projected for enhanced 360^{o} display (mirrored sets were used entirely for visual purposes and did not represent additional data). This analysis was performed on the entire LFRB stream data set (~37,000 reaches) then repeated by query for major tributaries of interest, including: Ichawaynochaway, Spring, Big Cypress, Pachitla, Chickasawhatchee, Kiokee, Kinchafoonee, Muckalee Creeks, and the main stem of the lower Flint River. The relationship between stream reach length and stream reach azimuth (for the 37,134 reaches in the LFRB) was evaluated by determining the mode of the reach lengths for each 5^{o} arc division above. Modes (n=36) were compared using Kruskal-Wallis One-Way Analysis of Variance on Ranks followed by Dunn's multiple comparison procedure (for unequal sample sizes) in SigmaPlot 11.0 (http://www.sigmaplot.com).

In-stream bedrock jointing measurements

To determine fracturing trends in regional limestone formations we located and measured joints occurring within the stream bedrock of two tributaries (one inside and one outside of the LFRB). Ichawaynochaway Creek, a 5th order tributary of the Flint River, lies mostly within Baker County, Georgia. Downstream portions of this stream have become deeply incised into the Ocala Limestone. A large number of semi-contiguous fracture (joint) sets were located within the streambed at low discharge (2011), starting approximately 0.5km upstream from the confluence of Ichawaynochaway Creek and the Flint River and continuing about 4 km upstream (Figure 4.2). Fracture azimuth, length and width (aperture), as well as distinguishing characteristics of joints (including sinuosity, degradation, and termination points) were recorded along approximately 3.5 km of streambed, separated by small sections of stream which were too deep to assess. Azimuths were determined using a Brunton Field Transit and navigational coordinates were gathered at the terminus of each fracture using a Garmin® Oregon 550 hand-held GPS. All accessible fractures (n= 125) within the streambed that were at least 2 meters long were measured. Fracture extents included only the portion of the fracture that was contained within the streambed, regardless of any continuation beyond the stream, i.e., into bank. For comparison, azimuth measurements were determined on 43 bedrock fractures at a second stream, outside of the Flint River Basin. These fractures were found in limestone streambeds in the main stem of Coheelee Creek, a 3rd order tributary of the lower Chattahoochee River, in Early County, GA (no length or GPS). Following field measurements, all Garmin shapefiles were downloaded into ArcGIS v.9 using DNRGarmin v.5.4.0.1, a freeware ArcView extension program created and available on the Minnesota Department of Natural Resources website (http://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html). New code was generated in ArcGIS v.9 which created an algorithm using length and azimuth data to generate location, direction and extent of each streambed fracture for mapping/display purposes. In-stream azimuths produced in ArcGIS were downloaded into the Boreland program to create rose diagrams for bedrock joints (36 5^{o} bins).

Phreatic cave conduit measurements

Existing cartography on three water-filled caves in the LFRB was evaluated to compare the orientation of underground conduit passageways with the regional trends found in stream orientation and bedrock fracturing. Radium Springs (Dougherty County, GA), Chameleon (Dougherty County, GA) and Pineland Blue Cave (Double Springs Cave, Baker County/Mitchell County, GA) were previously explored and mapped by divers using a knotted permanent line, with compass readings made with an UW Compass at ~3 meter intervals. Results were confirmed using radio cave (radio location) technology which resulted in 85 % confidence, usually within 1.5 meters (Paul DeLoach, personal communication). Each cave map was enlarged and printed onto 11x17 paper, oriented north and secured on a flat, level surface. Lines were drawn through the center of all cave passages estimated to be at least 3 meters in length and a Brunton compass was used to determine the orientation of each measurable passageway. Conduit azimuth data was analyzed using above methods and rose diagrams were generated with 18 bin divisions of 10^{o} arcs (larger bin divisions were used in cave analysis to account for cumulative error by multiple users).

Results

Stream reach azimuth analysis

Analysis of all stream and river reach orientations within the LFRB (n=37,134) indicated a dominant trend of N-S reaches (Figure 4.3) with two lesser sets of reaches running E-W and N45W. Other trends appeared ~N24W, N20E and N40E. The evaluation of individual tributaries within the LFRB also reflected the major N-S reach trend with lesser sets around N45W and E-W (Figure 4.4). Major distinctions among tributaries included a pronounce N45W trend in Big Cypress Creek which was repeated in the Ichawaynochaway, Pachitla, Spring, Kinchafoonee and Muckalee Creek data. This trend became slightly less prominent towards the mid- and southeastern portion of the basin, particularly in the reaches of the lower Flint River. Approximately mid-basin, Chickasawhatchee and Kiokee Creek, as well as the lower Flint displayed stronger NNE trends compared to streams west and north of these tributaries.

Stream reach length analysis showed multi-modal distribution of reach lengths for 36 (5^{o} arc) divisions (Figure 4.5). One-Way ANOVA on reach length modes (n=36) failed initial normality test and Kruskal-Wallis on Ranks indicated significant differences between modes (P = <0.001). Results of Dunn's pairwise multiple comparisons procedures demonstrated significant differences between stream length modes for bin divisions (Figure 4.6).

In-stream bedrock joint trend analysis

Fracture azimuths measured in limestone bedrock outcrops within Ichawaynochaway Creek (n=125) showed a dominant N-S jointing trend with lesser sets occurring around N12E, N22E, N20W, N38W, and E-W (Figure 4.7). These joints occurred in two different bed types of friable, weathered limestone which were interbedded throughout the 3.5 km site (Figure 4.8). Median joint length was 6.3 meters and ranged from 1.6 to over 50 meters. Median aperture of joints was 10 cm and ranged from 1- 40.6 cm. Joint length vs. joint azimuth was not formally evaluated since some fractures extended, but were not measurable, beyond the streambed and resulting analysis could have introduced a censoring bias. Coheelee Creek, in the Lower Chattahoochee basin, had bedrock fractures (n=43) which trended mostly N23W with lesser sets at N48W, N38W and E-W. These joints consisted mostly of fine-lined cracks occurring in clayey, creamy rhodolith limestone. This bedrock may have been part of the Suwannee Formation, which overlies and outcrops along with the Ocala Formation in this region (Miller, 1986).

