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Monitoring fish, benthic invertebrates, and physicochemical properties of surface water for evaluating nonpoint source pollution control in coastal agricultural watersheds

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Abstract: Many agricultural watersheds in the United States have impaired waterbodies due to nonpoint source pollution from agricultural activities and related processes. To understand the physical, chemical, and biological integrity of surface water in a coastal agricultural watershed, spatial and seasonal patterns of physicochemical and biological properties were investigated in Bayou Lacassine watershed (BLW) in Louisiana, United States. The relationship between the physicochemical and biological properties were also investigated. Sampling sites were located in the Bayou Chene and Lacassine Bayou subwatersheds within the BLW. Dissolved oxygen (DO), turbidity, conductivity, temperature, pH, total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), five-day biological oxygen demand (BOD_5), nitrate and nitrite-nitrogen (NO_3/NO_2-N), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total phosphorus (TP), chloride (Cl^-), fluoride (F^-), and sulfate (SO_4) were determined weekly from samples collected during 2012 to 2015. Fish and benthic invertebrate diversity and abundance in the two subwatersheds were determined in early summer and in fall of 2012 and 2013 at nine sites. Water quality was generally better at the most downstream site than at the most upstream site where agricultural intensity was highest, with significant differences in turbidity, TSS, TDS, TS, NO_3/NO_2-N, TKN, TP, and BOD_5. There was also seasonal variation for the water quality parameters due to variability in agricultural activities and climatic conditions within the watershed. Results of the relationship between physicochemical properties and fish community variables showed that species richness, diversity, and abundance were negatively affected by elevated TS, NO_3/NO_2-N, and conductivity. For the benthic invertebrates, diversity was negatively related to BOD_5. This study demonstrated unexpected longitudinal and seasonal patterns in physicochemical and biological properties of surface waters in a coastal agricultural watershed. This information is valuable in developing nonpoint source pollution control strategies for these subwatersheds.

Key words: agriculture—fish and macroinvertebrates—nonpoint source pollution—physicochemical and biological properties—water quality—watershed

Many agricultural watersheds in the United States have impaired waterbodies due to nonpoint source pollution from agricultural activities and related processes, such as soil erosion, fertilizer and pesticide application, agricultural drainage, and surface runoff (Lombardo et al. 2000; Poudel et al. 2010; Perez and Walker 2014). Water quality impairment can also be due to inputs from household septic systems (Poudel 2016) and natural sources such as wildlife, mineral deposits, and algal blooms. The impairment of waterbodies in agricultural watersheds can exhibit strong seasonality, corresponding with cropping seasons and related agricultural activities (Poudel et al. 2013). Similarly, agricultural watersheds can manifest spatial variation in water quality impairment due to differences in land use types, soils, nutrient inputs, and agricultural activities across the landscape (Demcheck et al. 2004; Mueller-Warrant et al. 2012; Poudel et al. 2013). The impairment of physical and chemical properties of surface waters can negatively impact biological communities due to, for example, hypoxia and harmful algal blooms (Zhou et al. 2008; Broussard and Turner 2009; Riseng et al. 2011; Budria 2017; Breitburg et al. 2018), increased levels of fecal bacteria (Brendel and Soupir 2017), elevated levels of suspended sediment (Basnyat et al. 1999; Riseng et al. 2011), or the presence of pesticides (Echeverría-Sáenz et al. 2012; Anderson et al. 2014, 2018).

The implementation of best management practices (BMPs) in agricultural watersheds has lowered nutrient loadings and improved biotic index scores (Maret et al. 2008), increased water clarity (Kronvang et al. 2005), and increased seagrass abundance (Greening et al. 2014). While these examples include cases where effects on biota were assessed, the effectiveness of BMPs is typically assessed solely by evaluating the physicochemical properties of surface waters (Yeung et al. 2017). However, measuring biological properties of surface waters is likely to provide more conclusive information on the effectiveness of BMPs in restoring the integrity of waterbodies (Karr 1993). As an example, invertebrate community indices were responsive to the adoption of stream health BMPs at deer farms in New Zealand (Rhodes et al. 2007). These BMPs included fencing to exclude deer from the streams, water troughs, culverts, buffer strips, and grazing management. Other studies have assessed the impacts of habitat, land use, and water quality on fish and/or benthic invertebrates in coastal watersheds (Helson and Williams 2013; Sawyer et al. 2004). While both fish and benthic invertebrates respond to environmental changes (Pilière et al. 2014), it appears that these two taxonomic groups

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are often affected by different water quality and habitat characteristics (Backus-Freer and Pyron 2015; Johnson and Ringler 2014). This makes monitoring of fish and benthic invertebrates complementary, such that assessments and monitoring for effectiveness of BMPs are best done by considering both of these taxonomic groups.

Water quality and nonpoint source pollution control issues are different in coastal watersheds in the southern United States than they are in most of the previously studied watersheds, due to the unique combination of specific agricultural activities and environmental conditions in coastal areas. Coastal agricultural watersheds in southwestern Louisiana (Huner et al. 2002; Poudel and Jeong 2009; Poudel et al. 2013; Poudel 2016) are good examples of this uniqueness. The main agricultural products in these watersheds include rice (*Oryza sativa* L.), soybeans (*Glycine max* [L.] Merr.), and sugarcane (*Saccharum officinarum* L.). Crawfish production and cattle farming (pasture) are other agricultural activities. Rice planting occurs from late February to early May, and the rice growing season continues, with ratoon harvest, until September, while crawfish production occurs from October to May (Huner et al. 2002). Rice fields are drained after crop harvesting through mid-spring depending on management practices such as winter-holding of water for weed control, water leveling of rice fields, water conservation, and crawfish production in rice fields. Crawfish ponds are drained from late spring to early summer. These watersheds are characterized by the lack of a substantial elevation gradient, small and slow-moving streams referred to as "bayous" in this part of the United States, tidal influence at the coastal part of the watersheds, the presence of swamps, and frequent flooding.

The specific objectives of this study were (1) to assess the presence of spatial variation (including a longitudinal gradient) in physicochemical water quality variables and in fish and benthic invertebrate abundance and diversity, (2) to assess the presence of temporal variation (including seasonal differences) in these variables, and (3) to assess the relationships between physicochemical properties of surface waters and fish and benthic invertebrate abundance and diversity. Information generated from this study will be beneficial for watershed managers and planners evaluating water quality and/or developing watershed management plans in coastal agricultural watersheds.

Materials and Methods

Study Area. This study was conducted in a coastal agricultural watershed in southwestern Louisiana, United States—the Bayou Lacassine watershed (BLW) in the Mermentau River Basin. The BLW consists of two subwatersheds: Lacassine Bayou and Bayou Chene subwatersheds (figure 1). Their key characteristics are given in table 1. Both subwatersheds were first included on the 303(d) list of impaired water bodies in 1999. The suspected causes of impairment were excess nutrients, sediments, turbidity, lead, organic enrichment, and low dissolved oxygen (DO) (table 1) (Louisiana Department of Environmental Quality, 1999 court ordered 303[d] list) (LDEQ 2000). Both waterbodies were not meeting fish and wildlife propagation uses as required by the Clean Water Act.

According to the Bayou Lacassine Watershed Plan (LDEQ 2009), BMPs covering a total of 21,030 ha were implemented in this watershed between 2004 and 2009. Major BMPs implemented included conservation crop rotation, seasonal residue management, nutrient and pest management, and irrigation land leveling. Similarly, BMPs covering a total of 58,274 ha were implemented in the Bayou Chene subwatershed between 2005 and 2015 (LDEQ 2016). These included conservation crop

Figure 1

Bayou Chene and Lacassine Bayou subwatersheds in Bayou Lacassine watershed (BLW), Louisiana, and the 15 water quality sampling sites in this study.

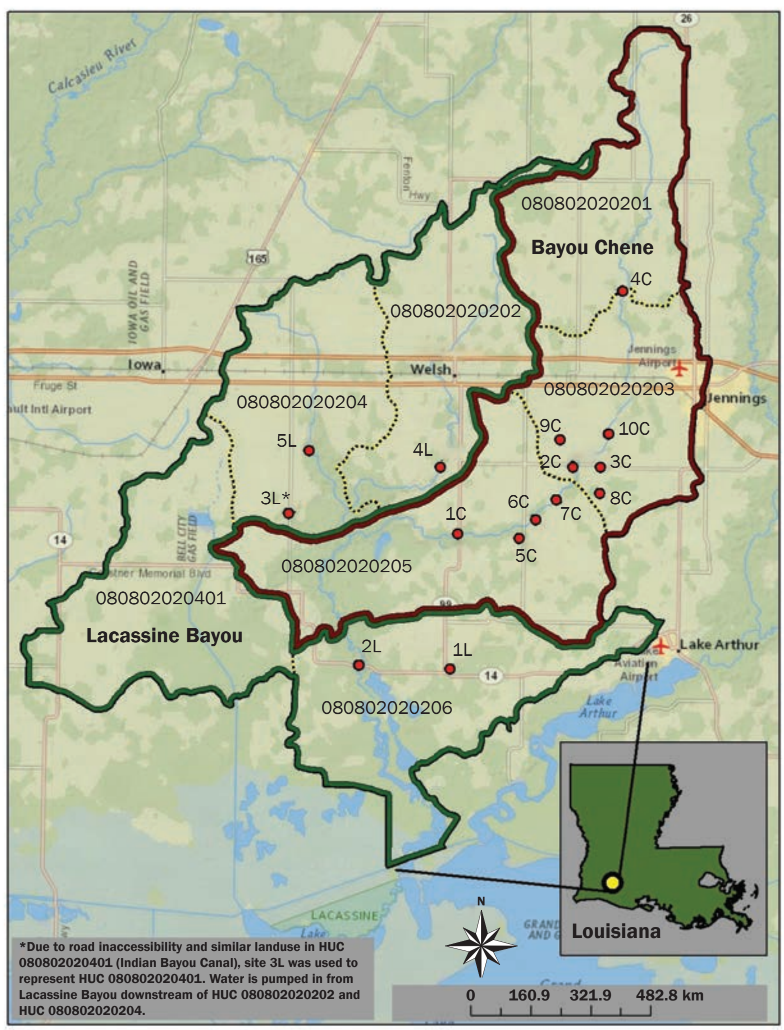

Table 1
Key characteristics of Bayou Chene and Lacassine Bayou subwatersheds of Bayou Lacassine watershed in Louisiana.

