

Using hydrogeomorphic patterns to predict groundwater discharge in a karst basin: Lower Flint River Basin, southwestern Georgia, USA

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ABSTRACT

Study region: The Lower Flint River Basin (LFRB): a karst catchment in southwestern Georgia, USA.

Study focus: Using the U.S. EPA Reach File 3 data set, we generated stream reach azimuths for all tributaries of the Lower Flint River Basin (LFRB) in southwestern Georgia, USA, then compared these results to regional bedrock jointing orientations and stream chemistry (indicating incoming groundwater discharge) in one tributary of the LFRB, Ichawaynochaway Creek. Our objective was to determine if stream bearing might be a useful predictor of increased groundwater discharge in streams of the LFRB where groundwater development has significantly impacted baseflows.

New hydrological insights for the region: We identified a dominant N-S trend in 44% of reaches in tributaries of the LFRB with lesser E-W, NNW, NW and NE trends. Bedrock joints and stream reaches in Ichawaynochaway Creek (a tributary of the Flint River) shared similar azimuth trends. When we compared stream reach orientation with known locations of enhanced groundwater inputs (previously detected by Rugel and others) we found that 55% of the time reaches in Ichawaynochaway Creek with increased groundwater discharge followed NW or NNW bearings (mean N49W). Further investigation to replicate these results in other tributaries of the LFRB is warranted and may help inform management strategies which could protect both ecological and economic interests in this region.

1. Introduction

The Upper Floridan Aquifer (UFA) is a carbonate aquifer which underlies the Coastal Plain of the southeastern United States (Miller, 1986). Karstification within the Ocala Limestone Formation, which forms the major water bearing unit of this aquifer, has resulted in high secondary permeability and heterogeneous connections with regional streams (Stringfield, 1966; Mosner, 2002;

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Jones and Torak, 2006). The UFA currently provides over 15 million cubic meters of groundwater per day for agricultural, municipal, industrial, and domestic use to portions of Alabama, Georgia, South Carolina, and all of Florida.

Withdrawal of groundwater from the Floridan Aquifer system rose 500% between 1950 and 2000 with the greatest increases occurring in the 1970's after the introduction of center pivot irrigation systems (Pierce et al., 1984; Johnston and Bush, 1988; Marcella and Berndt, 2005). The Lower Flint River Basin (LFRB), which lies within the Dougherty Plain physiographic district of southwestern Georgia, USA, underwent extensive agricultural development during this period. Because of the close hydraulic connection between the UFA and tributaries in the LFRB (Hicks et al., 1987), intensive withdrawal of groundwater and surface water has contributed significantly to reducing baseflows in and beyond the growing season (Stamey, 1996; Couch and McDowell, 2006; Rugel et al., 2012).

Streams in the LFRB host a diverse aquatic fauna, including multiple species of federally-listed and endangered mussels, which are adapted to the unique physiochemical and structural habitats of this basin (Golladay et al., 2004). Previous modeling suggests that current agricultural water usage increases the likelihood of extirpation of several species of mussels in these waters (Albertson and Torak, 2002; Peterson et al., 2011). Since farm-gate profits account for as much as 34% of regional revenues, a greater understanding of aquifer-stream interaction is essential to the protection of endemic aquatic fauna as well as the economic security of this heavily-allocated region (Boatright and McKissick, 2004).

Topographic near-surface features, such as lineaments and sinkhole development, have been used to determine the relationships between jointing, dissolution trends and well productivity in portions of the LFRB and other karst watersheds (Brook and Sun, 1986; Hyatt and Jacobs, 1996; White, 1999; Dinger et al., 2002), however, these relationships remain understudied in many sub-basins of the LFRB where groundwater use is impacting low flows and threatening endangered and listed aquatic species. Identifying hydrogeomorphic patterns in regions where withdrawals are currently reducing baseflow may help predict surface and sub-surface connectivity and support prudent resource management of this and other heavily-developed catchments.

Our objective was to examine large and small scale hydrogeomorphic patterns at the near surface of a karst basin to determine their usefulness as predictors of enhanced groundwater discharge. To this end, we assessed basin-level river and tributary reach orientations (azimuths) in the LFRB to ascertain patterns in reach bearing within the basin. Secondly, we conducted field measurements of instream bedrock jointing azimuths within one major tributary of the LFRB, Ichawaynochaway Creek, which is heavily developed for groundwater use. We compared these findings to stream azimuths of sections of Ichawaynochaway Creek where increased groundwater inputs were detected in a previous study (Rugel et al., 2016) to determine whether reach bearing might be a useful predictor of enhanced groundwater discharge in this and other tributaries.

2. Site description and methods

2.1. Study site

The study site lies within the Dougherty Plain and Fall Line Hills physiographic districts of southwestern Georgia, USA (Fig. 1). The LFRB consists of approximately 15,100 km² of gently rolling, well-drained Coastal Plain with a slope around 2 m/km (Hicks et al., 1987). Average annual temperature is 16 °C and rainfall averages 1320 mm per year with regional evapotranspiration rates of around 60% (Lawrimore and Peterson, 2000). Row crop agriculture and pasture lands account for over 50% of land use, with remaining acreage in pine plantation, deciduous forest, and depressional wetlands. The region is heavily developed for agriculture with more than 6000 irrigation systems permitted to remove approximately 5×10^6 m³ of water per day from regional groundwater and surface water sources (Hook et al., 2005). According to USGS gaging data these permitted withdrawals amount to 30% of mean flow, 43% of median flow and greater than 200% of the minimum flow of the Flint River at Bainbridge, GA (USGS stream gage 02356000, Jan. 1, 2000 to Oct. 18, 2018; https://waterdata.usgs.gov/ga/nwis/uv/?site_no=02356000&PARAMeter_cd=00065,00060,00062; Accessed Oct. 2018).

2.2. Hydrogeological setting

The Southeastern US Coastal Plain is underlain by a series of carbonate formations from the Paleogene period which overlie deeper Cretaceous clastic rocks (Applin and Applin, 1944; Stringfield, 1966). Together these layers form a wedge-shaped series of hydrogeologic units that underlie much of the Coastal Plain region of Alabama, Georgia, South Carolina, and all of Florida. These carbonate formations (including the Ocala Limestone) consist mainly of uncemented marine sediments which thin in a northwesterly direction where they interfinger and outcrop along the inside margin of the Fall Line Hills (Hicks et al., 1987). Collectively they thicken in a southeasterly direction towards the Gulf of Mexico and the Atlantic Ocean (Miller, 1992).

