# Effects of Flooding and Drought on Water Quality in Gulf Coastal Plain Streams in Georgia

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## ABSTRACT

**Since 1994, water-quality constituents have been measured monthly in three adjacent Coastal Plain watersheds in southwestern Georgia. During 1994, rainfall was 650 mm above annual average and the highest flows on record were observed. From November 1998 through November 2000, 19 months had below average rainfall. Lowest flows on record were observed during the summer of 2000. The watersheds are human-dominated with row-crop agriculture and managed forestlands being the major land uses. However, one watershed (Chickasawhatchee Creek) had 10 to 13% less agriculture and greater wetland area, especially along the stream. Suspended particles, dissolved organic carbon, $NH_4$–N, and soluble reactive phosphorus concentrations were greater during wet and flood periods compared with dry and drought periods for each stream. Regional hydrologic conditions had little effect on $NO_3$–N or dissolved inorganic carbon. Chickasawhatchee Creek had significantly lower suspended sediment and $NO_3$–N concentrations and greater organic and inorganic carbon concentrations, reflecting greater wetland area and stronger connection to a regional aquifer system. Even though substantial human land use occurred within all watersheds, water quality was generally good and can be attributed to low stream drainage density and relatively intact floodplain forests. Low drainage density minimizes surface runoff into streams. Floodplain forests reduce nonpoint-source pollutants through biological and physical absorption. In addition to preserving water quality, floodplain forests provide important ecological functions through the export of nutrients and organic carbon to streams. Extreme low flows may be disruptive to aquatic life due to both the lack of water and to the scarcity of biologically important materials originating from floodplain forests.**

LITTLE INFORMATION is available on how annual variations in the timing and distribution of rainfall affect surface water quality. This is of particular interest in the Gulf Coastal Plain because the sandy well-drained soils characteristic of the region are prone to nutrient leaching and sediment erosion. In southwestern Georgia, row-crop agriculture has expanded with the development of center pivot irrigation in the mid 1970s (Hicks et al., 1987; Harrison, 2001). Regionally, the development of extensive agriculture has been associated with degraded surface water quality, especially if riparian forests are cleared (Lowrance et al., 1983, 1984). Thus, there is a concern about the degradation of surface and ground water quality as human land use intensifies.

Southwestern Georgia can receive abundant precipitation, averaging about 1270 mm per year (Golden and Hess, 1991). However, large annual variability occurs and most recording stations report twofold differences between annual minimum and maximum rainfall over the period of record during the 20th century (Golden and Hess, 1991). The region is prone to extreme hydrologic events. Frontal or tropical weather systems circulate humid air from the Gulf of Mexico and can produce heavy rainfall and extended flooding throughout the year (Golden and Hess, 1991). Major floods in the southwest portion of the state occurred in 1925, 1948, 1994, and 1998. Extended droughts result from persistent high-pressure systems, which prevent influx of moisture from the Gulf of Mexico (Golden and Hess, 1991). Extended droughts occurred during the 1930s, 1950s, and 1980s. The region was in a moderate to severe drought from the fall of 1998 through January of 2001.

Since 1994, we have been monitoring water quality in three adjacent watersheds on the Gulf Coastal Plain in southwestern Georgia. Specific objectives of the study were to examine seasonal variation in water quality, how unusual hydrologic events (record flooding and extended drought) influence water quality, and how differences in geology and the distribution of riparian wetlands influence water quality.

## STUDY SITE

### Geology

We studied three adjacent watersheds (Pachitla Creek, Upper Ichawaynochaway Creek, and Chickasawhatchee Creek) in the Ichawaynochaway Creek drainage (Fig. 1), which is a major tributary of the lower Flint River, on the Gulf Coastal Plain of southwestern Georgia. The streams originate in the Fall Line Hills physiographic district. Their flows begin as seeps and springs emanating from the Claiborne aquifer. Downstream, the Chickasawhatchee and Ichawaynochaway Creeks flow into the Dougherty Plain, which is classified as mantled karst topography. A surface layer of sands and clays 1 to 40 m thick covers the area (Hayes et al., 1983). Beneath is the Ocala Limestone, an extensively fractured and porous rock layer often exhibiting high hydraulic conductivity. The Ocala Limestone is the principal water bearing strata for the Upper Floridan Aquifer, a regionally important water resource (Hicks et al., 1981). Chemically, the Upper Floridan has significant dissolved calcium bicarbonate (91–256 mg/L alkalinity as $CaCO_3$), circumneutral pH (6.9–7.4), and nitrate concentrations well within drinking water standards (0.47–2.50 mg/L) (Hicks et al., 1987).

Low topographic relief in combination with porous surface geology results in low stream drainage density and a dominance of subsurface water flow in regional hydrology (Hicks et al., 1987). Major streams and their tributaries have channels incised within the Ocala Limestone and are perennial; smaller streams with channels above the Ocala Limestone tend to be intermittent (Beck and Arden, 1983; Hayes et al., 1983). Ichawaynochaway and Chickasawhatchee Creeks flow through

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**Abbreviations:** DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; PCA, principal components analysis; PIM, particulate inorganic matter; POM, particulate organic matter; SRP, soluble reactive phosphorus.