Phreatic cave conduit trend analysis

Analysis of conduit development in phreatic caves within the LFRB showed that all three caves had some passageways which trended in the NNW direction, ~N45W (Figure 4.9). This tendency was most prevalent in the Pineland Blue and Radium Springs Caves. When analyzed collectively all caves shared an additional set of conduits in the N62E direction. Pineland Blue Cave also showed an orthogonal set of passageways around N62W, a trend that was weakly shared by Radium Springs Cave. The strongest azimuth orientation for conduits in Chameleon Cave was in the E-W direction with other sets which centered ~N56W. None of the caves displayed a dominant N-S conduit trend.

Discussion

Stream reach trends

Stream reaches with N-S orientations (175^{o} - 4^{o} arc) occurred 46% more frequently than other reach azimuth trends. Length vs azimuth analysis displayed multi-modal distribution and indicated that the shortest reaches in the LFRB followed N-S and E-W trends, followed by NNW and NNE reaches. The most frequently occurring N-S trend was not present in cave conduit orientations (which usually follow regional jointing patterns; Freeze and Cherry, 1979; Hicks et al., 1987); therefore, it appeared to represent a neo-tectonic pattern at the near surface. Fluvial geomorphology in this region formed during the pre-Pleistocene, most likely Pliocene, series (Stringfield, 1966) when tributary drainage eroded through late Tertiary and Quaternary sediments which unconformably lay over earlier Eocene (Ocala) formations. Tertiary (tectonic) trends are repeated within the fluvial geomorphologic record; therefore, it seems that drainage in the LFRB has at least partially adjusted to the older tectonic template (Melton, 1959).

Approximately mid-basin, the major NW-SE trend detected in stream reach orientations on the western side of the LFRB, appears to display increasing NE-SW reaches (apparent in stream reaches in Chickasawhatchee Creek). Interpretations of present stress fields for this region include observations that the Gulf Coastal Plain has encountered flexure and isostatic rebound from erosional processes occurring in the Appalachian chain, causing expansion away from the continent (toward the Gulf of Mexico) while an opposing trend has acted to create maximum compression directed from the Atlantic (NW-SE), perpendicular to the Appalachian orogeny (Zoback and Zoback, 1980). What appeared to be “scatter” (multi-directional trends) in the rose diagrams of reaches around the middle of the basin could reflect the expression of these opposing stress processes. Other explanations for this shift in stream reach direction include regional jointing from layer-parallel extension associated with minor isostatic uplift (Robin J. McDowell, personal communication). Tributaries to the south and east of this mid-line, such as Kiokee Creek and the lower Flint River, display a more distinct pattern of NE-SW reaches.

Stream bedrock jointing trends

The comparison between bedrock jointing patterns in Ichawaynochaway (Lower Flint River Basin) and Coheelee Creek (Lower Chattahoochee River Basin) provided an opportunity to contrast the influences of differing basin position and geological strata on localized jointing patterns, and to compare these trends with stream reach orientation and drainage patterns in and out of the LFRB. Ichawaynochaway Creek and Coheelee Creek displayed some similarities in stream bedrock joint orientations in the NNW direction, ~N20W and N38W, as well as a shared E-W trend; however, the dominant joint set in Ichawaynochaway Creek was found in the N-S direction, similar to the pattern for reach orientations in that stream as well as the rest of the LFRB. While Coheelee Creek joints had some NNW trends like those found in stream reaches in the western portion of the LFRB (Spring Creek and Ichawaynochaway Creek and tributaries), there was no dominant N-S trend which dominated in the LFRB). Coheelee Creek lies in the Lower Chattahoochee Basin, further west of any stream analyzed in this study. Tributaries of the lower Chattahoochee River have undergone uplift along the crest of the Chattahoochee Anticline as opposed to Flint River tributaries which are more influenced by dissolution along a shallow complimentary syncline (Stephenson and Veatch, 1915) which may explain the lack of N-S trends in the Coheelee fractures.

Phreatic cave conduit trends

All phreatic caves passageways shared some NNW azimuths. This orientation is consistent with tectonic fracturing trends (NW-SE) aligned parallel to the original primary stress field for this region, which have directed regional solutioning patterns in the NNW orientation (Zoback and Zoback 1980). Brook and Allison (1983) previously reported that passageways in other caves within the Dougherty Plain trended along N43W and N48E directions (below the Pelham Escarpment). These findings are consistent with the dominant azimuths of conduits in both Pineland and Radium Caves. While Radium and Pineland development appear to follow regional joint trends, Chameleon Cave may have been more influenced by solutioning along bedding planes. Palmer (1991) examined conduit azimuths in 500 caves throughout the world and found that 57 % of cave passageways formed along bedding and/or jointing planes, with most developing along jointing trends when jointing predominated. Limestone formations in the LFRB often act as a single hydraulic unit (Miller, 1992) and solutioning along through-going joints may have dominated over bedding influences in Pineland and Radium Springs Caves. In contrast, the major trend in the Chameleon Cave was E-W, with a lesser group of passageways aligned around N56W. Maps, and divers' comments, noted a greater degree of curvilinearity within Chameleon Cave compared to Pineland Blue and Radium Springs Caves as well as undulating floor and ceiling patterns within conduit galleries. Palmer (1991) found that bedding control dominated the solutioning patterns within cave systems which exhibited curvilinear trends. This supports the proposition that bedding rather than jointing planes could have directed the development of conduits within Chameleon Cave. In addition, this cave is closer to land surface, and dissolution patterns may have been influenced by expansion and uplift processes during formation (Radium and Pineland are ~11 and 16 m below Chameleon, respectively, according to median depth of gallery ceilings).