Dissolution during the Pleistocene enlarged fractures and conduit passageways consistent with jointing within these formations, ultimately creating the Upper Floridan Aquifer (UFA) (Stringfield, 1966; Miller, 1986; Florea et al., 2007). Within the LFRB, this karstified aquifer is overlain by undifferentiated sediments of upper Oligocene limestone and Miocene clays and sands, mantled by an unconsolidated overburden of Neogene sediments and confined below by the Eocene Lisbon Formation. The UFA ranges from a few meters thick in northwestern portions of the Dougherty Plain (updip extent) to over 150 m in the southeasterly direction as it approaches the Pelham Escarpment and the Tifton Upland District. It may be confined, semi-confined or unconfined in the study area depending on depth and condition of overburden. Transmissivity in the UFA within the LFRB ranges from 1.9×10^2 m²d⁻¹ to 1.0×10^5 m²d⁻¹ (Hicks et al., 1987).

Tributaries in the LFRB, including Kinchafoonee, Muckalee, Ichawaynochaway, Chickasawhatchee, and Spring Creek, begin as

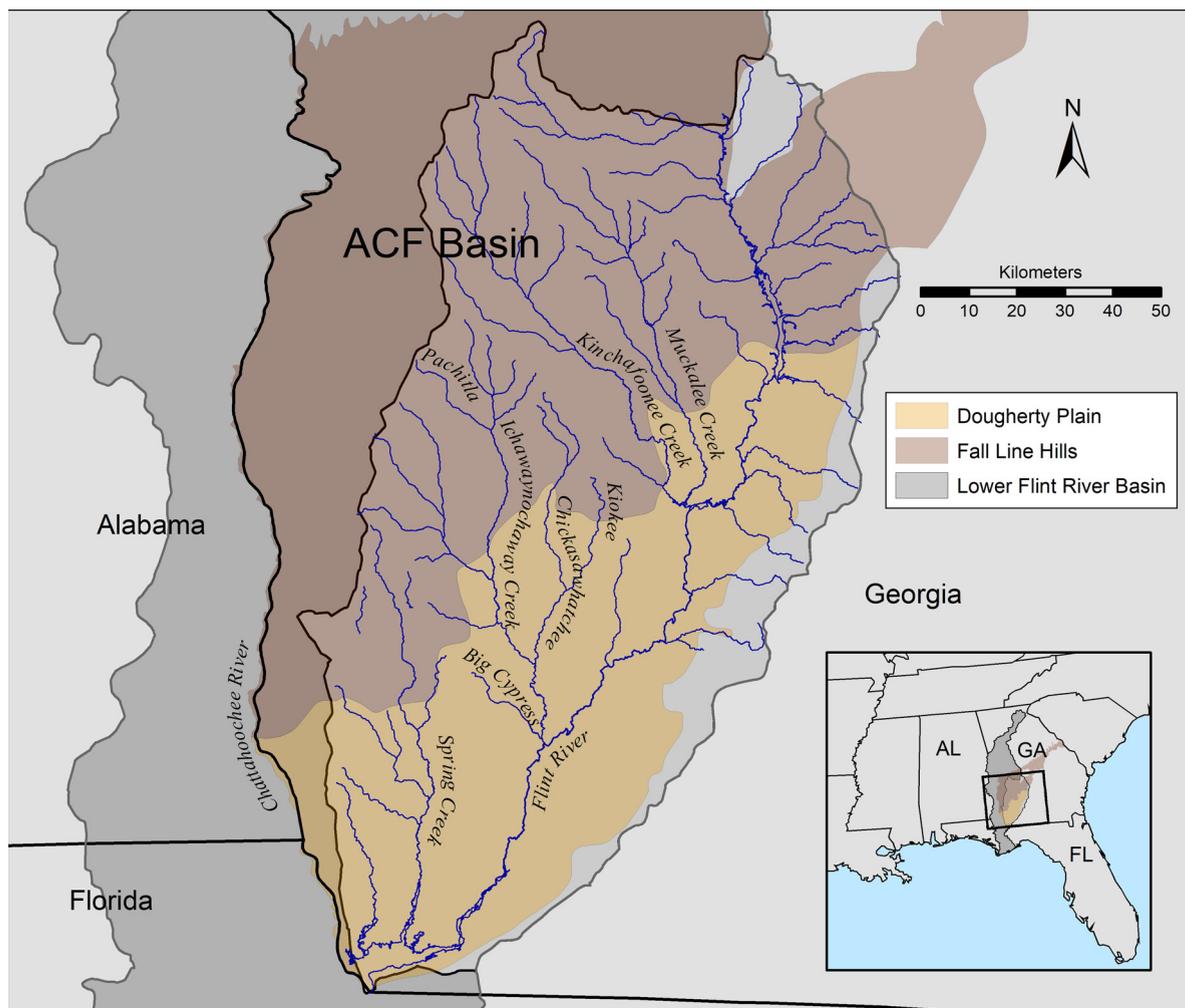


Fig. 1. Map of study area showing tributaries in the Lower Flint River Basin (LFRB) located in the Dougherty Plain and the Fall Line Hills within the greater Apalachicola-Chattahoochee-Flint (ACF) Basin (dark grey) in southeastern USA (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

seeps and springs inside the Fall Line Hills and flow across the Dougherty Plain into the lower Flint River. Karstification of underlying limestone and erosion of overburden in this region has directed much of the surface drainage below ground and established a close hydraulic connection between surface water and groundwater (Hicks et al., 1987; Mosner, 2002; Torak and Painter, 2006; Rugel et al., 2012).

3. Methods

3.1. Stream, tributary and river reach orientation analysis

The U.S. EPA Reach File Version 3 (RF3) for the Conterminous United States (1:100,000-scale Digital Line Graph hydrography) was used to determine orientation trends (azimuths) of all reaches in the LFRB (stream, river and tributary; herein described as “stream segments” or “stream reaches”). These include all reaches within the RF3 data set, excluding portions of the streams or rivers which are impounded (see below).

To segment the original line file, a Visual Basic script was generated in an ArcView v.3 extension adapted for ArcGIS v.9 (Jenness, 2007). The code (pathfind.avx) dissected the continuous reach line data at all stream turns greater than 20° to characterize stream segment azimuth and length for each resulting stream, tributary and river reach (Fig. 2). A 20° cutoff was deemed sufficient to account for deviations in GPS waypoint and hydrograph data while capturing most directional changes [since rivers in the LFRB display an angular drainage pattern, changing mostly in 45° turns; Twidale, 2004]. Polygon data that represented lakes, wetlands, or reservoirs in the original file were manually excluded from the analysis.

