THE CALCASIEU-SABINE BASIN

The Calcasieu-Sabine Basin consists of two semi-distinct hydrologic units, the Calcasieu River basin and the Sabine River basin, which is continuous between Louisiana and Texas. This study is confined to the Louisiana region east of the Sabine River to Louisiana Highway 27 (Figure 25). Fresh, intermediate, and brackish marshes dominate this estuary (Figure 26 and Table 8).

The Calcasieu, Sabine, and Neches rivers are the principal sources of freshwater inflow into this region. The Sabine and Calcasieu rivers follow a north-south gradient, whereas the Neches River flows into Sabine Lake from the northwest. Additionally, an east-west flow occurs between the basins via the Gulf Intracoastal Waterway (GIWW) and existing canals on the Sabine National Wildlife Refuge. The hydrology of this area is affected by a complex combination of riverine freshwater inflow, Gulf of Mexico tides, precipitation, and wind effects on water level and directional flow. The Sabine River is the dominant influence across most of the basin in moderating gulf salinity and tidal fluctuations. Observations by U.S. Fish and Wildlife Service personnel reveal that strong and prolonged south and southeast winds result in large volumes of Gulf of Mexico water being pushed into Calcasieu and Sabine lakes, which causes the water level in the marshes to rise (Paille 1996). A similar effect on marsh water level has been observed during periods of low barometric pressure in the region (Paille 1996).

History of Hydrologic Modifications to the Calcasieu-Sabine Basin

Calcasieu River, Calcasieu Ship Channel, and Calcasieu Lake

The lower Calcasieu River and the Calcasieu Ship Channel (CSC) have been maintained for navigation since 1874, when the U.S. Army Corps of Engineers (USACE) first constructed a 5-ft-deep x 80-ft-wide x 7,500-ft-long navigation channel through the outer bar of Calcasieu Pass, between Calcasieu Lake and the Gulf of Mexico. In 1903, the CSC was deepened to 13 ft, and between 1937 and 1940, the channel was enlarged to 250 ft wide and 30 ft deep. Finally, in 1968 the ship channel was substantially widened again to 400 ft and dredged to its current depth of 40 ft (Figure 27; Waldon 1996). Prior to the initial dredging of the CSC, there was a 3.5-ft-deep shoal at the mouth of the Calcasieu River (War Department 1897). This natural bar acted as a constriction, minimizing saltwater and tidal inflow into the basin. Removal of the channel mouth bar, coupled with subsequent widening and deepening of the CSC, allowed increased saltwater and tidal intrusion into the estuary, resulting in catastrophic marsh loss, tidal export of vast quantities of organic marsh substrate, and an overall shift to more saline habitats in the region (USDA 1994). In addition, the CSC permits the upriver flow of denser, more saline water as a saltwater wedge. In 1968, the USACE completed construction of the Calcasieu River Saltwater Barrier on the Calcasieu River north of the city of Lake Charles. This barrier minimized the flow of the saltwater wedge into the upper reaches of the Calcasieu River to protect agricultural water supplies. The structure consists of a lock and a flood control barrier with five adjustable gates. Table 9 summarizes historical modifications to the Calcasieu River, Calcasieu Lake, and the CSC.

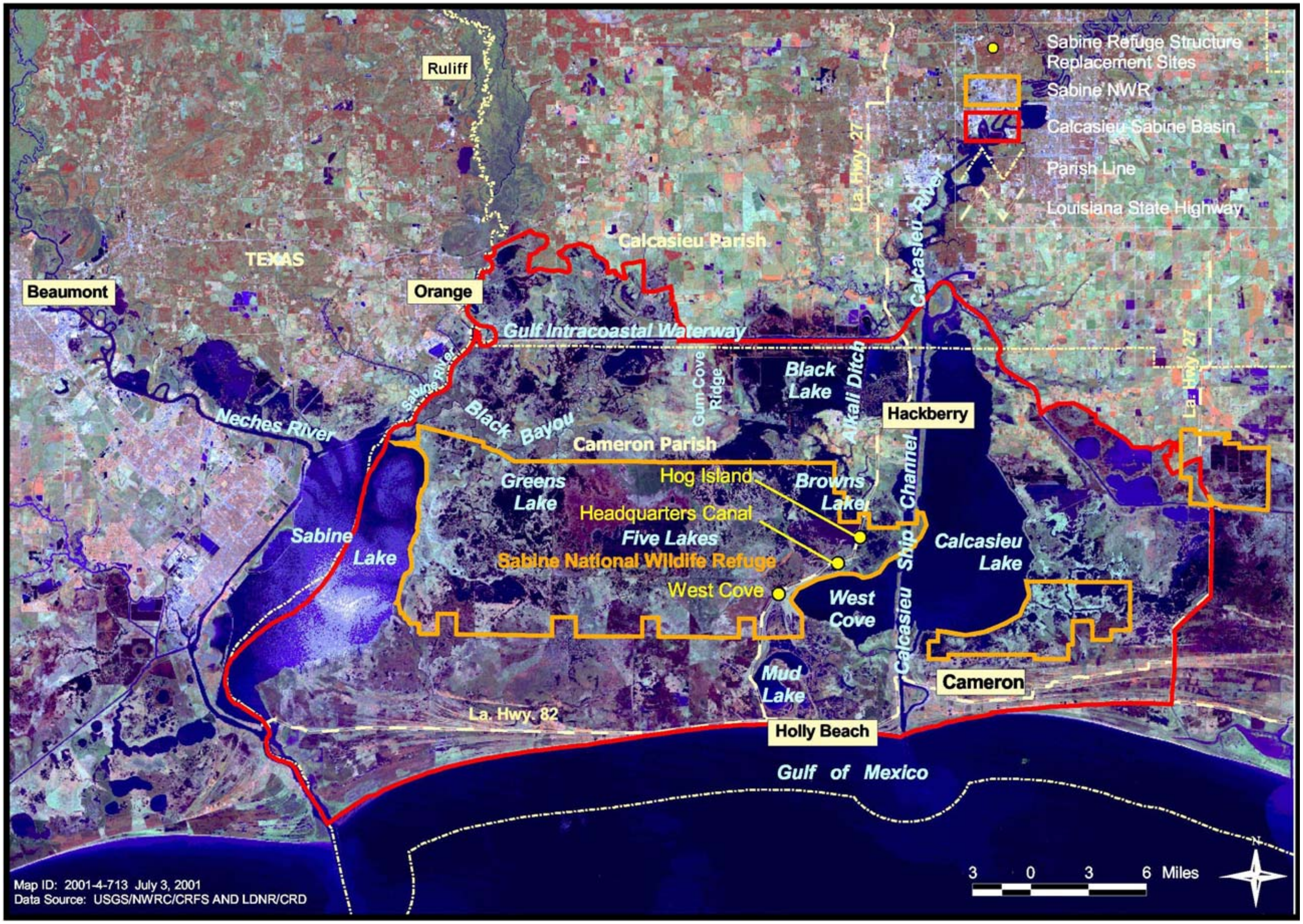

Figure 25. Physical and geographical features of the Calcasieu-Sabine Basin.

Figure 26. Calcasieu-Sabine Basin wetland habitat types (after Chabreck and Linscombe 1997).

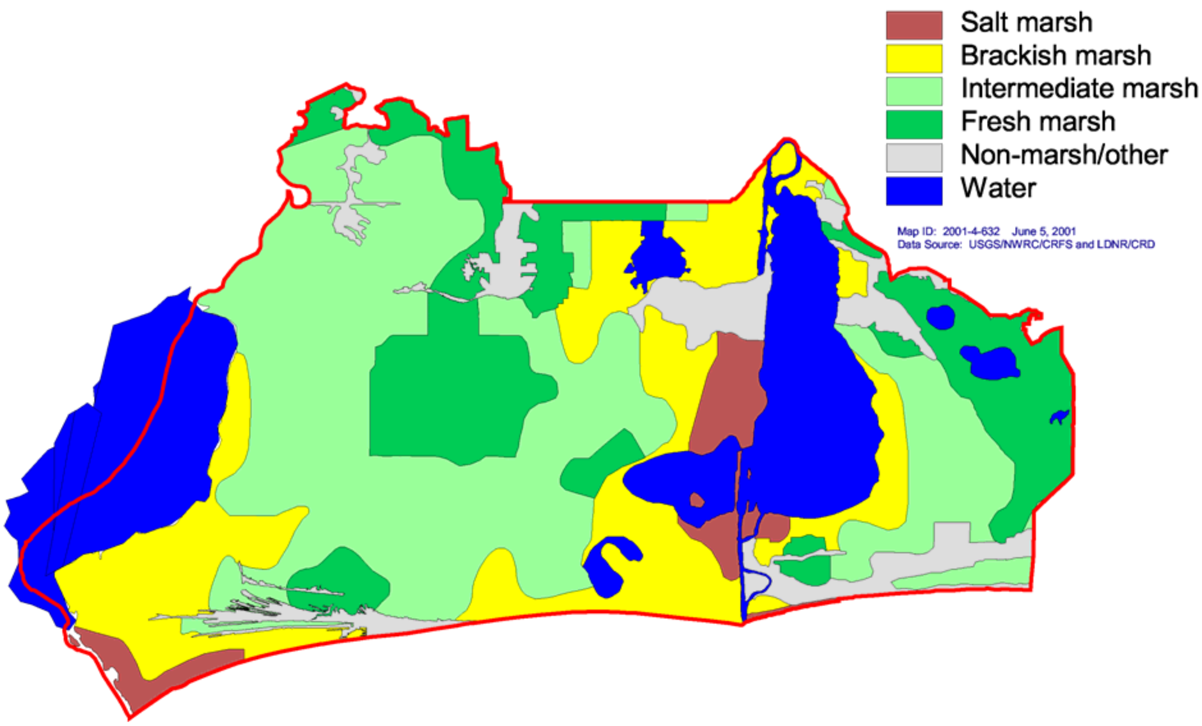

Table 8. Wetland and aquatic habitat acreages in the Calcasieu-Sabine Basin (after Chabreck and Linscombe 1997).

Habitat type	Acres	Percent of total cover
Fresh marsh	101,397	18
Intermediate marsh	206,949	37
Brackish marsh	114,192	20
Salt marsh	22,244	4
Non-marsh/other	48,747	9
Water	65,698	12
Total =	559,227	100

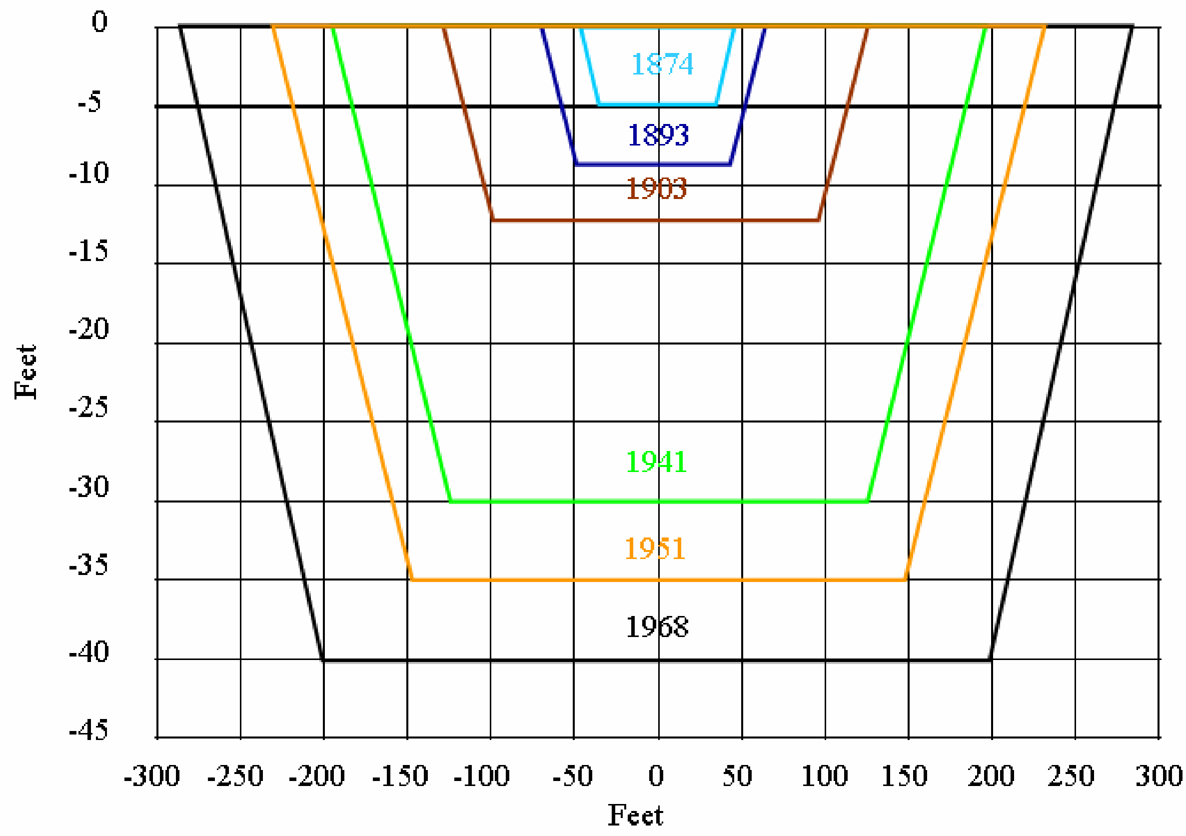

Figure 27. Historical channel dimensions of the Calcasieu Ship Channel.

Table 9. Historical alterations to the hydrology of the Calcasieu River, Calcasieu Lake, and Calcasieu Ship Channel (adapted from USDA 1994).

Year	Activity
1874	Dredged channel to 80 ft wide and 5 ft deep (USACE 1891 and 1912).
1880s	Re-dredged channel five times because of siltation (USACE 1891 and 1912).
1893	Dredged lake bars at head of Calcasieu Pass to 8 ft deep and constructed a revetment on either side of channel (USACE 1912).
1894-1902	Dredged channel three times (USACE 1912).
1900	Jetties 1.5 mi in length were placed at the mouth of Calcasieu Pass (USACE 1923).
1903	Dredged a channel 12 ft deep and 200 ft wide between the jetties at the mouth of Calcasieu Pass (USACE 1923).
1941	Calcasieu Ship Channel (CSC) was completed. It was 30 ft deep and 250 ft wide. The CSC ran from Lake Charles through portions of Calcasieu Lake, Long Point Lake, and into the Gulf of Mexico to the 32-ft depth contour (USACE 1951).
1951	CSC was enlarged to 35 ft deep and the jetties were extended into the Gulf of Mexico to the 10-ft depth contour. The jetties were 8,050 ft and 8,620 ft long (USACE 1951).
1968	CSC was enlarged to a depth of 40 ft and a bottom width of 400 ft (USDA 1993).

Only portions of the CSC are dredged annually. Approximately 75% of the dredged material is placed in upland and offshore disposal sites, but the remaining 25% is used for beneficial means, to create marsh. Since 1975, records of the Louisiana Department of Natural Resources (DNR) Coastal Management Division and the Sabine National Wildlife Refuge indicate that approximately 1,400 ac of marsh have been restored through this beneficial use. Potentially, 50% of the dredged material could be used for this purpose.

The primary saltwater barrier in the Calcasieu Basin is the USACE-maintained Calcasieu Lock, located approximately two miles east of the CSC. This sector-gated lock, which opened in 1950, was designed to prevent saltwater intrusion into the Mermentau Basin, and is operated primarily for navigation. The lock has a 75-ft-wide by 1,194-ft-long chamber with a 13-ft sill. During flooding events, the structure is often operated for drainage of the Mermentau Basin to the east. Operating the structure for drainage often becomes problematic for lock operators because of delays incurred to navigation during this time, when the lock is draining and the current through the structure is too swift for traffic to safely navigate through the gates. The USACE is thus continually trying to balance lock operation for flood control to local communities and Mermentau Basin drainage with the needs of waterborne commerce. A feasibility study by the USACE to build a new lock with a larger chamber is under way (personal communication, Stan Green, USACE New Orleans District).

Sabine River, Neches River, and Sabine Lake

The Sabine River has a drainage area of approximately 9,325 mi^2 entirely in Texas and Louisiana. In the vicinity of Orange, Texas, the river bisects the GIWW, where it widens into Sabine Lake before narrowing and draining into the Gulf of Mexico. The Sabine-Neches Ship Channel is maintained to a depth of 42 ft and a width of 400 ft. It forks at the Neches River to Beaumont, Texas, and up the Sabine River to Orange. The hydrology in this area is complex, in part because of the effect of the GIWW, which flows bi-directionally through the area, and the effects of the Toledo Bend Reservoir—located roughly 100 mi upstream from the GIWW—which regulates flows to the south.

