Evaluating Inverted Siphons as a Means of Mitigating Salinity Intrusion in the Keith Lake/Salt Bayou System, Jefferson County, Texas

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Executive Summary

In recent years, increased rates of salinity intrusion in the Keith Lake/Salt Bayou coastal wetland system of Jefferson County, Texas, have affected the productivity and integrity of freshwater wetland components. Historically, Salt Bayou was a fresh to intermediate wetland that transitioned into brackish conditions near the downstream confluence with Taylor Bayou and Sabine Lake. Construction of the Gulf Intracoastal Waterway in1933, however, severed Salt Bayou from approximately 60 percent of the upper drainage basin, thus eliminating the primary source of freshwater inflow to the wetland as well as a natural connection to Sabine Lake. For decades, direct precipitation has been the main source of freshwater for this wetland and the only source available to ameliorate salinity intrusion. Presently, two sources of saline water contribute to sustained increases in salinity throughout the system. These two sources include (1) the Keith Lake Fish Pass which connects Keith Lake/Salt Bayou to the Sabine-Neches Waterway and the Sabine Lake Estuary and (2) erosion of the beach ridge along the McFaddin National Wildlife Refuge property which allows Gulf seawater to wash into interior marshes during high tides and storm surges.

Historically, this coastal wetland was exposed to saline waters via relatively short-term, small-scale local connections to tidally influenced waters or infrequent, large-scale storm surge events from which it recovered. The present large-scale, persistent sources of saline water entering through the Fish Pass or over the beach ridge, combined with the lack of freshwater inflow to flush the system and two relatively recent major hurricane events (Rita and Ike) exacerbate wetland loss. Area land managers at the J.D. Murphree Wildlife Management Area and McFaddin National Wildlife Refuge recognize the importance of maintaining a balance between the historical freshwater wetland function, which is presently threatened, and the contemporary estuarine functions which also are important. Therefore, land managers are interested in evaluating management strategies which can increase freshwater resources and reduce salinity intrusion. This study was designed to explore the effectiveness of using passive, inverted siphons to supply freshwater from the watershed north of the Gulf Intracoastal Waterway to specified locations within the wetland to mitigate high salinity levels. In this manner, the siphons would hydrologically reconnect and restore a part of the historic function of Salt Bayou.

As part of this study, data was collected at 11 locations in and around the Keith Lake/Salt Bayou system from December 2005 to April 2007. These included water quality, water level, and velocity measurements, as well as a bathymetric survey; additional data was obtained from other sources. This data then was used to develop and calibrate a high resolution, three-dimensional baroclinic hydrodynamic and salinity transport simulation model of the region using the SELFE modeling software. The model domain encompassed the open water features of Salt Bayou, including the Fish Pass, and other external drivers such as the Sabine-Neches Waterway, the Gulf Intracoastal Waterway, Sabine Lake, and the Gulf of Mexico. The model then was used to evaluate the effectiveness three siphon-flow rate scenarios (constant flow: $1.42 m^3/s$ and $2.48 m^3/s$, and a linearly decreasing flow: $1.42 m^3/s$ decreasing to $0 m^3/s$) at each of three locations (Star Lake, Willow Lake, or the Salt Bayou Outfall) for the target year of 2003. Model results showed that all siphon locations were able to reduce salinity within a local area, but the extent of salinity reduction varied throughout the year. The Star Lake siphon, installed in the upper reaches of the system, yielded a broader reduction in salinity, particularly in the westernmost areas. This was most likely a function of the location enhancing the natural downstream pattern of flow in the system. The Willow Lake and Salt Bayou Outfall siphons, located in the center of the system, primarily have a localized effect on salinity reduction. These locations may work against the natural circulation patterns in the system and also may be rendered less effective by prevailing winds driving surface flows to the north and east in the Salt Bayou. Overall, barring water supply and engineering feasibility issues which were not explored in this study, passive, inverted siphons were shown to be an effective method for providing freshwater to reduce salinities across the Salt Bayou system.

1. INTRODUCTION

1.1. Background

Located in Jefferson County, near Sabine Pass, Texas, the Keith Lake/Salt Bayou wetland system covers 78,241 acres and is protected in large part by McFaddin National Wildlife Refuge (58,800 acres), J.D. Murphree Wildlife Management Area (Salt Bayou Unit 15,300 acres), and Sea Rim State Park (4,141 acres). Although this system is but a remnant of what was once a much larger watershed extending north as far as Beaumont, Texas, in the southeastern corner of the state (Figure 1.1), it is still a large wetland complex composed of hydraulically connected shallow lakes and small bayous (Figure 1.2). Historically and still importantly, this coastal wetland serves as a winter home for ducks, geese, and other migratory waterfowl, which are part of a diverse assemblage of freshwater to brackish vegetation and marsh fauna. However, a combination of natural processes and human activities, most notably navigation channels, has modified the landscape connecting what was once a predominantly freshwater wetland system to tidal waters with marine salinities. Over time, the influx of saline water has contributed to a significant change in and loss of freshwater marsh vegetation throughout a wide area of the wetland. At the same time, there has been an increase in the production of estuarine fish and shellfish species as access points facilitate ingress and egress through various control structures and the Keith Lake Fish Pass (USDA/SCS 1976, Stelly 1980, Fisher 1988, Joint Water Management Concept Plan1990). Under current conditions, the system serves as an important site for wetland flora, migratory waterfowl, and estuarine species. *At issue then is finding a balance between the historical freshwater wetland function and the more contemporary estuarine functions which are controlled by the balance of fresh and salt water in the system.*

In recent decades following the reopening and restructuring of the Keith Lake Fish Pass (Fish Pass) in 1977, the system has slowly transitioned towards estuarine conditions with negative consequences to the freshwater wetland components. Freshwater plants are dying and the soils, no longer held together by growing roots or accreting from peat accumulation, are eroding. In addition, the often windy conditions in this region create wave action which further mechanically erodes emergent vegetation, increasing the area of open water (N. Kuhn, TPWD *pers. comm.*).

O'Connell (2006) cited similar patterns of erosion in the coastal wetlands of the Louisiana Chenier Plain. In large measure, the changes observed in Salt Bayou are a reflection of the strong influence of the Keith Lake Fish Pass as it permits a continuous exchange of large volumes of saline water from the Sabine-Neches Waterway (SNWW, Fisher 1988). However, land subsidence, which is considered a factor in the initial formation of these coastal marshes (Lay and O'Neil 1942), presents an additional challenge, along with relative sea level rise and erosion of the beach ridge, for this system. *The goal of this study is to develop a hydrodynamic and salinity transport model for the Keith Lake/Salt Bayou wetland system for use in modeling and evaluating proposed salinity mitigation scenarios to inform management decisions.*

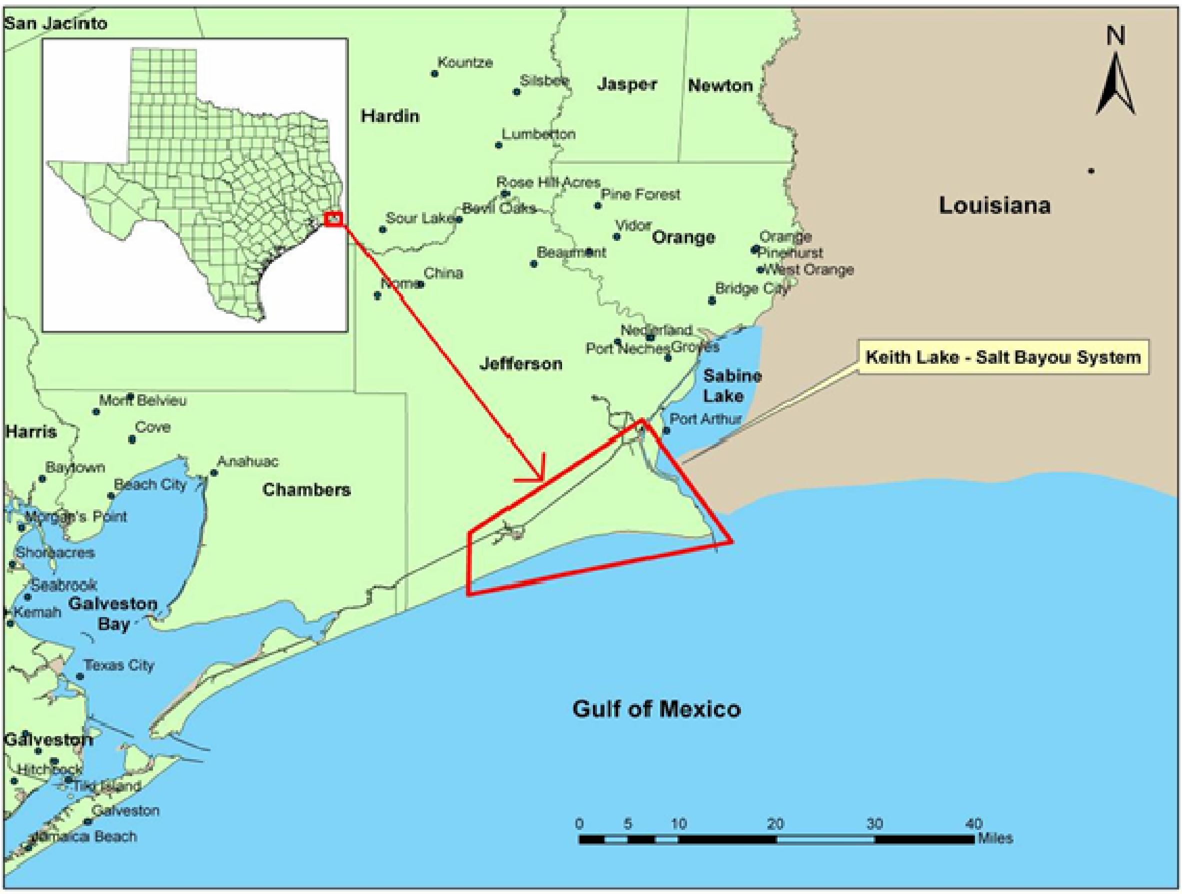

Figure 1.1 Location of Salt Bayou wetland system in Jefferson County, Texas.

Figure 1.2 Important features of the Salt Bayou wetland system in Jefferson County, Texas. The present site of the Keith Lake Fish Pass corresponds to the historic location of Little Keith Lake, which was filled in with dredge spoil in 1966.

1.2. Recent Threats and Mitigation Efforts

Wetland conditions within the Salt Bayou watershed have been threatened and deteriorating since construction of the Gulf Intracoastal Waterway (GIWW) in 1933. Once constructed, the GIWW severed as much as 60% of the historic upper watershed which once extended as far as Stowell, Texas (Fisher 1988), cutting off a major supply of freshwater to the wetlands, lakes, and channels in Salt Bayou. With two exceptions, Salt Bayou historically was characterized as a fresh to intermediate wetland marsh with salinities averaging less than 4ppt (USDA/SCS 1976). Spatially, the salinity gradient increased towards the lower reaches, near the historic confluence with Taylor Bayou and Sabine Lake, where brackish conditions were common as a result of tidal action. Storm surges associated with tropical storms and hurricanes also contribute to periodic influxes of saline water across the system (Table 1.1; Lay and O'Neil 1942, Joint Water Management Concept Plan 1990). However, in the last century, water navigation projects have restricted surface run-off and instream flow from the upper watershed and, in addition to erosion of the beach ridge, have facilitated the influx of saline Gulf waters to the interior marsh (Table 1.2, Figure 1.2). Accelerated rates of local land subsidence and relative sea level rise also affect marsh elevation and the structure of wetland plant communities. In this system, land subsidence and conversion of marsh to open water has been identified in localized areas north of Clam Lake on the McFaddin NWR and attributed to decades of hydrocarbon production (Morton *et al.* 2001). Presently, there are three main threats to the system: (1) lack of freshwater inflow, (2) saltwater intrusion through the Fish Pass, and (3) saltwater overwash along the eroded southern beach ridge (Figure 1.3). Further land subsidence and relative sea level rise may exacerbate these threats in the long term.

Tables 1.1 and 1.2 provide a detailed timeline of events that have shaped the hydrological and ecological conditions of the Keith Lake/Salt Bayou System. The first major alteration to the natural hydrology occurred with construction of the GIWW in 1933. In addition to breaking the hydrological connection to the upper watershed, channel dredging bisected the watershed cutting off the natural outflow into Taylor Bayou and subsequently into Sabine Lake. This bisection also created two access points for estuarine organisms and saltwater to enter the now isolated southern portion of the watershed (USDA/SCS 1976). These access points correspond to the present day location of the Star Lake and Salt Bayou control structures (Figure 1.2, 1.3). The Star Lake control structure is located where the GIWW crossed the historic upper Salt Bayou watershed, and the Salt Bayou control structure is where the GIWW crossed the lower reaches.

Table 1.1 Timeline of hurricanes and tropical storm events affecting the hydrological and ecological conditions of the Keith Lake/Salt Bayou system. All events were recorded from the National Weather Service and National Hurricane Center.

Date	Tropical Storm or Hurricane Event
1865	Hurricane landfall along Texas/Louisiana border, storm surge inundates Calcasieu Lake and Grand Chenier, September 13
1866	Tropical storm landfall at Port O'Connor, July 15
1871	Three hurricanes land on the Texas coast, June 2-3, June 9, September 30-October 2
1877	Hurricane landfall on Texas coast, September 15-17
1879	Hurricane landfall along upper Texas coast, August 22-23
1882	Tropical storm landfall at Sabine Pass, September 14
1886	Tropical storm landfall near Sabine Pass, June 14; flooded the coast several miles inland and inundated Sabine Pass with 7ft of water.
	Hurricane (Category 2) near Sabine Pass, October 12; flooded the coast up to 20 miles inland
1888	Hurricane landfall at Galveston, July 5
1891	Hurricane landfall near Sabine Pass, July 13
1895	Tropical storm landfall at Bolivar Peninsula, October 6
1897	Hurricane (Category 1) landfall in western Louisiana, September 13, Sabine Pass inundated with 6ft of water and rice fields in Taylor Bayou were destroyed
1898	Tropical storm landfall at Bolivar Peninsula, September 28
1900	Hurricane (Category 4) landfall Galveston Island, September 9
1915	Hurricane (Category 3) landfall west of Galveston Island, August 17
1932	Hurricane (Category 4) landfall south of Galveston Island, August 14
1938	Hurricane (Category 1) western Louisiana, August 14; high tides on upper Texas coast
1940	Hurricane (Category 2) east of Sabine Pass, August 7; storm surge 21.1'
1941	Tropical storm landfall west of Sabine Pass, September 15
1942	Hurricane (Category 1) landfall near Galveston, August 21; storm surge 7' at High Island
1943	Hurricane (Category 1) landfall at Bolivar Peninsula, July 27; 17.76" rainfall at Beaumont
1946	Tropical storm landfall east of Sabine Pass, June 16
1947	Hurricane (Category 1) landfall at Galveston Island, August 24; 3.6' tide at Sabine Pass
1957	Hurricane Audrey (Category 4) landfall east of Sabine Pass, June 27
	Tropical Storm Bertha landfall east of Sabine Pass, August 9
1959	Hurricane Debra (Category 1) landfall east of Freeport, July 24
1961	Hurricane Carla (Category 4) landfall near Port Lavaca, September 11
1963	Hurricane Cindy (Category 1) landfall near High Island, September 17
1970	Tropical Storm Felice landfall north of Galveston, September 15
1979	Tropical Storm Claudette landfall near Sabine Pass, July 2; 13" rainfall at Port Arthur
1980	Tropical Storm Danielle landfall near Galveston, September 5; 17" rainfall at Port Arthur
1983	Hurricane Alicia (Category 3) landfall Galveston Island, August 18
1982	Tropical Storm Chris landfall near Texas/Louisiana border, September 11
1986	Hurricane Bonnie (Category 1) landfall west of Sabine Pass, June 16
1987	Unnamed tropical storm landfall near Texas/Louisiana border, August 9

Date	Tropical Storm or Hurricane Event
1989	Hurricane Chantal (Category 1) landfall at High Island, August 1; caused beach erosion
	Hurricane Jerry (Category 1) landfall at Galveston, October 16
1998	Tropical Storm Frances landfall at Corpus Christi, September 11; storm surge 5.4ft at Sabine Pass
2005	Hurricane Rita (Category 3) landfall at Sabine Pass, September 24
2007	Hurricane Humberto (Category 1) landfall at McFaddin NWR, September 13
2008	Hurricane Ike (Category 2) landfall at Galveston Island, September 13

Historically, prior to construction of the railroad between Port Arthur and Sabine Pass in 1861 and the Port Arthur Canal (later part of the Sabine-Neches Waterway) in 1899, estuarine organisms had access to Salt Bayou via its connection with Taylor Bayou which emptied into Sabine Lake. No other direct access existed, except during flood events when sheet flow connected Little Keith Lake to Sabine Lake. (Little Keith Lake was filled with dredge spoil in 1996 but originally was located in the vicinity of the present day Fish Pass.) After construction of the railroad, which ran on an elevated berm, local residents reported flooding problems in Salt Bayou. A cut through the railroad berm relieved flooding and created a direct connection between Little Keith Lake and Sabine Lake (more specifically, the Port Arthur Canal). In the mid-1870's, construction of a small boat canal allowed modest access without causing major impacts to the freshwater conditions within system. It is likely this boat canal utilized the existing railroad cut. According to an 1898 letter from the Secretary of War (Gillham 1989), when the Port Arthur Canal was connected to Sabine Pass (1899), dredge spoil was deposited along the canal thus closing the *entrance* to Little Keith Lake and sealing off any direct hydrological connection (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*).

As a result of the continual deepening and widening of the Port Arthur Canal, a connection to Little Keith Lake reformed. This likely occurred during the 1920's when the ship channel was dredged to 150ft wide by 30ft deep. In 1933, when the GIWW was constructed, the U.S. Army Corps of Engineers (USACE) constructed a water control structure between Little Keith Lake and the ship channel. This structure, along with those installed concurrently on the GIWW at the Star Lake and Salt Bayou outfalls, eventually fell into disrepair, again resulting in saltwater intrusion to the system. In 1966, dredging-related activities on the SNWW resulted in formation of a spoil levee and the filling in of Little Keith Lake. This subsequently sealed any connection between Salt Bayou and the SNWW and Sabine Lake (USDA/SCS 1976, Joint Water Management Concept Plan 1990).

