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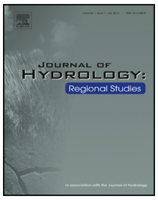

Delineating groundwater/surface water interaction in a karst watershed: Lower Flint River Basin, southwestern Georgia, USA

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ABSTRACT

Study region: Karst watershed in Lower Flint River Basin (LFRB), southwestern Georgia, USA.
Study focus: Baseflow discharges in the LFRB have declined for three decades as regional irrigation has increased; yet, the location and nature of connectivity between groundwater and surface water in this karstic region are poorly understood. Because growing water demands will likely be met by further development of regional aquifers, an important management concern is the nature of interactions between groundwater and surface water components under natural and anthropogenic perturbations. We conducted coarse and fine-scale stream sampling on a major tributary of the Lower Flint River (Ichawaynochaway Creek) in southwestern Georgia, USA, to identify locations and patterns of enhanced hydrologic connectivity between this stream and the Upper Floridan Aquifer.
New hydrological insights for the region: Prior water resource studies in the LFRB were based on regional modeling that neglected local heterogeneities in groundwater/surface water connectivity. Our results demonstrated groundwater inputs were concentrated around five of fifty sampled reaches, evidenced by increases in multiple groundwater indicators at these sites. These five reaches contributed up to 42% of the groundwater detected along the entire 50-km sampling section, with ~24% entering through one groundwater-dominated tributary, Chickasawhatchee Creek. Intermittent flows occurred in two of these upstream reaches during extreme drought and heavy groundwater pumping, suggesting reach-scale behaviors should be considered in resource management and policy.

1. Introduction

Groundwater is being increasingly utilized to serve a growing worldwide demand for freshwater (Shah et al., 2000; Gleick et al., 2009). Approximately 60% of all global groundwater use is for agricultural irrigation, which is mainly consumptive (Postel, 1999; WWAP, 2012). Intensive groundwater extraction has been shown to reduce stream baseflows, resulting in increased water temperatures, lowered dissolved oxygen, diminished assimilative capacity, reduced habitat complexity,

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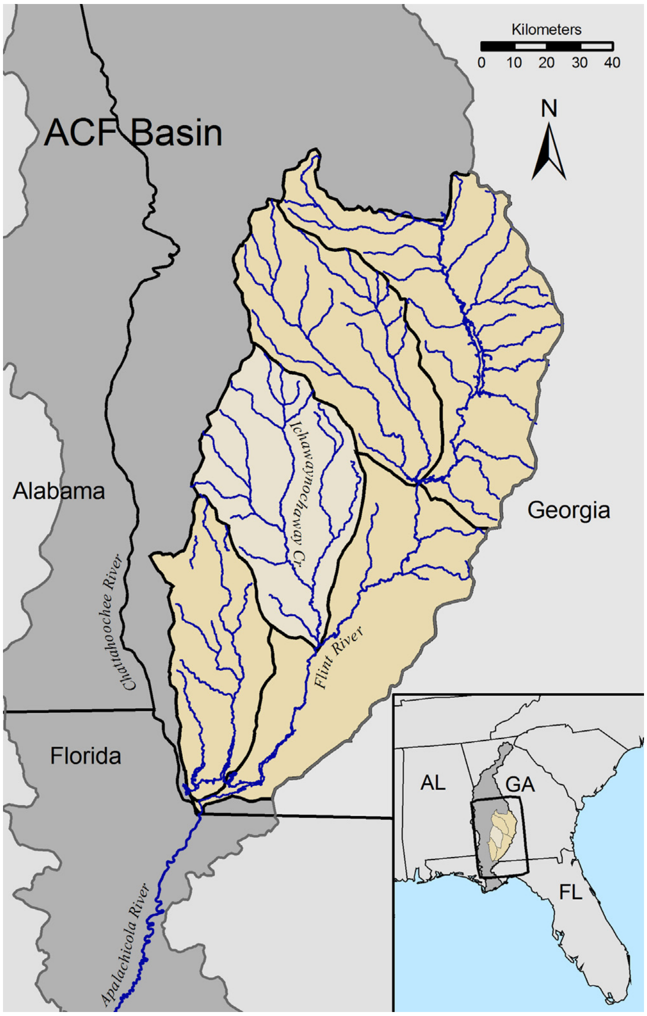

Fig. 1. Map of Lower Flint River Basin and Ichawaynochaway Basin within the larger Apalachicola-Chattahoochee-Flint River Basin in the southeastern United States.

and negative impacts on stream, riparian and upland biota (Stromberg et al., 1996; Bunn and Arthington, 2002; Golladay et al., 2004; Light et al., 2005; Zektser et al., 2005; Torak and Painter, 2006; Rugel et al., 2012).

It has become increasingly apparent that groundwater and surface water should be managed as a single resource (Woessner, 2000; Winter, 2001; Sophocleous, 2002); however, hydrologic connectivity in karst watersheds is poorly understood compared to alluvial, glacial and volcanic systems. High transmissivity in karst aquifers makes them ideal for the development of groundwater (Driscoll, 1986); however, this also exposes both groundwater and streams to over-extraction and degradation (Seitzinger et al., 2006). Because future freshwater demands will likely escalate the development of karst aquifers, the susceptibility of these systems will continue to increase, making it essential to discern the complexity of flow paths between surface and subsurface components.

The Apalachicola-Chattahoochee-Flint (ACF) River basin is a 50,000 km^2 watershed in the southeastern US. The ACF has its headwaters in northern Georgia and occupies portions of Georgia, Alabama and Florida, discharging into the Gulf of Mexico at Apalachicola Bay. Upper reaches of the ACF support fast-growing urban populations while water in the lower portion sustains agricultural irrigation, recreation, power generation, tourism, shrimping and oyster industries, in addition to populations of threatened and endangered aquatic biota. The Lower Flint River Basin (LFRB) is an economically important agricultural sector within the lower ACF (Fig. 1) generating $1.9 billion in farm gate revenues for the state (McKissick, 2004). Intensive irrigation in this region is mostly maintained using groundwater from the Upper Floridan Aquifer (UFA). This prolific carbonate aquifer underlies most of the southeastern US Coastal Plain and supplies over $15 \times 10^9\ \mathrm{m}^3\ \mathrm{d}^{-1}$ (15 GL/d) of water to more than ten million people in the southeastern US corridor (Marcella and Berndt, 2005). Between 1970 and 2000, irrigated acreage in the LFRB increased more than ten-fold, from 59,000 to 607,000 ha (590–6070 km^2), accounting for over half of statewide (Georgia) totals (Torak and Painter, 2006). Agricultural pumping in the LFRB has been correlated with seasonal declines in groundwater and surface water levels (Stamey, 1996; Couch and McDowell, 2006; Jones and Torak, 2006; Rugel et al., 2012). Reduced floodplain inundation and the replacement of wetland forests by upland species in lower portions of the ACF have also occurred during the period in which irrigation has intensified (Darst and Light, 2008; Torak and Painter, 2006).

In 2006, low flows, exceptional drought and declining mussel populations prompted the US Fish and Wildlife Service to designate 1863 river kilometers in the lower ACF as Critical Habitat for federally-listed mussels. Federal, state and regional management groups are currently in the process of assessing the economic impact of this designation on 45 counties across Alabama, Florida and Georgia. Decades of litigation between these states have failed to resolve water sharing conflicts (Ruhl, 2005); however, legal proceedings and stakeholder-driven negotiations within the ACF remain ongoing. Judicious water resource planning for this basin requires accurate and detailed hydrological information to support sustainable water resource allocation while protecting regional freshwater, estuarine and marine ecosystems.

Previous water investigations in the LFRB have primarily focused on groundwater development studies to support municipal water supplies (Brook and Sun, 1986; Hicks et al., 1987). Other regional analyses utilized modeling to predict basin-wide impacts of groundwater development on streams and threatened aquatic biota (Torak et al., 1996; Albertson and Torak, 2002; Mosner, 2002; Jones and Torak, 2006). While it is evident that the UFA is hydrologically connected to tributaries within the LFRB, there is little information on the nature of these connections and their direct influence on regional water budgets and water quality. The objective of this research was to characterize spatial and temporal variation of hydrologic connectivity between the UFA and a major tributary of the Lower Flint River (Ichawaynochaway Creek) and to identify characteristic features of high exchange settings.

The Ichawaynochaway basin lies in a portion of the LFRB with the highest levels of combined groundwater and surface water withdrawals in the state (Couch and McDowell, 2006). Previous analyses have shown that, in the thirty year period following expansion of agricultural pumping, median 7-day minimum flows in Ichawaynochaway Creek were reduced to 61% of their pre-irrigation levels, with the most rapid baseflow recessions corresponding to periods of heaviest groundwater withdrawals (Rugel et al., 2012). The sustainability of current water usage, dwindling baseflows, and the presence of threatened and endangered aquatic species in this region make gathering information on groundwater/surface water interaction a high priority on federal, state and local resource management levels.

Because flow in karst catchments can be influenced by multiple factors, such as depositional origin, jointing and local hydraulic gradients (Jennings, 1985; Freeze and Cherry, 1989; Mangin, 1994), we hypothesized that groundwater/surface water exchange between the UFA and Ichawaynochaway Creek would exhibit both spatial and temporal heterogeneity. More precisely, we expected groundwater to enter the creek discontinuously, through preferential flow paths, as opposed to homogeneous seepage along the stream length. We also predicted that water quality and discharge would be affected locally (at the reach scale) by both natural and anthropogenic stressors in the basin, such as drought and pumping. We tested these predictions using a series of coarse and fine-scale stream sampling protocols to detect incoming groundwater, and then used principal components analysis and a simple end-member mixing model to distinguish the relative contribution of groundwater and other source waters to Ichawaynochaway Creek. Finally, we attempted to characterize distinguishable features of reaches with enhanced connectivity in order to inform land and water planning in this and other karst basins.

