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Multi-Use Management in the Atchafalaya River Basin: Research at the Confluence of Public Policy and Ecosystem Science

Micah Bennett
Southern Illinois University Carbondale

Kelley Fritz
Southern Illinois University Carbondale

Anne Hayden-Lesmeister
Southern Illinois University Carbondale

Justin Kozak
Southern Illinois University Carbondale

Aaron Nickolotsky
Southern Illinois University Carbondale

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NSF IGERT PROGRAM IN WATERSHED SCIENCE AND POLICY

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BY
MICAH BENNETT[1,a], KELLEY FRITZ[2,a], ANNE HAYDEN-LESMEISTER[3,b], JUSTIN KOZAK[4,b], AND AARON NICKOLOTSKY[5,b]

SOUTHERN ILLINOIS UNIVERSITY CARBONDALE
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[1] micahgbennett@siu.edu
[2] k.a.fritz@siu.edu
[3] aehayden@siu.edu
[4] jkozak@siu.edu
[5] nickolotsky@siu.edu

[a] Department of Zoology & Center for Ecology
[b] Environmental Resources & Policy Program

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List of Common Acronyms, Abbreviations and Symbols

°C	degrees Celsius
ABFS	Atchafalaya Basin Floodway System
ABP	Atchafalaya Basin Program
ADWMA	Atchafalaya Delta Wildlife Management Area
ARB	Atchafalaya River Basin
ARMI	Amphibian Research and Monitoring Initiative
Audubon	National Audubon Society, Baton Rouge, LA
Bd	*Batrachochytrium dendrobatidis*
BFI	baseflow index
BLR	Butte La Rose
C	carbon
cfs	cubic feet per second
CO_2	carbon dioxide
crawfishermen	Louisiana Crawfish Producers Association-West
CV	coefficient of variation
DNRA	dissimilatory nitrate reduction to ammonium
DO	dissolved oxygen
EPA	Environmental Protection Agency
Fe^{3+}	ferric iron
GIS	Geographic Information System
GIS-MCDA	GIS-Multicriteria Decision Analysis
GIWW	Gulf Intercoastal Waterway

IBA	Important Bird Area
IHA	Indicators of Hydrologic Alteration
IPCC	Intergovernmental Panel on Climate Change
LCPRB	Louisiana Crawfish Promotion and Research Board
LDE	large-river deltaic estuary
LDNR	Louisiana Department of Natural Resources
LDWF	Louisiana Department of Wildlife and Fisheries
LMB	largemouth bass
LSU	Louisiana State University
MSA	Metropolitan Statistical Area
N	nitrogen
N_2	dinitrogen gas
N_2O	nitrous oxide
NEPA	National Environmental Policy Act
NGO	non-governmental organization
NH_4^+	ammonium
NLCD	National Land Cover Database
NMFS	National Marine Fisheries Service
NO	nitric oxide
NO_2^-	nitrite
NO_3^-	nitrate
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System

NRIAS	Natural Resource Inventory and Assessment System
NWI	National Wetlands Inventory
ORCC	Old River Control Complex
ORCS	Old River Control Structure
PC	principal component
PCA	principal components analysis
psu	practical salinity unit
Qal	alluvium
Qnl	natural levees
RCC-I	Regeneration Condition Class I
RPB	Research and Promotion Board
Si	silicon
SO_4^{2-}	sulfate
TAG	Technical Advisory Group
TNC	The Nature Conservancy
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WMA	Wildlife Management Area
WMU(s)	Water Management Unit(s)

Chapter 1. Introduction

Ecologically distinct, economically productive, and culturally significant, the Atchafalaya River Basin (ARB) is a place truly unlike any other. Amidst its sleepy bayous and vistas of baldcypress and Spanish moss, it is home to a tumultuous history of intense competition and human influence. Central to Cajun culture and synonymous with crawfish, the ARB is the backbone of the regional economy and heart of a distinctive American people. However, it is also tasked with protecting major cities – including Baton Rouge and New Orleans – from catastrophic flooding while providing a throughway for shipping to the Gulf of Mexico, producing crude oil and natural gas, and serving as habitat for important flora and fauna. The multiple, sometimes conflicting, uses of resources in the ARB have resulted in a substantially human-altered system that is in a state of ecological decline.

The ARB is the nation's largest continuous river swamp (Demas et al. 2001), beginning at the confluence of the Red, Mississippi, and Atchafalaya Rivers at the Old River Control Structure, near Simmesport, Louisiana (Figure 1.1). The largest distributary of the Mississippi River, the Atchafalaya River now receives a mandated 30 percent of the combined daily flow of the Mississippi and the Red Rivers. This controlled regime occurs because the ARB is a chief component of the Mississippi River and Tributaries Project's flood management system. After the catastrophic 1927 flood, Congress directed the U.S. Army Corps of Engineers to develop the Mississippi River and Tributaries Project – a system of floodways, levees and channel engineering that would allow a project flood of three million cfs to pass to the Gulf of Mexico safely (U.S. Army Corps of Engineers 2007). The Old River Control Complex, completed in 1963, was constructed to prevent the Atchafalaya River from capturing the Mississippi River after decades of river engineering projects and development within the Mississippi River Basin

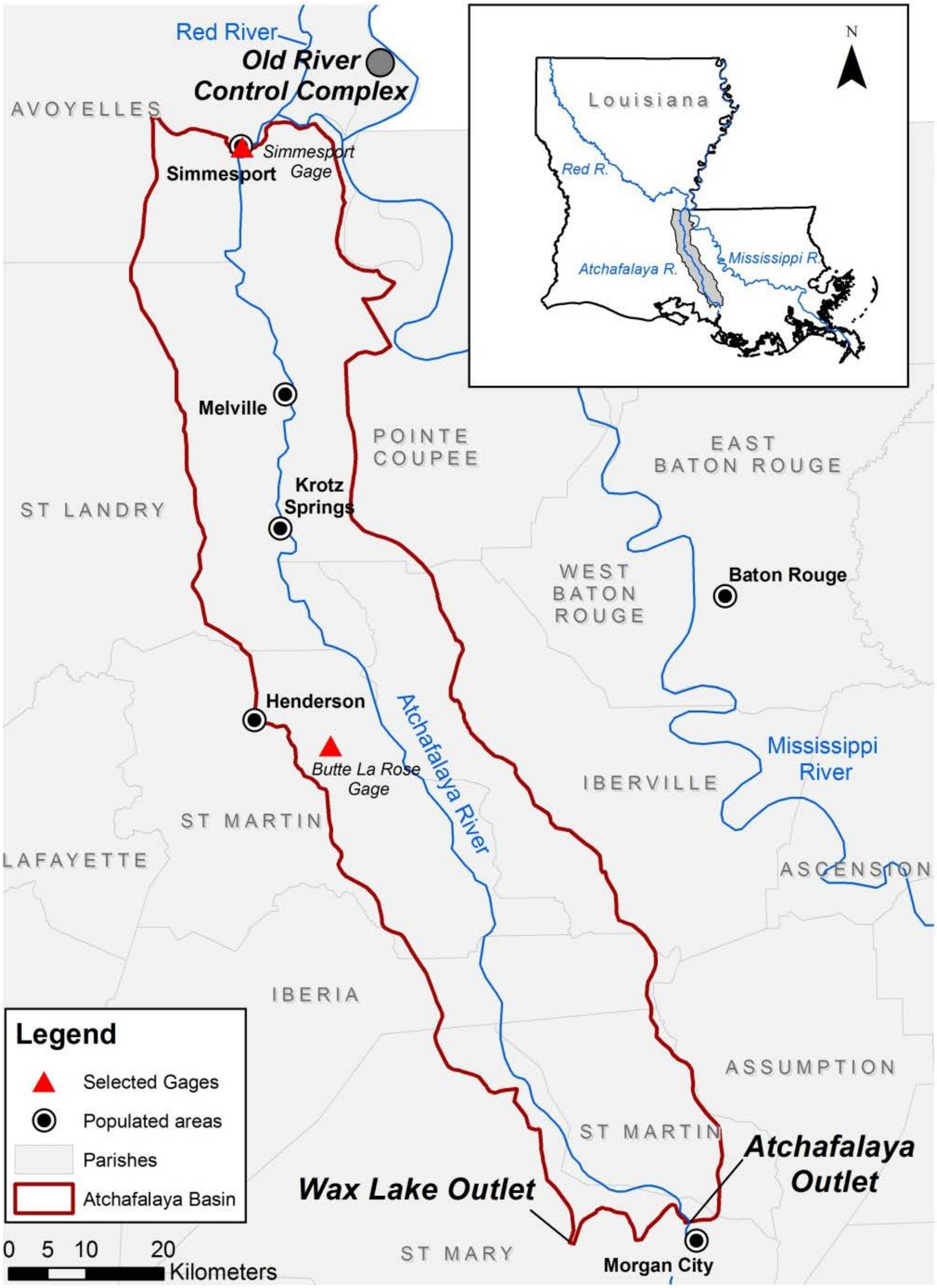

Figure 1.1. Map of the levee-enclosed portion of the Atchafalaya River Basin, Louisiana, USA.

increased the flow of water down the Atchafalaya River (Reuss 2004). The average discharge of the Atchafalaya River, at ~229,000 cfs, is among the top five in the nation (Demas et al. 2001). The ARB Floodway is 25-35 km wide, confined by the east and west guide levees (designed to hold back floodwaters), and extends over 200 km upstream to downstream. A little less than half of the land within the ARB is publically owned (about 1,619 km^2) by the state or federal government, with the majority of land (1,772 km^2) held by private individuals or entities (Ford and Nyman 2011). The ARB and its outlets contain approximately 3,581 km^2 of forested wetlands and 2,092 km^2 of marshland (Demas et al. 2001). These marshlands are significant as the two deltas of the Atchafalaya River - the Atchafalaya Delta and Wax Lake Delta - are the only areas of the Louisiana coast that are gaining land (Couvillion et al. 2011).

The ARB contains the largest continuous expanse of bottomland hardwood forests in the nation, and this, in addition to its cypress swamps, bayous, lakes and marshes, provides valuable habitat for wildlife (U.S. Army Corps of Engineers n.d., Ford and Nyman 2011). There are approximately 45 species of mammals in the ARB including bobcat (*Lynx rufus*), coyote (*Canis latrans*), beaver (*Castor canadensis*), white-tailed deer (*Odocoileus virginianus*), and the endangered Louisiana black bear (*Ursus americanus luteolus*) (Ford and Nyman 2011). The ARB is also home to over 20 species of amphibians and 50 species of reptiles, most notably the American alligator (*Alligator mississippiensis*) (Dundee and Rossman 1989). Over 200 species of birds utilize the variety of habitats in the ARB and delta including bald eagle (*Haliaeetus leucocephalus*), wood stork (*Mycteria americana*), yellow-crowned night heron (*Nyctanassa violacea*), and painted bunting (*Passerina ciris*) (U.S. Fish and Wildlife Service 2006, National Audubon Society 2012a). The ARB and delta are located within the Mississippi Flyway, an important migratory route for approximately 40% of North America’s waterfowl (National

Audubon Society 2012b). Both the ARB and delta are recognized as Important Bird Areas by the National Audubon Society and BirdLife International (National Audubon Society 2012c). Natural islands in this delta, and those constructed of dredge material, provide valuable nesting sites for birds such as black skimmers (*Rynchops niger*), gull-billed terns (*Gelochelidon nilotica*), least terns (*Sternula antillarum*), and mottled ducks (*Anas fulvigula*) (Leberg et al. 1995, Holbrook et al. 2000) and serve as valuable habitat for juvenile fishes (Thompson and Deegan 1983).

In freshwater habitats of the ARB, the annual flood pulse is important for crawfish and finfish production, which bring in millions of dollars annually in direct sales (Alford and Walker 2013). The ARB is the center of the wild crawfish harvest in Louisiana (Isaacs and Lavergne 2010) and is home to more than 100 freshwater fish species, including the endangered pallid sturgeon (*Scaphirhynchus albus*), and dozens of ‘occasional’ visitors to freshwater from the ocean and estuary. The ARB is one of the most popular recreational fishing destinations in the state (Holloway et al. 1998), and its productivity and discharge are significant factors in the health and abundance of coastal fisheries, including oysters, in Louisiana and the northern Gulf of Mexico as well (Chesney et al. 2000). The ARB’s dynamic hydrology affects aquatic habitats, creating seasonally-changing water quality and chemistry conditions that cause temporal shifts in zooplankton and invertebrate communities and the fish communities that utilize them (Rutherford et al. 2001, Colon-Gaud et al. 2004, Halloran 2010).

The ARB and delta present a number of management challenges, many centering around, but not limited to, water quality and sedimentation (Demas et al. 2001). Since 1932 approximately 2.5 billion cubic meters of sediment have been deposited in the floodway. This sediment deposition can lead to community shifts that convert cypress swamps to bottomland hardwood forests, while areas outside of the floodway are suffering from subsidence issues, which can also threaten cypress regeneration. Nitrogen from agricultural fertilizer use in the Mississippi River watershed is a common contaminant in the waters of the ARB that is transported to the Gulf of Mexico where it contributes to a large hypoxic zone (Demas et al. 2001, Ford and Nyman 2011). Large areas of the Floodway suffer seasonal hypoxia due to man-made alterations in hydrology that inhibit flow, and the extent of this problem has almost doubled in the last half-century (Bryan and Sabins 1979). Managers need to develop new strategies to combat these issues and mitigate their effects, but often the dynamics and feedbacks in the system are not well understood.

Besides the complexity of the ecosystem, contentious and conflicting relations among various stakeholders pose additional challenges. Stakeholders in the ARB can roughly be broken down into 12 distinct groups based on shared interests and motivations. Certainly, management actions benefiting one group may have adverse effects on another group. Acknowledging such conflict is essential for moving the decision-making process forward, and understanding the trade-offs associated with actions is essential for making wise management decisions. This report is designed to facilitate the flow of information among various groups so that adaptive management strategies can be implemented.

To that end, in this report we:

- Present an overview of the ARB, including its physical setting, history of use and management, current use and management, and the state of scientific knowledge in the ARB;
- Examine the multiple stakeholder groups and motivations/concerns with regard to management of the ARB and creation of relevant policies;

- Evaluate the current governance structure and propose an approach to improve restoration efforts in the ARB by focusing on a results-based sense of common purpose among its stakeholders.
- Quantify potential trade-offs among ecosystem services based on the current flow regime at Old River Control Structure, including an original model to estimate the potential denitrification of the ARB, using a compilation of published and unpublished data and studies to identify flow-ecology relationships that will facilitate communication among various stakeholders, and to visually simplify complex feedbacks and interactions in the natural system; and
- Conclude with identification of significant research gaps as well as some specific recommendations for action.

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Chapter 2. A History of the Atchafalaya River Basin

The Atchafalaya River Basin (ARB) has had a tumultuous history of land use through anthropogenic manipulation of the main channel of the river system. In order to fully understand the policies and economics governing the ARB, one must first look at the myriad of natural and man-made situations that have been present within the ARB. To comprehend the decisions that culminated in one of the United States' most important engineering structures, the Old River Control Structure (ORCS), we will discuss the evolution of the Mississippi River Delta Plain and the intricacies of the Mississippi River and Red River interaction.

The concept of the entire Mississippi River delta switching over time to a different location is based upon the early research of Russell (Russell 1936, 1939, 1940) and Fisk (Fisk 1938, 1944, 1947, 1952, 1955) among others. It is important to note that we are in the timeframe of the Atchafalaya-Wax Lake deltaic complex, and according to the delta cycle concept, the Mississippi River will at some time permanently change course and occupy the ARB as it proceeds to the Gulf of Mexico outlets at Atchafalaya and Wax Lake Bays (Roberts 1998, Blum and Roberts 2012).

The recent addition of the Atchafalaya/Wax Lake lobe to the Mississippi River delta complexes plays a large role in determining the physical fate of the ARB. During the Holocene the lowermost portion of the Mississippi River has migrated across its deltaic plain to form six distinct lobes - the Maringouin, Teche, St. Bernard, LaFourche, Plaquemines/Balize, and Atchafalaya-Wax Lake (Blum and Roberts 2012). The oldest complex is the Maringouin, which formed around 7,500 to 5,000 years ago, and the youngest is the Atchafalaya-Wax delta, which began forming approximately 500 years ago. The deltaic complex with the largest area was the St. Bernard complex with a size of ~15,470 km^2; the Maringouin complex was a close second with a size of ~15,030 km^2. The smallest size belongs to the present-day Atchafalaya-Wax Lake complex at ~2,800 km^2 (Roberts 1997).

Another historical component of why and how the ARB is managed includes the formation of the area located approximately ten miles northeast of present day Simmesport, Louisiana near the southwest corner of the state of Mississippi (Figure 2.1). The formation of this area during the Holocene included the merging of the Red River with the Mississippi and the creation of the Atchafalaya River as a major distributary to the Mississippi River (Fisk 1944). During the 14th Century the Red River and Mississippi River ran essentially parallel to each other in a north-south alignment (Figure 2.2) (Fisk 1955). A bend formed on the western bank of the Mississippi River and began encroaching westward towards the Red River. During the 16th Century this bend (now known as Turnbull's Bend) captured the Red River and abandoned the old Red River channel. This event also created the Atchafalaya River by capturing and reusing the abandoned Bayou des Glaises channel, which was an old course of the Mississippi River (Figure 2.2) (Fisk 1952). This channel switching episode was the onset of the Mississippi River changing course over the Atchafalaya deltaic plain into the current day Atchafalaya-Wax Lake deltaic complex (Roberts 1998).

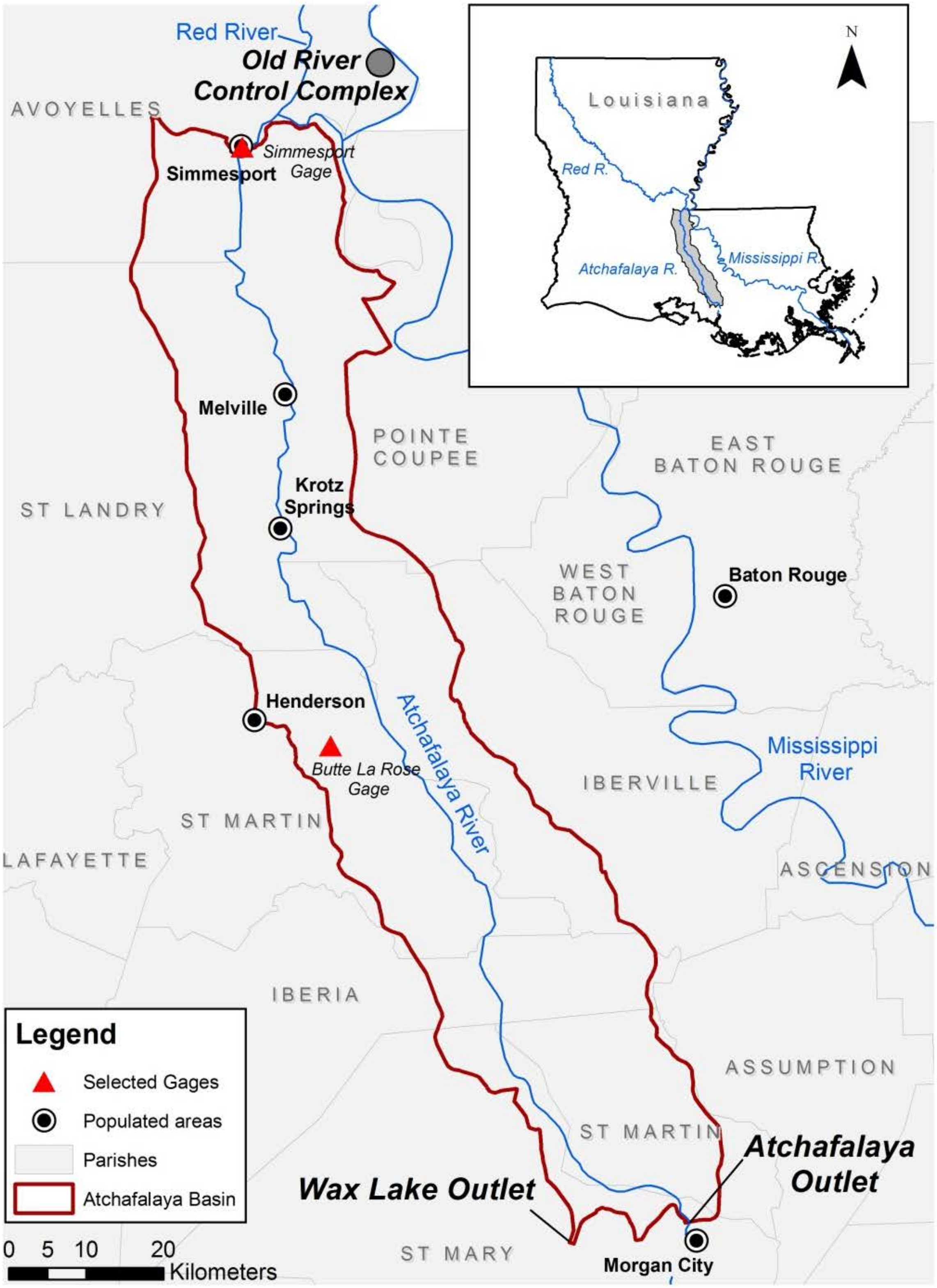


Figure 2.1. Map of the levee-enclosed portion of the Atchafalaya River Basin, Louisiana, USA.

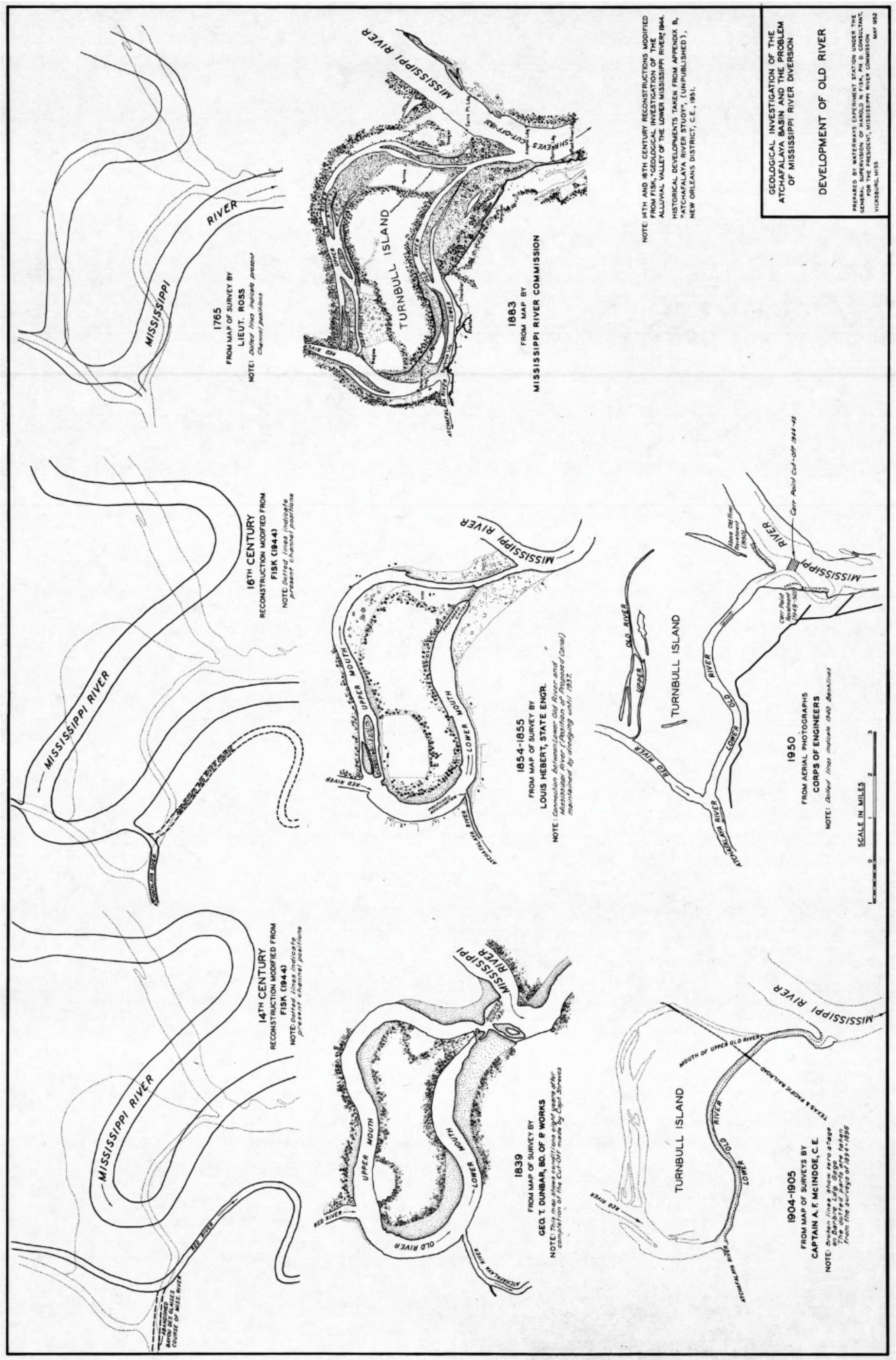


Figure 2.2. Illustrations representing the evolution of the Old River area ranging from the 14th century to the mid 20th century, Atchafalaya River Basin, Louisiana (from Fisk, 1952).

2.1. Early Settlement and Development

Prior to European colonization efforts, the ARB area was inhabited by the Houma, Chitimacha, Tunica-Biloxi, Opelousa, and Atakapa Tribes (Wells 2001). The Choctaw arrived in Louisiana after 1760 and called the river “hacha falaia” meaning long river. Spanish and French trappers, traders, and explorers began to populate the Louisiana area in the 17th century (Weddle 1991), with the cities of New Orleans and Baton Rouge founded in 1718 and 1719 respectively. New Orleans was founded by the French under Jean-Baptiste Le Moyne de Bienville and in 1722 became the capitol of New France. Baton Rouge was also founded by the French as a military post and grew as a transportation hub, eventually becoming the state capitol in 1849. During the French and Indian War the Acadians were expelled by the British from Nova Scotia, New Brunswick and Maine (Faragher, 2005). Some of the Acadians began migration to what is now the state of Louisiana. These migrants were known as Cajuns and brought with them all the trappings of their culture, including fishing, hunting, and agricultural practices. This influx of European populace into the area, especially the location and development of New Orleans and Baton Rouge, played a large role in the management of the ARB, a dynamic that continues to the present day (Wells 2001).

In the early part of the 19th century there was a concerted effort to improve the navigability of the Mississippi River. One of the most popular solutions was to shorten the length of the Mississippi River by cutting off bends in the river to provide a more linear, rather than sinuous, path. This was usually accomplished by dredging the land between the pinch point of the main channel and damming, or leveeing, the bow in the bend in order to disconnect this area from the main channel. In 1831, this was attempted by H. M. Shreve at Turnbull’s Bend on the Mississippi River (Figure 2.2) (Reuss 2004). Over the decades, the isolated bend accumulated silt and sediment in both its northern arm, known as Upper Mouth, and the southern arm, known as Lower Mouth (Figure 2.2). If left to run their natural courses the Mississippi River and combined Red and Atchafalaya Rivers would have again run parallel and isolated due to the Upper and Lower Mouths filling in (Keown et al. 1986). However, decisions and policies were set in motion that would keep the Lower Mouth (this segment is now called Old River or Lower Old River) dredged and open for transportation and economic capabilities between the Mississippi River and Red/Atchafalaya River systems until the middle of the 20th century (Keown et al. 1986).

The ARB is tied directly to the fluvial system of the Mississippi River. Therefore, the levees-only debate, which began in the late 1840s, and the subsequent levees-only policy, which had influence until the middle of the 20th century, affected the physical characteristics of flood control and waterways in Louisiana (Reuss 1985, Pabis 1998). The authorization of the Mississippi Delta Survey by Congress in 1851 led to a report by Andrew A. Humphries and Henry L. Abbot in 1861 that detailed the Lower Mississippi River Valley from just south of the confluence of the Ohio River to where the Mississippi River discharges into the Gulf of Mexico (Humphreys and Abbot 1861). This report attempted to quell the debate concerning such engineering practices as levees-only flood control and meander cutoffs. It concluded that meander bend cutoffs “raise the floods below them” and that levees-only could be an effective policy (Humphreys and Abbot 1861). Numerous formulas and speculations concerning levees contained within the report turned out to be flawed; however, the report and its influence endured for decades due to its thoroughness and because other scientists used it as a springboard for further research (Reuss 1985 p. 185). Conflict and castigation by Humphries and prominent engineer James Buchanan Eads of other engineers, who advocated for more diverse flood control strategies, may have helped promulgate the levees-only mentality for so long (Barry 1997, Pabis 1998).

The lasting effects of the levees-only policy culminated in the tragedy of the Flood of 1927 (Pabis 1998). The Flood of 1927 killed between 250 and 500 people, inundated over 16 million acres, and decimated 41,000 buildings, with 162,000 homes being flooded (Reuss 1982). Some estimate the death toll to be higher due to imprecise accounting methods (Barry 1997). This tragic event led to the Mississippi River and Tributaries Act of 1928 and the Jadwin Plan (Reuss 2004).

The Jadwin Plan cost approximately $296 million and included the construction of levees from Cape Girardeau, Missouri south along the Mississippi River, and a system of floodways (Reuss 1982). The goal of the plan was to disconnect the channel from the floodplains via the use of a system of reinforced levees and divert excess floodwaters into large floodways. One of the floodways included in the Jadwin Plan was the ARB Floodway. In order to reduce flooding potential of the cities of New Orleans and Baton Rouge, the ARB Floodway was designed to withstand the levels of a project flood and capture (or divert) about one half of the Mississippi River's flow at flood stage (known as the project flood) (Reuss 1982). It had many different components in order to achieve this goal, including guide levees approximately 22.5 km apart and three separate, yet connected, inner floodways: the West Atchafalaya Floodway, the East Atchafalaya Floodway (later renamed Morganza Floodway), and the main channel ARB Floodway.

2.1.1. Old River Control Structure

In order to provide the storage capacity for the ARB Floodway to relieve the flooding stressors on major Lower Mississippi River cities there needed to be a control structure capable of diverting floodwaters into the Atchafalaya. Therefore over the next few decades studies were completed, plans were designed, and the hinge pin structural control element of the Jadwin Plan began to take shape (Reuss 2004).

Because one-quarter of the Mississippi River's discharge was being naturally captured by the ARB by 1950, and the Atchafalaya has a steeper gradient and shorter path than the Mississippi River, it was thought that the Mississippi River avulsion would occur within the near future (Fisk 1952). The Old River Control Structures proposed by the U.S. Army Corps of Engineers (USACE) would attempt to cease the avulsion of the Mississippi River through the use of a controlled diversion that would encompass many engineered structures that were spatially isolated from one another at various channel features (Aslan et al. 2005). In the middle of the 20th century, as the Atchafalaya continued to accept more water from the Mississippi River, prevailing thought was that the Mississippi River would capture and overtake the Atchafalaya no later than 1975 (Reuss 2004).

The current configuration of the Old River Control Structure includes the engineered features of a low sill structure, hydroelectric facility, overbank control structure, auxiliary structure, and lock and dam facility (Figure 2.3). In addition to the facilities at the Old River Control Complex, part of the current flood control plans include the use of the Morganza Floodway and the West Atchafalaya Floodway during extreme events, the Wax Lake Outlet Structure, and the main Atchafalaya Floodway and all of its various levees, locks, and control structures (Figure 2.4). Each one of these components is critical to the floodway system working appropriately and for the Jadwin Plan to come to fruition.

Figure 2.3. Photographs showing: (a) the auxiliary control structure, (b) the S. A. Murray, Jr. Hydroelectric Power Facility (U.S. Army Corps of Engineers, New Orleans District 2009), *(c) the low sill control structure and overbank structure* (U.S. Army Corps of Engineers, New Orleans District 2009), *(d) the Old River Lock* (U.S. Army Corps of Engineers, New Orleans District 2009), *and (e) the auxiliary structure* (U.S. Army Corps of Engineers, New Orleans District 2009).

Primary authorization for most of the improvements within the ARB comes from the Mississippi Rivers and Tributaries project (Saucier 1998). The Mississippi River Commission published a report in 1953 that suggested that the Old River area would accommodate a control structure that could hold the Mississippi River in place and allow for controlled interbasin water exchange between the Mississippi, Red, and Atchafalaya Rivers. The report recommended the Atchafalaya River receive 30% of the annual, latitudinal flow of the Mississippi and Red Rivers to approximate the 70/30 flow ratio that existed in 1950. This recommendation was made policy in the Flood Control Act of 1954. The entire Old River Control Project cost $67 million when completed in 1962, seven years after construction began and 8 years after Congress authorized it in the Flood Control Act of 1954 (Saucier 1998).

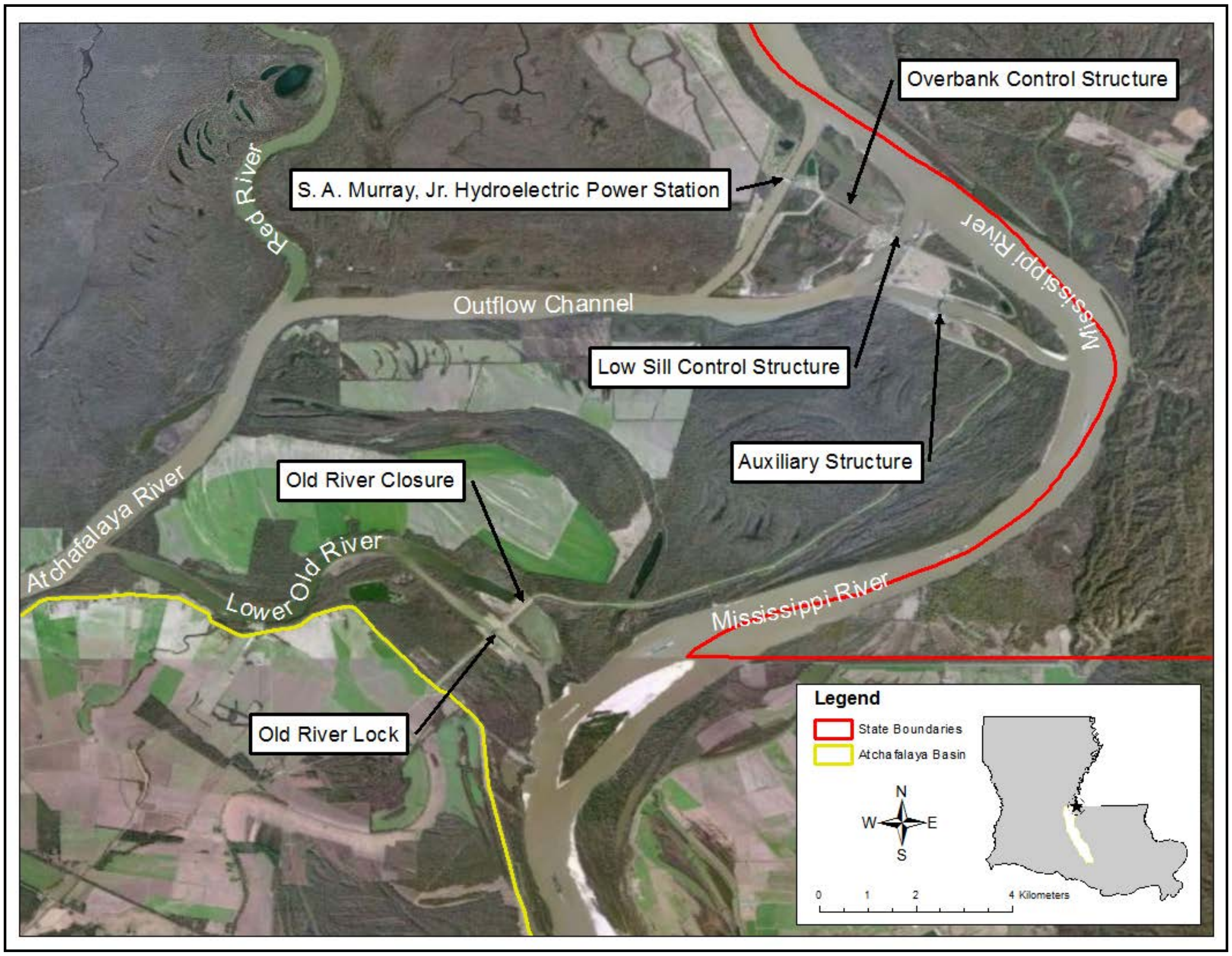


Figure 2.4. Map showing the locations of the major components of the Old River Control Complex.

The Old River Control Project and associated floodways were planned and developed to specifications that would meet or exceed the project design flood (Figure 2.5). The design flood was conceived from the Mississippi River and Tributaries project and was developed during 1954 and 1955 through cooperation between the Weather Bureau, the Army Corps of Engineers, and the Mississippi River Commission (U.S. Army Corps of Engineers 2007). The storm with the greatest discharge potential under the proposed floodways was identified through the study of historical storms, runoff potential, storm dynamics, flood frequencies, and other meteorological factors. In 1956 this was adopted as the foundation for the project flood flow line. The peak discharge capacity at the latitude of the Red River Landing is 3,030,000 cfs and has been validated by a Mississippi River Commission review following the 1973 flood (U.S. Army Corps of Engineers 2007).

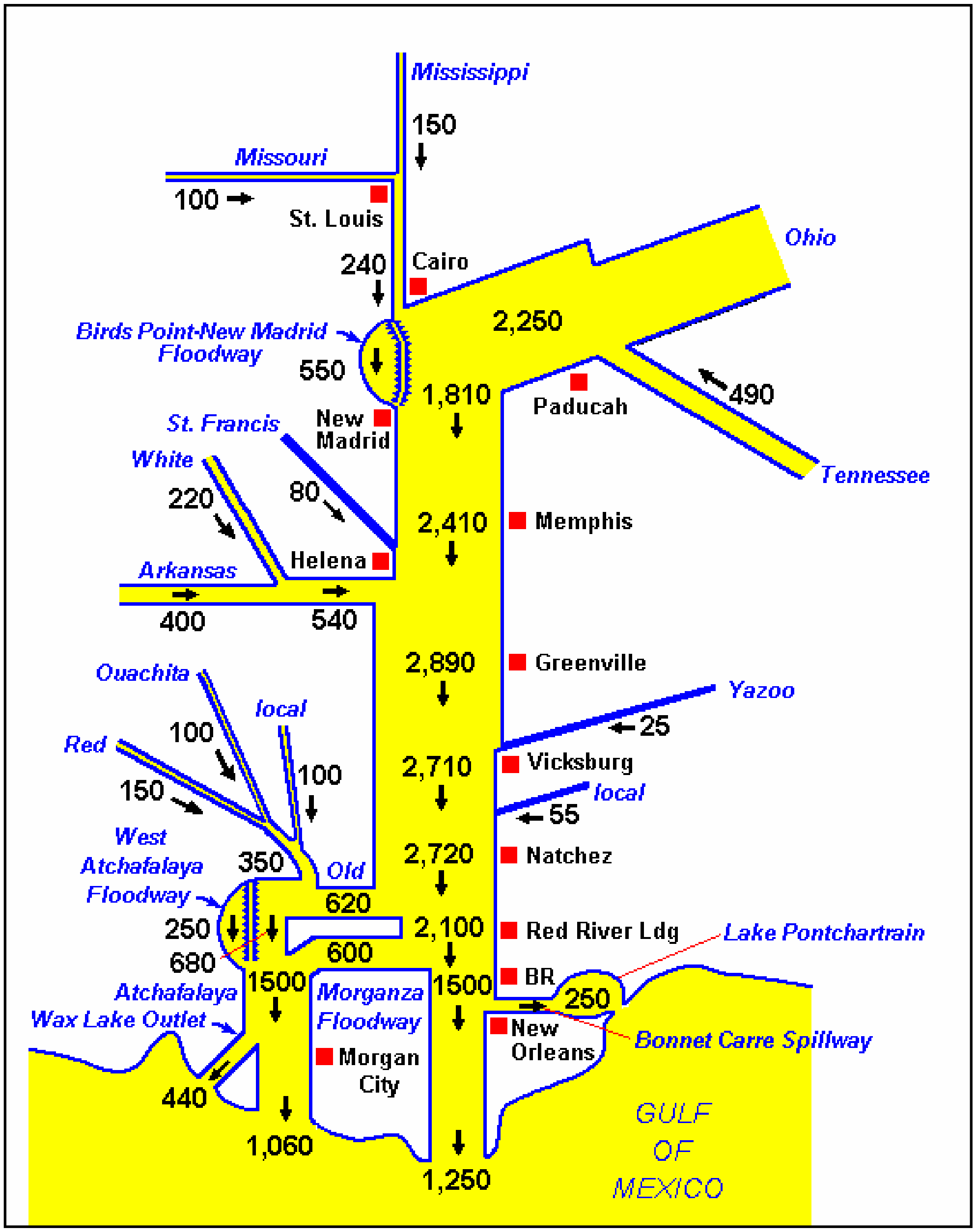


Figure 2.5. : Illustration showing the design project flood discharge allocations throughout the Lower Mississippi River Valley-numbers represent thousands of cfs. (U.S. Army Corps of Engineers 2007).

The low sill control structure (Figure 2.3) is the center of the Old River Control Complex. It was finished in 1959, with the inflow and outflow channels being completed in 1960. The reinforced concrete control structure is 172.5 m wide and is composed of 11 gate bays (each 13.4 m wide), with the three center bays lower than the eight outer bays. The design of the weir heights vary from -1.5 m below sea level to 3 m above sea level. The inflow channel is 0.8 km in length and 304.8 m wide at its bottom. The outflow channel is 11.2 km in length and 274.3 m wide at its bottom (Saucier 1998).

The overbank control structure (Figure 2.3) assists in the dispersal of floodwater during extreme events. It was finished in 1959 and has been used fewer than 10 times since its completion. The structure is designed with 73 gate bays (each 13.4 m wide) and is 1023 m long. The weir height elevation is 15.8 m above sea level (Saucier 1998).

The auxiliary structure (Figure 2.3) was born of the devastating flood of 1973. The floodwaters that year found a welcome path down the ARB due to reduced discharge capacity in the Lower Mississippi River from channel improvements. Therefore the low sill control structure carried the brunt of the floodwaters passing over it. The end result was the destruction of a 20.4 m tall wing wall used to guide the water into the structure and a large scour hole that exposed a 15.2 m section of the 27.4 m support pilings (U.S. Army Corps of Engineers, New Orleans District 2009). Emergency repairs throughout the ordeal helped stabilize and save the structure.

The auxiliary structure is a reinforced concrete structure that is located just southeast of the low sill control structure. It was finished in 1986 and has an inflow channel that diverts water from the Mississippi River just downstream of the inflow diversion for the low sill dam. The outflow channel of the auxiliary structure enters the outflow channel of the low sill control structure just downstream of the low sill control structure. The auxiliary structure is 134.7 m long and has six gate bays, each one 18.9 m wide (U.S. Army Corps of Engineers, New Orleans District 2009). The design elevation of the weir crest is 1.5 m above sea level. The inflow channel is 3 km long and 152.4 m wide at its bottom and the outflow channel is 1.4 km long and 144.8 m wide at its bottom (Saucier 1998).

In the late 1970s investors began researching the possibility of using the energy potential of the 6 m difference in elevation between the Mississippi River and the Atchafalaya River (Reuss 2004). In 1985, the construction began for a $520 million power plant. The S.A. Murray, Jr. Hydroelectric Power Station (Figure 2.3) is the largest prefabricated power plant structure in the world (U.S. Army Corps of Engineers, New Orleans District 2009). It became operational in 1990 and is operated by the Louisiana Hydroelectric Corporation. The power plant is capable of generating 192-megawatts and the flow is adjusted daily to account for the 70/30 diversion policy, with an average discharge of 2,800 cms (Reuss 2004). The inflow channel for the power station diverts water from the Mississippi River just upstream of the inflow channel for the low sill control structure. The outlet channel for the power station joins the outlet channel for the low sill control structure a few kilometers downstream of the low sill control structure (Figure 2.4).

The Old River Lock (Figure 2.3, Figure 2.4) and closure are located on the eastern end of what was once the Lower Mouth of Turnbull’s Bend. The lock and channel are kept open and operational for transportation between the Mississippi, Red, Ouachita-Black, and Atchafalaya Rivers (Saucier 1998). The portion of the Old River directly north of the lock was disconnected from the main channel flow by a dam closure structure. The navigational lock project began in 1958 and was finished in 1963. On average, 15 commercial boats go through the complex every day. Most of the barges are carrying “petroleum, chemicals, agricultural, and aggregate products” (U.S. Army Corps of Engineers, New Orleans District 2009). The navigational lock is 362.7 m long, 22.9 m wide, and 3.6 m below sea level (Saucier 1998).

The ARB is home to three floodways, the continually used Main Atchafalaya Basin Floodway, the smaller, the never used West Atchafalaya Floodway, and the Morganza Floodway. The West Atchafalaya Floodway (Figure 2.6) is about 9.5 km wide and 51.5 km long and is located downstream of the mouth of the Red River. It is situated between the West Atchafalaya River levee and the West Atchafalaya Basin protection levee and has never been operated during a flood event (Saucier 1998). This floodway has been designed to handle 250,000 cfs and has been estimated that it will be used less than once every hundred years since it will only carry excess waters that cannot be handled by the Main Atchafalaya Basin and Morganza Floodways (Saucier 1998).

The Morganza Spillway (Figure 2.6) is located on the western bank of the Mississippi River about 56.3 km north of Baton Rouge. It was used as a replacement for the proposed East Atchafalaya Basin Floodway that was in the original plans (Reuss 2004). The Morganza Spillway, the designed intake feature for the floodway, was constructed in 1953 at a cost of $20 million. The reinforced concrete structure is made up of 125 vertical lift gated openings, with each opening being 8.6 m (Saucier 1998). The floodway was designed to carry a maximum of 600,000 cfs during a project flood (Saucier 1998). The Morganza Spillway was partially operational during the floods of 1973 (42 gates opened) and 2011 (17 gates opened).

The Main Atchafalaya Basin Floodway (Figure 2.6) begins near the downstream end of the Morganza and West Atchafalaya Floodways and extends south to the Wax Lake Outlet and Atchafalaya Bay. This floodway is positioned between two protection or “guide” levees, approximately 24.1 km apart, located on the east and west sides of the floodway (Saucier 1998). The operation of the Main Atchafalaya Basin Floodway includes levees, drainage improvements, floodgates, locks, and the Wax Lake Outlet (Table 2.1) (U.S. Army Corps of Engineers n.d.). Constructed in 1987, the Wax Lake Outlet was designed to discharge 30% of the flow from the ARB into the Gulf of Mexico, while the remaining 70% of the flow would be conveyed through the Lower Atchafalaya River channel into Atchafalaya Bay (Saucier 1998). The Main Atchafalaya Basin Floodway is designed to carry about 1,500,000 cfs during the project flood of 3,000,000 cfs at the latitude of Old River, with 440,000 cfs going through the Wax Lake Outlet and 1,060,000 cfs going down the Lower Atchafalaya River (Saucier 1998); (U.S. Army Corps of Engineers 2007) (Figure 2.5).

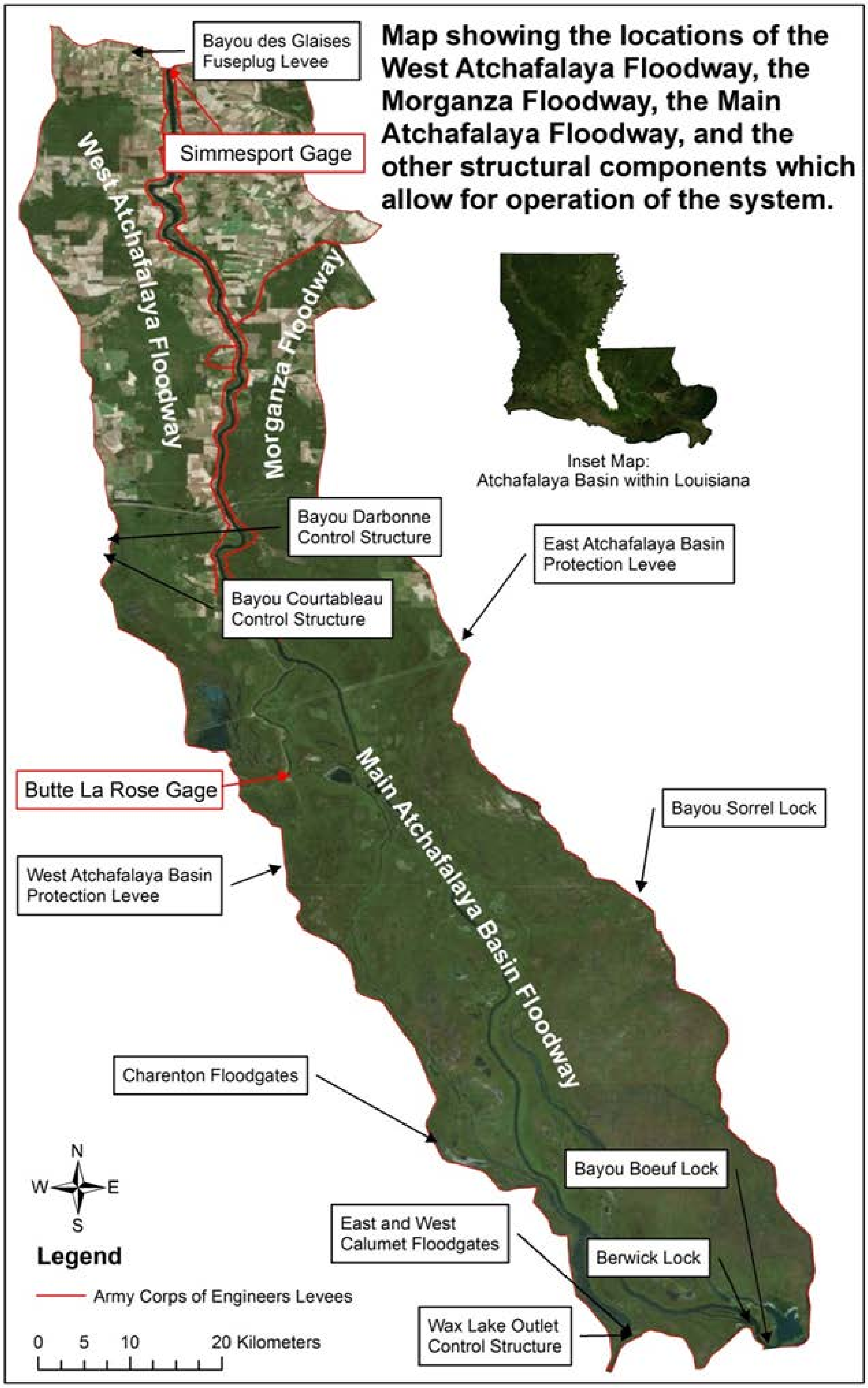


Figure 2.6. Map showing the locations of the West Atchafalaya Floodway, the Morganza Floodway, the Main Atchafalaya Floodway, and the other major structural components which allow for operation of the system.

Table 2.1. Characteristics of the major components of the Atchafalaya Basin Floodway (Saucier, 1998).

Structural Feature	**Year Constructed**	**Characteristics**
East Atchafalaya Basin Protection Levee		Levee system is 171.72 kilometers long. Acts as a guide levee for the Atchafalaya Basin.
West Atchafalaya Basin Protection Levee		Levee system is 207.12 kilometers long. Acts as a guide levee for the Atchafalaya Basin.
East Atchafalaya River Levee		Levee system is 84.49 kilometers long.
West Atchafalaya River Levee		Levee system is 108.63 kilometers long.
Bayou des Glaises Fuseplug Levee		12.88 kilometers in length. Allows for floodwaters to be diverted into the West Atchafalaya Floodway.
Mansura Hills to Hamburg Levee		20.5 miles in length. Protects from Mississippi-Red River backwater flooding.
Levees West of Berwick		Levee system is 90.93 kilometers long.
Berwick Lock	1951	Has a usable length of 91.44 meters.
Bayou Sorrel Lock	1952	Two bay lock that is 240.79 meters long.
Bayou Boeuf Lock	1955	Two bay lock that is 346.25 meters long.
East and West Calumet Floodgates	1950	Reinforced concrete structure, each floodgate 49.07 meters long.
Charenton Floodgates	1948	Reinforced concrete structure 53.34 meters long.
Bayou Courtableau Control Structure	1956	Five 3.05m x 4.57m x 71.32m concrete box culverts.
Bayou Darbonne Control Structure	1941	One 3.05m x 3.05m x 80.77m concrete box culvert.
Wax Lake Outlet	1941	Additional outlet to divert floodwater to the Gulf of Mexico. Outlet channel is 25.27 kilometers long.

2.2. Physical Features

2.2.1. Physiographic Region, Land Use and Topography

The ARB lies entirely within the Mississippi Alluvial Plain of the Coastal Plain Province of the Atlantic Plain Division (Fenneman and Johnson 1946). The major structural feature controlling delineation of the Mississippi Alluvial Plain is the Mississippi Embayment, a trough that has served as a depositional basin since the Cretaceous Period (Stearns 1957, Cox and Van Arsdale 2002, Blum and Roberts 2012). This physiographic division as categorized by Fenneman & Johnson (1946) runs longitudinally from the coast of Louisiana up to Cairo, Illinois at the confluence of the Mississippi and Ohio Rivers.

The modern ARB is confined between east and west guide levees that have severed the connection between the river and historically connected Lake Fausse Point and Verret Swamps, reducing the ARB area from approximately 8,345 km^2 to its current extent of approximately 3,960 km^2 (Piazza In press.). Another set of levees is located adjacent to the Atchafalaya main channel in the northern portion of the ARB, channelizing flow in the northern portion of the ARB. These internal levees extend approximately 83 km from the ORCS to Sherburne Wildlife Management Area (WMA) on the left bank (east side) and approximately 94 km to Butte La Rose on the right bank (west side). Construction of these structures has allowed limited development and agriculture in the northern portion of the ARB (generally north of I-10). Although this land is part of the federally designated floodway, the West and Morganza Floodways are never or rarely activated (respectively), allowing small scale development and agriculture at the higher elevations in these northern floodways (Figure 2.7, Table 2.2). Elevations in the ARB range from below sea level to approximately 15 m.

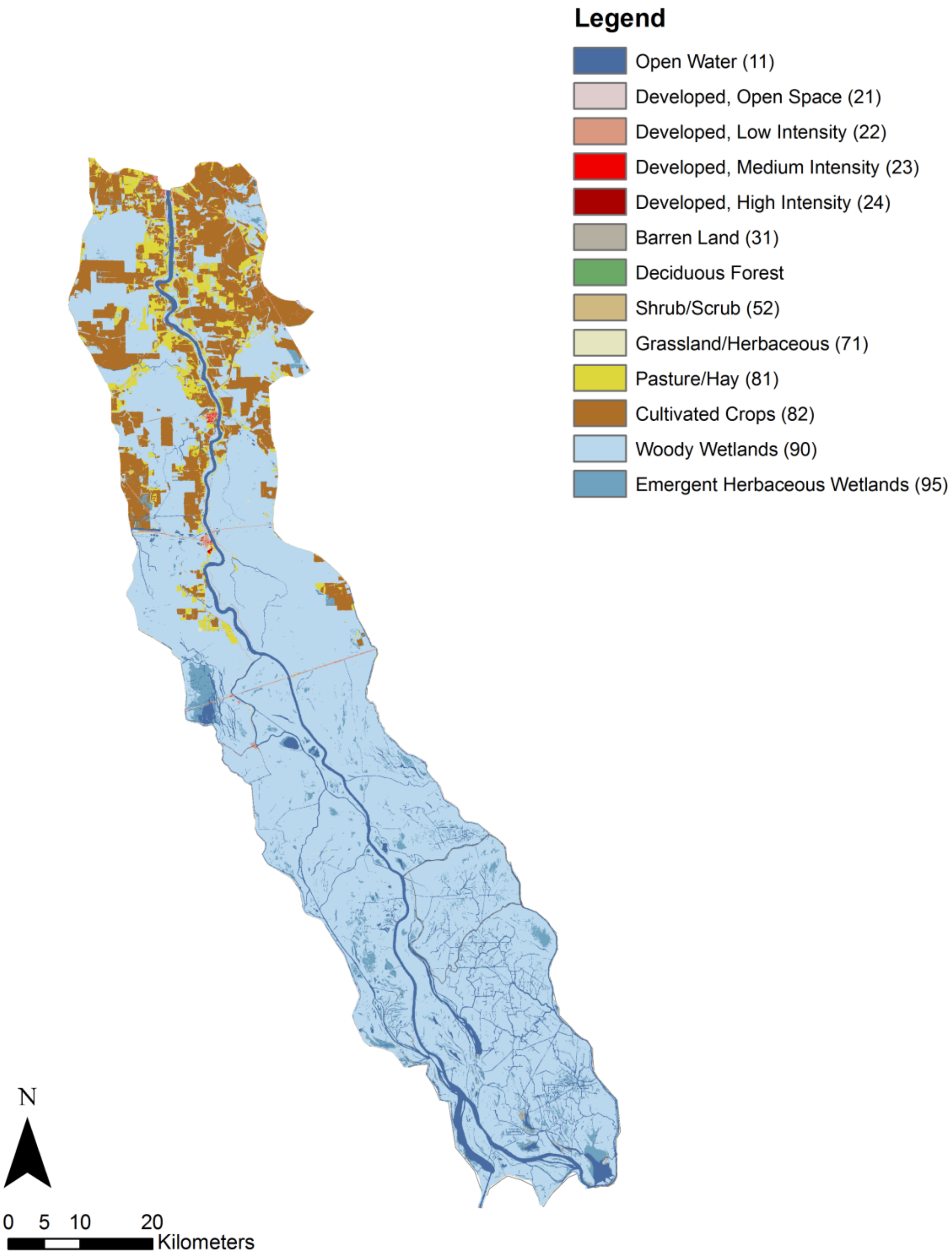


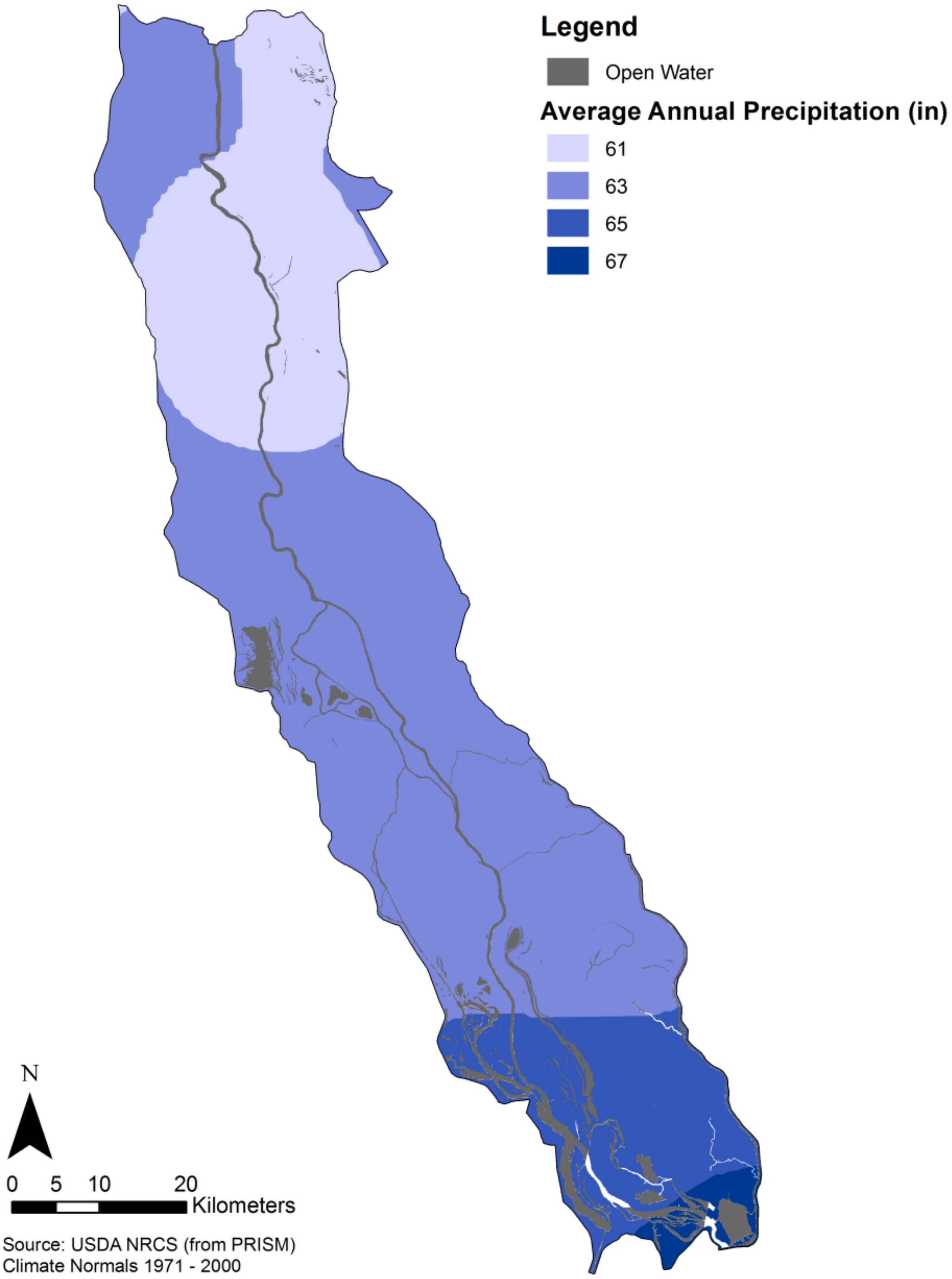
Figure 2.7. Map showing land cover types present in the ARB. Data obtained from 2006 National Land Cover Database (Fry et al. 2011).

Table 2.2. Land cover in the Atchafalaya River Basin. Data obtained from National Land Cover Database (NLCD)2006 (Fry et al. 2011).