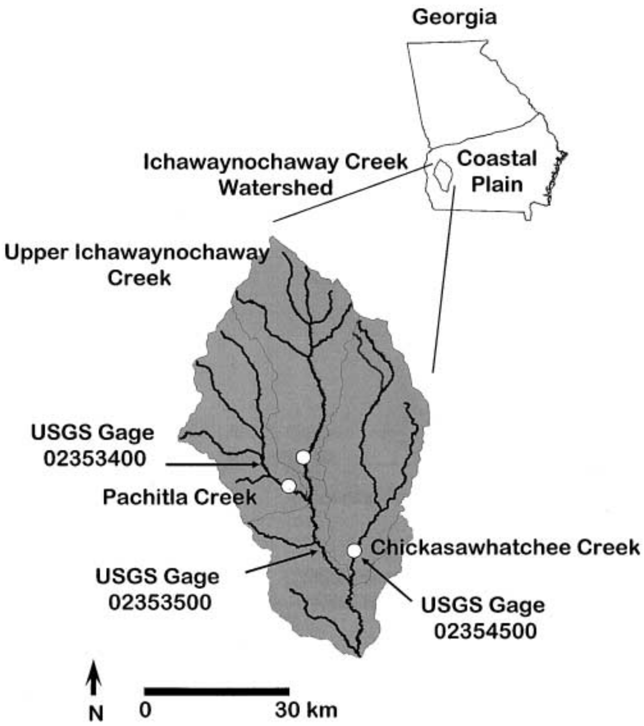

**Fig. 1. The Ichawaynochaway Creek watershed, located in southwestern Georgia. Circles indicate the location of sampling sites at the base of the three watersheds. Locations of U.S. Geological Survey (USGS) stream gaging stations are indicated by arrows.**

areas where they are in contact with the Upper Floridan aquifer. Base flows in these streams are supported largely from discharges from the aquifer (Hicks et al., 1987).

## Land Cover and Land Use

The watersheds range in size from 65 800 to 86 800 ha (Table 1). In 1990, row-crop agriculture and managed forestlands were the dominant land use within each watershed. Pachitla Creek and Upper Ichawaynochaway Creek watersheds had very similar land use (approximately 50% agriculture and 30% forest). Chickasawhatchee Creek had 10 to 13% less agriculture and greater wetland area than the other sites. Much of the wetland area within the Chickasawhatchee watershed is the Chickasawhatchee Swamp, a substantial wetland complex adjacent to the lower portion of the creek. It is the second-largest southern deepwater swamp and riparian wetland in Georgia, exceeded in areal extent by only the Okefenokee Swamp of southeastern Georgia (Georgia News, 2000). Urban development was minimal in each of the three watersheds.

Since the beginning of the study in 1994, agricultural lands have increased by about 20% in the region (Litts et al., 2001). In 1999, approximately 85% of agricultural lands were irrigated, mostly by withdrawals from the Upper Floridan Aquifer (Litts et al., 2001). In Georgia, permits are issued for surface and ground water withdrawals; however, there is no requirement for reporting actual water use (Thomas et al., 2001). In 2000, statewide estimates of irrigation amounts were 247 mm with most water use in southwestern Georgia (Harrison, 2001; Thomas et al., 2001). At that level, water use is approximately 20% of long-term average annual precipitation.

The three study streams originate in headwater swamp and wetland complexes. An intact riparian forest occurs along most of the streams and is composed of flood tolerant hardwoods, bald cypress [*Taxodium distichum* (L.) Rich.] and red cedar [*Juniperus virginiana* L. var. silicicola (Small) A.E. Murray]. All of the streams tend to be highly stained, particularly during high flows when streamflow is dominated by discharge from swamps and wetlands.

**Table 1. Land use estimates for subwatersheds in the Ichawaynochaway Basin. Estimates were derived from 1990 Landsat Thematic Mapper imagery.**

| | Pachitla Creek | Upper Ichawaynochaway Creek | Chickasawhatchee Creek |
|---|---|---|---|
| **Subcatchment** | | | |
| **Agriculture, %** | **51.9** | **54.9** | **42.0** |
| **Forested, %** | **31.8** | **30.4** | **32.2** |
| **Clearcut, %** | **7.5** | **7.0** | **9.7** |
| **Wetlands, %** | **8.4** | **7.5** | **15.8** |
| **Urban, %** | **0.4** | **0.2** | **0.3** |
| **Catchment area, ha** | **65 800** | **78 500** | **86 800** |

## Hydrology

A long-term streamflow monitoring station (continuous 1940–present, USGS Gage 02353500) is located on the mainstem of lower Ichawaynochaway Creek between its confluence with Pachitla Creek and Chickasawhatchee Creek (Fig. 1). Other gaging stations are located on Pachitla Creek (02353400) and Chickasawhatchee Creek (02354500). However, those stations are not long term and only include a partial record for the study. Therefore, the Pachitla and Chickasawhatchee stations could not be used to evaluate the magnitude of floods and droughts or to characterize regional hydrological conditions. For the periods of record, average monthly discharge was compared between Ichawaynochaway Creek and the other stations. Average monthly discharges were highly correlated (Fig. 2); thus, we used the Ichawaynochaway Creek station to characterize regional hydrology.

Winter is the primary season when ground water recharge occurs in the Dougherty Plain. During winter, both the regional water-table level and regional streamflow increase in response to extended storms (Hayes et al., 1983). Inundation of riparian areas generally occurs in late winter. During summer, most of the precipitation is lost through evapotranspiration; thus, ground water recharge is minimal, and the water table declines. As a result, riparian areas are dry and streams are at seasonal low flow.

Our study included both average and unusual hydrologic

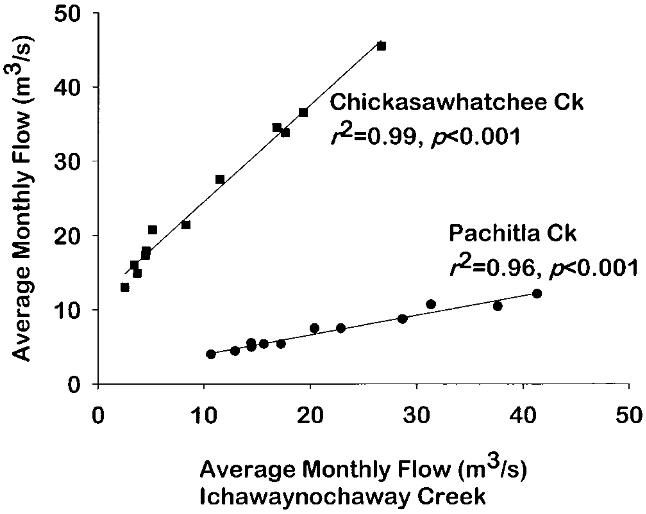

**Fig. 2. Linear regressions of average monthly flow from gaging stations on Chickasawhatchee and Pachilta Creeks compared with Ichawaynochaway Creek.**