In the years following filling of Little Keith Lake, the estuarine function of the wetland, along with recreational and commercial fishing reportedly declined (USDA/SCS 1976). Although this information cannot be verified for the Keith Lake/Salt Bayou system, it is known that impoundment of the Neches and Sabine rivers in 1965 and 1966 impacted productivity of the shrimp fishery in the Sabine Lake estuary (White and Perret 1974, TDWR 1981). Efforts to reverse this reported decline led to the Keith Lake Water Exchange Pass Fish and Wildlife Development plan (USDA/SCS 1976), which recommended construction of a “relatively shallow, straight line channel” 3,100 feet long, 150 feet wide, and six to eight feet deep.

This recommendation, however, was in contrast to the original, meandering channel design proposed by local land managers C.D. Stutzenbaker (TPWD) and J. Neaville (Soil Conservation Service). In fact, local land managers were not provided an opportunity to review or comment on the final plans as presented in the USDA/SCS report, and the plan was approved as written with ecological consideration passed over for ease of project implementation (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*).

Table 1.2 Timeline of events affecting the hydrological and ecological conditions of the Keith Lake/Salt Bayou system. Information is taken from the Joint Water Management Concept Plan (1990) unless otherwise noted.

Date	Event
pre-1860	Although Salt Bayou drainage basin begins near Stowell, Texas (Fisher 1988), watershed features are not well-defined until Star Lake. The watershed then drains from Star Lake through Five-mile and Ten-mile cuts into Shell Lake. Water from Johnson, Keith, and Little Keith Lake drains west toward Shell Lake and then north toward the confluence with Taylor Bayou. No natural connection exists between Little Keith Lake and Sabine Lake, though flood events cause sheet flows over a low marsh into Sabine Lake.
1861	Eastern Texas Railroad Company constructs a rail line connecting Beaumont, Port Arthur and Sabine Pass (Handbook of Texas Online)
1862	Local citizens report that the railroad berm blocks sheet flow from Salt Bayou into Sabine Lake causing flooding in Salt Bayou; consequently a cut (gully) is made through the railroad berm to relieve flooding in Salt Bayou thus connecting Little Keith Lake to Sabine Lake.
mid-1870s	Mr. Keith opens a row boat canal from Little Keith Lake to Sabine Lake, possibly utilizing the existing cut through the railroad berm (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*)
1898	Port Arthur Canal and Dock Company, Kansas City Railroad, and Gulf Railroad connects the Port Arthur Canal to the Sabine Channel (a 75ft wide by 6ft deep channel from Sabine Pass to Taylor's Bayou; Alperin 1977), forming part of the future Sabine-Neches Waterway (SNWW).
	Dredge spoil closes the entrance to the existing boat canal between Little Keith Lake and Sabine Lake (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*)
1901	Rice growers on Taylor's Bayou report salinity in irrigation water used for rice fields (Alperin 1977)
1908	SNWW dredged to 100ft wide by 9ft deep (Alperin 1977)
1916	SNWW dredged to 25ft depth (Alperin 1977)
1922	SNWW widened to 125ft (Alperin 1977)
1924	Severe drought and peat fires result in conversion of marsh areas in Salt Bayou to open water (Lay and O'Neill 1942)
1927	SNWW dredged to 150ft wide by 30ft deep (Alperin 1977)
	Dredging activities along the SNWW likely hastened the reconnection with Little Keith Lake (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*)
1933	Gulf Intracoastal Waterway (GIWW) constructed across Jefferson County separating Salt Bayou from upper watershed and its confluence with Taylor Bayou and Sabine Lake.
	Water control structures installed on the GIWW at Star Lake and Salt Bayou outfall. A third structure reconnects Little Keith Lake with the SNWW, and later a natural stream is expanded to improve boat access between Keith Lake and Little Keith Lake (USDA/SCS 1976, J. Sutherlin, J.D. Murphree WMA, *pers. comm.*) This provides estuarine species with three access points to the system.
1946	SNWW dredged to 400ft wide by 36ft deep (Alperin 1977)
1947	Clam Lake Oil field discovered and begins production.
1950	TPWD acquires land for the J.D. Murphree WMA (so named in 1963).
1958	Shell Lake Oil field discovered and begins production
early 1960s	Hurricanes Audrey (1957) and Carla (1961) likely damaged the existing water control structures along the GIWW and Little Keith Lake so that they were no longer functioning and allowed for the free exchange of tidal waters
1965	Impoundment of the Neches River and formation of Lake Sam Rayburn reservoir (Handbook of Texas Online)
	SNWW dredged to 40ft depth (from 1965-1972, Alperin 1977)

Date	Event
1966	Impoundment of the Sabine River and formation of Toledo Bend Lake reservoir (Handbook of Texas Online)
	As part of SNWW dredging activity, dredge spoil is deposited into Little Keith Lake closing off the connection between Little Keith Lake and Sabine Lake.
1972	TPWD acquires land for Sea Rim State Park.
1977	Keith Lake Water Exchange Pass plan approved by TPWD, Coastal Soil and Water Conservation District, and the USDA SCS, February 23 (USDA/SCS 1976)
	Keith Lake water exchange pass (Keith Lake Fish Pass) connects Keith Lake and Sabine Lake. The channel is straight, 155ft. wide by 5.5ft. deep, September.
1980	McFaddin NWR established
1988	Keith Lake Fish Pass expands to 300ft. wide by 10ft. deep (Fisher 1988) with 10-15ft depths
1989	Hurricane Jerry destroys a portion of State Highway 87
1989	Water control structure installed at the junction of Star Lake and the GIWW, west of Perkin's Levee on McFaddin NWR. This structure served to replace the open pipes connecting the system to the GIWW, which later were sealed off. (P. Walther, McFaddin NWR, *pers. comm.*)
1995	Water control structure installed at Salt Bayou Outfall to replace the previous control structure which had been in disrepair since the 1960's, hence sealing this direct connection to tidal waters (J. Sutherlin, J.D. Murphree WMA, *pers. comm.*)
1998	Tropical Storm Frances damaged the beach ridge, removing much of the sand resulting in regular overwash events during high tides
2001	Keith Lake Fish Pass scours to a depth of 12ft. (Moffatt and Nichol 2001)
2005	Hurricane Rita contributes to erosion along the beach ridge (P. Walther, McFaddin NWR, *pers. comm.*)
2008	Hurricane Ike exacerbates erosion along the beach ridge and inundating Salt Bayou with a storm surge greater than 10ft (P. Walther, McFaddin NWR, *pers. comm.*)
2009	USACE evaluating impacts of dredging SNWW to an authorized 48ft deep (J. Stokes, USACE, *pers. comm.*)

In September 1977, the exchange pass was dredged to meet the specifications outlined by the USDA/SCS (a straight channel 150ft wide x 5ft deep, 1976). This reopening of the exchange pass into what is now the Keith Lake Fish Pass allowed a greater range of tidal inflow to reach Keith Lake and the associated chain of lakes, resulting in increased open water salinities and rates of erosion within the wetland (Wern 1979, Stelly 1980, O'Connell 2001). Over time, tidal action widened and deepened the Fish Pass so that by 1988, the Fish Pass had expanded to 300ft wide and 10ft deep (Fisher 1988). This allowed the salinity gradient to impact interior marshes upstream of Keith Lake, which included marshes near Johnson Lake, Salt Bayou, Shell Lake, Salt Lake, Fence Lake and Knight Lake (Joint Water Management Concept Plan 1990) and areas further west. Today, the predominant source of saltwater to the system enters via the Fish Pass (Fisher 1988), with consequences to freshwater

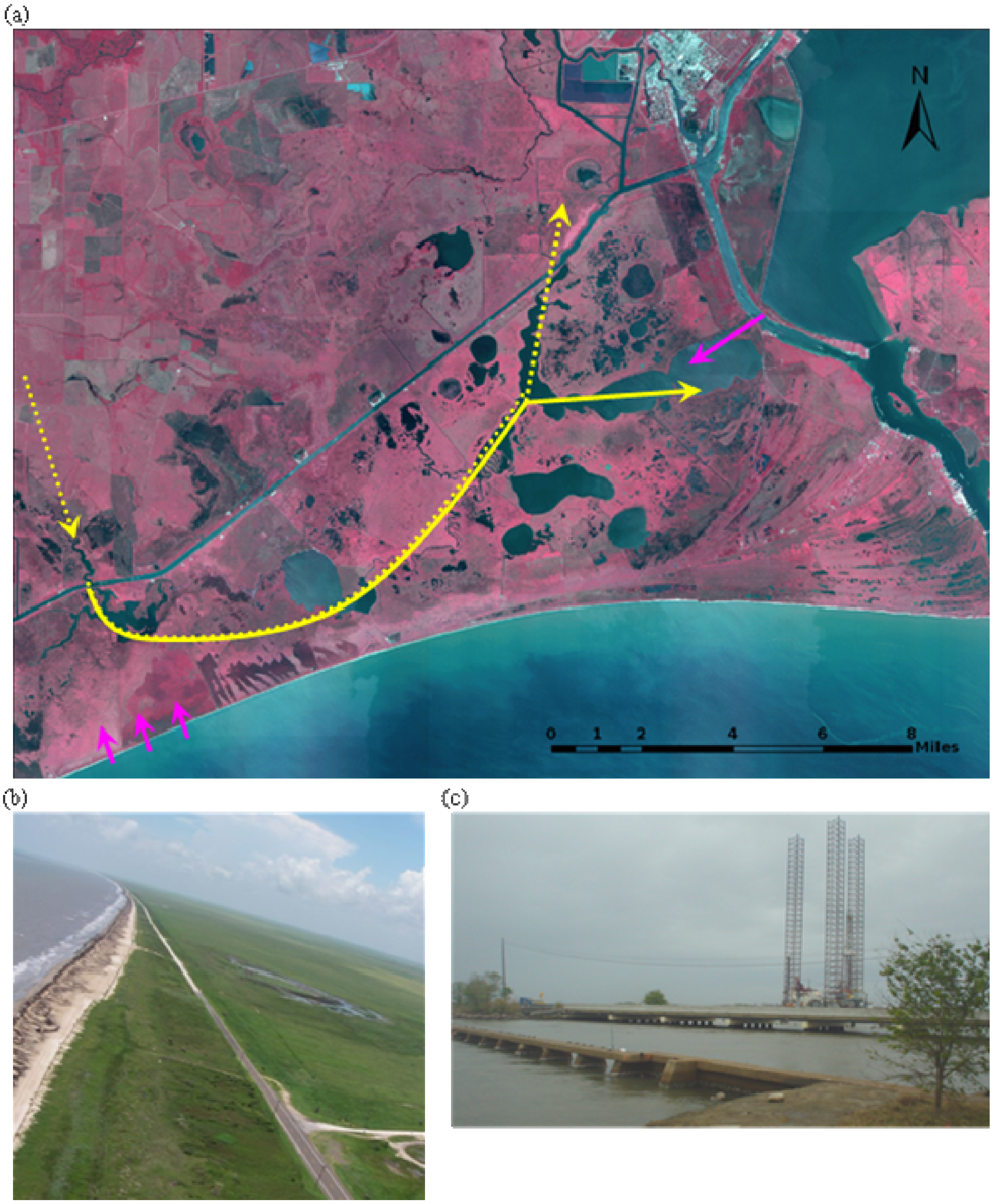

Figure 1.3 a) Historic (dotted yellow) and current (solid yellow) direction of flow in Salt Bayou. Flow of water from the upper watershed was cut off after construction of the GIWW in 1933. Similarly, the natural downstream flow was disrupted. Upon reopening the Fish Pass in 1977, the predominant direction of flow was out through Keith Lake and the Fish Pass. Salinity intrusion to the wetland occurs via the Fish Pass and overtopping events along the beach ridge (pink arrows), b) view of beach ridge west of McFaddin NWR entrance, c) Keith Lake Fish Pass with view of a barge/oil platform passing in the SNWW.

conditions in the eastern portion of the watershed. For nearly a century, the primary source of freshwater to the marshes has been from direct precipitation over the area (USDA/SCS 1976, Joint Water Management Concept Plan 1990). While annual precipitation averages 58 inches in the region (City of Port Arthur precipitation gauge, 1976-2007), this is not a sufficient source of freshwater to offset existing saltwater intrusion.

The Salt Bayou coastal wetlands are part of a unique system, known as the Gulf Coast Chenier Plain, which developed in areas bounded by natural levees formed from old beach ridges (cheniers). However, after several decades of salinity influence on the eastern end and following Hurricane Rita in 2005, increased coastal erosion along the beach ridge permitted greater frequency of overtopping events allowing Gulf waters to inundate marshes along the southern boundary of the system. These events occur west of Perkin's Levee (on Five-mile Cut) and therefore affect the interior, western end of the marsh which was previously insulated from large-scale salinity impacts (Figure 1.2, Patrick Walther, USFWS *pers. comm.*). At the time of this writing however, the entire system is suffering from recent large-scale impacts of Hurricane Ike. In September 2008, the entire Salt Bayou watershed, including Keith Lake, was inundated by the hurricane's storm surge, which covered the marsh in greater than 10ft of water (Berg 2009) and further eroded the beach ridge along the southern boundary. As of December 9, 2008, salinities across most of McFaddin National Wildlife Refuge (McFaddin NWR) remain elevated at 20ppt, and the marsh showed signs of stress with large areas (~300 to 400 acres) having been converted to open water. Detached and dying marsh plants were accumulating in the channels, causing major blockages which affect water flow (P. Walther, USFWS *pers. comm.*)

Two ongoing projects that will impact the system include modifications to the Fish Pass to reduce salinity intrusion and channel dredging to deepen the SNWW. Thus rather than reduce existing levels of salinity, modifications to the Fish Pass may serve only to offset potential impacts resulting from increased currents and salinity intrusion associated with the deepening of the SNWW from the current authorized depth of 40ft to 48ft (presently under feasibility study by the USACE, J. Stokes, USACE, *pers. comm.*). Nonetheless, a recent study of the Fish Pass (funded by the Texas General Land Office (GLO)) provided alternatives for channel weir designs to reduce salinity intrusion while still allowing boat access through the pass (Moffatt and Nichol 2001). Building on that study and following input from local land managers and stakeholders, the USACE currently is evaluating the effectiveness of several possible Fish Pass modifications to reduce salinity intrusion while maintaining the ability for fish ingress and egress under the most likely future scenario of a 48ft channel being in place.

Changes to the Fish Pass alone, however, are not likely to be sufficient to control the salinity gradient throughout the system, especially in times of low local precipitation. Consensus among system managers is that even with modifications to the Fish Pass there will still be too much saltwater entering the system and contributing to erosion and conversion of emergent marsh into shallow muddy lakes. Therefore, to combat all sources of salinity, land managers are considering the use of passive, inverted siphons (hereafter referred to as *siphons*) to bring fresh water from the north side of the GIWW into the wetland at critical junctions so as to maintain enough inflow to push the salinity gradient down through the system. Siphons, when combined with a coordinated operational strategy of existing internal structures to control flow through the system, present a potential means of protecting and enhancing the wetland system.

The foundation for these management activities began in 1990 through the *Salt Bayou Project Joint Water Management Concept Plan*. This plan integrates conservation activities of the three entities responsible for managing adjacent sections of this wetland, including J.D. Murphree Wildlife Management Area (WMA), Sea Rim State Park, and McFaddin NWR. The plan outlines objectives and management actions for each section of the wetland with goals for maintaining selected indicator species from each of the fresh and intermediate marsh assemblages. In 2003, TPWD and J.D. Murphree WMA further identified specific desired conditions for the system. Although these were developed to guide studies of modifications to the Fish Pass, they too provide management goals for the study presented here (N. Kuhn, TPWD, *pers. comm.*).

- <u>Salinities</u> entering the system should be reduced so that they range 0-10ppt at the intersection between Keith and Johnson lakes, except during drought or following tropical storm events, and the salinity gradient should decrease, becoming fresher west of the Fish Pass.

- <u>Water velocities</u> through the Fish Pass should be reduced to lessen the erosive forces.

- <u>Marine fisheries</u> ingress, egress, and productivity should not be negatively impacted.

- Plant diversity and soil conditions should be restored to maintain the historic biodiversity and the west-to-east gradient of fresh to brackish marsh plant species, as well as to provide conditions for marsh accretion to off-set subsidence and relative sea-level rise.

1.3. Project Goals

This study effort contributes to these goals by providing a detailed three-dimensional hydrodynamic and salinity transport model of the Keith Lake/Salt Bayou system which is then used to evaluate specific salinity mitigation strategies. Such a model can evaluate a range of management strategies from projects which would require major investment, such as the installation of freshwater siphons to connect the system to an upland watershed, to the identification of simple, cost-effective measures, such as coordinating the use of existing internal salt barriers which when enacted protect substantial percentages of wetland. Following discussions with local land managers and other stakeholders, however, the specific project goals were refined to focus on evaluating the ability of freshwater siphons to mitigate salinity intrusion during a typical year. Land managers expressed interest in being able to identify structures and practices to manage endemic salt intrusion, as opposed to extreme events. Considering the three primary threats to the system, stakeholders elected to evaluate the potential for freshwater siphons to mitigate high salinities. This mitigation strategy was selected, since the USACE had already begun evaluating new designs for the Fish Pass to reduce salinity intrusion and since overtopping along the Gulf beach ridge as a more recent threat was not well understood and deemed too complicated to model at the time.