Table Land Cover. Land cover in the Atchafalaya River Basin.			
NLCD Value	**NLCD Code**	**Area (km^2)**	**Percent of ARB**
11	Open water	257.9	7
21	Developed, open space	0.3	<1
22	Developed, low intensity	32.0	1
23	Developed, medium intensity	1.7	<1
24	Developed, high intensity	0.3	<1
31	Barren land	6.2	<1
41	Deciduous forest	0.1	<1
52	Shrub/scrub	2.6	<1
71	Grassland/herbaceous	23.2	1
81	Pasture/hay	137.6	4
82	Cultivated crops	486.0	13
90	Woody wetlands	2618.5	70
95	Emergent herbaceous wetlands	151.1	4

Land cover data was obtained from the 2006 National Land Cover Database (Fry et al. 2011), and ARB percentages were calculated using an area of 3,716 km^2, (the levee-enclosed portion of the ARB, which excludes the Wax Lake and Atchafalaya Deltas). The majority of the ARB (74%) is classified as wetlands; with 70% being woody wetlands and 4% classified as emergent herbaceous wetlands. Approximately 17% of the ARB is under agricultural production (13% cultivated crops and 4% pasture/hay). Soybeans are the most prevalent cultivated crop (7% of the ARB), followed by double-crop winter wheat/soy (1.5%) and rice (1.5%) (USDA NASS n.d.). All other crops, including corn, are cultivated in <1% of the ARB. Only ~1% of the ARB is otherwise developed; most development (0.9%) is considered low intensity. Seven percent of the ARB is open water, and the remaining ~ 1% is barren land, deciduous forest, shrub/scrub, and grassland/herbaceous (Figure 2.7; Table 2.2).

Louisiana has a humid subtropical climate, characterized by long hot summers and mild winters. Precipitation occurs year round, with slightly higher amounts in the summer months. In the ARB, annual precipitation amounts range from 61 inches in the northern portion to 67 inches in the southernmost portion of the ARB (Figure 2.8). Average annual minimum temperatures in the ARB range from 55 - 57° F while annual average maximum temperature is 77°F. The ARB is susceptible to both tornadoes and hurricanes; Louisiana has averaged 37 tornadoes per year for the period of 1991 – 2010 (U.S. Department of Commerce NOAA n.d.). The region is dominated by moist, warm maritime air masses from the Gulf of Mexico and the prevailing wind direction is from the south or south-southeast. Short-lived (≤ 4 days) incursions of continental polar air occur in the winter and spring. Average relative humidity during the afternoon is ~60 – 65% and higher at dawn, ~90%. The sun shines ~60% of the time in the summer and ~50% of the time during the winter (USDA NRCS n.d.).



Source: USDA NRCS (from PRISM)
Climate Normals 1971 - 2000

Figure 2.8. Map showing average annual precipitation amounts for the ARB, based on data from 1971 – 2000. Data obtained from USDA NRCS.

2.2.2. Geology.

The ARB is located south of the major structural trough known as the Mississippi Embayment and at the northern margin of the Gulf Coast Continental Margin Basin, which began developing during rifting associated with the break-up of Pangaea during the late Triassic – early Jurassic. During the early – middle Jurassic, the developing ARB was disconnected from marine influence, allowing the formation of thick evaporite deposits. The ARB became connected to the Atlantic Ocean during the late Jurassic, and thick sedimentary shelf, shore and fluviodeltaic sequences unconformably overlie Jurassic deposits (Harry and Londono 2004).

Sea levels were 115 – 135 m lower than present during the latest Pleistocene glaciations, which allowed the Mississippi River to incise and discharge into the coastal ocean at the shelf margin. Rapid eustatic sea level rise during deglaciation began approximately 19 thousand years ago (ka). The Mississippi Valley began filling with sediment in response to this sea level rise approximately 12 ka, although progradation of the Mississippi River delta lobes did not occur until sea levels stabilized, approximately 7.5 - 7 ka (Blum and Roberts 2009, 2012). The Atchafalaya River represents the site of an ongoing fifth avulsion, although the process was arrested (at least temporarily) with human intervention and the construction of the Old River Control Complex.

All surficial deposits in the ARB are Holocene in age and consist of a variety of alluvial deposits, which can broadly be categorized as natural levees (Qnl) and alluvium (Qal) (Figure 2.9). Natural levees consist of silty clay to very fine sand present adjacent to courses of major past and present rivers. Most deposits are brown – gray in color except those derived from the Red River, in which case deposits are reddish-brown in color. Alluvium consists of all other alluvial valley deposits and consist primarily of clay to silty clay (some sand may be present in localized areas). Colors are generally the same as described above ("Louisiana geologic map data" n.d.) More precisely, alluvium deposits can be divided into distributary complexes of the Atchafalaya, backswamp deposits, crevasse splay deposits, and lacustrine deposits where open water bodies have filled in (Snead et al. 2000) as the delta-switching process has progressed (Roberts 1998).

The geologic history outlined above culminated in Louisiana's position as one of the top oil and gas producing states in the nation. The organic-rich clays in the fine-grained sedimentary deposits, along with high rates of sedimentation and subsidence, allowed the right mix of temperature and pressure for the optimal maturation of hydrocarbons. Overlying stratigraphic (sandstone) traps and structural traps created by evaporite migration allowed large hydrocarbon reservoirs to form (Lindstedt et al. 1991).

Total production of oil and gas has declined since the peak in the the early 1970s (Lam 2012) (Figures 2.10 and 2.11). Louisiana is still the number one oil producer in the nation, although most production has shifted from state-owned and leased lands to off-shore production on federally leased waters (Figure 2.11). For example, in 2010 approximately 88% of oil produced in Louisiana was from offshore federally-owned waters. Natural gas production has increased in recent years; of the ~104.8 million cubic meters produced in 2010, 40% was produced in federal waters. Louisiana is currently ranked 3rd of natural gas producing states when off-shore production is included (Lam 2012). Although many wells in the ARB are no longer in operation, the legacy of oil and gas development lives on. Numerous canals dredged for oil and gas development have altered flow regimes dramatically, causing water quality and sedimentation issues.

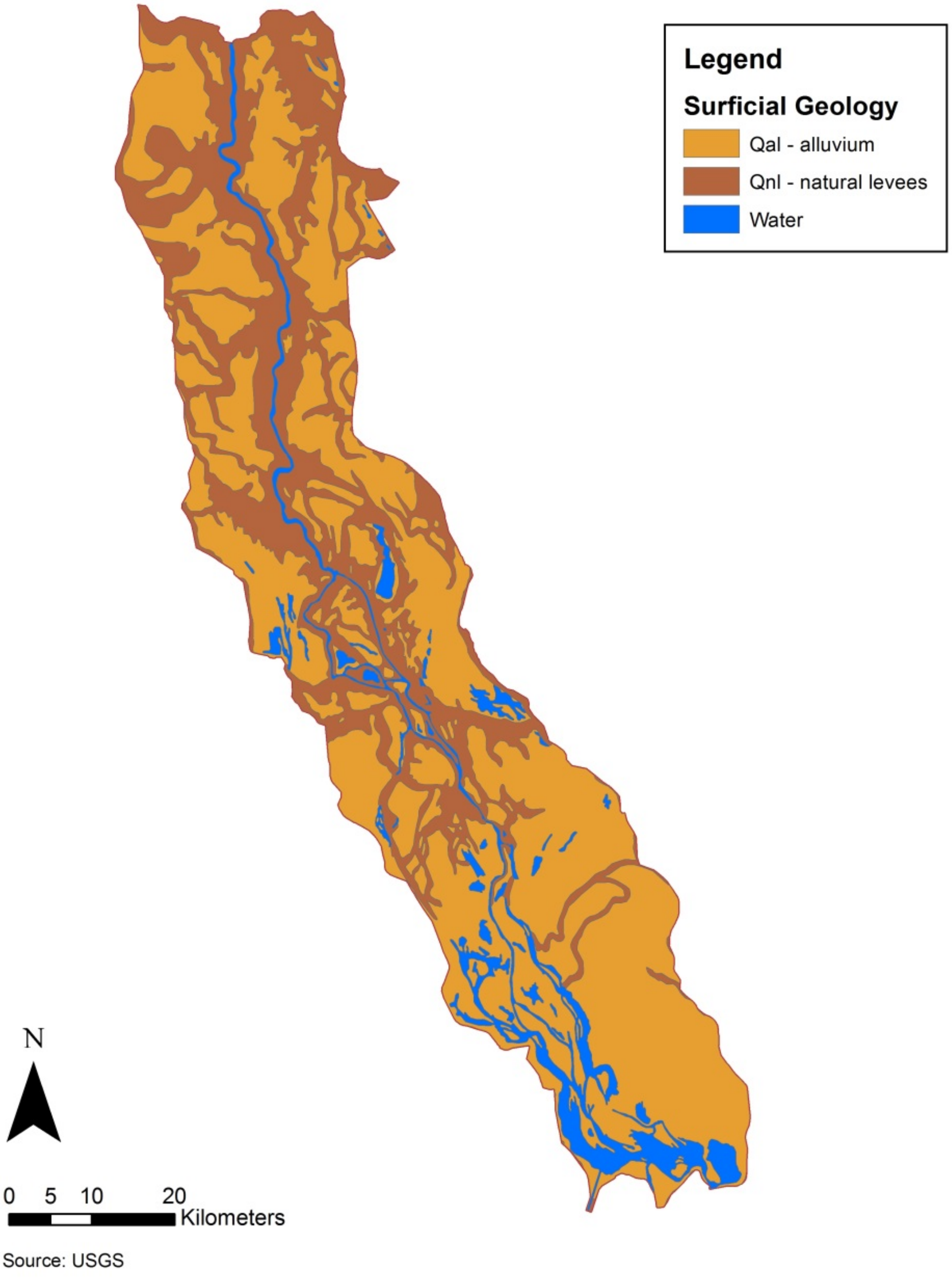


Figure 2.9. Map showing generalized surficial geology of the ARB. All surficial deposits are Holocene in age.

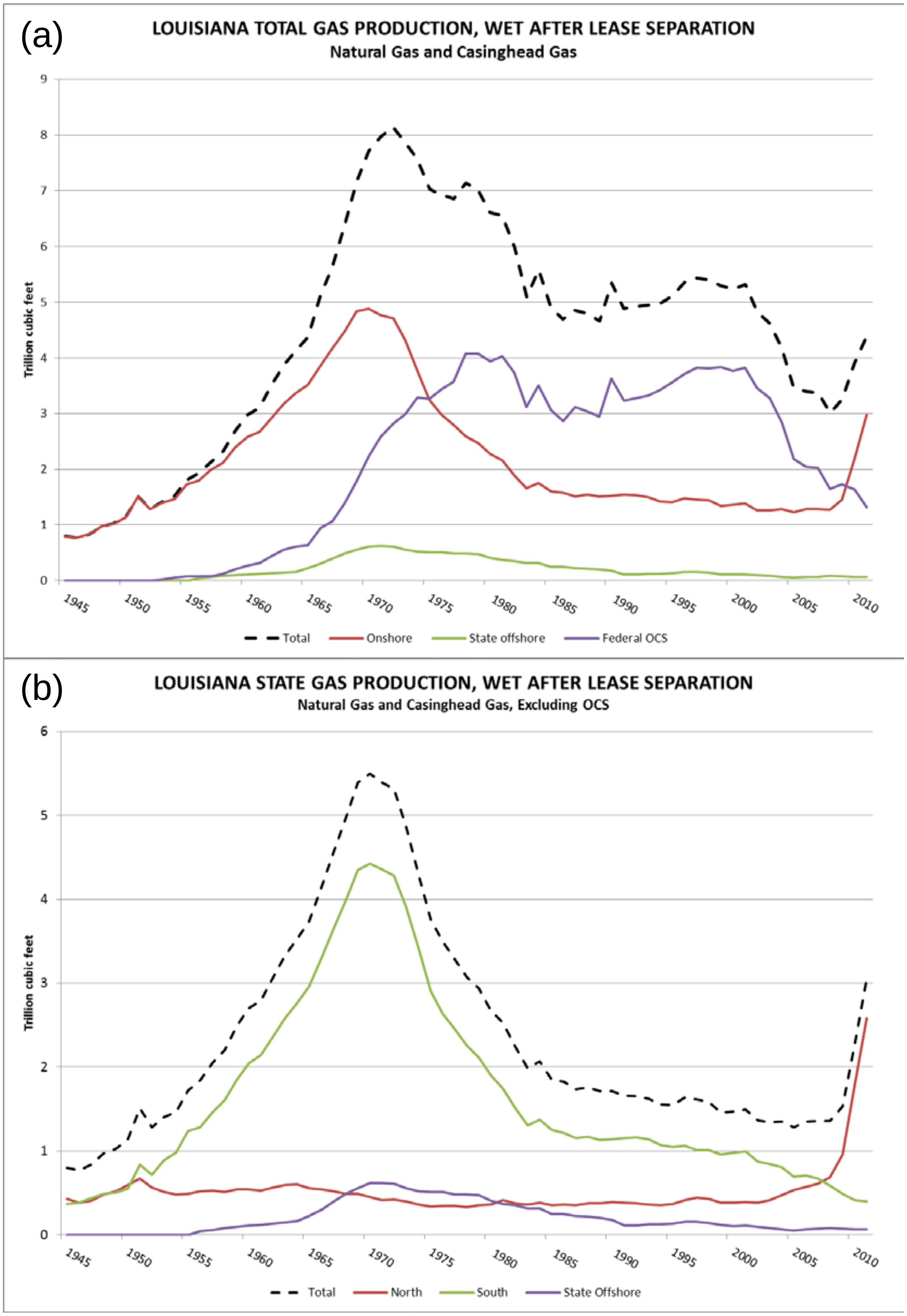


Figure 2.10. (a) Natural gas production for Louisiana from 1945 – 2010, including production on federal offshore continental shelf. (b) Natural gas production for Louisiana from 1945 – 2010, excluding production on federal offshore continental shelf. The ARB is located in the South Region. Data obtained from Louisiana Mid-Continent Oil and Gas Association (Louisiana Mid-Continent Oil and Gas Association n.d.).

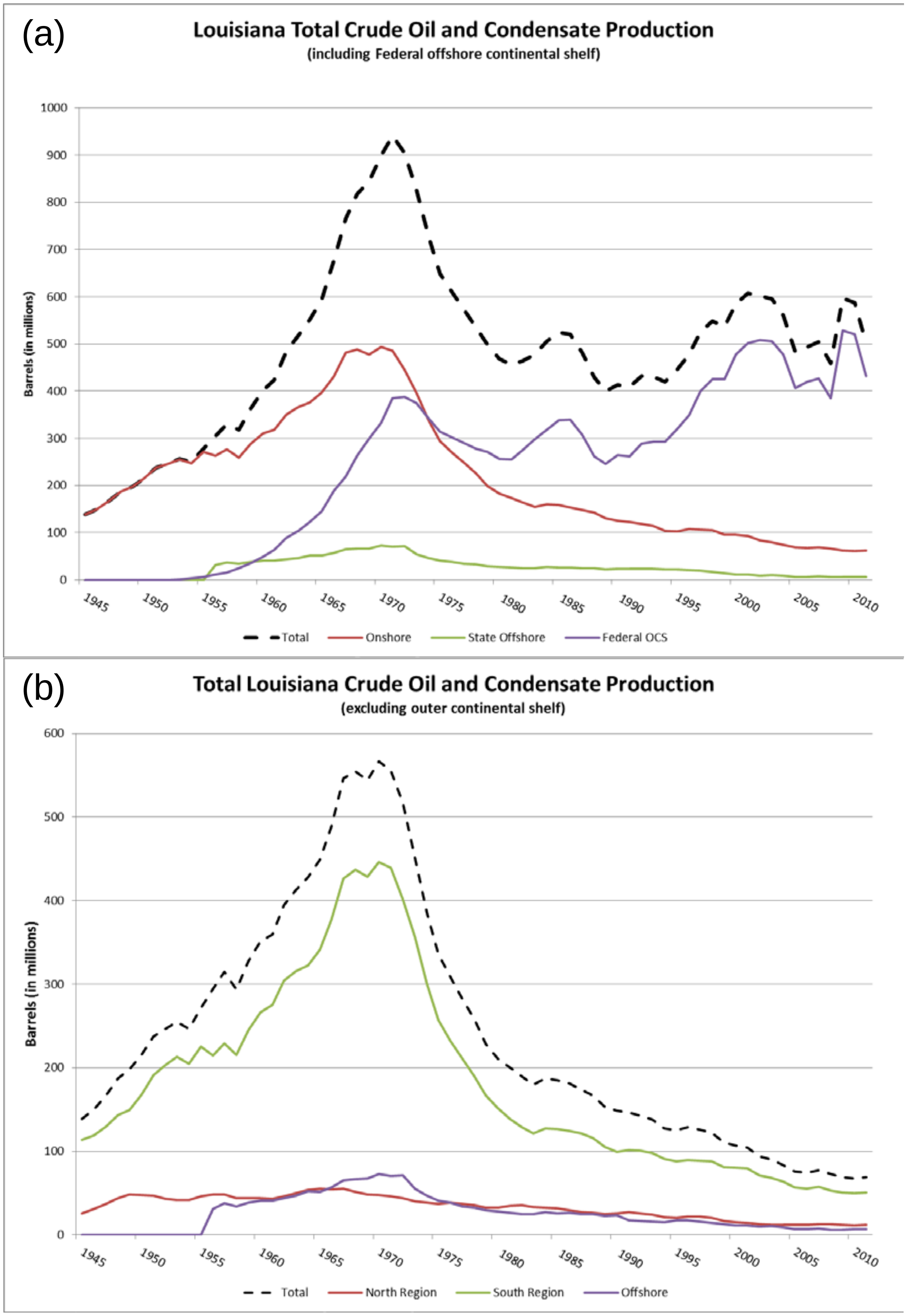


Figure 2.11. (a) Crude oil production for Louisiana from 1945 – 2010, including production on federal offshore continental shelf. (b) Crude oil production for Louisiana from 1945 – 2010, excluding production on federal offshore continental shelf. The ARB is located in the South Region. Data obtained from Louisiana Mid-Continent Oil and Gas Association (Louisiana Mid-Continent Oil and Gas Association n.d.).

2.2.3. Soils.

Soils in the ARB were all derived from recent alluvium; as such, most belong to the soil orders Inceptisols and Entisols (Figure 2.12; Table 2.3). Both orders are typified by very weak soil development, which is due to the dynamic nature of the riverine swamp and the fact that soil-forming processes are hindered by frequent erosion and deposition of new materials. Soil texture ranges from clay to loamy, and over half of the soils in the ARB are classified as hydric, which means they formed under saturated conditions. Hydric classification is important because this condition must be present in order for an area to be considered a jurisdictional wetland (USDA NRCS n.d.).

Based on a geographic information system (GIS) analysis using the 2006 STATSGO2 soil data obtained from the U.S. Department of Agriculture National Resources Conservation Service (USDA NRCS n.d.) along with taxonomic classifications from USDA soil surveys for Louisiana (USDA NRCS n.d.), at least 80% of the soils in the ARB belong to soil orders Inceptisols and Entisols (the actual amount is greater; this was determined by summing the areas of Soil Map Units containing only Inceptisols and Entisols, Figure 2.12). Approximately 60% of the ARB soils are considered hydric.

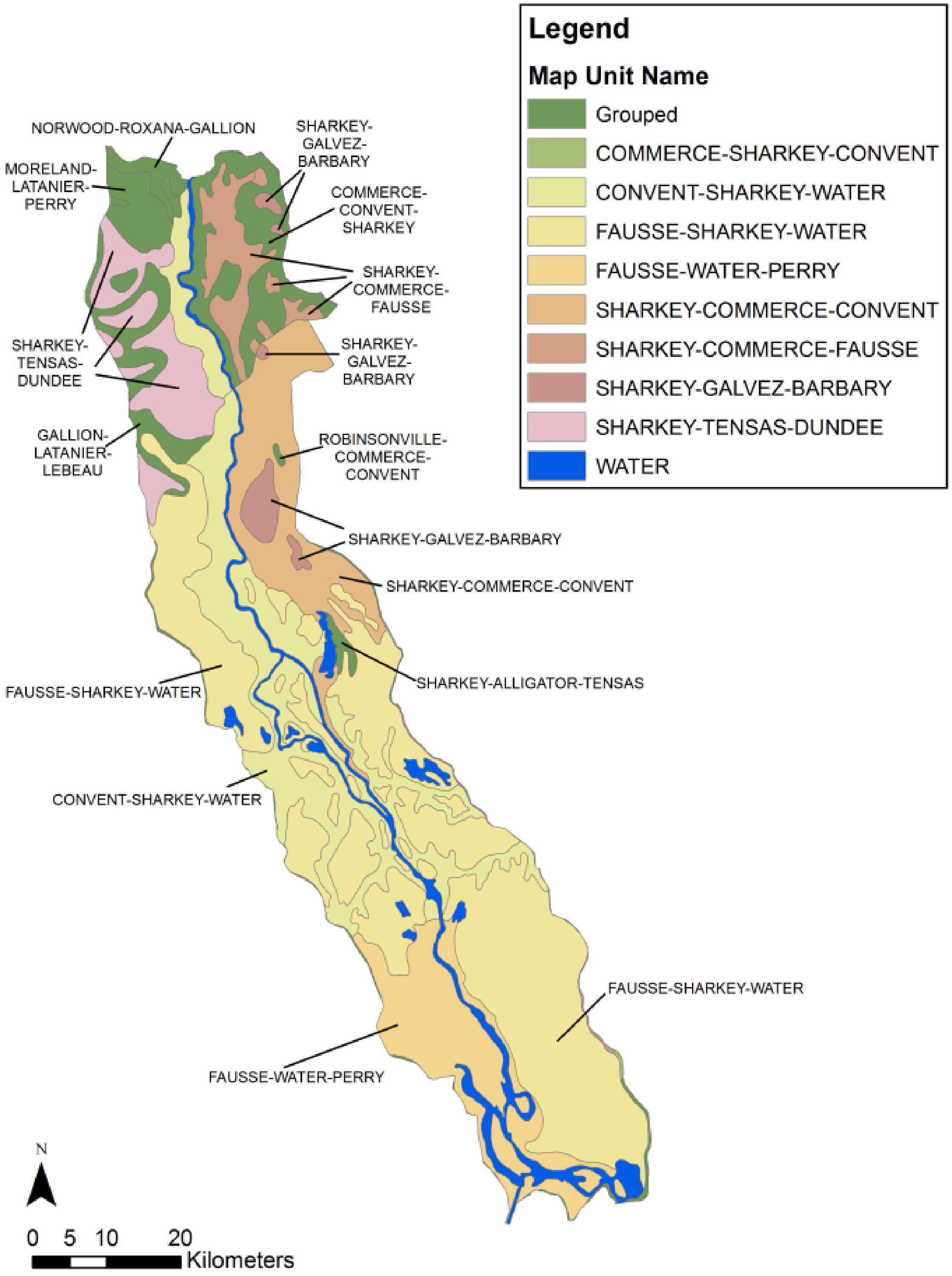


Figure 2.12. Map of soil associations present in the ARB. Data obtained from NRCS U.S. General Soil Map (USDA NRCS n.d.).

Table 2.3. Soil map units. Data obtained from Soil Data Mart (USDA NRCS n.d.) *and Published soil surveys for Louisiana* (USDA NRCS n.d.).

Map Unit Name	Soil Order(s)	Texture and landform position	Hydric	Total in ARB (km^2)
ALLIGATOR-SHARKEY-TENSAS	Inceptisols, Inceoptisols, Alfisols	Loamy and Clayey Low Terraces and Floodplains	N	7.7
BALDWIN-IBERIA-GALVEZ	Alfisols, Vertisols, Alfisols	Loamy and Clayey Low Terraces and Floodplains	N	2.9
COMMERCE-CONVENT-SHARKEY	Entisols, Entisols, Inceptisols	Loamy and Clayey Aluvial Natural Levees and Low Terraces	N	200.0
COMMERCE-SHARKEY-CONVENT	Entisols, Inceptisols, Entisols	Sandy and Loamy Alluvial Natural Levees and Low Terraces	N	1.8
CONVENT-SHARKEY-WATER	Entisols, Inceptisols, na	Loamy and Clayey Low Terraces and Floodplains	Y	612.9
DUNDEE-BALDWIN-SHARKEY	Alfisols, Alfisols, Inceptisols	Loamy and Clayey Aluvial Natural Levees and Low Terraces	N	71.1
FAUSSE-BARBARY-WATER	Entisols, Entisols, na	Loamy and Clayey Low Terraces and Floodplains	N	11.3
FAUSSE-SHARKEY-WATER	Entisols, Inceptisols, na	Loamy and Clayey Low Terraces and Floodplains	Y	1302.3
FAUSSE-WATER-PERRY	Entisols, na, Inceptisol	Loamy and Clayey Low Terraces and Floodplains	N	358.7
GALLION-LATANIER-LEBEAU	Alfisols, Mollisols, Vertisols	Sandy and Loamy Alluvial Natural Levees and Low Terraces	Y	42.2
MORELAND-LATANIER-PERRY	Mollisols, Mollisols, Inceptisols	Loamy and Clayey Low Terraces and Floodplains	N	74.8
NORWOOD-ROXANA-GALLION	Entisols, Entisols, Alfisols	Loamy and Clayey Low Terraces and Floodplains	N	31.7
ROBINSONVILLE-COMMERCE-CONVENT	Entisols, Entisols, Entisols	Loamy and Clayey Low Terraces and Floodplains	N	4.6
SHARKEY-ALLIGATOR-TENSAS	Inceptisols, Inceptisols, Alfisols	Loamy and Clayey Low Terraces and Floodplains	N	13.3
SHARKEY-BALDWIN-IBERIA	Inceptisols, Alfisols, Vertisols	Loamy and Clayey Low Terraces and Floodplains	N	6.6
SHARKEY-COMMERCE-CONVENT	Inceptisols, Entisols, Entisols	Loamy and Clayey Low Terraces and Floodplains	N	335.0
SHARKEY-COMMERCE-FAUSSE	Inceptisols, Entisols, Entisols	Loamy and Clayey Low Terraces and Floodplains	N	136.7
SHARKEY-GALVEZ-BARBARY	Inceptisols, Alfisols, Entisols	Loamy and Clayey Low Terraces and Floodplains	N	63.9
SHARKEY-TENSAS-DUNDEE	Inceptisols, Alfisols	Loamy and Clayey Low Terraces and Floodplains	Y	224.0
WATER	na	Water	N	213.5
Data obtained from 2006 NRCS U.S. General Soil map (STATSGO2) soil data set and USDA Louisiana parish soil surveys				

2.2.4. Hydrology and Sediment

2.2.4.1. Hydrology. The hydrograph of the Atchafalaya River closely mirrors that of the Mississippi River given the mandated flow distribution that sends approximately 25% of the Mississippi River flow down the Atchafalaya River each year (Hupp et al. 2008, Meade and Moody 2010). Highest discharges typically occur between January and May, and there are several peaks during this interval that may last from 1 – 2 weeks. Because the Atchafalaya River is a low-gradient system where overall relief is minimal, large areas of the ARB remain inundated for extended periods of time. While this is a natural occurrence in riverine swamps, the hydroperiod for some areas has been substantially altered due to the labyrinth of canals and associated spoil banks created for various uses, including oil and gas exploration/development, logging, navigation and flood control (Hupp et al. 2008). Such alteration has led to blockage of natural flow pathways and the opening of many dredged canals has led to two major hydrological problems: areas that receive excessive sedimentation due to high connectivity with the main channel, and those that experience hypoxia due to disconnection from the main channel

(Hupp et al. 2008). The problem is more pronounced at low to moderate flows, as spoil banks block historic northwest to southeast flow patterns (Kaller et al. 2011).

Further complicating the understanding of ARB hydrology is that rivers of the Coastal Plain physiographic province have received less study than higher-gradient rivers (Hupp 2000), so less is known about baseline conditions. A recent unpublished analysis reveals that marked changes have occurred in the past half century. Repeat discharge measurements were made by USACE from 1955 – 1976 for the Atchafalaya mainstem and several side channels and distributaries. Comparison of these discharges with recent discharge measurements made during 2010 – 2011 reveal changing flow patterns over the last half century. In the late 1950s, a large amount of water left the main channel and was distributed to west and east sides of the ARB (>60%) even at low flow conditions. Because channel geometry has changed due to anthropogenic influences (widened and deepened), conveyance capacity has increased. This increased capacity, along with disconnection of side channels, has caused a reduction in off channel flow (only ~12% during low flow). Even at typical annual high flows (~260 – 290k cfs) there is little overbank flow (D. Kroes, U.S. Geological Survey, personal communication).

A variety of management objectives for the ARB require a greater understanding of flow patterns in the ARB. Obtaining such information (especially for remote areas) can be difficult given the lack of gages off of main channels. Sabo et al. (1999a,b) attempted to document flow patterns in the lower ARB by monitoring gages. Another potential way to examine water distribution/flow patterns at different water levels that has been employed in the ARB involves the use of Landsat imagery (classification of land v. clear water v. turbid water). Allen et al. (2008) describe first steps toward using such imagery (collected from 1985 – 2006) to 1) examine distributions of land and water at a range of stages; and 2) examine turbid water distribution. Overall, inundation percent for the entire ARB was significantly related to gage level at Butte La Rose (BLR), although this relation broke down somewhat when examining individual water management units (WMUs) (9 of 13 significantly related to gage level at BLR) (Allen et al. 2008). While there are limitations with this methodology (resolution, limited ground-truthing, number of images), further classification of Landsat imagery has continued since publication of the 2008 paper, and reclassified data and advanced analyses are available online at the U.S. Geological Survey (USGS)/Atchafalaya Basin Program Natural Resource Inventory and Assessment System (NRIAS). Figure 2.13 illustrates annual variability for the BLR gage.

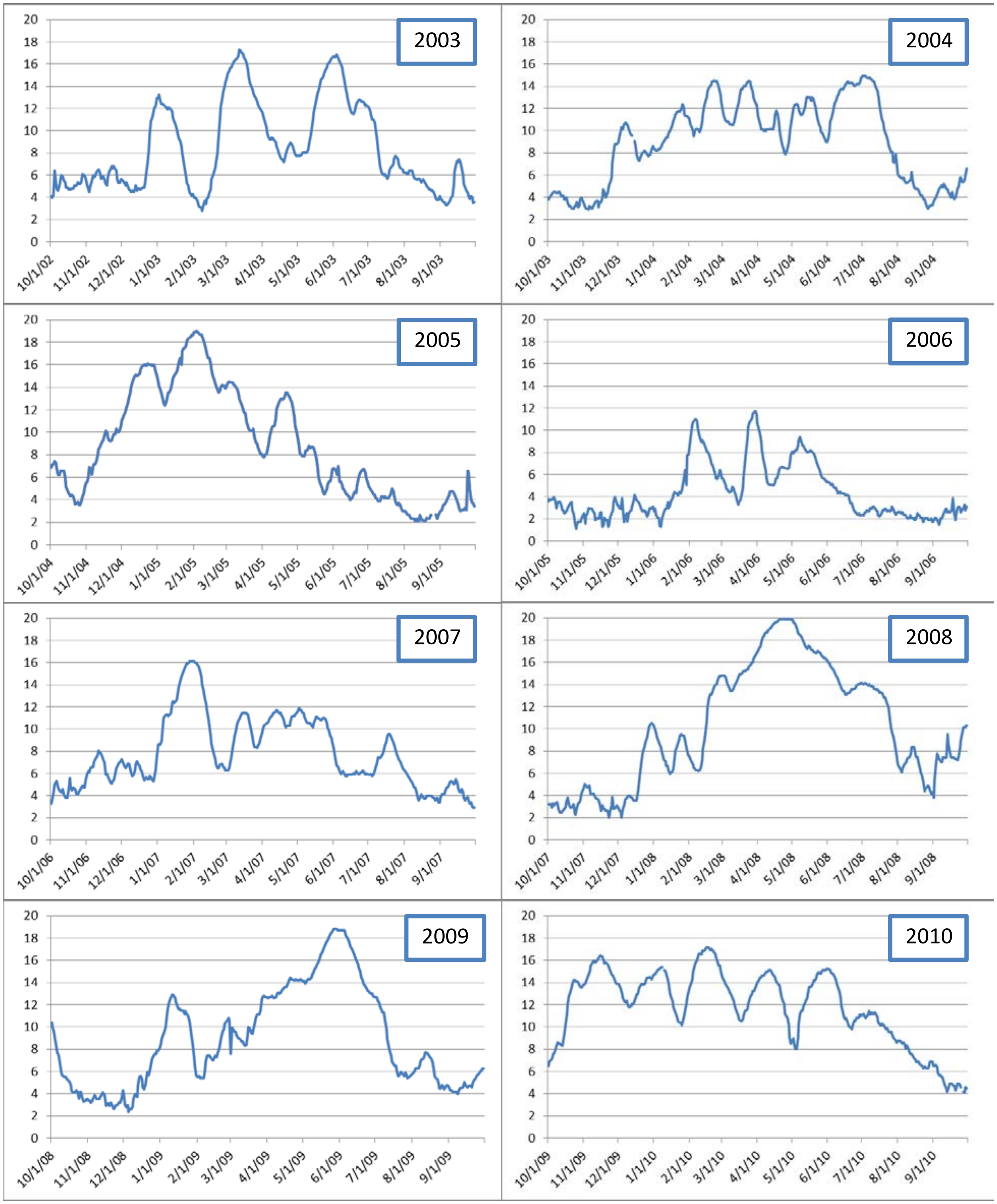


Figure 2.13. Hydrographs for water years 2003 – 2010. Y-axis represents stage (in feet) at Butte La Rose gage (USGS gage 7381515).

2.2.4.2. Sediment. Sediment budgets are important, especially in Louisiana where coastal land loss rates are exceptionally high, representing ~90% of all coastal wetland loss in the United States. The USGS analyzed repeat imagery of Louisiana's coast from 1932 – 2010 and estimated a net loss of approximately 4,877 km^2 over this time period (Couvillion et al. 2011), and according to the less optimistic scenario in Louisiana's 2012 Coastal Master Plan, an additional 4530 km^2 could be lost over the next 50 years if no action is taken (Louisiana Coastal Restoration and Protection Authority n.d.). Trends were reported for 1985 – 2010, and indicate an average annual wetland loss rate of 42.9 km^2 $year^{-1}$ (Couvillion et al., 2011). It is important to note that coastal zones are always in the process of both building and eroding, with the active lobe generally representing ~40% of the coastline (S. Bentley, LSU School of the Coast and Environment, personal communication). However, the typical delta cycle has been altered due to the construction of levees such that wetlands no longer receive mineral sediment input that would support continued land construction. Also, the reduction in sediment loads by at least half combined with relative sea level rise, has led to accelerated land loss over the past century (Blum and Roberts 2012).

Given the ecological and economic importance of these coastal wetlands, using water and sediment for the nourishment of coastal wetlands is now a major goal of river management (in addition to the more traditional management goals regarding flood control and navigation) (Allison et al. 2012). Louisiana's Coastal Master Plan (2012) lists land building and flood risk reduction as the two main factors that drive decisions regarding project development. The plan lays out over 100 projects designed to slow coastal land loss by taking advantage of natural processes (e.g. high sediment loads during flood pulses). The ultimate success of such projects requires understanding of complex natural systems in order to make effective engineering decisions, and such studies of the Mississippi-Atchafalaya system have been on the rise in past years.

For example, subsidence and climate change are both important since potential land gains may be overwhelmed by these other factors. Subsidence rates are variable in coastal Louisiana and there is disagreement among researchers regarding what geologic processes are most important. It is generally recognized that subsidence is due to some combination of sediment compaction, isostatic adjustment and/or structural influence such as fault reactivation or salt tectonics (Dokka et al. 2006, Allison and Meselhe 2010, Dokka 2011, Blum and Roberts 2012). Current subsidence rates obtained from modern instrumentation range from 3 – 25 mm per year depending on location, although it is important to note that stratigraphic data support lower time-averaged rates over the Holocene, ranging from 3 – 8 mm per year (Blum and Roberts 2009). However, even using these more conservative time-averaged estimates, Blum & Roberts (2009) conclude that significant land loss will occur even if sediment loads are restored to conditions that existed prior to major anthropogenic modifications to the Mississippi River due to more rapid relative sea level rise. However, recent studies indicate that plant responses to increased carbon dioxide (CO_2) could offset land loss by increasing organic matter production (Langley et al. 2009).

Climate change is another major challenge facing coastal Louisiana. Regardless of the scenario used in Intergovernmental Panel on Climate Change (IPCC) models, sea levels are projected to rise worldwide by at least 0.2 m by the end of this century due to the combined effects of thermal expansion and input from melting ice (IPCC n.d.); other models predict up to 1.0 m worldwide (Allison and Meselhe 2010). Although IPCC models predict that northern portions of the Mississippi River Basin will receive more precipitation and southern portions less than currently, research indicates that the average annual discharge of the Mississippi River Basin is unlikely to change (<1%) (Nohara et al. 2006). However, changes in timing, frequency, or locus of precipitation are not addressed, and such shifts could affect sediment loads. Finally, some climate models suggest that increased warming will increase the frequency and intensity of cyclonic tropical storms, which may increase coastal erosion rates during these extreme events (Allison and Meselhe 2010).

The ARB is of particular interest because the Atchafalaya Delta and the Wax Lake Delta (a man-made outlet that was completed in 1942) are presently the only areas along the Louisiana coast that are gaining land (although this gain is not enough to offset overall coastal loss). These deltas became subaerial (land exposed above low tide) during the sediment pulse associated with the 1972 - 73 floods on the Mississippi River (Roberts et al. 1980).

Sediment discharges to oceans are difficult to determine, and often the terminal stations used to estimate amounts of suspended sediment are located hundreds of kilometers upstream of the river mouth. For example, many past water and sediment budgets for the Mississippi River relied on the station at Tarbert Landing, located just downstream of ORCS and 492 km upstream of Head of Passes (considered 0 km) (Allison et al. 2012). The deltaic environment through which water and sediment passes before ultimately entering the ocean can serve as a sediment source or sink, and dynamics in this region (often termed the large-river deltaic estuary or LDE) are not well understood. Further complicating the issue is that sediment discharge is spatially and temporally varied. Even at sites that are considered to have long and fairly complete periods of record, suspended sediment discharge is typically only measured twice a month at most (perhaps more during high-magnitude events). Individual measurements are generally accurate within ~10 – 15% given cross-sectional and vertical velocity differences along with inability to measure sediment concentration at all depths (Meade and Moody 2010).

Estimates of suspended sediment discharge prior to 1900 indicate that ~400 – 500 million metric tons of sediment per year were transported via the Mississippi River and its distributaries to the coast of Louisiana (Kesel et al. 1992, Meade and Moody 2010). These amounts might be an overestimate of middle to late Holocene averages due to intensification of agriculture and associated erosion in the MRB over the previous decades. How much of this sediment was transported into the ARB is unknown. Although recent studies of suspended sediment loads vary somewhat, all indicate at least a 50% reduction from pre-1900 estimates. Blum and Roberts (2009) calculated an average suspended sediment load of 205 metric tons per year for the lower Mississippi River (including the ARB) using gaging station data for years 1976 – 2006. Meade and Moody (2010) report a slightly smaller average annual load based on sediment data from 1987 – 2006 (~ 172 million metric tons year^{-1}). Although dams are often cited as the major reason for this reduction, the authors report that sediment trapping by dams accounts for only about half of this decrease. Other factors also play a role in the decline, including: 1) anthropogenic structures (e.g., channel revetments) that have trapped/eliminated previously existing sediment sources and 2) watershed-scale erosion control measures that have been effective at reducing sediment supply. The authors suggest that these changes have caused a shift from a transport-limited to a supply-limited system (Meade and Moody 2010).

Transport-limited systems are typified by hydraulic regimes that are incapable of moving all the sediment supplied to a system from its surrounding watershed, resulting in overall aggradation of a system. In contrast, supply-limited systems generally have enough energy to move all sediment supply and thus excess energy is devoted to erosion and/or channel degradation. Natural and/or anthropogenic modifications can cause a river system to transition from one state to another. As noted above, extensive human-induced engineering modifications, which accelerated during the mid-1900s, disconnected the Mississippi River from many of its natural interactions with sediment-rich storage locations (floodplains and banks) (Horowitz 2010, Meade and Moody 2010). Around this time, a substantial shift in the sediment-discharge relationship was observed at the Mississippi River at Tarbert Landing gaging site. From 1950 – 1966, suspended sediment concentration clearly increased with increasing discharge. However, from 1967 – 2007, this trend was not observed; instead, sediment concentrations remained essentially constant regardless of discharge. The trend observed over the time period from 1967 – 2007 is typical of a supply limited system (Meade and Moody 2010).

One study indicated that as much as 60% of the suspended sediment load from the Mississippi River is diverted through ORCS (Mossa and Roberts 1990), but more recent studies indicate that less suspended sediment is diverted through ORCS (~20 - 30%) (Kesel et al. 1992, Meade and Moody 2010, Allison et al. 2012). In addition to receiving suspended sediment from the Mississippi River, the Atchafalaya also accepts the full sediment load from the Red River, inferred to be on average 36.8 million tons/year for water years 2008 – 2010 (this amount was indirectly calculated by subtracting the amount calculated at the ORCS outlet structures from the Simmesport load) (Allison et al. 2012).

Bedload in large, low-gradient sand bed rivers is even more difficult to quantify than suspended sediment load for a number of reasons. One of the major difficulties is that the term bedload can be difficult to define as it changes depending on discharge. At low discharges, very little to no sand travels in suspension and accounts for the entire bedload. However, at higher discharges, significant amounts of sand move both as bedload (by bedform migration) and in suspension. Sampling at the bed-water interface is a particular challenge. Traditional bedload sampling devices change flow patterns and thus may give inaccurate results; the capacity of the samplers may also serve as a limitation (Nittrouer et al. 2008). Additionally, tidal influences at river mouths complicate measurements of sediment flux. Finally, bedload transport is highly temporally variable; less frequent high discharges are likely responsible for most of the sediment transport that affects channel morphology, and peak sediment discharges in the Mississippi River system typically precede peak water discharges (Mossa 1996). The bedload component in large river systems is typically a small percentage of overall sediment load, and studies often exclude it and assume that it represents ~ 5 – 10% of the overall sediment budget, representing a potential underestimate in sediment budgets (Nittrouer et al. 2008). According to a recent bedload study utilizing a multi-beam swath profiler to obtain bathymetric data, Nittrouer et al. (2008) indicated that bedform wavelength and height vary considerably with discharge. Quantifying these components are important not only for understanding sediment fluxes but also because this shifting bed topography alters the roughness and shear stress components that are important to quantify for hydraulic modeling efforts.

Understanding sediment dynamics is important not only for coastal restoration efforts, but also because of the ecosystem services provided by sediment sinks in the deltaic environment, such as contaminant storage and carbon sequestration. As stated, the two deltas associated with the ARB (Atchafalaya Delta and Wax Lake Delta) are currently prograding and many of the open-water areas in the ARB have been transitioning to land since the 1800s, though due to subsidence some areas in the southernmost portion of the ARB are experiencing an increase in open water area. Such a change is consistent with deltaic processes at work during a delta lobe-switching event. Based on an analysis of historical maps and imagery, Allen (2010) found that Grand Lake had an areal extent of 491 km^2 in the early 1800s, has been reduced to an area of only ~ 196 km^2 currently. The historical extent of Grand Lake encompassed what are now the separate water bodies of Lake Fausse Point, Lake Rond, Lake Chicot, Flat Lake, Duck Lake and Six Mile Lake. Infilling began in the 1800s but accelerated with the sediment pulse associated with the major Mississippi River flood of 1927. From the late 1950s to the early 1980s, the conversion rate increased so that an average of 3.8 km^2 of open water was converted to land each year. This rate slowed substantially from the early 1980s on, so that no net land conversion occurred. However, this was partially due to the fact that Lake Fausse Point was dredged to maintain open water; further, this lake is no longer connected to the modern ARB as it is outside of the west protection levee (Allen, 2010).

Recent studies have attempted to quantify sediment storage amounts within the Mississippi River large-river deltaic estuary, including the ARB. Allison et al. (2012) examined the fate of suspended sediment once it reached the bifurcation point of the Mississippi-Atchafalaya. Using data from long-term gaging stations in addition to existing studies, the authors calculated a detailed water and suspended sediment budget for the lower Mississippi and Atchafalaya Rivers for water years 2008 – 2010 (October 1, 2007 – September 30, 2010). Using a mass balance approach, the authors found that up to 44% of the suspended sediment load as measured at the latitude of ORCS is stored upstream of the outlets into the Gulf of Mexico (Allison et al. 2012); as much as 75% of the sand fraction of the Mississippi River is stored upstream of New Orleans. Net basin storage was 23.1 million tons year $^{-1}$ and 67.5 million tons year $^{-1}$ for the ARB and Mississippi Rivers, respectively. Suspended sediment loads measured at the combined Atchafalaya outlets (Wax Lake and Morgan City) and at the Mississippi outlet (Belle Chasse) were 48.4 and 88.3 million tons, respectively. The years studied were actually above the median yearly discharge measured for 1950 – 2007, so sediment delivery to the coast is likely to be less than during lower discharge years. Incorporating this more nuanced understanding regarding sediment storage in floodplain/channel environments upstream of the river outlets indicates a more severe supply-limited condition than previously understood.

Hupp et al. (2008) examined sedimentation patterns within the central Atchafalaya. Twenty transects (each w/ 4 – 6 sampling points that were categorized as levee, transition or backswamp) were monitored for three years (2000 – 2003). Mean annual sediment deposition rates were variable (2 – 42 mm year^{-1}) and not necessarily well correlated with landscape position. Five statistically different clusters of sedimentation rate were identified based on some combination of the following factors that influenced spatial distribution: geomorphic position, hydroperiod, hydraulic connectivity, and number of sediment source inputs. Sites with the highest accretion rates were characterized by a long hydroperiod, high connectivity to several sources of turbid water, and hydraulic damming (which occurs when flow vectors meet and stagnate, allowing particles to drop out of suspension) (Hupp et al. 2008). Finally, the authors used the spatial distribution of these clusters to calculate potential annual sediment retention of 6.7 million tons for the ARB, which is within an order of magnitude of the annual storage estimated by Allison et al. (2012).

Hydrology is considered a master variable in wetland systems (Poff et al. 1997, Hupp 2000, Mitsch and Gosselink 2007), and sediment dynamics are closely tied to hydrology. Sediment in the ARB is viewed as both a blessing (when it nourishes the coast) and a curse (when past fishing spots are converted to dry land). Managing sediment in ways outlined in Louisiana’s Comprehensive Master Plan for a Sustainable Coast (2012) requires a more nuanced understanding of these systems and their interactions in order to design cost-effective projects.

2.3. Water Quality and Nutrients

2.3.1. Pollution Sources

Water quality and pollution are of serious concern in the ARB as these aspects affect and control many ecosystem processes and human uses of the ARB's fresh water. From a regulatory standpoint, almost the entire ARB is considered "impaired" by the U.S. Environmental Protection Agency (EPA), with 57.9 km of bayou, almost 1619 km^2 of freshwater wetlands and almost 1036 km^2 of the estuary listed under section 303(d) of the Clean Water Act as of 2006 (Table 2.4) (Environmental Protection Agency 2012). The main causes of impairment, as listed by EPA, are mercury and dissolved oxygen for wetlands, dissolved oxygen and total dissolved solids for rivers and streams (with other causes of impairment such as nitrate/nitrite, phosphorus, sulfates and atrazine, also affecting substantial portions of listed stream segments), and dissolved oxygen and fecal coliform bacteria for the estuary (Environmental Protection Agency 2012). Permitted discharging facilities under the National Pollutant Discharge Elimination System (NPDES) are sparsely but widely distributed throughout the ARB floodway, consisting of oil production and manufacturing facilities, shipyards and a few small municipalities.

Table 2.4. Impaired waters of the Atchafalaya Basin under Section 303d of the Clean Water Act. Data obtained from Environmental Protection Agency, 2012.

Waterbody/Location	**Waterbody Type**	**Size**	**Units**
Atchafalaya Bay and Delta and Gulf waters to state three-mile limit	Estuary	391	mi^2
Bayou Maringouin – headwaters to East Atchafalaya Basin levee	River	18	mi
Crow Bayou, Bayou Blue and tributaries	River	18	mi
East Atchafalaya Basin and Morganza Floodway – south to I-10 canal	Wetlands, freshwater	195840	acres
West Atchafalaya Basin Floodway – Simmesport to Butte La Rose Bay and Henderson Lake	Wetlands, freshwater	199040	acres

2.3.2. Hypoxia

Even from this brief regulatory overview, it is clear that low dissolved oxygen has a major effect on water quality in the ARB. While low oxygen levels occur seasonally in most lowland riverine swamps, especially during summer months and along the bottom (Baker et al. 1991), the frequency of hypoxia (defined as oxygen concentration < 2 mg L^{-1}) in the ARB has almost doubled since the 1970s (Bryan et al. 1998). The extent of hypoxia has also increased as sedimentation and main-channel dredging have disconnected bayous and backswamps from regular inputs of oxygen-rich water from the river channel (Bryan et al. 1998, Sabo et al. 1999a). The extent and duration of hypoxia in the ARB is likely affected by several factors such as hurricanes, wind and tidal patterns, organic matter retention (and associated respiration and oxygen depletion by microorganisms), nutrient levels, and aquatic vegetation (Bryan and Sabins 1979, Hern et al. 1980, Stern et al. 1986, Bryan et al. 1998, Sabo et al. 1999a, Colon-Gaud et al. 2004); however, the prevalence of the problem seems to be most closely associated with local flow paths and disconnection between the main channel and side channels and bayous (Sabo et al. 1999a) – a result of increased sedimentation and spoil pile development from dredging (Sabo et al. 1999a, 1999b). As water enters the bayous and backswamps during the spring flood pulse, areas that normally would have drained by mid-summer remain inundated due to lack of flow connections to main channels (or due to opposing flow paths that slow water flow). As water temperatures rise in these stagnant waters, increased metabolism and reduced oxygen capacity promote hypoxia.

2.3.3. Transformation and Export of Nutrients and Pollution

2.3.3.1. Nitrogen. While nutrient pollution (nitrogen and phosphorus) in the ARB likely contributes somewhat to eutrophication and subsequent hypoxia in these freshwater environments, the nutrients exported from the ARB into Atchafalaya Bay and surrounding coastal areas are major drivers of hypoxia in the Gulf of Mexico (Rabalais et al. 2007). Nitrogen is generally the limiting nutrient for phytoplankton growth in marine and coastal systems, but this can often shift seasonally as different environmental factors gain dominance. In the ARB delta, dissolved silica (Si) and phosphorus are closer to limiting during spring, when discharge (and nitrogen loading) is highest; but the system as a whole is nitrogen-limited throughout most of the year (Turner et al. 2007). Increased nitrogen exports from agricultural fertilizers in the upper Mississippi River watershed, mainly in the form of nitrate (NO_3^-), thus have a major impact on community and food web dynamics in the Gulf. Excess nitrate promotes eutrophication, phytoplankton blooms, and hypoxia (Rabalais et al. 2002). The ARB transports approximately 25% of the total annual nitrogen and the same proportion of NO_3^- and nitrite (NO_2^-) from the Mississippi River watershed (Turner et al. 2007), which make up almost 50% of the total annual nitrogen load in the ARB (Xu 2006a).

Perhaps the single most important process that removes nitrogen from terrestrial and aquatic ecosystems is denitrification. In this mostly microbially-mediated process, nitrate and nitrite are reduced to dinitrogen gas (N_2) via bacterial processing, with nitric oxide (NO) and nitrous oxide (N_2O) gas produced to a much lesser extent in the process. Biological or respiratory denitrification is carried out by facultative anaerobic bacteria under anoxic conditions, which makes the use of nitrogen oxides energetically favorable for use in respiration in the absence of oxygen gas (Groffman 1994, Groffman et al. 1999). Although respiratory denitrification appears to be the most prevalent form of N removal in fresh water (Seitzinger et al. 2002, Helton et al. 2010, Rivera-Monroy et al. 2010), other biological and abiological processes can transform or sequester nitrogen. Anaerobic bacterial oxidation of ammonium (NH_4^+) produces N_2 by combining nitrite with ammonium and thus results in permanent nitrate removal (Burgin and Hamilton 2007). The process, referred to as anammox, was only discovered in the 1990s and is not fully understood but may be important in systems with low labile carbon or low carbon:nitrogen ratios (Burgin and Hamilton 2007). Dissimilatory nitrate reduction to ammonium (DNRA) is another pathway by which bacteria reduce nitrate directly to ammonium, either through fermentation or by chemolithoautotrophic bacteria. Fermentative DNRA is thought to be favored in environments with high labile carbon and low nitrate and sulfur concentrations (Tiedje 1988, Burgin and Hamilton 2007), and chemolithoautotrophic DNRA is favored in high carbon systems with high sulfur concentrations (Burgin and Hamilton 2007). In general, oxygen is the most energy-yield-efficient electron acceptor, followed (in order) by NO_3^-, ferric iron (Fe^{3+}) and sulfate (SO_4^{2-}) (Burgin and Hamilton 2007). Additional investigation is needed to provide information about the relative importance of these forms of nitrate reduction for total N loss from aquatic systems. In the few studies documenting these processes in freshwater systems, dissimilatory nitrate reduction to ammonium made up between ~5% and 60% (6 studies) of total nitrate removal and anammox made up ~10-15% (1 study) (Burgin and Hamilton 2007). Other biologically-mediated processes retain nitrate within the ecosystem, usually for shorter periods. Vascular plants, periphyton, phytoplankton and microbes can uptake nitrate directly and can have dominant influences on nitrogen export and retention in fluvial systems (Bowden 1987, Arango et al. 2008, Halloran 2010, Mulholland and Webster 2010).

In addition to biological transformations, many abiotic processes remove or sequester nitrogen. There are several chemical reactions catalyzed non-biologically that produce nitrogen gas from nitrate, referred to as chemodenitrification. These reactions, the most common of which are acid-catalyzed destruction of nitrite, most often produce NO as a product but can also produce NO_2^- and N_2. Chemodenitrification can be important under certain environmental conditions (e.g., frozen soils) but is not thought to be a major contributor to the global nitrogen cycle (Tiedje 1988). Organic nitrogen can also be sequestered in fluvial systems via mineralization and storage in sediments (Bowden 1987). Although denitrification potential of many freshwater habitats is high and the process is a significant contributor to nitrate removal in freshwater ecosystems (Scott et al. 2008, Rivera-Monroy et al. 2010), the ultimate fate of nitrate (permanent removal from the system via N_2 gas or further cycling and transport) in most systems is largely unknown (Hall 2003).

The ARB is a significant sink for organic nitrogen and total nitrogen, removing approximately 27% (Xu 2006b) and 14% (Xu 2006a), respectively, of the annual loadings (1978-2002); however, its role in inorganic nitrogen retention and removal appears to be much smaller. Denitrification rates in the ARB are generally comparable to those in other coastal Louisiana freshwaters under similar conditions and treatments (especially at background and high NO_3^-

additions; Table 2.5). Yet studies examining ARB-wide concentrations and total fluxes from the ARB have shown essentially no (Turner et al. 2007) or only slight (BryantMason and Xu 2013) differences in NO_3^- concentrations between water entering (measured at Simmesport, LA) and leaving (measured at Morgan City, LA, or Wax Lake Outlet) the ARB. The ARB retained, through denitrification or sequestration in plants or sediments, only about 4% of the NO_3^- entering the ARB during the major flooding of 2011 (BryantMason and Xu 2013) and is generally a net source of NO_3^-+NO_2^- nitrogen to the Gulf, exporting 2.3% more mass of these forms than entered the ARB from 1978 to 2002 (Xu 2006b; see also Turner et al. 2007). Differences in retention of the different forms of nitrogen indicate the influence of biological and physical processes on nitrogen transformation. Retention of organic nitrogen was strongly (positively) correlated with discharge, potentially indicating a large role for retention in sediments and organic matter; export of NO_3^-+NO_2^- nitrogen was not correlated with discharge, but negative balances (export) occurred mostly from mid-summer to late fall, when temperatures are elevated, potentially indicating greater control by biological processes (e.g., nitrification) (BryantMason and Xu 2006, Xu 2006a). However, plant growth, low oxygen, high acidity or low phosphorus conditions could limit nitrification in backwaters during the summer (Bowden 1987). A recent study of nitrogen isotopes in the ARB, which was able to distinguish nitrate sources, found no evidence for significant nitrification or denitrification in the ARB (BryantMason et al. 2013).

Table 2.5. Characteristics and findings from denitrification studies in the ARB.

Location	**Habitat**	**Nitrogen Enrichment (mg L^{-1} NO$_3$)**	**Temperature (Celsius)**	**Denitrification Rate (umol N m^{-2} h^{-1})**	**Reference**
ARB	cypress-tupelo	0.186		89.2-416.5	Boustany et al. 1998
Davis Pond	freshwater marsh	0-2		5.7-274.9	Gardner 2008
ARB	bottomland hardwood	1	22	2.41	Scaroni et al. 2011
ARB	cypress-tupelo	1	22	2.98	Scaroni et al. 2011
ARB	lake	1	22	3.57	Scaroni et al. 2011
Davis Pond	freshwater marsh	1		131.5	Gardner 2008
Davis Pond	freshwater marsh	1.4		10.48	Lindau et al. 2009
ARB	bottomland hardwood	5	22	6.85	Scaroni et al. 2011
ARB	cypress-tupelo	5	22	10.15	Scaroni et al. 2011
ARB	lake	5	22	109.4	Scaroni et al. 2011
Lake Cataouatche	freshwater benthic sediment	50		10.7-280.1	Iwai 2002
ARB	bottomland hardwood	50	22	49.58	Scaroni et al. 2011
ARB	cypress-tupelo	50	22	62.14	Scaroni et al. 2011
ARB	lake	50	22	134	Scaroni et al. 2011
Davis Pond	freshwater marsh	50		280.06	Lindau et al. 2009
Lake Cataouatche	freshwater benthic sediment	88.57		137.9	Miao et al. 2006
ARB	cypress-tupelo	100	8	0.18-77.17	Lindau et al. 2008
ARB	cypress-tupelo	100	22	0.18-163.6	Lindau et al. 2008
ARB	cypress-tupelo	100	30	0.18-289.6	Lindau et al. 2008
Lake Cataouatche	freshwater benthic sediment	177		241.8	Miao et al. 2006
ARB	cypress-tupelo	186		59.5-1338.6	Boustany et al. 1999
Davis Pond	freshwater marsh	8.85-17.7		92-214	DeLaune et al. 2005
Lake Cataouatche	freshwater benthic sediment	background		0.2-2.0	Iwai 2002
Lake Cataouatche	freshwater benthic sediment	background		9.8	Miao et al. 2006
Big Mar	freshwater benthic sediment	background		0.0-2.8	DeLaune and Jugsujinda 2003
ARB	bottomland hardwood	background	22	1.61	Scaroni et al. 2011
ARB	cypress-tupelo	background		29.0-89.2	Boustany et al. 1997
ARB	cypress-tupelo	background	8, 22, 30	0.18-14.23	Lindau et al. 2008
ARB	cypress-tupelo	background	22	1.16	Scaroni et al. 2011
ARB	lake	background	22	0.41	Scaroni et al. 2011
Davis Pond	freshwater marsh	background		0.65	Lindau et al. 2009

Based on BryantMason and Xu (2012) and BryantMason et al. (2012), flow-through floodplain swamps and wetlands like the ARB are insignificant in terms of denitrification and substantial engineering would be necessary to make the ARB function to remove more nitrate through denitrification. This idea is corroborated by a recent study, model and meta-analysis of nutrient retention in so-called “transient storage” areas–such as slow-moving pools and flow-through wetlands –that were found to contribute little to nutrient retention in most freshwater systems examined (Powers et al. 2012). While first- and second-order streams in Wisconsin often had higher maximum nitrate processing rates, they also had lower minimum rates and generally accounted for <30% of nitrate uptake. This pattern appears broadly applicable, as transient storage areas across many freshwater systems in a meta-analysis (small streams, large rivers, wetlands) contributed an average of 43% to nutrient reduction, even under the assumption of higher processing in these areas compared to areas with higher velocity (Powers et al. 2012). This finding is in contrast to much conventional understanding of denitrification in freshwater lowlands that suggests that restoring flow to backwaters should promote denitrification by increasing nitrate inputs, increasing water residence time, and promoting contact with soils (Pinay et al. 2002, Lindau et al. 2008).

Water residence time is a key factor in nitrate export in both freshwater and estuarine environments (Nixon et al. 1996, Pinay et al. 2002, Perez et al. 2011) as longer residence times allow NO_3^-+NO_2^- to diffuse into benthic sediments where most denitrification occurs (Rivera-Monroy et al. 2010). Water regime also determines the cycles of anoxic and oxic conditions in soils that influence denitrification rates (Pinay et al. 2002). Powers et al. (2012) emphasize that, even if uptake efficiency is low, denitrification and nitrogen retention in transient storage areas could still be important simply by virtue of the long residence times, and thus the total nutrient mass, in these habitats. Although they based their initial study on headwater streams and wetlands in Wisconsin, the general trade-off Powers et al. (2012) propose seems useful and applicable for the ARB. They hypothesize that the total contribution to nutrient retention by a nutrient sink (such as flooded backwaters) is limited by: 1) uptake efficiency (e.g., denitrification rate) within the sink; 2) residence time of water in the sink; and 3) rate of transfer of nutrients (i.e., strength of hydrologic connection) from source to sink (e.g., main channel to flooded backwater)(Powers et al. 2012). If uptake efficiency does decline as water velocity decreases, there is a trade-off between uptake efficiency and water residence time (Powers et al. 2012) that has been exacerbated in the ARB by disconnecting floodplain waterbodies and soils from higher-nitrate waters from the main channel. In the ARB floodway, it is not clear from current research if the average flood cycle increases nitrogen retention by allowing water to interact with floodplain soils, or, as apparently was the case with the flood of 2011 (BryantMason and Xu 2013), whether flooding propels water through the system quickly, resulting in little or no retention. Although the potential of the ARB as a nitrate sink may be high, the current configuration of the ARB does not allow for sufficient time and area of contact with high-nitrate flood waters to reduce ARB-wide nitrate concentrations before its waters enter the Gulf.

Many studies of coastal wetlands and freshwater diversions in Louisiana do, however, document significant (40% to > 90%) removal rates for in-flowing nitrate-rich waters (Lane et al. 1999, 2003, Rivera-Monroy et al. 2010). In a study of the ARB coastal region, nearshore areas (< 10 m depth) had a NO_3^- removal efficiency of 40-47%, which amounted to 36-42% of the total NO_3^- in the outflow of the ARB (Lane et al. 2002). In the Fourleague Bay system, which receives most of its input from the ARB, approximately 50% of NO_3^- entering the upper Bay may be lost via denitrification (Smith et al. 1985). Dissolved inorganic nitrogen uptake (including denitrification and all forms of retention) increased with fresh water residence time (time to replace water in the Bay; 0.162 – 0.623 months) and temperature (~15-27 °C) from February and March (~30-70%) to April (>90%) (Lane et al. 2010, Perez et al. 2011). When ARB discharge was high during the winter and early spring, export of nitrate from Fourleague Bay to the Gulf of Mexico was about 60%, while the Bay acted as a nitrate sink during lower discharge of the summer and fall when nutrient inputs decreased and tidal influences grew in importance (Lane et al. 2002, 2010, Perez et al. 2011). Many freshwater and coastal wetlands in Louisiana are similarly efficient at nitrogen retention, despite being flow-through systems; thus, it is unclear why the ARB floodway would exhibit such low retention. In large rivers with high sediment loads, NO_3^- uptake or demand should decrease relative to NH_4^+ demand due to less autotrophic metabolism (Tank et al. 2008). Greater particulate transport in large rivers would also increase water column cation exchange that could serve to uptake more NH_4^+ (Tank et al. 2008). These factors would increase NH_4^+ uptake over NO_3^-, consistent with the whole-system patterns of nitrogen species flux currently known for the ARB (Xu 2006a, 2006b).

