FISH ASSEMBLAGE RESPONSE FOLLOWING A HURRICANE-INDUCED FISH KILL IN THE LOWER ROANOKE RIVER, NORTH CAROLINA

FINAL REPORT

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Abstract.—We investigated lower Roanoke River fish community responses following anoxic conditions and a resulting fish kill caused by Hurricane Isabel on 18 September 2003. Using boat-mounted electrofishing gear, we surveyed fish assemblages at fixed sampling sites on the lower Roanoke River one month after the hurricane in 2003 and each August from 2004–2006. We compared post-hurricane fish assemblages to those collected during August 2001 and 2002 and at two of the three sites one week prior to the hurricane in 2003. One month after the hurricane and associated fish kill, the number of species at the two lower Roanoke River sites had decreased by over 50%, and relative abundances of most remaining species were drastically reduced. The resulting fish assemblages were dominated by juvenile clupeids, eastern silvery minnow *Hybognathus regius*, bowfin *Amia calva*, and white catfish *Ameiurus catus*. Previously abundant sportfish such as largemouth bass *Micropterus salmoides* and bluegill *Lepomis macrochirus* were absent or represented by only a few individuals. The number of species and relative abundances of most species increased steadily as the lower Roanoke River fish assemblages recovered within a few years following Hurricane Isabel. Results from this study indicate that lower Roanoke River fish assemblages can recover from catastrophic disturbances. We emphasize the need to identify areas of refugia and to elucidate fish movement patterns in response to future large-scale disturbances.

Periods of hypoxia (dissolved oxygen < 2 mg/L) and subsequent fish kills are frequent occurrences in coastal river systems and estuaries following major flood events and hurricanes. In 1960, Hurricane Donna caused deoxygenation and extensive fish and invertebrate kills after decomposition of suspended organic material in Florida Bay (Tabb and Jones 1962). In portions of the Chesapeake Bay, dissolved oxygen was reduced following Tropical Storm Agnes in 1972 (Boesch et al. 1976), and fish kills were reported in Charleston Harbor and its tributaries following Hurricane Hugo in 1989 (Knott and Mortore 1991; Van Dolah and Anderson 1991). In North Carolina, hypoxia—intensified by animal and human waste spills—occurred in the Cape Fear and Northeast Cape Fear Rivers following extensive flooding caused by Hurricanes Bertha and Fran in 1996 (Mallin et al. 1999). In 2001, large scale fish kills occurred after flooding and subsequent deoxygenation in two major river systems of eastern Australia (Kennelly and McVea 2002), and in 2004, hypoxia caused by Hurricane Charley resulted in fish kills in the Peace River and Charlotte Harbor estuarine system in Florida (Stevens et al. 2006). Although hurricane-induced fish kills can alter fish assemblage structure, the effects are usually short-lived, and biological recovery can occur within a few months (Tabb and Jones 1962; Knott and Mortore 1991; Van Dolah and Anderson 1991; Bouchon et al. 1994; Stevens et al. 2006).

On 18 September 2003, Hurricane Isabel inundated northeastern North Carolina with heavy winds, rain, and storm surge that flushed organic material and anoxic water from the floodplains adjacent to the lower Roanoke River and its tributaries into the river proper. Dissolved oxygen concentrations rapidly decreased in the main river channel and remained at or near 0 mg/L for 10–12 days (Appendix A). As a result of the anoxic conditions, an extensive fish kill occurred, and approximately 93,000 dead fish were observed throughout 25 km of the lower Roanoke River between Williamston and the river mouth (NCDWQ 2003). Fish assemblage sampling had been conducted in the hurricane-affected portion of the lower Roanoke River during 2001, 2002, and one week prior to the hurricane in 2003. By comparing these samples to collections made three successive years following Hurricane Isabel, we attempted to examine the response of lower Roanoke River fish assemblages to the hurricane-induced fish kill. Specific project objectives were to: 1) document the immediate effects of Hurricane Isabel on fish assemblages of the lower Roanoke River and 2) assess fish assemblage response during the three-year period following the fish kill.

Methods

Study area.—The Roanoke River originates in the Appalachian Mountains of western Virginia and flows southeastward for approximately 660 km until it empties into the Albemarle Sound in northeastern North Carolina. The river drains approximately 25,000 km^2, most of which is located in the upper portion of the basin in Virginia (Figure 1). A chain of three reservoirs impound the Roanoke River on and above the fall line near North Carolina's border with Virginia. These reservoirs are operated for flood control and hydroelectricity, and the largest of the three, John H. Kerr reservoir, regulates much of the flow in the North Carolina portion of the river. The river section below the fall line in North Carolina is often referred to as the lower Roanoke River. We conducted fish assemblage sampling in the lower Roanoke River and specifically concentrated our efforts in the river stretch flowing from Williamston, North Carolina to the river mouth at the western end of the Albemarle Sound.

Site descriptions.—Fish assemblage collections were conducted at three fixed sampling sites on the lower Roanoke River in North Carolina. The sites were selected to represent typical habitats found in the downstream portion of the lower Roanoke River. The sites included inside bends, outside bends, and shallow flats with abundant aquatic vegetation and woody debris. Some sites were adjacent to floodplain swamps, and other sites were bordered by high bluff shorelines. The most upstream site was approximately 1.5 km downstream of US 17 near Williamston; the second site was 2 km downstream of Jamesville; and the third site was 1 km upstream of Plymouth (Figure 1). One sample was conducted at each site during August of 2001 and 2002 and at the Jamesville and Plymouth sites one week prior to Hurricane Isabel in early September 2003. We returned to the Jamesville and Plymouth sites one month after the hurricane in October 2003 to examine the fish assemblages following the fish kill, and we assessed fish assemblage response at all three lower Roanoke River sites by conducting one sample at each site during August of 2004, 2005, and 2006.

Fish sampling.— During daylight hours, a boat-mounted electrofishing unit (pulsed DC; Smith-Root 7.5 GPP) was used to collect fishes along 400 m of both shorelines within a site (800 m total) and along 200 m in the mid-channel of the site. All observed, stunned fish were netted and placed into an oxygenated live well. To collect darters and other species that do not exhibit positive buoyancy in response to electrofishing, the netter periodically swept the dip net through vegetation and along the substrate in shallow areas. An additional ten-minute catfish sample, consisting of low-voltage, low-pulse electrofishing, was conducted after the shoreline and mid-channel samples were completed. After each sampling run (i.e., shoreline, mid-channel, or catfish), fish were identified to species and measured to the nearest millimeter total length. Most fish were released into the sample site, but some specimens were frozen or preserved in 10% formalin and taken to the laboratory for identification and measurement.

Data analysis.—The number of species present in each sample was examined as an index to determine trends in the entire fish assemblage. Fish assemblage data were also organized into species groups to simplify analysis. Most groups were organized at the taxonomic family level; however, largemouth bass *Micropterus salmoides*, common carp *Cyprinus carpio*, darter species *Etheostoma* spp., and yellow perch *Perca flavescens* were placed into unique groups distinct from other members of their respective families (Table 1). Additionally, six less abundant species were placed into a group labeled 'other'. Rare species, those found in less than 5% of the samples, were omitted from analysis. The relative contribution of the species groups in the 2003 pre-Isabel and post-Isabel samples was compared to describe the change in fish assemblage structure one month after Hurricane Isabel.

Resemblance measures can be used to quantify the similarity between two or more fish assemblages by comparing characteristics such as species presence or abundance (Gauch 1982; Romesburg 1990). The percent similarity index (PSI; Renkonen 1938) is a resemblance measure that is widely used in ecology to quantify similarity between fish assemblages based on relative abundance data (Kwak and Peterson *in press*). PSI values range from 0% (completely different) to 100% (identical assemblage structure). Previous authors have considered values of PSI and other similar resemblance measures greater than 70% to indicate very similar or stable fish assemblages (Horn 1979; Pennington et al. 1983; Matthews 1985; Matthews et al. 1988; Peterson and Bayley 1993). The PSI was used to compare the similarity of lower Roanoke River fish assemblage samples among sampling periods. To calculate the PSI, the species group abundances for all sample sites were first combined into one pooled fish assemblage for each sampling period (2001, 2002, 2003 pre-Isabel, 2003 post-Isabel, 2004, 2005, and 2006). Second, the species group abundances were standardized to percentages by dividing the abundance of each species group by the total number of fish in the sample and multiplying by 100. Third, the similarity, P, between sampling periods j and k was calculated as:

$$P_{jk} = \sum \text{minimum}\,(p_{ji},\, p_{ki}),$$

where p_{ji} and p_{ki} are the relative abundances of species group i in sampling period j and k, respectively, and minimum indicates that the smaller of the two relative abundances is used in the summation. The PSI among all possible combinations of sampling periods was calculated and a PSI resemblance matrix was produced.

Fish assemblages were sequentially clustered using hierarchical cluster analysis based on resemblance measures (Romesburg 1990; Kwak and Peterson 2007), grouping the most similar pairs of assemblages until all assemblages were contained in one cluster. The results were graphically displayed in a dendrogram that facilitates interpretation of fish assemblage relationships. Average-linkage hierarchical cluster analysis was used to reveal relationships among lower Roanoke River fish assemblages based on PSI values, and these relationships were evaluated to assess similarities of fish assemblages collected before and after the hurricane-induced fish kill.

Hurricane effects on fish species and species groups of interest were documented by examining trends in relative abundances indexed as catch-per-unit-effort (CPUE) and expressed as number of fish per sample site. Length frequency histograms were constructed to examine the population size structure of selected species during each sampling period. Fish collected from all sample sites during each sample period were combined for length frequency analysis.

Results

A total of 7,325 individual fish representing 49 species and 17 families were collected from the 19 samples taken during this project (Table 2). Six rare species were present in only one sample and were omitted from analysis. Resident fish species common to southeastern warmwater streams were most prevalent, but diadromous and estuarine species also were present in several samples. Cyprinidae and Centrarchidae were the dominant families by number, and Percidae, Ictaluridae, and Amiidae were also relatively abundant.

Immediate hurricane effects

At the Jamesville site, 631 individuals representing 33 species were collected during the 2003 pre-Isabel sample. Sunfish *Lepomis* spp. dominated the fish assemblage composition one week prior to the hurricane with 241 individuals collected (Figure 2). Chain pickerel *Esox niger*, largemouth bass, bowfin *Amia calva*, and catfish *Ameiurus*, *Ictalurus* and *Noturus* spp. also were relatively abundant, whereas yellow perch, darters, longnose gar *Lepisosteus osseus*, American eel *Anguilla rostrata*, and clupeids *Alosa* and *Dorosoma* spp. were present in low abundances. In the 2003 post-Isabel sample (one month after the storm), only 130 individuals were collected representing 23 species at the Jamesville site. Four species collected after Hurricane Isabel were not present in the pre-Isabel sample. Thus, 18 of the 33 (55%) species that were present before the hurricane in the Jamesville site were not collected. Following the hurricane, clupeids and minnows (see Table 1) dominated the fish assemblage composition at the Jamesville site (Figure 2). Although numbers of catfish and bowfin were lower after the hurricane than before, these species groups remained relatively abundant in the Jamesville site after the fish kill. Sunfish abundance was dramatically lower than the pre-Isabel sample, while largemouth bass, which were previously abundant, and darters were not collected in the post-Isabel sample.