The Toledo Bend Reservoir, located on the border between Texas and Louisiana approximately 90 mi north from Sabine Lake, was constructed for power generation and as a reservoir for irrigation water. It was finished in 1968, and power generation began there in 1969. It covers an area of 284 mi^2, and a volume of about 4.45 million ac-ft (Waldon 1996). An average of 4.28 million ac-ft of water are released every year from Toledo Bend, but that number has varied widely since operation began, from 1.1 million to 7.9 million ac-ft. Releases are gauged to provide at least a 1,500-cfs discharge at Ruliff from October to April and a 3,000-cfs discharge from May to September (Rumsey 1996).

Three other reservoirs are located on the Texas side of the Sabine River basin: Martin Lake, Lake Fork Reservoir, and Lake Tawakoni. The three combined cover a total drainage basin area of 1,379 mi^2 and hold 1.75 million ac-ft.

There are six reservoirs on the Neches River: B. A. Steinhagen Lake, Sam Rayburn Reservoir, Lake Nacadoches, Lake Tyler, Lake Palestine, and Lake Athens. Together these reservoirs drain 12,034 mi^2 and hold 3.57 million ac-ft.

Sabine Pass was first dredged for navigation in 1880. Prior to this, the river had an outer bar depth of 1.1 m (3.5 ft). In 1880, a channel 6 ft deep x 70-100 ft wide was dredged through the bar (War Department 1890). Over time, the channel was progressively deepened to its present depth of 40 ft. The Sabine-Neches Canal (later to become the Sabine-Neches Ship Channel) was constructed in the early 1900s, when the USACE dredged the channel along the west bank of Sabine Lake to a depth of 9 ft and a width of 100 ft. In 1914-16, the channel was deepened to 25 ft and extended to Beaumont, Texas. This deepening led to the first reports of saltwater intrusion in the channel (Wilson 1981). In 1922, the Sabine-Neches Ship Channel was deepened again to 30 ft. Since that time, the channel has gradually been deepened and widened to its present dimensions of 40 ft deep and 400 ft wide. Figure 28 illustrates the incremental expansions of the channel to its current cross-section. The Sabine-Neches channel was dredged into the western upland bank of Sabine Lake, and dredged material was placed eastward to form much of Pleasure Island. Saline water from the Gulf of Mexico travels up the channel, resulting in an atypical estuarine salinity gradient in that it does not follow the usual north-south salinity gradient. Instead, Sabine Lake exhibits higher salinities in its lower and upper reaches and lower salinities in its central portion.

More hydrologic alterations are being made or being planned in the Sabine and Neches rivers and the Sabine-Neches Ship Channel. A proposal to deepen and widen the Sabine-Neches Ship Channel to 45-55 ft deep and 500 ft wide is currently undergoing feasibility analysis by the USACE Galveston District and the Jefferson County, Texas, Navigation District. Saltwater intrusion in the Neches River near Beaumont, Texas, has, in the past, necessitated the release of large quantities of water from the Sam Rayburn Reservoir to prevent saltwater contamination into Beaumont's industrial, agricultural, and municipal freshwater intakes. Plans to construct a permanent saltwater barrier in the Neches River at Beaumont were developed in the 1960s, and the project is currently under construction. This would lessen the need for discharge by the Sam Rayburn Reservoir, which may result in increased salinity in upper reaches. Table 10 provides a detailed history of hydrologic alterations to the Sabine River and Sabine-Neches Ship Channel.

Prior to construction of the Sabine-Neches Canal and port development in Texas, all of the Sabine and Neches river inflows went directly into Sabine Lake. Construction of the Sabine-Neches Ship Channel and the deepening of both rivers, in conjunction with increased withdrawals of freshwater upstream for industry and agriculture, have resulted in major changes in system hydrology and saltwater intrusion in both Texas and Louisiana. The channel also funnels freshwater inflows more directly to the gulf, largely bypassing the adjacent marshes in Louisiana and Texas. In addition to the effect of changes in the distribution of freshwater inflow, the timing of inflow has been altered by construction of the Toledo Bend Reservoir. In the spring, when system inflows are generally highest, water is retained in the reservoir to be released later in summer. The effects of this change in hydrology on renewable resources in the Sabine-Neches estuary remain poorly understood.

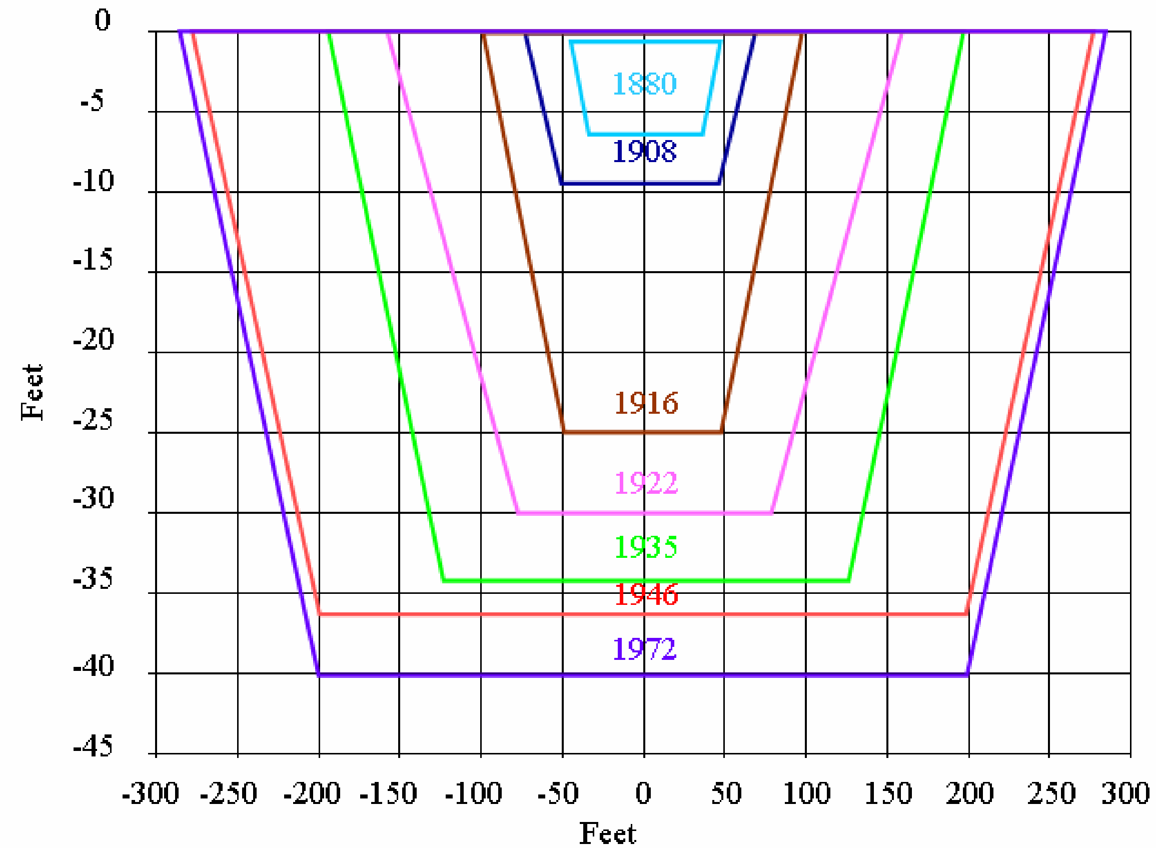

Figure 28. Historical channel dimensions of the Sabine-Neches Ship Channel.

Table 10. Historical alterations to the hydrology of the Sabine River and the Sabine-Neches Ship Channel (adapted from USDA 1994).

Year	Activity
1870s	Several dredging projects were implemented but were of little success because of equipment breakdown and re-silting (USACE 1977).
1890s	Rice farming became a thriving business along Taylor's Bayou.
1897-99	Kansas City Railroad, Gulf Railroad, and the Port Arthur Channel and Dock Company dredged a 75-ft-wide x 25-ft-deep canal from the north end of Sabine Pass to Taylor's Bayou (USACE 1977).
1901	Rice growers along Taylor's Bayou, Texas, suffered saline contamination to their irrigation water, due to a combination of a drought, increased drain on the freshwater supply, and modifications to the Port Arthur Canal. Later that year saltwater-contaminated irrigation water was found in the Neches River above Beaumont (USACE 1977).
1901	Oil was discovered south of Beaumont at what is now known as the Spindle Top Oilfield. The Sabine and Neches rivers experienced an increasing demand for navigational use due to industrial demands (USACE 1977).
1906	The federal government acquired, free of charge, the privately dug Port Arthur Canal (USACE 1977).
1908	The Sabine-Neches Canal excavation was completed, to a 9-ft deep, 100-ft wide channel. The channel extended north from the Port Arthur Canal to the west side of Sabine Lake, up the Neches River to Beaumont, and up the Sabine River to Orange, Texas (USACE 1977).
1912	The Port Arthur Canal became part of the Sabine-Neches Ship Channel (USACE 1977).
1916	A project to deepen the Sabine-Neches Ship Channel to 25 ft was completed. A saltwater barrier was installed 6 mi north of Port Arthur to reduce the problems of saltwater contamination of freshwater supplies (USACE 1977).
1920-29	Construction of the east and west jetties was completed in lieu of dredging. As a result of jetty construction, a 25-ft-deep channel was scoured through the river mouth bars between the jetties (USACE 1977).
1922	The Sabine-Neches Ship Channel was widened from 100 ft to 125 ft (USACE 1977).
1922	Legislation was authorized to modify the existing Port Arthur Canal and the Sabine-Neches Ship Channel to 30 ft deep and 150 ft wide (USACE 1947, 1989).
1923	After a salinity study, the USACE concluded that the lock should be removed. Subsequently, a bypass channel was constructed around the lock (USACE 1977).
1927	Widening of the Port Arthur Canal to 200 ft and the Sabine-Neches Ship Channel, below the mouth of the Neches River, to 150 ft was authorized.
1935	The Port Arthur Canal was authorized for a width of 250 ft and a depth of 34 ft. The Sabine-Neches Ship Channel was authorized for a width of 250 ft and a depth of 32 ft (USACE 1947).
1938	The U.S. Congress authorized the enlargement of the Port Arthur Canal to 400 ft and the Sabine-Neches Ship Channel to 350 ft (USACE 1947).
1946	Legislation was passed authorizing the deepening of the Sabine Pass outer bar channel to 37 ft, the deepening of the Port Arthur Canal and Sabine-Neches Ship Channel to 36 ft, the widening of the Sabine-Neches Ship Channel to 400 ft, and the widening of a segment of the Sabine-Neches Ship Channel between the Sabine and Neches rivers to 150 ft (USACE 1982).
1972	Authorized improvements were completed that provide a 500-ft-wide x 40-ft-deep channel from the Gulf of Mexico to Port Arthur, a 400-ft-wide x 40-ft-deep channel from Port Arthur up the Neches River to Beaumont, and a 200-ft-wide x 30-ft-deep channel from the mouth of the Neches River up the Sabine River to Orange (USACE 1982).

The Gulf Intracoastal Waterway

The GIWW from the Sabine River to the Calcasieu River was constructed in 1913-14 with a width of 40 ft and a depth of 5 ft. In 1925, the channel was enlarged to 100 ft wide x 9 ft deep. Prior to the deepening of the CSC in the late 1930s, the GIWW reach from the Sabine River to the Calcasieu River was deepened to 30 ft to facilitate navigation to the Port of Lake Charles. This section was then known as the Lake Charles Deep Water Channel. In 1941, the channel was thereafter maintained as part of the GIWW, at a depth of 12 ft and a width of 125 ft (USDA 1994).

Construction of the GIWW significantly altered regional hydrology by connecting the two major ship channels. Prior to the construction of the GIWW, the Calcasieu and Sabine estuaries were mostly distinct and were more influenced by the Calcasieu and Sabine rivers, respectively. The Gum Cove Ridge once separated the Sabine Basin from the Calcasieu Basin, with little water exchange between the basins. A combination of events dramatically altered the hydrology of what was once the separate Calcasieu and Sabine basins, merging them into the present-day Calcasieu-Sabine Basin. Removing the mouth bars and deepening the CSC and the Sabine-Neches channels, as well as the GIWW and interior canals bisecting the Gum Cove Ridge (Figure 25), made the region hydrologically indistinct, which caused water flow and salinity patterns of one basin to profoundly affect those patterns of the other basin. In addition to effectively combining the two basins, the GIWW cut off all of the natural bayous and upland sheet flow that historically affected marshes, and channelized more freshwater inflow more directly to the Gulf of Mexico, partially bypassing the marshes. Table 11 provides a detailed history of hydrologic alterations to the GIWW.

Land Management and Wetland Restoration in the Calcasieu-Sabine Basin

Land stewardship through hydrologic management has enjoyed a long history in the Calcasieu-Sabine Basin. Hydrologic management and shoreline protection are the mainstays of coastal restoration in the basin. Water control structures are operated both passively and actively in this area. Virtually all hydrologic management focuses on controlling salinity and minimizing tidal fluctuations by constructing and operating levees, weirs, and a variety of gated structures. A 1990 inventory of such water control structures identified 174 individual structures in the interior and along the perimeter of the basin (Marcantel 1996).

Management of the Sabine National Wildlife Refuge

The largest wetland management efforts in Louisiana take place on the Sabine National Wildlife Refuge (SNWR). The 194-mi^2 refuge, established in 1937, comprises seven units that contain interspersed fresh, intermediate, brackish, and saline marshes. The largest coastal marsh refuge on the gulf coast, the SNWR is bound on the east by Calcasieu Lake, on the west by Sabine Lake, on the north by the Northline Canal, and on the south by the Southline Canal. These refuge habitats support diverse fish and wildlife populations,

Table 11. Historical alterations to the hydrology of the Gulf Intracoastal Waterway (GIWW; adapted from USDA 1994).

Year	Activity
1910	Congress authorized construction of an inland waterway, 5 ft deep x 40 ft wide, from the Sabine River to the Mermentau River (USACE 1978).
1913-15	Construction of a waterway between the Sabine and Calcasieu rivers was completed (USACE 1978).
1925	The U.S. Government owned a continuous inland waterway between the Mississippi and Sabine rivers to Orange (USACE 1978).
1925	U.S. Congress authorized the enlargement of the inland waterway, Gulf Intracoastal Waterway (GIWW), to 100 ft wide x 9 ft deep.
1927	An enlargement was completed of the GIWW from the Sabine River to the Calcasieu River, of 125 ft wide x 30 ft deep (USACE 1928). This portion of the GIWW is known as the Lake Charles Deep Water Channel. It was authorized for the period 1935-41 (USACE 1978, 1983).
1941	The Calcasieu Ship Channel was completed. Federal maintenance of the Lake Charles Deep Water Channel was deauthorized and the channel was thereafter maintained as part of the GIWW (USACE 1978, 1983).
1942-49	The GIWW was deepened to its current depth of 12 ft (USACE 1978, 1983).

including more than 250 bird species, 132 fish species, 36 reptile and amphibian species, and 28 mammal species.

The SNWR refuge was established to serve as a refuge and breeding ground for migratory birds and other wildlife, as specified by these objectives:

• To manage, protect, and enhance coastal marsh habitats for wildlife, especially for wintering waterfowl;
• To maintain throughout the refuge "natural" vegetative types, those traditional to coastal marshes;
• To protect and maintain appropriate habitats for threatened and endangered species; and,
• To provide wildlife-oriented recreation and interpretive opportunities for the public to enjoy.

Habitat management techniques used on the SNWR include prescribed marsh burning, cattle grazing, and manipulation of water level and salinity. Over the years, substantial marsh loss has occurred through human-induced degradation from channelization and the accompanying saltwater intrusion and impoundment within pools 1A, 1B, and 3, in addition to natural events such as hurricanes. Major efforts are currently under way to rebuild the marshes and prevent further loss. Appendix C presents a summary of events and activities at the SNWR since it was established in 1938.

Salinity Control

Several water control structures have been constructed at strategic hydrologic connection points with Calcasieu Lake to minimize the effects of saltwater intrusion from the CSC into perimeter wetlands. Permitting access for estuarine organisms during critical periods while simultaneously maintaining appropriate salinity regimes for interior marshes often proves difficult for refuge managers. Managers strive to achieve a balance between reducing the stress to wetland plants caused by waterlogging and saltwater intrusion, and permitting sufficient access into interior marshes for estuarine-dependent organisms. This balance is partially accomplished through the operation of water control structures at the West Cove, Hog Island Gully, and Headquarters canals (Figure 25). The Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) specified the replacement of three primary gated control structures at these sites. The previous structures, constructed in 1981, did not provide discharge potential adequate to remove excess water from the surrounding area, and could not be operated to effectively prevent saltwater intrusion. The new structures are nearly four times larger and will accommodate greater flows, which will improve drainage and enhance operational capabilities. The new structures are operated electronically, or manually in the event of loss of electrical power.