Characteristic	Bayou Chene	Lacassine Bayou
Total area (catchment size; ha)	45,672	63,699
Percentage of total area under*		
Cropland (%)	69.5	59.0
Aquaculture (%)	7.5	2.0
Pastureland (%)	6.2	13.9
Developed (%)	7.8	6.0
Wetlands (%)	8.8	17.3
Others (%)	0.3	1.8
Year of inclusion on 303(d) list	1999	1999
Suspected causes of water quality impairment	Organic enrichment, low dissolved oxygen	Phosphorus, nitrogen, turbidity, TSS, TDS, lead, organic enrichment, low dissolved oxygen
Louisiana Department of Environmental Quality water quality subsegment	LA050603	LA050601

*Land use area developed from the 2013 NASS cropland data layer of USDA National Agricultural Statistics Service database (USDA NASS 2013).

rotation, irrigation land leveling, prescribed grazing, nutrient management, residue and tillage management, no-till, irrigation water management, integrated pest management, dry seeding, and pesticide management. Agencies and programs involved in the implementation of BMPs in BLW included the Office of Soil and Water Conservation, Section 319 funds, USDA Natural Resources Conservation Service, Louisiana Department of Agriculture and Forestry, local soil and water conservation districts, resource conservation and development districts, and Louisiana Master Farmer Program. It is very likely that more than one BMP was implemented on the same piece of land.

Sampling, Field Measurements, and Laboratory Analyses. Weekly water quality monitoring was done at 10 sampling locations (sites 1C to 10C) in the Bayou Chene subwatershed and five sampling sites (sites 1L to 5L) in the Lacassine Bayou subwatershed (figure 1). Sites were selected on the basis of factors including land use type, implementation of BMPs, and accessibility. Sampling duration and the number of sampling events are presented in table 2. To achieve more intensive sampling of areas with major agricultural activities, six additional sites that represented the tributaries of Bayou Chene were added in August of 2014. While water quality sampling for sites 1L, 2L, 3L, 4L, 5L, and 7C ended on March 26, 2015, sampling at the remaining sites was continued until May 21, 2015, to capture conditions during the late spring season. Site 7C was dropped due to sampling safety risks. Consequently, the variability in the number of sampling events among sites reflects differences in the sampling period rather than differences in sampling frequency. Surface water temperature, turbidity, pH, conductivity, and DO were determined in the field using a YSI Sonde attached to a handheld data logger (model 6820 with 650MDS, YSI Incorporated, Yellow Springs, Ohio). Other water quality parameters were determined from water samples collected weekly with the use of a Van Dorn sampler. Laboratory analyses, using Standard Methods (Clesceri et al. 1998), quantified total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), five-day biological oxygen demand (BOD_5), nitrate/nitrite-nitrogen (NO_3/NO_2-N), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total phosphorus (TP), chloride (Cl^-), fluoride (F^-), and sulfate (SO_4). During each sampling event, a single in-stream measurement and a single grab sample were collected at each site at the center of the main flow of the stream and at one-half the total water depth when the stream was less than 2 m deep, or at 1 m depth when the stream was over 2 m deep. The average water depth of sampling locations ranged from 0.27 m at site 9C, to 4.33 m at site 2L (table 2). While sites 9C, 7C, and 4C had less than 1 m average water depth, sites 3L, 8C, 3C, 5L, 1L, 10C, and 4L had average water depth between 1 to 2 m, and sites 1C, 2C, 6C, 5C, and 2L had average water depth greater than 2 m. Except for flood events, water depths did not vary much during the year. Prior to the collection of water samples, sampling equipment was rinsed with ambient water. Based on the Jennings weather station, which is located within the watershed, average annual rainfall during this study (2012 to 2015) was 1,742 mm, which exceeded the longer-term (1980 to 2011) annual rainfall average of 1,524 mm.

Biological sampling was conducted for benthic invertebrates and for fish. Both groups of organisms were collected at nine sites (1L to 5L, 1C to 4C) during four sampling periods. These sampling periods covered two seasons (summer and fall) during each of two years (2012 and 2013). Summer samples were collected during May and/or June, and fall samples during September and/or October. In order to get better representation of the fish community, fish sampling was done using both cast and dip nets. A 3.66 m radius and 9.53 mm mesh size net was used to collect fish samples. Fish from 20 net casts (5 casts in 4 different areas at a site) were combined into one sample. For each dip net sample, we sampled for 20 minutes (5 minutes at each of 4 different spots at a site). Fish were identified to the species level (except for one individual for which only genus-level identification was possible). A total of 9,390 fish were collected. These fish belonged to 26 species and 12 families; western mosquitofish (*Gambusia affinis*) were very abundant throughout, gizzard shad (*Dorosoma cepedianum*) were common at a single site, and the other species were generally encountered in low numbers (table 3). Fish that could not be identified in the field or that were kept as voucher specimens were euthanized; other fish were released upon identification and quantification.

To collect benthic invertebrates, sediment samples were taken with a Petite Ponar grab (four replicates per site during each sampling period) and sieved in the field (500 μm screen). The >500 μm material was fixed in formalin (10%) with a Rose Bengal stain. Samples were later preserved (70% ethanol with 5% glutaraldehyde), sorted (animals separated from the detritus), and identified. A total of 9,731 individual organisms were collected and identified. All individuals were identified to at least the taxonomic level of order. The benthic invertebrates collected belonged to 19 orders; the most abundant

Table 2

Water quality sampling sites, average depth, sampling duration, and number of samples collected in Bayou Chene and Lacassine Bayou subwatersheds in Bayou Lacassine watershed (BLW) in southwestern Louisiana.

Site*	Latitude, longitude	Water depth (m)	Sampling duration	Number of samples
Bayou Chene				
4C	30.275391°, 92.712085°	0.68(±0.04)**	June 21, 2012, to May 21, 2015	146
10C	30.206619°, 92.719992°	1.87(±0.06)	Aug. 7, 2014, to May 21, 2015	40
9C	30.201783°, 92.751417°	0.27(±0.03)	Aug. 7, 2014, to May 21, 2015	40
3C	30.187192°, 92.728492°	1.32(±0.03)	June 21, 2012, to May 21, 2015	148
2C	30.187167°, 92.739286°	2.58(±0.03)	June 21, 2012, to May 21, 2015	148
8C	30.175217°, 92.723658°	1.31(±0.04)	Aug. 7, 2014, to May 21, 2015	40
7C	30.164992°, 92.754453°	0.49(±0.01)	Aug. 7, 2014, to Mar. 26, 2015	32
6C	30.156875°, 92.768478°	2.65(±0.05)	Aug. 7, 2014, to May 21, 2015	40
5C	30.151283°, 92.774653°	3.28(±0.06)	Aug. 7, 2014, to May 21, 2015	40
1C	30.146556°, 92.817319°	2.43(±0.03)	June 21, 2012, to May 21, 2015	148
Lacassine Bayou				
5L	30.193833°, 92.917050°	1.33(±0.03)	June 21, 2012, to Mar. 26, 2015	140
4L	30.186683°, 92.830100°	1.90(±0.03)	June 21, 2012, to Mar. 26, 2015	140
3L	30.154917°, 92.929017°	1.08(±0.03)	June 21, 2012, to Mar. 26, 2015	140
2L	30.070017°, 92.878733°	4.33(±0.03)	June 21, 2012, to Mar. 26, 2015	140
1L	30.066867°, 92.824817°	1.74(±0.02)	June 21, 2012, to Mar. 26, 2015	140

*Sites are arranged upstream to downstream in each subwatershed.

**Numbers in parentheses are the standard errors of means.

Table 3

Mean number of fish collected at sites in the Bayou Chene and Lacassine Bayou subwatersheds for 20 cast net throws and 20 minute dipnetting.

Family	Species	Common name	4C	3C	2C	1C	5L	4L	3L	2L	1L
Belonidae	*Strongylura sp.*	Needle fish	0	0	0	0.3	0	0	0	0	0
Catostomidae	*Carpiodes cyprinus*	Quillback	0	0	0	0	0	0.5	0	0	0
	Ictiobus bubalus	Smallmouth buffalo	0	0	0.3	0.3	0	0	0	0	0
Centrarchidae	*Elassoma okefenokee*	Okef. pygmy sunfish	0	0	0	1.0	0.3	0	0	0.8	0.8
	Lepomis auritus	Redbreast sunfish	1.3	0	0	0	0.8	0	0.5	0	0
	Lepomis cyanellus	Green sunfish	0	0.5	0	0	0	0.5	0	0	0.3
	Lepomis gibbosus	Pumpkinseed sunfish	1.8	0.3	1.3	1.8	0.5	1.8	1.8	1.3	4.3
	Lepomis humilis	Orange-sp. sunfish	0.5	0	0	0.3	0.3	0	0.5	0	0
	Lepomis macrochirus	Bluegill sunfish	0	0	0.5	0.5	0.3	1.0	2.5	0.8	3.5
	Lepomis marginatus	Dollar sunfish	0	0	0	0	0	0	0	0	0.3
	Lepomis symmetricus	Bantam sunfish	0	0.3	0	0	0.3	0.3	0	0.3	0.5
	Pomoxis annularis	White crappie	0	0.8	1.0	1.3	2.5	2.0	1.3	0.3	2.0
	Pomoxis nigromaculatus	Black crappie	0	0	0	0	0	0	12.8	0	0.3
Clupeidae	*Dorosoma cepedianum*	Gizzard shad	0	0.5	0.8	10.0	2.8	3.3	1.5	116.0	2.0
Cyprinidae	*Ictiobus niger*	Buffalo carp	0	0	0	0	0	0.3	0	0	0
Fundulidae	*Fundulus chrysotus*	Golden topminnow	0	0	0	0	0	0.3	0.3	1.5	0.3
Hiodontidae	*Hiodon alosoides*	Goldeye	0	0	0	0.3	0	0	0	0	0
	Hiodon tergisus	Mooneye	0.3	0	0	0	0	0	0	0	0
Ictaluridae	*Ictalurus punctatus*	Channel catfish	0.5	0.3	1.8	0.8	0	1.8	0	0	0.8
Lepisosteidae	*Atracosteus spatula*	Alligator gar	0	0.3	0	0	0	0	0	0	0
	Lepisosteus oculatus	Spotted gar	0	0	0	0.8	0	0	0.3	0.3	0
	Lepisosteus platostomus	Shortnose gar	0	0	0.8	0.3	0	0.5	0	0	0
Mugilidae	*Mugil cephalus*	Flathead grey mullet	0	0.5	0	0.3	0.3	0.3	0	0	0.3
Poeciliidae	*Gambusia affinis*	Western mosquitofish	159.0	200.3	94.3	62.3	117.3	93.8	967.0	208.3	195.0
	Heterandria formosa	Least killifish	0	2.5	0.8	1.3	2.8	3.8	14.3	7.8	8.5
Scianidae	*Aplodinotus grunniens*	Freshwater drum	0.3	0	0	0	0	0	0	0	0.3

were aquatic worms, leaches, clams, flies (mainly chironomid larvae), mussels, and snails (table 4).