At the Plymouth site, 409 individuals representing 23 species were captured during the 2003 pre-Isabel sample. Sunfish dominated the fish assemblage composition prior to the hurricane with 234 individuals collected (Figure 3). Minnows, yellow perch, and largemouth bass also were relatively abundant, and chain pickerel, bowfin, catfish, and darters were present in low abundances. In the 2003 post-Isabel sample, we collected 702 individuals representing 15 species at the Plymouth site. Four species collected after Hurricane Isabel were not present in the pre-Isabel samples. Thus, we failed to collect 12 of the 23 (52%) species that were present before the hurricane in the Plymouth site. Although more individuals were collected after the hurricane than before, minnows composed the majority (95%) of the post-Isabel sample, and the remaining species were represented by only a few individuals (Figure 3). Bowfin abundance was reduced following the hurricane, but they remained one of the more abundant species. Sunfish abundance was much lower following the hurricane than before, and only one largemouth bass in the post-Isabel sample was collected at the Plymouth site. Further, no yellow perch or darters were collected following Hurricane Isabel.

Recovery period

The number of species collected in the Williamston site was similar among annual samples during the recovery period in 2004, 2005, and 2006 but did not return to the pre-Isabel levels collected in 2001 and 2002 (Table 3). At the Jamesville site, the number of species collected during each year of the recovery period also was similar and was only slightly higher than the 2003 post-Isabel sample. Additionally, the number of species collected at the Jamesville site during the recovery period was higher than the number collected in 2001 and 2002, but it did not return to the level collected in the 2003 pre-Isabel sample. In contrast with the other two sites, the number of species collected during 2004, 2005, and 2006 at the Plymouth site was much higher than the 2003 post-Isabel sample. Additionally, more species were collected in 2004 and 2005 at the Plymouth site than were collected during any of the pre-Isabel samples. In 2006, however, fewer species were collected than the two previous years, but the number of species remained similar to pre-Isabel samples.

The hierarchical cluster analysis based on the PSI resemblance matrix for combined sample sites (Table 4) revealed similarities in fish assemblages among sampling periods. Fish assemblages collected during 2005 and 2006 were very similar, indicating apparent stabilization of the fish assemblages in the later portion of the recovery period (Figure 4). Additionally, three clusters were formed when the dendrogram was cut at a 70% PSI level. The fish assemblage collected during the 2003 post-Isabel sample period was least similar to all other samples and formed a single, unique cluster. Fish assemblages from 2001, 2002, and 2004 sample periods were similar and clustered together. Fish assemblages collected during the 2003 pre-Isabel, 2005, and 2006 sample periods also were similar and clustered together.

Response of individual species and groups

Largemouth bass. — Relative abundance of largemouth bass appeared to be highest at the Plymouth site except during the 2003 pre-Isabel sampling period when 57 largemouth bass were collected from the Jamesville site (Figure 5). There were no distinct trends in CPUE at any of the sample sites before the hurricane. However, largemouth bass relative abundance substantially decreased one month after the fish kill and increased at all sites during each year of the recovery period (Figure 5). At the Williamston site, largemouth bass CPUE in the 2005 and 2006 samples was similar to CPUE in the 2001 sample but did not return to the CPUE documented in 2002. Although largemouth bass CPUE at the Jamesville site did not return to the relatively high level documented in the 2003 pre-Isabel sample, it was higher than the 2002 level within one year after the fish kill. At the Plymouth site, largemouth bass CPUE was higher in 2005 than the 2003 pre-Isabel sample and was much higher in 2006 than in all previous samples.

In addition to reductions in relative abundance, the size structure of the lower Roanoke River largemouth bass population differed between the two sampling periods. In the years prior to the hurricane, largemouth bass population size structure appeared to be expanding, as the population shifted from predominantly small fish with a few adults to a more even distribution with larger size classes (Figure 6). In the 2003 post-Isabel sample, the only largemouth bass collected was 278 mm in length. Most largemouth bass collected one year after the fish kill in 2004 were small (< 200mm), but adult fish were present in the population (Figure 7). In 2005, small largemouth bass remained prevalent, but fish in larger size classes were collected. As relative abundance increased in 2006, small fish remained the majority of the largemouth bass population with a few larger fish present.

Bluegill.—Relative abundance of bluegill *Lepomis macrochirus* followed similar trends as largemouth bass relative abundance. Prior to the hurricane, bluegill CPUE appeared to increase and was relatively high at the Jamesville and Plymouth sites in the 2003 pre-Isabel sample (Figure 8). Additionally, the bluegill population size structure appeared to be expanding during the pre-Isabel years, as larger, adult bluegill were more abundant in the 2003 pre-Isabel sample than in previous years (Figure 9). One month after the fish kill, however, bluegill CPUE was significantly reduced (Figure 8), and most of the remaining bluegill were small adults (Figure 10). Bluegill CPUE remained low one year after the fish kill at the Williamston and Jamesville sites, but at the Plymouth site, bluegill CPUE was similar to the 2003 pre-Isabel sample (Figure 8). The bluegill collected during 2004, however, were mostly young-of-year (YOY) fish <50mm (Figure 11). Bluegill relative abundance increased in 2005 and remained similar in 2006 at the Williamston and Jamesville sites, whereas bluegill CPUE decreased at the Plymouth site in 2005 but, in 2006, increased to the highest level of the study (Figure 8). Bluegill CPUE at the Williamston and Jamesville sites was similar to 2001 and 2002 conditions in 2005 and 2006, but the relative abundance at the Jamesville site did not return to the relatively high level of the 2003 pre-Isabel sample. In 2005 and 2006, the bluegill population size structure appeared to expand after the fish kill, as YOY bluegill were less abundant and larger fish were more abundant than in 2004 (Figure 11).

Yellow perch.—Yellow perch were relatively abundant in the Jamesville and Plymouth sites before Hurricane Isabel (Figure 12), and the length frequency histograms indicated relatively even distribution of multiple size classes, including large fish, in the 2003 pre-Isabel sample (Figure 13). Abundance was drastically reduced following the fish kill with only 1 fish collected at the Jamesville site and 0 fish at the Plymouth site (Figure 12). Yellow perch recovery appeared to occur within one year at both sites, as 2004 CPUE was almost 100% greater than the 2003 pre-Isabel level. Large yellow perch were absent from the 2004 sample, however, and approximately 50% of yellow perch collected were YOY fish <100mm (Figure 13). Yellow perch CPUE declined at the Jamesville and Plymouth sites in 2005 and 2006, but larger yellow perch were collected during these years as the size structure expanded (Figure 14).

Darters.—Darters also were relatively abundant before Hurricane Isabel; however, CPUE declined between the 2002 and 2003 pre-Isabel sampling periods (Figure 15). Darter CPUE was further reduced following the fish kill; no darters were collected from the Jamesville or Plymouth sites in the 2003 post-Isabel sample, and darters were absent from all sample sites in 2004. Darters were present in the 2005 samples, and relative abundance increased at the Jamesville and Plymouth sites in 2006. By 2006, darter relative abundance was similar to 2003 pre-Isabel conditions at the Jamesville site and was higher than 2003 pre-Isabel conditions at the Plymouth site. In the years after the fish kill, however, darter CPUE did not return to the relatively high levels found in 2002.

Catfish.—White catfish *Ameiurus catus* were the most abundant species of the Ictaluridae family in all samples (Table 2). However, all catfish species that were collected, with the exception of margined madtom *Noturus insignis*, were included in the analysis. At the Williamston site, relative abundance of all catfish was higher in 2004 than in the pre-Isabel samples, and CPUE remained high throughout the recovery period (Figure 16). At the Jamesville site, there was no difference in CPUE between the 2003 pre-Isabel and 2003 post-Isabel samples, and catfish CPUE was similar in all samples throughout the study. There was a slight decrease in catfish relative abundance between the 2003 pre-Isabel and 2003 post-Isabel samples at the Plymouth site. CPUE quickly rebounded in 2004, however, and remained similar to levels collected before the hurricane throughout the recovery period.

Bowfin.—Bowfin are prevalent throughout the lower Roanoke River and were collected in every sample during this study. Bowfin CPUE was lowest at the Williamston site but remained relatively constant in all sample periods (Figure 17). The highest bowfin relative abundance occurred at the Jamesville site in the 2003 pre-Isabel sample. CPUE at the Jamesville site substantially decreased after the fish kill in the 2003 post-Isabel sample, but bowfin relative abundance remained higher than was documented in the 2001 and 2002 samples. Bowfin CPUE increased in 2004 at the Jamesville site and remained similar throughout the recovery period. There were no apparent trends in bowfin CPUE at the Plymouth site before Hurricane Isabel, and there was only a slight decrease in bowfin relative abundance between the 2003 pre-Isabel and 2003 post-Isabel sample periods. Relative abundance appeared to increase at the Plymouth site during the recovery period.

Discussion

The deoxygenation that occurred in the lower Roanoke River after Hurricane Isabel was caused by natural flushing of anoxic water and organic debris from the expansive flood plain, and the subsequent, hurricane-induced fish kill caused dramatic changes in lower Roanoke River fish assemblage structure. One month after Hurricane Isabel, we found fewer species and lower abundances of remaining species than were present in the pre-Isabel sample. The resulting fish assemblages were unique among other sample periods and mostly consisted of minnows, clupeids, bowfin, and catfish. Although the 2003 post-Isabel sample was conducted in October and all other samples were conducted in August or September, we attribute the reductions in species and abundance to the fish kill and not to temporal differences in sample collections.

Because the hurricane-induced fish kill was the result of anoxia, we expected to collect tolerant species in the post-Isabel sample. Our results indicate that catfish and bowfin were relatively abundant in the post-Isabel fish assemblage samples. White catfish, which were the predominant catfish species in our samples, are considered tolerant of pollution and disturbance (NCDWQ 2006) and have been documented in fish assemblages following a hurricane-induced fish kill in the Peace River, Florida (Stevens et al. 2006). Similarly, bowfin are known for surviving in anoxic environments because they can utilize atmospheric oxygen by gulping air into a specialized swim bladder, which acts as a modified lung (Jenkins and Burkhead 1993). Tolerance of low dissolved oxygen and specialized adaptations allowed white catfish and bowfin to survive during the fish kill event, and as a result, Hurricane Isabel appeared to have little influence on catfish and bowfin populations for the duration of this study.

Eastern silvery minnow *Hybognathus regius* was the most prevalent species in the post-Isabel fish assemblage near Plymouth, and clupeids, which mostly consisted of juvenile alosine species (blueback herring *Alosa aestivalis*, alewife *Alosa pseudoharengus*, and American shad *Alosa sapidissima*), composed the majority of the post-Isabel fish assemblage near Jamesville. Although abundances were low, we also collected sunfish, largemouth bass, yellow perch, and suckers *Erimyzon oblongus* and *Moxostoma* spp. in the 2003 post-Isabel samples. Previous research indicates that recolonization following stream defaunation is rapid and can begin as soon as habitat conditions improve (Peterson and Bayley 1993, Sheldon and Meffe 1994). Thus, we hypothesize that, rather than remaining in the sample sites and surviving the hurricane-induced fish kill, individuals of these relatively intolerant species had begun recolonization of the lower Roanoke River within one month after dissolved oxygen concentrations returned to suitable levels.