Data on azimuths and lengths of segments (.dbf) were exported into Microsoft Excel® then azimuths were loaded into a Boreland

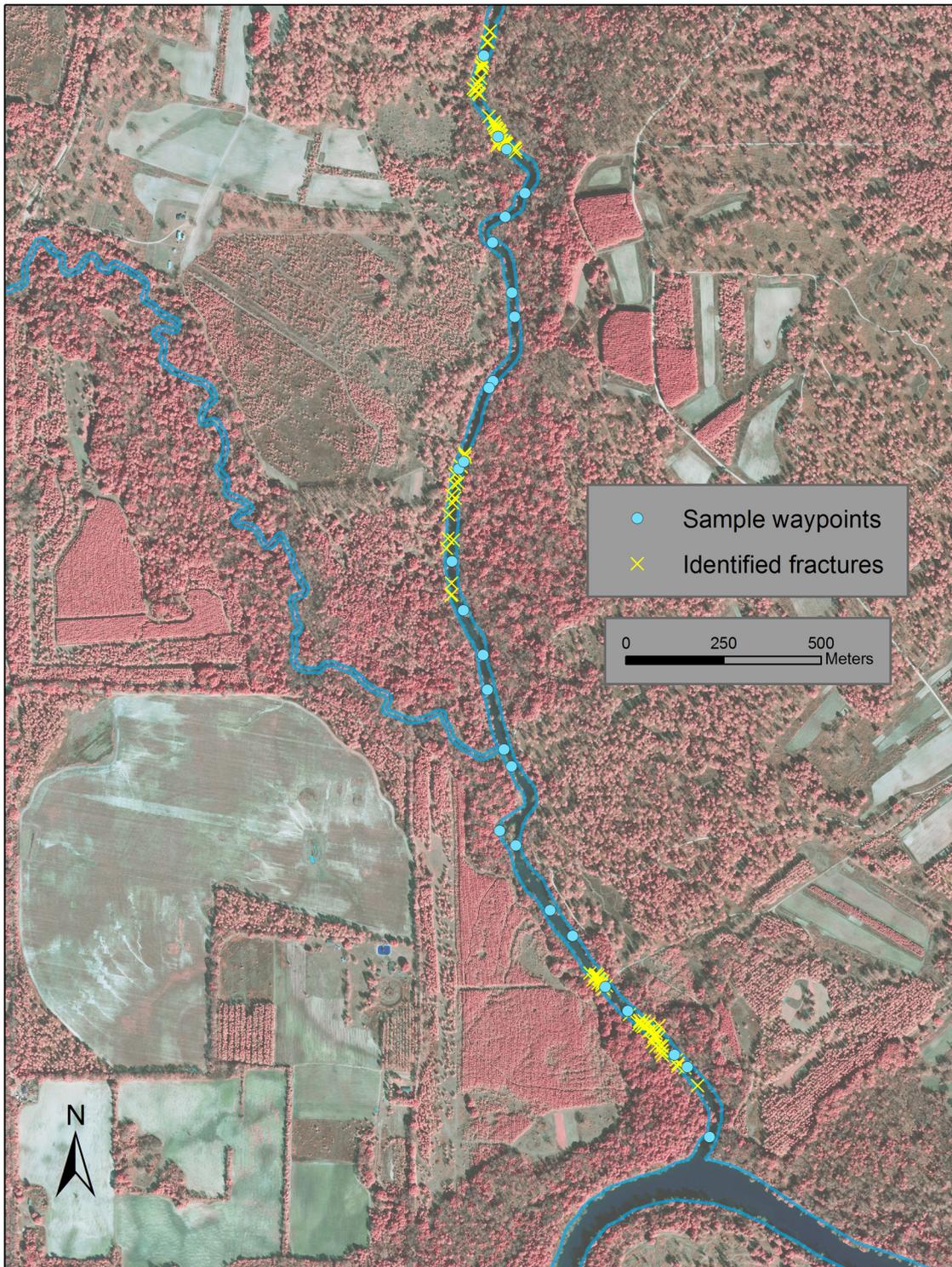


Fig. 2. Location of semi-contiguous bedrock fractures measured in Ichawaynochaway Creek directly above confluence with the Flint River (lower right), Baker County, southwestern GA, USA (yellow “x” represents location only, not orientation) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

C++ program (<http://www.borland.com/>) to generate rose diagrams (circular histograms; Fracture Rose v.1.0.3.1, jdowd@uga.edu). These diagrams generated 36 bin divisions of 5° arcs with mirrored sets projected for enhanced 360° display. Mirrored sets were for visual purposes only and did not represent additional data. Supplementary tools used to create the 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 with 5° arc divisions were generated for the entire LFRB stream segment data set (n = 37,134) then repeated separately on major tributaries of interest, including Ichawaynochaway, Spring, Big Cypress, Pachitla, Chickasawhatchee, Kiokee, Kinchafoonee, and Muckalee Creeks, and the main stem of the lower Flint River. Azimuths between 90 and 180° were then rotated clockwise by 90° and combined with the observed azimuths between 0 and 90° to generate histograms of entire LFRB and Ichawaynochaway Creek to examine the relationship between stream segment length, azimuth and frequency.

3.2. Instream bedrock jointing measurements

To assess regional jointing trends, bedrock joints (fractures in outcropping Ocala Limestone) were visually surveyed and measured in the field along adjoining segments of lower Ichawaynochaway Creek (Figs. 1 and 2). This stream is a major tributary of the LFRB and has experienced a 49% decline in low flow metrics compared to pre-development years (pre and post- 1970; Rugel et al., 2012). Downstream portions of this stream are deeply incised into the Ocala Limestone of the UFA and joints are visible in the stream bedrock.

A semi-contiguous set of fractures beginning approximately 0.5 km upstream from the confluence of Ichawaynochaway Creek and the Flint River and continuing approximately 4 km upstream, was measured at low discharge during 2011 drought flows (Fig. 2).

All accessible fractures measuring at least 2 m in length were chosen for the analysis (n = 130). Fracture azimuths, lengths and widths, as well as distinguishing characteristics of joints (sinuosity, degradation, and termination points) were recorded along approximately 3.5 km of streambed [excluding small sections (approximately 5–15 m) where fractures were immeasurable due to deep water]. Navigational coordinates were gathered at the terminus of each fracture using a Garmin® Oregon 550 hand-held GPS and azimuths were taken using a Brunton Field Transit adjusted 4.6°W for regional declination (<https://www.ngdc.noaa.gov/geomag-web/#declination>; Accessed April 2011). Fracture extents (lengths) included only that portion of the fracture contained within the streambed, regardless of continuation beyond the stream, i.e., into bank.

Following field reconnaissance, shapefiles were downloaded into ArcGIS v.9 using DNRGarmin v.5.4.0.1, a freeware ArcView extension program created and made available by the Minnesota Department of Natural Resources (<http://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html>). Additional code was written to generate the location, direction and extent of each fracture for mapping/display purposes. Instream azimuths were used to produce rose diagrams for comparing bedrock joint trends (36 5° bins). As above, azimuths of fractures between 90 and 180° were rotated clockwise by 90° and combined with the observed azimuths between 0 and 90° to generate histograms for comparison and analysis.