Significance and further avenues of research

A NW-SE directional trend (~N20W- N45W), was apparent in all stream reach, stream joint and cave conduit data sets. This major NNW trend is consistent with interpretations of jointing that occurred in response to relaxation of the primary stress field in place for this region throughout the early Paleozoic erathem (Engelder, 1985). During that time, compaction increased pressure in a SE-NW direction as the African plate accreted into the North American plate resulting in the Allegheny (Appalachian) Orogeny. Subsequent rifting of the North American continent created a passive continental margin upon which current Gulf Coastal stratigraphy was emplaced at alternating sea levels (Stringfield, 1966). Following sedimentation and release of pressure, tectonic fracturing occurred parallel to the primary stress field in this region, which appears to have encouraged subsequent solutioning (in the Quaternary) and the major NNW orientation of phreatic cave conduits. Further tectonic movements during Tertiary time resulted in relaxation of maximum pressure and reorganization of the primary stress field explaining opposing orthogonal joint sets found in the NE-SW direction (Melton, 1959). Both tectonic (Tertiary) and neo-tectonic (post-Miocene) processes appear to have encouraged regional solutioning patterns in the LFRB, since they are found in the older (cave conduits) as well as the more recent stream and joint orientations. Further neo-tectonic fracturing as a result of exfoliation, compensatory uplift and crustal expansion, may account for multiple orthogonal trends found in stream reaches and bedrock joints (N20W, N20E, and E-W; Stearns and Friedman, 1972, McDowell et al., 2012). The presence of the N-S trend in stream bedrock and its absence in any cave conduits suggested that the N-S pattern emerged in the more recent series and has been superimposed upon older stress patterns. Multiple observations during field evaluations of Ichawaynochaway Creek bedrock joints indicated that N-S fractures often terminated into one or more other joints, confirming their more recent formation. This pattern is likely a result of recent parallel extension from isostatic uplift in response to dissolution of overlying sediments (McDowell et al., 2012).

It is clear that commonalities exist in conduit, joint and fluvial orientations in the LFRB. While this would seem to be intuitive, the exact orientation and frequency of these trends was previously undetermined for this region at this scale. The results of this study may now be combined with existing hydrological and geochemical data for this region to help determine how and to what extent regional and localized hydrogeomorphic patterns may interact to influence hydraulic connectivity in these watersheds. For example, previous results reported in Chapter 3 of this document showed that significant amounts of groundwater from the UFA entered Ichawaynochaway Creek through relatively few reaches within the stream. By comparing the azimuths of reaches where these hydrologic interactions were located, it can be seen that ~30% of the time these exchanges occurred in reaches with N45W orientations (Figure 4.10). This azimuth corresponds with the dominant directional trend found in the phreatic cave conduits as well as one of the major trends found in both stream reaches and bedrock joints. While the precise mechanism facilitating the exchange of groundwater and surface water at these sites remains uninvestigated, these results provide a starting point for examining such questions.

Karst dissolution patterns can be affected at multiple scales by a myriad of influences, including: temperature, partial pressure of CO_2, precipitation, grain size, bedding thickness and lithology, permanent stresses inherent to the rock, quality and thickness of overburden, bacterial processes, slope, downcutting, hydrostatic pressures and quality and quantity of discharge (Jennings, 1985; Palmer, 1991; Driscoll, 1986). The methods in this study, which are readily transferrable to other watersheds, revealed some of the hydrogeomorphic patterns which have encouraged hydrological connectivity between surface, near-surface and sub-surface levels. These findings highlighted large and small-scale heterogeneities in bedding, slope and position in the watershed which have affected and likely continue to affect hydraulic gradients, dissolution patterns and hydrologic budgets within this basin.

The economic vitality of the LFRB is currently linked to intensive groundwater and surface water extraction; however, the deleterious effects of seasonal agricultural pumping on summer baseflows in tributaries of the LFRB have already been established (Rugel et al., 2012). Since small scale interactions have significant impact on basin-wide hydrologic budgets (Chapter 3, this document), further understanding of the precise interactions between the UFA and tributaries in this basin is merited and crucial to the development of sustainable and effective water management planning in this region. Comparing this information with existing data on presence and richness of species of concern in these tributaries, such as federally-endangered mussels and their host fish, will be beneficial in clarifying which reaches in this basin might support future recruitment, translocation and protection of these species. In addition, a more complete understanding of the density, intersection and influence of reach length relationships would be warranted for this region since both stream reach and conduit length can drive dissipation of energy in surface water and groundwater systems and influence biological, chemical, dissolution, uptake and dispersion processes within these systems (Doyle et al., 2003; Cardenas, 2008; Covington et al., 2012). Ideally these data could be used to distinguish regions of greatest concern for groundwater and stream capture thus reducing threats to both vulnerable stream biota and regional agricultural infrastructure.

Conclusion

Stream reaches, bedrock jointing and cave conduit formation within the LFRB shared some directional patterns including a NNW and NNE trend across most data sets, consistent with Tertiary period fracturing. Conduit formation in the deepest caves, Pineland Blue and Radium Springs, was dominated by the NNW trend; however, this trend was not shared with Chameleon Cave which exhibited more E-W passageways. Stream reaches in the LFRB displayed a dominant N-S trend which occurred up to 57% more often than other reach directions. Other major trends in stream orientation (NE-SW) agreed with regional tectonic jointing patterns. The NW-SE trend was gradually replaced (approximately mid-basin) by stream reaches trending NE-SW. Bedrock joints in Ichawaynochaway Creek were dominantly N-S with lesser sets at NW-SE, NE-SW and E-W, while Coheelee Creek, in the Lower Chattahoochee Basin, had major jointing sets in the NW-SE direction with a lesser E-W set. Surface fluvial geomorphology appears to be semi-adjusted to the Tertiary tectonic template; however, the dominant trend in N-S reaches in this region (which does not exist in sub-surface conduit trends) suggests an influence of neo-tectonic patterns on surface processes in this basin. Comparisons of these orientations with existing data on stream discharge, chemistry and biota would be vital to informing sustainable water resource management in this highly-allocated system.