conditions. During 1994, Tropical Storm Alberto and a number of other tropical storms resulted in near record precipitation (1920 mm total, 650 mm above average) in southwestern Georgia. The highest streamflow on record occurred during July 1994. Streams in the region remained at or above average discharge during the summer and fall of 1994 and through the spring of 1995 (Fig. 3). Streams also had above average flows from winter 1997 to spring 1998. In 1993, 1996, and 1997, hydrologic conditions were more typical of average conditions, with high flows in late winter and spring and lower flows in summer and autumn. In November 1998, a period of below normal rainfall began. For the next 24 months, streamflows were generally below long-term averages, with only five months recording average or greater amounts of rainfall. The lowest flows on record occurred during the summer of 2000 (Fig. 3).

## METHODS

### Water Quality Analyses

Since 1994, surface-water samples were taken monthly during stable flow periods at the base of the three watersheds (Fig. 1). Generally, storm pulses were avoided, but samples were taken during many high flow periods. Surface grab samples were collected in well-mixed areas with measurable flow. Sampling areas were in places with observable current; slack- or backwater areas were avoided. Three samples were collected in acid-washed polypropylene bottles at each site, stored on ice, and transported to the laboratory for processing, which occurred within 24 h. In the laboratory, measured volumes of water were filtered onto preweighed glass fiber filters (Gelman [Ann Arbor, MI] A/E, 1 μm), which were dried, weighed, ashed (500°C, 1 h), and reweighed to determine particulate organic matter (i.e., POM, mass loss on combustion) and particulate inorganic matter (i.e., PIM, residual mass) (Wallace and Grubaugh, 1996).

Water passing through the filter was separated into aliquots for subsequent analysis (dissolved organic carbon [DOC], dissolved inorganic carbon [DIC], $NO_3$–N, $NH_4$–N, and soluble reactive phosphorus [SRP]). Dissolved carbon subsamples were stored at 4°C and analyzed within a month of sampling using a Shimadzu (Kyoto, Japan) TOC-5050 analyzer. The $NH_4$–N subsamples were preserved with sodium phenolate, stored at 4°C, and analyzed within a month. The $NO_3$–N and SRP subsamples were frozen (−20°C) and analyzed within 3 to 6 mo. The $NH_4$–N, $NO_3$–N, and SRP concentration was determined with a Lachat (Milwaukee, WI) Quikchem 8000 using a flow-injection colorimetric method (Lachat Instru-

