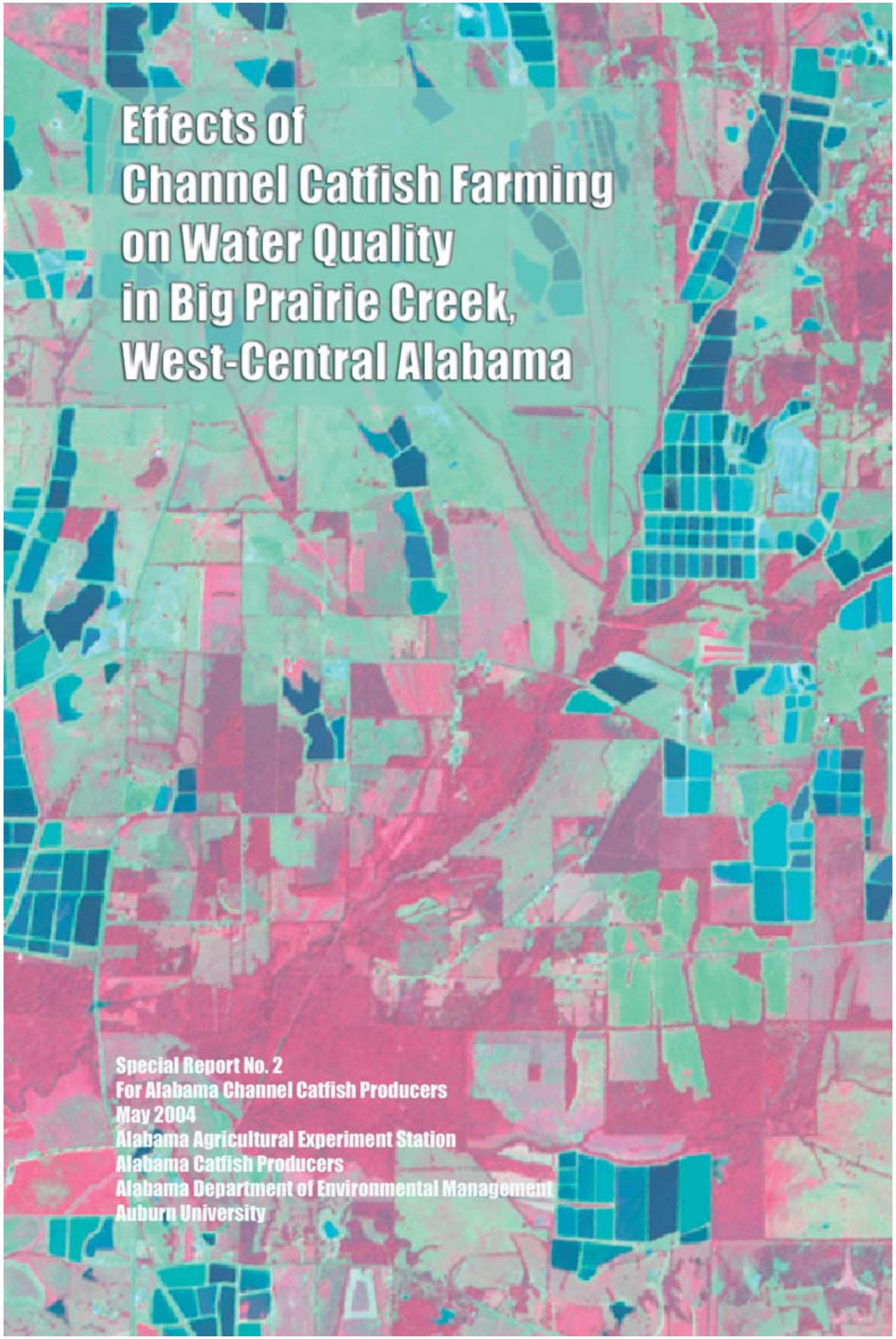


Effects of Channel Catfish Farming on Water Quality in Big Prairie Creek, West-Central Alabama

Special Report No. 2
For Alabama Channel Catfish Producers
May 2004
Alabama Agricultural Experiment Station
Alabama Catfish Producers
Alabama Department of Environmental Management
Auburn University

CONTENTS

First Printing 1M, May 2004

Cover image: Closeup of catfish ponds along Big Prairie Creek
in Hale County, Alabama, from NASA satelite image
(http://edcimswww.cr.usgs.gov/pub/imswelcome/).

http://www.auburn.edu
http://www.ag.auburn.edu/aaes

EFFECTS OF CHANNEL CATFISH FARMING ON WATER QUALITY IN BIG PRAIRIE CREEK, WEST-CENTRAL ALABAMA

O. Silapajarn, C.E. Boyd, K. Silapajarn, and P.L. Chaney

INTRODUCTION

Channel catfish, *Ictalurus punctatus,* are cultured in earthen ponds filled with groundwater from wells or by surface runoff. Fish are provided a commercial diet, and annual feed input to ponds typically is 8,000 to 16,000 kg/ha. About 20 to 30 percent of nitrogen and phosphorus applied in feed is recovered in fish at harvest *(7)*. The remainder of the nitrogen and phosphorus from feed enters pond ecosystems and promotes phytoplankton blooms. Ponds are aerated mechanically, especially during nighttime, to prevent low dissolved oxygen concentration, and aeration creates water currents that tend to resuspend and maintain solids in suspension. Water in catfish ponds usually has higher concentrations of nitrogen, phosphorus, total suspended solids, organic matter, and biochemical oxygen demand than natural surface waters in the vicinity *(8)*. Sodium chloride often is applied to ponds as a countermeasure against possible nitrite toxicity in fish *(21),* and copper sulfate frequently is used to control microorganisms responsible for off-flavor in fish *(23)*.

About 78,000 ha in the United States are devoted to catfish culture, and over 95 percent of this area is located in Alabama, Arkansas, Louisiana, and Mississippi *(18)*. The production areas are concentrated in seven counties in Alabama, two counties in Arkansas, one parish in Louisiana, and 12 counties in Mississippi. In these areas, catfish farming is a major activity that influences land and water use.

The United States Environmental Protection Agency (USEPA) has developed draft effluent regulations for aquaculture in the United States *(14)*. Pond aquaculture was excluded from effluent limitation guidelines, but concentrated aquatic animal production facilities (CAAPFs) are subject to National Pollution Discharge Elimination System (NPDES) permits. Warm water CAAPFs are ponds, raceways, or other similar structures that discharge at least 30 days per year. Closed ponds that dis-

---

The Silapajarns are graduate students and Boyd is a professor in the Department of Fisheries and Allied Aquacultures; Chaney is an associate professor in the Department of Geology and Geography.

charge only during periods of excess runoff and facilities that produce less than 45,454 kg (100,000 pounds) of aquatic animals per year are not designated as CAAPFs *(14)*.

The Alabama Department of Environmental Management (ADEM) is preparing effluent regulations for aquaculture in Alabama. The main feature of these regulations will be the adoption of best management practices (BMPs) to reduce the volume and improve the quality of aquaculture effluents *(5,9)*. The USEPA also suggested BMPs for use in pond aquaculture *(28)*.

There has been considerable concern over pond effluents, and a large effort has been devoted to developing methods for reducing the potential of catfish farms and other aquaculture facilities to pollute surface waters in the United States. Nevertheless, few studies of the impacts of aquaculture facilities on stream water quality have been conducted. With respect to catfish farming, Boyd *(2)* and Tucker and Lloyd *(22)* compared concentrations of water quality variables in catfish pond waters with those of nearby streams. The catfish pond waters had higher concentrations of most variables than did stream waters. However, Boyd et al. *(8)* reported no differences in water quality between samples collected upstream and downstream of catfish farms on eight streams in Alabama. More studies are needed to ascertain if effluents from channel catfish farms negatively impact stream water quality. About half of the area devoted to catfish farming in Alabama is thought to be located in the basin of Big Prairie Creek in Hale, Marengo, and Perry Counties. Thus, the present study was designed to evaluate the influence of catfish farm effluents on Big Prairie Creek and its tributaries.

METHODS

Sampling Locations

The sampling program included the following water bodies: Big Prairie Creek, tributaries of Big Prairie Creek, the Black Warrior River above and below the confluence of Big Prairie Creek, and control streams without catfish farms on watersheds but in the same ecoregion as Big Prairie Creek and its tributaries.

The Big Prairie Creek watershed is situated primarily in Hale County and within the Blackland Prairie ecoregion, but it begins in the Fall Line Hills ecoregion in Perry County and some tributaries originate in the Blackland Prairie in Marengo County. The Big Prairie Creek watershed is depicted in Figure 1 and in satelite imagery on page 28. The Alabama Soil and Water Conservation Committee considers the watershed depicted in Figure 1 to be two watersheds: Little Prairie Creek and Big Prairie Creek. The Little Prairie Creek watershed is the area north and west of BP-5. The Alabama Soil and Water Conservation Committee considers Big German Creek (Figure 2) to be part of the Little Prairie Creek watershed; however, because this watershed actually drains into Big Prairie Creek, the watersheds were combined for purposes of this study. Sampling stations BP-1 to BP-6 were in Big Prairie Creek; six tributaries were sampled at stations T-3 to T-8; station BW-7 is upstream of the confluence of Big Prairie Creek with the Black Warrior River and station BW-8 is

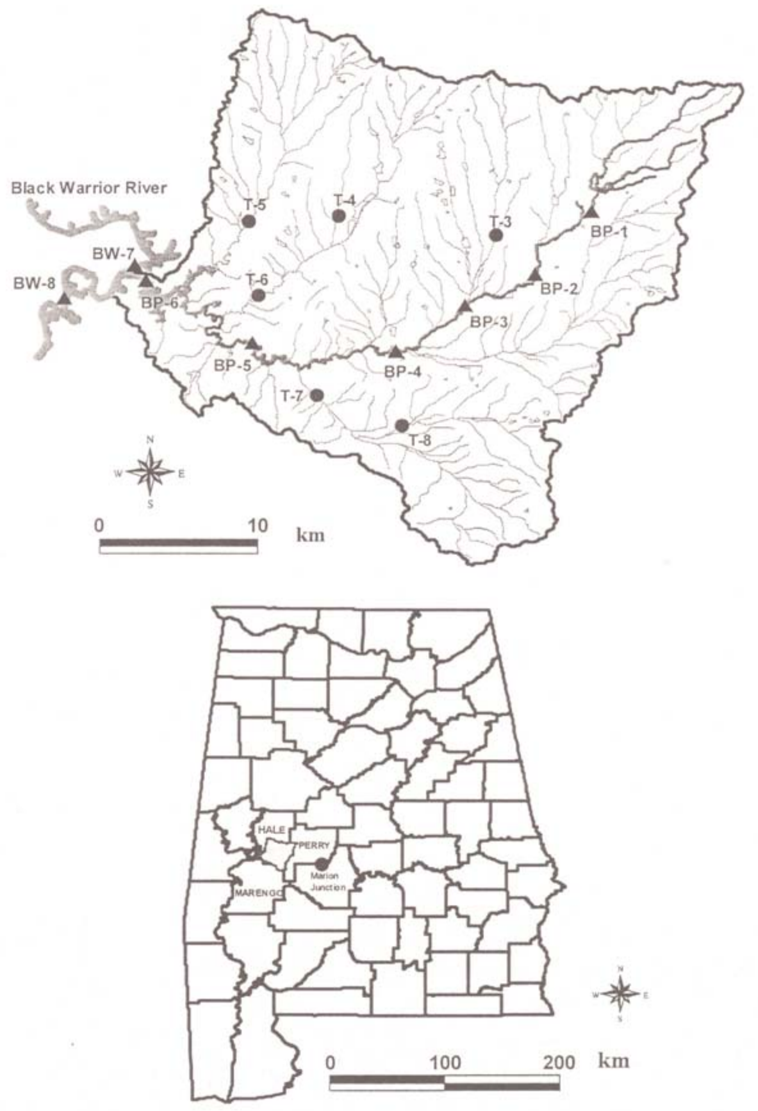


Figure 1. The Big Prairie Creek watershed and location of sampling stations in Big Prairie Creek (BP-1 to BP-6), its tributaries (T-3 to T-8), and Black Warrior River (BW-7 and BW-8). The location of Hale, Marengo, and Perry Counties and Marion Junction in Alabama also are shown. Boundaries of Big Prairie Creek watershed from Geological Survey of Alabama website (http://www.gsa.state.al.us).

downstream of the confluence. Big Prairie Creek forms a shallow, natural lake, Lake Demopolis, downstream of BP-5, and station BP-6 is in this lake (Figure 2). For purposes of this study, Lake Demopolis is considered a part of Big Prairie Creek. Locations of control streams, C-10 to C-15 are shown in Figure 3. Names of the tributaries and control streams and geocoordinates of sampling stations are provided in Table 1.

No catfish farms were located on Big Prairie Creek basin upstream of station BP-1. There were catfish farms on watersheds of all tributaries of Big Prairie Creek selected for sampling, but based on information available, there apparently were no commercial catfish farms on control stream watersheds. Of course, there may have been a few ponds that had been stocked with catfish, but catfish ponds were not a significant land use.

Water samples were collected at approximately one-month intervals beginning May 17 2001 at stations BP-1 to BP-6, BW-7, and BW-8, July 15 2001 for stations C-10 to C-15, and November 16 2001 for stations T-3 to T-8. Sampling was continued at all stations until August 10 2002. Samples were dipped from water surfaces. A 2-L sample from each station was placed on ice in an insulated chest. A 60-mL sample for bacteriological examination was confined in a sterile plastic bag and also stored in the insulated chest. A 500-mL sample was preserved with 1.0 mL of nitric acid for copper analysis. Samples were collected during the same day and analyses were initiated the next day.

Water Analyses

Water temperature and dissolved oxygen concentration were determined with a polarographic dissolved oxygen meter and thermistor at the time of sampling. The 2-L water samples were analyzed by methods listed in Table 2 for water quality variables. Copper was extracted from the acidified sample by separation into methyl isobutyl ketone and determined by atomic absorption spectrophotometry *(10)*.

Microbial examination included enumeration of total coliforms, fecal coliforms, and fecal streptococci. Membrane filter methods *(10)* were used for the enumeration of total coliform, fecal coliform, and fecal streptococcus bacteria. Sterile, gridded membrane filters were placed on sterile, 47-mm, magnetic filter holders and water samples were passed through the filters. Filters were then placed on the appropriate media and incubated for 24 to 48 hours. Three replicates of each sample were carried through the procedure. Tests were conducted for false positive colonies on media, and colony counts for samples were corrected accordingly. Microbial counts were reported as total number of colonies (organisms) per 100 mL of water.

The microbiological methods are outlined below, and the composition of media may be found in Clesceri et al. *(10)*. Total coliform determinations were made using m-Endo medium. Membrane filters were placed on absorbent pads saturated with m-Endo medium and sealed in a petri dish. The petri dishes were placed in a watertight bag, put in a water bath at 35ºC for 24 hours, and colonies were then counted. Total coliform colonies were characterized by a red color with a metallic sheen. From 10 to 20 percent of the colonies were taken for verification by inoculating them into lauryl tryptose broth. Gas formed in lauryl tryptose broth after 48 hours of incubation

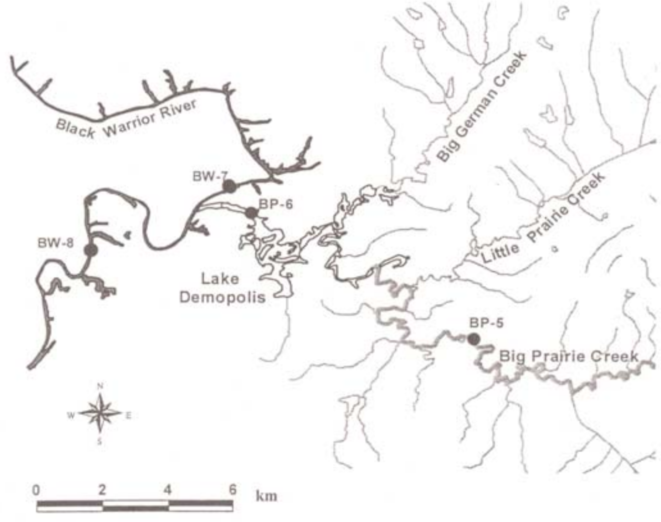


Figure 2. Lake Demopolis.

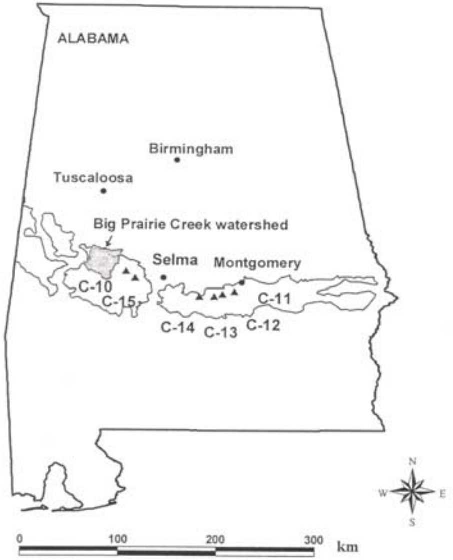


Figure 3. The distribution of the Blackland Prairie ecoregion in Alabama and locations of the control streams (C-10 to C-15). Boundaries of watersheds from Geological Survey of Alabama website (http://www.gsa.state.al.us).