Freshwater Impoundment

Three rain-fed freshwater impoundments on the refuge are managed at higher water levels to enhance waterfowl habitat. The largest of the three is the 41.2-mi^2 Unit 3 (also called Pool 3). This impoundment was constructed in 1951 in the center of the refuge by leveeing off an unbroken marsh and holding water at high levels to increase the water-to-marsh ratio in the unit. Two smaller impoundments constructed in 1959, Units 1A and 1B, encompass 8.1 mi^2 and 2.8 mi^2, respectively, on the eastern side of the refuge (USDA 1994).

Cattle Grazing and Prescribed Marsh Burning

Long growing seasons—aided by a subtropical climate and the high growth potential of marsh vegetation—often lead to the accumulation of thatch or old growth, if this material is not burned or removed by herbivores. New vegetative growth may be restricted by a decreased access to sunlight through the previous year's growth or a buildup of thatch. In an effort to maintain specific refuge areas as subclimax communities, which are favorable to waterfowl and wildlife, grazing has been used on the SNWR to open up dense vegetation, depress perennial plants, encourage growth of annual grasses and sedges, and reduce tall clump grasses and increase creeping grasses.

Cattle have grazed on the refuge since its inception in 1937. Grazing areas exist primarily on ridges, their adjoining slopes, and the surrounding marshes. A traditional socioeconomic practice on the refuge, grazing has been defended as a management tool that produces habitat conditions favorable to waterfowl. Another benefit is that cattle grazing is responsible for allowing the population of at least one butterfly species to survive in the cheniers of Louisiana (Ross 1995). Cattle grazing is now very limited and is currently being phased out on the SNWR. Its benefits to wildlife are being replaced by prescribed burning. (Personal communication, Chris Pease, SNWR manager).

Fire has played an integral part in resource management on the SNWR. Prescribed marsh burning on the refuge is designed to reduce hazardous fuel buildups and to maintain plant diversity. Other goals and objectives, such as improving wildlife diversity, managing furbearers, enhancing interpretive and environmental education opportunities, improving oil and gas management, and meeting research goals, are indirectly affected by the use of fire. From 1987 to 1997, refuge staff have ignited 37 prescribed burns on 184.4 mi^2 to help achieve resource management objectives.

Cameron-Creole Watershed Management

The Cameron-Creole Watershed Project (Figure 29) covers approximately 176 mi^2 in Cameron Parish, Louisiana. The area is bounded by the GIWW on the north; Calcasieu Lake and Calcasieu Pass on the west; Louisiana Highway 27, Little Chenier Ridge, and Creole Canal on the east; and the Gulf of Mexico and Mermentau River on the south.

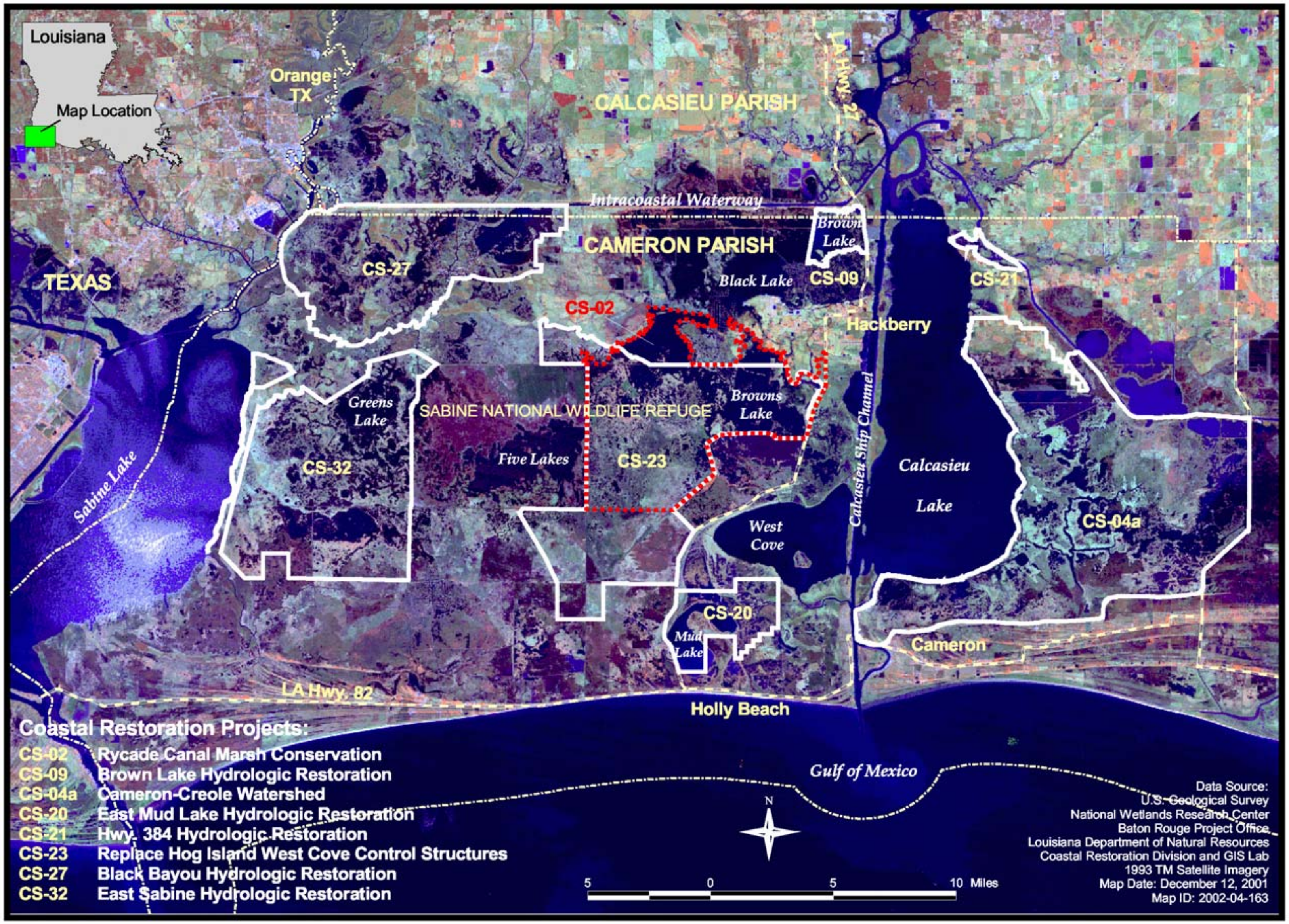

Figure 29. Planned or constructed hydrologic restoration projects in the Calcasieu-Sabine Basin.

Because of severe saltwater intrusion and tidal scour, marshes in the area were converting to open water (USDA 2001). To counter this conversion, the Cameron-Creole Watershed Project was initiated cooperatively by the Soil Conservation Service, Gulf Coast Soil and Water Conservation District, Cameron Parish Police Jury, Cameron Parish Gravity Drainage Districts 3 and 4, the Miami Corporation, and the U.S. Fish and Wildlife Service, SNWR. The water control structures began operation in 1989. The project is managed by the refuge managers of the Cameron Prairie Refuge.

The first phase of the project resulted in the construction of a 19-mi levee along the eroding shoreline of Calcasieu Lake. A water control structure at Grand Bayou was designed to allow access by fishermen via a boat bay, along with four gated bays set below marsh level. The water control structures at Lambert and Peconi bayous are four gated bays with vertical slots to allow ingress and egress of marine organisms. The structures at Mangrove and Noname bayous are four bays set on fixed-crest weirs, with one weir on each structure having vertical slots to allow for marine organism movement. In addition to the main water control structures, five culverts and four stoplog structures were installed on the eastern edge of the project, and eight flapgated culverts were installed on the GIWW to the north. These structures allow additional freshwater inflow to offset salinity from saltwater intrusion. The most recent published monitoring report (USDA 1995, Floyd 1997) has shown that land acreages have returned to 1972 levels, and it is expected that with continued structure operation, this recovery trend will endure.

Hydrologic Restoration and Protection Projects Funded by the State and Federal Governments

All of the following projects, with the exception of the Rycade Canal project, were funded by the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA).

East Mud Lake

The Calcasieu Ship Channel (CSC) is connected hydrologically to Mud Lake by West Cove and East Mud Lake wetlands. The CSC provides an avenue for rapid movement of high-salinity water (up to 32 ppt) and accompanying increases in turbidity and possible tidal scouring of the organic marsh substrate. Construction of Highway 27 to the west and Highway 82 to the south have caused decreased drainage from the western and southern areas of the project (Figure 29). Another management problem is dealing with excessive water levels that remain over the surface of the marsh for prolonged periods. The East Mud Lake Hydrologic Restoration Project is designed to prevent wetland degradation by reducing rapid fluctuations in water, reducing salinity, preventing prolonged periods of marsh inundation in the project area, and enhancing regeneration of desired emergent and submergent vegetation. This project was completed in 1996 and is expected to increase vegetative health.

Project monitoring indicates that this project has at this point had no statistical difference in either project or reference area with regard to residential or transient fisheries. The recent droughts probably have contributed to the inability to draw any valid conclusions from the monitoring to date (Weifenbach 2000). More recent preliminary monitoring results indicate that the conditions are improving at East Mud Lake.

Black Bayou

The Black Bayou Hydrologic Restoration Project is currently under construction. It is located approximately 18 mi west-northwest of Hackberry, Louisiana, in northwest Cameron and southwest Calcasieu parishes (Figure 29). The project is bordered to the north by the GIWW, to the south by Black Bayou, to the east by Gum Cove Ridge, and to the west by the Sabine River. The total project area is approximately 40 mi^2, which includes approximately 10 mi^2 of fresh and intermediate marsh, 11.5 mi^2 of brackish marsh, and 18 mi^2 of open water. The project's objectives are to prevent further marsh loss by implementing structural and nonstructural measures, including spoil bank repair, plugs, weirs, vegetative plantings, and terracing. The remaining components of the Black Bayou project will complete the protection of this area when they are constructed. The project encourages introduction of Sabine River water via the GIWW to create a hydrologic head that increases freshwater retention time and reduces saltwater intrusion and tidal action in the Black Bayou watershed.

Louisiana Highway 384

The Louisiana Highway 384 Hydrologic Restoration Project comprises 1.8 mi^2 of deteriorated wetlands located along the northeast shoreline of Calcasieu Lake (Figure 29). The project area is bounded by Calcasieu Lake to the west, the GIWW to the east, and higher-elevation prairie formations to the north and south. Construction and progressive deepening of the CSC radically altered the area's hydrology by increasing the height and duration of tidal fluctuations, which in turn increased water levels and saltwater intrusion into the low-salinity marshes surrounding Calcasieu Lake.

The project plan called for the construction of structural features—including plugs, weirs, gated culverts, and bank stabilization—to improve hydrologic conditions within the project area. By reducing rapid water exchange and restricting saltwater intrusion, future conditions in the project area will resemble the low-energy conditions under which these marshes were self-sustaining. Project construction was completed in 2000.

Brown Lake

Located south of the GIWW and east of Highway 27 (Figure 29), the Brown Lake Hydrologic Restoration Project calls for installing water control structures, rehabilitating or constructing levees and terraces, and planting vegetation. The water control structures are designed to reduce the extreme fluctuations in salinity and water levels on the project site, while providing adequate freshwater inflow. Construction of the levees and terraces will increase the marsh edge habitat, dissipate wave energy on shorelines, and promote the establishment and growth of submerged aquatic vegetation. The vegetative plantings will provide an additional seed source to vegetate exposed mudflats and help stabilize and protect eroding shorelines. The project is on hold pending possible design modifications to ensure project effectiveness. This area has also been selected as a recipient site for the beneficial use of dredged material from the CSC.

East Sabine Lake

The East Sabine Lake Hydrologic Restoration Project is located in the western third of the SNWR, extending to the east bank of Sabine Lake (Figure 29). The Sabine-Neches Ship Channel is a major avenue for saltwater intrusion in the region's fresh, intermediate, and low-salinity brackish marshes. This project, now in the planning phase, strives to control channel-induced saltwater intrusion by installing adjustable water control structures in interior bayous and canals. The project was recently approved for Phase I (engineering and design) feasibility funding but had not been authorized for construction at the time of this writing.

Rycade Canal

Completed in 1994, the Rycade Canal Marsh Conservation Project restored a more natural hydrology to the project site by reducing saltwater intrusion and rapid tidal fluctuations from the CSC through Black Lake and into the Rycade Canal. Restoration was accomplished through the installation of two gated control structures, one in Rycade Canal, and the other through an oilfield levee to the west (Figure 29). The project was funded by the state of Louisiana through the Coastal Wetlands Trust Fund.

Death of the Saw Grass Marsh in the Chenier Plain

Very little biological documentation exists of Chenier Plain habitats prior to the 1930s. However, abundant evidence indicates that the area was substantially fresher then than now. Both O'Neil (1949) and a 1951 Soil Conservation Service vegetative type map of Cameron Parish show broad expanses of unbroken saw grass (*Cladium jamaicense*) marsh (USDA 1951; Figure 30). Saw grass is found in fresh and intermediate marshes and tolerates salinities between 0 and 2 ppt (Penfound and Hathaway 1938). At the time of the 1951 survey, saw grass marsh covered approximately 475 mi^2 of Cameron Parish and was the dominant vegetative community. Additional evidence that the Chenier Plain was historically much fresher than it is now includes the following:

• Cypress trees (*Taxodium distichum*), with a salinity tolerance of 2 ppt (Chabreck 1972), lined Black Bayou as recently as the 1930s. This is significant because vegetative

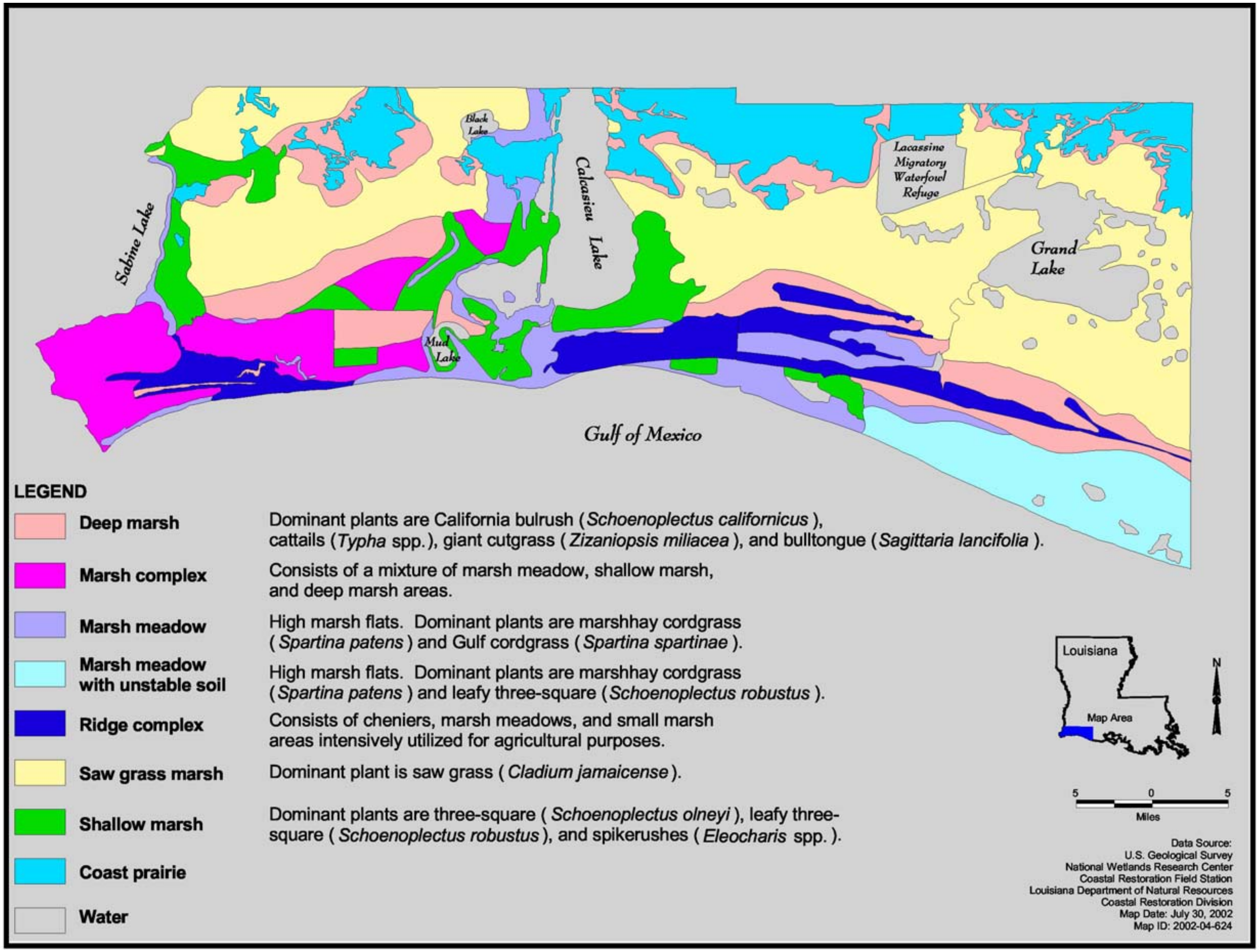

Figure 30. Wetland habitats of Cameron Parish, Louisiana, in 1951 (after USDA 1951).

type maps of 1949, 1968, 1978, and 1988 indicate that much of Black Bayou meandered through brackish marsh, which, due to elevated salinities, could no longer support cypress tree growth (O'Neil 1949; Chabreck et al. 1968; Chabreck and Linscombe 1978, 1988).