2. DATA COLLECTION

To develop a detailed three-dimensional hydrodynamic and salinity transport model of the Salt Bayou watershed, TWDB staff collected or obtained bathymetric, hydrologic, meteorological, and water quality data from various locations throughout the system as well as data from the Gulf of Mexico. Field data collection began in December 2005 and continued until April 2007. TWDB staff collected long-term ambient water quality data from seven locations within the Salt Bayou watershed south of the GIWW (Table 2.1, Figure 2.2). Photo images of the system and monitoring locations are shown in Figures 2.3 and 2.4. In partnership with the U.S. Geological Survey (USGS), data was collected at a further four sites in the GIWW and SNWW. Site selection was based on discussion with local land managers and in consideration of the needs for model development and goals of the project. In addition, records were obtained for data previously collected by other entities, as well as information on potential physical structures, management strategies, and desired outcomes for wetland management of this system. The resulting model was then applied to a target year which had typical hydrological conditions. The model was run for this target year with and without various management scenarios operational.

2.1. Data Collection

2.1.1. Bathymetry

In April 2007, under an agreement with the Texas Parks and Wildlife Department (TPWD), TWDB collected bathymetric data throughout the Salt Bayou system. These data were collected to support the hydrodynamic and salinity transport modeling effort and were not designed to determine water volumes or to aid in navigation. Data collection was performed on April 10 – 12, 2007, using a Knudsen 200kHz echosounder integrated with differentially corrected global positioning system navigation equipment. The data was processed using HydroEdit software developed by TWDB (Furnans 2006) to convert water depth measurements to bathymetric elevations by subtracting depths from the water surface elevations at the time of measurement. Water surface elevations were recorded at five locations within the Salt Bayou system (Table 2.1)

In addition to TWDB field data and to improve the bathymetric surface models representing the entire system, other bathymetric datasets made available from prior studies were incorporated. These included data from surveys conducted during projects sponsored by the J.D Murphree WMA and McFaddin NWR in June 2002 (Michael Rezsutek, TPWD *pers. comm.*) and by Exxon-Mobil (as part of the Golden Pass Pipeline project) in July 2006 (Bryan Trimm, Exxon-Mobil *pers. comm.*). Total coverage from all bathymetric surveys is shown in Figure 2.1. In areas where no bathymetric data were available, TWDB made water-depth approximations based on field observations and general knowledge of system characteristics. Additional details related to Salt Bayou bathymetry are provided in *Appendix A* and in the TWDB report, *Hydrographic Survey of the Keith Lake-Salt Bayou System* (Pothina *et al.* 2007).

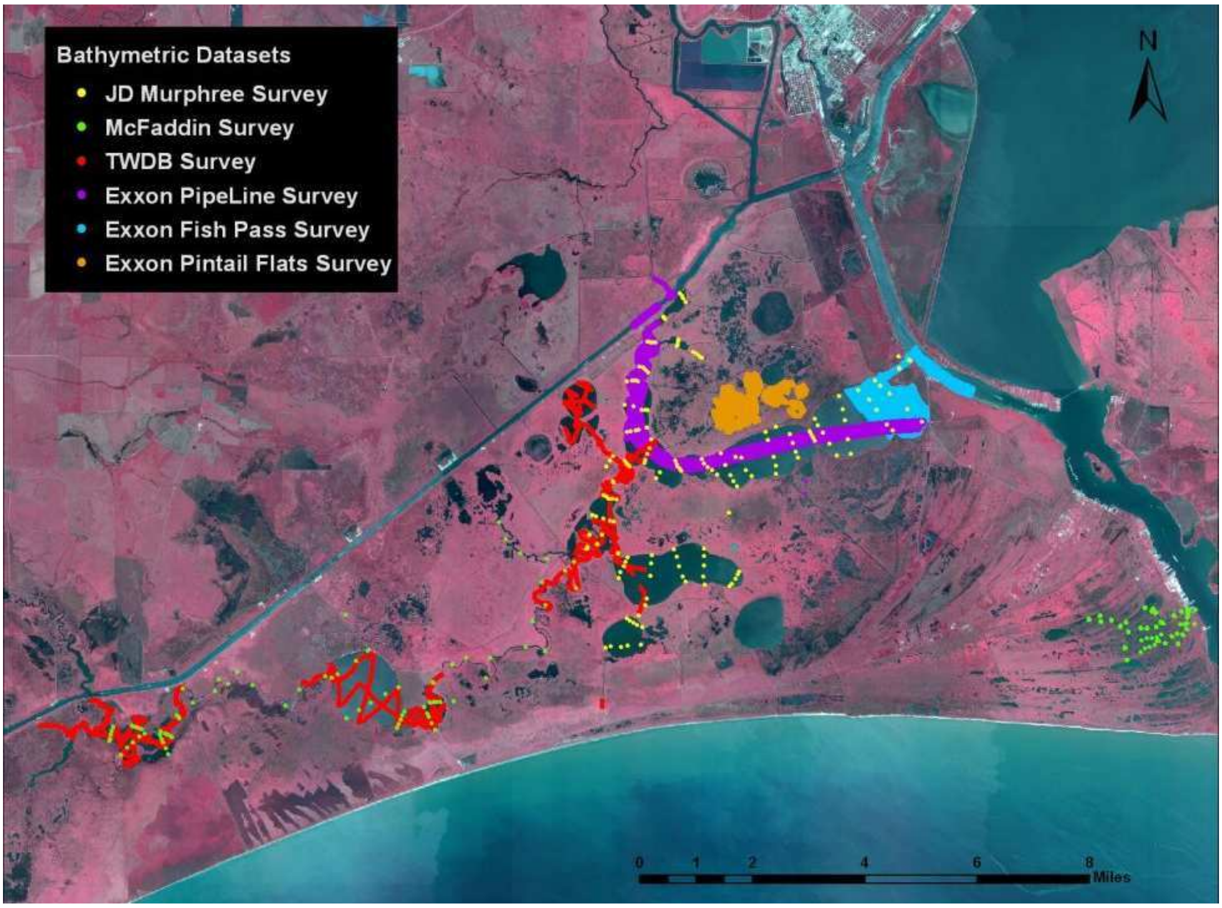

Figure 2.1 Location of bathymetric data collection in Salt Bayou watershed. Surveys were conducted between 2002 - 2006 by several entities, including TWDB, TPWD, USFWS, and Exxon-Mobil.

2.1.2. Velocity and Discharge

Long-term deployments of Sontek Argonaut acoustic Doppler velocity meters in either up-looking or side-looking configurations measured water velocities at eight locations (Table 2.1, Figure 2.2), including: Sabine Pass (USGS1), Fish Pass (USGS2), Port Arthur Canal (USGS3), GIWW at Salt Bayou Outfall (USGS4), channel between Mud and Shell lakes (JDM2), lower Ten-mile Cut (JDM 4), upper Ten-mile Cut (MCF1), and lower Five-mile Cut (MCF2). The meters record average velocity in a cone-shaped section extending either horizontally (side-mounted, side-looking configuration) or vertically (bottom-mounted, up-looking configuration) through a significant part of the channel cross-section. Additionally, short term measurements of channel discharge were taken on two dates (February 21 and April 10, 2007) at four locations (JDM2, JDM4, MCF1, and MCF2) by measuring water flow across channel widths using an acoustic Doppler current profiler mounted on an independent flotation device (SonTek RiverCAT System).

2.1.3. Water Quality

Long-term deployments of water quality instrumentation were conducted at eight locations (Table 2.1, Figure 2.2), including the Fish Pass (USGS2), intersection of Keith and Johnson lakes (JDM1), channel between Mud and Shell lakes (JDM2), southern edge of Salt Lake (JDM3), lower Ten-mile Cut (JDM4), upper Ten-mile Cut (MCF1), lower Five-mile Cut (MCF2) and GIWW near Star Lake (MCF3). For this study, focal water quality parameters included water level, temperature, specific conductivity, and salinity. Each of the long-term data sets was collected using one of the following instruments: Coastal Leasing Macro CTD, Eureka Manta, Greenspan CTD350, Solinst 3001LTC. With assistance from the TPWD (J.D. Murphree WMA), USFWS (McFaddin NWR), and Jefferson County Drainage District No. 6 (DD6), additional water quality data were collected or obtained.

Table 2.1 Monitoring Stations in or adjacent to the Keith Lake/Salt Bayou system. J.D. Murphree WMA stations are semi-monthly point measurements. All other sites collected continuous data. Water quality parameters include temperature, conductivity, salinity and in some cases pH and dissolved oxygen.

Station Name	Latitude	Longitude	Description	Parameters	Collecting Agency
7300	29.76056° N	93.93806° W	Keith Lake off HWY 87	Water Quality, Level	DD6
7600	29.68444° N	94.03278° W	Marsh Unit at Hwy 87 and Park Rd 69	Water Quality, Level	DD6
7800	29.69167° N	94.08056° W	Upper Ten-mile Cut on Clam Lake Road	Water Quality, Level	DD6
8000	29.68528° N	94.18417° W	Star Lake Control Structure at Chevron Duck Camp	Water Quality, Level	DD6
8120	29.79278° N	94.00944° W	Salt Bayou Control Structure at GIWW, marsh side	Water Quality, Level	DD6
JDM1	29.75599° N	93.97210° W	Junction of Johnson Lake and Keith Lake	Water Quality, Level	TWDB
JDM2	29.74290° N	94.02954° W	Junction of Shell Lake and Mud Lake near Demayah's Dock	Water Quality, Level, Velocity	TWDB
JDM3	29.71260° N	94.02060° W	Southern edge of Salt Lake	Water Quality, Level	TWDB
JDM4	29.71980° N	94.04127° W	Lower Ten-mile Cut	Water Quality, Level, Velocity	TWDB
MCF1	29.68964° N	94.08294° W	Upper Ten-mile Cut on Clam Lake Road	Water Quality, Level, Velocity	TWDB
MCF2	29.68958° N	94.11942° W	Lower Five-mile Cut	Water Quality, Level, Velocity	TWDB
MCF3	29.68211° N	94.19662° W	GIWW near Star Lake	Water Quality, Level	TWDB
USGS1	29.71000° N	93.85278° W	Sabine Pass near Sabine Pass, TX	Level, Velocity	USGS
USGS2	29.77500° N	93.94167° W	Keith Lake Fish Pass at Hwy 87	Water Quality, Level	USGS
USGS3	29.79167° N	93.95083° W	Port Arthur Canal in the SNWW	Level, Velocity	USGS
USGS4	29.79139° N	94.00972° W	GIWW near Salt Bayou Control Structure	Level, Velocity	USGS
C	29.74260° N	94.02982° W	Junction of Shell Lake and Mud Lake near Demayah's Dock	Water Quality	JDM WMA
F	29.79279° N	94.00956° W	Shell Lake at the Salt Bayou Control Structure, marsh side	Water Quality	JDM WMA
I	29.77570° N	93.94216° W	Entrance to Keith Lake Fish Pass at the junction with the SNWW	Water Quality	JDM WMA
O	29.74423° N	93.98930° W	Southern edge of Johnson Lake	Water Quality	JDM WMA
Q	29.72001° N	93.99248° W	Eastern edge of Salt Lake	Water Quality	JDM WMA
T	29.72223° N	94.04061° W	Lower Ten-mile Cut (Gar Flats – Old Wooden Weir)	Water Quality	JDM WMA

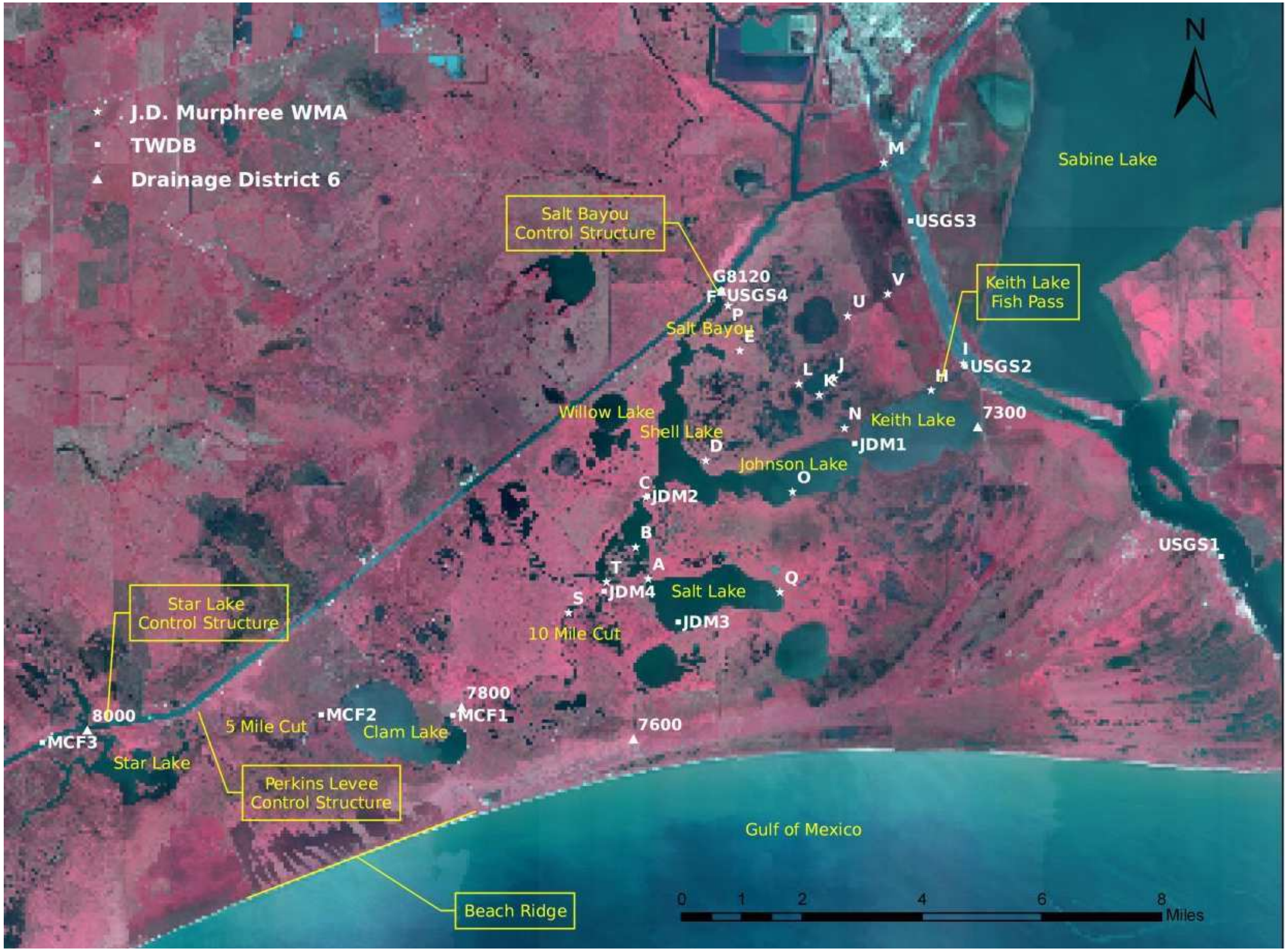

Figure 2.2 Features of the Salt Bayou wetland system and locations of water monitoring stations supported by three entities; J.D. Murphree WMA (sites A-V), TWDB (sites JDM1-4, MCF1-3, and USGS1-4), and DD6 (sites 7300, 7600, 7800, 8000, and 8120).

Figure 2.3 a) Star Lake Control Structure on the GIWW, b) Upper Five-mile Cut with GIWW in background, c) Five-mile cut, d) MCF2 station on Five-mile cut, e) Clam Lake juncture with upstream entrance to Ten-Mile Cut, f) MCF1 at upper Ten-Mile Cut, Clam Lake in background and downstream is to the left.

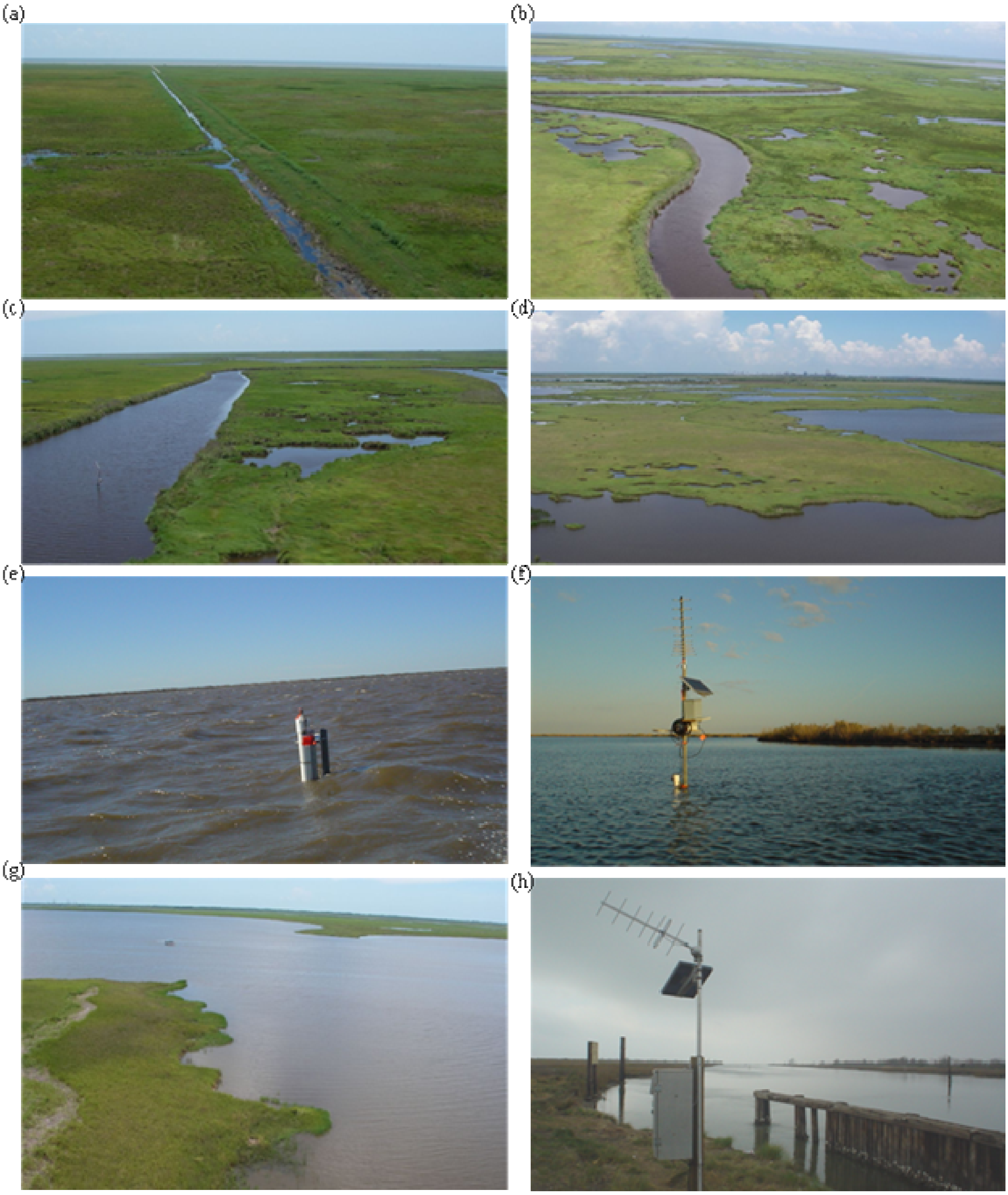

Figure 2.4 a) Perkin's Levee with Gulf of Mexico in background; downstream is to the left, b) Ten-mile Cut and surrounding marsh, c) JDM4 station on Ten-mile cut, d) Ten-mile marsh, e) JDM3 station in Salt Lake, f) JDM2 station in Mud Lake, g) Juncture of Johnson Lake and Keith Lake where JDM1 station was located, h) USGS2 station at the Fish Pass.