2. Material and methods

2.1. Study site and hydrogeological setting

The study was carried out within the Ichawaynochaway basin (USGS HUC 8 hydrologic region 03130009) in the Dougherty Plain District of the Coastal Plain Province in southwestern Georgia, USA (Fig. 1). This drainage basin consists of approximately 2874 km^2 within Baker, Calhoun, Clay, Dougherty, Early, Miller, Randolph, Stewart, Terrell, and Webster counties. Most samples for the study were collected within Baker County with a small number in Calhoun County. All stream sampling was conducted on Ichawaynochaway Creek, a fifth-order tributary of the lower Flint River, which emerges from seeps and springs draining the Fall Line Hills (northwestern boundary of the Dougherty Plain) and terminates into the Flint River at the southern tip of Baker County, Georgia. Land use is dominated (approximately 50%) by row-crop farming of wheat, corn, cotton and peanuts supported by seasonal irrigation (April–September). Remaining acreage is a mixture of deciduous hardwood and longleaf pine/wiregrass forest, isolated marshes and cypress-gum wetlands (Couch and McDowell, 2006). Average regional slope is 2.4 m/km (Hicks et al., 1987). Mean air temperature in the Ichawaynochaway basin ranges from 6 to 20 °C in cooler months (October–March) to 18–31 °C during warmer months (April–September; http://www.ncdc.noaa.gov/cdo-web/, accessed July 2014).

Annual precipitation averages 1320 mm of which at least 790 mm is lost to evapotranspiration (Lawrimore and Peterson, 2000). Drought conditions dominated prior to this study with a deficit in 2007 rainfall of −323 mm (compared to record annual mean; National Climate Data Center, www.ncdc.noaa.gov/cag; accessed September 2015). While there was a slight increase in annual precipitation in 2008 and 2009, 85–90% of that rain fell during winter months (October–April). In 2010 and 2011, 35–61% of rainfall occurred during the summer months; however, total precipitation was −228 mm and −331 mm below the annual mean (2010 and 2011, respectively).

Hydrogeology of the 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). Moderate to mature karstification within the Ocala Limestone Formation has resulted in high secondary permeability and the formation of the Upper Floridan

Aquifer which underlies portions of South Carolina, Georgia, Alabama and most of Florida (with the exception of the NW Florida panhandle; Miller, 1986). High transmissivity within the region (4.6×10^3 –2.3×10^4 m^2 d^{-1}) allows for extensive municipal, industrial, rural and agricultural water withdrawals (Couch and McDowell, 2006). The lower boundary of the UFA in this region is the mostly impervious Lisbon Formation followed (in descending order) by the Claiborne Group (Claiborne and Clayton aquifers) and the Cretaceous (Providence) aquifer. Along with the UFA, these formations pinch out updip approaching the northwestern portion of the Dougherty Plain and Fall Line Hills and thicken downdip in a southeasterly direction toward the Gulf of Mexico. Thickness of the UFA in the study area is approximately 8–82 m (Clark and Zisa, 1976; Hicks et al., 1987). The aquifer is thinly confined by overburden in this area but may be unconfined where erosional features exist, including sinkholes and incised streambeds (Miller, 1986; Warner, 1997). Streams in this region can be hydraulically connected to the UFA through springs, fractures, conduits and stream bedrock. Aquifer recharge normally occurs during winter months when evapotranspiration rates are low.

2.2. Sampling protocols

2.2.1. End member sampling 2009–2011

To distinguish the composition of source components and identify longitudinal inputs of groundwater to the stream, samples were collected from three end members within the Ichawaynochaway basin between 2009 and 2011 (precipitation, deep groundwater and wetlands; one shallow aquifer was sampled during the study but was not included in the end-member calculation; Torak et al., 1996). Rainfall was collected for approximately two hours during storms by placing an acid-washed 13 × 20 cm Pyrex® glass pan approximately 50 cm above the ground surface in an open area (no canopy within 20 m). All collections (five between October and December, 2009, and six between June and July in 2010) were made at a single location on the grounds of the Joseph W. Jones Ecological Research Center (JWJERC) in Baker County, Georgia. Rainfall samples used to determine $\delta^{18}O$ and δD were transferred to glass scintillation vials, filled to capacity, capped with nipple caps to remove air, and sealed with tape to prevent atmospheric contamination (Kendall and Caldwell, 1998). Samples for cation and anion analysis were filtered through ashed 0.45 μm Millipore® glass filters, transferred to 20 mL scintillation bottles, and frozen until analysis. Atmospheric conditions including temperature, relative humidity, wind speed and direction were recorded for each rain event.

Groundwater samples were collected from thirteen wells located throughout the Ichawaynochaway basin between October and November of 2009. All wells were within a 2-km buffer on either side of Ichawaynochaway Creek, from Morgan, Georgia, in the upper portion of the basin, to approximately 2 km from the confluence of Ichawaynochaway Creek and the Flint River (lower Baker County). Few standardized monitoring wells are available in this region; therefore, groundwater samples were collected from house and small farming wells which access the UFA (no center pivots), most of which were in daily use. As precise borehole widths and depths were unavailable, best judgement was used to purge wells (Wilde et al., 1998) by opening spigots full force for 10 min prior to collection. This alternative procedure was based on an estimated average well depth of 15–38 m with water table depths between 3 and 15 m and a pumping rate of approximately 20 L/min. Wells which were not in daily use or were estimated to be deeper were drained for 15–20 min. If tanks were present, samples were taken from in-line spigots before tank. All samples were prepared for analysis following methods above (this section). Navigational coordinates were collected at each wellhead using a Garmin Oregon® 550 GPS unit. Wells were resampled in August of 2011.

One shallow aquifer well 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 third of the study area on JWJERC property (approximately 3 m below the land surface) and represented the only identifiable surficial groundwater well within the study area developed for sampling. The well was purged for ten minutes using a peristaltic pump and water was collected and prepared for analyses as above.

Two depressional wetlands (Pond 68 and Pond 51) were sampled in May 2008 to determine if these surface features shared a connection with shallow or deep groundwater. Collections were made using a long-handled scoop and samples were prepared for analyses as above. Exceptional drought conditions prevailed during most of the remaining study period which prevented filling and resampling of these ephemeral wetlands during 2009 and 2010. Pond 51 was resampled in August 2011.

2.2.2. Longitudinal runs (LRs) 2010

The heterogeneous nature of Ichawaynochaway Creek, including bed, flow, solar insolation and temperature, suggested that groundwater inputs would be difficult to locate utilizing these parameters and easiest to detect following general mixing of incoming groundwater with the stream. An initial coarse-scale (LR) study was designed to identify locations where sustained changes in stream chemistry parameters [including specific conductance, Ca^{2+} and stable isotope values ($\delta^{18}O$ and δD)] indicated incoming groundwater entering the stream at the reach scale. Once identified, finer scale (SR) sampling was used to further reveal the exact location and driver of these inputs.

Longitudinal sampling runs (LRs) were conducted on Ichawaynochaway Creek to detect coarse-scale interaction between the UFA and this tributary. To eliminate the influence of overland flow, all readings and samples were taken under baseflow conditions during summer or fall months (between June and November 2010). A 50-km section of the stream was sampled three times, commencing at the downstream confluence of Ichawaynochaway Creek and the Flint River and working in an