Successful recolonization following a disturbance depends upon representative source populations having unrestricted access to the affected area, provided that the habitat returns to similar conditions (Bayley and Osborne 1993; Peterson and Bayley 1993; Sheldon and Meffe 1994). We did not sample unaffected areas in the 2003 post-Isabel sample period and were not able to identify potential source populations. However, dissolved oxygen concentrations upstream of our study area, measured at fixed monitoring stations (USGS 2003), remained adequate for fish survival throughout the fish kill period. Thus, fish from portions of the lower Roanoke River upstream of Williamston could have recolonized the hurricane-affected stretch. This is likely the case for the juvenile alosine species that were collected in the 2003 post-Isabel samples. These species are typically spawned in upper reaches of the river, and juveniles move downstream while outmigrating to Albemarle Sound and eventually to the Atlantic Ocean. Additional water quality monitoring efforts during the fish kill period indicate dissolved oxygen concentrations also remained adequate for fish survival in oligohaline portions of central Albemarle Sound (NCDWQ 2007). Thus, the Albemarle Sound may have served as refugia during the fish kill, and some fish may have evaded the fish kill by actively migrating downstream into the Albemarle Sound in response to declining dissolved oxygen concentrations. Fish from the Albemarle Sound and upstream portions of the Roanoke River may have been a source population for recolonization of the hurricane-affected portions of the lower Roanoke River. We recommend that future studies attempt to identify areas of refugia and fish movement in response to deoxygenation events.

After initial recolonization, lower Roanoke River fish assemblages appeared to steadily recover in the years following the fish kill. The number of species and abundances of most species increased within one year after the fish kill, and as a result, the fish assemblages collected in 2004 were dissimilar to fish assemblages collected in the 2003 post-Isabel sampling period. Numbers of species and relative abundances of most species continued to increase in the second year after the fish kill, and the hierarchical cluster analysis indicated that fish assemblages present in 2005 were similar to those from the 2003 pre-Isabel sample, suggesting fish assemblage recovery within two years after the hurricane-induced fish kill. However, the resemblance measure (PSI) did not account for population size structure, and although abundances of most species were similar to pre-Isabel levels in 2005, most populations contained higher proportions of smaller individuals than they did before the hurricane. Thus, we cannot infer a full recovery by 2005. In 2006, fish assemblages remained similar to 2005 and 2003 pre-Isabel samples, while abundances of most species continued to increase. Size structures of bluegill and yellow perch appeared similar to pre-Isabel conditions, but largemouth bass populations were still lacking larger fish that were present in the 2003 pre-Isabel samples. Additionally, the number of species did not return to pre-Isabel levels in the Williamston and Jamesville sites. Thus, we were unable to declare full recovery in the sample sites by the end of this study. Nonetheless, lower Roanoke River fish assemblages were substantially improved within three years of the hurricane-induced fish kill.

The extended recovery period indicated by our results is inconsistent with previous studies, which document rapid recovery with fish assemblages returning to pre-fish kill conditions within one to three months (Tabb and Jones 1962; Knott and Mortore 1991; Van Dolah and Anderson 1991; Stevens et al 2006). In these studies, fishes from adjacent source populations quickly migrated into the affected area. The effects of Hurricane Isabel, however, were widespread, and similar fish kills were reported in nearly all Albemarle Sound tributaries (NCDWQ 2003), further reducing fish from potential source areas. Our results indicate a low abundance of intolerant fish one month after the hurricane, and the majority of fish collected in 2004 were small fish that presumably were spawned after the fish kill. Thus, we hypothesize that, after an initial recolonization by a few adults that may have evaded the fish kill, recovery in the lower Roanoke River following Hurricane Isabel is dependent upon *in situ* production. *In situ* production has been documented as a mechanism for fish assemblage recovery following severe drought in Midwestern streams (Larimore 1955; Bayley and Osborne 1993). Although natural production appears sufficient for fish assemblage recovery, multiple years are required for population size structure and abundance to rebuild.

Hurricane frequency in the North Atlantic basin (the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico) has increased over the last decade, and researchers anticipate a persistent period of high activity for the near future (Goldenberg et al. 2001; Webster et al. 2005). Therefore, hurricane-induced fish kills may occur more frequently during the predicted cycle of increased hurricane activity. Lower Roanoke River fish assemblages can recover from a hurricane-induced fish kill, but fisheries managers and anglers should expect variable trends in fish assemblage structure for several years while conditions improve.

Management Recommendations

1. Continue annual monitoring of lower Roanoke River fish assemblages.
2. Identify fish movement patterns in response to future large scale disturbances.
3. Identify areas of refugia during future fish kills by sampling in non-affected areas.

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TABLE 1.— Species groups used for analysis of lower Roanoke River fish assemblage data collected during the summers of 2001 through 2006.

Species Group	Species	Common Name	Family
Bowfin	*Amia calva*	Bowfin	Amiidae
Catfish	*Ameiurus catus*	White catfish	Ictaluridae
	Ameiurus natalis	Yellow bullhead	Ictaluridae
	Ameiurus nebulosus	Brown bullhead	Ictaluridae
	Ictalurus furcatus	Blue catfish	Ictaluridae
	Ictalurus punctatus	Channel catfish	Ictaluridae
	Noturus gyrinus	Tadpole madtom	Ictaluridae
Clupeids	*Alosa aestivalis*	Blueback herring	Clupeidae
	Alosa pseudoharengus	Alewife	Clupeidae
	Alosa sapidissima	American shad	Clupeidae
	Dorosoma cepedianum	Gizzard shad	Clupeidae
Common carp	*Cyprinus carpio*	Common carp	Cyprinidae
Darters	*Etheostoma fusiforme*	Swamp darter	Percidae
	Etheostoma olmstedi	Tessellated darter	Percidae
	Etheostoma serrifer	Sawcheek darter	Percidae
American eel	*Anguilla rostrata*	American eel	Anguillidae
Largemouth bass	*Micropterus salmoides*	Largemouth bass	Centrarchidae
Longnose gar	*Lepisosteus osseus*	Longnose gar	Lepisosteidae
Minnows	*Cyprinella analostana*	Satinfin shiner	Cyprinidae
	Notemigonus crysoleucas	Golden shiner	Cyprinidae
	Notropis hudsonius	Spottail shiner	Cyprinidae
	Umbra pygmaea	Eastern silvery minnow	Cyprinidae
Other	*Aphredoderus sayanus*	Pirate perch	Aphredoderidae
	Enneacanthus obesus	Bay anchovy	Engraulidae
	Fundulus diaphanus	Banded killifish	Fundulidae
	Gambusia holbrooki	Eastern mosquitofish	Poeciliidae
	Paralichthys sp.	Flounder	Paralichthyidae
	Scartomyzon rupiscartes	Striped mullet	Mugilidae
Chain pickerel	*Esox niger*	Chain pickerel	Esocidae
Striped basses	*Morone americana*	White perch	Moronidae
	Morone saxatilis	Striped bass	Moronidae
Suckers	*Erimyzon oblongus*	Creek chubsucker	Catostomidae
	Moxostoma macrolepidotum	Shorthead redhorse	Catostomidae
	Moxostoma pappillosum	V-lip redhorse	Catostomidae
Sunfish	*Centrarchus macropterus*	Flier	Centrarchidae
	Enneacanthus gloriosus	Bluespotted sunfish	Centrarchidae
	Lepomis auritus	Redbreast sunfish	Centrarchidae
	Lepomis gibbosus	Pumpkinseed	Centrarchidae
	Lepomis gulosus	Warmouth	Centrarchidae
	Lepomis macrochirus	Bluegill	Centrarchidae
	Lepomis microlophus	Redear sunfish	Centrarchidae
	Pomoxis nigromaculatus	Black crappie	Centrarchidae
Yellow perch	*Perca flavescens*	Yellow perch	Percidae

TABLE 2.— Total number of fish collected and number of samples containing individual species from the lower Roanoke River during the summers of 2001 through 2006. Nineteen samples were collected during the study.

Species	Common Name	Family	Totals	Samples
*Trinectes maculatus**	Hogchoker	Achiridae	1	1
Amia calva	Bowfin	Amiidae	247	19
Anguilla rostrata	American eel	Anguillidae	59	16
Aphredoderus sayanus	Pirate perch	Aphredoderidae	57	5
*Carpiodes cyprinus**	Quillback	Catostomidae	1	1
Erimyzon oblongus	Creek chubsucker	Catostomidae	35	9
Moxostoma macrolepidotum	Shorthead redhorse	Catostomidae	10	6
Moxostoma pappillosum	V-lip redhorse	Catostomidae	15	2
Centrarchus macropterus	Flier	Centrarchidae	5	2
Enneacanthus gloriosus	Bluespotted sunfish	Centrarchidae	20	6
Lepomis auritus	Redbreast sunfish	Centrarchidae	314	18
Lepomis gibbosus	Pumpkinseed	Centrarchidae	391	13
Lepomis gulosus	Warmouth	Centrarchidae	9	5
Lepomis macrochirus	Bluegill	Centrarchidae	733	19
Lepomis microlophus	Redear sunfish	Centrarchidae	571	18
Micropterus salmoides	Largemouth bass	Centrarchidae	334	18
Pomoxis nigromaculatus	Black crappie	Centrarchidae	43	9
Alosa aestivalis	Blueback herring	Clupeidae	148	13
Alosa pseudoharengus	Alewife	Clupeidae	74	3
Alosa sapidissima	American shad	Clupeidae	52	13
Dorosoma cepedianum	Gizzard shad	Clupeidae	37	13
*Dorosoma petenense**	Threadfin shad	Clupeidae	5	1
*Brevoortia tyrannus**	Atlantic menhaden	Clupeidae	1	1
Cyprinella analostana	Satinfin shiner	Cyprinidae	95	9
Cyprinus carpio	Common carp	Cyprinidae	65	13
Hybognathus regius	Eastern silvery minnow	Cyprinidae	2267	18
Notemigonus crysoleucas	Golden shiner	Cyprinidae	137	6
Notropis hudsonius	Spottail shiner	Cyprinidae	549	18
Anchoa mitchilli	Bay anchovy	Engraulidae	11	3
*Esox americanus**	Redfin pickerel	Esocidae	2	1
Esox niger	Chain pickerel	Esocidae	110	12
Fundulus diaphanus	Banded killifish	Fundulidae	25	6
Ameiurus catus	White catfish	Ictaluridae	223	19
Ameiurus natalis	Yellow bullhead	Ictaluridae	6	3
Ameiurus nebulosus	Brown bullhead	Ictaluridae	2	2
Ictalurus furcatus	Blue catfish	Ictaluridae	3	2
Ictalurus punctatus	Channel catfish	Ictaluridae	16	8
Noturus gyrinus	Tadpole madtom	Ictaluridae	16	3
*Noturus insignis**	Margined madtom	Ictaluridae	1	1
Lepisosteus osseus	Longnose gar	Lepisosteidae	39	16
Morone americana	White perch	Moronidae	63	6
Morone saxatilis	Striped bass	Moronidae	2	2
Mugil cephalus	Striped mullet	Mugilidae	13	5
Paralichthys sp.	Flounder	Paralichthyidae	19	7
Etheostoma olmstedi	Tessellated darter	Percidae	119	8
Etheostoma serrifer	Sawcheek darter	Percidae	5	2
Etheostoma fusiforme	Swamp darter	Percidae	44	5
Perca flavescens	Yellow perch	Percidae	322	17
Gambusia holbrooki	Eastern mosquitofish	Poeciliidae	9	3