Data Analyses. Means and ranges were determined for all of the physicochemical variables at each of the monitoring sites. The presence of differences among sites and among seasons was determined for each of the physicochemical variables with analyses of variance (one-way ANOVA), followed (where overall effects were significant) by pairwise comparisons using Tukey-Cramer honestly significant difference (HSD) tests. For the fish and macroinvertebrate data, spatial differences were analyzed by one-way ANOVA, while differences between seasons and years were analyzed by two-way ANOVA (with the interaction factor dropped from the model when this factor was not significant). The relationships between the physicochemical and biological properties (abundance and diversity data for fish and benthic invertebrates) and the presence of temporal changes for the fish and benthic invertebrate data were determined by regression analysis. All statistical analyses were conducted in JMP (SAS Institute Inc. 2009).

Results and Discussion

Spatial Patterns. In Bayou Chene, average values for TSS, TDS, TS, NO_3/NO_2-N, TKN, TP, F^-, SO_4, and conductivity were lower at the most downstream site (1C) than at the most upstream site (4C), by 18.7% to 60.3% (table 5). The same pattern was observed for Lacassine Bayou, where average values for turbidity, TSS, TDS, TS, NO_3/NO_2-N, TKN, TP, BOD_5, F^-, and conductivity at downstream site 2L were lower by 23.0% to 50.7% compared to upstream site 4L (table 6). A similar spatial pattern, with water quality improving with distance away from the more-developed upstream areas, has been observed for enteric bacteria (Mallin et al. 2000) and BOD (Yoon et al. 2015). The present study's data are indicative of a better water quality downstream. Potential reasons for the poorer water quality upstream include the upstream presence of concentrated agricultural activities, the downstream presence of riparian buffers and wetlands that improve surface water quality by enhancing nutrient uptake, sediment retention, litter decomposition (Whigham et al. 1988; Johnston 1991), and the dilution effect due to increased volume of water downstream.

In Bayou Chene, the downstream reduction in nutrients and suspended sediment was not accompanied by an increase in DO (e.g., the DO level at the furthest downstream site was 53.4% lower than it was at our furthest upstream site). We believe that site-specific factors were responsible for the latter. Water depth was very low (table 2), and the water flow appeared to be relatively fast at upstream site 4C, providing more opportunity for air/water exchange of oxygen (O_2). In contrast, DO values were low at the downstream site 1C, a site with typically slow water flow and a buildup of decomposing vegetation.

The analysis of fish community and benthic invertebrate densities also showed spatial variation and a longitudinal gradient. Statistically significant differences among

Table 4
Mean densities (number m^{-2}) of benthic organisms collected at the sites in the Bayou Chene and Lacassine Bayou subwatersheds for four grabs at each of four sampling events.

Class	Order	Common name	4C	3C	2C	1C	5L	4L	3L	2L	1L
Malacostraca	*Amphipoda*	Amphipod	24	54	11	8	16	57	394	16	19
	Decapoda	Decapod crustaceans	11	14	8	24	35	35	3	38	41
	Isopoda	Isopod crustaceans	0	0	3	0	0	0	0	46	0
Branchiopoda	*Diplostraca*	Water fleas etc.	0	0	0	0	3	3	0	8	3
Maxillopoda	*Calanoida*	Calanoid copepods	0	3	0	5	8	24	49	19	5
Insecta	*Plecoptera*	Stoneflies	0	3	0	0	0	3	0	0	0
	Coleoptera	Beetles	11	16	3	3	27	11	11	8	19
	Diptera	True flies	242	217	579	68	625	364	152	84	106
	Ephemeroptera	Mayflies	84	11	11	5	73	24	3	30	14
	Lepidoptera	Moths and butterflies	0	3	5	3	0	3	0	0	0
	Odonata	Dragon- and damselflies	5	33	11	5	87	16	5	60	106
	Trichoptera	Caddisflies	8	0	0	0	0	0	0	5.4	0
Hirudinea	*Rhynchobdellida*	Jawless leeches	152	103	117	111	106	43	76	49	84
Oligochaeta	*Lumbriculida*	Aquatic worms	334	1,769	1,421	954	1,457	565	3,269	666	1,109
Bivalvia	*Veneroida*	Clams	90	73	63	198	82	11	5,342	98	313
	Mytiloida	Mussels	0	0	5	5	0	3	1,671	19	8
Gastropoda	*Basommatophora*	Physid snails	0	0	14	19	14	38	22	35	5
	Neotaenioglossa	Hydrobid snails	8	5	27	46	22	0	1,375	19	27
	Architaenioglossa	Viviparid snails	0	0	98	149	0	0	0	0	0

Table 5

Average and range values for dissolved oxygen (DO), turbidity, conductivity, pH, temperature, five-day biological oxygen demand (BOD_5), total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), nitrate/nitrite-nitrogen (NO_3/NO_2-N), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total phosphorus (TP), chloride (Cl^-), fluoride (F^-), and sulfate (SO_4) concentrations for the 10 water quality monitoring sites in Bayou Chene subwatershed in southwestern Louisiana (June of 2012 to May of 2015).

Variable	4C	10C	9C*	3C†	2C	8C†	7C	6C	5C	1C
DO (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	6.46(±0.21)a	4.56(±0.48)b	5.23(±0.47)ab	3.81(±0.23)bc	3.98(±0.23)bc	3.51(±0.45)bc	4.58(±0.45)bc	3.39(±0.47)bc	3.44(±0.43)bc	3.01(±0.21)c
Range	2.03 to 13.94	0.33 to 10.60	0.56 to 11.30	0.39 to 12.14	0.39 to 13.14	0.40 to 11.46	0.72 to 10.22	0.24 to 9.56	0.28 to 9.20	0.27 to 12.83
Turbidity (NTU)										
n	146	40	40	148	148	40	32	40	40	148
Mean	332.79(±31.03)ns	234.95(±36.53)ns	197.20(±41.65)ns	273.91(±26.25)ns	297.13(±28.61)ns	241.94(±41.84)ns	162.73(±17.30)ns	217.88(±33.07)ns	209.12(±33.78)ns	239.17(±23.82)ns
Range	40.20 to 1,650.70	52.60 to 1,261.60	28.80 to 1,316.50	11.70 to 1,508.90	30.20 to 1,649.70	45.90 to 1,211.00	72.30 to 521.00	60.20 to 1,160.00	51.40 to 1,145.40	17.80 to 1,613.80
TSS (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	197.64(±28.28)a	129.77(±30.68)ab	106.55(±28.31)ab	112.65(±17.16)b	111.76(±11.76)b	121.50(±36.67)ab	70.75(±9.78)b	78.90(±7.53)b	78.80(±7.76)b	78.38(±5.62)b
Range	18.00 to 2,997.00	22.00 to 925.36	17.00 to 1,072.00	8.67 to 2,189.00	13.00 to 1,197.00	29.00 to 1,532.29	29.00 to 308.00	29.00 to 282.00	16.00 to 301.00	4.00 to 519.00
TDS (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	454.50(±51.61)a	392.46(±70.38)ab	377.65(±58.76)ab	401.52(±39.11)ab	385.22(±33.11)ab	338.10(±48.56)ab	268.75(±14.26)ab	305.42(±36.36)ab	303.72(±40.45)ab	292.87(±19.44)b
Range	91.00 to 5,125.00	77.00 to 2,510.00	163.00 to 2,404.00	78.00 to 3,643.00	82.00 to 2,603.00	104.00 to 1,860.00	121.00 to 455.00	118.00 to 1,348.00	124.00 to 1,454.00	29.00 to 1,608.00
TS (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	656.84(±75.51)a	523.07(±106.54)ab	484.07(±87.19)ab	506.53(±55.19)ab	499.99(±42.84)ab	456.20(±70.76)ab	329.81(±19.88)ab	378.22(±37.84)ab	376.55(±41.95)ab	373.16(±23.15)b
Range	172.00 to 5,959.00	221.00 to 3,745.00	158.00 to 3,517.00	154.00 to 6,374.00	168.00 to 3,227.00	197.00 to 2,383.00	200.00 to 750.00	191.00 to 1,355.00	187.00 to 1,566.00	63.00 to 1,834.00
NO_3/NO_2-N (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	0.50(±0.03)a	0.33(±0.04)abc	0.33(±0.05)abc	0.38(±0.03)abc	0.47(±0.04)ab	0.20(±0.02)c	0.24(±0.02)c	0.27(±0.03)bc	0.28(±0.03)bc	0.34(±0.02)c
Range	0.13 to 2.33	0.13 to 1.63	0.13 to 1.76	0.13 to 2.36	0.13 to 2.31	0.13 to 0.56	0.13 to 0.64	0.13 to 0.84	0.13 to 0.97	0.13 to 1.35
TKN (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	2.75(±0.21)a	2.39(±0.33)ab	3.08(±0.41)a	2.34(±0.19)ab	2.23(±0.14)ab	2.28(±0.22)ab	1.71(±0.10)ab	2.02(±0.18)ab	1.95(±0.18)ab	1.97(±0.11)b
Range	0.08 to 12.61	0.15 to 11.39	0.43 to 12.09	0.08 to 15.04	0.08 to 9.16	0.08 to 6.76	0.31 to 2.75	0.10 to 5.67	0.08 to 6.46	0.08 to 7.21
SRP (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	0.06(±0.01)ns	0.08(±0.01)ns	0.08(±0.01)ns	0.07(±0.01)ns	0.06(±0.01)ns	0.08(±0.01)ns	0.06(±0.01)ns	0.08(±0.01)ns	0.07(±0.01)ns	0.07(±0.01)ns
Range	0.03 to 0.58	0.03 to 0.29	0.03 to 0.33	0.03 to 0.68	0.03 to 0.42	0.03 to 0.29	0.03 to 0.17	0.03 to 0.30	0.03 to 0.30	0.02 to 1.02
TP (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	0.53(±0.05)a	0.41(±0.06)ab	0.43(±0.06)ab	0.43(±0.03)ab	0.48(±0.04)ab	0.35(±0.04)ab	0.27(±0.02)b	0.31(±0.03)b	0.30(±0.03)b	0.36(±0.02)b
Range	0.05 to 3.53	0.15 to 2.21	0.03 to 1.97	0.08 to 3.14	0.11 to 3.59	0.11 to 1.41	0.10 to 0.52	0.13 to 0.98	0.11 to 1.12	0.03 to 1.32
BOD_5 (mg L^{-1})										
n	138	34	33	140	141	35	31	34	36	141
Mean	6.63(±0.52)ab	8.86(±1.71)a	7.25(±1.37)ab	4.76(±0.38)b	5.75(±0.37)ab	5.88(±0.89)ab	7.39(±1.67)ab	4.95(±0.84)ab	5.63(±1.25)ab	4.96(±0.42)b
Range	2.00 to 39.82	2.33 to 40.84	2.00 to 40.21	2.00 to 33.96	2.00 to 31.80	2.00 to 24.83	2.00 to 39.99	2.00 to 24.62	2.00 to 39.87	2.00 to 39.53
Cl^- (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	33.26(±1.14)ab	29.16(±1.72)abc	36.83(±2.84)a	34.14(±1.15)ab	29.85(±1.09)abc	26.99(±1.48)bc	26.37(±1.40)bc	25.35(±1.27)c	25.09(±1.28)c	26.50(±0.97)c
Range	9.92 to 98.56	0.10 to 52.37	10.18 to 80.60	5.08 to 113.02	0.97 to 77.12	7.62 to 43.41	9.43 to 43.96	9.25 to 43.13	9.06 to 42.93	5.21 to 69.67
F^- (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	0.33(±0.02)a	0.21(±0.03)bc	0.19(±0.03)bc	0.26(±0.02)abc	0.29(±0.02)ab	0.18(±0.02)bc	0.14(±0.02)c	0.16(±0.02)c	0.17(±0.02)c	0.24(±0.02)bc
Range	0.04 to 1.49	0.04 to 0.79	0.04 to 0.74	0.04 to 1.22	0.04 to 1.43	0.04 to 0.67	0.04 to 0.38	0.04 to 0.56	0.04 to 0.58	0.04 to 1.06