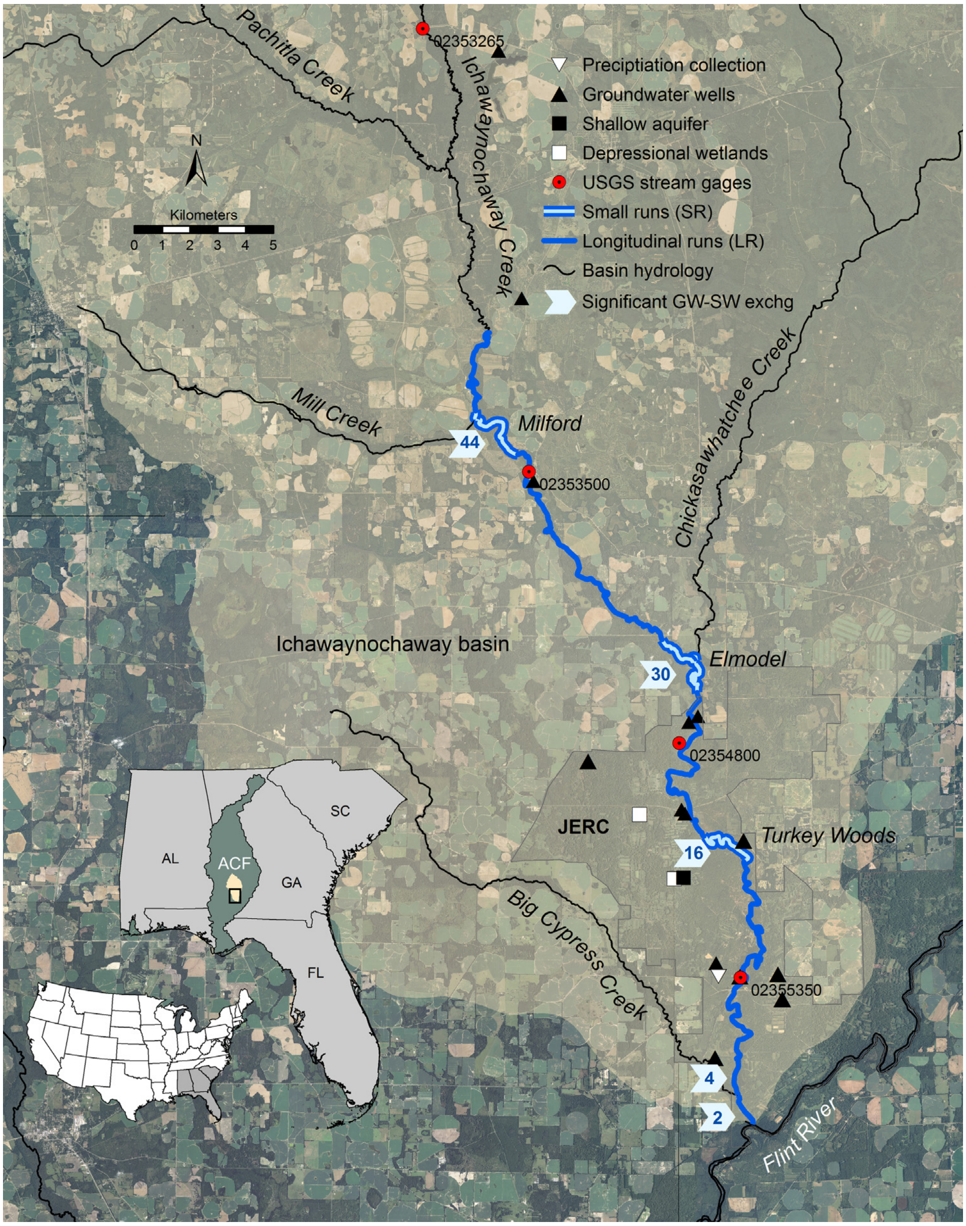

Fig. 2. Map showing geographical setting and locations of all collection sites within the Ichawaynochaway basin. Arrows indicate reaches where significant changes in specific conductance were consistently detected, suggesting groundwater inputs from Upper Floridan Aquifer. USGS stream gage on Ichawaynochaway Creek at Morgan, Georgia (2353265, top center of map), was used as upstream discharge reference throughout study.

upstream direction (Fig. 2). All testing was conducted from a small motorboat at 1-km intervals along the stream section (6/10 depth, mid-channel). Water depth, pH, temperature and specific conductance were measured using a hand-held Hydrolab Quanta, calibrated daily before each run. Whole water samples for cation, anion and isotope analyses were collected through Teflon® tubing with a Little Giant® Pony Pump (purged for approximately 30 s between samples) into 200 mL acid-washed Nalgene® polycarbonate bottles. Samples for cation and anion analysis were kept on ice, returned to the laboratory within six hours, filtered and frozen. Samples for stable isotope analysis were prepared and stored as above (Section 2.2.1). Navigational coordinates were taken at each sampling site during all LR runs. Minor differences in replicating collection points occurred during individual runs due to varying stream discharge and navigability issues; however, this did not constitute a substantial offset at the 1-km scale.

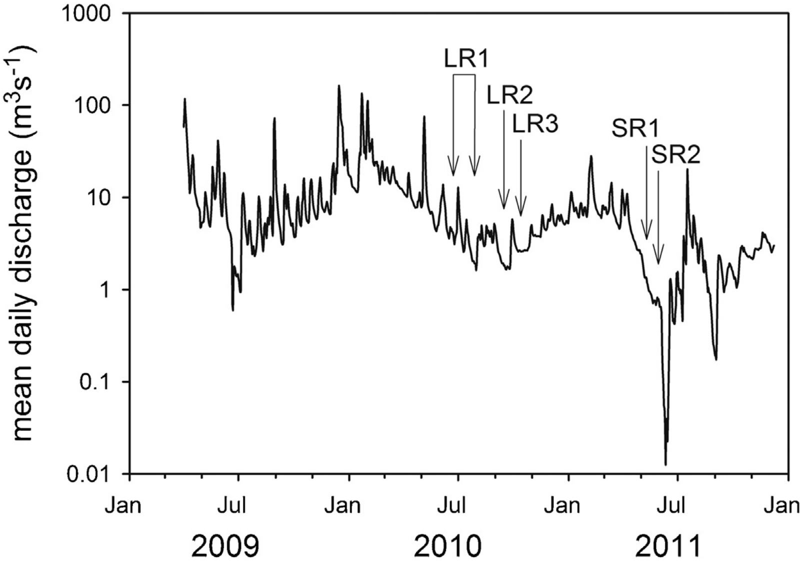

Fig. 3. Discharge of Ichawaynochaway Creek recorded at USGS stream gage at Morgan, Georgia (2353265), used throughout study as upstream discharge reference (hydroperiod March 2009–December 2011).

2.2.3. Short runs (SRs) 2011

Three 3-km reaches were selected for resampling in 2011 (from within the original 50-km section) to examine groundwater/stream interaction at a finer scale. Sampling was conducted under summer baseflow conditions during a period of intensive groundwater pumping and exceptional drought (Fig. 3). Selection criteria required each SR site contain a central kilometer where significant changes in specific conductance (Δ SpCond) were detected during 2010 LR sampling runs (>2 μS/cm/km; see Section 4.2) flanked by contiguous reaches (1 km upstream and 1 km downstream) where little or no changes were observed (<2 μS/cm/km). This ensured that changes occurring in the central kilometer of interest would not be confounded by adjacent inputs. The 3-km reaches were sampled at 200 m intervals on two occasions (SR1 and SR2 collections). With the exception of scale, all protocols followed those used in 2010 LRs. The order of SR sites from upstream to downstream was: Milford (M), Elmodel (E) and Turkey Woods (TW). The first sampling (M1, E1 and TW1) occurred in May 2011 and was repeated in June 2011 (M2, E2 and TW2).

The USGS stream gage 02353265 at Morgan, Georgia (Fig. 3) was used as an upstream discharge reference during the study. This gage showed daily stream discharge during LR collections averaged 3.5 and 2.6 m^3 s (3500 and 2600 Lps; June and October, 2010, respectively). In 2011, discharge was 1.07 m^3 s (1070 Lps) during SR1, dropping to approximately 0.04 m^3 s (40 Lps) during SR2.

3. Theory/calculation

3.1. Principal components analysis

Principal components analysis (PCA) can be used to provide a preliminary understanding of water quality signatures for end-member mixing analysis in order to determine which components contribute to the greatest variability in data sets (Christophersen and Hooper, 1992).

For this study, a PCA was performed in MATLAB (R2014b; The MathWorks, Inc., Natick, Massachusetts, USA) to estimate components and component scores for the correlation matrix between six water quality variables (specific conductance, pH, calcium, nitrate, and two isotopic ratios: $^{18}O/^{16}O$ and $D/^{1}H$). Factor scores were then used to plot each water quality variable as well as dummy variables which represented values from coarse and small scale stream sampling runs (LR1, LR2, LR3, SR1 and SR2) and end members: Groundwater, Wetland, and Rainfall.

3.2. Groundwater contribution to streamflow

As carbonic acid in infiltrating soil water reacts with limestone structure in karst systems, dissociated ions, including Ca^{2+}, are released into the sub-surface and discharged into hydraulically-connected surface waters (Hem, 1970; Driscoll, 1986). In this study, calcium concentration was entered into a simple mixing model to estimate gross and reach-scale contributions of Floridan aquifer discharge to Ichawaynochaway Creek during 2010 and 2011 sampling (Katz et al., 1997). The following three-member mixing equation, adapted from Kincaid (1998), assumed minimal contribution from shallow groundwater and was unweighted for discharge (flow data unavailable at sampling scale).

$$X = \frac{\left(R_s - \left(R_p + R_w\right)\right)}{\left(R_a - \left(R_p + R_w\right)\right)} \tag{1}$$

where X = fraction of groundwater in stream sample, $R_s = [Ca^{2+}]$ in stream sample, $R_p = [Ca^{2+}]$ in precipitation, $R_a = [Ca^{2+}]$ in aquifer (UFA groundwater), $R_w = [Ca^{2+}]$ in depressional wetlands.

3.3. Stable isotope analysis

Naturally occurring stable isotopes of water, such as ^{16}O and ^{18}O as well as ^{1}H and ^{2}H (deuterium, or D), undergo fractionation as they move through the hydrologic cycle. As condensation occurs, precipitation may become more enriched or depleted in the ratios of these isotopes dependent upon storm origin, direction and altitude, as well as season and duration of rainfall (Gonfiantini et al., 1998; Kendall and Coplen, 2001). ^{18}O generally retains the signature of its source (such as precipitation or stream) but is known to undergo fractionation when exposed to calcite within the carbonate system (Jennings, 1985). Both ^{18}O and deuterium may become enriched within clouds as storms move inland and "rain out" lighter isotopes (^{16}O and ^{1}H). This affects the ratio of oxygen and hydrogen isotopes remaining in the cloud, causing enrichment in subsequent rainfall. These stable isotopes may also be affected (normally enriched) by post-rainfall evaporative effects, such as temperature during condensation and evaporation which occurs during throughfall, ponding, and soil infiltration (Dawson and Ehleringer, 1998). Deuterium depletion is usually an indication of storm origin, for example, tropical versus arid storm source.