3.3. Stream reaches with enhanced groundwater discharge

During a previous study (Rugel et al., 2016), stepwise increases in groundwater inflows were detected in some reaches along a 50 km study section of Ichawaynochaway Creek [using specific conductance, calcium, nitrates, alkalinity and stable isotopes ($\delta^{18}\text{O}$ and δD)]. Sampling at 1 km intervals, specific conductance (highly correlated with calcium in the study site) increased an average of 1 $\mu\text{S}/\text{cm}/\text{km}$ moving downstream along the 50 km section; however, significantly greater increases (per km) were repeatedly detected in some stream reaches, suggesting incoming groundwater and enhanced surface-subsurface connectivity around those locations.

For the present study, we assumed this incoming groundwater was generated from a point slightly upstream from where it was detected, therefore, we projected waypoints 50 m upstream from each collection point in the 2016 study, to represent the presumed origin of incoming groundwater and account for downstream mixing (Fig. 3). We then determined the azimuth of the stream reach segments where each projected point was located (n = 150).

Azimuths between 90 and 180° were rotated clockwise by 90° and combined with the observed azimuths between 0 and 90° to generate histograms of all projected points. A Gaussian Normal fit was estimated using the MATLAB (Version: 9.3.0.713579, R2017b) function "normfit." The Kolmogorov-Smirnov test was used to test the null hypothesis that stream reaches where enhanced groundwater was detected shared the same distribution as all reaches sampled within Ichawaynochaway Creek. Finally, we generated a rose diagram which represented the orientation trends in all reaches where specific conductance increased $\geq 2\mu\text{S}/\text{cm}/\text{km}$ (100% or above the mean change (1 $\mu\text{S}/\text{cm}/\text{km}$) detected along the stream route.

4. Results

4.1. Stream, tributary and river reach azimuth analysis

Analysis of all stream, tributary and river reaches within the LFRB (n = 37,134) showed a dominant azimuth trend in the NS direction (Fig. 4). Other lesser trends were oriented EW and approximately N45 W. Additionally, a NNW trend around N24 W and two weaker NNE trends (~N20E and N40E) were present. Stream reaches with a NS bearing occurred 44% more frequently than reaches with any other azimuth trend but were more often shorter than other trends (Fig. 5).

When tributaries of the LFRB were examined individually, they also reflected the dominant N–S trends with lesser E–W and NW trends (Fig. 6) similar to the composite LFRB data set. Major distinctions between these tributaries included a pronounced NW trend in Big Cypress Creek (as dominant as the N–S trend). Strong NW trends are also seen in the Ichawaynochaway, Pachitla, Spring, Kinchafoonee, and Muckalee Creeks (western and northern side of basin; Fig. 6). This trend became less prominent around the

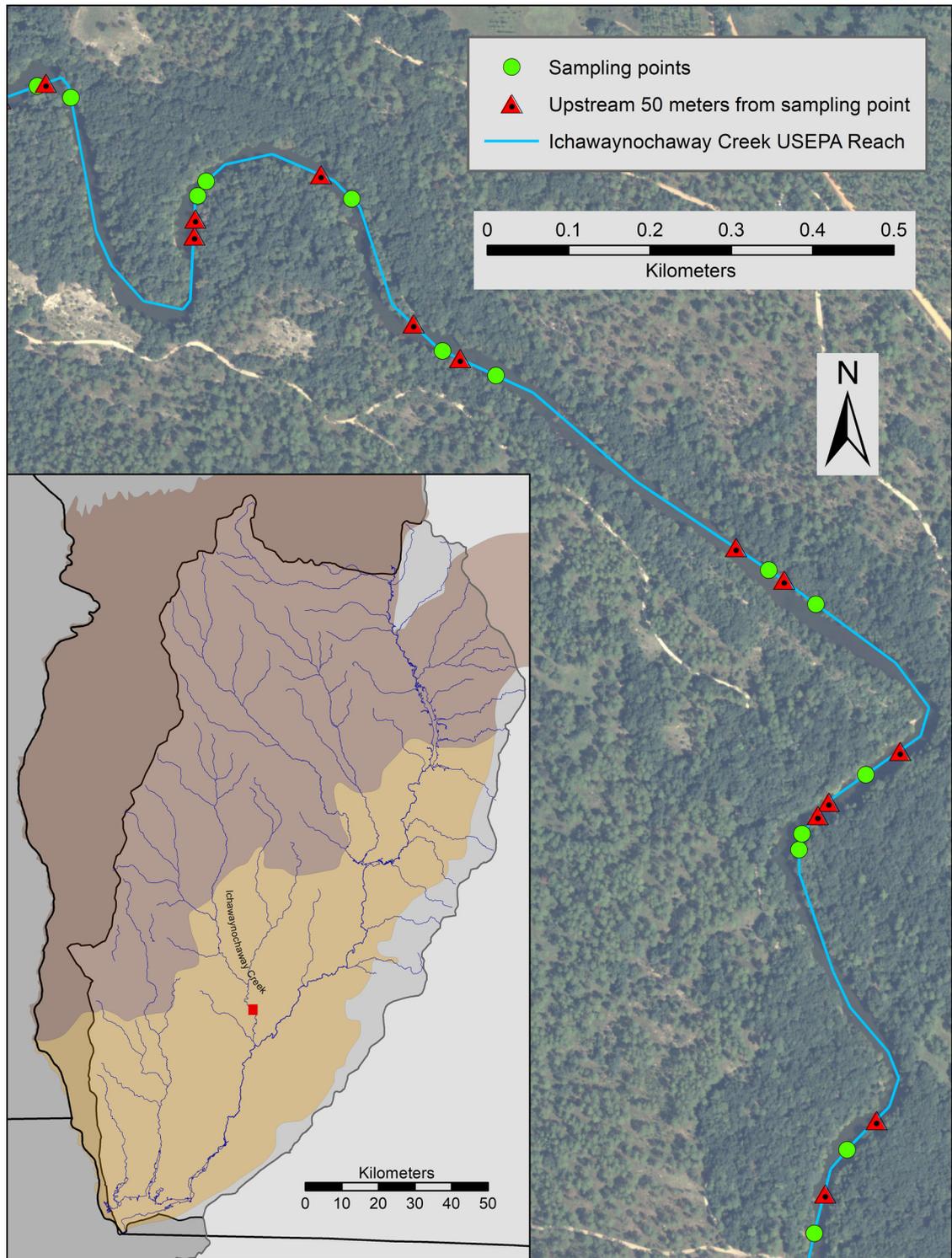


Fig. 3. A representative portion (~ 5 km) of the 50 km section of Ichawaynochaway Creek sampled by [Rugel and others \(2016\)](#) showing fit of U.S. EPA Reach File 3 overlain on 2013 NAIP Imagery. This reach is located within the larger study area (see small red box in insert). Visual Basic script was used to create vectors at each creek turn and generate azimuths for resulting stream reaches in the entire LFRB. Stream samples were previously collected by [Rugel and others \(2016\)](#) at each green sampling point seen here. Red triangles represent projected locations 50 m upstream from sampling points (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