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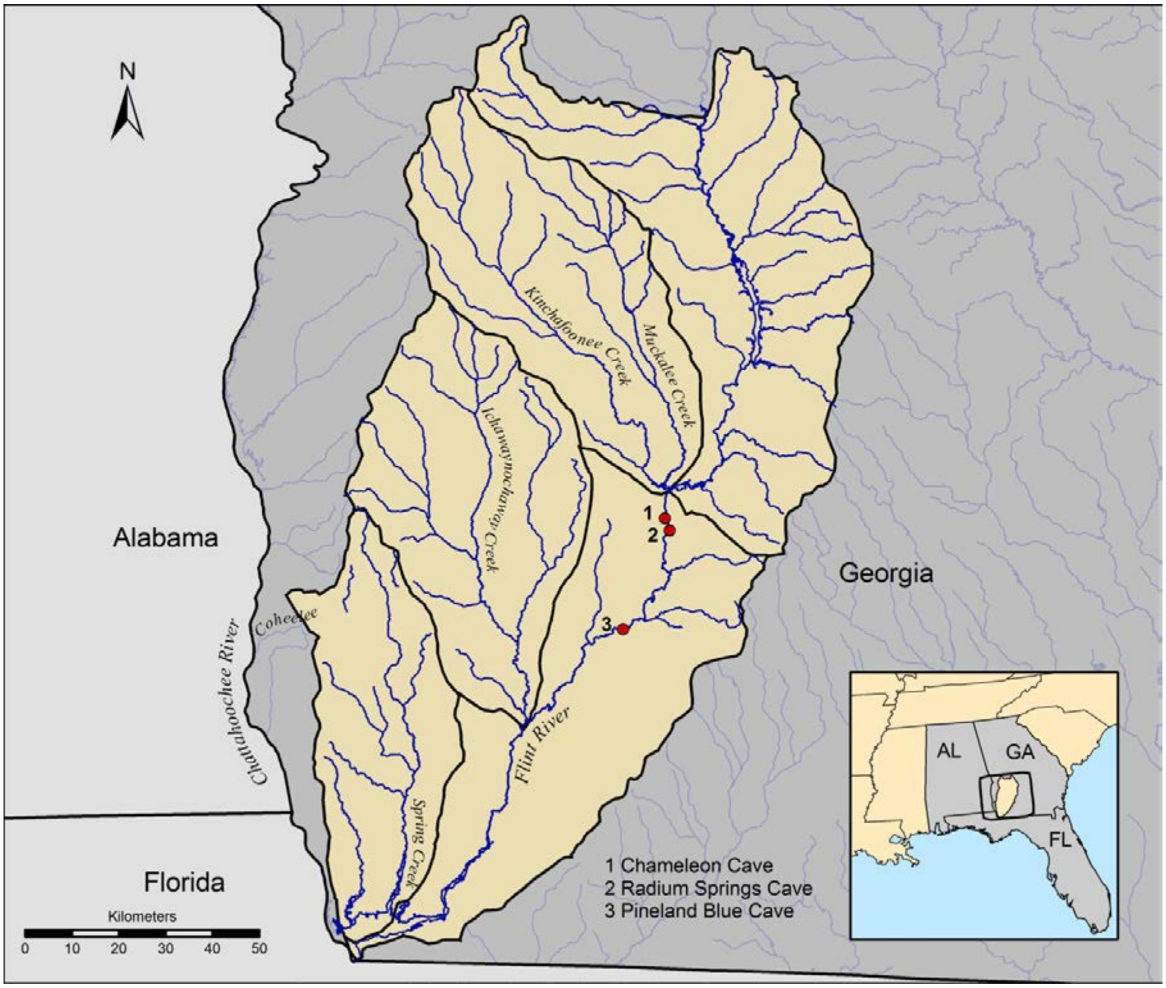

Figure 4.1. Map of study area showing the Lower Flint River Basin (LFRB) in southwestern Georgia, USA, including major tributaries of the lower Flint River, Coheelee Creek (Lower Chattahoochee River Basin) and the location of Chameleon, Radium Springs and Pineland Blue (Double Springs) Caves.