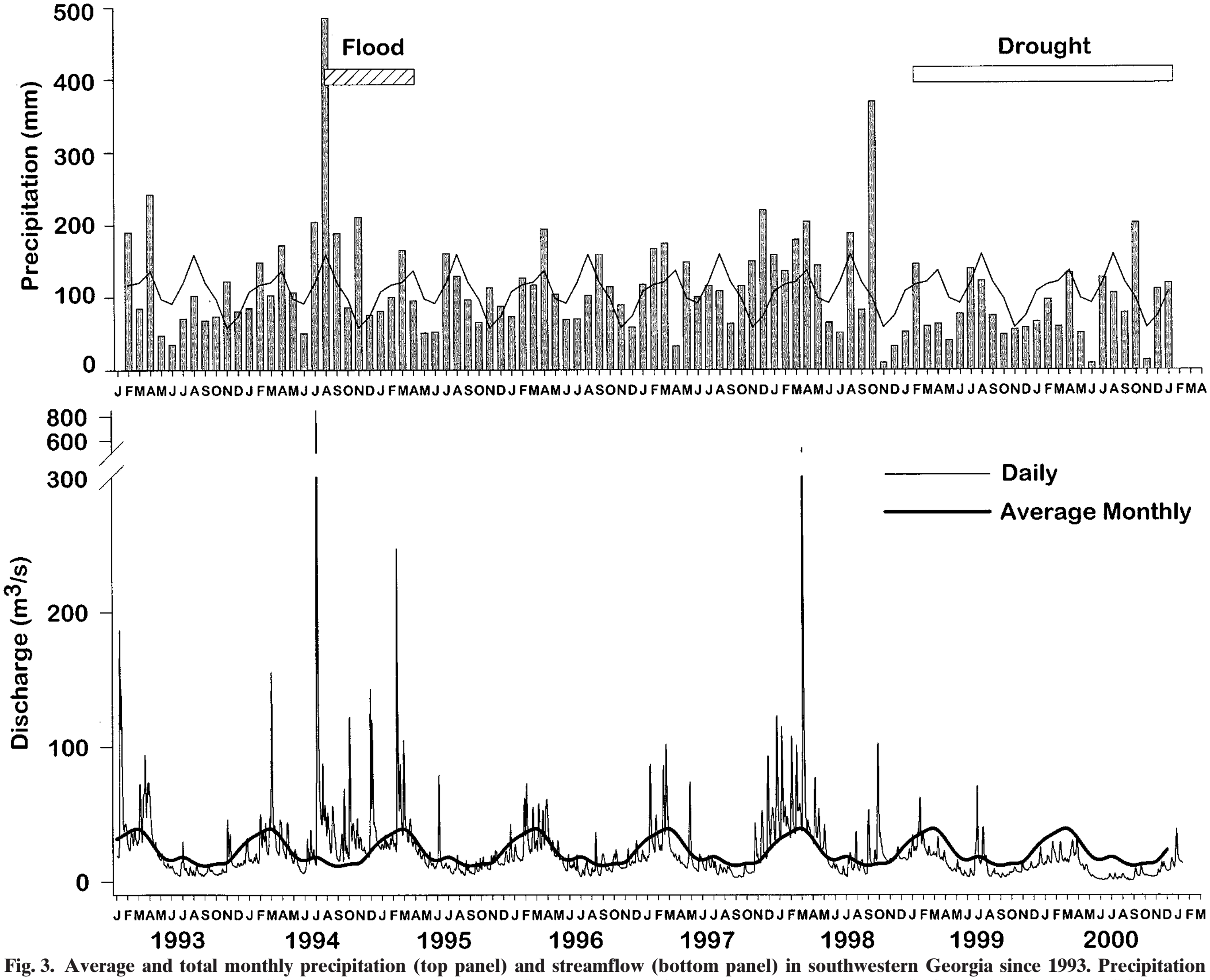

**Fig. 3. Average and total monthly precipitation (top panel) and streamflow (bottom panel) in southwestern Georgia since 1993. Precipitation data are from the National Climate Data Center Drought Series database. Streamflow data are from U.S. Geological Survey (USGS) Gage 02353500 on Ichawaynochaway Creek.**

ments, 2001). On each collection date a set of bottle blanks (i.e., a set of collection bottles filled with ultrapure water) was prepared and analyzed with samples to detect and correct for possible contamination. Dissolved carbon and nutrient analyses included check standards to ensure instrument precision. Detection limits for each analysis were determined and recorded according to standard methods (Anonymous, 1999).

## Data Analyses

Prior to data analysis, raw data (i.e., sample replicates) were subjected to a quality assurance procedure to detect possible outliers. In this type of data, outliers (aberrant replicates) are most often large values caused by inadvertently suspending sediments during a sample collection. Outliers can also result from contamination in collecting equipment or labware. Our approach involved two steps. First, we calculated means and standard deviations for each constituent by site and date combinations (i.e., sample). The average standard deviation (study-wide) was also determined for each constituent. Then, standard deviations for each constituent were compared with study-wide standard deviations. If a sample standard deviation was greater than five times the study-wide standard deviation, then that set of replicate observations was flagged as potentially containing an outlier. In the second step, a Grubbs Test (Grubbs and Beck, 1972) was used to objectively identify outlying observations from each set of replicate samples. Those observations identified as outliers were deleted from the larger data set. This procedure only eliminates a sample replicate that differs from the other two replicates collected at the same time. This procedure would not eliminate a sample (i.e., group of replicates) that was unusual for a particular water quality constituent. Less than 0.3% of sample replicates collected were recognized as outliers.

Following outlier analysis, the average concentration of each constituent was calculated for each sample date and analyzed in several ways. Principal components analysis (PCA) was used as a form of exploratory data analysis and was intended to visualize broad trends in the data; the procedure was used to develop hypotheses rather than test them. Principal components analysis is an eigenvector method of ordination that reduces a data set containing many variables to a smaller number of composite variables (components or axes), indicating the strongest covariation among variables within the first few axes. The PCA options were Euclidean distance and cutoff $r^2$ set at 0.25 (McCune and Mefford, 1995). The decision to interpret two axes was based on broken-stick eigenvalues. The results of the ordination were examined in two ways. First, each stream was designated with separate symbols to see if differences between watersheds were apparent. Second, different symbols were used to contrast seasonal and record flooding from seasonal dry periods and the extended drought to see if there were differences in water quality that could be related to regional hydrologic conditions (see Table 2).

Confidence ellipses (50% significance level) were estimated to objectively determine the central tendencies of sample points for the groups listed above (e.g., Nolan, 1999). The confidence ellipses show where specified percentages of sample scores should occur, assuming a bivariate normal distribution (SAS Insight, 1993). The means and standard deviations of sample scores are used to determine the major and minor axes ($x$ and $y$) of the ellipse. Directional orientation of the ellipse is determined by the covariance of sample scores (Nolan, 1999; SAS Insight, 1993).

Based on the results of the PCA, seasonal and study-wide median values were compared to examine variation in each water quality constituent between streams and over the course of the study. Comparisons were performed using an analysis of variance (ANOVA) on ranks followed by a Tukey's Studentized Range Test (Helsel and Hirsch, 1992; Spahr and Wynn, 1997). Median values were compared to reduce the

**Table 2. Median concentrations of water quality parameters by season. Seasons were defined as Drought (January 1999–December 2000), Dry (July–December 1995, 1996, 1997, 1998), Wet (January–June 1994, 1996, 1997, 1998), and Flood (July 1994–May 1995). Values in parentheses are interquartile ranges for ranked values and sample sizes (Helsel and Hirsch, 1992). For each stream and parameter, values with different letters are significantly different (analysis of variance [ANOVA] on ranks followed by Tukey's Studentized Range Test, $p < 0.05$).**