2.2. Data Management

TWDB and USGS staff, under contract by TWDB, collected field data for this project. Data collected by USGS underwent standard USGS quality control procedures and was delivered to TWDB in final form. Data collected by TWDB staff underwent a semi-automated quality control procedure. Raw water quality data files from multiple instrument types for a given monitoring location were automatically converted to a common ASCII text format and merged together. Data in this common format was examined and compared against spot-check field measurements taken with an independent instrument during each visit. Based on these examinations and field notes, spurious data were identified and marked for deletion. A final processed data file containing the entire period of record with spurious data removed was generated for each monitoring location. All data files were stored as space delimited ASCII text files. All original and intermediate data files, processing scripts, and records of deleted data points were archived. All field data collected for this project are in digital form and available from TWDB upon request. Additional sources of data available in this system are listed in Table 2.2 and where applicable also are available on request.

Table 2.2 Additional sources of data

Source	Years	Description
Wern (1979)	1978 -1979	Monthly average salinities
Fisher (1988)	1984 -1986	Water Quality, Velocity and Level
TPWD Coastal Fisheries	1986 - Present	Semi-monthly water quality at random locations
J.D. Murphree WMA	1988 - Present	Semi-monthly water quality at fixed locations
TWDB Datasonde Program	1991 - Present	Water Quality, Level in Sabine Lake
Moffat and Nichol (2001)	2001 - 2002	Water Quality, Velocity and Level
USACE	2001 - 2002	Salinity
Drainage District 6	2007 - Present	Water Quality, Level

3. HYDRODYNAMIC AND SALINITY TRANSPORT MODEL

3.1. Background

TWDB uses a variety of two-dimensional (2-D) depth averaged and three-dimensional (3-D) hydrodynamic and salinity transport models to produce high-resolution, dynamic simulations of estuarine conditions over long-term periods covering a year or more. These models allow us to understand circulation patterns and transport phenomenon within an estuary and to simulate the effects of various management strategies. This chapter describes the development of a hydrodynamic and salinity transport model for the Keith Lake/Salt Bayou system and its application for the evaluation of some management strategies aimed at reducing salinity levels throughout the system.

3.2. Choice of Model

In choosing a model for the Keith Lake/Salt Bayou system, the physical features of the watershed were considered along with the capabilities required to conduct scenarios proposed by local land managers. Salt Bayou is composed of a series of shallow lakes (typically 2.5 to 3ft deep), interconnected by narrow channels (ranging 5ft to 100ft in width), and surrounded by low lying marshes. Keith Lake is the easternmost lake in the system and via a deep, narrow fish pass connects the entire Salt Bayou watershed to the larger Sabine Lake estuary and the saline waters of the Gulf of Mexico. Strong prevailing winds have a significant effect on directional water movement within the system. The system is isolated from 60% of its historical upper watershed, including its downstream drainage basin, Taylor Bayou, by construction of the GIWW (Fisher 1988). Hence, local rainfall and evaporation are important factors in the balance between fresh and saline water.

With these factors in mind, the following features were considered important to selection of the hydrodynamic model:

- A peer-reviewed track record in modeling estuarine systems
- Ability to model cross-scale features efficiently, such as simultaneously modeling narrow channels, small lakes, and the Gulf of Mexico
- Ability to accurately model the effect of wind
- A turbulence closure model to capture the transfer of wind energy into the water column
- A robust wetting and drying feature for low lying marsh areas
- Salinity and (water) temperature transport capabilities
- Ability to use spatially variable rainfall, solar flux, and air temperature data
- A 3-D baroclinic capability to capture stratification effects in the Sabine-Neches Waterway
- In-house experience with using the selected model

TWDB's in-house hydrodynamic and salinity transport model, TxBLEND, originally was proposed for use in this project. TxBLEND is a version of the BLEND model, developed by Dr. William Gray of Notre Dame University, which has been developed further over many years by TWDB engineers for use in the shallow bays and estuaries of Texas (Matsumoto 1991, 2005). While TxBLEND is the primary model used by TWDB in many studies along the Texas coast, a closer look at the challenges and requirements to developing a model for the Salt Bayou system revealed that TxBLEND would be inadequate. TxBLEND is a 2-D, depth-averaged model which does not include a turbulence closure model, temperature transport, or wetting and drying.

After careful consideration, the SELFE model (version 2.0d) was chosen as the best model for use in this system. SELFE is a recently developed, unstructured-grid hydrodynamic circulation model designed for effective simulation of 3-D baroclinic circulation across river-to-ocean scales (Zhang and Baptista 2008). It uses a semi-implicit finite-element Eulerian-Lagrangian algorithm to solve the shallow water equations and is written to realistically address a wide-range of physical processes, including atmospheric, oceanic, and riverine forcings. The numerical algorithm is high-order, stable, and computationally efficient. It also naturally incorporates the wetting and drying of tidal flats. SELFE has been extensively tested against standard ocean/ coastal benchmarks and applied to a number of bays and estuaries around the world (Foreman *et al.* 2005, Oliveira *et al.* 2006, Dias *et al.* 2009, Wang *et al.* 2008). It has been used and tested internally by TWDB for several years (Zhang 2006, 2008).

3.3. Model Domain

Model development for the Salt Bayou system began with construction of a triangular finite-element grid, primarily using SMS grid generation software (SMS 2008). The grid domain covers the lakes and bayous present within the Salt Bayou watershed (south of the GIWW) and extends west through the Fish Pass into the Sabine Lake system, including both the SNWW and GIWW, and finally connects to the Gulf of Mexico. Grid density was adjusted to provide higher detail in areas of interest and where needed to resolve physical features or for model stability. Two final grids thus were developed and are named KLGrid_20080421 (*base grid*, Figure 3.1) and KLGrid_20080506 (*marsh grid*, Figure 3.2). The key difference between the two grids is that the *base grid* covers the open water segments of the area, while the *marsh grid* also includes a portion of the marshes present in the system. Table 3.1 summarizes the main features of the two computational grids.

Table 3.1 Description of two model grids developed for the Salt Bayou system.

Name	Number of Computational Nodes	Number of Computational Elements	Description
Base Grid, KLGrid_20080421	21,216	35,744	Final grid without marsh areas
Marsh Grid, KLGrid_20080506	57,622	111,631	Final grid with marsh areas

The final vertical grid resolution was set at six layers to provide a good balance between computational expense and ability to capture necessary flow features. For development of the base and marsh grid models, available bathymetry data (described previously in *Section 2.1.1 Data Collection: Bathymetry*) was interpolated to the open water nodal locations in the computational mesh. *Marsh grid* elevations were set using the 30m Digital Elevation Model from the USGS National Elevation Dataset. The Texas Natural Resource Information Systems higher resolution coastal LIDAR data could not be obtained in time to be included in the model.

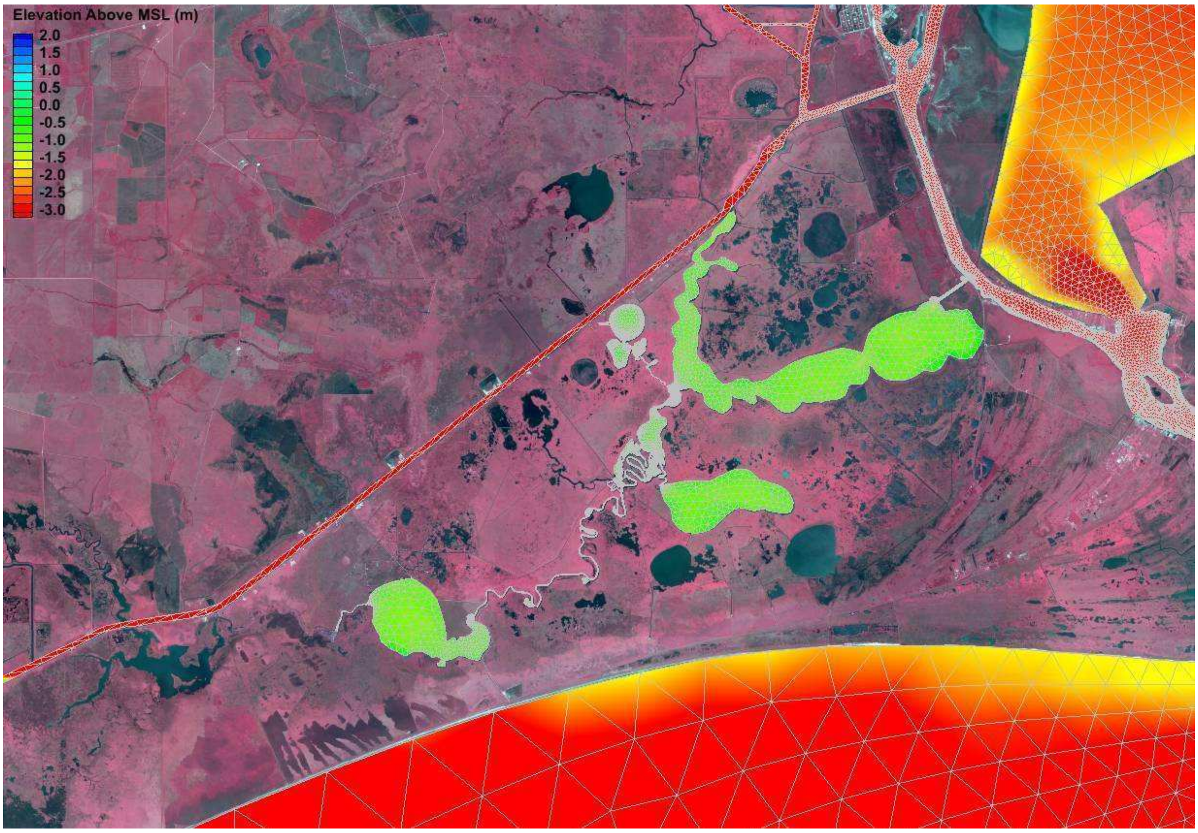

Figure 3.1 Base Grid (KLGrid_20080421) showing open water areas of the Salt Bayou wetland system included in the model domain.

Although the *marsh grid* model was tested, no production simulations were conducted on this grid. Given the coarse resolution of the marsh elevation data and the higher computational cost associated with using the *marsh grid*, all calibration, scenario runs, and model results described in this report were conducted using the *base grid*. Hereafter, any further reference to *the model* implies use of the base grid. The marsh grid and the LIDAR data are mentioned in this report as resources that are available to benefit future studies.

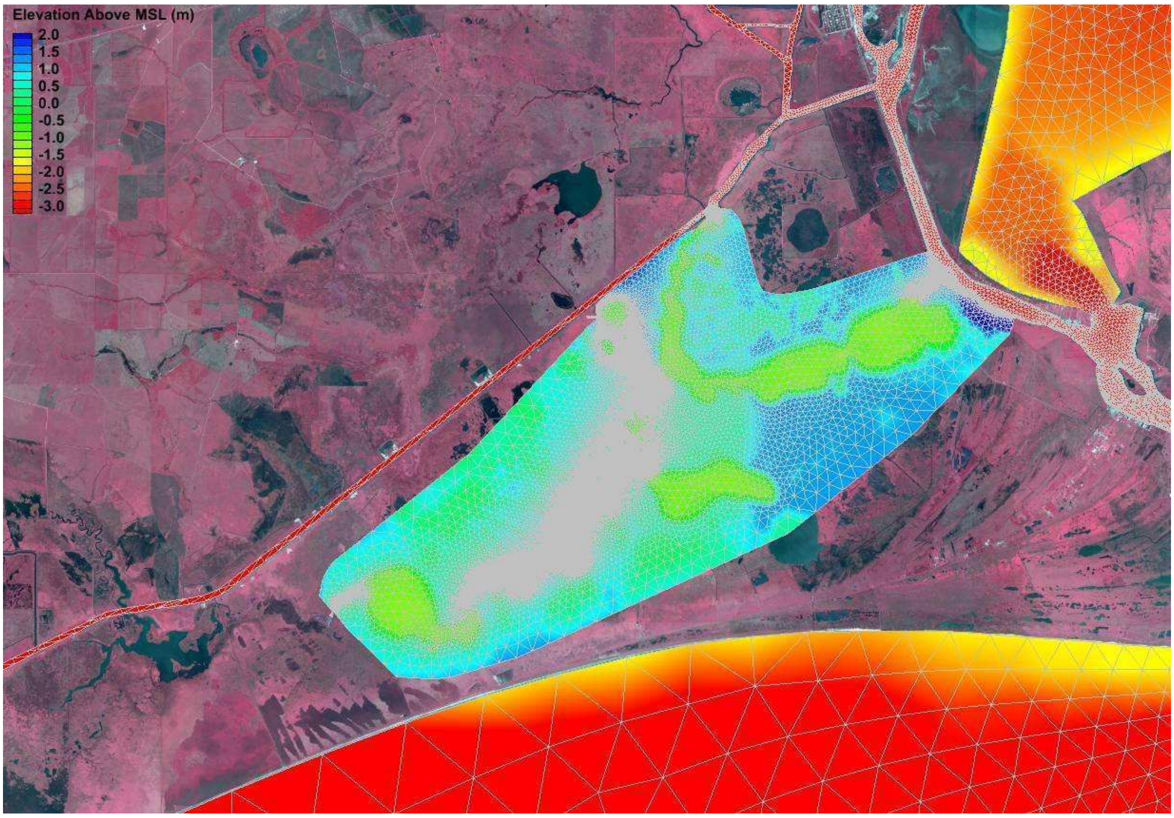

Figure 3.2 Marsh Grid (KLGrid_20080506) showing open water and wetland areas of the Salt Bayou system included in the model domain.

3.4. Model Boundary Conditions

3.4.1. Inflows

Keith Lake and the Salt Bayou watershed are influenced by several sources of freshwater inflow. In the model, these river boundary conditions are represented by five model inflow points corresponding to the Sabine and Neches rivers, Black Bayou, Taylor Bayou and the local Salt Bayou drainage basin south of the GIWW (Figure 3.3). Daily inflow values for these boundary conditions were taken from the TWDB coastal hydrology dataset, which is estimated according to methods documented in Longley (1994). This dataset uses USGS streamflow gauge measurements for the relevant watersheds (Table 3.2) along with rainfall-runoff estimates for ungauged watersheds calculated from the Texas Rainfall-Runoff (TxRR) model. In addition to gauged and ungauged sources of inflow, the historical dataset is adjusted for known diversions and return flows in the watershed. Diversion and return flow data is provided by the Texas Commission on Environmental Quality and is only available through 2005. Together, the gauged, modeled, diverted, and returned flows are combined to provide an estimate of daily surface water inflows for the five model inflow points shown in Figure 3.3.

Within the Keith Lake/Salt Bayou system, however, stream gauges are not present and so estimated inflows applied to the Salt Bayou Watershed model inflow point (boundary condition) are strictly determined by rainfall-runoff using TxRR. The TxRR watershed delineation for Salt Bayou is shown in Figure 3.4. The TXRR estimated inflow time series for this watershed is prone to having peak flows during rainfall events and zero flows in between events, but this pattern is not representative of instream flows within the system. Therefore, to make the inflow time series comparable to observed field data, a minimum inflow of $0.6m^3/s$ (21.18cfs) was imposed at this boundary condition. Otherwise, when TXRR estimates were $>0.6m^3/s$, the TXRR estimated inflow value was applied. Field data was available for a short period of time, but did not overlap with the modeling period and so could not be used to directly set inflows in the model.