• Water from Calcasieu Lake was fresh enough to be used in the irrigation of rice fields in Cameron Parish around 1875-1910 (David Richard, Stream Companies, Inc., personal communication). Water from Calcasieu Lake must have been essentially fresh during this period, because rice is adversely affected by water salinities that exceed 0.6 ppt (Hill 2001).

• In the early 1900s, lower Calcasieu Lake was considered marginal habitat for oysters (*Crassostrea virginica*) because of the frequency of freshwater and low-salinity events there. Oysters, which inhabit waters within the salinity range of 5-30 ppt (Galtsoff 1964), are now found throughout much of the Calcasieu Lake bottom (USDA 1994).

In contrast to these formerly fresh conditions in Calcasieu Lake, average salinities at five Cameron Prairie Refuge monitoring stations within Calcasieu Lake ranged from 8.01 to 11.66 ppt during 1994-95. The CSC is undoubtedly the major cause of increased salinity in the Calcasieu Basin.

A region-wide die-off of saw grass and other freshwater and intermediate vegetation occurred from the 1950s through the early 1960s. The causes of this massive habitat change merit discussion. Staggering habitat losses following Hurricane Audrey in 1957 can be attributed to the combined effects of altered basin hydrology, saltwater intrusion, oilfield produced-water discharges, storm-related flooding, a series of droughts, and nutria herbivory.

Produced-water discharges are a byproduct of oil and gas extractions. Oil and gas reservoirs have a natural water layer (called formation water) that, being denser, lies under the hydrocarbons. To achieve maximum oil recovery, additional water is usually injected into the reservoirs to help force the oil to the surface. Both formation and injected water are eventually produced along with the hydrocarbons. At the surface, produced water is separated from the hydrocarbons, treated to remove as much oil as possible, and then either discharged into the sea or injected back into the wells. In addition, some installations are able to inject produced water into other suitable geological formations. Produced water typically contains some hydrocarbons, benzene, and toluene, and exceeds 200 ppt salinity. In Cameron Parish, produced waters were discharged directly into adjacent marshes.

Evidence suggests that Hurricane Audrey struck an ecosystem that had been weakened by major hydrologic alterations such as the CSC, the GIWW, and the Sabine-Neches Ship Channel. It is not unreasonable to presume that the area may have fully recovered from that event had the integrity of the ecosystem not already been so severely compromised.

Hurricane Audrey made landfall at Cameron, Louisiana, on 15 June 1957. Maximum tides ranged from 10.4 ft to 13.9 ft (Valentine 1976). Saw grass that remained in Cameron Parish after Hurricane Audrey, some still healthy and some salt-stressed, began to die in 1958 during a time when spring and summer droughts concentrated soil salinities. During this period, soil salinities often exceeded 16 ppt and were recorded as high as 25 ppt. The nutria (*Myocastor coypus*) population was at its peak in western Cameron Parish. Nutria dug up and ate the roots and rhizomes of several plant species, including saw grass, resulting in total die-off, except in areas where impounded water moderated salinities and nutria only thinned stands (Valentine 1976). By 1962, nearly all of the saw grass marsh in Cameron Parish had died.

Opinions differ on the causes and extent of the demise of the historical expanses of saw grass marsh in the Louisiana Chenier Plain. Some coastal experts contend that much of the saw grass marsh was already dead when Hurricane Audrey arrived (Alan Ensminger, Louisiana Landowners Association, personal communication). This belief is based on the hypothesis that the combination of saltwater intrusion up tidal channels, the systemic discharge of hypersaline produced waters into the marsh from oil and gas exploration activities, and nutria herbivory are to blame for the death of the saw grass community. Most coastal experts do agree that Hurricane Audrey—and later, Hurricane Carla, on 9 September 1961—caused the export of vast quantities of saw grass detritus to the Gulf of Mexico.

Chicot Aquifer Depletion

The Chicot Aquifer system in Louisiana is a massive sand outcrop underlying all of southwestern Louisiana from the southern portions of Vernon and Rapides parishes, south to the Gulf of Mexico, and east and west to the Atchafalaya and Sabine Rivers, respectively (Figure 31). In Calcasieu and Cameron parishes the aquifer has been divided into three distinct sand units separated by clay beds called the “200-foot,” “500-foot,” and “700-foot” sands. The Louisiana Department of Transportation and Development (LDOTD) has documented the occurrence of high-chloride water in the Chicot Aquifer system in the coastal zone and in isolated areas north of the coast (Nyman 1984). Groundwater withdrawals associated with irrigation and industrial pumping have elevated the freshwater-saltwater interface in all three aquifer units, resulting in reversal of the natural southerly freshwater flow and a northward movement of saltwater in the aquifer.

USGS investigations revealed local areas that are particularly susceptible to saltwater encroachment, including Lake Charles, where chloride concentrations have been increasing by about 0.025 ppt/yr in the 700-foot sand. These changes generally correspond to changes in pumping centers and resultant saltwater coning. Saltwater coning causes saline water to rise to a higher elevation in the aquifer, in a conical configuration around the pumping center.

Most of the concerns associated with saltwater in the 200-foot sand are tied to the coastal saltwater wedge that extends from 5 mi to nearly 40 mi north from the Gulf of Mexico. Nyman (1984) found evidence of northern encroachment of the saltwater wedge in northern Cameron Parish. The northward movement of the saltwater wedge has yet to cause major freshwater supply problems because the aquifer is generally more than 400 ft thick, and there is usually sufficient distance between the bottoms of wells and the freshwater base to minimize saltwater coning. Still, any activities that significantly increase the use of the

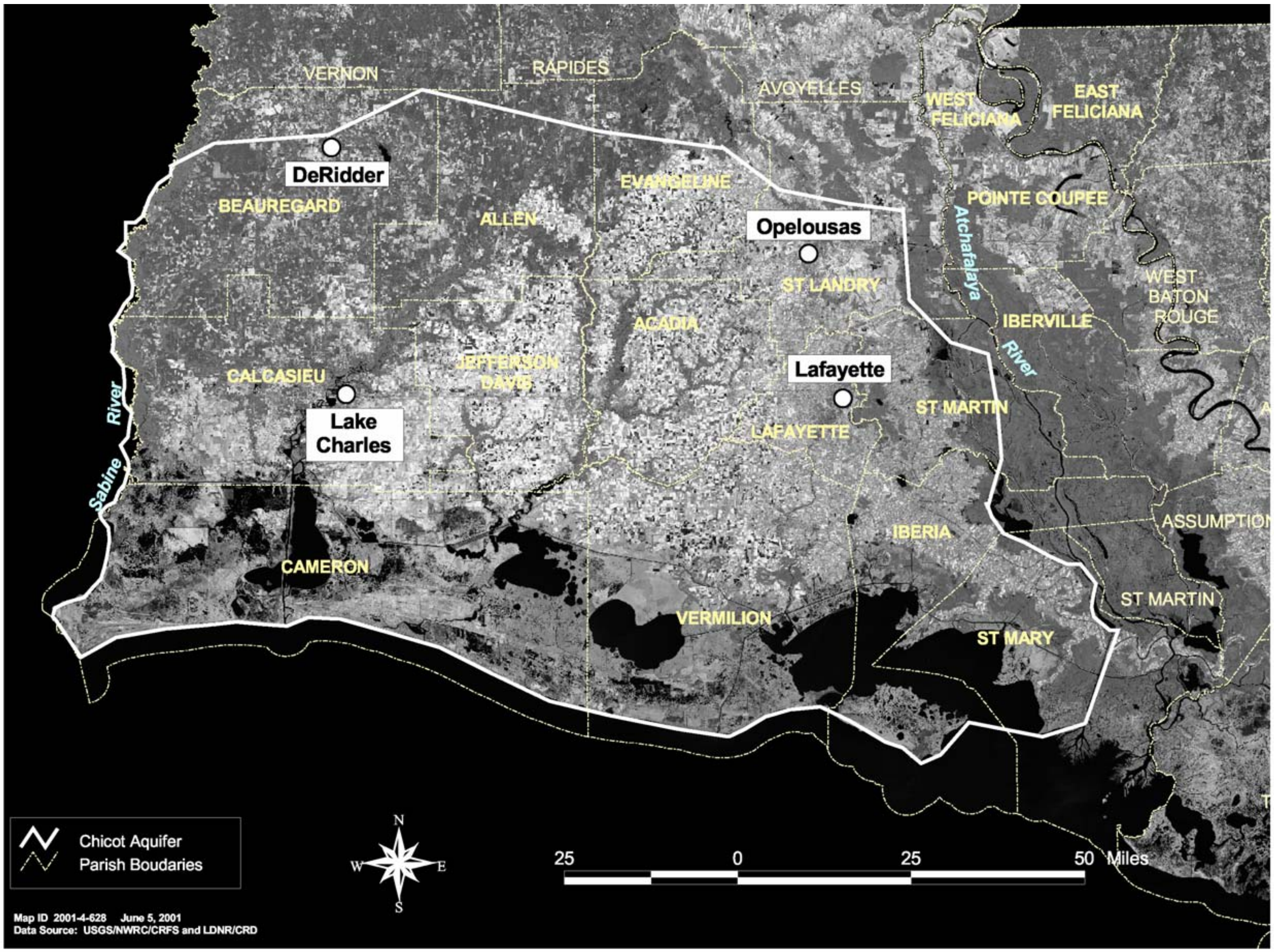

Figure 31. Approximate subaerial extent of the Chicot Aquifer in Louisiana.

Chicot Aquifer should be carefully evaluated in terms of the potential risk of shortening the life of the water supply.

The Sabine River Diversion Canal, which went into operation in 1981, reduced the pumping of groundwater for industrial needs and diminished the potential for saltwater coning and saltwater wedge encroachment in the 500-foot and 700-foot sands in the Lake Charles industrial area (Nyman 1984). However, more recent evidence suggests that the diversion canal may have provided only temporary relief (Lovelace 1998). Samples from one well near a pumped public supply well in Lake Charles indicate that the chloride concentration there has increased at a rate of about 0.03 ppt/yr since 1991. Compounding the fact that there is already a saltwater intrusion problem in the Lake Charles industrial area, a risk remains that substantial diversion of the Sabine River to Texas or deepening of the Sabine-Neches Ship Channel may render water in the Sabine River Diversion Canal less suitable or unsuitable for industrial uses due to saltwater intrusion. Unfortunately, these circumstances could once again create a need to increase pumping of aquifer water, leading to consequent saltwater coning and encroachment.

Ongoing irrigation pumping from the Chicot Aquifer should be considered when evaluating the potential for saltwater contamination of the Chicot Aquifer. Pumping for rice irrigation results in lowering of water levels in the upper and 200-foot sands, and large increases in the northerly hydraulic gradient. This leads to a greater velocity of groundwater movement from the south, and a potential increase in the rate of saltwater movement (Lovelace 1998).

A potential threat to the health of the aquifer comes from various electric utilities that are interested in setting up business in Southwestern Louisiana. These plants would pump large volumes from the aquifer for cooling during the production of electric power that would be sold out of state. Louisiana is currently in the early process of developing a much-needed ground and surface water policy for the state.

General usage of both surface water and groundwater supplies in Calcasieu, Cameron, and Vermilion parishes has declined appreciably since peaks in 1975-80. Nevertheless, in Vermillion Parish the use of surface water for rice irrigation increased by 37%, to 54.73 million gallons/day, and groundwater usage for rice irrigation increased by 19%, to 0.99 million gallons/day, between 1990 and 1995. These increases occurred concomitant with a 15,728- ac (16%) increase in irrigated acreage (Lovelace 1991; Lovelace and Johnson 1996).

The Trans-Texas Water Program, the Sabine River Authority, the Sabine River Compact, and Texas Senate Bill 1

Interstate demands on water may play a large role in the future status of the Calcasieu-Sabine Basin. The Trans-Texas Water Program (TTWP) was a water resources planning process designed to identify the most acceptable methods for meeting future water needs in 32 counties in southeastern Texas that include approximately one-third of the state's population. An evaluation of presently available water supplies estimated that the Houston area would require supplemental water supplies from new sources or from outside the immediate area by 2050 (TWDB 2001).

Recommendations for the program included the transfer of surplus "state" waters from basins having surplus supplies to basins that experience water shortages. To this end, the Toledo Bend Reservoir was identified as critical for meeting future water needs in all of the Southeast Texas study area. This is an attractive water supply option for the state of Texas because the Sabine River Compact, signed between Louisiana and Texas in 1953, allows for each state to withdraw up to 50% of the Sabine River's inflow. The Sabine River Compact was signed by representatives from Texas and Louisiana and approved by the federal government. The purpose of the Compact is to provide for an equitable apportionment of the waters of the Sabine River and its tributaries between the states of Louisiana and Texas; to encourage the development, conservation, and utilization of the Sabine River; and to establish a basis for cooperative planning and action by the states for the construction, operation, and maintenance of projects for water conservation and utilization.

Geographically, the Sabine River Compact regulates apportionment of the Sabine River between the states at the point where the river first touches the Louisiana border at the north end of Toledo Bend Reservoir, near Logansport, Louisiana. The compact places the river's water in one of two broad categories: "stored water," water stored in reservoirs, or "free water," which is not in reservoirs and appears as natural stream flow. The compact dictates that after 1 January 1953, all waters withdrawn by either state are deducted from that state's apportionment in accordance with the compact. The state of Texas can, however, draw from any other reservoir that is entirely within the state borders, without violating the compact. This action has an unmeasured effect on Louisiana, since the inflows to the Sabine River would be decreased.

In addition, the compact created an interstate Sabine River Commission that consists of two members from each state and a federal government representative appointed by the President of the United States. The Commission is charged with administration of the Sabine River Compact.

While this agreement was satisfactory for both Louisiana and Texas in 1953, a lot has changed in the area since then. Human population growth and technological advances in the region have resulted in water demands that are dramatically greater than anything that could have been forecast nearly a half century ago when the Sabine River Compact was conceived. Moreover, major federal environmental policies have been enacted—such as the National Environmental Policy Act, Clean Water Act, and Coastal Zone Management Act—that may supercede the Sabine River Compact. Thus, a good argument can be made that the Sabine River Compact is outdated and in need of renegotiation.

Each of the two states has its own independent Sabine River Authority. The Sabine River Authority of Texas is a governmental agency created in 1949 as a conservation and reclamation district with responsibilities to control, store, preserve, and distribute for useful purposes the waters of the Sabine River and its tributary system. In Louisiana, the Sabine

River Authority provides mainly for economic development, public recreation, hydroelectric power, and water for agricultural and industrial uses through the use of the Sabine River and its tributaries.

In 1997, the Texas Legislature adopted Texas Senate Bill 1, which put an end to all water planning activities under the TTWP and began a new programmatic statewide water planning process known popularly as "Senate Bill 1" (SB1). SB1 is cooperatively administered by the Texas Water Development Board (TWDB), the Texas Parks and Wildlife Department (TPWD), and the Texas Natural Resources Conservation Commission (TNRCC). The objective of SB1 is to develop a water plan that will "... provide for the orderly development, management, and conservation of water resources and preparation for, and response to drought conditions, in order that sufficient water will be available at a reasonable cost to ensure public health, safety, and welfare; further economic development; and protect the agricultural and natural resources of the entire state." To this end, Texas was divided into 16 major water-planning districts. Within each district, a Regional Water Planning Group was established to develop a Regional Water Plan. Upon completion, the Regional Water Plans will be submitted to the TWDB, TPWD, and TNRCC to jointly synthesize the regional plans into a cohesive State Water Plan for Texas.