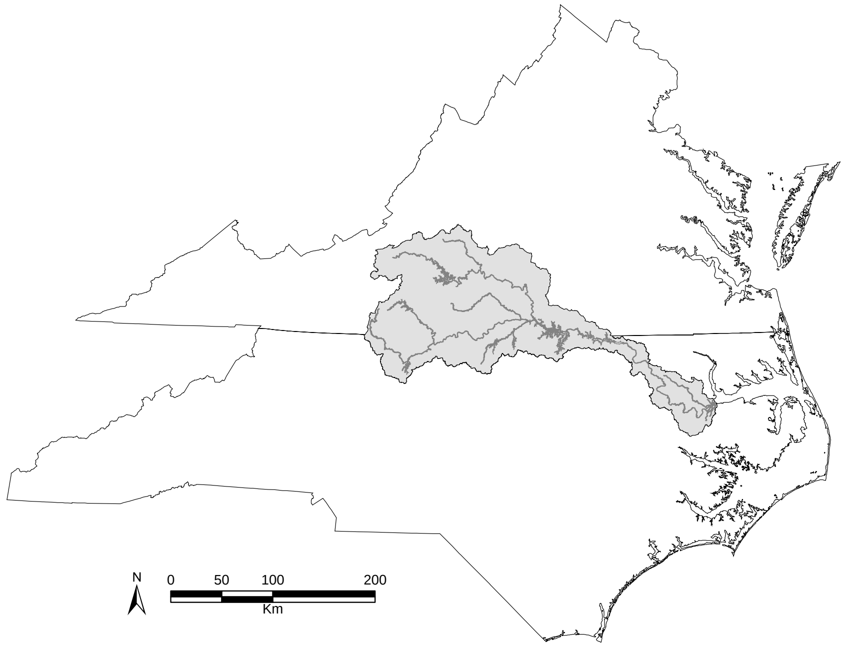
*Species was found in only one sample (<5% of total) and was omitted from analysis.

TABLE 3.—Number of fish species collected from three sample sites on the lower Roanoke River during the summers of 2001 through 2006. The Williamston site was not sampled in 2003.

Sample Site	2001	2002	Pre-Isabel 2003	Post-Isabel 2003	2004	2005	2006
Williamston	19	23			17	18	18
Jamesville	18	18	31	19	20	22	20
Plymouth	20	22	23	15	26	29	22

TABLE 4.—Percent similarity resemblance matrix for lower Roanoke River fish assemblages collected during the summers of 2001 through 2006.

Sample Period	2001	2002	Pre-Isabel 2003	Post-Isabel 2003	2004	2005	2006
2001	100	75	62	50	73	60	64
2002	75	100	47	69	83	44	48
Pre-Isabel 2003	62	47	100	22	48	82	81
Post-Isabel 2003	50	69	22	100	68	19	19
2004	73	83	48	68	100	47	46
2005	60	44	82	19	47	100	89
2006	64	48	81	19	46	89	100



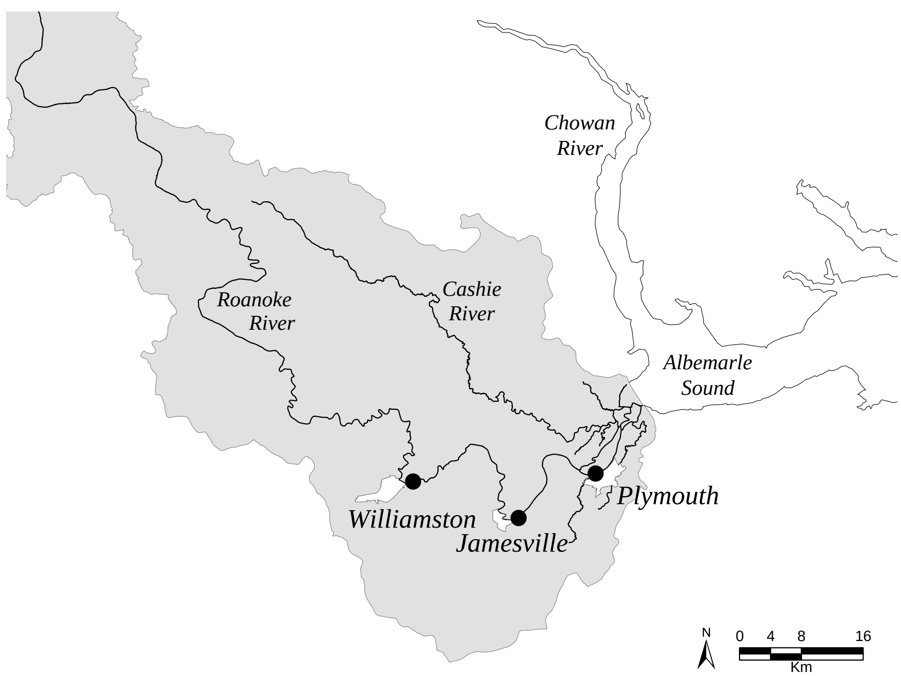


FIGURE 1.—Roanoke River Basin in Virginia and North Carolina. Lower Roanoke River fish assemblage sampling sites are indicated by darkened circles.

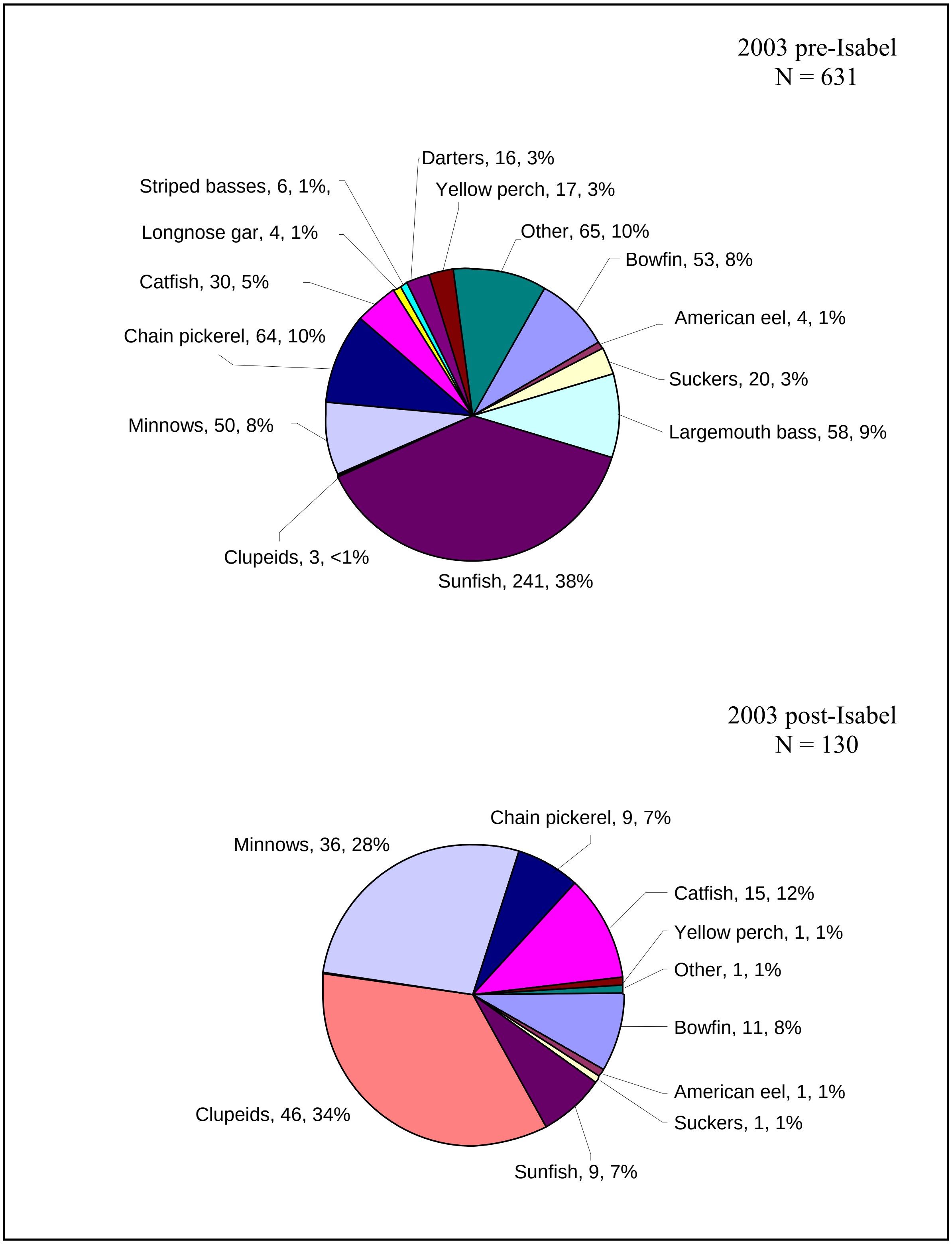


FIGURE 2.—Fish assemblage composition for the Jamesville sampling site on the lower Roanoke River during the 2003 pre-Isabel and 2003 post-Isabel sampling periods. Category labels indicate species group, number collected, and percentage of total individuals sampled.