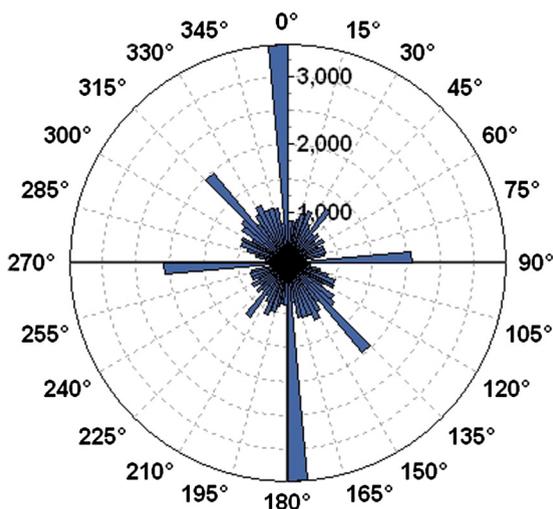


Fig. 4. (left) Rose diagram showing azimuth trends of all stream and river reaches (n = 37,134) within the Lower Flint River Basin, southwestern GA, USA.

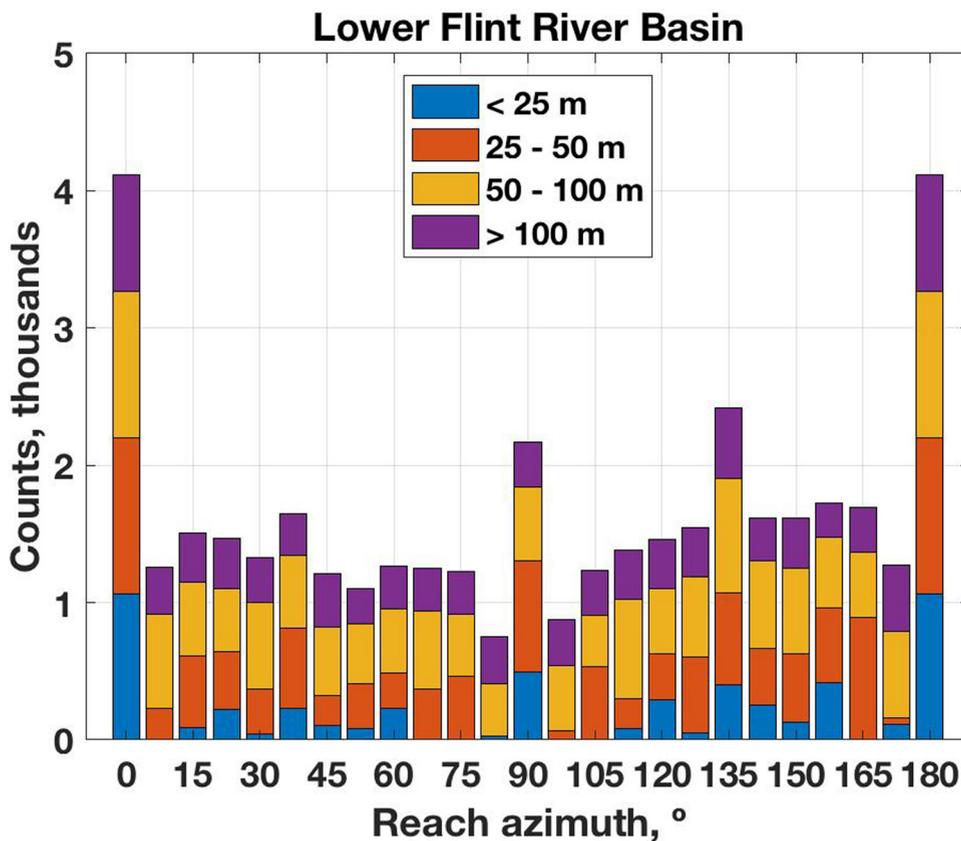


Fig. 5. (below) Histogram showing reach azimuth, count and length of reaches in entire Lower Flint River Basin (n = 37,134), in southwestern Georgia, USA. Reaches with N-S azimuths (0 and 180°) were most numerous and more often shortest; Other major azimuth trends found at E-W (90°) and around N45 W (135°). Degrees were converted to 0–180 for analysis. MATLAB Version: 9.3.0.713579 (R2017b).