TABLE 1. IDENTIFICATION OF SAMPLING STATIONS BY STREAM NAMES, LOCATIONS ON ROADS, AND GEOCOORDINATES

Sampling station	Stream name and location	Geocoordinates
BP-1	Big Prairie Creek, County Road 48 at Reynolds Chapel	N 32° 37.171´ W 87° 29.360´
BP-2	Big Prairie Creek, County Road 20, near New Bern	N 32° 34.970´ W 87° 31.247´
BP-3	Big Prairie Creek, County Road 10, near Sunshine	N 32° 33.822´ W 89° 33.592´
BP-4	Big Prairie Creek, State Road 25, near Mt. Sinai Church	N 32° 32.167´ W 37° 35.965´
BP-5	Big Prairie Creek, State Road 69, near Oak Grove	N 32° 32.508´ W 87° 40.835´
BP-6	Big Prairie Creek, off County Road 16, behind Buck's Restaurant	N 32° 34.899´ W 87° 45.001´
BW-7	Black Warrior River, County Road 16, Lock 5 Park	N 32° 35.180´ W 87° 44.689´
BW-8	Black Warrior River, off County Road 2, near Arcola	N 32° 33.977´ W 87° 47.110´
T-3	Whitsitt Creek, County Road 16, west of New Bern	N 32° 36.297´ W 87° 32.632´
T-4	Jack's Branch, County Road 16, east of Cedarville	N 32° 36.857´ W 87° 37.261´
T-5	Big German Creek, County Road 16 west of Cedarville	N 32° 36.755´ W 87° 40.937´
T-6	Little Prairie Creek, State Road 69 south of Casemore	N 32° 34.120´ W 87° 40.649´
T-7	Cottonwood Creek, County Road 12 east of Prairieville	N 32° 30.584´ W 87° 38.591´
T-8	Greer's Creek, State Road 25, south of Laneville	N 32° 29.488´ W 87° 35.741´
C-10	Duncan Creek, County Road 12, near Vaiden Field	N 32° 29.747´ W 87° 22.576´
C-11	Chaney Creek, U.S. Highway 80, near mile marker 127	N 32° 18.575´ W 86° 22.497´
C-12	Pintlala Creek, U.S. Highway 80, near mile marker 121	N 32° 17.100´ W 86° 29.003´
C-13	Tallawassee Creek, U.S. Highway 80, near mile marker 116	N 32° 16.160´ W 86° 33.898´
C-14	Big Swamp Creek, U.S. Highway 80, near mile marker 108	N 32° 15.973´ W 86° 41.630´
C-15	Kendrick Creek, U.S. Highway 80, near mile marker 68	N 32° 26.392´ W 87° 17.500´

verified a colony as coliform. Fecal coliform determinations were made using m-FC medium. Filters were placed in petri dishes, saturated with m-FC medium, put in watertight bags, and incubated for 24 hours at 44.5ºC. After incubation, colonies of fecal coliform were counted. Positive colonies were various shades of blue. From 30 to 40 percent of positive colonies were taken for verification using mannitol media. Fecal streptococcus determinations were made using mE agar. Filters were transferred to petri dishes containing mE agar and incubated in a water bath for 48 hours at 41ºC. After incubation, filters were transferred to EIA agar and incubated for an additional 20 minutes at 41ºC. Pinkish to red colonies developing a black to reddish-brown precipitate under the filter were indicative of fecal streptococcus. From 30 to 40 percent of the positive colonies were taken for identification. Small amounts of bacterial material were inoculated into tubes of brain heart-infusion broth and incubated for 24 hours at 35ºC. A few drops of media were then placed on a slide and several drops of 3 percent hydrogen peroxide added. The appearance of bubbles indicated that a colony was not fecal streptococcus. The other colonies were fecal streptococcus and were identified as gram-positive ovoid cells.

TABLE 2. METHODS OF ANALYSES FOR SEVERAL WATER QUALITY VARIABLES

Variable	Method	Reference
pH value	Electrometric method (4500-H$^+$ B)	Clesceri et al., 1998
Turbidity	Nephelometric method (2130 B)	Clesceri et al., 1998
Total suspended solids	Total suspended solids dried at 103-105ºC (2540 D)	Clesceri et al., 1998
Total alkalinity	Titration method (2320 B)	Clesceri et al., 1998
Total hardness	EDTA titrimetric method (2340 B)	Clesceri et al., 1998
Specific conductance	Laboratory method with conductivity meter	Clesceri et al., 1998
Chloride	Mercuric nitrate method (4500-Cl$^-$ C)	Clesceri et al., 1998
Total ammonia nitrogen	Phenate method (4500-NH$_3$ F)	Clesceri et al., 1998
Nitrate nitrogen	NAS reagent	Anonymous, undated
Soluble reactive phosphorus	Ascorbic method (4500-P E)	Clesceri et al., 1998
Total nitrogen	Persulfate digestion with ultraviolet screening method (4500-NO$_3^-$ B)	Gross and Boyd, 1998 Clesceri et al., 1998
Total phosphorus	Persulfate digestion with ascorbic acid finish	Gross and Boyd, 1998
5-day biochemical oxygen demand	5-day BOD test (5210 B)	Clesceri et al., 1998

Stream Flow

The stream channel cross section was measured at BP-1 and BP-5 by standard surveying procedures, and a staff gauge was installed at each station to permit stage height measurement. Stage height measurements allowed the cross-sectional area to be estimated for any stream stage. Mean stream velocity was estimated by the float method according to instructions provided by Yoo and Boyd *(26)*. On each sampling date, stage height and stream velocity were measured, stream cross-sectional area was estimated from stage height, and stream velocity was calculated by the following equation:

$$Q = Av$$

where Q = stream flow (m^3/sec), A = cross-sectional area of stream (m^2), and v = mean stream velocity (m/sec).

Rainfall

The nearest rainfall gauging station to Big Prairie Creek watershed is at Marion Junction (Figure 1). This location is about 30 km from BP-1 and nearly 44 km from BP-5. Rainfall data from this gauging station were available from the Agricultural Weather Information Services website (http://www.awis.com).

Pond Area

The area of the Big Prairie Creek watershed devoted to channel catfish ponds was estimated from Landsat 7TM satellite imagery for April 2000 *(26)*. A Geographic Information Systems (GIS) known as ArcGIS version 8.2 *(11,12)* was then used to digitize the boundary of the ponds within the watershed and compute their area.

Data Analysis

Water quality data were organized to facilitate different comparisons as follows:

- In order to show changes in water quality along the length of Big Prairie Creek, grand means for each station in the creek were plotted beginning with BP-1 as kilometer 0 and continuing downstream to BP-6 near the confluence of Big Prairie Creek (Lake Demopolis) with the Black Warrior River.
- Seasonal patterns in water quality and month to month variation were depicted by plotting monthly averages in groups as follows: station BP-1 (called upper Big Prairie Creek); stations BP-2 to BP-6 (referred to as lower Big Prairie Creek); stations T-3 to T-8 (tributaries); and stations C-10 to C-15 (control streams).
- Stations with catfish ponds on watersheds (downstream Big Prairie Creek and tributaries) were compared with control streams by the analysis of variance, and the multiple comparison of means were tested by Tukey method at the 95 percent significant level. Station BP-1 was omitted from this comparison because it is not in the Blackland Prairie like all other stations.
- The lower Big Prairie Creek stations (BP-2 to BP-6) were compared with the upper Big Prairie Creek station (BP-1) by student t-test at the 95 percent significant level.

- The possible influence of Big Prairie Creek inflow on water quality in the Black Warrior River was assessed by comparing stations upstream (BW-7) and downstream (BW-8) from the confluence of the creek with the river using student t-test at the 95 percent significant level.
- Grand means for coliform organisms and *Streptococcus* abundance were compared for BP-1, BP-5, T-7, and C-14 by the analysis of variance, and the multiple comparison of means were tested by Tukey method at the 95 percent significant level.

RESULTS

Water Quality

Water temperature

Average water temperature in Big Prairie Creek was around 22ºC from BP-1 to BP-5 (Figure 4). Average temperature at BP-6 was about 24ºC. The higher temperature resulted because of greater input of solar radiation to the open area of Lake Demopolis than to the tree-lined reach of the stream.

Average monthly water temperatures were quite similar among the four categories of stations (Figure 4). Lowest temperatures were 11ºC in January and highest were 28 to 29ºC in July 2002.

There was no difference in grand means for water temperature among downstream Big Prairie Creek, tributaries, and control stream stations (Table 3). Likewise, upper and lower stations on the Black Warrior River had similar water temperatures (Table 4).

pH

The pH of Big Prairie Creek increased from 6.75 at BP-1 to 7.95 at BP-6 (Figure 5). The creek originates in acidic soils of the Fall Line Hills and flows onto the Blackland Prairie near BP-2. Soils of the Blackland Prairie usually are alkaline, for there are deposits of limestone. The increase in pH is of geologic origin rather than of anthropogenic origin.

Monthly pH averages were always lower in upper Big Prairie Creek than at other stations (Figure 5). The lowest pH value at BP-1 was 5.7 in January 2002 and the greatest was 7.3 in July 2002. Average values for other station groups were about 7.2 and highest ones were around 8.2. Although there was not a clear seasonal trend in pH data, values tended to be greater in warm months.

Grand means for pH ranged from 7.56 to 7.90 (Table 3). Tributaries had a higher pH than lower Big Prairie Creek, but they were similar in pH to control streams. Control streams did not differ from lower Big Prairie Creek in pH. There was no difference in pH between upper and lower stations on the Black Warrior River (Table 4).

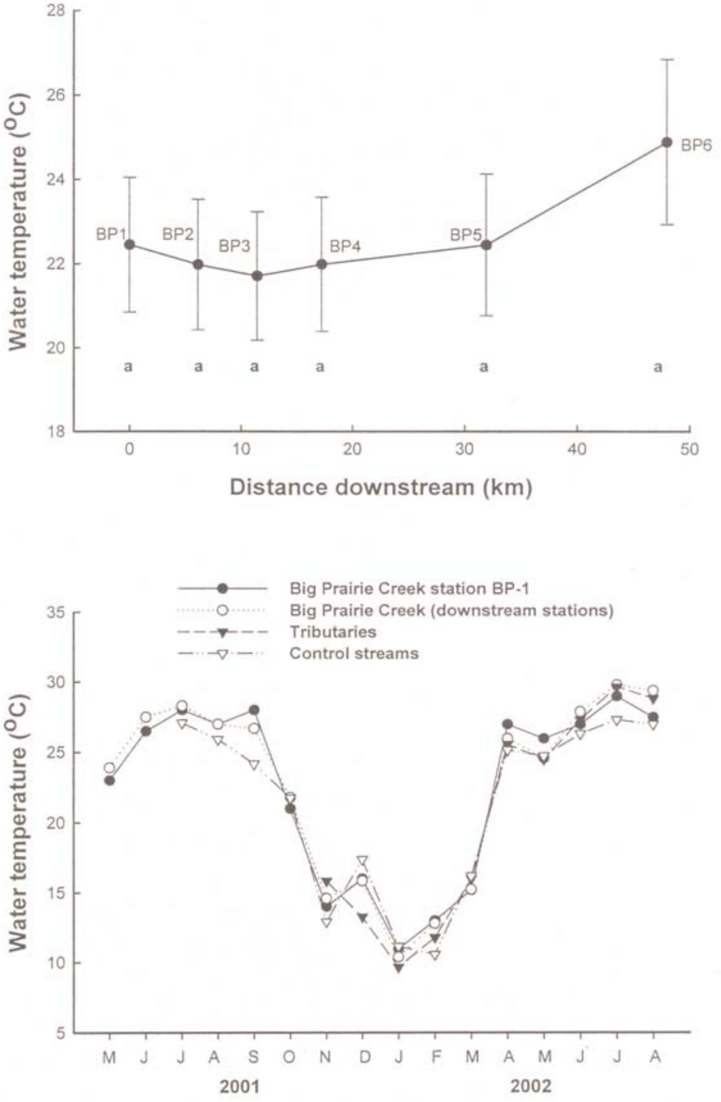


Figure 4. Upper: Averages and standard deviations for water temperature at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly water temperatures at station BP-1 and monthly averages for water temperature at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

TABLE 3. AVERAGE WATER QUALITIES AMONG DOWNSTREAM BIG PRAIRIE CREEK, TRIBUTARIES, AND CONTROL STREAM STATIONS[1]

Variables	T-3 to T-8	BP-2 to BP-6	C-10 to C-15
Water temperature (ºC)	24.91 ± 7.78a (10.0 - 34.0)	22.61 ± 6.60a (10.0 - 34.0)	22.30 ± 6.25a (8.0 - 30.0)
pH (standard units)	7.90 ± 0.31b (7.26 - 8.49)	7.56 ± 0.52a (6.00 - 8.80)	7.78 ± 0.37a b (6.71 - 8.70)
Dissolved oxygen (mg/L)	8.04 ± 2.87a (2.30 - 14.00)	7.79 ± 1.86a (4.90 - 14.80)	6.55 ± 2.34a (1.35 - 13.60)
Turbidity (NTU)	24.02 ± 28.30a (3.05 - 193)	24.39 ± 16.65a (3.40 - 166)	60.01 ± 78.13a (2.00 - 412)
Total suspended solids (mg/L)	19.3 ± 22.98a (0.0 - 103)	21.39 ± 30.02a (1.0 - 171)	35.10 ± 47.70a (1.0 - 248)
Total alkalinity (mg/L)	108.53 ± 60.14b (20.63 - 297.8)	60.47 ± 30.56a (18.13 - 156.6)	87.55 ± 34.99b (18.00 - 209.5)
Total hardness (mg/L)	109.93 ± 52.86a (23.07 - 231.9)	95.67 ± 42.44a (30.55 - 249.4)	121.84 ± 49.38a (44.73 - 284.3)
Specific conductance (µmhos/cm)	319.8 ± 155.2b (104.5 - 733)	202.7 ± 98.6a (57.4 - 512)	226.1 ± 78.4a (79.4 - 456)
Chloride (mg/L)	21.90 ± 12.24b (4.70 - 74.9)	18.33 ± 12.77b (2.15 - 71.9)	11.70 ± 5.73a (3.40 - 31.5)
Total ammonia nitrogen (mg/L)	0.349 ± 0.495b (0.012 - 3.51)	0.260 ± 0.440ab (0.010 - 3.45)	0.152 ± 0.136a (0.001 - 0.82)
Nitrate nitrogen (mg/L)	0.359 ± 0.228b (0.018 - 0.93)	0.384 ± 0.238b (0.022 - 1.23)	0.055 ± 0.087a (0.001 - 0.55)
Soluble reactive phosphorus (mg/L)	0.113 ± 0.202a (0.007 - 1.10)	0.062 ± 0.090a (0.000 - 0.64)	0.021 ± 0.051a (0.002 - 0.21)
Total nitrogen (mg/L)	1.65 ± 1.26a (0.12 - 9.08)	1.40 ± 1.17a (0.33 - 9.80)	1.06 ± 1.42a (0.17 - 12.66)
Total phosphorus (mg/L)	0.26 ± 0.35a (0.04 - 2.13)	0.18 ± 0.26a (0.02 - 2.33)	0.14 ± 0.12a (0.02 - 0.71)
5-day biochemical oxygen demand (mg/L)	3.96 ± 3.59b (0.50 - 16.6)	3.09 ± 2.16ab (0.55 - 16.8)	2.48 ± 1.52a (0.45 - 9.9)
Copper (mg/L)	0.0025 ± 0.0021a (0.0000 - 0.0122)	0.0030 ± 0.0026a (0.0002 - 0.0135)	0.0031 ± 0.0036a (0.0001 - 0.0225)

[1] Averages ± standard deviations and minimum and maximum values (in parentheses) for water quality variables in six tributaries of Big Prairie Creek (T-3 to T-8), five stations of downstream reach of Big Prairie Creek (BP-2 to BP-6), and six control streams without catfish farms on watersheds (C-10 to C-15).
Means indicated by the same letter did not differ at the 0.05 probability level as determined by Tukey Test.

TABLE 4. AVERAGE WATER QUALITIES ON UPPER AND LOWER STATIONS ON THE BLACK WARRIOR RIVER[1]

Variables	BW-7	BW-8	t-test (p-value)
Water temperature (ºC)	23.66 ± 7.29 (10.0 - 32.0)	24.41 ± 7.76 (10.0 - 7.7)	0.78
pH (standard units)	7.42 ± 0.37 (6.75 - 7.90)	7.45 ± 0.35 (6.90 - 8.11)	0.81
Dissolved oxygen (mg/L)	8.59 ± 1.34 (6.0 - 11.0)	8.54 ± 1.19 (7.0 - 10.8)	0.91
Turbidity (NTU)	14.95 ± 15.56 (4.8 - 70.8)	14.13 ± 9.63 (4.5 - 34.7)	0.86
Total suspended solids (mg/L)	10.88 ± 15.11 (1.0 - 64.0)	18.00 ± 37.43 (1.0 - 151)	0.49
Total alkalinity (mg/L)	32.56 ± 15.73 (0.0 - 58.89)	43.05 ± 32.23 (17.5 - 143.2)	0.29
Total hardness (mg/L)	90.55 ± 20.84 (53.46 - 131.9)	92.54 ± 21.80 (53.46 - 125.2)	0.81
Specific conductance (µmhos/cm)	213.7 ± 49.20 (150.2 - 301)	221.7 ± 50.64 (156.5 - 307)	0.66
Chloride (mg/L)	16.37 ± 7.38 (6.85 - 33.99)	15.91 ± 5.91 (6.85 - 25.99)	0.86
Total ammonia nitrogen (mg/L)	0.153 ± 0.124 (0.029 - 0.491)	0.089 ± 0.055 (0.014 - 0.211)	0.07
Nitrate nitrogen (mg/L)	0.416 ± 0.143 (0.132 - 0.695)	0.451 ± 0.203 (0.127 - 0.726)	0.59
Soluble reactive phosphorus (mg/L)	0.021 ± 0.051 (0.002 - 0.210)	0.010 ± 0.009 (0.0 - 0.032)	0.39
Total nitrogen (mg/L)	0.93 ± 0.24 (0.53 - 1.43)	0.91 ± 0.38 (0.47 - 1.94)	0.92
Total phosphorus (mg/L)	0.07 ± 0.09 (0.006 - 0.41)	0.06 ± 0.03 (0.004 - 0.12)	0.71
5-day biochemical oxygen demand (mg/L)	1.68 ± 1.04 (0.30 - 4.2)	1.77 ± 0.89 (0.60 - 3.4)	0.80
Copper (mg/L)	0.0030 ± 0.0020 (0.0005 - 0.0085)	0.0060 ± 0.0066 (0.0004 - 0.0238)	0.30

[1] Averages ± standard deviations and minimum and maximum values (in parentheses) for water quality variables at stations upstream (BW-7) and downstream (BW-8) from confluence of Big Prairie Creek with Black Warrior River.