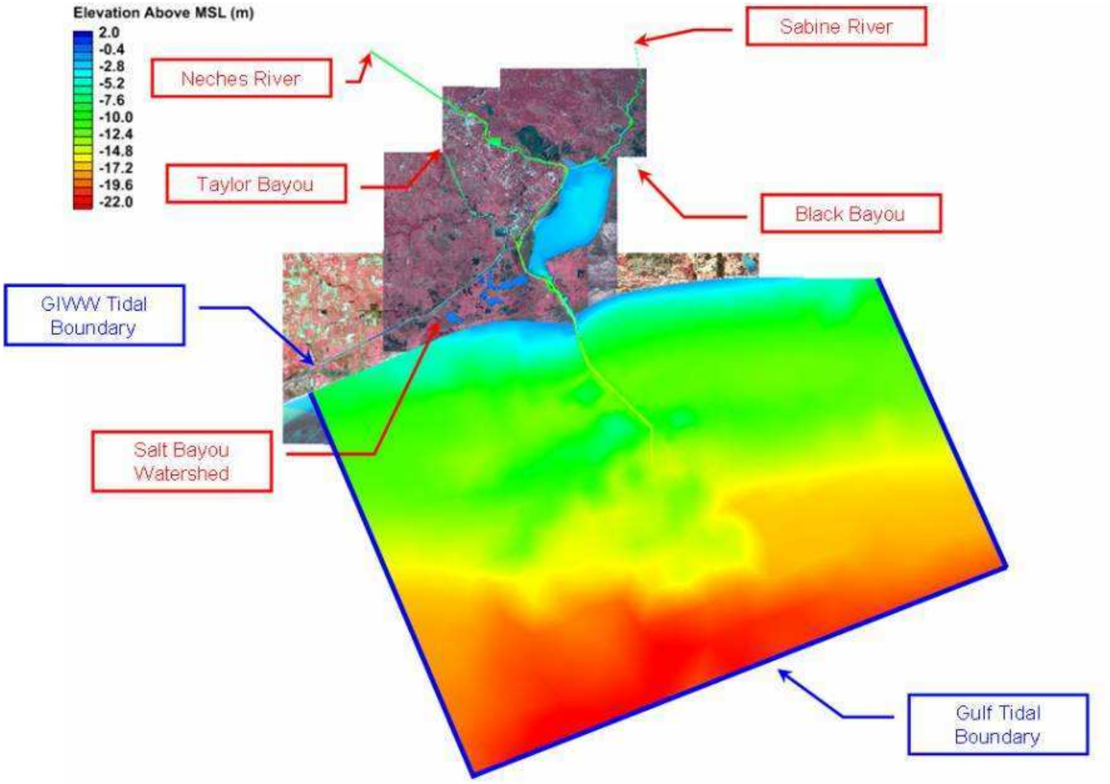

Figure 3.3 Five model inflow points corresponding to major sources of freshwater inflow (red boxes, Sabine and Neches rivers, Taylor and Black bayous, and the local Salt Bayou watershed) and two tidal boundaries (blue boxes, Gulf of Mexico and western arm of the GIWW) applied to the model.

Table 3.2 USGS streamflow gauges used for determining coastal hydrology and daily surface water inflows to the study area.

Stream Gauge	Description
8030500	Sabine River near Ruliff
8031000	Cow Bayou near Mauriceville
8041000	Neches River at Evadale
8041700	Pine Island Bayou near Sour Lake
8041500	Village Creek near Kountze

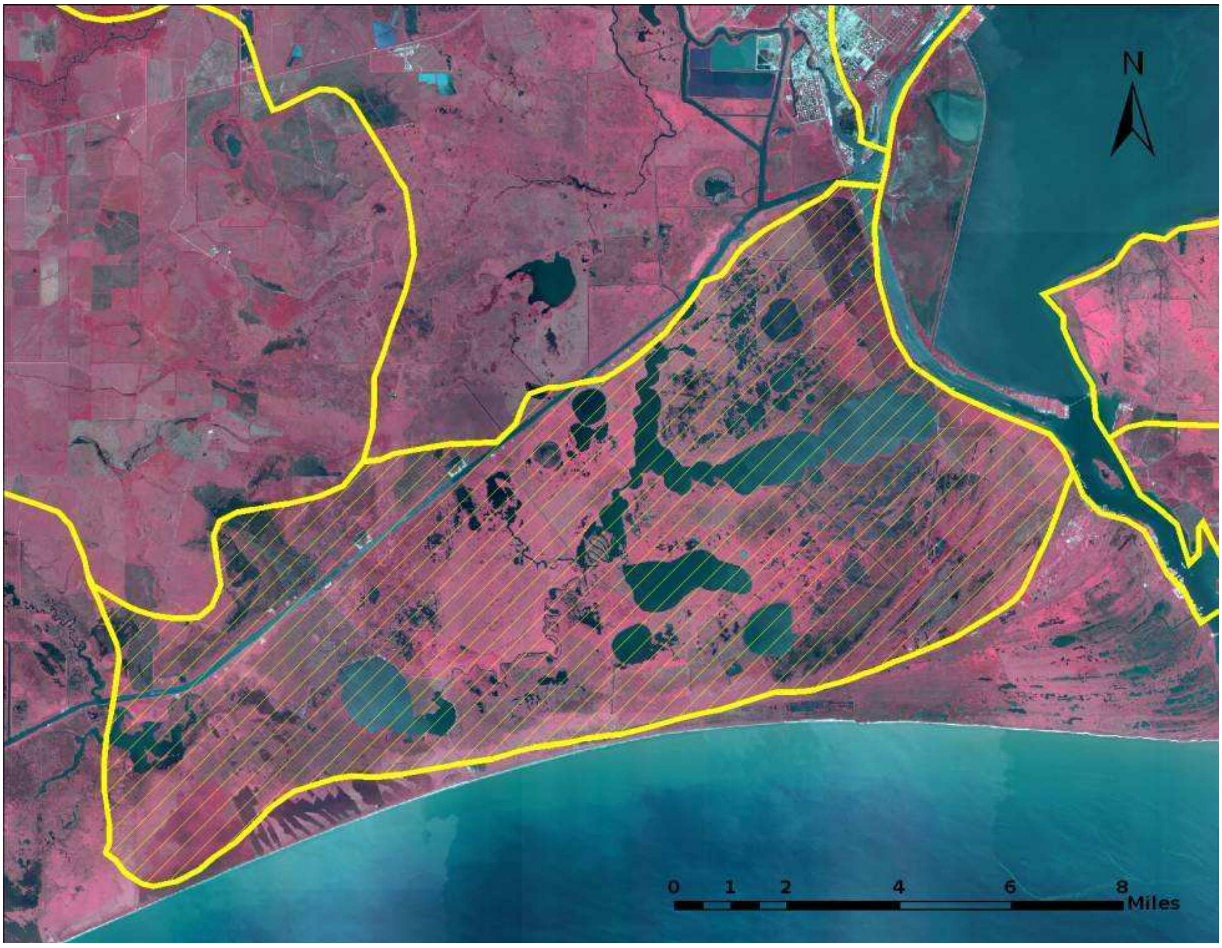

Figure 3.4 Watershed boundaries used by the TxRR model to estimate rainfall-runoff and streamflow in ungauged watersheds. The Salt Bayou coastal watershed designation (hatched area) was used to calculate stream flow for the Salt Bayou Watershed inflow point in model simulations (see Figure 3.3).

3.4.2. Tides

Tidal elevations for Sabine Pass (DNR ID#016) were obtained from the Texas Coastal Ocean Observation Network (TCOON, *http://lighthouse.tamucc.edu/TCOON/HomePage*) and applied at the Gulf open boundary in SELFE. Attempts were made to use alternate datasets including the ADCIRC ec2001_v2e Tidal Database (Mukai 2002), but these did not perform well. The time lag between tide at Sabine Pass and the open Gulf boundary of the model were not significant. A tidal boundary also was applied at the western end of the GIWW based on data from the DD6 Level Gauge at the Highway 124 bridge (Sensor ID #8100).

3.4.3. Meteorology

Time-varying and spatially non-uniform meteorology was used to drive the model. A large portion of the meteorology data was obtained from the North American Regional Reanalysis (NARR) dataset (*http://www.emc.ncep.noaa.gov/mmb/rreanl/*). This dataset has a 32km spatial resolution and a three hour temporal resolution. The dataset includes wind field, air temperature, precipitation, and solar radiation. NARR data was used for the period prior to 2004, but NARR precipitation data was replaced by higher resolution 4km NEXRAD Stage III precipitation data from 2004 onwards (*http://www.srh.noaa.gov/anonymous/wgrfc/qpe_xmrg/*).

3.4.4. Salinity

Time varying salinity boundary conditions were specified at three locations: (1) Gulf of Mexico boundary, (2) upper reaches of Five-mile Cut, and (3) the western end of the GIWW. Salinity data was compiled from several sources including the TPWD Coastal Fisheries Monitoring Program (offshore), TPWD J.D. Murphree WMA semi-monthly data, and TWDB data.

3.4.5. Initial Conditions for model calibration

Initial conditions for salinity were constructed manually by considering the available TWDB and TPWD data throughout the system (Figure 3.5). Temperature transport in the model had a fast response to solar radiation and so it was not necessary to develop an initial temperature distribution. Instead, initial conditions for temperature were based on January temperatures, ranging 15-20°C in the system and set to 15°C throughout the domain.

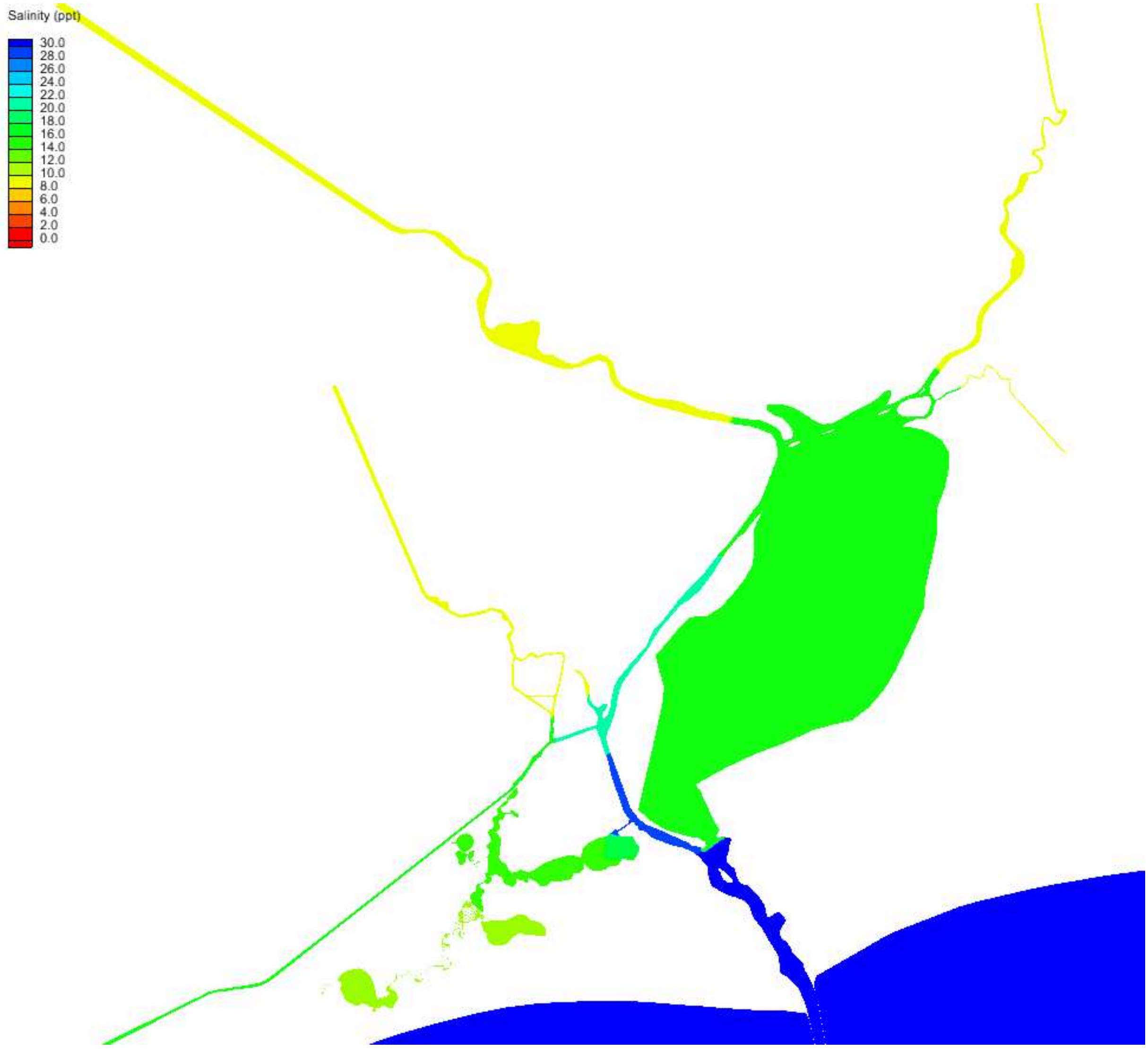

Figure 3.5 Schematic representing the initial conditions for salinity in the 2006 model run.

3.5. Model Calibration

3.5.1. Details

Hydrodynamics in SELFE were calibrated by comparing model results for water surface elevation, velocity, salinity, and temperature to field collected data at eleven sites throughout the system for the year 2006. A description of data collected by TWDB and obtained from other sources is available in the section on *Data Collection* (Section 2.2).

Model parameters initially were set to values recommended by the documentation and the developer (SELFE 2007). For the most part, model parameters were maintained at these recommended values. The calibration process mainly consisted of improving model boundary conditions and filling gaps in data with additional sources of data or better estimates. Model runs were conducted in baroclinic mode with a two-day ramp up period for tides and a one-day ramp up period for wind with a model time step of 45 seconds. The implicitness factor was set at 0.6. A minimum diffusivity of $10^{-6}m^2/s$ was used throughout the grid, while a maximum diffusivity was set to $10^{-2}m^2/s$ in the estuary and $10m^2/s$ in the Gulf of Mexico. The bottom drag coefficient (Cd) was set to 0.0025 throughout the domain, and the quadratic drag formulation option was used. The evaporation, precipitation, heat budget, and Coriolis modules were used.

A sensitivity analysis was conducted with respect to different turbulence closure and transport schemes available as options in the SELFE model (Zhang and Baptista 2008). The choice of turbulence closure did not have a noticeable effect on the model results. The turbulence closure scheme used was a two-and-a-half equation *k - kl* model with Kantha and Clayson's stability function (Umlauf and Burchard (2003) as modified by Galperin *et al.* (1988)). For the transport schemes, both the Euler-Lagrangian transport option and the mass conservative upwinding option were tested. The upwind scheme was able to match field data better but showed little salinity stratification in the Sabine-Neches waterway. The Euler-Lagrangian scheme showed strong salinity stratification in the waterway but was unable to capture the dynamics of salinity transport as accurately as the upwind option. Since, little data was available to determine whether stratification was a regular event in the Sabine-Neches waterway the stratification issue was not explored further, and the upwind scheme was chosen. A copy of the calibrated model parameter input file *param.in* can be found in *Appendix B*. Electronic versions of all calibrated model input files along with source code for SELFE 2.0d are available from TWDB.

The next few sections discuss comparisons of the calibrated model runs with 2006 field data (Figures 3.6-3.9). We present model versus field data comparisons for water surface elevation, salinity, and temperature at six monitoring sites, USGS2, JDM1, JDM2, JDM3, JDM4, and MCF1 (see Figure 2.2 for site locations). In each composite figure, graphs for each site are arranged in an East-West orientation, with the top, left figure (a) representing the eastern-most site, USGS2 at the Fish Pass, and the bottom, right figure (f) representing the western-most site, MCF1 in upper Ten-mile Cut. Velocity comparisons are presented for six sites, USGS1, USGS2, JDM2, JDM4, MCF1 and MCF2. These are arranged in a similar East-West orientation, with the top, left figure (a) representing the eastern-most site, USGS1 at Sabine Pass, and the bottom, right figure (f) representing the western-most site, MCF2 in Five-mile Cut. The model also was compared at other locations throughout the Sabine Lake-Salt Bayou complex using data collected by TWDB, TPWD, TCOON, and USGS. The model behavior at these other sites was similar to the representative sites presented here.

3.5.2. Calibration Results for Water Surface Elevation

In general, there is very good agreement between the model results for water surface elevation and collected field data (Figure 3.6). The field data is not referenced to a vertical datum so the data shown in the figure are de-meaned values. This comparison technique is complicated by gaps in the data as can be seen in Figures 3.6e, f. In Figure 3.6b, the field data seems to show a long term trend of increasing water surface elevation at JDM1 that is not captured by the model even though the model correctly captures smaller surface elevation features. An analysis of the data, field notes, and photographs suggests that this is not a trend but rather an artifact of the temporary installation platform sinking into the mud over the year long deployment.

Further west in the system, water surface elevation begins to be influenced more by the inflow boundary condition being imposed at the Salt Bayou watershed inflow boundary. The western inflow boundary input is estimated from NEXRAD rainfall data which causes some discrepancies between the model and data. Figures 3.6e (JDM4) and 3.6f (MCF1) show large spikes in water surface elevation that are model artifacts and do not match field data. These spikes are caused by large inflow events estimated by the TxRR model from NEXRAD rainfall data and applied at the Five-mile Cut inflow boundary. JDM4 and MCF1 are located in narrow channels. In reality, an increase in water surface elevation at these sites would cause over banking flows into the marsh. Since the marsh is not included in the *base grid* version of the model used for this project, these large inflow events show up as abnormally high elevations.