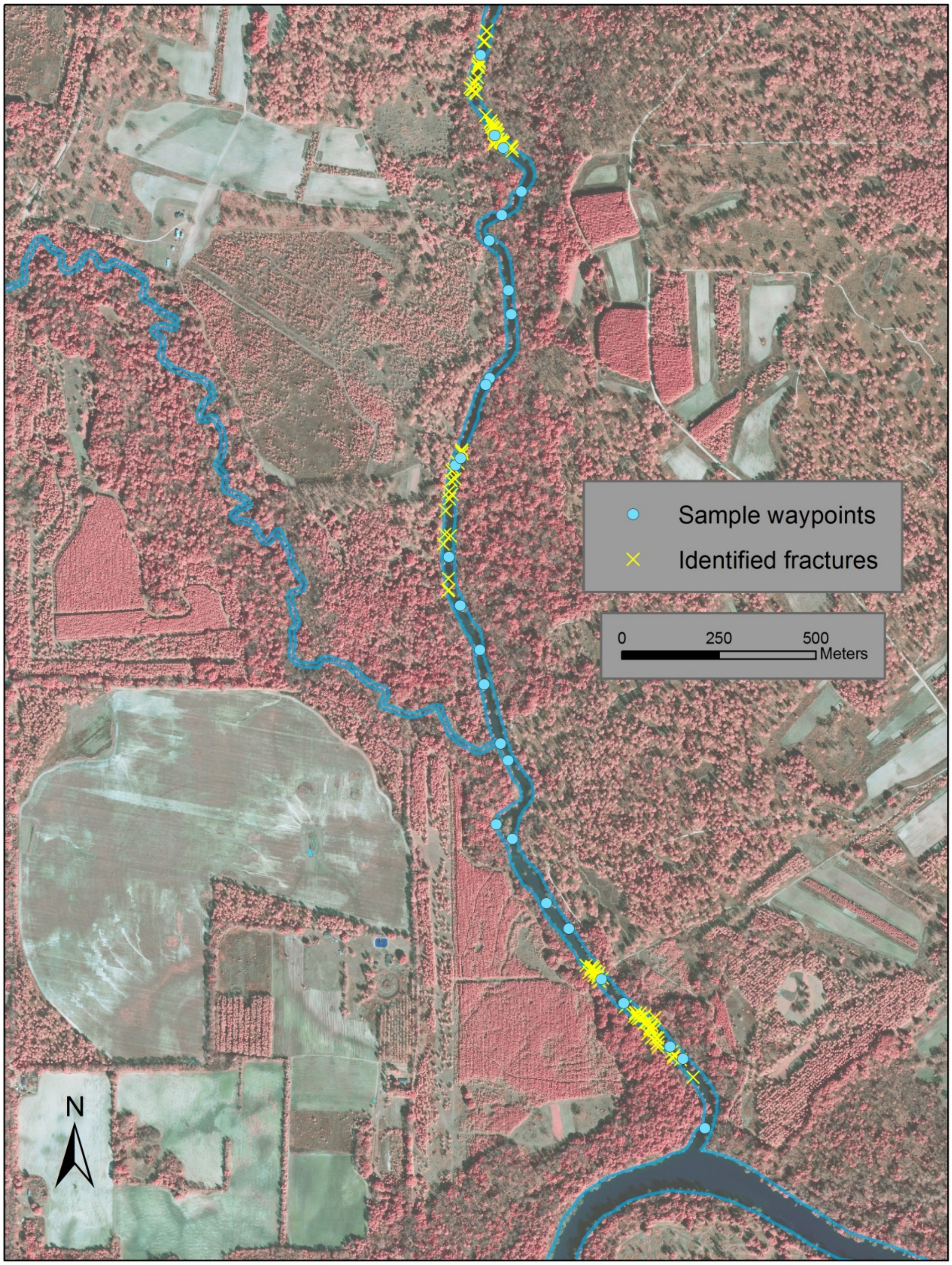

Figure 4.2. Location of semi-contiguous bedrock fractures (joints) outcropping directly above confluence of Ichawaynochaway Creek and Flint River, Baker County, southwestern GA, USA.

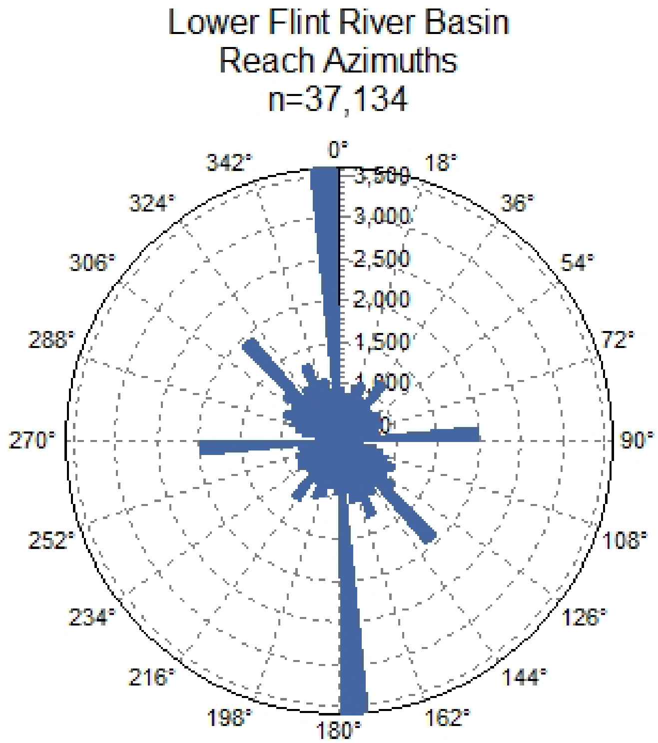

Figure 4.3. Rose diagram showing trends in orientation (azimuth) of all stream and river reaches within the Lower Flint River Basin, southwestern GA, USA.

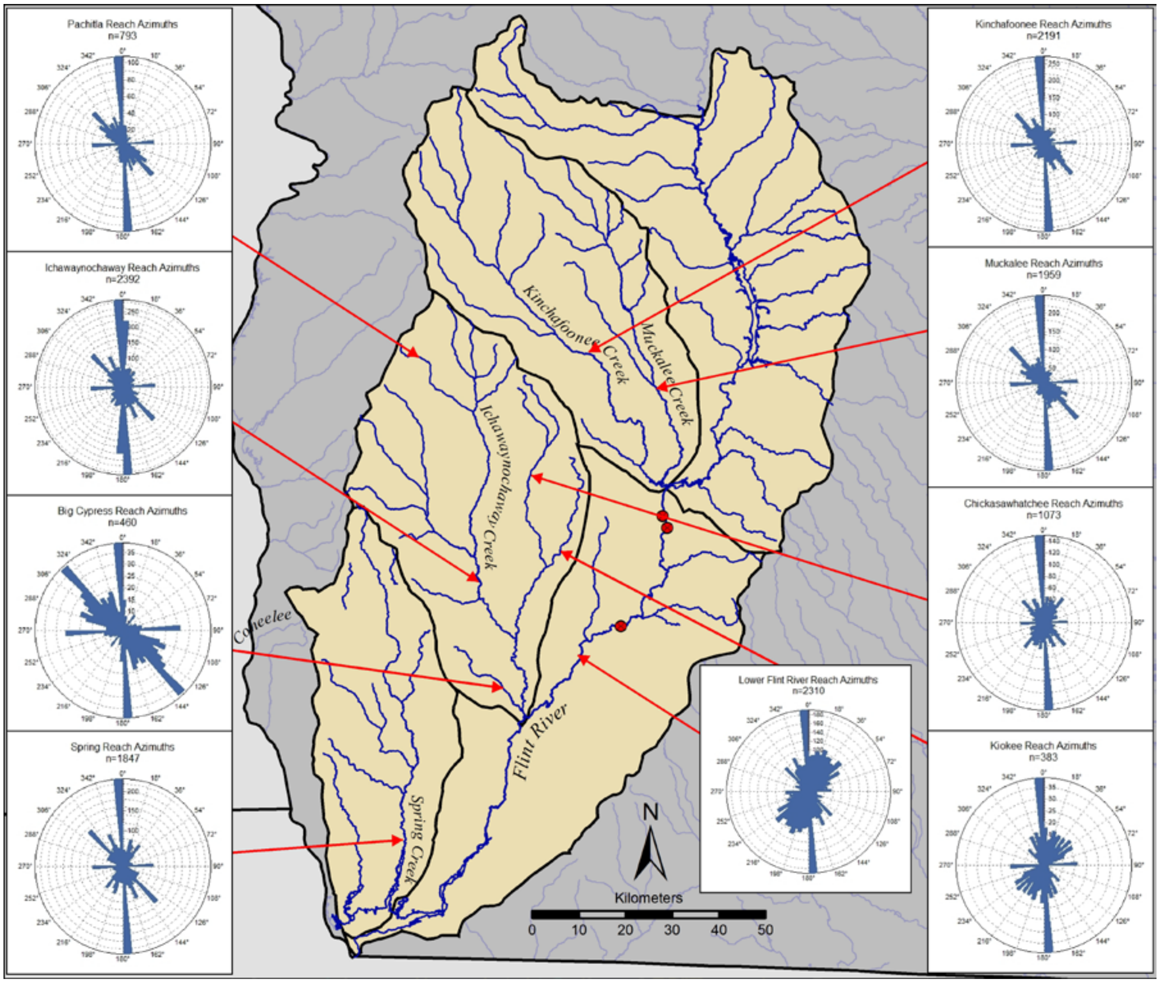

Figure 4.4. Rose diagram showing trends in orientation (azimuth) of stream and river reaches of major tributaries of within the Lower Flint River Basin, southwestern GA, USA.