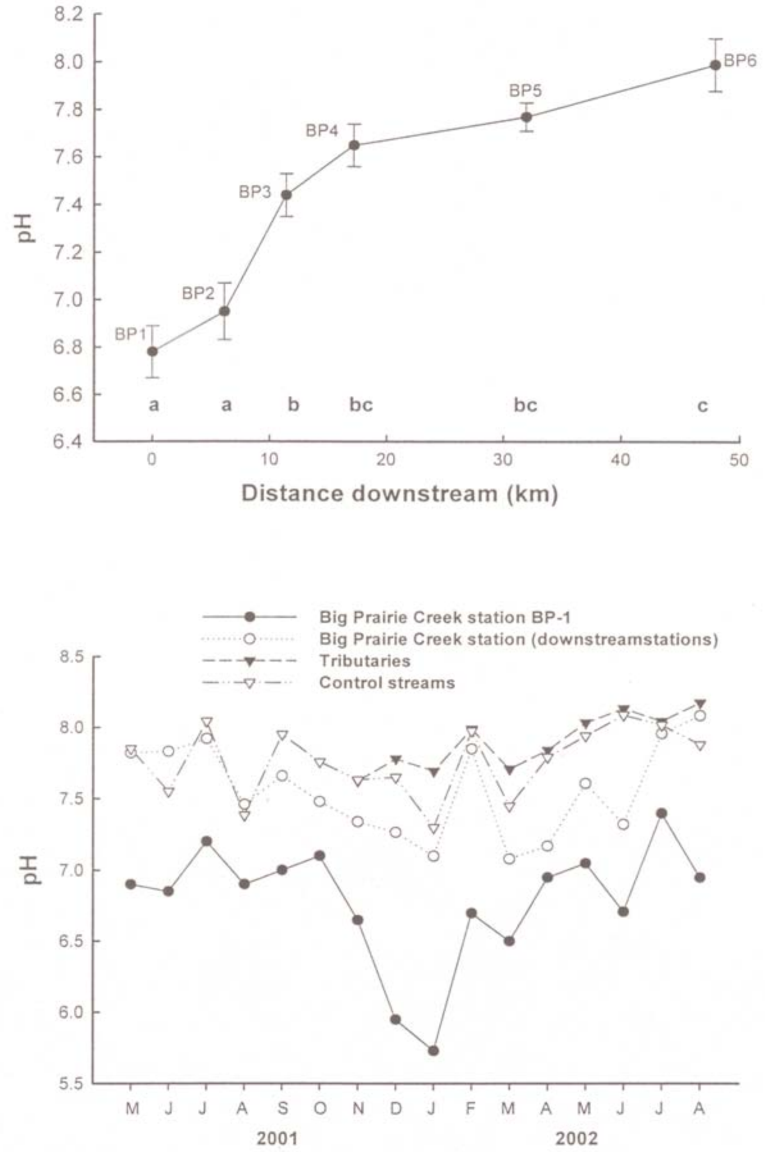


Figure 5. Upper: Averages and standard deviations for pH at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek.
Lower: Monthly pH at station BP-1 and monthly averages for pH at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

Dissolved oxygen

Concentrations of dissolved oxygen averaged between 6.9 and 7.7 mg/L between BP-1 and BP-5 (Figure 6). However, dissolved oxygen concentration averaged about 9.7 mg/L at BP-6 and was higher than average concentrations at several of the other stations in Big Prairie Creek. The high concentration of dissolved oxygen at BP-6 resulted because this station is in the lake formed by the creek. There is more sunlight and greater resident time of water, which allows more phytoplankton growth.

Monthly dissolved oxygen concentrations followed similar trends among the station groups (Figure 6). Concentrations averaged 8 to 11 mg/L in winter when water temperature was lowest, and 4 to 8 mg/L in summer when water temperature was greater. The lowest averages for dissolved oxygen were at BP-1 and in the control streams. This suggests that there was more photosynthesis by aquatic plants in lower Big Prairie Creek and tributaries than in the upper reach of Big Prairie Creek.

There were no differences in grand means for dissolved oxygen concentration among stations on lower Big Prairie Creek, tributaries, and control streams (Table 3). Also, upper and lower stations on the Black Warrior River did not differ in dissolved oxygen concentration (Table 4).

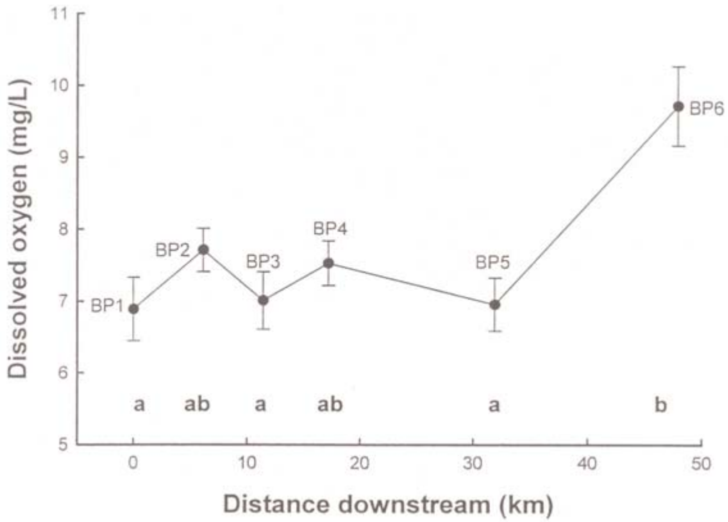
Turbidity and total suspended solids

Turbidity averaged 12 nephelometric turbidity units (NTUs) at station BP 1, and ranged from 22 to 33 NTU at stations in lower Big Prairie Creek (Figure 7). A similar pattern was observed in total suspended solids concentration with values of 6 mg/L at BP-1 and 32 mg/L at BP-3 (Figure 8). Upstream of BP-1, Big Prairie Creek passes through woodland, while there are pastures, row crops, catfish farms, and homesteads along the reach from BP-2 to BP-5. Thus, the increase in turbidity and concentration of total suspended solids in lower reaches of Big Prairie Creek likely resulted from anthropogenic sources. However, the source cannot be linked directly to catfish farms.

Water velocity decreased and hydraulic retention increased at BP-6 in Demopolis Lake. This encourages sedimentation of suspended solids and lessens turbidity, but the clearing effect was counteracted by turbidity created by phytoplankton growth in the lake.

Turbidity and total suspended solids concentrations were very high, 410 NTU and 230 mg/L, respectively, in control streams on the first sampling date as a result of heavy rains, which apparently did not occur on the Big Prairie Creek watershed (Figures 7 and 8). After this event, trends were similar among the station groups, and the greatest turbidities (50 to 100 NTU) and largest concentrations of suspended solids (50 to 100 mg/L) usually were in winter months (Figures 7 and 8).

Turbidity and total suspended solids concentrations were highly variable among stations and over time. Although grand means of turbidity and suspended solids were numerically about three-fold and two-fold greater, respectively, in control streams than at stations in lower Big Prairie Creek and tributaries, the differences were not significant (Table 3). Upper and lower stations of the Black Warrior River did not differ in turbidity or total suspended solids concentration (Table 4).



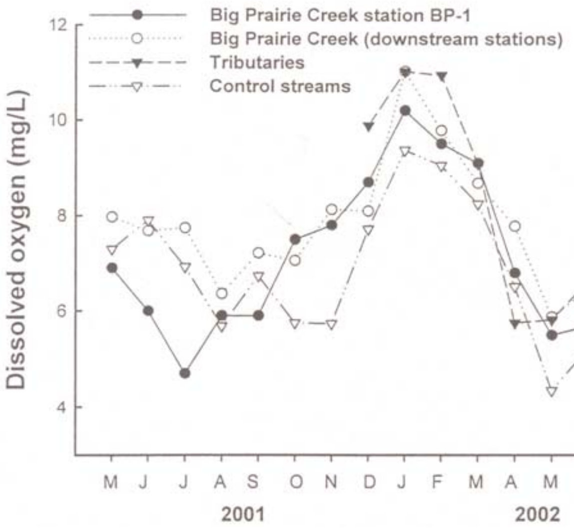


Figure 6. Upper: Averages and standard deviations for dissolved oxygen at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek.
Lower: Monthly dissolved oxygen at station BP-1 and monthly averages for dissolved oxygen at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

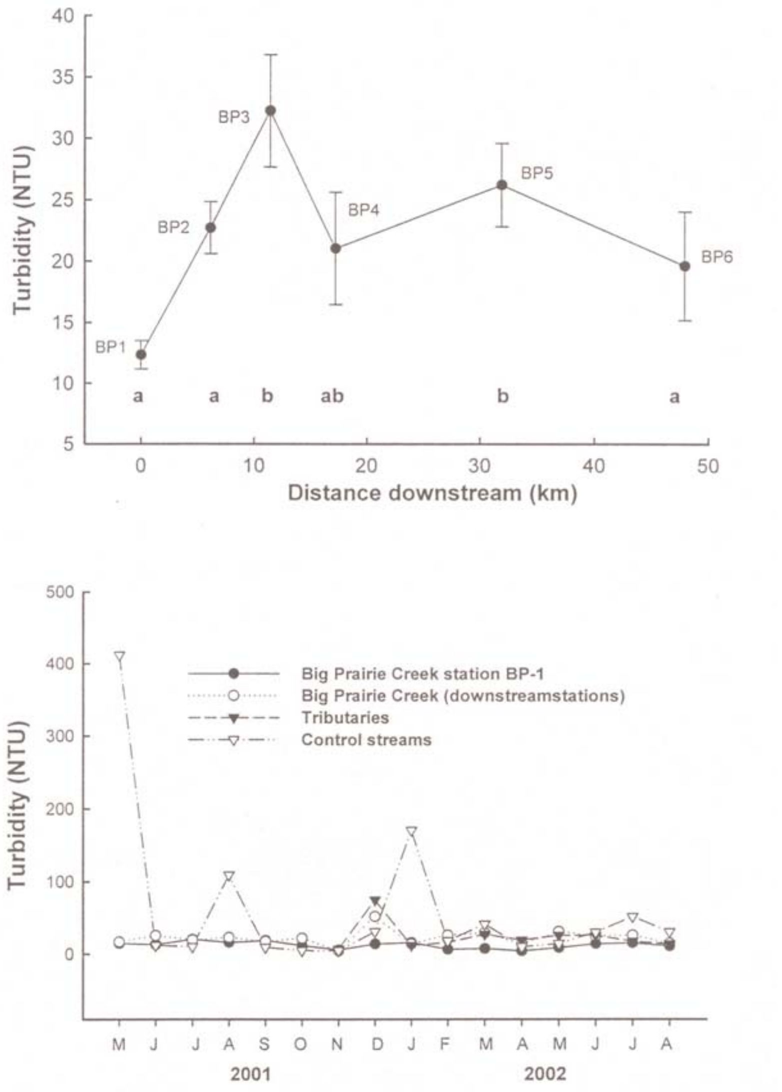


Figure 7. Upper: Averages and standard deviations for turbidity at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek.
Lower: Monthly turbidity at station BP-1 and monthly averages for turbidity at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

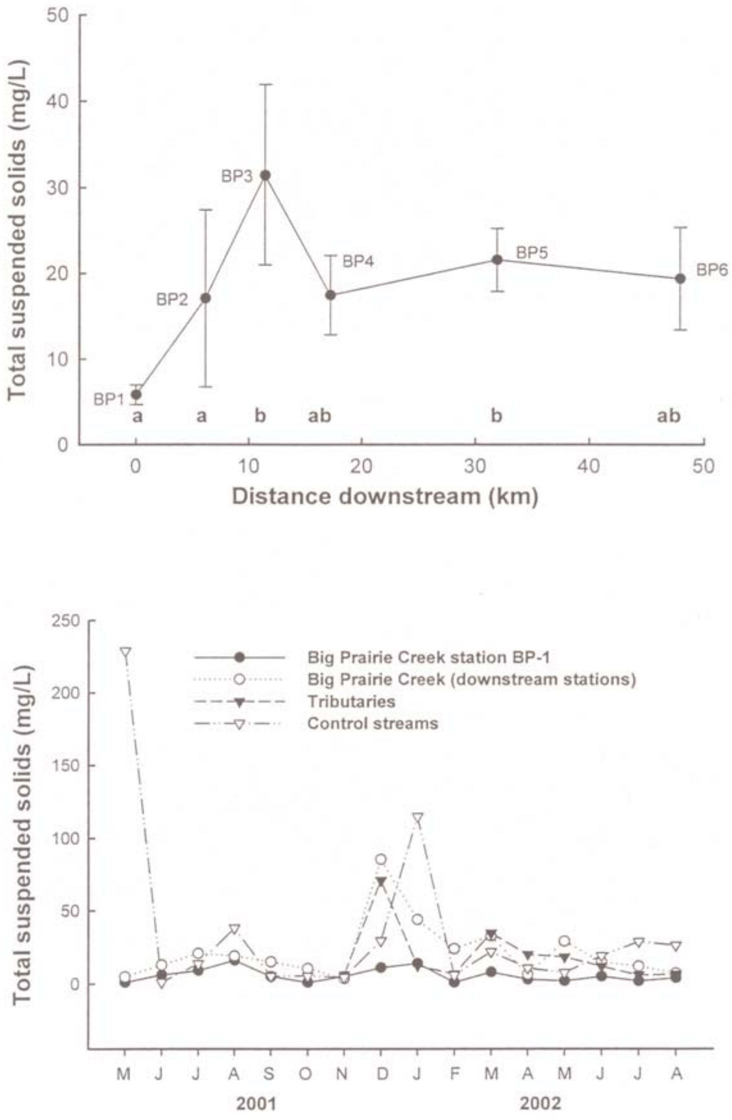


Figure 8. Upper: Averages and standard deviations for total suspended solids at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek.
Lower: Monthly total suspended solids at station BP-1 and monthly averages for total suspended solids at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

Total alkalinity and total hardness

Concentrations of total alkalinity increased from about 18 mg/L at BP-1 to 88 mg/L at BP-5 (Figure 9). Total hardness increased from 22 mg/L to 125 mg/L between these two stations (Figure 10). These increases resulted from contact of stream water with limestone formations of the Blackland Prairie, and it has no relationship to catfish farming. Of course, the rolling terrain and moderate alkalinity waters of the Blackland Prairie make the area highly desirable for catfish farming.

Total alkalinity concentrations were relatively constant at around 20 mg/L throughout the year at BP-1 (Figure 9). At other stations, declines and increases in concentrations observed from one date to the next in all station groups were probably weather related. Rainfall would result in runoff that is lower in alkalinity and hardness than base flow, which sustains the stream in dry weather. Lowest monthly averages were around 45 mg/L total alkalinity and 70 mg/L total hardness, while highest values were about 140 mg/L total alkalinity and 185 mg/L total hardness (Figure 10).

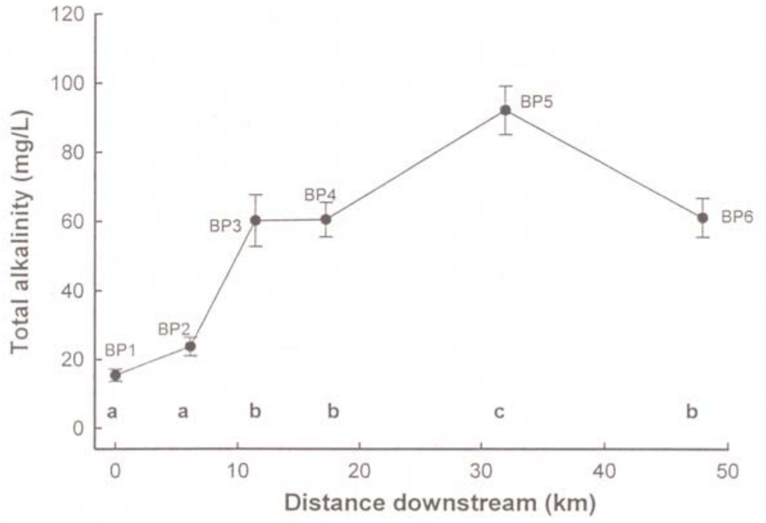
Grand means of total hardness concentration did not differ among station groups (Table 3). However, total alkalinity averaged less for lower Big Prairie Creek than for tributaries and control streams. The tributaries and control streams occur entirely in the Blackland Prairie, while part of the Big Prairie Creek basin drains acidic soils of the Fall Line Hills. However, this is not a satisfactory explanation, for total hardness was as high at stations on downstream Big Prairie Creek as in tributaries and control streams. There obviously is some source of acidity in Big Prairie Creek that lowers total alkalinity. The source could not be identified from the results of this study. Total alkalinity and total hardness concentrations did not differ between upstream and downstream stations on the Black Warrior River (Table 4).