Table 5 continued

Variable	4C	10C	9C*	3C†	2C	8C†	7C	6C	5C	1C
SO_4 (mg L^{-1})										
n	146	40	40	148	148	40	32	40	40	148
Mean	4.82(±0.23)a	4.90(±0.37)ab	3.52(±0.40)bc	3.39(±0.18)c	4.67(±0.22)ab	3.42(±0.28)bc	4.18(±0.21)abc	4.22(±0.20)abc	4.14(±0.23)abc	3.92(±0.15)bc
Range	0.23 to 16.57	1.10 to 15.31	0.06 to 10.09	0.06 to 12.49	0.06 to 18.43	0.04 to 7.85	1.80 to 6.77	1.91 to 7.14	1.28 to 7.50	0.06 to 11.20
Conductivity (µS cm^{-1})										
n	146	40	39	148	148	40	32	40	40	148
Mean	237.04(±8.07)ab	208.10(±9.65)abc	227.30(±15.86)abc	245.87(±9.30)a	213.49(±7.25)bc	191.35(±10.03)bc	180.87(±8.50)c	177.60(±8.14)c	174.52(±7.92)c	184.75(±6.27)c
Range	55.00 to 795.00	102.00 to 354.00	65.00 to 409.00	38.00 to 666.00	40.00 to 487.00	79.00 to 344.00	94.00 to 260.00	93.00 to 318.00	92.00 to 307.00	44.00 to 427.00
pH										
n	146	40	40	148	148	40	32	40	40	148
Mean	7.15(±0.02)a	7.06(±0.03)ab	7.06(±0.03)ab	6.97(±0.02)bc	7.02(±0.01)b	6.90(±0.03)cd	7.01(±0.03)bc	6.88(±0.03)cd	6.88(±0.03)cd	6.85(±0.02)d
Range	6.52 to 7.54	6.60 to 7.43	6.63 to 7.59	5.41 to 7.52	6.48 to 7.43	6.30 to 7.27	6.47 to 7.33	6.46 to 7.19	6.40 to 7.22	6.43 to 7.28
Temperature (°C)										
n	146	40	40	148	148	40	32	40	40	148
Mean	20.02(±0.60)ns	19.31(±1.04)ns	18.43(±1.10)ns	20.37(±0.60)ns	20.74(±0.58)ns	18.99(±1.05)ns	18.85(±1.22)ns	19.40(±1.01)ns	19.41(±1.00)ns	20.60(±0.56)ns
Range	3.05 to 30.92	7.10 to 29.60	3.87 to 27.31	3.88 to 30.46	4.66 to 30.21	6.04 to 28.73	7.83 to 29.22	8.14 to 29.12	8.28 to 28.91	4.16 to 30.37

Notes: *n* = sample size. ns = not significant. Numbers given in parentheses are the standard error of means. Values across the row with different letters are significantly different at 0.05 probability level by Tukey-Kramer honestly significant difference (HSD) Test. From upstream to downstream, the Bayou Chene flows through Site 4C to Site 10C to Site 2C to Site 7C to Site 6C to Site 5C to Site 1C.

*Site 9C drains to Site 2C.

†Sites 3C and 8C drain to Site 7C.

sites were detected for several of the fish and benthic invertebrate density and/or diversity measures (table 7). Though trends were variable, densities and diversities were, for example, typically higher at sites 3C and 1C than they were at site 4C and higher at sites 3L and 1L than at site 4L (table 7). These results show that the biological integrity for water bodies in this watershed was generally higher downstream than it was at upstream sites—opposite from the more typical pattern of water quality being highest at upstream sites (Wynes and Wissing 1981) though in line with the physicochemical data.

Temporal Patterns. Physicochemical properties of surface water in BLW showed very strong seasonal patterns (figures 2a to 2j). Dissolved O_2 levels were highest (averaging 7.7 mg L^{-1}) in January and lowest in August (averaging 2.1 mg L^{-1}). Monthly averages declined sharply from February to May, and then remained low until levels started to increase in October, with averages of around 5.0 mg L^{-1} measured for November and December. Thus, April to October is the period that DO conditions require special attention in this watershed, as DO levels decline to levels associated with hypoxia and impact invertebrate and fish communities (Baden et al. 1990; Briggs et al. 2017). Although lower DO levels coincided with higher water temperatures, a closer look at conditions during the February to May period reveals that lower DO values also coincided with high turbidity, TDS, and nutrient levels. Consequently, the lower DO levels during these months are expected to be due to a combination of variables—work on the hypoxia situation in the northern Gulf of Mexico has demonstrated that underlying mechanisms can be quite complex (Bianchi et al. 2010). While reducing water temperatures (e.g., by increasing riparian vegetation) would aid in improving DO levels in these waterbodies, minimizing inputs of sediments, nutrients, and other dissolved substances could also be very beneficial.

Various factors likely contributed to the high turbidity and high levels of solids and nutrients during the March to May period. While agricultural activities during the preceding winter season are typically limited, rainfall is quite high during the months of January and February. Consequently, this may have resulted in runoff from dry and barren fields. Winter-killed grasses in pasturelands and the livestock there may also have contributed (Poudel 2016), along with the large flocks of overwintering geese in the subwatersheds. Early spring is also a time for the drainage of crawfish ponds and rice fields. Wet planting of rice requires drainage from rice fields during these months, which contributes to high sediment loads (LSU AgCenter 2014). Another likely contributing factor is runoff from fertilizer applied to the rice fields being prepared for spring planting.

With regard to the seasonality of fish community, very high numbers of mosquitofish were caught at some sites during summer fish sampling, which appeared to have resulted in a lower overall fish community diversity during summer than fall (table 8). This diversity difference disappeared when mosquitofish were excluded from the analysis. It is well known that mosquitofish can handle low-O_2 conditions (Stoffels et al. 2017), in part due to their ability to gulp air from the air/water interface. No other obvious seasonal differences existed for the fish community metrics. While it was anticipated that especially the fish abundance would have shown a seasonal effect in response to the low summer DO levels in these bayous, the fall sampling conducted during September/October may have been too early in the fall to allow the fish community to recover from the hypoxia period. It is also possible that the resident biota are adapted to low-O_2 conditions. Research with both natural and laboratory populations has demonstrated that the evolution of resistance to environmental stressors can occur rapidly (Oziolor

Table 6

Average and range values for dissolved oxygen (DO), turbidity, conductivity, pH, temperature, five-day biological oxygen demand (BOD_5), total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), nitrate/nitrite-nitrogen (NO_3/NO_2-N), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total phosphorus (TP), chloride (Cl^-), fluoride (F^-), and sulfate (SO_4) concentrations for the five water quality monitoring sites in Lacassine Bayou subwatershed in southwestern Louisiana (June of 2012 to March of 2015).