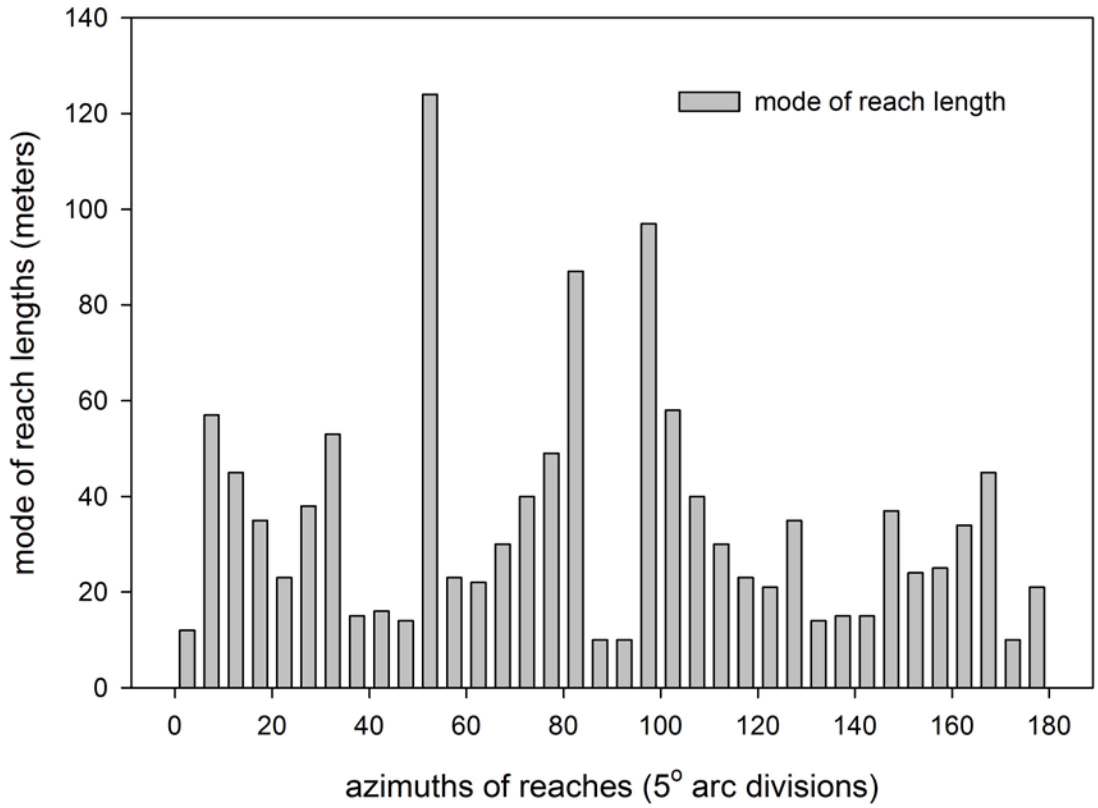

Figure 4.5. Mode of reach length versus reach azimuth (36 5° arc divisions) for all reaches in the LFRB (n=37,134).

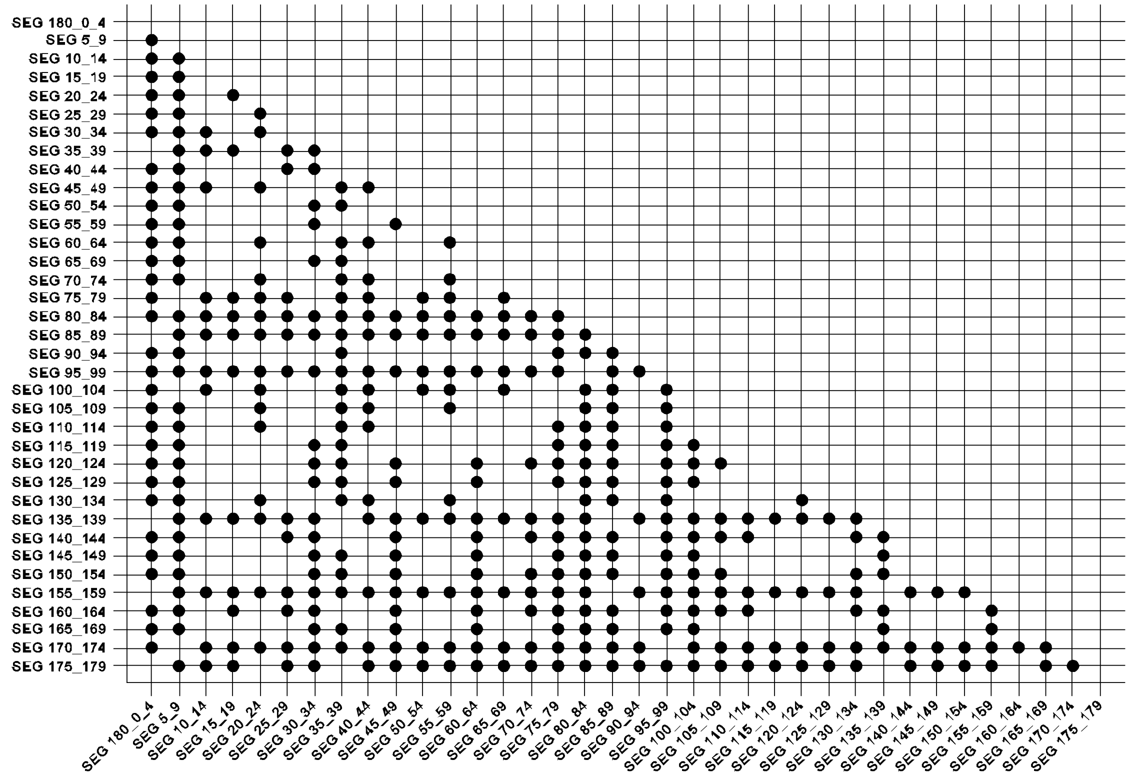

Figure 4.6. Results of multiple comparison procedures (Dunn's Method, P<0.05) for 36 (5^{o} arc) divisions (symbol indicates significant difference).