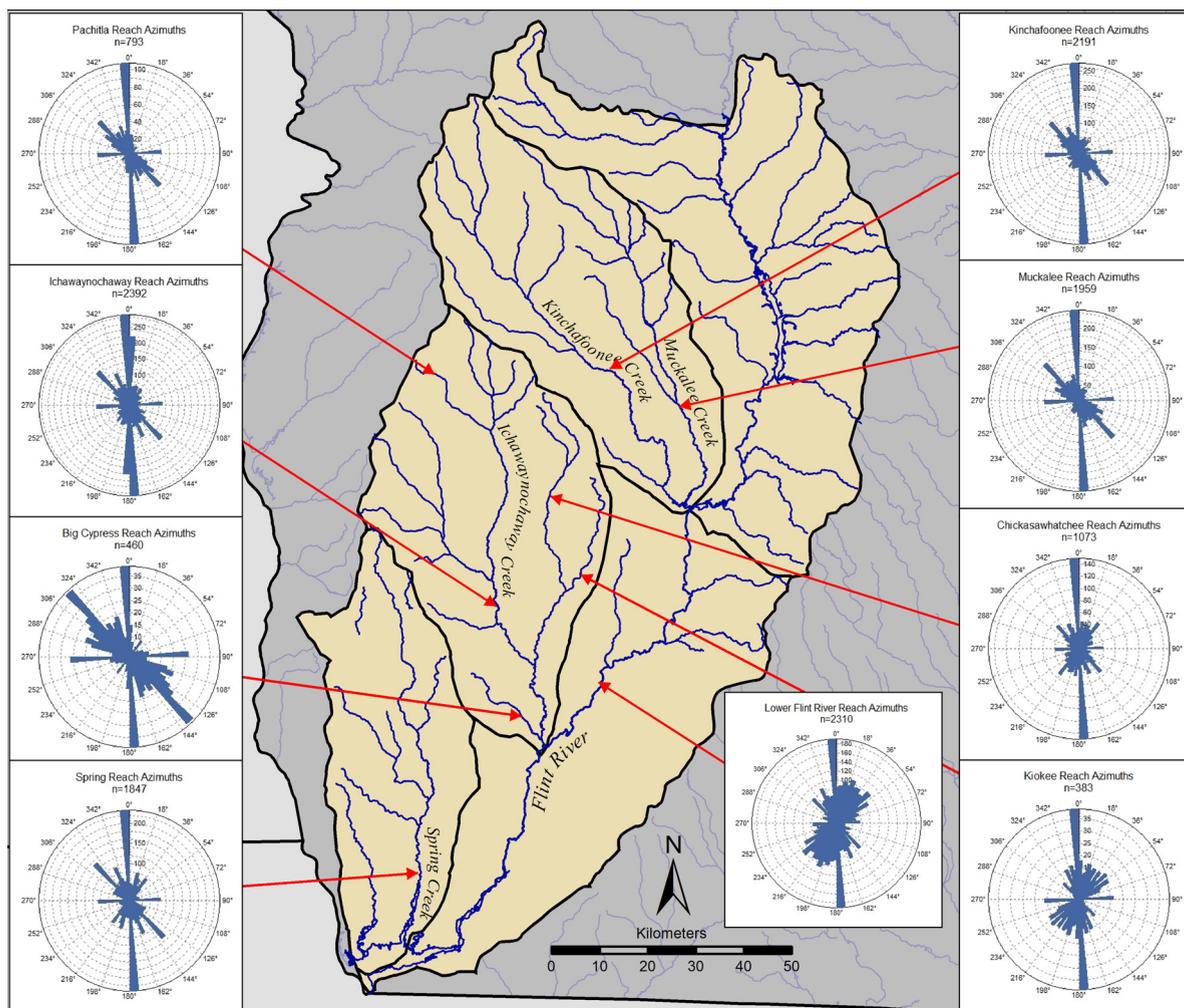


Fig. 6. Trends in orientation of stream and river reaches of major tributaries within the LFRB, southwestern GA, USA, including: 1) Spring Creek ($n = 1847$); 2) Big Cypress Creek ($n = 460$); 3) Ichawaynochaway Creek ($n = 2392$); 4) Pachitla Creek ($n = 793$); 5) Kinchafoonee Creek ($n = 2191$); 6) Muckalee Creek ($n = 1959$); 7) Chickasawhatchee Creek ($n = 1073$); 8) Kiokee Creek ($n = 383$); and, 9) lower Flint River branch ($n = 2310$).

southeastern portion of the basin, particularly in reaches of the lower Flint River. Chickasawhatchee and Kiokee Creek (mid-basin) and the main stem of the lower Flint River, which displayed stronger (but scattered) N, NNE and NE trends compared to streams west and north of these tributaries.

4.2. Instream bedrock joint trend analysis

Bedrock joint azimuths measured in limestone outcrops within Ichawaynochaway Creek ($n = 130$; Figs. 7 and 8) showed some similarities to trends in reach azimuth for this tributary (see Section 4.1.), with N-S joints occurring most frequently, followed by lesser and more scattered NW and NE sets. Median joint length was 6.3 m and ranged from 1.6 to over 50 m. Median aperture of joints was 10 cm (from 1.0 to 40.6 cm). Joint length versus joint azimuth was not formally evaluated since some fractures extended, but were not measurable, beyond the streambed.

4.3. Reaches with increased groundwater discharge

Fig. 9 shows a histogram of the frequency of stream reaches of all samples collected by Rugel and others (2016; See Section 3.3) along a 50 km section of Ichawaynochaway Creek as a function of stream reach azimuth. The stacked bars indicate the degree to which specific conductance increased in stream samples along the collection route with different bearings. These increases represent the difference in specific conductance (interpreted as incoming groundwater) between sampling points (1 km apart) along the stream. A constant distribution (uniform fit) of incoming groundwater was found in 65% of all reaches sampled, however, a peak in specific

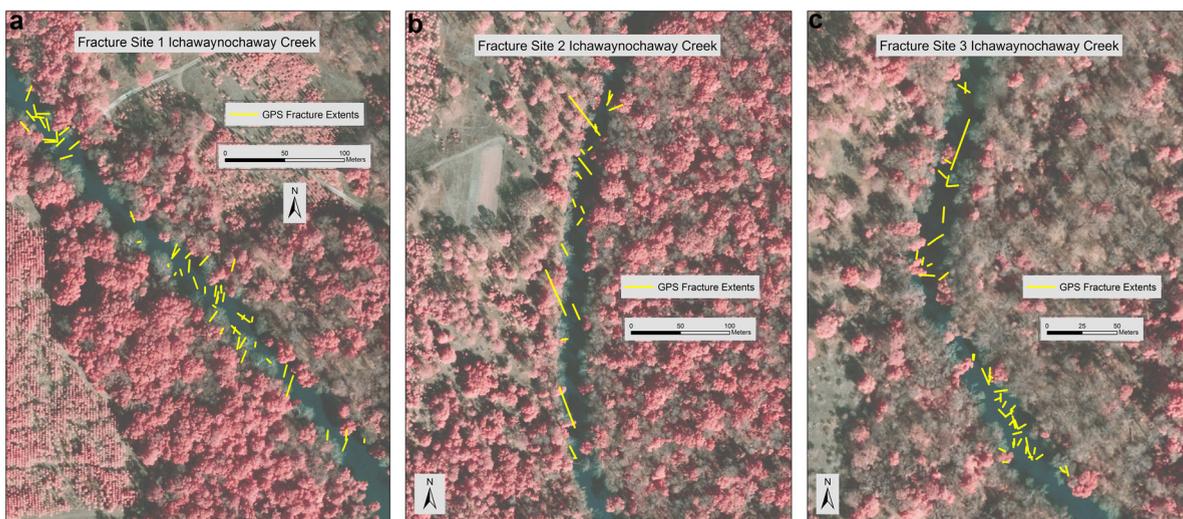


Fig. 7. Location, orientation, and extent of instream bedrock fractures (joints) measured within Ichawaynochaway Creek (n = 130) in the Lower Flint River Basin, southwestern Georgia, USA, projected on 2011 National Agriculture Imagery Program (NAIP) aerial near infrared photography in ArcGISv.9. Fracture site 1, 2 and 3, are semi-contiguous, (downstream to upstream), along ~4 km of streambed starting 0.5 km upstream from the Flint River confluence (see Fig. 2).

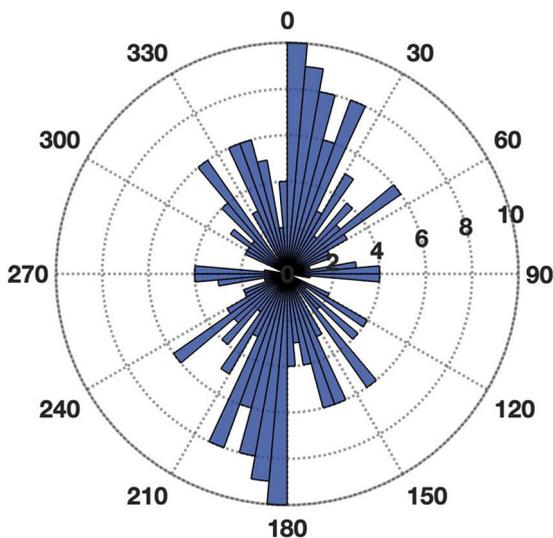


Fig. 8. Rose diagram of instream bedrock fractures (joints) measured in Ichawaynochaway Creek (n = 130) in the Lower Flint River Basin, southwestern Georgia, USA showing dominant N-S trend with multiple NNW and NNE trends.

conductance was found in 35% of the reaches. These increases occurred most often in reaches bearing NW and NNW, precisely, around the mean reach azimuth of $138.09 \pm 11.75^\circ$ (N42 W; centroid of the Gaussian fit). The Kolmogorov-Smirnov test on the Gaussian fit failed to show that the Gaussian fit could be rejected, (KS-stat = 0.394, p = 0.26).