| Parameter† | Season | Pachitla Creek | Upper Ichawaynochaway Creek | Chicasawatchee Creek |
|---|---|---|---|---|
| POM, mg/L | Drought | 1.231a (0.911–1.638, 21) | 1.248a (0.730–1.537, 21) | 0.732a (0.438–1.116, 21) |
| | Dry | 1.362a (1.105–1.842, 22) | 1.503ac (1.174–2.059, 22) | 1.095a (0.825–1.497, 18) |
| | Wet | 2.051b (1.592–2.522, 20) | 2.283bc (1.848–2.680, 21) | 1.348b (0.959–2.175, 19) |
| | Flood | 3.135b (1.782–3.662, 11) | 3.000b (2.067–3.740, 11) | 2.683b (2.157–3.377, 9) |
| PIM, mg/L | Drought | 2.042a (1.045–3.155, 21) | 1.988a (1.206–2.377, 21) | 0.838a (0.470–1.655, 21) |
| | Dry | 2.225a (1.639–3.460, 22) | 2.614b (2.105–3.923, 22) | 1.616a (1.336–2.373, 18) |
| | Wet | 5.440b (3.957–7.086, 20) | 4.891c (3.783–7.083, 21) | 2.910b (2.257–5.332, 19) |
| | Flood | 8.195b (5.983–12.945, 11) | 6.350c (5.958–10.030, 11) | 5.333c (4.738–7.123, 9) |
| DOC, mg/L | Drought | 3.178ab (2.556–4.640, 21) | 4.258a (3.113–4.648, 21) | 4.603a (0.010–10.102, 21) |
| | Dry | 3.077a (2.612–3.753, 22) | 3.979a (3.246–4.887, 22) | 7.687a (5.654–11.454, 18) |
| | Wet | 3.750ab (3.092–4.654, 20) | 5.211ab (3.944–6.397, 21) | 7.580a (5.741–9.195, 19) |
| | Flood | 5.348b (3.266–8.027, 11) | 8.273b (4.555–10.246, 11) | 8.044a (3.221–10.833, 9) |
| $NO_3$–N, μg/L | Drought | 465.0a (325.6–547.3, 21) | 665.1a (531.5–865.3, 21) | 299.0a (92.4–822.3, 21) |
| | Dry | 407.3a (358.6–459.0, 22) | 624.4a (514.7–778.8, 22) | 177.3a (98.2–532.9, 18) |
| | Wet | 365.4a (260.3–432.7, 20) | 484.3a (401.4–729.4, 21) | 176.6a (105.5–336.2, 19) |
| | Flood | 287.9a (229.8–486.7, 11) | 441.4a (346.5–734.1, 11) | 148.2a (142.9–204.6, 9) |
| $NH_4$–N, μg/L | Drought | 13.72a (10.35–24.27, 21) | 16.34a (10.52–24.86, 21) | 12.49a (8.43–27.84, 21) |
| | Dry | 17.01a (11.75–23.13, 22) | 17.97a (11.24–22.29, 22) | 12.44a (6.82–16.33, 18) |
| | Wet | 32.68b (24.05–44.41, 20) | 30.32b (24.18–41.77, 21) | 22.90b (18.02–44.90, 19) |
| | Flood | 54.98c (41.21–63.04, 11) | 57.46c (45.66–64.70, 11) | 26.49b (18.39–45.95, 9) |
| SRP, μg/L | Drought | 2.425a (1.855–3.033, 21) | 2.077a (1.463–3.006, 21) | 2.672a (1.699–3.111, 21) |
| | Dry | 3.326ab (2.231–4.198, 22) | 2.794ab (1.878–3.726, 22) | 3.323ab (3.2423–4.147, 18) |
| | Wet | 3.802b (3.074–4.854, 20) | 3.967b (2.655–4.280, 21) | 4.319b (3.336–4.235, 9) |
| | Flood | 4.257b (3.108–4.563, 11) | 3.897b (3.336–4.328, 11) | 3.798b (3.243–4.147, 18) |
| DIC, mg/L | Drought | 4.152a (3.319–5.083, 21) | 3.122a (2.744–3.413, 21) | 21.626a (13.975–29.994, 21) |
| | Dry | 4.580a (3.549–5.515, 22) | 3.155a (2.783–3.310, 22) | 15.990a (14.591–24.980, 18) |
| | Wet | 5.064a (4.162–5.627, 20) | 2.382a (1.746–3.073, 21) | 15.088a (11.260–22.389, 19) |
| | Flood | 5.182a (4.812–5.723, 11) | 2.558a (2.230–3.216, 11) | 15.990a (12.933–21.853, 9) |

† DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; PIM, particulate inorganic matter; POM, particulate organic matter; SRP, soluble reactive phosphorus.

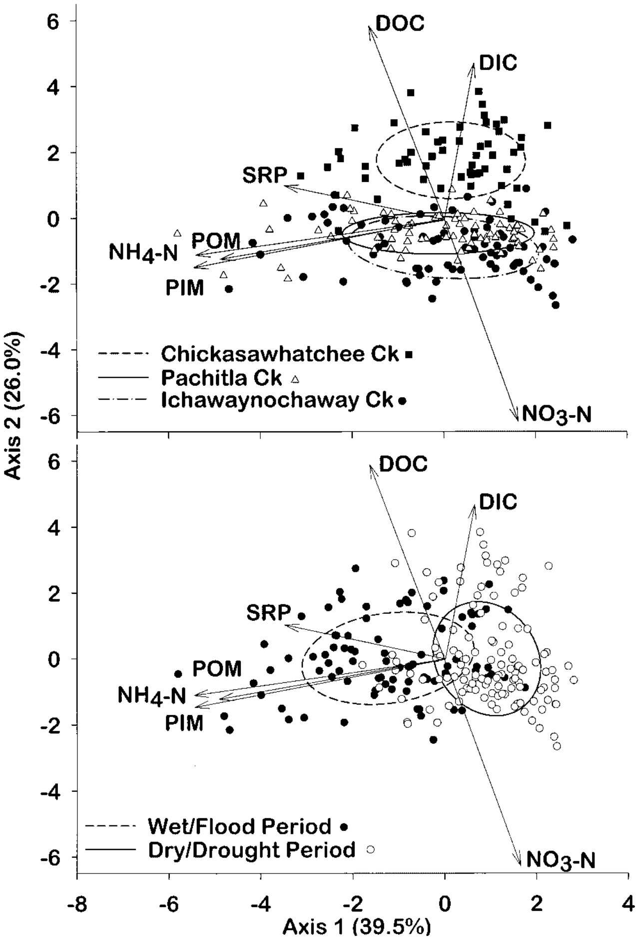

**Fig. 4. Principal components analysis ordinations for water quality parameters for Pachitla, Ichawaynochaway, and Chickasawhatchee Creeks. The top panel highlights differences between streams. The bottom panel is the same ordination highlighting differences between hydrologic seasons. Enclosed areas represent 50% confidence ellipses.**

influence of outliers and other deviations from normality common in water quality data (e.g., Spahr and Wynn, 1997). Seasonal medians were based on two "hydrologic" seasons derived from long-term climatic and hydrologic conditions (e.g., Golladay et al., 2000; and Table 2): January–June tends to have moisture surpluses with streams often at high flow and the floodplain inundated; July–December tends to be a period of moisture deficits with the floodplain typically dry. Seasonal values for typical years were contrasted with the period of above average flows (July 1994–May 1995) and the drought (January 1999–December 2000).

