Water-Level Decline in the Apalachicola River, Florida, from 1954 to 2004, and Effects on Floodplain Habitats

By Helen M. Light[1], Kirk R. Vincent[2], Melanie R. Darst[1], and Franklin D. Price[3]

[1] U.S. Geological Survey, 2010 Levy Avenue, Tallahassee, Florida 32310.
[2] U.S. Geological Survey, 3215 Marine , E-127, Boulder, Colorado 80303.
[3] Florida Fish and Wildlife Conservation Commission, 350 Carroll Street, Eastpoint, Florida 32328.

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Conversion Factors, Acronyms, and Abbreviations

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
river mile* (rm)	1.609	river kilometer
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic yard (yd^3)	0.7646	cubic meter
part per million (ppm)	1.0	milligram per liter

*See Glossary for definition.

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called “Sea Level Datum of 1929.”

ACF	Apalachicola-Chattahoochee-Flint
AMO	Atlantic Multidecadal Oscillation
FFWCC	Florida Fish and Wildlife Conservation Commission
NWFWMD	Northwest Florida Water Management District
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Glossary

Channel change refers to physical changes in a river channel, such as widening, deepening, or changes in slope, which can result in a change in the water level for a given discharge. Channel change can also refer to minor rerouting of the channel locally, such as meander cutoffs or bend easings to straighten bends in the river.

Climate year is an informal term used in this report to define the annual period from April 1 through March 31. This period was used in analysis of low discharges in order to avoid splitting low-flow periods that typically occur in summer and fall. (See water year.)

Equivalent-stage discharge is an informal term used in this report to represent the discharge in the recent period having the same water-surface elevation as a specified discharge had during the pre-dam period. For example, the selected discharge of 15,000 cubic feet per second at the Chattahoochee gage had a pre-dam stage of 49.22 feet, and 25,700 cubic feet per second is the "equivalent-stage discharge" in the recent period that has that same water-surface elevation. Determining equivalent-stage discharge is a necessary first step in determining the decrease in duration of inundation from pre-dam to recent periods.

Gage or streamgage refers to a long-term streamflow gaging station at which a time-series of stage measurements (elevation of river surface) have been recorded, and measurements of instantaneous streamflow discharge may have been made.

High bottomland hardwood forests grow on the higher elevations of the floodplain (levees and ridges) that are usually inundated for 2 to 6 weeks each year. High bottomland hardwoods are dominated by sweetgum and hackberry.

Joining point is an informal term used in this report to indicate the stage or discharge at which pre-dam and recent stage-discharge relations merge. The joining point discharge is a large value at the upstream-most site, and gradually decreases with distance downstream. For any given site, the joining point identifies the stage or discharge above which the proportion of flow moving over the floodplain is large enough that physical changes that occurred in the main river channel at that site have no noticeable effect on river stage.

Lag time is an expression for the time it takes for water passing an upstream gage to reach a downstream location. All lag times used in this report represent average travel times from Chattahoochee to downstream locations. Analyses in this report were based on daily mean values, thus lag times were expressed in whole days, rather than hours. Discharge at Chattahoochee was related to stage 1 day later at Blountstown, 2 days later at Wewahitchka and RM 35, and 3 days later at Sumatra. Methods used to determine lag times are described in the text.

Loop stream is an informal term used by Light and others (1998) to describe a type of floodplain stream or slough in which water diverted from the main river enters at the head of the stream, flows a few miles in the stream channel through the floodplain, and returns to the river at the mouth of the stream. An intermittent stream of this type is fed by the river and receives no direct upland runoff, thus when water levels in the river are too low, the stream stops flowing.

Low bottomland hardwood forests are present on low ridges and flats where continuous flooding averages 2 to 4 months per year. Low bottomland hardwoods are dominated by water hickory, overcup oak, swamp laurel oak, and green ash.

Percent duration of inundation is the percentage of time that a particular location is inundated by water. Percent duration of inundation, which is a term used to describe hydrologic conditions on the floodplain, is numerically equal to percent exceedance in this report; however, that is not always the case in other contexts. Percent duration of inundation in the floodplain can be different than percent exceedance calculated from streamflow data, because some topographic features in the floodplain, such as swamp depressions, may retain water long after flood waters recede. Thus, the reader is cautioned that percent duration of inundation values in this report are based solely on river stage, without any adjustments to account for site-specific variations in floodplain topography. (See percent exceedance.)

Percent exceedance is the percentage of time that a specified streamflow discharge is equaled or exceeded during a given time period. In this report, percent duration of inundation, which is a term used to describe hydrologic conditions on the floodplain, is numerically equal to percent exceedance. (See percent duration of inundation.)

Pre-dam period is an informal term used in this report to refer to the time period before substantial physical changes occurred in the Apalachicola River. This period ends in May 1954, which is when Jim Woodruff Dam was completed and the filling of Lake Seminole was initiated. Riverbed degradation which resulted from the trapping of streambed sediment in the reservoir, was the primary cause of the water-level decline in the upper reach of the river. Beginning in 1956, a variety of other channel-altering activities took place over a period of many years that probably also contributed to the water-level decline, particularly in the nontidal lower reach. Thus, the use of the term “pre-dam” is not intended to imply that scour downstream from the dam as a result of sediment trapping in the reservoir was the only cause of channel change.

Reach refers to a length subdivision of the Apalachicola River. The upper reach begins just below Jim Woodruff Dam at river mile 106.3 and extends about 29 miles downstream to the Blountstown gage at river mile 77.5. The middle reach is the longest reach, about 36 miles long, ending at the Wewahitchka gage at river mile 41.8. The nontidal lower reach is the shortest reach, about 21 miles long, and ends at the Sumatra gage at river mile 20.6. The tidal reach of the river is not discussed in this report. In reality, there is no precise boundary between the tidal and nontidal reaches, but rather a transitional zone in which tidal influence is minimal at the upper end (occuring only at very low flows) and gradually increases downstream. For practical purposes in this report, the boundary between tidal and nontidal was established at the Sumatra gage; however, during low-flow conditions, tidal influence occurs at the Sumatra gage and probably also extends upstream to some undetermined point.

Recent period is an informal phrase used in this report to indicate the decade from October 1, 1994, to September 30, 2004. This period was chosen to be long enough to include a mix of both flood and drought years, but short enough to exclude data from earlier periods during which water levels were still changing.

River mile (rm) refers to a reference frame of distances along the river channel. In this report, river mile values are those depicted on the most recent U.S. Geological Survey quadrangle maps that were available in 2005. These river mile distances are similar to, but not exactly the same as, the most recent navigation mile system used by U.S. Army Corps of Engineers. Slight differences in distance reference frames are to be expected because the river moves and changes length through time in response to various processes, both natural and anthropogenic.

Stage refers to the elevation of water surface of a river at a particular time and place.

Stage-discharge rating refers to a standard U.S. Geological Survey stage-discharge relation based on instantaneous observations of stage and direct measurements of discharge made at a streamflow gaging station. (See stage-discharge relations.)

Stage-discharge relations are defined by best-fit lines or curves in which river stage is related to river discharge. Three types of relations are used in this report: (1) standard U.S. Geological Survey stage-discharge ratings; (2) nonstandard relations in which stage at a downstream gage is related to discharge at the upstream-most gage at Chattahoochee, Florida; and (3) interpolated nonstandard relations in which stage at a between-gage site is related to discharge at the Chattahoochee gage, based on interpolation between relations at the closest upstream and downstream gages. (See stage-discharge rating.)

Streamgage or gage refers to a long-term streamflow gaging station at which a time-series of stage measurements (elevation of river surface) have been recorded, and measurements of instantaneous streamflow discharge may have been made.

Thalweg is the deepest part of the river channel.

Tupelo-cypress swamps are present in the lowest elevations of the floodplain where continuous flooding averages 4 to 9 months per year. Swamps are dominated by water tupelo, bald cypress, and ogeechee tupelo.

Water-level decline, as applied to streamflow, can refer to three situations. This report primarily addresses the situation characterized by a long-term decrease in river stage for a particular streamflow discharge, and a long-term shift in the stage-discharge relation for a site. Such declines result from some type of channel change, which usually occurs over a period of years. Another type of water-level decline, which is also addressed in this report but is not described in as much detail as the first type, refers to a long-term decrease in the amount of water delivered from the upstream watershed. Both of these types of water-level declines cause periods of low water levels to become more frequent and longer in duration. Water-level decline can also refer to short-term fluctuations in stage during the passage of a flood, but this meaning is not used in this report.

Water year is defined as the annual period from October 1 through September 30. This period was used in analysis of high discharges in order to avoid splitting flood events that typically occur in winter and spring. (See climate year.)

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Abstract

From 1954 to 2004, water levels declined in the nontidal reach of the Apalachicola River, Florida, as a result of long-term changes in stage-discharge relations. Channel widening and deepening, which occurred throughout much of the river, apparently caused the declines. The period of most rapid channel enlargement began in 1954 and occurred primarily as a gradual erosional process over two to three decades, probably in response to the combined effect of a dam located at the head of the study reach (106 miles upstream from the mouth of the river), river straightening, dredging, and other activities along the river. Widespread recovery has not occurred, but channel conditions in the last decade (1995–2004) have been relatively stable. Future channel changes, if they occur, are expected to be minor.

The magnitude and extent of water-level decline attributable to channel changes was determined by comparing pre-dam stage (prior to 1954) and recent stage (1995–2004) in relation to discharge. Long-term stage data for the pre-dam period and recent period from five streamflow gaging stations were related to discharge data from a single gage just downstream from the dam, by using a procedure involving streamflow lag times. The resulting pre-dam and recent stage-discharge relations at the gaging stations were used in combination with low-flow water-surface profile data from the U.S. Army Corps of Engineers to estimate magnitude of water-level decline at closely spaced locations (every 0.1 mile) along the river. The largest water-level declines occurred at the lowest discharges and varied with location along the river. The largest water-level decline, 4.8 feet, which occurred when sediments were scoured from the streambed just downstream from the dam, has been generally known and described previously. This large decline progressively decreased downstream to a magnitude of 1 foot about 40 river miles downstream from the dam, which is the location that probably marks the downstream limit of the influence of the dam on bed scour. Downstream from that location, previously unreported water-level declines progressively increased to 3 feet at a location 68 miles downstream from the dam, probably as a result of various channel modifications conducted in that part of the river.

Water-level declines in the river have substantially changed long-term hydrologic conditions in more than 200 miles of off-channel floodplain sloughs, streams, and lakes and in most of the 82,200 acres of floodplain forests in the nontidal reach of the Apalachicola River. Decreases in duration of floodplain inundation at low discharges were large in the upstream-most 10 miles of the river (20–45 percent) and throughout most of the remaining 75 miles of the nontidal reach (10–25 percent). As a consequence of this decreased inundation, the quantity and quality of floodplain habitats for fish, mussels, and other aquatic organisms have declined, and wetland forests of the floodplain are changing in response to drier conditions. Water-level decline caused by channel change is probably the most serious anthropogenic impact that has occurred so far in the Apalachicola River and floodplain.

[1] U.S. Geological Survey, 2010 Levy Avenue, Tallahassee, FL 32310.
[2] U.S. Geological Survey, 3215 Marine Street, E-127, Boulder, CO 80303.
[3] Florida Fish and Wildlife Conservation Commission, 350 Carroll Street, Eastpoint, FL 32328.

This decline has been exacerbated by long-term reductions in spring and summer flow, especially during drought periods. Although no trends in total annual flow volumes were detected, long-term decreases in discharge for April, May, July, and August were apparent, and water-level declines during drought conditions resulting from decreased discharge in those 4 months were similar in magnitude to the water-level declines caused by channel changes. The observed changes in seasonal discharge are probably caused by a combination of natural climatic changes and anthropogenic activities in the Apalachicola-Chattahoochee-Flint River Basin. Continued research is needed for geomorphic studies to assist in the design of future floodplain restoration efforts and for hydrologic studies to monitor changes in the future flow regime of the Apalachicola River as water management and land use in this large tri-state basin continue to change.

Introduction

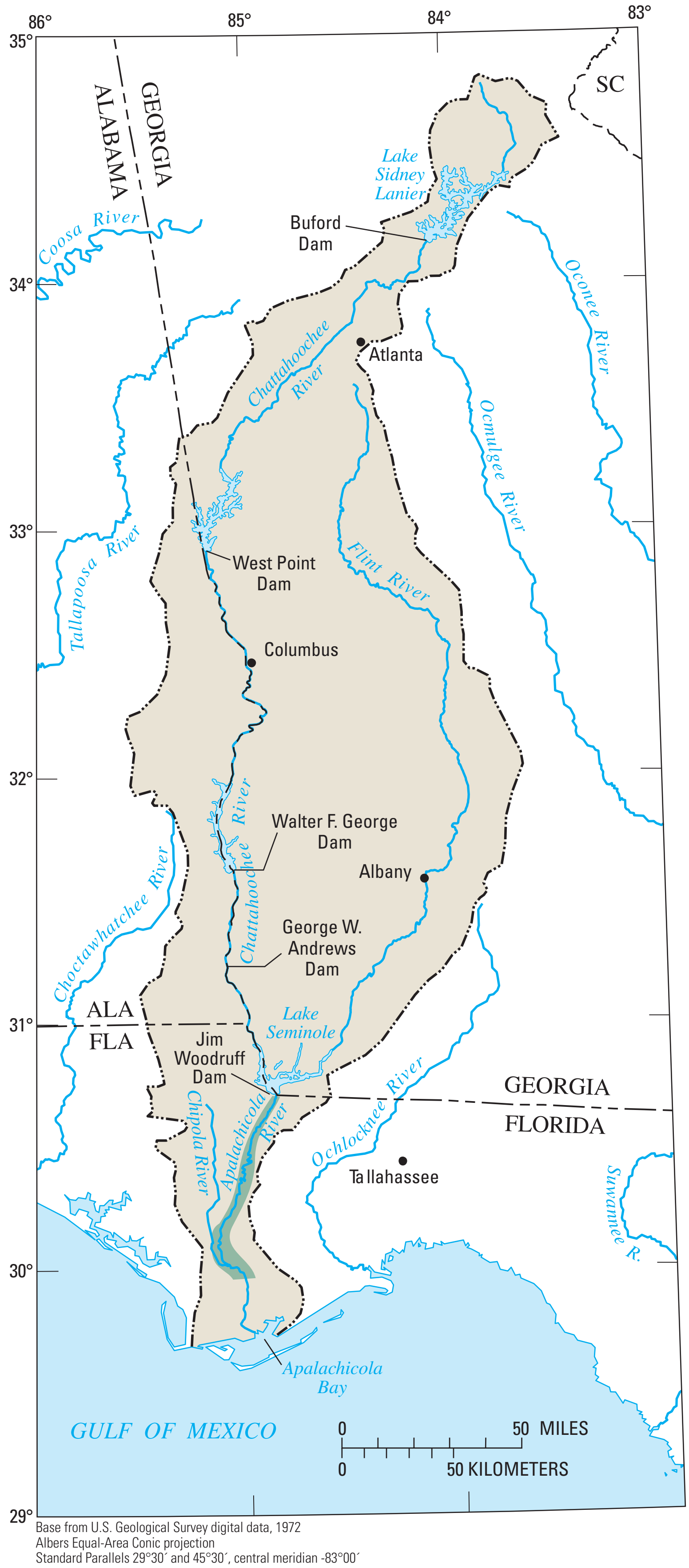
Large coastal plain rivers of the southeastern United States have extensive forested floodplains with a diversity of aquatic and wetland habitats that are strongly influenced by river levels (Wharton and others, 1982; Mitsch and Gosselink, 2000). Streams, sloughs, ponds, lakes, and swamps in the floodplain alternately connect and disconnect as river levels fluctuate. Complex relationships exist between biological communities in floodplain habitats and river levels, with floral and faunal distributions varying spatially, seasonally, and annually as the river rises and falls (Welcomme, 1979; Bayley, 1995; Power and others, 1995).

In floodplains along the 86-mi (mile) nontidal reach of the Apalachicola River (figs. 1 and 2), there are more than 200 mi of off-channel floodplain sloughs, streams, and lakes that are directly influenced by river-level fluctuations (Light and others, 1998). These off-channel waterbodies provide extensive habitat for fishes and other aquatic organisms. More than 80 percent of the freshwater and anadromous fish species found in the Apalachicola River are known to spend some part of their life cycle in floodplain habitats (Light and others, 1998; Stephen J. Walsh, U.S. Geological Survey (USGS), written commun., 2006). In addition, tree species richness in 82,200 acres of swamps and bottomland hardwoods bordering the Apalachicola River is among the highest of North American river floodplains (Leitman and others, 1984; Brinson, 1990). Tree composition and recruitment in this vast wetland forest corridor is primarily determined by the flow regime of the river.

Water-level declines caused by channel change in the upper reach of the river, and the impact on floodplain habitats resulting from these declines, are described in previous reports (Simons, Li, and Associates, 1985; Light and others, 1998; U.S. Army Corps of Engineers (USACE), 2001a). Until recently, these declines were thought to be limited primarily to the upper reach and its floodplain, which constitutes about 20 percent of the total floodplain area of the nontidal river. Based on the water-level declines attributable to channel changes in the middle and nontidal lower reaches that are documented in this report, it is now known that water levels in most of the remaining 80 percent of the nontidal floodplain declined at about the same time as water levels declined in the upper reach. As a consequence, almost all of the nontidal river and floodplain is now experiencing longer and more frequent periods of low water levels than prior to 1954, increasing the amount of time that woody substrate along channel banks is exposed; floodplain streams are dewatered, isolated, or not flowing; and swamps and bottomland hardwood forests are dry.

A conceptual diagram illustrating the causes of long-term water-level decline in rivers and the consequences on river-floodplain habitats is presented in figure 3. Two types of changes can potentially decrease long-term water levels: physical changes in the channel or a reduction in the amount of water delivered from upstream. Physical changes in the channel, such as channel enlargement or increased flow velocity, can change stage-discharge relations, resulting in a long-term decrease in river stage (water level) in relation to streamflow discharge (volumetric rate of flow). In contrast, reductions in the amount of water delivered from upstream do not change stage-discharge relations. Temporary changes in water level may occur during droughts or when streambed topography is rearranged during the passage of a flood. Where a water-level decline persists for many years, or the decline increases in magnitude over many years, the decline is probably the result of fundamental changes in either the geomorphology of local channels or the hydrology of the upstream watershed, or both.

Channel widening and deepening has occurred throughout much of the river (USACE, 2001a; Price and others, 2006), and is the apparent cause of the long-term changes in stage-discharge relations documented in this report. A certain amount of channel change is natural in meandering streams (such as the Apalachicola River) as the stream migrates across the floodplain (Gilbert, 1877; Mackin, 1948; Hupp, 2000). Natural channel migration, however, occurs without a change in channel size. Sediment is eroded from the cut-bank on the outside of a bend and deposited on point bars a short distance downstream. As the point bar accretes laterally, the older area of the bar becomes colonized with trees, so that channel width and depth remain relatively constant over time as the channel migrates across the floodplain. Channel enlargement can result from an increase in the magnitude or frequency of peak floods caused by climate change or watershed urbanization (Leopold and others, 2005). There is no evidence, however, that channel changes in the Apalachicola River have been caused by increased flow. Along certain rivers, the channel can widen substantially (but not deepen) during a catastrophic flood, although this widening is followed by gradual narrowing during subsequent decades (Schumm and Lichty, 1963). The Apalachicola River, in contrast, enlarged gradually and has not recovered by narrowing. Therefore, the channel widening and deepening that occurred in the Apalachicola River was probably caused by anthropogenic activities along the river.



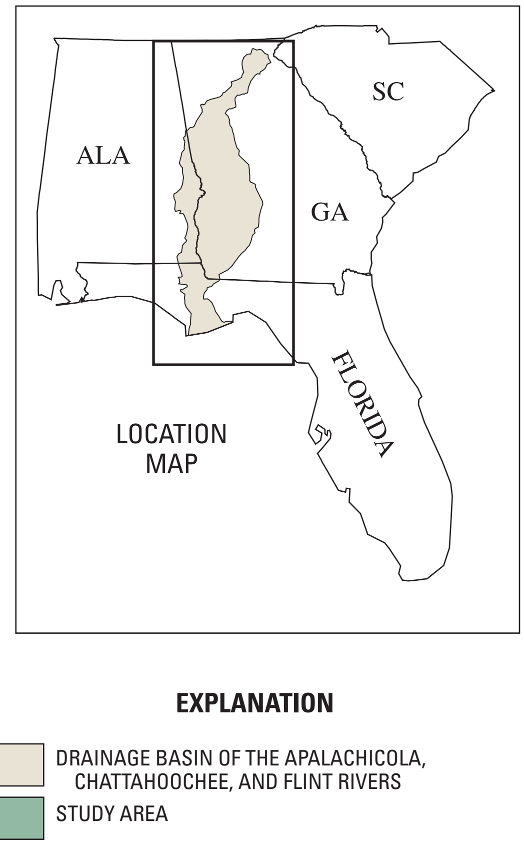
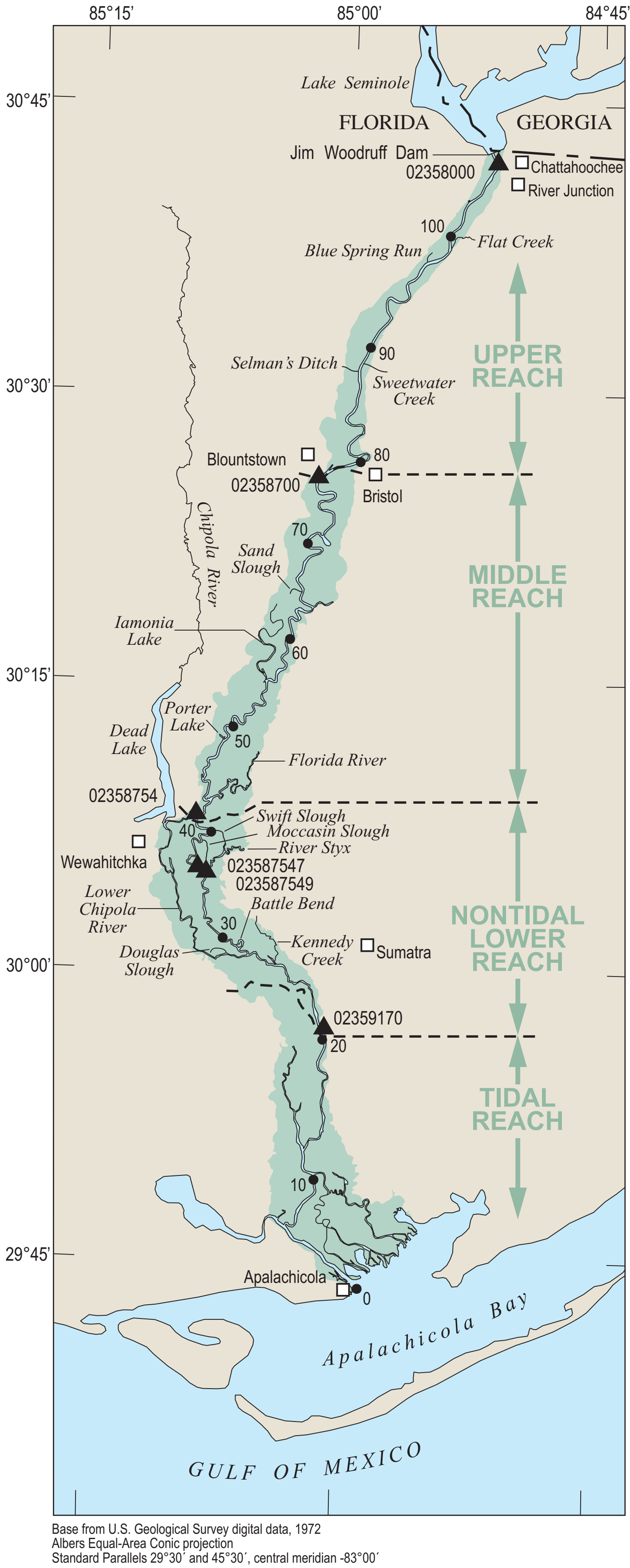


Figure 1. Drainage basin of the Apalachicola, Chattahoochee, and Flint Rivers in Florida, Georgia, and Alabama.



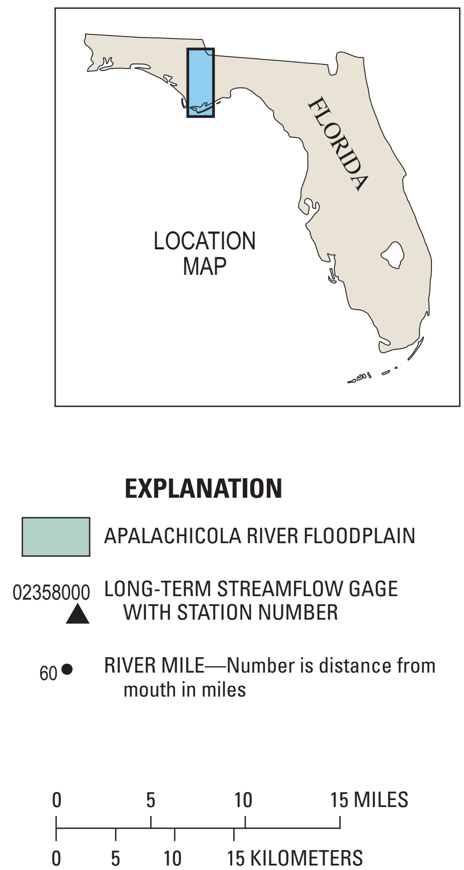


Figure 2. Major reaches of the Apalachicola River and location of long-term streamflow gaging stations.

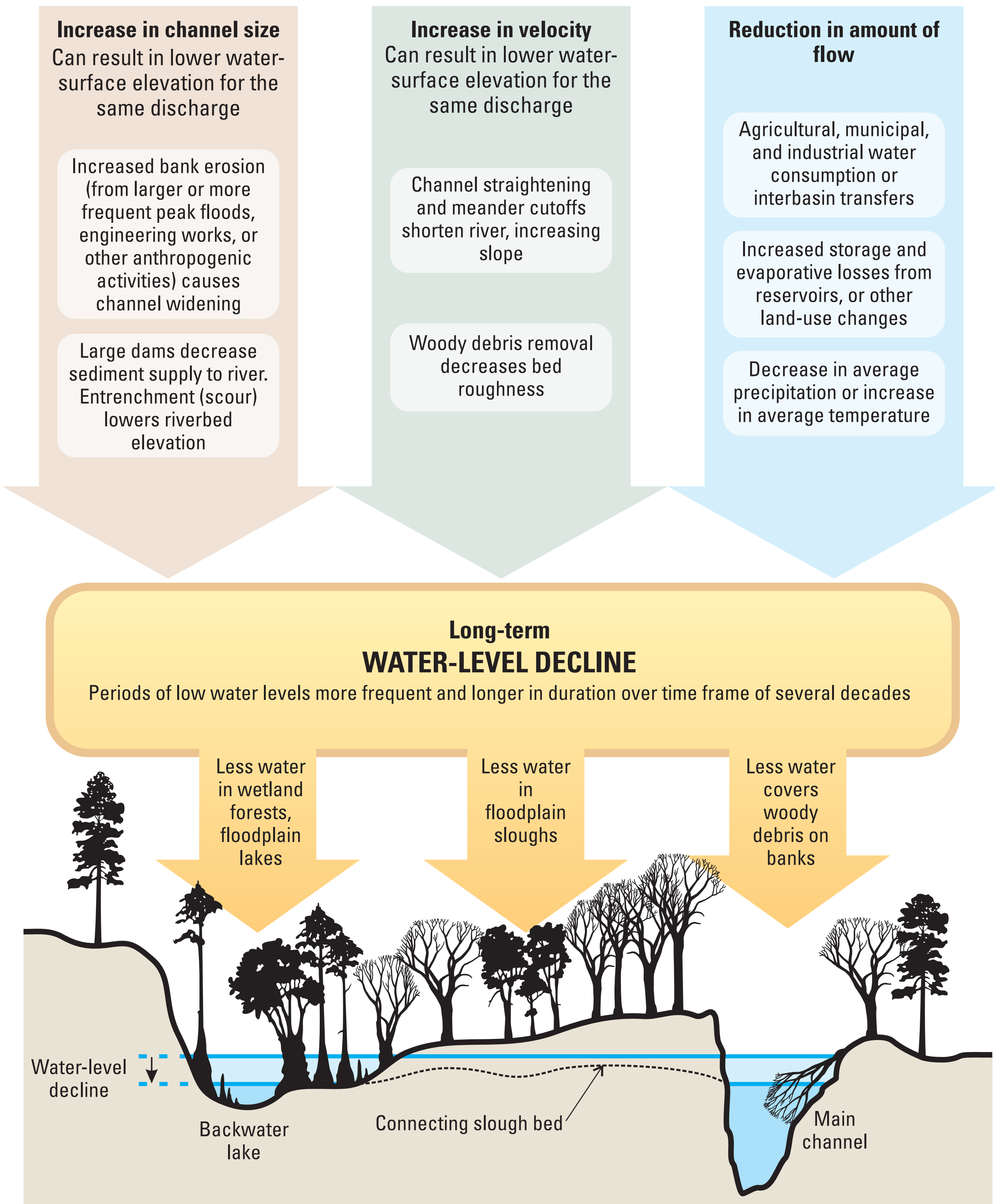


Figure 3. Possible causes of long-term water-level decline in rivers and resulting impacts on river-floodplain habitats.