Variable	5L	4L	3L	2L*	1L
DO (mg L^{-1})					
n	140	140	140	140	140
Mean	4.53(±0.23)a	3.98(±0.24)ab	3.28(±0.18)b	4.08(±0.17)ab	3.52(±0.22)b
Range	0.35 to 12.66	0.36 to 13.31	0.42 to 11.17	0.34 to 10.87	0.30 to 12.34
Turbidity (NTU)					
n	140	140	140	140	140
Mean	138.47(±18.82)bc	242.97(±28.72)a	108.46(±15.03)c	135.82(±16.38)bc	193.55(±24.56)ab
Range	3.20 to 1,521.60	22.30 to 1,629.70	4.00 to 1,254.60	5.60 to 1,497.40	6.10 to 1,502.70
TSS (mg L^{-1})					
n	140	140	140	140	140
Mean	59.91(±6.15)ab	79.90(±8.22)a	32.71(±2.51)b	39.40(±3.39)b	78.64(±11.53)a
Range	8.00 to 601.00	3.95 to 666.00	3.95 to 178.00	3.95 to 290.00	3.95 to 1,079.00
TDS (mg L^{-1})					
n	140	140	140	140	140
Mean	269.44(±18.73)ab	339.88(±29.03)a	216.08(±13.39)b	232.11(±26.28)b	292.51(±26.99)ab
Range	57.00 to 2,015.00	65.00 to 2,133.00	33.00 to 1,124.00	63.00 to 3,572.00	72.00 to 2,342.00
TS (mg L^{-1})					
n	140	140	140	140	140
Mean	328.51(±24.30)ab	420.29(±35.51)a	251.62(±15.12)b	250.75(±12.96)b	376.14(±39.12)a
Range	119.00 to 2,825.00	150.00 to 2,482.00	94.00 to 1,290.00	98.00 to 1,180.00	115.00 to 3,613.00
NO_3/NO_2-N (mg L^{-1})					
n	140	140	140	140	140
Mean	0.32(±0.03)b	0.43(±0.04)a	0.32(±0.03)b	0.28(±0.02)b	0.33(±0.03)ab
Range	0.13 to 2.37	0.13 to 2.56	0.13 to 1.73	0.13 to 1.24	0.13 to 1.50
TKN (mg L^{-1})					
n	140	140	140	140	140
Mean	1.55(±0.09)b	2.20(±0.14)a	1.63(±0.09)b	1.44(±0.08)b	1.77(±0.10)b
Range	0.08 to 5.94	0.08 to 12.35	0.08 to 6.50	0.08 to 5.13	0.08 to 7.53
SRP (mg L^{-1})					
n	140	140	140	140	140
Mean	0.09(±0.01)a	0.06(±0.01)b	0.06(±0.01)b	0.06(±0.01)b	0.06(±0.01)b
Range	0.01 to 0.61	0.03 to 0.41	0.01 to 0.41	0.01 to 0.44	0.03 to 0.63
TP (mg L^{-1})					
n	140	140	140	140	140
Mean	0.34(±0.02)a	0.39(±0.02)a	0.32(±0.02)ab	0.25(±0.01)b	0.37(±0.03)a
Range	0.10 to 1.91	0.09 to 1.83	0.04 to 1.33	0.04 to 1.06	0.05 to 2.64
BOD_5 (mg L^{-1})					
n	133	133	133	136	136
Mean	4.37(±0.33)ab	5.40(±0.37)a	4.11(±0.32)b	3.58(±0.26)b	4.23(±0.31)ab
Range	2.00 to 37.13	2.00 to 27.84	2.00 to 31.82	2.00 to 28.37	2.00 to 32.73
Cl^- (mg L^{-1})					
n	140	140	140	140	140
Mean	34.47(±2.01)ab	29.95(±1.20)bc	27.12(±1.28)c	25.18(±1.37)c	37.78(±2.04)a
Range	4.20 to 122.85	4.18 to 74.89	8.81 to 115.33	6.60 to 151.49	0.55 to 184.27
F^- (mg L^{-1})					
n	140	140	140	140	140
Mean	0.21(±0.02)ab	0.28(±0.02)a	0.22(±0.02)ab	0.18(±0.02)b	0.21(±0.02)b
Range	0.03 to 1.21	0.04 to 1.51	0.04 to 1.53	0.02 to 1.51	0.04 to 1.19
SO_4 (mg L^{-1})					
n	140	140	140	140	140
Mean	7.71(±0.35)a	5.46(±0.27)b	4.85(±0.36)bc	4.08(±0.19)c	3.87(±0.25)c
Range	0.06 to 30.17	0.03 to 18.43	0.06 to 38.27	0.33 to 17.74	0.06 to 20.70
Conductivity (µS cm^{-1})					
n	140	140	140	140	140
Mean	245.40(±12.33)a	211.82(±7.38)ab	183.51(±6.60)bc	163.08(±6.34)c	218.88(±9.48)a
Range	34.00 to 769.00	34.00 to 491.00	78.00 to 541.00	47.00 to 639.00	35.00 to 744.00
pH					
n	140	140	140	140	140
Mean	7.28(±0.02)a	6.96(±0.01)b	6.85(±0.02)cd	6.91(±0.02)bc	6.81(±0.02)d
Range	6.25 to 8.22	6.48 to 7.49	6.20 to 7.60	6.40 to 7.67	6.27 to 7.27
Temperature (°C)					
n	140	139	140	140	140
Mean	20.02(±0.61)ns	20.23(±0.63)ns	19.85(±0.60)ns	20.89(±0.59)ns	20.36(±0.63)ns
Range	4.62 to 31.65	4.57 to 30.44	3.70 to 29.55	5.74 to 31.63	4.10 to 31.19

Notes: *n* = sample size. ns = not significant. Numbers given in parentheses are the standard error of means. Values across the row with different letters are significantly different at 0.05 probability level by Tukey-Kramer honestly significant difference (HSD) Test.

*From upstream to downstream, Lacassine Bayou Site 5L and Site 4L drain to Site 2L (Site 1C from Bayou Chene also drains to Site 2L). Sites 3L and 1L drain into different areas.

et al. 2014; Xie and Klerks 2003). The presence of an overall temporal trend in the fish community was assessed by comparing 2012 with 2013 data. No significant differences were detected between the two years (table 8). There were also no significant trends detected by regression analyses using the four time points (data not shown).

For the benthic invertebrates, both abundance and diversity generally increased during the two-year period that this sampling was conducted (figure 3). Benthic invertebrate density increased with time for both bayous combined (R^2 = 0.929; p = 0.0361), but these trends were not statistically significant for either Bayou Chene (R^2 = 0.210, p = 0.542) or Lacassine Bayou (R^2 = 0.759, p = 0.129) separately. Biodiversity parameters showed a more consistent increase with time. For Bayou Chene, the regression of the Shannon diversity index, H', was not quite statistically significant (R^2 = 0.815, p = 0.097), while it was significant for the number of taxonomic orders (R^2 = 0.916, p = 0.043). In Lacassine Bayou, the biodiversity increased over time for both the diversity index parameter (R^2 = 0.904, p = 0.049) and the number of taxonomic orders (R^2 = 0.991, p = 0.004). While the four sampling points are insufficient for providing solid evidence for a temporal trend, this provides some indication that water quality is improving as a consequence of introduced management practices. Evidence provided below ("Relationship between Physicochemical Characteristics and Fish and Benthic Invertebrates") supports the notion that the organismal data agree with results for established physicochemical water quality measures. There may be a lag time to such an agreement. Research evaluating the effectiveness of forestry BMPs indicates that results for water quality variables may be more informative than results from biomonitoring when monitoring is done shortly after implementation of BMPs, since the ecological changes may have a slower response time (Yeung et al. 2017).

Relationship between Physicochemical Characteristics and Fish and Benthic Invertebrates. The biomonitoring results were correlated to those of the physicochemical monitoring. For the fish community variables, regressions were statistically significant for three of the physicochemical variables (TS, NO_3/NO_2-N, and conductivity) and three of the fish community metrics (number of species, H', and abundance on basis of cast net sampling), with all the relationships indicating lower fish abundance and diversity at higher levels of TS and nutrients (table 9). For example, the biodiversity index H' was clearly lower for sites with TS levels exceeding 300 mg L^{-1} (figure 4a). It is well documented that fish community diversity is typically negatively affected by eutrophication (Heiskary and Bouchard Jr. 2015), though some tolerant species may replace some of the sensitive ones. While eutrophication is more likely to result in increased biomass, certain effects on fish abundance appears to depend on specific habitat conditions (Artigas et al. 2013). High levels of suspended sediment or high turbidity are known to negatively affect fish diversity and abundance (Richardson and Jowett 2002).

For the benthic community data, relationships with the physicochemical data were statistically significant only for the biodiversity (as expressed by the number of taxonomic orders represented in the samples) and the BOD_5 (table 10). It is not surprising that there was a significant effect for this biodiversity variable; taxon richness measures are particularly responsive to environmental stressors (Carlisle and Clements 1999). The diversity was inversely related to the BOD_5 (figure 4b). A high BOD_5 value is likely to result in low DO levels in the water, and anoxic sediments typically have a benthic community dominated by the few groups (notably oligochaetes and tolerant chironomid taxa) that can handle these conditions. It is noticeable that the relationships between biomonitoring and physicochemical properties were more pronounced for the fish community than the

Table 7

Results from comparisons among sites for the abundance and diversity variables quantified for the fish and benthic invertebrate collections at the Bayou Chene and Lacassine Bayou sites. Shown are ANOVA *p*-values (*p* < 0.05 are shown in bold) and mean values at each of the sites. Results for pairwise comparisons are shown for those variables that differed significantly among sites. Means sharing a letter (a or b) did not differ significantly in pairwise comparisons using Tukey honestly significant difference (HSD).