# RESULTS

## Multivariate Analysis

The first two axes of the PCA explained 65% of the variation in the water quality data. In the ordination biplot (Fig. 4), points represent site and date sample scores. The vectors indicate the importance of particular water quality constituents in explaining variation in the analysis. Longer vectors have a greater weight, while proximity to an axis indicates the degree of correlation with that principal component. Particulate inorganic matter, POM, and $NH_4$–N were strongly negatively correlated with Axis 1 ($r^2 = 0.81$, 0.81, and 0.65, respectively). Soluble reactive P was weakly negatively correlated with Axis 1 ($r^2 = 0.33$). Dissolved organic C and DIC were positively correlated with Axis 2 ($r^2 = 0.63$, and 0.40, respectively) while $NO_3$–N was negatively correlated with Axis 2 ($r^2 = 0.69$). Wet and flood periods and dry and drought periods tended to separate along Axis 1 while streams separated along Axis 2. The separation is apparent in the 50% confidence ellipses (Fig. 4). For all streams, the wet and flood periods tended to have higher PIM, POM, $NH_4$–N, and SRP concentrations than the dry and drought periods. Chickasawhatchee Creek tended to have higher DOC and DIC, and lower $NO_3$–N than the other streams.

## Water Quality Comparison by Hydrologic Season and Stream

Particulate organic matter, PIM, $NH_4$–N, and SRP concentrations tended to be significantly greater during wet and flood periods compared with dry and drought periods for each stream (Table 2). While there was a general trend of higher concentration with increasing degree of flooding (i.e., flood > wet > dry > drought), a broad overlap of ranges in concentration occurred. A weaker influence of hydrologic season was observed for DOC, which was significantly greater during flood periods compared with dry periods in Pachitla and Ichawaynochaway Creeks (Table 2). Hydrologic season had little effect on $NO_3$–N or DIC concentrations in the streams.

Study-wide median concentrations of several water quality constituents were also different among streams. Chickasawhatchee Creek had significantly lower POM, PIM, and $NO_3$–N than either of the other sites (Table 3). The DOC and DIC concentrations in Chickasawhatchee were significantly greater than the other sites. There was

**Table 3. Study-wide median concentrations of water quality parameters for Pachitla, Upper Ichawaynochaway, and Chickasawhatchee Creeks. Values in parentheses represent interquartile ranges for ranked values and sample sizes (Helsel and Hirsch, 1992). Across a row medians with different letters are significantly different (analysis of variance [ANOVA] on ranks followed by Tukey's Studentized Range Test, $p < 0.05$).**

| Parameter† | Pachitla Creek | Upper Ichawaynochaway Creek | Chickasawhatchee Creek | ANOVA *p* value |
|---|---|---|---|---|
| POM, mg/L | 1.565b (1.125–2.143, 74) | 1.848b (1.217–2.455, 79) | 1.042a (0.735–1.602, 67) | 0.0003 |
| PIM, mg/L | 2.964b (1.594–4.721, 74) | 3.429b (2.111–5.656, 79) | 1.657a (0.711–3.316, 67) | 0.0001 |
| DOC, mg/L | 3.523a (2.694–4.640, 74) | 4.555b (3.508–6.003, 79) | 7.512c (3.221–10.834, 67) | 0.0001 |
| $NO_3$–N, μg/L | 396.5b (308.9–486.7, 74) | 572.1c (422.4–747.4, 79) | 187.0a (98.2–471.8, 67) | 0.0001 |
| $NH_4$–N, μg/L | 23.99a (13.59–36.29, 74) | 22.45a (14.27–38.97, 79) | 18.04a (10.72–29.78, 67) | 0.04 |
| SRP, μg/L | 3.317a (2.330–4.325, 74) | 3.123a (1.879–4.227, 79) | 3.433a (2.629–4.319, 67) | 0.3 |
| DIC, mg/L | 4.805b (3.692–5.515, 74) | 2.984a (2.289–3.301, 79) | 17.75c (12.82–24.98, 67) | 0.0001 |

† DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; PIM, particulate inorganic matter; POM, particulate organic matter; SRP, soluble reactive phosphorus.

no difference in $NH_4$–N or SRP concentrations between streams.

# DISCUSSION

## Hydrologic Influences

The PCA suggests two gradients influencing water quality. Axis 1 represents a hydrologic gradient ranging from record flooding to drought conditions. Axis 2 reflects geological and landcover differences between watersheds including degree of connection with the Upper Floridan Aquifer and amount and distribution of wetland area. Particulate organic matter, PIM, DOC, and $NH_4$–N were under strong hydrologic control, with higher concentrations generally observed during wet or flooded conditions. Soluble reactive P concentrations were also slightly higher during wetter periods. Hydrologic control reflects the strong linkage between low-gradient streams and their floodplains. Suspension of POM results from both the percolation of water upward through soils and erosion from soil surfaces in areas of turbulent flow (Wainright et al., 1992). Particulate inorganic matter originates from similar mechanisms and greatest concentrations occur when surface erosion transports soil particles into streams (Arheimer and Liden, 2000). Particulate inorganic matter transport may be enhanced if there are disturbed areas adjacent to streams (Arheimer and Liden, 2000). High PIM concentrations can also result from resuspension of sediments deposited during previous floods.