Channel enlargement began in 1954 and occurred primarily as a gradual erosional process over two to three decades, probably in response to the combined effect of engineering projects along the river. Although various navigational improvements have been conducted on the Apalachicola River since the 1800s, the intensity of those activities greatly increased in the 1950s after Congress mandated that the USACE construct a dam and maintain a 9- by 100-ft (foot) navigation channel. After construction in 1954 of Jim Woodruff Dam at the head of the river (fig. 2), mobile streambed sediment (sand) was trapped in the reservoir created by the dam (Lake Seminole) and deepening of the bed of the Apalachicola River downstream from the dam occurred as a result (Simons, Li, and Associates, 1985). Riverbed degradation, and its consequences in terms of decreased floodplain inundation, has been well documented downstream from dams in other rivers, including low-gradient, sand-bedded rivers similar to the Apalachicola River (Galay, 1983; Ligon and others, 1995). Bends in the Apalachicola River were straightened by excavation of meander cutoffs and bend easings in 1956 and 1969, and river-training dikes were constructed from 1963 to 1970 (USACE, 1986). Dredging in the deepest part of the channel (thalweg), disposal of dredged material, and removal of woody debris over much of the length of the river were conducted annually from 1956 to 2001 (USACE, 2001a). During the 1970s, however, dredged material disposal practices were changed and the amount of annual wood removal was decreased in order to reduce environmental impacts of the navigation project on the river ecosystem.

Regarding the amount of water delivered from upstream, average annual discharge appears relatively unchanged. Minimum flows have decreased, however, and the seasonal distribution of flows has changed. At the streamflow gaging station on the Apalachicola River at Chattahoochee (fig. 2), very low discharges of 5,000 ft^3/s (cubic feet per second) or less occurred in 5 of the last 23 years (1981–2004), but not at all in the previous 53 years (USGS, 2006a). Monthly flow duration analyses indicate that fall and winter discharges have increased, and spring and summer discharges have decreased, based on a comparison of the earliest and latest 30 years in the period of record at this streamgage (1929–2004). Many natural changes and anthropogenic alterations have occurred in this large tri-state basin that could have contributed to changes in flow; however, hydrologic analysis to determine the relative contribution of causal factors has not been conducted.

Recovery of floodplain off-channel aquatic habitats altered by water-level decline in the Apalachicola River has been a long-standing concern of various State and Federal agencies. The restoration of habitats within a complex hydrologic system such as the Apalachicola River, however, is not a simple process. Many difficulties have been encountered in the restoration efforts conducted so far. Understanding the causes and magnitude of the water-level declines and identifying the reaches that have been most affected can help guide future prevention and recovery measures.

Purpose and Scope

This report describes the water-level decline that occurred in the Apalachicola River from 1954 to 2004 as a result of long-term changes in stage-discharge relations. This investigation was conducted by the U.S. Geological Survey (USGS) in cooperation with the Florida Fish and Wildlife Conservation Commission (FFWCC) and other agencies as part of a study to describe and quantify impacts of water-level declines on floodplain habitats of the Apalachicola River to help guide restoration efforts. The specific objectives of this report are to:

(1) Document stage-discharge relations at streamflow gaging stations prior to 1954 and during a recent period (1995–2004). This was done by relating stage data from five streamgages to discharge data from the upstream-most gage at Chattahoochee, Fla., using a procedure involving streamflow lag times.

(2) Estimate stage-discharge relations for the same time periods at closely spaced locations between the streamgages. This was done by using a combination of streamgage records and low-flow water-surface profile data.

(3) Estimate the water-level decline at closely spaced locations along the river and to determine average water-level decline by reach for selected discharges.

(4) Determine the consequence of the water-level decline on duration of inundation of the floodplain.

(5) Describe specific effects of the water-level decline on selected floodplain habitats and general effects on the overall floodplain.

(6) Discuss related issues: (a) changes in water levels attributable to long-term changes in monthly discharge, (b) recovery and restoration efforts, and (c) research needs.

The study area includes the nontidal reach of the Apalachicola River from the Chattahoochee gage at rm (river mile) 105.7 to the Sumatra gage at rm 20.6 (fig. 2). Data analysis was conducted from July 2001 to December 2005. Data in this report came from ongoing data-collection programs within the USGS and USACE that were conducted independent of this study, with the exception of field data collected at selected floodplain sites discussed in objective 5.

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Angel Alvarez, ETI Professionals Inc.; Eleanor R. Griffin, Sara LoVetere, J. Dungan Smith, USGS, (Boulder); John C. Good, Suwannee River Water Management District; Keith R. Smith, volunteer. Joanne U. Brandt, USACE, provided historical information about navigation improvements made to the river. Information regarding effects of the water-level decline on floodplain habitats was received from Stephen J. Walsh, USGS; James D. Williams, retired USGS; Charles L. Mesing, Eric A. Long, and Theodore S. Hoehn, FFWCC; Jerry W. Ziewitz, U.S. Fish and Wildlife Service (USFWS); and James M. Barkuloo, retired USFWS. Assistance in describing natural and anthropogenic factors affecting flow in the Apalachicola-Chattahoochee-Flint (ACF) River Basin was received from Richard L. Marella, USGS; Mary M. Davis, The Nature Conservancy; Steven F. Leitman, Damayan Water Project; David W. Hicks, Joseph W. Jones Ecological Research Center; Sergio Fagherazzi and Paul H. Ruscher, Florida State University. Assistance with literature review was received from Grayal E. Farr, volunteer.

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Setting

The Apalachicola River is the largest river in Florida, and the fourth largest river in the southeastern United States, in terms of mean annual discharge (Iseri and Langbein, 1974). The river is formed by the confluence of the Chattahoochee and Flint Rivers, and the drainage basin of all three rivers covers 19,600 mi^2 (square miles) in Florida, Georgia, and Alabama. The Chattahoochee and Flint Rivers drain the upstream-most 90 percent of the basin in Georgia and Alabama (fig. 1). The Apalachicola River and its largest tributary, the Chipola River, lie in the downstream-most 10 percent of the drainage basin, which is primarily in Florida. The Apalachicola River is in the Coastal Lowlands physiographic area (Puri and Vernon, 1964), which is generally low in elevation.

The Apalachicola River is an alluvial, low-gradient, meandering river with an average water-surface gradient of 0.00009 in the nontidal reach. The river surface falls about 41 ft from the head at Jim Woodruff Dam to the Sumatra gage. The sinuosity of the nontidal river (1.44) is moderately high but not “torturous,” and falls within the range typical of low-gradient meandering rivers (Knighton, 1984). The Apalachicola River is about 106 mi long; however, the downstream-most 20.6 mi is considered tidal and is not addressed in this report. In reality, there is no precise boundary between the tidal and nontidal reaches, but rather a transitional zone in which tidal influence is minimal at the upper end (occurring only at very low flows) and gradually increases downstream. For practical purposes, the boundary between tidal and nontidal was established at the Sumatra gage (fig. 2); however, during low-flow conditions, tidal influence occurs at the Sumatra gage and probably also extends upstream to some undetermined point. Bed sediments throughout most of the river are sand, except in areas of low velocity on channel margins where finer sediments accumulate, and in high velocity areas of the upper reach where gravel, rock, or limestone bedrock can be found locally (USACE, 2001a; Jerry W. Ziewitz, USFWS, oral commun., 2006).

The Apalachicola River at Chattahoochee, Fla., had an average discharge of 21,900 ft^3/s and a median discharge of 15,900 ft^3/s for the period of record (1929–2004). All discharge values in this report are from the streamflow gaging station at Chattahoochee. Flooding typically occurs in January through April, with low flows in September through November (Leitman and others, 1984). The highest recorded daily mean discharge was 291,000 ft^3/s on March 20, 1929; the lowest was 3,900 ft^3/s on November 15, 1987. A minimum flow of 5,000 ft^3/s has been strictly maintained with reservoir releases by USACE since the summer of 2000. The climate of the Apalachicola River Basin is humid subtropical with a growing season of about 270 days. Average annual rainfall is 56 in. (inches), with the highest monthly averages occurring in the summer and the lowest averages in the fall.

The ACF River Basin has an unusually high diversity of flora and fauna. The Apalachicola River is in one of the Nation’s biodiversity hotspots, as recognized by The Nature Conservancy (Stein and others, 2000). More than 70 different species of trees grow in the Apalachicola River floodplain, which is the largest forested floodplain in Florida (112,000 acres of nontidal and tidal freshwater forests). The nontidal floodplain forest (82,200 acres) is predominantly palustrine wetlands according to the wetland classification system of the USFWS (Cowardin and others, 1979; Reed, 1988). The ACF Basin has the highest species density of amphibians and reptiles on the continent north of Mexico (Kiester, 1971), and the largest diversity of fish fauna among the Gulf Coast river drainages east of the Mississippi River (Dahlberg and Scott, 1971). Sixteen fish species have been listed for protection by Federal or State agencies (Couch and others, 1996). Of the western Florida river drainages, the ACF River Basin has the largest number of freshwater gastropod and bivalve species and the largest number of endemic mollusk species (Heard, 1977).

Construction of Jim Woodruff Dam, which impounds Lake Seminole at the head of the Apalachicola River where the Chattahoochee and Flint Rivers join, began in 1950 and was completed in 1954, with filling of the reservoir accomplished from 1954 to 1957. Upstream from Jim Woodruff Dam are 15 other mainstem dams and reservoirs (13 on the Chattahoochee River and 2 on the Flint River) (USACE, 1996). Buford Dam, which impounds the largest reservoir on the ACF system (Lake Sidney Lanier) is located on the upper Chattahoochee River upstream from Atlanta (fig. 1), and was completed in the same year as Jim Woodruff Dam (1954). Three other large Federal dams, Walter F. George,

George W. Andrews, and West Point, were completed in 1963, 1963, and 1974, respectively. Flow regulation is conducted at Federal dams for Congressionally authorized purposes of flood control, hydropower, navigation, fish and wildlife management, recreation, and water supply. Eleven other non-Federal mainstem dams and reservoirs were built for power generation at various times beginning in 1834. Management of non-Federal reservoirs does not affect seasonal distribution of streamflow in the ACF river system.

Methods

The objective of this report, to quantify water-level decline caused by changes in stage-discharge relations, was accomplished by comparing pre-dam stage (prior to 1954) to recent stage (1995–2004) in relation to discharge. For this comparison, it was important for estimates of pre-dam stage to be calculated using the same types of data and the same analytical methods as were used to calculate estimates of recent stage. Two types of data were available from both the pre-dam and recent period: long-term streamflow gage data and low-flow water-surface profile data. Both types of data were combined in this analysis to estimate the magnitude and extent of water-level decline at closely spaced locations along the river.

Description of Basic Data

Long-term streamflow gage records analyzed in this report are summarized in table 1. Analyses of pre-dam and recent data throughout this report were based on data at five of the six streamflow gaging stations present along the nontidal Apalachicola River: Chattahoochee, Blountstown, Wewahitchka, RM 35, and Sumatra. Data from the RM 36 gage were not used except for two daily mean values during the peak of the July 1994 flood that were adjusted for use at the RM 35 gage location. At all gages downstream from Chattahoochee, the only type of data used in this report was daily mean stage. At the Chattahoochee gage, daily mean stage, daily mean discharge, and instantaneous measurements of stage and discharge were used.

The two water-surface profiles used in this report (fig. 4) were computed by USACE for time periods when the discharge was 9,300 ft^3/s at the Chattahoochee gage. The water-surface profile used to represent recent conditions was a provisional, unpublished 1995 water-surface profile for 9,300 ft^3/s at Chattahoochee, which was prepared using HECRAS Version 3.1.2 (USACE, Mobile District, unpublished data, 2005). The profile was computed from survey data collected between May 30, 1994, and January 6, 1995, and represents existing conditions before that season's dredging, as the intention of the surveyors was to stay ahead of the dredging for that year.

Table 1. Streamflow gaging station records used for stage and discharge analyses of the Apalachicola River, Florida.

[A break in the record is indicated only when periods of missing record are greater than 1 year. River miles represent approximate distance upstream from the mouth. USGS, U.S. Geological Survey; USACE, U.S. Army Corps of Engineers]

Station name and number	Abbreviated name	Agency operating the gage	Location, in river miles	Period of record	Type of record used in this report
Apalachicola River at Chattahoochee 02358000	Chattahoochee	USGS	105.7	Oct. 1, 1928 – Sept. 30, 2004[1]	Daily mean stage Daily mean discharge Discharge measurements
Apalachicola River near Blountstown 02358700	Blountstown	USACE	77.5	Oct. 1, 1928 – Sept. 30, 2004	Daily mean stage
Apalachicola River near Wewahitchka 02358754	Wewahitchka	USACE	41.8	Oct. 18, 1955 – Sept. 5, 1957 Oct. 1, 1965 – Sept. 30, 1982 Oct. 1, 1988 – Sept. 30, 1996 Sept. 4, 1998 – Sept. 30, 2004	Daily mean stage
Apalachicola River at River Mile 36 023587547	RM 36	USACE	36.0	Nov. 14, 1991 – Sept. 30, 1996	Daily mean stage
Apalachicola River at River Mile 35 023587549	RM 35	USACE	35.3	Sept. 4, 1998 – Sept. 30, 2004	Daily mean stage
Apalachicola River near Sumatra 02359170	Sumatra	USGS	20.6	May 11, 1950 – Sept. 30, 1959 Sept. 1, 1977 – Sept. 30, 2004	Daily mean stage

[1] Chattahoochee stage data prior to December 16, 1939, were collected at the River Junction gage, which was 0.9 miles downstream from its present location. For discharge data greater than 100,000 cubic feet per second collected at the River Junction site, daily mean stage and stages associated with discharge measurements were adjusted to the present gage location and used in analyses in this report.

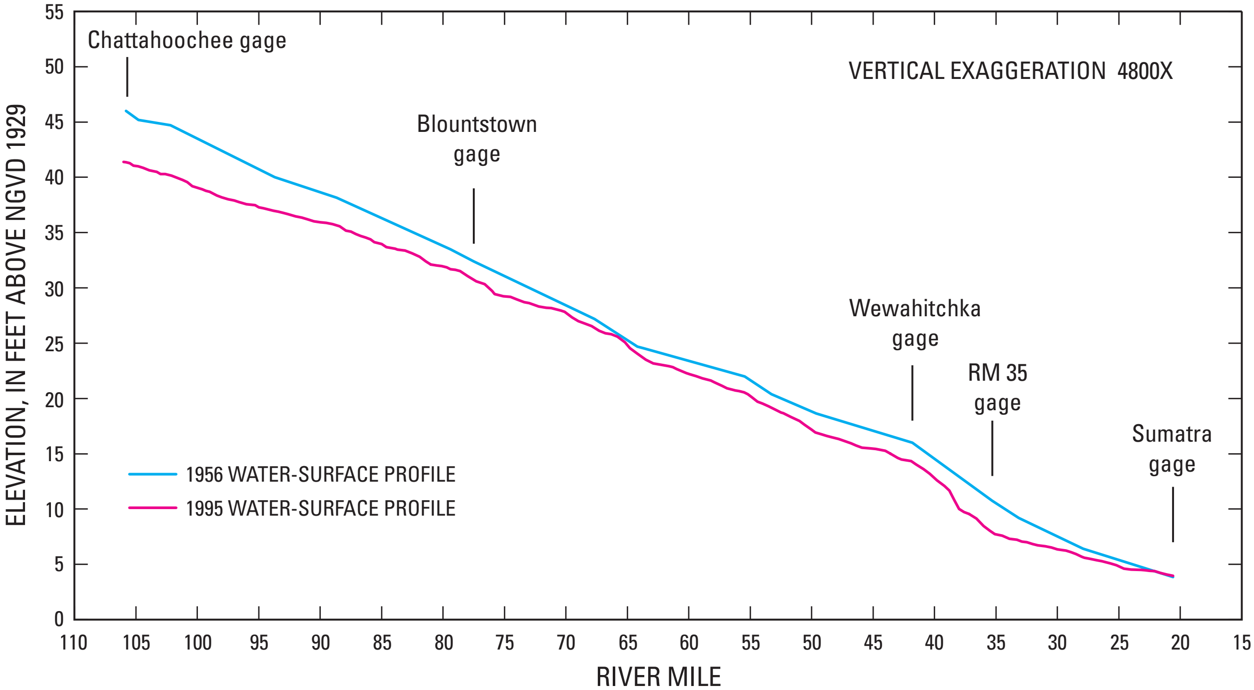

Figure 4. Water-surface profiles developed in 1956 and 1995 for the nontidal reach of the Apalachicola River, Florida, for a discharge of 9,300 ft^3/s at Chattahoochee streamgage. The 1956 water-surface profile is from Plate 43A of Design Memorandum No. 1 (U.S. Army Corps of Engineers, 1955). Design Memorandum No. 1 is dated December 15, 1955 (with transmittal to the Division Engineer December 23, 1955); however, Plate No. 43A is dated March 1956 with the notation: "This Plate is a supplement to Plate No. 43". Apparently computations for this water-surface profile were completed after the report was transmitted and were made an official supplement to the report after-the-fact. The 1995 water-surface profile is provisional (USACE, Mobile District, unpublished data, 2005).

The water-surface profile used to represent pre-dam conditions was developed in March 1956. The profile is entitled "Computed W.S. Profile after dredging, Q=9300 c.f.s." on Plate No. 43A of Design Memorandum No. 1 (USACE, 1955). Original data files for the 1956 profile were not available, so points were manually digitized from the graph. Although the length of the river has changed since 1956, the profile included the locations of eight fixed landmarks (including gage sites). The profile was adjusted between those fixed landmarks to match river locations on the present-day profile.

Dredging was conducted annually, thus profiles called "before dredging" or "after dredging" were intended to represent conditions before or after actual or planned dredging for that season. As mentioned, the 1995 profile was intended to represent conditions prior to that season's dredging. The 1956 profile, in contrast, was labeled "after dredging." A "before dredging" water-surface profile at 9,300 ft^3/s for the earlier timeframe, if it had existed, would have been preferable for our analysis. Fortunately, however, the 1956 "after dredging" profile compares favorably with average pre-dam stage from long-term gage data. Details of this comparison are discussed in the section entitled "Interpolated Stage-Discharge Relations between Streamgages."

Stage-Discharge Relations at Streamgages

Stage decline caused by channel enlargement results in a lower water level for the same amount of discharge. An appropriate method for measuring this type of water-level decline is to analyze changes in stage-discharge relations over time at streamflow gaging stations. Traditionally, this type of analysis is done by examining standard stage-discharge relations that relate stage at a particular streamgage to discharge at the same gage. The traditional method was used in this report to measure the water-level decline at the Chattahoochee gage. At a flow of 10,000 ft^3/s, the decline from pre-dam stage to recent stage at the Chattahoochee gage was 4.8 ft. (This decline was determined by comparing pre-dam and recent stage-discharge relations described in the section entitled "Pre-dam, Recent, and Period-of-Record Stage-Discharge Relations.")

The traditional method could not be used for measuring water-level decline downstream from Chattahoochee, because standard stage-discharge relations were not available for the pre-dam period at most of the downstream gages. Thus, a nonstandard approach was developed in which downstream stage was related to discharge at the upstream-most gage at Chattahoochee. This nonstandard approach allowed water-level declines to be estimated at all gage locations and at between-gage sites by the same method. Also, the ability to compare water-level declines at many different river miles to each other was greatly simplified by calculating stage at all sites in relation to discharge at a single upstream site (Chattahoochee).

Water-level decline estimated by both the traditional and nontraditional methods was compared at one downstream location (Wewahitchka gage), and results were found to be similar. At a discharge of 10,000 ft^3/s, a water-level decline of 1.6 ft was reported by the USACE using the traditional method (USACE, 2001a); a similar decline of 1.5 ft was determined by the USGS in this report using the nonstandard approach.

River stage at a streamgage is a direct result of the discharge at the gage and the channel conditions at or just downstream from that gage. Discharge at a gage also determines the stage at downstream sites, but the correlation is complicated by time-dependent factors, including the travel time of water, changing conditions of water stored on the floodplain, and tributary inflows. Thus, relations of stage at five downstream gages to discharge at the Chattahoochee gage have increasing error with increasing distance downstream. Error analyses are provided for all stage-discharge relations presented in this report so the results can be used with an understanding of their inherent limitations.

Error can be partially reduced by accounting for lag time, which is an expression of the time it takes for water passing Chattahoochee to reach a downstream location. Lag time, which can be measured in various ways, typically varies with discharge. The relation of lag time to discharge in the Apalachicola River is complex, however, because the travel time of flow in off-channel sloughs and overbank flow on the floodplain is different than in the main channel and can be variable depending upon antecedent conditions, rate of rise and fall of flood peaks, or other factors. For practical reasons, a single lag time that was approximately correct for all flows was derived for each gage downstream from Chattahoochee.

Lag times were calculated in whole days because daily mean values were used in all analyses. The most suitable lag time was determined by the following steps:

(1) For each gage, a series of two or three graphs was created in which stage at the downstream gage was related to discharge at Chattahoochee. A different lag time was used for each graph. In the first graph of the Blountstown series, for example, each Chattahoochee discharge value for a particular day was plotted in relation to the stage observed at the Blountstown gage on that same day (lag of 0 days). In the second graph, each Chattahoochee discharge value for a particular day was plotted in relation to the stage observed at the Blountstown gage on the next day (lag of 1 day).

(2) Polynomial curves were fitted to each plot in the series, and the lag time associated with the curve having the lowest root mean squared error was determined to be the most suitable lag time for that gage. The resulting "best" lag times were 1 day for the Blountstown gage, 2 days for both the Wewahitchka and RM 35 gages, and 3 days for the Sumatra gage.

Selection of Pre-dam and Recent Periods

Selection of pre-dam and recent time periods for analysis was based on an examination of the timing of water-level decline at four gages during low-flow conditions. Average annual stage at four gages for a narrow range of low discharges (9,500-10,500 ft^3/s) at Chattahoochee are shown in figure 5. Stages were averaged for each climate year (April 1–March 31) to avoid splitting low-flow periods that typically occur in summer and fall. At the Chattahoochee gage, stage data prior to 1939 are not shown because they were collected at a different location 0.9 mi downstream from the present location (see footnote in table 1). Chattahoochee stage data from 1929 to 1938 were affected by this minor location change because of the water-surface slope of the river. Chattahoochee discharge data during that time period, however, were unaffected by the movement of the gage, because tributary inflow between the two locations was too small to have a measurable effect on river discharge. Thus, stage data at the Blountstown gage from 1929 to 1938 (for Chattahoochee discharges between 9,500 and 10,500 ft^3/s) are included in figure 5, but Chattahoochee stages during that time period are not.

Annual averages in figure 5 are color coded to indicate major drought years and major flood years, based on the drought and flood years listed in tables 2 and 3. Not all of the major flood years listed in table 3 appear in figure 5, because discharges between 9,500 and 10,500 ft^3/s, which are relatively low discharges, did not occur in the following major flood years: 1948, 1949, 1964, 1966, 1973, and 1975.

The data shown in figure 5 indicate a tendency for annual averages to be lower during drought years and higher during flood years, particularly at the Blountstown and Wewahitchka gages. In most cases, the occurrence of lower stage in drought years and higher stage in flood years was probably an artifact of the method in which downstream stage is related to upstream discharge. In major flood years, wetter than normal antecedent conditions result in higher than normal stages downstream for a given Chattahoochee discharge, because water coming out of floodplain storage is added to main channel flow. For the same discharge at Chattahoochee in a drought period, the stage downstream may be lower than normal because of dry antecedent conditions with little or no water contributed from floodplain storage. Even so, a difference in antecedent conditions did not account for the drop in average stage from 1980 to 1981. It is possible that changes in sand scour and deposition patterns during severe drought could temporarily lower the riverbed. This may have occurred when the major drought of 1981 followed an unusually long period of higher than normal flows in the preceding two decades (1960–1980). Previous analyses identified 1958 to 1980 as a period when mean discharge was higher than normal regionally, not only in rivers of the ACF Basin, but also in several other southeastern rivers (Leitman and others, 1984).

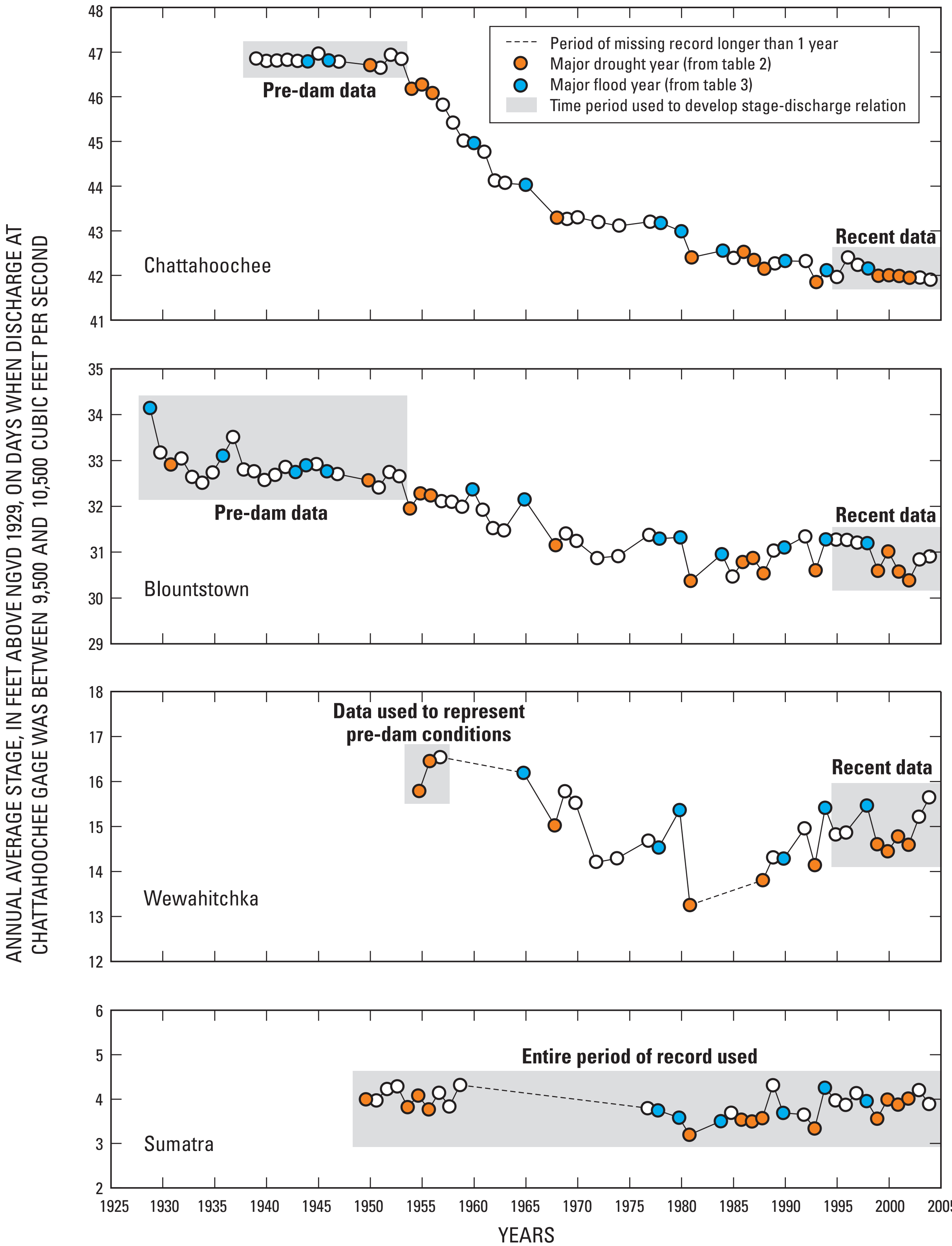

Figure 5. Time series of stage during low-flow conditions in the Apalachicola River, Florida, showing time periods used to develop stage-discharge relations. Lag times, as defined in glossary, were used to relate stage at streamgages to discharge at Chattahoochee streamgage. Annual analysis was based on climate years (April 1–March 31). Stages at Chattahoochee streamgage from 1929 to 1938 are not shown, because they were collected at a different location (see text). Not all of the major flood years listed in table 3 are shown, because discharges between 9,500 and 10,500 ft^3/s did not occur in some of those years.

Table 2. Lowest flow years in the period of record for the Apalachicola River at Chattahoochee, Florida.

[Analysis is based on climate year of April 1 to March 31 to avoid splitting low-flow periods that typically occur in summer and fall. Groups of consecutive years are shaded]

Year	Lowest mean discharge, in cubic feet per second, and rank for consecutive period indicated (rank of 1 is the lowest)					
	1 day		30 days		365 days (annual mean)	
	Discharge	Rank	Discharge	Rank	Discharge	Rank
1931	5,120	7	5,440	6		
1950					13,700	9
1954	5,010	6	5,250	3	11,400	2
1955	5,160	9	5,450	7	12,000	4
1956					13,400	7
1968					13,600	8
1981	4,980	5	5,590	8		
1986	4,430	2	5,260	4		
1987	3,900	1				
1988	4,430	3	4,680	1	11,400	3
1993	5,150	8				
1999			5,700	9	10,200	1
2000	4,530	4	4,700	2	12,900	6
2001			5,890	10	12,100	5
2002	5,250	10	5,420	5	15,100	10

Table 3. Highest flow years in the period of record for the Apalachicola River at Chattahoochee, Florida.

[Analysis is based on water year of October 1 to September 30 to avoid splitting high-flow periods that typically occur in winter and spring. Groups of consecutive years are shaded]

Year	Highest mean discharge, in cubic feet per second, and rank for consecutive period indicated (rank of 1 is the highest)					
	1 day		30 days		365 days (annual mean)	
	Discharge	Rank	Discharge	Rank	Discharge	Rank
1929	291,000	1	175,200	1	35,700	1
1936	144,000	8				
1943	142,000	9				
1944	141,000	10	86,300	6		
1946					29,400	10
1948			77,800	9	33,500	5
1949			75,000	10	35,500	2
1960	154,000	7				
1964			86,700	5	34,600	3
1965					31,100	8
1966	162,000	6	95,000	3		
1973					33,300	6
1975			83,300	7	32,700	7
1978	165,000	5				
1980			79,600	8		
1984					29,400	9
1990	177,000	4				
1994	203,000	3	92,100	4		
1998	227,000	2	97,000	2	34,600	4

Jim Woodruff Dam was completed and filling of Lake Seminole began in May 1954. Water-level decline at the Chattahoochee gage located 0.6 mi downstream from the dam began later that year, presumably as a result of riverbed degradation caused by the trapping of sediment in the lake. Consequently, data prior to May 1, 1954, were selected to represent the pre-dam period at the Chattahoochee and Blountstown gages. Because Wewahitchka had no data prior to 1954, the 2 years of stage data measured shortly afterwards (1955–1957) were used in this report as an estimate of pre-dam stage at Wewahitchka.