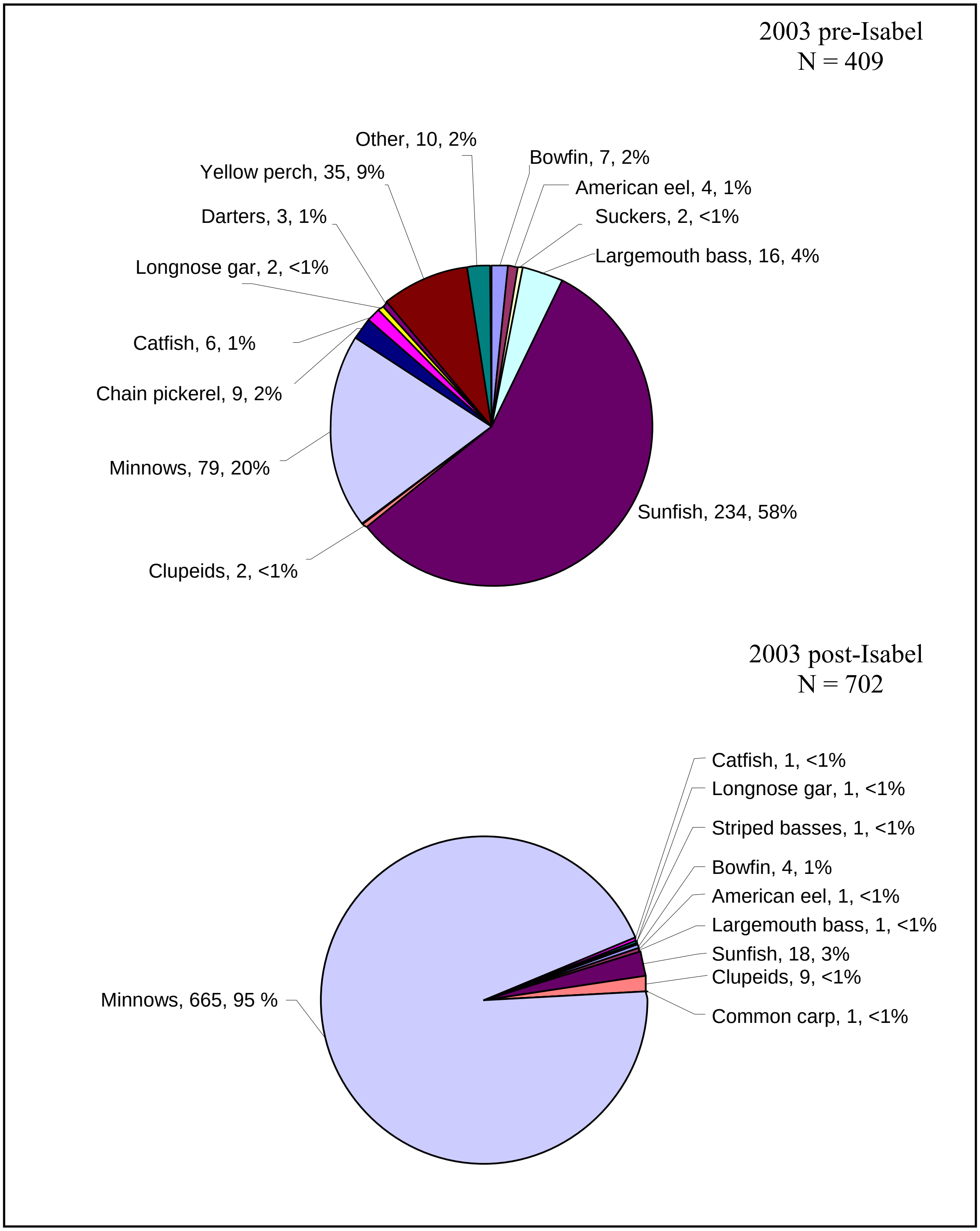


FIGURE 3.—Fish assemblage composition for the Plymouth sampling site on the lower Roanoke River during the 2003 pre-Isabel and 2003 post-Isabel sampling periods. Category labels indicate species group, number collected, and percentage of total individuals sampled.

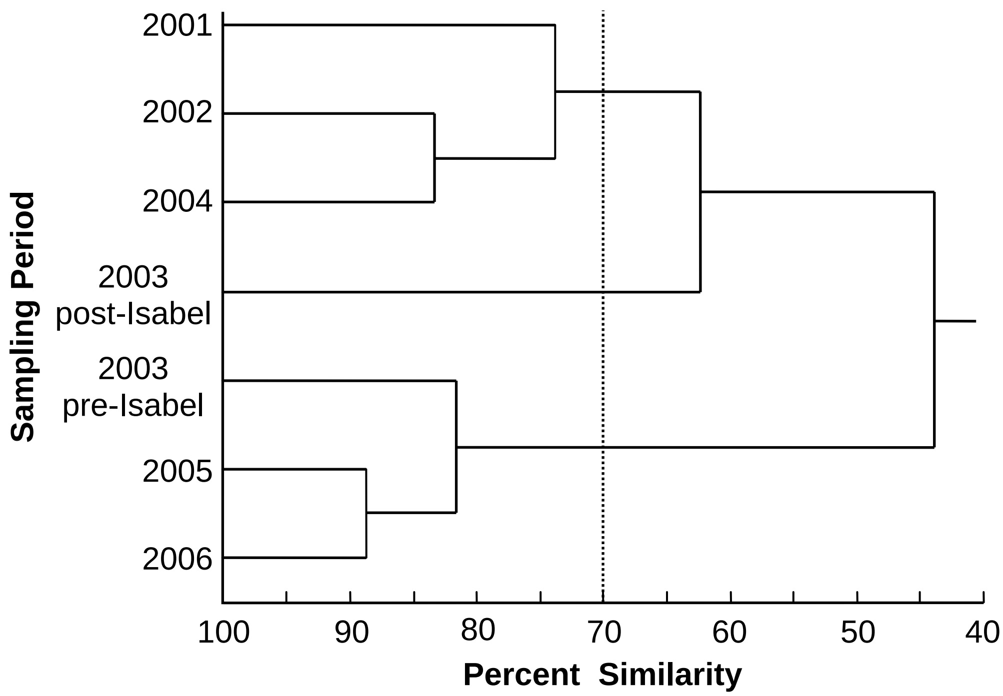


FIGURE 4.—Dendrogram of lower Roanoke River fish assemblages collected during seven sampling periods from 2001 through 2006. The dendrogram is a result of average-linkage hierarchical cluster analysis based on the Percent Similarity Index resemblance matrix. The dashed line, which forms three clusters, represents a cut point for classifying the fish assemblages at 70% similarity.

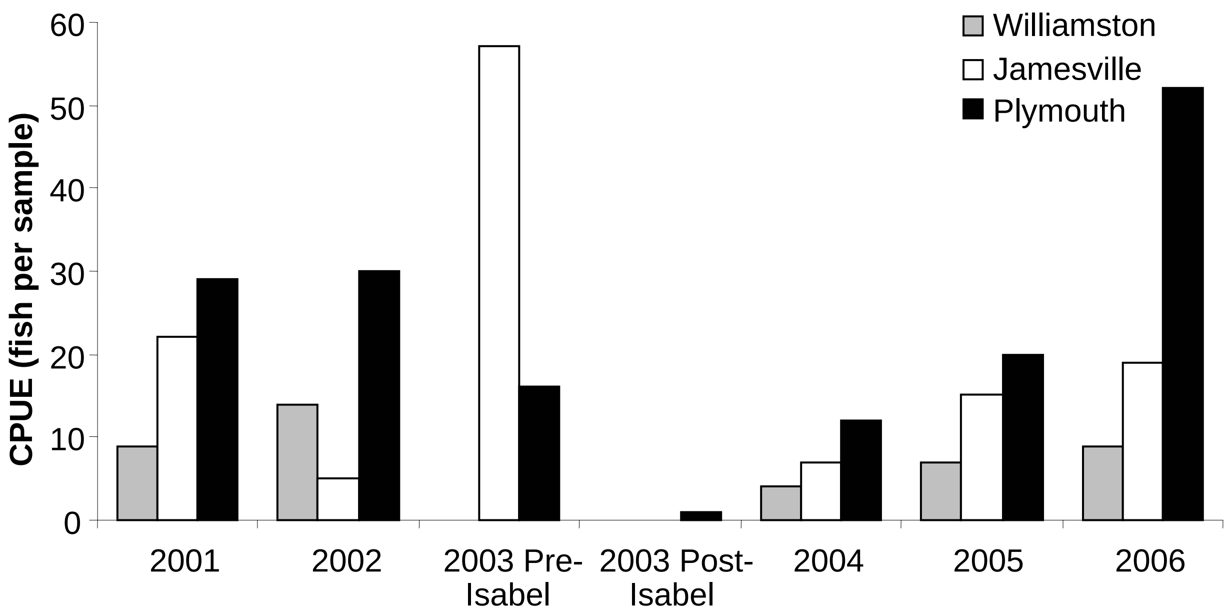


FIGURE 5.—Relative abundance of largemouth bass from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. The Williamston site was not sampled in 2003. However, largemouth bass were not collected during the 2003 post-Isabel sample at the Jamesville site.

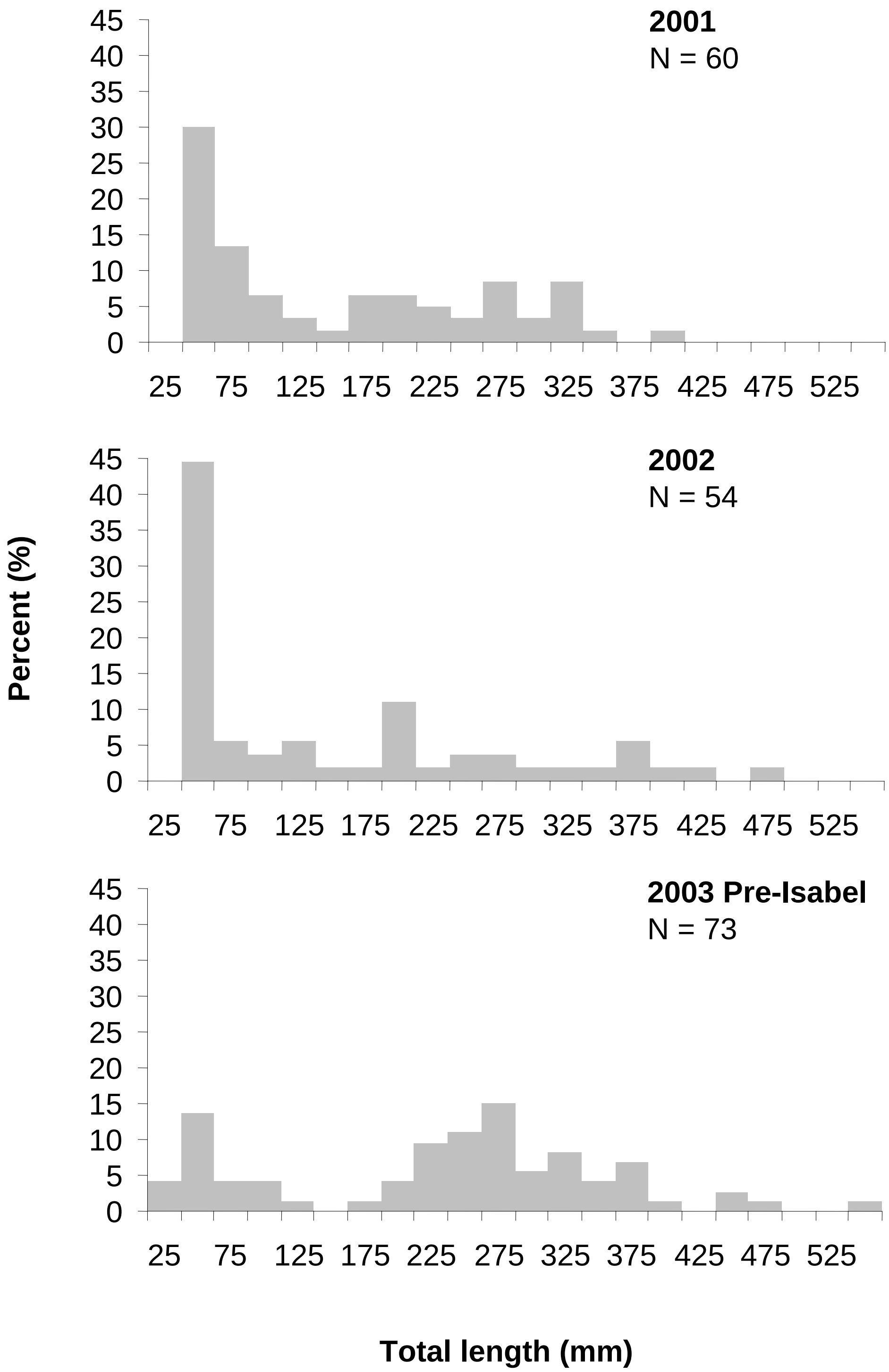


FIGURE 6.—Length frequency distributions of largemouth bass collected from the lower Roanoke River before Hurricane Isabel in 2001, 2002, and 2003.