At the time of this writing, the draft Region H (Houston Region) plan recommends strategies to address projected water shortages that do not include inter-basin transfers of Sabine River water toward Houston. Instead, the plan recommends strategies that address the projected water shortages through new reservoir development, conservation, and renewal, and expansion of existing water contracts. The inter-basin transfer of water from the Sabine Basin remains a long-term strategy, however, not within the SB1 50-yr planning time frame. Reasons cited for not selecting this strategy include inconsistency with the Texas Water Code, opposition to the strategy in east Texas, and potential freshwater inflow impacts to the Sabine Lake estuary.

Draft plans for water management in East Texas call for no substantial diversion of the Sabine River at this time, although there are several strategies that call for the withdrawal of relatively small individual amounts of freshwater from the Sabine River, Toledo Bend Reservoir, the Neches River, or the SRA Canal, which leads off of the Sabine River near Orange, Texas. The good news is that these withdrawals do not collectively constitute a tremendous amount of water. Ignoring renewal of existing contracted water withdrawal amounts, the projected need equates to roughly 140 cfs, compared to an average flow on the Sabine River of approximately 8,600 cfs, with drought inflows that drop lower than 3,000 cfs.

Calcasieu-Sabine Basin Hydrologic Analyses

Data Sources

In order to gain a better understanding of salinity and freshwater inflow dynamics in the Calcasieu-Sabine basin, historical salinity, water level, riverine discharge, and rainfall data were obtained from federal and state agencies and universities in both Louisiana and Texas. Data sources included the Sabine National Wildlife Refuge (SNWR), the Texas Water Development Board (TWDB), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), the National Oceanographic and Atmospheric Administration (NOAA), the National Weather Service (NWS), the U.S. Fish and Wildlife Service (USFWS), Louisiana State University (LSU), the Louisiana Department of Wildlife and Fisheries (LDWF), the Louisiana Department of Environmental Quality (LDEQ), the Cameron Prairie Refuge (CPR - part of the Southwestern Louisiana Refuge Complex), and the Louisiana Department of Natural Resources (LDNR). Most of the data were collected monthly, but for months with multiple observations, we calculated the monthly mean before including those data in the analyses.

Salinity data were collected at 39 stations in the SNWR (Figure 32), with more than 1,300 discrete monthly observations obtained. Monthly salinity sampling on the SNWR extends back to 1966-67 at 15 SNWR stations, although sampling at six of those stations was terminated after 15-24 years. Sampling at the remaining stations began in 1989-90, except at two stations where sampling began in 1983 and continued for three years or less. Salinity data from Sabine Lake were collected by the TWDB at 1-2-hr intervals at three locations in the lake, designated as upper, middle, and lower stations (Figure 32). The lower station was sampled from 1990 to 2000, the middle station was discontinued in August 1995, and the upper station has only been collecting data since May 1995. We calculated monthly means for data analysis.

The LDWF conducts fishery-independent sampling as part of its program to monitor populations of commercially important species. The agency's established stations were sampled once or twice per month, and salinity readings were collected at the time of the sample. We included in our analyses observations from five of these stations in the Calcasieu Lake area (Figure 32). We also included salinity data from CPR/SNWR stations (Figure 32). The records of six stations (EC1-EC6), while somewhat spotty, span from the mid- to late 1960s to July 1995. Sampling at the other four stations (EC7-EC10) started near 1988 and continued through July 1995.

Additional sporadic salinity observations at other stations in the Calcasieu-Sabine Basin were obtained from NOAA. Data at these stations were collected sporadically, ranging from 1969 to 1997. The analyses included 37 stations (28 from the Calcasieu Basin and 9 from the Sabine Basin) with enough observations ($n > 48$) for analysis (Figure 32).

River discharge and water level data were collected by the USGS. The data were averaged by month, then log transformed to better approximate the normal distribution. River discharge at the Ruliff, Texas, station (USGS 08030500), located approximately 15 mi north of the GIWW, and Calcasieu River water level at the Kinder, Louisiana, station (USGS 08015500), located approximately 25 mi north of Lake Charles, Louisiana, were used in the analysis. Water level at Kinder was used as a surrogate for discharge since the discharge data for the Calcasieu River were inadequate for this analysis. Daily rainfall data were obtained from the National Weather Service and totaled by month. Rainfall data from the Hackberry

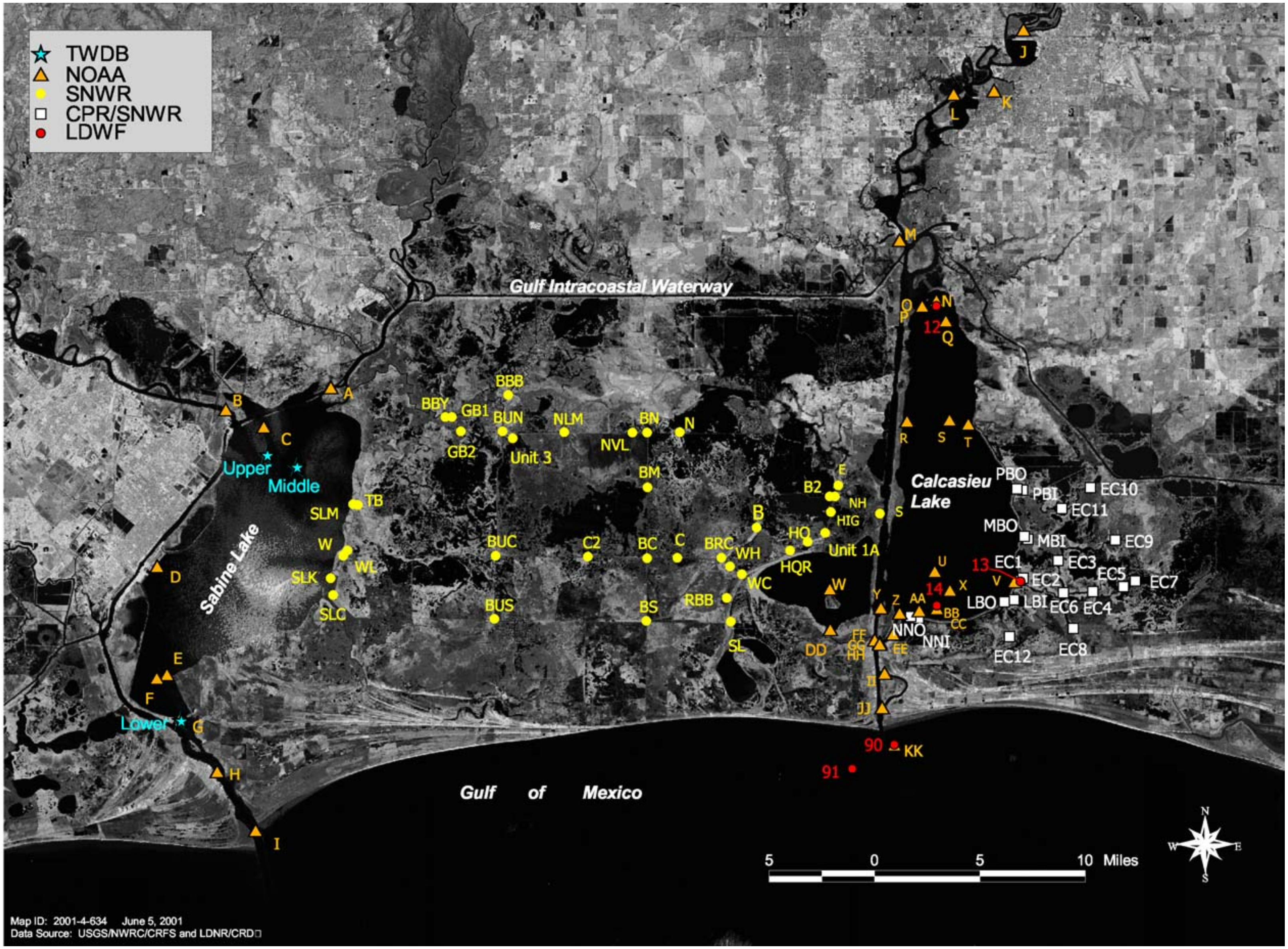

Figure 32. Map of stations where salinity data was obtained for Calcasieu-Sabine Basin data analysis.

station at the SNWR headquarters were used in the analysis because this is a central location in the study area.

Data Analyses and Results

A General Linear Models approach was used to look at the response of salinity at each station to temporal and environmental variables (Neter et al. 1990). Although the Toledo Bend Reservoir, completed in 1968, would seem to be an apparent restriction to water flow, gauged inflows—which include input from both the Sabine and Neches rivers into Sabine Lake—increased significantly ($P < 0.0001$), from a mean of 14,880 cfs before the construction of the reservoir to 16,600 cfs after construction. Sabine River discharge at Ruliff, Texas, also increased significantly ($P < 0.0001$), from a mean of 4,942 cfs before construction to 8,680 cfs after. Unfortunately, salinity was not adequately monitored prior to construction to allow testing of the impact of the reservoir on the salinity of Sabine Lake.

Sabine Lake Area

At four of the nine NOAA stations in the Sabine Lake area, we identified a strong negative relationship between salinity and Sabine River discharge at Ruliff, meaning that increased discharge there is related to decreased salinity and that this relationship is statistically significant. At only one station (Station B) was salinity significantly negatively related to Calcasieu River water level at Kinder (Table 12). Due to the proximity of this station to the SNWR, we presume that this negative relationship is due to hydrology at this station being similar to the prevailing conditions at Calcasieu River and Calcasieu Lake in terms of drainage area and navigation channel configuration. Thus, this finding probably indicates a correlation between hydrologically similar areas and not a true stage/salinity relationship.

Sabine National Wildlife Refuge

We determined significant relationships in the comparison of salinities at SNWR stations to Sabine River discharge, Calcasieu River water level, precipitation, and time. Salinities at most of the stations were negatively related to Sabine River discharge at Ruliff and Calcasieu River water level at Kinder (Table 13). Salinities at several stations also demonstrated a non-linear seasonal component, generally decreasing over the year. Salinities were significantly negatively related to rainfall at three of the stations (Stations B, NH, and WH).

Salinities at the stations in the SNWR were more strongly influenced by Sabine River discharge than by Calcasieu River water level at Kinder (Table 13). This was probably due to a combination of factors, including the rapid loss of Calcasieu River freshwater inflows down the CSC, the substantially smaller size of the Calcasieu River compared to the Sabine River, and a greater isolation of the Calcasieu River and Calcasieu Lake from the SNWR by

Table 12. Summary of NOAA stations in the Calcasieu-Sabine Basin at which significant relationships were detected between salinities and environmental factors in a GLM analysis, reported by data source. Significant relationships of individual variables with salinity (P<0.05, adjusted for multiple comparisons) are indicated by "neg" and "pos" for a negative and a positive relationship, respectively. Highly significant relationships (P<0.0001) are indicated by an underline. Station locations are pictured in Figure 32.

NOAA station	Overall P>F	Sabine River discharge at Ruliff	Calcasieu River water level at Kinder
Sabine Lake			
A	0.0001	neg	
B	0.0001		neg
F	0.0001		
I	0.0001		
H	0.0001	neg	
G	0.0001		
E	0.0002		
D	0.0002	neg	
C	0.0001	neg	
Calcasieu Lake			
GG	0.0001		
EE	0.0001	neg	
Z	0.0001	neg	
AA	0.0001	neg	
CC	0.0001	neg	
X	0.0001	neg	
U	0.0001	neg	
O	0.0001	neg	
V	0.0001	neg	
BB	0.0001	neg	
W	0.0008	neg	
DD	0.0001	neg	
FF	0.0001	neg	
II	0.0001	neg	
JJ	0.0001		
T	0.0001	neg	neg
M	0.0001	neg	neg
K	0.0001		neg
N	0.0001	neg	
S	0.0001	neg	
R	0.0001	neg	
P	0.0001	neg	
KK	0.0003		
L	0.0001		neg
HH	0.0001	neg	neg
Q	0.0001	neg	neg
Y	0.0001		neg
J	0.0006		

Table 13. Summary of SNWR, NOAA, LDWF, and Cameron-Creole Watershed stations in the Calcasieu-Sabine Basin at which significant relationships were detected between salinities and environmental factors in a GLM analysis, reported by data source. Significant relationships of individual variables with salinity (P<0.05, adjusted for multiple comparisons) are indicated by "neg" and "pos" for a negative and a positive relationship, respectively. Highly significant relationships (P<0.0001) are indicated by an underline. Station locations are pictured in Figure 32.

SNWR station	Overall P>F	Sabine River discharge at Ruliff	Calcasieu River water level at Kinder	Rain at Hackberry	Year	Month
SNWR stations						
B	0.0001	neg	neg	neg		
B2	0.0001	neg	neg		pos	neg
BBB	0.0001	neg				
BBY	0.0001	neg				neg
BC	0.0001	neg	neg			
BM	0.0001	neg				
BN	0.0001	neg	neg			
BRC	0.0001					
BS	0.0001	neg	neg			
BUC	0.0001	neg				
BUN	0.0001	neg				
BUS	0.0001	neg				
C	0.0001		neg			
C2	0.0001	neg				
E	0.0001		neg			neg
G2	0.0019					
GB1	0.0001	neg	neg			neg
GB2	0.0001	neg	neg			neg
HIG	0.0001		neg		pos	neg
HQ	0.0001	neg	neg			neg
HQRS	0.0001		neg			
L4	0.0034					
N	0.0001	neg				
NH	0.0001	neg	neg	neg	pos	neg
NLM	0.0001	neg				
NVL	0.0001	neg				
RBB	0.0001					
S	0.0001	neg	neg			
SL	0.0001	neg				
SLC	0.0001	neg				
SLK	0.0001	neg				neg
SLM	0.0001	neg				neg
TB	0.0001	neg				neg
UNIT 1A	0.0313					
UNIT 3	0.0001					
WC	0.0001	neg	neg			
WL	0.0001	neg	neg			neg
WH	0.0001		neg	neg		

Table 13. (continued).

Station	Overall P>F	Sabine River discharge at Ruliff	Calcasieu River water level at Kinder	Rain at Hackberry	Year	Month
NOAA stations						
Calcasieu Basin						
25	0.0001	neg	neg			neg
90	0.0003					
1	0.0001					
11	0.0001	neg				
12	0.0001	neg				
13	0.0001	neg				
14	0.0001	neg				
18	0.0008	neg				
19	0.0001	neg				
2	0.0001	neg				
20	0.0001	neg				
21	0.0001	neg				
22	0.0001					
26	0.0001	neg	neg		pos	neg
27	0.0001		neg		pos	neg
28	0.0001	neg				
31	0.0001	neg				
29	0.0001	neg				
295040093204000	0.0001		neg			
3	0.0001	neg				
30	0.0001	neg				
301432093135700	0.0006				neg	
4	0.0001	neg				
5	0.0001	neg				
6	0.0001	neg				
719	0.0001	neg	neg			
730	0.0001	neg	neg			neg
94	0.0001		neg			neg
Sabine Basin						
24110050	0.0001					
24110100	0.0001	neg				
24120050	0.0001					
24120100	0.0002				neg	
24120150	0.0002	neg				
24120200	0.0001	neg				
93087 2	0.0001	neg			neg	
93214 2	0.0001		neg		neg	
93300 2	0.0001					

Table 13. (continued).

Station	Overall P>F	Sabine River discharge at Ruliff	Calcasieu River water level at Kinder	Rain at Hackberry	Year	Month
LDWF stations						
12	0.0001	neg	neg			neg
13	0.0001	neg	neg			neg
14	0.0001	neg	neg		neg	neg
90	0.0001		neg			neg
91	0.0001		neg		neg	neg
Cameron-Creole Watershed stations						
EC1	0.0001	neg	neg		pos	neg
EC2	0.0001	neg	neg			
EC3	0.0001	neg				
EC4	0.0001	neg				
EC5	0.0001	neg				
EC6	0.0001	neg				
EC7	0.0001				neg	
EC8	0.0001				neg	
EC9	0.0001				neg	
EC10	0.0001	neg			neg	

water control structures adjacent to the CSC. In 1981, fixed-crest weirs with radial-arm tainter gates were constructed at Hog Island Gulley and West Cove Canal. Additionally, a 4-ft-diameter flapgated culvert was installed to control water exchange between Headquarters Canal and Shell Canal. As a result, only at the stations near the east end of the refuge do Calcasieu River water levels show a greater influence on salinities than does Sabine River discharge. The connections with Sabine Lake at the west end of the SNWR are much more open, and the canal system there can move Sabine Lake water more rapidly into remote areas. Thus salinities at most SNWR stations, especially those to the west and north, show a stronger relation to Sabine River discharge than to Calcasieu River water level. Neither of the impounded areas sampled on the SNWR (Unit 1A or Unit 3) exhibited significant relationships between salinity and either Sabine River discharge or Calcasieu River water level (Table 13). Figure 33 illustrates the relationship between salinity, Sabine River discharge, and Calcasieu River stage at six representative locations across the refuge.