The so-called “recent period” was selected as the decade from October 1, 1994, to September 30, 2004. This period includes a mix of both flood and drought years, but excludes data from earlier periods when water levels were still changing (fig. 5). In the 1980s and early 1990s, stages at Chattahoochee continued to decline slightly. At Blountstown, water levels have not changed substantially since the 1970s. At Wewahitchka, data indicate that a partial recovery of the water-level decline may have occurred over the last two decades, although the amount of missing data in the 1980s at this site lends uncertainty to this assumption. Stable water levels at Blountstown and a recovery trend at Wewahitchka may have occurred because of changes that were made in the navigation project in the 1970s to reduce environmental impacts on the river ecosystem.

At the Sumatra gage, pre-dam and recent data were not differentiated, because little difference was observed in average stages between the 1950s and the most recent decade this far downstream (fig. 5). Average stages from 1977 to 1993 were slightly lower than either the earlier or later period, but considering the error associated with the relation of stage at Sumatra to discharge measured 85 mi upstream, it seemed reasonable to conduct analyses of Sumatra data on the entire period of record.

Pre-dam, Recent, and Period-of-Record Stage-Discharge Relations

Stage at multiple gages was related to discharge at Chattahoochee in 14 separate stage-discharge relations developed for the specific time periods and discharge ranges listed in table 4. The relations are shown in a single graph in figure 6, and are enlarged and shown individually in 22 graphs in appendixes I through V. The difference between pre-dam and recent stage is greatest at low flows and decreases with increasing flow. Pre-dam and recent relations come together at a high discharge referred to in this report as the joining point, which varies among the gage sites principally by decreasing discharge in the downstream direction. The joining point represents the discharge above which physical changes that occurred in the main river channel have had no noticeable effect on river stage. Effects of channel change disappear when most of the flow is out of bank and moving over the floodplain. Stage-discharge relations during overbank flows can change in response to changes in floodplain elevation or

Table 4. Time periods, range of discharges, and other information about stage-discharge relations developed from long-term streamgage data for analysis of water-level decline in the Apalachicola River, Florida.

[Stage-discharge relations developed for this report relate stage at all gages to discharge at Chattahoochee gage using lag time as indicated below and as defined in glossary. Relations were developed only for the specific time period and range of discharges indicated. Breaks in the time period are indicated only when periods of missing record are greater than 1 year. Pre-dam and recent ratings merge at a relatively high flow, referred to in this report as the “joining point,” which is further described in the text. n, number of values used in relation. ft^3/s, cubic feet per second]

River mile location	Name of stage-discharge relation	Daily mean values used (or other data as indicated)		Range of discharges for which relation was developed, in ft^3/s	Joining point flow, in in ft^3/s	Lag time, in days
		Time period	n			
105.7	Chattahoochee pre-dam	Dec. 1939 – April 1954	5,269	5,000 – 188,000	188,000	0
	Chattahoochee recent	Oct. 1994 – Sept. 2004	3,579	5,000 – 188,000		
	Chattahoochee period of record (for flows greater than 188,000 ft^3/s)	Oct. 1928 [1] – Sept. 2004	17	188,000 – 291,000		
77.5	Blountstown pre-dam	Oct. 1928 – April 1954	9,313	5,000 – 135,000	135,000	1
	Blountstown recent	Oct. 1994 – Sept. 2004	3,598	5,000 – 135,000		
	Blountstown period of record (for flows greater than 35,000 ft^3/s)	Oct. 1928 – Sept. 2004	55	135,000 – 291,000		
41.8	Wewahitchka pre-dam	Oct. 1955 – Sept. 1957	677	5,000 – 65,000	65,000	2
	Wewahitchka recent	Oct. 1994 – Sept. 1996; Sept. 1998 – Sept. 2004	2,517	5,000 – 65,000		
	Wewahitchka period of record (for flows greater than 65,000 ft^3/s	Oct. 1955 – Sept. 1957; Oct. 1965 – Sept. 1982; Oct. 1988 – Sept. 1996; Sept. 1998 – Sept. 2004	364	65,000 – 203,000		
35.3	RM 35 estimated pre-dam	Three values from 1951, 1954, and 1956 water-surface profiles (USACE, U.S. Army Corps of Engineers, 1955)		5,000 – 52,000	52,000	2
	RM 35 recent	Sept. 1998 – Sept 2004	2,096	5,000 – 100,000 [2]		
	RM 35 estimated high flow	Two daily mean values during peak of July 1994 flood, adjusted from RM 36 gage		100,000 – 203,000		
20.6	Sumatra period of record (for flows less than 100,000 ft^3/s) [3]	May 1950 – Sept. 1959; Sept. 1977 – Sept. 2004	12,635	5,000 – 100,000	25,000 [4]	3
	Sumatra period of record (for flows greater than 100,000 ft^3/s) [3]	May 1950 – Sept. 1959; Sept. 1977 – Sept. 2004	39	100,000 – 227,000		

[1] Stage data collected prior to December 1939 at the River Junction gage site (about 0.9 mile downstream from the present Chattahoochee gage location) were adjusted using methods described in the text, so that data from the record flood of 1929 could be used in development of this relation.

[2] The entire RM 35 recent relation was based on recent data; however, because of a lack of data in other time periods, the part of this relation above the joining point of 52,000 ft^3/s was used in analyses to represent the period-of-record relation (which assumes no difference between pre-dam and recent stage above 52,000 ft^3/s).

[3] The period-of-record relation at Sumatra was divided into an upper and lower relation because of the difference in sample sizes (n). Error statistics vary widely between the two discharge ranges.

[4] Although no differentiation was made at the Sumatra gage between pre-dam and recent stage, an estimated joining point was needed for calculating interpolated relations between the RM 35 and Sumatra gages.

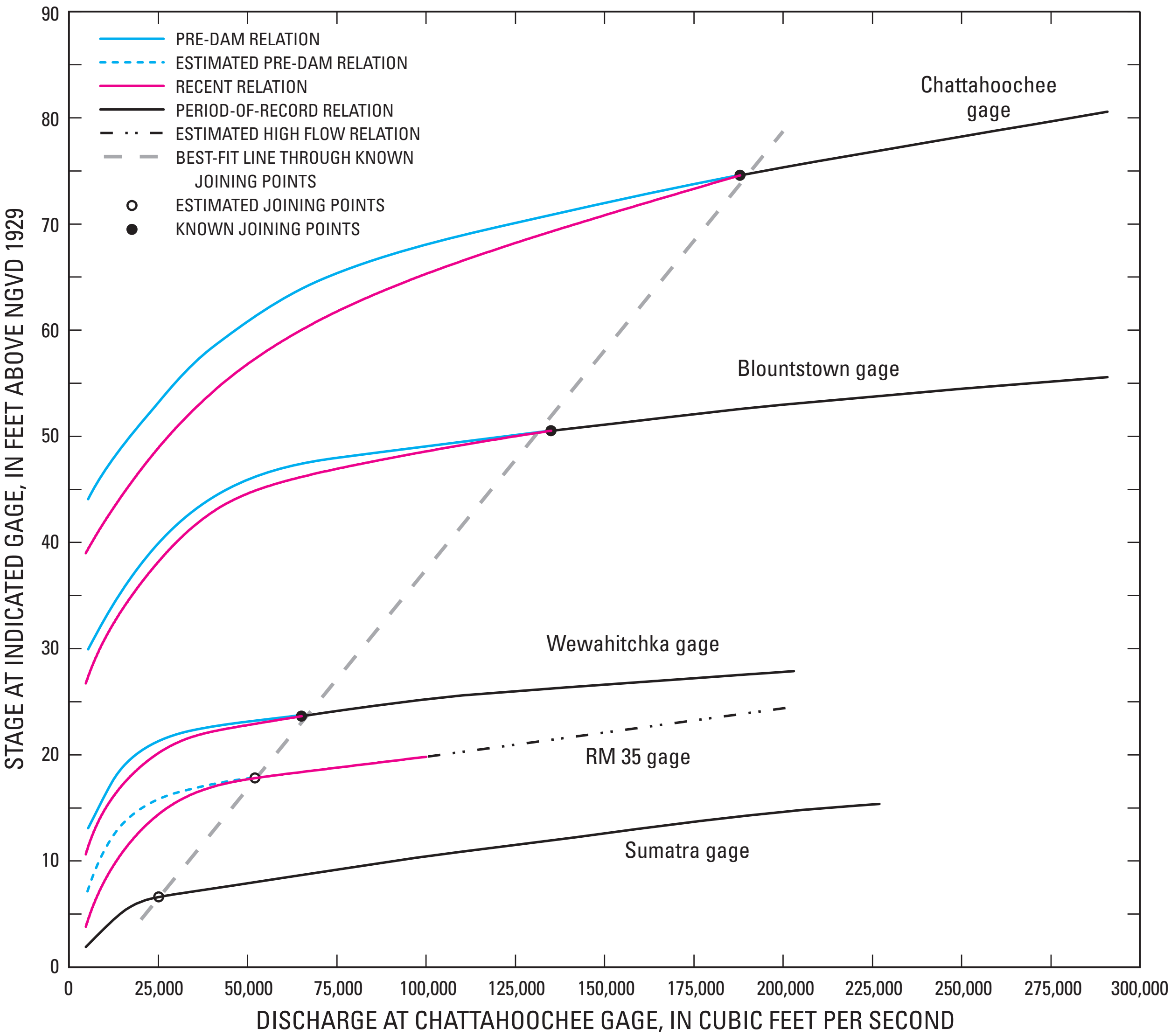

Figure 6. Stage at five streamgages on the Apalachicola River in relation to discharge at Chattahoochee, Florida, with known and estimated joining points for pre-dam and recent relations. Relations at streamgages downstream from Chattahoochee were developed using lag times as defined in glossary. An estimated joining point was needed for Sumatra, even though there is only one curve at that site, so that interpolated pre-dam and recent relations could be developed between RM 35 and Sumatra.

hydraulic roughness (changes in land use, forest maturity, or installation or removal of roadway embankments). These factors, however, have not changed enough along this river in 50 years (1954–2004) to cause a noticeable change in stage at high flow.

Stage-discharge relations at Chattahoochee, Blountstown, and Wewahitchka had joining points determined from actual data that were 188,000, 135,000, and 65,000 ft^3/s, respectively. A best-fit straight line was drawn through these three known points on figure 6 and projected "downward" to estimated joining points at RM 35 and Sumatra, namely where the best-fit line intersected the stage-discharge relation for those two downstream sites. The joining point at RM 35 gage (52,000 ft^3/s) was used to estimate the RM 35 pre-dam relation, which is described later in this section. Although Sumatra had only one relation (for the whole period of record), the joining point at the Sumatra gage (25,000 ft^3/s) was needed for calculating interpolated pre-dam and recent relations between the RM 35 and Sumatra gages, which are discussed in the section entitled "Interpolated Stage-Discharge Relations between Streamgages."

Several factors probably contribute to the magnitude of the joining point flow at any particular location, including the amount of channel enlargement, the elevation of the floodplain, and the ratio of main channel width to floodplain width. Actual and estimated stages at joining points in relation to

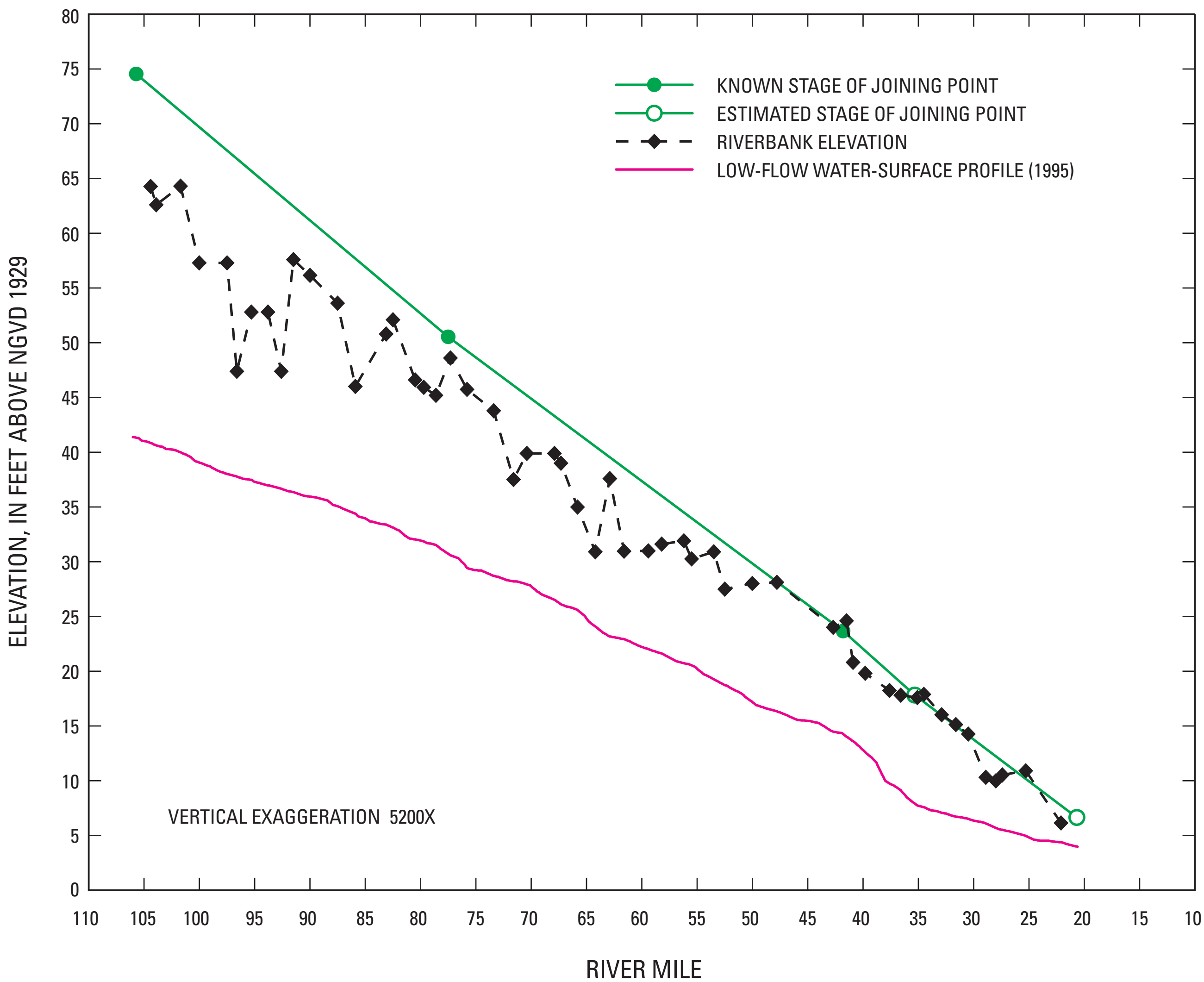

Figure 7. Stage of joining points in relation to riverbank elevation and water surface at low flow in the Apalachicola River, Florida. Procedures for determining joining points (the points at which pre-dam and recent stage-discharge relations merge) are described in the text, and these points are graphically illustrated on figure 6. Riverbank elevations are the top-of-bank elevations on the lowest side of surveyed cross sections (U.S. Army Corps of Engineers, 2001a). The 1995 low-flow water-surface profile was developed for 9,300 ft^3/s at Chattahoochee and is provisional (USACE, Mobile District, unpublished data, 2005).

riverbank heights from 53 main-channel cross-section surveys are shown in figure 7 (USACE, 2001a). Bank heights in any given cross section are typically higher on one side of the river than the other. The bank heights used in figure 7 are the bank elevations of the low side in each cross section.

Figure 7 shows that the joining point stage is 10 ft above bank level in the upper reach and gradually decreases downstream until the joining point stage is essentially the same as bank level in the nontidal lower reach. This progressive lowering of the relative elevation of the joining point stage is probably due to the following reasons. The width of the main channel at Chattahoochee is about 10 percent of the width of the floodplain, whereas the width of the main channel in the nontidal lower reach is only about 1 percent of the width of the floodplain (fig. 2). In addition, in the lower reaches of the river, a substantial amount of river water leaves the main channel and is carried by large side-channel streams even during low-flow conditions. Lastly, the amount of channel enlargement that has occurred is greater at Chattahoochee than in the nontidal lower reach, as evidenced by the difference between pre-dam and recent stage-discharge relations at low flow (fig. 6). Because of these differences, the main channel in the upper reach conveys a relatively large proportion of the discharge during overbank flows and, therefore, water-level decline caused by channel change in the upper reach is still evident when water levels rise well above bank height.

The 22 graphs in appendixes I through V are arranged in pairs with two different scales on the horizontal (discharge) axis. The first graph in each pair has a horizontal axis showing the full range of discharge (from 0 to either 220,000, 240,000, or 300,000 ft^3/s, depending upon data available for that gage). The second graph in each pair has a horizontal axis showing discharges up to 60,000 ft^3/s only. Two pairs of graphs (A–B and C–D) are provided for every gage with an additional third pair of graphs for the Chattahoochee gage (E–F). Graphs A and B show the relations with averages of daily mean values in selected discharge increments. Increment sizes were 1,000 ft^3/s for discharges up to about 30,000 ft^3/s and increased with increasing discharges greater than 30,000 ft^3/s. Increment sizes at the highest discharges were optimized to accommodate small sample sizes. Graphs C and D show the relations with daily mean values.

Graphs E and F in appendix I (Chattahoochee) show the relations developed for this report with individual discharge measurements and with the two USGS ratings used in the recent period for computing published discharges. At gaging stations, discharge measurements are routinely conducted at various times during the year to directly determine the volumetric rate of flow (discharge) of the river. Discharge measurements are the basic data from which standard stage-discharge ratings are created. Graphs E and F are included as a check to show how relations developed for this report compare with the original data that were used to estimate daily mean discharge values at Chattahoochee.

All of the stage-discharge relations (except the pre-dam relation for RM 35) were made by fitting a hand-drawn line through the averages of daily mean values in selected discharge increments (shown in graphs A and B in apps. I–V). The points defining the hand-drawn line were manually digitized, then entered into a curve-fitting software program to generate a formula for the line (app. VI) and error statistics on the fit of the line to the daily mean values (table 5). The average ranges of 95-percent confidence limits for stage-discharge relations are 0.04 ft at 10,000 ft^3/s, 0.10 ft at 50,000 ft^3/s, and 0.44 ft at various high flows ranging from 100,000 to 250,000 ft^3/s (table 5).

Three stage-discharge relations (Chattahoochee pre-dam relation, Chattahoochee period of record relation for high flows, and RM 35 estimated relation for high flows) included some daily mean values that were collected at nearby sites less than a mile away.

(1) The Chattahoochee pre-dam relation was based primarily on stage and discharge data from December 16, 1939, to April 30, 1954, when the Chattahoochee gage was located at the US 90 highway bridge (its present location). From October 1, 1928, to December 15, 1939, the gage was located at the railroad bridge at River Junction, about 0.9 mi downstream from its present location. River Junction daily mean values greater than 100,000 ft^3/s were adjusted to account for the drop in stage from the US 90 bridge to the railroad bridge and were added to the 1939–1954 data to improve the pre-dam relation at higher flows. This correction, which increased with discharge and ranged from 0.89 ft at 100,000 ft^3/s to 1.09 ft at 291,000 ft^3/s, was determined from a comparison of stages at River Junction and the present gage for similar discharges, and from water-surface slope calculations between the Chattahoochee and Blountstown gages.

(2) Adjusted River Junction daily mean values were also added to the data used to create the period of record relation for high flows greater than 188,000 ft^3/s at Chattahoochee. Two discharge measurements made prior to 1939 were adjusted to the present gage location and are included in graph E of appendix I.

(3) The RM 35 estimated relation for high flows was based on two daily values that were adjusted from measured values at the RM 36 gage, which was located 0.7 mi upstream from the RM 35 gage. These two values occurred during the peak of the July 1994 flood.

Methods for estimating the RM 35 pre-dam relation are illustrated in figure 8. The first step involved the development of a pre-dam straight-line distance interpolation relation which was estimated by the following calculation. The river-mile distance from the Wewahitchka gage to the RM 35 gage was divided by the total river-mile distance from the Wewahitchka gage to the Sumatra gage. The resulting proportion was then multiplied by the difference between the Wewahitchka stage and the Sumatra stage for each discharge increment, and subtracted from the Wewahitchka pre-dam stage to yield the straight-line distance interpolation stage for RM 35 for that discharge.

The RM 35 pre-dam straight-line distance interpolation relation, although helpful as a guide, could not be used "as is" because it did not account for the fact that the slope from Wewahitchka to RM 35 is steeper than any other reach of the river. The RM 35 pre-dam relation was estimated at the low end using actual data consisting of three stage values from water-surface profiles developed for Chattahoochee discharges of 5,860 ft^3/s (October 1954), 7,340 ft^3/s (August 1951), and 9,300 ft^3/s (March 1956) (USACE, 1955). At the high end, the relation was drawn through the estimated joining point of 52,000 ft^3/s from figure 6. The remainder of the RM 35 pre-dam relation between 9,300 and 52,000 ft^3/s was visually estimated using the RM 35 recent relation as a lower guide and a RM 35 pre-dam straight-line distance interpolation relation as an upper guide.

Table 5. Error statistics for stage-discharge relations developed from long-term streamgage data on the Apalachicola River, Florida.

[Stage-discharge relations developed for this report relate stage at all gages to discharge at Chattahoochee gage using lag times as defined in glossary. Relations were developed only for the specific range of discharges indicated. Error statistics could not be generated for the RM 35 estimated pre-dam and RM 35 estimated high flow relation, because they were visually estimated from limited data. n, number of daily mean values used to create relation; ft, feet; ft^3/s, cubic feet per second]

Name of stage-discharge relation	Range of discharges for indicated relation, in ft^3/s	n	Fit of relation to daily mean values			Range of 95-percent confidence limits at selected discharges[2]		
			R^2	Root mean square error[1]	F statistic	Range (+/-), in ft	at	Discharge, in ft^3/s
Chattahoochee pre-dam	5,000 – 188,000	5,269	0.998	0.21	568,933	0.01	at	10,000
						0.02	at	50,000
Chattahoochee recent	5,000 – 188,000	3,579	0.997	0.33	173,715	0.02	at	10,000
						0.03	at	50,000
Chattahoochee period of record (for flows greater than 188,000 ft^3/s)	188,000 – 291,000	17	0.984	0.26	440	0.18	at	200,000
						0.23	at	250,000
Blountstown pre-dam	5,000 – 135,000	9,313	0.993	0.40	247,816	0.01	at	10,000
						0.03	at	50,000
Blountstown recent	5,000 – 135,000	3,598	0.980	0.74	30,049	0.04	at	10,000
						0.10	at	50,000
Blountstown period of record (for flows greater than 135,000 ft^3/s)	135,000 – 291,000	55	0.940	0.39	194	0.21	at	200,000
						0.38	at	250,000
Wewahitchka pre-dam	5,000 – 65,000	677	0.949	0.68	2,491	0.11	at	10,000
						0.29	at	50,000
Wewahitchka recent	5,000 – 65,000	2,517	0.967	0.64	12,354	0.04	at	10,000
						0.12	at	50,000
Wewahitchka period of record (for flows greater than 65,000 ft^3/s	65,000 – 203,000	364	0.809	0.40	251	0.12	at	100,000
						0.22	at	150,000
RM 35 recent	5,000 – 100,000	2,096	0.968	0.69	10,524	0.05	at	10,000
						0.16	at	50,000
Sumatra period of record (for flows less than 100,000 ft^3/s)	5,000 – 100,000	12,635	0.922	0.49	21,349	0.02	at	10,000
						0.03	at	50,000
Sumatra period of record (for flows greater than 100,000 ft^3/s)	100,000 – 227,000	39	0.511	1.46	9	0.97	at	150,000
						1.21	at	200,000
			Averages at selected discharges			0.04	at	10,000
						0.1	at	50,000
						0.44	at	various discharges from 100,000–250,000

[1] Also known as fit standard error.

[2] Because confidence limits vary with discharge, two values were selected for each relation to indicate the typical range.

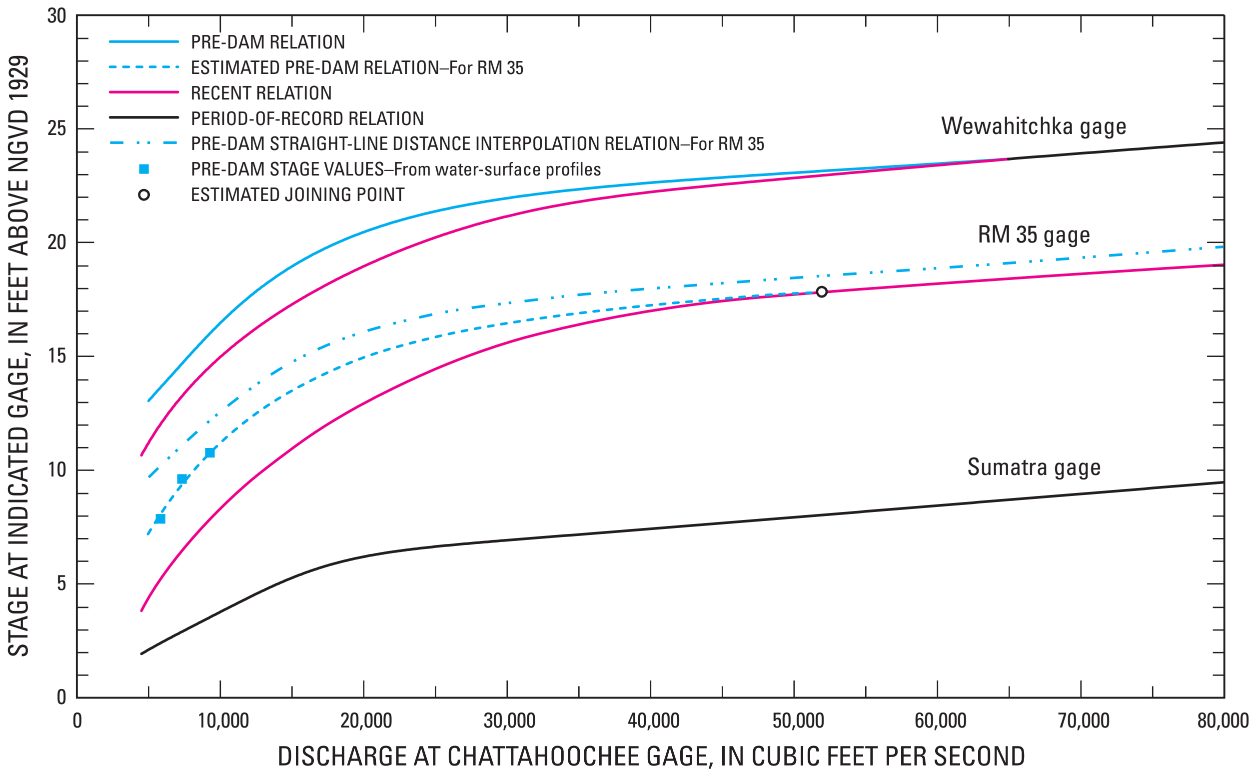

Figure 8. Data used to estimate pre-dam stage at the RM 35 streamgage in relation to discharge in the Apalachicola River at Chattahoochee, Florida. The RM 35 pre-dam stage-discharge relation was drawn through three pre-dam stage values from water-surface profiles, then visually estimated to join the recent relation at the estimated joining point, using the recent relation as a lower guide and the pre-dam straight-line distance interpolation relation (calculated from pre-dam Wewahitchka and Sumatra relations) as an upper guide. The estimated pre-dam relation does not coincide with the pre-dam straight-line distance interpolation relation for reasons discussed in text. Relations were developed using lag times as defined in glossary.

Interpolated Stage-Discharge Relations between Streamgages

Two types of data were combined to produce interpolated stage-discharge relations between the gages. Stage-discharge relations at gages provide detailed information about stages that might be expected at all discharges ranging from lowest to highest, but only near gage locations. Water-surface profiles provide detailed information about stages at all locations, but only for a single discharge (9,300 ft^3/s).

Water-surface profile data and long-term gage data compare favorably at the gage locations (fig. 9). Differences between the two types of data at the gage locations are listed in table 6. The average difference is 0.19 ft after adjusting for an explainable error at Chattahoochee that applies only to a limited distance in the vicinity of that site. The error at Chattahoochee occurred because the pre-dam water-surface profile was developed in 1956 after more than one-half foot of decline had already occurred at the gage from riverbed degradation resulting from the trapping of sediment in Lake Seminole. Adjustments for this local error, shown in parentheses in table 6, were calculated using the following steps:

(1) An adjusted value for pre-dam long-term gage data at the Chattahoochee gage (45.84 ft) was calculated by averaging all stages that occurred at discharges between 8,800 and 9,800 ft^3/s (9,300 ±500 ft^3/s) from 1954 to 1956.

(2) A difference of 0.08 ft for Chattahoochee pre-dam data was determined from the difference between the adjusted value for pre-dam long-term gage data (45.84 ft) and the 1956 water-surface profile data (45.92 ft).

(3) The average of all differences (0.19 ft) was calculated using 0.08 ft for the pre-dam Chattahoochee difference (instead of 0. 57 ft).