Fig. 10 is a rose diagram of the azimuths of stream reaches where specific conductance increased $\geq 2\mu\text{S}/\text{cm}/\text{km}$ (100% or more above the mean increase of $1\mu\text{S}/\text{cm}/\text{km}$) in the aforementioned stream study (Rugel et al., 2016). The figure shows the largest increases in conductance detected during that study were found in reaches with NNW and NW orientations. Specifically, of all reaches where specific conductance increased $\geq 2\mu\text{S}/\text{cm}/\text{km}$, 55% had NNW or NW bearings (34% NW; 21% NNW). Mean azimuth for those reaches was $311.32 \pm 10.82^\circ$ (N48.69W $\pm 10.82^\circ$) and mode was $325.62 \pm 14.01^\circ$ (N34.40W $\pm 14.01^\circ$).

5. Discussion

5.1. Stream reach, bedrock joint, and groundwater discharge trends

In this study, using the U.S.EPA RF3, we were able to identify several prevailing trends in reach orientations within the LFRB. The

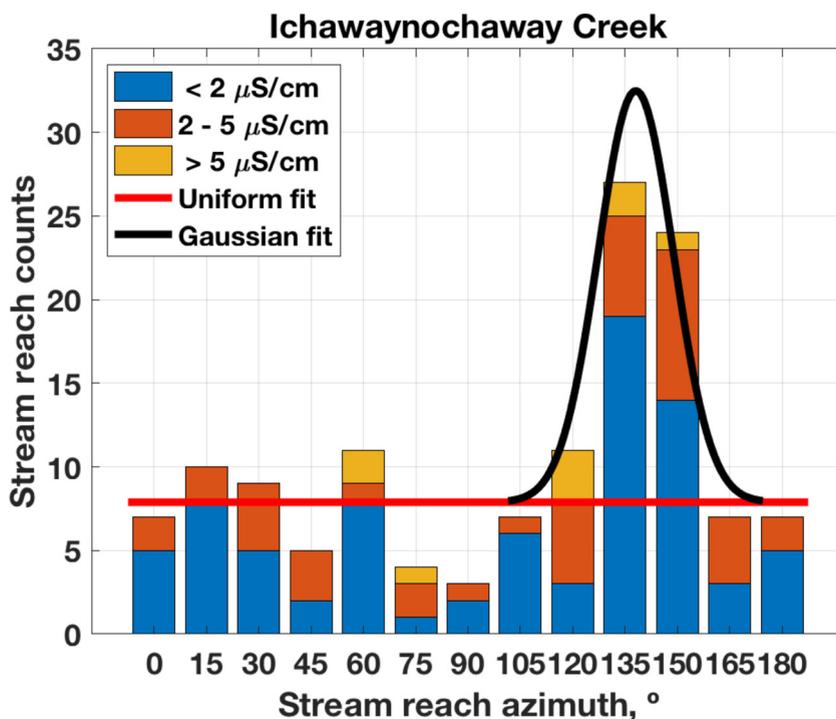


Fig. 9. Observed specific-conductance increases as a function of reach azimuth in Ichawaynochaway Creek. Best-fit lines for a uniform change (red) along with a Gaussian fit (black “peak”) indicated 35% of reaches with increased groundwater occurred around N42 W ($138 \pm 11.75^\circ$). Degrees were converted to 0–180 for analysis. MATLAB Version: 9.3.0.713579 (R2017b) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

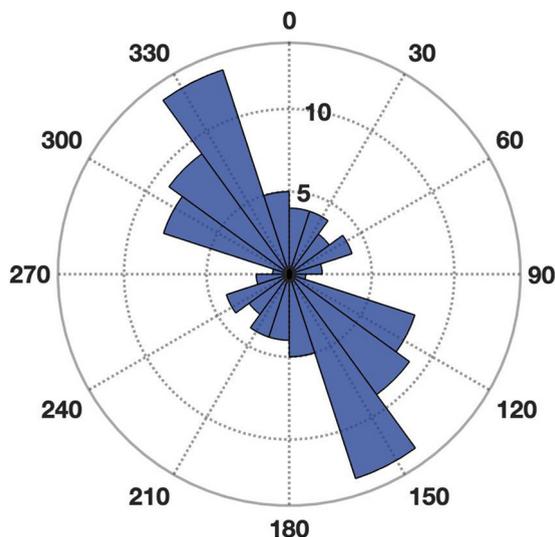


Fig. 10. Rose diagram (10° bins; $n = 53$) showing dominant NNW and NW azimuth trend ($N48.69W \pm 10.82^\circ$) of stream reaches in Ichawaynochaway Creek where groundwater inputs were detected (increases $\geq 100\%$ above the mean change in specific conductance/km; Rugel et al., 2016).

dominant reach azimuth throughout the entire LFRB was N–S (Fig. 4) with secondary trends bearing E–W, NW–SE and NE–SW. As expected, many of these trends were reflected in individual tributaries of the LFRB, with variations within the basin which will be discussed later in this section (Fig. 6). Not surprisingly, bedrock jointing patterns measured in outcrops within Ichawaynochaway Creek, shared similarities with some reach azimuths for that stream, with a dominant N–S trend and lesser E–W and NW–SE trends (Figs. 6 and 8). The fact that both large and small-scale hydrogeomorphic trends (stream orientation and joint orientation) shared similarities is not unexpected, as fluvial geomorphology often aligns with regional jointing (Melton, 1959; Stringfield, 1966; Freeze

and Cherry, 1979; Hancock and Engelder, 1989). However, a pivotal finding of the current study is that where significant changes in groundwater discharge were detected in Ichawaynochaway Creek [by Rugel et al., 2016] the stream reaches followed NW or NNW bearings (mean $N48W \pm 10.82^\circ$; Fig. 10) 55% of the time.

Despite their ubiquity, the N-S reaches appear to be less hydraulically connective in the Ichawaynochaway tributary. It is possible that these reaches may not interact with deeper, more active dissolution features in this portion of the basin which follow NW-SE trends. To ensure that the N-S trend was not an artifact fabricated by the Fracture Rose program we re-ran RF3 data back through MatLab with identical results. The fact that the N-S trend was also present in the Ichawaynochaway joints measured in the Ocala Limestone outcrops, suggests that the trend is real and not an artifact of the RF3 data set or other programs used in this study.