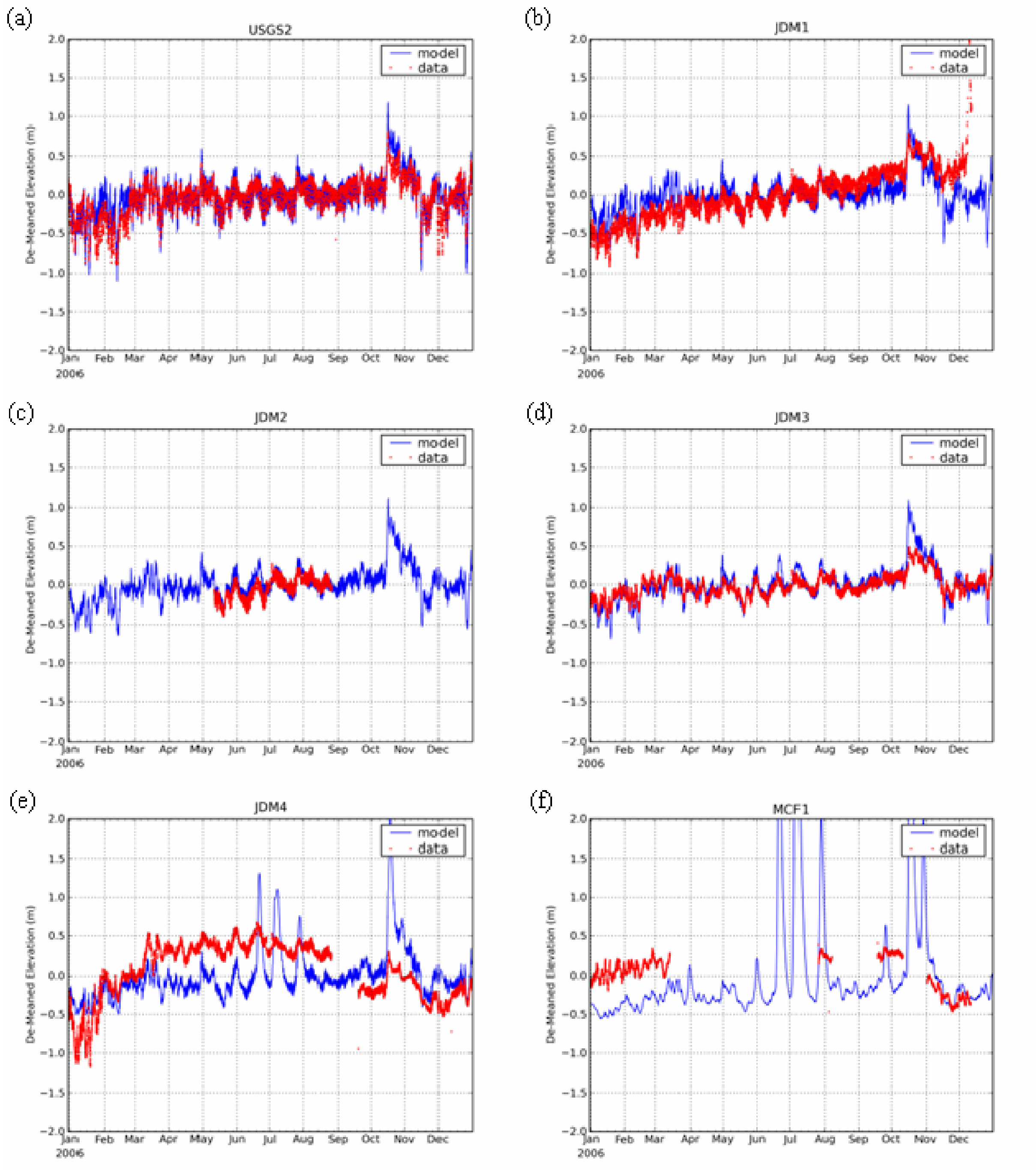

Figure 3.6 Model generated surface water elevations compared to empirical measurements of surface elevation data, at six long-term monitoring sites, (a) USGS2, (b) JDM1, (c) JDM2, (d) JDM3, (e) JDM4, and (f) MCF1.

3.5.3. Calibration Results for Velocity

The model captures water velocities in the eastern part of the system fairly well. Figure 3.7 and 3.8 show that modeled water velocities match field data reasonably well at Sabine Pass (USGS1), the Fish Pass (USGS2), and the intersection of Shell Lake and Mud Lake (JDM2). All three sites are strongly influenced by tides. Modeled velocities capture magnitude better than phase, and further calibration focusing on velocities should enable the model to better simulate the velocity phase.

Field measurements and model results demonstrate a marked decrease in tidal influence between the Fish Pass (USGS2), Shell Lake (JDM2), and lower Ten-mile Cut (JDM4, compare Figure 3.7a-d). This is consistent with results from Fisher (1988) showing that flow rates in Ten-mile Cut are only slightly affected by tidal ranges. Additionally, model data at JDM4 captures the salient features of instream flow except during large inflow events (Figure 3.7d) although magnitudes of modeled velocity are generally higher than values measured in the field. Adjustment of model bottom friction to account for the presence of aquatic plants may improve this behavior. This location is also affected by the manner in which inflows are applied to the Salt Bayou Watershed inflow boundary (effectively the upstream reach of Five-mile Cut) and the absence of wetlands to ameliorate inflows. Figure 3.8d demonstrates through the long duration signal that can be seen superimposed over tidal fluctuations. This longer signal is caused by flows imposed at the Salt Bayou Watershed inflow boundary.

Moving west, in the upper reaches of Ten-mile Cut (MCF1) and in Five-mile Cut (MCF2) the model does not correctly capture velocities (Figure 3.7e-f and Figure 3.8e). As discussed previously, the western part of the model domain is strongly influenced by the methods for estimating and applying inflows at the Salt Bayou Watershed boundary and by the absence of marshes which leads to the absence of overbanking flows in the current model. Improvement of modeled water velocities in the model domain will require solving these issues.

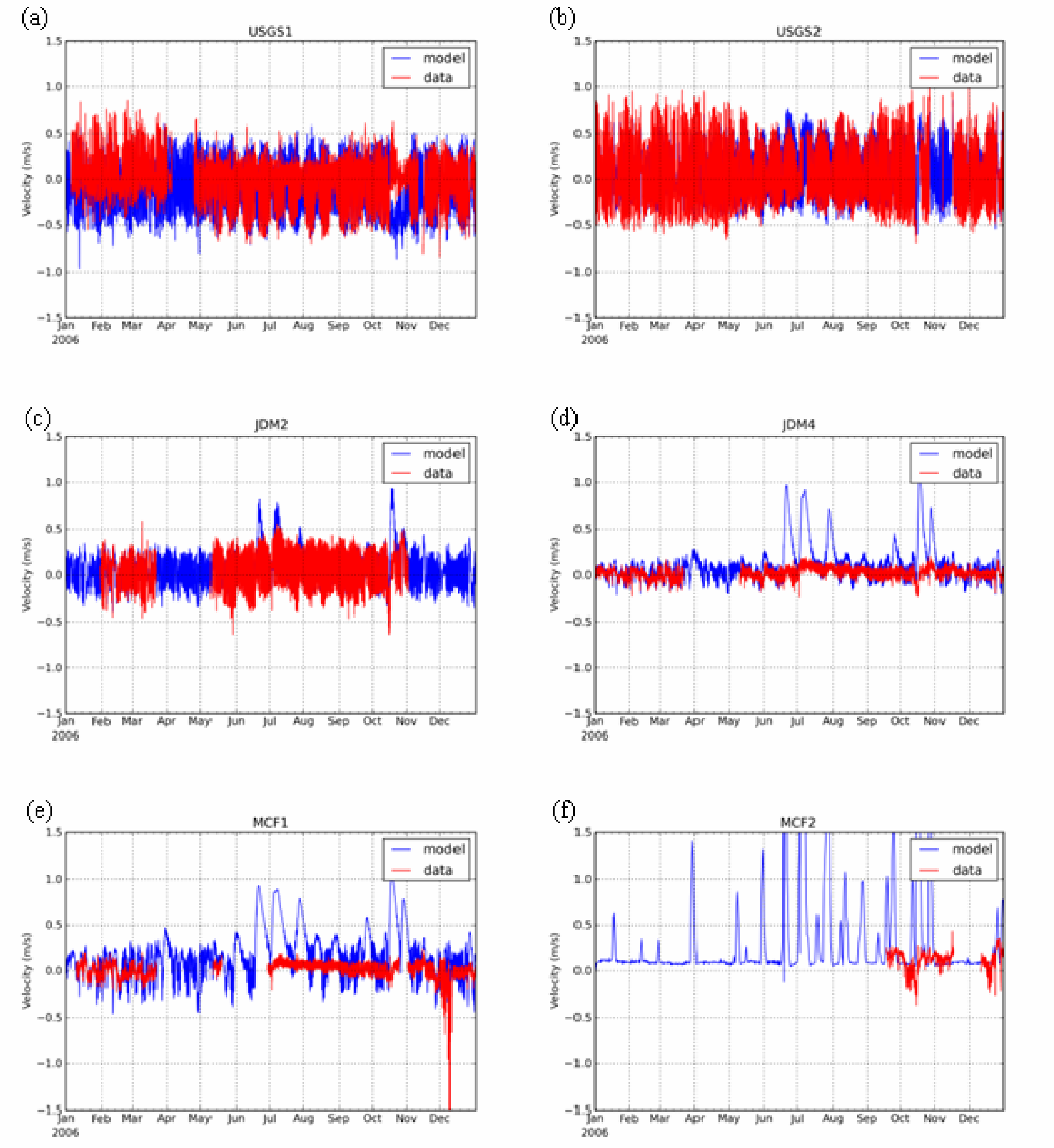

Figure 3.7 Model generated water velocities for 2006 compared to empirical measurements of water velocities, at six long-term monitoring sites, (a) USGS1, (b) USGS2, (c) JDM2, (d) JDM4, (e) MCF1, and (f) MCF2. Positive velocity indicates downstream movement of water.

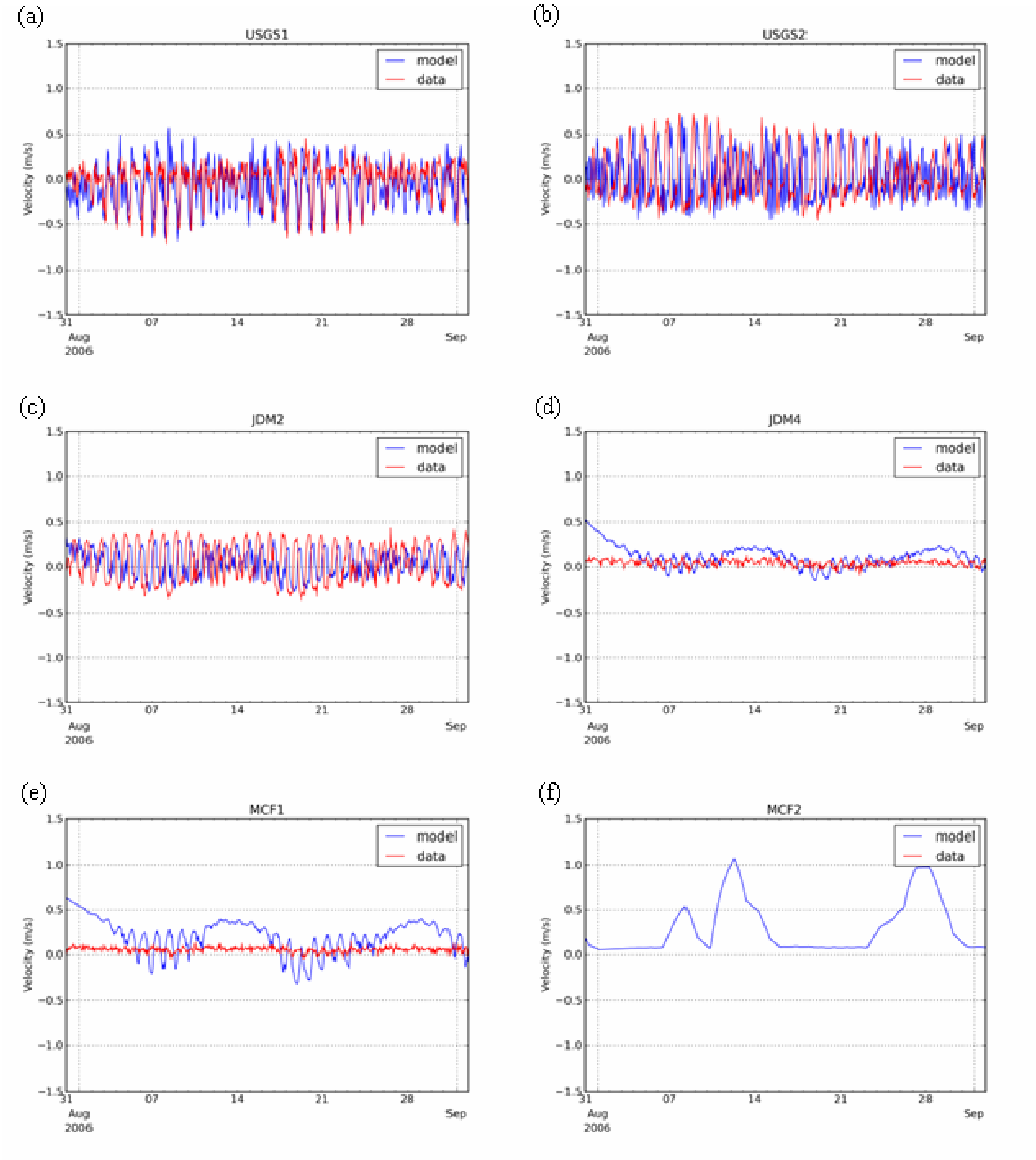

Figure 3.8 Model generated water velocities for August 2006 compared to empirical measurements of water velocities, at six long-term monitoring sites, (a) USGS1, (b) USGS2, (c) JDM2, (d) JDM4, (e) MCF1, and (f) MCF2.

3.5.4. Calibration Results for Salinity

The model captures major salinity trends during 2006 reasonably well, but misses some spikes in salinity and otherwise tends to underpredict salinity (Figure 3.9). Figure 3.9a shows the model's ability to represent salinity at the Fish Pass, which in a sense is the driver of salinity throughout the system. Figures 3.9c to 3.9f show the model's ability to capture salinity trends throughout the system. From simulations, we know that the westernmost sites are influenced more by the rainfall-runoff estimates from TxRR than by conditions associated with the Fish Pass.

Figure 3.9b (JDM1) shows model results at the intersection between Johnson Lake and Keith Lake, the primary location for which J.D. Murphree WMA has set a target salinity for wetland management. The model's response at this location was carefully examined. While the model captures most major salinity swings, there are a significant number of events missed by the model. Further analysis showed that there is a complex balance between four sources of water:

(1) Freshwater inflows primarily from the Sabine and Neches rivers,
(2) Saline water coming from the GIWW,
(3) Saline water tidally forced into the system from the Gulf of Mexico, and
(4) Water (fresh or saline) flowing from Star Lake on the western side of the system.

The first three sources form a balance that determines the salinity of water being pushed into the system through the Fish Pass, whereas the volume and salinity of water flowing downstream from Star Lake determines the extent of salinity intrusion into the system. High salinities in Star Lake and Five-mile Cut seem to be determined by factors other than the Fish Pass. These factors were not explored in the model but likely are related to erosion along the beach ridge and subsequent overwash from the Gulf of Mexico into marshes west of Perkin's Levee (Figure 1.2)

The Keith Lake/Johnson Lake area of the system seems to lie in a transition zone where salinity shifts based on the balance between sources of water entering the system. The constantly shifting balance creates a continual flux of saline and freshwater pulses traveling back and forth through the system (Figure 3.10). This is in contrast to the natural West-to-East, fresh-to-saline gradient which historically characterized Salt Bayou. This highly transient and complex balance is difficult for the model to capture.

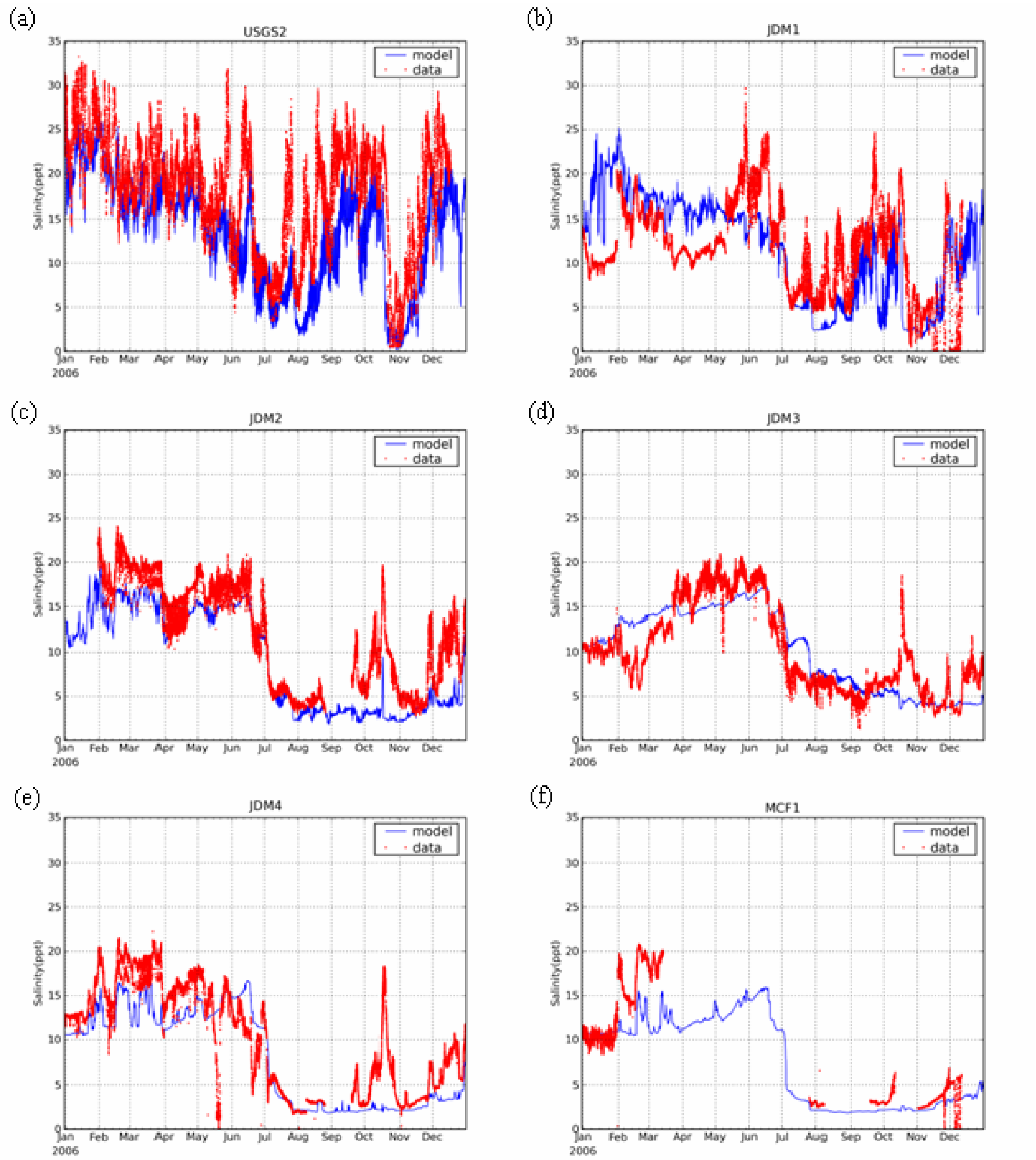

Figure 3.9 Model generated surface water salinity compared to empirical measurements of salinity, at six long-term monitoring sites, (a) USGS2, (b) JDM1, (c) JDM2, (d) JDM3, (e) JDM4, and (f) MCF1.