Variable	*p*	4C	3C	2C	1C	5L	4L	3L	2L	1L
Number of fish species	0.102	3.25	4.50	5.25	7.00	5.00	7.75	5.75	6.00	7.50
Diversity index H'	**0.020**	0.19a	0.16a	0.43a	0.84a	0.39a	0.71a	0.30a	0.79a	0.73a
Diversity index H' (w/o *G.a.**)	**0.033**	0.49b	0.89ab	1.27ab	1.32ab	0.99ab	1.70a	0.92ab	0.64ab	1.48ab
Number of fish per cast net throw	**0.001**	0.05b	0.14b	0.23b	0.71b	0.30b	0.41b	1.05b	5.91a	0.54b
Number of fish per minute dipnetting	**0.020**	8.1b	10.2ab	4.8b	3.3b	6.1b	5.1b	49.1a	10.9ab	10.4ab
Number of fish per minute dipnetting (w/o *G.a.**)	0.555	0.18	0.15	0.13	0.23	0.21	0.38	0.73	0.53	0.65
Benthos density (individuals m^{-2})	**<0.001**	970b	2,304b	2,375b	1,606b	2,554b	1,201b	12,372a	1,201b	1,859b
Number of benthos orders	0.906	4.63	4.88	4.88	4.94	5.25	4.75	5.19	5.69	5.69
Benthos diversity index H'	0.190	1.21	0.89	0.99	1.02	0.80	0.92	0.81	1.17	1.08

*Western mosquitofish (*Gambusia affinis*) excluded due to occasional extreme numerical dominance.

Figure 2

Average monthly (a) dissolved oxygen; (b) turbidity; (c) total suspended solids (TSS), total dissolved solids (TDS), and total solids (TS); (d) nitrate/nitrite-nitrogen (NO_3/NO_2-N) and total Kjeldahl nitrogen (TKN); (e) soluble reactive phosphate (SRP) and total phosphorus (TP); (f) five-day biological oxygen demand (BOD_5); (g) chloride (Cl^-), fluoride (F^-), and sulfate (SO_4); (h) conductivity; (i) pH; and (j) surface water temperature for Bayou Chene and Lacassine Bayou in Bayou Lacassine watershed, Louisiana (June of 2012 to May of 2015).

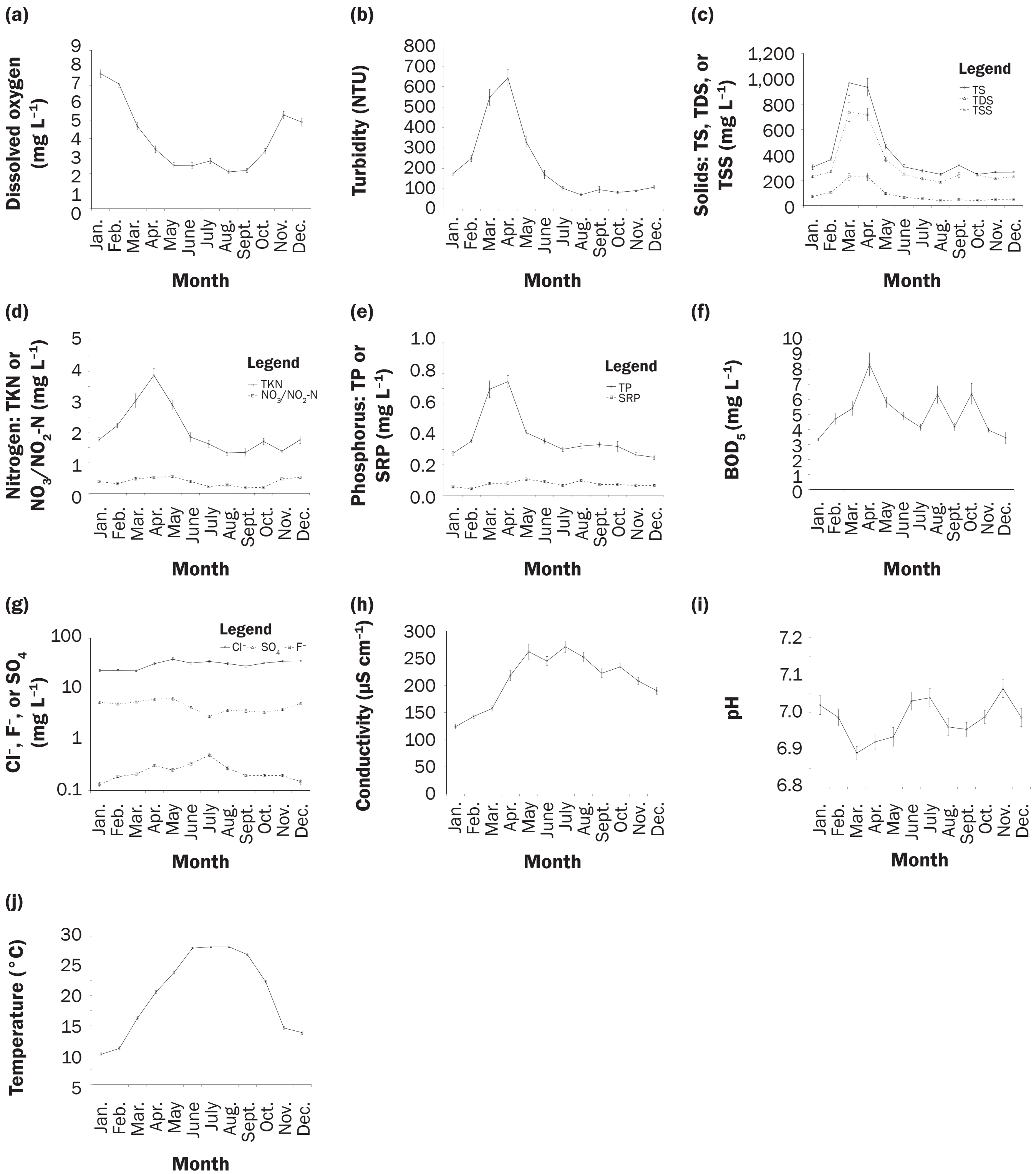

Table 8

Comparisons of fish community variables between seasons and between years. Values are (least-square) means ± se, with *p*-values for season and year effects of two-way ANOVA ($p < 0.05$ are shown in bold). None of the season × year interactions were significant and were therefore removed from the ANOVA model.

Variable	Summer	Fall	*p*	2012	2013	*p*
Number of species	5.89 ± 0.55	5.67 ± 0.55	0.779	6.28 ± 0.55	5.28 ± 0.55	0.211
Diversity index H' (all spp.)	0.38 ± 0.09	0.63 ± 0.09	**0.045**	0.51 ± 0.09	0.50 ± 0.09	0.983
Diversity index H' (w/o *G.a.**)	1.11 ± 0.14	1.05 ± 0.14	0.774	1.19 ± 0.14	0.96 ± 0.14	0.231
Number of fish per cast net throw	1.07 ± 0.57	1.01 ± 0.57	0.943	1.09 ± 0.57	0.99 ± 0.57	0.899
Number of fish per min. dipnetting	14.8 ± 4.8	9.2 ± 4.8	0.414	14.8 ± 4.8	9.2 ± 4.8	0.420
Number of fish per min. dipnnetting w/o *G.a.*	0.28 ± 0.11	0.42 ± 0.11	0.385	0.26 ± 0.11	0.44 ± 0.11	0.255

*Western mosquitofish (*Gambusia affinis*) excluded due to occasional extreme numerical dominance.

benthic community. This may be a function of the physicochemical monitoring's focus on the water column rather than the sediment, though it may also be a consequence of the lower detail in benthic invertebrate identification (identification to order level rather than the species-level identification done for fish). Benthic invertebrates generally respond more directly to water quality measures than is the case for fish communities (Johnson and Ringler 2014).

Summary and Conclusions

In the present study's coastal watershed, water quality was better at the downstream sites than at the upstream sites. This unusual longitudinal pattern was observed for both the physicochemical variables measured and the fish and benthic invertebrates. Water quality appeared inversely related to land use intensity and the prevalence of agricultural activities in the watershed and positively related to the presence of wetlands and marshes. Temporal differences were also observed in this watershed. Strong seasonal patterns were observed for the physicochemical variables, with water quality being lowest in spring and summer, due to a combination of anthropogenic factors (chiefly agricultural activities) and climatic factors such as temperature and rainfall. Abundance and biodiversity data for the benthic invertebrates provided some indication that water quality is improving. Observed relationships between physicochemical variables and biological properties confirmed that the physicochemical variables were reflective of ecological integrity of the watershed. This study confirms the need for considering both spatial and temporal variation in water quality when assessing the integrity of surface water bodies in agricultural watersheds.

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References

Anderson, B., B. Phillips, J. Hunt, K. Siegler, J. Voorhees, K. Smalling, K. Kuivila, M. Hamilton, J.A. Ranasinghe, and R. Tjeerdema. 2014. Impacts of pesticides in a Central California estuary. Environmental Monitoring and Assessment 186:1801-1814.

Anderson, B.S., B.M. Phillips, J.P. Voorhees, X. Deng, J. Geraci, K. Worcester, and R.S. Tjeerdema. 2018. Changing patterns in water toxicity associated with current use pesticides in three California agriculture regions. Integrated Environmental Assessment and Management 14:270-281.

Artigas, J., E. García-Berthou, D.E. Bauer, M.I. Castro, J. Cochero, D.C. Colautti, A. Cortelezzi, J.C. Donato, A. Elosegi, C. Feijoó, A. Giorgi, N. Gómez, L. Leggieri, I. Muñoz, A. Rodrigues-Capítulo, A.M. Romaní, and S. Sabater. 2013. Global pressures, specific responses: Effects of nutrient enrichment in streams from different biomes. Environmental Research Letters 8:014003.

Backus-Freer, J., and M. Pyron. 2015. Concordance among fish and macroinvertebrate assemblages in streams of Indiana, USA. Hydrobiologia 758:141-150.

Baden, S.P., L.O. Loo, L. Pihl, and R. Rosenberg. 1990. Effects of eutrophication on benthic communities including fish: Swedish west coast. Ambio 19:113-122.

Basnyat, P., L.D. Teeter, K.M. Flynn, and B.G. Lockaby. 1999. Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. Environmental Management 23:539-549.