Additionally, one of the controls on denitrification is nitrate concentration, and this could be a major factor in the ARB delta and the Gulf of Mexico. During low fall and winter river discharge (with low nitrogen loading rates), NO_3^- and lack of organic matter may limit denitrification. As N supply increases (with increasing discharge from the ARB), denitrification will respond concomitantly until hypoxia inhibits nitrification (conversion of ammonia to NO_3^-) during warmer periods and denitrification is once again NO_3^--limited (Boynton et al. 1995, Childs et al. 2002, Perez et al. 2011). Despite the fact that anoxic conditions are necessary for denitrification, under low nitrate conditions anoxia inhibits nitrification, an important source of nitrate, and increases the residence time of remaining nutrients (ammonia), potentially forming a negative feedback loop that reinforces eutrophic conditions and hypoxia (Childs et al. 2002). This feedback could also take place in freshwater habitats of the ARB since nitrate is usually taken up rapidly (1-3 days at > 22 °C), and nitrate may be limiting after this point if high concentrations of nitrate are not continuously supplied in the water (Lindau et al. 2008, Rivera-Monroy et al. 2010, Scaroni et al. 2011).

2.3.3.2. Phosphorus. While phytoplankton populations in the Gulf of Mexico tend to be N-limited throughout much of the year, more extensive sampling across the northern Gulf has documented substantial phosphorus and light limitation in some areas (Quigg et al. 2011), agreeing with projections of future conditions based on changes in fertilizer use (Turner et al. 2003). The ARB apparently plays a major role in driving primary production in the northern Gulf of Mexico west of the Mississippi River. Phytoplankton populations in areas offshore from Atchafalaya Bay are frequently resource limited. They are limited by N before the spring flood pulse, by light, through turbidity from the river sediment plume, and then by phosphorous in the late spring and summer as N levels are substantially elevated (Quigg et al. 2011). Modeling and some observations suggest that this phosphorus limitation may strongly affect the spatial distribution of phytoplankton growth and hypoxia formation. Phytoplankton populations begin to grow but their nitrogen uptake is limited by the amount of phosphorus (which is also necessary for growth) in the water. This delays their growth and shifts a portion of primary production driven by riverine inputs westward during spring and early summer periods of high discharge (Sylvan et al. 2006, 2011, Laurent et al. 2012). This results in less organic matter flux to sediments near the Mississippi delta but more flux to areas near Atchafalaya Bay and farther west (Laurent et al. 2012). Phosphorous limitation is less prevalent in the Atchafalaya coastal region than the Mississippi delta region because of its shallowness. Sediment denitrification in shallow areas of Atchafalaya Bay can remove bioavailable nitrogen more efficiently than the Mississippi delta, resulting in a decrease in the N:P ratio and reducing phosphorus limitation (Laurent et al. 2012). Although little is known about the cycling and fate of phosphorous in the ARB, it is clear that this element, and the ARB’s role in its delivery, is a critical factor in Gulf hypoxia (Quigg et al. 2011). Organic matter entering the Gulf from the Mississippi River only accounts for about 23% of the zone of hypoxia (Green et al. 2006b), thus as the ARB becomes a net exporter of sediment (Xu 2010) and organic material (Lambou and Hern 1983), its role may become more significant.

2.3.3.3. Carbon. Large rivers and floodplains are important locations for cycling of organic matter and carbon. Dissolved carbon and organic matter are critical drivers of other biological processes such as denitrification and phytoplankton blooms in the Gulf (Turner et al. 2007, Rivera-Monroy et al. 2010). The ARB retains approximately 16% of the total organic carbon entering the ARB (Xu and Patil 2005), including 35% of inflowing particulate (suspended) organic carbon, but exports more dissolved organic carbon than enters the ARB (Lambou and Hern 1983). This pattern is driven by the flooding regime in the ARB whereby overflow areas retain particulate carbon perhaps due to sediment deposition, but export dissolved carbon through decomposition of leaf litter during these periods; non-overflow areas are generally exporters of particulate and dissolved forms of carbon (Lambou and Hern 1983).

The ARB has substantially higher concentrations of dissolved organic carbon, and almost two-fold higher concentrations of lignin phenols (chemicals derived from plant material), neutral sugars, amino acids, than the Mississippi River. Dissolved organic carbon concentrations from the Red River are higher than the Mississippi River as well, but this only accounts for approximately 14% of the increase in dissolved carbon in the ARB over the Mississippi River. The most likely explanation for the increase in dissolved organic carbon in the ARB is its extensive interaction with the floodplain compared to the main-channel Mississippi River, in which around 90% of the floodplain has been disconnected from the river (Baker et al. 1991). The composition of lignin phenols indicates a dominant gymnosperm source (e.g., conifers); and since the Red River is dominated by grasses and hardwood trees (angiosperms), the likely source is from cypress needles and wood in the ARB floodway. Additionally, analyses of amino acids and sugars in the ARB and Mississippi River document the occurrence of fresh, less-altered, and more bioavailable dissolved organic matter in the ARB, highly indicative of a dominant floodplain source. This is further supported by the fact that higher concentrations of dissolved organic matter were found during peak litterfall (September-November).

Discharge accounts for approximately 86% of the variation in dissolved organic carbon flux, with export of dissolved organic carbon being highest during the spring flood pulse from April to early June (Shen et al. 2012). Loading and retention of total organic carbon are also positively related to discharge (Xu and Patil 2005). The ARB and its floodplain connectivity are thus crucially important to carbon dynamics in the lower Mississippi River and Gulf of Mexico. The Mississippi-Atchafalaya River system accounts for 0.8-1.1% (~2.7 Tg y^{-1}) of global riverine dissolved organic carbon conveyed to the ocean (250-360 Tg yr^{-1}), with the ARB accounting for approximately 35% of the average dissolved organic carbon export from the system (Shen et al. 2012). Despite its importance, the ARB is often not incorporated into carbon budgets or models of the effects of riverine material delivery on Gulf coastal processes like phytoplankton blooms and hypoxia (Shen et al. 2012). The possibility that ARB exports of dissolved organic carbon, due to their greater bioavailability, may contribute more to hypoxia development than exports from the Mississippi River, which are derived from C_3 and C_4 plants from grasslands of the Midwest (Turner et al. 2007), should be further explored. Although the ARB still sequesters much of its incoming sediment, the ARB could become a net exporter of total organic carbon (particulate as well as dissolved) if sediment deposition decreases after silting in of deep-water habitats as has been predicted by some (Lambou and Hern 1983).

There are three distinct aquatic floodplain habitats in the ARB – green-water, black-water, and brown-water habitats. Green-water habitats have high surface water temperatures, low velocity, high dissolved oxygen and high dissolved oxygen differential (surface dissolved oxygen –bottom dissolved oxygen). Green-water sites usually occur in the summer when water levels are low, current is slow, and phytoplankton productivity is high (Davidson et al. 2000). Green-water sites get their name from the high phytoplankton densities that make the water appear green (Sager and Bryan 1981). Black-water habitats have moderate velocity, high Secchi disk values, and low dissolved oxygen cause by high levels of organic decay and respiration. Black-water habitats occur when decomposing matter from the inundated forests is swept into the channel following the flood-pulse. High velocity, low Secchi disk values, and minute dissolved oxygen differential typify brown-water habitats, such as Atchafalaya River and associated channels. Brown-water habitats occur when the water level is high during late spring and early summer. Green-water habitats have the highest abundances of cladocerans and copepods, but the communities are dominated by a few species, while brown and black-water habitats have higher diversity of cladocerans and copepods, but relatively lower abundances when compared with green-water habitats (Davidson et al. 2000).

Zooplankton community assemblages and diversity may be closely linked with water chemistry and environmental variation such as surface water temperature, dissolved oxygen concentration, specific conductance, and current velocity. These variables change seasonally with the annual ARB flood-pulse, thus zooplankton communities undergo temporal shifts in species peak abundances as a result of changing seasonal hydrology (Davidson et al. 1998). Thus as locations change seasonally from green, brown and black-water habitats the zooplankton community changes as well.

2.4. Biota

2.4.1. Vegetation and Forests

Forested wetlands occur throughout the southeastern United States along river floodplains. For much of the growing season the forest floor is inundated with standing water. Bottomland hardwood forests are seasonally inundated while deep-water swamps are often continuously flooded. Cypress (*Taxodium distichum*) and tupelo (*Nyssa aquatica*) are the two most important wetland tree species. Bottomland hardwood areas are usually dominated by red maple (*Acer rubrum*), ash (*Fraxinus* sp.), American elm (*Ulmus americana*), and oaks (*Quercus* sp.). These hardwood communities may contain some non-dominant cypress. Cypress-tupelo dominated communities are found in areas with long inundation periods and poorly drained soils (Conner and Day 1982). These forested wetlands are suffering major declines throughout their range. Heavy logging from 1890-1925 resulted in the loss of the last virgin stands of bald-cypress (Conner and Toliver 1990). Since 1937, more than half of the forested wetlands in the lower Mississippi valley have vanished (Conner and Day 1982).

The ARB Floodway is the largest continuous swamp in the United States and contains over 358,000 ha of forested wetlands (Demas et al. 2001). Human alterations to the hydrology of these delicate systems such as the construction of canals and pipelines, alteration to existing waterways such as dredging for navigation, and flood control measures, have imperiled forested wetlands. Many forested wetlands have been impounded by spoil banks from the maintenance of these waterways (Conner and Day 1982). More prolonged and deeper flood events due to sea-level rise and subsidence threaten coastal forested wetlands (Conner and Toliver 1990). These areas are also threatened by salt-water intrusion.

The timber trade began in Louisiana around 1700, and up until the 1790s, French settlers often used cypress timber as a cash crop to pay for imported goods. Cypress wood was desirable, as it was known to be durable, easily manipulated, and rot resistant. Early loggers preferred to cut trees during the drier months when the ground was solid; however, logging continued from boats during the wetter months when the water was high. Cypress timber is not very buoyant so loggers would girdle trees in the summer months so the trees would die and dry out. Then when the water was high, the loggers would return, cut the trees, and float them out of the swamp. Settlers floated logs in channels that had been dug from the swamp to the sawmills, then used the water from the ditches to power the sawmills (Conner and Buford 1998).

The Homestead Act of 1866, which prohibited private ownership of swamplands, was repealed by the Timber Act of 1876 at which point large-scale logging began in earnest (Conner and Buford 1998). Swamplands were then made available for private ownership and sold for 12.5 cents to $1.25 per acre. In 1876, Louisiana cypress lumber mogul, Frank B. Williams, paid 25 cents an acre for thousands of acres of swampland in the ARB (Burns 1980). Logging increased dramatically from 1890-1925 due to development of the pullboat, expansions of the railroad system and a massive marketing campaign by cypress dealers including Frank B. Williams (Burns 1980, Conner and Buford 1998). Nearly 7.08 million m^3 of cypress had been harvested in Louisiana by 1900. Nearly all of the virgin timber was removed by 1925, and of the original standing stock only 10% persisted by 1933. Some small scale harvesting of cypress continued. Many of the original cypress stands have not recovered; however, second growth timber standing stocks continue to increase. Old growth cypress is much more durable than second growth cypress. An unstable cypress timber market has resulted from uncertainty regarding its strength and rot resistance, difficult harvest conditions, and wetland regulations (Conner and Buford 1998).

Today, most cypress stands are moderately dense second growth stands with high basal areas. Cypress and tupelo regeneration can occur through seed germination and stump sprouting (coppicing). Helicopters and skidders have been used in harvesting timber in swamps (Conner and Buford 1998). Aust et al. (2006; 1997) examined the effects of disturbance from helicopter and ground-based skidding timber removal on a cypress-tupelo wetland in Alabama. The skidder treatments decreased soil aeration and increased soil moisture, which favored the flood tolerant tupelo over less flood tolerant species, Carolina ash (*Fraxinus caroliniana*) (Aust et al. 1997). A higher proportion of tupelo occurred in the skidder treatment by stand age seven. A satisfactory reestablishment of overstory species occurred in both the helicopter and the skidder treatments; however, the overstory communities varied. The skidder treatment was dominated by tupelo while the helicopter treatment had a more even distribution among five different species (Aust et al. 1997). By stand age 16, rapid tupelo stocking (at more than 4000 stems/ha) occurred, in both the helicopter and skidder treatment, primarily via stump sprouting. Total biomass had reached 20% of that of the non-harvested reference site and was predicted to recover by stand age 70. Rapid stump sprouting, flood tolerance, and seasonal deposition of nutritive sediments were responsible for the swift recovery of the site (Aust et al. 2006).

Stump sprouting is also likely dependent on the size of the stump and the height of the cut. Short pondcypress (*Taxodium distichum* var. *nutans*) stumps (< 70 cm) sprout more frequently than taller stumps and increasing stump diameter reduces the incidence of live sprouts. It is unknown whether differences in sprouting occur between pondcypress and baldcypress (Ewel 1996). (Conner et al. 1986) reported abundant sprouting of baldcypress stumps in the first growing season after cutting; however, 75% of sprouts died in subsequent years. Tupelo seems to follow a similar pattern with prolific sprouts after one season and then stump decay in subsequent seasons resulting in sprout mortality. Just 9-18% of tupelo stumps in study plots in the ARB had live sprouts remaining after six years (Kennedy 1982). Mortality of baldcypress sprouts 10 years after cutting is low; although it is unlikely the surviving sprouts will develop into mature trees due to the deterioration of the stumps (Keim et al. 2006). Stump sprouting may not be counted on as a successful method of regeneration for baldcypress or tupelo (Kennedy 1982, Conner et al. 1986, Keim et al. 2006). Keim et al. (2006) speculated that since baldcypress sprouts grew best on drier sites with low overstory competition, and these settings are favorable to seed germination, then stump sprouting may have little value for regenerating more frequently flooded sites. Stump sprouting may not be successful for regeneration on its own but it may provide a source of seeds (Ewel 1996).

Both baldcypress and tupelo will regenerate successfully in areas with damp and often inundated soils, and flood intolerant competitors (Conner and Buford 1998). Neither baldcypress nor tupelo seeds will germinate underwater (Demaree 1932, DeBell and Naylor 1972). Baldcypress seedlings exhibit rapid early growth reaching 20-36 cm in height their first year and nearly doubling that growth their second year. This rapid growth is a strategy to avoid submergence in the growing season, as 4-5 weeks of total submergence will kill seedlings (Conner and Buford 1998). Thus cypress require periods of low flow for optimal regeneration. Due to this pulsed regeneration, both cypress and tupelo typically occur in even-aged stands (Conner and Day 1982).

If conditions are poor for stump sprouting or seed germination, planting may be necessary for regeneration. Attempts at ensuring regeneration by planting tupelo have been unsuccessful; however, baldcypress have been planted and grown successfully. In Mississippi, plantation-grown cypress reached 21 m in as little as 41 years (Conner and Buford 1998). Nutria herbivory poses a threat to cypress regeneration. Conner et al. (1986) reported that nutria herbivory was responsible for 35% of seedlings loss in the study. Nutria herbivory has been so severe that the Soil Conservation Service made a recommendation, in the 1950's, to discontinue baldcypress planting until a solution to the nutria problem could be found. Herbivory control methods must be developed in order for successful regeneration to occur (Conner and Buford 1998).

Faulkner et al. (2009) developed estimates of cypress-tupelo regeneration in the Lower ARB using remote sensing and GIS. About 106,000 ha were identified as cypress-tupelo forest, about 43% of the total floodway area and 13% of the total cypress-tupelo forest in Louisiana. They calculated that small, isolated areas totaling 6,175 ha, or only about 5.8% of the cypress-tupelo forest in the ARB, had potential for regeneration. They also identified 24,525 ha of cypress-tupelo forest, about 23% of the cypress-tupelo forest in the ARB, as permanently flooded and unable to support regeneration. The areas of cypress-tupelo forest that cannot regenerate will most likely become dominated by shrubs that are capable of regenerating in inundated areas (Faulkner et al. 2009).

Not only does continuous flooding negatively impact regeneration, it also stresses trees, reducing productivity (Dicke and Toliver 1990, Conner and Day Jr 1992, Conner et al. 1993), increasing mortality (Harms et al. 1980), and resulting in changes in species composition (Conner et al. 1981, Conner and Day Jr 1988, Conner and Brody 1989, Dicke and Toliver 1990).

Harms et al. (1980) examined the effects of flooding up to 3 m deep in a mixed deciduous hardwood swamp caused by the impoundment of a 26 km segment of the Ocklawaha River in Florida. Species, diameter, and water depth were important factors affecting morality following 3 years of inundation. Mortality decreased with decreasing water levels (< 1 m) and increasing tree diameter (>38 cm). Baldcypress and swamp tupelo were the least affected by flooding. Harms et al. (1980) suggested that diameter can be used as a proxy for tree vigor, with larger trees having more root surface area available for the production of root adaptations that increase flood tolerance (water roots).

Dicke and Toliver (1990) investigated the effects of continuous versus seasonal flooding on cypress-tupelo stands in the ARB near Bayou Pigeon. Both water tupelo and baldcypress had similar basal area growth rates in the continuous flooding stand while baldcypress grew nearly two times faster than water tupelo in the seasonally flooding stand. Mortality of small water tupelo was also higher than baldcypress in the seasonally flooding stand. Dicke and Toliver (1990) predicted that continuous flooding will favor a mix of water tupelo and baldcypress while seasonally flooding stands will become dominated by baldcypress.

Flood regime can cause dramatic shifts in forest community structure. Natural flooding conditions may produce closed canopy communities dominated by baldcypress and tupelo. These closed canopy communities have increased shading which can reduce understory growth including that of baldcypress and tupelo seedlings. Permanent flooding may cause reduced recruitment of baldcypress and tupelo and cause dramatic mortality for the less flood tolerant species. As tree mortality increases so does light penetration through the canopy, allowing for the invasion of species such as buttonbush (*Cephalanthus occidentalis*), water hyacinth (*Eichhornia crassipes*), and duckweed (*Lemna minor* and *Spirodela polyrrhiza*). Increasing length of dry periods can lead to invasion of shade tolerant species such as ash and maple (Conner et al. 1981).

The effects of flooding can be complicated and compounded by increased salinity due to salt-water intrusion. Pezeshki (1990) examined the effects of soil anaerobiosis and salinity (51 mol m^{-3} NaCl) on baldcypress and water tupelo. When exposed to freshwater flooding water tupelo maintained close to normal net photosynthesis rates but height growth decreased by 36%. Freshwater flooding caused a 40% decrease in net photosynthesis but no decrease in height growth for baldcypress. When exposed to both flooding and salinity baldcypress exhibited a 46% decrease in net photosynthesis and a 56% decrease in height growth, while water tupelo exhibited a 24% decrease in net photosynthesis and a 54% decrease in height growth (Pezeshki 1990). Although baldcypress and water tupelo co-occur in seasonally inundated wetland forests, and carry out similar ecological roles, they respond differently to stressors, and have different energetic costs and adaptations for dealing with the same stressors. Multiple stressors may impact survival more than any one stressor alone (Effler and Goyer 2006).

2.4.2. Macroinvertebrates

Louisiana leads the nation in and wild harvest and aquaculture of crawfish and the ARB is the heart of wild crawfish harvest in Louisiana (McClain and Romaire 2007). Both aquaculture and wild crawfish harvests are composed of two species, the red swamp crawfish (*Procambarus clarkii*) and the white river crawfish (*P. zonangulus*) (McClain et al. 2007). The red swamp crawfish is the most favored in the marketplace and often is more numerous in catch than the white river crawfish. The pulsed seasonal inundation typical of large river floodplains is ecologically important to both species. The red swamp crawfish is an opportunistic spawner, spawning anytime environmental conditions are appropriate, while the white river crawfish spawn only in the fall and winter. Mating occurs in open water and the females retain sperm in seminal receptacles until they withdraw into burrows to spawn. Fertilized eggs are attached to the female's swimmerets and incubated for approximately 3 weeks. After molting twice, hatchling crawfish detach from the female's swimmerets but stay near her for several weeks. The female and hatchlings must leave the burrow within a limited amount of time to reduce cannibalism and death (McClain and Romaire 2007). The vertical burrows dug by crawfish are usually 40-90 cm deep (McClain and Romaire 2004). Burrows are typically inhabited by one female or a male and female pair. Burrows provide defense against predators, safe spawning locations, and help protect crawfish from periods of drying by providing moist and humid conditions. The chimney-like entrance to the burrow is constructed of excavated mud and is usually sealed by a mud plug (McClain and Romaire 2007). The entrance will remain sealed until enough moisture is present to soften the mud plug. Current crawfish aquaculture practices imitate the seasonal flood pulse events that occur in large river-floodplain systems (McClain and Romaire 2004).

Alford and Walker (2013) modeled the effect of the seasonal flood pulse on fisheries production in the ARB and found that crawfish catches corresponded positively with the duration and magnitude of inundation. Pollard et al. (1982) examined biological productivity in the inundated bottomland hardwood swamp of Henderson Lake in the ARB and found that both adult fish and crawfish exploit the moving water's edge – an ephemeral zone on the leading edge of rising water and the tailing edge of receding water. Following the waters moving edge exposes crawfish to additional food such as detritus and exposes adult fish to crawfish prey (Pollard et al. 1982). The dynamic hydrology of the ARB is extremely important for crawfish production.

Another commercially important species is the blue crab (*Callinectes sapidus*). Blue crabs occur along the Atlantic coast of North America and in the Gulf of Mexico. Blue crabs will mate spring through fall. After mating male crabs remain in the estuary while the female crabs move into nearshore waters to spawn. The eggs are incubated on the female's swimmerets. The larvae (zoea) are transported inshore by ocean currents and develop to megalopal, or post-larval, stage by the time they reach the coastal marshes. The crabs develop in these coastal marshes until they reach adulthood (Coleman 1999). Crab recruitment and harvest have been closely linked to high river discharge and low salinity. These effects could be physiological or environmental (lower predation, increased abundance of food, etc.) (Guillory 2000).

Blue crabs are an important product in the seafood industry in Louisiana. Blue crabs are harvested via traps (Coleman 1999). Lost or abandoned traps continue to catch crabs and can pose serious threats to blue crab populations and to fish due to bycatch (Guillory 1993). In March 2012, the Marine Stewardship Council recognized Louisiana's blue crab fishery as a sustainable fishery; making it the only officially recognized sustainable blue crab fishery in the world (Louisiana Department of Wildlife and Fisheries 2012c).

The ARB is also home to an amphidromous river shrimp *Macrobrachium ohione,* which migrates from near-shore ocean habitat to upriver habitat during larval development. Larger females migrate downstream towards the estuary as they become reproductive. This migration peaks in the spring as spawning season starts in mid-April. After spawning, the embryos hatch after about 18 days of incubation. Newly hatched larvae require saltwater in order to molt to stage 2, the first feeding stage (Bauer and Delahoussaye 2008). Females must release larvae within 3 days drift time of the estuary in order for the larvae to survive without molting or feeding (Rome et al. 2009). Juveniles then migrate upriver from the estuary to the freshwater adult habitat. The juveniles migrate at night in bands at the edge of the river near the bank where the water velocity is low, possibly to reduce the energy required to swim upstream (Bauer and Delahoussaye 2008). This migration upstream also occurs in mid-summer due to the low water and thus lower current velocity at that time. Juveniles migrate only at night, perhaps to reduce the risk of predation. Juveniles likely spend the daylight hours on the bottom feeding and developing (Bauer and Delahoussaye 2008). Given developmental times and swimming speed, Bauer and Delahoussaye (2008) calculated that it would take 125 days for an embryo spawned in the estuary to reach Butte La Rose as a juvenile. Swarms of juvenile shrimp can reach an estimated 5,000-6,000 per m^2 representing large biomass, energy, and nutrient subsidy from the estuary to upstream habitats (Bauer and Delahoussaye 2008).

Historically, *M. ohione* occurred as far north as the Ohio River (Bauer and Delahoussaye 2008). Bauer and Delahoussaye (2008) postulated that the decline of the northern populations of *M. ohione* could be due to river control structures, such as the Old River Control structure. These structures could cut off migrating juveniles from upstream adult habitat and thus limit recruitment. Riverbank structures such as wing dams and revetments change the velocity and direction of flow along the bank where juveniles migrate. Migrating juveniles may become disoriented or scattered by these changes in flow (Bauer and Delahoussaye 2008).

Oysters, mainly the Eastern or American oyster (*Crassostrea virginica*), have been utilized in the Gulf of Mexico region for food and commerce for millennia. Native American tribes throughout the region used oysters for food, to make tools, and for trading and early Western settlers valued the oysters as a food source (Waldman 2006). Oysters continue to be an important source of food, as well as construction and fill materials, but their recruitment, in light of substantial hydroengineering and coastal change over the last century, is highly variable.

Oyster recruitment and growth are mainly controlled by salinity and temperature. Oyster spawning is optimal at temperatures > 25 °C and oyster setting or spat formation (the period in which larval oysters attach to the reef and begin growth) occurs optimally at salinities of 18-22 practical salinity units (psu; sea water is 35 psu) (Chatry et al. 1983, Pollack et al. 2011). Although oysters can survive very low salinities (< 2 psu for up to 60 days), optimal conditions for growth are at salinities between 14 and 28 psu (Galtsoff 1964); however, in Louisiana mortality from marine predators (e.g., snails called oyster drills in the family Muricidae) and parasites (mainly the protist *Perkinsus marinus*) at salinities above 15 psu limits production in habitats with higher salinities (La Peyre et al. 2009). Growth tends to increase in concert with temperature, but mortality can occur with exposure to extreme low (< 8 °C) or high (32-34 °C) temperatures (Galtsoff 1964, Eberline 2012).

These complex relationships vary spatially and over the lifetime of an individual, ensuring that there is a dynamic landscape of oyster recruitment and production in the Gulf. Some populations (e.g., nearer to freshwater inputs) are negatively affected by greater freshwater inflow (which decreases salinity below physiological tolerances or limits feeding and decreases growth; Figure 2.14). Others further from the coastline and at higher salinities are positively affected by more freshwater, as salinities decrease and allow for greater growth and decreased parasite and predation mortality (Turner 2006, La Peyre et al. 2009). Further complexity is introduced by examining lag effects of freshwater, as freshwater inflow one to two years prior may affect oyster abundance in the year of interest (Buzan et al. 2009). Deciding whether to use commercial landings, which are complicated by variations in effort and oyster price, or fishery-independent data is an additional complication that has hampered range-wide conclusions (Buzan et al. 2009, Turner 2009). These complexities partly explain the conflicting findings surrounding freshwater inflow and oyster production. Whether increased freshwater inflow positively or negatively influences oyster production may be determined by many site-specific factors such as oyster reef distribution and broad generalizations may be difficult (Buzan et al. 2009).

Limited long-term data is available for oyster production in the ARB coastal region. Using data from density surveys from the Louisiana Department of Wildlife and Fisheries conducted from 1998-2010 on five public seed grounds in the Vermilion, East and West Cote Blanche, and Atchafalaya bays (Louisiana Department of Wildlife and Fisheries 2009, 2010a), mean density of seed oysters per sample (2-5 replicate 1 m^2 quadrats at each of the five reefs) was negatively related to mean daily gage height at the Butte la Rose gage (a proxy for freshwater output from the Atchafalaya River) for the same year based on a linear regression (Figure 2.15; $R^2 = 0.49$, $p = 0.007$). These results are similar to the findings of Turner (2006) who found a negative relationship between freshwater inputs and commercial oyster landings. Adult ("sack") oyster density was negatively ($R^2 = 0.31$) and significantly ($p = 0.05$) related to mean daily gage height one year prior (Figure 2.16). This pattern is the opposite found by Buzan et al. (2009) in which increased freshwater inflow produced increased sack-sized oysters one to two years later, although these data are for density and not abundance. Seed oyster density was positively ($R^2 = 0.14$) but not significantly ($p = 0.20$) related to the mean daily gage height two years prior. Freshwater inputs from the ARB do apparently affect salinity levels even in coastal areas and oyster beds to the west of Atchafalaya Bay (Vermilion, East and West Cote Blanch bays) (Figure 2.17) (Louisiana Department of Wildlife and Fisheries 2010a) and may be stressing oyster populations by depressing salinity near or below physiological tolerance limits. While these available data provide some indication of a relationship, more detailed studies specifically designed to test this connection should be conducted in the ARB delta. Freshwater inflow may be having negative impacts on oyster production currently, but more information is needed to determine if a different hydrologic regime could aid production (La Peyre et al. 2009).

Louisiana’s management strategy for oysters is unique in that the state owns public oyster seed grounds from which individuals can take seed stock for their private oyster reefs; this helps maintain a healthy supply of juveniles in protected areas (also allowing for some harvest in these public areas) and is one factor in the high productivity of the Louisiana oyster fishery (Louisiana Department of Wildlife and Fisheries 2010a, Eberline 2012). Despite this approach, which is aimed at maintaining sustainability of populations, estimated oyster stock size of both seed and sack oysters has decreased in recent years from peaks in the early 2000s despite the fact that oyster landings from both public and private grounds have increased or remained similar since that time (Louisiana Department of Wildlife and Fisheries 2010a). In addition to overharvest, natural disturbances, such as hurricanes, and human modification to flow regime and coastal processes are detrimentally impacting oyster populations. As seen above, regional processes interact with global climate dynamics to influence the local environmental parameters important to oyster recruitment and production (Galtsoff 1964, La Peyre et al. 2009, Eberline 2012). A more in-depth understanding of how these processes interact with anthropogenic alterations such as freshwater diversions (which introduce a human and political behavior component to the environmental characteristics of interest) to affect the health and sustainability of oyster populations is needed (La Peyre et al. 2009, Eberline 2012).

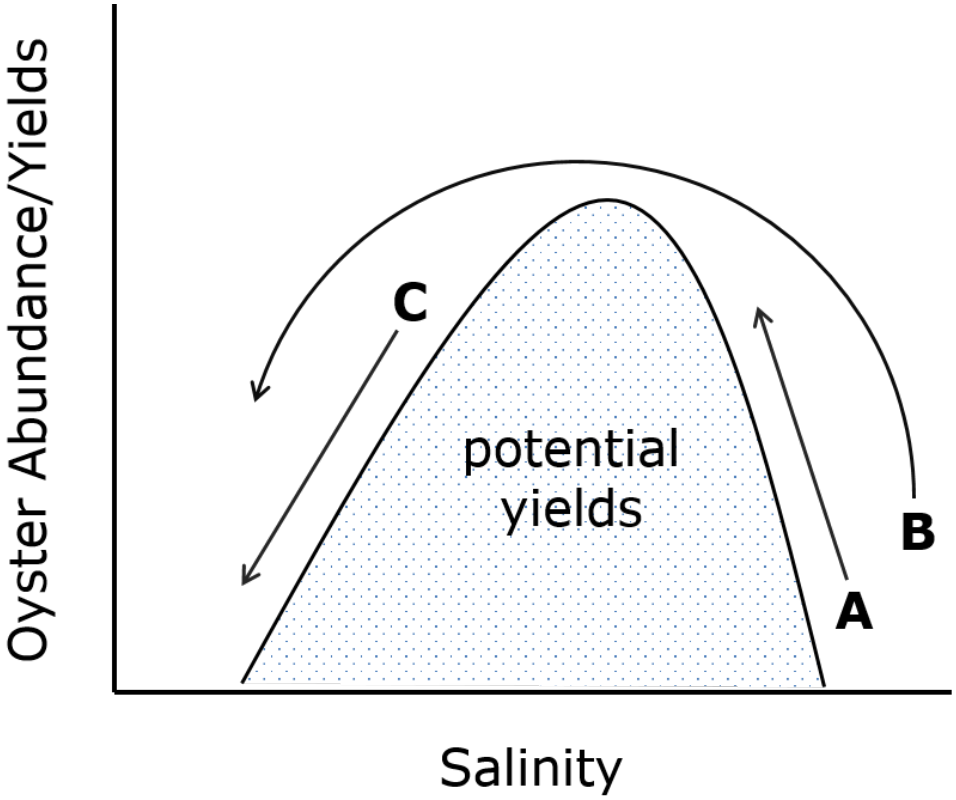


Figure 2.14. Hypothesized effects of freshwater inflow on oyster abundance/yields for an estuary. Oyster reefs in the Gulf of Mexico exist within a salinity tolerance of 10 to 30 psu. Oyster reefs on the high end of the salinity optimization curve will respond positively (line A) or negatively (line B) to freshening, depending on how low salinity drops in response to freshwater inflow. Oyster populations will decrease upon freshening when located on the less saline side of the optimum curve (line C). Figure and legend modified from (Turner 2006).

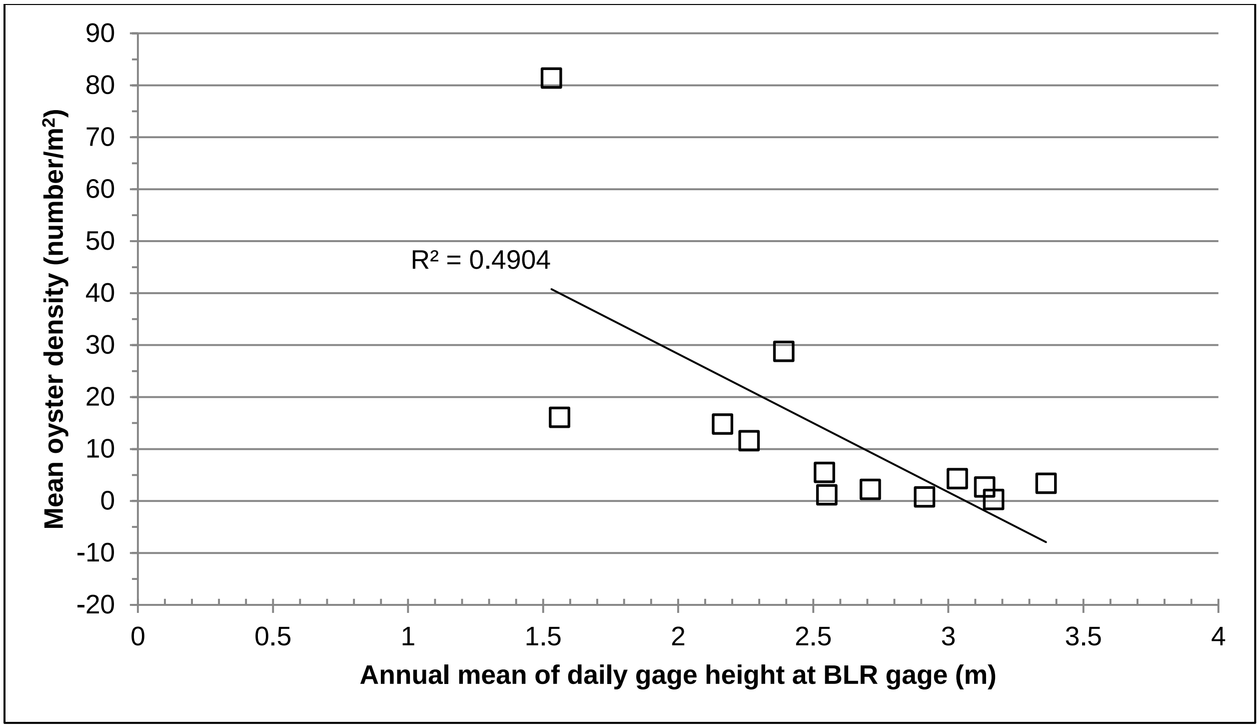


Figure 2.15. Linear regression of juvenile (seed) oyster density in Atchafalaya Bay region and annual mean of daily gage height at Butte la Rose (USGS gage 7381515) from 1998-2010.

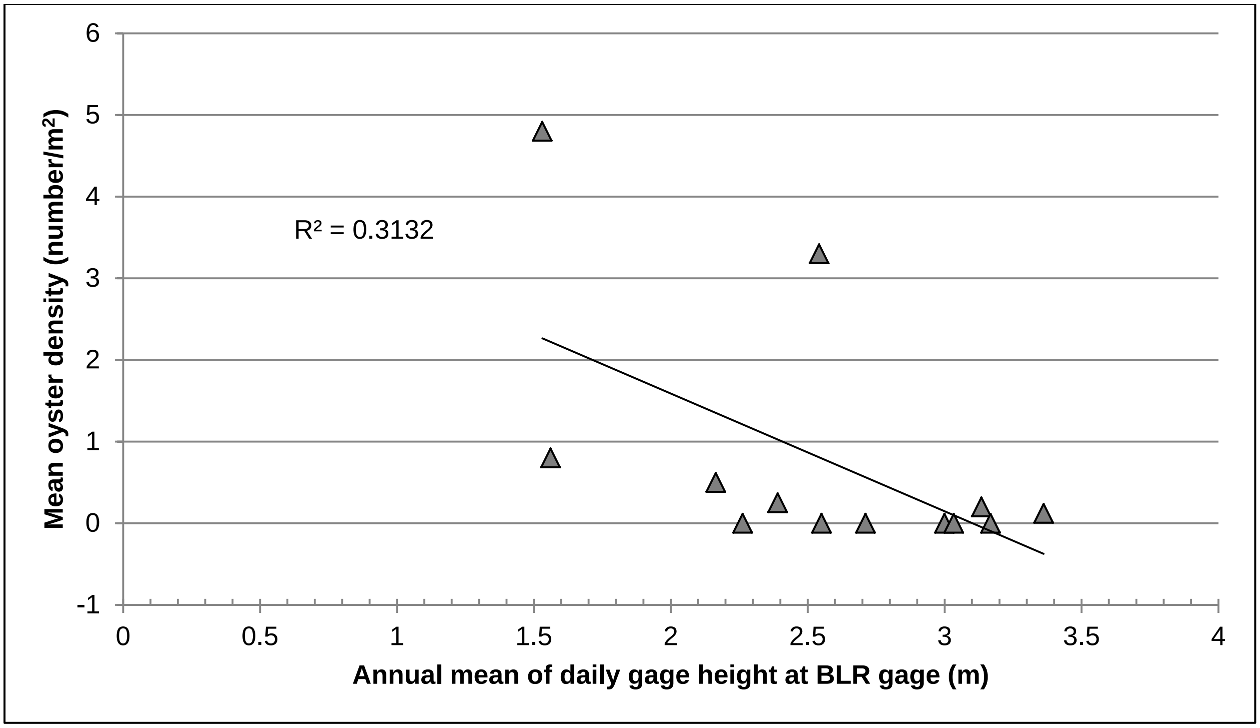


Figure 2.16. Linear regression of adult (sack) oyster density in Atchafalaya Bay region and annual mean of daily gage height at Butte la Rose (USGS gage 7381515) from 1998-2010.

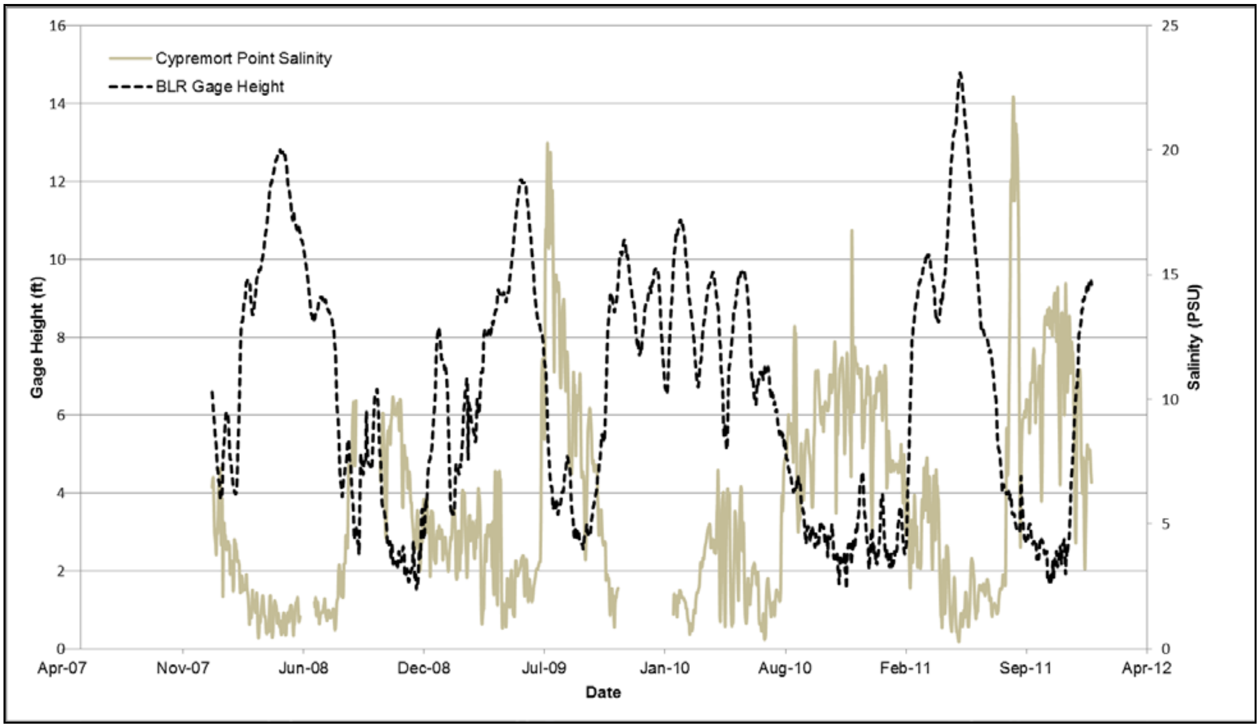


Figure 2.17. Salinity in Vermilion Bay (Cypremort Point USGS gage 07387040) and gage height at Butte la Rose (USGS gage 7381515) from January 2007 – December 2011.

2.4.3. Fishes

Although highly modified by humans, the ARB still contains a diversity of freshwater habitats, such as lakes, bayous, swamps, and backwaters, characteristic of the historic floodplain of the Lower Mississippi Valley (Lambou 1990, Halloran 2010). Thus the ARB also contains a diverse assemblage of lowland freshwater fishes with over 100 recorded species (Lambou 1990) (Appendix A). In addition to these freshwater floodplain habitats, the ARB empties into a large estuary complex and thus also contains over 30 estuarine and marine fish species tolerant of a range of salinity levels (Thompson and Deegan 1983). Over 180 freshwater, estuarine and marine species have been documented in the Atchafalaya-Fourleague Bay system since 1966 (Thompson and Peterson 2003). In freshwater, cyprinids (minnows) and centrarchids (sunfish) are the most species-rich groups with 30 and 14 species, respectively. In the delta, sheepshead minnow (*Cyprinodon variegatus*), gulf menhaden (*Brevoortia patronus*), bay anchovy (*Anchoa* *mitchilli*), gulf killifish (*Fundulus grandis*), and striped mullet (*Mugil cephalus*) are the most common species (Thompson and Deegan 1983).

Several species in the ARB are listed as endangered or threatened. While little is known about its population in the ARB, the federally endangered pallid sturgeon (*Scaphirhynchus albus*) is regularly collected above and below the Old River Control Structure and may represent an isolated population as dispersal upstream through Old River is unlikely (Killgore et al. 2007, U.S. Fish and Wildlife Service 2007). The State of Louisiana also protects the pallid sturgeon with 'endangered' status and prohibits taking or harassment of the fish. Two other freshwater fish species in the ARB are of conservation concern but are not officially protected. The paddlefish (*Polyodon spathula*) is ranked as 'rare,' the third most endangered category, by the Louisiana Natural Heritage Program but is fairly common throughout much of its range in North America. It is regulated by recreational fishing regulations in Louisiana (30" total length max limit; two fish per person bag limit) and commercial fishing is prohibited (Louisiana Department of Wildlife and Fisheries 2012a, 2012b). The bluehead shiner (*Pteronotropis hubbsi*) is ranked as 'imperiled,' the second most endangered category, by the Louisiana Natural Heritage Program because of limited distribution and small population sizes in the state, and is found in the southeastern U.S. in lowland backwaters of the Red, White, Ouachita and Atchafalaya rivers in Texas, Arkansas and Louisiana (Ranvestel and Burr 2002). The pallid sturgeon and paddlefish are large-river specialists (although paddlefish also inhabit reservoirs) and are sensitive to destruction of spawning habitats and flow regime changes. Although much is still unknown about behavior, the species travel long distances (paddlefish in particular are migratory) and are detrimentally affected by dam construction. The bluehead shiner relies on vegetated backwater swamps and oxbows for spawning and is particularly affected by silting-in of these habitats

(Ranvestel and Burr 2002) that has been occurring in lake habitats in the ARB since the middle of the last century (McManus 2002).

The ARB is one of the most popular recreational fishing destinations in Louisiana and supports abundant populations of common sport fish such as black and temperate basses (*Micropterus* spp. and *Morone* spp.), crappie (*Pomoxis* spp.), catfishes (Ictaluridae) and bluegill (*Lepomis macrochirus*) (Holloway et al. 1998, Sabo et al. 1999a, Alford and Walker 2013). The ARB also supports several productive commercial fisheries with annual total landings of finfish and shellfish ranging from 5.9 to 11.5 million kg and valuing $8.9 to $24.1 million annually. Fish standing stocks for the ARB have been estimated at 22,500 – 208,000 kg km^{-2} (Bryan and Sabins 1979, Lambou 1990). The most economically lucrative commercial fisheries in the ARB are for catfish (mainly *Ictalurus* spp. and *Pylodictis olivaris*), buffalo (*Ictiobus* spp.) and shad (*Dorosoma* spp.). Shad are not typically consumed, but are used as bait in traps for the foremost fishery in the ARB – crayfish (Alford and Walker 2013). Commercial landings of shad, catfish, suckers (Catostomidae) in the ARB averaged more than 3 million kg between 1999 and 2009 (Alford and Walker 2013).

Coastal and marine fisheries are also important to the economy of Louisiana, largely supported by the nutrient-rich waters of the Mississippi and Atchafalaya Rivers (Chesney et al. 2000). As the ARB delta and its islands grow from sediment deposition, the region plays an increasing role as a nursery for several important fisheries including striped mullet, gulf menhaden, Atlantic croaker (*Micropogonias undulatus*), and blue catfish (*Ictalurus furcatus*) (Thompson and Deegan 1983).

Although the ARB supports reasonable fish diversity and productive fisheries despite its physical alteration, the system faces chronic habitat issues that can limit fish populations. As the

ARB stores increasing amounts of sediment from the Mississippi and Red Rivers, deep-water lake habitats in the ARB have gradually silted in (McManus 2002, Hupp et al. 2008, Allison et al. 2012). These deep-water habitats support large numbers of game fishes due to their generally higher dissolved oxygen and lower temperature (Sabo et al. 1999b) and can support higher biomass and diversity of aquatic plants that serve as habitat refugia for many fish species.

Another well-documented problem facing fish populations in the ARB is chronic hypoxia (defined as dissolved oxygen (DO) < 2 mg/L) that occurs as stagnant flood waters warm in summer months, increasing respiration from bacterial decomposition and depleting oxygen. This phenomenon can be widespread throughout the ARB, covering thousands of hectares and occurring from 4-20 weeks of the year — throughout the reproductive periods of many fishes (Bryan and Sabins 1979, Sabo et al. 1999a, 1999b). Hypoxia has been shown to limit the distribution and abundance of larval and adult fishes in the ARB (Fontenot et al. 2001, Halloran 2010) and can negatively impact growth (Aday et al. 2000) and reproduction (Brunet 1997, Engel 2003) of several species. Such impacts to the individual organism, and at the population, community and ecosystem levels, are well-demonstrated for freshwater, estuarine, and marine fishes and other aquatic organisms in general (Stewart et al. 1967, Davis 1975, Pollock et al. 2007). Hypoxia in the ARB is likely exacerbated by agriculture-derived nutrient enrichment of water entering the ARB from the upper and middle Mississippi River watershed that promotes eutrophication (Smith et al. 2006); however, the physical driver is the existence of local low- or non-turbulent flow paths created by numerous canals that sometimes oppose each other in the direction of flow. These low-flow pathways, in combination with the late spring/early summer timing of the flood pulse, insure that water stagnates and warms, lowering oxygen levels (M.D. Kaller, Kelso, Halloran, & Rutherford, 2010; Sabo et al., 1999a). This dynamic between flood pulse and subsequent water stagnation and de-oxygenation has been suggested as an explanation of lowered abundance and recruitment for many fishes during years of greater flood duration (> ~ 157 days) (Alford and Walker 2013) but is extremely spatially complex and complicated to address (Sabo et al. 1999a, 1999b).

Limited access to the floodplain due to physicochemically unstable or unsuitable conditions (e.g., low DO, high pH) could be a major factor limiting fish production in the ARB. Fishes in temperate lowland rivers, including the ARB, that rely on infrequent floodplain inundation for larval recruitment and growth may be subject to substantial annual variation in survival and abundance due to the variation in annual flow patterns and compounded by worsening physicochemical conditions (e.g., hypoxia, drying) on the floodplain following the flood pulse (Fontenot et al. 2001, Halloran 2010). Facing such unstable or unsuitable conditions in the floodplain, fishes in the ARB, and lowland temperate rivers in general, exhibit what are likely adaptations to such habitats. Larvae of many species aggregate at the water surface, which enhances the probability of being transported by surface flow out of the floodplain as waters receded. Surface aggregation would also allow the larvae to utilize the more highly oxygenated surface layer of water (Halloran 2010).

The Flood Pulse Concept emphasizes the importance of floodplain habitats to the reproduction, growth and survival of large-river fishes (Junk et al. 1989). The concept, developed mainly based on information from large tropical rivers like the Amazon, may be less applicable for temperate river-floodplain ecosystems where flooding is less predictable and peak flooding events only infrequently coincide with reproductive periods of fish (Benke et al. 2000, Hupp 2000, Hupp et al. 2008). However, flood control and navigation efforts have greatly altered the hydrology and connections between rivers and floodplains in North America, which could limit our ability to infer the same relationships as in relatively less altered tropical rivers. Some have challenged components of the Flood Pulse Concept. For instance, Galat and Zweimüller (2001) reviewed the habitat use of fishes in four large rivers in the United States and Europe and concluded that 50% to 85% of fishes in these rivers depend on fluvial habitats in the main channel for some portion of their life cycle, rejecting the primacy of floodplain habitats in fish reproduction. This may hold true in the ARB as (Halloran 2010) found that peaks in larval recruitment rarely coincided with widespread flood events. Instead, individual species groups responded differently to aspects of the flood pulse. Percids (mostly darters) spawned in the weeks following the spring flood pulse and had dramatic annual variation due to differences in flood magnitude and timing. Larval shad (*Dorosoma*) were found in the floodplain following flows that approached or exceeded bankfull discharge. Centrarchids (sunfish and black basses) utilized floodplains during intermediate levels of connectivity, with crappie and bass spawning during temporary spikes in the hydrograph and sunfish having a protracted spawning period during lower water levels into the summer. Thus, rather than a community-level response to a flood pulse as envisioned in the Flood Pulse Concept, each species responded somewhat differently to flood events but did utilize floodplain habitats under certain flood conditions (Halloran 2010).

Indeed, it is estimated that over half of the fish species in the ARB utilize flooded areas for spawning or rearing young and over half use these habitats for feeding (Lambou 1990). Recent evidence also indicates that floodplain inundation is critical to growth and reproduction of many species in large lowland temperate rivers. Accounting for the coincidence of higher temperatures and flood events has revealed heavier reliance on floodplains by fishes in temperate river-floodplain systems like the lower Mississippi than previously thought (Schramm, Jr. et al.

2000, Schramm, Jr. and Eggleton 2006, Jones and Noltie 2007, Zeug et al. 2009). Catfishes in particular were shown to heavily utilize floodplain resources during floods when water temperatures exceed 15 °C but not at other times (Schramm, Jr. et al. 2000, Schramm, Jr. and Eggleton 2006). The authors thus recommend management strategies that will increase the retention and warming of water on the floodplain to promote conditions under which fishes can utilize floodplain habitats for growth and reproduction. However, in the ARB, the retention and warming of floodplain water is one of the key links in the chain of causation leading to chronic hypoxia. As described above, sedimentation has reduced habitat complexity and areas of DO refugia in floodplain habitats throughout the ARB, which may contribute to the widespread detrimental impacts of hypoxia (Sabo et al. 1991, 1999a). The tradeoff between the thermal optima for fish utilizing floodplain habitats (determined by the timing and duration of the flood pulse) and the stagnation and subsequent hypoxia caused by local disconnection from flow paths may prove to be a difficult balancing act. Both ARB-wide (flow regime) and local (local flow paths) components of fish habitat need to be evaluated for their contribution to healthy fish populations and ecosystem functioning.

2.4.4. Amphibians and Reptiles

The ARB provides habitat for more than 20 species of amphibians and 50 species of reptiles (Appendix B) (Dundee and Rossman 1989). The diverse terrestrial and aquatic habitat types, including swamps and large rivers, provide valuable habitat for the wide range of herpetofauna found in the ARB. Amphibians are important in food-web dynamics because they are abundant and are key links between trophic levels. The amphibian species of the ARB are largely composed of frogs and toads. USGS monitors amphibian populations for declines and evaluates their responses to pollutants, disease, and climate change. This monitoring is part of the Amphibian Research and Monitoring Initiative (ARMI), which began in 2002 (Waddle 2011).

The ARMI program was developed by USGS as part of a directive by the President and Congress to Interior Department agencies, to create a program to monitor, research, and conserve amphibians in the face of a global amphibian decline. The ARMI program's objectives include, evaluation of the conservation status and distribution of amphibian populations in the U.S., understanding the dynamics of population declines and their causes, and providing research based information on management and restoration of amphibian populations (U.S. Geological Survey 2012).

Amphibian call surveys conducted from 2002-2006, in Atchafalaya National Wildlife Refuge (NWR), and the Sherburne and Indian Bayou WMAs were used to develop a model that can estimate the occupancy dynamics of the entire assemblage of anuran amphibians, rather than the single-species models that were previously used. This multi-species approach better instructs management decisions about a community than the previous single species estimates (Walls et al. 2011).

The ARMI program is also pursuing other research questions within the ARB, including factors that influence amphibian distribution such as pesticides and water quality. Other research includes examining atrazine, a herbicide that affects amphibian health and distribution. Researchers are also investigating how the shifting hydroperiods and inundation depths, whether attributable to climate change or human alterations, affect the distribution of amphibian species (Waddle 2011).

A chytridiomycete fungus, *Batrachochytrium dendrobatidis* (*Bd*), is the cause of chytridiomycosis (Longcore et al. 1999), which has been linked to amphibian declines around the world (Skerratt et al. 2007). Chytridiomycosis interferes with electrolyte transport through the skin, which causes cardiac arrest (Voyles et al. 2009). The presence of *Bd* in Louisiana was first officially recorded in 2007 from larval anurans collected in 2003 from 11 sites in Louisiana and Mississippi, including sites in the ARB (Drake et al. 2007). Rothermel et al., (2008) found a total prevalence of *Bd* infection of 17.8% among amphibians in the southeast. In the ARB, *Bd* was present in *Acris crepitans*, *Psuedacris crucifer*, *P. fouquettei*, & *Hyla chrysoscelis* collected from the Sherburne WMA. Despite the presence of *Bd* in the ARB and its prevalence across the southeast, few of the infected individuals in the study showed signs of chytridiomycosis (Rothermel et al. 2008).

The ARB is also home to many reptilian species, most notably the American alligator (*Alligator mississippiensis*). Alligators occur from North Carolina to central Texas, with the largest population, nearly 2 million, occurring in Louisiana (Louisiana Department of Natural Resources n.d.). Alligators occur in a wide range of aquatic habitats ranging from swamps to rivers and even brackish water in some instances (Elsey and Woodward 2010). Louisiana contains over 1.8 million ha of alligator habitat composed of over 1.2 million ha of coastal marshes, ~ 303,000 ha of cypress-tupelo swamp, ~141,000 ha of dewatered wetlands, almost 84,000 ha of the ARB swamp, and ~ 19,000 ha of lakes (Louisiana Department of Natural Resources n.d.).

Louisiana’s alligator population was not always as robust as it is today. Alligators have been exploited since the 1800s and in 1962 the Alligator harvest season was closed due to the overharvest of alligators in previous years. Alligator harvest was prohibited from 1962 through August 1972. In 1967, the alligator was listed on the Endangered Species Act. By 1974, the alligator population had greatly increased and Louisiana successfully petitioned the Secretary of the Interior to remove the alligator from the Endangered Species Act in certain parishes and eventually it was removed statewide. Beginning 1972 Louisiana gradually started opening alligator harvest season in certain parishes and by 1981 the season opened statewide. Between 1962 to 1972 a series of state and federal laws to regulate "harvest distribution, allocation of take, methods of harvest and possession, transportation and export of live alligators, alligator skins and their products were enacted" (Louisiana Department of Wildlife and Fisheries 2010b).

Alligators are managed as a commercial and renewable resource by the Louisiana Department of Wildlife and Fisheries. Each year surveys are conducted to determine nest density. Nest densities, harvest parameters, population estimates, and environmental evaluation determine final harvest levels. Alligator harvest season takes place in September in order to target adult male and immature alligators while excluding adult females, which are usually in interior marshes at this time of year. Depending on the quality of the habitat, the Louisiana Department of Fish and Wildlife allows a harvest ratio ranging from one alligator per about 22 ha to one alligator per ~ 200 ha. The 2009 non-marsh alligator tag allotment for cypress-tupelo swamp outside the Atchafalaya was one tag per about 64 ha, while the allotment for the ARB was one tag per ~200 ha. The area of the ARB open for harvest includes permanent water cypress-tupelo swamps as determined by LDWF methodology in 1985 (Louisiana Department of Wildlife and Fisheries 2010b).

The Louisiana alligator program staff is involved in a number of research projects including those to monitor alligator populations and harvest regulations, and farming and ranching practices. The staff is also involved with other alligator research, in cooperation with researchers from various universities (Louisiana Department of Wildlife and Fisheries 2010b). With the development of the sustainable harvest program overexploitation of alligators is no longer a concern. However, alligators still face other threats such as habitat loss due to increased agriculture, water diversion, pollution, and saltwater intrusion (Elsey and Woodward 2010). Hurricanes and the associated saltwater intrusion can also pose a threat to alligators.

In September 2005, Hurricane Rita generated a storm surge that flooded thousands of acres of coastal marsh with saltwater. Salinity remained high in the marsh of the Rockefeller Wildlife Refuge due to a severe drought that occurred after the hurricane. Many dead alligators were observed following the saltwater intrusion. Blood samples taken from living alligators in the months (February to August 2006) following Hurricane Rita showed elevated levels of a stress hormone, corticosterone, as the drought persisted. After considerable rainfall in July and August 2006, levels of corticosterone in sampled alligators began to decrease. This prolonged lack of freshwater impeded reproduction, as no nests were found in Rockefeller Refuge in June of 2006 (Lance et al. 2009). In most years, large rain events follow hurricanes and the alligator population is not as affected as it was following Hurricane Rita. The following year a large number of nests were found on Rockefeller Refuge indicating that the effects on salt-water intrusion are temporally limited and do not pose long-term risks to alligator populations (Lance et al. 2009).

2.4.5. Birds

The ARB and delta serve as valuable habitat for over 200 species of birds (Appendix C) (U.S. Fish and Wildlife Service 2006). Both the ARB and the Atchafalaya Delta are located within the Mississippi Flyway, an important migratory route for approximately 40% of North America’s waterfowl (National Audubon Society 2012a). The ARB and the Atchafalaya Delta are both recognized as Important Bird Areas (IBA’s) by the Audubon Society, a partner of BirdLife International, which is a global coalition for the conservation of birds (National

Audubon Society 2012b). IBAs provide crucial wintering, breeding, or migratory habitat for at least one species of bird. At least one of four conditions must be fulfilled in order for a site to be recognized as an IBA. It must support a species that is threatened or endangered, a species that is vulnerable due to its occurrence in one specific habitat, a species that is vulnerable because of its limited range, or finally a species or assemblage that is vulnerable because it congregates in high densities. IBAs are recognized as State, Continental, or Global level IBAs based on their conservation importance (National Audubon Society 2012b).

The ARB is recognized as a state level IBA. It is a nesting site for bald eagles (*Haliaeetus leucocephalus*) and important forest habitat for many other birds of prey. In late summer and early fall, globally important numbers of wood storks (*Mycteria americana*) inhabit in the ARB. Many Audubon WatchList species, such as painted buntings (*Passerina ciris*), and prothonotary, Kentucky, and Swainson's warblers, (*Protonotaria citrea*, *Oporornis formosus*, and *Limnothlypis swainsonii*) and breed in the ARB. The cypress swamps in the ARB provide valuable breeding habitat for large numbers of yellow-crowned night herons (*Nyctanassa violacea*). Many Neo-tropical migratory species use the ARB as a valuable stopover habitat (National Audubon Society 2012c). The ARB was also the home of the ivory-billed woodpecker (*Campephilus principalis*) and the Bachman's warbler (*Vermivora bachmanii*) both of which are now presumed to be extinct.

The ivory-billed woodpecker was widespread across the southeastern U.S. It inhabited the extensive seasonally inundated forests along large rivers, its range also extended into adjacent upland forests (Jackson 2004). Its disappearance corresponds with the increase in logging activities in its native hardwood forests habitat (McIlhenny 1941). The last population of ivory-billed woodpeckers was documented in the Singer Tract, a more than 32,000 ha tract of old-growth bottomland hardwood forest in Madison Parish, LA (Tanner 1966). The Singer Tract was logged and the last documented ivory-billed woodpecker was seen in 1944. A subspecies population of ivory-billed woodpeckers also occurred in Cuba and sightings in the mid 1980's are the last widely accepted sightings (Jackson 2004). Although recent sightings continue across the southeast all have been refuted most commonly as mistaken identifications of pileated woodpeckers (*Dryocopus pileatus*) (Fitzpatrick et al. 2005, Sibley et al. 2006).

The Bachman's warbler has a story similar to the ivory-billed woodpecker. The Bachman's warbler may have been a cane thicket specialist that disappeared after cattle grazing, fire and flood control efforts, and land clearing for agriculture annihilated its dense canebrake habitat (Remsen 1986).