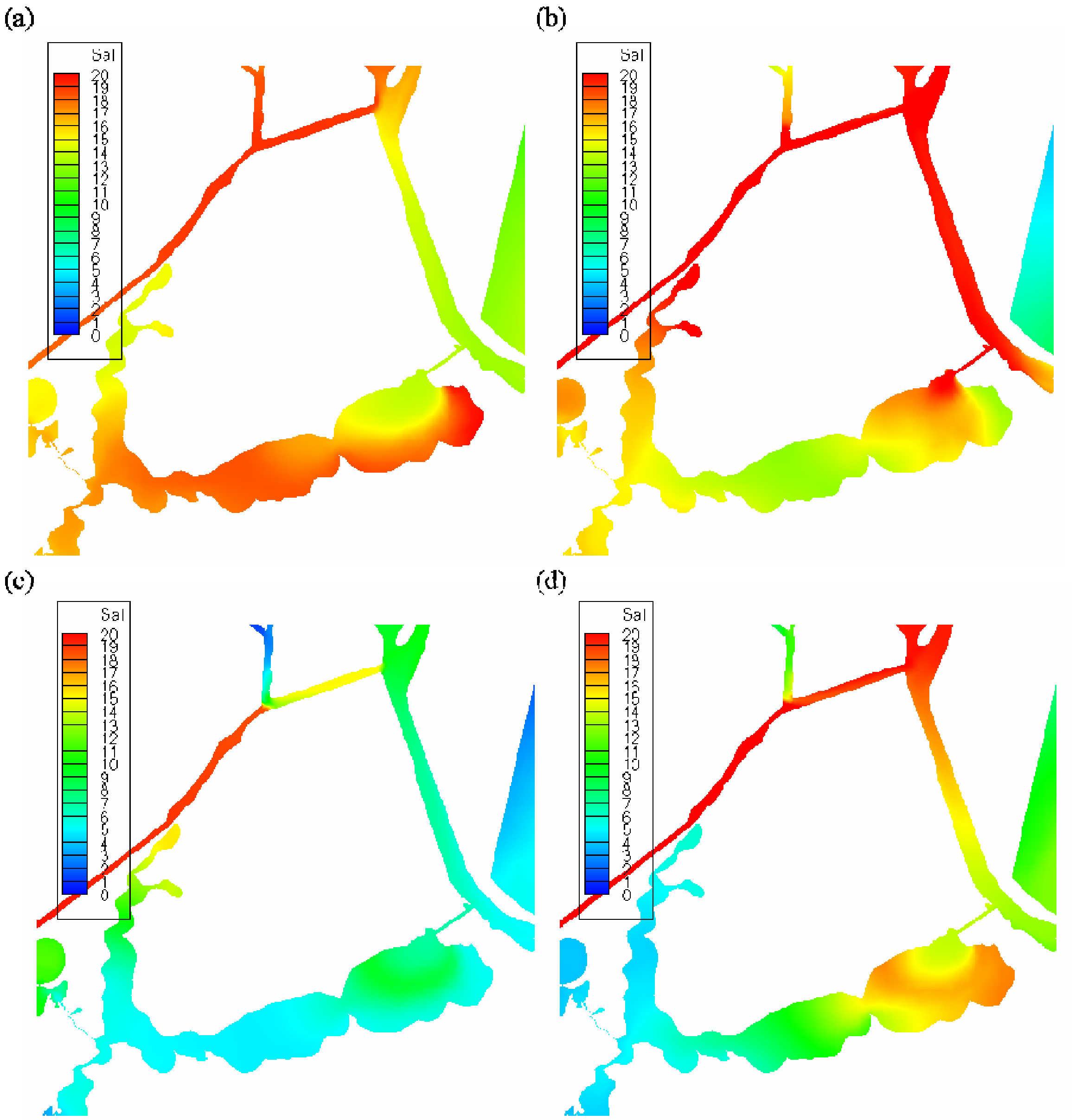

Figure 3.10 Model generated surface water salinity in the Salt Bayou system reveals ever-changing patterns of salinity zonation responding to shifts in the balance of four sources of water (a) day 55 (February 24, 2006), (b) day 168 (June 17, 2006), (c) day 204 (August 23, 2006), and (d) day 357 (December 23, 2006).

3.5.5. Calibration Results for Temperature

The model shows excellent agreement between simulated water temperatures and field data for 2006 (Figure 3.11). This is surprising since no effort was made to calibrate the temperature module in the model. It is our assumption that the relatively shallow nature of the system precluded much lateral temperature transport, and the temperature variations were mostly due to direct heating by solar radiation. Note also that the temperature profiles of field data are almost identical at all sites.

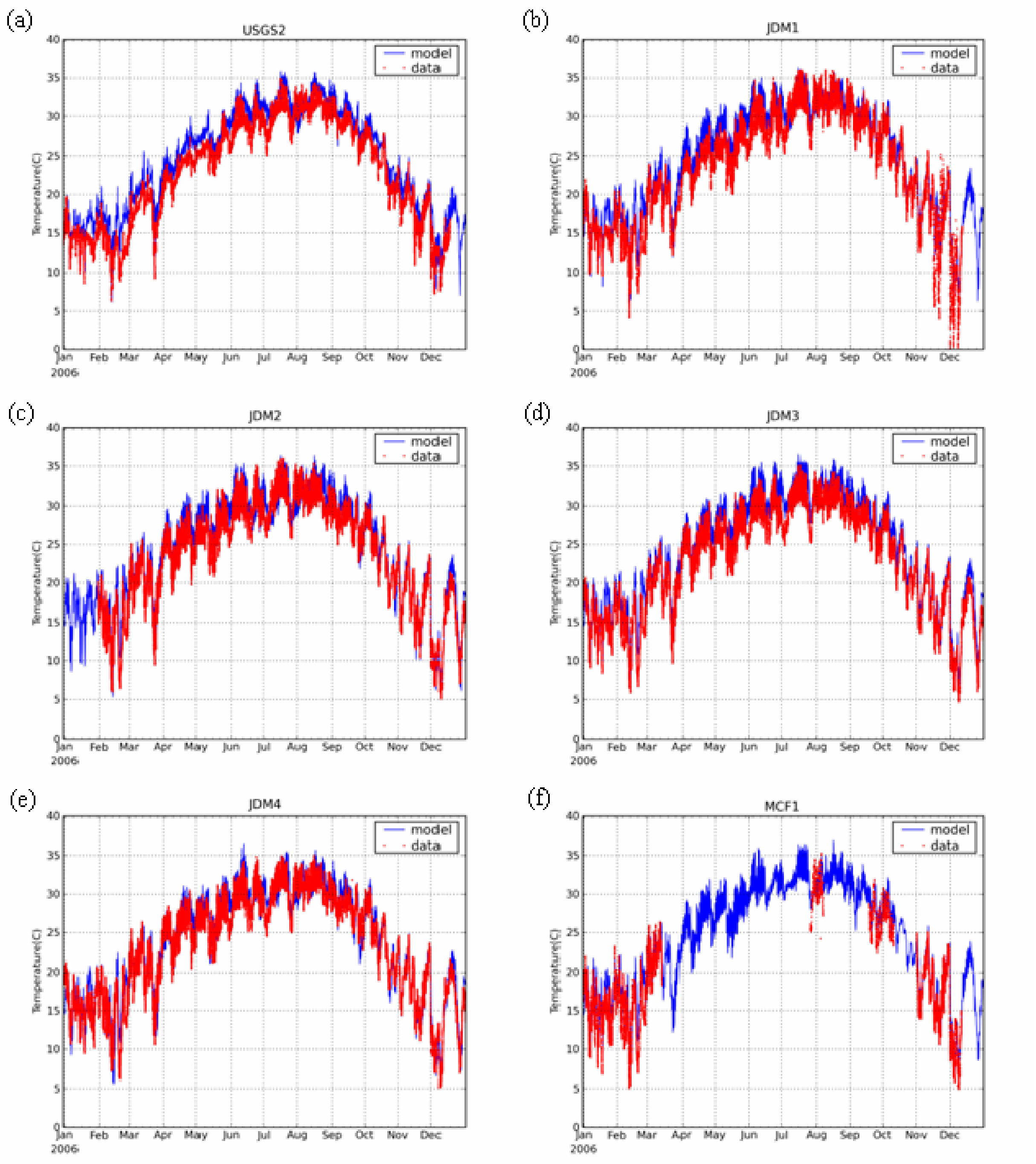

Figure 3.11 Model generated surface water temperatures compared to empirical measurements of surface water temperature, at six long-term monitoring sites, (a) USGS2, (b) JDM1, (c) JDM2, (d) JDM3, (e) JDM4, and (f) MCF1.

3.5.6. Summary of Model Calibration

The inflow and salinity boundary conditions at Five-mile Cut have emerged as a critical parameter in the modeling of this system, and model results are sensitive to the specifications of these boundary conditions. The inflow boundary at this location is determined solely on rainfall-runoff estimates, which are not as robust as inflows estimated using USGS stream gauge data. (No USGS stream gauges are located within the Salt Bayou watershed.) Therefore, the estimation of inflows at this location may be inaccurate for a number of reasons:

(1) The spatial resolution of NEXRAD precipitation data is much lower prior to 2004 making estimates for those years less accurate.

(2) Rainfall-runoff estimates used to model inflows at Five-mile Cut are based on an existing watershed delineation used in the TWDB coastal hydrology dataset for Sabine Lake and does not accurately delineate the Keith Lake/Salt Bayou system. For example, in Figure 3.4, the TxRR watershed delineation includes a portion of land north of the GIWW which does not actually drain into Salt Bayou, but rather into the GIWW. The TxRR watershed boundary also excludes areas west of Star Lake. The western boundary of this watershed lies 4.5 miles west of Star Lake (Fisher 1988); none of this area is included though it likely provides an important source of runoff to Salt Bayou.

(3) The hydrodynamic model presently applies TxRR inflow estimates for the entire watershed at upper Five-mile Cut. A more accurate approach would be to apply estimates of localized runoff at multiple inflow locations throughout the system.

(4) The hydrodynamic model (*base grid,* Figure 3.1) excludes certain regions, such as Wild Cow Bayou (refer to Figure 1.2), that may be sources or sinks of water.

(5) A lack of information regarding the operation of the control structure at the juncture of Star Lake and Five-mile Cut, which is used to isolate Star Lake from the rest of the system, creates uncertainty in streamflow through Five-mile Cut.

Salinity at Five-mile Cut is even more difficult to determine than inflows. In the present model, TWDB field data was used to set this boundary condition for the 2006 calibration runs, but in other years (*i.e.,* 2003), data availability is sporadic. Efforts to relate the 2006 salinity data at Five-mile Cut to data available over a longer period, such as precipitation, were not successful. Salinity at Five-mile Cut appears to be dependent mainly on factors further west in the system, rather than the Fish Pass. The highlighted areas of Figure 3.12 show periods when the interior marsh (as represented by MCF2 at Five-mile Cut) had higher salinities than Keith Lake, suggesting a western salinity source. This was confirmed with an evaluation of the timing of salinity peaks which showed that the peaks recorded at MCF2 traveled east through the system.

The western GIWW boundary condition also emerged as being more important than originally expected. Water moving eastward along the GIWW enters the SNWW and influences salinity at the Fish Pass. While reasonable estimates of salinity and water surface elevation were generated using data from TPWD and DD6, a larger scale model that includes surrounding bays may be necessary to obtain better estimates of flows and salinities in the GIWW.

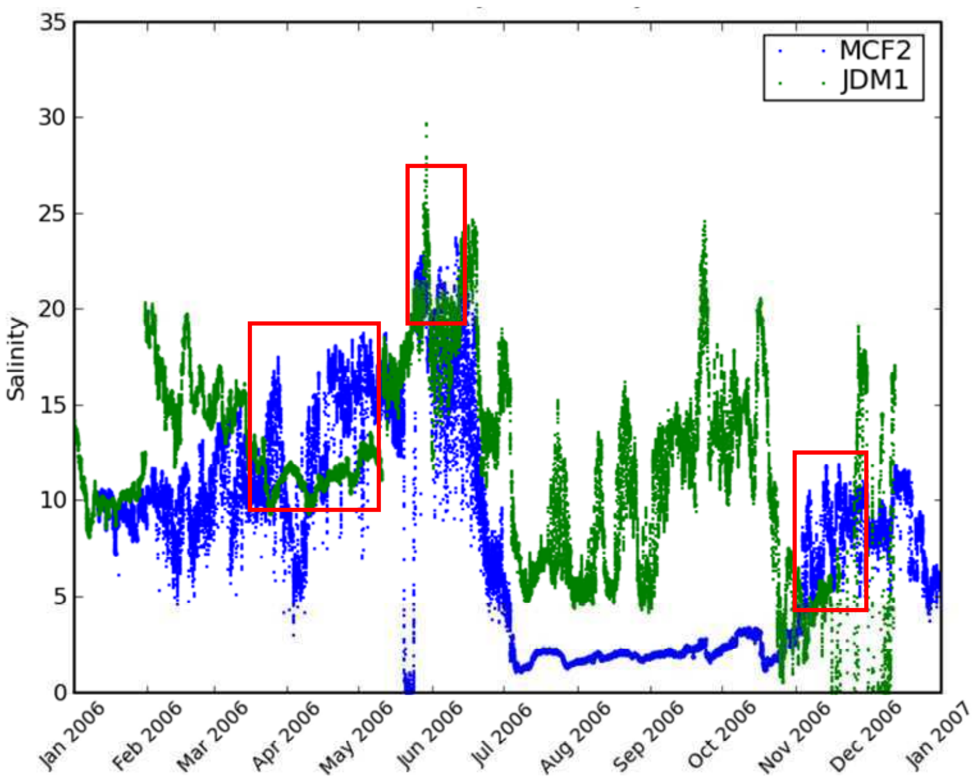

Figure 3.12 Salinity data collected from opposite ends of the system, JDM1 at the junction of Keith Lake and Johnson Lake near the Fish Pass (green) and MCF2 in lower Five-mile Cut (blue), show periods when salinity is higher at MCF2 in the western portion of the system, suggesting an additional source of salinity to the interior marsh.

4. DEVELOPMENT OF MANAGEMENT SCENARIOS

4.1. Feasibility

We developed a hydrodynamic and salinity transport model for the Keith Lake/Salt Bayou system to serve as a tool for evaluating the potential for various management strategies to reduce salinity levels in the system. Following a series of meetings, area wildlife managers and other stakeholders requested that TWDB evaluate the effectiveness of passive, inverted siphons to bring freshwater from the watershed north of the GIWW into Salt Bayou. This mitigation strategy is based on the notion that water levels are higher in the marshes and lakes to the north of the GIWW than south of the GIWW. This difference in water level then can be used to drive flow through a siphon, installed under the GIWW, and into Salt Bayou, bringing a new source of freshwater into the southern marsh complex.

In partnership with Jefferson County Drainage District No. 6 (DD6), water level gauges were installed to enable comparisons of water levels on either side of the GIWW. Using data from 2007 and part of 2008 for three gauge locations, Stupka’s Camp Upstream (north of GIWW), Chevron Duck Camp Marsh, and Salt Bayou Outfall Marsh (both south of GIWW, Figure 4.1), we determined the following. Water level at Stupka’s Camp Marsh is generally higher than at the two locations in the southern marsh. However, there are times when the levels are lower on the north side of the GIWW (Figure 4.2). Water levels at the two locations south of the GIWW do not follow the same trends, indicating that the pressure head available to run a siphon is spatially variable. A more complete study of the availability of water on the north side of the GIWW and a better estimate of pressure head available to drive water through the siphon is needed to truly understand the feasibility of such a project to provide freshwater to the marsh.

Figure 4.1 Three water level gauges installed and maintained by the Jefferson County DD6. These water level gauges enabled comparisons of water levels on either side of the GIWW at candidate locations for the installation of freshwater siphons. The gauges are, from east to west, Salt Bayou Outfall Marsh, Stupka's Camp Upstream (north of GIWW, but near Willow Lake), and Chevron Duck Camp Marsh (near the original upstream source for Star Lake).

4.2. Siphon Locations

The stakeholder group selected three potential siphon locations for scenario testing, Star Lake Control Structure, Willow Lake, and the Salt Bayou Control Structure (Figure 4.3). Locations were based on two criteria: (1) availability of a water source close to the GIWW in the northern marsh and (2) presence of an appropriate receiving water body close to the GIWW in the southern marsh. At each location we assume the inverted siphon to be a single 5ft diameter high-density polyethylene (HDPE) pipe. Siphon size was determined based on stakeholder input, taking into account the approximate cost of laying a single length of pipe.