Figure 4.7. Remote sensing view of location, direction and extent of stream bedrock fractures (joints) measured within Ichawaynochaway Creek (n=125) in the Lower Flint River Basin, southwestern Georgia, USA, projected on 2011 National Agriculture Imagery Program (NAIP) aerial near infrared photography in ArcGISv.9 (downstream to upstream: Fracture site 1,2, and 3).

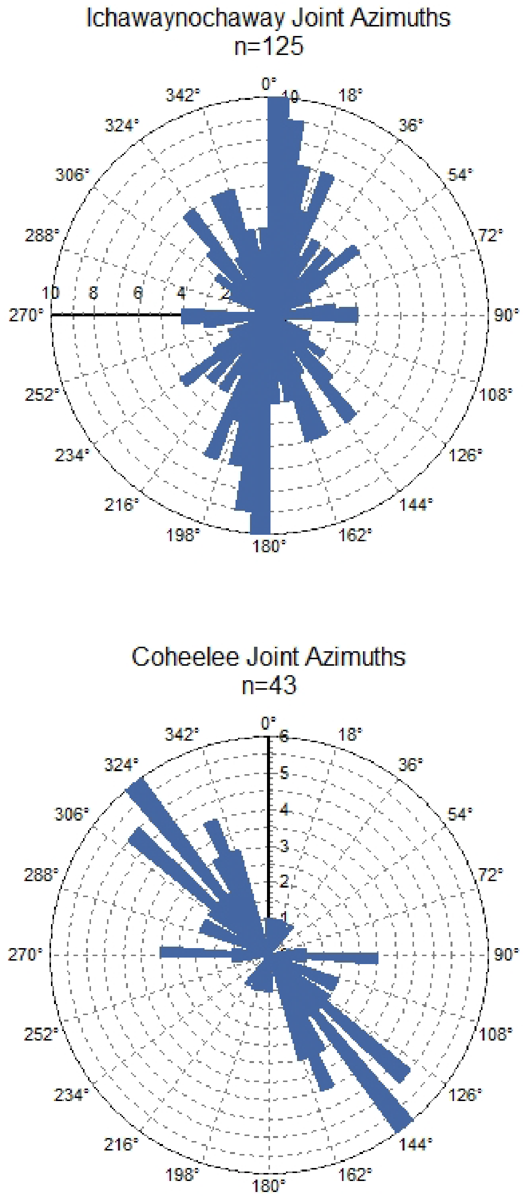

Figure 4.8. Rose diagram showing trends in orientation (azimuth) of stream bedrock joints in Ichawaynochaway Creek (n=125) in the Lower Flint River Basin, and Coheelee Creek (n=43) in the Lower Chattahoochee River, southwestern GA, USA.