In low-gradient streams, DOC leaches from organic matter accumulated on the surface of floodplains and riparian wetlands. In the southeastern Coastal Plain, higher DOC concentrations are generally associated with streams having intact riparian forests (Spruill, 2000). The higher concentrations we generally observed during floods result from the dominance of surface and shallow subsurface flow across the floodplain, bypassing DOC absorption that might occur with deeper flow paths (i.e., aquifer discharge) (Sedell and Dahm, 1990; Dosskey and Bertsch, 1994; Spruill, 2000).

Ammonium N is a common form of N in waterlogged wetland soils (Mitsch and Gosselink, 1993) and the higher concentrations we observed during floods probably reflect leaching from floodplain soils. Alternating periods of flooding and drying and alternating aerobic and anaerobic conditions have been shown to stimulate inorganic nitrogen release from soils (e.g., Reddy and Patrick, 1975).

Soluble reactive P is generally not considered mobile in soils; however, anoxic soil conditions that occur during flooding promote increased SRP concentrations (Jordan et al., 1993; Spruill, 2000). Under anoxic conditions, reduction of iron oxyhydroxides stimulates release of SRP bound to soil or organic particles (Jordan et al., 1993; Spruill, 2000). Elevated SRP concentrations we observed during higher flow periods are certainly consistent with those observations.

We observed declines in concentrations of POM, PIM, DOC, $NH_4$–N, and SRP during low-flow and drought periods, which we attribute to streams being largely disconnected from floodplains. While some subsurface flow of water probably enters streams during dry periods, subsurface flow paths favor retention of particles, DOC, and $NH_4$–N (Sedell and Dahm, 1990; Dosskey and Bertsch, 1994). In addition, as floodplain soils dry, increasing oxygen concentration would not favor the formation or release of $NH_4$–N or SRP from soil (Jordan et al., 1993; Spruill, 2000).

## Geological and Land Cover Influences

Chickasawhatchee Creek had consistently higher DOC concentrations than the other streams. Dissolved organic C generally originates in wetland soils and concentrations in streams are often proportional to wetland area within watersheds (Dosskey and Bertsch, 1994; Gergel et al., 1999). Higher DOC concentrations reflect the greater wetland area in the lower Chickasawhatchee watershed and indicate that substantial DOC export from the Chickasawhatchee Swamp is occurring. Greater DIC concentration in Chickasawhatchee Creek indicates a stronger hydrologic connection to the Upper Floridan Aquifer than the other streams (Hicks et al., 1987).

Alterations in stream water quality are often associated with human land use within watersheds. In particular, conversion of natural vegetation to agriculture, silviculture, or other uses increases inorganic nitrogen, phosphorus, and suspended sediment concentration (Johnson et al., 1997; Heathwaite et al., 2000). Even though substantial human land use has occurred within the Ichawaynochaway Creek watershed, concentrations of common nonpoint-source pollutants ($NO_3$–N, SRP, and suspended sediment) were generally lower than that reported for other agricultural areas (e.g., Johnson et al., 1997; Spahr and Wynn, 1997; Nolan, 1999; Schilling and Libra, 2000). Low nonpoint-source pollutant levels appear to be a general characteristic of the Dougherty Plain and lower Flint River watershed (e.g., Frick et al., 1996).

We attribute the maintenance of water quality to several factors. Most agricultural operations are in uplands away from stream and river corridors. This has left extensive intact riparian areas, primarily mature second-growth bottomland forests. Streamside forests are an effective buffer for nutrients and sediment runoff from agricultural land (Lowrance et al., 1984). Stream drainage density is also low, particularly on the Dougherty Plain (Hicks et al., 1987). This, in combination with low topographic relief and sandy well-drained soils, results in subsurface flow paths dominating regional hydrology (Hicks et al., 1987). Water movement through soils favors the removal of common pollutants associated with agricultural operations (Frick et al., 1996).

# SIGNIFICANCE

While current conditions appear to protect water quality, several issues should be of concern in the development of watershed management plans. Presently, most riparian forests in southwestern Georgia are in private ownership. Forests along streams are maturing and a cycle of forest harvest is beginning. Forest harvest has been accelerated by drought conditions, which facilitate access to bottomland forest (personal observation). Overharvesting of streamside forests may diminish buffer capacity of water quality.

In addition to their role in preserving water quality, the Chickasawhatchee Swamp and floodplain forests may also provide important ecological functions within the region. Floodplain forests are productive and a portion of this productivity, litterfall, is seasonally deposited on floodplain soils. Litter is then partially degraded by microbial activity and a portion is exported during seasonal flood pulses along with other important nutrients. Exported organic carbon is an important food resource for aquatic communities (Dosskey and Bertsch, 1994) and natural nutrient subsidies stimulate instream productivity. Aquatic productivity in Chickasawhatchee Creek, Lower Ichawaynochaway Creek, and Flint River may be dependent on exported material derived from floodplain forests. During droughts or periods of high water withdrawal, this natural linkage between streams and floodplains is disrupted. Thus, extreme low flows may be disruptive to aquatic life not only because of lack of water but also due to the scarcity of biologically important materials originating from floodplain forests.

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## REFERENCES

Anonymous. 1999. Standard methods for the examination of water and wastewater. American Public Health Assoc., Washington, DC.

Arheimer, B., and R. Liden. 2000. Nitrogen and phosphorus concentrations from agricultural catchments—Influence of spatial and temporal variables. J. Hydrol. 227:140–159.

Beck, B.F., and D.D. Arden. 1983. Hydrogeology and geomorphology of the Dougherty Plain. Georgia Southwestern College, Americus.

Dosskey, M.G., and P.M. Bertsch. 1994. Forest sources and pathways of organic matter transport to a blackwater stream: A hydrologic approach. Biogeochemistry 24:1–19.

Frick, E.A., G.R. Buell, and E.E. Hopkins. 1996. Nutrient sources and analyses of nutrient water-quality data, Apalachicola–Chattahoochee–Flint River Basin, Georgia, Alabama, and Florida, 1972–90. U.S. Geol. Survey Water-Resour. Investigations Rep. 96-4101. USGS, Reston, VA.