Bianchi, T.S., S.F. DiMarco, J.H. Cowan Jr., R.D. Hetland, P. Chapman, J.W. Day, and M.A. Allison. 2010. The science of hypoxia in the northern Gulf of Mexico: A review. Science of the Total Environment 408:1471-1484.

Breitburg, D., L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, D.J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G.S. Jacinto, K.E. Limburg, I. Montes, S.W.A. Naqvi, G.C. Pitcher, N.N. Rabalais, M.R. Roman, K.R. Rose, B.A. Seibel, M. Telzewski, M. Yasuhara, and J. Zhang. 2018. Declining oxygen in the global ocean and coastal waters. Science 359:46, eaam7240.

Brendel, C., and M.L. Soupir. 2017. Relating watershed characteristics to elevated stream *Escherichia coli* levels in agriculturally dominated landscapes: An Iowa case study. Water 9(154):18.

Briggs, K.B., J.K. Craig, S. Shivarudrappa, and T.M. Richards. 2017. Macrobenthos and megabenthos responses to long-term, large-scale hypoxia on the Louisiana continental shelf. Marine Environmental Research 123:38-52.

Broussard, W., and R.E. Turner. 2009. A century of changing land-use and water-quality relationships in the continental US. Frontiers in Ecology and the Environment 7:302-307.

Budria, A. 2017. Beyond troubled waters: The influence of eutrophication on host-parasite interactions. Functional Ecology 31:1348-1358.

Carlisle, D.M., and W.H. Clements. 1999. Sensitivity and variability of metrics used in biological assessments of running waters. Environmental Toxicology and Chemistry 18:285-291.

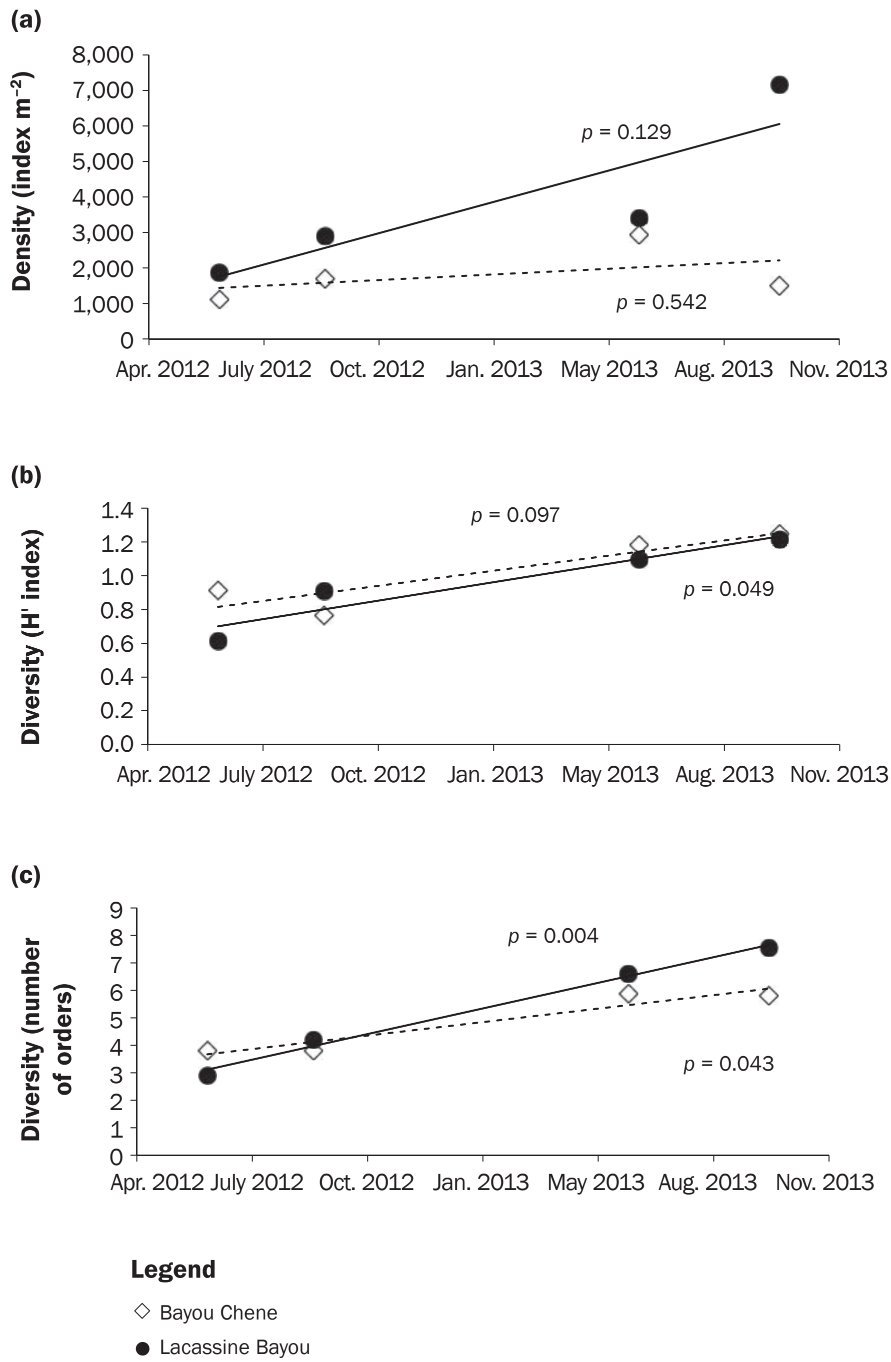
Clesceri, L.S., A.E. Greenberg, and A.D. Eaton., eds. 1998. Standard Methods for the Examination of Water and Wastewater, 20th edition. Washington, DC: American Public Health Association.

Demcheck, D.K., R.W. Tollett, S.V. Mize, S.C. Skrobialowski, R.B. Fendick, Jr., C.M. Swarzenski, and S. Porter. 2004. Water quality in the Acadian-Pontchartrain drainages, Louisiana and Mississippi, 1999-2001. US Geological Survey Circular 1232. Reston, VA: US Geological Survey.

Echeverría-Sáenz, S., F. Mena, M. Pinnock, C. Ruepert, K. Solano, E. De la Cruz, B. Campos, J. Sánchez-Avila, S. Lacorte, and C. Barata. 2012. Environmental hazards of pesticides from pineapple crop production in the Río Jiménez watershed (Caribbean Coast, Costa Rica). Science of the Total Environment 440:106-114.

Figure 3

Temporal variation in the benthic invertebrate community in Bayou Chene and Lacassine Bayou. (a) Average values for the invertebrate density, (b) their diversity index H', and (c) the number of taxonomic orders were regressed on the sampling month. The solid line is for Lacassine Bayou and the broken line is for Bayou Chene.



Greening, H., A. Janicki, E.T. Sherwood, R. Pribble, and J.O.R. Johansson. 2014. Ecosystem response to long-term nutrient management in an urban estuary: Tampa Bay, Florida, USA. Estuarine, Coastal and Shelf Science 151:A1-A16.

Heiskary, S.A., and R.W. Bouchard Jr. 2015. Development of eutrophication criteria for Minnesota streams and rivers using multiple lines of evidence. Freshwater Science 34:574-592.

Helson, J.E., and D.D. Williams. 2013. Development of a macroinvertebrate multimetric index for the assessment of low-land streams in the neotropics. Ecological Indicators 29:167-178.

Huner, J.V., C.W. Jeske, and W. Norling. 2002. Managing agricultural wetlands for waterbirds in the coastal regions of Louisiana, USA. Waterbirds 25(Special Publication 2):66-78.

Johnson, S.L., and N.H. Ringler. 2014. The response of fish and macroinvertebrate assemblages to multiple stressors: A comparative analysis of aquatic communiteies in a perturbed watershed (Onondaga Lake, NY). Ecological Indicators 41:198-208.

Johnston, C.A. 1991. Sediment and nutrient retention by freshwater wetlands: Effects on surface water quality, Critical Reviews in Environmental Control 21:5-6, 491-565, doi: 10.1080/10643389109388425.

Karr, J.R. 1993. Defining and assessing ecological integrity: Beyond water quality. Environmental Toxicology and Chemistry 12:1521-1531.

Kronvang, B., E. Jeppesen, D.J. Conley, M. Søndergaard, S.E. Larsen, N.B. Ovesen, and J. Carstensen. 2005. Nutrient pressures and ecological responses to nutrient loading reductions in Danish streams, lakes and coastal waters. Journal of Hydrology 304:274-288.

LDEQ (Louisiana Department of Environmental Quality). 2000. Louisiana Nonpoint Source Management Plan, Volume 6, State of Louisiana Water Quality Management Plan. Baton Rouge, LA: Office of Environmental Assessment, Louisiana Department of Environmental Quality.

LDEQ. 2009. Bayou Lacassine Watershed Implementation Plan. Baton Rouge, LA: Louisiana Department of Environmental Quality.

LDEQ. 2016. Bayou Chene Watershed Implementation Plan. Baton Rouge, LA: Louisiana Department of Environmental Quality.

LSU AgCenter (Louisiana State University AgCenter). 2014. Louisiana Rice Production Handbook. Baton Rouge, LA: LSU AgCenter, Louisiana State University.

Lombardo, L.A., G.L. Grabow, J. Spooner, D.E. Line, D.L. Osmond, and G.D. Jennings. 2000. Section 319 Nonpoint Source National Monitoring Program Successes and Recommendations. Raleigh, NC: North Carolina State University Water Quality Group, Biological and Agricultural Engineering Department, North Carolina State University.

Mallin, M.A., K.E. Williams, E.C. Esham, and R.P. Lowe. 2000. Effect of human development on bacteriological water quality in coastal watersheds. Ecological Applications 10(4):1047-1056.

Maret, T.R., D.E. MacCoy, and D.M. Carlisle. 2008. Long-term water quality and biological responses to multiple best management practices in Rock Creek, Idaho. Journal of the American Water Resources Association (JAWRA) 44(5):1248-1269, doi: 10.1111/j.1752-1688.2008.00221.x.