The Atchafalaya Delta is recognized as an IBA of global priority. This IBA occurs on the only actively building delta in Louisiana. The expansion of the delta is forming an emergent marsh area (National Audubon Society 2012d). Sediment is commonly dredged from the area to maintain the river as a shipping lane. The Louisiana Department of Wildlife and Fisheries has utilized this dredged material in the construction of a series of islands in the Atchafalaya Delta Wildlife Management Area (ADWMA) (Leberg et al. 1995).

These islands serve as essential habitat for the largest breeding colonies of black skimmers (*Rynchops niger*) and gull-billed terns (*Gelochelidon nilotica*) in Louisiana. The nearest colony of similar magnitude is more than 500 km away (Mallach and Leberg 1999). Most dredged material islands are only used within the first year they are formed and as new islands become available each year the colonies relocate. Rapid vegetation growth occurs on the islands, facilitated by the warm moist climate of the Louisiana coast. Vegetation can reach densities that impede visibility at ground level by the second growing season, thus limiting the islands' usefulness as a colony site. Most islands are composed of sand-silt substrate with intermittent patches of shell substrate (Leberg et al. 1995). Little vegetation grows on either shell or sand substrates during the first year; however, after 2-3 years, shell substrates have less vegetation growth than sand substrates (Mallach and Leberg 1999).

Least terns (*Sternula antillarum*) and gull-billed terns nest at a higher frequency on shell substrate rather than sand substrate while black skimmers nest at higher frequencies on sand substrate. This is likely due to the sequence in which nesting is initiated. Least terns nest first on shell substrate and prevent gull-billed terns and black skimmers from nesting within the colony. Gull-billed terns nest second and choose unoccupied sites with shell substrates. Finally, black skimmers nest last and choose shell sites among gull-billed terns but begin to nest outside of the gull-billed tern colony as shell sites become occupied and crowding increases (Leberg et al. 1995). Black skimmers strongly preferred nest sites on shell substrate when given the choice between shell and sand substrate (Pius and Leberg 2002). The preference of shell substrates is likely due to increased reproductive success. Shell substrate nests were more cryptic and had a larger average proportion of eggs hatch (Mallach and Leberg 1999).

These important islands are maintained by the continual dredging of the delta to maintain shipping lanes. Lower water levels mean less dredging is needed to maintain shipping lanes. This reduces the dredged material available for the construction of new islands, limiting the ability of seabirds to move colonies to new islands (Mallach and Leberg 1999). The addition of shell to existing islands in years of low water conditions may increase the appeal of these islands to nesting birds (Leberg et al. 1995). The addition of 2.5 cm of shell to islands enticed numerous terns and black skimmers and became the core of nesting activity on those islands (Mallach and Leberg 1999). Extra management effort to provide nesting habitat may be important as a 2005 statewide survey of wading and seabird nesting colonies found that black skimmers, least terns, and gull-billed terns all suffered strong declines in breeding pair numbers since 1976 (Green et al. 2006a).

Non-migratory mottled ducks (*Anas fulvigula*) also utilize the dredge-spoil islands for nesting. Mottled ducks mostly nested in moderately dense shrub habitat composed of goldenrod (*Solidago sempervirens*) and interspersed baccharis shrubs (*Baccharis halimifolia*). Nest density estimates for these islands (1.3 nests/ha) were higher than estimates for other Gulf Coast locations. Estimates of nest success for these islands were larger than estimates for non-island nesting mottled ducks (Holbrook et al. 2000).

These dredge islands also provide a valuable stopover for migrants and wintering habitat for waterfowl. The reddish egret (*Egretta rufescens*), yellow-crowned night heron, and brown pelican (*Pelecanus occidentalis*), are species of concern in the delta. This IBA provides valuable habitat for wintering waterfowl, such as American wigeon (*Anas americana*), northern pintail (*Anas acuta*), northern shoveler (*Anas clypeata*), gadwall (*Anas strepera*), mallard (*Anas platyrhynchos*), and others (National Audubon Society 2012d). Earlier pairing and pairing in higher proportions have been observed in female mallards overwintering in the delta (Johnson and Rohwer 1998). Blue-winged teals have also been documented nesting earlier in the delta than in their primary breeding range (Johnson and Rohwer 2007).

2.4.6. Mammals

The ARB contains the largest contiguous expanse of bottomland hardwood forest in the United States and thus supports a diverse mammal community. Over 30 native species are known from the ARB, including 9 bats, and more than 10 carnivores (Appendix D) (Lowery 1974). Many mammals found in the ARB rely heavily on floodplain habitats and the dynamic relationship between the river and floodplain. As the largest contiguous river swamp remaining in the United States, the ARB is regionally and globally important in maintaining a high diversity of aquatic-associated mammals.

One of the highest-profile mammals in the ARB is the Louisiana black bear (*Ursus americanus luteolus*), a federally threatened subspecies of bear currently found only in Louisiana. Two of only four known sub-populations (including one reintroduced population in the Red River Basin north of the ARB) occur in northern and coastal portions of the ARB. The bears mainly inhabit bottomland hardwood forests of varying dominance (bald cypress, bald cypress-tupelo, river birch-sycamore, oak-hickory, and others) but can also utilize other habitats such as saltwater and freshwater marshes, wooded levees and canals, and agricultural fields. Like other bears, the Louisiana Black Bear is adaptable to human-modified landscapes and human encounters as long as there remain relatively remote, isolated forest habitats for denning, foraging and raising young (U.S. Fish and Wildlife Service 1995, Benson 2005). Brush thickets, tree roots and cavities, and other dense or cryptic habitats are selected as dens during winter for overwintering and raising cubs; however, the Louisiana black bear appears to be relatively active year-round and may only overwinter briefly when not birthing cubs (Hightower et al. 2002, Crook 2008). Destruction and modification of forest ecosystems is the major cause of decline and imperilment in the Louisiana black bear and many other large mammals. In 1980, preferred bottomland hardwood habitat had been reduced by more than 80% of pre-settlement habitat area, and human development continues to fragment forest habitat, threatening the long-term viability of the species (U.S. Fish and Wildlife Service 1995). The ARB represents one of the few large areas of relatively undeveloped and contiguous forest patches remaining in the United States and is thus critical for the survival of the Louisiana Black Bear.

Another large carnivore, the cougar (*Puma concolor*), is also native to Louisiana and potentially found in the ARB. Until recently, the latest confirmed evidence of cougars in Louisiana was in l975; however, in 2002, a cougar was seen just outside of the west protection levee of the ARB in St. Martin Parish and analysis of scat confirmed it was a North American cougar (Leberg et al. 2004). Two subspecies of cougar could be responsible for the most recent occurrences. The historic range of the Florida panther (*Puma concolor coryi*) includes Louisiana, but the subspecies is restricted to approximately 8000 km^2 in south-central Florida (Comiskey et al. 2002). Cougars in other parts of North America are known to disperse hundreds of kilometers (Stoner et al. 2008), and the Florida panther has been confirmed as far north as central Georgia (Pavey 2011). The subspecies of cougar in east Texas has been expanding its range and has been shown to travel over 480 km, so it could theoretically travel the 275 km to the recent sighting areas (Logan and Sweanor 2000, Leberg et al. 2004). The ARB remains the best habitat for cougars in Louisiana and (assuming that habitat in the ARB would support the same density of cougars) could potentially support a cougar population less than half the size (35 individuals) of the Florida population (78 individuals). The lack of consistent sightings or road kills suggests that there is currently no stable population in the state (Leberg et al. 2004).

In early settlement times, Louisiana was an importer of fur; however, beginning in the 1900s, as muskrat (*Ondatra zibethicus*) trapping for nuisance control started and fur processors saw the quality of muskrat pelts, a large fur industry began. From 1913 to 1960, muskrat pelts made up 63-97% of total fur production, reaching a high in 1945 of more than 8 million pelts and bringing in over $12 million. In the late 1930s, the nutria (*Myocaster coypus*), a large rodent from South America, was introduced to Louisiana in part to control invasive aquatic plant growth. The species became a popular import and quickly increased in population. The nutria, although eventually hated by landowners and trappers, became a dominant species in the fur and meat trades in the 1960s and overtook muskrat in terms of pelt quantity and price. Other species consistently in the top five fur producing species for the state include mink, raccoon, opossum and skunk (Lowery 1974). Louisiana was ranked as the highest fur producer in the country until the industry took a downturn in the 1990s (Atchafalaya Basin Program 2012).

2.4.7. Invasive Species

2.4.7.1. Invasive plants. Introduced (non-native) and invasive (introduced and expanding range) species are increasingly common in freshwaters and are a major concern to managers and stakeholders in the ARB. Some of the most worrisome of these non-native species are plants. The ARB currently contains seven non-native aquatic plants, four of which have rapidly expanded their ranges from the point of introduction. Alligatorweed (*Alternanthera philoxeroides*), watermilfoil (*Myriophyllum spicatum*), and water lettuce (*Pistia stratoites*) have been serious nuisances in other localities (Julien et al. 1995, Gordon 1998), but have not proven to be problems in the ARB. Others are more problematic.

Water hyacinth (*Eichhornia crassipes*) was introduced to Louisiana in the late 1800s from South America as an ornamental pond plant and has expanded its range in the U.S. to 15 continental states and Hawaii, Puerto Rico, and the Virgin Islands (USDA NRCS 2012). It is currently distributed throughout the ARB and is currently one of the most abundant macrophytes in the system (Walley 2007). Hydrilla (*Hydrilla verticillata*), a native of southeast Asia, was discovered in Florida in the 1960s and by 1970 had expanded to all major drainages in the state (Langeland 1996). It is currently distributed throughout the eastern U.S. and to California, Arizona, and Washington (USDA NRCS 2012). Common salvinia (*Salvinia minima*), an aquatic fern native of Central and South America, expanded from Florida after being flooded from ornamental ponds in 1928 (Small 1931). It was first documented in Louisiana in 1980 (Landry 1981) and is now a dominant plant in the ARB (Walley 2007). Giant salvinia (*Salvinia molesta*), an aquatic fern from Brazil, was first documented in South Carolina in 1995 and is a more recent addition to the flora of the ARB having been first found in 2006 (Walley 2007).

These four invasive aquatic plants all have rapid growth and can cover an expanse of water quickly. Water hyacinth, for instance, can double its population size in 6-18 days (Mitchell 1976) and hydrilla can produce up to 6,000 new tubers per square meter from a single shoot (Sutton et al. 1992). These fast-growing plants form dense mats on the surface (water hyacinth, common and giant salvinia) or in the water column (hydrilla). Vegetation covering the surface can prevent oxygen exchange and promote hypoxia (Caraco and Cole 2002). Invasive plants can also shade out native submerged aquatic vegetation (Mitchell and Gopal 1991), decreasing diversity and potentially affecting the invertebrate community and food quality for fishes and other organisms (O'Hara 1967, Hansen et al. 1971, Toft et al. 2003, Colon-Gaud et al. 2004). For instance, the proportion of fish in the diet of largemouth bass decreased substantially as hydrilla beds expanded in Henderson Lake (Mason 2002). On the other hand, hydrilla beds may also serve as refugia from hypoxia by providing local areas of high DO to fish and invertebrates (Troutman et al. 2007). These potential refugia may pose a hazard, however, if aquatic organisms are trapped in dense hydrilla beds as water levels drop. Dense mats of invasive plants can also severely impede recreation by making boating and swimming impossible or undesirable. Invasive aquatic plants in the ARB thus play a major role in ecosystem processes and functions and pose a risk to the system.

Chinese tallow (*Sapium sebiferum*) is a deciduous tree native to eastern Asia and has been introduced repeatedly into the United States as an ornamental and potential oil crop, beginning as early as 1772 by Benjamin Franklin (Louisiana Aquatic Invasive Species Task Force 2005). Chinese tallow possesses advantages over native trees, such as higher growth and reproduction and lower pest loads, and is often found in single-species stands (Baldwin 2005, Leonard 2008). Chinese tallow is thus an aggressive invader of bottomland hardwood forests in Louisiana and the ARB (DeWeese et al. 2007) and is found throughout the entire state of Louisiana (Louisiana Aquatic Invasive Species Task Force 2005). Chinese tallow forests may provide lower habitat and food quality for some migratory birds, although some birds gain more energy from Chinese tallow fruit than other native food sources (Baldwin 2005). Chinese tallow leaves also break down more quickly than native hardwood leaves and can affect aquatic communities by altering ecosystem properties like dissolved oxygen dynamics and decomposition (Leonard 2008).

Various management approaches have been suggested for control of invasive aquatic plants and many of these have been implemented in the ARB. Henderson Lake in the ARB underwent seasonal lowering of water levels (40-60% of the bottom exposed) during approximately 90 days in the fall of 1996-1997 and 2000-2001 to try to control the growth of hydrilla (Mason 2002, Walley 2007). Louisiana subsequently spent $1 million applying the herbicide fluridone to large portions of the lake and implemented a smaller spring draw-down with herbicide application in spring 2006 (Walley 2007). A five-year plan of annual draw-down and herbicide treatment began in 2007 and the state has spent hundreds of thousands of dollars for pesticide application (Burgess 2007). Despite these efforts, invasive aquatic plants continue to pose problems to the ARB and its residents, and the water draw-downs affect recreation and water-based businesses (Walley 2007, Burgess 2007). These aquatic nuisance species continue to spread in the ARB, many through cutting and transport by boats through canals and bayous (Walley 2007) and new invasive species continue to be added to the fauna.

2.4.7.2. Invasive invertebrates. According to the USGS, the ARB currently contains three nonindigenous invertebrates. The water flea *Daphnia lumholtzi*, a cladoceran crustacean, is native to east Africa, India and eastern Australia and was likely introduced into Texas (1990) with shipments of Nile perch for aquaculture. It is now widely distributed throughout the eastern and central United States as far north as the Great Lakes and in some areas in the western U.S. (Benson et al. 2012a). Its large size, allowing it to escape predation, and its spread through fish stocking and boating are the likely mechanisms contributing to its spread. It is a tropical species and its populations are thus limited by temperature extremes. Little is known about its overall impacts, but it is not thought to compete strongly with native cladocerans (Benson et al. 2012a). In the ARB, water flea abundance is positively associated with high dissolved oxygen saturation and low current velocity, termed “green water” habitats, which coincided with lower river stage during summer (Davidson Jr and Kelso 1997, Davidson et al. 2000).

The Asian clam (*Corbicula fluminea*) is a freshwater mollusc native to many parts of Southeast Asia, Africa and Australia. It is thought to have been introduced directly as a food item in immigrant communities or indirectly through the fish trade but has spread throughout the United States since its first introduction to Washington in 1938. The mechanism of its wide and rapid dispersal is not known. The clams are a major nuisance as biofoulers as they congregate in and clog pipes and canals, causing problems for power plants, water supply systems and other facilities. Although Asian clam can dominate benthic communities in rivers and streams, little is known about its impacts to aquatic ecosystems. Many native fishes have modified their feeding habits to consume Asian clam, sometimes to such an extent that they dominate the diet (Foster et al. 2012). The species has apparently not been studied in the ARB.

The zebra mussel (*Dreissena polymorpha*) is native to the Black, Caspian, and Azov Seas in eastern Europe. Since its introduction to the Great Lakes in the late 1980s via ballast water exchange it has spread throughout most of the eastern and central United States. Like the Asian Clam, zebra mussels are notorious biofoulers, clogging intake pipes and canals of various facilities and prompting expensive repairs and cleaning efforts. Ecological impacts of zebra mussels have been profound and well-documented. Due to their highly efficient filtering abilities and large populations, Zebra Mussels have caused massive declines in diatom abundance (80-90%) and chlorphyll-a (60-70%), altering water clarity and nutrient contents, and reducing food availability for native molluscs and zooplankton (Benson et al. 2012b). Zooplankton biomass in the Hudson River, for instance, declined by 70% after mussel invasion due to a reduction in body size of large zooplankton and reduced abundance of microzooplankton, indicating direct competition for food and direct predation on microzooplankton (MacIsaac et al. 1995). In the ARB, zebra mussels were found to be limited by high temperatures and low oxygen during summer months, with adult mortality documented at daily minimum temperatures of 29 °C (floodplain) – 32.5 °C (river channel) as hypoxia developed. These conditions, which are widespread in the ARB and occur naturally during summer in most subtropical lowland rivers, appear to limit zebra mussel populations in these regions (Mihuc et al. 1999).

2.4.7.3. Invasive fishes. Invasive fishes have been increasingly ubiquitous and high-profile in the United States. Over 500 species of fishes have been introduced to the U.S., and at least 75 are considered established, having expanded their range significantly beyond the point of introduction and maintaining reproductive populations (Fuller et al. 1999). In the ARB, there are four nonnative fish species, all of which are carps (Family Cyprinidae). The black carp (*Mylopharyngodon piceus*), native to eastern Asia, was introduced accidentally with another invasive fish, the grass carp (*Ctenopharyngodon idella*) used to control aquatic weeds in ponds, and continued to be brought over for food and control of aquatic pests. It escaped from flooded hatchery ponds in Missouri and has spread to Arkansas, Mississippi, Illinois and Louisiana. Black carp are effective molluscivores and could have a potentially devastating impact on the native mollusk fauna. Although many introduced individuals are likely triploid and sterile, and reproduction has not been documented in the wild, the long (> 15 year) life-span of black carp and their continued accidental introduction make them a potential long-term problem for aquatic systems in the U.S. Additionally, all individuals examined in Louisiana have been diploid and capable of reproducing (Nico and Neilson 2012a).

The grass carp was first imported from Asia in the 1960s to control aquatic vegetation in ponds and subsequently spread into reservoirs and rivers, expanding its range to include 45 states. The grass carp has had significant effects on freshwater ecosystems by altering food web structure (decreasing aquatic macrophytes, competing with native herbivores such as crayfish and fish) and increasing nutrient levels in the water through high excretion rates. The grass carp is now well-established in the U.S. although some states have increased measures to insure that released fish are sterilized (triploid)(Nico and Neilson 2012b).

The silver carp (*Hypophthalmichthys molitrix*) is endemic to eastern Asia and was introduced to the U.S. in the early 1970s to control phytoplankton in ponds and reservoirs and as a food fish. It has since expanded its range to 12 states and is established (with documented reproduction) in Louisiana and throughout the Mississippi River region. Although specific impacts have yet to be thoroughly investigated, the diet of the silver carp overlaps with adults of some native fishes such as gizzard shad (*Dorosoma cepedianum*) and bigmouth buffalo (*Ictiobus cyprinellus*), and the species may compete with larval fishes and mussels for plankton (Nico and Neilson 2012c).

The bighead carp (*Hypophthalmichthys nobilis*), native to central and southern China, was introduced into the U.S. in the 1970s to improve water quality for aquaculture and has spread to more than 20 states and spawns throughout its new range. Like the silver carp, bighead carp filter plankton from the water column and may compete with native larval fish and adult mussels, paddlefish, buffalo and shad (Nico and Neilson 2012d). In the ARB specifically, state fisheries data reveal sporadic, usually low numbers of the four non-native carps, a pattern that seems to be replicated in other states (Nico and Neilson 2012d). Niche modeling based on broad-scale climate, topography and river discharge indicated that much of the North American continent is suitable for Grass and Silver carp and much of the eastern half of North America is suitable for bighead and black carp (Herborg et al. 2007). The study also highlights the invasion potential for several species of nonindigenous snakehead (Family Channidae) to the ARB, as models for six of the 10 species examined showed high suitability for Louisiana and the ARB (Herborg et al. 2007). No snakehead species have been found in Louisiana or the ARB; however, an established northern snakehead population in central Arkansas upstream in the Mississippi River drainage makes dispersal into the ARB a future possibility (Adams 2009).

2.4.7.4. Invasive mammals. The nutria was imported from South America in the late 1930s to southern Louisiana for fur production but spread across the state as managers and landowners wanting to control invasive weeds (e.g., water hyacinth) released them across state waters, including the ARB. Reaching its height in coastal Louisiana of approximately 20 million in the late 1950s, the nutria population dropped sharply after wetland plants had been decimated and with severe climatic events including hurricanes, and freezing temperatures. Although they quickly became a nuisance to farmers, landowners, and trappers, nutria eventually became the dominant fur bearer in the fur industry until its collapse in the 1990s due to consumer preference. Despite the desired intent that nutria could control exotic plants, the species actually facilitates wetland invasion by massive reduction of native marsh vegetation (Lowery 1974). Exclosure experiments in the Wax Lake and Atchafalaya deltas have documented substantial decreases in plant biomass and changes in community structure in areas exposed to nutria grazing (and when combined with waterfowl grazing) as opposed to those areas where nutria are excluded (Fuller et al. 1984, Elaine Evers et al. 1998). Severe reduction in plant biomass has serious implications for coastal wetland restoration (Fuller et al. 1984, Elaine Evers et al. 1998). Recent genetic evidence indicates that nutria were introduced from many native populations (11 genetic clusters identified) but have spread widely from the points of introduction with no geographic pattern of genetic relatedness. These data suggest that high gene flow/dispersal would hinder local eradication efforts (Robertson and Gemmell 2004) or those methods relying on ties between a single native source population and introduced populations of invasive species (Klima and Travis 2012).

As is apparent from the above list of invasive species and their serious potential and realized impacts to native flora and fauna, the ARB is faced with a growing aquatic nuisance species problem that threatens native communities, both human and non-human. Especially with regard to invasive plants, these species can fairly rapidly change ecosystem states, forcing out native species and making freshwater environments unsuitable for fishing, swimming, boating and other recreational and commercial activities. Although the state of Louisiana reportedly spent $75,000 in 2002 on invasive species control and prevention efforts, in 2012 (Duda et al. 2002), the budget was over $8 million within the Department of Wildlife and Fisheries alone (State of Louisiana 2011), almost 4% of the Department's budget. This expense may increase as more invasives come to Louisiana and those that are currently in the state expand their range. Florida, for instance, which is one of the worst states in terms of aquatic plant invasions, had a FY 2004-2005 budget of almost $35 million for aquatic invasive plant control (Bureau of Invasive Plant Management, Florida Department of Environmental Protection 2005). As a key recreational hotspot for Louisiana, the ARB is and will be a major battleground for invasive species control.

2.5. Summary

This chapter provided an overview of the cultural, historical, geologic, and ecological context of the ARB as well as its modern development as a floodway and the impacts of this transition on natural and human communities. The ARB's rich cultural heritage and riveting social history is paralleled by great biological diversity that is expected of one of the largest river-floodplain ecosystems in the world. The Cajun culture, with its origins in the 18th century, has deep connections to the ARB's landscape and transcends current economic and political boundaries. The bayous and swamps of the ARB support diverse fisheries and contain more than 400 documented vertebrate species and countless invertebrates and plants.

These riches have occurred for some time now in the context of modern development and control that at times threatens to diminish or destroy them. Due to Congressional mandates in the 1950s for the Old River Control Structure, the ARB has experienced significant modification to its natural regimes. Ongoing resource extraction and maintenance activities have further altered hydrologic and sediment dynamics in the ARB, which in turn have profound effects on ecological communities and functions. We turn next, in Chapter 3, to the modern economic uses of the ARB and the legal framework guiding both its uses and its protection.

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Chapter 3: Socioeconomics and Governance of the Atchafalaya River Basin

3.1. Demographics

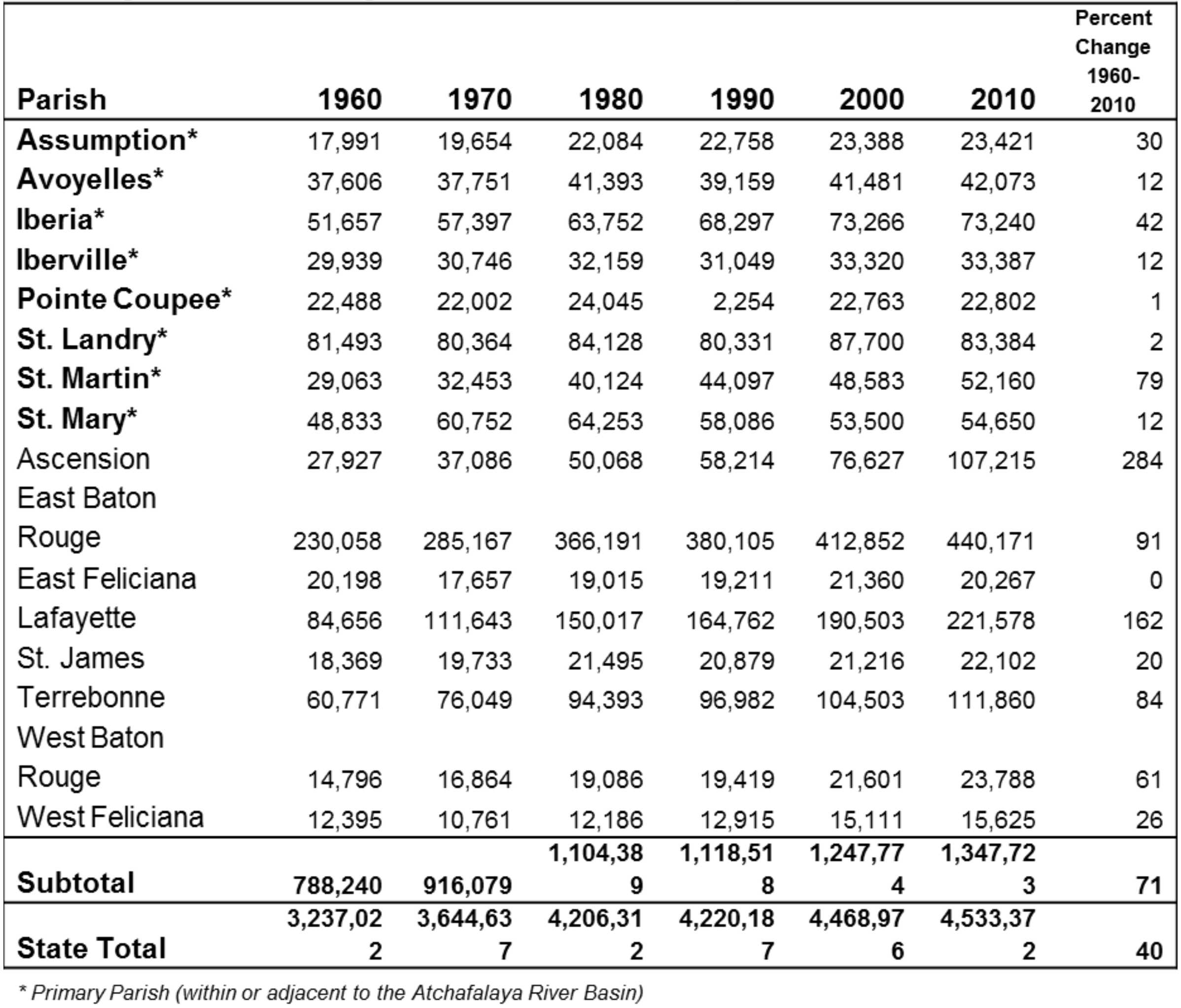
The Atchafalaya River Basin (ARB) contains parts of seven Louisiana Parishes and borders one other (Figure 3.1). Accurate population counts for residents within the ARB are difficult to ascertain as many of the properties scattered throughout the ARB are only used seasonally or part time. However, there are several small communities within the guide levees including Simmesport (pop. 2,161), Melville (pop. 1,041), and Krotz Springs (pop. 1,198; U.S. Census Bureau 2011). Since the socioeconomic influence of the ARB extends well beyond these eight primary parishes, the following discussion includes all parishes within 25 miles of the east and west guide levees to include the areas most directly influenced by the ARB; a reasonable commuting distance for daily visitation and employment.

The estimated total population of the eight primary ARB parishes in 2010 was 385,117, approximately 8.5 % of the state total (Table 3.1). This is a drop from approximately 10 % of the state total in 1960. However, when considering all parishes within 25 miles of the east and west guide levees there is an estimated population of 1,347,723, or approximately 30 % of the total state population, up from 24 % in 1960 and an increase of 100,000 residents since the 2000 census (U.S. Census Bureau 2011). These figures include the Baton Rouge metropolitan area but exclude the New Orleans metropolitan area. Population growth in the region has not been consistent through the decades. From 1960 to 1980 the population of the ARB parishes increased at a faster rate than the U.S. average. This is thought to be the result of increased employment opportunities in the region as the petrochemical industry developed (U.S. Army Corps of Engineers 2012). During the 1980s the population growth rate dropped below the national average largely due to the out-migration and unemployment that resulted from a

Figure 3.1. The area of socioeconomic influence of the Atchafalaya River Basin, Louisiana.

restructuring of the petrochemical industries that moved operations from the mainland offshore (U.S. Army Corps of Engineers 2012). Since 1990, the rate of population growth for the region, as a whole, has rebounded and currently attracts an increasing percentage of the state's population.

Table 3.1. Population trends for Atchafalaya River Basin parishes of Louisiana. Source: U.S. Census Bureau 2010).



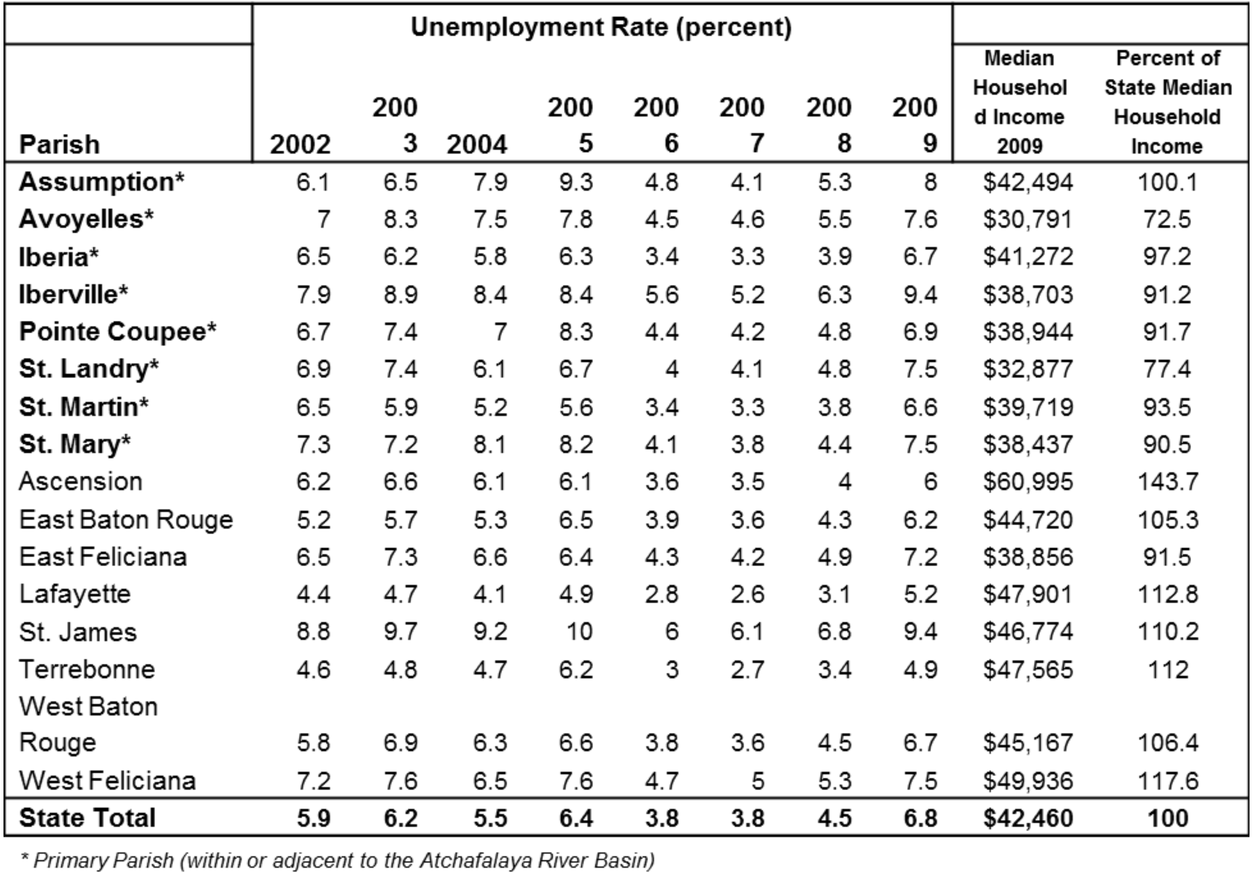
Parish	1960	1970	1980	1990	2000	2010	Percent Change 1960-2010
Assumption*	17,991	19,654	22,084	22,758	23,388	23,421	30
Avoyelles*	37,606	37,751	41,393	39,159	41,481	42,073	12
Iberia*	51,657	57,397	63,752	68,297	73,266	73,240	42
Iberville*	29,939	30,746	32,159	31,049	33,320	33,387	12
Pointe Coupee*	22,488	22,002	24,045	2,254	22,763	22,802	1
St. Landry*	81,493	80,364	84,128	80,331	87,700	83,384	2
St. Martin*	29,063	32,453	40,124	44,097	48,583	52,160	79
St. Mary*	48,833	60,752	64,253	58,086	53,500	54,650	12
Ascension	27,927	37,086	50,068	58,214	76,627	107,215	284
East Baton Rouge	230,058	285,167	366,191	380,105	412,852	440,171	91
East Feliciana	20,198	17,657	19,015	19,211	21,360	20,267	0
Lafayette	84,656	111,643	150,017	164,762	190,503	221,578	162
St. James	18,369	19,733	21,495	20,879	21,216	22,102	20
Terrebonne	60,771	76,049	94,393	96,982	104,503	111,860	84
West Baton Rouge	14,796	16,864	19,086	19,419	21,601	23,788	61
West Feliciana	12,395	10,761	12,186	12,915	15,111	15,625	26
Subtotal	**788,240**	**916,079**	**1,104,389**	**1,118,518**	**1,247,774**	**1,347,723**	**71**
State Total	**3,237,022**	**3,644,637**	**4,206,312**	**4,220,187**	**4,468,976**	**4,533,372**	**40**

** Primary Parish (within or adjacent to the Atchafalaya River Basin)*

There are two Metropolitan Statistical Areas (MSA) within 25 miles of the ARB levees including Baton Rouge and Lafayette (Figure 3.1; U.S. Census Bureau 2011). The Baton Rouge MSA includes portions of nine parishes, 7 of which are within the 25 mile socioeconomic buffer

(East Baton Rouge, Ascension, Iberville, Pointe Coupee, West Baton Rouge, East Feliciana, and West Feliciana). The city is home to Louisiana State University and is the state capital. The population of the Baton Rouge MSA was approximately 791,300 in 2009 with East Baton Rouge and Ascension parishes showing strong growth in the 2010 census (U.S. Census Bureau 2011). The Lafayette MSA includes portions of six parishes, four of which are within the 25 mile socioeconomic buffer (Lafayette, St. Landry, St. Martin, and Iberia). In 2009, the Lafayette MSA had a population of 264,400 with Lafayette and St. Martin parishes experiencing above average population growth between 2000 and 2010 and St. Landry and Iberia parishes experiencing population declines over the same time period (U.S. Census Bureau 2011).

Table 3.2. Unemployment trends and income for Atchafalaya Basin parishes of Louisiana (U.S. Census Bureau 2010).



	Unemployment Rate (percent)									
Parish	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Median Household Income 2009**	**Percent of State Median Household Income**
Assumption*	6.1	6.5	7.9	9.3	4.8	4.1	5.3	8	$42,494	100.1
Avoyelles*	7	8.3	7.5	7.8	4.5	4.6	5.5	7.6	$30,791	72.5
Iberia*	6.5	6.2	5.8	6.3	3.4	3.3	3.9	6.7	$41,272	97.2
Iberville*	7.9	8.9	8.4	8.4	5.6	5.2	6.3	9.4	$38,703	91.2
Pointe Coupee*	6.7	7.4	7	8.3	4.4	4.2	4.8	6.9	$38,944	91.7
St. Landry*	6.9	7.4	6.1	6.7	4	4.1	4.8	7.5	$32,877	77.4
St. Martin*	6.5	5.9	5.2	5.6	3.4	3.3	3.8	6.6	$39,719	93.5
St. Mary*	7.3	7.2	8.1	8.2	4.1	3.8	4.4	7.5	$38,437	90.5
Ascension	6.2	6.6	6.1	6.1	3.6	3.5	4	6	$60,995	143.7
East Baton Rouge	5.2	5.7	5.3	6.5	3.9	3.6	4.3	6.2	$44,720	105.3
East Feliciana	6.5	7.3	6.6	6.4	4.3	4.2	4.9	7.2	$38,856	91.5
Lafayette	4.4	4.7	4.1	4.9	2.8	2.6	3.1	5.2	$47,901	112.8
St. James	8.8	9.7	9.2	10	6	6.1	6.8	9.4	$46,774	110.2
Terrebonne	4.6	4.8	4.7	6.2	3	2.7	3.4	4.9	$47,565	112
West Baton Rouge	5.8	6.9	6.3	6.6	3.8	3.6	4.5	6.7	$45,167	106.4
West Feliciana	7.2	7.6	6.5	7.6	4.7	5	5.3	7.5	$49,936	117.6
State Total	**5.9**	**6.2**	**5.5**	**6.4**	**3.8**	**3.8**	**4.5**	**6.8**	**$42,460**	**100**

** Primary Parish (within or adjacent to the Atchafalaya River Basin)*

Historically, residents of Louisiana have household incomes lower than the national average (Table 3.2). This characteristic still holds true today, though there has been a closing of this gap in recent decades. In 2009, median household income in the state of Louisiana was \$42,460, roughly \$9,000 less than the national median household income. Of the primary ARB parishes, only Assumption Parish (\$42,494) exceeded the 2009 state median household income average. Only one of the ARB parishes, Ascension Parish, exceeded the national median household income while nine of the fourteen fell short of the state median (U.S. Census Bureau 2011).

3.2. Socioeconomics

Like most of the wetlands in south Louisiana, the ARB is a working landscape. The mild climate and an abundance of natural resources have attracted economic investment and development for more than a century. Today, it is intensively used by a number of commercial, industrial and recreational stakeholders who are deeply tied to the condition of the ARB for their livelihoods. Stakeholders, therefore, are heavily invested, and consequently, very interested in decisions and actions that affect the future of the ARB. The Louisiana Department of Natural Resources (LDNR) Master Plan aims to “conserve, restore, and enhance (where possible) the natural habitat and give all people the opportunity to enjoy the Atchafalaya Experience” (Atchafalaya Basin Advisory Committee 1998). The natural habitat and the ecological functions of the ARB are the foundations for substantial economic, ecological, social, and cultural value that constitute the “Atchafalaya Experience.” Depending on one’s vantage point, the experience might include commercial fishing or timber harvesting, recreational hunting and birding, or tourism that illuminates the distinct culture of the ARB or the unique and internationally recognized ecosystems that make up the ARB. This variety of values brings with it a diverse and extensive group of stakeholders that depend on the ARB for their livelihoods as well as many NGOs and various governmental agencies. The socioeconomic forces in the ARB vary in scale from local and regional importance (flood control, recreational and commercial fisheries, hunting), to national (Cajun culture, navigation, oil and gas extraction) to global importance (habitat, biodiversity, birding).

3.2.1. Flood Control

At the top of the list of socioeconomic forces in the ARB is flood control. The United States Army Corps of Engineers (USACE), directed by Congress after the 1927 flood, developed the ARB into a principal floodway of the Mississippi River and Tributaries Project designed to pass 1.5 million cfs safely from the Mississippi and Red rivers to the Gulf of Mexico during extreme flood events. During flood conditions all other socioeconomic considerations in the ARB are secondary. This is to ensure that the port cities of Baton Rouge and New Orleans, as well as the surrounding parishes, are protected from destructive flood waters. In the unprecedented flood of 2011, the ARB Floodway proved its worth. Relying on the Lower ARB and the Morganza floodways to pass approximately 692,000 cfs and 182,000 cfs of the flood waters respectively (the West Atchafalaya Floodway was not utilized), the ARB floodway system (Figure 3.2) played a major role in the Mississippi River and Tributaries Project flood prevention plan, an overall effort estimated to have avoided $100 billion in damages in 2011 alone (U.S. Army Corps of Engineers 2011). In addition to the flood control efforts in Louisiana, this figure includes the damages avoided through flood water retention in upstream reservoirs, the operation of the Bird’s Point Floodway in Missouri, and the extensive levee systems throughout the Mississippi River Basin.

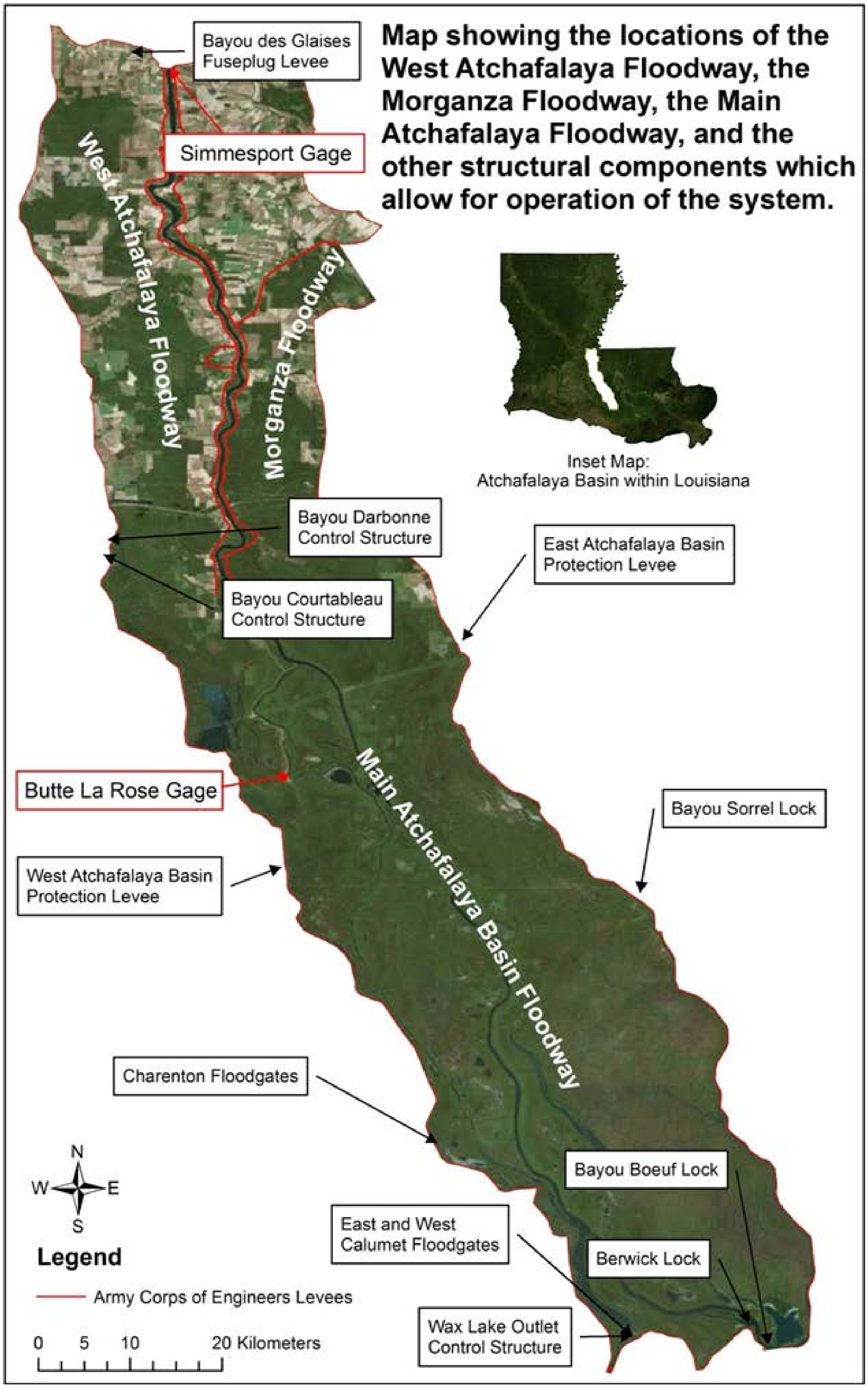


Figure 3.2. Map showing the location of the West Atchafalaya Floodway, the Morganza Floodway, the Main Atchafalaya Floodway, and the other major components which allow for operation of the system.

While the flood control capacity of the ARB may have helped mitigate damage costs at a national scale, it was a burden at the local and regional scale. The 2011 flood event impacted ARB residents and users, the oil and gas industry, navigation, agriculture, sport and commercial fisheries, fish and wildlife, and the tourism industry (Table 3.3; Carlson et al. 2012). During the flood (1) navigation was restricted and locks were closed, (2) oil and gas production experienced a reduction of approximately 2,000 barrels (bbl) per day and 17.9 thousand cubic feet (MCF) per day, respectively, (3) approximately 95,500 acres of crops and pasture and 370 acres of aquaculture were inundated, (4) wildlife management areas, wildlife refuges, and boat launches were closed, (5) infrastructure was damaged, (6) fishing opportunities were reduced, (7) wildlife was displaced, including the threatened Louisiana Black Bear, and (8) several fish kills were reported in the ensuing months.

Table 3.3. Summary of economic impact data for the Atchafalaya River Basin, Louisiana – 2011 flood event. Adapted from the 2011 Atchafalaya Basin Inundation Data Collection and Damage Assessment Project, Louisiana Geological Survey, 2012.

Economic Sector	Agency/Stakeholder	Impact to	Economic Impact
Agriculture	LSU-Ag	Crop and livestock	$44,969,387
Wildlife	LDWF	Black Bear and Deer	$870,000
Fisheries			Unknown
Infrastructure	LDWF	Repairs at WMAs	$93,200
Infrastructure	LDOTD	Response and Repairs	$3,402,945
Infrastructure	St Mary Parish	Repair Boat Launches	$3,000,000
Infrastructure	Private	Homes, camps, boat launches	$583,715
Crude Oil Production	Private	Shut-in production	$2,448,072
Natural gas Production	Private	Shut-in production	$612,071
Tourism	USACE	WMAs	$384,000
Navigation			Unknown
		Total	$56,363,390

The total economic impact of the flood in the ARB cannot be estimated due to a lack of available information, the known impact is estimated to be greater than $56,000,000 (Carlson et al. 2012). Though that figure is economically significant for the ARB at a local scale, it is just a fraction of the total costs avoided nationally as estimated by the USACE. This trade-off between local, non-flood control interests and national flood control efforts is the essential story of the ARB. Without the flood mitigating abilities of the ARB Floodway, the nation would experience a much greater impact to commerce and social well-being. There are few arguments against the necessity of a flood control system and the ARB's role in the larger Mississippi River and Tributaries project. Rather, the debates surround the management of the ARB during non-flood years (see *Governance* below).

3.2.2. Navigation

Navigation is a major socioeconomic force in the region. The Atchafalaya River and Gulf Intracoastal Waterway (GIWW) are major shipping routes in and out of the Gulf of Mexico. Notably, they connect petrochemical processing facilities on the Mississippi River with extraction facilities in the Gulf and along the coast. Navigation, through the commerce clause of the U. S. Constitution, is considered to be of economic and strategic national importance so it takes top billing as a socioeconomic driving force during non-flood periods. The dredging of canals and rivers to maintain navigation in the ARB, historically, has been prioritized over other considerations like ecological health. The Atchafalaya River serves as part of a transportation network that connects the Red and Mississippi Rivers with the GIWW and, by proxy, the entire Gulf Coast. The Atchafalaya River provides a shorter route between the Gulf and GIWW and the Mississippi River, but this advantage has not been fully utilized due to the Simmesport Railroad Bridge which the coast guard considers a hazard to navigation during high water (U.S. Army Corps of Engineers 2012).

There are two major locks operating in the Lower ARB Floodway (Figure 3.2). The Bayou Sorrel Lock, located along the eastern guide levee of the ARB connects the Mississippi River at Port Allen to the GIWW and the Gulf of Mexico through the Atchafalaya River at Morgan City. Known as the Alternate Gulf Intracoastal Waterway Morgan City – Port Allen route, the Bayou Sorrel Lock passed an average of 22 million tons annually with 8,839 average lockages per year from 2001-2010 (U.S. Army Corps of Engineers, unpublished data). The Bayou Boeuf Lock, located just south of Morgan City, connects the GIWW on the east side of the Atchafalaya River to the Gulf of Mexico, the ARB and the GIWW west of the Mississippi. The Bayou Boeuf Lock averaged 24.9 million tons and 13,653 lockages per year over the 2001 – 2010 time period (U.S. Army Corps of Engineers, unpublished data). In the upper ARB, the Old River Lock located near the ORCS passed 7.6 million tons through 3,239 lockages per year over the 2001 – 2010 time period (U.S. Army Corps of Engineers, unpublished data). The tonnage passing through the Bayou Sorrel and the Old River locks represents approximately 5 percent of total inland domestic waterborne traffic; the tonnage passing through the Bayou Boeuf Lock represents approximately 12 percent of coastwise domestic waterborne traffic (U.S. Army Corps of Engineers n.d.). The majority of the cargo shipped through these routes is petroleum, chemicals, agriculture, and aggregate products.

3.2.3. Oil and Gas

The crude oil and natural gas industry has a long history in the ARB and it has certainly left its imprint on the landscape. Oil and gas activities began in the ARB in the 1920s and continue to the present day. The southern portion of the Lower Floodway is crisscrossed with oil and gas canals, features that have altered the hydrology of the ARB and negatively impacted ecosystem health. A GIS analysis of a 2007 statewide dataset shows 3,888 oil and gas wells and

64 oil and gas fields within the ARB guide levees. A report from Carlson et al. (2012) estimates there were 592 producing wells in the ARB during the 2011 flood event. While production rates are dependent on a variety of economic factors such as the current market price of crude oil and natural gas and high water conditions, the ARB produces approximately 1,000,000 barrels of oil and 130,000 cubic feet of natural gas per month (Carlson et al. 2012).

3.2.4. Agriculture

Agriculture is another driving socioeconomic force in the ARB region. In the eight ARB parishes there are over 870,000 acres of land in agricultural production with a gross farm value in excess of $700 million in 2011 (Louisiana State University Agricultural Center 2012). The largest acreage and highest value crops in the region are soybeans, sugarcane, and rice. Accurate acreage counts are unavailable for the Atchafalaya Floodway system but nearly all agriculture production in the ARB is located at the northern end in the West Atchafalaya and Morganza floodways. Because the rest of the ARB is either unsuitable for agricultural practices or it is prohibited due to its wetland status, the area can be loosely approximated. The 154,000 acre West Atchafalaya Floodway (U.S. Army Corps of Engineers, unpublished data) has never been utilized for flood control purposes and as such, has been well developed for agriculture. In 1979, van Beek et al. (1979) estimated 50,000 acres in the West Floodway, a number that is undoubtedly conservative for today’s real acreage. The 71,500-acre Morganza Floodway (U. S. Army Corps of Engineers, unpublished data) has only been utilized twice in its history so it is also well developed for agriculture. The Morganza Floodway was completely flooded during the 2011 flood event resulting in the inundation of approximately 95,500 acres of cropland (Carlson et al. 2012). While very susceptible to large flood events, the agriculture industry in the ARB is a significant market contributor for the region.

3.2.5. Timber

The timber industry of coastal Louisiana, once a major producer of baldcypress lumber and wood products, has shown a marked decline in production compared to historic logging rates. Nearly all of the virgin baldcypress stands in coastal Louisiana were clear-cut for timber harvest by the 1930s, and this holds true for the ARB. The baldcypress stands that exist today are second-growth, even-aged stands that followed this extensive period of harvest (Conner and Toliver 1990). The downturn of the timber industry occurred because of unsustainable clear cutting, an increase in the quantity of protected lands in the ARB, increased cost of extraction, and other market forces like the Save Our Cypress Coalition. Comprised of conservation groups, businesses, and civic organizations, the Coalition’s goal is to prevent the clear cutting of baldcypress and other unsustainable forestry practices in coastal Louisiana. A report to the Louisiana Governor from the Coastal Wetland Forest Conservation and Use Science Working Group estimates that 80% of the areas being logged will be unable to naturally regenerate (Coastal Wetland Forest Conservation and Use Science Working Group 2005). Faulkner et al. (2009) estimate only 5.8% (15,259 acres) of the cypress-tupelo forests in the Lower Atchafalaya Basin Floodway are capable of naturally regenerating and over 23% (60,602 acres) are unable to regenerate naturally or artificially. This is a serious problem not only for the timber industry but also for Louisiana’s cultural identity (cypress is the state tree) and the tourism industry, and could have significant impacts on habitat for migratory and forest breeding birds and the Louisiana black bear. The Coalition’s effort resulted in an agreement by many companies not to sell cypress mulch from coastal Louisiana, notably Wal-Mart, The Home Depot, and Lowes. While legal baldcypress harvest has ceased in the ARB there are pine and hardwood timber harvests occurring in the eight ARB Parishes, with some of this activity occurring in the West

Atchafalaya and Morganza floodways at the northern end of the ARB. While estimates are limited to harvest at the parish scale and not necessarily harvests within the ARB, estimated total stumpage value of severed timber from the eight ARB parishes was $10,273,000 in 2011 (Louisiana Department of Agriculture and Forestry 2012).

3.2.6. Fisheries

Fisheries, commercial and recreational, are a mainstay of ARB communities. The ARB supports several productive fisheries with annual total landings of finfish and shellfish valuing $8.9 to $24.1 million annually (Alford and Walker 2013). Perhaps the most recognizable of these fisheries is the commercial wild crawfish industry. In 2010, the wild harvest of crawfish in the state of Louisiana yielded 16.6 million pounds at $13.3 million (Louisiana State Univeristy Agricultural Center 2010). Though wild crawfish harvests only account for approximately 12% of total crawfish harvest in the state, wild crawfishing remains an integral part of the culture as well as the economic livelihood of the ARB; the average commercial crawfisherman has been operating for 20 years (Isaacs and Lavergne 2010). According to Louisiana residence commercial fisherman’s license files, in 2008, 78.2 % of commercial wild crawfish harvesters lived in the four parishes within or near the ARB (Assumption, Iberville, St. Martin, and St. Mary Parish). In a 2009 commercial wild crawfish harvester survey, over 91% of respondents identified the ARB as the location where they harvested most of their crawfish and approximately 90% of those respondents reported selling their catch to dealers in Atchafalaya Parishes (Isaacs and Lavergne 2010), indicating an important sector of the market for these parishes. Though there is no season for wild crawfish harvesting, the majority of the catch occurs in the spring when water levels rise (March – June). Wild crawfish harvests are dependent on the timing and duration of the annual floodwater event, which results in highly variable annual catches. During the 20 year period from 1988 to 2008, commercial wild crawfish harvests in the state of Louisiana experienced a low of 392,000 lbs. in 2000, a high of 49.7 million lbs. in 1993, an average of 16.8 million lbs. per year, and an average dockside value of $12.10 million per year (Isaacs and Lavergne 2010).

Commercial landings of catfish and suckers in the ARB averaged over 2.5 million kg (5.5 million lbs.) between 1999 and 2009 (Alford and Walker 2013). Alligators, turtles, bullfrogs, and crabs are also commercially harvested in the ARB. Total estimated harvest biomass of all commercial fisheries in the ARB is 20 million kg (44 million lbs.) annually (Lambou 1990, Sabo et al. 1999).

3.2.7. Oysters

Oyster resources in Louisiana, some of the most valuable in the nation, are a multifaceted contributor to the economy of the ARB region and coastal Louisiana. Industries surrounding harvest of live and dead oysters and their products contribute substantially to Louisiana's economy as well as providing many ecological benefits to Louisiana's estuarine environment.

The commercial oyster fishery provides almost $300 million annually ($30-50 million in direct sales) to Louisiana's economy, and the state consistently accounts for over 50% of Gulf landings and about 34% of national landings (Piazza et al. 2005, Turner 2006, Louisiana Department of Wildlife and Fisheries 2010, Eberline 2012). At the outlet of the Atchafalaya River is the Atchafalaya/Cote Blanche/Vermillion Bay complex which contains a 541,787 acre public seed ground (Louisiana Department of Wildlife and Fisheries 2010). In the ARB, oysters do not have a large spatial footprint and production is low compared to other oyster grounds in Louisiana (Bryan P. Piazza, personal communication), however, conditions in the ARB can impact adjacent oyster grounds. Public oyster grounds are primarily a source of seed oysters for transplant to private leases but also provide a supply of sack-sized oysters (≥3”) able to be taken directly to market. The combination of public grounds and private leases helps keep Louisiana’s oyster industry a national leader in production (Louisiana Department of Wildlife and Fisheries 2010).

More than just food, oysters also have a place in Louisiana’s other industry, with shells being used in the construction of highways, roads, and levees, and as a poultry feed additive (U.S. Army Corps of Engineers 1993, Louisiana Department of Wildlife and Fisheries 2010). Unfortunately, the extractive use of oyster shells reduces the amount of available substrate for oyster larvae and can negatively impact reefs. Hard, clean substrate is needed for larval oyster attachment and oyster spat growth, necessities for viable oyster reefs. To counter this reduction in habitat, the Louisiana Department of Wildlife and Fisheries deposits cultch material made up primarily of reclaimed native shells on public oyster grounds to build and enhance reefs, an ongoing practice since 1919. Shell dredging, which began in Louisiana around 1914, was a means to acquire the needed substrate material but the practice was banned by the Louisiana legislature in all state-owned water bottoms in 1999 due to ecological concerns. Currently, a far greater amount of shell is removed from public oyster grounds than is returned for habitat development and enhancement (Louisiana Department of Wildlife and Fisheries 2004). In order to offset the removal of substrate habitat, the LDWF often supplements reclaimed native shells on public oyster grounds with other suitable cultch material such as limestone or crushed concrete (Louisiana Department of Wildlife and Fisheries 2004).

Residents of the ARB and coastal Louisiana benefit from oysters not only as an extractive resource but also for their supporting and regulating services. Oysters are recognized ecologically as “ecosystem engineers” because of their significant effects on ecosystem processes (e.g., substrate stability, water quality) and the survival and distribution of other coastal species (Jones et al. 1994, Micheli and Peterson 1999). Oyster reefs provide the majority of the hard substrate in coastal Louisiana that is required habitat by many sessile invertebrate species and is also used as shelter and forage habitat by many species of crabs, worms, other invertebrates, and fish. Further, the filter feeding capacity of oysters positively impacts estuarine water quality and oyster reefs also play a role in stabilizing shorelines. Piazza et al. (2005) examined the potential of using created oyster shell reefs, like those created by the LDWF on public seed grounds, as a sustainable shoreline protection strategy in Louisiana. Their results suggest that, unlike many traditional structural approaches, these reefs are sustainable over time and that small fringing reefs in low-energy environments may be useful in protecting shorelines (Piazza et al. 2005). The ecological dynamics of oysters have serious implications for other industries, like coastal fisheries, that are dependent on good estuarine health.

3.2.8. Recreation and Tourism

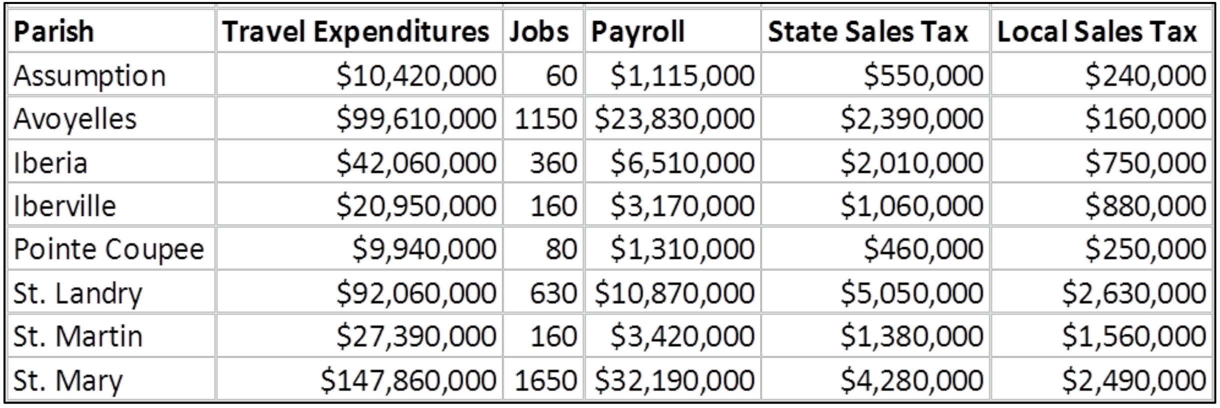
In addition to commercial fisheries, the other major regional socioeconomic force is recreation. The ARB is touted as a sportsman's paradise (Atchafalaya Basin Program 2012), where hunting and fishing are the dominant attractions (Table 3.4). The ARB is the most important source of inland recreation and the most popular recreational freshwater fishery in Louisiana (Holloway et al. 1998). Birding and camping are also large draws to the region. These recreation activities are largely dependent on the ARB's boat launches since the majority of the ARB can only be reached using watercraft. Public boat launches serve as gateways from one realm to another (Lumpkin 2003), from the developed world into the ARB's unique wetland environment. As very few roads exist within the ARB (Interstate 10 is the only road to completely cross the Lower Atchafalaya Floodway) levee roads and the access points they provide are critical for maintaining the recreational quality of the ARB and the livelihoods of the communities that depend on this segment of the economy. GIS analysis shows approximately 36 public boat launches that access the ARB.

During 2004-2010 there were 716,871 visitors to the Atchafalaya Welcome Center (Atchafalaya Basin Program 2012). These visits and their associated expenditures are significant contributions to the local economies of the ARB parishes (Table 3.5). Birding is another popular draw to the region with over 250 species of birds found in the ARB and its 29 known rookeries. Further, approximately 50% of migratory bird species in the North American Flyway use the ARB each year (Lindau et al. 2008). Another draw is the Cajun culture that calls the ARB home. An amalgamation of Hispanic, French, German, Anglo-American, and Native American peoples, the Cajun culture is experienced through the unique food, music, and traditions of the region. Finally, there is a small but growing eco-tourism industry in the ARB. Swamp tours are the most well-established, but kayak and canoe trips are increasing in popularity as people get comfortable with the ARB setting and realize the ease of access to the natural wonders of the ARB.

Table 3.4. Hunting and fishing licenses sold by vendors in and/or to residents of the parishes of the Atchafalaya Basin in Louisiana in 2010. Source: Louisiana Department of Wildlife and Fisheries.

Resident recreational fishing licenses	66,510
Non-resident recreational fishing licenses	5,128
Resident hunting licenses	37,923
Non-resident hunting licenses	776
Commercial fishing and hunting licenses	12,241

Table 3.5. Economic impact of travel in the Atchafalaya Basin parishes of Louisiana in 2010. Source: The Economic Impact of Travel on Louisiana Parishes 2010, Louisiana Office of Tourism.