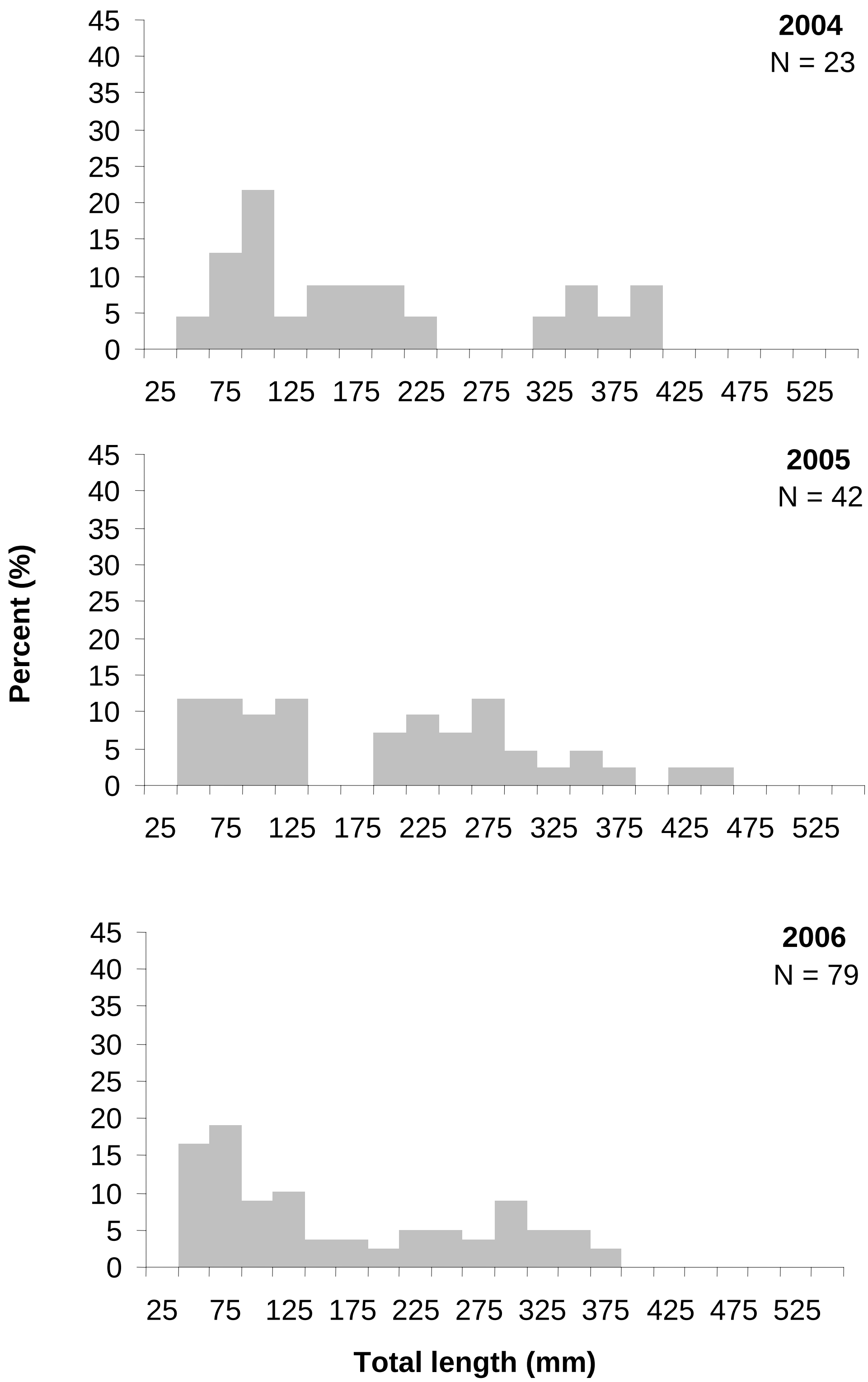


FIGURE 7.—Length frequency distributions of largemouth bass collected from the lower Roanoke River during the recovery period after Hurricane Isabel in 2004, 2005, and 2006.

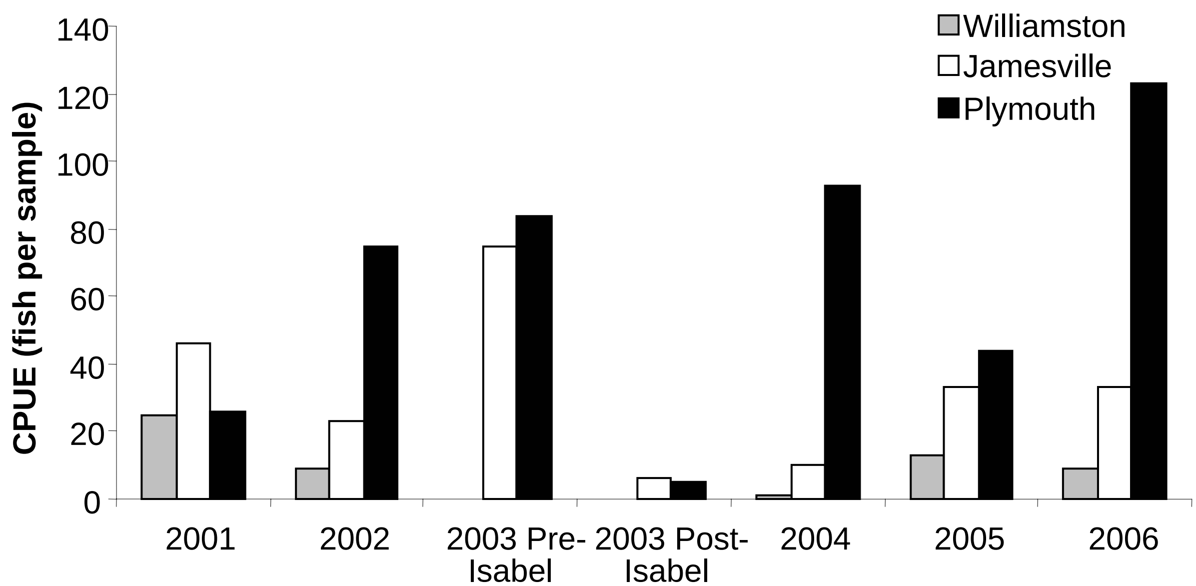


FIGURE 8.—Relative abundance of bluegill from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. The Williamston site was not sampled in 2003.

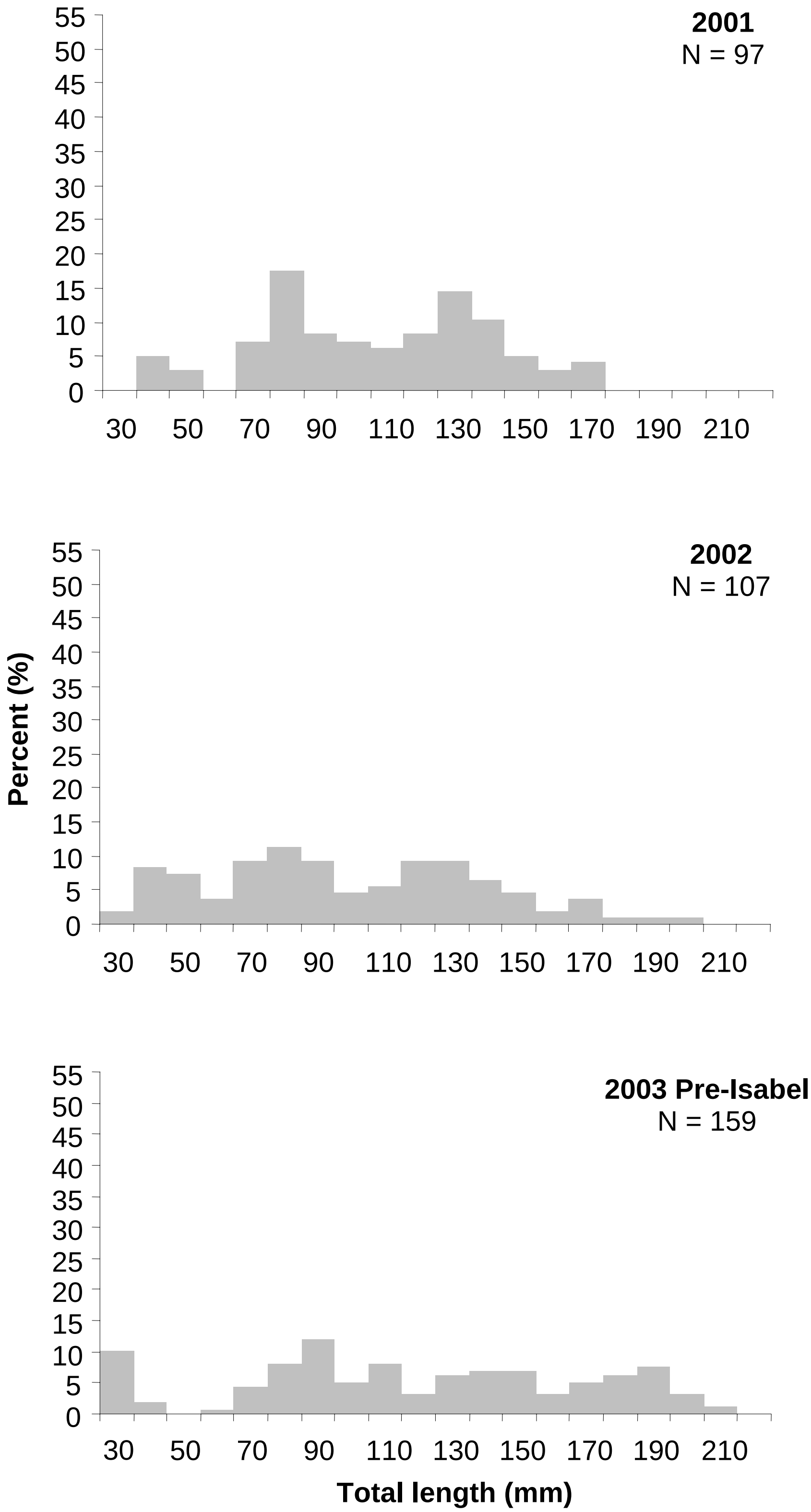


FIGURE 9.—Length frequency distributions of bluegill collected from the lower Roanoke River before Hurricane Isabel in 2001, 2002, and 2003.

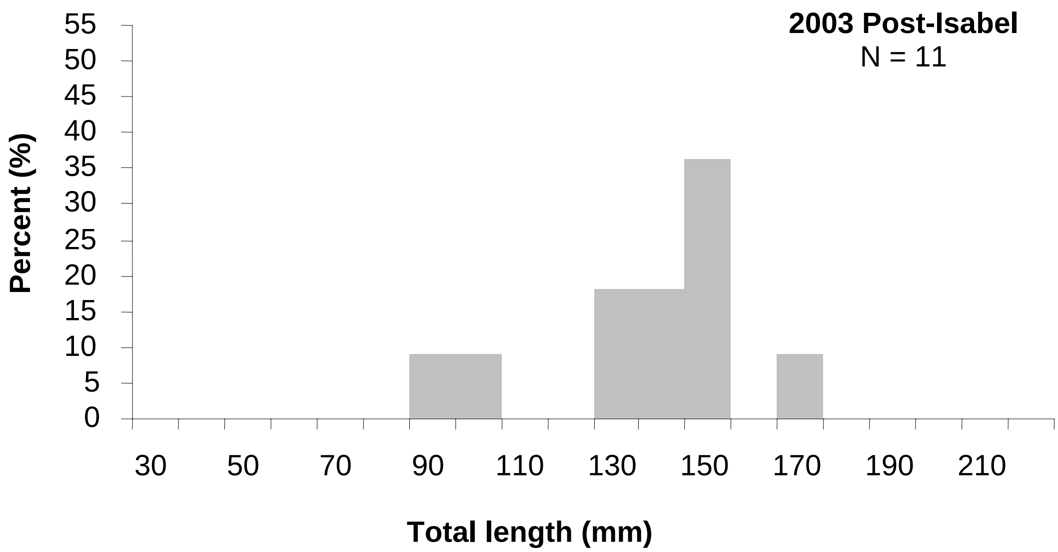


FIGURE 10.—Length frequency distribution of bluegill collected from the lower Roanoke River during the 2003 post-Isabel sampling period.