Water-surface profiles are compared to straight-line interpolations of stage between all gages except RM 35 in figure 9. Over most of the river's length, the results of the two methods compare favorably. In the nontidal lower reach, however, straight-line interpolation without the benefit of RM 35 data results in large errors in both the actual stage and the magnitude of the water-level decline. The problem is that the two largest changes in water-surface slope in the entire 85 mi of

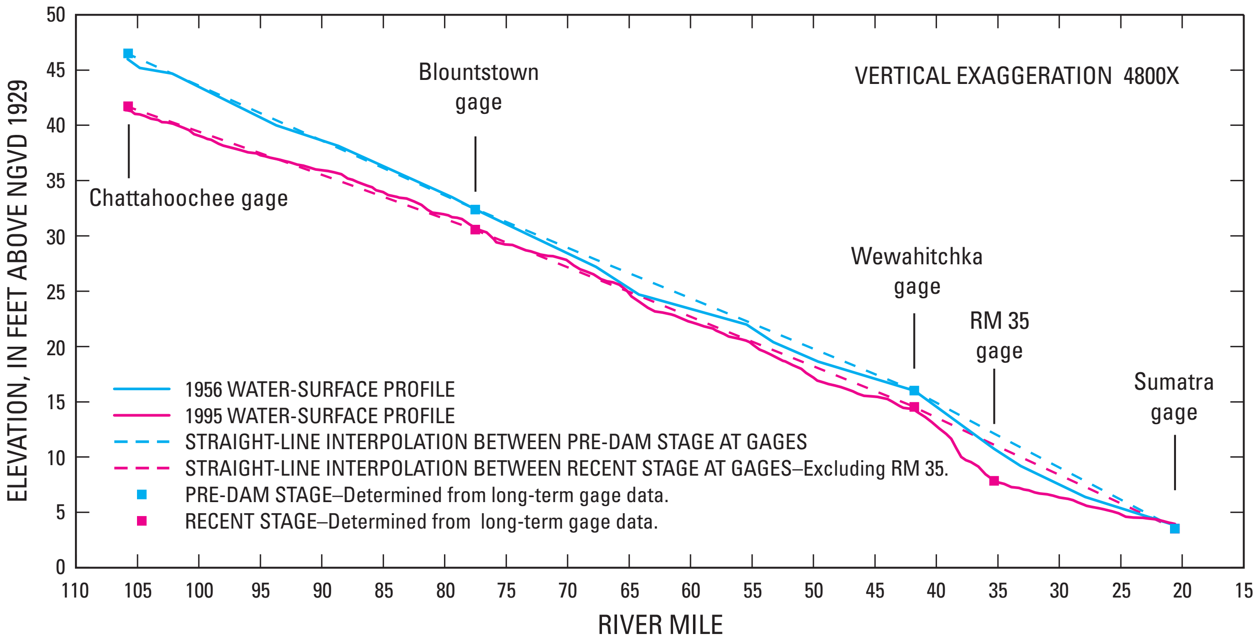

Figure 9. Comparison of water-surface profiles and stage values from long-term streamgage data for the nontidal reach of the Apalachicola River, Florida. All profile and stage data represent water levels at a Chattahoochee flow of 9,300 ft^3/s using approximate lag times defined in glossary. Water-surface profiles were computed by U.S. Army Corps of Engineers (see fig. 4). Pre-dam and recent stages from long-term streamgage data are from stage-discharge relations developed for this report.

Table 6. Comparison of stage in water-surface profiles to stage at long-term streamgages on the Apalachicola River, Florida.

[Stage from long-term gage data were determined using stage-discharge relations developed in this report, except for the values in parentheses, which reflect an adjustment for a local error at Chattahoochee (see discussion in text). Although this local error could not be corrected in the interpolated relations between gages developed for this report, average difference based on the adjusted value in parentheses better represents river-wide error in the water-surface profile data. ft^3/s, cubic feet per second; +/-, plus or minus; USACE, U.S. Army Corps of Engineers]

Gage	Time period	Stage at indicated gage, in feet, for discharge of 9,300 ft^3/s at Chattahoochee gage[1]		Difference (+/-), in feet
		From long-term gage data	From water-surface profiles[2]	
Chattahoochee	Pre-dam	46.49 (45.84)[3]	45.92	0.57 (0.08)[3]
	Recent	41.72	41.33	0.39
Blountstown	Pre-dam	32.38	32.40	0.02
	Recent	30.57	30.72	0.15
Wewahitchka	Pre-dam	16.00	16.00	0.00
	Recent	14.54	14.27	0.27
RM 35	Recent	7.84	7.89	0.05
Sumatra	Pre-dam	3.54[4]	3.85	0.31
	Recent		3.97	0.43
			Average	0.24 (0.19)[3]

[1] Stage at gages downstream from Chattahoochee were determined using lag times as defined in glossary.
[2] Pre-dam profile is from Plate No. 43A of Design Memorandum No. 1 (USACE, 1955). Recent profile is provisional, unpublished data (USACE, written commun., 2005).
[3] Values in parentheses were adjusted for a local error at Chattahoochee based on methods described in text.
[4] Pre-dam and recent periods were not distinguished at Sumatra because they were similar. This value is based on the period of record at this gage.

the nontidal river occur at the Wewahitchka and RM 35 gages. From Wewahitchka to RM 35 is a 6.5-mi reach with the steepest slope in the entire nontidal river, and downstream from RM 35 is a 14.7-mi reach with the lowest slope. For this reason, all available data were used to estimate a pre-dam stage-discharge relation at RM 35 (fig. 8). Admittedly, this estimated relation has considerable uncertainty associated with it; however, figure 9 demonstrates why the use of an estimated pre-dam RM 35 stage-discharge relation, along with its companion for the recent period, is a better method for interpolating stage-discharge relations between Wewahitchka and Sumatra than a method that excludes the RM 35 data.

Interpolated stage-discharge relations for estimating stage at all locations between gages (at every 0.1 rm) in relation to discharge at Chattahoochee were developed using a series of interpolation formulas that varied among three flow ranges (low, intermediate, and high). In the low-flow range (9,300 ft^3/s and less), the interpolation formulas use slope calculations based on stage data in water-surface profiles (app. VII.A). In the high-flow range (joining-point flow and greater), the formulas use slope calculations based on straight-line river-mile-distance interpolations between gages (app. VII.B). In the intermediate-flow range (between 9,300 ft^3/s and the joining-point flow), the formulas generate a mathematically smoothed curve beginning at the water-surface profile stage for 9,300 ft^3/s and ending at the straight-line river-mile-distance interpolated stage (averaged from both pre-dam and recent relations) at the joining-point flow (app. VII.C).

Selected examples of interpolated relations in each reach shown in figure 10 help explain how the formulas in appendix VII operate. Known stage for 9,300 ft^3/s from water-surface profiles are identified in each interpolated rating to show the data upon which the low end of the relation was based (fig. 10). One of the examples in figure 10B, head of Sand Slough at rm 65.2, was chosen to show pre-dam and recent stage at a location where little water-level decline occurred, based on the water-surface profiles in figure 9. Three of the examples, mouth of Flat Creek (fig. 10A), mouth of stream to Porter Lake (fig. 10B), and head of Moccasin Slough (fig. 10C), are discussed further in the "Results and Discussion" section. Although this report does not specifically address water-level decline in the lower Chipola River, two of the relations shown in figure 10C can be used to determine decline at the upper and lower end of that river: (1) at the Wewahitchka gage, located close to the head of the Chipola River Cutoff, which feeds the upper end of the lower Chipola River; and (2) at the mouth of the lower Chipola River at rm 27.9.

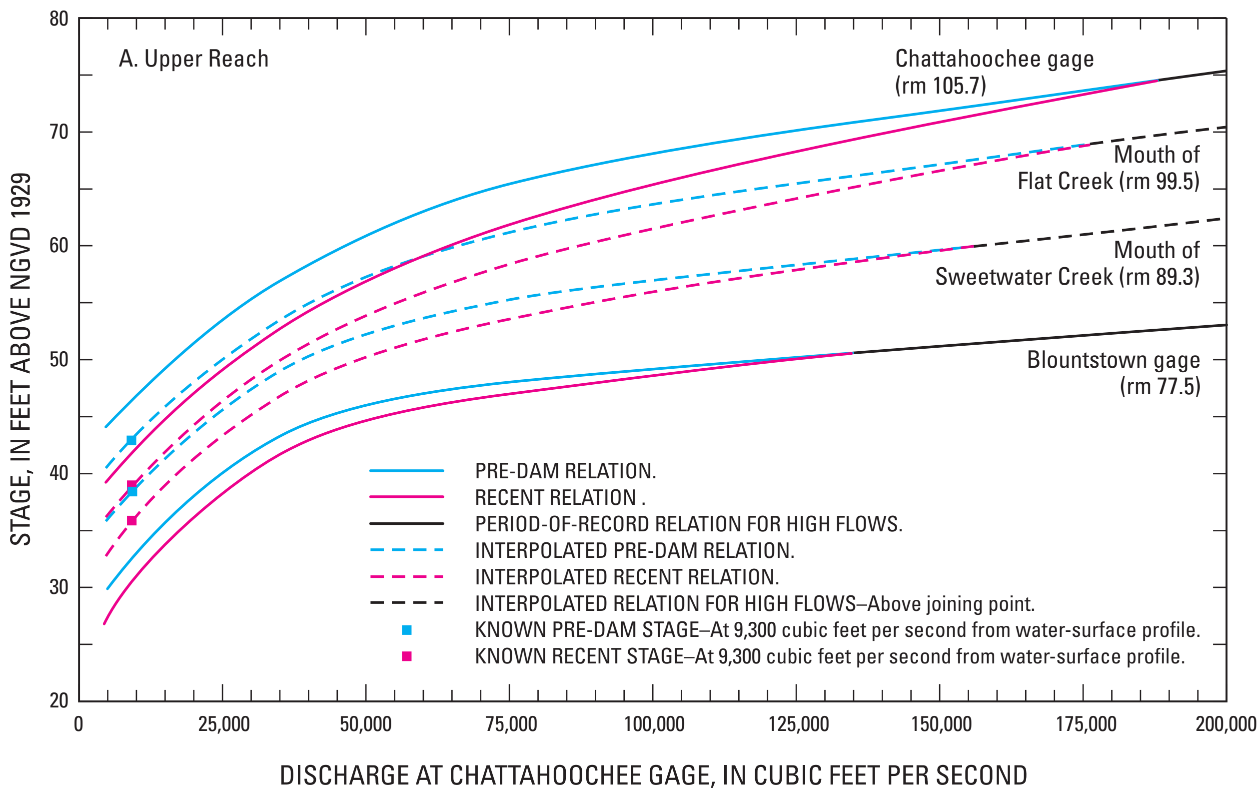

Figure 10. Interpolated stage at selected sites between streamgages in relation to discharge in the Apalachicola River at Chattahoochee, Florida, in (A) upper reach, (B) middle reach, and (C) nontidal lower reach. Relations at streamgages downstream from Chattahoochee were developed using lag times as defined in glossary. Range of stage and discharge shown on axes varies among the three graphs to focus on flows below joining points in each reach.

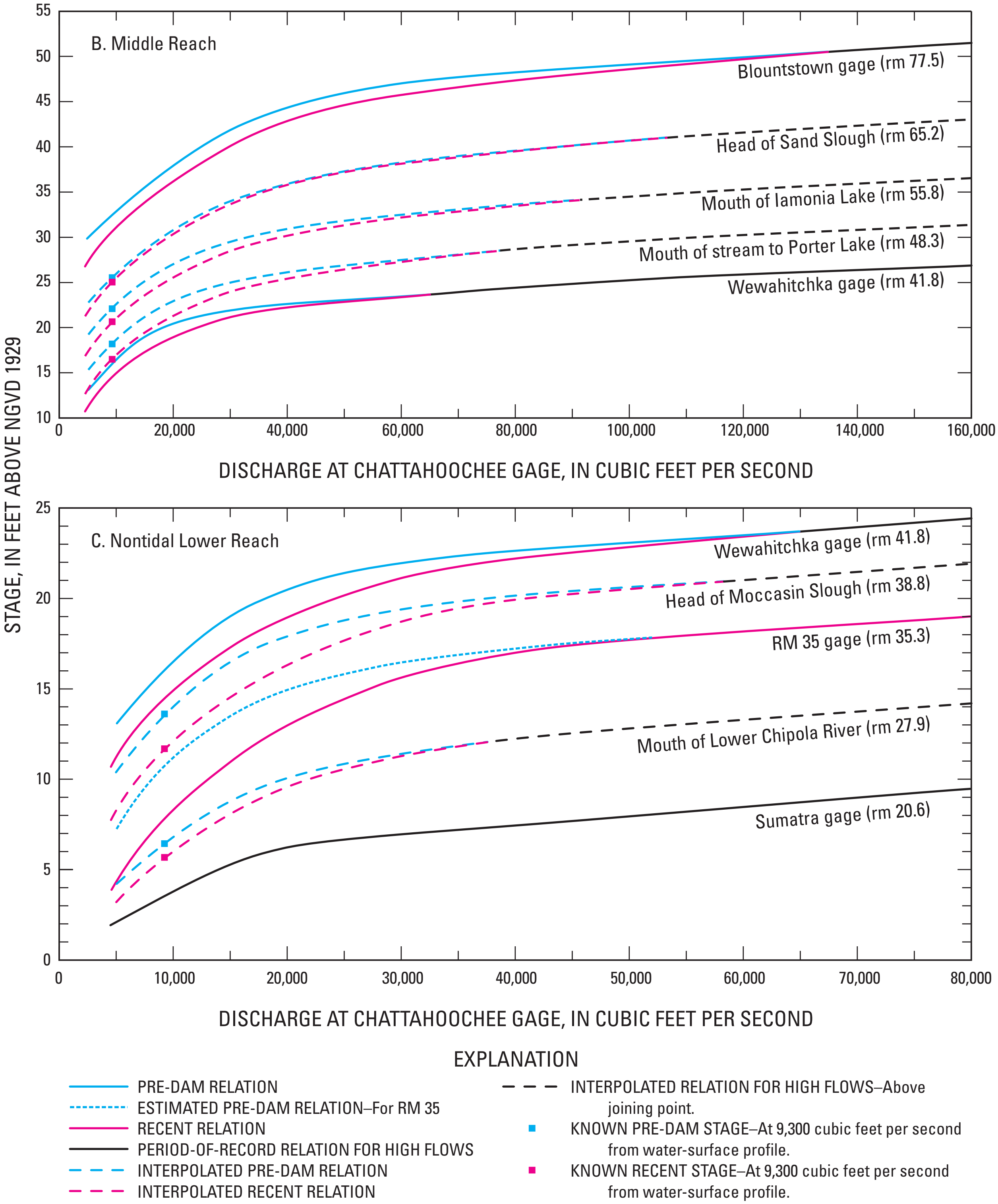

Figure 10. (Continued) Interpolated stage at selected sites between streamgages in relation to discharge in the Apalachicola River at Chattahoochee, Florida, in (A) upper reach, (B) middle reach, and (C) nontidal lower reach. Relations at streamgages downstream from Chattahoochee were developed using lag times as defined in glossary. Range of stage and discharge shown on axes varies among the three graphs to focus on flows below joining points in each reach.

Errors associated with the interpolation methods cannot be quantified, but an additional analysis of the methods used to interpolate between-gage relations shows hypothetical worst-case error in a comparison of test cases (fig. 11). In this figure, stage-discharge relations at three gages based on actual data from long-term records are compared to hypothetical cases in which the gage data were ignored and the relation was developed by the interpolation methods used in this report. At the Blountstown gage site, for example, interpolated stage-discharge relations were developed from data at the Chattahoochee and Wewahitchka gages, ignoring the existing data from the Blountstown gage. Similarly, interpolated stage-discharge relations were developed at the Wewahitchka site using Blountstown and Sumatra gage data, and at the RM 35 site using Wewahitchka and Sumatra gage data.

The departures shown in the hypothetical worst-case tests in figure 11 are greater than would be expected for the between-gage interpolated relations for three reasons:

(1) In two test cases, Blountstown and Wewahitchka, it was assumed that gage data did not exist and interpolations were conducted over long distances, 63.9 and 56.9 rm respectively. The actual distances over which interpolations were made are considerably shorter (28.2, 35.7, 6.5, and 14.7 rm).

(2) In two test cases, Wewahitchka and RM 35, information about the nearby (and large) slope changes on the river are ignored, whereas actual calculations include information that accounts for these slope changes.

(3) Error resulting from the interpolation method approaches zero near the gages, so the departures of the type shown on figure 11 would not apply to the relations for sites close to gages.

Stage-discharge relations defined by a set of paired discharge and stage values are listed in digital table files for each gage site and for each site spaced every 0.1 rm between the gages. These digital files are on the compact disk (CD) in the map pocket of this report and a description of their contents is provided in appendix VIII. The files on the CD contain a total of 1,704 relations (5 pre-dam and 5 recent relations at gages, plus 847 interpolated pre-dam and 847 interpolated recent relations between gages). Each relation is defined by about 500 points at the discharge increments shown in the annotated example in appendix VIII.A. Appendixes VIII.B and C describe the organization of files in EXCEL format and flat file format, respectively.

Developing a list of points that define each relation was determined to be the most practical way to generate and present large numbers of stage-discharge relations that are provided on the CD. Future users of these data can easily convert selected point lists to equations for stage-discharge relations using any curve-fitting software (similar to those listed in app. IV), and can then use those equations to estimate water-level decline at specific locations in the nontidal river for any discharge. The methods presented in this report, and the interpolated (between-gage) stage-discharge relations provided on the CD, were developed primarily for the purpose of making reasonable estimates of the amount of water-level decline that occurred between the pre-dam period and the recent period. The interpolated relations may be useful for other purposes, but the methods and inherent assumptions used to develop the relations should be evaluated before these relations are used for other applications.

Water-Level Decline and Floodplain Effects

The magnitude of water-level decline at a particular location is the difference between the pre-dam and recent stage-discharge relations at that site. An example of this difference using pre-dam and recent relations at the Chattahoochee gage is shown in figure 12. For a given discharge, the recent stage minus the pre-dam stage yields the change in water level at that discharge. At the Chattahoochee gage, the decline is greatest at low discharges and systematically decreases with increasing discharge. This same trend, with a few minor exceptions, occurs at the other gages as well. At all locations, the amount of the decline decreases to zero at the joining point where pre-dam and recent relations merge (not shown in fig. 12). Water-level declines attributable to channel change were calculated at closely spaced locations (every 0.1 rm) for 14 selected discharges to show variation at different locations under different flow conditions.

Approximate Decrease in Duration of Inundation Caused by Channel Change

Impacts of water-level decline on biological habitats and communities in the floodplain cannot be adequately determined from direct measurements of water-level decline alone. Statistics derived from streamflow records, such as changes in the duration or frequency of inundation, are necessary for describing changes in long-term hydrologic conditions on the floodplain. The following methods were used to calculate the approximate decrease in duration of inundation attributable to channel change, which is used in several analyses in this report.

The first step in determining the decrease in duration of inundation is to calculate what is informally referred to as “equivalent-stage discharge.” In the example in figure 13, the selected discharge of 15,000 ft^3/s at the Chattahoochee gage had a pre-dam stage of 49.22 ft, and 25,700 ft^3/s is the “equivalent-stage discharge” in the recent period with that same water-surface elevation. Another way of describing this concept is that an additional 10,700 ft^3/s would be required in the recent period to replicate the stage associated with 15,000 ft^3/s during the pre-dam period.

The next step is to determine the percent exceedance for both the initial selected discharge and its corresponding equivalent-stage discharge. “Percent exceedance” is the term commonly used to describe the percentage of time that a specified streamflow discharge is equaled or exceeded during a given time period. Percent exceedance is used to determine “percent duration of inundation,” which is the percentage of

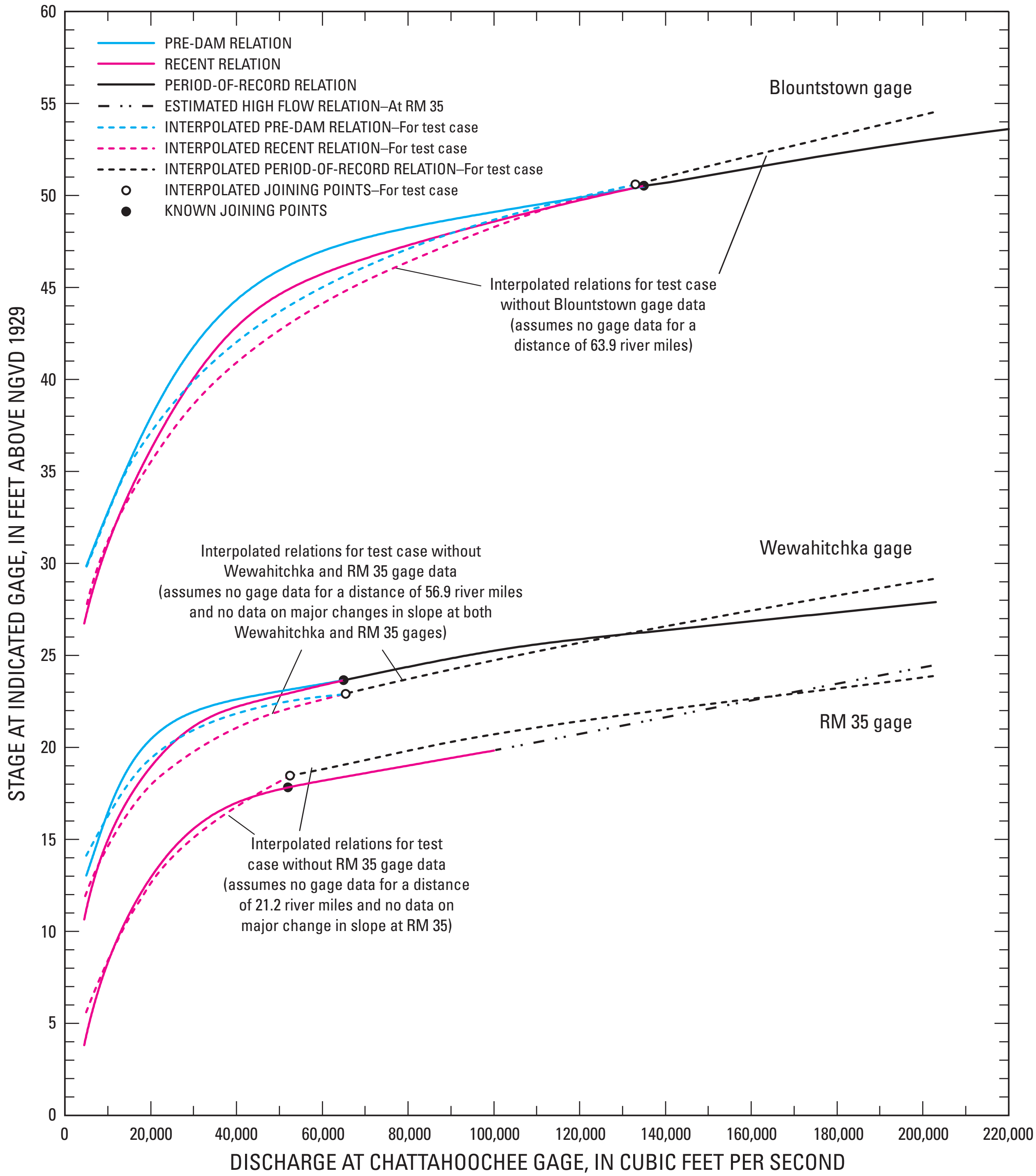

Figure 11. Stage-discharge relations based on long-term records at streamgages on the Apalachicola River, Florida, compared to hypothetical test cases in which streamgage data were ignored and relations were developed by interpolation methods used in this report. The departures shown in these hypothetical worst-case tests are greater than would be expected for the between-gage interpolated relations developed in this report (see discussion in text). Relations were developed using lag times as defined in glossary.

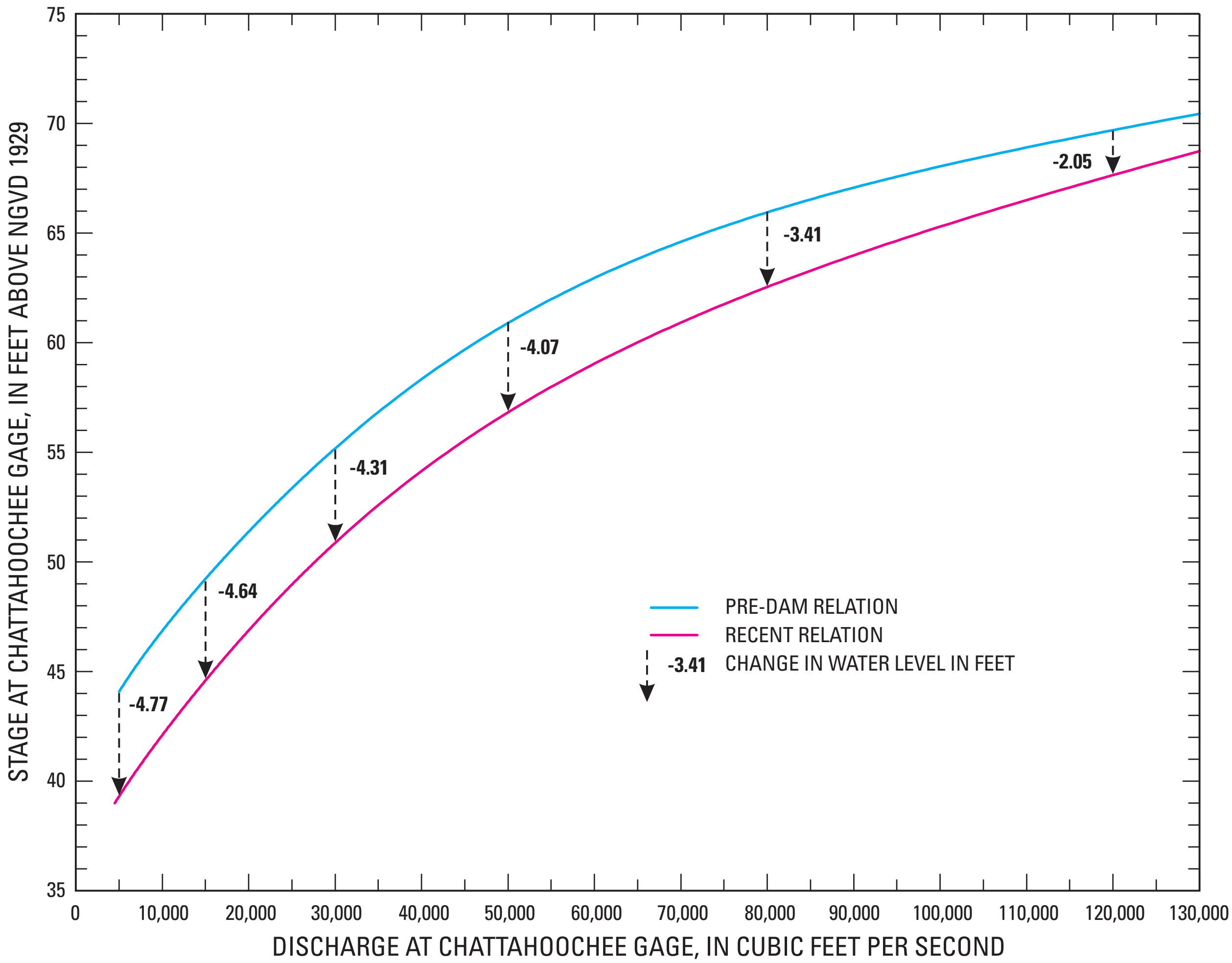

Figure 12. Water-level decline resulting from difference between pre-dam and recent stage-discharge relations at the Chattahoochee streamgage on the Apalachicola River, Florida, for selected discharges. The magnitude of the decline is greatest at low discharges and systematically decreases at higher discharges.

time that a particular location is inundated by water and is the preferred term for describing hydrologic conditions on a floodplain. Percent duration of inundation and percent exceedance can be treated as numerically equal with certain caveats:

(1) The area of inundated floodplain is greatest when river levels are high and decreases with decreasing stage, but there are a few low areas of the floodplain that remain inundated by river water even at minimum flow, such as the beds of permanently connected floodplain streams or very low swamp forests. (Details on the amount of floodplain area that is inundated at various discharges can be found in Light and others, 1998.) All percent exceedance values, even those for very low discharges, can be used to define the percent duration of inundation of some areas of the floodplain, but they may not necessarily apply to the entire floodplain.

(2) Low topographic features of the floodplain with a bowl-like shape, such as swamp depressions, may retain water long after flood waters recede or may refill after heavy rains. Such areas would experience longer periods of inundation than those assumed from river stages. Swamps receiving water from seepage off nearby bluffs or local upland drainage areas can also have water perched above the elevation of the river surface during low water. In these areas, the actual percent duration of inundation is different than percent exceedance calculated from streamflow data. The reader is cautioned that percent duration of inundation values in this report are based solely on river stage, without any adjustments to account for site-specific variations in floodplain topography or other sources of water supplied to the floodplain independent of river flow.