Parish	Travel Expenditures	Jobs	Payroll	State Sales Tax	Local Sales Tax
Assumption	$10,420,000	60	$1,115,000	$550,000	$240,000
Avoyelles	$99,610,000	1150	$23,830,000	$2,390,000	$160,000
Iberia	$42,060,000	360	$6,510,000	$2,010,000	$750,000
Iberville	$20,950,000	160	$3,170,000	$1,060,000	$880,000
Pointe Coupee	$9,940,000	80	$1,310,000	$460,000	$250,000
St. Landry	$92,060,000	630	$10,870,000	$5,050,000	$2,630,000
St. Martin	$27,390,000	160	$3,420,000	$1,380,000	$1,560,000
St. Mary	$147,860,000	1650	$32,190,000	$4,280,000	$2,490,000

The relatively recent development of the recreation and tourism industries in the ARB is a turn from the predominantly extractive economy of the area. Historically, the ARB was utilized as a producer of fur, timber, fish, crawfish, oil and gas. Providing the only deep water access to the Gulf in the 200 mile stretch between the Mississippi and Calcasieu Rivers, the ARB is ideally located for access to Gulf resources as well as providing reliable transportation for goods extracted from and transported through the ARB itself. The increasingly diverse but still developing economy of the ARB that now includes recreation and tourism is a much-needed buffer to the boom and bust nature of many extractive resource markets, especially the oil and gas industry in the ARB and the all but defunct fur and timber industries. In an exploratory analysis of the extent of external influences on the economy of resource-extraction communities of Lafayette and St. Mary’s parishes Gramling and Freudenburg (1990) found a high degree of local susceptibility to external shocks to the oil and gas industry highlighting the importance of a diversified local economy. The regional economy and local interests would realize increased economic stability and longevity from concerted and directed efforts to bolster the multi-use characteristics of the ARB’s socioeconomic driving forces.

The considerable value attributed to the various ecosystem services, especially those that do not have a direct economic value, should also be noted. The ARB is five times more ecologically productive than any other river basin in North America (Atchafalaya Basin Program 2012). Using an energy analysis, Cardoch and Day Jr. (2001) calculated the nonmarket value of the net primary production of the Atchafalaya and Wax Lake deltas to be $723 million in 1988, and if delta accretion continues at its current pace, to be $756 million in 2058.

3.3. Stakeholders

The stakeholders of the ARB stand to gain by incorporating ecosystem management with economic development; however, there are resource use conflicts that make this easier said than done. As early as 1977, van Beek et al. pointed out two resource complexes at odds in the ARB. The first complex includes natural resources like food, raw materials and recreation that are largely maintained by natural processes. The second resource complex includes navigation, flood control, and mineral extraction, the maintenance of which requires human alteration of the environment. The conflict stems from “the annual overbank flooding and dewatering regime as required for fish, wildlife, forest, and recreational purposes, and the channelization, canal dredging, and deposition of spoil. The latter actions, as associated with flood control, navigation, and mineral extraction, have favored channel flow at the expense of overbank flow, increasing siltation in lakes and backswamps and interrupting backwater circulation with adverse effects on water quality.” (van Beek et al. 1977 p. 6). In short, one group of stakeholders relies on the natural productivity of the ARB and the other relies on altering the natural environment for flood control, navigation, and to extract resources. Current management plans are an attempt to implement a compatible use of the ARB’s resources. Management decisions are therefore an attempt at a desirable annual water level variation that preserves or restores environmental quality and minimizes negative impacts on stakeholders by maintaining the socioeconomic productivity of the ARB.

Conflict among stakeholders, such as the hotly contested public access versus private property rights dilemma, is one dynamic that has hindered restoration efforts. Efforts to restore or maintain the environmental quality of the Atchafalaya to sustain the natural production of the system have been ongoing for many years but have produced mixed results. Private property owners in the ARB are reticent to cooperate with restoration efforts that seek to locate project features on their land because they feel these may irreversibly alter their land. They also fear that if public tax dollars are used to construct project features on their land it will undermine their private property rights and encourage trespass. Property owners in the ARB already deal with trespass from commercial and recreational fishermen and hunters, a dilemma that has occupied state courtrooms for several decades. The fishermen and hunters assert that they have a right to fish and hunt in the waters of the ARB because they see it as public domain; an understandable assertion since the ARB can be considered a public good in its entirety when it is used for flood control. However, the courts have decided that though the waters over private property may be navigable in fact and possibly the result of the public good of flood control, neither of these determinations under state or federal law permit hunting and fishing in those areas. Further confounding the issue is the notion that static laws do not reflect the dynamic, changing physical landscape in the ARB, forcing courts to decide based on legal necessity and the primacy of private property rights and less on the actual physical conditions in the ARB. In any case, these decisions are more symbolic than substantial as monitoring and enforcement of the law are cost-prohibitive.

Another confounding factor for stakeholders and managers is the rapidly changing landscape of the ARB. Human impacts resulting from altering the landscape to better suit industries like oil and gas extraction and navigation have modified the connectivity of the floodplain. This has created substantial uncertainty in the science and scientists' abilities to predict system response to management actions leading to stakeholder distrust of those making management decisions and a diminishing confidence in the ability of projects to protect their livelihoods.

More recently there has been a push for coordinated efforts between the USACE, state agencies, and conservation groups to improve practices for channel maintenance and land management in ways that promote a more productive environment. These efforts, however, are bound by federal and state laws, congressional mandates, and a limited state budget.

3.4. Governance

There are two separate, ongoing projects in the ARB: the Atchafalaya Basin project and the Atchafalaya Basin Floodway System (ABFS) project. In the remainder of this chapter this distinction is important to remember. When the discussion involves the development of the floodway and the construction of flood control features, it pertains to the Atchafalaya Basin project. When the discussion considers state-level initiatives and efforts beyond flood control in the ARB (fish and wildlife, water quality, public access, etc.), it pertains to the ABFS project.

The Atchafalaya Basin project was authorized by Congress in the Flood Control Act of 1928 as part of the larger Mississippi Rivers and Tributaries project designed to mitigate destructive floods on the lower Mississippi River. The scope of the Atchafalaya Basin project includes all of the levees, control structures, outlets, and channels in the West Atchafalaya, Morganza, and Main Atchafalaya floodways constructed to ensure the effective and efficient conveyance of flood water. It is maintained and operated by the USACE, who views the project as their primary mission in the ARB for two reasons. First, the project authorization pre-dates other ongoing projects in the ARB and also most environmental regulations, historically, a contentious point between the USACE and other agencies and interests (Reuss 2004). Second, and more importantly, when Congress recognized flood control as a proper activity of the federal government in the Flood Control Act of 1936, they invoked both the commerce clause and the spending clause of the U.S. Constitution, stating: "It is recognized that destructive floods upon the rivers of the United States, upsetting orderly processes… and impairing and obstructing *navigation*, highways, railroads, and other channels of commerce between the States, constitute a menace to *national welfare*" (emphasis added). This effectively established the primacy of the flood control mission in all future management decisions in the ARB.

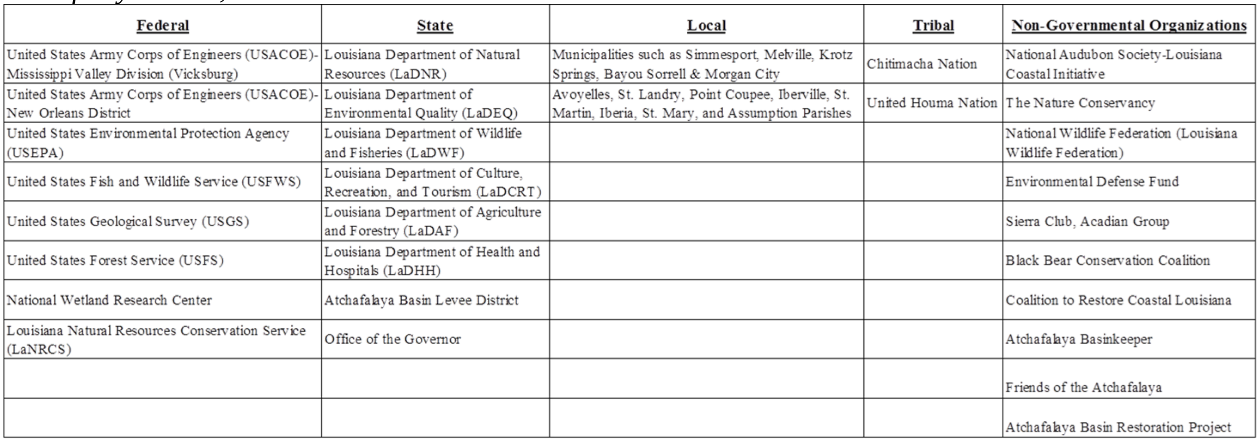
The ABFS project was authorized and funded through the Water Resources Development Act of 1986. The project grew out of growing state and local concerns over the detrimental environmental impacts of the Atchafalaya Basin project. A coordinated effort between federal and state agencies, the ABFS project is a comprehensive plan for a balanced approach to water resources problems in the Main Atchafalaya Floodway; the West Atchafalaya and Morganza floodways are not within the scope of this project. At the federal level the lead agency is the USACE; at the state level it is the LDNR. In authorizing this project the Congress recognized the need to balance environmental quality and flood control efforts, however, it was still defined as a flood control project in which the fish and wildlife enhancement benefits provided shall be considered to be national in scope.

A brief foray into the evolution of environmental policy in the United States is required to preface any discussion on the governance of the ARB. The development and implementation of environmental policy in the United States has been a convoluted affair that delves into the notion of state's rights and Federalism (Stewart 1977). Prior to the mid-20th century, state and local governments were primarily responsible for the regulation of the environment and actions or activities that would result in pollution of the environment. In Hardin's (1968) seminal paper "Tragedy of the Commons," he suggests that the environment must be protected when common resources are being used for economic gain. (Hardin 1968) proposed that two different routes could be taken in controlling pollution and regulating the environment, a command and control approach or a market-based approach.

The environmental governance of the United States has primarily taken the command and control approach (Keohane et al. 1998). This is apparent in its modern environmental regulations, which take a top-down approach in the development of environmental policies and a bottom-up approach in supporting the regulations. There is a trickle-down effect of policy from the Federal government (three branches of government and associated federal agencies) through state governments and agencies to local municipalities, counties, and parishes (Table 3.6). The trickle-down regulations result in business, industry, and user groups being required to comply to the maximum extent practicable with the rules. Typically this occurs through the use of best management practices derived from the best available technology and the best available science.

The notion of top-down and bottom-up environmental regulatory policy can be explored when looking at the effects of the Clean Water Act on the ARB. The Clean Water Act of 1972 is derived from the Federal Water Pollution Control Act of 1948. The goal and intent of the Clean Water Act "is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The main components of the Clean Water Act include: setting standards (such as effluent limitation guidelines) concerning the discharge of pollutants into navigable

Table 3.6. Governmental and non-governmental organization (NGO) stakeholder groups active in the Atchafalaya Basin, Louisiana.



Federal	**State**	**Local**	**Tribal**	**Non-Governmental Organizations**
United States Army Corps of Engineers (USACOE)-Mississippi Valley Division (Vicksburg)	Louisiana Department of Natural Resources (LaDNR)	Municipalities such as Simmesport, Melville, Krotz Springs, Bayou Sorrell & Morgan City	Chitimacha Nation	National Audubon Society-Louisiana Coastal Initiative
United States Army Corps of Engineers (USACOE)-New Orleans District	Louisiana Department of Environmental Quality (LaDEQ)	Avoyelles, St. Landry, Point Coupee, Iberville, St. Martin, Iberia, St. Mary, and Assumption Parishes	United Houma Nation	The Nature Conservancy
United States Environmental Protection Agency (USEPA)	Louisiana Department of Wildlife and Fisheries (LaDWF)			National Wildlife Federation (Louisiana Wildlife Federation)
United States Fish and Wildlife Service (USFWS)	Louisiana Department of Culture, Recreation, and Tourism (LaDCRT)			Environmental Defense Fund
United States Geological Survey (USGS)	Louisiana Department of Agriculture and Forestry (LaDAF)			Sierra Club, Acadian Group
United States Forest Service (USFS)	Louisiana Department of Health and Hospitals (LaDHH)			Black Bear Conservation Coalition
National Wetland Research Center	Atchafalaya Basin Levee District			Coalition to Restore Coastal Louisiana
Louisiana Natural Resources Conservation Service (LaNRCS)	Office of the Governor			Atchafalaya Basinkeeper
				Friends of the Atchafalaya
				Atchafalaya Basin Restoration Project

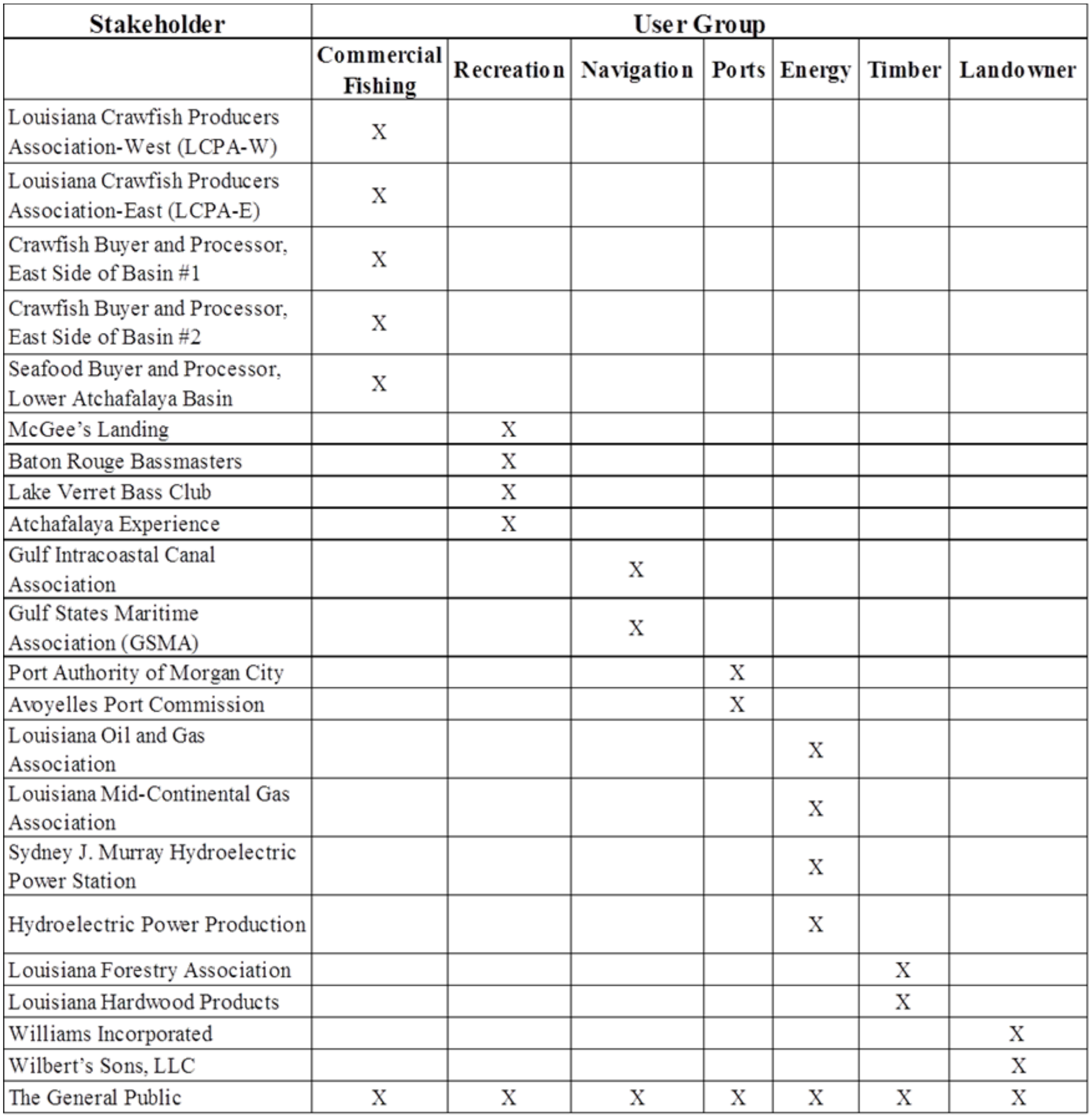
waterways, establishing the National Pollutant Discharge Elimination System (NPDES), and setting forth the impetus of the 404 “cut and fill” permits for development within a waterway. Congress authorized the establishment of the Environmental Protection Agency (EPA) in order to develop the rules and regulations for the implementation of the Clean Water Act.

The rules and regulations established by the EPA trickle down to states typically in the form of mandates (sometimes unfunded) and conditions attached to grants. There has been controversy related to federalism in environmental policies, especially in funding procedures and best available science (Esty 1996). The trickle-down process is necessary due to the limited resources of federal agencies and the varied and expansive geography of the United States. The bottom up approach is also critical for local support and expertise in regional issues and concerns. In the case of the ARB, the LDNR is an authorized agent of the EPA to regulate the water resources of the Louisiana to the same, or more stringent, standards as the federal government. Therefore, the LDNR has promulgated state rules and regulations that mirror their federal counterparts. This includes the ability to issue industrial, municipal, and other permits for the discharge of waters into navigable waterways and to enforce the state's environmental policies.

The LDNR follows the lead of the EPA and relays and enforces the rules and regulations to local governments (cities, counties, and parishes). This again is typically done in the form of permits and grant conditions requiring the local governments to achieve the same environmental standards as the state (and federal) governments. Larger local governments (population of 10,000 or greater) are at the forefront of reviewing development plans, inspecting pollution concerns, and enforcing the environmental standards. Local and state governments are typically the entities that enforce the rules and regulations on user groups, businesses, and industry (Table 3.7). Exceptions to this trickle down notion includes development of state, federal, and tribal lands and the issuance of 404 permits, which are promulgated directly from the nearest USACE District.

Federal, state, local, and tribal governmental agencies (Table 3.6) are not the only stakeholders who assist in the promulgation of policies for the ARB. Non-governmental organizations (Table 3.6) also play a role in the decision-making process. These organizations typically advocate for policy positions consistent with their missions and goals. They also provide for education of the general public, industries, and policy makers on the use of sound scientific practices. Scientific research often is accomplished through in-house scientists, out-sourced to consultants, or through partnerships with academia. A recent trend with non-governmental organizations is to become landowners or project managers in order to test new management techniques and showcase actions with successful results. This is the case with the Nature Conservancy and the Audubon Society.

Table 3.7. Business and industry stakeholder organizations and their user group type, Atchafalaya Basin, Louisiana.



Stakeholder	User Group						
	Commercial Fishing	Recreation	Navigation	Ports	Energy	Timber	Landowner
Louisiana Crawfish Producers Association-West (LCPA-W)	X						
Louisiana Crawfish Producers Association-East (LCPA-E)	X						
Crawfish Buyer and Processor, East Side of Basin #1	X						
Crawfish Buyer and Processor, East Side of Basin #2	X						
Seafood Buyer and Processor, Lower Atchafalaya Basin	X						
McGee’s Landing		X					
Baton Rouge Bassmasters		X					
Lake Verret Bass Club		X					
Atchafalaya Experience		X					
Gulf Intracoastal Canal Association			X				
Gulf States Maritime Association (GSMA)			X				
Port Authority of Morgan City				X			
Avoyelles Port Commission				X			
Louisiana Oil and Gas Association					X		
Louisiana Mid-Continental Gas Association					X		
Sydney J. Murray Hydroelectric Power Station					X		
Hydroelectric Power Production					X		
Louisiana Forestry Association						X	
Louisiana Hardwood Products						X	
Williams Incorporated							X
Wilbert’s Sons, LLC							X
The General Public	X	X	X	X	X	X	X

In order to arrive at a successful, sustainable environmental policy it is critical to understand the interaction of executive branch agencies (the EPA, Army Corp of Engineers, Louisiana Department of Natural Resources, etc.), non-governmental organizations (The Nature Conservancy, Audubon, Sierra Club, etc.), and science (models, peer-reviewed articles, etc.)

with policy-makers. Consider a triangle with policy makers in the middle and regulators, NGOs, and science as the sides. The policy makers must make decisions that are best for the majority their constituents based upon the input from the regulators implementing the policy, watchdog groups, and the best available science.

The idea of social and economic assessment of a project prior to its development has its roots in the National Environmental Policy Act (NEPA) of 1969 (Gramling 2006). NEPA requires that federal agencies, or other agencies that use federal monies for their project, first assess and mitigate any adverse effects prior to the construction of the project. NEPA attempts to "utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decision-making which may have an impact on man's environment." This process includes the components of understanding baseline conditions, scoping of social impacts, and anticipating responses that are derived from the impacts (Gramling 2006).

3.4.1. USACE ABFS Master Plan

After the enactment of NEPA, the USACE joined in an agreement with the National Wildlife Federation to cease the controversial dredging of the main channel of the Atchafalaya until an environmental impact statement was completed. The environmental impact statement was developed through a multi-interest, interdisciplinary approach (U.S. Army Corps of Engineers 1982). This approach involved the formation of the Atchafalaya Basin Steering Group, comprised of representatives from the National Wildlife Federation, Louisiana State University, and state and federal agencies. The environmental impact statement was completed in 1976; however, the completed draft was never released due to the expressed interest by stakeholders to expand the study to include the unauthorized features of the floodway project for resource preservation and management (U.S. Army Corps of Engineers 1982). This enlarged directive culminated in the Atchafalaya Basin Floodway System, Louisiana Feasibility Study, which included the final environmental impact statement. The purpose of the study included (1) a review the Atchafalaya Basin Floodway portion of the Mississippi Rivers and Tributaries Project to develop a plan to safely transport the project flood, (2) a review the operations of the Old River Control Structure, and (3) the development of a management plan to protect the environmental resources of the ARB (U.S. Army Corps of Engineers 1982).

The USACE finalized and issued their first Atchafalaya Basin Floodway System Master Plan (USACE Master Plan) in 2000. The USACE Master Plan was developed by federal, state, and local agencies and special interest groups to serve as a guide for the use and development of the natural and constructed resources of the project. This plan also provides the foundations of how the USACE has been authorized to manage the ARB. The USACE Master Plan needs to evolve in accordance with the USACE' mission: (1) operation of the floodway, (2) acquisition of lands and easements from private land owners, and (3) construction and maintenance of access points and restoration projects (U.S. Army Corps of Engineers, New Orleans District n.d.). The USACE Master Plan was recently updated and issued in June 2012. The updated plan calls for review and updating of the USACE Master Plan every 5 years. This is critical due to the dynamic nature of the physical attributes of the ARB (such as effects from flooding events), as well as effects of changing public valuation of the resources within the ARB.

The updated USACE Master Plan has a different primary purpose than its predecessor. It attempts to address public concerns, balance competing interests, and minimize adverse impacts on the biological and physical environment while maximizing public access and use of public lands (U.S. Army Corps of Engineers, New Orleans District n.d.). The document contains background and historical information on the ARB to serve as a guide for how the USACE manages the ARB and how the USACE may address environmental restoration in the future.

The USACE Master Plan follows the legacy of the 1982 environmental impact statement in regards to the notion of distinct Water Management Units (WMUs). The environmental impact statement defines WMUs as areas within the Lower Atchafalaya Basin Floodway where natural processes and human interactions have combined to produce distinct environmental and hydrological subdivisions (U.S. Army Corps of Engineers 1982). The environmental impact statement also recommended that these units be designed to restore historical overflow patterns, ensure proper water movement through the units, restrict sediment movement and deposition in the units, and supply nutrients and organic matter to the estuarine area and the Gulf of Mexico (U.S. Army Corps of Engineers 1982).

The modified goal for the WMUs in the updated USACE Master Plan is to prolong the life expectancy of productive habitat that will become scarce over time (primarily aquatic and baldcypress-tupelo gum habitats) by managing sediments and water circulation patterns. (U.S. Army Corps of Engineers, New Orleans District n.d.). This modified goal will be accomplished using channel closures, openings, and realignments; modifying heights of natural or constructed levees; and restoring or creating natural or constructed channels improve circulation within WMUs (U.S. Army Corps of Engineers, New Orleans District n.d.).

There are thirteen WMUs within the Atchafalaya Basin Floodway System (Figure 3.3). Of these thirteen WMUs, five were selected as pilot units-Buffalo Cove, Henderson Lake, Beau Bayou, Flat Lake (also called the East Grand Lake Study Area), and Cocodrie Swamp. These WMUs were selected based upon their potential for restoring historical flow conditions. The Buffalo Cove and Flat Lake WMUs were chosen as the first two units on which to concentrate

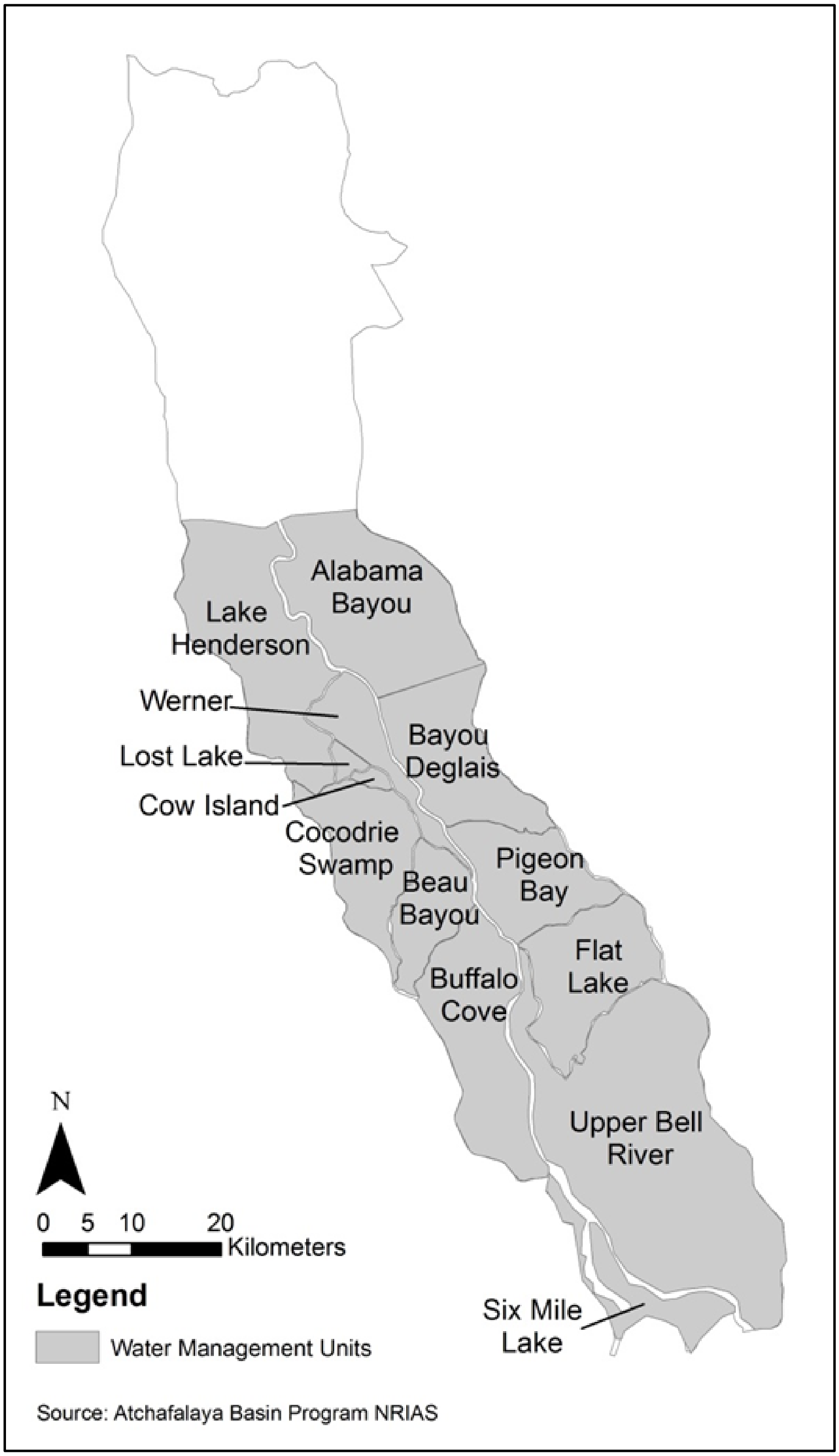


Figure 3.3. Water Management Units within the Atchafalaya Basin, Louisiana. Source: Atchafalaya Basin Program NRIAS.

restoration efforts. Construction activities began in 1995 in the Buffalo Cove WMU and included gapping existing canal banks, lowering, raising, or building weirs, reopening selected closures, constructing sediment traps, closing existing gaps and cuts that bring sediment into sensitive areas, and adding additional diversions in lower sediment environments (U.S. Army Corps of Engineers, New Orleans District n.d.). The Flat Lake WMU is waiting for funding to be secured and an implementation schedule to begin project construction. Adaptive management strategies are being employed to determine the validity of the pilot WMU projects. The remaining WMUs are currently unscheduled and unfunded (U.S. Army Corps of Engineers, New Orleans District n.d.).

3.4.2. Louisiana ABFS State Master Plan

The USACE work in the ARB was limited because of a lack of state funding. When Congress authorized and funded the ABFS project in 1986, Louisiana was required to develop and approve a plan and enter into cost/share agreements with the USACE. Any environmental protection, recreation, or public access project in the ARB requires state matching funds, so a state plan was needed for management to proceed. The Atchafalaya Basin Floodway System Louisiana Project State Master Plan (State Master Plan) was published in June 1998 by the Atchafalaya Basin Advisory Committee. It was developed by the Public Access, Environmental Easement, Water Management, and Recreation Working Groups under the supervision of the Policy Group. The LDNR served as the lead agency, at the direction of then-Governor Mike Foster Jr., and as Technical Advisors to the Working Groups, which included the USACE, Louisiana State University, sportsmen's organizations, landowners, and environmental groups (Figure 3.4). Their roles were to collect pertinent information about public needs and interests, develop partnerships with the USACE and other federal agencies, and reach consensus on project plans.

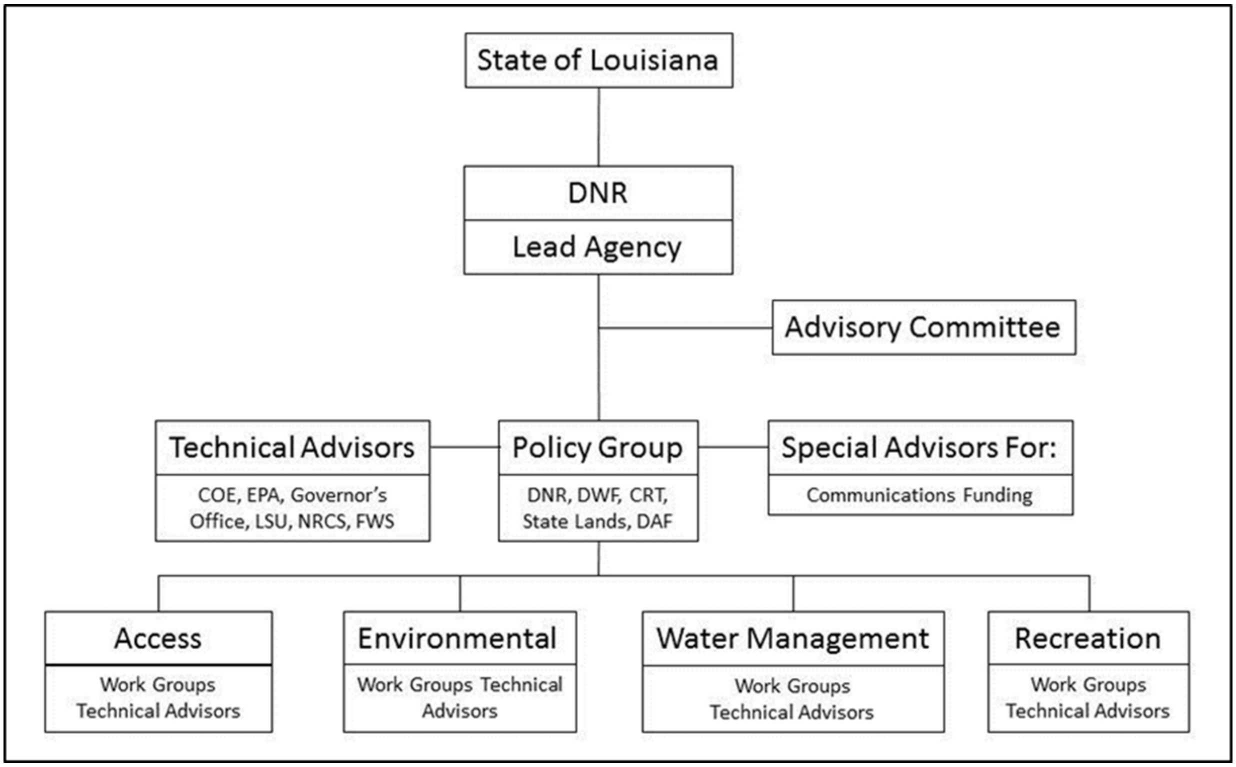


Figure 3.4. Agency relationship to develop the Atchafalaya Basin Project State Master Plan, Louisiana. Adapted from the Atchafalaya Basin Project State Master Plan, Louisiana, 1998.

The geographic area of the State Master Plan encompasses 838,000 acres bounded by Simmesport and U.S. 190 on the north, Morgan City on the south, and on the east and west by the protection levees. The plan presents an idealized future based on reasonable expectations of what can be accomplished with a concerted effort and widespread public support (Atchafalaya Basin Advisory Committee 1998). There are three main focal points of the project: regional and ecosystem needs, resource capabilities and suitabilities, and expressed public interest and desires. It recommended restricting development within the ARB levees to water management and environmental restoration projects. It emphasized preserving the environmental, cultural, and historic integrity of the area through enhanced public access while maintaining a diversity of livelihoods where human institutions take a stewardship approach to the abundant resources of the ARB. The State Master Plan, influenced by the USACE of Engineers decision to divide its own work program into four tasks, focuses its efforts on Public Access, Environmental Easements, Water Management, and Recreation. The stated mission is to "conserve, restore, and enhance (where possible) the natural habitat and to give all people the opportunity to enjoy the Atchafalaya Experience" (Atchafalaya Basin Advisory Committee 1998).

The State Master Plan was drafted in accordance with federal and state laws and regulations, particularly those pertaining to environmental protection, public health and safety, funding requirements, and the USACE' regulations governing the ARB. Concordantly, it recognizes several limitations and constraints to ARB restoration and improvement projects. As established by the Water Resources Development Act of 1986, the primary function of the ARB is flood control so any development is limited to projects that do not affect the flood carrying capacity (Atchafalaya Basin Advisory Committee 1998). Navigation is another limiting factor. The main channel of the Atchafalaya River and the Gulf Intracoastal Waterway Alternate Route are federally maintained waterways open to barge traffic, therefore, the maintenance of navigational channels is another undertaking that is sometimes, unfortunately, to the detriment of restoration and development projects. Of the 595,000 acres included in the Atchafalaya Basin Floodway System, Louisiana Project, 338,000 acres are owned by approximately 2,000 private landowners (Don Haydel, Atchafalaya Basin Program, personal communication). Environmental and development easements must be acquired before restoration projects can move forward on these lands, potentially limiting the scope of projects. A final limiting factor noted in the State Master Plan is sedimentation. Whether natural or anthropogenic in its delivery, sedimentation can impact public access projects and alter the ecological make-up of areas of the ARB.

Public access for fish and wildlife oriented recreation is a main goal of the State Master Plan. By providing access the state strives to achieve a balance between public use, environmental protection, and landowner rights. To aid this endeavor, Congress authorized the USACE to acquire 70,000 acres in fee title, less minerals, for public access from willing sellers in the ARB. To date they have acquired 47,323 acres for public access (Atchafalaya Basin Program 2012). Also dedicated to Public Access in the State Master Plan are several areas managed by the Louisiana Department of Wildlife and Fisheries, including the 15,000-acre Atchafalaya National Wildlife Area Refuge (owned by USFWS), the 26,000 acre Attakapas Island Wildlife Management Area, and the 10,232 acre Sherburne Wildlife Management Area. The State also dedicated lands to the project for public access and recreation purposes including 150,000 acres of lake beds and navigable waterways, 450 acres of non-severed lands acquired from the Bureau of Land Management, and approximately 30,000 acres donated by Dow Chemical Company. The dedication of these lands to the State Master Plan does not change ownership of the lands and they will continue to be used for mineral production, selective timber harvest, and campsite leases, provided these uses do not interfere with the USACE or State project goals (Atchafalaya Basin Advisory Committee 1998).

The State Master Plan notes some jurisdictional issues regarding public access. In general, public access is limited to State-owned lands, USACE fee purchase lands, USFWS lands, and all natural navigable state waterways. With large areas of the ARB privately owned, there are points of contention, notably that not all navigable waterways are public domain. Banks and any land above the ordinary high water mark are privately owned areas even when submerged and public use of private lands places a burden of liability on the property owner. The State recommends giving some responsibility to recreational boat tour operators to comply with private property laws, informing the public of the existence of private waterways, and encouraging private landowners to allow some public use by passing legislation that limits liability. The State Master Plan also calls for upgrading existing roads and constructing new roads to improve access to the ARB. These roads are an attempt to reduce the traffic on private service roads on top of levees, a practice that is generally allowed but not favored for safety reasons and the potential for interference with operations and maintenance.

Environmental easements in the State Master Plan have a two-fold purpose: developmental control and environmental protection. The aim of the developmental control portion of the easement is to maintain the unrestricted flood control needs of the ARB and to prevent the destruction of fish and wildlife habitat. The environmental protection portion of the easement aims to preserve fish and wildlife habitat and maintain the “wet and wild” environmental appeal of the ARB. The easements prohibit industrial development, permanently habitable structures, the conversion of land to other uses, and the harvest of certain sizes of timber. The easements provide guidelines for methods of cutting timber that promotes sustained yield practices. Other activities allowed on environmental easements are private ownership, mineral production, and recreation. The State Master Plan identifies for additional environmental easement purchases all remaining privately-owned land in the ARB, except for natural ridges. All State owned lands are also subject to the environmental easement restrictions (Atchafalaya Basin Advisory Committee 1998).

Monitoring responsibilities on federal environmental easement lands fall to the Louisiana Department of Agriculture and Forestry and the USACE. The State is tasked with inspecting all easements in the ARB at least twice a year, providing the required administrative and support services, meeting monthly with the USACE to discuss violations or exemptions, and providing quarterly reports of inspection activities (Atchafalaya Basin Advisory Committee 1998). The USACE is also tasked with bi-annual inspections for violations or exemptions and is required to contact owners concerning violations or exemptions. Enforcement on federal environmental easements is the responsibility of the USACE and the U.S. Department of Justice with the State serving as a witness at hearings and participating in pre-trial conferences. Monitoring and enforcement activities on State-owned lands are the responsibility of the State Land Office and the Louisiana Department of Wildlife and Fisheries.

Water management projects in the ARB are a response to nearly 200 years of hydrologic manipulation. The removal of log jams, the building of levees, channelization, dredging, and the conversion to a floodway has resulted in an increased rate of environmental change in the ARB. In addition, economic exploitation for petroleum and timber extraction, among other activities, led to the construction of pipelines and canals that further altered the natural hydrologic cycle within the ARB. The State Master Plan strives to restore or preserve the natural habitat of the ARB for the public benefit of the culture, education, economy, and recreation of Louisiana. The goal of water management projects is to "prolong the expected life of some habitats that may become scarce through time (primarily aquatic and cypress/tupelo habitats) by managing sediments, while at the same time achieving a healthy water circulation pattern that will maintain or restore water quality" (Atchafalaya Basin Advisory Committee 1998). Though the State Master Plan advocates improved environmental quality through water management projects, the construction of these projects is the responsibility of the USACE as required by the Water Resources Development Act of 1986.

The State's responsibilities for water management projects are limited. Since the benefits of these projects are considered national in scope, per the Water Resources Development Act of

1986 the federal government pays 100% of the cost of the enhancement features and 75% of the operation and maintenance costs; the State picks up the remaining share (Table 3.8). The State provides technical and engineering advice for design and construction as well as a letter of intent to the USACE concerning the cost-share agreement for the project's operation and maintenance.

Table 3.8. State and federal cost/share breakdown for the Atchafalaya Basin Floodway System Project, Louisiana. Source: Atchafalaya Basin Project State Master Plan, Louisiana, 1998.

	Federal	Non-Federal
Public Access: Fee purchase of land, less minerals,		
from willing sellers,	100%	0%
Dedication of State lands + Dow donation	0%	100%
Purchase of environmental/development easements	100%	0%
Operation/maintenance of access and easement lands	75%	25%
Purchase of easements for water management projects	100%	0%
Dedication of State lands for water management projects	0%	100%
Construction of water management projects	100%	0%
Operation/maintenance of water management projects	75%	25%
Land purchase and construction of recreation projects*	50%	50%
Operation/maintenance of recreation projects	0%	100%

**The State must purchase the land using its own funds. The cost is then credited against the State's share of the total (land + development) costs.*

The State is also responsible for several monitoring and maintenance activities. The Department of Wildlife and Fisheries is tasked with controlling nuisance aquatic vegetation, monitoring water quality, and sampling aquatic organisms to determine the effectiveness of the project. The Department of Agriculture and Forestry is tasked with monitoring the condition of trees and vegetation throughout, and in response to, the project. The LDNR has a multitude of tasks, including engineering consultation for project design, working with the oil and gas industry to encourage good practices like gapping spoil banks to improve water flow, maintaining cuts and gaps in spoil banks, and setting up an oversight committee of federal, state, and private interests to serve in an advisory role. Since State Master Plan water management activities can affect other ongoing projects, careful coordination with other State and Federal programs is required to meet the project's water management goals.

The final section of the work program is recreation, which includes ARB activities like camping, hiking, cycling, wildlife-viewing, horseback-riding, boating, fishing, hunting, and swimming. The State Master Plan recreation mission is to work with the USACE to provide a range of facilities and features that optimize accessibility and encourage public use of the ARB and also expands on the USACE work by providing interpretive and educational facilities that enhance the public's interaction with the ARB. Recreational needs projections by the Statewide Comprehensive Outdoor Recreation Plan of the Louisiana Department of Culture, Recreation and Tourism in 1997 cited a deficit in recreational features in the ARB. The Louisiana Office of Tourism also reported a deficit detailing the need for "visitor centers to provide an overview and directions, interpretive centers to immerse visitors in the natural spell cast by the ARB, and nature trails that provide an incentive to stay longer" (Atchafalaya Basin Advisory Committee 1998). The Office of Tourism and the Recreation Working Group also point out that when made easily accessible and user-friendly, the market area for recreation in the ARB is international in scope, unlike the limited market area detailed in the Statewide Comprehensive Outdoor Recreation Plan assessment (Atchafalaya Basin Advisory Committee 1998). An extensive inventory of the recreational opportunities led to several planning objectives for improving recreation in the State Master Plan. The first objective is to create or enhance primary or secondary entry points so the plethora of opportunities the ARB has to offer are presented to the visitor. The idea is to give the visitor a reason to get out of the car and want to see more. Another objective is to incorporate all of these access points into a broader network that leads the visitor through the entire ARB which would create a situation in which the visitor feels they still have more to see and thus make them more likely to return. The final overarching objective is to provide these recreation opportunities in a way that preserves the natural wonder of the ARB for future generations to enjoy (Atchafalaya Basin Advisory Committee 1998).

Table 3.9. Atchafalaya Basin Advisory Committee. Source: Atchafalaya Basin Project State Master Plan, Louisiana, 1998.

Atchafalaya Basin Advisory Committee

- State agencies involved in the Basin
- Federal agencies involved in the Project
- Representatives of the Governor and LA Legislature
- Parish and Local Officials
- The Atchafalaya Basin Levee District
- Police Representatives from Basin Parishes
- Louisiana Landowner Association
- Environmental Groups
- Industry Representatives
- Fishing and Hunting Clubs
- Commercial Fishing and Crawfishing Representatives
- Private citizens with an interest in the Basin

Implementation of the State Master Plan is the responsibility of the USACE with the State of Louisiana acting as a cooperative partner. The jurisdictional authority for the protection and oversight of Federal interests in the ARB are the sole responsibility of the New Orleans District Engineer (Atchafalaya Basin Advisory Committee 1998). Operation and maintenance of recreation and environmental features is tasked to the appropriate State agencies under the supervision of the USACE. The functions and responsibilities of all involved state agencies were outlined in a Memorandum of Understanding, which also established a standard operating procedure for any actions in the ARB. The State also formed the Atchafalaya Basin Advisory

Committee to provide guidance and advice as the State Master Plan is implemented (Table 3.9), however, the committee proved to be dysfunctional and has been disbanded (Stephen Chustz, LDNR, personal communication).

There are four phases to implementation of the Master Plan at the state level. The first phase, the preliminary planning phase, involved the drafting of the State Master Plan and was completed with the publication of the document. The second phase, the Advanced Planning Phase, involved presenting the plan at meetings statewide to promote it, solicit additional input, and develop public support for the State Master Plan. The LDNR managed the work of this phase with assistance from the Policy Group and all Working Groups. This phase ended in 1999 with the presentation of the State Master Plan to the governor and the legislature for approval and funding. Next is the Implementation Phase. This phase is ongoing as individual projects are completed and require operation and maintenance while others continue to be developed. The final phase is the Operation Phase. This phase entails ensuring the proper functioning of public access points, water management projects, and recreation features and the monitoring of environmental easement lands (Atchafalaya Basin Advisory Committee 1998).

While project construction on public lands is performed by the USACE, the State has multiple concurrent responsibilities regarding project implementation. Tasks pertaining to Public Access include developing a Wildlife Management Area on USACE fee-title lands and developing a joint management agreement for all public lands in the ARB. Environmental Easement tasks include inspections and monitoring of easement lands and assisting the USACE as needed. Water Management tasks include inspecting and monitoring projects, representing the state in all water management projects conducted by the USACE, operating water management projects, and cutting and maintaining gaps in pipeline canals. Finally, recreation program tasks are to purchase the 1,500 acres required by the State Master Plan to begin development of recreation features, to work with non-federal sponsors of several sites to plan and develop recreation projects and to create a marketing program for local and national markets to increase use of the ARB. Any work performed for these State tasks is under the direction of the Project Director and the Research Board with assistance from the Advisory Committee (Figure 3.5).

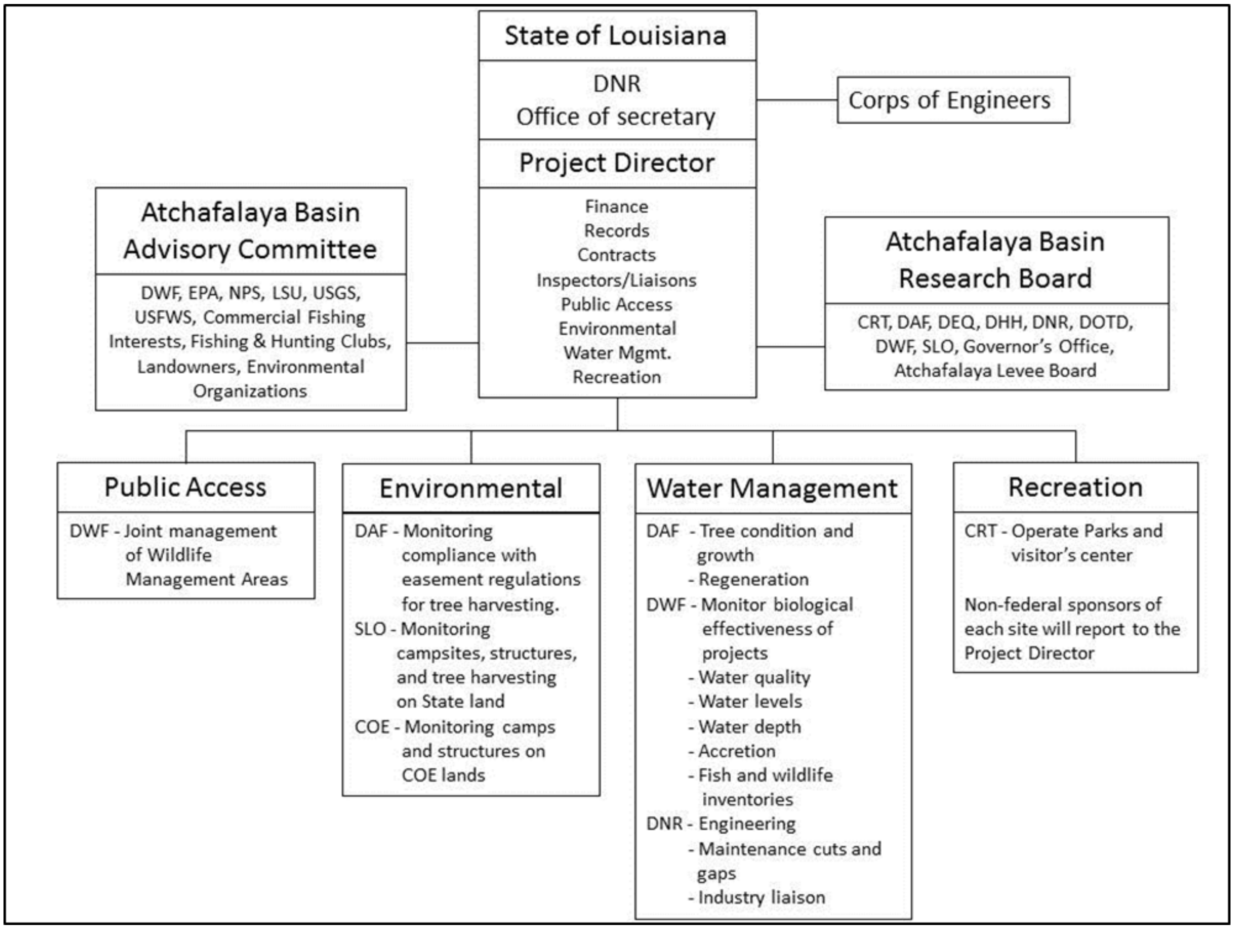


Figure 3.5. Organization for the implementation of the Atchafalaya Basin Project State Master Plan, Louisiana. Adapted from the Atchafalaya Basin Project State Master Plan, Louisiana, 1998.

In response to a recommendation from the USACE, the State Master Plan budget includes funds for additional Department of Wildlife and Fisheries personnel to serve as ARB rangers. The USACE recommended establishing a subordinate law enforcement entity with police powers and arrest authority to protect public and private interests in the ARB. They argued that the state, federal, and local agencies with legislatively-mandated enforcement authorities were insufficient to protect all public and private use and natural resource features of the ARB. The Department of Wildlife and Fisheries has the authority to enforce fish and game and boating safety laws, and the Sheriff of each Parish in the ARB has power to enforce criminal law. The State Master Plan recognized that neither enforcement organization had the resources necessary to meet its needs so the plan included a proposal for the funding of additional DWF personnel (Atchafalaya Basin Advisory Committee 1998).

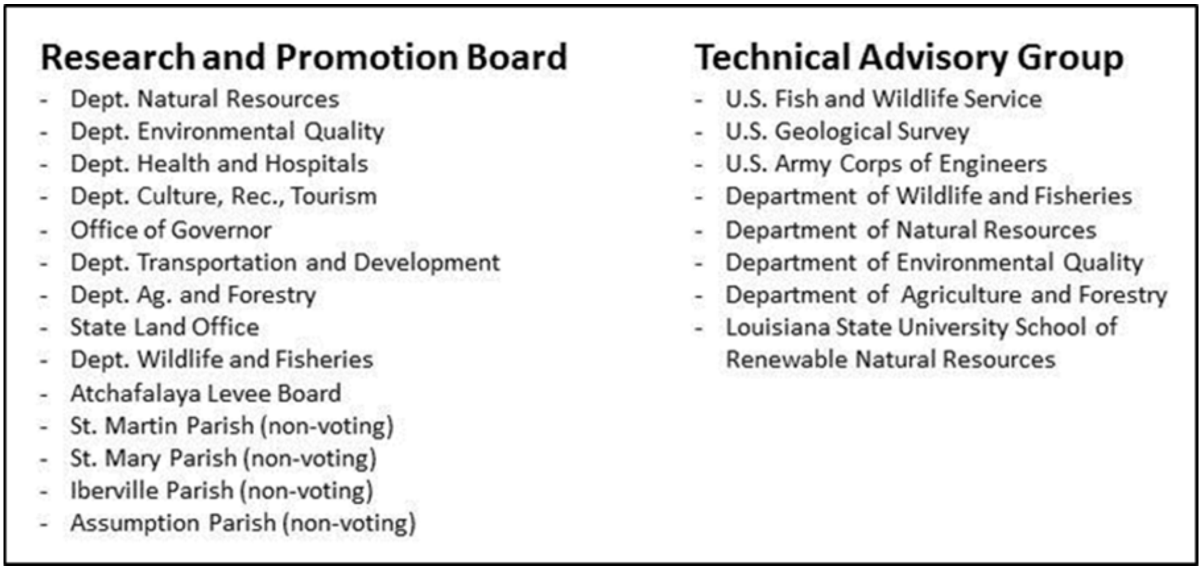
As the State Master Plan for the ARB is part of the USACE Atchafalaya Basin Floodway System, LA Project, and interest in the ARB is international in scope, there is a need for complimentary plans and programs. These plans aim to promote the ARB as a destination for recreation and tourism while maintaining its environmental appeal and flood control capabilities. One such plan is the Atchafalaya Trace Heritage Project, which focused on the Cajun Culture that is central to the ARB. The Heritage Project recognized the unique blend of people that reside in the communities in and around the ARB and help give the ARB the mystique and color of this distinct southern Louisiana heritage. The Heritage Project goals included the development of additional areas of interest to visitors and providing an economic boost to the regional economy. Gateway communities and routes to the ARB were established to enhance a visitor’s experience of the Atchafalaya through educational enrichment and cultural immersion. In 2006, the U.S. Congress designated this area as the Atchafalaya National Heritage Area, which includes the ARB and 14 surrounding Louisiana parishes. One other program of note is the Coastal Restoration Program. This congressionally authorized Federal/State Project calls for the protection and restoration of coastal marshes and an effort to build additional land with the silt carried by rivers to the Gulf. This project is impacted by the Atchafalaya Project and the State Master Plan so careful coordination and collaboration is needed to best serve the public interest.

Public participation was a major component in drafting the State Master Plan. The public included industry, landowner, fishing and hunting club representatives, commercial fishing and crawfishing interests, environmental organizations, interested citizens, and all relative local, state and federal agencies. The first phase in developing the plan was from January 1997 to April 1998 and included forty meetings. Each meeting was limited to a single section of the Plan. At these meetings the plan was debated, additional information and viewpoints were solicited, and consensus was reached. Quarterly meetings of the Advisory Committee were held to provide an opportunity for review and comment, which were then included in the discussion of the plan at the next meeting.   The Final Working Draft was presented to the Advisory Committee on January 22, 1998. The second phase of public participation, from May 1998 to March 1999, involved several activities to be completed by the Atchafalaya Basin Advisory Committee. They were required to serve as messengers to promote the State Master Plan to, and answer questions from, interested clubs and organizations; conduct public hearings throughout the state to explain the plan, develop support, and solicit input; prepare an Executive Summary for distribution; develop a General Agreement with the USACE; and present the State Master Plan to the Governor and State Legislature for approval and funding.

In 1999, the Louisiana Legislature unanimously approved the State Master Plan for the ARB and budgeted $85 million over 15 years for public access, environmental easement, water management, and recreation projects. The State Master Plan is up for renewal every 15 years, at which time projects, goals, and visions for the ARB will be reevaluated and a new State Master

Plan will be drafted for approval and funding. Also in 1999, the Louisiana Legislature authorized the Atchafalaya Basin Program (ABP) to act on behalf of the state to implement and manage the State Master Plan. The ABP, created in 1998 as an arm of the LDNR, has no permitting or regulatory authority, but it is authorized to enter into agreements with parishes, towns, the Levee District, and state and federal agencies involved in the ARB to advance conservation, restoration, enhancement, and recreation projects. The ABP also meets regularly with USACE representatives to coordinate projects and activities in the ARB.

In 2008, the Regular Session of the Louisiana Legislature adopted Act 606 to codify a transition in public policy from a focus on the recreational component of the State Master Plan to water resource management and enhanced water access. The Act authorized the ABP to create an Annual Plan for the ARB that is consistent with the State Master Plan and identifies ongoing or proposed projects in the ABFS that require State funding in the next fiscal year. The Act requires the Annual Plan to be distributed to members of the legislature at least 30 days before the start of each legislative session for review and approval. There are three project categories in the Annual Plan: water quality/management, access, and other. To help LDNR develop the Annual Plan, Act 606 established the ABP Research and Promotion Board (RPB) and the Technical Advisory Group (TAG). The 14-member RPB (Table 3.10) is tasked with identifying and prioritizing projects, determining the eligibility of proposed projects, holding public hearings to solicit ideas and vet the plan, and submitting the final Annual Plan to the LDNR Secretary. The nine-member TAG (Table 3.10), chaired by the Louisiana Department of Wildlife and Fisheries, is tasked with ensuring the best science is used in restoring and preserving the ARB ecosystem. TAG members review, evaluate, and approve all water management and water quality projects included in the Annual Plan. This group of scientists and resource experts are confirmed by the Atchafalaya Basin Oversight Committee of the Louisiana Legislature. Each group meets publicly several times a year to develop the Annual Plan. After these meetings and two sets of public hearings required by Act 606, the Draft Annual Plan is submitted to the Louisiana Coastal Protection and Restoration Authority for review to ensure it is consistent with the Master Plan for Coastal Protection and Restoration. Once approved it is then submitted to the Louisiana Legislature. The first Atchafalaya Basin Annual Plan was approved in 2009 for fiscal year 2010 and included $3.5 million for water management, access, and habitat restoration projects.



Research and Promotion Board

- Dept. Natural Resources
- Dept. Environmental Quality
- Dept. Health and Hospitals
- Dept. Culture, Rec., Tourism
- Office of Governor
- Dept. Transportation and Development
- Dept. Ag. and Forestry
- State Land Office
- Dept. Wildlife and Fisheries
- Atchafalaya Levee Board
- St. Martin Parish (non-voting)
- St. Mary Parish (non-voting)
- Iberville Parish (non-voting)
- Assumption Parish (non-voting)

Technical Advisory Group

- U.S. Fish and Wildlife Service
- U.S. Geological Survey
- U.S. Army Corps of Engineers
- Department of Wildlife and Fisheries
- Department of Natural Resources
- Department of Environmental Quality
- Department of Agriculture and Forestry
- Louisiana State University School of Renewable Natural Resources

Table 3.10. Atchafalaya Basin Program Research and Promotion Board and Technical Advisory Group members. Adapted from the Atchafalaya Basin Program Annual Plan, 2011.

Additionally, Act 606 created the Atchafalaya Basin Conservation Fund to help finance projects in the Annual Plan. The Act requires that 75 percent of the money allocated to the Fund in any fiscal year be used for water management, water quality, or access projects and the remaining 25 percent be used to complete ongoing projects or to fund ARB projects that fulfill the goals of the larger State Master Plan. A constitutional amendment passed in 2010 provides a dedicated source of funding for the Atchafalaya Basin Conservation Fund when certain criteria are met; however, these criteria have not been realized yet, so funding for project implementation is wholly dependent on state and federal appropriations (Atchafalaya Basin Program 2012).

Act 606 helped maintain the focus of the State Master Plan by adhering to expressed desires and the public interest. It mandated the inclusion of the public in the development process for the Annual Plan. This is a turn from the heavy-handed, top-down approach that was used to establish the ARB as a floodway to a more inclusive management process that encourages involvement at the local and regional scales. By requiring an Annual Plan to be drafted and made public every year, the Act has set the table for an adaptive management approach to the environmental restoration and management of the ARB.

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Chapter 4. The Evolving Management of the Atchafalaya River Basin: Sources of Conflict and Suggestions for Resolution

4.1. Introduction

The recognition of complex bio-physical relationships and significant uncertainty in our understanding of ecosystem functioning has led to the development of learning-based approaches to natural resource management such as adaptive management (Holling 2005). Strong interdependence among resource users in natural resource systems revealed the need for managers to broaden learning-based management approaches to include the social components of environmental problems (Balint et al. 2011), since not only are ecosystems changing over time but also the human groups that depend on them (Ostrom 2007). These collaborative management approaches aim to incorporate the social issues of natural resource management by including resource users throughout the decisionmaking process to produce outcomes that are locally relevant and responsive to the socioeconomic needs of resource users.

Collaborative adaptive management combines the principles of adaptive management and collaborative management approaches to address both ecological uncertainty and the social components of problems. The merging of the two approaches came about because adaptive management without collaboration in multi-use resource systems can lack legitimacy, and collaborative management without learning-by-doing is unable to effectively address emerging biophysical problems (Berkes 2009). A collaborative adaptive management approach can enhance the institutional flexibility for managing socio-ecological systems, allowing managers of these complex human and natural systems to better deal with, and adapt to, change (Fernandez-Gimenez et al. 2008). This adaptability is because it is more aligned with the needs of resource users at multiple scales than adaptive management alone, and is more attentive to learning and adapting to physical and ecological changes in the system than collaborative management alone (Berkes 2009). Further, it provides the structure to incorporate local resource knowledge and social issues with scientific principles and natural resource policy through a management approach that links scientists, resource users, government managers, and stakeholders in collaborative problem solving (Charles 2004, Armitage et al. 2008).

Ecological and social uncertainty is acknowledged as inherent to environmental decision-making and is best addressed with collaborative, adaptive decision-making processes that recognize the value of multiple sources and types of knowledge for problem solving (Armitage et al. 2008). However, the differences in values and interests among interdependent stakeholders and managers make conflict a permanent feature of environmental decision-making (Dietz et al. 2003). This chapter draws inferences from recent, collaborative work in the Atchafalaya River Basin (ARB), Louisiana to appraise sources of conflict between local stakeholders and managers. We are guided by two research questions: 1) What are the sources of conflict and mistrust for local stakeholders in the current state-level decision-making process for conservation, restoration, and enhancement projects in the ARB? and 2) How can a more collaborative decision-making process effectively deal with these issues and improve management results? Section II of this chapter highlights the socioeconomic importance and the resource use landscape of the ARB and details the structure and process of state-level management efforts. Section III examines the first question by identifying sources of conflict in the current decision-making process based on ongoing work in the ARB. In Section IV, we address question 2 by considering the potential for collaborative adaptive management in the ARB. We then introduce a pilot project designed to mitigate conflict and mistrust through improved communication between scientists, managers, and stakeholders, specifically by advocating approaches designed to facilitate learning and knowledge transfer among stakeholder groups.