Most of the SNWR stations showed no long-term trend in salinity, although 6 stations out of 38 exhibited significant trends over the length of record (Table 14). At stations Unit 1A, BM, BUS, B2, and C2, salinities increased significantly over time, but at Station BN, the salinity decreased significantly (Table 14).

The greatest salinity increase in the SNWR occurred at Station B2, which is at the east end of the refuge (Figure 32). Salinity there increased from an average of 7.62 ppt in 1990 to 14.17 ppt in 1999 (Table 14), a potentially large enough change to have a strong influence on the surrounding non-impounded marshes. The area is currently classified as brackish marsh, dominated by *Spartina patens*. The current salinity regime at Station B2 is at this species' upper limit, and a continued salinity increase could stress and kill *S. patens* and result in its replacement with either *Spartina alterniflora* or open water. Likewise, the intermediate marshes surrounding stations BUS and C2 are in danger of undergoing vegetation shifts due to salinity increases from about 1 ppt to nearly 4 ppt (Table 14). Intermediate marshes make the transition to brackish marshes at 4-5 ppt (Chabreck 1972).

The decrease in salinity at Station BN is particularly noteworthy considering the salinity increase at the nearest station to the south, Station BM. Station BN's salinity pattern is probably due to the shoaling of Beach Canal just south of its intersection with Northline Canal between the two stations. Beach Canal was last dredged around 1982 to a depth of about 4 ft. It has since filled in, so that it is now less than 2 ft deep, and by 1995 had become impassable to boat traffic (personal communication, Roy Walter, SNWR). This has probably hindered the northward flow of water along Beach Canal to Station BN, reducing the influence of the CSC on salinity via the West Cove Canal and Hog Island Gully structures.

Average annual salinities on the SNWR are within the tolerance levels of the fresh, intermediate, and brackish marshes there (Figure 34). In general, non-impounded marshes on the western side of the refuge are fresher, with average annual salinities consistent with fresh, intermediate, and brackish marshes. An analysis of the average salinities for each season reflects a distinct seasonality in the salinity regime of the SNWR (Figure 35). Fresher conditions during the winter and spring, driven by higher riverine inflows and precipitation, exert a strong influence across the SNWR. As the growing season progresses, riverine

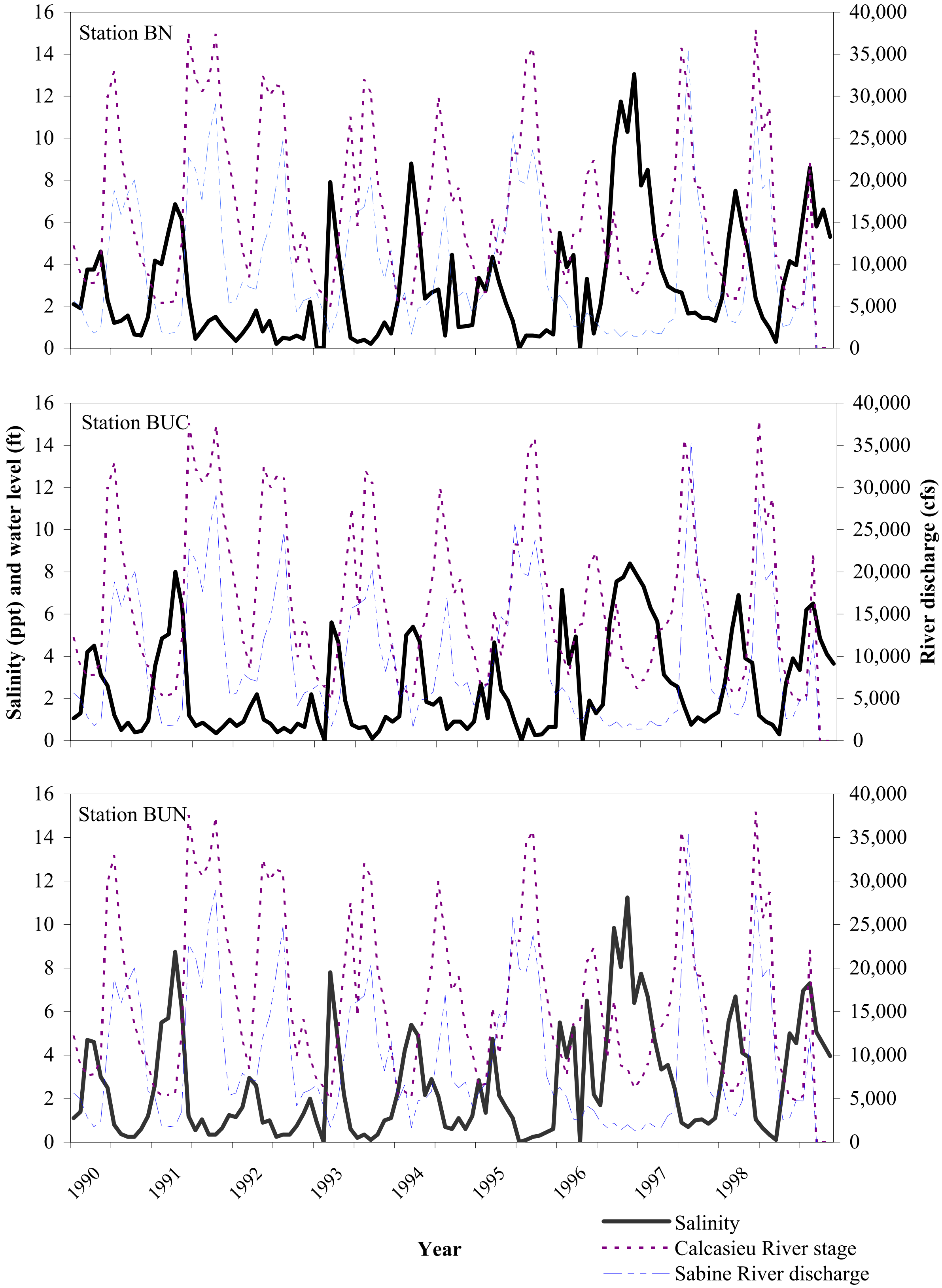

Figure 33. Monthly means of Sabine River discharge, Calcasieu River stage, and salinity at six Sabine National Wildlife Refuge salinity-monitoring stations. Station locations are illustrated on Figure 32.

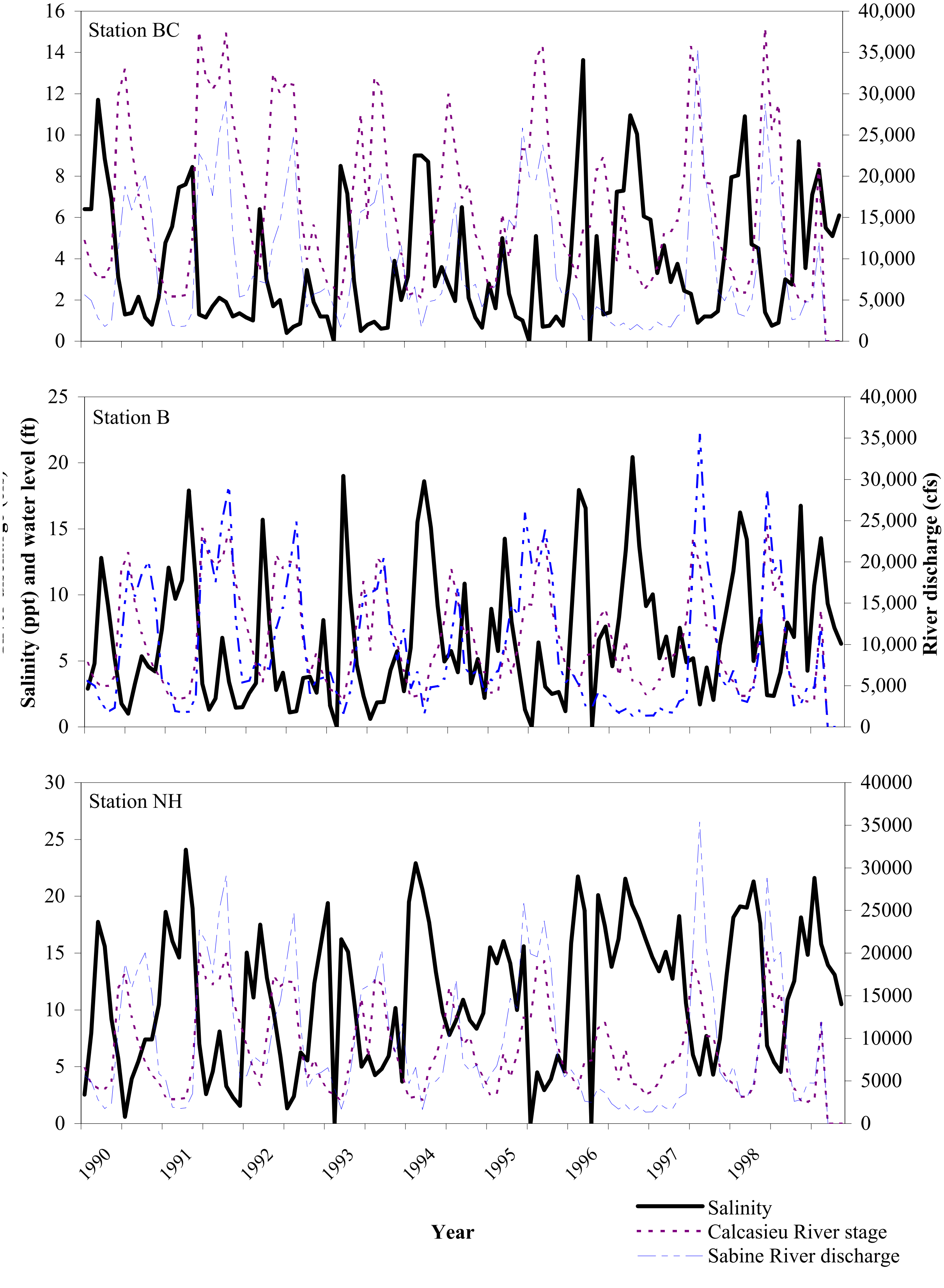

Figure 33 (continued).

Table 14. Significant trends in long-term salinity record at the SNWR. Salinity change is the average salinity at the beginning and the end of the period, as predicted from the regression line. Station locations are pictured in Figure 32.

SNWR station	Period of record	Salinity change	Coefficient of change	F-Value	Number of observations	P>F
Unit 1A	1991-99	1.61-2.50	0.1108	25.36	94	0.0001
BM	1990-99	1.39-4.65	0.3882	16.14	99	0.0001
BUS	1990-99	1.04-3.93	0.3072	14.08	106	0.0003
B2	1990-99	7.62-14.17	0.7279	12.87	106	0.0005
BN	1966-99	5.69-3.23	-0.0745	12.05	289	0.0006
C2	1990-99	1.35-3.75	0.2664	9.05	106	0.0033

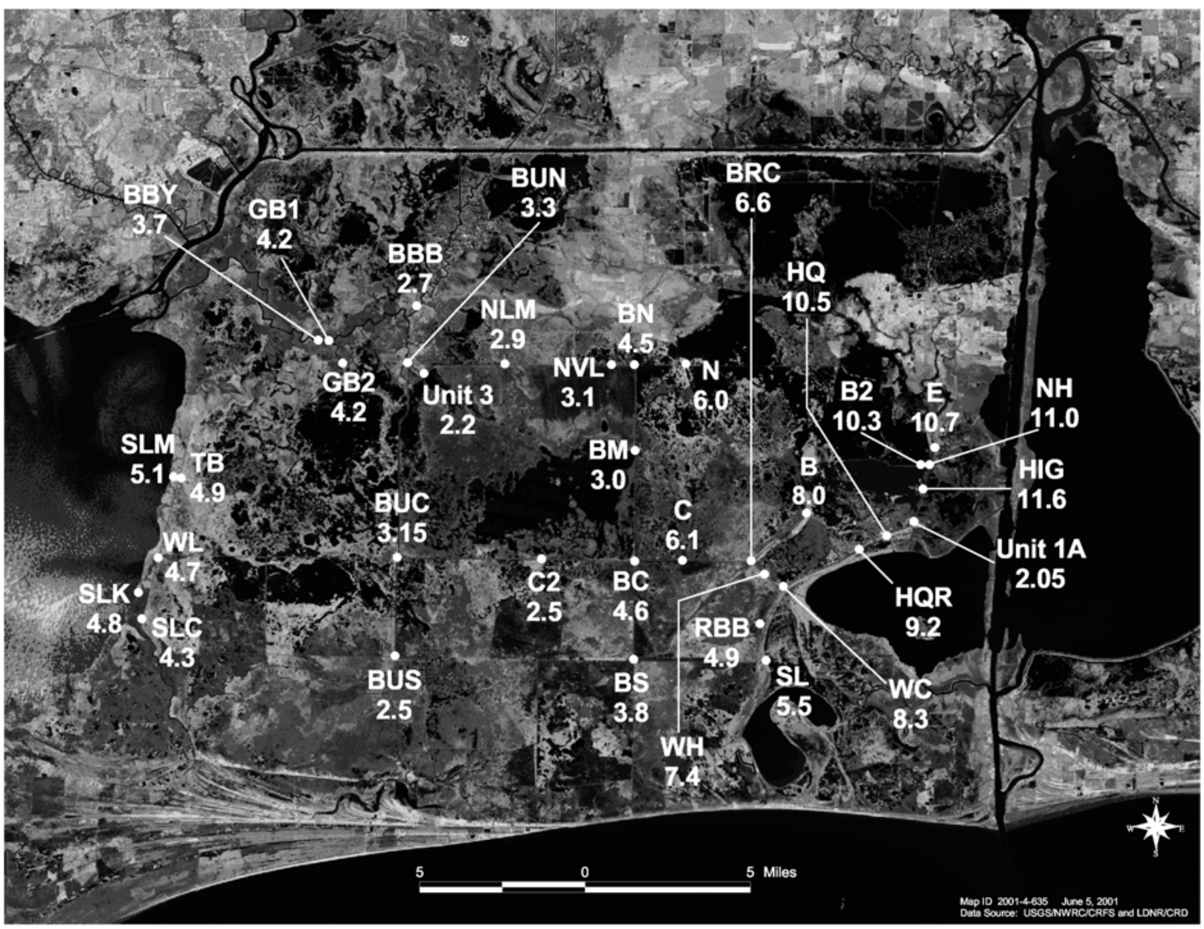

Figure 34. Average salinities (ppt) at stations on the Sabine National Wildlife Refuge.

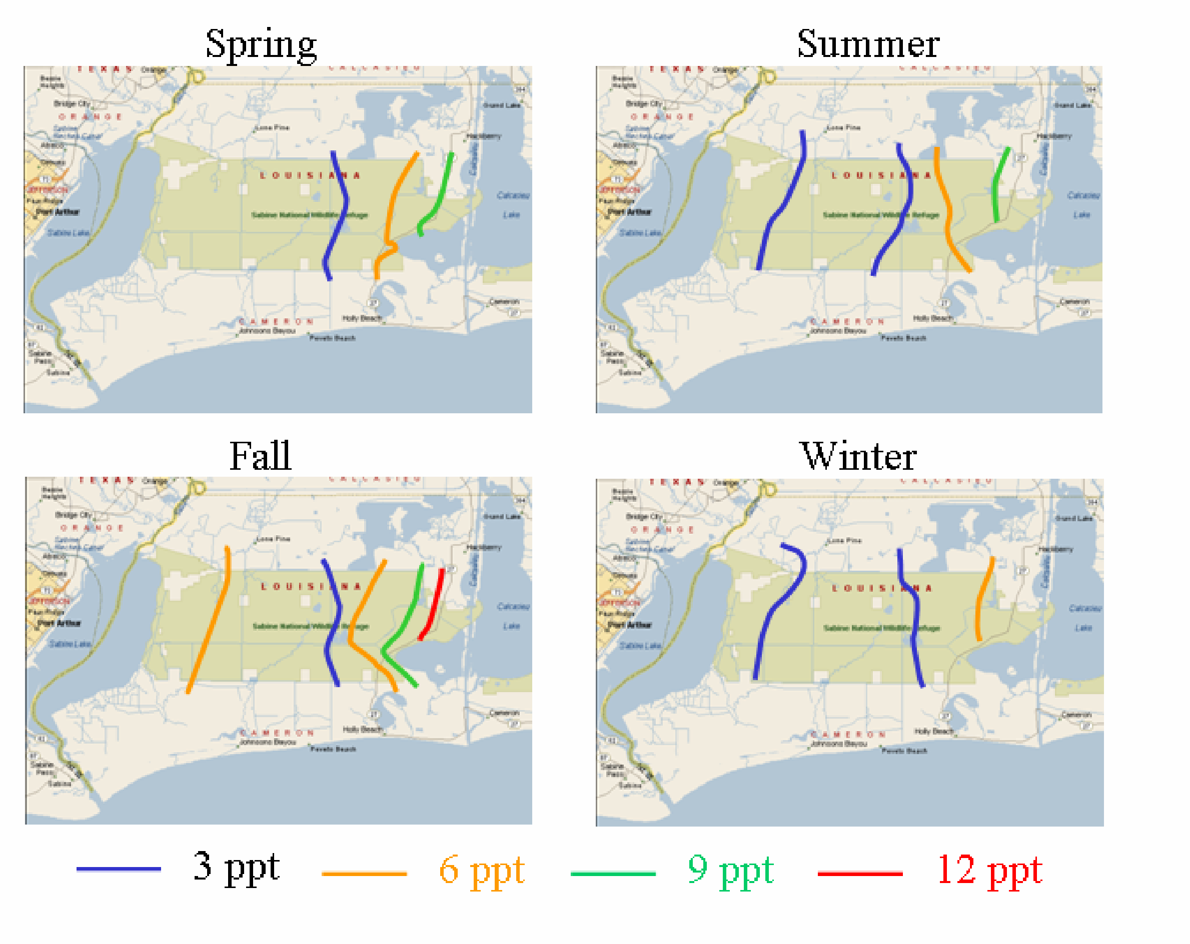

Figure 35. Seasonal isohalines on the Sabine National Wildlife Refuge based on monthly samples collected by refuge personnel, 1966-2000.

inflows and rainfall are reduced. By the mid- to late growing season, salinities on the SNWR increase with increasing tidal saltwater influence from both major ship channels.