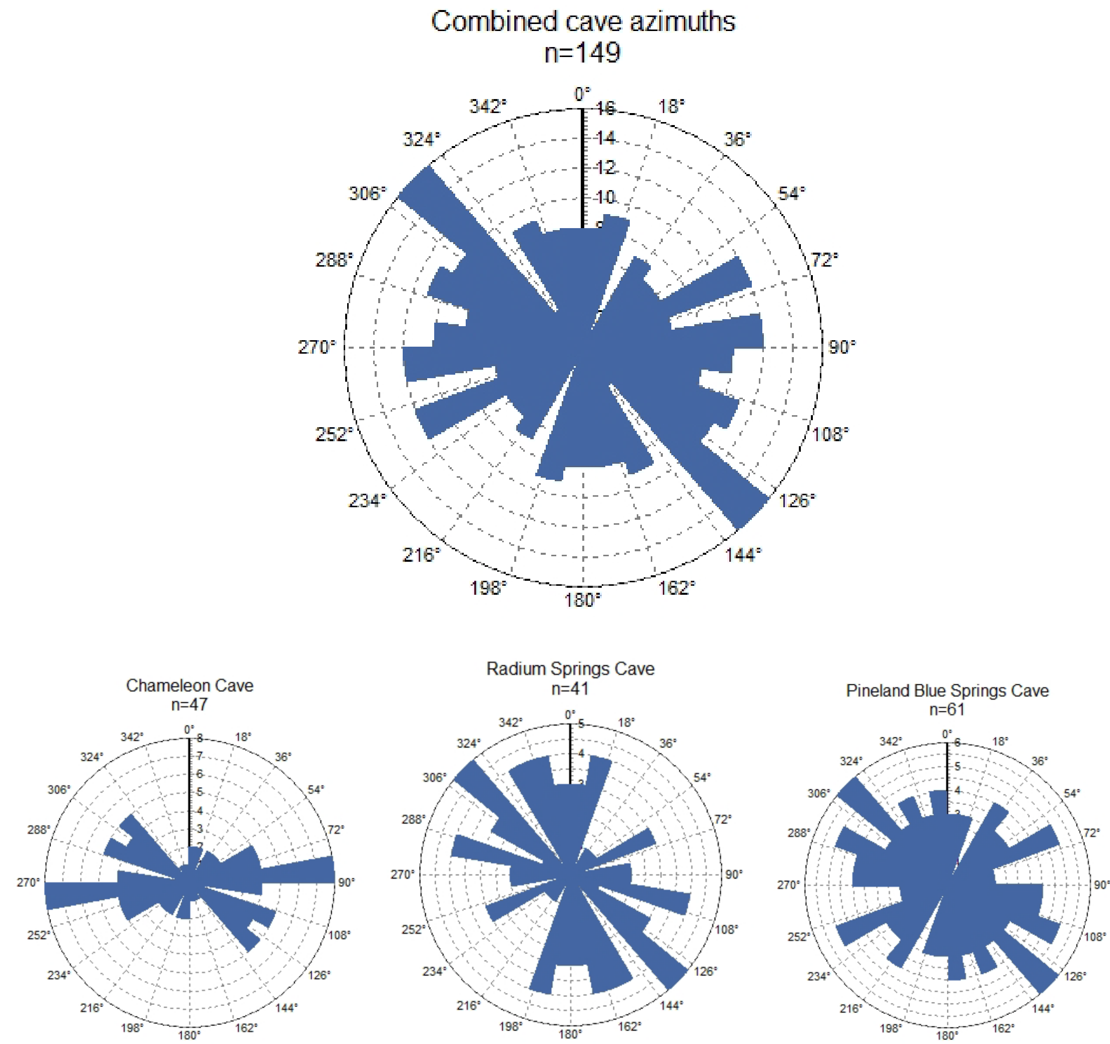

Figure 4.9. Rose diagrams showing trends in orientation (azimuth) of mapped conduits in all three underwater caves (combined, left), and individually: Chameleon (Dougherty County), Radium Springs (Dougherty County), and Pineland Blue (Baker/Mitchell County) Caves within the Lower Flint River Basin, southwestern GA, USA.

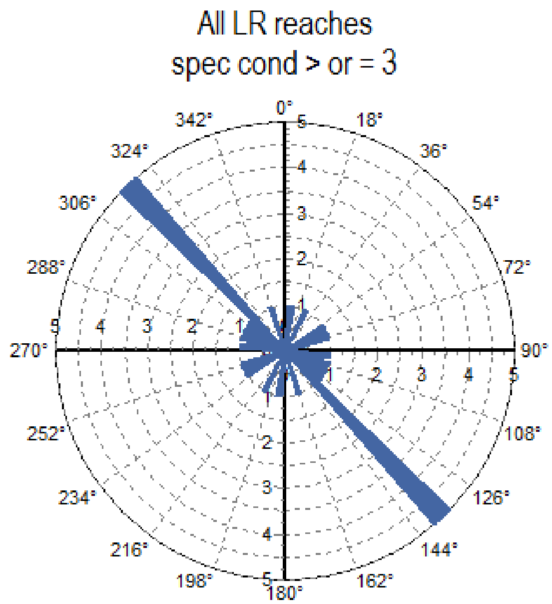

Figure 4.10. Orientation of stream reaches where significant interaction repeatedly occurred between the Upper Floridan Aquifer and Ichawaynochaway Creek during longitudinal sampling runs in 2010 (*see* Chapter 3, this document).

CHAPTER 5

CONCLUSION

This study makes a significant contribution to understanding the spatial and temporal heterogeneities inherent in the interactions of the UFA with tributaries in the LFRB. Results confirmed the high degree of exchange between groundwater and surface water components and showed that tributaries in this basin have been significantly impacted by agricultural pumping since irrigation intensified in the 1970s. Flow duration analysis on Ichawaynochaway and Spring Creek indicated reduced streamflows, including lowered median 7-day low flows that were 51% and 61%, of their pre-irrigation values for Spring Creek and Ichawaynochaway Creek, respectively. Early summer and annual baseflow recession curves for Ichawaynochaway Creek became steeper in the post-irrigation record concurrent with periods of seasonal and annual groundwater and surface water extraction in this region. These data showed that lost water accounted for 12 and 18% of lowest median monthly discharge in Spring and Ichawaynochaway Creek, respectively, resulting in extreme low flows and non-flowing conditions in historically perennial streams.

Results of coarse and fine scale sampling on Ichawaynochaway Creek showed that the UFA contributed from 5-29% of summer baseflows in 2010 increasing to as much as 72% at extremely low discharge in the 2011 sampling period. Calcium and specific conductivity, which indicated increased groundwater discharge, showed an almost perfect correlation during 2010 longitudinal runs (LRs) and suggested that up to 42% of the total groundwater inputs entering the stream came through five out of the fifty reaches sampled. Chickasawhatchee Creek delivered between 9-23% of these inputs during the 2010 sampling period.

Comparisons of hydrogeomorphic attributes at the surface, near surface and sub-surface indicated that stream reaches, bedrock jointing and cave passageway orientations in the LFRB shared directional similarities (NW-SE and NE-SW). Stream reach direction and stream bedrock jointing exhibited major N-S azimuth trends which suggested solutioning along neo-tectonic jointing trends, while cave conduit orientations were more consistent with tectonic (Tertiary) jointing patterns in this region (strongest in deepest caves). Stream reaches where groundwater inputs were found to be significantly greater during the 2010 LR sampling were oriented 30% more often in the NW-SE (N45W) direction. Further comparison of these hydrogeomorphic trends with available data on discharge, stream chemistry and species of interest (such as endangered mussels), will be useful for increasing our understanding of how hydrogeomorphology may be driving regional groundwater and surface water interaction and aquatic population dynamics in these groundwater-dependent systems. Ideally, these results would be used to inform the judicious placement of productive wells which avoid capture both of baseflow and endangerment of vulnerable aquatic species in specific locations within the stream.

Groundwater and surface water are interconnected hydrologic components which must be understood, allocated and protected as an integrated hydrologic resource (Stanford and Ward, 1993; Woessner, 2000; Winter, 2001; Sophocleous, 2002; Hancock et al., 2005). The consequences of groundwater and surface water extraction, and ensuing loss of baseflow, can be both immediate and long term, threatening ecosystem function in aquatic, riparian and upland habitats, as well as the underlying aquifer (Stamey, 1996;

Alley et al., 1999; Culver et al., 2000; Light and Darst, 2005; Allums et al., 2012). The deleterious effects of flow removal are ultimately transmitted to receiving estuarine and marine waters, resulting in both economic and environmental damage to downstream ecosystems which depend on adequate freshwater inputs. World-wide water use currently appropriates around 50% of global runoff and is growing at twice the rate of the population (WWAP, 2012). Growing tension between stakeholders, communities, states, and nations over the ownership and allocation of limited water resources will continue to demand worldwide attention (Shah et al., 2000; Ruhl, 2005, Strand, 2010).

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