4.2. Study Area and Management Framework

The ~3715 km^2 ARB in Louisiana (Figure 4.1) is a complex system of bayous, navigation channels, and oil and gas canals. It begins at the confluence of the Mississippi and Red Rivers near Simmesport, LA and discharges 225 km south into the Gulf of Mexico. Bounded by east and west guide levees 24 to 40 km apart, it serves as the principal floodway of the Mississippi River and Tributaries Project and is an important navigation route between the Mississippi River and the Gulf of Mexico. The southern and central portion of the ARB is a mix of open water, cypress-tupelo forests, and bottomland hardwood forest while the northern, drier portion is heavily used for agriculture and commercial forestry. The region is home to commercial fisheries valued between $9 and $24 million dollars annually with wild crawfish harvests accounting for about half of that figure (Alford and Walker 2013). An estimated 50% of the migratory birds in North America stop in the ARB each year (Lindau et al. 2008) making it a destination for recreationists. The ARB is also touted as a “sportsman’s paradise,” with hunting and fishing as the main draws. At the local level it is the home of Cajun culture, a unique ethnic group that exerts an enormous impact on the state’s culture, and to a lesser extent, its economy (Gramling and Hagelman 2005). Approximately half of the ARB is privately owned and the other half is federal and state lands and waters.

Managers of the ARB need to negotiate a wide range of spatial (horizontal) and bureaucratic (vertical) scales. Spatially, the ARB’s direct interaction with the Gulf of Mexico is important, so management decisions that could potentially alter flow or sediment loads into the Gulf require approval by the Louisiana Coastal Protection and Restoration Authority. Also,

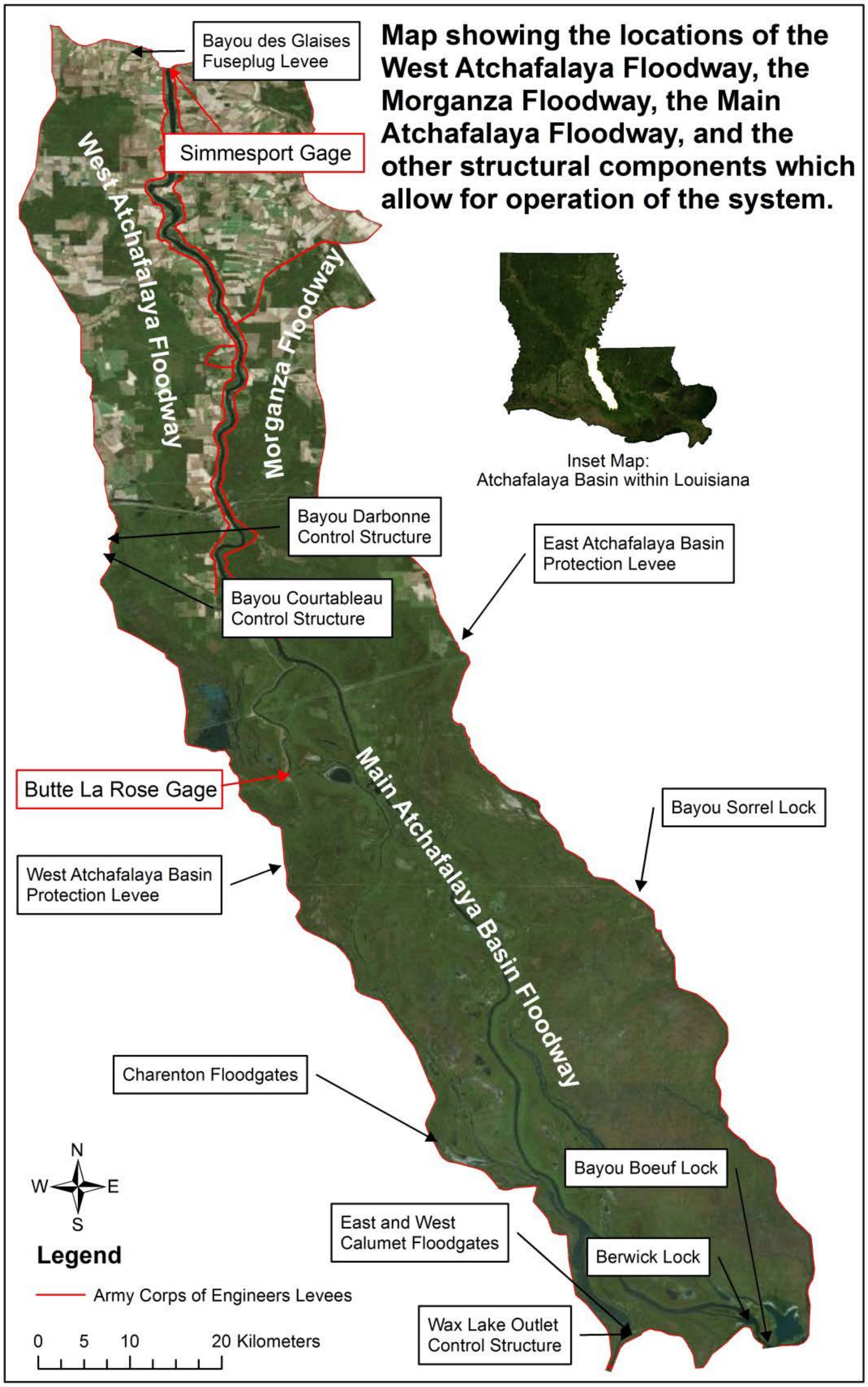


Figure 4.1. Map of the major structural engineered features of the Atchafalaya River Basin.

upstream conditions as far as the Missouri and Ohio River valleys are relevant to management decisions as the amount and quality of water flowing through those upstream basins have a direct effect on the hydrologic and ecological conditions in the ARB. Bureaucratically, water management projects for flood control and navigation and water quality projects are federal responsibilities of the U.S. Army Corps of Engineers. At the state level, water resource management of the ARB is the responsibility of the Louisiana Department of Natural Resources – Atchafalaya Basin Program (ABP) whose goal is to conserve, restore, and enhance the natural habitat of the ARB through collaboration with the U.S. Corps of Engineers (Atchafalaya Basin Advisory Committee 1998). At the local level, Parish governments recently had their role in management decisions expanded, acquiring one vote on the Research and Promotion Board (discussed below), but historically their involvement focused on access and recreation projects and avoided water quality projects because of controversy among constituent stakeholders (Don Haydel, Atchafalaya Basin Program, personal communication).

The economic incentives in the ARB are not always aligned with the condition of local ecosystems. The ABP must balance two conflicting water resource-use complexes in the ARB (van Beek et al. 1977). The first complex includes natural resources like food, raw materials, and recreation, which are largely maintained by natural processes such as overbank flooding and dewatering regimes. The second complex includes navigation, flood control, and mineral extraction, which require human alterations of the physical environment like channelization, canal dredging, and the deposition of dredge spoil. The latter actions favor channel flow at the expense of overbank flow which has increased siltation in lakes and back swamps and has interrupted backwater circulation, adversely effecting water quality (van Beek et al. 1977, Hupp et al. 2009, Kaller et al. 2011).

The ABP was established in 1998 with a primary focus on recreation in the ARB, but in 2005, this focus shifted to water resources management and public access. To codify this shift in public policy, the Louisiana Legislature passed Act 606 (LA R.S. 2008, House Bill No. 1135), creating the current structure and process for restoration management of the ARB (Atchafalaya Basin Program 2012). The Act also established a decision-making process that focuses on the development of an Annual Plan, increasing the flexibility of managers to adapt to changing environmental and socioeconomic conditions in the ARB. This transition to an adaptive, multi-use management approach brought with it a strong commitment to scientific principles and more transparency to the decision-making process through increased public involvement.

The annual plan process is driven by two groups (Figure 4.2) including a nine-member Technical Advisory Group (TAG) and a 14-member Research and Promotion Board (RPB). The TAG is composed of resource experts from state and federal agencies and is tasked with applying a scientific approach to restoration and resource promotion in the ARB. The RPB oversees the Annual Plan process, adopts criteria, determines eligibility, approves projects for the Annual Plan, and is required to hold public hearings prior to the adoption of the plan (Atchafalaya Basin Program 2012). There are two sets of public hearings each year. The first hearings invite the public to submit water resource projects for inclusion in the Annual Plan. These proposed projects are reviewed and evaluated by the TAG for scientific validity and then presented to the RPB for approval and inclusion in the Annual Plan. The second hearings are used to present the proposed Annual Plan to the public for input and comment.

The agencies involved in the Annual Plan process are responsible for monitoring the conditions of the ARB, and the requirements of Act 606 provide the necessary structure and communication pathways to facilitate institutional learning. This institutionalization of adaptive management principles allows decision-makers to manage the uncertainty in the system through monitoring, and creates the opportunity to make appropriate adjustments to management decisions over time (Charles 2007). This is an important policy direction for the ARB as ecological uncertainty will persist and a growing number of stakeholder groups must be considered in management decisions. However, persistent conflicts and mistrust between local stakeholders and managing agencies reveal shortcomings of the current approach.

Technical Advisory Group

- US Fish and Wildlife Service
- US Geological Survey
- US Army Corps of Engineers
- Dept. Wildlife and Fisheries
- Dept. Natural Resources
- Dept. Environmental Quality
- Dept. Ag. and Forestry
- LSU, Sch. Renewable Nat. Resources.

Research and Promotion Board

- Dept. Natural Resources
- Dept. Environmental Quality
- Dept. Health and Hospitals
- Dept. Culture, Rec., Tourism
- Office of Governor
- Dept. Transportation and Development.
- Dept. Ag. and Forestry
- State Land Office
- Dept. Wildlife and Fisheries
- Atchafalaya Levee Board
- St. Martin Parish (non-voting)*
- St. Mary Parish (non-voting)
- Iberville Parish (non-voting)
- Assumption Parish (non-voting)

Figure 4.2. Members of the Research and Promotion Board and Technical Advisory Group for the Atchafalaya Basin Program.

4.3. Conflict and its Sources

The management issues of the ARB are framed by scientific uncertainty, deep disagreements on facts and values, differing viewpoints, and a lack of consensus, all of which undermine trust and prevent cooperation. The strong interdependence among resource users and the ecological trade-offs inherent in those uses contribute to the challenge of devising effective governance regimes (Ostrom et al. 1999). Negotiating this interdependence requires trust and understanding by stakeholders, both of management decisions and in the actions of other resource users. Without this dynamic, as is the case in the ARB, there is little opportunity for stakeholders to collaborate in the decision-making process and therefore little incentive to cooperate. This has undermined management efforts. The following case study reveals some key sources of conflict and mistrust for local stakeholders in the current state-level approach to conservation, restoration, and enhancement projects in the ARB.

4.3.1. Cocodrie Swamp

The Cocodrie Water Management Unit is located in the western part of the central portion of the ARB (Figure 4.3). The dominant features of the Cocodrie Water Management Unit include the historical remnants of the old Bayou La Rose, the man-made canal of the present-day Bayou La Rose, the Cocodrie Swamps, and the Panatec Canal. The main environmental perturbations in this area include low dissolved oxygen levels and sedimentation of the historic waterways which are a result of a lack of river inflows from the upper end of the Cocodrie Water Management Unit through the swamps. The causes of these conditions are rooted in the anthropogenic manipulation of the canals and the oilfield access roads. Creation of more efficient canals, development of oilfield roads, and maintenance dredging operations have diverted discharge from historic waterways and created barriers to overland flow in the form of fairly uniform spoil banks. Sedimentation has also drastically reduced the spatial extent of the low-lying swamps and created problems of inflow and outflow relating to these crucial low-lying areas.

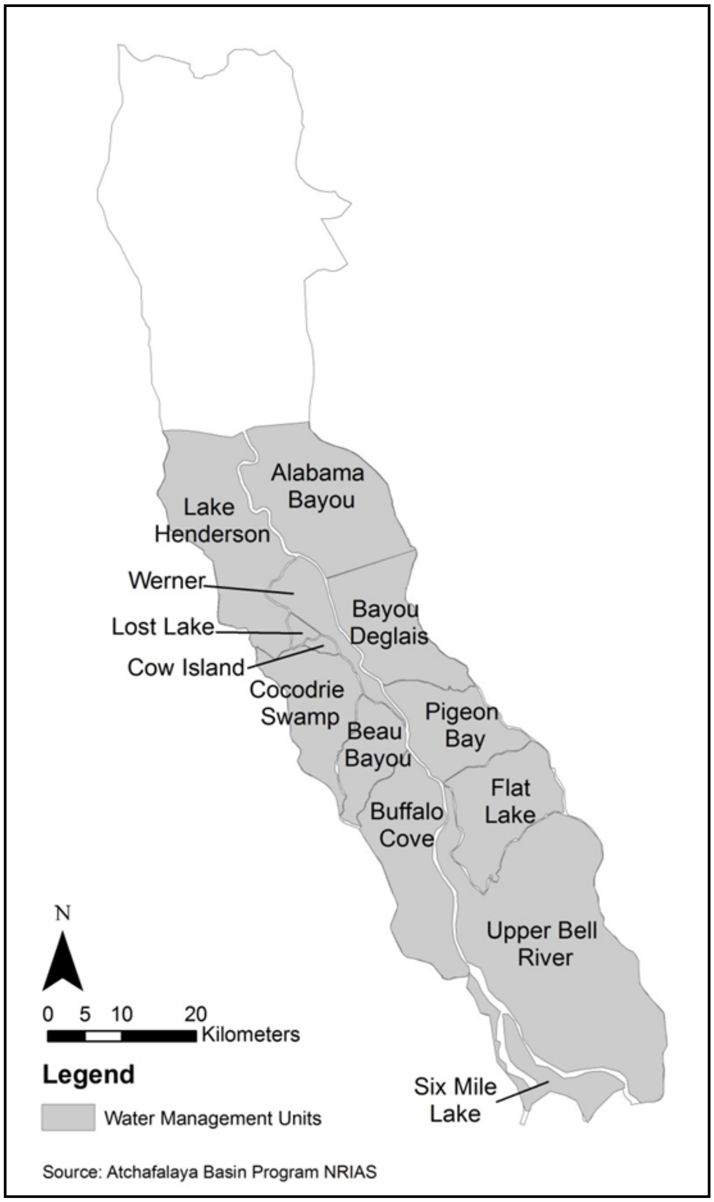


Figure 4.3. Map showing the location of the Water Management Units within the Atchafalaya Basin (Source: Atchafalaya Basin Program NRIAS).

Over the last decade, the ABP has worked towards the restoration of a more natural hydrologic regime throughout the ARB. The ABP has solicited suggestions for projects from various stakeholder groups through listening meetings and public comment sessions. In 2009, the Louisiana Crawfish Producers Association-West (crawfishermen) proposed a project for the Cocodrie Swamp Water Management Unit, which would promote overland flows out of the channels and into low-lying swamps and remnants of historic channels, or bayous. The primary concern of the crawfishermen focused on the reduced area of swamps and refugia for finfish and crawfish. The accretion of sediment within the historic Bayou La Rose has led to portions of the natural bayou and surrounding swamp being disconnected from freshwater inflows contributing to reductions in species and fishable areas.

The RPB, as part of the FY 2011 Annual Plan, approved and allocated $1,082,500 for engineering, design and construction of the Cocodrie Swamp Project (Atchafalaya Basin Program n.d.). The ABP proposed project would enhance water circulation and water quality in the unit for sport and commercial fisheries through the use of freshwater diversions, dredging of accumulated sediment, debris removal, and gapping of spoil banks to improve freshwater flow connection, circulation, and drainage (Figure 4.4). Currently, the ABP has begun to identify landowners and to contract for engineering services for the project.

After the crawfishermen reviewed the proposed plans they withdrew their approval of the project. This withdrawal of approval and support seemed based on two notions (Grissom, Ken n.d., n.d.). First, the project did not address the crawfishermen’s desire to have the historic remnants of Bayou La Rose reconnected to the anthropogenic system of canals and modified bayous, which would allow for access into the crawfish grounds of the historic Bayou La Rose. Today the historic Bayou La Rose is typically devoid of water and the crawfishermen would like to see that changed. Second, the crawfishermen contends that public funds should not be used since the oil and gas companies who constructed the access canals should pay for the gapping of the banks, which are the primary constructed features of the proposed project. They argue that the oil and gas companies did not follow the conditions of their permits during construction and dredging of the canals by placing the spoils of the construction onto the banks of the channels.

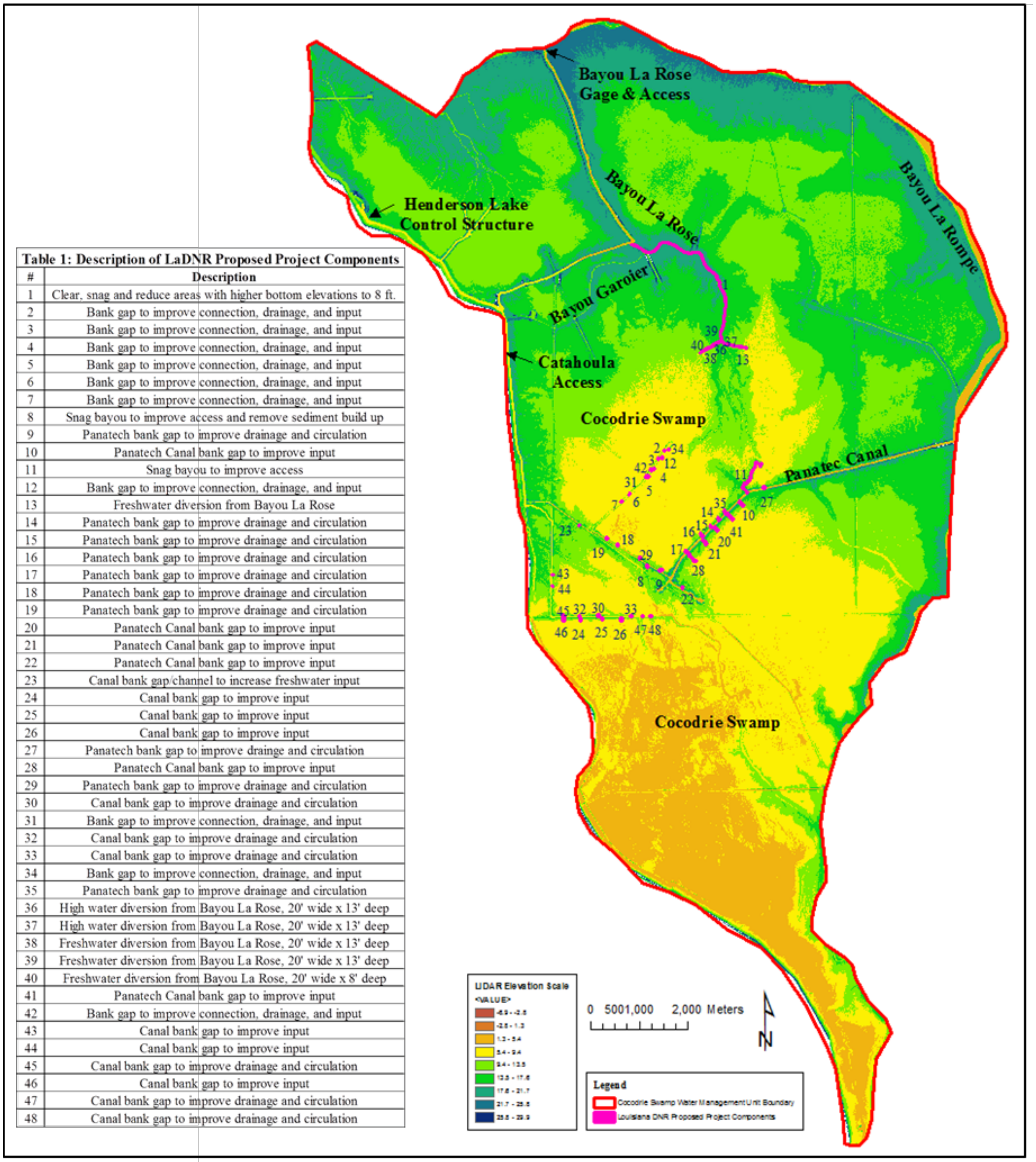


Table 1: Description of LaDNR Proposed Project Components

#	Description
1	Clear, snag and reduce areas with higher bottom elevations to 8 ft.
2	Bank gap to improve connection, drainage, and input
3	Bank gap to improve connection, drainage, and input
4	Bank gap to improve connection, drainage, and input
5	Bank gap to improve connection, drainage, and input
6	Bank gap to improve connection, drainage, and input
7	Bank gap to improve connection, drainage, and input
8	Snag bayou to improve access and remove sediment build up
9	Panatech bank gap to improve drainage and circulation
10	Panatech Canal bank gap to improve input
11	Snag bayou to improve access
12	Bank gap to improve connection, drainage, and input
13	Freshwater diversion from Bayou La Rose
14	Panatech bank gap to improve drainage and circulation
15	Panatech bank gap to improve drainage and circulation
16	Panatech bank gap to improve drainage and circulation
17	Panatech bank gap to improve drainage and circulation
18	Panatech bank gap to improve drainage and circulation
19	Panatech bank gap to improve drainage and circulation
20	Panatech Canal bank gap to improve input
21	Panatech Canal bank gap to improve input
22	Panatech Canal bank gap to improve input
23	Canal bank gap/channel to increase freshwater input
24	Canal bank gap to improve input
25	Canal bank gap to improve input
26	Canal bank gap to improve input
27	Panatech bank gap to improve drainge and circulation
28	Panatech Canal bank gap to improve input
29	Panatech bank gap to improve drainage and circulation
30	Canal bank gap to improve drainage and circulation
31	Bank gap to improve connection, drainage, and input
32	Canal bank gap to improve drainage and circulation
33	Canal bank gap to improve drainage and circulation
34	Bank gap to improve connection, drainage, and input
35	Panatech bank gap to improve drainage and circulation
36	High water diversion from Bayou La Rose, 20' wide x 13' deep
37	High water diversion from Bayou La Rose, 20' wide x 13' deep
38	Freshwater diversion from Bayou La Rose, 20' wide x 13' deep
39	Freshwater diversion from Bayou La Rose, 20' wide x 13' deep
40	Freshwater diversion from Bayou La Rose, 20' wide x 8' deep
41	Panatech Canal bank gap to improve input
42	Bank gap to improve connection, drainage, and input
43	Canal bank gap to improve input
44	Canal bank gap to improve input
45	Canal bank gap to improve drainage and circulation
46	Canal bank gap to improve input
47	Canal bank gap to improve drainage and circulation
48	Canal bank gap to improve drainage and circulation

Figure 4.4. Map showing the location and description of the Atchafalaya Basin Program's Cocodrie Swamp Water Quality Project components.

These spoil banks are the primary culprit in the disconnection of flows from the channels into and out of the swamps. Therefore, the crawfishermen believe that the constructor and maintainer of the access canals and bayous should fund the project that mitigates their prior actions.

As the proposed project stagnated with non-approval from the stakeholders, the National Audubon Society-Baton Rouge (Audubon) office was approached by the ABP to assist in building consensus with the crawfishermen. The use of a non-governmental organization to build relationships, find technical answers through sound scientific studies and approaches, and understand stakeholders' apprehension that may transcend economic, political, cultural, and environmental barriers is often unique in the field of water resource management. Audubon attempted to be a mediator using meetings to explain the current best available science and provide a rationale why the proposed project would be beneficial to crawfishermen. They also relayed the concerns of crawfishermen to the ABP. During spring 2012, Audubon performed investigative trips in the project area for the purposes of collecting flow data at various discharge levels and survey data to assist with calibrating a "nested" model. This resulted in Audubon suggesting the ABP develop a "nested" hydraulic model of the Cocodrie Swamp project area within a larger model of the entire ARB that models flows and sediment. The ABP is currently seeking additional funding sources to develop the "nested" model to provide a visualization tool to the stakeholders showing the flow and sedimentation effects of the project. Audubon also attempted to explain that an adaptive management approach should be taken that provides funding for continued monitoring and modification of the project's components based on future successes and failures.

There are lessons to be learned from the struggle to implement the Cocodrie Water Management Unit project. These lessons focus on the notion of trust between parties and on the importance of stakeholder involvement in the project development process. This experience reveals that stakeholder involvement is crucial to the success of public projects, and their involvement - beginning with the proposal - should continue throughout and beyond the implementation of the project. Trust and stakeholder capital could have been built by involving stakeholders more in the design stages of the proposed project. This could have included stakeholder and ABP participation in a design charrette; a collaborative forum for stakeholders to share project ideas that can then be vetted with the scientific, social, and environmental realities of the project area. Working through the ideas and perceived constraints for the project in a structured, collaborative manner improves the chances of reaching the best compromise, or solution, for the project. Further, stakeholders can learn that open-mindedness and trust are critical attributes when participating in public projects that are focused on improvements for their specific industry. Face-to-face meetings debating contentious issues are usually more productive than the venting of frustrations through the media or in public hearings. These “sit downs” often can produce aspects of an issue that all parties can agree upon. This “middle ground” of agreement should be what stakeholder involvement strives for. Instead, the ex-post attempt at collaboration fell far short of creating substantive involvement because it did not allow stakeholders to claim ownership of the project.

4.3.2. Discussion

The Cocodrie Swamp example highlights some of the sources of conflict for local stakeholders in the current decision-making process for conservation and restoration projects in the ARB. The majority of these restoration project ideas come from local stakeholders whose approval of developed projects affects their successful implementation; projects without public support are met with mistrust and have been destroyed (Daniel E. Kroes, TAG member, USGS, personal communication, 11/29/12). The Annual Plan approach is a more transparent process for managing the ARB; however, stakeholders are frustrated when managers cannot do what they want, when they want it, and how they want it (Charles Reulet, LDNR, personal communication, 11/20/12). Projects developed using the best available science are undermined by this inability to communicate science to local stakeholders. The public hearings of the Annual Plan process are insufficient for effective collaboration given the low level of involvement of local stakeholders.

To consider how to deal with these issues and facilitate improved collaboration, we first critique the current decision-making process with four necessary ingredients for effective, collaborative adaptive management (Charles 2007). The absence of these necessary ingredients can have strong negative implications for the sustainability and resilience of the social-ecological system (Armitage et al. 2008). We then follow with a technical approach to improve science communication to facilitate a more collaborative decision-making process.

1. A diverse management portfolio.

Just as biological diversity contributes to the resilience of ecosystems (Schindler et al. 2010), a diverse portfolio of management options can contribute to resilient management institutions (Charles 2007). The policy transition to a water resources management focus in the ARB resulted in an increased diversity of project types and a more balanced approach to ecosystem management. The Annual Plan process enables managers to incorporate new information and changes to the landscape into future plans. Managers of the ARB need this diverse portfolio as the hydrological conditions in the ARB can cause substantial changes in the landscape, altering the feasibility of certain projects and favoring others. Currently, stakeholders in the ARB are able to contribute to this management portfolio through project proposals at public hearings; however their ability to contribute beyond the project proposal stage is limited and remains a source of conflict in the ARB.

2. Robust management.

The uncertainties inherent in systems like the ARB make it risky to rely on management approaches that depend on high levels of controllability. Therefore, management plans need to be flexible to allow for the uncertain nature of the system (Charles 2007). The Annual Plan process gives managers the flexibility to adapt to changes in the bio-physical system. This robust management approach is also important for dealing with significant, random events like floods and hurricanes. However, the lack of collaboration with stakeholders can inhibit the ability of managers to avoid unintended socioeconomic impacts such as reduced access to traditional fishing grounds. Managers need the same flexibility to address emerging socioeconomic issues along with ecological issues. As ecological uncertainty and socioeconomic change will not disappear from the ARB, and long-term regional resource use decisions need to be made, increased management flexibility through collaboration with resource users and stakeholders will be necessary to mitigate conflict and avoid unintended social consequences in the ARB.

3. Full use of the knowledge base.

Successful collaborative adaptive management approaches depend on the full use of the knowledge base. Modern approaches to management rely on formal science, often ignoring the large quantities of traditional knowledge that have accumulated over time to users of the resource through their direct interaction with the local environment and communities (Charles 2007). Two key roles for the knowledge base are (1) assessing the state of the system at a given time and (2) monitoring that system over time. While Act 606 mandates public hearings, it provides no formal structure for ongoing public involvement in the decision-making process. Management of the ARB is lacking in its use of traditional knowledge as a supplement to the more formal science relied upon by managers. Limited personnel and funding currently strain the monitoring capabilities of state and federal agencies in the ARB. Bringing the vast stores of traditional knowledge and the monitoring potential of stakeholders such as commercial fishermen and private landowners into the management framework of the ARB through collaboration can improve the understanding of the system and the decision-making capabilities of the ABP. Further, including stakeholders in the decision-making process can reduce conflict as it incentivizes cooperation among stakeholders and managers because stakeholders now have a hand in creating the future of the ARB.

4. Institutional reform.

Collaborative adaptive management requires the capacity for institutional reform. As new knowledge becomes available and physical and socioeconomic systems change, institutions need to be able to adapt to the changing management landscape. Not only do management portfolios need to be resilient, but so also do the management institutions themselves (Charles 2007). Management of the ARB has undergone significant changes in the past 15 years. However, ongoing conflicts that contribute to waning support for the current approach, disinterest in unproductive public hearings, and mistrust of management decisions all indicate a need for further reform. The Atchafalaya Basin Program has already shown the capacity for institutional reform through the passage of Act 606, now it needs to build upon its successes and reassess its shortcomings - primarily the approach to stakeholder collaboration.

Clearly, there are shortcomings to the adaptive management approach in the ARB. The public hearings to solicit project ideas and present developed project ideas are inadequate to address stakeholder concerns and foster cooperation through understanding. Our experience highlights the need for a third party – an NGO in this case - to step in and serve as a bridging institution to facilitate communication and the spread of information between different levels of governance, bring together science and local resource knowledge using innovative approaches, and provide an arena for trust building and conflict resolution (Folke et al. 2005, Berkes 2009). This role is important in multi-use systems like the ARB that are influenced by complex vertical and horizontal scales. When effective, they establish learning networks that accumulate social capital and work to ensure the decision-making process is robust and resilient (Berkes 2009). A primary purpose of the ABP is to coordinate federal, state, and local conservation and restoration efforts in the ARB, and in this it has been successful; it has been much less successful coordinating with local resource users; seeking consensus and cooperation for a project that has already been developed, as with the Cocodrie Swamp project, still amounts to a backdoor inclusion of stakeholder interests. In short, the current decision-making process lacks the required communication pathways with stakeholders to facilitate a collaborative approach to adaptive management in the ARB.

4.4. A Technical Approach to Improved Stakeholder Collaboration in the ARB

Geographic Information Systems (GIS) have developed into powerful, low-cost tools for decision-makers. The ability to present large quantities of spatial data provides an excellent way to communicate science with non-technical audiences and can present different scenarios for management decisions in near real-time. The following GIS project, in its preliminary stages, is designed to improve collaboration and reduce conflict between landowners - a key stakeholder group - and decision-makers in the ARB. In addition to the foundational work of collecting and analyzing existing spatial data, potential avenues forward are also considered.

4.4.1. TNC GIS Suitability Analysis For Landowner Outreach

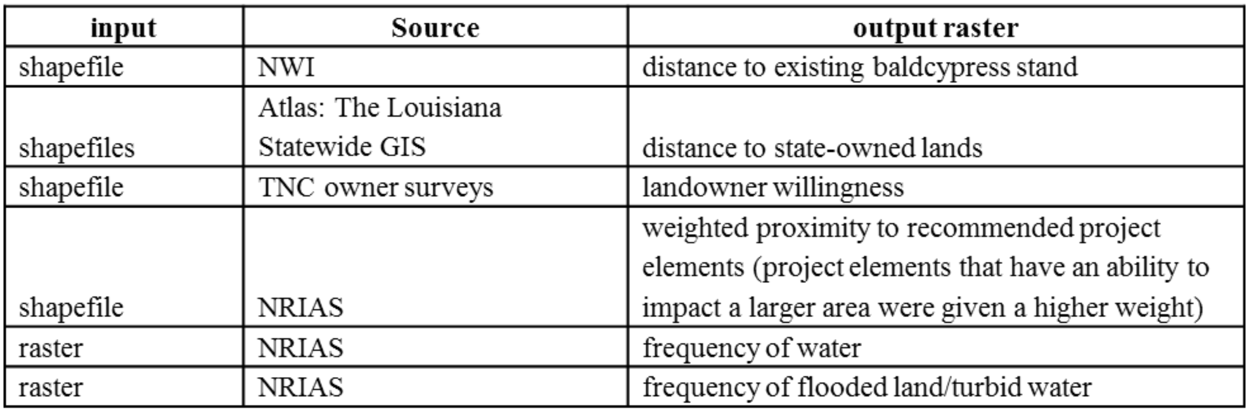
4.4.1.1. Introduction and goals. Decades of research, personal observation, and experience have convinced both stakeholders and agencies working within the ARB that hydrologic connectivity and forest health are issues that need to be addressed to maintain the ecological integrity of the ARB. This has resulted in the development, authorization, and funding of several large-scale, multi-feature, water management projects through the Annual Plan process. The effectiveness of individual restoration project features hinge in part upon the spatial characteristics of the chosen site. However, funding issues and a reluctance by landowners to site project features on their property in the ARB has stalled project implementation. Landowners question whether changes to their property will achieve the intended results and fear that, if successful, the improved hydrology would encourage trespass by other stakeholders in the ARB. Without the cooperation of specific landowners, the effectiveness and cost-effectiveness of water management projects can be compromised. To address these issues, non-governmental organizations (NGOs) may be able to play a unique role in changing the communication dynamics in the ARB to facilitate more productive collaborations between government agencies and landowners. The mission and core values of many NGOs include a commitment to non-confrontational, collaborative approaches that respect local cultures while remaining committed to the best available conservation science.

The Nature Conservancy (TNC) and Southern Illinois University collaborated on a preliminary GIS suitability analysis to identify land parcels in the ARB with attributes that indicate a higher likelihood for successful restoration projects and to effectively communicate that information to landowners in the ARB. Because forest health and water quality are such important issues, the preliminary GIS analysis focused on data sets that could help guide decisions regarding hydrologic reconnection and/or baldcypress regeneration. This GIS suitability analysis provides the foundation for a GIS – Multicriteria Decision Analysis (GIS-MCDA) framework that can be updated and modified as spatial data improves, and perhaps more importantly, provides a way to visually communicate information to landowners in the ARB in the future. The GIS-MCDA approach merges spatial decision making and multicriteria decision analysis so relevant quantitative and qualitative information can be considered in the decision-making process (Malczewski 2006). Decision makers routinely receive technical input regarding modeling/monitoring studies, risk assessment, cost-benefit analyses, and stakeholder desires, but no instructions on how to determine the importance of each input (Kiker et al. 2005). The process is potentially useful in the ARB, a situation involving many objectives, many stakeholders, and a high degree of uncertainty. The long-term goal of the project is to provide an outreach and learning tool for organizations to use in environmental decision-making contexts (for example, land protection programs and/or implementation of restoration projects in the ARB).

4.4.1.2. Methods. The GIS analysis was performed for the Flat Lake Water Management Unit (Figure 4.2) for two reasons. First, the East Grand Lake water quality/water management project proposed in the 2012 Atchafalaya Basin Program Annual Plan encompasses all of the Flat Lake Water Management Unit as well as the northern portion of the Upper Belle River Water Management Unit (Figure 4.2). The project consists of features intended to alleviate channelized flow and realign historic north-south sheetflow patterns. The report states: "The success of the entire East Grand Lake Upper Region and East Grand Lake Project area hinges on the implementation of a suite of construction projects that complement each other in order to keep the water moving from north to south throughout the region" (Atchafalaya Basin Program 2012). Thus, a piecemeal approach is not ideal and landowner resistance could undermine successful implementation of the project. Second, the area overlaps with baldcypress stands identified as regeneration condition class I (RCC-I), the regeneration class with the highest potential for natural regeneration; an important distinction since only 5.8% of baldcypress-tupelo forest in the ARB is classified as RCC-I (Faulkner et al. 2009).

Six datasets were used and modified (Table 4.1) to identify areas most suitable for restoration projects. Three of the data sets reflect naturally occurring hydrologic and biological processes (ecological suitability factors), while the other three attempt to take in to consideration potential anthropogenic factors that may affect the success of potential restoration projects (socioeconomic suitability factors).

Table 4.1. Data sources and modifications for final rasters.



input	Source	output raster
shapefile	NWI	distance to existing baldcypress stand
shapefiles	Atlas: The Louisiana Statewide GIS	distance to state-owned lands
shapefile	TNC owner surveys	landowner willingness
shapefile	NRIAS	weighted proximity to recommended project elements (project elements that have an ability to impact a larger area were given a higher weight)
raster	NRIAS	frequency of water
raster	NRIAS	frequency of flooded land/turbid water

a. **Ecological suitability factors.** These factors attempt to account for the physical and biological processes currently occurring in the ARB.

i. *Frequency of water*.

Numerous anthropogenic modifications have altered flow patterns and hydroperiod within the ARB. An understanding of these hydrologic parameters is necessary for suitability analyses aimed at potential baldcypress regeneration efforts or hydrologic connectivity. The

ARB is a complex, low-gradient system characterized by significant hydrologic uncertainty; however, recent research offers greater insight into these physical processes in the ARB.

Allen et al. (2008) reclassified Landsat images into dry land or water at nine different stages at the Butte La Rose (BLR) gage (Figure 4.1). Since the time of publication, more images have been analyzed and reclassified, resulting in a total of 30 images at stages ranging from 1.6 ft. to 21.2 ft. at the BLR gage (Atchafalaya Basin Program n.d.). Raster calculator was used on the classified images so the frequency of water could be determined; pixel values range from 0/30 (never inundated) to 30/30 (inundated in every image).

ii. Water quality

Although hypoxia is naturally occurring, there is evidence that flow alterations have affected water quality and increased hypoxia in the ARB (Sabo et al. 1999a, 1999b). Dredging and channelization have led to the disconnection of backswamps, causing forest health to deteriorate as essential nutrients from the main channel are cut off from these more remote areas. Connectivity to the main channel can be used as a proxy for nutrient availability to assess water quality.

Landsat images were also classified into six distinct classes based on wetness and turbidity characteristics as follows: 1) dry land; 2) open turbid water; 3) open non-turbid water; 4) flooded land turbid water, 5) flooded land non-turbid water; and 6) aquatic vegetation (Atchafalaya Basin Program n.d.). Open turbid water generally consisted of main channels in the system so flooded land – turbid water was the main category of interest as a proxy for main-channel connectivity. Flooded land – turbid water was reclassified to a value of 1 and all other categories were reclassified to a 0 value. Raster calculator was then used again to determine the frequency of flooded land – turbid water, with resulting values ranging from 0/30 to 29/30.

iii. *Potential existing baldcypress sites.*

Classified land cover data from the U.S. Fish and Wildlife Service National Wetlands Inventory was mosaicked for the area of interest ("National Wetlands Inventory" n.d.). Baldcypress are the only needle-leaf deciduous trees in the study area and are designated by PF02 in the National Wetlands Inventory-; only those units beginning with this designation were selected (Faulkner et al. 2009). The Euclidean distance tool was then used on these selected parcels to create a distance raster.

b. **Socio-economic suitability factors.** These factors incorporate social and economic factors that may affect project feasibility. For instance, approximately half of the ARB is privately owned, and landowner attitudes toward restoration projects can indicate the perceived legitimacy of specific restoration projects. Strong resistance would contraindicate certain restoration locations on cost-effectiveness grounds given the past actions of locals to undermine unpopular management actions.

i. *Distance to state-owned lands.* Parcel data with land owner attributes were used to select state-owned lands. Agencies are likely to be supportive of planned restoration measures so proximity to state-owned lands is important when attempting to implement connectivity measures. The Euclidean distance tool was used on the state-owned parcels to create a distance raster.

ii. *Landowner willingness*

Parcel data with land-owner attributes were supplemented with previously-conducted TNC landowner surveys. The surveys were conducted to examine potential landowner willingness to enter into conservation easements and then used as a proxy to gauge landowner willingness to implement restoration measures aimed at improving forest health and water quality. A numeric willingness attribute field was added, with 1 = not at all willing and 5 = very willing. The shapefile was then converted to a raster.

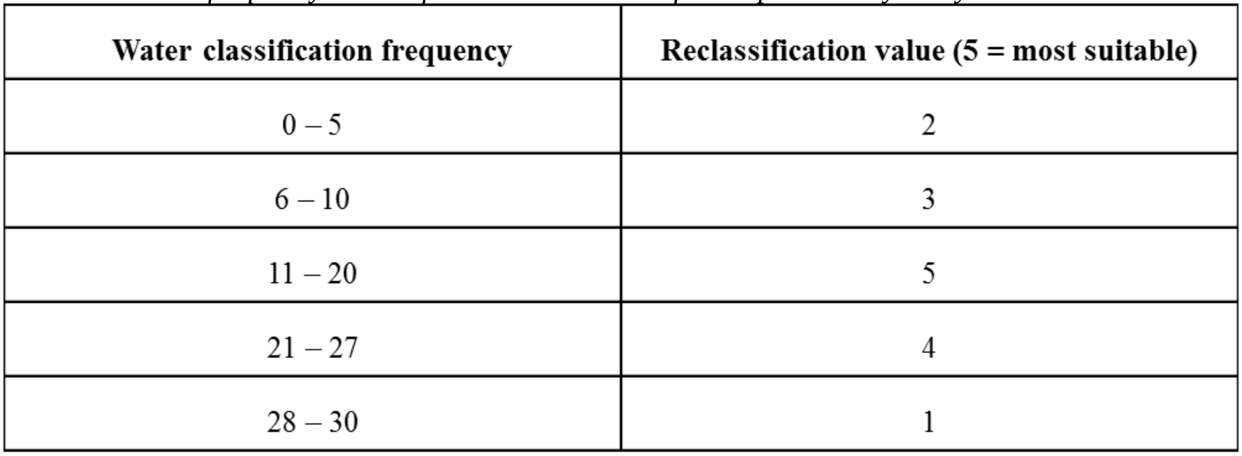
iii. Weighted proximity to recommended East Grand Lake project elements

A total of 173 project elements (including bank reduction/gap development, re-establishment of water inputs, and clean-outs) have been recommended by the TAG for funding in order to improve freshwater input and restore more natural flow patterns in East Grand Lake. Project element locations were selected for areas with identified need for improvement and where specific project elements are likely to be cost-effective based on site characteristics (Atchafalaya Basin Program n.d.). Landowner agreement was not considered. Generally, project elements are designed to improve flow between Assessment Units (subunits of Water Management Units) or to improve flow into a specific Assessment Unit. Assessment Units represent areas that “may be expected to experience similar water quality conditions at a given elevation and river level” (Atchafalaya Basin Program n.d.). We account for the potential impact area of each project feature by adding Assessment Units to the analysis. Project elements affecting Assessment Units with large potential impacts were given greater weight in the final raster surface.

4.4.1.3. Final analysis steps. Final output rasters were resampled to a cell size of 30 m and reclassified to a common ranking scheme (1 – 5) so cells with the highest ranking were considered most suitable for restoration projects (Table 4.2). Using the weighted overlay tool, each raster data set can be assigned a weight in order to produce a final single suitability surface (Figure 4.5).

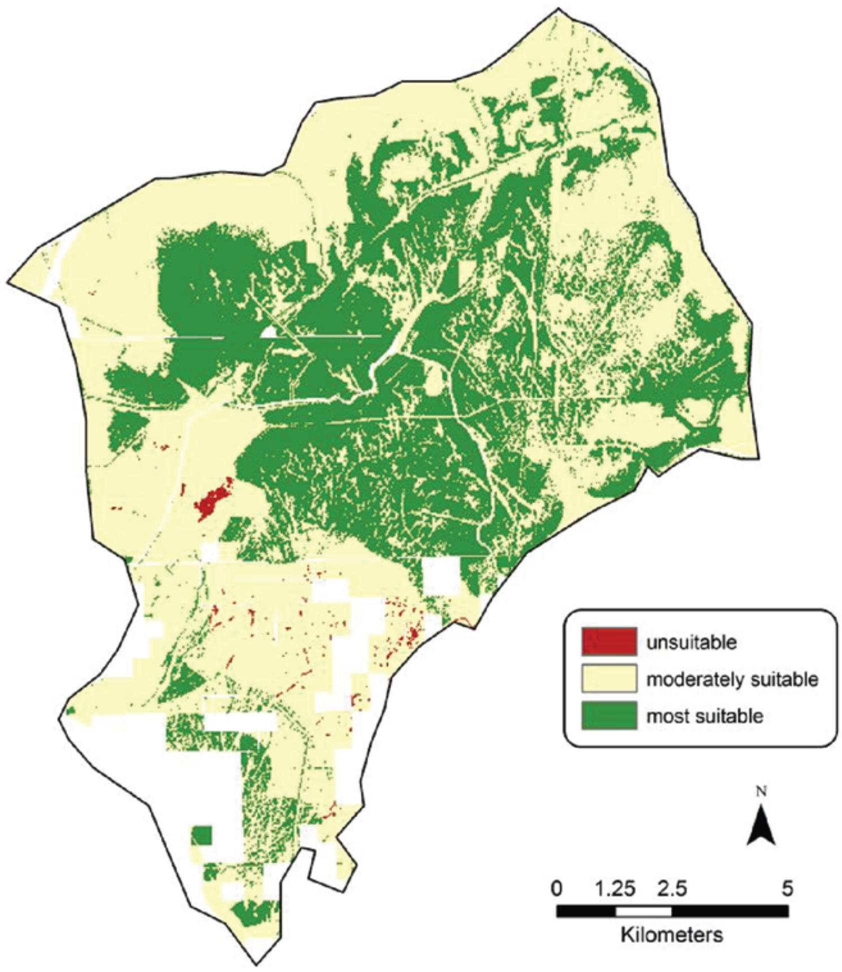
4.4.1.4. Results. The single resulting output surface indicates areas that are most suitable, suitable or not suitable for restoration projects. It is important to note that the weighting decisions at this point are solely for purposes of illustrating the process and do not represent a final product. In the example provided regarding baldcypress restoration (Figure 4.5), the combined ecological suitability factors were given greater weight (70% of total) than the combined socio-economic suitability factors (30% of total). As the project progresses, stakeholder input will be sought for final reclassification values where needed, which may result in a different surface.

Table 4.2. Water frequency reclassification scheme used for the preliminary analysis.



Water classification frequency	Reclassification value (5 = most suitable)
0 – 5	2
6 – 10	3
11 – 20	5
21 – 27	4
28 – 30	1

4.4.1.5. Advantages and limitations of a GIS-MCDA approach. An advantage to this approach is that once input rasters are created, the weighting can be easily changed depending on the particular restoration project goal. For example, in a suitability analysis aimed at identifying sites that have a high potential for baldcypress regeneration, the frequency of water and frequency of flooded land/turbid water (used as a proxy for forest health) might be given much greater weight than the other layers. However, if the suitability analysis is geared towards implementing hydrologic reconnection, proximity to recommended project elements and landowner willingness can be given greater consideration.



Raster	weight (%)
frequency of water	30
frequency of flooded land/turbid water	20
distance to existing baldcypress	20
weighted proximity to recommended project elements	10
distance to state-owned lands	10
Landowner willingness	10

Figure 4.5. An example of an output suitability surface for potential baldcypress regeneration in the Flat Lake WMU. Now that input rasters have been created, weights can be changed according to expert and/or local stakeholder inputs.

While this approach may lead to improved and more legitimate management decisions, potential drawbacks are worth noting. Even in areas where high-quality, high-resolution spatial datasets are available, there is significant difficulty in accurately modeling ecological processes. Such limitations should be clear to all involved so that efforts can be made to obtain the best possible data for the decision situation. As spatial data sets and modeling efforts continue to improve, the level of uncertainty can be lessened.

Continued development and refinement of such an approach could allow increased stakeholder involvement throughout the planning process. One complicating issue, however, is that certain attributes are not readily available in a spatial data format (e.g. cultural importance, scenic beauty) (Strager and Rosenberger 2006). Incorporating such data into the currently existing GIS analysis maybe challenging but is important for a collaborative approach to management in the ARB. Participatory GIS can be practiced in a number of forms and has been used to successfully incorporate citizen involvement in a variety of natural resources management contexts (Meredith et al. 2002, Balram et al. 2003, Nyerges et al. 2006, Jankowski 2009). One relatively low cost and low technology way to incorporate GIS here may simply be to sit down with identified relevant stakeholders, interview them, and let them define culturally significant areas on regular topographic maps/aerial photographs, similar to an approach advocated for incorporating local knowledge in New England fisheries (St. Martin 2001). Identified areas could later be digitized and used directly in the weighted analysis, or as an overlay to highlight areas of concern. For situations where a higher level of technological integration is desired (for example, visualizing scientific issues involving uncertainty), a GIS professional could be present at a public meeting to help guide stakeholders through various exploratory scenarios, updating maps for instant visualization and immediate integration of local knowledge. Alternatively, because public meetings can often be contentious, content can be made available online and provide an alternate forum for feedback (Jankowski et al. 2009).

However, before implementing any particular approach, it is important to consider the audience and their willingness to use and access various technological resources.

4.5. Conclusion

The history of the ARB and the strong interdependence of its stakeholders ensure that conflict will continue in the ARB. The past two decades have produced sweeping changes to the management of the ARB; a transition that needed to balance increased local control of the system with the federal requirement of flood control while also preventing the degradation of the ARB's considerable natural resources. We suggest that a collaborative component is missing from the decision-making process and that this is negatively impacting management efforts. Currently, NGOs are stepping in to bridge the communication gaps between decision-makers and local stakeholders in the ARB with limited success. More direct involvement of stakeholders in the decision-making process would facilitate collaboration through a continuous line of communication with the ABP. In this chapter, we offer a technical solution towards that end with a key stakeholder group. Many important steps towards improved management of the ARB have been taken. Now, the institutions with the power to enact changes to management must learn from their previous decisions, adapt their framework to better manage the remaining issues, and begin the process all over again.

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Chapter 5. Using Flow-ecology Relationships to Evaluate Potential Ecosystem Service Trade-offs and Complementarities in the Atchafalaya River Basin

5.1. Introduction

Ecosystem services are the fundamental benefits that ecological systems provide to humans through their natural functions and processes (Daily et al. 2000). Freshwater ecosystems such as wetlands and floodplain swamps provide many of the most highly-valued services among ecosystem types, including direct water supply, flood mitigation, and waste treatment (Costanza et al. 1997). Freshwater systems are highly managed and controlled in much of the United States and worldwide, often in order to maximize certain ecosystem services such as electricity generation (hydropower dams), water delivery (irrigation canals or reservoirs), or flood control (dams and levees). Such management decisions affect the multitude of other services freshwater systems provide, yet these dynamics are complex and not always considered in management actions.

Some ecosystem services are complementary and may respond similarly to a management action. For example, clear-cutting may decrease both moisture/rainfall and wood production in tropical forests (Bennett et al. 2009), or maintaining river flows for drinking water will also maintain river services such as waste removal and recreation opportunities. Other ecosystem services may have divergent responses to management actions, resulting in trade-offs in which an increase in one service results in the reduction of another. For example, in freshwater systems, removing water for irrigation or water supply can have a direct negative effect on other services such as hydropower generation, transportation, and waste removal (Rodríguez et al. 2006). Complementary and trade-off relationships such as these are often characterized by nonlinear relationships, thresholds, and feedbacks that are not well understood (Rodríguez et al. 2006, Bennett et al. 2009). Understanding the complex relationships among multiple ecosystem services is crucial to adaptive and collaborative ecosystem management (Rodríguez et al. 2006, Bennett et al. 2009, Raudsepp-Hearne et al. 2010).

The Atchafalaya River Basin (ARB) in Louisiana, the largest contiguous bottomland hardwood swamp in North America, provides many ecosystem services and resources to society valued in the billions of dollars annually. Provisioning services, those which provide direct goods (Millennium Ecosystem Assessment 2005), are the most well-known and are valued monetarily in the ARB. For instance, finfish and shellfish fisheries in the ARB produce 5.9-11.5 million kg in landings valued at $8.9-$24 million annually (Alford and Walker 2013). Regulating services, those that maintain living conditions for humans, are less tangible but include services such as crop pollination, flood mitigation, and water purification. Supporting services may be even less appreciated by the public, but are the underlying ecosystem processes that produce direct services. For instance, denitrification is the microbial transformation of nitrate (NO_3^-) to atmospheric nitrogen and removes agricultural pollutants from freshwater ecosystems (Mitsch et al. 2001). The ARB is generally a net source of nitrogen to the Gulf of Mexico, exporting 2.3% more mass of nitrate and nitrite (NO_2^-) than entered the ARB from 1978 to 2002 (Xu 2006, Turner et al. 2007, BryantMason and Xu 2013). Maximizing denitrification has been identified as a potential way to decrease the hypoxic zone in the Gulf of Mexico (Mitsch et al. 1999, 2001, Mitsch and Gosselink 2007). Other supporting services include other nutrient cycles, primary production, and soil formation (Millennium Ecosystem Assessment 2005, Rodríguez et al. 2006). Cultural services such as aesthetic or spiritual value and recreational opportunities are also provided by the ARB, but are less valued economically; however, recreational fishing provides significant economic benefits to Louisiana and communities near the ARB, as it is the most popular recreational fishery in the state (Holloway et al. 1998).

Despite the importance of the ARB in terms of ecosystem services, many functions (and resulting services) of the ARB are degraded due to large-scale and local water management problems resulting from its primary management for flood control and navigation. While there is interest in altering the mandated flow regime in the ARB, the many stakeholders and services in the ARB make such a decision difficult to implement.

Since it became operational, various stakeholder groups have raised the possibility of altering the Congressionally-mandated flow regime at Old River Control Complex (ORCC). The current flow distribution reflects the annual conditions that existed in 1950; therefore, 70% of the combined flow from the Red and Mississippi rivers is allocated to the Mississippi River, and 30% is allocated to the Atchafalaya River. As a general practice, this 70-30 split is maintained on a daily basis (Water in the Basin Committee 2002, Reuss 2004).

Different user groups have advocated for various changes. Farmers in the Red River basin would like to see less Mississippi River water diverted during the growing season to reduce crop losses associated with flooding, whereas fish and wildlife and environmental interests generally advocate for more water, not less. During the draft Environmental Impact Statement process in the 1970s and early 1980s, the U.S. Army Corps of Engineers (USACE) considered 10 different ORCC operation plans at one point, but ultimately resisted any major change, allowing only that warranted short-term changes may occur periodically (Reuss 2004). From 1983–2012, the flow distribution was changed 9 times through requests to the Louisiana Governor's Office (Appendix E; Water in the Basin Committee 2002; Don Haydel, Atchafalya Basin Program, pers. comm.).

The feasibility of changing the flow regime was again addressed by the Water in the Basin Committee in its 2002 report to then-Governor M.J. Foster. Their task was to examine potential changes to the flow regime and make recommendations concerning water management in the ARB. Based on interviews with various stakeholders, they found that user groups generally wanted more water in backswamp areas, but felt that timing and duration of such releases was important and had serious concerns regarding the potential negative impacts to certain user groups. The committee's final recommendations included continuation of short-term changes to flow regime under certain circumstances (using Butte La Rose as the control gage), and stressed that flow changes are only effective at certain stages given barriers that block flow into backswamp areas. According to the report, these flow impediments need to be addressed before flow reallocation can be successful; further, addressing these issues may limit the need for changes to the flow regime if water can enter backswamp areas at lower stages (Water in the Basin Committee 2002).

Increased knowledge of the complementarities and trade-offs among ecosystem services will allow policy-makers to better understand the impacts of various management decisions on ecosystem services and stakeholder cooperation in the ARB. In an attempt to evaluate these relationships, we analyzed trends in 20 ecosystem service-related variables in relation to hydrology within the ARB since 1963 and identified complementary and trade-off relationships among ecosystem services.

5.2. Materials and Methods

5.2.1. Study Area

The ARB is located in south-central Louisiana (Figure 5.1) and contains the largest continuous area of bottomland hardwood forest in the U.S., along with cypress-tupelo swamps, lakes, marshes, bayous, and man-made canals (Ford and Nyman 2011). The Atchafalaya River is the largest distributary of the Mississippi River, and following the devastating flood of 1927 it became a principal floodway of the Mississippi River & Tributaries Project. Then, in the mid-1900s, the ARB was recognized as the site of an ongoing delta-switching event. If left to its natural state, it was feared that the Mississippi River would permanently change its course. Such an avulsion would be economically devastating given the significant port infrastructure of the lower Mississippi (Fisk 1944, 1952, Reuss 2004). To prevent this the USACE built the ORCC, which became operational in 1963, to keep the Mississippi River on its current path to the Gulf of Mexico (Saucier 1998). The ARB receives a mandated 30% of the combined flows of the Mississippi and Red Rivers through the ORCC (Alford and Walker 2013); the Corps aims to maintain this 70–30 split on a daily basis during normal flow conditions (Joe Harvey, USACE, personal communication). Due to its designation as a federal floodway, the fluvial system has undergone extensive anthropogenic modifications (see Chapter 2 for details); today the ARB is enclosed by levees spaced on average 25 km apart. These east and west guide levees have severed the connection between the river and historically connected swamps, and reduced the ARB from approximately 8,345 km^2 to its current extent of 3715 km^2.

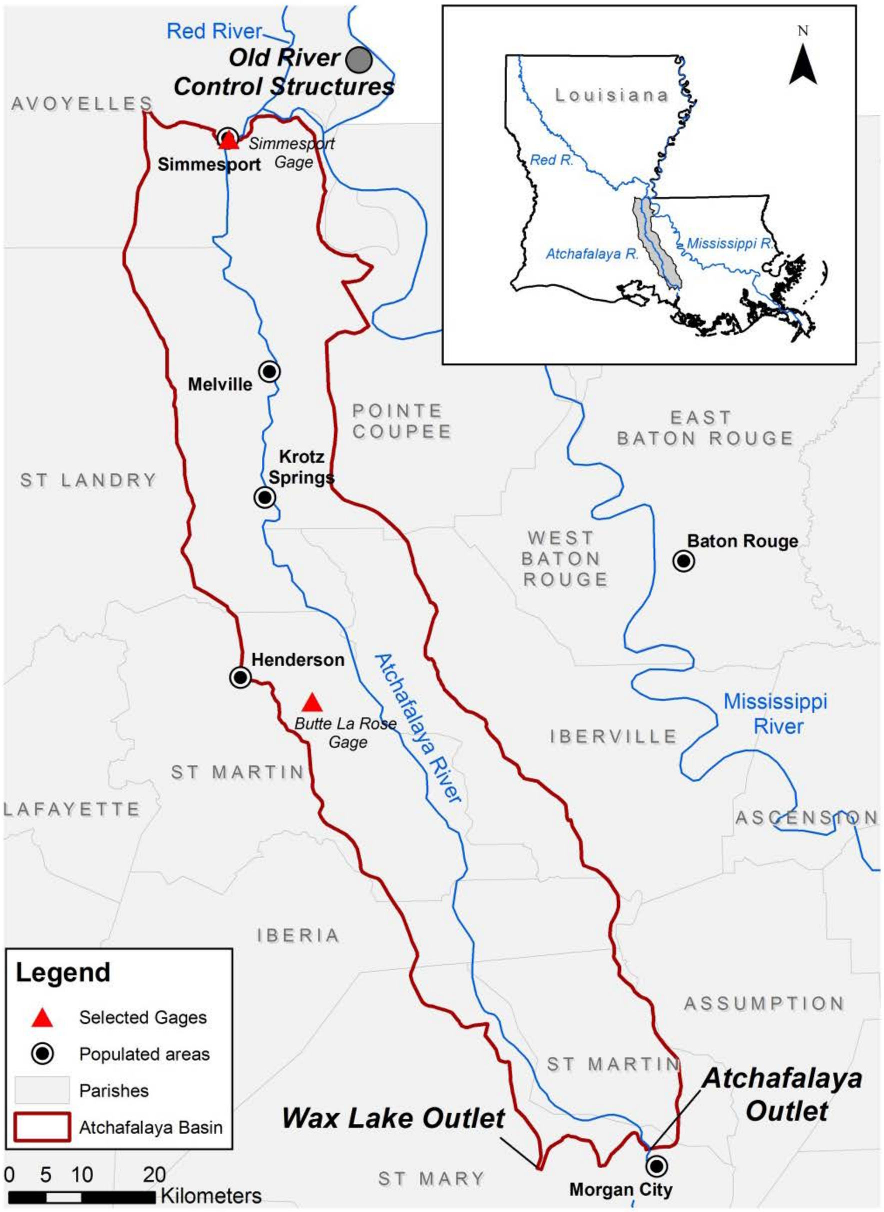

Figure 5.1. The Atchafalaya River Basin in central Louisiana with relevant features shown.

Our study relates basin-wide ecosystem services to discharge at the Simmesport gage (U.S. Geological Survey – USGS – Gage 07381490; USACE Gage 03045; Figure 5.1), located at river mile 4.9. The denitrification model (see below) examines potential denitrification and relies on stage at the Butte La Rose gage for calculations (BLR; USGS gage 07381515; U.S. Army Corps of Engineers gage 03120; Figure 5.1). Given the spatial constraints of the existing predicted inundation data obtained from the Atchafalaya Basin Program's Natural Resource Inventory and Assessment System (NRIAS), the model looks at potential denitrification only in the southern portion of the ARB (1756 km^2) (Figure 5.2). The Butte La Rose gage, located at river mile 64.8 is an important baseline for existing inundation data in the ARB (Allen et al. 2008).

Figure 5.2. Study area for denitrification model after applying exclusion criteria.

5.2.2. Hydrologic Data

The Simmesport and Butte La Rose gages have been operated by the U.S. Army Corps of Engineers (USACE) since 1887 and 1928, respectively. Both gages collect stage height at 7 a.m. daily. Daily data from the BLR and Simmesport gages were analyzed from January 1, 1963 to October 15, 2012; dates that correspond to the current flow release policy of the ARB (i.e. post-ORCC). A total of 74 dates were removed due to the measurement having a negative value of -901 for that date. If a value was removed from one data set it was also removed from the other. The longest resulting gap in the record was 14 days. Although the BLR gage is recognized as being an important gage for understanding the hydrology of the ARB (Alford and Walker 2013), we wanted to explore ecosystem services in the context of potential management decisions such as changes to the flow regime at the ORCC. Therefore we chose the Simmesport gage, located just downstream of the structure, to examine the statistical relationships between flow and ecosystem services.

A hydrologic analysis was performed to determine that discharge at Simmesport can be used as a proxy for discharge at the Butte La Rose gage without any lag adjustment. The statistical relationship between stage height at the two gages is strong (linear regression, $R^2 = 0.94$). Further, hydrographs and histograms for gage height and discharge from both gages show the same trends and long term cycles (Figure 5.3ab). Flow in the ARB is characterized by high flows in the spring months (March – May) and low flows during late summer to early fall (August – October) (Figure 5.4).