These results are novel to this basin but in agreement with previous observations in adjoining portions of the LFRB where jointing trends influenced regional dissolution and groundwater flow. Brook and Sun (1986) showed that 79% of specific capacity in wells measured in Dougherty County could be attributed to proximity to joints and/or joint intersections. In addition, Brook and Allison (1983) concluded that sinkhole formation in Dougherty County was influenced by a conjugate set of fractures around N35 W and N40E and hypothesized these jointing sets were propagated upward from basement rocks into the younger overlying sediments. Hyatt and Jacobs (1996) also showed that, after record rainfalls during Tropical Storm Alberto in 1994, 312 sinkholes formed in Albany, GA, following joint-controlled linear trends, including N55 W, N45E, and N5W orientations.

In the basin-scale analysis, we were able to detect where reach bearing trends deviate across the LFRB (Fig. 6). For example, while the N-S trend dominated in almost all tributaries, the NW-SE trend was equally strong in Big Cypress Creek. In fact, the southwestern and northern tributaries in the LFRB showed stronger reach azimuth trends in the NW-SE direction (Big Cypress, Spring, Ichawaynochaway, Pachitla, Kinchafoonee and Muckalee Creeks) with less pronounced trends in NE-SW reaches. This pattern began to shift in the central and southeastern tributaries where, after the N-S trend, reaches had either a mixture of NE-SW and NW-SE reaches (Chickasawhatchee Creek) or showed a greater occurrence of NE-SW reaches (Kiokee Creek and lower stem of the Flint River) compared to the rest of the basin. While the reason for this shift is unclear and outside the scope of this study, it may be a relic of transitional Atlantic and Gulf Coast stress fields in this region (Zoback and Zoback, 1980).

We can conjecture that if stream reaches throughout the LFRB make these directional transitions then jointing patterns may also reflect those changes. As these transitions occur across the basin, if in fact they are driven by jointing trends, groundwater discharge might be found in stream reaches following orientations in those emergent trends. Some of the transitional patterns found in this study are reflected in the orientational changes in joints measured in upland outcrops around this region (McDowell, 2012).

5.2. Significance and further avenues of research

The results of this study are notable and suggest that further ground truthing of jointing patterns and locations of groundwater discharge in other tributaries of the LFRB is warranted. If predictable patterns emerge, they may be useful to water resource management for creating strategies which protect reaches where increased groundwater is detected. These studies may be aided by LiDAR as well as available remote sensing data sets for wetlands, vegetation and lineaments (Cahalan and Milewski, 2018). Remaining questions to be answered include whether groundwater discharge is enhanced in NW-SE directions in other tributaries in the southwestern and northern portions of the basin with similar NW-SE reaches. Does discharge follow a different pattern in tributaries in the southwestern portion of the LFRB where reaches trend more towards NE-SW bearings? Is groundwater discharge enhanced around creek vertices where these orientations, or joints, intersect? Does length of reach influence discharge?

Stream reversals (due to natural or anthropogenic causes) create losing stream conditions leading to baseflow capture and risk of groundwater contamination. Some portions of the LFRB, including the Ichawaynochaway and Spring Creek sub-basins, are already restricted from further development due to the deleterious effects of irrigation on low flows in these areas (Couch and McDowell, 2006; Rugel et al., 2016). These two sub-basins have the highest density of groundwater and surface water permits in the state in a region where streams cut deep into the Ocala Limestone. If reproducible in other sub-basins, the methods used in this study could potentially identify and predict where groundwater discharge is occurring in other major tributaries of the LFRB, guiding management strategies into areas where the greatest protection is needed. This might include regulating (and incentivizing) additional distance between groundwater wells and vulnerable stream reaches or requiring additional buffering requirements in those riparian zones, while allowing other areas of less vulnerability to be developed.

Groundwater discharge affects multiple stream parameters including residence time, hyporheic exchange, temperature, bed transport, sorting, and nutrient loading. These physical factors ultimately affect biological complexity, productivity, and community structure in aquatic systems (Valett et al., 1996; Bunn and Arthington, 2002; Freeman et al., 2007). Identifying regions of groundwater discharge in the LFRB may help determine appropriate sites where populations of sensitive mussels and other groundwater-dependent stream species could be protected, translocated, or removed from reaches where excessive groundwater pumping may have negative and cascading effects on streamflow (Stamey, 1996; Albertson and Torak, 2002; Couch and McDowell, 2006; Peterson et al., 2011).

6. Conclusion

Analysis of stream reach orientations in the LFRB using the U.S. EPA Reach File 3 indicated a dominant N-S azimuth trend occurring up to 44% more often than other stream reach directions, with lesser trends oriented E-W, NW-SE and NE-SW. Directional trends in Ichawaynochaway Creek (a tributary of the LFRB) mimicked some jointing trends we measured in limestone bedrock in this stream which followed N-S, E-W and NW-SE orientations. When we compared these data to azimuths of stream reaches where

enhanced groundwater discharge was detected in a previous study on Ichawaynochaway Creek by Rugel and others (2016), we found that 55% of the time, groundwater discharge was notably higher in reaches which followed NW or NNW bearings (average bearing $N48.69W \pm 10.82^\circ$). These results indicate that disproportionate amounts of groundwater are entering the stream through a relatively small number of reaches with distinct stream orientations. Increased seepage at these sites may be the result of the stream following a major through-going joint or intersecting multiple regional jointing trends (Brook and Allison, 1983; Brook and Sun, 1986) and warrants further investigation.

The methods used in this study are relatively simple and immediately transferrable to other karst (and potentially fractured rock) basins where data exist, or could be collected, on locations of enhanced groundwater-surface water interaction. These methods exploit a readily available data set (RF3) for the entire conterminous U.S. and reveal trends in large and small-scale geological heterogeneity that can affect hydraulic gradients, dissolution patterns, and hydrologic budgets.

The LFRB is an economically-important region in the southeastern US which supports jobs, local economies and livelihoods related to agriculture dependent on irrigation. The basin is also home to endangered and threatened aquatic species which are endemic to these streams. Reproducing the results of this study in other portions of this basin may help identify reaches where groundwater is discharging (or at risk of baseflow capture) in other tributaries of the LFRB. Theoretically, these data could support the development of prudent water resource management to direct sensible strategies towards reaches which are most susceptible to gaining or losing conditions while allowing development in less vulnerable reaches, therefore protecting both economic and environmental interest in the basin.

Conflicts of interest

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

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Data for this analysis can be obtained through the Joseph W. Jones Research Center at Ichauway. Data at the Jones Center are archived in a long-term database, a curated repository for studies at Ichauway and the surrounding region. Data requests will be considered on an individual case basis and reasonable requests accommodated. Please contact kathleen.rugel@gmail.com for more information. The U.S. EPA Reach File 3 for the Conterminous United States can be accessed at <https://www.epa.gov/exposure-assessment-models/metadata-reach-file-1>. For information on Fracture Rose diagram program contact jdowd@uga.edu.

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