Specific conductance and chloride

Specific conductance increased downstream in Big Prairie Creek (Figure 11) from 52 mhos/cm at BP-1 to 305 mhos/cm at BP-5. A considerable portion of the increase is related to downstream increases in total alkalinity and total hardness concentrations. However, chloride concentrations also rose from 7 mg/L at BP-1 to 27 mg/L at BP-5 (Figure 12), and this contributed to increasing specific conductance downstream. Catfish farms are treated routinely with sodium chloride as a means of preventing nitrite toxicity *(21),* and the increase in chloride concentration in the stream no doubt resulted from catfish farm effluents.

Specific conductance fluctuated little over time at BP-1, and chloride concentrations were always below 12 mg/L (Figures 11 and 12). Stations on lower Big Prairie Creek fluctuated considerably in specific conductance and chloride concentration, but there was no particular seasonal trend. The greatest monthly averages were around 250 mhos/cm and 25 mg/L, respectively. Tributaries usually had higher monthly averages for specific conductance and chloride than lower Big Prairie Creek, and control streams tended to have even lower values.

Grand means for specific conductance were greater in tributaries than in lower Big Prairie Creek and control streams, but Big Prairie Creek and control streams did not differ in values of this variable (Table 3). Downstream Big Prairie Creek and the tributaries had higher average chloride concentrations than the control streams (Table



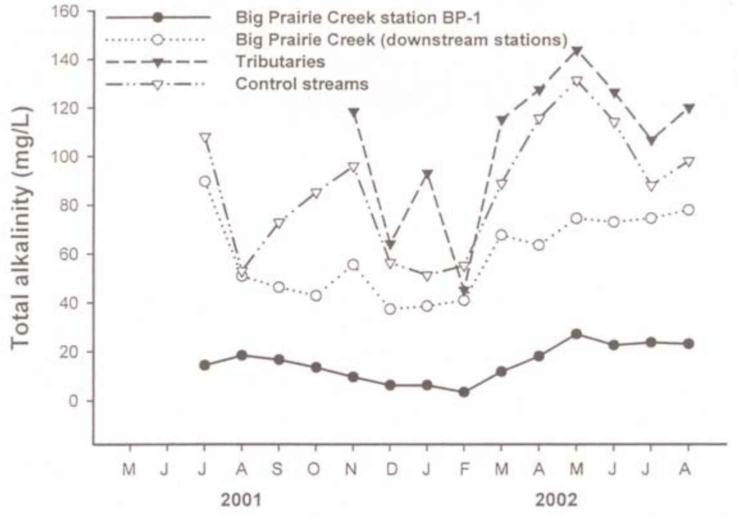


Figure 9. Upper: Averages and standard deviations for total alkalinity at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly total alkalinity at station BP-1 and monthly averages for total alkalinity at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

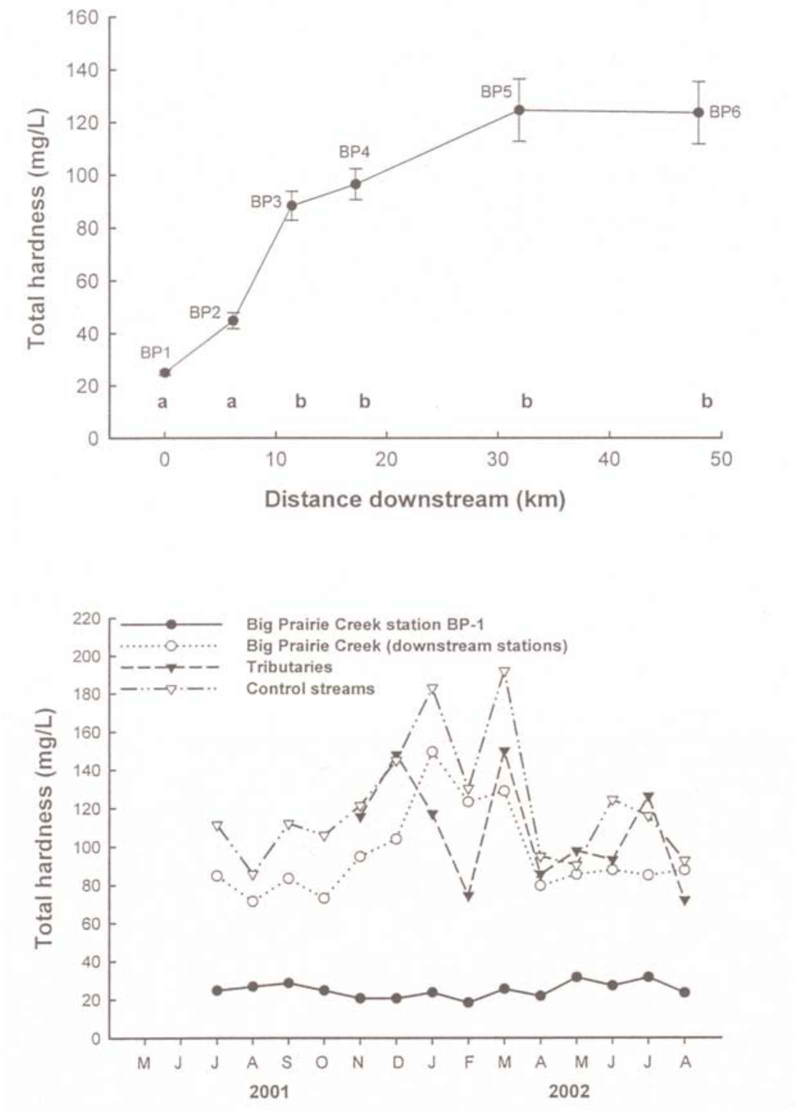


Figure 10. Upper: Averages and standard deviations for total hardness at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly total hardness at station BP-1 and monthly averages for total hardness at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

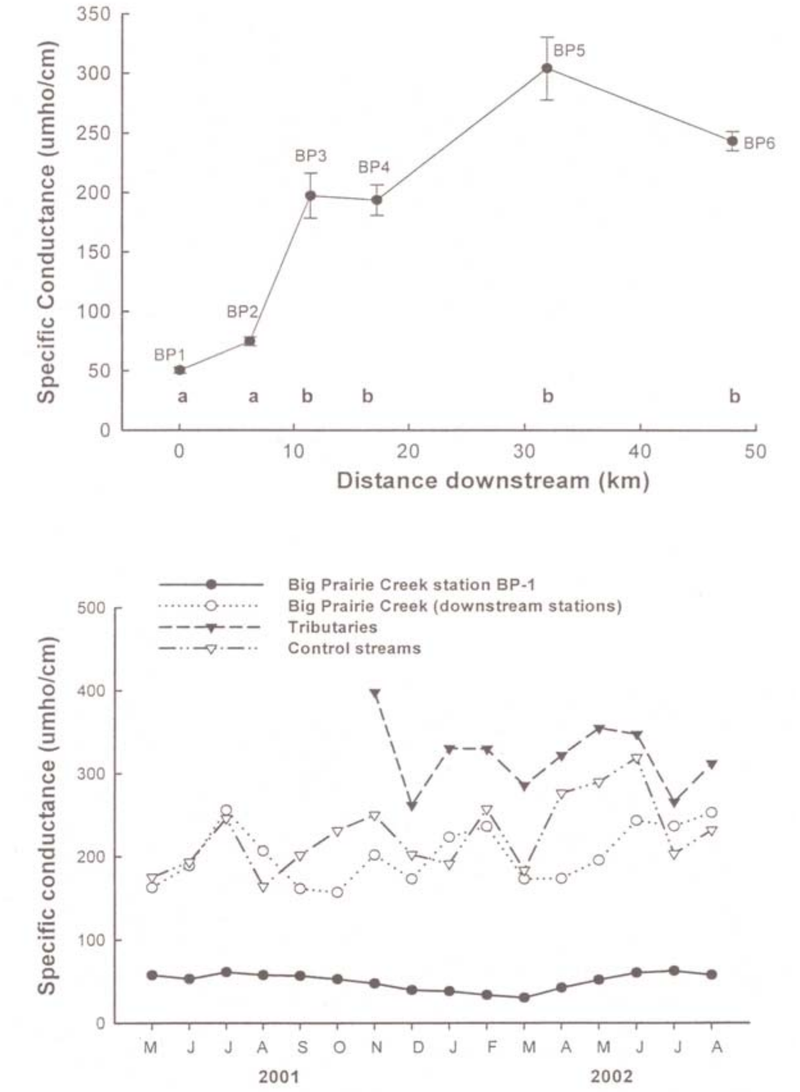


Figure 11. Upper: Averages and standard deviations for specific conductance at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly specific conductance at station BP-1 and monthly averages for specific conductance at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

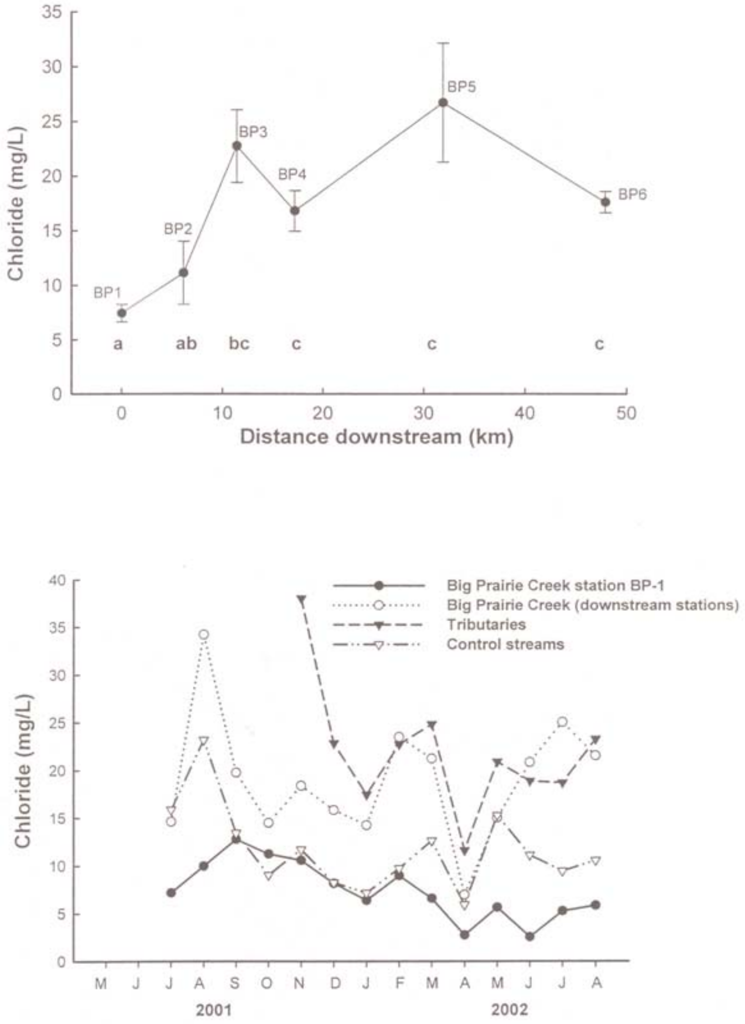


Figure 12. Upper: Averages and standard deviations for chloride at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly chloride at station BP-1 and monthly averages for chloride at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

3). Chloride concentration and specific conductance did not differ between upper and lower stations on the Black Warrior River (Table 4).

Total ammonia and nitrate nitrogen

Combined nitrogen concentrations tended to increase downstream in Big Prairie Creek (Figures 13 and 14). A peak total ammonia nitrogen concentration of 0.46 mg/L was reached at BP-3 and a peak nitrate nitrogen concentration of 0.54 mg/L was measured at BP-5. Downstream of these stations, concentrations of ammonia and nitrate declined (Figures 13 and 14). Apparently, the greatest input of ammonia occurred between BP-2 and BP-3. This input is thought to be mainly of anthropogenic origin. The decline in total ammonia nitrogen between BP-3 and BP-5 is the result of nitrification, because nitrate nitrogen continues to increase to station BP-5. The decline in both variables at BP-6 results from dilution by the lake and possibly also from uptake by aquatic plants.

Nitrification is a source of acidity in aquatic ecosystems. However, the amount of nitrification occurring in Big Prairie Creek was not enough to explain why alkalinity was less than in other Blackland Prairie streams.

Monthly averages in total ammonia nitrogen and nitrate nitrogen exhibited great fluctuations (Figures 13 and 14). The highest averages for total ammonia nitrogen were between 0.6 and 0.8 mg/L and occurred in winter and spring in lower Big Prairie Creek and tributaries. Nitrate nitrogen concentration seldom exceeded 0.5 mg/L, and values tended to be greater in lower Big Prairie Creek and tributaries than at BP-1 and in control streams. The highest nitrate nitrogen concentration of 1.8 mg/L occurred in control streams and possibly was the result of fertilizer use on watersheds for either agricultural or aquacultural purposes.

Both forms of combined nitrogen were higher in concentration in lower Big Prairie Creek and tributaries than in control streams (Table 3). Total ammonia nitrogen and nitrate nitrogen concentrations did not differ between upstream and downstream stations on the Black Warrior River (Table 4).

Soluble reactive phosphorus

Concentrations of this nutrient averaged 0.015 mg/L at BP-1 and between 0.041 and 0.095 mg/L at BP-2 to BP-5 (Figure 15). There was a drastic decline to 0.02 mg/L at station BP-6. The increase in soluble phosphorus is from anthropogenic sources, which could include traditional agriculture, catfish farming, and domestic wastes. The decline in soluble phosphorus at station BP-6 likely is the result of uptake by aquatic plants in Lake Demopolis and adsorption by sediment.

Soluble reactive phosphorus concentrations were remarkably stable over time at station BP-1 of Big Prairie Creek (Figure 15). This likely is because the watershed above this station is wooded and largely uninhabited. Concentrations tended to be greater and more variable at the other locations. Highest soluble reactive phosphorus concentrations tended to occur in early winter and early spring. Although soluble reactive phosphorus concentrations tended to be numerically larger in the downstream reaches of Big Prairie Creek and tributaries than in control streams, average

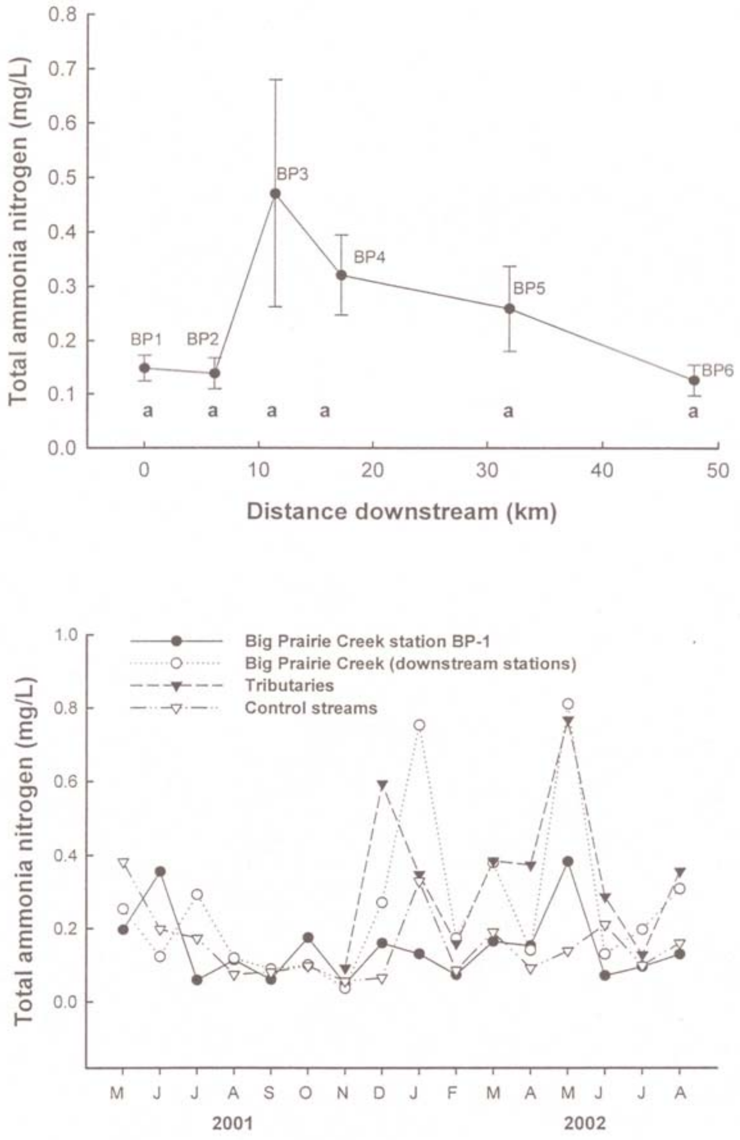


Figure 13. Upper: Averages and standard deviations for total ammonia nitrogen at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly total ammonia nitrogen at station BP-1 and monthly averages for total ammonia nitrogen at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