Mueller-Warrant, G.W., S.M. Griffith, G.W. Whittaker, G.M. Banowetz, W.F. Pfender, T.S. Garcia, and G.R. Glannico. 2012. Impact of land use patterns and agricultural practices on water quality in the Calapooia River Basin of

Table 9

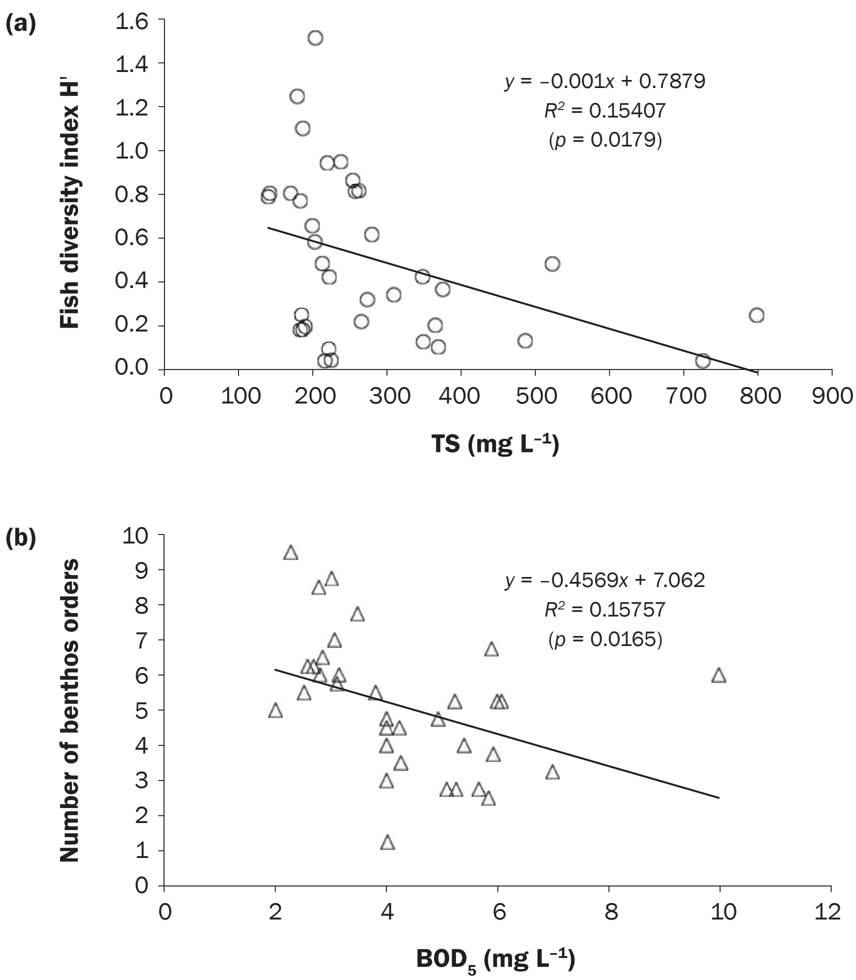
Results from regression analyses of fish community variables on select water quality variables. Shown are *p*-values for the regressions and a sign (in parenthesis) whether it was a positive or negative relationship. *P*-values < 0.05 are shown in bold.

Variable	Number of species	Diversity index H'	Abundance 1 (cast net)	Abundance 3 (dip net)
DO	0.5013 (–)	0.3178 (–)	0.5267 (+)	0.1651 (–)
Total solids	**0.0259 (–)**	**0.0179 (–)**	0.0836 (–)	0.2271 (–)
Nitrate/nitrite-nitrogen	0.1108 (–)	**0.0276 (–)**	0.4000 (–)	0.2919 (–)
SRP	0.5327 (–)	0.2050 (–)	0.4846 (+)	0.4262 (+)
BOD_5	0.6744 (+)	0.3325 (–)	0.3378 (–)	0.3068 (–)
Turbidity	0.0642 (–)	0.0558 (–)	0.3086 (–)	0.2762 (–)
Conductivity	0.0956 (–)	**0.0481 (–)**	**0.0317 (–)**	0.7814 (–)

Notes: DO = dissolved oxygen. SRP = soluble reactive phosphorus. BOD_5 = five-day biological oxygen demand.

Figure 4

Relationships between benthos and fish diversity measures and the physicochemical properties of surface water measured at the same site during the two weeks prior to the biological sampling. Results are shown for (a) the fish diversity index H' over total solids (TS) and (b) benthos diversity (number of orders) over the five-day biological oxygen demand (BOD_5).



western Oregon. Journal of Soil and Water Conservation 67(3):183-201, doi:10.2489/jswc.67.3.183.

Oziolor, E.M., E. Bigorgne, L. Aguilar, S. Usenko, and C.W. Matson. 2014. Evolved resistance to PCB- and PAH-induced cardiac teratogenesis, and reduced CYP1A activity in Gulf killifish (*Fundulus grandis*) populations from the Houston Ship Channel, Texas. Aquatic Toxicology 150:210-219, doi:10.1016/j.aquatox.2014.03.012.

Perez, M., and S. Walker. 2014. Improving water quality: A review of the Mississippi River Basin Healthy Watersheds Initiative (MRBI) to target U.S. Farm Conservation Funds, Working Paper. Washington, DC: World Resources Institute. https://wri.org/publication/MRBI.

Pilière, A., A.M. Schipper, A.M. Breure, L. Posthuma, D. De Zwart, S.D. Dyer, and M.A. Huijbregts. 2014. Comparing responses of freshwater fish and invertebrate community integrity along multiple environmental gradients. Ecological Indicators 43:215-226.

Poudel, D.D. 2016. Surface water quality monitoring of an agricultural watershed for nonpoint source pollution control. Journal of Soil and Water Conservation 71(4):310-326, doi:10.2489/jswc.71.4.310.

Poudel, D.D., and C.Y. Jeong. 2009. Manual composite sampling in edge-of-field surface runoff for assessing nonpoint source pollution from agricultural lands and residential areas. Journal of Soil and Water Conservation 64(5):324-335, doi: 10.2489/jswc.64.5.324.

Poudel, D.D., C.Y. Jeong, and A. DeRamus. 2010. Surface runoff water quality from agricultural lands and residential areas. Outlook on Agriculture 39(2):95-105.

Poudel, D.D., T. Lee, R. Srinivasan, K. Abbaspour, and C.Y. Jeong. 2013. Assessment of seasonal and spatial variation of surface water quality, identification of factors associated with water quality variability, and the modeling of critical nonpoint source pollution areas in an agricultural watershed. Journal of Soil and Water Conservation 68(3):155-171, doi:10.2489/jswc.68.3.155.

Rhodes, H.M., G.P. Class, and C.R. Townsend. 2007. Stream ecosystem health outcomes of providing information to farmers and adoption of best management practices. Journal of Applied Ecology 44:1106-1115.

Richardson, J., and I.G. Jowett. 2002. Effects of sediment on fish communities in East Cape streams, North Island, New Zealand. New Zealand. Journal of Marine and Freshwater Research 36:431-442.

Riseng, C.M., M.J. Wiley, R.W. Black, and M.D. Munn. 2011. Impacts of agricultural land use on biological integrity: A causal analysis. Ecological Applications 21:3128-3146.

SAS Institute Inc. 2009. JMP 8.0.2, Cary, NC: SAS Institute Inc.

Sawyer, J.A., P.M. Stewart, M.M. Mullen, T.P. Simon, and H.H. Bennett. 2004. Influence of habitat, water quality, and land use on macro-invertebrate and fish assemblages of a southeastern coastal plain watershed, USA. Aquatic Ecosystem Health and Management 7(1):85-99.

Table 10
Results from regression analyses of benthic invertebrate abundance (density) and diversity (number of orders, diversity index H') on select water quality variables. Shown are *p*-values for the regressions and a sign (in parenthesis) whether it was a positive or negative relationship. *P*-values < 0.05 are shown in bold.

Variable	Density	Number of orders	Diversity index
DO	0.0807 (–)	0.1213 (–)	0.9894 (–)
Total solids	0.5519 (–)	0.8879 (+)	0.5607 (+)
Nitrate/nitrite-nitrogen	0.4975 (–)	0.4407 (+)	0.2200 (+)
SRP	0.3918 (+)	0.9269 (+)	0.6547 (–)
BOD_5	0.2854 (–)	**0.0165 (–)**	0.1568 (–)

Notes: DO = dissolved oxygen. SRP = soluble reactive phosphorus. BOD_5 = five-day biological oxygen demand.

Stoffels, R., K. Weatherman, and S. Allen-Ankins. 2017. Heat and hypoxia give a global invader, *Gambusia holbrooki,* the edge over a threatened endemic fish on Australian floodplains. Biological Invasions 19:2477-2489.

USDA NASS (National Agricultural Statistics Service). 2013. USDA National Agricultural Statistics Service Cropland Data Layer. https://nassgeodata.gmu.edu/CropScape/.

Whigham, D.F., C. Chitterling, and B. Palmer. 1988. Impacts of freshwater wetlands on water quality: A landscape perspective. Environmental Management 12(5):663-671.

Wynes, D.L., and T.E. Wissing. 1981. Effects of water quality on fish and macroinvertebrate communities of the Little Miami River. Ohio Journal of Science 81:259-267.

Xie, L., and P.L. Klerks. 2003. Responses to selection for cadmium resistance in the least killifish, *Heterandria formosa*. Environmental Toxicology and Chemistry 22:313-320.

Yeung, A.C., A. Lecerf, and J.S. Richardson. 2017. Assessing the long-term ecological effects of riparian management practices on headwater streams in a coastal temperate rainforest. Forest Ecology and Management 384:100-109.

Yoon, T., C. Rhodes, and F.A. Shah. 2015. Upstream water resource management to address downstream pollution concerns: A policy framework with application to the Nakdong River basin in South Korea. Water Resources Research 51:787-805.

Zhou, M.J., Z.L. Shen, and R.C. Yu. 2008. Responses of a coastal phytoplankton community to increased nutrient input from the Changjiang (Yangtze) River. Continental Shelf Research 28:1483-1489.