Calcasieu Lake Area

In the Calcasieu Lake area, salinities at the LDWF stations were more significantly related to Calcasieu River water level at Kinder than to Sabine River discharge (Table 15). Salinity at all five of the stations was negatively related to water levels at Kinder, whereas salinity at only three of the five stations was significantly negatively correlated to Sabine River discharge. No significant relationships between salinity and rainfall could be detected at any of the LDWF stations.

Salinities at 21 of the 28 NOAA stations in the Calcasieu Lake area were negatively related to Sabine River discharge at Ruliff, whereas salinities at 7 stations were negatively related to Calcasieu River water level at Kinder (Table 12). No significant relationships between salinity and rainfall could be detected at any of the NOAA stations. Salinities at stations north of the GIWW on the Calcasieu River (stations J-L, Figure 32) were strongly related to Calcasieu River water levels, yet salinities at stations near the northern end of Calcasieu Lake and near the confluence of the Calcasieu River with the GIWW (stations M-T) showed a strong relationship to both Sabine River discharge and Calcasieu River water level. This reflects the east-west connection of the two river systems created by the GIWW. The GIWW provides a direct conduit for Sabine River water to influence salinities near the northern end of Calcasieu Lake. Given the high degree of saltwater intrusion resulting from the CSC, water from the Sabine River helps to moderate salinities in this area. Unfortunately, the GIWW also provides a conduit for higher-salinity water from the CSC to invade the marshes north of the SNWR and has greatly contributed to the loss of marshes near the Alkali Ditch and Black Lake.

Only one of the 30 NOAA stations (Station K in the Calcasieu Basin) showed a significant increasing salinity trend over its sampling period, 1971-90 (Table 16). Salinities at Station KK in the Gulf of Mexico showed a marginally significant increasing trend over the period 1982-88, whereas salinities at Station II decreased over the sampling period 1970-90. One of the five LDWF stations (Station 14) showed a significant declining trend in salinity over the period 1967-98 (Table 17).

Cameron Prairie Refuge (Cameron-Creole Watershed)

At stations in the Cameron Prairie National Wildlife Refuge (part of the Southwestern Louisiana Refuge Complex), significant relationships between salinity and the temporal and environmental variables were noted for 10 of the 15 stations analyzed (Table 15). Three stations had a significant negative relationship to the temporal variable (year), which indicates a general linear reduction in salinity over the study period at these stations. Salinity data at these stations (EC7, EC9, and EC10) were collected from 1987 to 1995. No significant trends were observed for the other 7 CPR stations analyzed, although a decrease

Table 15. Summary of LDWF and Cameron-Creole Watershed stations in the Calcasieu-Sabine Basin at which significant relationships were detected between salinities and environmental factors in a GLM analysis, reported by data source. Significant relationships of individual variables with salinity ($P<0.05$, adjusted for multiple comparisons) are indicated by "neg" and "pos" for a negative and a positive relationship, respectively. Highly significant relationships ($P<0.0001$) are indicated by an underline. Station locations are pictured in Figure 32.

Station	Period of record	Overall P>F	Sabine River discharge at Ruliff	Calcasieu River water level at Kinder	Year	Month	Month^2 (non-linear)
LDWF stations							
12	1967-98	0.0001	$\underline{\text{neg}}$	$\underline{\text{neg}}$		$\underline{\text{neg}}$	$\underline{\text{pos}}$
13	1967-98	0.0001	$\underline{\text{neg}}$	$\underline{\text{neg}}$		$\underline{\text{neg}}$	$\underline{\text{pos}}$
14	1967-98	0.0001	$\underline{\text{neg}}$	$\underline{\text{neg}}$	neg	$\underline{\text{neg}}$	$\underline{\text{pos}}$
90	1982-98	0.0001		neg		$\underline{\text{neg}}$	$\underline{\text{pos}}$
91	1982-98	0.0001		neg	neg	$\underline{\text{neg}}$	$\underline{\text{pos}}$
Cameron-Creole Watershed stations							
EC1	1966-95	0.0001	$\underline{\text{neg}}$	$\underline{\text{neg}}$	pos	neg	pos
EC2	1967-95	0.0001	$\underline{\text{neg}}$	neg			
EC3	1966-95	0.0001	neg				
EC4	1966-95	0.0001	$\underline{\text{neg}}$				
EC5	1966-95	0.0001	$\underline{\text{neg}}$				
EC6	1967-95	0.0001	$\underline{\text{neg}}$				
EC7	1987-95	0.0001			$\underline{\text{neg}}$		
EC8	1987-95	0.0001			neg		
EC9	1988-95	0.0001			$\underline{\text{neg}}$		
EC10	1988-95	0.0001	neg		$\underline{\text{neg}}$		

Table 16. Long-term salinity trends at 37 NOAA stations in the Calcasieu-Sabine Basin. Coefficients with asterisks are significant at P<0.05, after adjusting for multiple comparisons.

Station	Period of record	Coefficient (ppt/month)	N	F-Value	P>F
A	1968-88	-0.2076	61	3.63	0.0615
B	1968-88	-0.2142	62	3.89	0.0531
C	1969-88	-0.1234	157	3.99	0.0474
D	1978-87	-0.2411	99	2.92	0.0907
E	1969-88	-0.2396	198	5.12	0.0247
F	1970-86	-0.0832	51	0.29	0.5905
G	1978-87	0.1569	106	0.58	0.4480
H	1969-88	-0.9162	62	9.79	0.0027
I	1978-88	0.1381	112	0.42	0.5160
J	1974-81	-0.3923	61	6.39	0.0142
K	1971-90	0.2099*	218	18.17	0.0001
L	1978-90	-0.0026	141	0	0.9845
M	1971-90	0.1216	211	2.17	0.1426
N	1985-90	0.0096	52	0	0.9823
O	1985-90	-0.0534	52	0.01	0.9038
P	1970-90	-0.2113	93	6.07	0.0156
Q	1988-96	-0.1435	73	0.26	0.6141
R	1970-90	-0.1726	73	1.79	0.1851
S	1970-90	-0.0985	68	0.56	0.4587
T	1970-88	0.0209	221	0.07	0.7846
U	1970-90	-0.4201	67	6.32	0.0144
V	1970-90	-0.1822	96	4.46	0.0373
W	1970-90	-0.1396	62	0.91	0.3431
X	1970-90	-0.2816	72	4.23	0.0435
Y	1974-81	0.4059	61	0.77	0.3844
Z	1970-90	-0.329	74	4.3	0.0418
AA	1970-90	-0.2294	72	2.3	0.1335
BB	1970-90	-0.0932	96	1.11	0.2949
CC	1970-90	-0.1636	72	1.25	0.2670
DD	1970-90	-0.2929	64	3.93	0.0518
EE	1970-90	-0.3366	72	4.62	0.0351
FF	1970-90	-0.1688	69	1.4	0.2409
GG	1970-90	-0.4053	74	6.2	0.0151
HH	1975-96	-0.1297	185	4.91	0.0280
II	1970-90	-0.5558	67	7.95	0.0064
JJ	1970-90	-0.3489	71	4.86	0.0308
KK	1982-88	0.9918	64	9.88	0.0026

Table 17. Long-term trends in salinity at the LDWF stations in the Calcasieu Basin. Coefficients with asterisks are significant at P<0.05, after adjusting for multiple comparisons.

LDWF station	Period of record	Coefficient (ppt/month)	N	F-Value	P>F
12	1967-98	-0.0658	372	3.66	0.0587
13	1967-98	-0.0682	372	4.43	0.359
14	1967-98	-0.1372*	366	15.86	0.001
90	1982-98	-0.1387	166	2.10	0.1492
91	1982-98	0.2721*	163	7.78	0.0059

in salinity at Station EC8 was marginally significant. The trends towards lower salinity observed at the four stations were probably due to the implementation of the Cameron-Creole Watershed Management Project.

In 1989, a levee and five variable-crested water control structures were constructed as part of the Cameron-Creole Watershed Management Project, to prevent saltwater intrusion from the CSC (USDA 2001). In a Before-After-Control-Impact (BACI) test (Underwood 1991) using the stations at the mouth of Grand Bayou, the construction of the levee system significantly affected the salinity at Station EC2 relative to Station EC1 ($P < 0.0001$), but the posterior test for significance was only marginally significant ($P < 0.0432$). Stations were established inside and outside of the other control structures, but the lack of pre-construction monitoring at these stations precluded a detailed BACI analysis. Salinities were generally lower inside the control structures at the mouths of Mangrove, Peconi, No Name, and Lambert bayous after the construction than in Calcasieu Lake stations located outside of the structures (Table 18), and significant differences (outside vs. inside) were detected at two of these locations (EC and Peconi Bayou). The average reduction in salinity across the structures (outside to inside) was 2-3 ppt.

Historical Habitat Shifts in the Calcasieu-Sabine Basin

Historically, the Calcasieu-Sabine Basin was vegetatively quite different than it is today. Historical vegetative type maps show that the region's wetlands were characterized by broad expanses of saw grass-dominated marsh, with other freshwater to brackish sub-dominates such as leafy three square, Olney's bulrush, wiregrass, and bulltongue, which are characteristic of a low-salinity estuary (O'Neil 1949; USDA 1951). There were relatively few areas of open water, excluding Calcasieu and Sabine lakes (O'Neil 1949). We utilize O'Neil's (1949) vegetative type map as a baseline to characterize wetland habitat shifts that have occurred over a nearly 50-yr period. Hydrologic alterations such as construction of the CSC, Sabine-Neches Ship Channel, and GIWW have led over time to significant losses of these wetland habitats in the SNWR due to saltwater and tidal intrusion. By 1968, much of the damage had been done when Robert H. Chabreck first began a series of vegetative and habitat surveys (Chabreck 1972). During repeat flyovers of the transects in 1978 and 1988, transitions in habitat type were delimited to produce habitat type maps for those years. In 1997, Chabreck and Linscombe revisited the same transects as in 1968, although their sampling regime differed somewhat from that of Chabreck's earlier work (Chabreck et al. 1968; Chabreck and Linscombe 1997).

We determined historical habitat shifts over the years 1949, 1968, 1978, 1988, and 1997 using digital versions of coastal vegetation maps produced from coastwide vegetative mapping efforts (O'Neil 1949; Chabreck et al. 1968; Chabreck and Linscombe 1978, 1988, 1997). These data are not accurate for showing detailed changes in land-water ratios but do present a very good composite of how wetland habitat types have changed over time.

Figure 36 illustrates the types of habitats identified in each of the mapping years and the direction of habitat shifts toward either fresher or more saline conditions for each of the

Table 18. Salinity differences of the water control structures around the perimeter of Calcasieu Lake in the Cameron-Creole Watershed. Significant differences (P<0.05) after adjusting for multiple comparisons are indicated with asterisks. The period of record includes 1994 and 1995.

Station pair	**Outside salinity (ppt)**	**Inside salinity (ppt)**	**F-value of difference**	**Degrees of freedom of the test**	**P>F (level of significance)**
EC1 and EC2	9.61	6.42	14.91	1 and 131	0.0002*
Lambert Bayou	9.31	7.00	4.33	1 and 36	0.0445
Mangrove Bayou	8.01	5.20	6.52	1 and 36	0.0150
No Name Bayou	11.66	9.07	7.07	1 and 36	0.0116
Peconi Bayou	8.38	5.00	7.66	1 and 36	0.0089*

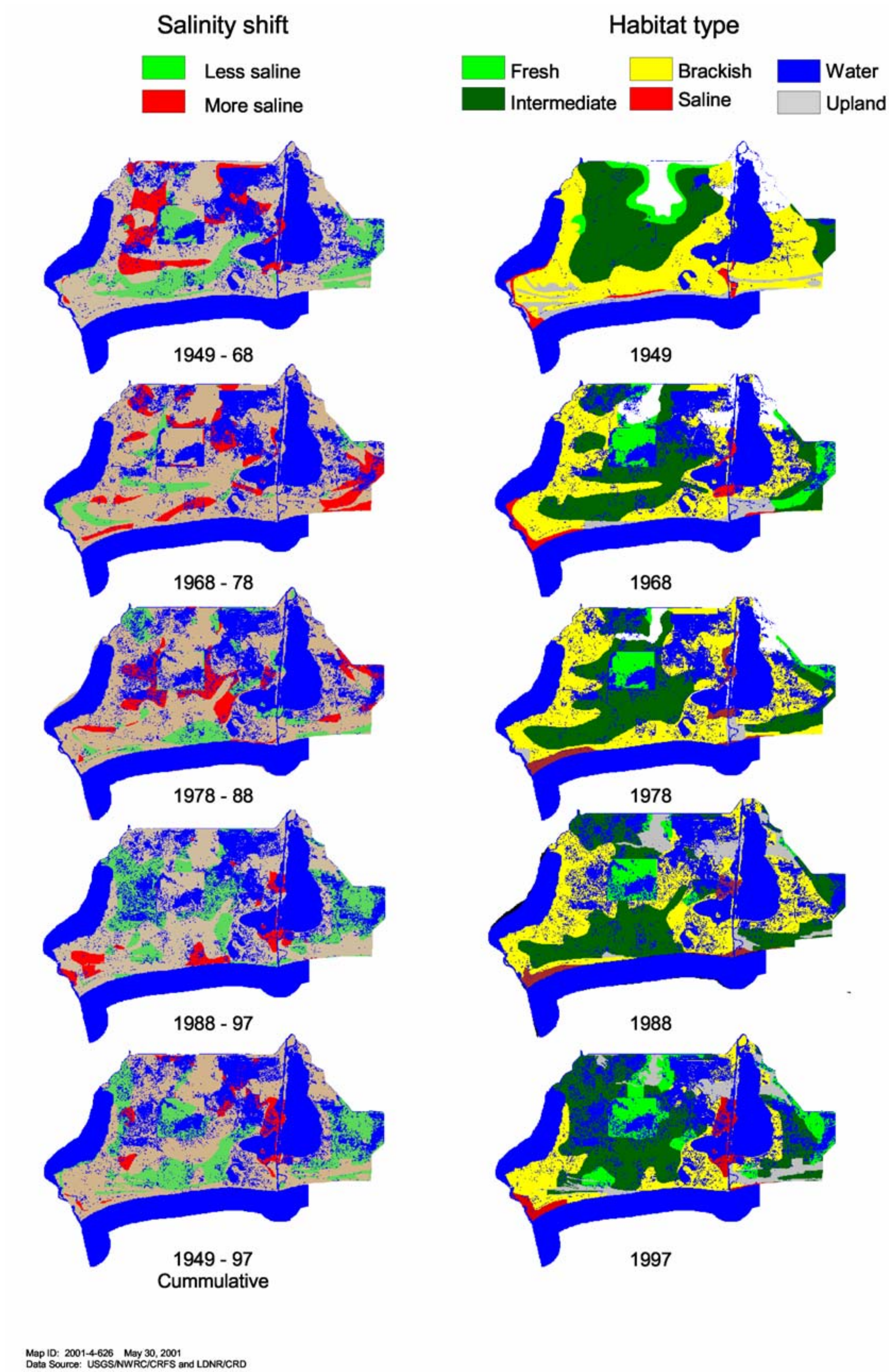

Figure 36. Wetland habitat and salinity shifts in the Calcasieu-Sabine Basin based on historical vegetative surveys, 1949-97.

years compared. For consistency, the O'Neil (1949) vegetation categories were reclassified into the four marsh type categories used in the other vegetative type maps (i.e., fresh, intermediate, brackish, or saline), based on the dominant species that O'Neil (1949) noted in each area (Table 6).