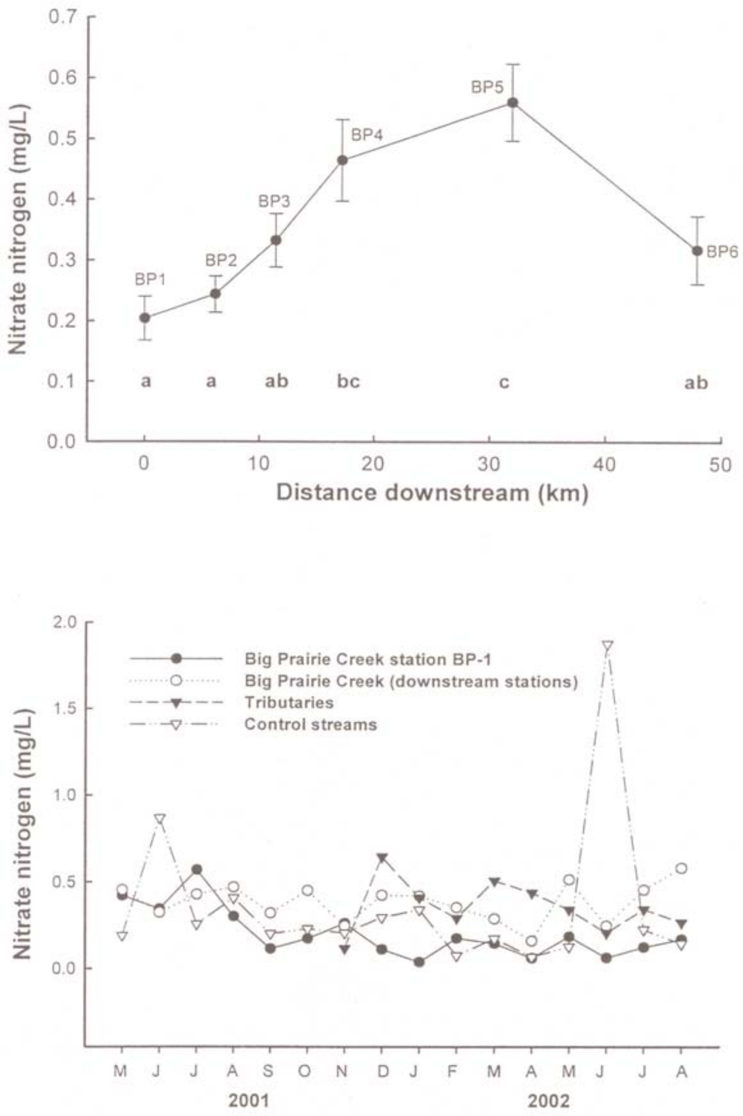
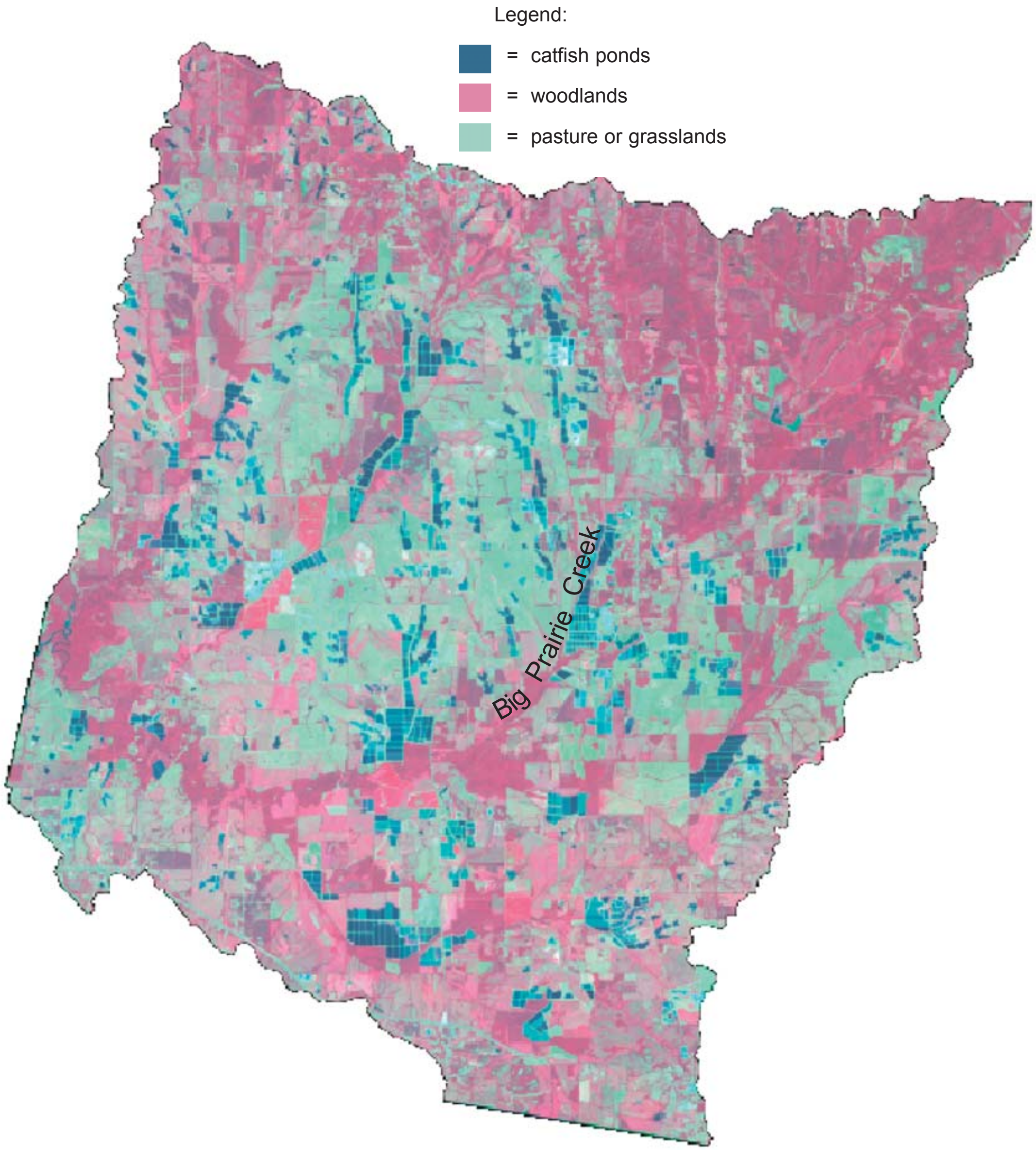


Figure 14. Upper: Averages and standard deviations for nitrate nitrogen at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly nitrate nitrogen at station BP-1 and monthly averages for nitrate nitrogen at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).



NASA satelite image showing Big Prairie Creek, west-central Alabama (http://edcimswww.cr.usgs.gov/pub/imswelcome/). Area of Big Prairie Creek Watershed is 66.396 ha; area of catfish ponds is 5,001 ha. Catfish ponds make up 7.5 percent of watershed area.

soluble reactive phosphorus concentrations did not differ from those of the control streams because of high variability (Table 3). Upstream and downstream sites on the Black Warrior River had similar concentrations of soluble reactive phosphorus (Table 4).

Total nitrogen and total phosphorus

Concentrations of total nitrogen increased from 0.72 mg/L at BP-1 to 1.98 mg/L at BP-3, while total phosphorus increased from 0.075 to 0.32 mg/L between these stations (Figures 16 and 17). Concentrations of these two variables tended to decline between BP-3 and BP-6. The increases were most likely of anthropogenic sources, but catfish farming is not the only source of nutrients resulting from human activities on watersheds.

Monthly averages for total nitrogen and total phosphorus were typically lower for station BP-1 than for other stations (Figures 16 and 17). Concentrations of these two variables fluctuated over time with no clear seasonal trends. The highest concentrations were around 1.6 mg/L for total nitrogen and 0.12 mg/L for total phosphorus at BP-1 and 2.6 mg/L and 0.6 mg/L, respectively, in lower Big Prairie Creek and tributaries. Usually, control streams had lower concentrations of total nitrogen and total phosphorus than lower Big Prairie Creek and tributaries but greater concentrations than station BP-1.

Grand means for total nitrogen and total phosphorus concentrations did not differ among lower Big Prairie Creek, tributaries, and control streams (Table 3), and upstream and downstream stations on the Black Warrior River did not differ in concentrations of these two variables (Table 4).

Biochemical oxygen demand

The biochemical oxygen demand was 1.8 mg/L at BP 1 and from 2.4 to 4.2 mg/L at other stations in Big Prairie Creek (Figure 18). The increase was probably the result of greater phytoplankton growth caused by anthropogenic inputs of nitrogen and phosphorus.

There was no clear seasonal trend in biochemical oxygen demand (Figure 18). However, concentrations tended to be lower at BP-1 and in control streams than in lower Big Prairie Creek and tributaries. The greatest monthly average in the tributaries was 8.8 mg/L.

Grand means for biochemical oxygen demand did not differ between lower Big Prairie Creek and tributaries. Lower Big Prairie Creek and control streams did not differ in biochemical oxygen demand, but tributaries had a greater average concentration of this variable than the control streams (Table 3). Also, concentrations of biochemical oxygen demand did not differ between upstream and downstream stations in the Black Warrior River (Table 4).

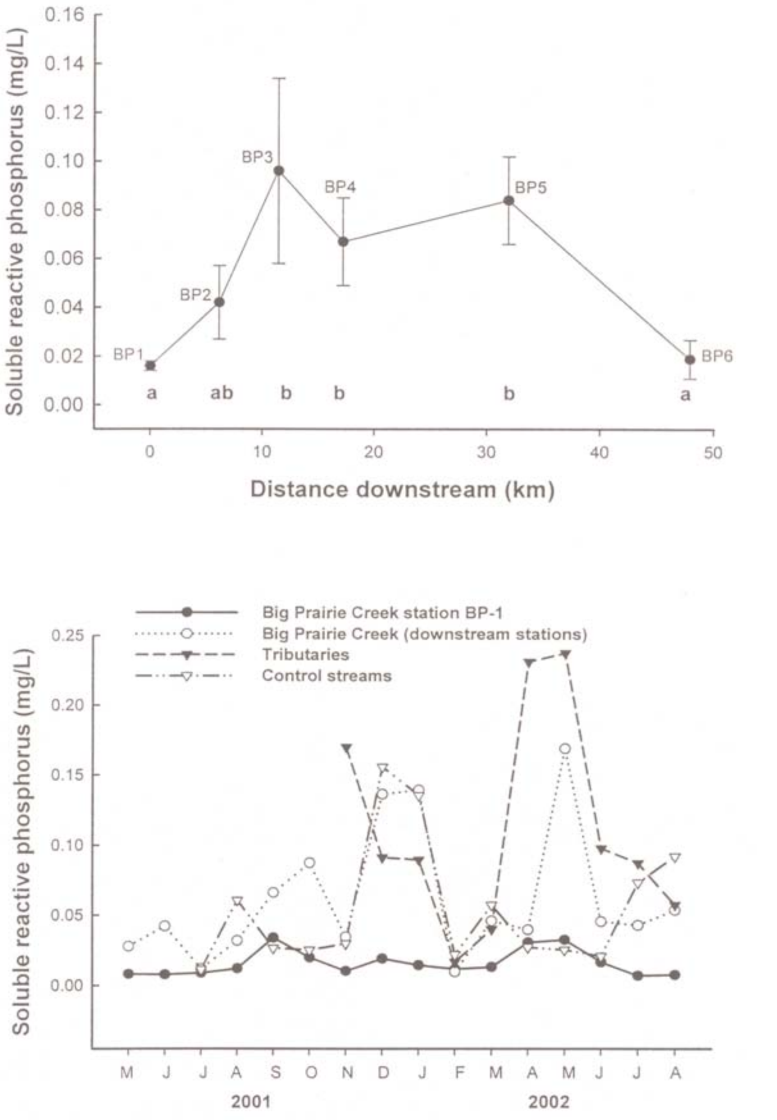


Figure 15. Upper: Averages and standard deviations for soluble reactive phosphorus at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly soluble reactive phosphorus at station BP-1 and monthly averages for soluble reactive phosphorus at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

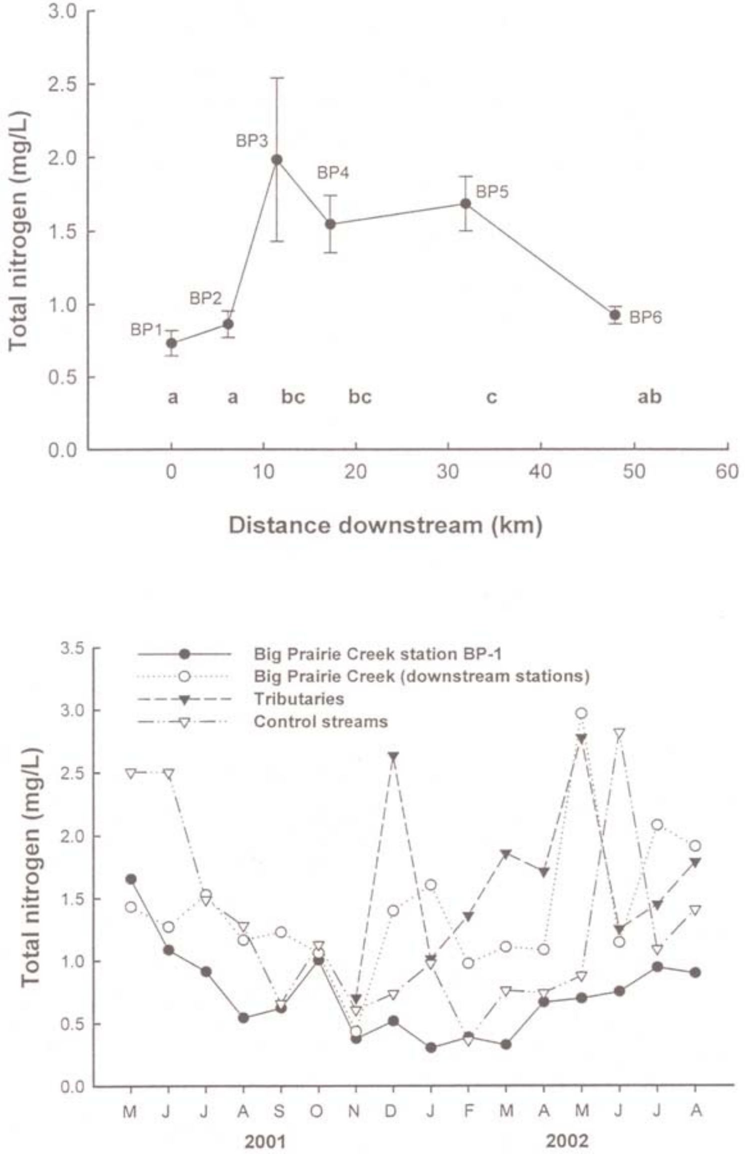


Figure 16. Upper: Averages and standard deviations for total nitrogen at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly total nitrogen at station BP-1 and monthly averages for total nitrogen at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

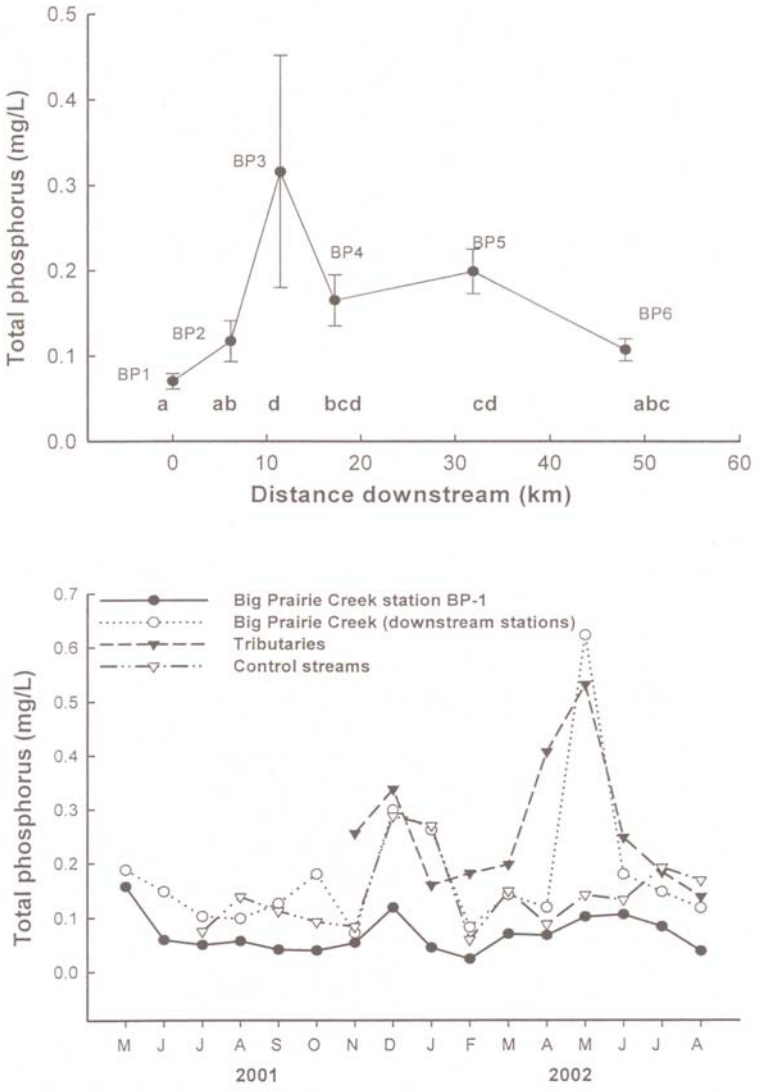


Figure 17. Upper: Averages and standard deviations for total phosphorus at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly total phosphorus at station BP-1 and monthly averages for total phosphorus at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