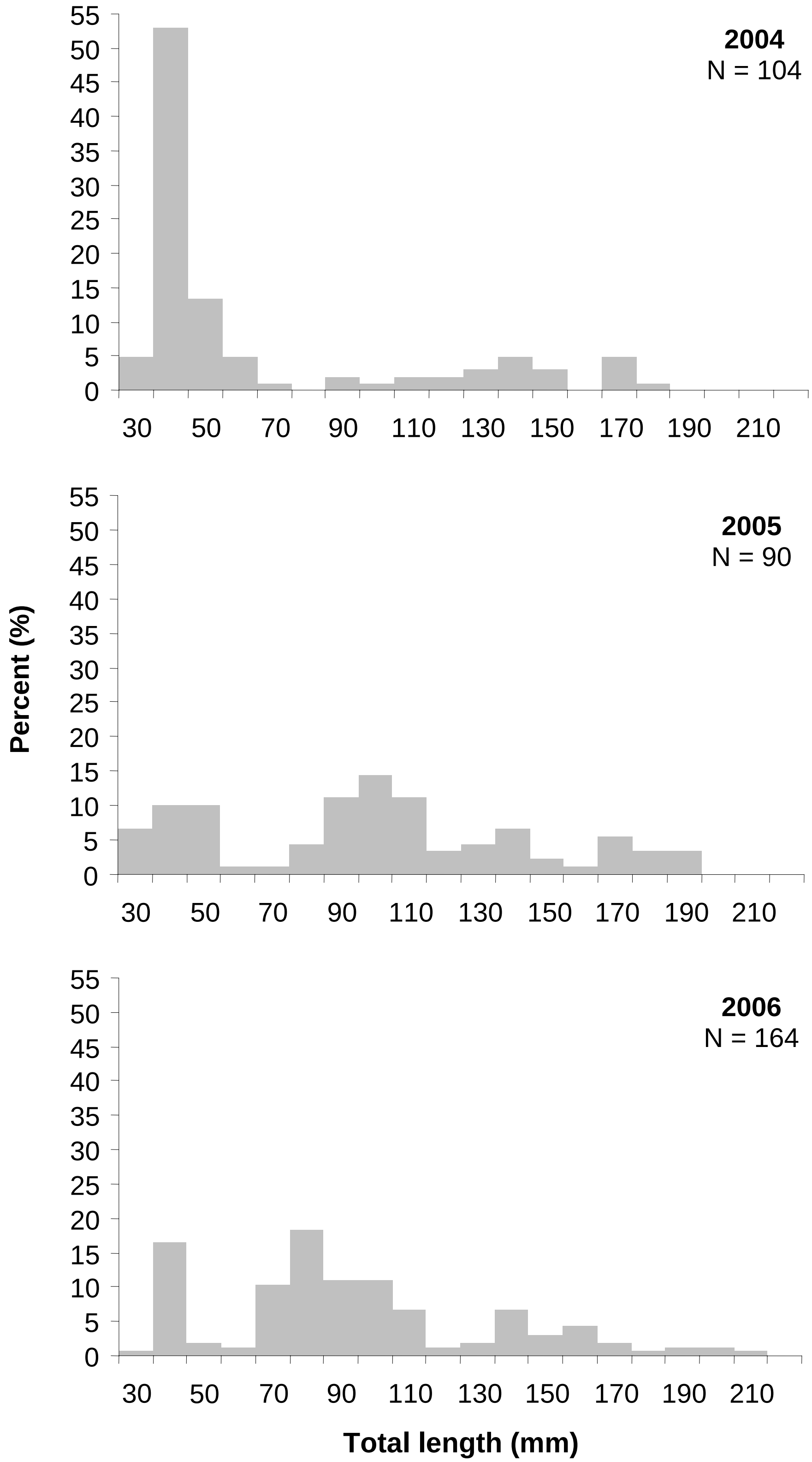


FIGURE 11.—Length frequency distribution of bluegill collected from the lower Roanoke River during the recovery period in 2004, 2005, and 2006.

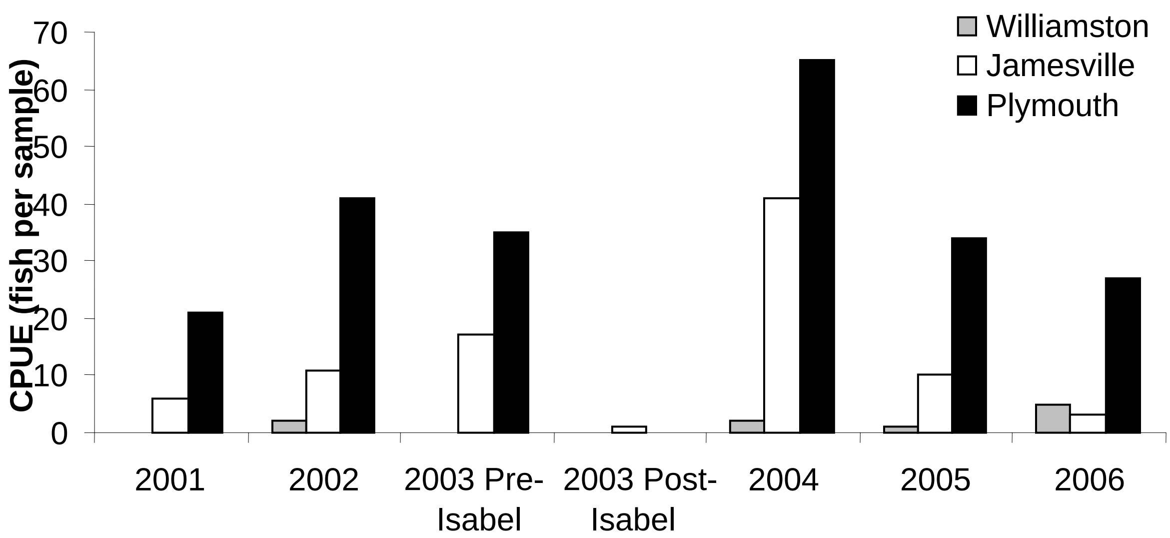


FIGURE 12.—Relative abundance of yellow perch from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. CPUE was 0 at the Williamston site in 2001 and at the Plymouth site in the 2003 post-Isabel sample, whereas the Williamston site was not sampled in either of the 2003 sample periods.

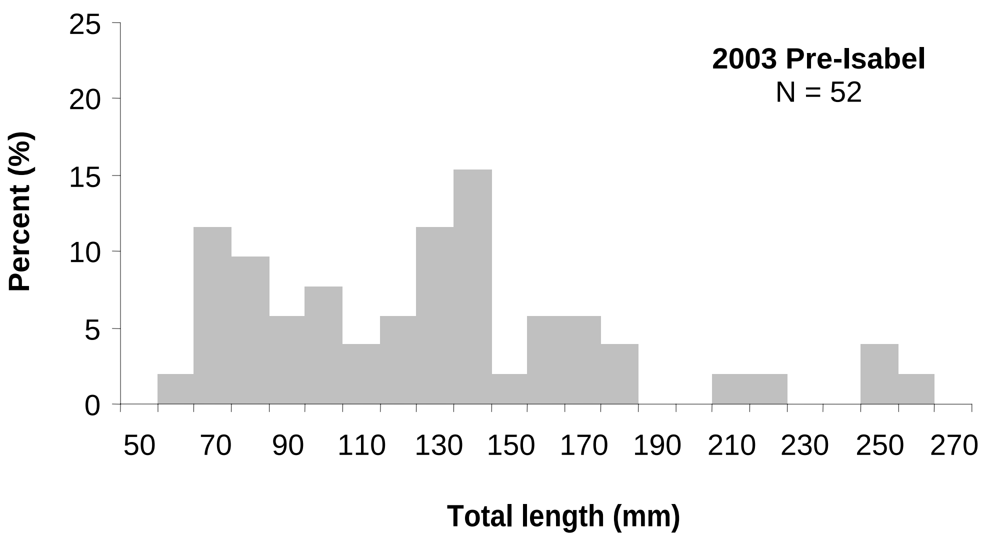


FIGURE 13.—Length frequency distribution of yellow perch collected from the lower Roanoke River before Hurricane Isabel in 2003.

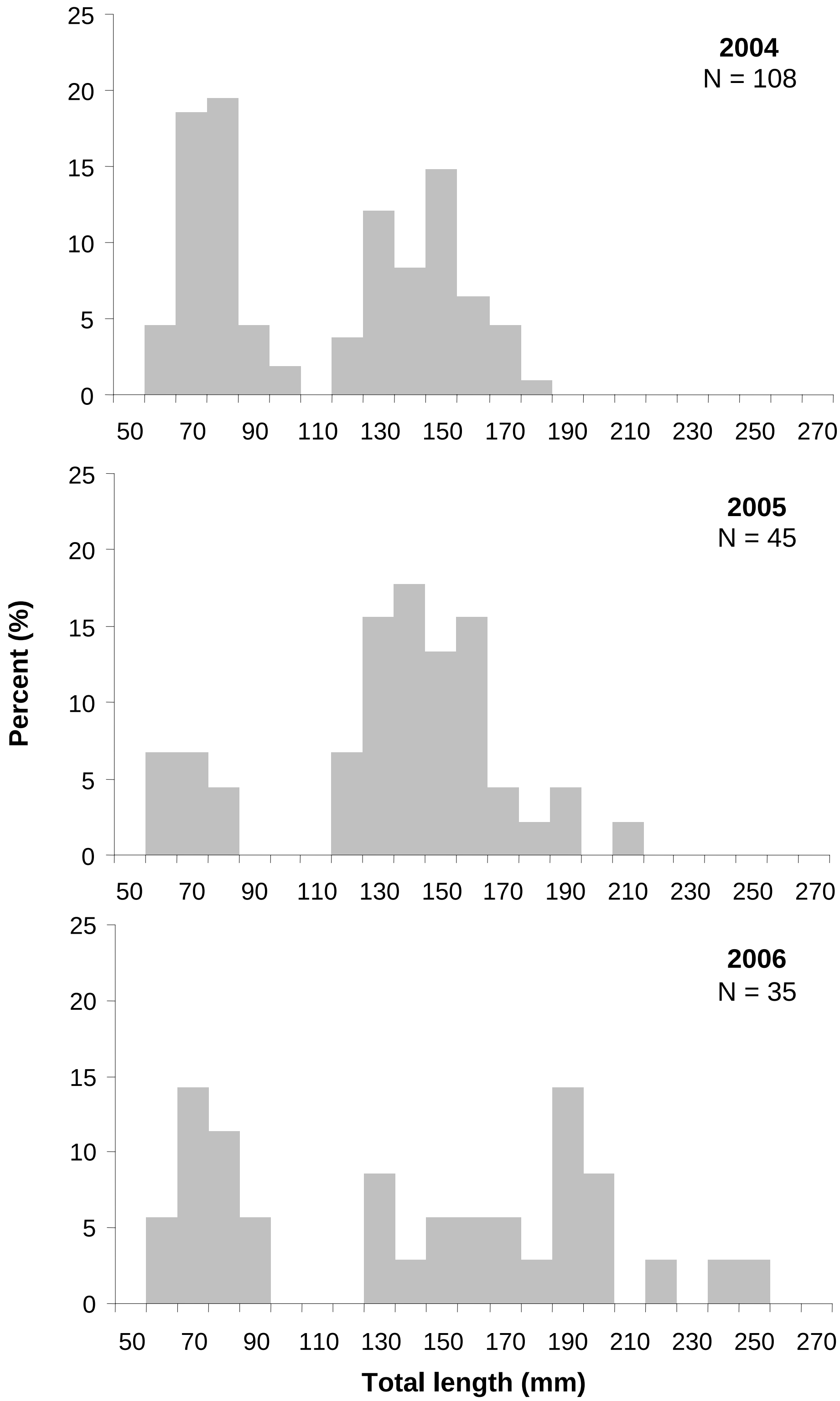


FIGURE 14.—Length frequency distributions of yellow perch collected from the lower Roanoke River during the recovery period in 2004, 2005, and 2006.