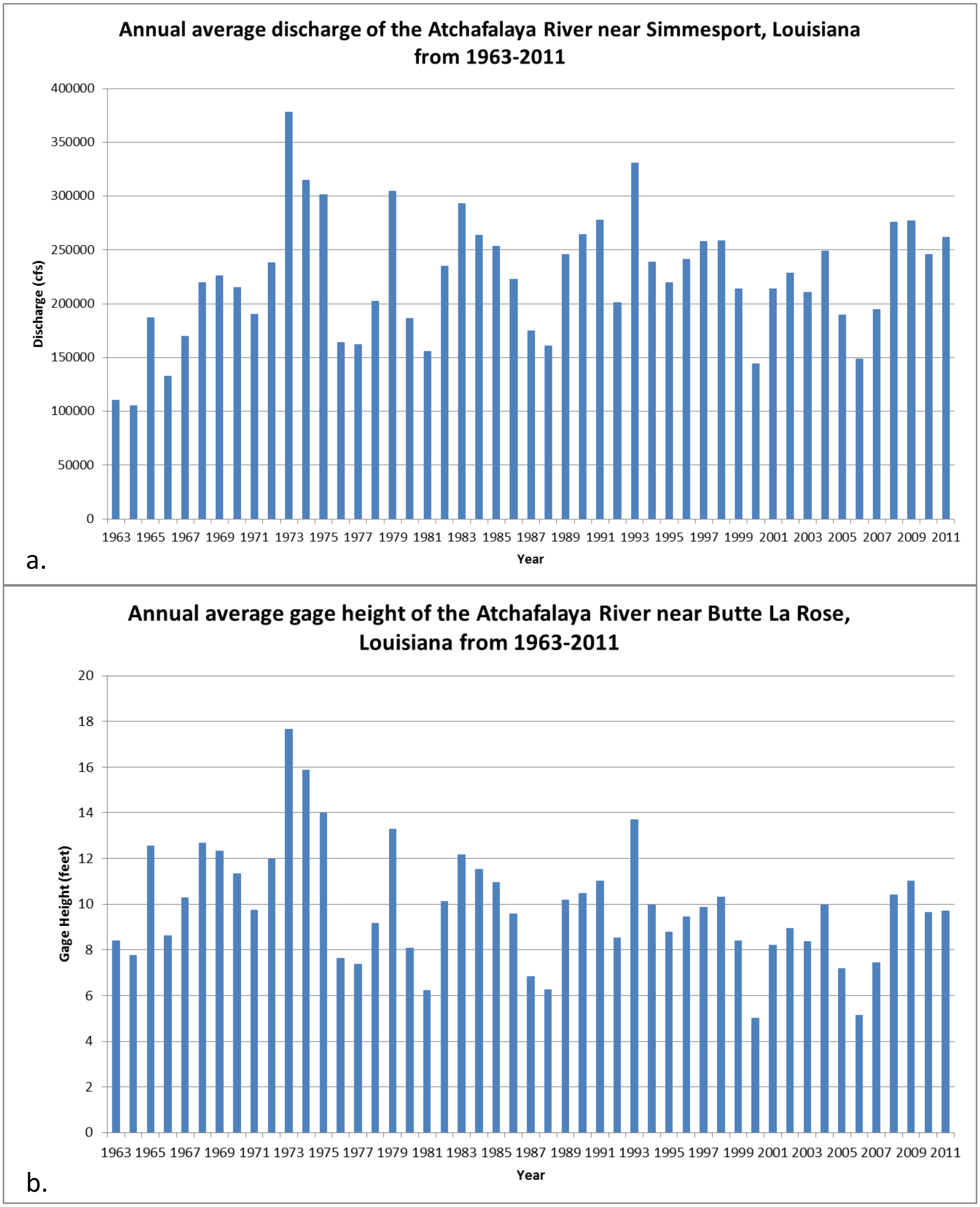

Figure 5.3. Comparison of mean annual discharge for Simmesport(a) and gage height for Butte la Rose (b) on the Atchafalaya River from 1963-2011.

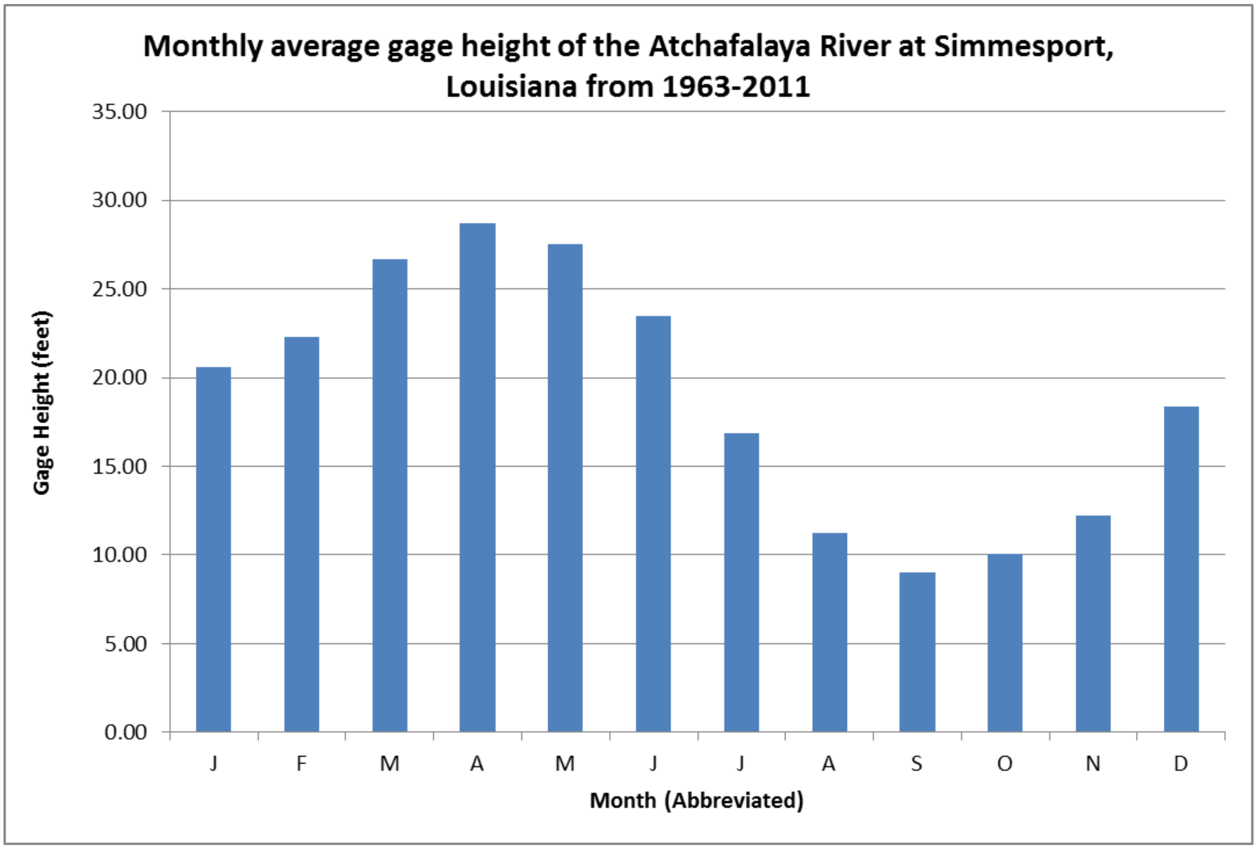

Figure 5.4. Mean monthly discharge at the Simmesport gage from 1963-2011.

We used Indicators of Hydrologic Alteration (IHA) software (Richter et al. 1996) to calculate 42 metrics of hydrologic variability for each year in the hydrology dataset (1963-2011). We combined monthly low-flow and monthly average flow data into seasonal metrics and excluded variables with missing data for a total of 23 hydrologic metrics from IHA. In addition, annual mean flow and coefficient of variation (CV) of daily flows were added for each year. Because animal populations can be strongly influenced by conditions during juvenile periods, and effects of flow may not show up in adult populations for several years, we also added lagged mean flow from one to five years (i.e., mean flow one year prior through five years prior) based on the time to maturity for the fish species of commercial and recreational importance in the ARB (see below). These calculations gave us a total of 30 hydrologic metrics (Table 5.1).

Table 5.1. Hydrologic variables used in analyses and their loadings on the three significant principal component axes. Percent of variation explained by each axis in parentheses.

Hydrologic Variable	**Description**	**PC1 Loading** (37.2%)	**PC2 Loading** (15.9%)	**PC3 Loading** (8.2%)
Mean flow	Average daily flows	**-0.28200**	0.08469	0.05495
Mean 1yr lag	Average daily flow 1 year prior	-0.10755	0.09451	-0.0648
Mean 2yr lag	Average daily flow 2 years prior	0.00250	-0.02979	-0.14518
Mean 3yr lag	Average daily flow 3 year prior	0.01408	-0.02624	**-0.24608**
Mean 4yr lag	Average daily flow 4 year prior	-0.02491	0.10759	**-0.30804**
Mean 5yr lag	Average daily flow 5 year prior	-0.01912	0.06587	**-0.24323**
CV	Coefficient of variation in daily flow	**0.16557**	**0.31569**	0.04993
Median flow	Median of daily flows	**-0.26697**	0.04545	0.07549
1-day minimum	Annual minimum 1-day means	**-0.25332**	-0.16847	0.03848
3-day minimum	Annual minimum 3-day means	**-0.25353**	-0.17109	0.01724
7-day minimum	Annual minimum 7-day means	**-0.25625**	-0.16807	0.01458
30-day minimum	Annual minimum 30-day means	**-0.26123**	-0.15160	0.02122
90-day minimum	Annual minimum 90-day means	**-0.25468**	-0.15591	0.03785
1-day maximum	Annual maximum 1-day means	**-0.20931**	**0.30296**	0.04333
3-day maximum	Annual maximum 3-day means	**-0.20771**	**0.30548**	0.04760
7-day maximum	Annual maximum 7-day means	**-0.20627**	**0.30745**	0.05425
30-day maximum	Annual maximum 30-day means	**-0.20691**	**0.30237**	0.07651
90-day maximum	Annual maximum 90-day means	**-0.22809**	**0.25484**	0.07087
Base Flow Index	7-day minimum flow divided by mean annual flow	-0.09381	**-0.33712**	-0.08165
Date of minimum	Julian date of minimum flow	-0.07578	0.13644	-0.05994
Date of maximum	Julian date of maximum flow	-0.06779	**-0.22707**	0.05371
Low pulse count	Number of occurrences of flow pulses below 25th percentile of daily flows	0.13927	0.03334	**-0.27765**
High pulse count	Number of occurrences of flow pulses above 75th percentile of daily flows	-0.15430	0.06588	-0.08474
Rise rate	Mean of all positive differences between consecutive daily flows	-0.12915	0.05390	**-0.42594**
Fall rate	Mean of all negative differences between consecutive daily flows	**0.18180**	-0.08989	**0.34004**
Reversals	Number of negative and positive changes in flow from one day to the next	-0.02633	-0.01410	**-0.55328**
Winter low flow	Average of monthly mean low flows Dec-Feb	**-0.22328**	0.00386	0.05263
Winter mean flow	Average of monthly mean flows Dec-Feb	**-0.18434**	-0.14534	0.05649
Spring mean flow	Average of monthly mean flows Mar-May	-0.11651	-0.13943	0.04620
Summer mean flow	Average of monthly mean flows Jun-Aug	-0.10607	-0.13396	-0.13124
Fall mean flow	Average of monthly mean flows Sept-Nov	**-0.18971**	**-0.19094**	-0.03353

5.2.3. Ecosystem Services Data

We obtained data on ecosystem services or related variables from public databases, reports, and papers (Table 5.2). Due to limitations on data availability, almost all ecosystem service variables were on an annual basis and those that were not were summed to match the other variables.

Table 5.2. Summary, description of all ecosystem service variables used.

Variable	**Abbrev.**	**Service Type Measured**	**Description**	**Collection Method**	**N (yrs, #missing)**	**Source**
Blue Catfish WPE[a]	BlueCatBio	Provisioning; commercial fisheries	Weight-per-effort (kg/ gill net-hour) of Blue Catfish (*Ictalurus furcatus*)	Gill net	18 (1992 – 2009, 0)	Alford & Walker 2011
Largemouth Bass CPE[a]	LMBcpe	Cultural/provisioning; recreational fisheries	Catch-per-effort (individuals/ electrofishing-hour) for Largemouth Bass (*Micropterus salmoides*) > 200 mm total length (TL)	Electrofishing	22 (1984 – 2009, 4)	Alford & Walker 2011
Crappie CPE[a]	CRcpe	Cultural/provisioning; recreational fisheries	Catch-per-effort (individuals per electrofishing-hour) for crappie (*Pomoxis* spp.) >150 mm TL	Electrofishing	22 (1984 – 2009, 4)	Alford & Walker 2011
Total buffalo biomass[a]	IctioBio	Provisioning; commercial fisheries	Biomass (kg/ gill net summed by year) of all buffalo (*Ictiobus*) species	Gill net	20 (1990 – 2009, 0)	Alford & Walker 2011
Gizzard Shad CPE[a]	Shadcpe	Provisioning; commercial fisheries	Catch-per-effort (individuals/ gill net-hour) of Gizzard Shad (*Dorosoma cepedianum*)	Gill net	18 (1992 – 2009, 0)	Alford & Walker 2011
Percent of Largemouth Bass age-1[a]	LMBage1	Cultural/provisioning; recreational fisheries	Percent of Largemouth Bass estimated as age-1 based on otolith age analysis of	Electrofishing/ laboratory analysis	13 (1990 – 2008, 6)	Alford & Walker 2011

			subsample			
Percent of Largemouth Bass age-2[a]	LMBage2	Cultural/provisioning; recreational fisheries	Percent of Largemouth Bass estimated as age-2 based on otolith age analysis of subsample	Electrofishing/ laboratory analysis	13 (1990 – 2008, 6)	Alford & Walker 2011
Percent of crappie age-1[a]	CRage1	Cultural/provisioning; recreational fisheries	Percent of crappie estimated as age-1 based on otolith age analysis of subsample	Electrofishing/ laboratory analysis	8 (1998 – 2008, 3)	Alford & Walker 2011
Percent of crappie age-2[a]	CRage2	Cultural/provisioning; recreational fisheries	Percent of crappie estimated as age-2 based on otolith age analysis of subsample	Electrofishing/ laboratory analysis	8 (1998 – 2008, 3)	Alford & Walker 2011
Commerical buffalo landings[a]	IctioLand	Provisioning; commercial fisheries	Total commercial landings (kg) of buffalo from dealers in the ARB	LDWF Commercial Trip Ticket Program reporting	11 (1999 – 2009, 0)	Alford & Walker 2011
Commerical catfish landings[a]	CatfishLand	Provisioning; commercial fisheries	Total commercial landings (kg) of catfish (*Ictalurus* spp.) from dealers in the ARB	LDWF Commercial Trip Ticket Program reporting	11 (1999 – 2009, 0)	Alford & Walker 2011
Commerical Gizzard Shad landings[a]	ShadLand	Provisioning; commercial fisheries	Total commercial landings (kg) of Gizzard Shad from dealers in the ARB	LDWF Commercial Trip Ticket Program reporting	11 (1999 – 2009, 0)	Alford & Walker 2011
NMFS Crawfish Landings	NMFScraw	Provisioning; commercial fisheries	Total commercial wild-caught crawfish landings (lbs)	Commercial reporting	41 (1968 – 2008, 0)	NOAA Fisheries database (Louisiana Crawfish Promotion and Research Board 2009)
LSU Crawfish Landings	WC2	Provisioning; commercial fisheries	Total commercial wild-caught crawfish landings (lbs)	Commercial reporting	22 (1987 – 2008, 0)	LSU/LDWF data (Louisiana Crawfish Promotion and Research Board

						2009)
Crawfish Landings/License	CPL	Provisioning; commercial fisheries	Total commercial crawfish landings (lbs) divided by total licenses issued	Commercial reporting	21 (1987 – 2008, 1)	LSU/LDWF data (Louisiana Crawfish Promotion and Research Board 2009)
Commercial wild crawfish landings	WCarb	Provisioning; commercial fisheries	Total commercial landings (kg) of wild-caught crawfish from dealers in the ARB	LDWF Commercial Trip Ticket Program reporting	9 (2000-2008, 0)	LSU/LDWF data (Louisiana Crawfish Promotion and Research Board 2009)
Seed oyster density	JuvOyster	Provisioning; commercial fisheries	Density (individuals/ m^2) of oysters from seed grounds near Atchafalaya Bay	Quadrat sampling	13 (1998 – 2010, 0)	(Louisiana Department of Wildlife and Fisheries 2009, 2010)
Old River Lockages	ORlock	Provisioning; transportation/industry	Number of lockage events at Old River Lock	Daily records	44 (1968 – 2011, 0)	USACE Navigation Data Center
Bayou Sorrell Lockages	BSlock	Provisioning; transportation/industry	Number of lockage events at Bayou Sorrell Lock	Daily records	44 (1968 – 2011, 0)	USACE Navigation Data Center
Modeled Potential Denitrification	PDenitr	Supporting; nutrient cycling/water purification	kg nitrogen removed via denitrification	Model results	49 (1963 – 2011, 0)	This study

[a] Detailed summary and descriptions, including sampling methodology, in Alford and Walker (2011)

5.2.3.1. Fisheries production. Production of finfish and shellfish populations for food is a major provisioning service in the ARB, including several freshwater fishes, crawfish, and oysters (which are influenced by the river outflow into the estuary). We used data from Alford and Walker (2013) to estimate relationships between annual hydrologic variables and several metrics of fish production. Alford and Walker (2013) provided annual mean abundance or biomass estimates for five commercial or recreational fish species, commercial landings data on three fish groups, and proportions of age-1 and age-2 individuals for two recreational fish species to evaluate lagged effects of flow (Table 5.2).

Data on commercial crawfish landings were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) Commercial Fisheries Statistics Database (NOAA Fisheries 2013) and the Louisiana Crawfish Promotion and Research Board (LCPRB; Louisiana Crawfish Promotion and Research Board 2009). The NOAA database provided data on commercial landings of wild-caught crawfish in Louisiana from 1949-2011 and the LCPRB publication contained commercial catch data in Louisiana from 1987-2007 from Louisiana State University (LSU) and the number of licenses issued from 1987-2008. We paired the LSU data with license data to control for variation in commercial effort by dividing the total pounds of catch by the number of licenses issued each year (1987-2007). Although these numbers are for the entire state of Louisiana, we assumed that trends in the data would largely reflect conditions in the ARB because its landings accounts for 83-98% of the wild-caught crawfish harvested in the state each year (Louisiana Crawfish Promotion and Research Board 2009). The LCPRB report also contained data on commercial crawfish harvest specifically for the ARB based on Louisiana Department of Wildlife and Fisheries (LDWF) Trip Ticket data from 2000-2008 which we used to explore patterns in addition to the larger statewide dataset.

Eastern oyster (*Crassostrea virginica*) populations are significantly influenced by freshwater inputs from coastal rivers as these affect salinity and temperature levels which further impact physiological tolerances and predator, disease, and parasite regimes (Galtsoff 1964, La

Peyre et al. 2009). The LDWF conducts annual oyster surveys on public seed grounds throughout coastal waters. Reports from these surveys provide mean density of seed oysters per sample from 2-5 replicate m^2 quadrats at each oyster reef. We used density data from these surveys conducted from 1998-2011 on five public seed grounds in the Vermilion, East and West Cote Blanche, and Atchafalaya bays, although these ARB-influenced grounds are relatively poor producers compared to other areas in Louisiana (Louisiana Department of Wildlife and Fisheries 2009, 2010).

5.2.3.2. River transportation. Transportation is another direct provisioning service provided by rivers (Rodríguez et al. 2006, Thorp et al. 2010). Barge transportation in inland waterways of the United States can be considerably impacted by both high and low flows (Lohr 2008, Kahn 2011, “Drought In Danger Of Beaching Mississippi Barges” 2012). We thus expected some relationship between inland waterway transportation and flow regime. We obtained inland waterway transportation data from the U.S. Army Corps of Engineers (USACE, personal communication) and the USACE Navigation Data Center (U.S. Army Corps of Engineers n.d.). Specifically, we obtained annual summaries of total lockage events (number of times a lock was operated) through the Old River (near Simmesport, LA) and Bayou Sorrell locks in the ARB (Figure 5.1).

5.2.3.3. Denitrification model. Denitrification is the transformation of nitrate and nitrite to atmospheric N_2 gas via microbial processes under anoxic conditions. It is an essential process in removing excess anthropogenic nitrogen from the water, and maximizing this function has been identified as a potential way to decrease the hypoxic zone in the Gulf of Mexico (Mitsch et al. 1999, 2001, Mitsch and Gosselink 2007). We developed a conservative model of denitrification to evaluate relationships with hydrology. Scaroni et al. (2011) provide estimates of potential denitrification from three habitat types in the ARB (bottomland hardwood, open water, cypress-tupelo forest. Other denitrification studies (Lindau et al. 2008, Scaroni et al. 2010) in the ARB used NO_3^- additions that were quite high (100 mg L^{-1}), and not representative of reported NO_3^- levels in the ARB (see below). In contrast, Scaroni et al. (2011) used a range of NO_3^- additions for potential denitrification estimates (none, 1, 5 and 50 mg L^{-1} NO_3^-).

Using classified land cover data from the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI; U.S. Fish and Wildlife Service 1979) and classified Landsat imagery (available for the southern portion of the ARB) obtained from the Atchafalaya Basin Program's NRIAS (Atchafalaya Basin Program n.d.), we estimated the area inundated under 41 predicted scenarios (gage heights of 1.6 feet to 21.22 feet in 0.5 feet increments) for each of the three habitat types studied by Scaroni et al. (2011) in ArcMap 10.0.

We re-classified NWI data from 110 categories into four more generalized categories following Faulkner et al. (2009): bottomland hardwood (BLH), cypress-tupelo (CT), open water (OW), and all other land types (X). To be conservative in our estimates, we excluded a polygon from analysis if there was uncertainty over which of the three generalized Scaroni et al. (2011) habitat categories it should be placed in or if it represented moving water (category X). Excluding areas of moving water from contributions to our denitrification estimates helps to conservatively account for the fact that shorter water residence time strongly inhibits water diffusion into soils and thus denitrification (Nixon et al. 1996, Pinay et al. 2002, Rivera-Monroy et al. 2010, Perez et al. 2011). Additionally, higher oxygen levels in these probable high-velocity waters could further hinder denitrification. To improve exclusion of moving water since the NWI data are over 25 years old, we also excluded areas we classified as frequently turbid moving water based on an analysis of 30 existing Landsat images at different stage heights (obtained from NRIAS). These are areas which likely experience higher water velocities during flooding (Allen et al. 2008). These images had been reclassified as: 1) Dry land; 2) Open, turbid water: 3) Open, non-turbid water; 4) Flooded land, turbid water; 5) Flooded land, non-turbid water; and 6) Floating aquatic vegetation. The 30 images were reclassified so that all values except "open water – turbid" were equal to 0; "open water – turbid" was reclassified to a value of 1. Raster calculator was then used to determine frequency of open turbid water for all 30 images and the Natural Jenk's classification was utilized to define frequency classes. All cells greater than or equal to 24 were classified as very frequently turbid (therefore high riverine connectivity and by proxy high enough velocity to warrant exclusion from open water classification).

Allen et al.'s (2008) analysis of Landsat imagery also suggests that some areas of the ARB are not significantly influenced by basin-wide hydrologic conditions and are not represented by gage height at the BLR gage; these areas (Alabama Bayou, Lost Lake, Werner, and Cow Island water management units) were therefore excluded from further analyses.

After excluding these areas from the analysis, we were left with a total model area of 1756 km^2 (Figure 5.2). The NWI shapefile was converted to a raster and combined with the 41 predicted inundation rasters (classified as either land or water). For each predicted inundation, the NWI raster was combined with the inundation raster to produce an output raster with a unique value for each combination of the two parent rasters. The area inundated for each of the three land classes was then calculated for each of the 41 scenarios (Figure 5.5).

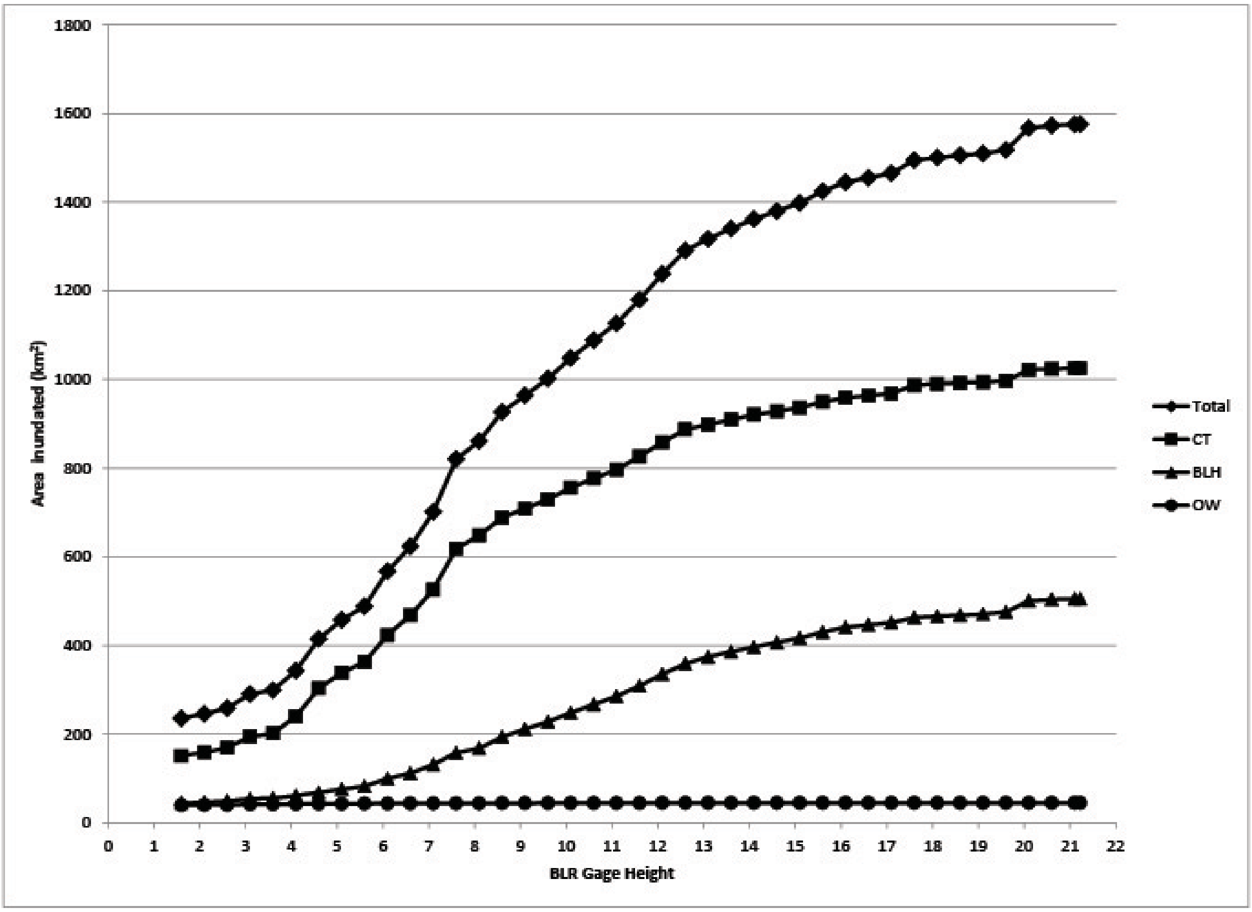

Figure 5.5. Area of land inundated with increasing BLR gage height for total area and three habitat types used in the denitrification model. CT = cypress tupelo, BLH = bottomland hardwood; OW = open water.

We applied the Q_{10} method to adjust denitrification reaction rates with changing temperature using Q_{10}=2 (Stanford et al. 1975, Schramm et al. 2009). Average monthly water temperature to the nearest degree was calculated using available data from Little Bayou Long in the ARB (USGS gage 295011091184300, years 2007-2012). We used these monthly temperature averages to calculate a separate denitrification rate for each month based on the original maximum rates of potential denitrification under 1 mg L^{-1} NO_3^- (22 °C) addition reported by Scaroni et al. (2011) in each of the three habitats (Table 5.3). We multiplied these new rates by the area of each habitat inundated to estimate basin-wide maximum potential denitrification under each inundation scenario for each month (kg N day^{-1}). By using potential denitrification rates after 1 mg L^{-1} NO_3^- addition, we assume that incoming water from the main channel during inundation contains at least this much NO_3^-, which agrees with reported concentrations from the lower Mississippi River and the ARB of around 1 mg L^{-1} NO_3^- (Mitsch et al. 1999, Turner et al. 2007, Sprague et al. 2011). Using realistic concentrations of nitrate has been suggested as a major factor for making potential denitrification estimates more useful for management decisions (Rivera-Monroy et al. 2010).

Table 5.3. Monthly rates of denitrification based based on peak rates in Scaroni et al. (2011) *and applying a* $Q_{10}=2$ *transformation for temperature. *Peak rates from Scaroni et al.* (2011) *at 22 °C listed in first row.*

Month	Mean Monthly Temperature, °C (2007-2012)		Denitrification Rate (g N ha^{-1} day^{-1})	
		Cypress-Tupelo	Bottomland Hardwood	Open Water
--	22	10.0*	8.1*	12.0*
January	13	5.4	4.3	6.4
February	15	6.2	5.0	7.4
March	18	7.6	6.1	9.1
April	20	8.7	7.1	10.4
May	25	12.3	10.0	14.8
June	28	15.2	12.3	18.2
July	30	17.4	14.1	20.9
August	30	17.4	14.1	20.9
September	28	15.2	12.3	18.2
October	24	11.5	9.3	13.8
November	18	7.6	6.1	9.1
December	14	5.7	4.7	6.9

After obtaining basin-wide estimates for potential denitrification under each inundation scenario and monthly temperature, we used daily stage data from the BLR gage from 1963 to 2011 and calculated annual potential denitrification values based on the areas of each habitat that were newly inundated during each flood pulse. Calculating denitrification for only newly inundated areas helped account for the fact that constantly inundated sites can have lower denitrification than periodically inundated sites. Periodic inundation causes intermittent aerobic conditions and stimulates nitrification and C mineralization, promoting denitrification upon rewetting and maintaining populations of facultatively anaerobic microorganisms (Groffman and Tiedje 1988, Groffman 1994). Pulses were identified by using a smoothed curve (based on a 5-day moving average) to identify rising limbs on the annual hydrograph. We subtracted the basin-wide potential denitrification at the base of each identified pulse (trough before the pulse) from the denitrification total at the peak of the pulse. We then multiplied this value by 4 days, which is the average time to peak denitrification rate for the three habitat types in the Scaroni et al. (2011) experiments. Using this approach, we calculated total potential denitrification (kg N removed) for each year. We used these data to relate total potential denitrification to mean annual discharges similarly to the other ecosystem services data.

5.2.4. Statistical analyses.

Hydrologic variables are often highly correlated with each other, which can cause problems for statistical analyses. For that reason, we used principal components analysis (PCA) to reduce the 30 hydrologic variables (Table 5.1) to a few uncorrelated axes (Olden and Poff 2003). The basic idea of PCA is to reduce a large set of correlated variables to a few uncorrelated variables that contain the most important features (explain the most variance) of the original set (Zuur et al. 2007). It does this by finding directions (called principal components) along which variation in the dataset is highest; these principal components are new variables that are linear combinations of the original ones (Ringnér 2008). A broken stick model was used to select important component axes (Jackson 1993). The broken stick model randomly divides a stick of unit length into the same number of pieces as there are PC axes; the pieces are put in order of decreasing length, and only PC axes that have larger eigenvalues than the length of the corresponding piece of stick are used (Borcard et al. 2011). Analyses were conducted in the R environment (v. 3.0.0) using the packages ‘stats’ and ‘vegan’ (R Core Team 2012).

Each of the 20 individual ecosystem services explored was treated as a dependent variable in a multiple linear regression with the retained significant principal components as independent variables. While ecological relationships can often be nonlinear, limitations of our datasets did not allow development of strong nonlinear models. Previous attempts have been made to relate fisheries metrics in the ARB to flow regime (including our data source for fisheries metrics, Alford and Walker 2013); however, these models may have been overfitting considering the small sample size and the strong role that outliers played in the nonlinear models when actual points are plotted (not in the original publication graphs). With a small to moderate sample size, simpler linear models with fewer parameters are less prone to overfitting if data can be adequately described by linear regression (Hawkins 2004). All models were examined to ensure that assumptions of normality (Shapiro-Wilk test, normal probability plots) and homogeneity of variance were met. Where assumptions of normality were not met, data were transformed and in all cases this normalized the data so that further analyses could be conducted. Ecosystem service variables exhibiting significant relationships with hydrologic principal component axes were plotted against those axes separately for visualization. A correlation matrix (using Pearson correlation coefficients) was created to visualize trade-offs and complementarities among ecosystem services through time and in relation to flow. All analyses were performed using the ‘stats’ package in the R environment or SigmaPlot (11.0; Systat Software, Inc., Chicago, IL).

5.3. Results

5.3.1. Hydrologic Variable Reduction

The PCA revealed many of the hydrologic variables to be highly correlated (Figs. 5.6, 5.7; Table 5.1). A broken stick model indicated that the first three principal components (PCs) were significant (eigenvalues higher than length of broken stick) and these were retained for subsequent analyses. The three principal components explained a combined 61.2% of variation in the hydrologic variables (Table 5.1). Many variables had strong negative loadings on PC1 including mean flow, the 10 minimum and maximum flow variables (e.g., three-day min and max), mean winter low flow, winter mean flow, and fall mean flow (Figs. 5.6; Table 5.1). Positive values on PC1 were associated with higher fall rate and CV of flow. PC2 had strong negative loadings for base flow index, date of maximum flow, and fall mean flow; and strong positive loadings for CV of flow and the five maximum flow variables (Figure 5.6, Table 5.1). PC3 had strong negative loadings for number of flow reversals, rise rate, low pulse count, and the three-, four-, and five-year lags; and strong positive loadings for fall rate (Figure 5.7, Table 5.1). Summarizing trends in the three PC axes: PC1 constitutes a contrast between years with higher flow (negative loadings) and more variable flow (positive); PC2 indicates a contrast between years with stable flow (BFI; negative loadings) and floods later in the year and those with more variable flow (positive); and PC3 represents a contrast between years with rapidly rising, variable, and low-pulse flows (negative loadings) and years with rapidly falling pulses (positive).

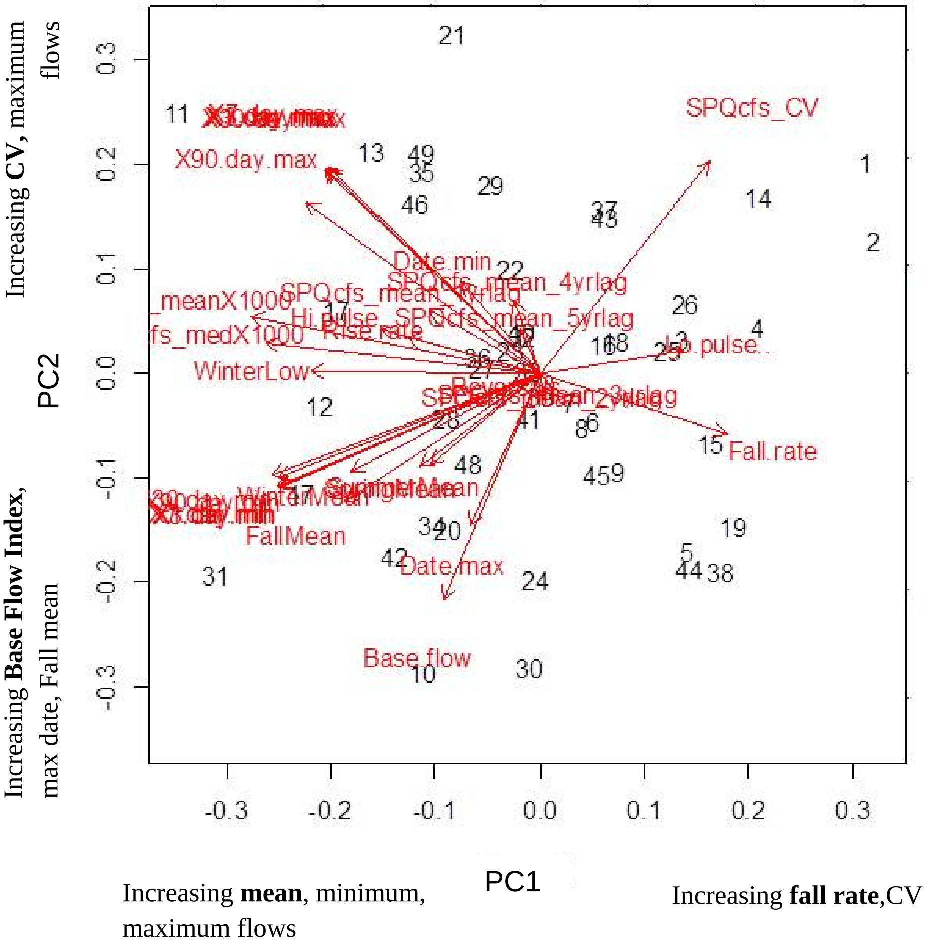

Figure 5.6. Plot of principal component axes 1 (x-axis) and 2 (y-axis) showing correlations among hydrologic variables. Red vectors indicate magnitude and direction of association of hydrologic variables. Numbers indicate position of years (numbered sequentially) in PCA space. Flow variable codes from Table. 5.1. Text along PC axes show flow variables most highly correlated with axis (bold = single most highly correlated).

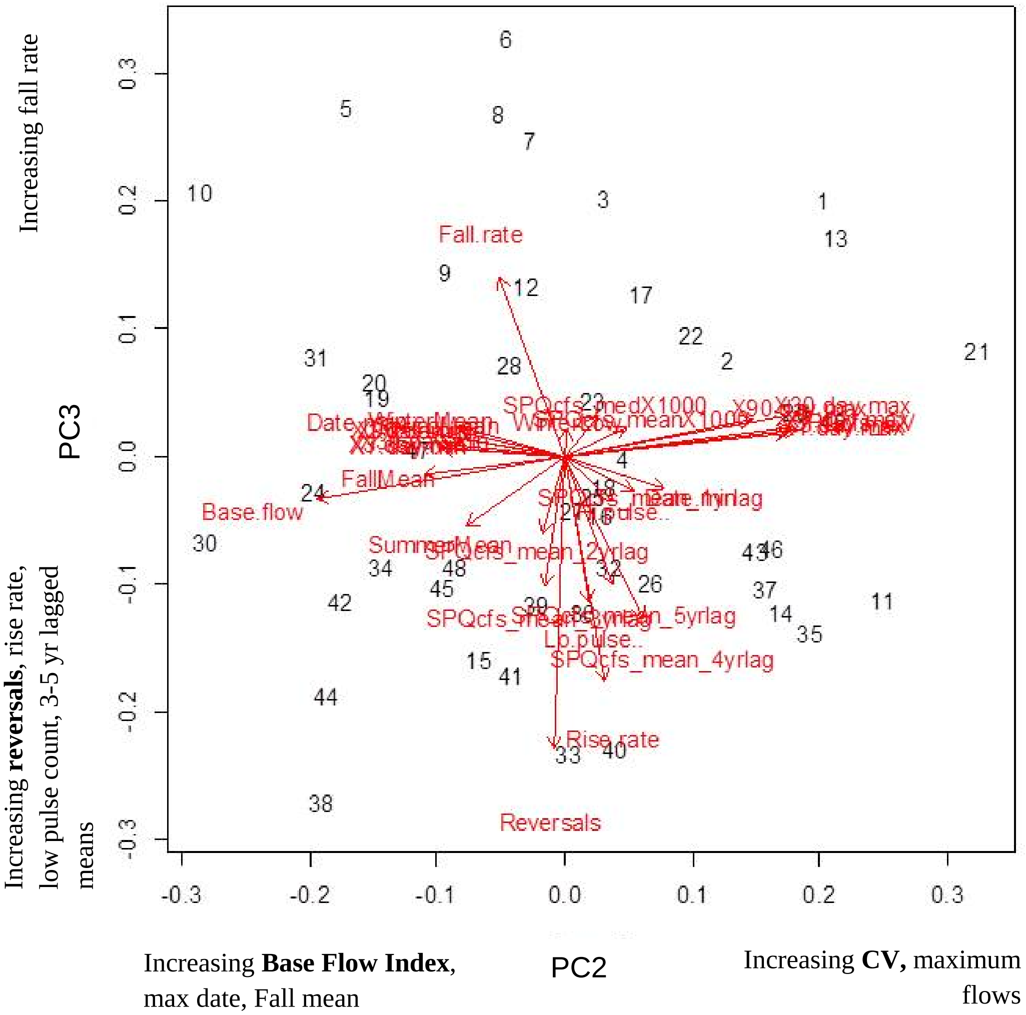

Figure 5.7. Plot of principal component axes 2 (x-axis) and 3 (y-axis) showing correlations among hydrologic variables. Red vectors indicate magnitude and direction of association of hydrologic variables. Numbers indicate position of years (numbered sequentially) in PCA space. Flow variable codes from Table. 5.1. Text along PC axes show flow variables most highly correlated with axis (bold = single most highly correlated).

5.3.2. Denitrification Model

Calculated annual potential denitrification values for each year from 1963 – 2011 ranged from 5394 – 17420 kg N (Table 5.4). The modeled denitrification values were negatively and significantly related to mean annual discharge ($R^2 = 0.17$, $p = 0.0021$). That is, years with higher discharge had lower N removal via denitrification according to our model.

Table 5.4. Modeled total N removed by denitrification in cypress-tupelo, bottomland hardwood, and lake habitats in the ARB from 1963-2011.

Year	Total Potential Denitrification (kg N)	Year	Total Potential Denitrification (kg N)
1963	8976	1988	5394
1964	15078	1989	9128
1965	10916	1990	8561
1966	15384	1991	5409
1967	14298	1992	16947
1968	9843	1993	5904
1969	10872	1994	7019
1970	12868	1995	12229
1971	13941	1996	14815
1972	12396	1997	6349
1973	7911	1998	12097
1974	9382	1999	5661
1975	8806	2000	16568
1976	10641	2001	11675
1977	13872	2002	10914
1978	11600	2003	16357
1979	10786	2004	15212
1980	12335	2005	11116
1981	17420	2006	13324
1982	16425	2007	13147
1983	7319	2008	14041
1984	7920	2009	12834
1985	13861	2010	10300
1986	14300	2011	11905
1987	10797		

5.3.3. Relationships Between Ecosystem Services and Hydrology

Of the 20 variables describing ecosystem services, eight were significantly related to at least one of the hydrologic PC axes according to the results of multiple linear regression (Table 5.5). Three variables – Old River lockage operations, potential denitrification, and juvenile oyster density – were positively related to PC1, indicating positive association with high CV and fall rate and negative association with high mean, minimum, and maximum flow. Two variables – NMFS crawfish landings and crappie catch-per-effort – were negatively related to PC1, indicating positive association with higher mean, minimum, and maximum flows and negative association with high CV and fall rate. Crappie catch-per-effort was positively related to PC2, associated with higher CV and maximum flows and therefore negatively associated with higher base flow index, floods later in the year (max date), and high mean fall flows. Old River lock operations and potential denitrification were negatively associated with PC2, positively related to more stable flows and large floods later in the year. Juvenile oyster density was also marginally negatively related to PC2. Four variables – NMFS crawfish landings, Old River lockage operations, and Largemouth Bass and crappie catch-per-effort – were negatively related to PC3 and therefore associated with rapidly-rising, variable, and low-pulse flows. Proportion of crappie that were age-2 was also marginally negatively related to PC3. The two other statewide crawfish variables – LSU crawfish landings and crawfish landings per license – were positively associated with PC3 and therefore higher in years with quickly dropping pulses (fall rate).

Table 5.5. Results of multiple regression of ecosystem service variables and hydrologic PC axes. Bold adjusted R^2 values indicate significant relationships with at least one hydrologic PC. (following page)→

Dependent Var.	Adj.R^2	Const			PC1			PC2			PC3		
		Coeff	t	p	Coeff	t	p	Coeff	t	p	Coeff	t	p
[§]NMFScraw	**0.37**	6.477	111.9	**	-0.08	-4.838	**	0.02	0.784	ns	-0.10	-2.716	**
WC2	**0.25**	15849558.4	5.706	**	-322913.9	-0.432	ns	-923125.6	-1.118	ns	4453337.4	2.290	*
[§]CpL	**0.17**	4.113	25.45	**	0.001	0.003	ns	0.0113	0.235	ns	0.245	2.236	*
ARBcraw	0.49	57625230.9	3.451	*	-141823.4	-0.483	ns	675328.3	1.954	ns	743478.8	0.725	ns
ORlock	**0.47**	2900.8	44.43	**	64.71	2.959	**	-61.27	-2.153	*	-179.3	-4.223	**
BSlock	0.00	8879.2	51.32	**	-47.1	-0.812	ns	-22.43	-0.297	ns	149.73	1.331	ns
PDenit	**0.37**	11527.6	31.24	**	272.9	2.513	*	-821.4	-4.93	**	-232.1	-1.00	ns
[§]JuvOyster	**0.54**	2.051	2.587	*	0.467	2.838	*	-0.363	-2.177	~	0.410	0.756	ns
[§]LMBcpe	**0.27**	3.353	12.50	**	-0.07	-0.868	ns	0.016	0.188	ns	-0.607	-3.201	**
[§]CRcpe	**0.50**	2.450	7.786	**	-0.20	-2.199	*	0.231	2.311	*	-0.948	-4.264	**
[§]BlueCatBio	0.26	0.701	4.004	**	-0.03	-0.762	ns	0.043	1.378	ns	0.137	1.293	ns
[§]BuffBio	0.00	4.930	10.56	**	-0.13	-1.132	ns	0.019	0.181	ns	-0.458	-1.538	ns
[§]ShadCPE	0.04	0.213	2.276	*	0.010	0.520	ns	-0.028	-1.678	ns	-0.016	-0.281	ns
[†]LMBage1	0.20	0.733	6.253	**	-0.03	-1.075	ns	0.0254	0.881	ns	0.0929	1.240	ns
[†]LMBage2	0.00	0.349	2.395	*	-0.004	-0.113	ns	0.0287	0.802	ns	-0.087	-0.929	ns
[†]CRage1	0.51	1.098	3.783	*	0.037	1.174	ns	0.045	1.232	ns	0.338	1.607	ns
[†]CRage2	0.33	-0.32	-0.85	ns	-0.09	-2.166	ns	0.048	0.997	ns	-0.628	-2.266	~
[§]ShadLand	0.00	13.07	29.34	**	-0.003	-0.034	ns	-0.006	-0.065	ns	0.317	1.089	ns
[§]CatfishLand	0.00	14.26	123.8	**	-0.002	-0.110	ns	0.009	0.410	ns	-0.075	-0.994	ns
[§]BuffLand	0.00	13.79	52.63	**	0.012	0.247	ns	0.064	1.227	ns	0.0009	0.0050	ns

Variable codes:NMFScraw = NMFS crawfish landings; WC2 = LSU crawfish landings; CpL = crawfish per license; ARBcraw = ARB wild crawfish harvest; ORlock = lockage events at Old River; BSlock = lockage events at Bayou Sorrell; PDenitr = potential denitrification; JuvOyster = juvenile oyster density; LMBcpe = largemouth bass catch-per-effort; CRcpe = crappie catch-per-effort; IBio = buffalo biomass-per-effort; BlueCatBio = blue catfish weight-per-effort; Shadcpe = shad catch-per-effort; LMBage1=proportion of largemouth bass age-1; LMBage2 = proportion of largemouth bass age-2; CRage1 = proportion of crappie age-1; CRage2 = proportion of crappie age-2; ShadLand = shad landings; CatfishLand = catfish landings; BuffLand = buffalo landings.

5.3.4. Relationships Among Ecosystem Services

The correlation matrix with Pearson correlations (Table 5.6) provided a slightly different picture of relationships between ecosystem services and hydrology than multiple regression, with differences mostly due to significant or marginally significant relationships where multiple regression showed marginal or no significance; however, this approach allowed us to visualize and assess trade-offs and complementarities by examining the direct relationships among ecosystem services across years in addition to comparing flow relationships. Positive correlation coefficients reveal ecosystem services exhibiting complementary relationships and identify services that should respond similarly to flow manipulation. Negative correlations coefficients identify trade-offs among services and those that should have divergent responses to flow alteration.

Based on this framework, several ecosystem service variables exhibited complementary relationships driven by flow (i.e., positive correlation coefficients between variables that are related in the same way to a hydrologic variable; Table 5.6). Old River lock operations and juvenile oyster density were positively related, as were two recreational fisheries production metrics (crappie and bass catch-per-effort). Additionally, two recreational fisheries production metrics were positively related to crawfish production metrics (LMB age-1 with three state-wide crawfish landings variables; crappie age-1 with ARB crawfish landings). There were more hydrology-related trade-offs (i.e., negative correlation coefficients between variables that are related in opposite ways to a hydrologic variable) than complementary relationships exhibited by services (Table 5.6). Denitrification was negatively related to two crawfish production metrics (NMFS statewide landings and ARB landings). Two recreational fisheries metrics were negatively related to two crawfish production metrics (LMB and crappie catch-per-effort with

LSU statewide crawfish landings and crawfish-per-license). One commercial fisheries metric (blue catfish biomass) was negatively related to oyster density; and oyster density was also negatively related to LMB age-1.

Table 5.6. Correlation matrix of all hydrologic and ecosystem service variables. P-values above the diagonal; Pearson r values below the diagonal. Bold, large font r values indicate significant relationships ($p < 0.05$). Bold, small font r values indicate marginally significant relationships ($p < 0.1$). Significant p values in bold italics; marginally significant p values in italics only. Blue boxes indicate complementary (positive r) or trade-off (negative r) likely driven by hydrology (same or different sign, respectively, in relationship with first four columns). (following page)→

	Q	PC1	PC2	PC3	NMFS craw	WC2	CpL	ARB craw	OR lock	BS lock	PDenitr	Juv Oyster	LMB cpe	CRcpe	BuffBio	Blue CatBio	Shadcpe	LMB age1	LMB age2	CR age1	CR age2	Shad Land	CatfishLand	BuffLand
Q		***0.00***	0.20	0.55	***0.01***	0.13	0.84	*0.08*	***0.00***	0.23	***0.00***	***0.01***	0.26	0.85	0.94	***0.03***	0.48	***0.02***	0.99	0.51	0.50	0.40	0.53	0.82
PC1	**-.96**		1	1	***0.00***	*0.09*	0.81	0.17	***0.00***	.27	***0.046***	***0.01***	0.61	0.95	0.86	***0.04***	0.37	*0.09*	0.91	0.89	0.43	0.28	0.43	0.83
PC2	.19	.00		1	0.64	0.40	0.91	***0.01***	*0.07*	0.83	***0.00***	*0.06*	0.76	*0.097*	0.96	0.33	0.12	0.28	0.43	***0.04***	0.87	0.67	0.98	0.18
PC3	.09	.00	.00		***0.03***	***0.01***	*0.09*	*0.07*	***0.00***	.12	.43	*0.06*	***0.00***	***0.00***	0.30	***0.03***	0.46	*0.09*	0.36	*0.06*	0.37	0.11	.21	.84
NMFScraw	**.36**	**-.43**	-.07	**-.31**		***0.00***	***0.03***	***0.00***	0.19	.31	***0.02***	0.14	0.58	0.83	***0.04***	0.32	0.81	***0.04***	0.71	0.26	0.70	0.20	0.31	0.10
WC2	0.34	**-.38**	-.19	**.54**	**.81**		***0.00***	***0.01***	0.25	0.84	0.24	0.71	*0.06*	*0.07*	*0.07*	0.92	0.15	***0.00***	0.20	0.70	0.71	0.58	0.28	0.91
CpL	-0.04	.06	.03	**.38**	**.48**	**.72**		***0.04***	0.51	0.55	*0.07*	0.30	*0.08*	***0.03***	0.21	0.93	*0.09*	***0.00***	0.15	0.19	0.73	0.71	0.19	0.94
ARBcraw	**.62**	-.50	**.77**	**.62**	**.99**	**.86**	**.74**		0.11	.63	*0.05*	0.24	0.52	0.26	0.58	0.26	0.12	0.11	0.28	***0.03***	0.47	0.25	0.68	0.11
ORlock	**-.57**	**.48**	**-.28**	**-.56**	.20	-.26	-.15	-.57		***0.02***	0.14	***0.00***	0.27	0.51	0.52	0.30	0.18	*0.05*	0.53	0.44	0.90	0.37	0.63	0.90
BSlock	-.19	-.17	-.03	.24	.16	.05	-.14	.19	**-.35**		0.32	0.42	0.33	0.53	0.80	0.29	0.17	0.17	0.17	0.52	0.12	***0.03***	0.20	0.46
PDenitr	**-.43**	**.29**	**-.56**	-.11	**-.34**	-.27	**-.41**	**-.66**	.23	-.15		0.72	0.92	0.57	0.75	0.65	0.23	0.61	0.60	0.52	0.44	0.73	0.59	*0.06*
JuvOyster	**-.69**	**.69**	**-.51**	**-.52**	-.41	-.14	-.36	-.44	**.74**	-.23	.10		0.98	0.63	0.44	***0.02***	0.73	***0.01***	0.35	0.44	0.24	0.23	0.78	0.43
LMBcpe	-.25	.12	.07	**-.59**	-.12	**-.46**	**-.44**	.27	.25	.22	.02	.01		***0.00***	0.77	0.14	0.44	0.82	0.26	0.56	0.81	0.71	*0.06*	0.62
CRcpe	-.04	.01	**.36**	**-.60**	-.05	**-.45**	**-.53**	.45	.15	.14	-.13	.16	**.74**		0.14	0.20	0.29	0.87	0.58	0.79	0.62	0.25	0.53	0.96
BuffBio	0.02	-.04	.01	-.25	**.46**	**.44**	.31	.21	-.15	.06	-.08	.25	.08	.36		*0.05*	0.66	0.92	0.88	0.64	0.72	0.73	*0.09*	0.31
BlueCatBio	**.53**	**-.49**	.24	**.53**	.25	.03	.02	.42	-.26	.26	-.11	**-.65**	-.38	-.32	**-.46**		0.47	0.40	0.97	0.15	0.71	0.49	0.29	0.55
Shadcpe	-.18	.23	-.38	-.19	.06	.38	**.43**	-.56	.33	-.34	.30	.11	-.20	-.27	.11	-.18		0.29	0.39	0.82	0.78	***0.00***	0.88	0.53
LMBage1	**.62**	**-.49**	.32	**.49**	**.57**	**.77**	**.80**	.72	**-.56**	.41	-.15	**-.83**	.07	-.05	-.03	.27	.33		0.19	0.18	0.56	0.85	0.44	0.94
LMBage2	.00	.03	.24	-.28	-.11	-.39	-.42	-.53	.19	.40	-.16	-.38	.34	.17	.04	.01	-.28	-.39		0.46	0.15	0.69	0.13	0.70
CRage1	.27	-.06	**.73**	**.68**	.45	.18	.52	**.85**	-.32	-.27	-.26	-.32	.24	.12	-.20	.56	.09	.53	-.31		0.20	0.12	0.12	0.24
CRage2	.28	-.32	-.07	-.36	.17	.17	-.14	-.37	.05	.59	.32	-.47	.10	.21	.15	-.16	.12	.24	.56	-.51		0.18	0.48	0.25
ShadLand	.28	-.36	.15	.51	.42	.22	-.15	.43	-.30	**.64**	-.12	-.39	-.14	-.40	-.12	.23	**-.85**	-.09	.19	-.65	.58		0.99	0.33
CatfishLand	-.21	.26	-.01	-.41	-.34	-.41	-.48	-.16	.16	.42	-.18	.10	**.62**	.23	**.54**	-.35	-.05	-.35	.63	-.64	.33	-.01		0.88
BuffLand	.08	.07	.44	.07	.52	.04	.03	.57	.04	.25	**-.59**	-.27	-.18	-.02	-.34	.20	-.21	.04	-.18	.51	-.51	.32	-.05	

Variable codes: *Q = annual discharge; PC1-3 = principal components 1-3; NMFScraw = NMFS crawfish landings; WC2 = LSU crawfish landings; CpL = crawfish per license; ARBcraw = ARB wild crawfish harvest; ORlock = lockage events at Old River; BSlock = lockage events at Bayou Sorrell; PDenitr = potential denitrification; JuvOyster = juvenile oyster density; LMBcpe = largemouth bass catch-per-effort; CRcpe = crappie catch-per-effort; IBio = buffalo biomass-per-effort; BlueCatBio = blue catfish weight-per-effort; Shadcpe = shad catch-per-effort; LMBage1 =proportion of largemouth bass age-1; LMBage2 = proportion of largemouth bass age-2; CRage1 = proportion of crappie age-1; CRage2 = proportion of crappie age-2; ShadLand = shad landings; CatfishLand = catfish landings; BuffLand = buffalo landings.*

In almost all cases, ecosystem service variables that shared significant correlations with a particular hydrologic component had correlations of the same sign with each other, although they were not always significant. Three ecosystem service variables – NMFS crawfish landings, Largemouth Bass and crappie catch-per-efforts – were significantly (negatively) correlated with hydrologic PC3 but were negatively correlated with each other. A dozen ecosystem service variables had significant correlations with each other even though they were not themselves correlated with the hydrologic principal components (Table 5.6), indicating that other factors besides hydrology may be playing a role in these relationships.

5.4. Discussion

5.4.1. Ecosystem Services

We do not regard the significant relationships between ecosystem services and hydrologic variables to be necessarily useful predictively both because of uncertainty in the models and because of the difficulty in implementing flow standards based on the hydrologic PCs. However, the significant relationships with hydrology do reveal potential trade-offs and complementarities among ecosystem services in the ARB that can be useful from a management standpoint.

Unlike previous work (Alford and Walker 2013) we found no relationships between commercial fisheries and hydrology except for crawfish landings and blue catfish abundance (Tables 5.5, 5.6). Several recreational fisheries metrics were related to aspects of flow variability and small flood frequency. Juvenile oyster density (not included in Alford and Walker 2013) was also negatively related to flow magnitude (mean flow) (Tables 5.5, 5.6). Our results differ from Alford & Walker (2013) due to the different statistical approaches used. Alford & Walker (2013) used a curve-fitting procedure that produced models with many parameters that were greatly affected by outliers, although data points were not included in published graphs. We initially approached our modeling with a similar approach but abandoned this when it was clear that single outliers drove the curvilinear patterns. Our regression models generally had fewer parameters relative to the sample size and may be less prone to overfitting (Hawkins 2004). Despite the considerable differences, our results do corroborate Alford & Walker's (2013) in that there are significant relationships among multiple fisheries variables and flow regime. However, the specific discharge targets they discuss as maximizing fisheries production need to be more rigorously evaluated. Our approach was meant to identify general relationships between ecosystem services and flow regime to highlight potential complementarities and trade-offs. These relationships should also be further evaluated with finer-scale experiments.

Many of our findings are supported by previous ecological work. Some relationships for fisheries corroborate studies of the Flood Pulse Concept (Junk et al. 1989) for temperate fishes. Blue Catfish are known to extensively use floodplain habitats for food during warm inundation events (Schramm, Jr. et al. 2000, Eggleton and Schramm, Jr. 2004, Schramm, Jr. and Eggleton 2006) and abundance in our model was significantly related to high flow conditions (Tables 5.5, 5.6). Other catfishes like Flathead Catfish (which make up a portion of commercial catfish landings in the ARB; Alford & Walker 2013) may use floodplains less (Eggleton and Schramm, Jr. 2004, Schramm, Jr. and Eggleton 2006), and total commercial catfish landings were not related to hydrology (Table 5.6). Crappie are not strongly dependent on floodplains (Gutreuter et al. 1999) but spawning and recruitment have been linked to small flood pulses (Halloran 2010). Concordant with this, crappie abundance (catch-per-effort) and recruitment (proportion age-1) were positively related to aspects of increased flow variability and small flood frequency (Tables 5.5, 5.6). Denitrification is substantially affected by cycles of oxic and anoxic conditions in floodplain soils that are driven by flooding patterns (Ponnamperuma 1972, Keeney 1973, Reddy and Patrick 1975, Groffman 1994, Pinay et al. 2002); and in our study, modeled denitrification values were positively related to flow variability (i.e., more frequent cycling of flooded and non-flooded soils).

5.4.2. Denitrification Model

Our goal for the denitrification model was not to provide predictive power but to examine relative magnitudes based on area of inundation, land cover type, and hydrograph characteristics (specifically the number and timing of pulses). Our denitrification model, which incorporates only area of land flooded under a certain river stage and temperature, does not take into account many of the factors influencing denitrification in the ARB. Thus, there are important caveats and limitations to our denitrification model.

While all factors controlling denitrification are not completely understood, there is strong evidence that flow regime (especially frequency, duration, timing, and magnitude) controls nitrogen cycling in part by determining the phases of anoxic and oxic conditions in soils, where most denitrification takes place (Ponnamperuma 1972, Keeney 1973, Reddy and Patrick 1975, Groffman and Tiedje 1988, Pinay et al. 2002). Nitrogen flux also varies seasonally, affecting denitrification rates (Arheimer and Wittgren 2002, Schramm et al. 2009), and this is not incorporated into our model. Nutrient enrichment has also been occurring in much of the lower Mississippi River for decades and thus NO_3^- limitation may be less of a factor controlling denitrification in the ARB (Groffman 1994). Soil nitrate was variable in one study in the ARB but averaged > 16 mg L^{-1} (Scaroni et al. 2010), whereas values above 10 mg L^{-1} are often considered non-limiting for denitrification (Groffman 1994). Some areas of the ARB are disconnected from the main channel and likely do not receive nitrate-rich waters regularly, and these factors are not considered in our model. Local topography also affects flooding depth and duration, thus creating variation in biogeochemical processes at the scale of meters (Pinay et al. 1989, Pinay and Naiman 1991). Soil structure and carbon availability also strongly influences denitrification rates as different configurations allow for differences in microbial habitat at even smaller scales (cm to m). In floodplain soils with less than ~65% silt or clay, for instance, denitrification does not occur (Pinay et al. 2002). Soil texture may play a minimal role in denitrification, at least for the southern portion of the ARB, based on two lines of evidence. In 20 transects (4-5 individual sediment samples each) in the south-central portion of the ARB, only two had >35% sand (> 63 μm) present (Hupp et al. 2008). However, it is important to note that the percentages for each transect were averages of all the samples taken. Second, the authors state that, as expected, coarser grains tend to be found on levees and associated with splays. The percent area of natural levees decreases in the southern portion of the ARB where we are focusing modeling efforts, and these areas are less likely to be inundated given their higher elevation. Our model does incorporate plant community type – one of the key factors controlling denitrification at the landscape scale (Groffman 1994). Based on the above discussion, we view our estimates as approximations of potential denitrification and re-emphasize that they should not be used predictively (Schramm et al. 2009).