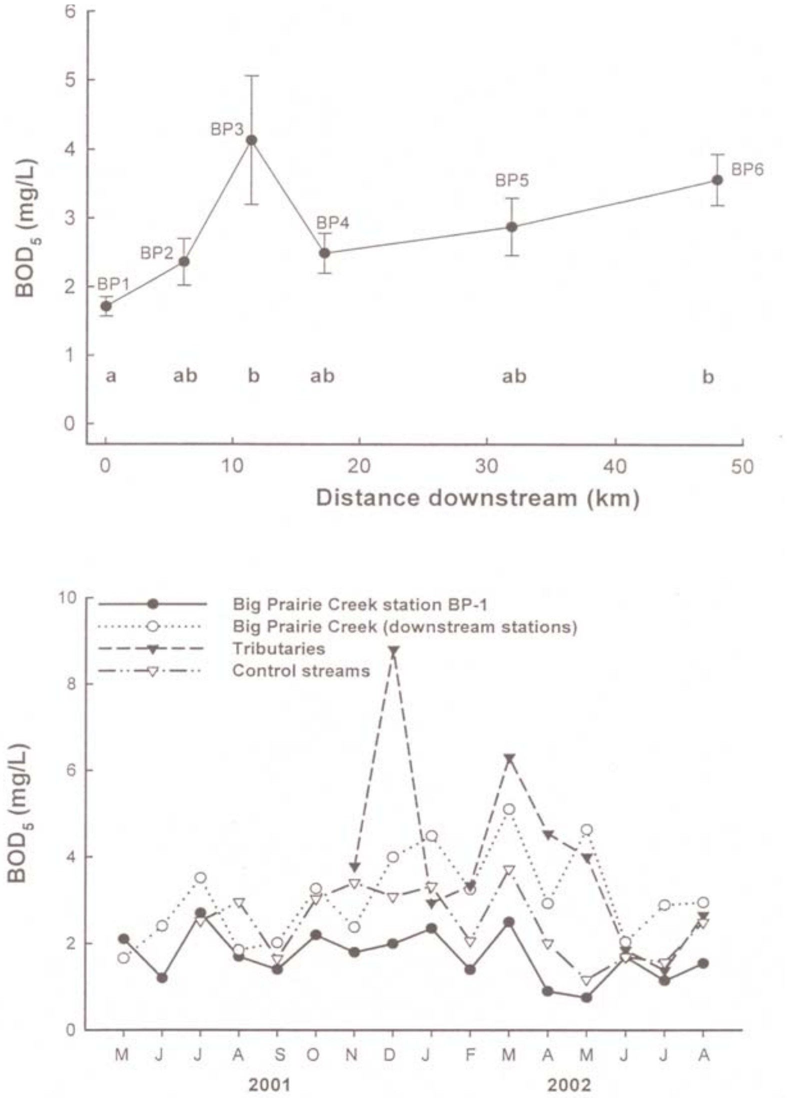


Figure 18. Upper: Averages and standard deviations for biochemical oxygen demand (BOD_5) at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly BOD_5 at station BP-1 and monthly averages for BOD_5 at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

Copper

There were slightly greater concentrations of copper at some stations on lower Big Prairie Creek than at BP-1 (Figure 19). However, the largest mean was only 0.0034 mg/L. The application of copper sulfate to catfish ponds located on the stream's basin has not caused high copper concentrations.

No seasonal pattern in copper concentration was evident in any of the station groups (Figure 19). The apparent downward trend in concentrations during the study cannot be explained, but it is not thought to be the result of analytical error. Grand means for copper concentrations did not differ among station groups or between upstream and downstream stations on the Black Warrior River (Tables 3 and 4).

Microbiological variables

There was extremely high variation in the abundances of total coliform organisms, fecal coliform organisms, and Streptococcus. Therefore, grand means for BP-1, BP-5, T-7, and C-14 did not differ (Figure 20).

Hydrology

Rainfall

Historical rainfall data and rainfall for the period August 2001 through July 2002 for Marion Junction, Alabama, are provided in Table 5. Normal annual rainfall based on 32 years of record was 129.22 cm (50.87 inches). The rainfall in the study area is thought to be similar to that of Marion Junction, for all the sampling sites on the creek and its tributaries were within 30 to 50 km of Marion Junction. Moreover, the land is rural, open, and rolling. There are no topographic features that should favor more rainfall at one location than the other. Nevertheless, in March 2002, there was a large rainfall event, measured by some local residents as 15 to 18 cm (6 to 7 inches) in 24 hours at Greensboro, Alabama, that was less at Marion Junction. The level of Big Prairie Creek was very high for several days after this event, so it is thought that the March data for Marion Junction probably underestimated rainfall on the Big Prairie Creek watershed. At least at Marion Junction, rainfall for the period August 1 2001 to July 31 2002 was 20.82 cm (8.20 inches) below normal.

Stream flow

Historical stream flow data for station BP-5 of Big Prairie Creek at Gallion, Alabama, and stream flow data for BP-1 and BP-5 measured during the study period (August 1 2001 – July 31 2002) are presented in Table 6. Because there was less than normal rainfall during the study period, stream flow was quite low at BP-5. The historical annual average was 427 m^3/minute (251 cubic feet per second), and the average for the study period was only 234 m^3/minute (137 cubic feet per second). Only one year of the record, 1941, had lower stream flow than observed during the study (Table 7). A regression equation was made using historical data from the United States Geological Service for 1941–1951 and omitting the stream flow data of the present study and the one year record resulting from the study in 1990 and 1991 by Kidd and

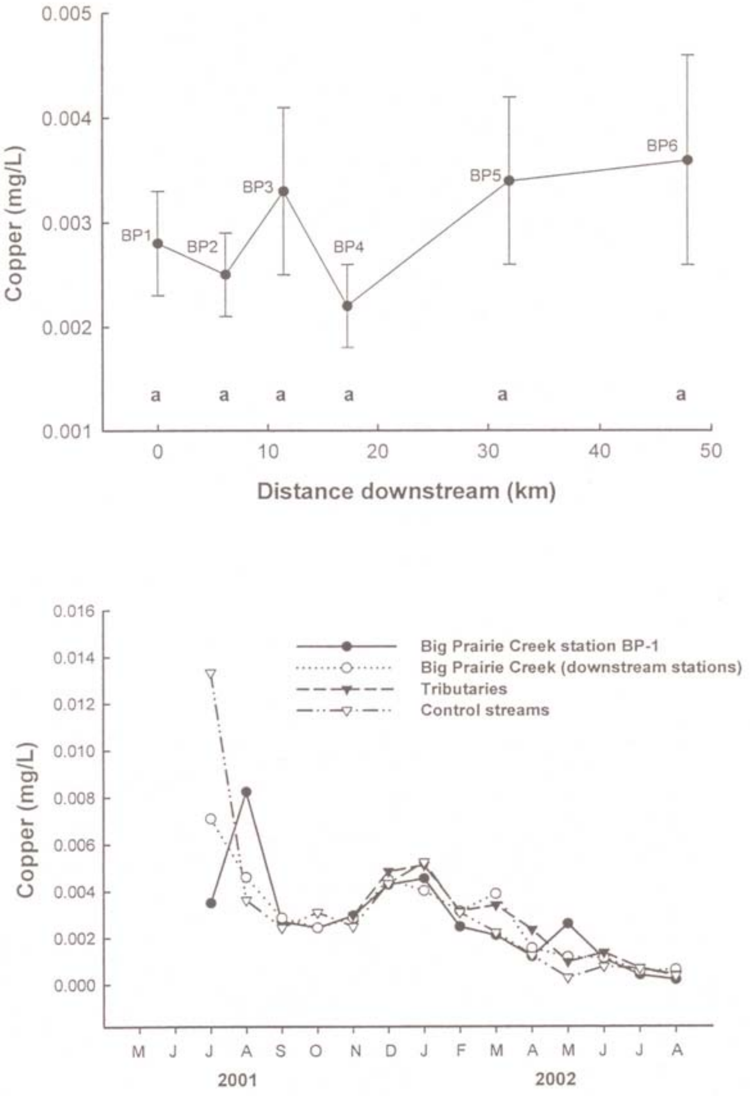


Figure 19. Upper: Averages and standard deviations for copper at six stations at different distances downstream (BP-1 is 0 km) in Big Prairie Creek. Lower: Monthly copper at station BP-1 and monthly averages for copper at stations BP-2 to BP-6, tributaries (T-3 to T-8), and control streams (C-10 to C-15).

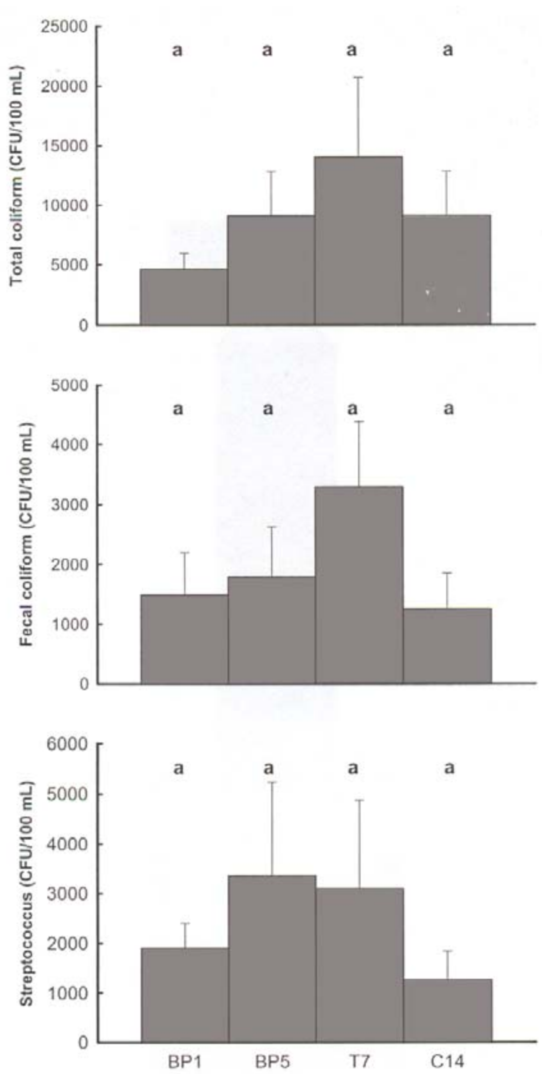


Figure 20. Average abundance of total coliform, fecal coliform, and *Streptococcus* at stations BP-1, BP-5, T-7, and C-14. Vertical lines above bars represent standard deviations.

TABLE 5. MAXIMUM, MINIMUM, AND NORMAL MONTHLY RAINFALL TOTALS FOR HISTORICAL PERIODS AND RAINFALL FOR STUDY PERIOD AT MARION JUNCTION, ALABAMA[1]

	2001-2002	Historical rainfall[2]		
Month	rainfall	Normal	Minimum	Maximum
August	14.38	8.40	0.25	17.32
September	7.80	9.12	0.51	17.42
October	7.42	6.22	0.56	22.28
November	4.78	10.64	1.04	37.64
December	10.01	12.27	5.33	23.80
January	11.63	10.92	3.23	28.02
February	9.09	12.22	3.33	21.92
March	10.85	15.77	3.86	30.18
April	2.34	11.05	0.61	29.95
May	10.01	8.94	0.99	26.95
June	7.62	11.05	0.38	26.75
July	14.05	12.62	1.68	32.44
Annual total	109.98	129.22		

[1] Historical periods include 1940-51 and 1983-2002; Study period is from August 2001 through July 2002; Values are in centimeters.

[2] Data obtained from annual reports of the former Southeast Agricultural Weather Service Center, Auburn, Alabama.

TABLE 6. AVERAGE, MINIMUM, AND MAXIMUM STREAM FLOW FOR HISTORICAL PERIODS AND AVERAGE STREAM FLOW FOR STUDY PERIOD ON BIG PRAIRIE CREEK[1]

	2001-2002 stream flow (m^3/min)		Historical stream flow[2] (m^3/min)		
Month	BP-1	BP-5	Average	Minimum	Maximum
August	30.7	94.4	88.3	8.3	138.0
September	14.4	38.3	113.0	3.0	530.0
October	8.0	44.4	16.6	6.2	33.1
November	9.7	20.0	194.0	13.1	1,341.0
December	5.0	28.6	449.0	87.0	1,741.0
January	78.4	303.0	700.0	143.0	2,834.0
February	32.7	108.0	926.0	190.0	1,575.0
March	679.0	2,038.0	1,306.0	575.0	2,788.0
April	17.8	62.5	588.0	69.0	2,017.0
May	6.3	26.4	440.0	18.5	1,885.0
June	6.0	42.6	118.0	12.4	412.0
July	12.1	12.2	180.0	8.3	945.0
Annual average	75.0	234	427.0		

[1] Historical data (1941-51) for BP-5 near Gallion, Alabama; Study data (August 1, 2001 through July 31,2002) at stations BP-1 and BP-5 on Big Prairie Creek; Stream flow in cubic meters per minute.

[2] Data taken from the website of the United States Geological Survey (http://www.usgs.gov).

TABLE 7. ANNUAL AVERAGES FOR STREAM FLOW ON BIG PRAIRIE CREEK[1] AND RAINFALL AT MARION JUNCTION, ALABAMA

Year[2]	Discharge m^3/min	Rainfall cm
1941	176	113.9
1942	417	123.1
1943	267	114.6
1944	565	152.3
1945	480	145.2
1946	433	159.5
1947	660	166.4
1948	639	155.7
1949	454	141.1
1950	283	124.6
1951	385	122.3
10/1/90–9/30/91[3]	471	143.6
8/1/01–4/31/02[4]	234	110.0

[1] Station BP-5 near Gallion, Alabama.

[2] Data for 1941-1951 were taken from the website for the United States Geological Survey (http://www.usgs.gov).

[3] Kidd and Lambert 1995.

[4] Current study.

Lambert *(16)*. The equation follows:

$$Q = 7.027 P - 537.62 \qquad r^2 = 0.77$$

where Q = stream flow at BP-5 in m^3/minute, and P = precipitation at Marion Junction in cm.

Using this equation, the predicted stream flow for the study period was 235 m^3/minute or almost exactly the quantity measured in the present study. Stream flow at BP-1 averaged 75.0 m^3/min (44.1 ft^3/sec) over the study. Thus, the flow at BP-5 was 3.1 times greater than at BP-1.

The area of the watershed above BP-5 is 44,290 ha (109,440 acres), and the runoff may be estimated as annual water volume divided by basin area. Average runoff calculated by this method was 51 cm (20.1 inches and agrees well with the value of about 44 cm (17.5 inches) given by Yoo and Boyd *(27)*. Runoff for the period of this study, August 1 2001 through July 31 2002 was only 28 cm (11.0 inches).

The area of the entire watershed of Big Prairie Creek was estimated as 66,396 ha (164,065 acres). The total area devoted to catfish ponds was 5,001 ha (12,357 acres). Of the total, 3,001 ha were located above station BP-5; the others were on watersheds of tributaries that entered Big Prairie Creek downstream of BP-5.