Habitat shifts in the Calcasieu-Sabine Basin from 1949 through 1997 show a long-term trend toward freshening of the central and eastern basin, and salinity increases adjacent to the CSC and some of the marshes near Sabine Lake.

Substantial variability in habitat types is evident from one comparison period to the next. The 1949-68 comparison reflects the loss of the saw grass marsh as a major vegetative community. Although the saw grass marsh was classified as intermediate in 1949, by 1960 saw grass was largely absent in the Calcasieu-Sabine Basin. The Sabine National Wildlife Refuge Pool Three impoundment was constructed during this period, appearing as fresh marsh on the 1968, 1978, 1988, and 1997 maps (Figure 36). A band of marsh running east-west, presumably in an area more hydrologically isolated from the effects of the CSC than much of the Calcasieu-Sabine Basin, shifted from brackish to intermediate marsh. The 1968-78 and 1978-88 profiles reveal site-specific shifts toward both more saline and fresher marsh types, with the latter period showing a dominance of more saline shifts. This trend was reversed during 1988-97, when, in large part, the areas that converted from intermediate to brackish from 1978 to 1988 shifted back toward the intermediate marsh type.

The spatial and temporal variability of these habitat shifts shows that this estuarine system is very dynamic. Given that these maps represent individual "snapshots," this is a very conservative picture of marsh type shifts over the past 50 years. In reality, vegetation dynamics in the Calcasieu-Sabine Basin are probably more variable than presented here.

Historical Causes of Landscape Change in the Calcasieu-Sabine Basin

We initiated an investigation of the specific causes of land loss and gain in the Calcasieu-Sabine Basin because we believe that a better understanding of the causes of loss will improve our understanding of the factors that influence ecosystem stability. We decided that an efficient way to achieve this goal would be to interview the various authorities in the areas of biology, ecology, and natural resource management who possess intimate knowledge of the historical events that impacted biological and hydrological processes and shaped the Calcasieu-Sabine ecosystem. Although much of this information is anecdotal in nature, it provides an interesting perspective on the causes of landscape change in the Calcasieu-Sabine Basin.

We held a meeting in December 1999 to consult with: John Walther, U.S. Fish and Wildlife Service (USFWS), retired, Sabine National Wildlife Refuge (SNWR) refuge manager; Jake Valentine, USFWS, retired, Gulf Coast NWR refuge biologist; Herb Bell, USFWS, SNWR assistant refuge manager; Terry Delaine, USFWS, SNWR assistant refuge manager; and Tommy Michot, Ph.D., USGS National Wetlands Research Center wildlife biologist.

Dr. Robert H. Chabreck, Louisiana State University, and David Richard, Stream Properties, Inc., provided further review of and comment on the findings produced by our panel of experts.

Each expert shared specific knowledge of the causes of land loss at particular sites in the Calcasieu-Sabine Basin, and, if known, when that loss occurred over the periods 1956-78 and 1978-90. The panel members then reached consensus on the various causes of landscape change. Each Calcasieu-Sabine site discussed was assigned a number (Figure 37). We summarize these causes of landscape change, identifying each of these areas by its corresponding Coast 2050 mapping unit (LCWCRTF/WRCA 1998):

Area 1 (Perry Ridge Unit):

Land loss in this area was caused by hydrologic alterations arising from major navigation channels that induced saltwater intrusion and tidal scour. The present-day Gulf Intracoastal Waterway (GIWW) between Sabine Lake and Calcasieu Lake was renamed the Sabine Deep Water Ship Channel during the period 1927-41 and had authorized dimensions of 125 ft wide by 30 ft deep. This was contiguous with the Sabine-Neches Ship Channel and later with the Calcasieu Ship Channel (CSC) in 1941. These channels increased tidal circulation and saltwater intrusion into the historically fresh saw grass marsh system. Over time, the Sabine Deep Water Ship Channel began to silt in and the circulation pattern diminished somewhat. Completion of the Toledo Bend Reservoir in 1963 promoted a more continuous freshwater inflow into the basin year-round, rather than the historical seasonal pattern of higher inflows in the winter and spring and lower inflows in the summer and fall.

Areas 2 (Black Bayou Unit):

Saltwater intrusion, produced-water discharge, and tidal scour killed the historical saw grass marsh in this area. The Coast 2050 Region 4 Regional Planning Team indicated that land loss in this area was due to altered hydrology and shoreline erosion on the Sabine Lake shore (LCWCRTF/WRCA 1998).

Area 3 (Willow Bayou Unit):

Oilfield canal construction leveed off this area. It became hydrologically isolated, and the dredging of Green’s Bayou allowed saltwater intrusion to occur. The soft organic soils eroded rapidly after canal construction. Green’s Bayou presently supports a weir that allows boat passage. Nutria herbivory is also identified as a cause of loss in this area.

Area 4 (Willow Bayou Unit):

Although the loss map indicates this area was lost before 1978, the loss probably occurred after 1978. Saltwater intrusion from Willow Bayou and nutria herbivory caused the die-off of the California bulrush (*Schoenoplectus californicus*) marsh.

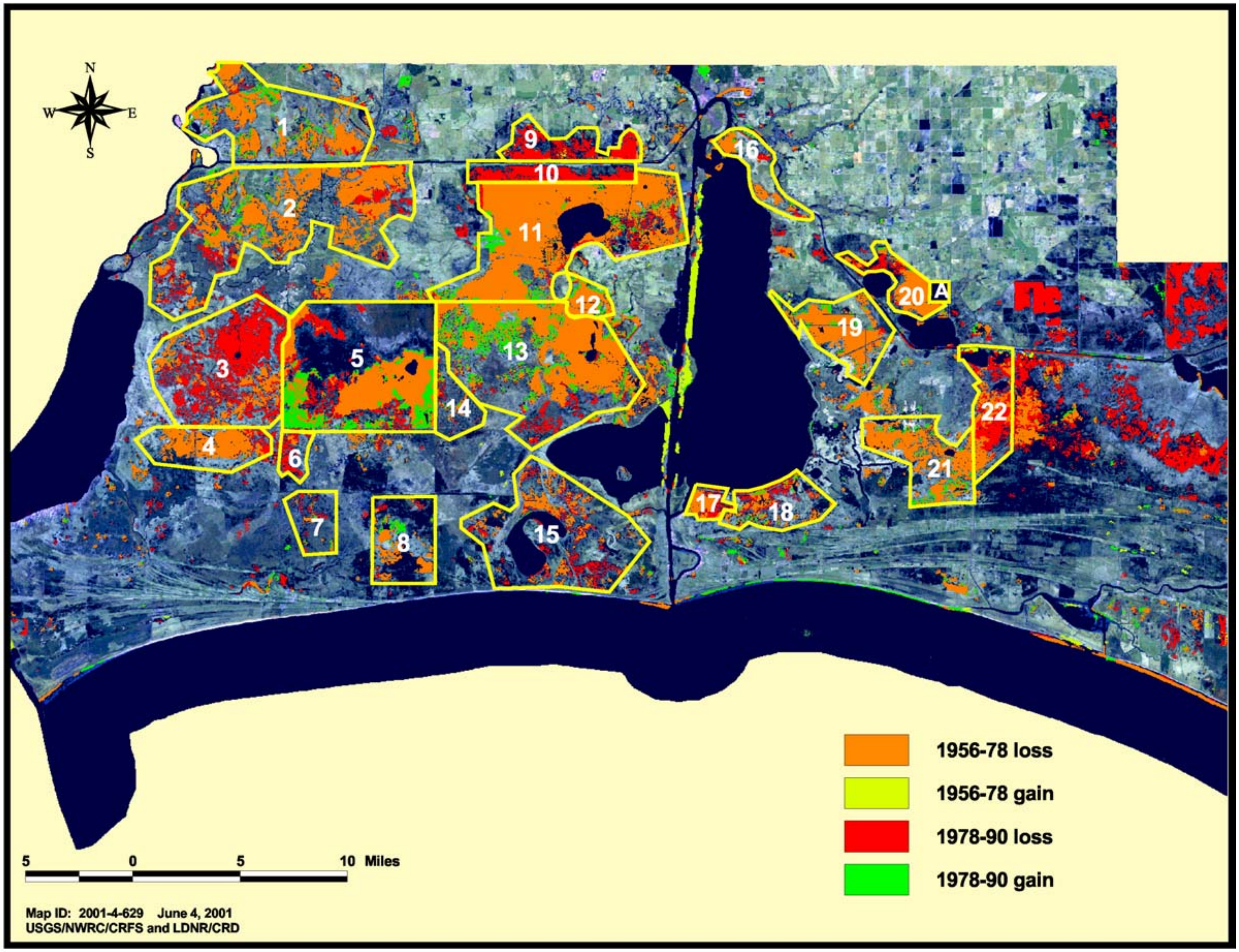

Figure 37. Historical trends in landscape change for the Calcasieu-Sabine Basin.

Area 5 (Sabine Pool 3 Unit):

Sabine Pool 3 was completed in 1952 as a waterfowl impoundment and was also managed for bass fishing for many years. The water level there was kept artificially high (1.5 ft over marsh surface). The loss in this area was almost entirely due to poor management practices. Also, the geographic placement of the water control structures at this site is not optimal for maintaining desired water levels because they are not placed to take advantage of prevailing winds during periods when refuge managers desire lower water levels. The Coast 2050 Region 4 Regional Planning Team indicated that land loss in this area was also caused by Hurricanes Audrey and Carla in 1957 and 1961, respectively (LCWCRTF/WRCA 1998).

Area 6 (Southeast Sabine Unit):

This is part of the freshest (non-impounded) unit in the Calcasieu-Sabine Basin (Unit 4). The loss in the western end of the unit was initiated by fishermen and hunters. Their outboard motors would cut channels in the shallows, and eventually the channels opened up, eroding the marsh and allowing saltwater intrusion in that area.

Area 7 (East Johnson's Bayou Unit):

Oilfield activity in this area created a network of canals that allowed saltwater intrusion from the Burton Sutton Canal. Produced-water discharges also killed marsh in this area.

Area 8 (Second Bayou Unit):

This is an impounded area known as "Four Mile Square." Overtopping of Highway 82 here during storm tides resulted in pooling of saltwater and loss of intermediate marsh.

Area 9 (Clear Marais Unit):

Land in this area was lost through saltwater intrusion originating in the CSC, and tidal scour due to bank erosion on the GIWW from navigation. Another cause of loss is impoundment that held water levels too high for emergent vegetation to establish successfully.

Area 10 (Black Lake and West Black Lake units):

This area was under forced drainage for cattle grazing until 1980. During this period, organic marsh soils oxidized such that the marsh surface elevation was substantially lowered. When cattle grazing was abandoned and the area re-flooded, emergent marsh species could not tolerate the flooding. The area is currently managed for bass fishing and as a waterfowl impoundment. The Coast 2050 Region 4 Regional Planning Team indicated that land loss in this area was also related to storms (LCWCRTF/WRCA 1998).

Area 11 (Black Lake and West Black Lake units):

Land loss in this area was caused by saltwater intrusion from produced-water discharge and from the CSC. This was historically a saw grass marsh, but new vegetation could not grow fast enough after a die-off to prevent the erosion of the organic soils. Development of the Hackberry oilfield was started in the 1920s and the saw grass marsh died before Hurricane Audrey hit in 1957.

Area 12 (Brown Lake Unit):
Produced water was discharged through oilfield activities here for many years and is believed to have killed this marsh, in conjunction with saltwater intrusion from the CSC. The produced-water discharge was shut down in 1984-85.

Area 13 (Brown Lake Unit):
Saltwater intrusion from the CSC, produced-water discharge, nutria herbivory, and the effects of hurricanes Audrey and Carla each caused land loss in this area, especially in the saw grass and other fresh areas. The Coast 2050 Region 4 Regional Planning Team indicated that in years with high rainfall, interior marsh ponds are often colonized by California bulrush and other intermediate wetland species (LCWCRTF/WRCA 1998).

Area 14 (Brown Lake Unit):
When oilfield canals were dug in this area, levees were constructed with continuous borrow pits that allowed saltwater intrusion to follow along the borrow pits and impact marshes adjacent to those pits.

Area 15 (Mud Lake Unit):
Oilfield activity around the Mud Lake area created a network of access roads and borrow ditches that allowed saltwater intrusion from Calcasieu Lake's West Cove.

Area 16 (Big Lake Unit):
Marsh loss is this area was caused by oilfield canals and saltwater and tidal intrusion from the CSC.

Area 17 (Southwest Cameron-Creole Watershed Unit):
Marsh loss is this area was caused by saltwater and tidal intrusion from the CSC.

Area 18 (Southwest Cameron-Creole Watershed Unit):
Saltwater and tidal intrusion from the CSC, in addition to hurricanes—Audrey in 1957 and Carla in 1961—caused the loss of the marshes in this area, through flooding and saltwater intrusion. The subsidence rate is also believed to be higher in this area than in other parts of the Calcasieu-Sabine Basin.

Area 19 (South end of the Big Lake Mapping Unit):
East-west canals were cut by North American Land Company steam dredges prior to 1900, which resulted in breaching of the Calcasieu Lake rim. This area was farmed for rice; freshwater from inside Calcasieu Lake was used to irrigate rice fields from around 1875 until 1910. Saltwater and tidal invasion (salinities up to 30 ppt) associated with the deepening of the CSC in the 1940s, coupled with the loss of freshwater inflow from the Pleistocene terrace due to construction of the GIWW, contributed to marsh loss.

Area 20 (Sweet/Willow Lakes Unit):

This area was a solid marsh until marsh buggies were used in the 1950s to mash down the marsh to create duck ponds. Around 1925-28, the levee encompassing the brine pit in Area 20A broke and saltwater from the brine pit killed much of this fresh marsh. The use of brine pits and the pumping of produced water into adjacent marshes were abandoned in this area in 1948 when injection wells began to be used for brine disposal. There are still about 45 producing oil wells in this area.

Erosion of the north bank of the GIWW has resulted in a direct hydrologic connection with both Willow Lake and Sweet Lake. The CWPPRA Sweet Lake/Willow Lake Shore Protection Project is addressing this problem.

The Coast 2050 Region 4 Regional Planning Team indicated that land loss in this area was due to altered hydrology, flooding, and storms (LCWCRTF/WRCA 1998).

Area 20A (Sweet/Willow Lakes Unit: Section 36):

This area was owned by North American Land and Sweet Lake Land & Oil and leased to Union Oil Company of California at the turn of the century. It was utilized as a produced-water disposal pit for the oil withdrawn from the Sweet Lake Unit in the 1920s. It is now about 4 ft deep because of levee deterioration.

Area 21 (Cameron-Creole Watershed Unit):

Loss of the historical saw grass marsh in this area is attributable to saltwater intrusion from the CSC in the 1950s. The whole area began dying after cuts were made through the Calcasieu River channel mouth bar in the late 1930s and early 1940s. Marsh deterioration occurred through progressive dying of the standing saw grass. When Hurricane Audrey hit in 1957, the saw grass system was already dead or dying, and the hurricane’s storm surge cleared away the dead and deteriorated saw grass stands. Much of the saw grass was killed by the discharge of produced water from localized oil wells.

Area 22 (Cameron-Creole Watershed Unit):

Saltwater intrusion from the Creole Canal and Calcasieu Lake through the Calcasieu Ship Channel killed some of the marsh vegetation, and tidal action eroded the highly organic soils in this area.

These findings reveal that, in most areas, a combination of human-induced hydrologic changes, sometimes accompanied by severe storm events, has resulted in virtually all of the habitat changes and land losses in the Calcasieu-Sabine Basin. The hydrologic alteration that has had the most impact is the CSC, a major avenue for saltwater and tidal intrusion, which has caused extremely severe marsh losses. Secondary causes of landscape change include oil- and gas-related activities such as canal construction, incidental impoundment, and produced-water discharge; historical natural resource management practices that are no longer employed; agriculture through intentional impoundment of the marsh for wildlife management and cattle grazing; and nutria herbivory and trapping canals.