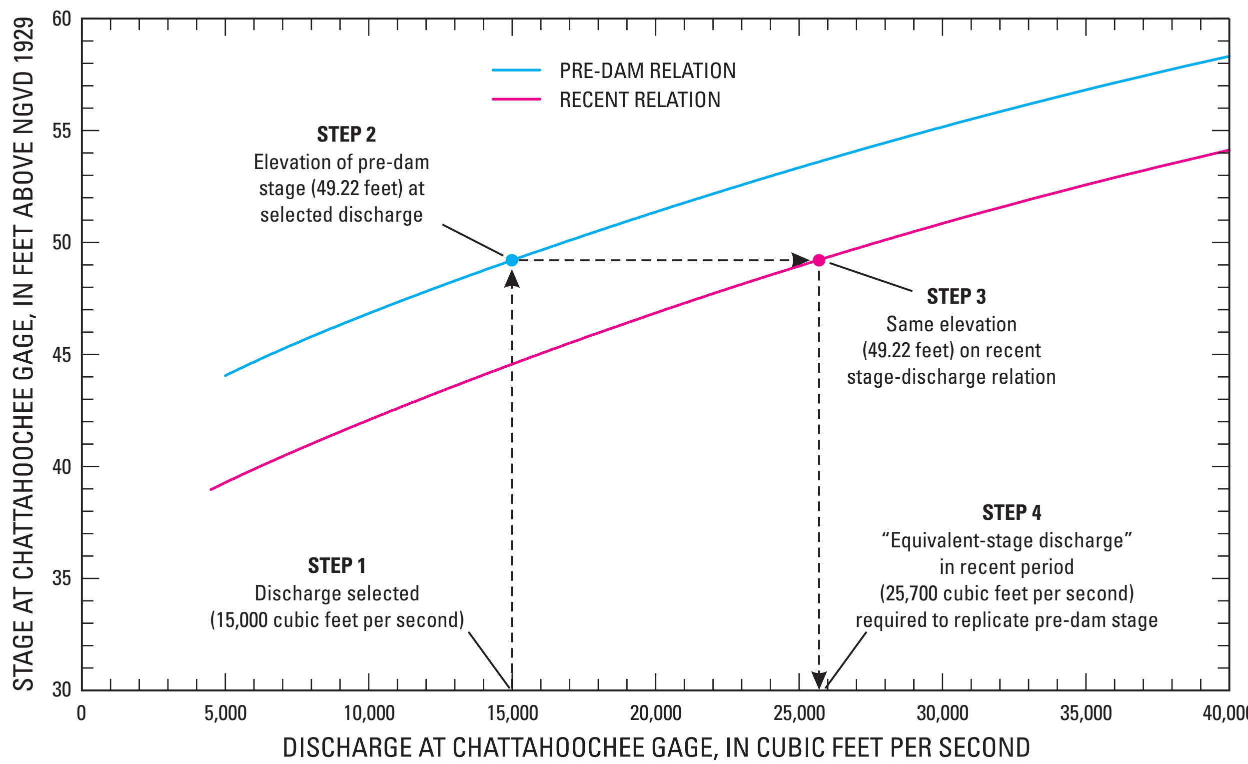

Figure 13. Example of determination of the "equivalent-stage discharge" in the recent period that is required to replicate a pre-dam stage using data for the Chattahoochee streamgage on the Apalachicola River, Florida. Calculation of "equivalent-stage discharge" is a necessary step in estimating changes in long-term flow statistics, such as duration of inundation, that have resulted from changes in stage-discharge relations from 1954 to 2004. In this example, 15,000 ft^3/s at Chattahoochee had a pre-dam stage of 49.22 feet, and 25,700 ft^3/s is the "equivalent-stage discharge" in the recent period that has that same water-surface elevation.

Percent exceedance is calculated from streamflow records for a defined time period, and the results vary depending upon the time period chosen. Selection of the time period is determined by the objective of the analysis. If the objective were to compare actual floodplain inundation in the pre-dam period to that in the recent period, the first step would be to determine equivalent-stage discharges using pre-dam and recent stage-discharge relations. These different discharges for pre-dam and recent conditions, indicative of the physical changes in the channel, would then be used to calculate percent exceedance based on the two different periods of flow records (pre-dam and recent, respectively). The difference in duration of inundation resulting from these calculations would reflect the combined effects of both the physical changes in the channel and changes in discharge between the two periods. Studies addressing the full extent of hydrologic change that has occurred in floodplain habitats should include the combined effects of both of these types of water-level changes. An analysis of this type, however, is not within the scope of this report. Changes in discharge are complex because of substantial seasonal and annual variability, and causes of those changes are unclear. Although a limited description of changes in water levels caused by changes in discharge is addressed for comparison purposes in the section entitled "Long-Term Changes in Monthly Discharge," the primary objective of this report is to present details about the water-level decline caused by channel changes, independent of changes in flow.

If the same time period is used to calculate percent exceedance from pre-dam stage-discharge relations and percent exceedance from recent relations, then the difference between them represents the decrease in floodplain inundation that has occurred as a result of channel changes only (independent of changes in flow). This allows the consequences of channel changes to be determined without the additional complication of flow differences between earlier and later time periods. In most of the analyses in this report, actual conditions in the recent period of 1995 to 2004, reflecting the effects of water-level decline attributable to channel change, were compared to the approximate natural conditions that would have occurred in that same period if this water-level decline had *not* occurred. This comparison shows the approximate difference in duration of floodplain inundation with and without channel change during the recent period.

The recent period was compared to a 30-year contemporary period and two other earlier periods (fig. 14). The recent period should not be assumed to represent average or typical conditions because it is the driest decade of the later period. At discharges less than 30,000 ft^3/s, the recent period is more similar to the driest decade in the early period (1949-58) than to either the earlier or the later 30-year periods. The recent period, however, is an excellent time period for evaluating the effects of water-level decline on biological habitats during extreme low-flow events. Extreme events can be an important factor affecting the species of trees that will colonize or thrive in floodplain forests, the long-term survival of sensitive aquatic species such as endangered mussels, and many other biological processes in the floodplain. If the objective of the analysis is to describe the effects of water-level declines under more typical conditions, however, periods longer than 10 years (preferably 20-30 years or longer) should be used.

Calculations of percent exceedance for the recent period based on both the pre-dam and recent relations are illustrated in the example in figure 15A. The initial selected discharge of 15,000 ft^3/s and its corresponding equivalent-stage discharge of 25,700 ft^3/s in figure 15A are the same values generated by the example steps in figure 13. In the final calculation step in figure 15A, the percent exceedance of the equivalent-stage discharge (20.6) minus the percent exceedance of the initial selected discharge (45.3) yields a change of -24.7 percent. This is the approximate decrease in duration of inundation during the recent period that resulted from water-level decline caused by channel change at the Chattahoochee gage. Figure 15B illustrates the same calculation, which was made separately for the individual years 2000 and 2003, showing large differences in durations from year to year. Because of this annual variability, it is important not to draw conclusions about durations for a multiple-year period, as shown in figure 15A, and apply them to individual years. Biological stress caused by adverse hydrologic conditions may not be evident when examining durations for the 10-year period, but vulnerable species could be extirpated locally by conditions occurring in the driest year of this decade.

Approximate decreases in duration of inundation caused by channel change, as determined from 1995 to 2004 flow durations, were calculated at closely spaced locations (every 0.1 rm) for 14 selected discharges to show variation at different locations and under different flow conditions. Approximate decreases in duration of inundation were also calculated for each year of the 1995 of 2004 period at three example locations selected to show specific effects of water-level decline on biological habitats of the floodplain. At these three locations, duration data were calculated only for the seasons during which hydrologic conditions are important to the organisms utilizing those habitats. Inundation of floodplain forests, for example, has little effect on tree growth and survival during the dormant season, so duration calculations were made only on water-level data during the growing season for that particular case study. Elevation data at these three sites were collected in previous studies or for other purposes in the present study. Sources of the elevation data are cited in each case.

Changes in Seasonal Distribution of Discharge

Long-term changes in the seasonal distribution of discharge were evaluated by comparing monthly discharge in the two 30-year periods shown in figure 14 (1929–1958 and 1975–2004). Both periods included major droughts and large floods (tables 2 and 3) and had similar average discharges. Although anthropogenic effects on runoff and streamflow are not new—some beginning in the 1800s—many anthropogenic activities prevalent in the later period were minimal or nonexistent in the earlier period. For example, the later period begins just after the completion of the last of the five large Federal reservoirs that were constructed from 1954 to 1974 for various flow regulation purposes (USACE, 1996). Large increases in agricultural water use occurred with the advent of center-pivot irrigation systems in southwest Georgia beginning in the 1970s (Pierce and others, 1984). Municipal water use was much greater in the later period, especially in metropolitan Atlanta, which has experienced large increases in population (Marella and others, 1993; Couch and others, 1996; Atlanta Regional Commission, 2006).

To compare these two 30-year periods, the first step involved isolating daily discharge values by month. For example, the daily mean discharge values for every January day in the earliest 30-year period were combined into one dataset having 930 values. Then five selected streamflow duration statistics (10, 25, 50, 75, and 90 percent exceedance) were developed for that “January” dataset. For example, the discharge equaled or exceeded in 10 percent of the days in January (49,780 ft^3/s in the early period) represents the discharge that typically occurred in January during very wet conditions. The discharge equaled or exceeded in 90 percent of the days in January (11,700 ft^3/s in the early period) represents the discharge that typically occurred in January during drought conditions. The same five selected duration statistics were calculated for each month in the later period using the same methods.

In a final analysis, water-level changes caused by changes in monthly discharge were compared to the water-level declines caused by channel changes. Because water-level changes resulting from changes in flow are complex, varying seasonally, annually, and by location along the river, this comparison of both types of water-level declines was made at only one example location (Blountstown gage), and only for median flow conditions (50 percent exceedance) and drought conditions (90 percent exceedance). Water-level changes caused by both channel changes and flow changes were calculated individually, by the following methods, and then combined to show the relative contribution of each to the total long-term change in monthly water levels at the selected site.

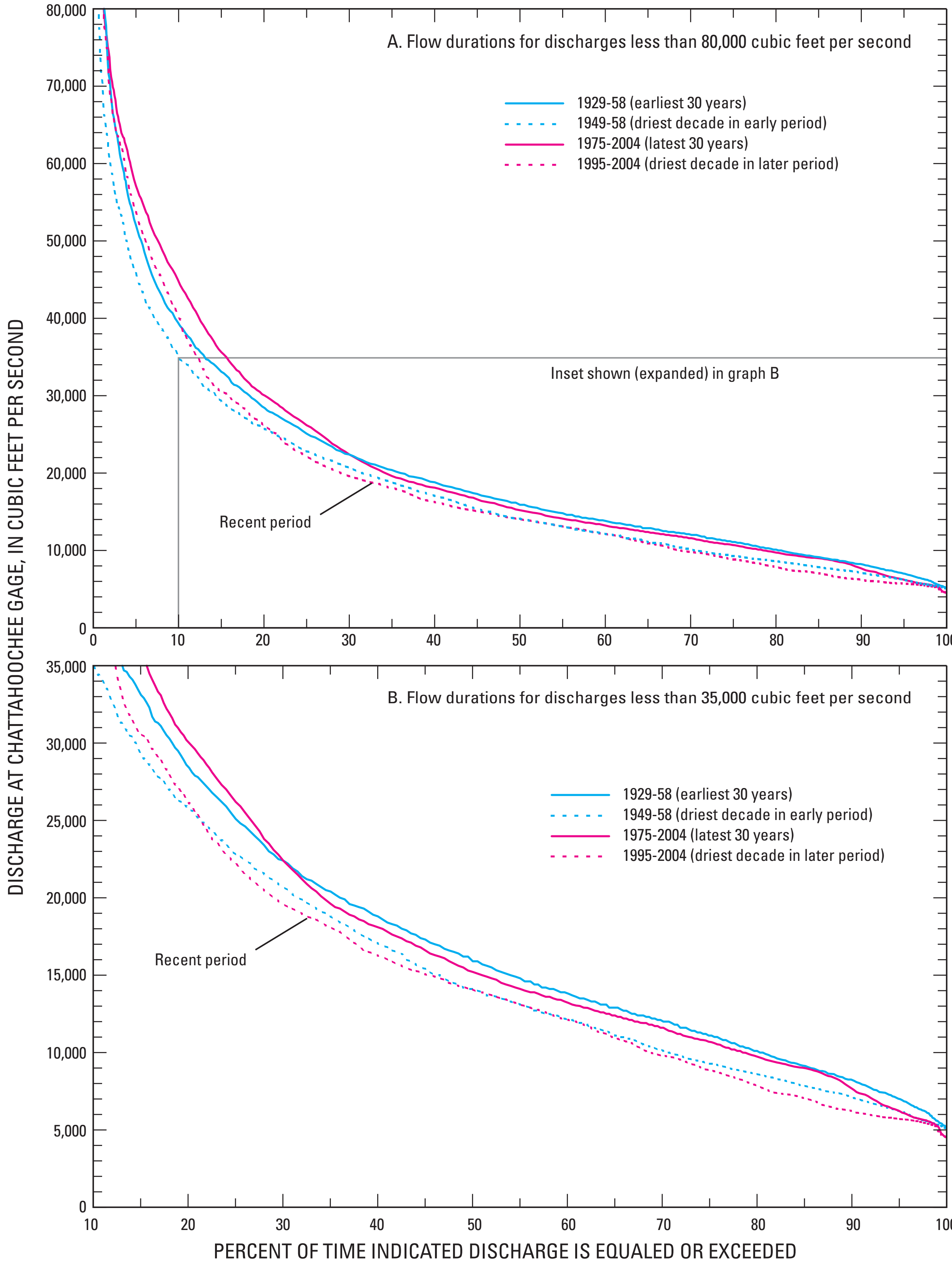

Figure 14. Flow durations for the recent period (1995–2004) compared to three other periods at the Apalachicola River at Chattahoochee, Florida, (A) for discharges less than 80,000 ft^3/s, and (B) for discharges less than 35,000 ft^3/s. With regard to flow durations, the recent decade including the severe drought of 1999–2002 was more similar to the decade including the severe drought of 1954–56 than it was to either of the longer 30-year periods.

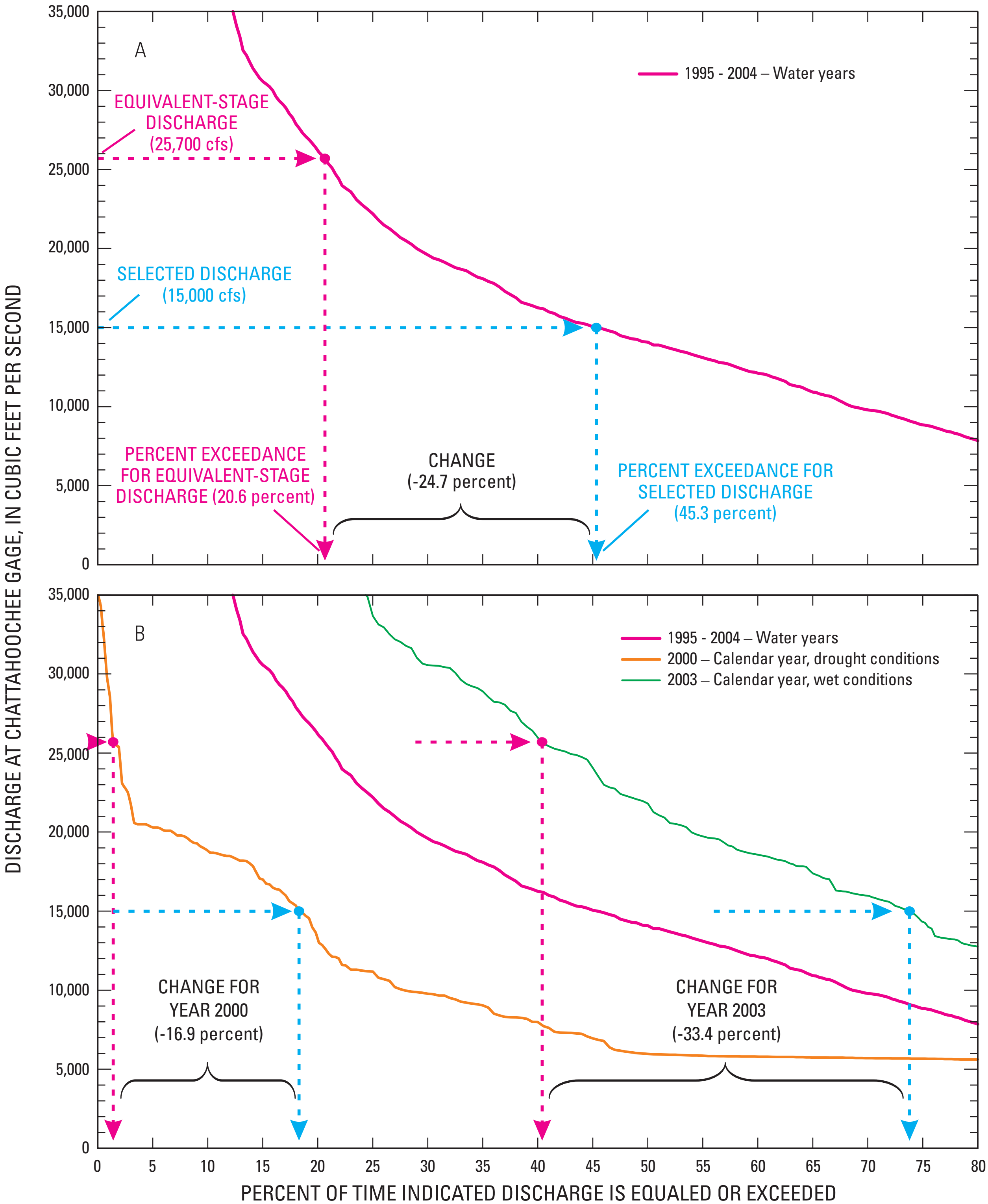

Figure 15. Example of determination of approximate decrease in duration of inundation caused by channel changes using data for the Chattahoochee streamgage on the Apalachicola River, Florida, (A) for the entire recent period (1995-2004), and (B) for one dry year (2000) and one wet year (2003). In graph A, percent exceedance of the equivalent-stage discharge (20.6 percent) minus the percent exceedance of the initial selected discharge (45.3 percent) yields the approximate change in duration of inundation resulting from water-level decline caused by channel change (-24.7 percent). See figure 13 for methods used to determine the equivalent-stage discharge. Graph B shows the same calculations which were made separately for individual years to show an example of annual variability.

(1) To calculate water-level changes attributable to changes in discharge, streamflows from both the early period (1929–1958) and the later period (1975–2004) were converted to stage using the same stage-discharge relation (the recent relation for the Blountstown gage), and then differences in stage between the two periods were determined for each month. The same stage-discharge relation was used for both time periods to isolate the effects of flow changes from the effects of channel changes. These results show the consequences of changes in flow assuming the present channel shape.

(2) To calculate water-level declines attributable to channel changes, streamflows from the later period only (1975-2004) were converted to stage using both the pre-dam (pre-1954) and recent (1995-2004) stage-discharge relations at the Blountstown gage, and the water-level decline was determined from the difference in those two stages. The same time period of flow data (1975-2004) was used to calculate pre-dam and recent stage to isolate the effects of channel changes from the effects of changes in discharge.

Results and Discussion

A summary of the water-level decline that occurred throughout nearly all of the nontidal Apalachicola River as a result of changes in stage-discharge relations from 1954 to 2004 is discussed in this section. The effects of water-level decline on long-term duration of inundation and selected floodplain habitats are also discussed.

Magnitude and Extent of Water-Level Decline

The magnitude of the water-level decline in relation to distance along the river at 14 selected discharges is shown in figure 16. The lowest lines in figure 16 indicate that the largest stage declines occurred at the lowest discharges, which was anticipated in the discussion of figure 12. The 14 lines in figure 16 parallel one another with fairly consistent spacing. This pattern reflects the fact that all stage-discharge relations (apps. I-V) have a generally similar shape. There are minor departures, however, from this general pattern. In the vicinity

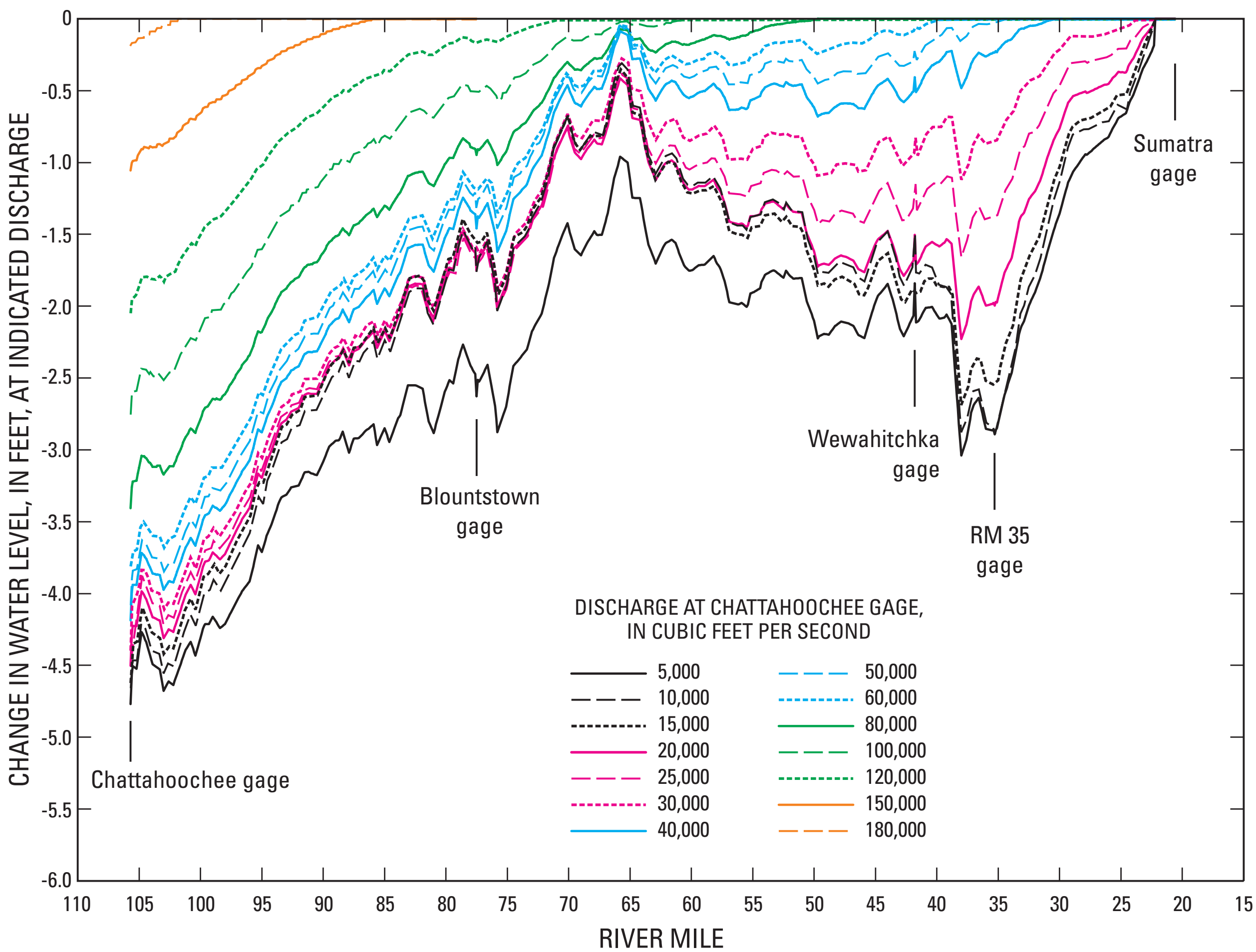

Figure 16. Patterns of water-level decline, at various discharges, that occurred along the nontidal Apalachicola River, Florida, as a result of long-term changes in stage-discharge relations from 1954 to 2004. Physical changes in the river channel caused the changes in stage-discharge relations, thus the decline is greatest at low discharges when all streamflow is contained within the channel, and least at high discharges when much of the runoff is flowing over the floodplain.

of the Wewahitchka gage, for example, the stage decline for 15,000 ft^3/s is slightly greater than the decline for 10,000 ft^3/s, indicating that some aspect of channel change in that vicinity was atypical. If the amount of channel widening at different elevations on the banks did not progressively decrease with increasing stage, crossed lines would occur on figure 16. At Wewahitchka, channel widening at the elevation associated with 15,000 ft^3/s (higher up on the bank) may have been greater than the amount of channel widening that occurred at the elevation associated with 10,000 ft^3/s (lower down on the bank). Considering that dredged material disposal has occurred along the riverbank at this and many other sites (USACE, 2001a), widening could have been atypical in some cases.

The largest water-level decline occurred at rm 105.7, just downstream from Jim Woodruff Dam, and the decline progressively decreased downstream to rm 66. Downstream progressing riverbed degradation is to be expected where a dam traps the sediment (sand in this case) of the streambed (Galay, 1983; Simons, Li, and Associates, 1985; Ligon and others, 1995). Sand in the streambed below the dam is naturally mobilized and transported downstream during large streamflow events. Prior to dam construction, those transported sediments were replaced by sand from upstream sources, but that does not occur now that the dam is in place because sediments are trapped in the reservoir. The consequence is a progressive lowering of the streambed surface, with greater magnitude of bed decline near the dam and lesser magnitude downstream. Other factors could also have contributed to the water-level decline. Dredging permanently removed streambed sediment from the channel environment and lowered the streambed surface when it was accompanied by disposal of dredged material on the floodplain (a common practice prior to 1973), but the relative contribution of this practice to bed lowering has not yet been determined. In addition, channel widening, which was documented using a time series of aerial photographs, has been relatively widespread throughout the entire nontidal river (Price and others, 2006) and probably also contributed to the water-level decline upstream from rm 66.

The near absence of water-level decline at most discharges in the vicinity of rm 66 is anomalous and not easily explained, considering that channel widening, which was relatively widespread along the entire river, occurred in this reach as well. It is telling that the trend toward progressively lessening declines moving downstream from the dam ended at rm 66, with a trend reversal of progressively increasing declines downstream from this location. River mile 66 probably marks the downstream limit of the influence of Jim Woodruff Dam with regard to riverbed degradation, because it is not obvious how the presence of the dam could have contributed to the increasing declines downstream from this location. Water-level declines downstream from rm 66 are likely the result of channel widening and other more localized factors.

The large and abrupt increase in water-level decline in the vicinity of rm 38 is unique within the pattern shown on figure 16. Widespread and repetitive activities (including annual maintenance dredging, disposal, and woody debris removal) probably contributed to this water-level decline, but do not explain why the decline was larger in this particular location. In addition to normal maintenance activities, meander cutoffs and bend easings were excavated in 1957 and 1969 to straighten the lower reach of the river within a few miles upstream and downstream from RM 35. Widening of the river channel was particularly large (50 percent increase in average width) in the vicinity of bend easings upstream from RM 35 (Price and others, 2006). In addition, a substantial amount of channel deepening was measured in cross-section surveys downstream from RM 35 in the vicinity of the two largest meander cutoffs (Price and others, 2006). Upstream-progressing riverbed degradation is a predictable consequence when a river reach is shortened by meander cutoffs (Galay, 1983).

The fact that the water-level decline was negligible near the Sumatra gage site is to be expected. The Sumatra gage is located at the approximate boundary between the nontidal and tidal reaches of the Apalachicola River. Near the mouth of an alluvial river that flows into the sea, the surface of the river must always merge smoothly with sea level irrespective of any channel changes that may take place.

Certain small-magnitude aspects of the pattern of water-level decline (fig. 16) are likely the result of errors. The sharp change in the decline (for all discharges except the very highest) just downstream from the Chattahoochee gage, and the abrupt “uptick” in many of the lines at the Wewahitchka gage are examples. The methods for developing stage-discharge relations at gages and between-gage sites were different. Thus the values in figure 16 at the exact gage locations were determined differently than the values 0.1 rm upstream and downstream from the gages (and at all locations between gages). As explained in the “Methods” section, stage-discharge relations at the five gage sites were developed using only the long-term streamgage records at those sites, whereas a combination of water-surface profile data and streamgage records were used to develop interpolated relations at between-gage sites at closely spaced intervals of 0.1 rm. The interpolated between-gage relations were based primarily on water-surface profile data at low flows, with a gradually increasing use of the long-term gage data in the interpolations at higher discharges. Table 6 and figure 9 show that the water-surface profile data are in general agreement with stages determined from long-term gage records. Minor discrepancies at Chattahoochee and Wewahitchka, however, are large enough to be visible in figure 16. In the first case, the decline shown at the exact Chattahoochee gage location is more accurate than those shown in about the first 3 rm downstream from the gage. This is because the between-gage declines were based on water-surface profiles developed in 1956 after more than 0.5 ft of decline had already occurred at the gage from riverbed degradation resulting from sediment trapping in Lake Seminole. The declines at the exact location of the Wewahitchka gage are also probably more accurate than the between-gage declines. The uptick at Wewahitchka provides an example of the error that is possible in the between-gage declines at the lower discharges, which were based primarily on the water-surface profile data.

The magnitude of the declines at the gage sites is graphically presented in figure 17A (and listed on the left side of app. IX) in relation to 14 selected discharges. The decline at the Chattahoochee gage is more than twice the decline at any other gage at all discharges shown, and exceeds 2 ft even at discharges as high as 120,000 ft^3/s. At discharges in the 25,000 to 100,000 ft^3/s range, the second largest decline is at the Blountstown gage. At the lowest flows, the second largest decline is at the RM 35 gage.

The detailed data shown by river mile in figure 16 is summarized by major reaches of the river in figure 17B (and listed on the right side of app. IX). As expected, the upper reach has the greatest declines at all discharges shown. Declines in the middle reach at discharges of 20,000 ft^3/s and less are relatively similar to those in the lower reach.

Effects of Water-Level Decline on Floodplain Habitats

Effects of the long-term water-level decline on hydrologic conditions in floodplain habitats are described in this report primarily in terms of decreases that have occurred in percent duration of inundation. Actual duration of inundation in the recent period, reflecting the effects of water-level decline, were compared to the approximate natural duration of inundation that would have occurred in that same period if water levels had not declined. Figure 18 shows these approximate decreases in duration of inundation in relation to distance along the river for 14 selected discharges. Approximate decreases in duration of inundation at the gage sites and average decreases for reaches of the river are shown in figure 19 for those same 14 selected discharges.