The relative ratios of $^{18}O/^{16}O$ (referred to as $\delta^{18}O$) and $D/^{1}H$ (referred to as δD) are therefore informative for distinguishing the degree of variation in source waters and the relative influence of surface and sub-surface processes on water in these systems. To this end, end member and stream samples collected between 2009 and 2010 were analyzed for these isotopes relative to Vienna Standard Mean Ocean Water (VSMOW) reference standard (Kendall and Coplen, 2001) and reported in parts per thousand (‰);

$$\delta^{18}O = \left(\left(\frac{\left(^{18}O/^{16}O\right)\text{ sample}}{\left(^{18}O/^{16}O\right)\text{ VSMOW}}\right) - 1\right) 1000 \tag{2}$$

and

$$\delta D = \left(\frac{\left(\left(D/^{1}H\right)\text{ sample}\right)}{\left(\left(D/^{1}H\right)\text{ VSMOW}\right)} - 1\right) 1000 \tag{3}$$

3.4. Water quality assessment

Agricultural applications of fertilizers and organic nutrients from livestock production are ubiquitous within the LFRB (Allums et al., 2012). The interconnected nature of surface and sub-surface drainage in this and other karst systems makes these watersheds particularly vulnerable to water quality degradation. To determine the presence, concentration and movement of nutrients between surface and subsurface components in the Ichawaynochaway basin, precipitation (2009–2010), groundwater (2009) and LR stream samples (2010) were evaluated for NO_3-N concentration (Allan, 1995) using methods described below (Section 3.5).

3.5. Sample analysis

Whole water samples were analyzed for calcium at the JWJERC using flame atomic absorption spectroscopy on a PerkinElmer 5100 (2010) and a PerkinElmer AAnalyst^{TM} 400 (2011) with addition of a lanthanum/hydrochloric acid mixture to increase sensitivity (3500-Ca B. Atomic Absorption Spectrometric Method). Nitrate concentrations (NO_3-N) were determined at JWJERC on a Lachat QuikChem® 8500 by flow injection analysis adapted from Lachat procedures 10-107-04-1-B. Stable isotope values were assessed by the UGA Center for Applied Isotope Studies in Athens, GA. $\delta^{18}O$ and δD were determined by using high temperature pyrolysis at 1440 °C to convert water to H_2 and CO on a Thermo thermal conversion elemental analyzer (TCEA), followed by individual measurement of $^{18}O/^{16}O$ and D/H values on a Thermo Delta XL plus stable isotope mass spectrometer.

Strict quality controls were maintained throughout all analyses including calibrations using instrument blanks and standards, verified at the beginning, end and every 10–15 samples, as well as duplicates and spikes at twenty sample intervals.

Unless otherwise indicated, all statistical analyses were performed using SigmaPlot 11.0 (Systat Software, Inc., San Jose, California, USA) at $\alpha = 0.05$ significance level.

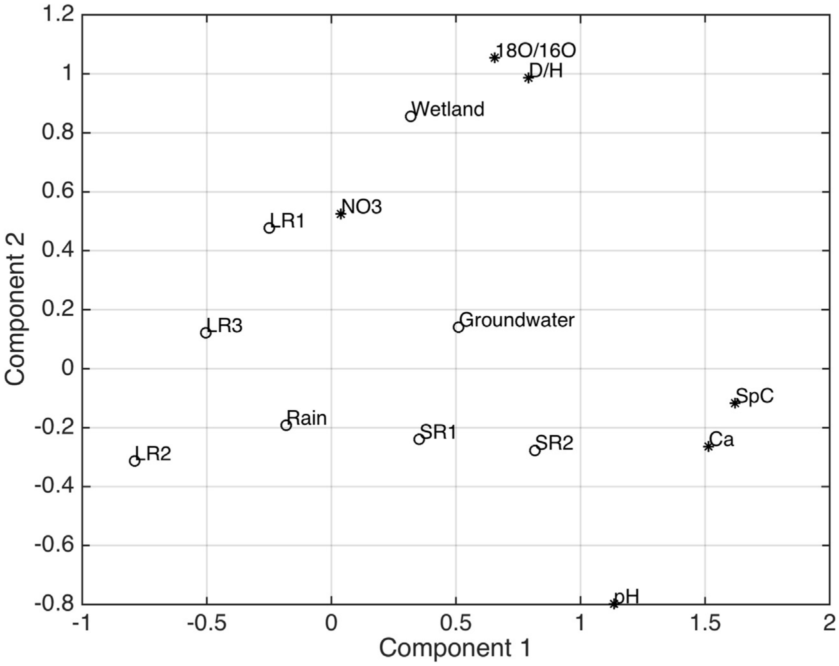

Fig. 4. Results of principal components analysis on six stream parameters [calcium, specific conductance, nitrate, pH and stable isotope ratios (^{18}O and D)] along with dummy variables for end members, LR (2010) and SR (2011) samples. PCA confirmed 49% of variation in water chemistry of the 50-km stream study section was explained by a component associated with groundwater (Axis 1) and a second component (wetland) explained 27% of additional variation (Axis 2). Streamflow sources varied under different baseflow conditions.

4. Results

4.1. Principal components analysis

Principal components analysis indicated two dominant components that explained 69% of the variability in the stream sampling data. The first component (Axis 1, Fig. 4) explained 42% of the variation and corresponded to elevated pH, specific conductance, and calcium concentration. The second component (Axis 2) explained an additional 27% of the variation and was associated with higher isotopic variability and lower pH. Groundwater weighed heavily on the first component while the second component was more associated with wetlands or possibly soil water. Inclusion of a third component (not shown) cumulatively explained 88% of the variation in these data and was associated with nitrate as well as calcium and groundwater. The stream sampling runs loaded on the first component (groundwater) from SR2, SR1, LR1, LR3, and LR2 (greatest to least). LR1 also loaded on the second component (wetlands), and to nitrate.

4.2. Floridan aquifer contribution

End-member analysis reinforced the findings that significant inputs of groundwater were entering Ichawaynochaway Creek throughout the study period. Longitudinal (LR) sampling indicated Floridan groundwater constituted from 0 to 24% of stream flows during LR1, 2–25% during LR2 and 3–25% during LR3. These ranges represent a continuum from upstream to downstream, with the lowest concentrations in upstream reaches and the highest concentrations accumulating downstream (max–min in Table 1). During finer scale SR sampling in 2011, groundwater composed approximately 26% of baseflow upstream (around Milford) increasing to 42% at the most downstream SR site (Turkey Woods) during SR1. As streamflow decreased during the SR2 sampling, groundwater accounted for 70% of baseflow upstream at Milford decreasing to 38% of flows downstream at Turkey Woods. Data from the locations of high aquifer/stream interaction (around Sites # 2, 4, 16, 30 and 44) showed that 30–42% of the groundwater detected throughout the entire study entered the stream through these five reaches (see Section 4.4).

4.3. Stable isotope analysis

Both stable isotope and physicochemical analyses distinguished end members from one another (Fig. 5, Table 2). Groundwater samples were slightly more enriched in $\delta^{18}O$ compared to precipitation. Rainfall samples indicated variation in both $\delta^{18}O$ and δD, reflecting the wide range in duration and sources of storms recorded during the collection period (mix of inland and tropical storms). The shallow aquifer was more enriched in $\delta^{18}O$ and δD compared to (deep) groundwater and

Table 1
Physiochemical characteristics of stream samples from Ichawaynochaway Creek (2010–2011) and end members (2008–2011) in Ichawaynochaway basin, southwestern Georgia, USA.

	Temp (°C) max–min	pH max–min	Depth (m) max–min	Sp.cond. (μS/cm) max–min	Ca^{2+} (mg/L) max–min	NO_3-N (mg/L) max–min	
Longitudinal runs (LRs)							
LR1	n = 51	30.04–26.13	7.84–7.18	5.17–0.20	155–83	14.50–2.60	1.58–0.84
LR2	n = 51	20.22–18.03	7.98–7.30	4.25–0.12	122–54	14.90–2.90	1.35–0.96
LR3	n = 51	19.12–16.53	7.92–7.31	4.33–0.25	122–55	14.90–3.26	1.33–1.13
Short runs (SRs)							
Milford 1 (M1)	n = 16	21.45–19.72	7.98–7.79	1.75–0.20	142–131	17.87–14.67	
Elmodel 1 (E1)	n = 16	26.35–24.32	8.10–7.86	2.00–0.10	180–163	21.10–17.48	
Turkey woods 1 (TW1)	n = 16	25.20–23.69	8.23–7.59	2.90–0.20	184–181	23.01–17.36	
Milford 2 (M2)	n = 16	28.18–25.30	7.96–7.63	1.50–0.17	267–238	36.66–27.72	
Elmodel 2 (E2)	n = 16	29.04–26.49	8.10–7.86	1.50–0.17	230–213	28.69–21.03	
Turkey woods 2 (TW2)	n = 16	28.36–25.48	8.10–7.80	2.50–0.25	216–205	25.94–21.80	
						Ca^{2+} (mg/L) mean (std. dev.)	NO_3-N (mg/L) mean (std. dev.)
Precipitation							
2009	n = 5					0.09 (0.07)	0.08 (0.06)
2010	n = 6					0.22 (0.29)	0.09 (0.05)
Groundwater wells							
2009	n = 13					51.14 (9.11)	1.87 (1.56)
2011	n = 13					51.30 (8.93)	
Shallow aquifer							
2011	n = 1					0.02	
Depressional wetlands							
2008	n = 2					5.03 (Pond 68)	
2011	n = 1						2.63 (Pond 68) 1.25 (Pond 51)

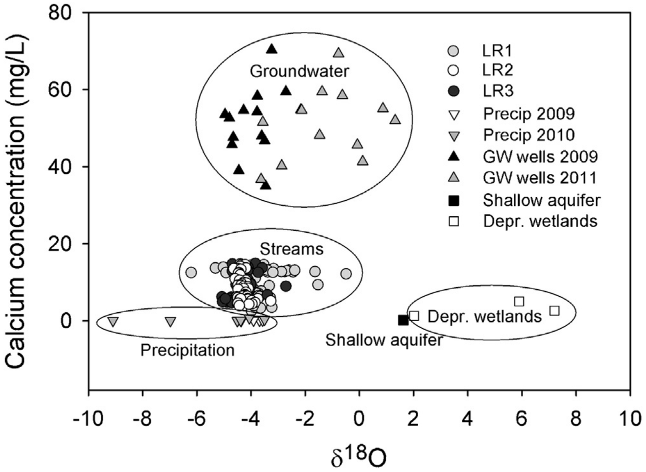

Fig. 5. Calcium concentration versus δ^{18}O values (‰) of end members and surface waters collected within Ichawaynochaway basin in southwestern GA.