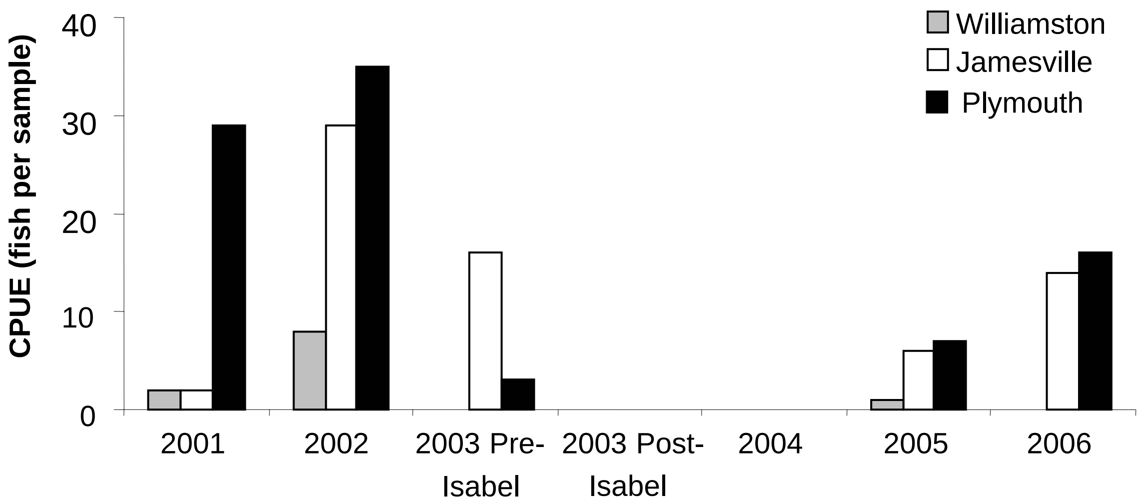


FIGURE 15.—Relative abundance of darters from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. The Williamston site was not sampled in 2003, but CPUE was 0 at the Jamesville and Plymouth sites during the 2003 post-Isabel sample and 0 at all sites in 2004.

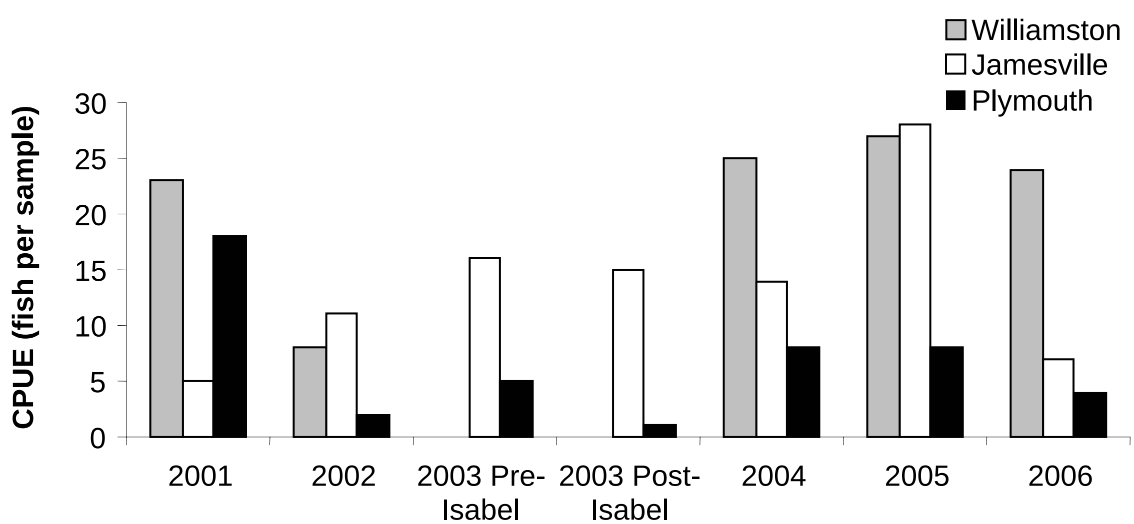


FIGURE 16.—Relative abundance of catfish from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. The Williamston site was not sampled in 2003.

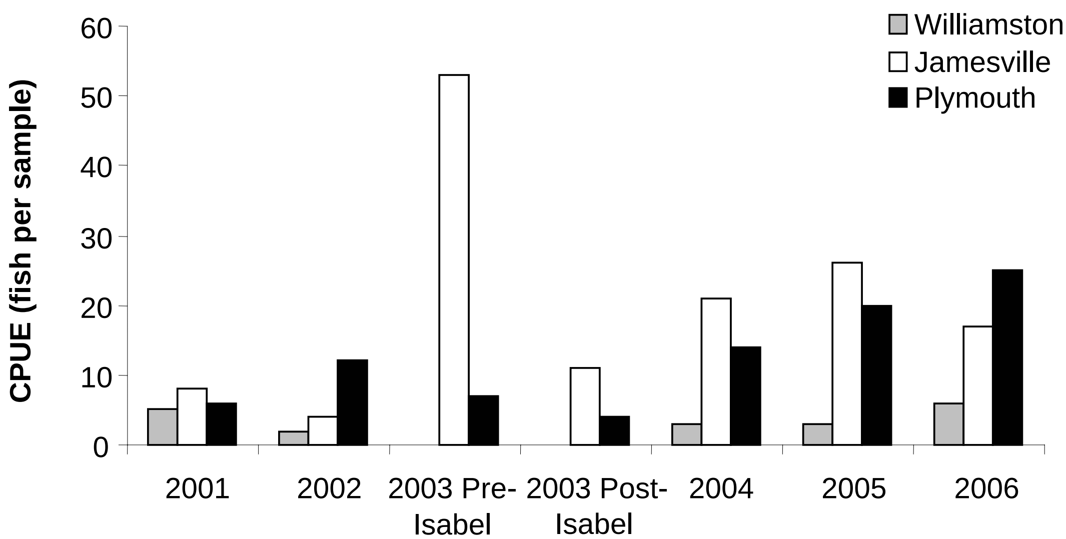


FIGURE 17.—Relative abundance of bowfin from lower Roanoke River fish assemblage collections made during the summers of 2001 through 2006. The Williamston site was not sampled in 2003.

APPENDIX A.—Daily mean, minimum, and maximum dissolved oxygen (DO) concentrations recorded at U.S. Geological Survey stream gauging stations 02081094 (Jamesville) and 0208114150 (Plymouth). All data are approved for publication.

	Jamesville			**Plymouth**		
Date	Mean DO (mg/L)	Minimum DO (mg/L)	Maximum DO (mg/L)	Mean DO (mg/L)	Minimum DO (mg/L)	Maximum DO (mg/L)
9/18/2003	5.8	4.9	6.4	5.3	4.1	6.9
9/19/2003	3.8	2.8	5.8	3.3	2.6	4.1
9/20/2003	2.1	1.3	2.8	1.4	0.2	2.6
9/21/2003	0.9	0.3	1.4	0.2	0.2	0.2
9/22/2003	0.1	0.0	0.4	0.2	0.2	0.2
9/23/2003	0.0	0.0	0.1	0.2	0.2	0.2
9/24/2003	0.0	0.0	0.1	0.2	0.2	0.2
9/25/2003	0.0	0.0	0.1	0.2	0.2	0.2
9/26/2003	0.0	0.0	0.1	0.2	0.2	0.2
9/27/2003	0.0	0.0	0.1	0.2	0.2	0.2
9/28/2003	0.1	0.0	0.1	0.2	0.2	0.2
9/29/2003	0.1	0.1	0.4	0.2	0.2	0.2
9/30/2003	0.7	0.3	1.1	0.2	0.2	0.3
10/1/2003	1.3	1.0	1.6	0.3	0.2	0.3
10/2/2003	1.8	1.5	2.3	0.6	0.2	1.7
10/3/2003	2.8	2.2	3.8	2.4	1.7	2.7
10/4/2003	3.4	2.8	3.8	2.9	2.3	3.2
10/5/2003	3.6	3.1	4.4	3.1	2.6	3.3
10/6/2003	3.2	2.9	3.7	2.8	2.6	3.0
10/7/2003	3.0	2.9	3.0	2.9	2.7	3.2
10/8/2003	2.9	2.8	3.0	2.9	2.6	3.0
10/9/2003	2.6	2.5	2.8	3.0	2.6	3.3
10/10/2003	2.5	2.4	2.7	3.0	2.9	3.2
10/11/2003	2.5	2.4	2.7	2.6	2.4	3.0
10/12/2003	2.8	2.6	3.0	2.7	2.4	3.0
10/13/2003	3.0	2.9	3.1	3.1	2.9	3.3
10/14/2003	3.1	3.0	3.1	3.0	2.8	3.2
10/15/2003	3.2	3.0	3.4	3.3	3.1	3.5
10/16/2003	3.4	3.3	3.4	3.6	3.4	3.8
10/17/2003	3.4	3.3	3.6	3.7	3.6	3.9
10/18/2003	3.7	3.5	4.0	4.1	3.7	4.4
10/19/2003	4.1	3.9	4.4	4.2	4.0	4.4
10/20/2003	4.3	4.2	4.5	4.7	4.4	4.9
10/21/2003	4.3	4.2	4.6	4.8	4.7	5.1
10/22/2003	4.4	4.3	4.7	4.7	4.6	4.9
10/23/2003	4.7	4.5	4.8	4.8	4.6	5.0
10/24/2003	4.8	4.6	5.1	5.0	4.8	5.2
10/25/2003	5.3	5.1	5.5	5.0	4.8	5.3
10/26/2003	5.6	5.5	5.7	5.5	5.2	5.9
10/27/2003	5.3	5.0	5.5	6.0	5.8	6.1
10/28/2003	5.3	5.0	5.5	5.8	5.6	6.0
10/29/2003	5.8	5.5	6.1	6.0	5.6	6.2
10/30/2003	5.6	5.3	5.9	6.0	5.7	6.2
10/31/2003	5.8	5.7	6.0	5.7	5.5	5.9