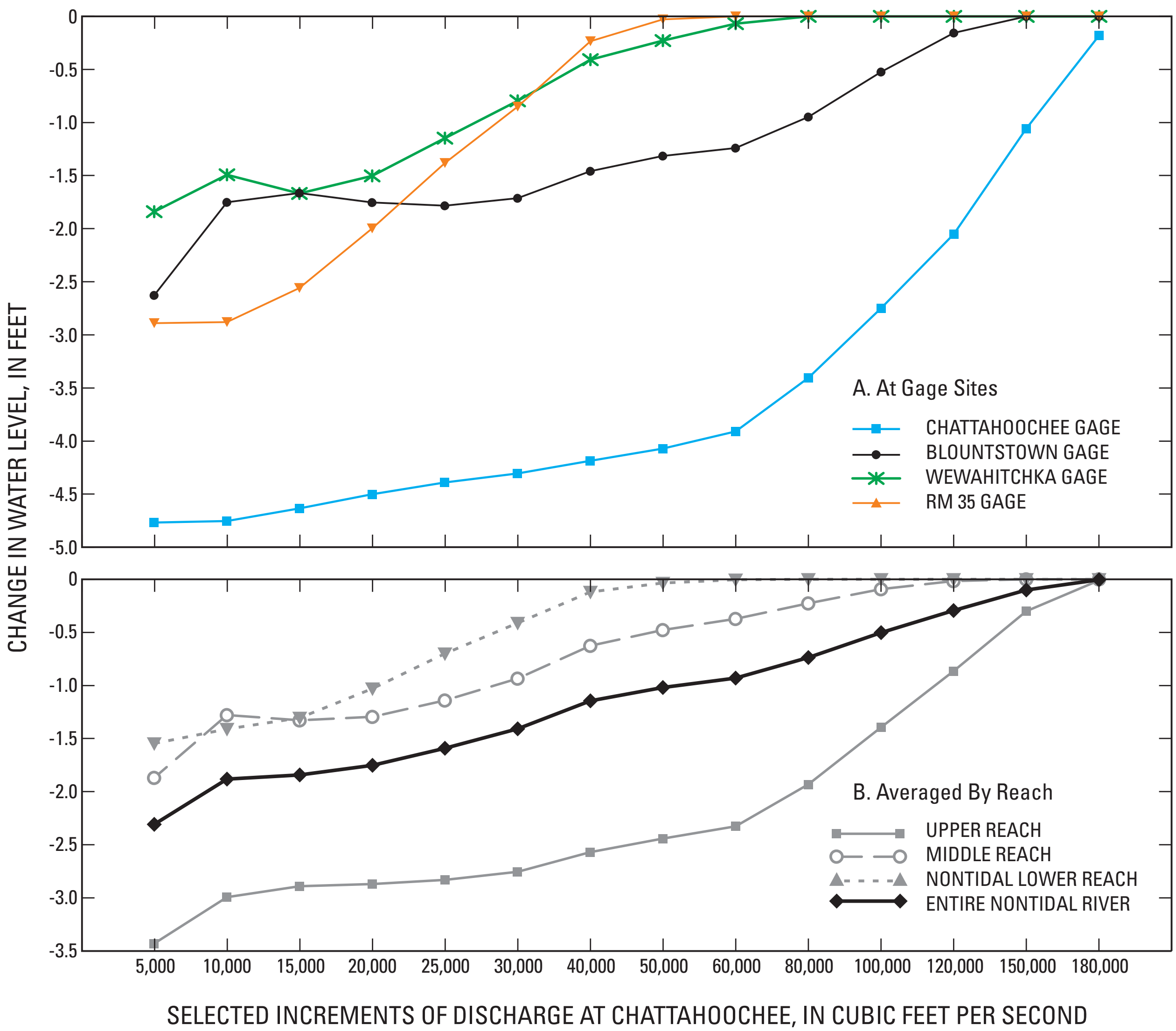

Figure 17. Water-level decline, at various discharges, that occurred along the nontidal Apalachicola River, Florida, as a result of long-term changes in stage-discharge relations from 1954 to 2004 (A) at streamgage sites, and (B) averaged by reach. Physical changes in the river channel caused the changes in stage-discharge relations, thus the decline is greatest at low discharges when all streamflow is contained within the channel, and least at high discharges when much of the runoff is flowing over the floodplain.

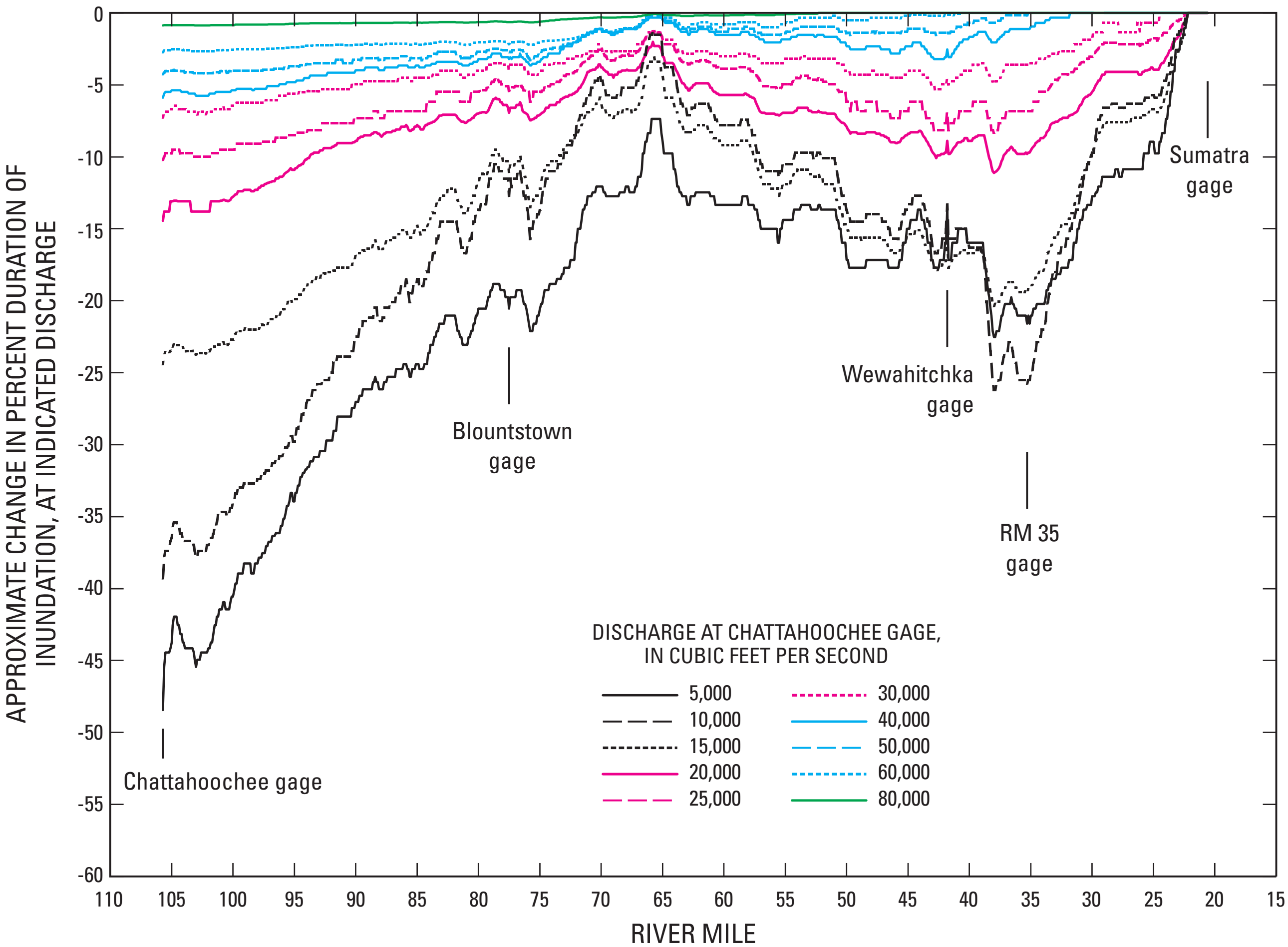

Figure 18. Patterns of approximate decreases in percent duration of inundation, at various discharges, that occurred along the nontidal Apalachicola River, Florida, as a result of long-term changes in stage-discharge relations from 1954 to 2004. These results represent the difference between duration of inundation under actual conditions in the recent period (water years 1995–2004), reflecting the effect of water-level decline, and the duration of inundation that would have occurred in that same period if water levels had not declined. Calculations were made in a series of steps, described in the methods, starting with the pre-dam and recent stage-discharge relations. NOTE: Duration values are dependent on the time period used for calculating them (1995–2004 in this case) and would be different if a different time period were used.

Appendix X lists the values resulting from each step of the calculation process used to generate the results shown in figure 19. This appendix is a three-part table with equivalent-stage discharges shown in part A, the corresponding percent exceedance values in part B, and approximate decreases in duration of inundation in part C. The values in part C of appendix X are the same values as shown in figure 19.

Similar to figure 16, the greatest decreases in inundation shown in figures 18 and 19 occur at the lowest discharges, with minor departures from this general pattern. The reasons for the departures are twofold: (1) some aspect of channel change in that vicinity may have been atypical (as explained in the discussion of fig. 16), and (2) differences in durations can vary depending upon which part of the flow duration curve is involved in the change from the pre-dam discharge to the recent equivalent-stage discharge (as illustrated in fig. 15).

Large decreases in percent duration of inundation of about 20 to 45 percent occurred in the upstream-most 10 mi of the upper reach for discharges of 5,000, 10,000, and 15,000 ft^3/s (fig. 18). As expected, these decreases were greater than at any other location along the river. But for all other discharges, decreases in duration of inundation in the upper reach were relatively similar to decreases in much of the middle and lower reaches. This differs from the results shown in figure 16, in which the magnitude of water-level declines in the upper reach were substantially greater than in the middle and lower reaches for all discharges. Dissimilar results in these two figures are primarily due to differences in floodplain topography between the reaches. In the lower reach, adjacent floodplains are lower in relation to river stage and the floodplain is wider and has lower relief than in the upper reach (figs. 2 and 7). In addition, a substantial amount of river flow

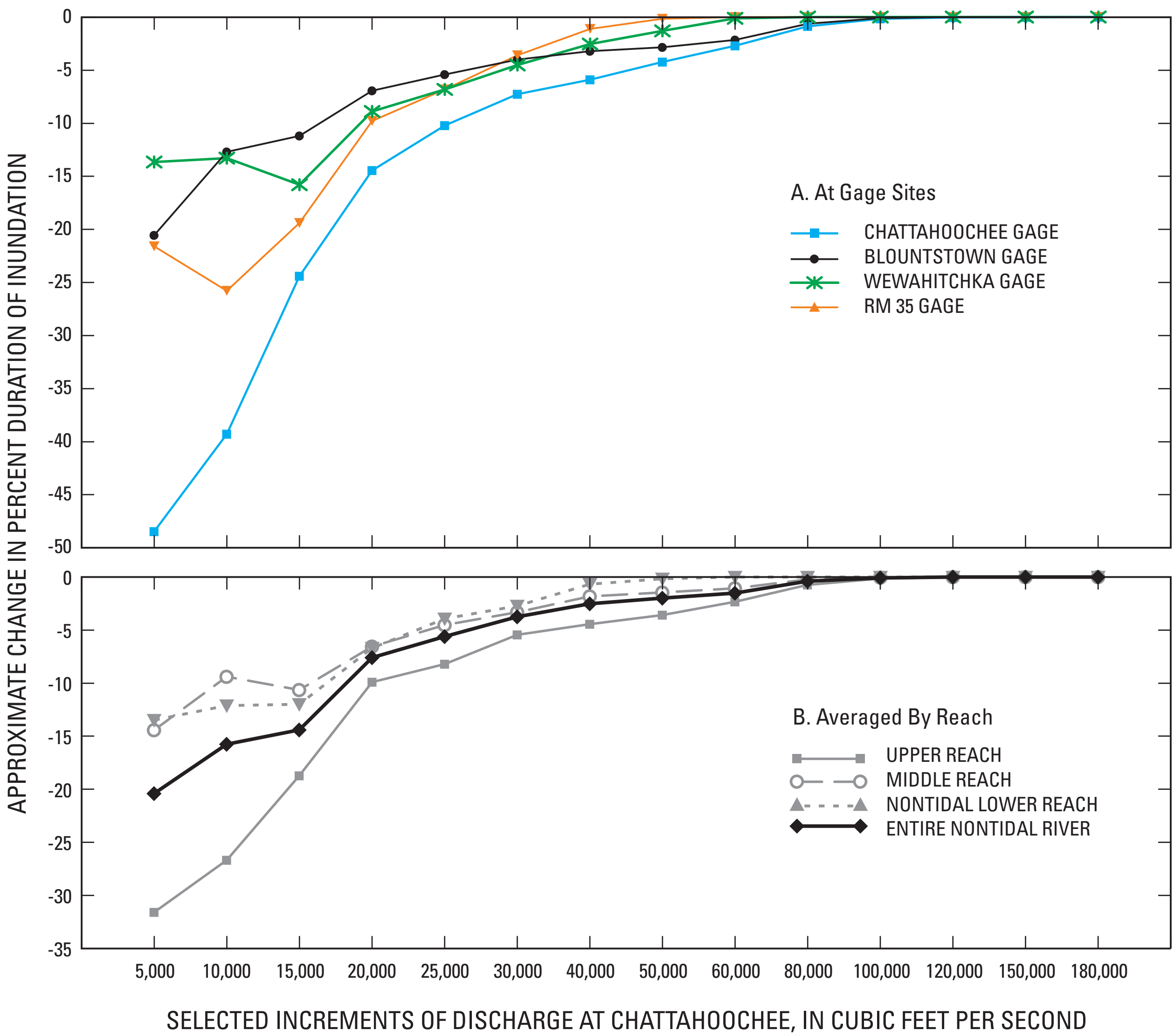

Figure 19. Approximate decreases in percent duration of inundation, at various discharges, that occurred along the nontidal Apalachicola River, Florida, as a result of long-term changes in stage-discharge relations from 1954 to 2004 (A) at streamgage sites and (B) averaged by reach. These results represent the difference between duration of inundation under actual conditions in the recent period (water years 1995–2004), reflecting the effect of water-level decline, and the duration of inundation that would have occurred in that same period if water levels had not declined. Calculations were made in a series of steps, described in the methods, starting with the pre-dam and recent stage-discharge relations. NOTE: Duration values are dependent on the time period used for calculating them (1995–2004 in this case) and would be different if a different time period were used.

leaves the main channel and is carried by large side-channel streams even during low-flow conditions. As a result, a difference in river stage is usually associated with a larger difference in discharge at downstream sites than at upstream sites. For a discharge of 30,000 ft^3/s, for example, the water-level decline shown in figure 17 for the Blountstown gage (1.7 ft) was more than twice the decline that occurred at the Wewahitchka gage (0.8 ft). Yet the equivalent-stage discharge required in the recent period to replicate the pre-dam stage for 30,000 ft^3/s is similar between the two sites (35,500 $ft^{3/}s$ at Blountstown, 36,500 ft^3/s at Wewahitchka; app. X, part A). Consequently, the approximate decrease in duration of inundation as a result of that water-level decline is slightly greater at Wewahitchka (4.5 percent) than at Blountstown (4.0 percent) (fig. 19) in spite of the substantially smaller water-level decline at Wewahitchka.

Specific Examples of Habitat Alteration

Determining the effects of water-level declines on particular species or biological communities in the floodplain requires an understanding of the seasonal habitat needs of those particular organisms. Decreases in duration of inundation caused by water-level decline in the river are calculated for different seasonal periods in each of the following examples to describe conditions that are important to the organisms that are dependent upon those sites. Although analyses of floodplain effects in this report are based primarily on decreases in duration of inundation, a variety of other types of streamflow statistics can be used to evaluate the effects of water-level decline on floodplain habitats.

Access to cool-water refuges for striped bass.—At one time, the native Gulf Coast race of the striped bass (*Morone saxatilis*) was a commercially and recreationally important species with widespread distribution in most rivers along the Gulf of Mexico. Currently, the last remnant population appears to exist only in the Apalachicola River system (Wooley and Crateau, 1983; Lukens, 1988). Construction of dams and impoundments that have blocked passage to spawning grounds and cool-water refuges, and widespread use of agricultural chemicals have been cited as possible reasons for the rapid decline of the Gulf Coast striped bass, which occurred from about 1940 to 1960 (Wooley and Crateau, 1983; Van Den Avyle and Evans, 1990; Striped Bass Technical Task Force, 2005). Annual stocking is now required to maintain harvestable population levels, because natural reproduction is extremely limited (ACF Striped Bass Technical Committee, 2004).

Adult striped bass, which cannot tolerate the warm ambient water temperatures of rivers and reservoirs, require access to cool-water refuges for summer survival (Moss, 1985; Coutant, 1985 and 1987; Lukens and Barkuloo, 1990; Van Den Avyle and Evans, 1990; Zale and others, 1990). Striped bass typically move into cooler waters in May and remain there through October (Van Den Avyle and Evans, 1990). Adult striped bass larger than 10 pounds are more vulnerable to summer temperature stress than smaller individuals (Wooley and Crateau, 1983). Although individuals up to 48 pounds have been reported from the upper Apalachicola River, they usually do not exceed 25 or 30 pounds (Charles L. Mesing, Florida Fish and Wildlife Conservation Commission, written commun., 2006). To provide adequate access for these large adult fish, cool-water streams probably need to be at least 3 ft deep during the warm season (May-October).

More than a dozen perennial cool-water streams in the upper reach of the Apalachicola River, as well as springfed streams in the lower reach of the Flint River, have been identified as thermal refuges for adult striped bass during the warm season (Lukens and Barkuloo, 1990; Van Den Avyle and Evans, 1990; Charles L. Mesing, Florida Fish and Wildlife Conservation Commission, written commun. 1995). One of these cool-water refuge streams is Flat Creek, which drains 52 mi^2 in an upland area adjacent to and east of the upper reach of the Apalachicola River (fig. 2; Light and others, 1998). The downstream-most 2 mi of Flat Creek flows through the Apalachicola River floodplain before it empties into the main river channel at rm 99.5 (fig. 20). Temperatures in Flat Creek during the summer are cooler than river temperatures because this creek is fed partly by ground water.

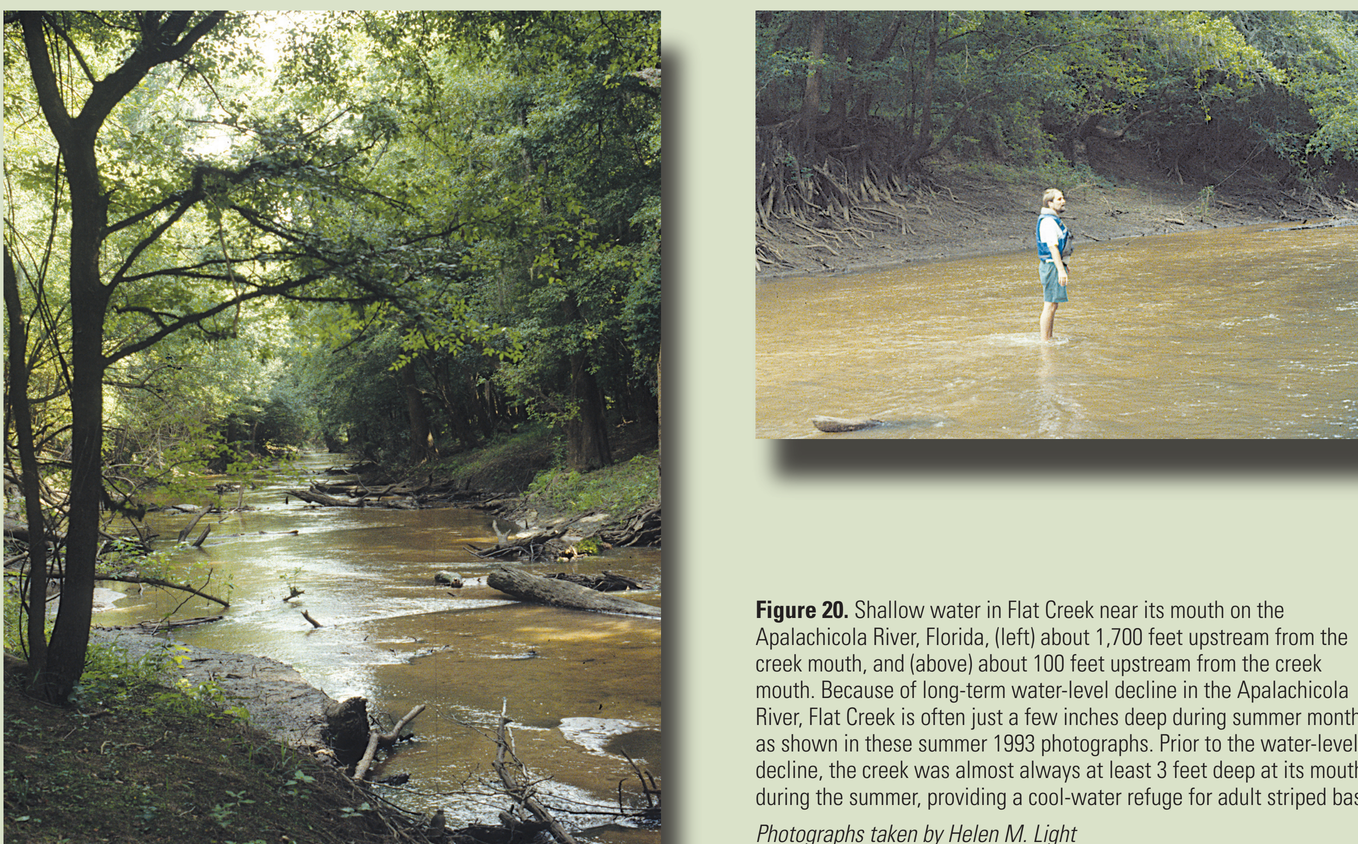

Figure 20. Shallow water in Flat Creek near its mouth on the Apalachicola River, Florida, (left) about 1,700 feet upstream from the creek mouth, and (above) about 100 feet upstream from the creek mouth. Because of long-term water-level decline in the Apalachicola River, Flat Creek is often just a few inches deep during summer months, as shown in these summer 1993 photographs. Prior to the water-level decline, the creek was almost always at least 3 feet deep at its mouth during the summer, providing a cool-water refuge for adult striped bass.

Photographs taken by Helen M. Light

The availability of thermal refuge habitat in Flat Creek and other cool-water streams in the upper reach of the Apalachicola River has been severely reduced by water-level decline since 1954. These streams are often too shallow during summer to provide access for adult striped bass (fig. 20). In the recent period from 1995 to 2004, the percentage of time in May through October that the mouth of Flat Creek was at least 3 ft deep has been reduced by more than half because of water-level decline (fig. 21). If channel changes had not occurred, cool-water refuge would have been available in Flat Creek about 90 percent of the time in the months of May through October during the 10 years of the recent period. Because of water-level decline, however, cool-water refuge was available only about 40 percent of the time during this period. In addition, there was not a single year in the recent period (1995–2004) that Flat Creek was available for adult striped bass continuously throughout the thermal refuge season of May through October (fig. 21). By comparison, if water-level decline had not occurred, availability 100 percent of the time during the thermal refuge season would have occurred in 6 out of 10 years, with more than 70 percent availability in 9 out of 10 years (all years except 2000).

By severely reducing access to critical habitat in cool-water streams, water-level decline in the Apalachicola River probably contributed, in part, to the historical decline and the present low numbers of the Gulf Coast race of striped bass. Water depths in more than a dozen Apalachicola River tributaries known to be thermal refuge streams are no longer sufficient to provide access for adult striped bass when river discharge drops below 8,000 ft^3/s, with the exception of Selman's Ditch, which was artificially dredged and deepened many years ago. Excavation to deepen the mouths of other cool-water refuge streams has provided only short-term benefits (Long, 2004; Striped Bass Technical Task Force, 2005) (see section entitled "Future Trends and Potential for Restoration").

Persistence of flowing-water habitat for listed mussels.—In the past 50 years, a precipitous decline in freshwater mussels appears to have occurred in the ACF Basin, similar to the decline that has occurred throughout the southeastern United States (Brim Box and Williams, 2000). Causes of the decline in the ACF Basin, although not quantitatively documented, probably include construction of dams and impoundments, dredging and channel modifications, excess sedimentation from erosion as a rsult of poor agricultural practices, introduction of the Asian clam (*Corbicula fluminea*), and pollution (Neves and others, 1997; Brim Box and Williams, 2000).

Many species of freshwater mussels, including threatened and endangered species, exhibit high mortality in the absence of flowing water and the ensuing hypoxic conditions (Johnson and others, 2001; USFWS, 2003; Golladay and others, 2004). Perennial flowing streams in the floodplain that have upland drainage areas, such as Flat Creek, are common in the upper reach of the Apalachicola River. Listed mussels, however, have not been found in these streams, with the exception of the Shinyrayed pocketbook (*Lampsilis subangulata*), which was last seen in 1962 and apparently extirpated since then

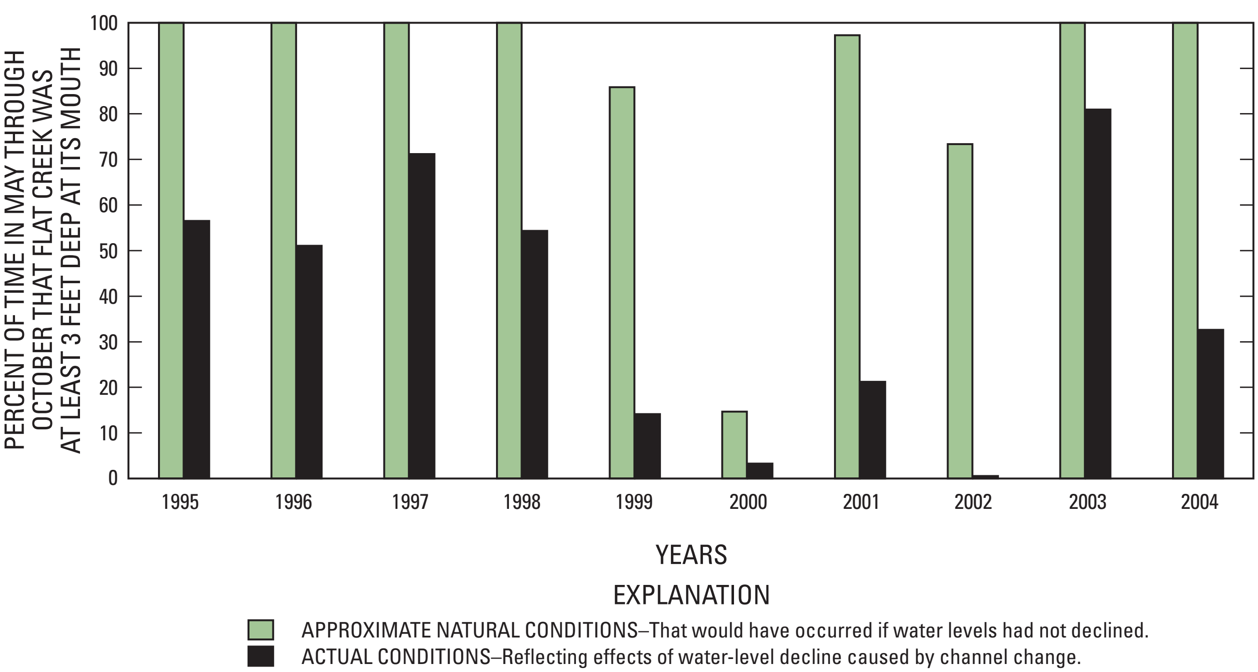

Figure 21. Effects of water-level decline on the availability of thermal refuge habitat for adult striped bass in Flat Creek on the Apalachicola River, Florida, from 1995 to 2004. Water depths at the creek mouth were based on a cross-section survey in 1993 120 feet upstream from the mouth of the creek where it empties into the upper reach of the Apalachicola River at river mile 99.5.

(USFWS, 2003). The absence of rare mussels in floodplain streams of the upper reach could be related to the drastic reductions in mussel populations reported for the mainstem of the upper Apalachicola River, an area that once harbored an abundant and diverse mussel fauna as recently as 50 years ago (Brim Box and Williams, 2000).

Floodplain streams in the middle and nontidal lower reaches of the Apalachicola River are a different type of stream than the perennial streams of the upper reach. Some of the largest off-channel water bodies, like Iamonia Lake and Florida River, may receive minor contributions from upland runoff, but are largely controlled by backwater from the main river channel. Many of the smaller streams and sloughs are what have been informally called “loop streams” by Light and others (1998), where water diverted from the Apalachicola River enters at the head of the stream, flows a few miles along the stream through the floodplain, and returns to the river at the mouth of the stream. Loop streams are fed by the river and receive no direct upland runoff, and can be perennial or intermittent depending on whether or not the streambed elevation is below minimum river levels. An intermittent loop stream stops flowing when the water level of the river is lower than the elevation of the streambed. Some of these streams are dewatered completely when river levels are low; others become a series of stagnant, isolated pools along the streambed (fig. 22). These pools can become hypoxic during extended periods of isolation, especially in warm weather. Further details about streams and sloughs of the Apalachicola River floodplain, including descriptions of their periodic connection and disconnection to the main river channel, and photographs of the major stream types, can be found in Light and others (1998).

Swift Slough and Moccasin Slough, two loop streams in the nontidal lower reach with similar channel widths and lengths, are fed by the Apalachicola River at their heads and empty into the River Styx at their mouths (fig. 2). Moccasin Slough is an intermittent stream that alternately connects and disconnects to the main river channel, depending upon river levels. Moccasin Slough flows when river levels are high enough for the stream to be connected to the main channel, and has small isolated pools along the bed when river levels are too low to enter the stream at its head (fig. 22). In the recent period, Moccasin Slough was disconnected and experienced no flow for extended periods during dry years (fig. 23). Continuous periods of disconnection in the drought years of 1999, 2000, 2001, and 2002 were estimated to be as long as 12, 28, 7, and 7 weeks, respectively. Moccasin Slough was a perennial stream prior to water-level decline in the

Figure 22. Comparison of flowing and nonflowing conditions in Moccasin Slough in the lower reach of the Apalachicola River, Florida. Moccasin Slough is a “loop stream” in which water diverted from the Apalachicola River enters at its head, flows about 2 miles through the floodplain, and returns to the river at the slough mouth. Moccasin Slough was a perennial flowing stream prior to 1954, similar to photograph (left), because river levels were always high enough for water to enter the stream and maintain flowing-water conditions. Because of water-level decline in the river, Moccasin Slough now becomes disconnected for extended periods during dry years, similar to photograph (above), with stagnant, isolated pools along a streambed that is mostly dewatered.