Georgia News. 2000. Historic purchase protects vital water resources. The Nature Conservance of Georgia. Winter 2000. p. 4–5.

Gergel, S.E., M. Turner, and T.K. Kratz. 1999. Dissolved organic carbon as an indicator of the scale of watershed influence on lakes and rivers. Ecol. Applic. 9:1377–1390.

Golden, H.G., and G.W. Hess. 1991. Georgia: Floods and droughts. p. 239–243. *In* National Water Summary 1988–1999. U.S. Geol. Survey Water-Supply Paper 2375. USGS, Reston, VA.

Golladay, S.W., K. Watt, S. Entrekin, and J. Battle. 2000. Hydrologic and geomorphic controls on suspended particulate organic matter and transport in Ichawaynochaway Creek, Georgia, USA. Arch. Hydrobiol. 149:655–678.

Grubbs, F.E., and G. Beck. 1972. Extension of sample sizes and percentage points for significance tests of outlying observations. Technometrics 14:847–854.

Harrison, K.M. 2001. Agricultural irrigation trends in Georgia. p. 114–117. *In* K. Hatcher (ed.) Proc. of the 2001 Georgia Water Resour. Conf., Athens, GA. 26–27 Mar. 2001. Univ. of Georgia, Athens.

Hayes, L.R., M.L. Maslia, and W.C. Meeks. 1983. Hydrology and model evaluation of the principal artesian aquifer, Dougherty Plain, southwest Georgia. U.S. Geol. Survey, Atlanta, GA.

Heathwaite, L., A. Sharpley, and W. Gburek. 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. J. Environ. Qual. 29:158–166.

Helsel, D.R., and R.M. Hirsch. 1992. Statistical methods in water resources. Elsevier, Amsterdam.

Hicks, D.W., H.E. Gill, and S.A. Longsworth. 1987. Hydrogeology, chemical quality, and availability of groundwater in the upper Floridan Aquifer, Albany Area, Georgia. U.S. Geol. Survey Water-Resour. Investigations Rep. 87-4145. USGS, Reston, VA.

Hicks, D.W., R.E. Krause, and J.S. Clarke 1981. Geohydrology of the Albany area, Georgia. U.S. Geol. Survey, Atlanta, GA.

Johnson, L.B., C. Richards, G.E. Host, and J.W. Arthur. 1997. Landscape influences on water chemistry in midwestern stream ecosystems. Freshwater Biol. 37:193–208.

Jordan, T.E., D.L. Correll, and D.E. Weller. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. J. Environ. Qual. 22:467–473.

Lachat Instruments. 2001. Methods manual for automated ion analyzers. Lachat Instruments, Milwaukee, WI.

Litts, T., H. Russell, A. Thomas, and R. Welch. 2001. Mapping irrigated lands in the ACF river basin. p. 79–83. *In* K. Hatcher (ed.) Proc. of the 2001 Georgia Water Resour. Conf., Athens, GA. 26–27 Mar. 2001. Univ. of Georgia, Athens.

Lowrance, R., R.L. Todd, and L.E. Asmussen. 1983. Waterborne nutrient budgets for the riparian zone of an agricultural watershed. Agric. Ecosyst. Environ. 10:371–384.

Lowrance, R., R. Todd, J. Fail Jr., O. Hendrickson Jr., R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374–377.

McCune, B., and M.J. Mefford. 1995. PC-ORD: Multivariate analysis of ecological data. MjM Software Design, Gleneden Beach, OR.

Mitsch, W.J., and J.G. Gosselink. 1993. Wetlands. Van Nostrand Reinhold, New York.

Nolan, B.T. 1999. Nitrate behavior in ground waters of the southeastern USA. J. Environ. Qual. 28:1518–1527.

Reddy, K.R., and W.H. Patrick, Jr. 1975. Effect of alternate aerobic and anaerobic conditions on redox potential, organic matter decomposition, and nitrogen loss in a flooded soil. Soil Biol. Biochem. 7:87–94.

SAS Insight. 1993. User's guide. Version 6. 2nd ed. SAS Inst., Cary, NC.

Schilling, K.E., and R.D. Libra. 2000. The relationship of nitrate concentration in streams to row crop land use in Iowa. J. Environ. Qual. 29:1846–1851.

Sedell, J.R., and C.N. Dahm. 1990. Spatial and temporal scales of dissolved organic carbon in streams and rivers. p. 261–279. *In* E.M. Perdue and E.T. Gjessing (ed.) Organic acids in aquatic ecosystems. John Wiley & Sons, New York.

Spahr, N.E., and K.H. Wynn. 1997. Nitrogen and phosphorus in surface waters of the Upper Colorado River Basin. J. Am. Water Resour. Assoc. 33:547–560.

Spruill, T.B. 2000. Statistical evaluation of effects of riparian buffers on nitrate and ground water quality. J. Environ. Qual. 29:1523–1538.

Thomas, D.L., K.A. Harrison, J.E. Hook, G. Hoogenboom, R.W. McClendon, L. Wheeler, W.I. Segars, J. Mallard, G. Murphy, M. Lindsay, D.D. Coker, T. Whitley, J. Houser, S. Cromer, and C. Myers-Roche. 2001. Status of agricultural water pumping: A program to determine agricultural water use in Georgia. p. 101–104. *In* K. Hatcher (ed.) Proc. of the 2001 Georgia Water Resour. Conf., Athens, GA. 26–27 Mar. 2001. Univ. of Georgia, Athens.

Wainright, S.C., C.A. Couch, and J.L. Meyer. 1992. Fluxes of bacteria and organic matter into a blackwater river from river sediments and floodplain soils. Freshwater Biol. 28:37–48.

Wallace, J.B., and J.W. Grubaugh. 1996. Transport and storage of FPOM. p. 191–216. *In* F.R. Hauer and G.A. Lamberti (ed.) Methods in stream ecology. Academic Press, San Diego, CA.