Table 2
Isotopic values of relative ^{18}O/^{16}O and D/H for end members in Ichawaynochaway sub-basin (2008–2011) and 2010 longitudinal sampling (LRs) on Ichawaynochaway Creek, Baker County, Georgia, USA [including slope/y-intercept of Local Meteoric Water Line (LMWL)].

	δ^{18}O (‰) mean (std.dev)	δD/H (‰) mean (std.dev)	Slope/y-intercept of LMWL	
Precipitation				
2009	$n=5$	−4.11 (0.60)	−18.10 (7.60)	11.08/28.08
2010	$n=6$	−5.42 (2.16)	−25.02 (9.68)	5.72/4.37
Groundwater wells				
2009	$n=13$	−3.19 (0.70)	−19.52 (2.11)	-0.54/-21.67
2011	$n=13$	−3.22 (0.27)	−18.58 (1.51)	4.23/-4.95
Shallow aquifer depressional Wetlands	$n=1$	1.62	−9.18	–
2008	$n=2$	6.55	16.45	–
2011	$n=1$	1.44	2.69	–
Longitudinal runs (LR)		δ^{18}O (‰) max–min	δD/H (‰) max–min	Slope/y-intercept of LMWL
LR1	$n=51$	−1.53–(−6.21)	−11.23–(−24.50)	0.07/−16.51
LR2	$n=51$	−3.27–(−4.64)	−27.21–(−32.65)	−0.60/−32.51
LR3	$n=51$	−2.71–(−5.07)	−16.41–(−24.46)	−0.12/−21.09

precipitation (Fig. 6). Depressional wetland samples had the highest enrichment of all end members for both stable isotopes, presumably due to preferential removal of ^{16}O and H^1 during evapotranspiration.

Stream samples ranged along a continuum (isotopically) between end members during 2010 LR collections (Table 2). Most LR stream samples (as well as end members) fell around the Local Meteoric Water Line (LMWL) for Georgia river waters (Kendall and Coplen, 2001 Fig. 6). Local meteoric water lines represent averages of inter-annual and intra-annual variability between δ^{18}O and δD within a region and reflect the combined effects of storm source, relative humidity, temperature, evaporation and enrichment or depletion on originating precipitation (Ingraham, 1998). With the exception of precipitation samples, most samples during the study had lower slopes (δD/δ^{18}O) compared to the LMWL, indicating evaporative effects on the sample group as a whole.

While no longitudinal (upstream to downstream) trends were detected in mean isotopic values, there was substantial variation in δ^{18}O values along the stream route during LR1, with increases in δ^{18}O occurring at approximately 10 sample sites (Fig. 7). Increases at these sites were less obvious during LR2 and LR3. LR2 samples were significantly more depleted in δD compared to the other LRs and fell to the right of and below the LMWL (Kruskal–Wallis One Way Analysis of Variance on Ranks, $p<0.001$, df = 2). In contrast, LR3 stream samples plotted above and to the left of the LMWL.

4.4. End member and stream chemistry variation of longitudinal runs (LRs)

Water quality parameters for end members and stream samples are found in Table 1. Pearson product-moment on LR stream samples indicated a strong positive correlation between specific conductance and calcium during all 2010 LR sampling (median $r^2=0.96$, all df = 50, all $p<0.001$; Fig. 8). Both parameters, associated with groundwater in the PCA (Section 4.1), increased in the downstream direction. Calcium was also positively related to increasing pH for all LRs ($r^2=0.62$, 0.72 and 0.74 for LR1, LR2 and LR3, respectively).

While the median downstream increase in specific conductance between 1-km sampling sites was 1.00 ± 00 μS/cm/km (for all LRs), significantly greater changes were repeatedly detected around five of the fifty collection points [Note: Several

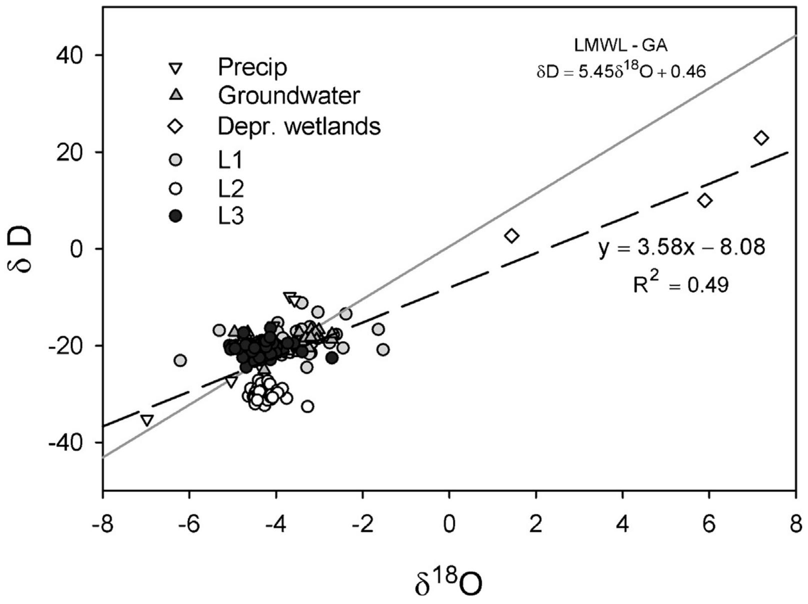

Fig. 6. Isotopic values (‰) for $\delta^{18}O$ and δD in end member and surface water samples (2010 LRs) compared to the Local Meteoric Water Line for river water in Georgia (Kendall and Coplen, 2001).

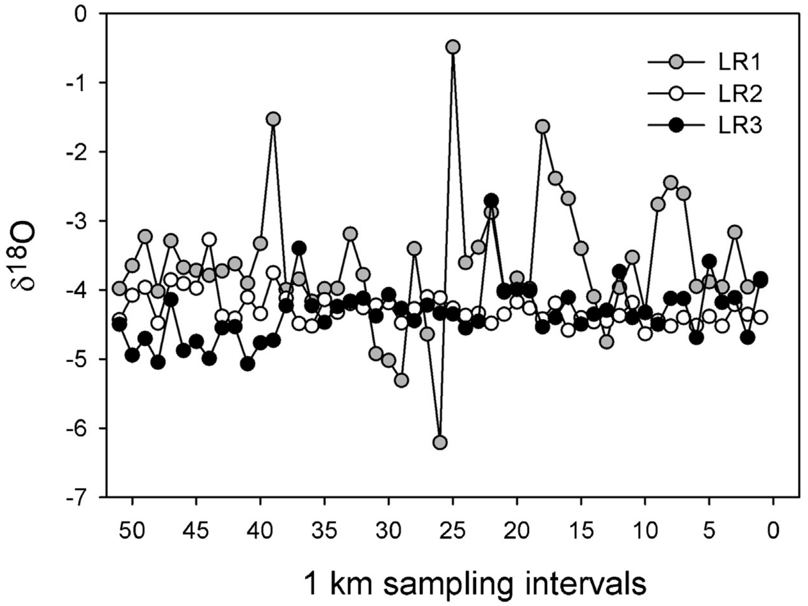

Fig. 7. Longitudinal profile of $\delta^{18}O$ values in surface water samples (2010 LRs) on Ichawaynochaway Creek, southwestern Georgia, USA. Substantial variation in $\delta^{18}O$ values occurred during LR1, with significant enrichment in $\delta^{18}O$ occurring around eight reaches. Five of these sites were near or slightly downstream from the five locations where incoming groundwater was detected by changes in specific conductance (see Section 4.4). Increases at these sites were less obvious during LR2 and LR3.

other sites, particularly above and below Milford, also showed substantial changes in specific conductance between sampling reaches. The analysis and discussion are focused on reaches in which increases occurred at least two out of three (or more) of the LR runs, acknowledging that changes in these other locations warrant further investigation]. Stepwise increases in specific conductance within these reaches ranged from 2 to 15 μS/cm. These changes, suggesting increased groundwater inputs within these reaches, were repeatedly identified in the vicinity of Sites #2, 4, 16, 30, and 44 during LR sampling runs (Fig. 9).