Photographs taken by Helen M. Light

Apalachicola River, and permanent flowing water conditions would have been continuously maintained in Moccasin Slough throughout the recent drought of 1999 to 2002 if water levels in the river had not declined.

Because Moccasin Slough probably has been an intermittent stream since the early 1980s, with nonflowing conditions lasting weeks or months during dry years, the slough has not been suitable habitat for threatened or endangered mussels that depend on continuously flowing water to maintain oxygenation. Consequently, no listed mussels have been found there. Many species of fish are intolerant of hypoxic or nonflowing conditions as well, including fish identified as host species necessary to support the larval phase of mussel reproduction. The blackbanded darter (*Percina nigrofasciata*) has been identified as a potential host species for the endangered fat threeridge (*Amblema neislerii*) (USFWS, 2003). Darters as a group generally inhabit flowing waters and would be unlikely to survive in the isolated pools of intermittent floodplain streams (Kuehne and Barbour, 1983; Leitman and others, 1991).

Swift Slough, by comparison, was a perennial stream until recently (July 2006) and harbored a relatively abundant and diverse mussel fauna, including the largest population of fat threeridge known to inhabit floodplain streams of the Apalachicola River (USFWS, 2003; EnviroScience, Inc., 2006). Swift Slough was observed to be disconnected for the first time on record in late July 2006 (Charles L. Mesing, FFWCC, written commun., 2006), as a result of very low flow in the river (5,100 ft^3/s) in combination with a higher than normal streambed elevation in the first 700 ft of the head of the slough (1.3 ft higher than during the previous observation in August 2000). Sand from a large shoal in the main river channel immediately upstream of the slough may have been deposited in the slough during a longer than normal high water period (exceeding 6 months) in 2003 and a major flood event (maximum daily mean discharge of 158,000 ft^3/s) in 2005.

The only floodplain streams known to have live populations of listed mussels are those with persistent flowing water. Fat threeridge populations were reported in Kennedy Creek (EnviroScience, Inc., 2006) in a location having perennial flow (Light and others, 1998). One live purple bankclimber (*Elliptoideus sloatianus*) was found in River Styx in 2000 (Theodore S. Hoehn, Florida Fish and Wildlife Conservation Commission, written commun., 2006). Flow in River Styx is typically sluggish during low-flow periods, but this backwater slough has not been known to disconnect completely from the Apalachicola River. Dead shells of fat threeridge and purple bankclimber were found in two small unnamed intermittent streams between rm 30.0 and rm 30.3 that flow (when river levels are high enough) from the Apalachicola River to Douglas Slough (Jerry W. Ziewitz, USFWS, written commun., 2000). It is not known if the dead shells washed in from the river or were the remains of live mussels that succumbed to adverse conditions in these streams when the streams stopped flowing. Several fat threeridge and purple bankclimber mussels were found in the main channel of the river

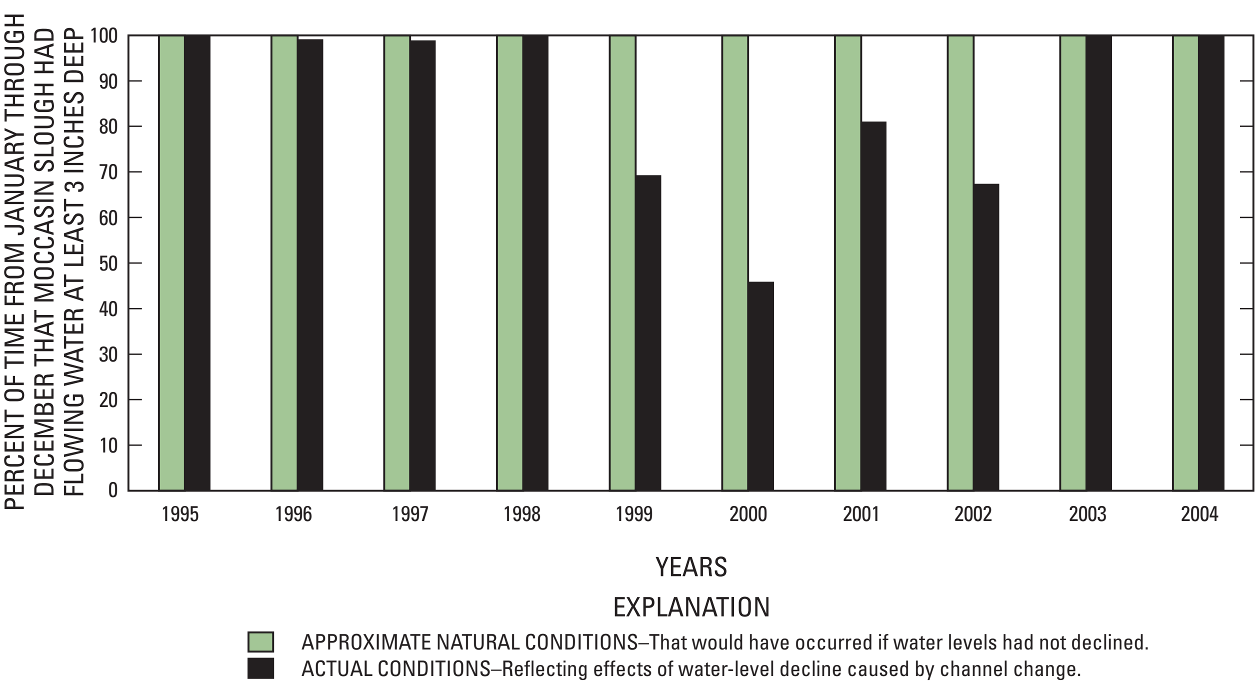

Figure 23. Effects of water-level decline on persistence of flowing-water habitat in Moccasin Slough on the Apalachicola River, Florida, from 1995 to 2004. These results are based on an elevation survey of the streambed in the head of Moccasin Slough and observations of flowing and non-flowing conditions in 2001 and 2002 compared to simultaneous stage measurements at RM 35 streamgage.

at the mouths of these unnamed streams, but no live mussels were found in the streams themselves (Jerry W. Ziewitz, USFWS, written commun., 2001; Payne and Miller, 2002; EnviroScience, Inc. 2006).

It has been hypothesized that floodplain streams in the nontidal lower reach could support mainstem mussel communities by serving as a core reproductive population for these species (James D. Williams, USGS, oral commun., 2006). Water-level decline in the Apalachicola River, however, appears to be an important limiting factor for rare mussels because of its effect on the persistence of flowing water conditions in floodplain streams of the nontidal lower reach.

Duration of inundation in tupelo-cypress swamps.—Tupelo-cypress swamps are found in the lowest elevations of the forested floodplain where the longest periods of inundation occur. Low bottomland hardwood trees grow on slightly higher elevations where inundation periods are shorter. The long duration of inundation and deep flooding that occurs in tupelo-cypress swamps controls forest composition primarily through a process of exclusion, drowning the seedlings of most bottomland hardwood species before they can become established (Hosner, 1960; Light and others, 1993, 2002). The seedlings of water tupelo (*Nyssa aquatica*) and bald cypress (*Taxodium distichum*) are more likely to survive flooding in swamps because they grow tall much faster than bottomland hardwood species (Harms, 1973; Brown, 1984). Solitary individuals of bald cypress grow well at higher elevations in the floodplain, and even do well when planted on upland sites, but natural stands with large numbers of bald cypress trees, as shown in figure 24, occur only where flooding lasts long enough to limit competition from drier habitat species. Limited competition is also a necessary prerequisite for the establishment of water tupelo trees, but unlike bald cypress, water tupelo requires wet conditions to thrive in the seedling stage and will not grow well under drier conditions (Applequist, 1959; Hosner and Boyce, 1962; Dickson and others, 1965). Where flooding has decreased in depth or duration, species of trees most commonly found in bottomland hardwood forests will successfully invade tupelo-cypress swamps, changing the swamps to a drier forest type.

Elevations and tree compositions of sampling points near Porter Lake in the middle reach of the Apalachicola River were surveyed by Leitman and others (1984) and reanalyzed as part of this study to show the effects of water-level decline on swamp forests. Because of its proximity to a stream that connects Porter Lake to the Apalachicola River at rm 48.3, water levels in swamps at the sampling area are directly controlled by river stage. Thus, percent duration of inundation calculated by the methods used in this report can be applied directly without any adjustments for water retention in topographic depressions. Inundation of floodplain forests has little effect on tree growth and survival during the dormant season, so duration calculations were made only on water-level data during the growing season of March 1-November 24 (last and first 32 ºF freeze dates at the Quincy, Florida, weather station, 1971-2000).

Figure 24. Tupelo-cypress swamp near Porter Lake in the middle reach of the Apalachicola River, Florida, during a summer low-water period. The trees in this photograph are primarily cypress, with dark, distinct "water lines" on swollen trunks several feet above ground that were formed during the high water season in winter and early spring. Duration of inundation in this swamp is considerably shorter than it was before 1954, because of long-term water-level decline in the Apalachicola River.

Photograph taken by Helen M. Light

During the 10 years of the recent period, duration of inundation in the growing season at the average elevation of the tupelo-cypress swamp at this site was 29 percent, based on actual conditions reflecting the effects of water-level decline caused by channel change (fig. 25). The approximate duration of inundation in the growing season that would have occurred in this swamp if water levels had not declined was 47 percent. Thus, the water-level decline in the river has shortened the duration of inundation in the growing season in the tupelo-cypress swamp at Porter Lake to the extent that hydrologic conditions in the swamp are now more similar to natural conditions associated with the low bottomland hardwood forest (19 percent) than to conditions previously associated with the swamp.

A preliminary assessment of vegetative changes indicates that Porter Lake swamps are shifting to a drier forest composition. Based on a comparison of historical (1979) to present (2005) composition and a comparison of the present canopy to the present subcanopy (using younger trees as an indication of the future canopy), a change has occurred in forest composition of about 10 to 20 percent toward a drier forest type in the Porter Lake tupelo-cypress swamp. Because forest composition changes slowly, the full impact of the hydrologic change may not occur for many more years. Other effects of altered hydrology may be slower growth rates, higher mortality rates, and reduced density. The composition of low and high bottomland hardwood forests may also change in response to drier conditions.

Effects on Floodplain Habitats: An Overview

The specific examples given at Flat Creek, Moccasin Slough, and Porter Lake swamp illustrate the impacts of water-level decline on floodplain habitats. The reduction in availability of cool-water refuge by more than half in Flat Creek, the conversion of the previously perennial Moccasin Slough to an intermittent stream with no flow for weeks or months during dry years, and the alteration of hydrologic conditions in tupelo-cypress swamps near Porter Lake to the extent that tupelo-cypress swamps are changing to a different and drier forest type, represent only a few examples of the impacts that have occurred in floodplain habitats as a result of water-level decline caused by channel change. Water-level declines in the river have substantially changed long-term hydrologic conditions in more than 200 mi of off-channel floodplain sloughs, streams, and lakes and in most of the 82,200 acres of floodplain forests in the nontidal reach of the Apalachicola River (fig. 18; Light and others, 1998). Figure 26 illustrates some of the other effects that decreasing river levels have on floodplain habitats.

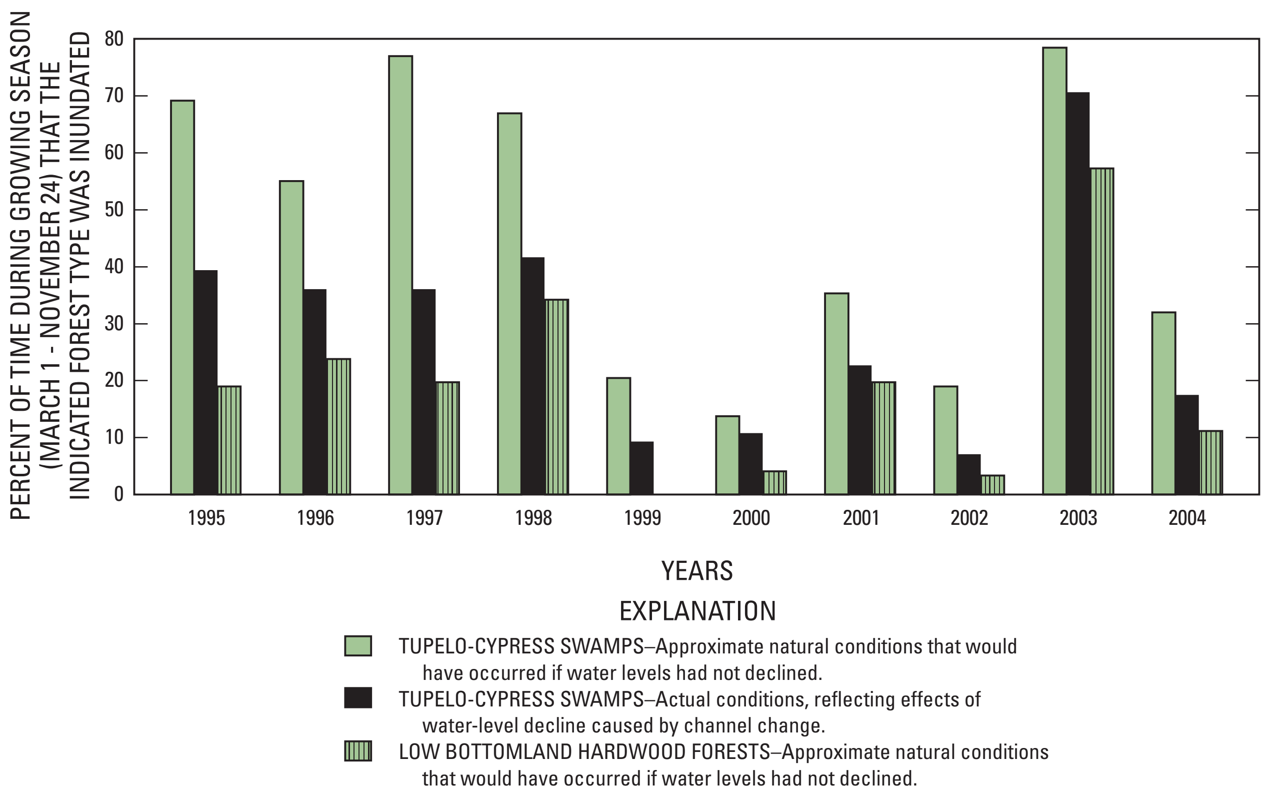

Figure 25. Effects of water-level decline on the duration of inundation in tupelo-cypress swamps near Porter Lake in the middle reach of the Apalachicola River, Florida, from 1995 to 2004. Because of water-level decline caused by channel change, the average duration of inundation during the growing season in Porter Lake swamps decreased from 47 to 29 percent, and is now more similar to the natural conditions associated with low bottomland hardwood forests (19 percent).

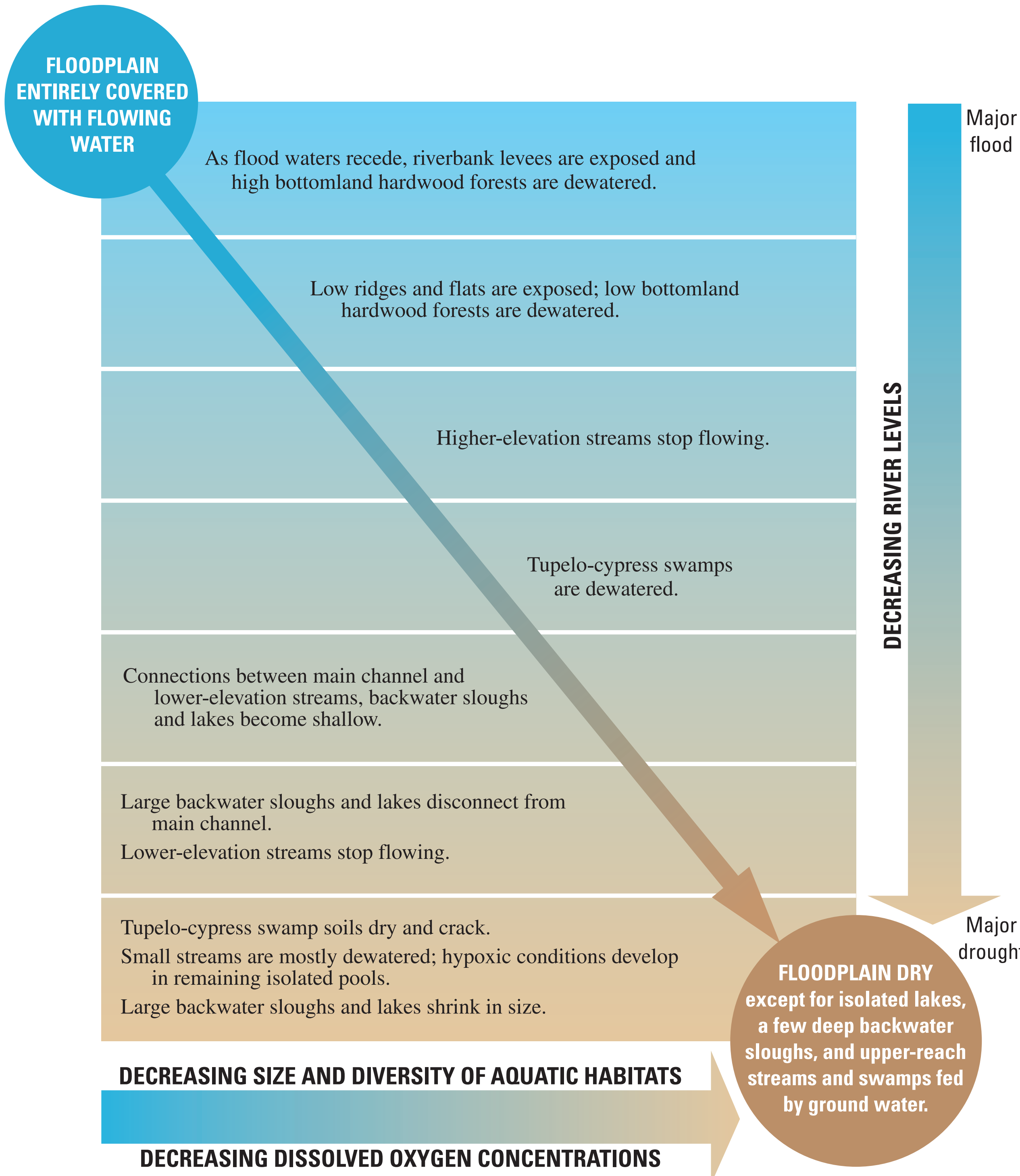

Figure 26. Conceptual relation between conditions in floodplain habitats and decreasing river levels in the nontidal Apalachicola River, Florida. A fluctuating flow regime is a natural characteristic of this river system, and all conditions shown occur naturally at various times in some floodplain habitats. Long-term water-level declines in the river, however, have substantially increased the frequency and duration of nonflowing, disconnected, hypoxic, and dewatered conditions in the floodplain.

Except during the highest floods, when the floodplain is entirely covered with water moving in a downstream direction, the river-floodplain corridor contains a constantly changing mixture of terrestrial and aquatic habitats as water levels fluctuate seasonally and annually between the wet and dry extremes shown in figure 26. The high diversity of habitat types and hydrologic conditions in the Apalachicola River floodplain helps explain the high biological diversity of this system. All of the habitat conditions shown in figure 26 occur periodically in some parts of the floodplain in response to the naturally fluctuating flow regime of this system. The frequency and duration of conditions at the dry end of the spectrum, however, have increased substantially because of long-term water-level declines. Nonflowing, hydrologically disconnected, and dewatered conditions occur much more often as a result of the decline, with important consequences on water quality, particularly dissolved oxygen concentrations. Based on over 900 water-quality measurements made in various floodplain habitats of the Apalachicola River from 2001–2004, mean dissolved oxygen concentrations were 6 ppm (parts per million) in flowing waters, 5 ppm in nonflowing backwaters connected to the main channel, 4 ppm in backwaters that had been isolated from the main channel less than 6 weeks, and less than 2 ppm in backwater areas that had been isolated from the main channel more than 6 weeks (Stephen J. Walsh, USGS, written commun., 2006). Ponds and lakes remaining in the floodplain shrink in size from evaporation and infiltration during extended periods of low water levels, reducing the amount of aquatic habitat connected to the main river channel to 200 acres or less during severe droughts (Light and others, 1998).

Long-term hydrologic changes in floodplain habitats of the Apalachicola River described so far in this report were caused by channel changes only. Changes in the amount of water delivered from upstream were not included in the calculations of decreased duration of inundation presented in figures 18, 19, 21, 23, and 25, because effects of water-level declines caused by changes in stage-discharge relations were calculated independent of changes in flow (see section entitled “Approximate Decrease in Duration of Inundation Caused by Channel Change”). A discussion of additional hydrologic changes that have occurred as a result of changes in flow is necessary in this general overview of the effects of water-level decline on floodplain habitats.

Long-term changes in monthly discharge.—Average discharge in the earliest 30 years (1929–1958) and latest 30 years (1975–2004) in the period of record at the Chattahoochee gage was very similar (21,200 and 21,500 ft^3/s, respectively), but the seasonal distribution of flows has changed. Figure 27 compares monthly streamflow statistics (10, 25, 50, 75, and 90 percent exceedance) in these two periods. During median conditions (fig. 27C), fall and winter discharges increased and spring and summer discharges decreased, with the greatest changes in February (23 percent more discharge) and April (22 percent less discharge). During drought conditions (90 percent exceedance, fig. 27E), discharge decreased in all months except February, with the greatest decreases in April, May, July, and August (28, 24, 26, and 29 percent less discharge, respectively).

Long-term changes in the monthly discharge in the Apalachicola River are probably caused by a combination of natural climatic changes and anthropogenic activities in the ACF Basin, some of which are listed below. Although numerous reports have addressed most of these activities and changes, there is no comprehensive summary describing the degree to which each of the factors have affected streamflow in the Apalachicola River. In the following discussion, the order in which various factors are addressed does not necessarily imply order of importance. Trend analyses relating discharge to climate, which is not within the scope of this report, would be necessary to understand the degree to which anthropogenic effects have contributed to the observed changes in monthly discharge.

Climatic differences may have contributed, in part, to differences in monthly discharge between the earlier and later periods. Large increases in median February and March discharge in the Apalachicola River (fig. 27C), for example, were also observed in two smaller, undammed rivers nearby to the east and west (Suwannee River at Ellaville, Choctawhatchee River near Bruce; USGS, 2006b,c). In many north Florida streams, including the Apalachicola River, winter streamflow increased from 1940–1969 to 1970–1999 (Kelly, 2004). This increase was attributed to a long-term cyclical pattern in Atlantic Ocean sea-surface temperatures called the Atlantic Multidecadal Oscillation (AMO) in which 1940 to 1969 was a warm phase and 1970 to 1999 was a cool phase. In that comparison, the increase in average annual flow in the Apalachicola River during the recent cool phase (1970–1999) was less than all other north Florida streams examined, possibly because streamflow decreased at all Flint River stations during that period—a trend atypical of the southeastern United States in general. It is important to understand the effect of the AMO and other long-term climatic patterns (such as the El Niño Southern Oscillation) on Apalachicola River flow, because these natural cycles can alternately “disguise or accentuate” the effects of anthropogenic activities (Enfield and others, 2001).

Flow regulation is carried out by USACE through the management of reservoir storage and releases at three Federal dams along the Chattahoochee River (Buford, West Point, and Walter F. George; fig. 1) (USACE, 1989; 2006a). Reservoirs impounded by George W. Andrews and Jim Woodruff Dams are essentially run-of-river projects and are not normally used for flow regulation. Although reservoir operations vary from year to year depending upon river levels, climatic conditions, and water management needs, operations generally follow pool-level guidelines called “action zones” to meet project purposes for each reservoir (USACE, 2006a,b). Management for flood control typically includes releases of water in the fall (October-December) to lower reservoir pool levels in advance

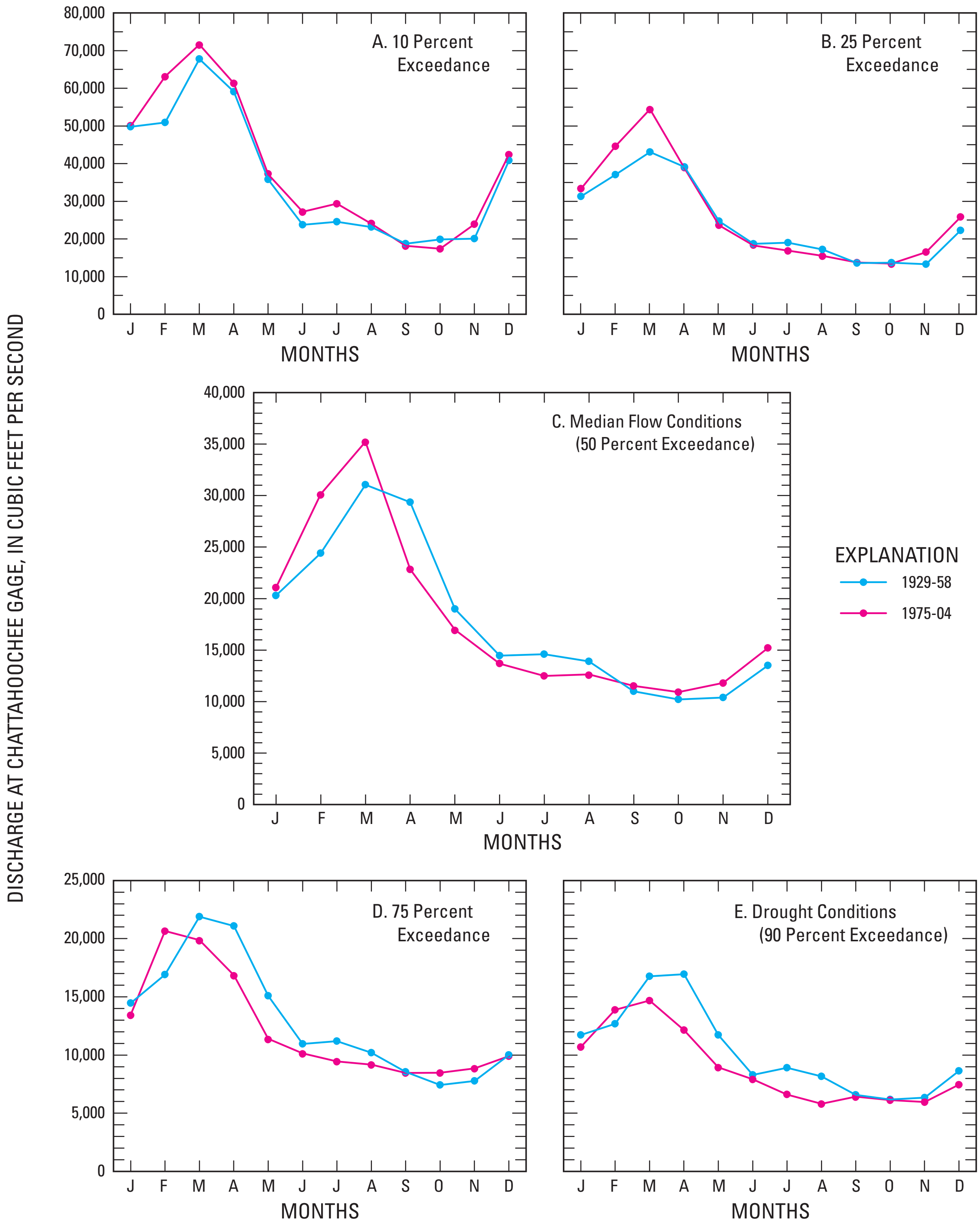

Figure 27. Monthly streamflow statistics for the earliest 30 years (1929–58) and the latest 30 years (1975–2004) in the period of record at the Chattahoochee streamgage on the Apalachicola River, Florida. Discharge values shown were equaled or exceeded, for the percent of time indicated, in the given month of the specified 30-year period. For example, graph A shows discharges that were equaled or exceeded only 10 percent of the time, representing very wet conditions. Graph E shows discharges that were equaled or exceeded 90 percent of the time, representing drought conditions. Note that scales on vertical axes are different on every graph.

of the flood season (January-April). Refilling of the reservoir pools can begin as early as mid-February, but is accomplished primarily in April and May in advance of Memorial Day, the first major holiday of the recreational season (USACE, 2006a,b). Although the amount of water that can be stored in or released from Federal reservoirs is limited relative to the flow of the Apalachicola River, reservoir management may have contributed, in part, to decreased flow in April and May in the Apalachicola River during moderate and dry conditions (fig. 27C, D, and E). Reservoir operation objectives to maintain full reservoir pool levels during the summer recreational season, which ends with the Labor Day holiday (USACE, 2006b), may have affected summer flow in the Apalachicola River. On the other hand, releases from lake storage during summer and fall (June-December) were routinely made in the past to augment flow in the Apalachicola River to support navigation (USACE, 1986). If support of navigation is reduced in the future as a result of recent difficulties encountered by the USACE in obtaining a State permit for maintenance dredging of the navigation channel (Florida Department of Environmental Protection, 2005), the amount of summer flow augmentation may change.

Agricultural water use increased rapidly in the lower Flint River basin during the 1970s with the introduction of center-pivot irrigation systems (Pierce and others, 1984). The irrigation season is typically April through September, with peak irrigation volumes in May through August (Georgia Environmental Protection Division, 2006). Ground water is the primary source of irrigation withdrawals (Marella and others, 1993). Several studies have documented a strong connection between ground-water withdrawals and reduced streamflow in the lower Flint River basin (Hayes and others, 1983; Torak and others, 1996) with modeling results indicating effects on Apalachicola River flows, particularly during droughts (Torak and McDowell, 1996).