DISCUSSION

Water Quality

Big Prairie Creek has distinctly different water quality between station BP-1 above the inflow of catfish farm effluents and the downstream reach (BP-2 to BP-6) below the inflow of catfish farm effluents. The most striking differences are in pH, specific conductance, and concentrations of total alkalinity and total hardness (Table 8). These differences are not related to catfish farm effluents but to the occurrence of acidic soil in the watershed above BP-1 and the predominance of slightly alkaline soils and limestone outcrops on the watershed below BP-1. The higher concentrations of soluble reactive and total phosphorus, nitrate nitrogen, chloride, total suspended solids, and biochemical oxygen demand downstream of BP-1 possibly are related to catfish farm effluents, but other human activities on the watershed also may have contributed to increases in these variables. Other land uses on the Big Prairie Creek

TABLE 8. AVERAGE WATER QUALITIES ON UPPER AND LOWER STATIONS OF BIG PRAIRIE CREEK[1]

Variables	BP-1	BP-2 to 6	p-value for t-test
Water temperature (ºC)	22.45 ± 6.37 (11.0-29.0)	22.61 ± 6.60 (10.0 -34.0)	0.91
pH (standard units)	6.78 ± 0.43 (5.73 - 7.40)	7.56 ± 0.52 (6.08 - 8.80)	<0.01
Dissolved oxygen (mg/L)	6.89 ± 1.75 (4.50 - 10.2)	7.87 ± 1.86 (4.90 - 14.8)	0.11
Turbidity (NTU)	12.34 ± 4.66 (4.40 - 20.4)	24.38 ± 23.11 (3.40 - 166)	0.01*
Total suspended solids (mg/L)	5.81 ± 4.65 (1.00 - 16.0)	21.39 ± 30.02 (1.00 - 171)	0.01*
Total alkalinity (mg/L)	15.39 ± 7.34 (3.44 - 27.18)	60.47 ± 30.50 (8.13 - 156.60)	0.01*
Total hardness (mg/L)	24.98 ± 3.99 (18.38 - 31.6)	95.67 ± 42.44 (30.55 - 249.4)	0.01*
Specific conductance (µmhos/cm)	50.2 ± 10.3 (30.3 - 62.7)	202.7 ± 98.6 (57.4 - 512)	0.01*
Chloride (mg/L)	7.43 ± 3.05 (2.54 - 12.80)	19.02 ± 12.77 (2.15 - 71.98)	0.01*
Total ammonia nitrogen (mg/L)	0.148 ± 0.098 (0.049 - 0.384)	0.260 ± 0.44 (0.01 - 3.45)	0.1
Nitrate nitrogen (mg/L)	0.204 ± 0.144 (0.039 - 0.571)	0.384 ± 0.238 (0.022 - 1.232)	0.01*
Soluble reactive phosphorus (mg/L)	0.016 ± 0.009 (0.007 -0.034)	0.062 ± 0.090 (0 - 0.645)	<0.01*
Total nitrogen (mg/L)	0.73 ± 0.35 (0.32 -1.66)	1.40 ± 1.18 (0.33 - 9.80)	<0.014
Total phosphorus (mg/L)	0.07 ± 0.03 (0.02 - 0.15)	0.18 ± 0.26 (0.02 - 2.33)	<0.01*
5-day biochemical oxygen demand (mg/L)	1.71 ± 0.57 (0.75 - 2.70)	3.08 ± 2.16 (0.55 -16.8)	0.01*
Copper (mg/L)	0.003 ± 0.002 (0.0002-0.0082)	0.003 ± 0.0026 (0.0002 - 0.0135)	0.77

[1] Averages ± standard deviations and minimum and maximum values (in parentheses) for water quality variables in Big Prairie Creek upstream of catfish farms (BP-1) and in downstream reach receiving catfish farm effluents (BP-2 to BP-6)..

*Denotes statistical difference in means.

watershed are listed in Table 9. Most of the watershed is devoted to pasture or woodland, but about 10 percent is in cropland and nearly 5 percent in urban area.

All tributaries of Big Prairie Creek received the direct input of catfish farm effluents, and they had water quality similar to downstream stations (BP-2 to BP-6). Only pH, specific conductance, and concentrations of total alkalinity in tributaries exceed values in downstream Big Prairie Creek. These differences were the result of dilution in the downstream reach by waters originating on the acidic soils on the upper part of the watershed.

The comparison of water quality in tributaries of Big Prairie Creek with control streams allows the best evaluation of the effect of catfish farming on water quality. These streams all originated entirely in the Blackland Prairie and the control streams had a variety of other human activities but not catfish farms. Five of the control stream watersheds were dedicated primarily to three uses: cropland, pasture, or woodland (Table 9). Ratios of these three uses varied with Duncan and Chaney Creek watersheds having the most cropland (39.1 percent), Pintlala Creek having the most pastureland (63.7 percent), and Tallawessee Creek having the most woodland (51.7 percent). Kendrick Creek was listed as part of the Lower Catoma Creek, which contains part of the Montgomery area. However, it is on the western edge of the watershed near the Montgomery Municipal Airport. The actual watershed of Kendrick Creek may contain less urban area than the Lower Catoma Creek watershed in general, and have more pasture and woodland than indicated in Table 9.

The average land use for control stream watersheds were averaged and the following values obtained: cropland, 12.2 percent; pasture, 39.4 percent; woodland, 33.5 percent; urban, 9.5 percent; ponds and lakes (not catfish ponds), 3.0 percent; catfish ponds, 0 percent; other, 2.3 percent. Thus, other than catfish ponds, the main difference in land use between Big Prairie Creek and the control streams was more pasture and less woodland on the Big Prairie Creek watershed than on the watersheds of the control streams (Figure 21). There also was more urban area on the control stream watersheds than on Big Prairie Creek watershed, but this difference was caused by the high percentage of urban area on the Lower Catoma Creek watershed, and the actual watershed of Kendrick Creek, the control stream, probably has less. The main differences are the use of land for catfish ponds and more pasture relative to woodland on the Big Prairie Creek watershed. Nevertheless, all streams are within the Blackland Prairie ecoregion, and the land use, other than for catfish farming on the Big Prairie Creek watershed, is relatively similar among the watersheds. It follows that differences in water quality between Big Prairie Creek, and especially its tributaries, and the control streams, were likely the result of channel catfish farming.

The tributaries were higher than control streams in values of the following variables: specific conductance, chloride, total ammonia nitrogen, nitrate nitrogen, and biochemical oxygen demand. The greater concentrations of ammonia and nitrate nitrogen in the tributaries resulted from feed and fertilizer inputs to ponds. Nutrients entering ponds in fertilizer and feed increase phytoplankton activity, which increases the amount of organic matter in water. Thus, pond effluents tend to be higher in con-

TABLE 9. LAND USE FOR BIG PRAIRIE CREEK WATERSHED AND WATERSHEDS FOR CONTROL STREAMS[1]

Watershed	Cropland	Pasture	Woodland	Urban	Ponds, lakes	Catfish ponds	Other
				%			
Big Prairie Creek	9.8	53.5	23.3	4.7	1.2	7.5	0.0
Upper Boguechitto Creek[2]	39.1	33.1	20.0	3.1	4.2	0.0	0.4
Big Swamp Creek (C-14)	5.6	47.0	42.1	0.9	2.8	0.0	1.5
Tallawessee Creek (C-13)	9.4	33.2	51.7	1.2	3.0	0.0	1.5
Pintlala Creek (C-12)	5.1	63.7	23.5	2.2	3.2	0.0	2.3
Lower Catoma Creek[3]	2.0	20.0	30.0	40.0	2.0	0.0	6.0

[1] Source: Website for Alabama Soil and Water Conservation Committee (http://www.swcc.state.al.us).

[2] Duncan Creek (C-10) and Chaney Creek (C-11) are contained in this hydrologic unit.

[3] Kendrick Creek (C-15) is part of this hydrologic unit.

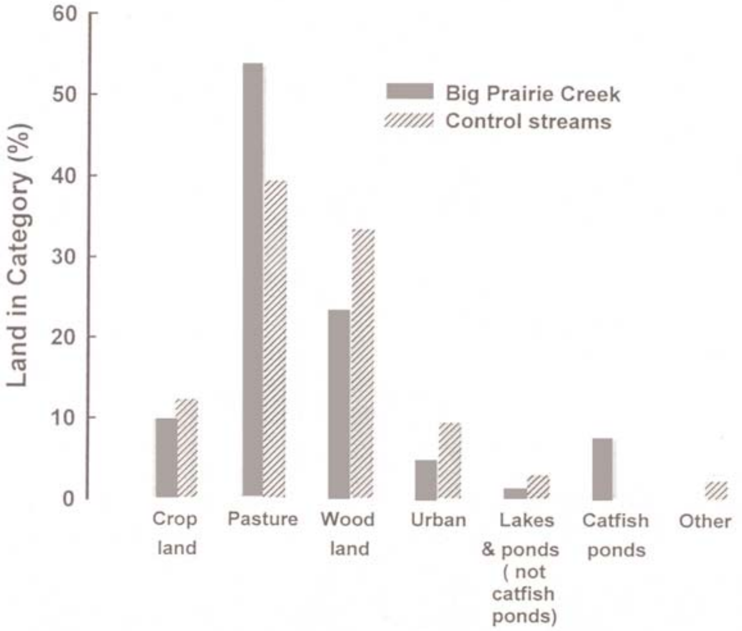


Figure 21. Comparison of land use categories for Big Prairie Creek watershed and control stream watersheds.

centrations of nitrogen, phosphorus, other nutrients, and biochemical oxygen demand than stream waters into which they are discharged. Finally, the application of sodium chloride to ponds causes greater chloride concentration and specific conductance in effluents.

A comparison of average water quality data for BP-6 and BW-7 (Table 10) revealed that pH and concentrations of total hardness, total alkalinity, and total phosphorus were greater in Big Prairie Creek than in the upper station on the Black Warrior River. However, when the upper and lower stations on the Black Warrior River were compared, there were no differences in any of the variables (Table 4). Dilution of the inflow from Big Prairie Creek by the Black Warrior River was sufficient to prevent an increase in concentrations of water quality variables even though they were higher in the creek than in the river upstream of the confluence with the creek.

Water discharged after storms and during the initial stage (first 75 percent of pond volume) of pond draining contains most of the mass of substances released into natural waters from aquaculture ponds. The concentrations of variables in overflow and initial draining effluent are essentially the same as those in pond water *(8)*. Thus, average concentrations of water quality variables at BP-1 and BP-5 were compared with those in catfish pond overflow and surface water (Table 11). Concentrations of dissolved oxygen and specific conductance did not differ greatly among pond water and stream water at BP-1 and BP-5, and the range in pH was only one pH unit. There were 4 to 13 times greater concentrations of other variables in pond water than in water at BP-1. Pond water was only slightly higher in concentrations of nitrate- nitrogen and soluble reactive phosphorus than stream water at BP-5. However, concentrations of biochemical oxygen demand, total phosphorus, total nitrogen, total ammonia nitrogen, chloride, turbidity, copper, and total suspended solids were two to seven times higher in pond water than in water at BP-5. These observations suggest that stream water diluted catfish farm effluents, but other processes also influenced water quality. Nitrification between BP-1 and BP-5 caused an increase in nitrate nitrogen concentration and a wider nitrate nitrogen:ammonia nitrogen ratio at BP-5. The ratio total phosphorus soluble reactive phosphorus was 3.2 at BP-1, 2.3 at BP-5, and 5.86 in pond water. Much of the phosphorus in pond water is contained in living and dead particulate matter. This suggests that particulate phosphorus in pond effluent was transformed to soluble reactive phosphorus by physical and biological degradation within Big Prairie Creek and tributaries.

Much of the water entering Big Prairie Creek between BP-1 and BP-5 passed through catfish ponds. The stream diluted the effluents and assimilated some of the potential pollutants before the water reached BP-5. Nevertheless, it is apparent that water quality in Big Prairie Creek deteriorates between BP-1 and BP-5. The degree of deterioration is not great. For example, the highest stream classification in Alabama for streams into which discharges are permitted is that of Outstanding Alabama Waters *(4)*. The quantitative guidelines for such streams are as follows: pH, 6.0 to 8.5; water temperature, ≤32ºC; dissolved oxygen, ≥6.0 mg/L; total ammonia nitrogen, ≤3.0 mg/L; 5-day biochemical oxygen demand, ≤15.0 mg/L; turbidity, ≤50 NTU; chloride, ≤230 mg/L. Water at BP-5, on average, was of better quality (Table 11) than the minimum guidelines for Outstanding Alabama Waters. In fact, there were

Table 10. Average Water Qualities In Big Prairie Creek and in the Black Warrior River[1]

Variables	BW-7	BW-8	p-value for t-test
Water temperature (ºC)	24.91 ± 7.78 (10.0 - 34.0)	23.66 ± 7.29 (10.0 - 32.0)	0.47
pH (standard units)	7.99 ± 0.45 (7.40 - 7.99)	7.42 ± 0.37 (6.75 - 7.42)	<0.01*
Dissolved oxygen (mg/L)	9.73 ± 2.20 (6.4 - 14.8)	8.59 ± 1.34 (6.0 - 11.0)	0.09
Turbidity (NTU)	19.6 ± 17.8 (5.9 - 60.5)	14.9 ± 15.5 (4.8 - 70.8)	0.62
Total suspended solids (mg/L)	19.44 ± 23.98 (2.0 - 90.0)	10.88 ± 15.11 (1.0 - 64.0)	0.08
Total alkalinity (mg/L)	61.28 ± 20.47 (29.70 - 103.0)	32.56 ± 15.73 (14.72 - 58.89)	<0.01*
Total hardness (mg/L)	123.86 ± 44.12 (75.27 - 209.3)	90.55 ± 20.84 (53.46 - 131.9)	<0.05*
Specific conductance (μmhos/cm)	243.8 ± 31.9 (181 - 291)	213.7 ± 49.2 (150 - 301)	0.05
Chloride (mg/L)	17.66 ± 3.66 (11.94 - 23.99)	16.37 ± 7.38 (6.85 - 33.99)	0.56
Total ammonia nitrogen (mg/L)	0.126 ± .117 (0.014 - .416)	0.153 ± 0.124 (0.029 - 0.491)	0.53
Nitrate nitrogen (mg/L)	0.319 ± 0.223 (0.022 - 0.727)	0.416 ± 0.143 (0.132 - 0.695)	0.15
Soluble reactive phosphorus (mg/L)	0.019 ± 0.031 (0 - 0.118)	0.021 ± 0.051 (0.002 - 0.210)	0.09
Total nitrogen (mg/L)	0.73 ± 0.35 (0.30 - 1.65)	1.40 ± 1.17 (0.33 - 9.80)	<0.01*
Total phosphorus (mg/L)	0.10 ± 0.05 (0.03 - 0.22)	0.07 ± 0.09 (0.0 - 0.41)	<0.01*
5-day biochemical oxygen demand (mg/L)	3.58 ± 1.50 (1.15 - 5.75)	1.68 ± 1.04 (0.30 - 4.20)	0.80
Copper (mg/L)	0.0036 ± 0.0036 (0.0003 - 0.0135)	0.003 ± 0.002 (0.0005 - 0.0085)	0.91

[1] Averages ± standard deviations and minimum and maximum values (in parentheses) for water quality variables inear confluence of Big Prairie Creek with Black Warrior River (BW-6) and Black Warrior River about 0.5 km upstream from Big Prairie Creek (BW-7)

*Denotes statistical significance.

Table 11. Average Concentrations of Water Quality Variables at Stations BP-1 and BP-5 of Big Prairie Creek Compared with Those in Catfish Pond Water

Variables	BW-1	Catfish pond water[1]	BP-5
pH (standard units)	6.8	7.6	7.8
Total suspended solids (mg/L)	6.1	81	24.2
Dissolved oxygen (mg/L)	6.9	8.4	7.0
Turbidity (NTU)	12.3	118	26.2
Specific conductance (µmhos/cm)	50	372	304
Chloride (mg/L)	7.6	87.1	28.8
Total ammonia nitrogen (mg/L)	0.14	1.20	0.17
Nitrate nitrogen (mg/L)	0.15	0.86	0.57
Total nitrogen (mg/L)	0.60	3.42	1.52
Soluble reactive phosphorus (mg/L)	0.019	0.117	0.092
Total phosphorus (mg/L)	0.061	0.686	0.214
Biochemical oxygen demand (mg/L)	1.66	11.0	3.23
Copper (mg/L)	0.0028	0.0092	0.0031

[1] Data for chloride *(21)* and copper *(17)* are for pond surface water. All other data are for storm overflow *(8).*

no instances where water at BP-5 did not comply with the guidelines for Outstanding Alabama Waters. Big Prairie Creek is classified for fish and wildlife propagation, which is a lower classification with less stringent guidelines than Outstanding Alabama Waters. These guidelines are water temperature, ≤32ºC; dissolved oxygen, ≥5.0 mg/L; and turbidity, ≤50 NTU. Moreover, Big Prairie Creek did not exceed the in-stream chloride standard of 230 mg/L recommended by USEPA *(25)* or the maximum copper concentration of 0.013 mg/L also suggested by the USEPA *(13)*.

Loads of water quality variables

The loads of water quality variables in Big Prairie Creek that can be attributed to all sources between BP-1 and BP-5 were estimated from concentrations of variables and stream flow data (Table 12). For example, the average concentrations of biochemical oxygen demand were 1.65 mg/L at BP-1 and 3.23 mg/L at BP-5, while stream flow averaged 75.0 m^3/min at BP-1 and 234.9 m^3/min at BP-5. The load of biochemical oxygen demand was 65,043 kg/year at BP-1 (1.65 $g/m^3 \times 75 \ m^3/minute \times 1{,}440 \ min/day \times 365 \ days/year$) and 398,790 kg/year at BP-5. The difference in the biochemical oxygen demand load at BP-5 and BP-1, 332,747 kg/year, is the load entering between the two stations.

Boyd et al. *(8)* made estimations of annual amounts of several variables discharged by channel catfish farming in west-central Alabama as follows: total suspended solids, 1,387.5 kg/ha; biochemical oxygen demand, 91.5 kg/ha; total nitrogen, 51.6 kg/ha; total phosphorus, 4.39 kg/ha. The area of catfish ponds above BP-5 is about 2,994 ha. Thus, based on the estimates given above, the input of these variables from catfish ponds to Big Prairie Creek and its tributaries would be as follows: total suspended solids, 4,154,175 kg/year; biochemical oxygen demand, 273,951 kg/year; total nitrogen, 154,490 kg/year; total phosphorus, 13,144 kg/year. These estimates represent the following percentages of the observed increases in the variables between BP-1 and BP-5: total suspended solids, 151.4 percent; biochemical oxygen demand, 82.3 percent; total nitrogen, 94.5 percent; total phosphorus, 55.6 percent. The largest discharge of total suspended solids from catfish ponds occurs during draining *(2,20)*. The coarse solids released from ponds would be expected to settle quickly and never reach the main channel of Big Prairie Creek. There also would be a decline in loads of the other three variables as a result of sedimentation before reaching the main channel. Nevertheless, comparison of the increase in loads of these four variables between BP-1 and BP-5 (Table 12) with estimated discharge from catfish ponds *(8)* suggests that catfish farming is a major contributor of total suspended solids, biochemical oxygen demand, total nitrogen, and total phosphorus to Big Prairie Creek.