Cumulative downstream increases in specific conductance and calcium were similar during all three LRs (69.00 ± 1.73 μS/cm and 11.85 ± 0.19 mg/L Ca^{2+}, respectively, over the 50-km section); however, the longitudinal profiles of these runs were less consistent. Fig. 8 shows the greatest variation in the relationship between these parameters occurred

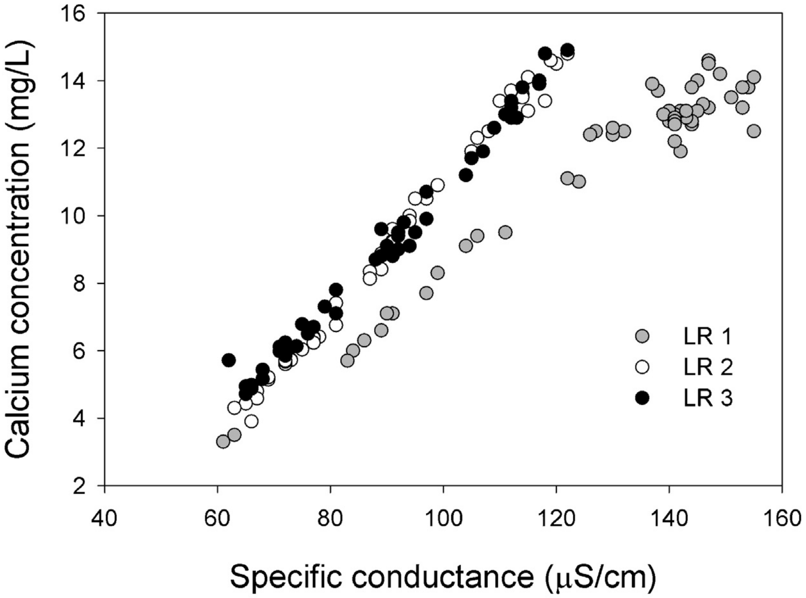

Fig. 8. Specific conductance versus calcium concentrations detected in 2010 stream samples collected during three longitudinal sampling runs (LRs) on Ichawaynochaway Creek, southwestern Georgia, USA (Pearson product-moment on LR stream samples indicated median $r^2 = 0.96$, all df = 50, all $p < 0.001$).

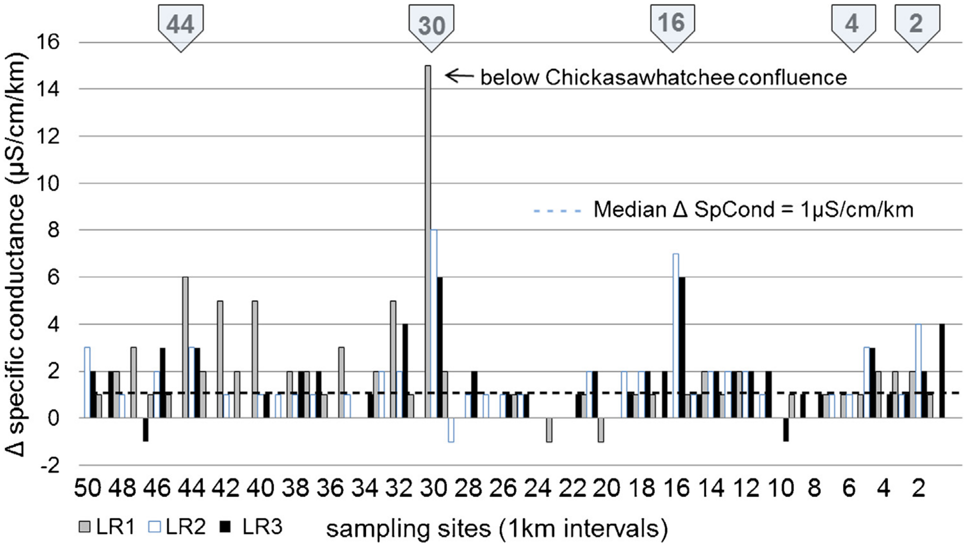

Fig. 9. Changes in specific conductance between sampling kilometers (Δ SpCond; downstream to upstream) detected during three longitudinal runs (LRs) in 2010 on Ichawaynochaway Creek. Arrows indicate consistent detection of significantly greater change in specific conductance between sampling reaches (>2 µS/cm/km), denoting increased groundwater inputs at these sites. Blank space on *x*-axis indicates no change in specific conductance between sampling kilometers.

during LR1 which was interrupted by a storm event (as stated previously, stable isotopes showed greatest variability during this run). Nitrate concentrations were also significantly different during LR1 sampling. While nitrate was generally higher in upstream reaches for all LRs (attenuating in the downstream direction), a sustained increase was noted in this parameter during LR1 between Sites #28–50 (following the storm; Fig. 10). Nitrate and pH were negatively correlated during LR2 and LR3 ($r^2 = 0.73$ and 0.48, respectively); however, no relationship was found between these parameters during LR1 sampling ($r^2 < 0.01$).

4.5. Stream chemistry variation within fine-scale short runs (SRs)

Results for all physicochemical parameters for 2011 SR collections are found in Table 1. Overall, specific conductance was higher in the stream during SR sampling (max. 184 µS/cm during SR1; 267 µS/cm during SR2) compared to 2010 LRs (max.

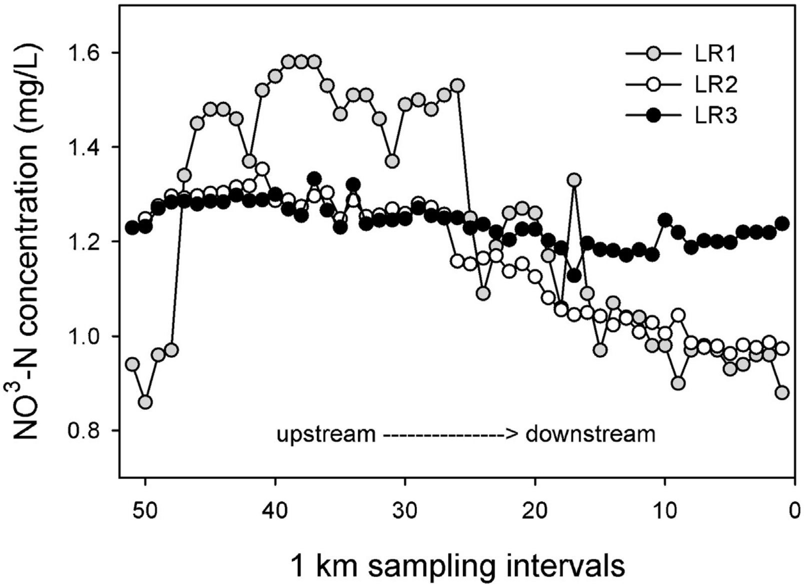

Fig. 10. Nitrate concentrations detected during 2010 longitudinal (LR) sampling on Ichawaynochaway Creek, southwestern Georgia, USA. Note higher nitrates in upstream reaches, particularly during LR1 (between sampling intervals 28–50, following a storm mid-collection), with levels attenuating downstream in both LR1 and LR2. Sustained LR3 nitrate levels may be due to higher concentration of nitrate-laden groundwater.

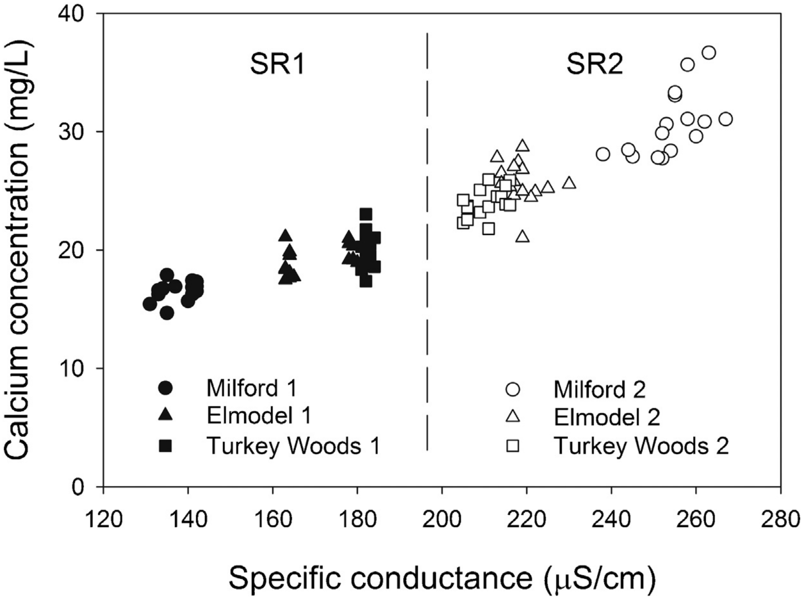

Fig. 11. Compilation of data from SR1 and SR2 collections showing calcium concentration versus specific conductance in stream samples collected in Ichawaynochaway Creek. Order of collection sites, upstream to downstream: Milford, Elmodel and Turkey Woods. Note calcium and specific conductance increased going downstream during SR1 but trend was reversed during SR2.

155 μS/cm). When SR1 site data were compiled longitudinally (to compare upstream/downstream trends), calcium was again positively correlated with specific conductance ($r^2 = 0.71$; Fig. 11), with both parameters increasing in the downstream direction as in LR sampling. During SR2, however, while both these factors remained correlated ($r^2 = 0.68$), they were found at highest concentrations upstream (Milford site) rather than downstream.