5.4.3. Model Uncertainty

Along with the sources of uncertainty for the denitrification model, it is important to note that we consider our study to be suggestive of general relationships among services with changes in flow. There is significant uncertainty in the models we present due to aggregation to annual time series, small sample size for some services, and correlation of hydrologic variables that complicates a mechanistic interpretation of relationships.

Aggregation of data into annual time series was necessary due to the nature of our study and limited data availability. However, this complicates interpretation of findings because many factors within a year could be contributing to the relationships. Even though we attempted to account for multiple flow variables in our models, many hydrologic metrics were correlated and multiple variables contributed strongly to the new hydrologic PC axes. This complicates interpretation from a management standpoint.

Several of the datasets had relatively small sample sizes. This may have contributed to conflicting results when multiple datasets were available for the same service (e.g., crawfish). Crawfish landings reported in Alford and Walker (2013) showed a near-linear positive relationship with discharge, while the effort-corrected landings we used showed no relationship with mean discharge (but was negatively related to flow variability, PC3) in multiple regression and one landings dataset was positively related to mean discharge (PC1) in the correlation matrix. Alford and Walker's (2013) dataset covered only 11 years from 1999-2009, whereas the other datasets covered 21 years from 1987-2008. While the Alford and Walker (2013) data does encompass a range of discharges, the other datasets span a slightly larger range, but more importantly span a larger time period during which the height of crawfish landings in the last ~40 years appears to have occurred (Louisiana Crawfish Promotion and Research Board 2009). Further, Alford and Walker (2013) used uncorrected landings data, which may be problematic due to variation in effort caused by price and other factors (Buzan et al. 2009, Turner 2009).

Our results for crawfish landings contrast with some common generalizations about hydrologic factors associated with improved crawfish harvest. For instance, a recent Louisiana crawfish management plan states that "maximum production of wild-caught crawfish always corresponds to so-called flood years in the Lower Mississippi River Valley" (Louisiana Crawfish

Promotion and Research Board 2009). This does not seem to be the case for the datasets we examined, including those uncorrected for commercial effort (Figure 5.8), although crawfish variables were positively related to low, quickly-rising floods (PC3) and mean and maximum flows (PC1; Tables 5.5, 5.6). The discrepancy highlights the need for a more nuanced analysis using finer-scale measurement of crawfish response and flow to evaluate other common assumptions. For instance, an ideal flood cycle for crawfish production is purported to include an early rise in November with mid-winter floods that maintain floodwaters until July followed by approximately two months of drought (Louisiana Crawfish Promotion and Research Board 2009). This could be tested with existing data by examining the relationship between previous winter discharge and crawfish landings (expected positive relationship) and between previous summer discharge (expected negative relationship).

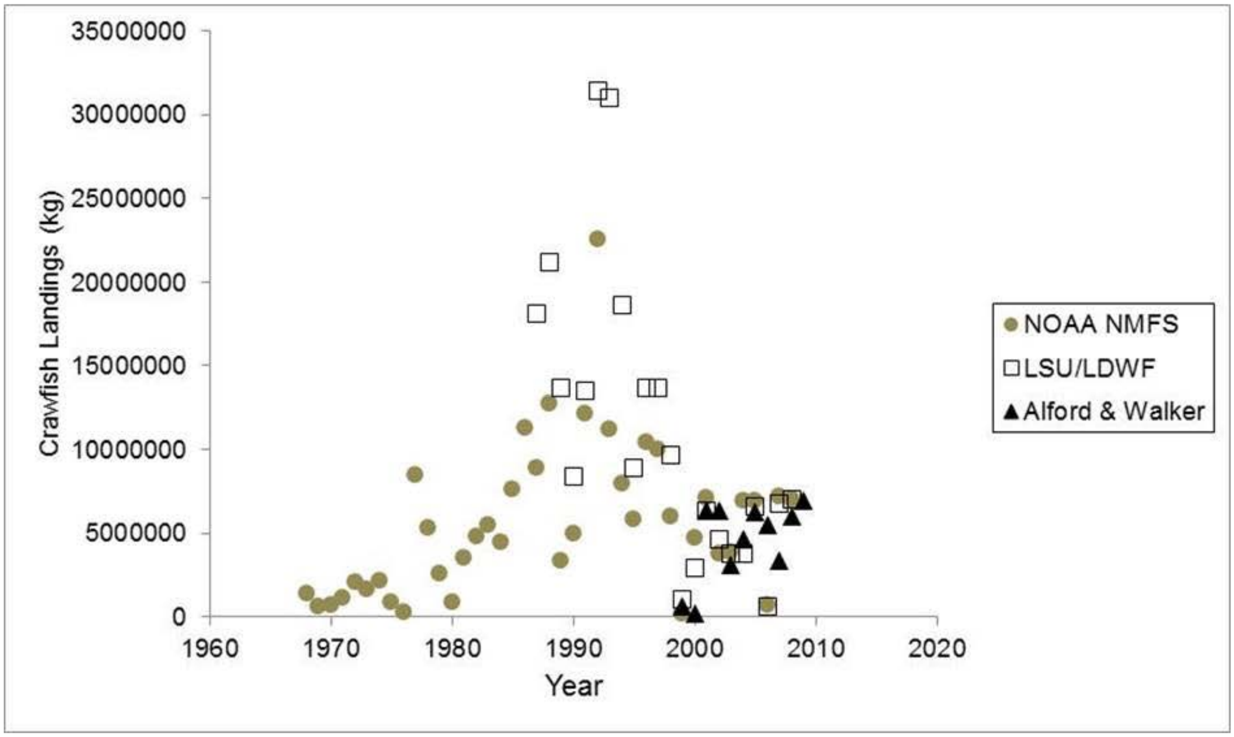

Figure 5.8. Annual commercial crawfish landings for three dataset illustrating temporal coverage.

5.4.4. Management Importance of Understanding Relationships Among Services

We see our approach as a useful frame for future data collection, as a stimulus for developing serious large scale flow-ecology experiments in the ARB, and as an important framework for improving adaptive co-management efforts in the ARB and other watersheds. Due to uncertainties in our data and models, further data collection at finer temporal and spatial scales is needed to evaluate specifics of our findings. An important aspect of this is to determine whether flow-ecology relationships are consistent across such scales. The tight flow control capabilities in the ARB provide a unique opportunity for large-scale experiments that could improve adaptive management and answer such questions (Richter and Thomas 2007, Konrad et al. 2011). Despite the federally mandated flow regime (30% of combined discharge of the Mississippi and Red rivers), there appears to be considerable flexibility in daily and seasonal releases (see Introduction) that could allow flow experiments without significant legal entanglements. The move in environmental management from adaptive management to adaptive co-management emphasizes that stakeholders must be directly involved in environmental decision-making for long-term sustainability of the process and resources (Berkes 2009). We believe the framework provided here allows for questions of stakeholder involvement to be asked more effectively. Each ecosystem service in the ARB is used by some set of stakeholders, whether beyond the confines of the ARB levees (e.g., denitrification, navigation, flood control) or more local resource users (e.g., commercial and recreational fishers). Knowing how these services trade-off or complement each other with changing flow regime allows stakeholders to recognize their natural allies and allows managers to identify areas of direct conflict in resource use. For instance, the oyster and navigation industries may be natural allies regarding flow management decisions because the ecosystem services they rely on appear to be complementary

(Table 5.6). On the other hand, there may be a need for conflict mediation between recreational (crappie, largemouth bass) and other fisheries (crawfish, oysters) because conditions promoting recreational fish production sometimes tend to reduce landings in these commercial fisheries (Table 5.6). Efforts to increase crawfish production may also promote nutrient loading to the Gulf of Mexico through reduced denitrification (Table 5.6).

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Chapter 6: Management Recommendations and Research Needs

6.1. Introduction

It is often difficult to diagnose issues and suggest recommendations in large river basins where a variety of stakeholders, authorities, services, and purposes exist together. This difficulty is compounded in the Atchafalaya River Basin (ARB) because of its distinction as the largest system of floodways in the Mississippi River and Tributaries Project. The recommendations below are not specific prescriptions for evolving the ARB into a more sustainable resource facility. Instead, they are intended to create a dialogue between managers and stakeholders for adaptive policies and future scientific investigations.

6.2. Hydrology and Fisheries

The mandated annual flow allocation (70/30) at Old River Control Structure is designed for flood control and not to benefit the ecological health of the ARB. The annual target allows for flexibility on a daily, monthly, and seasonal basis, although the 70/30 split has generally been maintained on a daily basis as a matter of policy. Major gains in creating a more dynamic flow regime may be achieved even within the strict flow mandate, given the right management goals and policies. More research is needed on whether ecologically-relevant flow changes can be made within the current 70/30 mandate or whether significant legislative changes to the Old River Control Structure policies are needed.

From 1929-1942, structural changes to the Mississippi River for navigation and flood control, including 16 bend cutoffs and levees on almost the entire lower portion of the river shortened the river by 245 km, restricting flooding to 10% of the former floodplain and significantly altering the river’s hydrology (Baker et al. 1991, Schramm et al. 2009). These changes resulted in decreased height and duration of the flood pulse, reducing it to two months from mid-March to mid-May, and creating a briefer and cooler pulse of water (Schramm et al. 2009). Duration of floodplain inundation when temperature exceeds 15 °C is now only about one month per year on average (compared to 4-5 months before channel modifications), and flood waters are also colder due to a deeper channel. This impedes warming of waters and shortens the window for fish utilization of floodplain resources (Schramm, Jr. et al. 2000, Schramm, Jr. and Eggleton 2006).

Although the Mississippi River has largely been cut off from its floodplain, the active floodplains that remain may still be important to many large-river fishes. Recent studies have shown extensive use of the floodplain by catfishes, but only when the flood pulse coincides with warmer temperatures (Schramm, Jr. et al. 2000, Schramm, Jr. and Eggleton 2006). Therefore one suggestion for floodplain ecosystem improvement may be to, where possible, delay the flood pulse by a few weeks to increase the amount of time the floodplain is inundated during warm periods. In the ARB, the Old River Control Structure provides an opportunity for adaptive management of the flow regime at the basin scale. Although the ARB has been reduced to about half of its historic area by levees, much of the floodplain in the lower two-thirds of the ARB is still active. However, in the ARB, delaying the flood pulse to improve floodplain use by fishes must be balanced by the severe hypoxia that develops in standing water in floodplains during summer – the extent and severity of which is a direct result of the magnitude and timing of the flood pulse. Currently, as floodplain water and backwater areas from the flood pulse begin to warm in the summer, algal blooms, and decomposition quickly remove oxygen from the water creating widespread hypoxic conditions by mid-late summer that result in fish kills and loss of ecosystem functions (Sabo et al. 1999a, 1999b, Fontenot et al. 2001). If the flood pulse was delayed, more water would be subject to warming and hypoxia during summer. Another suggestion for the ARB is thus to maintain an early spring flood pulse instead of a late spring/early summer pulse to reduce the extent of hypoxia (Sabo et al. 1999a, Rutherford et al. 2001). The timing of the pulse may thus induce a trade-off between fish access to the floodplain for food resources during the flood pulse and fish habitat and survival (as well as general ecosystem health) in floodplain habitats during the summer.

Changing the flow regime at ORCS may not have the desired effect if other factors affecting the altered hydrology are not addressed. There is a general need for increased exchange of water between main channel and backwater areas (Fontenot et al. 2001) and increasing the number of high-energy flow paths (Sabo et al. 1999a) so that accumulated organic matter which contributes to hypoxia can be flushed from floodplain areas by oxygen-rich, sediment free water (Rutherford et al. 2001). Water stagnation is particularly severe in the central region of the ARB between Grand Lake and the Intracoastal Canal. Water must flow from the main channel into and through all regions with enough momentum to transport crucial elements (oxygen, organic matter, nutrients) between river and swamp (Sabo et al. 1999b). Preserving and expanding remaining lake habitat would increase habitat diversity and improve oxygen conditions and fisheries (Sabo et al. 1999a). This vision relies on both basin-wide and local hydrology. However, improvement in flood pulse characteristics (water movement and depth) at the WMU scale may have the most benefits for water quality such as dissolved oxygen (Kaller et al. 2011).

6.3. Stakeholder Involvement and Decision-making

Adaptive and collaborative management solutions for the ARB need to include non-governmental, governmental, and local stakeholders in the entirety of the visioning and decision-making process. The Louisiana Legislature’s Act 606 (LA R.S. 2008, House Bill No. 1135) made management of the ARB more robust by institutionalizing adaptive management principles and requiring public involvement in the decision process. However, the management framework has two significant shortcomings: (1) the medium chosen for public participation and (2) the limited use of the available knowledge base.

The current medium for public participation in the management of the ARB is the public hearing. While public hearings are good for raising awareness and presenting findings and future plans, they can be classified as one-way communication. They are what Randolph (2004) refers to as a “tell us what you want, and we’ll go away and decide what to do” approach (p. 27). The TAG and Research and Promotion Board are not representative of the many non-governmental stakeholder groups affected by management decisions (see figure 4.2). The decision process begins as a bottom-up process that elicits project ideas from the public, but those ideas are then developed without public involvement and can be influenced by agency directives and institutional biases. The developed project is then presented to the public at the second meeting, becoming the top-down approach to restoration management that Act 606 was seemingly attempting to avoid. This lack of involvement in the project development process leads to a mistrust of management decisions, limits dialogue, and can prevent cooperation (Randolph 2004, Armitage et al. 2008). Further, public hearings provide little opportunity to mitigate intra-stakeholder conflict as they are seen as an opportunity for grandstanding and to promote one’s own interests (Charles Reulet, LDNR, personal communication). Good public involvement in decision-making should be an opportunity for collaboration and not a mechanism to drive a wedge further between competing stakeholder groups.

The second shortcoming of the current approach is the limited use of the full knowledge base throughout the Annual Plan process. The formation of the TAG is useful for dealing with uncertainty in the bio-physical system, but the lack of representation of local resource users often precludes the use of traditional knowledge and the social components of many of the issues in the ARB. The members of the TAG and the Research and Promotion Board work for agencies and institutions whose main focus is on the ecological service values of the ARB, not the social and cultural service values of those most dependent on the system. Their projects and proposals are often met with skepticism and outright mistrust and therefore lack public support (Dan Kroes, USGS, personal communication). While the commitment to science-based management and restoration gives the ABP the advantage of having science out front in the decision process, the use of stakeholder's traditional knowledge needs to be institutionalized as well.

The ABP has already embraced adaptive management principles in its decision process, now it needs to incorporate principles of collaborative management as well. Establishing an adaptive co-management approach to the ARB has the potential to increase the knowledge base for management decisions and mitigate conflict among stakeholders. Knowledge is power; sharing its development is sharing that power. The emphasis on the co-production of knowledge by linking resource users with managers establishes a relationship that deconstructs the dynamics of power that cause many of the conflicts with management decisions (Armitage et al. 2008). Such power-sharing relationships between managers and stakeholders can also help develop more effective management strategies (Arnold and Fernandez-Gimenez 2007, Fernandez-Gimenez et al. 2008).

The establishment of a non-technical Stakeholder Advisory Board to supplement the TAG and Research and Promotion Board in the decision-making process would institutionalize stakeholder involvement and facilitate an improved collaborative adaptive management process in the ARB. This group should consist of representatives of the multiple interest groups identified previously as well as members of local communities. There are many reasons to support this kind of stakeholder involvement: it promotes learning, builds trust, helps manage conflict, predicts effects of management actions, and promotes civic engagement (Fernandez-Gimenez et al. 2008). A Stakeholder Advisory Board would enable the inclusion of stakeholders throughout the entire Annual Plan process. To be effective, frequent collaboration with the TAG and Research and Promotion Board is necessary; stakeholders who participate in management need to believe their input actually affects decisions but the current public hearings do not facilitate this needed closure. This new group would increase the scope of input concerning management decisions enabling a greater use of the knowledge base. Also, the communication and shared discourse that a Stakeholder Advisory Board requires are prerequisites to conflict resolution. This inclusion of a Stakeholder Advisory Board in the governance structure of the ARB can be thought of as a social contract: they are given increased ownership of the system in exchange for responsibility and accountability for their actions. Also, the incentives are right since not only are members under pressure from their constituents and fellow community members but they are also dependent on the system themselves. Establishing a functional Stakeholder Advisory Board amid longstanding conflict and mistrust is no easy task and will most certainly require outside facilitation, a discussion that is beyond the scope of this chapter.

6.4. Property Rights: Takings and Liability

The laws that establish boundaries between public and private property and permissible uses of navigable waters were not drafted with a rapidly changing and significantly modified landscape in mind. The result is a management landscape that is unable to address ongoing conflicts to the detriment of long-term goals and the ecological health of the ARB. Currently, managers of the ARB are attempting to mitigate this rapid ecological change with a series of restoration projects designed to promote wildlife, forest health, and local flow modification.

On paper, laws are black and white. They determine what is allowed and what is not, where a boundary is and what rights the public has regarding that boundary. Interpreting these laws in the ARB is not so straightforward. Since its designation as a floodway in 1928, 22 natural waterways have been cut-off, new channels for freshwater distributions have been made, the main channel of the Atchafalaya River has enlarged by approximately 50,000 ft^2, and 449 miles of levees have reduced the ARB to 47% of its natural size (Reuss 2004; B. P. Piazza In press). These are just the features associated with flood control. Oil and natural gas operations have crisscrossed the ARB with over 500 access canals totaling more than 600 miles (Reuss 2004). All of these anthropogenic modifications have affected annual high and low water levels, impaired access to public lands, and changed the navigable status of many waters. Non-navigable streams have become navigable and navigable streams have been created or become non-navigable. This has led to disagreements over what uses these newly navigable waters can be put to and over who owns the land.

The result is a land of confusion that must rely on the courts to settle disputes, but the courts seem almost as confused. For example, in 1964 the First Circuit Court of Appeal of Louisiana found Six Mile Lake, located in the southern portion of the ARB, to be a stream and therefore the banks belonged to the riparian owner (*State v. Cockrell*, 162 So.2d 361. La.App.1st Cir., 1964). Nine years later in a different case, the Supreme Court of Louisiana found the same body of water to be a lake, which means the banks belong to the state (*State v. Placid Oil Co.*, 300 So.2d 154. La. 1974). There have been many similar cases since, most dealing with trespass as the ownership of the land under the water was in dispute (*Schoeffler v. Drake Hunting Club*, 05-499. La.App. 3 Cir. 1/4/06, 919 So.2d 822; *Buckskin Hunting Club v. Bayard*, 03–1428, p. 9. La.App. 3 Cir. 3/3/04, 868 So.2d 266, 272; and *State v. Barras*, 615 So.2d 285. La.1993). To encapsulate the difficult decisions courts are being asked to make on these issues we turn to the dissenting opinion in *State v. Barras* in which Louisiana Supreme Court Justice Dennis, citing La.C.C. art. 456, stated:

> “It is undisputed that the property upon which the defendants are accused of trespassing is within the Atchafalaya Basin, which contains navigable rivers and streams, and is also inside of levees in proximity to the waters. Therefore, the state had the burden of proving that the property was not part of the bank of a navigable river or stream under either of the statutory definitions. In my opinion, because of the complex topography, the uncertainties as to water sources, and other vicissitudes of the present case, even after viewing the evidence in the light most favorable to the prosecution, no rational trier of fact could have found beyond a reasonable doubt that the property in question was not subject to public use.” Id.

The managers of the ARB, by relying on the courts to settle disputes regarding the boundaries of land and water in the ARB on a case by case basis are unable to effectively address these ongoing issues. The courts can bring no clear resolution to the conflicts through their decisions. Further, in rendering a decision the courts are forced to take something that is dynamic and make it static. To be sure, this is not something that can be solved by the ABP or the USACE in their capacity as managers of the ARB. Their basin-wide mandates and the primacy of flood control preclude that. This is a situation in which the solutions can be facilitated by mangers and enforced by the courts, but must ultimately come from the resource users themselves. Unfortunately, the current institutional infrastructure in the ARB does not provide the necessary forum for these solutions to come to fruition.

6.5. Science Needs: Future Research

Identifying specific research needs for the ARB can aid scientists in tailoring investigations which can be of most benefit to the ARB. Of utmost importance are the continuation, improvement, and expansion of monitoring efforts in the ARB for adaptive and collaborative management. Monitoring assists scientists in realizing jumping off points for future research projects and provides an informational “measuring tool” for managers and stakeholders to understand the status of the ARB’s ecosystems. Expansion of the ecosystem services methods proposed in Chapter 5 could also be a valuable educational asset for managers and stakeholders showing the trade-off and complementary benefits of restoration projects, changing flow regime at Old River Control Structure, and policy decisions.

More knowledge is needed in the areas of biogeochemical cycles, invasive species, flow and sedimentation patterns, and fisheries production within floodplains. Understanding biogeochemical cycles involving the research of nitrogen, phosphorus, mercury, and carbon could be crucial to understanding the potential of the ARB in regards to pollution abatement, potential denitrification, and carbon sequestration. Investigating how invasive species, both flora and fauna, are evolving in the ARB at temporal and spatial scales is crucial in the designation of restoration projects and the overall management of the ARB. Knowing how and where flow patterns occur within the ARB at various stage levels will allow for local and basin-wide restoration efforts to be better managed for the particular services they have been designed to render. Fully understanding the seasonality and other lagged time attributes that are associated with fisheries and their habitat and spawning patterns within floodplains is critical to understanding floodplain connectivity, which could lead to more successful commercial fisheries.

The connectivity of environmental resources within the ARB requires a holistic, multi-disciplinary approach in order to unravel all of the intricacies of the ecosystems and achieve a full understanding of what and how processes occur. As previously mentioned, a robust and adaptive monitoring program is necessary to fill in gaps in the story of the ARB. Towards this end, a free and open exchange of scientific research and data is crucial for inter-disciplinary teams of scientists to use for investigating the ARB's management priorities. A data clearinghouse for biological, physical, social and GIS data could be implemented as an efficient "one stop shop" for researchers and teams to access governmental, academic, and traditional knowledge in order to progress the scientific method within the ARB.

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Appendix A: Fishes of the Atchafalaya River Basin and Delta

Taxonomy and Common Name	Scientific Name	Primary Habitat[1]	State Ranking[2]	Federal Status[3]	AFS Status[4]	Primary Source[5]	[notes]
Sturgeons - Acipenseridae							
Pallid Sturgeon	*Scaphirhynchus albus*		S1	E	E (same)	10	
Shovelnose Sturgeon	*Scaphirhynchus platorhynchus*					4	
Paddlefishes - Polyodontidae							
Paddlefish	*Polyodon spathula*		S3		V (same)	4	
Gars - Lepisosteidae							
Spotted Gar	*Lepisosteus oculatus*					4	
Longnose Gar	*Lepisosteus osseus*					4	
Shortnose Gar	*Lepisosteus platostomous*					4	
Alligator Gar	*Atractosteus spatula*				V	4	
Bowfins - Amiidae							
Bowfin	*Amia calva*					4	
Tarpons - Elopidae							
Ladyfish	*Elops saurus*	m/e				4	
Freshwater eels - Anguilidae							
American Eel	*Anguilla rostrata*	c				4	
Snake eels - Ophichthidae							
Speckled Worm Eel	*Myrophis punctatus*	m/e				4	
Herrings - Clupeidae							
Skipjack Herring	*Alosa chrysochloris*					4	

Gizzard Shad	*Dorosoma cepedianum*					4	
Threadfin Shad	*Dorosoma petenense*					4	
Gulf Menhanden	*Brevoortia patronus*	m/e				4	
Anchovies - Engraulidae							
Bay Anchovy	*Anchoa mitchilli*	m/e				4	
Mooneyes - Hiodontidae							
Goldeye	*Hiodon alosoides*					4	
Mooneye	*Hiodon tergisus*					4	
Pikes - Esocidae							
Grass Pickerel	*Esox americanus vermiculatus*					4	
Chain Pickerel	*Esox niger*					4	
Carps and Minnows - Cyprinidae							
Grass Carp*	*Ctenopharyngodon idella*					5	
Red Shiner	*Cyprinella lutrensis*					4	
Blacktail Shiner	*Cyprinella venusta*					4	
Common Carp*	*Cyprinus carpio*					4	
Cypress Minnow	*Hybognathus hayi*					4	
Mississippi Silvery Minnow	*Hybognathus nuchalis*					4	
Pallid Shiner	*Hybopsis amnis*					5	questionable; record from just W of the ARB levee in Douglas; range consistent with ARB in Page & Burr

Clear Chub	*Hybopsis winchelli*					2	questionable; range consistent with Page & Burr; no records from ARB in Douglas
Silver Carp*	*Hypopthalmichthys molitrix*					5	
Bighead Carp*	*Hypopthalmichthys nobilis*					5	
Ribbon Shiner	*Lythrurus fumeus*					4	
Cherryfin Shiner	*Lythrurus roseipinnis*					2	questionable; east edge of levee; range in Page&Burr does not include ARB; no records in Douglas
Redfin Shiner	*Lythrurus umbratilis*					5	
Sicklefin Chub	*Macrhybopsis meeki*				V(improved)	2	
Silver Chub	*Macrhybopsis storeriana*					4	
Golden Shiner	*Notemigonus crysoleucas*					4	
Emerald Shiner	*Notropis atherinoides*					4	
Blackspot Shiner	*Notropis atrocaudalis*					5	questionable; no records for/near ARB in Douglas; range in Page & Burr does not include ARB
River Shiner	*Notropis blennius*					4	
Bigeye Shiner	*Notropis boops*					5	questionable; no records for/near ARB in Douglas; range in Page & Burr does not include ARB

Ghost Shiner	*Notropis buchanani*					4	
Taillight Shiner	*Notropis maculatus*					4	
Chub Shiner	*Notropis potteri*					4	
Silverband Shiner	*Notropis shumardi*					4	
Weed Shiner	*Notropis texanus*					4	
Mimic Shiner	*Notropis volucellus*					4	
Pugnose Minnow	*Oposopoedus emilae*					4	
Bluntnose Minnow	*Pimephales notatus*					5	questionable; no records for/near ARB in Douglas; range in Page & Burr does not include ARB
Bullhead Minnow	*Pimephales vigilax*					4	
Flathead Chub	*Platygobio gracilis*					4	
Bluehead Shiner	*Pteronotropis hubbsi*		S2		V	7	
Suckers - Catostomidae							
River Carpsucker	*Carpiodes carpio*					4	
Quillback	*Carpiodes cyprinus*					4	
Blue Sucker	*Cycleptus elongatus*		S2S3		V (same)	4	
Creek Chubsucker	*Erimyzon oblongus*					1	
Lake Chubsucker	*Erimyzon sucetta*					1	
Smallmouth Buffalo	*Ictiobus bubalus*					4	
Bigmouth Buffalo	*Ictiobus cyprinellus*					4	
Black Buffalo	*Ictiobus niger*					4	
Striped Shiner	*Luxilus chrysocephalus*					2	

Spotted Sucker	*Minytrema melanops*					4	
Blacktail Redhorse	*Moxostoma poecilurum*					5	
Bullhead Catfishes - Ictaluridae							
Black Bullhead	*Ameiurus melas*					4	
Yellow Bullhead	*Ameiurus natalis*					4	
Brown Bullhead	*Ameiurus nebulosus*					4	
Blue Catfish	*Ictalurus furcatus*					4	
Channel Catfish	*Ictalurus punctatus*					4	
Black Madtom	*Noturus funebris*					2	Questionable; range extends only to Pearl R. (Page & Burr, Boschung & Mayden)
Tadpole Madtom	*Noturus gyrinus*					4	
Flathead Catfish	*Pylodictis olivaris*					4	
Pirate Perches - Aphredoderidae							
Pirate Perch	*Aphredoderus sayanus*					4	
Needlefishes - Belonidae							
Atlantic Needlefish	*Strongylura marina*					4	
Killifishes - Cyprinodontidae							
Sheepshead Minnow	*Cyprinodon variegatus*	e				8	
Golden Topminnow	*Fundulus chrysotus*					4	

Marsh Killifish	*Fundulus confluentus*	e/m				5	questionable but listed in Douglas as marine invader (no localities); no range in Page&Burr but says w to s AL
Gulf Killifish	*Fundulus grandis*	e				8	
Saltmarsh Topminnow	*Fundulus jenkinsi*	e				8	
Blackspotted Topminnow	*Fundulus olivaceus*					4	
Bayou Killifish	*Fundulus pulvereus*	e				8	
Rainwater Killifish	*Lucania parva*	f/e				4	
Livebearers - Poeciliidae							
Western Mosquitofish	*Gambusia affinis*					4	
Least Killifish	*Heterandria formosa*					4	
Sailfin Molly	*Poecilia latipinna*					4	
Silversides - Atherinidae							
Brook Silverside	*Labidesthes sicculus*					4	
Rough Silverside	*Membras martinica*	m/e				4	
Mississippi Silverside	*Menidia audens*					1, 5	
Inland Silverside	*Menidia beryllina*	f/e				8	
Pipefishes - Syngnathidae							
Gulf Pipefish	*Syngnathus scovelli*		S4			4	
Temperate Basses - Percichthyidae							
White Bass	*Morone chrysops*					4	

Yellow Bass	*Morone mississippiensis*					4	
Striped Bass	*Morone saxatilis*	a			V	4	
Sunfishes - Centrarchidae							
Flier	*Centrarchus macropterus*					4	
Green Sunfish	*Lepomis cyanellus*					4	
Warmouth	*Lepomis gulosus*					4	
Orangespotted Sunfish	*Lepomis humilis*					4	
Bluegill	*Lepomis macrochirus*					4	
Dollar Sunfish	*Lepomis marginatus*					1,2,5	
Longear Sunfish	*Lepomis megalotis*					4	
Redear Sunfish	*Lepomis microlophus*					4	
Spotted Sunfish	*Lepomis punctatus*					4	
Bantam Sunfish	*Lepomis symmetricus*					4	
Spotted Bass	*Micropterus punctulatus*					4	
Largemouth Bass	*Micropterus salmoides*					4	
White Crappie	*Pomoxis annularis*					4	
Black Crappie	*Pomoxis nigromaculatus*					4	
Pygmy Sunfishes - Elassomatidae							
Banded Pygmy Sunfish	*Elassoma zonatum*					4	
Perches - Percidae							
Mud Darter	*Etheostoma asprigene*					4	
Bluntnose Darter	*Etheostoma chlorosomum*					4	
Swamp Darter	*Etheostoma fusiforme*					4	

Slough Darter	*Etheostoma gracile*					4	
Cypress Darter	*Etheostoma proeliare*					4	
Logperch	*Percina caprodes*					4	
Bigscale Logperch	*Percina macrolepida*		S1S2			2	questionable; e&w side of levee near Ramah, LA; no ARB records in Douglas; range in Page & Burr does not include e. LA but introduced elsewhere
Blackside Darter	*Percina maculata*					2	questionable; near Ramah, LA; Douglas includes record outside w ARB levee
Saddleback Darter	*Percina vigil*					2	questionable; e edge of basin near Ramah, LA; no ARB records in Douglas; range in Page & Burr somewhat consistent
Sauger	*Sander canadense*					4	
Walleye*	*Sander vitreum*					5	
Drums - Scianidae							
Freshwater Drum	*Aplodintous grunniens*					4	
Silver Perch	*Bairdiella chrysoura*	m/e				2	
Sand Weakfish	*Cynoscion arenarius*	m/e				2	
Spotted Weakfish	*Cynoscion nebulosus*	m/e				2	
Spot Croaker	*Leiostomus xanthurus*	m/e				2	

Southern Kingcroaker	*Menticirrhus americanus*	m				6	
Atlantic Croaker	*Micropogonias undulatus*	m/e				2	
Black Drum	*Pogonias cromis*	m/e				2	
Red Drum	*Sciaenops ocellatus*	m/e				2	
American Stardrum	*Stellifer lanceolatus*	m/e				2	
Mullets - Mugilidae							
Striped Mullet	*Mugil cephalus*	f/m/e				4	
White Mullet	*Mugil curema*					4	
Gobies - Gobiidae							
Clown Goby	*Microgobius gulosus*					4	
Large-tooth Flounders - Paralichthyidae							
Bay Whiff	*Citharichthys spilopterus*	m/e				2	
Fringed Flounder	*Etropus crossotus*	m/e				2	
Southern Flounder	*Paralichthys lethostigma*	m/e				4	
American Soles - Achiridae							
Lined Sole	*Achirus lineatus*	m/e				2	
Hogchoker	*Trinectes maculatus*	f/e				4	
Porgies - Sparidae							
Sheepshead	*Archosargus probatocephalus*	m/e				2	
Pinfish	*Lagodon rhomboides*	e				8	
Longspine Porgy	*Stenotomus caprinus*	m				2	

Sleepers - Eleotridae							
Fat Sleeper	*Dormitator maculatus*	e				8	
Spinycheek Sleeper	*Eleotris pisonis*	e				8	
Large-scaled Spinycheek Sleeper	*Eleotris amblyopsis*	m/e/f				2	
Gobies - Gobiidae							
Lyre Goby	*Evorthodus lyricus*	e				8	
Violet Goby	*Gobioides broussonneti*	m/e				6	
Darter Goby	*Gobionellus boleosoma*	e				8	
Highfin Goby	*Gobionellus oceanicus hastatus*	e				8	
American Freshwater Goby	*Gobionellus shufeldti*	e				8	
Naked Goby	*Gobiosoma bosc*	e				2	
Sea Catfishes - Ariidae							
Hardhead Sea Catfish	*Arius felis*	m/e				8	
Gafftopsail Sea Catfish	*Bagre marinus*	m/e				8	
Mojarra - Gerreidae							
Silver Mojarra	*Eucinostomus argenteus*	m/e				8	
Jacks & Pompanos - Carangidae							
Crevalle Jack	*Caranx hippos*	m				8	
Atlantic Bumper	*Chloroscombrus chrysurus*	m				6	
Leatherjacket	*Oligoplites saurus*	m/e				2	
Atlantic Moonfish	*Selene setapinnis*	m				6	
Lookdown	*Selene vomer*	m				6	

Butterfishes - Stromateidae							
Gulf Butterfish	*Peprilus burti*	m				8	
American Harvestfish	*Peprilus paru*	m				6	
Searobins - Triglidae							
Bighead Searobin	*Prionotus tribulus*	m				8	
Snappers - Lutjanidae							
Grey Snapper	*Lutjanus griseus*	m				2	
Wenchman	*Pristipomoides aquilonaris*	m				2	
Tonguefishes - Cynoglossidae							
Offshore Tonguefish	*Symphurus civitatium*	m				2	
Blackcheek Tonguefish	*Symphurus plagiusa*	m				8	
Requiem Sharks - Carcharhinidae							
Bull Shark	*Carcharinus leucas*	m				3,5	
Stingrays - Dasyatidae							
Southern Stingray	*Dasyatis americana*	m				6	
Atlantic Stingray	*Dasyatis sabina*	m				2	
Toadfishes - Batrachoididae							
Gulf Toadfish	*Opsanus beta*	m				6	
Atlantic Midshipman	*Porichthys porosissimus*	m				6	
Clingfishes & Singlslits -							

Gobiesocidae							
Skilletfish	*Gobiesox strumosus*	m				6	
Spadefishes, Batfishes, & Scats - Ephippidae							
Atlantic Spadefish	*Chaetodipterus faber*	m				6	
Threadfins - Polynemidae							
Atlantic Threadfin	*Polydactylus octonemus*	m				6	
Combtooth Blennies - Blenniidae							
Freckled Blenny	*Hypsoblennius ionthas*	m				6	
Cutlassfishes - Trichiuridae							
Largehead Hairtail	*Trichiurus lepturus*	m				6	
Mackerels, Tunas, Bonitos - Scombridae							
Atlantic Spanish Mackerel	*Scomberomorus maculatus*	m				2, 6	
Puffers - Tetraodontidae							
Southern Puffer	*Sphoeroides nephelus*	m				6	
Stargazers - Uranoscopidae							
Southern Stargazer	*Astroscopus y-graecum*	m				2	

Lancer stargazer	*Kathetostoma albigutta*	m				2	
Sea Basses - Serranidae							
Rock Sea Bass	*Centropristis philadelphica*	m				2	
Porcupinefishes - Diodontidae							
Striped burrfish	*Chilomycterus schoepfii*	m				2	
Grunts - Haemulidae							
Pigfish	*Orthopristis chrysoptera*	m/e				2	
Skates - Rajidae							
Roundel skate	*Raja texana*	m				2	
Hammerhead, Bonnethead, & Scoophead Sharks - Sphyrnidae							
Bonnethead	*Sphyrna tiburo*	m/e				2	
Needlefishes - Belonidae							
Atlantic needlefish	*Strongylura marina*	m/f/e				2	
Pipefishes & Seahorses - Syngnathidae							
Gulf Pipefish	*Syngnathus scovelli*	m/f/e				2	
Lizardfishes - Synodontidae							
Inshore Lizardfish	*Synodus foetens*	m/e				2	
Lefteye							

Flounders - Bothidae							
Sash Flounder	*Trichopsetta ventralis*	m				2	
Phycid Hakes - Phycidae							
Southern Codling	*Urophycis floridana*	m				2	

1. Habitat listed for species other than freshwater, based on FishBase records and Page and Burr 2011; m = marine, f = freshwater, e = estuarine, a = anadromous, c = catadromous

2. Louisiana Natural Heritage Program; S1 = critically imperiled; S2 = imperiled; S3 = rare or localized; S4 = apparently secure; S5 = demonstrably secure; SX = extirpated

3. U.S. Fish and Wildlife Service; E = endangered; T = threatened

4. American Fisheries Society conservation status from Jelks et al. 2011 for freshwater species only; V = vulnerable; T = threatened; E = endangered; X = extinct; Xp = possibly extinct; Xn = extirpated in nature; in parentheses is population status change since 1989

5. Source of fish record. 1 = (Douglas 1974); 2 = FishNet2, www.fishnet2.net; 3 = (Gunter 1938); 4 = (Lambou 1990); 5 = LDWF fishery-independent sampling database 1990-2010 provided by B. Alford; 6 = (Perret et al. 1974); 7 = (Ranvestel and Burr 2002); 8 = (Thompson and Deegan 1983); 9 = (Thompson and Peterson 2003); 10 = (U.S. Fish and Wildlife Service 2007). Records from FishNet2 and the LDWF database were verified by comparing with Page and Burr (2011) and Douglas (1974) and questionable are noted with comments in ‘notes’ column.

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Appendix B: Herpetofauna of the Atchafalaya River Basin

	Family	**Scientific Name**	**Common Name**
Salamanders			
	Ambystomatidae		
		Ambystoma maculatum	Spotted Salamander
		Ambystoma opacum	Marbled Salamander
		Ambystoma talpoideum	Mole Salamander
		Ambytoma texanum	Small-mouthed Salamander
		Ambystoma tigrinum	Tiger Salamander
	Amphiumidae		
		Amphiuma tridactylum	Three-toed Amphiuma
	Plethodontidae		
		Desmognathus fuscus	Dusky Salamander
		Desmognathus auriculatus	Southern Dusky Salamander
		Eurycea quadridigitata	Dwarf Salamander
	Salamandridae		
		Notophthalmus viridescens	Eastern Newt
	Sirenidae		
		Siren intermedia	Lesser Siren
Frogs & Toads			
	Bufonidae		
		Bufo valliceps	Gulf Coast Toad
		Bufo woodhousii	Woodhouse's Toad
	Hylidae		
		Acris crepitans	Northern Cricket Frog
		Hyla chrysoscelis	Cope's Gray Treefrog
		Hyla versicolor	Gray Treefrog
		Hyla cinerea	Green Treefrog
		Hyla squirella	Squirrel Treefrog
		Pseudacris crucifer	Spring Peeper
		Pseudacris triseriata	Western Chorus Frog
	Microhylidae		
		Gastrophryne carolinensis	Eastern Narrow-mouthed Toad
	Ranidae		
		Rana catesbeiana	Bullfrog
		Rana clamitans	Green Frog
		Rana grylio	Pig Frog
		Rana sphenocephala	Southern Leopard Frog
Turtles			
	Chelydridae		
		Chelydra serpentina	Snapping Turtle

		Macrochlemys temminckii	Alligator Snapping Turtle
	Emydidae		
		Chrysemys picta	Painted Turtle
		Deirochelys reticularia	Chicken Turtle
		Graptemys kohnii	Mississippi Map Turtle
		Graptemys pseudogeographica	False Map Turtle
		Malaclemys terrapin	Diamond-backed Terrapin
		Pseudemys concinna	River Cooter
		Pseudemys floridana	Cooter
		Terrapene carolina	Eastern Box Turtle
		Terrapene ornata	Ornate Box Turtle
		Trachemys scripta	Slider
	Kinosternidae		
		Kinosternon subrubrum	Eastern Mud Turtle
		Sternotherus carinatus	Razor-backed Musk Turtle
		Sternotherus odoratus	Stinkpot
	Trionychidae		
		Apalone spinifera	Spiny Softshell
Lizards			
	Anguidae		
		Ophisaurus attenuatus	Slender Glass Lizard
	Iguanidae		
		Anolis carolinensis	Green Anole
		Sceloporus undulatus	Eastern Fence Lizard
	Scincidae		
		Eumeces fasciatus	Five-lined Skink
		Eumeces laticeps	Broad-headed Skink
		Scincella lateralis	Ground Skink
	Teiidae		
		Cnemidophorus sexlineatus	Six-lined Racerunner
Snakes			
	Colubridae		
		Coluber constrictor	Racer
		Diadophis punctatus	Ring-necked Snake
		Elaphe guttata	Corn Snake
		Elaphe obsoleta	Rat Snake
		Farancia abacura	Mud Snake
		Heterodon platyrhinos	Eastern Hog-nosed Snake
		Lampropeltis calligaster	Prairie Kingsnake
		Lampropeltis getulus	Common Kingsnake

		Lampropeltis triangulum	Milk Snake
		Nerodia clarkii	Salt Marsh Snake
		Nerodia cyclopion	Western Green Water Snake
		Nerodia erythrogaster	Plain-bellied Water Snake
		Nerodia fasciata	Southern Water Snake
		Nerodia rhombifera	Diamond-backed Water Snake
		Opheodrys aestivus	Rough Green Snake
		Regina grahamii	Graham's Crayfish Snake
		Regina rigida	Glossy Crayfish Snake
		Storeria dekayi	Brown Snake
		Storeria occipitomaculata	Red-bellied Snake
		Thamnophis proximus	Western Ribbon Snake
		Thamnophis sirtalis	Common Garter Snake
		Virginia striatula	Rough Earth Snake
	Elapidae		
		Micrurus fulvius	Eastern Coral Snake
	Viperidae		
		Agkistrodon contortrix	Copperhead
		Agkistrodon piscivorus	Cottonmouth
		Crotalus horridus	Timber Rattlesnake
		Sistrurus miliarius	Pygmy Rattlesnake
	Crocodilians		
		Alligator mississippiensis	American Alligator

Source: Dundee, H. A., & Rossman, D. A. (1989). The amphibians and reptiles of Louisiana. Baton Rouge and London: Louisiana State University Press.

All species included in list are those that occur in the seven major parishes of the basin: Avoyelles, St. Landry, Pointe Coupee, St. Martin, Iberville, Iberia, St. Mary.

Appendix C: Birds of the Atchafalaya River Basin

	Scientific Name	**Common Name**
Grebes		
	Podilymbus podiceps	Pied-billed Grebe
Cormorants		
	Phalacrocorax auritus	Double-crested Cormorant
Anhingas		
	Anhinga anhinga	Anhinga
Herons & Bitterns		
	Ardea herodias	Great Blue Heron
	Ardea alba	Great Egret
	Egretta thula	Snowy Egret
	Egretta rufescens	Reddish Egret
	Egretta caerulea	Little Blue Heron
	Egretta tricolor	Tricolored Heron
	Bubulcus ibis	Cattle Egret
	Butorides virescens	Green Heron
	Nycticorax nycticorax	Black-crowned Night-Heron
	Nyctanassa violacea	Yellow-crowned Night-Heron
Ibises		
	Eudocimus albus	White Ibis
	Platalea ajaja	Roseate Spoonbill
Storks		
	Mycteria americana	Wood Stork
American Vultures		
	Coragyps atratus	Black Vulture
	Cathartes aura	Turkey Vulture
Waterfowl		
	Anser albifrons	Greater White-fronted Goose
	Chen caerulescens	Snow (Blue) Goose
	Aix sponsa	Wood Duck
	Anas strepera	Gadwall
	Anas americana	American Wigeon
	Anas platyrhynchos	Mallard
	Anas discors	Blue-winged Teal
	Anas cypeata	Northern Shoveler
	Anas acuta	Northern Pintail
	Anas carolinensis	Green-winged Teal
	Aythya valisineria	Canvasback
	Aythya americana	Redhead
	Aythya collaris	Ring-necked Duck

	Aythya affinis	Lesser Scaup
	Bucephala albeola	Bufflehead
	Lophodytes cucullatus	Hooded Merganser
	Mergus serrator	Red-breasted Merganser
	Oxyura jamaicensis	Ruddy Duck
Hawks		
	Pandion haliaetus	Osprey
	Elanoides forficatus	Swallow-tailed Kite
	Ictinia mississippiensis	Mississippi Kite
	Haliaeetus leucocephalus	Bald Eagle
	Circus cyaneus	Northern Harrier
	Accipiter striatus	Sharp-shinned Hawk
	Accipiter cooperii	Cooper's Hawk
	Buteo lineatus	Red-shouldered Hawk
	Buteo platypterus	Broad-winged Hawk
	Buteo jamaicensis	Red-tailed Hawk
Falcons		
	Falco sparverius	American Kestrel
	Falco columbarius	Merlin
	Falco peregrinus	Peregrine Falcon
Turkeys		
	Meleagris gallopavo	Wild Turkey
Rails		
	Rallus elegans	King Rail
	Rallus limicola	Virginia Rail
	Porzana carolina	Sora
	Porphyrio martinica	Purple Gallinule
	Gallinula chloropus	Common Moorhen (Gallinule)
	Fulica americana	American Coot
Plovers		
	Pluvialis squatarola	Black-bellied Plover
	Charadrius semipalmatus	Semipalmated Plover
	Charadrius vociferus	Killdeer
Stilts		
	Himantopus mexicanus	Black-necked Stilt
Sandpipers		
	Tringa melanoleuca	Greater Yellowlegs
	Tringa flavipes	Lesser Yellowlegs
	Tringa solitaria	Solitary Sandpiper
	Actitis macularia	Spotted Sandpiper
	Calidris pusilla	Semipalmated Sandpiper

	Calidris mauri	Western Sandpiper
	Calidris minutilla	Least Sandpiper
	Calidris melanotos	Pectoral Sandpiper
	Calidris alpina	Dunlin
	Calidris himantopus	Stilt Sandpiper
	Gallinago delicata	Wilson's Snipe
	Scolopax minor	American Woodcock
	Limnodromus scolopaceus	Long-billed Dowitcher
Doves		
	Columba liva	Rock Dove
	Streptopelia decaocto	Eurasian Collared-dove
	Zenaida macroura	Mourning Dove
Cuckoos		
	Coccyzus erythropthalmus	Black-billed Cuckoo
	Coccyzus americanus	Yellow-billed Cuckoo
Barn Owls		
	Tyto alba	Barn Owl
Owls		
	Megascops asio	Eastern Screech-Owl
	Bubo virginianus	Great Horned Owl
	Strix varia	Barred Owl
Nightjars		
	Chordeiles minor	Common Nighthawk
	Antrostomus carolinensis	Chuck-will's-widow
	Antrostomus vociferus	Whip-poor-will
Swifts		
	Chaetura pelagica	Chimney Swift
Hummingbirds		
	Archilochus colubris	Ruby-throated Hummingbird
	Selasphorus rufus	Rufous Hummingbird
Kingfishers		
	Megaceryle alcyon	Belted Kingfisher
Woodpeckers		
	Melanerpes erythrocepahlus	Red-headed Woodpeckers
	Melanerpes carolinus	Red-bellied Woodpecker
	Sphyrapicus varius	Yellow-bellied Sapsucker
	Picoides pubescens	Downy Woodpecker
	Picoides villosus	Hairy Woodpecker
	Colaptes auratus	Northern Flicker
	Dryocopus pileatus	Pileated Woodpecker

Flycatchers		
	Contopus cooperi	Olive-sided Flycatcher
	Contopus virens	Eastern Wood-Pewee
	Empidonax flaviventris	Yellow-bellied Flycatcher
	Empidonax virescens	Acadian Flycatcher
	Empidonax alnorum	Alder Flycatcher
	Empidonax minimus	Least Flycatcher
	Sayornis phoebe	Eastern Phoebe
	Pyrocephalus rubinus	Vermilion Flycatcher
	Myiarchus crinitus	Great Crested Flycatcher
	Tyrannus tyrannus	Eastern Kingbird
	Tyrannus forficatus	Scissor-tailed Flycatcher
Vireos		
	Vireo griseus	White-eyed Vireo
	Vireo flavifrons	Yellow-throated Vireo
	Vireo solitarius	Blue-headed Vireo
	Vireo gilvus	Warbling Vireo
	Vireo philadelphicus	Philadephia Vireo
	Vireo olivaceus	Red-eyed Vireo
Jays & Crows		
	Cyanocitta cristata	Blue Jay
	Corvus brachyrhynchos	American Crow
	Corvus ossifragus	Fish Crow
Swallows		
	Progne subis	Purple Martin
	Tachycineta bicolor	Tree Swallow
	Stelgidopteryx serripennis	Northern Rough-winged Swallow
	Riparia riparia	Bank Swallow
	Petrochelidon pyrrhonota	Cliff Swallow
	Hirundo rustica	Barn Swallow
Titmice		
	Poecile carolinensis	Carolina Chickadee
	Baeolophus bicolor	Tufted Titmouse
Nuthatches		
	Sitta canadensis	Red-breasted Nuthatch
Creepers		
	Certhia americana	Brown Creeper
Wrens		
	Thryothorus ludovicianus	Carolina Wren
	Troglodytes aedon	House Wren

	Troglodytes hiemalis	Winter Wren
Kinglets		
	Regulus satrapa	Golden-crowned Kinglet
	Regulus calendula	Ruby-crowned Kinglet
Gnatcatchers		
	Polioptila caerulea	Blue-gray Gnatcatchers
Thrushes		
	Sialia sialis	Eastern Bluebird
	Catharus fuscescens	Veery
	Catharus minimus	Gray-cheeked Thrush
	Catharus ustulatus	Swainson's Thrush
	Catharus guttatus	Hermit Thrush
	Hylocichla mustelina	Wood Thrush
	Turdus migratorius	American Robin
Shrikes		
	Lanius ludovicianus	Loggerhead Shrike
Mockingbirds & Thrashers		
	Dumetella carolinensis	Gray Catbird
	Mimus polyglottos	Northern Mockingbird
	Toxostoma rufum	Brown Thrasher
Starlilngs		
	Sturnus vulgaris	European Starling (exotic)
Pipits		
	Anthus rubescens	American Pipit
Waxwings		
	Bombycilla cedrorum	Cedar Waxwing
Wood Warblers		
	Vermivora cyanoptera	Blue-winged Warbler
	Vermivora chrysoptera	Golden-winged Warbler
	Oreothlypis peregrina	Tennessee Warbler
	Oreothlypis celata	Orange-crowned Warbler
	Oreothlypis ruficapilla	Nashville Warbler
	Setophaga americana	Northern Parula
	Setophaga petechia	Yellow Warbler
	Setophaga dominica	Yellow-throated Warbler
	Setophaga pensylvanica	Chestnut-sided Warbler
	Setophaga magnolia	Magnolia Warbler
	Setophaga coronata	Yellow-rumped Warbler
	Setophaga virens	Black-throated Green Warbler
	Setophaga fusca	Blackburnian Warbler

	Setophaga pinus	Pine Warbler
	Setophaga discolor	Prairie Warbler
	Setophaga palmarum	Palm Warbler
	Setophaga castanea	Bay-breasted Warbler
	Setophaga cerulea	Cerulean Warbler
	Mniotilta varia	Black-and-White Warbler
	Setophaga ruticilla	American Redstart
	Protonotaria citrea	Prothonotary Warbler
	Helmitheros vermivorum	Worm-eating Warbler
	Limnothlypis swainsonii	Swainson's Warbler
	Seiurus aurocapilla	Ovenbird
	Parkesia noveboracensis	Northern Waterthrush
	Parkesia motacilla	Louisiana Waterthrush
	Geothlypis formosus	Kentucky Warbler
	Geothlypis philadelphia	Mourning Warbler
	Geothlypis trichas	Common Yellowthroat
	Setophaga citrina	Hooded Warbler
	Cardellina pusilla	Wilson's Warbler
	Cardellina canadensis	Canada Warbler
	Icteria virens	Yellow-breasted Chat
Tanagers		
	Piranga rubra	Summer Tanager
	Piranga olivacea	Scarlet Tanager
Grosbeaks, Sparrows, Buntings		
	Pipilo erythrophthalmus	Eastern Towhee
	Passerella iliaca	Fox Sparrow
	Melospiza melodia	Song Sparrow
	Melospiza lincolnii	Lincoln's Sparrow
	Melospiza georgiana	Swamp Sparrow
	Zonotrichia albicollis	White-throated Sparrow
	Zonotrichia leucophrys	White-crowned Sparrow
	Junco hyemalis	Dark-eyed Junco
	Cardinalis cardinalis	Northern Cardinal
	Pheucticus ludovicianus	Rose-breasted Grosbeak
	Passerina caerulea	Blue Grosbeak
	Passerina cyanea	Indigo Bunting
	Passerina ciris	Painted Bunting
	Spiza americana	Dickcissel
Blackbirds & Orioles		
	Dolichonyx oryzivorus	Bobolink

	Agelaius phoeniceus	Red-winged Blackbird
	Sturnella magna	Eastern Meadowlark
	Euphagus carolinus	Rusty Blackbird
	Quiscalus quiscula	Common Grackle
	Molothrus ater	Brown-headed Cowbird
	Icterus spurius	Orchard Oriole
	Icterus galbula	Baltimore Oriole
	Haemorhous purpureus	Purple Finch
	Haemorhous mexicanus	House Finch
	Spinus tristis	American Goldfinch
Pelicans		
	Pelecanus occidentalis	Brown Pelican
Terns		
	Gelochelidon nilotica	Gull-billed Tern
	Sternula antillarum	Least Tern
	Sterna forsteri	Forster's Tern
Skimmers		
	Rynchops niger	Black Skimmer

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Appendix D: Mammals of the Atchafalaya River Basin

Taxonomy & Common Name	**Scientific Name**	**State Ranking**[1]	**Federal Status**[2]
Opossum & Allies - Didelphimorphia			
American Opossums - Didelphidae			
Virginia Opossum	*Didelphis virginiana*		
Shrews & Moles - Order Soricomorpha			
Shrews - Soricidae			
Short-tailed Shrew	*Blarina brevicauda*		
Least Shrew	*Cryptotis parva*		
Moles - Talpidae			
Eastern Mole	*Scalopus aquaticus*		
Bats - Order Chiroptera			
Vespertilionid Bats - Vespertilionidae			
Southeastern Myotis	*Myotis austroriparius*		
Eastern Pipistrelle	*Pipistrellus subflavus*		
Big Brown Bat	*Eptesicus fuscus*	S1S2	
Hairy-tailed Bat	*Lasiurus borealis*		
Seminole Bat	*Lasiurus seminolus*		
Hoary Bat	*Lasiurus cinereus*		
Northern Yellow Bat	*Lasiurus intermedius*		
Evening Bat	*Nycticeius humeralis*		
Rafinesque's Big-eared Bat	*Plecotus rafinesquii*		
Free-tailed Bats - Molossidae			
Brazilian Free-tailed Bat	*Tadarida brasiliensis*		
Sloths, Anteaters & Armadillos - Order Cingulata			
Armadillos - Dasypodidae			
Nine-banded Armadillo	*Dasypus novemcinctus*		
Pikas, Rabbits & Hares - Order Lagomorpha			
Hares & Rabbits - Leporidae			
Eastern Cottontail	*Sylvilagus floridanus*		

Swamp Rabbit	*Sylvilagus aquaticus*		
Rodents - Order Rodentia			
Squirrels - Sciuridae			
Gray Squirrel	*Sciurus carolinensis*		
Fox Squirrel	*Sciurus niger*		
Eastern Chipmunk	*Tamias striatus*		
Southern Flying Squirrel	*Glaucomys volans*		
Beavers - Castoridae			
American Beaver	*Castor canadensis*		
New World Rats & Mice - Cricetidae			
Marsh Rice Rat	*Oryzomys palustris*		
Eastern Harvest Mouse	*Reithrodontomys humulis*	S3S4	
Fulvous Harvest Mouse	*Reithrodontomys fulvescens*		
White-footed Mouse	*Peromyscus leucopus*		
Cotton Mouse	*Peromyscus gossypinus*		
Golden Mouse	*Ochrotomys nuttalli*		
Hispid Cotton Rat	*Sigmodon hispidus*		
Eastern Wood Rat	*Neotoma floridana*		
Woodland Vole	*Microtus pinetorum*		
Common Muskrat	*Ondatra zibethicus*		
Old World Rats & Mice - Muridae			
Roof Rat*	*Rattus rattus*		
Norway Rat*	*Rattus norvegicus*		
House Mouse*	*Mus musculus*		
Nutria - Myocastoridae			
Nutria	*Myocastor coypus*		
Carnivores - Order Carnivora			
Dogs - Canidae			
Coyote	*Canis latrans*		
Red Wolf ^{X}	*Canis rufus*	SX	E
Red Fox	*Vulpes fulva*		
Gray Fox	*Urocyon cinereoargenteus*		
Bears - Ursidae			
American Black Bear	*Euarctos americanus*	S2	T
Raccoons - Procyonidae			
Northern Raccoon	*Procyon lotor*		

Weasels & Minks - Mustelidae			
Long-tailed Weasel	*Mustela frenata*	S2S4	
North American Mink	*Mustela vison*		
Spotted Skunk	*Spilogale putorius*	S1	
Nearctic River Otter	*Lutra canadensis*		
Skunks - Mephitidae			
Striped Skunk	*Mephitis mephitis*		
Cats - Felidae			
Cougar	*Puma concolor*	SH	E
Bobcat	*Lynx rufus*		
Manatees, Dugong & Sea Cow - Order Sirenia			
Manatees - Trichehidae			
West Indian Manatee	*Trichechus manatus*		E
Even-Toed Hoofed Mammals - Order Artiodactyla			
Deer - Cervidae			
White-tailed Deer	*Odocoileus virginianus*		
Bovids - Bovidae			
Bison^{X}	*Bison bison*		

1: Louisiana Natural Heritage Program conservation ranking, S1 = critically imperiled; S2 = imperiled; S3 = rare or localized; S4 = apparently secure; S5 = demonstrably secure; SX = extirpated;

2: U.S. Fish and Wildlife Service; E = endangered; T = threatened;

* = introduced

Sources:

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Appendix E: Proposed Changes in Flow at Old River Control Complex

Changes in flow distribution through the Old River Complex due to requests from the Governor's Office (from the August 2002 "Water in the Basin" report and subsequent documentation):

Date	**Requested Diversion**	**Reason**	**Duration**
May-June 1983	Held Red River Landing gage to 60.4' equal to 31.6% at the crest	To prevent the evacuation of the state penitentiary at Angola	16 Days
May 1991	Distribution of flow through the Old River Complex was reduced to 28.5% - 29.0%	Allowed for rapid receding of flood waters in the Red, Black, and Ouachita Rivers	21 Days
1993	Requested that the Mississippi River Commission reduce flows into the Atchafalaya Basin	Minimize the probability of a fish kill following extensive fish restocking after Hurricane Andrew	Denied
April 1996	Flow increased to 32%	Increase crawfish production	14 Days
March 2000	Flow increased to 32%	Increase crawfish production	16 Days
Feb. – March 2001	Flow increased to 32%	Increase Crawfish production	Approved 6 Days +
May 8, 2002	Increase requested to 32%	Increase crawfish production	Approved 2% for 2 weeks
March 2003	Increase to 32%	Water quality / Aquatic Resources	Approved 2% for 1 week
April 8, 2004	Requested Increase	Water Quality / Aquatic Resources	Approved 2% for 2 weeks
March 26, 2007	Requested increase	Increase crawfish production	Denied
May 1, 2012	Requested Increase	Increase crawfish Production	Denied
April 8, 2013	Requested Increase	Economic / Ecologic Impact	Approved 3% for 2 weeks

SCR 107 2001 Regular Session filed with the secretary of state 6/7/2001

Requests US Corp of Engineers to increase the flow of water into the Atchafalaya Basin to maintain a minimum stage of twelve feet National Geodetic Vertical Datum (NGVD) at the Butte La Rose gauge throughout the spring.

HCR 168 2001 Regular Session

Urges and requests the U.S. Army Corps of Engineers to increase the water flow rate from the Mississippi River into the Atchafalaya River through the Old River Control structure in Simmesport.

SCR 62 2002 Regular Session

Requests the executive assistant of Coastal and Marine Activities, office of the governor, and the director of the Atchafalaya Basin Program to jointly conduct an evaluation, and to make recommendations, as to how to improve the water quality in the Atchafalaya Basin. Report due to the House and Senate Natural Resources Committees by 9/30/2002.

It does not reference HCR 62, but, a report was submitted August 12, 2002 titled, "Louisiana Department of Natural Resources, Atchafalaya Basin Program, Water in the Basin Committee, Recommendations to the Governor". The report states that a "Water in the Basin" committee was one of 18 committees formed after the adoption of the Atchafalaya State Master Plan in 1998. The report used stage information from 1980-1999, where available and responses to surveys to arrive at its recommendations.

HCR 252 2003 Regular Session (not passed)

Memorializes the U.S. Army Corp of Engineers to examine water level and water quality issues in the Atchafalaya Basin and to report its findings prior to the 2004 R.S.

HCR 117 2012 Regular Session

Urges the governor to request that the U.S. Army Corps of Engineers increase the water flow at the Old River Control structure from the Mississippi River into the Atchafalaya Basin.

Sources:

Don Haydel, Atchafalaya Basin Program, personal communication

Water in the Basin Committee. 2002. Water in the Basin Committee Recommendations to the Governor. Atchafalaya Basin Program, Louisiana Department of Natural Resources, Baton Rouge, LA.