Table 12. Increase in Loads of Water Quality Variables Between BP-1 and BP-5 of Big Prairie Creek

Variables	BP-1	BP-5	Increase
Biochemical oxygen demand (kg/yr)	65,043	398,790	332,747
Total suspended solids (kg/yr)	239,683	2,982,750	2,743,067
Chloride (kg/yr)	299,008	3,546,665	3,247,657
Total ammonia nitrogen (kg/yr)	5,352	21,691	16,340
Nitrate nitrogen (kg/yr)	5,770	70,338	64,568
Soluble reactive phosphorus (kg/yr)	734	11,296	10,562
Total phosphorus (kg/yr)	2,661	26,314	23,653
Total nitrogen (kg/yr)	23,439	186,928	163,489
Copper (kg/yr)	115	387	272

The increase in chloride load between BP-1 and BP-5 was 3,247,657 kg/year. According to data collected by Tavares and Boyd *(21),* ponds are treated with about 1,250 kg/ha chloride (from sodium chloride) each year. Ponds between BP-1 and BP-5 receive around 3,750,000 kg/year of chloride. Thus, most of the increase in chloride load between BP-1 and BP-5 can be attributed to catfish farm effluents.

The use of copper sulfate in catfish ponds averages about 4 mg/L per year *(8,17)*. Thus, around 50,000 kg of copper is applied annually to ponds between BP-1 and BP-5. The load increase of 272 kg/yr of copper between the two stations is only 0.5 percent of the applied copper. This verifies the assumption that most of the copper applied to ponds precipitates and does not leave ponds in effluent *(8,17)*.

Microbiology

A study conducted in fall 1993 *(6)* gave the following averages for coliforms and streptococci in 24 catfish ponds in Hale County: total coliforms, 1,921 CFU/100 mL;

fecal coliforms, 135 CFU/100 mL; fecal streptococci, 199 CFU/100 mL. These values are considerably less than those found in streams during this study. The usual abundances in streams were as follows: total coliforms, 5,000 to 12,000 CFU/100 mL; fecal coliforms, 1,500 to 3,000 CFU/100 mL; fecal streptococci, 1,200 to 3,000 CFU/100 mL. The abundances of these organisms tended to be greater at BP-5 and T-7 than at BP-1 and C-14. However, because of the great variation, the means did not differ ($P>0.05$). Thus, catfish farming is not thought to be a major source of coliform and streptococci organisms. More likely, cattle, wild animals, and human sewage were the source of the organisms in the streams.

The abundance of coliform organisms found in the streams is not alarmingly high. It is common for surface waters in the United States to contain more than 2,000 CFU/100 mL of total coliform organisms *(24)* and waters containing up to 10,000 total coliforms/100 mL are considered permissible for public water supplies, provided water is chlorinated before use. However, the levels of fecal coliform organisms in the streams are much higher than the standard of 150 to 200 fecal coliforms/100 mL for bathing waters *(24)*. Moreover, streams classified for fish and wildlife propagation in Alabama have a total coliform limit of 200 cfu/100 mL *(4)*. The findings of this study suggest that streams in the Blackland Prairie are contaminated with coliform and streptococci organisms but the source of these organisms is not catfish farm effluents.

Hydrology

The Big Prairie Creek basin was estimated to have an area of 66,396 ha (164,065 acres). The water area devoted to channel catfish farming was 5,001 ha (12,357 acres). Thus, catfish ponds cover about 7.5 percent of the basin. The average depth of catfish ponds in Alabama is 1.62 m *(8)*. Thus, the water storage for catfish farming on the basin is 81 million cubic meters. This is equal to a water depth of 12.2 cm (4.72 in) over the entire basin. The storage capacity of the ponds is 23.9 percent of normal annual runoff, and 43.6 percent of runoff during the 1-year study period. However, according to Boyd et al. *(8)* ponds are drained about twice in 20 years. Evaporation and seepage from ponds in west-central Alabama was estimated *(3)* to exceed precipitation falling directly into ponds by an average of 76.2 cm (30 inches). Thus, the average storage volume for runoff can be calculated as follows:

$$\text{Runoff storage capacity } (\text{m}^3/\text{year}) = [\text{Pond area } (\text{m}^2) \times \text{Average pond depth (m)} \times \text{Fraction of ponds drained annually}] + [\text{Pond area } (\text{m}^2) \times \text{Evaporation excess (m)}]$$

$$\text{Runoff storage capacity} = [5{,}001 \text{ ha} \times 10^4 \text{ m}^2/\text{ha} \times 1.62 \text{ m} \times 0.05] + [5{,}001 \text{ ha} \times 10^4 \text{ m}^2/\text{ha} \times 0.762 \text{ m}] = 42.2 \times 10^6 \text{ m}^3/\text{year}$$

The annual runoff storage capacity is equivalent to 6.87 cm. However, farmers apply well water to ponds to supplement rainfall and runoff. Kidd and Lambert *(16)* estimated that the annual use of ground water from wells in catfish farming in 1991 and 1992 was 3,400 m^3/ha. Applying these data to Big Prairie Creek watershed, well water use would be 17×10^6 m^3/year and equivalent to 2.77 cm/year. This would reduce runoff storage capacity of ponds to 4.10 cm or 9.5 percent of annual runoff.

It is well known that ponds cause a reduction in runoff from small watersheds *(19)*, but the small reduction in runoff caused by ponds on Big Prairie Creek watershed would not affect stream flow greatly on years with normal rainfall. Moreover, discharge of Big Prairie Creek at BP-5 followed the same trend relative to rainfall in two, 12-month periods (October 1990–September 1991 and August 2001–July 2002) as it did during the period 1941–1951 when no catfish ponds were in the watershed (Figure 22). It is remarkable, but possibly coincidental, that average stream flow for 1990–1991 and 2001–2002 fell almost exactly on the regression line for the 1941–1951 stream flow measurements. Nevertheless, it appears that even on dry years, catfish ponds do not store enough runoff on the watershed to seriously affect the flow of Big Prairie Creek.

Ponds serve two hydrologic functions. They store runoff and detain it also. After a heavy rain, water levels increase above the top of overflow structures in ponds, and it often takes several days for the excess water to flow through ponds. In the winter and early spring in Alabama, many ponds discharge water continuously for several weeks in response to intermittent rainfall events *(27)*. Thus, ponds on the Big Prairie Creek possibly play a bigger role in reducing the peak of the stream flow hydrograph than in reducing stream flow. However, we did not have sufficient data on stream

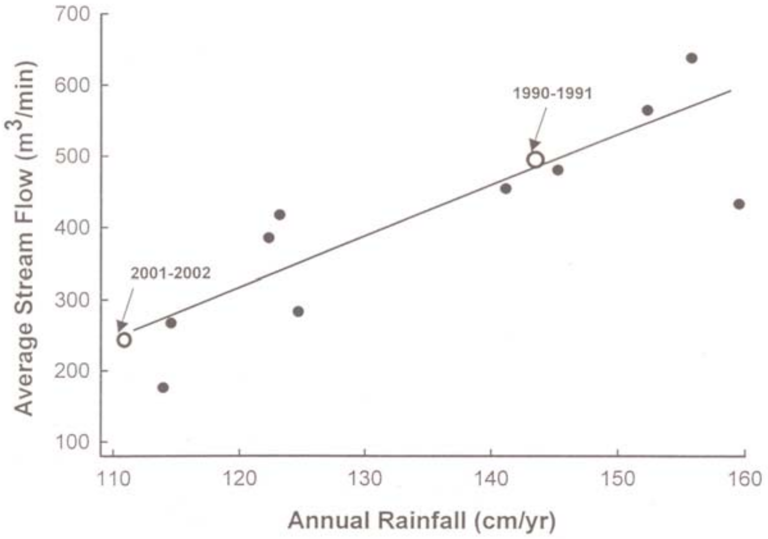


Figure 22. Regression line for annual rainfall at Marion Junction, Alabama and average annual stream flow at station BP-5 in Big Prairie Creek near Gallion, Alabama (1941-1951). The two open circles represent rainfall and stream flow for two, 12-month periods of measurement since catfish farming became a land use practice on the watershed.

flow for analyzing hydrographs of Big Prairie Creek before and after the advent of catfish farming in its basin.

Protection of Streams

The results of this study suggest that channel catfish farming has measurable impacts on stream water quality. However, in spite of the high density of farms on the Big Prairie Creek watershed, water quality is superior to the water quality standard for streams classified for fish and wildlife propagation other than for the microbiological standard. This perturbation was probably not related to catfish farming as control streams also had poor microbiological quality. Also, catfish farming has not altered stream flow in Big Prairie Creek.

Catfish farming is an important endeavor in the Blackland Prairie region bringing much needed income to this economically depressed region. It is anticipated that catfish farming will continue to increase, and inputs of potential pollutants to streams will increase. The Alabama Catfish Producers have collaborated with Alabama Department of Environmental Management, the United States Environmental Protection Agency, USDA Natural Resources Conservation Service, and Auburn University to develop BMPs for channel catfish farming *(9)*. These BMPs will be the major feature of the aquaculture effluent guidelines to be formulated by ADEM. Thus, it is anticipated that most farmers will adopt the BMPs, and this should assure that stream water quality will not deteriorate in the future as a result of channel catfish culture.

REFERENCES

1. Anonymous. Undated. Szechrome reagents for nitrate and nitrite analysis. Technical Data Sheet No. 239, Polysciences Europe GmbH, Eppelheim, Germany.

2. Boyd, C. E. 1978. Effluents from catfish ponds during fish harvest. Journal of Environmental Quality 7:59-63.

3. Boyd, C. E. 1987. Water conservation measures in fish farming, p. 88-91. In: Fifth Conference on Applied Climatology. American Meteorological Society, Boston, Massachusetts, USA.

4. Boyd, C. E. 2000. Water quality, an introduction. Kluwer Academic Publishers, Boston, Massachusetts, USA.

5. Boyd, C. E. and R. F. Hulcher. 2001. Best management practices for channel cat fish farming in Alabama. Alabama Agricultural Experiment Station, Auburn University, Alabama, Highlights of Agricultural Research 48 (fall):1-4.

6. Boyd, C. E. and M. Tanner. 1998. Coliform organisms in water of channel catfish ponds. Journal of the World Aquaculture Society 29:74-78.

7. Boyd, C. E. and C. S. Tucker. 1998. Pond aquaculture water quality management. Kluwer Academic Publishers, Boston, Massachusetts, USA.

8. Boyd, C. E., J. Queiroz, J. Lee, M. Rowan, G. N. Whitis, and A. Gross. 2000. Environmental assessment of channel catfish, *Ictalurus punctatus,* farming in Alabama. Journal of the World Aquaculture Society 31(4):511-544.

9. Boyd, C. E., J. F. Queiroz, G. N. Whitis, R. Hulcher, P. Oakes, J. Carlisle, D. Odom, Jr., M. M. Nelson, and W. G. Hemstreet. 2003. Best management practices for channel catfish farming in Alabama. Special Report 1, Alabama Catfish Producers, Montgomery, Alabama, USA.

10. Clesceri, L. S., A. E. Greenberg, and A. D. Eaton. 1998. Standard methods for the examination of water and wastewater, 20th edition. American Public Health Association, Washington, D.C., USA.

11. ESRI. 1999. Getting to know ArcView GIS, the geographic information system (GIS) for everyone. 3rd edition, Redlands, California, USA.

12. ESRI. 2001. Getting to know ArcGIS desktop, basic of Arcview, Arc editor and Arcinfo. Redlands, California, USA.

13. Federal Register. 1998. Environmental Protection Agency, Part IV, National recommended water quality criteria; notice; republication. Federal Register 63(237):68354-68364 (December 10), Office of the Federal Register, National Archives and Records Administration, Washington, D.C., USA.

14. Federal Register. 2002. Environmental Protection Agency, 40 CFR Part 451, Effluent limitations guidelines and new source performance standards for the concentrated aquatic animal production point source category: proposed rule. Federal Register 67(117):57872-57928 (September 12), Office of the Federal Register, National Archives and Records Administration, Washington, D.C., USA.

15. Gross, A. and C. E. Boyd. 1998. A digestion procedure for the simultaneous determination of total nitrogen and total phosphorus in pond water. Journal of the World Aquaculture Society 29:300-303.

16. Kidd, R. E. and D. S. Lambert. 1995. Hydrogeology and ground water quality in the Black Belt area of west-central Alabama, and estimated water use for aquaculture, 1990. United States Geological Survey, Water-Resources Investigations Report 94-4074, Tuscaloosa, Alabama, USA.

17. McNevin, A. 2003. Copper concentrations in channel catfish, *Ictalurus punctatus,* ponds treated with copper sulfate. Master's thesis. Auburn University, Alabama, USA.

18. National Agricultural Statistics Service. 2003. Catfish production, February and July. Agricultural Statistics Board, United States Department of Agriculture, Washington, D.C., USA.

19. Schoof, R. R. and G. A. Gander. 1982. Computation of runoff reduction caused by farm ponds. Water Resources Bulletin 18:529-532.

20. Schwartz, M. and C. E. Boyd. 1994. Effluent quality during harvest of channel catfish from watershed ponds. Progressive Fish-Culturist 56:25-32.

21. Tavares, L. H. S. and C. E. Boyd. 2003. Possible effects of sodium chloride on quality of effluents from Alabama channel catfish ponds. Journal of the World Aquaculture Society 34:217-222.

22. Tucker, C. S. and S. W. Lloyd. 1985. Water quality in streams and channel catfish *(Ictalurus punctatus)* ponds in west-central Mississippi. Technical Bulletin 129, Mississippi Agricultural and Forestry Experiment Station, Mississippi State, Mississippi, USA.

23. Tucker, C. S. and E. H. Robinson. 1990. Channel catfish farming handbook. Van Nostrand Reinhold, New York, New York, USA.

24. United States Environmental Protection Agency. 1977. Quality criteria for water. Office of Water and Hazardous Materials, USEPA, Washington, D.C., USA.

25. United States Environmental Protection Agency. 1988. Ambient water quality criteria for chloride - 1988. Office of Water, Criteria and Standards Division, USEPA, Washington, D.C., USA.

26. United States Geological Survey (USGS). 2000. Landsat 7TM April 2000. Reston, Virginia, USA.

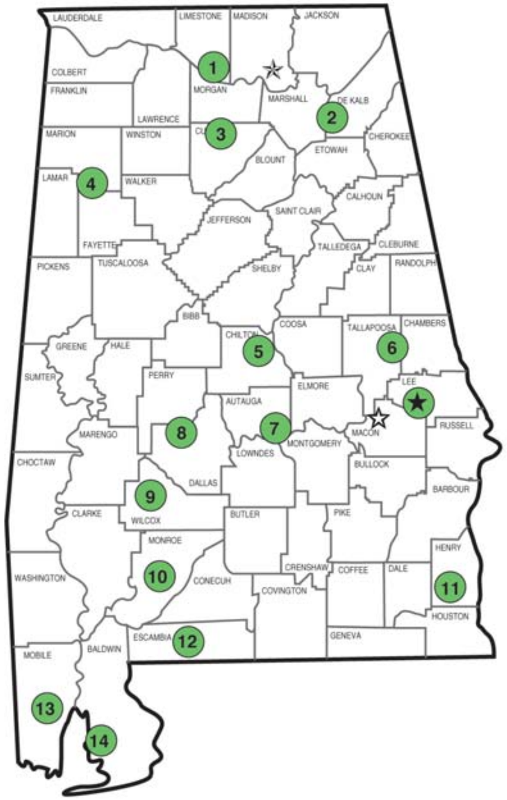
27. Yoo, K. H. and C. E. Boyd. 1994. Hydrology and water supply for aquaculture. Chapman and Hall, New York, New York, USA.

28. Whitman, C. T, G. T. Mehan, III, G. H. Grubbs, S. E. Grace, M. Rubin, J. Goodwin, and M. Jordan. 2002. Draft guidance for aquatic animal production facilities to assist in reducing the discharge of pollutants.Office of Science and Technology, U. S. Environmental Protection Agency, Washington, D.C., USA.

.

Alabama's Agricultural Experiment Station
AUBURN UNIVERSITY

With an agricultural research unit in every major soil area, Auburn University serves the needs of field crop, livestock, forestry, and horticultural producers in each region in Alabama. Every citizen of the state has a stake in this research program, since any advantage from new and more economical ways of producing and handling farm products directly benefits the consuming public.



Research Unit Identification

★ Main Agricultural Experiment Station, Auburn.
✭ Alabama A&M University.
☆ E. V. Smith Research Center, Shorter.

1. Tennessee Valley Research and Extension Center, Belle Mina.
2. Sand Mountain Research and Extension Center, Crossville.
3. North Alabama Horticulture Research Center, Cullman.
4. Upper Coastal Plain Agricultural Research Center, Winfield.
5. Chilton Research and Extension Center, Clanton.
6. Piedmont Substation, Camp Hill.
7. Prattville Agricultural Research Unit, Prattville.
8. Black Belt Research and Extension Center, Marion Junction.
9. Lower Coastal Plain Substation, Camden.
10. Monroeville Agricultural Research Unit, Monroeville.
11. Wiregrass Research and Extension Center, Headland.
12. Brewton Agricultural Research Unit, Brewton.
13. Ornamental Horticulture Research Center, Spring Hill.
14. Gulf Coast Research and Extension Center, Fairhope.