While fine-scale sampling was unable to elucidate the precise locations of groundwater/surface water exchange within reaches of high connectivity, it did succeed in detecting spatio-temporal heterogeneity between sites (Fig. 12). Overall, upstream SR sites (Milford and Elmodel) lost discharge during SR sampling (seen as $-\Delta$ SpCond between sampling points) while the downstream site (Turkey Woods) continued to show mostly gains (seen as $+\Delta$ SpCond between sampling intervals). This indicated losing reach conditions were occurring within both the Milford and Elmodel sites, particularly during SR2 sampling, when discharge became almost intermittent (Fig. 3). One exception was noted at Milford during SR1 by an increase

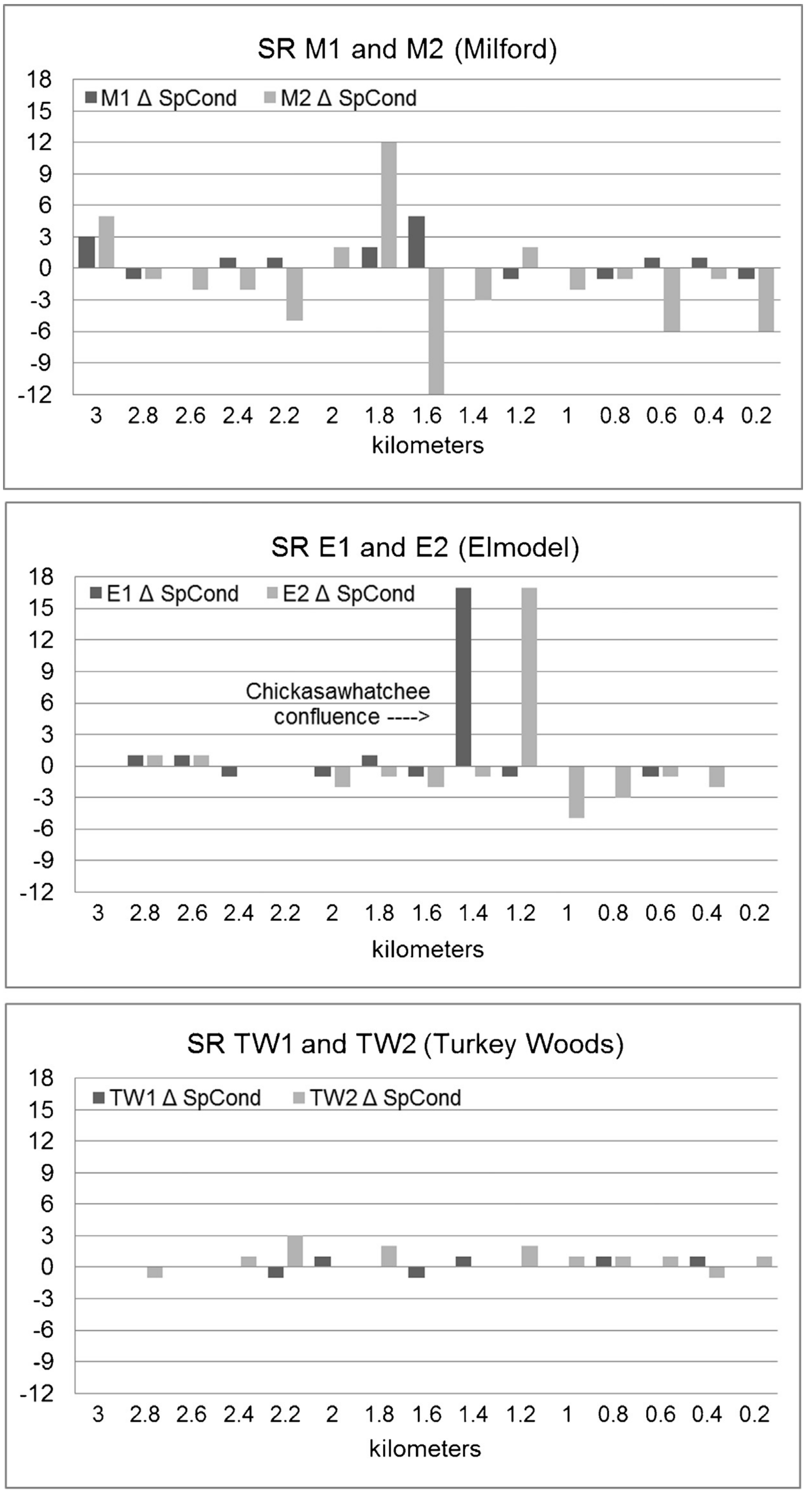

Fig. 12. Changes in specific conductance (Δ SpCond) detected within Ichawaynochaway Creek at 200 m intervals (0.2 km) during 2011 SR1 and SR2 collections [order of sites (upstream to downstream): Milford (M), Elmodel (E), and Turkey Woods (TW)]. Results suggested Milford and Elmodel were more susceptible to losing reach conditions than Turkey Woods site, particularly Milford during SR2 sampling (M2). Note: Large gain (12 μS/cm) followed by immediate loss (−12 μS/cm) in specific conductance during M2 collection (between 1.6–1.8 km) is thought to be sampling anomaly due to mussel die-off (see Section 5.1).

(mid-collection) in specific conductance of 12 μS/cm and an immediate (equal) decrease downstream. In addition, the Elmodel site continued to maintain significant gains around the Chickasawhatchee Creek confluence during both SR1 and SR2 (these exceptions will be discussed in Section 5.1 below).

5. Discussion

5.1. Groundwater/surface water connectivity and heterogeneity

This study supported the prediction that a substantial fraction of groundwater enters Ichawaynochaway Creek via discrete flow paths as opposed to graduated gains along the stream route. Both course and fine-scale sampling confirmed the high degree of connectivity and spatial and temporal heterogeneity of hydrologic interactions between the UFA and this major tributary in the LFRB. PCA results concluded that 42% of variation in the stream data could be explained by a groundwater component. Between 30 and 42% of all incoming groundwater detected during the study entered the stream around Sites # 2, 4, 16, 30 and 44, as indicated by increases in specific conductance (almost perfectly correlated with calcium concentrations) within these reaches. Long-term water monitoring data for the LFRB during this same period confirmed proportionate gains in alkalinity, indicative of groundwater, between these stream sections (Golladay, Unpublished results). Spikes of enriched δ^{18}O in stream samples also signaled the presence of groundwater entering from the aquifer around these locations during LR1. Enrichment in δ^{18}O at these sites was less obvious during LR2 and LR3 collections. This may have stemmed from a dilution of the isotopic signal from atmospheric differences during collections (LR1 was conducted in mid-summer while LR2 and LR3 sampling occurred during fall months), or it may indicate decreased hydraulic head in the UFA which resulted in reduced groundwater inputs during these latter sampling periods.

Stepwise increases in groundwater inputs along these reaches were less consistent during the 2011 SR collection period as discharge declined during exceptional drought and heavy groundwater pumping. SR sampling indicated that Turkey Woods (downstream) continued to gain groundwater under these conditions; however, Elmodel and Milford (upstream) lost streamflow to the aquifer and nearly ceased flowing (Fig. 3). Turkey Woods is located where land use is dominated by long leaf pine with no groundwater pumping. In contrast, upstream sites (Elmodel and Milford) are located where heavy agricultural land use and center pivot irrigation dominate (Fig. 2). The only substantial gains observed within the Elmodel site during SR sampling occurred just below the confluence of the Chickasawhatchee Creek where specific conductance increased 17 μS/cm during both SR1 and SR2, compared to the adjacent upstream sampling point. [Note: to determine the source of these significant increases, cursory testing was performed during SR sampling by measuring conductance for approximately thirty meters up into the Chickasawhatchee Creek (starting at the Ichawaynochaway/Chickasawhatchee confluence) where increasingly higher conductance was confirmed].

Discharge around the Milford site almost ceased during SR2 sampling as groundwater pumping and drought intensified during the summer months. Groundwater wells in the Ichawaynochaway basin in 2011 had the lowest water levels on record (1995–2012; http://nwis.waterdata.usgs.gov/ga/nwis/gwlevels/?site_no=311912084282901; accessed July 2014). Use of surface water as an irrigation source also becomes more common in these upper reaches as the UFA thins in this portion of the basin. Dredging to facilitate diversion of surface water into irrigation intakes can be observed in upstream reaches (Milford and above). This combination of both groundwater and surface water extraction has resulted in significantly more rapid baseflow recession in Ichawaynochaway Creek during periods of heavy irrigation (Rugel et al., 2012).

Diminishing flows in upstream reaches during 2011 SR2 sampling resulted in increased water temperatures and reduced thermal refugia for aquatic biota. Heavy mussel and clam mortality was observed while sampling upper reaches during SR2 (from Elmodel to above Milford). The anomalous increase and subsequent decrease in specific conductance detected in the middle of the Milford site during SR2 (Fig. 12) occurred directly downstream from a bivalve die-off and may have partially resulted from a lack of flushing flows around this collection point.

5.2. Water quality

The highest nitrate concentrations during the study were detected in groundwater wells in the uppermost portion of the basin (6.00 mg/L NO_3-N near Morgan, GA; 3.56 mg/L NO_3-N on Deer Run Plantation). This region approaches the furthest extent (updip) of the UFA, as well as the Claiborne, Clayton and Providence Aquifers, and is a major recharge area for these aquifers (Miller, 1992). Because the UFA is thinning in this region these two groundwater wells are likely accessing underlying aquifers (such as the Claiborne; Clark and Zisa, 1976); however, the outcropping of all these formations may facilitate the movement of water between these hydrological units.