Municipal and industrial water use in the ACF Basin has increased substantially since 1970. Municipal water use increased steadily from 1970 to 1990, whereas industrial water use increased from 1970 to 1980 and then leveled off (Marella and others, 1993). Comprehensive compilations of municipal and industrial water withdrawals and wastewater returns in this basin after 1990 have not been published, although estimated values were generated for missing data as part of a recent ACF flow-modeling project (USACE, 2004). Population in urban areas of Georgia has continued to increase, particularly in metropolitan Atlanta (Atlanta Regional Commission, 2006), and preliminary 2000 water-use estimates in the ACF Basin indicate that steady increases in municipal water withdrawals are continuing as well (Fanning, 2003; Richard L. Marella, USGS, written commun., 2006). Considerable seasonal variation can occur in the amount of municipal consumption (withdrawals minus returns). Municipal consumption in the ACF Basin from May through August was about twice that of November through April based on preliminary data for the year 2000.

Reservoir evapoprecipitation (evaporative losses and precipitation gains) results in lower flows in spring, summer, and early fall, when temperatures and evaporation rates are highest, and higher flows in winter, when evaporation rates are low and precipitation on reservoir surfaces adds directly to streamflow without interception by the forests that existed there before the reservoirs were built (USACE, 1996). Estimates of evapoprecipitation effects on streamflow have been made at the four largest Federal reservoirs by the USACE (1995, 1996). Evapoprecipitation is also occurring at the 12 smaller mainstem reservoirs on the Chattahoochee and Flint Rivers, 1,800 reservoirs on mapped tributaries of these two rivers (U.S. Environmental Protection Agency (USEPA), 1998; Alice Lawrence, USFWS, written commun., 2005), and 22,000 additional small reservoirs, including ponds on intermittent streams and isolated ponds used for irrigation and stock watering (Cowie, 2002; Davis, 2003; Georgia Spatial Data Infrastructure, 2006). Little is known about the hydrologic effects of these numerous farm ponds on ACF streamflow. In a detailed hydrologic study conducted in a stream basin with many stock-water reservoirs in an arid region (Wyoming), water losses attributable to reservoirs were about 30 percent of total basin streamflow (Culler, 1961). A similar hydrologic study is needed to determine the effects of reservoirs on streamflow in the humid southeastern United States.

Increases in impervious surfaces from urbanization have occurred in the ACF Basin, with the greatest increases occurring in metropolitan Atlanta. Increases in frequency and magnitude of high flows, and other changes in streamflow characteristics, are known to occur as a result of increased imperviousness (Bledsoe and Watson, 2001; Leopold and others, 2005). In the Upper Chattahoochee River basin, tributary stream basins with the largest percentage of impervious area had the highest peak flood flows (Rose and Peters, 2001) and the lowest baseflows (Calhoun and others, 2003). The degree to which this change in land use has changed mainstem streamflow is unknown. Updated estimates of the percentage of the watershed covered with impervious surfaces are needed, along with a better understanding of the runoff characteristics that existed in those areas prior to urbanization.

As described in figure 3, effects of water-level decline are the same for floodplain habitats regardless of the cause. Thus a comprehensive assessment of the impact of hydrologic alterations on floodplain habitats should address the combined effects of long-term changes in both channel conditions and the amount of water delivered from upstream. Water-level changes resulting from changes in flow, however, are complex because of substantial seasonal and annual variability. In addition, the effect of flow changes on duration of inundation varies with the location along the river, similar to the variability that occurs with channel changes. Although a full description of the effects of flow changes is not within the scope of this study, the combined effects of water-level change attributable to both channel changes and flow changes at one site (Blountstown gage) are presented for comparison purposes in figure 28.

During typical or median conditions (fig. 28A), changes in the seasonal distribution of flows have diminished the effect of channel change in the fall and winter, with large enough increases in February discharges to entirely cancel out the effects of channel change. In the spring and summer, however, decreased flows during median conditions have added to the effect of channel change in 5 consecutive months (April-August). During median conditions, the total water-level decline in April attributable to both channel change and flow changes is 4.3 ft (1.8 ft from channel changes plus 2.5 ft from flow changes).

During drought conditions (fig. 28B), total water-level declines in April, May, July, and August (3.5–4.1 ft) are approximately double the decline caused by channel change alone. Drought conditions in this figure refer to flows that are equaled or exceeded 90 percent of the time, which over the long-term represent conditions that occur on average 1 year out of every 10.

The combined effects of channel changes and fow changes are depicted in figure 28 for only one site (Blountstown gage), so the reader is cautioned that total water-level declines at sites with large channel-change declines can be greater than those

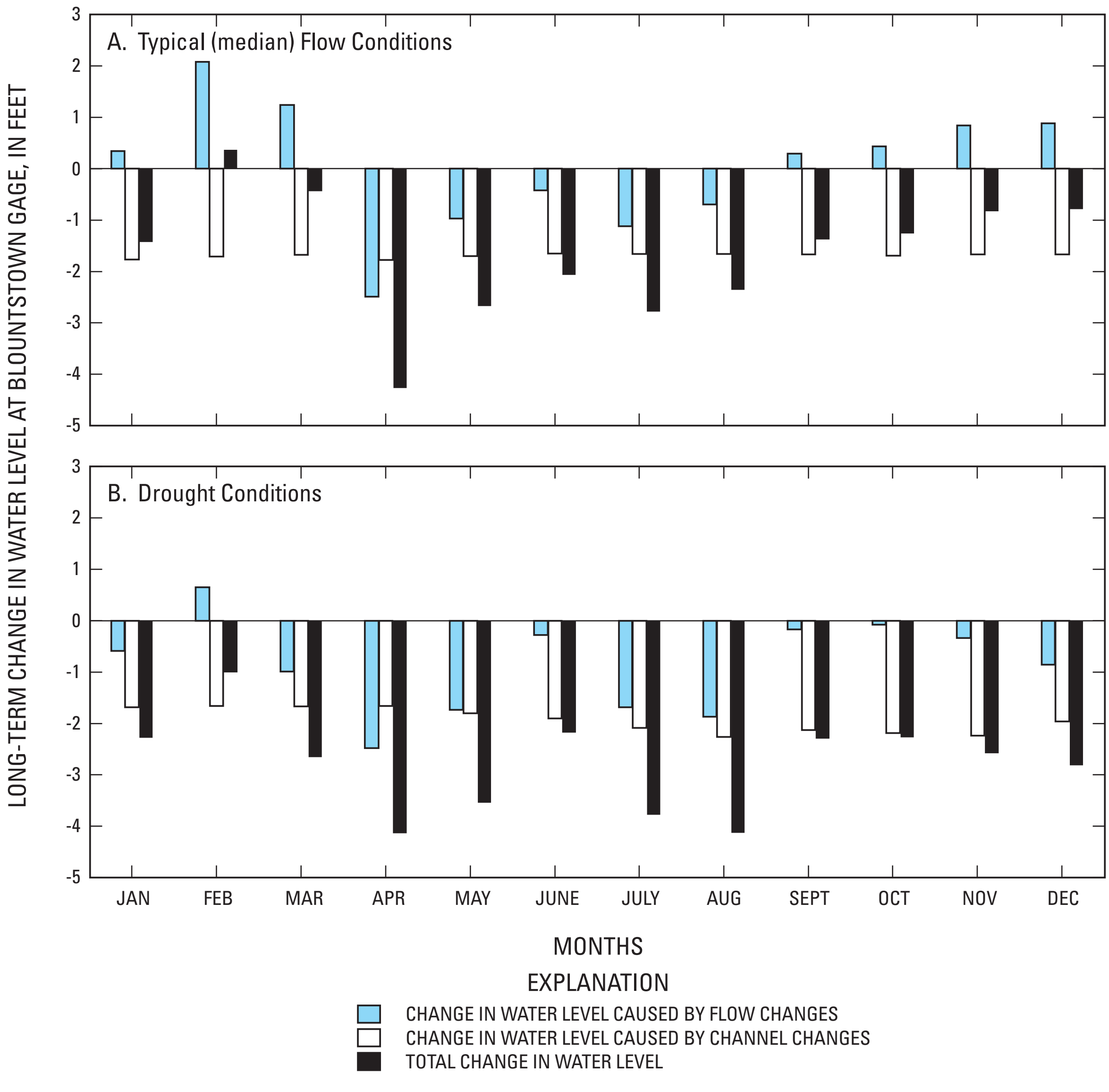

Figure 28. Long-term water-level changes attributable to the isolated effects of flow changes and channel changes, and their combined effect, at the Blountstown streamgage on the Apalachicola River, Florida, during (A) typical (median) flow conditions, and (B) drought conditions. In this figure, drought conditions represent flows that were equaled or exceeded 90 percent of the time. Water-level changes caused by changes in discharge were determined from the difference between earlier (1929–58) and later (1975–2004) discharge data from the Chattahoochee streamgage from figure 27C and E, using the recent Blountstown stage-discharge relation in figure 6. Water-level declines caused by channel changes were determined from the difference between pre-dam (pre-1954) and recent (1995–2004) stage calculations (using Blountstown stage-discharge relations in figure 6) for the 1975–2004 discharges shown in figure 27C and E.

shown. For example, the total water-level decline in April during drought conditions exceeds 5 ft at RM 35 (2.8 ft from channel changes plus 2.3 ft from flow changes) and is about 7 ft at Chattahoochee gage (4.7 ft from channel changes plus 2.3 ft from flow changes).

The observed declines in spring and summer flows are important because water levels influence many important biological processes during that time of year, with sensitive species especially vulnerable during drought conditions in hot weather. Greatest spawning activity for fishes in floodplain habitats of the Apalachicola River occurs in April and May, with high levels of spawning activity continuing for some species throughout the summer (Stephen J. Walsh, USGS, written commun., 2006). The need for cool-water refuge in floodplain streams for striped bass is greatest in the summer months when flows are low and river temperatures are high (Van Den Avyle and Evans, 1990). Low dissolved oxygen concentrations in isolated sloughs are most problematic for fish and mussels during summer for the same reasons (low flow and high temperature). Spring and early summer are the seasons of greatest tree growth (Conner and Day, 1992), and probably also the seasons when flooding has the largest influence on tree composition and recruitment in floodplain forests. Consequently, a better understanding of the causes of decreased spring and summer flow, and the trends in seasonal discharge that might be expected in the future, is critical in determining the full extent of the effects of long-term water-level declines on floodplain habitats and biological communities.

Future trends and potential for restoration.—Water-level decline caused by channel change slowed dramatically at some sites and ceased altogether at other sites about 20 to 30 years ago (fig. 5). At the Chattahoochee gage, streambed lowering is predicted to continue at a slow rate as long as sand continues to be trapped behind Jim Woodruff Dam. In a “worst-case” estimate by USACE, water-level decline was projected to be 1 ft in the next 40 years at the Chattahoochee gage (USACE, 2001a). It is possible that decreased slope in the upper 40 mi of the river, evident in a comparison of the 1956 and 1995 water-surface profiles in figure 4, will serve as a counter-balancing influence to downstream-progressing riverbed degradation. Future water-level decline in this reach may depend on the degree to which this decrease in slope acts to decrease both stream velocities and sand transport, which is unknown.

Partial recovery of the water-level decline at the Wewahitchka gage (fig. 5) may have occurred because of changes that were made in the navigation project in the 1970s to reduce environmental impacts on the river ecosystem. This partial recovery indicates that future channel change (except for minor deepening that may gradually continue because of the presence of the dam) could be minimized by avoiding the channel modification activities that caused the observed changes. Unfortunately, it is not yet clear which activities played the greatest role in channel enlargement, particularly channel widening. If the specific activities responsible for most of the widening could be identified and halted, there is a possibility that the river would narrow by natural processes, allowing a more widespread recovery of the water-level decline by some as yet unknown amount. Prevention efforts will be more effective when the causes of these changes are better understood.

Recovery options to raise water levels in selected reaches of the river could have large potential benefits, with low-water connections and flowing conditions restored to many miles of streams and sloughs, and a more natural flood regime restored to thousands of acres of floodplain forests. Large-scale projects, however, can be expensive, questionable with regard to feasibility, and pose the risk of negative unintended consequences.

One example of a potential large-scale restoration project to raise water levels is the rerouting of the river back through the bendway of the artificial meander cutoff at Battle Bend (fig. 29). The Battle Bend cutoff, which shortened the river by more than a mile, was the largest of seven artificial cutoffs and bend easings excavated by the USACE from 1956 to 1969 along the Apalachicola River, all of which were located in the lower reach. Although the difficulties involved in rerouting a river as large as the Apalachicola could prove to be a major engineering and construction endeavor, restoring the Battle Bend cutoff might reverse the channel deepening that has occurred in this straightened reach of the river, raising water levels for many miles upstream. Meander cutoffs were successfully restored on the Kissimmee River in central Florida, resulting in reflooding of floodplain marshes and rapid recovery of biological communities (Toth, 2005; Williams and others, 2006). Restoration of a meander cutoff of the Apalachicola River, however, may be considerably more difficult than bendway restoration on a smaller, lower gradient stream like the Kissimmee River.

Another example of a large-scale restoration project is a sand bypass or sand recycling project, which could move sand from the reservoir and deposit it in the thalweg of the upper reach of the river or move sand upstream to the upper reach of the river from large dredged material disposal sites in the lower reach. Preliminary evaluations of similar proposals in the Missouri River, however, describe high costs and many difficult logistical issues involved in sand bypass projects (USACE, 2001b; Engineering and Hydrosystems, Inc., 2002).

Local-scale remediation efforts do not raise water levels, but can increase the size and connectivity of limited areas of aquatic habitat by removing sediments and lowering bed elevations in selected sloughs or backwaters. Minor excavation in the mouths of floodplain streams and sloughs has been conducted along the Apalachicola River by the USACE since the 1980s in response to environmental concerns about the damage done to the river-floodplain system as a result of the navigation project. About a dozen small projects have been completed, involving excavation amounts ranging from 200 to 2,500 yd^3 (cubic yards) that were limited to areas in the mouths or heads of streams within 100 ft of the main channel (USACE, written commun., 2003).

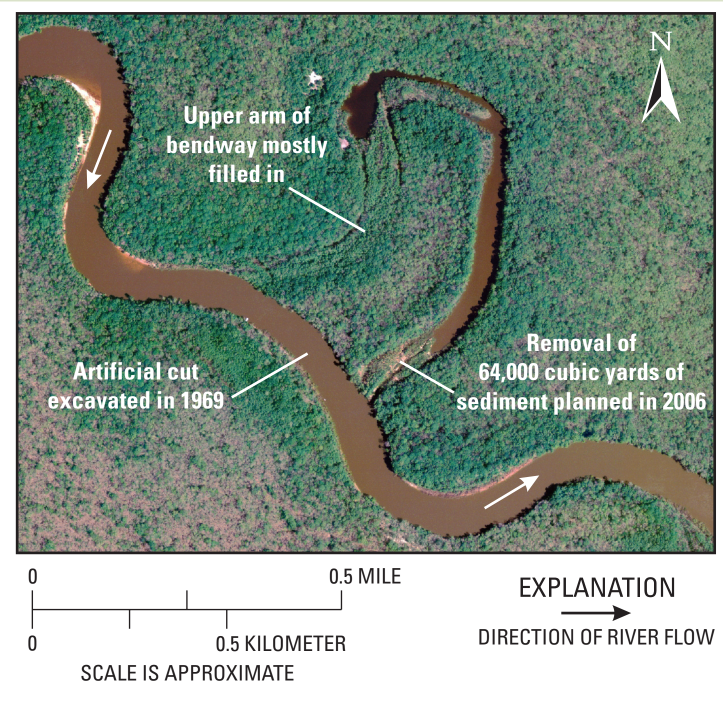

Figure 29. Artificial meander cutoff at Battle Bend in the lower reach of the Apalachicola River, Florida (location shown in fig. 2). This cutoff shortened the river by about 6,000 feet (U.S. Army Corps of Engineers, 1986). Photograph was taken in 2004 (source—Florida Department of Environmental Protection).

One type of local-scale remediation conducted by the USACE involved minor excavation of the mouths of perennial streams, mostly in the upper reach, to create deep pools of cool water for striped bass to use as thermal refuge. The first project of this type was conducted in 1997 in Blue Spring Run (fig. 2). Since then, five other cool-water spring runs and creeks in the upper reach and one stream in the upper part of the middle reach were dredged at their mouths to provide thermal refuge habitat at a discharge of 8,500 ft^3/s (USACE, written commun., 2003). These efforts were temporarily successful, but in most cases, creek mouths began to accumulate sediments within 1 to 3 years (Long, 2004; Striped Bass Technical Task Force, 2005). Excavation of thermal refuge streams is needed on a regular basis to assure long-term benefits (Charles L. Mesing, Florida Fish and Wildlife Conservation Commission, written commun., 2006).

Minor excavation of sediment blockages by the USACE in one middle reach slough and two lower reach sloughs was intended to increase connectivity between interior reaches of the sloughs and the main river channel. This excavation did not increase connectivity to any great extent, however, because additional internal sills continued to control the hydrologic connection to the main channel. Little is known about the mechanisms responsible for sediment blockages in middle and lower reach sloughs. Sand from dredged material disposal was apparently responsible for sediment blockages at some locations. Water-level decline in the middle and lower reach (not generally understood prior to this report) reduced connectivity of streams as well. Streambed elevations probably remained the same when river levels declined, causing many sloughs to be shallowly connected or disconnected from the main channel—a problem that probably cannot be remedied by minor excavation at the slough head or mouth.

FFWCC is currently involved in the final phases of a local-scale project for fisheries enhancement involving excavation of a large volume of sediments (64,000 yd^3) to remove a sill that is obstructing the lower arm of Battle Bend (fig. 29). The project is intended to create backwater habitat that will be connected to the main river channel at the currently maintained minimum flow of 5,000 ft^3/s. FFWCC plans to continue local-scale enhancement of this type and may explore the feasibility of large-scale projects in coming years (Michael J. Hill, Florida Fish and Wildlife Conservation Commission, oral commun., 2006).

In addition to excavation projects, improved conditions in floodplain habitats can also be accomplished by increasing flows in the spring and summer. For long-term changes in flow to occur, management solutions, such as increased water conservation, additional growth-management policies, and changes in reservoir operations, would be needed throughout the basin. Scientific investigations are needed to provide the supporting information necessary to evaluate and prioritize possible management solutions.

Research Needs

Natural conditions and anthropogenic influences are constantly changing in this complex river-floodplain system and in the large tri-state basin of which the Apalachicola is a part. Research needs change as well, both in terms of changing management priorities as well as changing environmental conditions. The following discussion is intended to highlight some of the key issues regarding water-level declines caused by both channel changes and flow changes that, to the authors' knowledge at the time of this writing (2006), have not yet been adequately addressed by the scientific community.

Although it is apparent that channel changes in the Apalachicola River were caused by some combination of various channel modifications (dam construction, meander cutoffs, dredging, dredged material disposal, and woody debris removal), the relative contribution of each of these activities is not known. Additionally, the precise geomorphic mechanisms that caused widespread channel widening are unclear. A geomorphological study, addressing fluid mechanics, sediment transport, bank erosion, and the history of mechanically removed sediment, is needed to determine which of these past actions played the greatest role in channel widening, based on the river's response to past actions. This research would provide a basis for evaluating the potential erosion and sedimentation effects of all future proposals to modify the channel, whether for navigational improvement, restoration, or other purposes. In addition, the study results could be used to develop a plan that details the actions (and inactions) needed to encourage channel narrowing and allows for the recovery of the water-level decline to the greatest extent possible.

A better understanding of geomorphological processes is also needed to answer important practical questions about sedimentation at sites being considered for local-scale remediation. Answers are needed to estimate the time it may take for sediments to accumulate after remediation so that the need for repeated excavation can be more accurately predicted. Where does sedimentation occur and at what rates? What is the travel path of sediment deposited in sloughs? Is sediment delivered to sloughs during high-flood events with water passing over the floodplain or during lower stages with water primarily contained within banks? Is the sediment composed of sand (which could only have been delivered from the main channel during high discharges)? Is it better to open the upstream end, the downstream end, or both ends of a cutoff oxbow in order to reduce subsequent sedimentation rates? Analyzing relevant historical data and monitoring sedimentation in sloughs is needed to address these questions.

The long-term changes in monthly discharges depicted in figure 27, and the resulting water-level changes shown in figure 28, provide useful preliminary information about trends in flow; however, this analysis is limited in scope and provides little information about the causes of the flow changes. A more comprehensive statistical analysis of flow-climate relations in the ACF Basin, based on observed discharges at the Chattahoochee gage in relation to meteorological data throughout the upstream watershed, is needed to understand the relative contribution of various natural and anthropogenic causes. A baseline flow-climate model could be developed by determining the amount of water that historically was delivered from the upstream watershed under a specified set of meteorological conditions. Such a model could be used to calculate differences between expected and observed flows in recent periods under similar meteorological conditions. Departures from expected streamflow could be compared to data on flow regulation, water use, and other anthropogenic influences to determine the relative contribution of nonclimatic (anthropogenic) factors to streamflow changes. The model could be used to estimate future changes in flow, based on potential changes in reservoir operation practices, changes in water use, or other changes. The model also could be used as a future real-time monitoring tool, with the potential to detect flow deficits that may not have been expected. Research based on flow-climate relations could complement recent work accomplished by USACE to reconstruct natural flows by making adjustments of observed flows based on known human influences (USACE, 1996, 2004), with each type of model serving as a cross-check for the other.

An equally critical research need that would help elucidate causes of decreased spring and summer flow is to update the comprehensive basinwide database of ACF water use that was last conducted using 1990 data (Marella and others, 1993). In that report, agricultural, municipal, and industrial water-use data collected every 5 years from 1970 to 1990 were presented to provide data on current water use at the time (1990) and to describe historical trends in water use for the 20 years leading up to that time. This time series data for water use has been helpful for documenting the history of anthropogenic influences in the basin and for providing trends upon which future projections of water consumption can be based. Up-to-date water-use data for the three most recent 5-year cycles, 1995, 2000, and 2005, are needed, particularly in light of the large increases in population that have occurred in the basin since 1990, and the large future increases projected for metropolitan Atlanta (Atlanta Regional Commission, 2006).

Continued research is needed to address the causes of hydrologic alterations and to better understand their effects on biological communities of the Apalachicola River floodplain. If declining populations of floodplain species are detected early, investigations of causal factors and possible solutions might lead to timely preventative measures. An understanding of biological responses to hydrologic change can help guide the design and prioritization of restoration efforts on the river, and will be needed to monitor the health of aquatic organisms and forest communities over time, as changing priorities for flow regulation and basinwide changes in land and water use influence the future flow regime of the river.

Summary and Conclusions

This report describes the magnitude and extent of the water-level decline that occurred in the nontidal Apalachicola River from 1954 to 2004 as a result of long-term changes in stage-discharge relations. In the upper reach of the river, which starts at Jim Woodruff Dam at the head of the river 106.4 mi (mile) upstream from the mouth and extends to rm (river mile) 77.5, the water-level decline has been known and generally described in previous reports and is described in more detail in this report. The magnitude and extent of the water-level decline in the middle reach (rm 41.8 to rm 77.5) and nontidal lower reach (rm 20.6 to rm 41.8), which is presented in detail in this report, has not been reported previously.

Channel widening and deepening, which occurred throughout much of the river, apparently caused the water-level decline. The channel enlargement occurred primarily as a gradual erosional process over two to three decades, probably in response to the combined effect of the dam, river straightening, dredging, dredged material disposal, woody debris removal, and other activities along the river. Although navigational improvements have been made on the Apalachicola River since the 1800s, channel modifications were conducted with greatest intensity from 1954 to the 1970s.

Periods of low water levels are now more frequent and longer in duration than prior to 1954, resulting in longer periods during which floodplain streams are dewatered, isolated, or not flowing, and swamps and bottomland hardwood forests are dry. Protection and restoration of biological habitats and communities was the primary motivation for this research, which was conducted in cooperation with the Florida Fish and Wildlife Conservation Commission to assist in fisheries enhancement of off-channel aquatic habitat of the Apalachicola River floodplain. Understanding how much water-level decline has occurred, which reaches of the river have been most affected, and why the decline has occurred were necessary first steps in finding solutions to the problems created by declining water levels.

The magnitude of water-level decline caused by channel changes was determined by comparing pre-dam stage (prior to 1954) and recent stage (1995–2004) in relation to discharge. Long-term stage data for the pre-dam and recent periods from five streamflow gaging stations were related to discharge data from the upstream-most gage at Chattahoochee, Florida, using a procedure involving streamflow lag times. Differences between pre-dam and recent relations are greatest at low flows, and gradually decrease with increasing discharge to a point at which the two relations merge, informally called the "joining point." This point is the stage or discharge above which the proportion of flow moving over the floodplain is large enough that physical changes that occurred in the main river channel at that site have no noticeable effect on river stage. The joining point is 10 ft (feet) above the top of the natural riverbank levee at the upstream-most site where the floodplain is about 10 times the width of the main channel, and gradually decreases with distance downstream until it is nearly the same height as the natural riverbank levee in the nontidal lower reach where the floodplain is about 100 times the width of the main channel.

The pre-dam and recent stage-discharge relations at the streamgage locations were used in combination with low-flow water-surface profile data from the U.S. Army Corps of Engineers to estimate magnitude of water-level decline at closely spaced locations (every 0.1 mi) along the river. Data included in digital files on a compact disk attached to this report can be used to calculate the water-level declines for any discharge at any of the closely spaced locations.

Water-level decline varied with location along the river, with the largest stage declines occurring at low flows. The largest water-level decline, 4.8 ft, occurred at rm 105.7, just downstream from Jim Woodruff Dam, and water-level declines progressively decreased downstream to 1 ft at rm 66. The large water-level decline downstream from the dam was caused primarily by the dam, because sediment trapped in the reservoir was not available to replace sand naturally scoured from the bed and transported downstream by the river. This process acted to lower the elevation of the riverbed, and was probably exacerbated by dredging of streambed sediment to improve navigation. River mile 66 probably marks the downstream limit of the influence of Jim Woodruff Dam with regard to riverbed degradation. Downstream from rm 66, the trend reversed and the decline progressively increased to 3 ft at rm 38. Although annual maintenance dredging, disposal, and woody debris removal occurred along the entire river and probably contributed to the relatively widespread channel widening and water-level declines throughout most of the river, these activities alone do not explain the large declines (2–3 ft) that occurred in the lower reach between rm 33 and rm 39. Declines in this vicinity may have been caused, in part, by channel straightening activities (meander cutoffs and bend easings) accomplished in and downstream from this 6-mi reach. Water-level decline decreased downstream from rm 33, and was negligible at the approximate upstream boundary of the tidal influence of the Apalachicola River at rm 20.6, which is to be expected.

Water-level declines in the river have substantially changed long-term hydrologic conditions in more than 200 mi of off-channel floodplain sloughs, streams, and lakes and in most of the 82,200 acres of floodplain forests in the nontidal reach of the Apalachicola River. Approximate decreases in duration of floodplain inundation that occurred as a result of water-level decline were estimated based on an analysis of daily mean discharge at the Chattahoochee gage from 1995 to 2004. Decreases in duration of floodplain inundation were greatest at low discharges at all sites. For discharges of 5,000 to 15,000 cubic feet per second, large decreases in percent duration of inundation occurred in the upstream-most 10 mi of the upper reach (20–45 percent), with decreases that were nearly as large continuing throughout most of the remaining 75 mi of the nontidal reach (10–25 percent).

The nature and magnitude of the hydrologic alterations of biological habitats on the floodplain that occurred as a result of the water-level declines were described using specific examples at three locations. Access to thermal refuge for striped bass was reduced by more than half in Flat Creek, a cool-water floodplain stream in the upper reach. Moccasin Slough, a perennial floodplain stream in the lower reach was converted to an intermittent stream with no flow for weeks or months during dry years. At a third site in the middle reach of the river near Porter Lake, tree composition in a tupelo-cypress swamp shifted to a drier mix of species, and the swamp could change to a different and drier forest type over time. Many other types of biological habitats have been affected by an increase in frequency and duration of nonflowing, hydrologically disconnected, hypoxic, and dewatered conditions in the floodplain.

Water-level decline caused by physical changes in the channel is probably the most serious anthropogenic impact that has occurred so far in the Apalachicola River and floodplain. This decline has been exacerbated, however, by long-term reductions in spring and summer flow, especially during drought periods. Although no trends in total annual flow volumes were detected, long-term decreases in discharge for April, May, July, and August were apparent, and water-level declines during drought conditions resulting from decreased discharge in those 4 months were similar in magnitude to the water-level declines caused by channel changes. These changes in monthly flows have large impacts on floodplain biota, because many important biological processes are influenced by floodplain inundation in spring and summer. Further research on flow-climate relations, linking discharge in the river to the meteorological conditions in the basin, is needed to understand the relative contribution of natural and anthropogenic causes of the observed declines in spring and summer flow.

Channel restoration to raise water levels could have large benefits for many miles of floodplain streams and thousands of acres of floodplain forest; however, restoration projects of this type typically are major engineering interventions that are expensive and logistically difficult to conduct. Restoration of floodplain streams and sloughs conducted so far have been small, local-scale excavation projects with relatively short-lived benefits (1–3 years). Geomorphic evaluations of proposed excavation projects for restoration, navigational improvements, or other purposes, are needed to optimize the success of such activities and to avoid unintended consequences that could lead to further water-level declines. Scientific studies aimed at understanding the precise geomorphic mechanisms that caused the channel widening, which remain unclear, are needed to assess the possibility of recovery by channel narrowing. Understanding the processes that deliver and deposit sediment in sloughs and other floodplain channels, which as yet is poorly known, will improve the success of future projects designed to enhance fisheries habitat. Continued research on biological communities in the floodplain is needed to assist in design and prioritization of restoration, and to monitor the health of aquatic organisms and forest communities as changes in water management and land use in this large tri-state basin affect the future flow regime of the Apalachicola River.

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