At upstream sites stream dredging and land-disturbing activities have resulted in degraded riparian areas (visual observation during sampling). Dredging and headcutting in these upper reaches have produced unstable banks and crumbling overburden. In some reaches, cattle are allowed to cross through this portion of the stream resulting in denuded riparian banks and increased sediment inputs into these reaches. The higher nitrate concentrations which were detected in the second half of the LR1 collection (Fig. 10; km 26–47) may reflect the relic of nitrate inputs driven into these stream reaches following the storm which interrupted LR1 sampling. Poor stream and riparian conditions do not allow for the processing of organic or inorganic nutrients which naturally would have been mitigated by biogeochemical processes within intact riparian buffers (Muenz et al., 2006). The combination of agricultural applications, livestock waste and degraded riparian zones in regions where aquifers are known to be thin and hydraulic connectivity high, makes this portion of the basin particularly vulnerable to groundwater and surface water degradation (Bredehoeft et al., 1982). Nitrate may enter the groundwater through leaching or via stream reversal. Conversely, nitrate-enriched groundwater in this portion of the basin may re-enter the creek under gaining stream conditions.

5.3. Chickasawhatchee Creek

As previously stated, incoming water from Chickasawhatchee Creek exerted considerable influence on the stream chemistry of Ichawaynochaway Creek throughout the entire study. Chickasawhatchee Creek is a major tributary of Ichawaynochaway Creek and drains the northeastern portion of the Ichawaynochaway basin, including the Chickasawhatchee Swamp. Chemical signatures of water from the Chickasawhatchee Creek and this swamp suggest that flow in this stream is dominated by Floridan groundwater inputs. A preliminary sampling performed at baseflow in 2007 showed stream calcium concentrations in Chickasawhatchee Creek were approximately 60 mg/L Ca^{2+}. A smaller upstream branch of this tributary, Little Spring Creek in the Chickasawhatchee Swamp, had calcium concentrations of 80 mg/L Ca^{2+}, the highest of any stream tested in the Ichawaynochaway basin during the entire study (2007–2011; Rugel, Unpublished results). Long-term alkalinity monitoring data on Little Spring Creek also substantiates the presence of significant groundwater contributions in this tributary (148.63 ± 2.55 mg/L as $CaCO_3$; Golladay, Unpublished results). Upward hydrologic gradients from the aquifer and low-lying land surfaces in this portion of the basin facilitate the exchange of surface water and groundwater from the UFA (Jones and Torak, 2006). Spikes in specific conductance immediately below the Chickasawhatchee confluence accounted for 9–24% of total increases in specific conductance detected in Ichawaynochaway during this study. While wetland inputs may also have contributed to increases in specific conductance (particularly during LR1), regional stream chemistry and hydrogeology suggests that the majority of these increases can be attributed to incoming groundwater.

In addition to significant groundwater inputs from Chickasawhatchee Creek, this tributary may also have contributed some of the water chemistry explained in the PCA as a wetland component. Wetland inputs, which would be isotopically-enriched and low in pH (See PCA, Axis 2; Fig. 4), would more likely have been entering when higher discharge reconnected this tributary with backwaters and the Chickasawhatchee Swamp, such as during LR1 (this may explain the variability of multiple parameters during this collection). Additional wetland influences may be coming from sloughs and drains tangential to Ichawaynochaway Creek, as opposed to any input from hydrologically-isolated wetlands tested in this study (which were chemically more similar to surficial groundwater).

Proposed solutions for mitigating declining streamflows in the LFRB have included the possible use of aquifer storage and recovery (ASR) between multiple aquifers underlying the Elmodel region (http://www.legis.ga.gov/legislation/en-US/display/20132014/SB/213). A demonstration project planned to remove groundwater from the UFA during periods of high flow and inject this water into the underlying Claiborne and Clayton Aquifers. It is anticipated that this groundwater will remain available for later removal to augment stream flows in Chickasawhatchee Creek during drought. Possible problems with the proposal include the recoverability and quality of this water when it is needed to augment low flows. Results of the current research indicated almost one quarter of the groundwater inputs entering Ichawaynochaway Creek were draining from the Elmodel region, suggesting ASR activities should proceed with caution so as to maintain the integrity of both surface waters and aquifers in this area.

5.4. Site characteristics of increased groundwater/surface water interaction

Stream reaches where increased groundwater inputs were detected during this study appeared to be associated with fracture and tributary flow. It should be noted that none of these significant exchanges occurred via large spring conduits, as these are not common within this stream.

Site #16 (Turkey Woods) is located in a portion of the basin noted for the presence of sinkholes in adjacent uplands, in addition to being aligned along the top northeastern edge of a large depressional feature called Mim's Drain (visual observation and Personal communication Golladay and Rasmussen). The formation of sinkholes within the LFRB and other karst basins has been shown to follow fracturing trends (NE–SW and NW–SE in this region) which encourage the dissolution of underlying carbonate formations and the development of preferential flow paths (Freeze and Cherry, 1979; Brook and Allison, 1983; 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. A large number of systematic fractures were noted within stream bedrock outcrops around Site #2. Similar systematic fracturing was observed upstream around Site #4. Although not all of these joints may be through-going, groundwater was observed coming directly through some of these features.

Three out of five of these reaches [#4, 30 (Elmodel), and 44 (Milford)] were directly downstream from connecting tributaries; however, only one of these streams, Chickasawhatchee Creek, was observed to be flowing during the 2010 and 2011 sampling period. Despite lack of visible flow at the other two minor confluences, some degree of hydrologic connectivity may have persisted via sediment seepage and hyporheic flow, which could have contributed to an enhanced groundwater signal. The confluences of these tributaries with Ichawaynochaway Creek also appear to mimic regional fracture intersections which may facilitate groundwater/surface water connectivity at these sites (Rugel and McDowell, unpublished data).

5.5. Significance of groundwater discontinuities on stream ecosystem

At the large scale, multiple aspects of stream morphology, habitat, and ecology, including channel width, solar insolation, temperature and net primary production vary continuously as basin area and flow increase (Vannote et al., 1980). Discontinuities controlling abiotic factors such as flow (including channel confluences), geology, and topography introduce further morphological variation not explained by basin size alone (Montgomery, 1999). At even smaller scales, channel bends, woody debris, boulders, and sediment transport processes create habitat patches and flow variation that locally affect stream biota (Pringle et al., 1988; Grossman et al., 1998; Bunn and Arthington, 2002; Walters et al., 2003). Within karstic environments, longitudinally discontinuous inputs of groundwater impose additional variation onto the habitat template. Stream chemistry data within our study area also indicated that relative contributions of end members to streamflow vary substantially under differing flow conditions.

Understanding heterogeneities in heavily-allocated basins is crucial for establishing management criteria which adequately protect vulnerable reaches and biota while preventing unnecessary restrictions in areas of lower risk. Water resource planning is currently based on large scale modeling and does not account for localized hydrological irregularities (Albertson and Torak, 2002; Jones and Torak, 2006). The results of the current study demonstrated that aquifer/stream interactions at the reach scale, which vary both spatially and temporally, significantly contribute to cumulative stream flows as well as water quality. Growing use of groundwater resources in this and other karst basins necessitates the incorporation of these irregularities into regional groundwater models to support prudent groundwater management and policy.

5.6. Future research opportunities

Evaluating the results of this study with available data on species of interest may potentially reveal how localized hydrologic patterns are affecting aquatic population dynamics. Comparing these results with existing data on presence and richness of listed mussels and their host fish, could be beneficial in clarifying which reaches might support future recruitment, translocation and protection of these species. Current modeling indicates that some mussel species in this region are eight times more susceptible to extirpation under current water usage (Peterson et al., 2011). Targeting protective management practices to reaches at greater risk of groundwater and stream capture (highlighted in the current study) may help to safeguard vulnerable stream biota while reducing negative impacts on regional agricultural economies. Finally, further hydrogeological analysis of systematic jointing and regional lineaments, including the use of LIDAR, is warranted in this basin and may produce valuable information to facilitate the prediction of groundwater/surface water interaction at landscape scales.

6. Conclusion

Intensive groundwater irrigation is correlated with stream baseflow declines; however, the location and nature of connectivity between surface waters and karst aquifers are difficult to predict. Longitudinal sampling conducted between 2010 and 2011 on Ichawaynochaway Creek in southwest Georgia, USA, detected stepwise inputs of groundwater from the Upper Floridan Aquifer, as evidenced by significant increases in specific conductance at five out of fifty reaches sampled. Both course and fine-scale sampling along the 50-km study stream section showed up to 42% of total groundwater inputs entered through discrete preferential flow paths located within these five major locations. As much as 24% of those increases came through a single tributary, Chickasawhatchee Creek, which is groundwater-dominated.

Principal components analysis confirmed that 49% of the variation in water chemistry of the 50-km stream section could be explained by a component associated with groundwater, with a second component (wetland) explaining 27% of additional variation. PCA also indicated that streamflow sources varied under different baseflow conditions. During record drought and intensive pumping in 2011, groundwater composed as much as 70% of low summer baseflow in some reaches of this stream. Upstream reaches of Ichawaynochaway Creek (from Elmodel to above Milford, GA) became losing and flow was intermittent as heavy pumping and exceptional drought persisted. Water quality in these reaches may also have been compromised by runoff from poor land management practices.

Results suggest that water resource development should consider reach-scale impacts, which cumulatively transmit large-scale consequences to water quantity and quality in the watershed. Finally, future resource planning and policy should account for the spatio-temporal flow variations between hydrologically-connected components within karst watersheds and implement protections in the most vulnerable exchange zones.

Conflict of interest

The authors declare that there are no conflicts of interest associated with this manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.11.011.

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