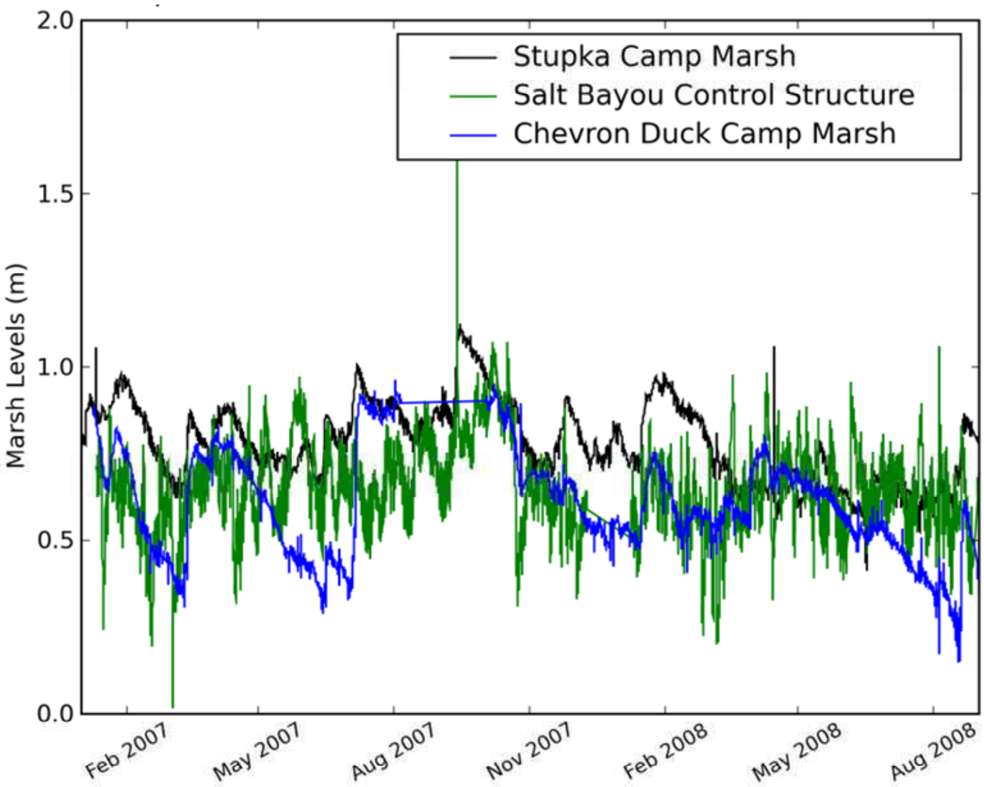

Figure 4.2 Comparison of water levels on the north side of the GIWW (black line, Stupka's Camp) to water levels on the south side of the GIWW (green line, Salt Bayou Outfall; blue line, Chevron Duck Camp). Water levels at the two locations south of the GIWW do not follow the same trends.

The three candidate locations for installation of a freshwater siphon include:

> Star Lake Control Structure (SL) – Location of a siphon at the head of Star Lake mimics the natural hydrology of the system prior to human alteration. Freshwater would be supplied by the northern section of Salt Bayou, north of the GIWW.
>
> *Note*: Star Lake has been excluded from the hydrodynamic model domain, for several reasons including: (1) it is typically hydrologically separated from the rest of the system by a levy and control structure on Five-mile Cut; (2) data on salinity trends in Star Lake are unavailable; and, (3) operations of the Five-mile Cut control structure are not known in sufficient detail for application in the model. For these reasons, it is difficult to include Star Lake in the hydrodynamic model. Hence, the Star Lake siphon inflow is actually applied at the Five-mile Cut inflow point in the model grid.

Willow Lake (WL) – was chosen as a reasonable receiving location, because of its proximity to Willow Slough and was considered to be a good source of freshwater (J. Sutherlin, TPWD *pers. comm*.).

Salt Bayou Outfall (SBO) – The Salt Bayou control structure was chosen as a receiving location, because it is a practical location for installing a siphon and has a water source nearby in the northern marsh.

Figure 4.3 Features of the Salt Bayou wetland system along with three proposed freshwater siphon locations, from east to west, Salt Bayou Outfall siphon, Willow Lake Siphon, and the Star Lake siphon. Because Star Lake was not included in the model domain, a fourth location, shown at the lower end of Five-mile Cut, represents the point at which estimated flows from the Star Lake siphon enter the system for model simulation.

4.3. Choice of Scenario Year

Area land managers are interested in the ability of structures and practices to mitigate endemic salt intrusion and not extreme events. Therefore, local stakeholders requested that mitigation scenarios be based on a year representing typical hydrology, precipitation, and biology for the system. To determine a typical year, we analyzed precipitation and freshwater inflow for the system using rain gauge data from the City of Port Arthur (NWS COOP ID#417172, 1977-2007) for precipitation and combined USGS stream gage data for Sabine-Neches freshwater inflows (1977-2006). Years were ranked according to their normalized deviation from a mean monthly distribution for both precipitation and inflow (Eq. 1). This ranking procedure calculated the seasonal distribution of precipitation and freshwater inflow for a particular year and compared both to the mean historical distribution of precipitation and inflow. Hence, a particular year may have a cumulative precipitation or freshwater inflow similar to the average annual value, but still may rank low if the seasonal distribution differs from the average historical distribution. The highest ranking years were considered to be most typical for the study area.

$$RankofYear = \sum_{SumOverMonthsinYear} \frac{MonthlyValue - nYearMonthlyMean}{< nYearMonthlyStdDeviation >} \tag{1}$$

After ranking all years for precipitation and inflow, 1985 and 2003 were determined to be the most representative of precipitation and inflow (Table 4.1). However, the stakeholder group suggested that conditions during 1985 may not be relevant for studying today’s management issues, especially considering data availability issues for that time period. Instead, stakeholders selected 2003 as the target year for evaluating the siphon management strategy. In addition, fisheries experts deemed 2003 as acceptable from a biological standpoint (J. Ditty, National Marine Fisheries and J. Tolan, TPWD, *pers. comm.*), in part because fisheries productivity (based TPWD Coastal Fisheries data) appeared consistent with patterns of inflow and other factors.

Table 4.1 Ten most typical years, for the period 1977-2007, as based on a ranking of the normalized deviation of precipitation or freshwater inflow from the mean annual distribution over the period of record.

Rank	**Precipitation (1977-2007)**		**Inflow (1977-2006)**	
	Year	**Normalized Deviate**	**Year**	**Normalized Deviate**
1	1997	6.022	1993	5.481
2	**1985**	6.303	1987	5.566
3	1983	6.928	**1985**	5.776
4	1995	7.715	1977	5.932
5	**2003**	7.887	1984	6.594
6	2007	7.960	**2003**	6.966
7	1994	8.094	1992	7.175
8	1977	8.244	1990	7.342
9	1981	8.394	2005	7.384
10	1996	8.509	1983	7.404

4.4. Siphon Flow Estimates

For simulation, siphon flows were estimated as the flow rate (V) provided by a single 5ft diameter HDPE siphon based on the Hazen-Williams friction loss equation (Eq. 2, Weiner and Matthews 2003, p. 122). Total siphon length of 1,600ft was based on the width and depth of the GIWW.

$$V_{HDPE} = k\ C\ R^{0.63}\ (h_f/L)^{0.54} \tag{2}$$

Where:

- k is a conversion factor for the unit system (k=1.318 for US customary units, k=0.849 for SI units)
- C is a roughness coefficient (set at C=155)
- R is the hydraulic radius
- h_f is the head loss (*i.e.*, difference between water levels on either side of the siphon)
- L is the total length of the siphon/pipe

Siphon flow estimates were developed by assuming that siphon flow is unidirectional, with no reverse flow when the water levels are higher in the marshes south of the GIWW. Using water level data available from 2007-2008 in this equation, the approximate flow supplied by a 5ft x 1,600ft siphon varied between 0 and 120cfs (0 to 3.4m^3/s; Figure 4.4). Since the estimated mean siphon flow was 54cfs at Star Lake and 52cfs at Willow Lake, 50cfs (1.42m^3/s) was chosen as reasonable approximation of flow that could be provided by a siphon in this region. This is an idealized situation in which we assume that the presence of the siphon does not affect the relative water levels and that the relative water levels are constant throughout the model run. In reality, the head of water present would decrease as water flows through the siphon and would vary due to relative changes in water levels to the north and south of the GIWW.

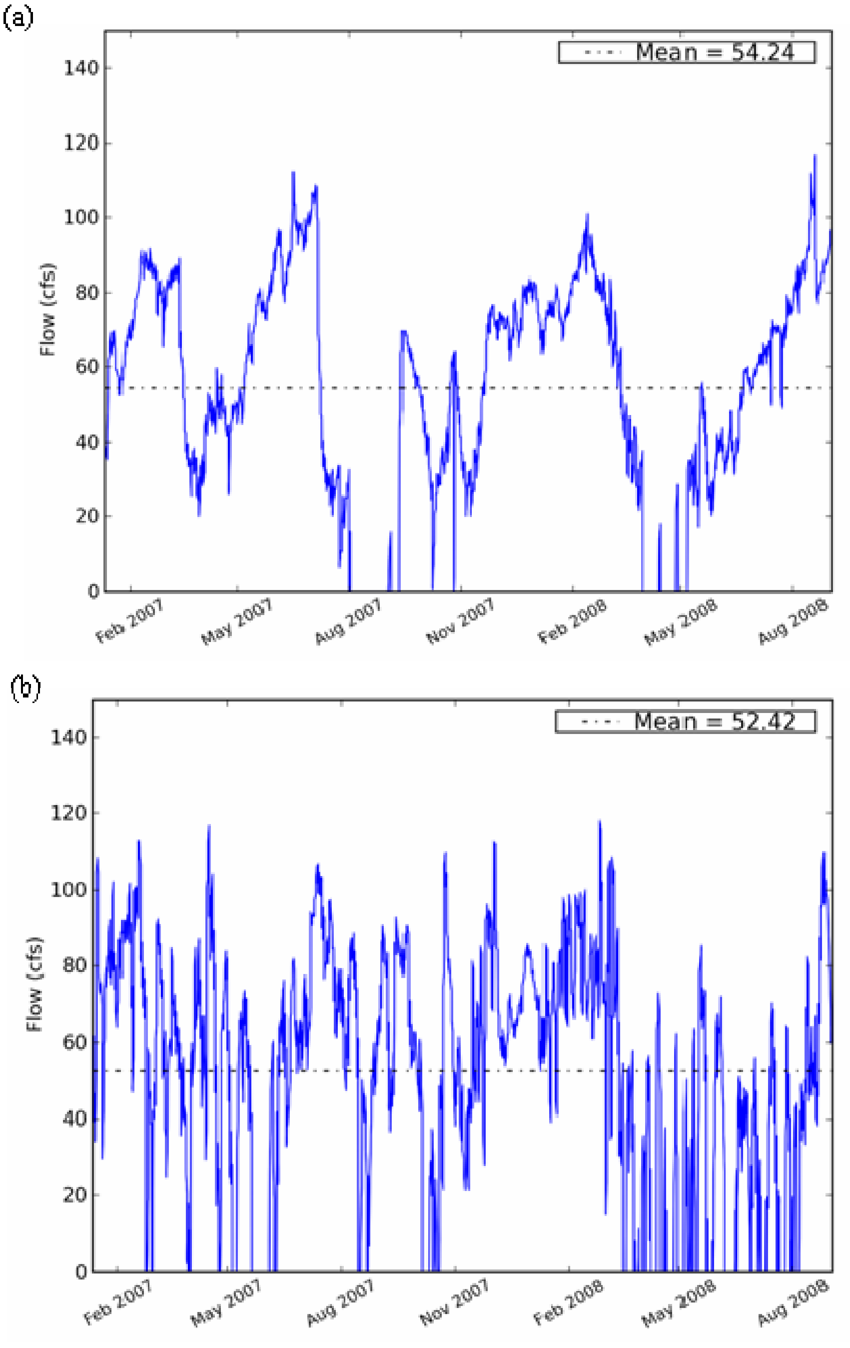

Figure 4.4 Estimated siphon flows for (a) Star Lake with a mean siphon flow of 54.24cfs and (b) Willow Lake with a mean siphon flow of 52.42cfs.

4.5. Scenarios Evaluated

A total of 12 scenarios were conducted to evaluate the salinity mitigation capabilities for each of the three proposed siphon locations (Star Lake, Willow Lake, and Salt Bayou Outfall) for the target year 2003. The scenarios can be divided into two sets based on their objective goals. The first set of scenarios included a full one-year simulation based on a reasonable, constant siphon flow of 1.42m^3/s (50cfs), to evaluate which location offered the best net salinity reduction in the system. The second set of scenarios included shortened two-month seasonal simulations, conducted for each of the three siphon locations, to evaluate the importance of siphon flow rate on salinity mitigation at that location. The differing flow rates consisted of:

1. A constant siphon flow of 1.42m^3/s (50cfs)
2. A constant siphon flow of 2.84m^3/s (100cfs)
3. A linearly decreasing siphon flow starting at 1.42m^3/s (50cfs) and decreasing to 0m^3/s over the two-month period

These abbreviated simulations were necessary, because the computational time associated with conducting individual year-long model runs was too long. Instead, two-month simulations were selected to capture conditions during August and September when salinity was highest in the system. The first siphon flow rate, 1.42m^3/s (50cfs), was based on the estimated average flow for a 5ft diameter siphon, as calculated in the previous section and as used in the one-year scenarios. The second siphon flow rate doubled the estimate to 2.84m^3/s (100cfs). The last siphon flow rate attempted to examine the effect of a decreasing flow over time as water levels on both sides of the siphons equalize. In reality, this reduction would not be linear and would depend on available water supply. A summary of the scenarios discussed in this report are presented in Table 4.2. Other scenarios, such as those with multiple active siphons, were simulated but are not presented since the results are similar to the individual siphon runs presented here.

Table 4.2 Summary description of 12 siphon flow scenarios evaluated for salinity mitigation at three locations, Salt Lake Control Structure (SL), Willow Lake (WL), and Salt Bayou Outfall (SBO).

Scenario Run Duration	**Siphon Inflow Rate**		
	1.42m^3/s	**2.84m^3/s**	**Flow decreases linearly 1.42m^3/s to 0m^3/s**
1-year runs (2003)	SL, WL, SBO	-	-
2-month runs (Aug & Sep 2003)	SL, WL, SBO	SL, WL, SBO	SL, WL, SBO

The effectiveness of each scenario was evaluated by comparing salinity levels at six representative locations throughout the system (Table 4.3, Figure 4.5). These sites do not necessarily correspond to the previously described data collection sites shown in Figure 2.3. Of particular importance to this study is the mitigation of salinity levels in Keith Lake. Sites 1 and 2 correspond to the Fish Pass and the junction between Keith Lake and Johnson Lake, respectively. Site 3 is near the Salt Bayou Outfall (control structure). Site 4 is near Demayah's Dock at the junction of Shell Lake and Mud Lake. Site 5 is in the center of Salt Lake, and Site 6 is in the center of Clam Lake.

Table 4.3 Description of six locations selected for evaluating salinity mitigation based on model results from 12 siphon flow scenarios.

Location	**Description**	**Latitude**	**Longitude**	**Nearby Field Sites**
SITE 1	Keith Lake Fish Pass	29.772291°N	93.946215°W	USGS2 JDM-I
SITE 2	Junction of Keith and Johnson Lake	29.754957°N	93.970782°W	JDM1 JDM-O
SITE 3	Salt Bayou Outfall (at control structure)	29.788773°N	94.010959°W	JDM-F
SITE 4	Junction of Shell and Mud lakes	29.742512°N	94.029728°W	JDM2 JDM-C
SITE 5	Center of Salt Lake	29.719398°N	94.013695°W	JDM3 JDM-Q
SITE 6	Center of Clam Lake	29.687554°N	94.102066°W	MCF1 MCF2

Figure 4.5 Location of six sites representative of conditions throughout Salt Bayou used for comparison of salinity mitigation results generated by 12 siphon flow scenarios.

5. RESULTS

5.1. Comparison of Recent and Historical Conditions

The study of the Keith Lake/Salt Bayou system began with the goal of providing local land managers a tool for evaluating management scenarios designed to reduce surface water salinity throughout the system. One overall goal held by staff at McFaddin NWR and J.D. Murphree WMA is to enhance the natural west-to-east pattern of freshwater flow through the system. In particular, TPWD and J.D. Murphree WMA have adopted a target salinity range of 0-10ppt for the intersection between Johnson and Keith lakes and are exploring other mechanisms to reduce salinity at this location and elsewhere in the system (N. Kuhn, TPWD, *pers. comm.*). The study described herein addresses both of these management goals under typical – as opposed to extreme – conditions.

Data collection for model development occurred primarily in 2006 and provided an extensive data set with high spatial and temporal resolution of the system. A range of historical precipitation, freshwater inflow, and salinity data also was available from various sources for additional analyses, including a comparative analysis of historical conditions versus the target year 2003 and model calibration year 2006. Analysis of these data sets shows:

1. Freshwater inflows to Sabine Lake and precipitation across the region (as determined by the City of Port Arthur rain gauge (NWS COOP ID#417172)) have different temporal distributions. Peak precipitation occurs in late summer to fall while peak freshwater inflows typically occur in the spring.

2. In addition to being ranked in this study as the 5th and 6th most typical year for precipitation (1977-2007) and freshwater inflows (1977-2006), respectively, year 2003 is within ±1s.d. of the mean for all months with respect to freshwater inflows and for 10 months (excluding May and September) with respect to precipitation. May 2003 had no recorded precipitation, while September was above normal with 12 inches of precipitation.

3. Year 2006 ranked in the bottom five years for both annual precipitation (rank is 29/32) and total freshwater inflow (rank is 26/30). Although the cumulative amount of precipitation and inflow for 2006 are not extremes, the seasonal distribution in 2006 is very different from the historical pattern.

4. Salinity varies both spatially and temporally within and between years.

5.1.1 Recent Versus Historical Hydrology

Precipitation and freshwater inflow were obtained for a 30 year period beginning in 1977. Both have strong patterns of inter-annual variability, but no long-term directional trends (Figure 5.1). Mean annual precipitation is 58 ± 12 inches, and mean annual total freshwater inflow to Sabine Lake is 192,143 ± 74,979cfs. In 2003, monthly precipitation mimicked the long-term mean pattern of seasonal precipitation (green line, Figure 5.2a); whereas, 2006 began with below normal precipitation and transitioned to above normal by mid-year (blue line, Figure 5.2a). Based on the definition of a typical year using the ranking procedure described in Section 4.3, these conditions resulted in 2003 ranking as the 5th most typical year for precipitation and 2006 as the 29th (out of 32 years). Freshwater inflow follows a similar trend in that 2003 ranks 6th and 2006 ranks 26th during a 30 year period. Figures 5.2b shows that inflows during January to April of 2006 are severely depressed relative to a typical year (*e.g.*, 2003) while October 2006 is well above the norm.

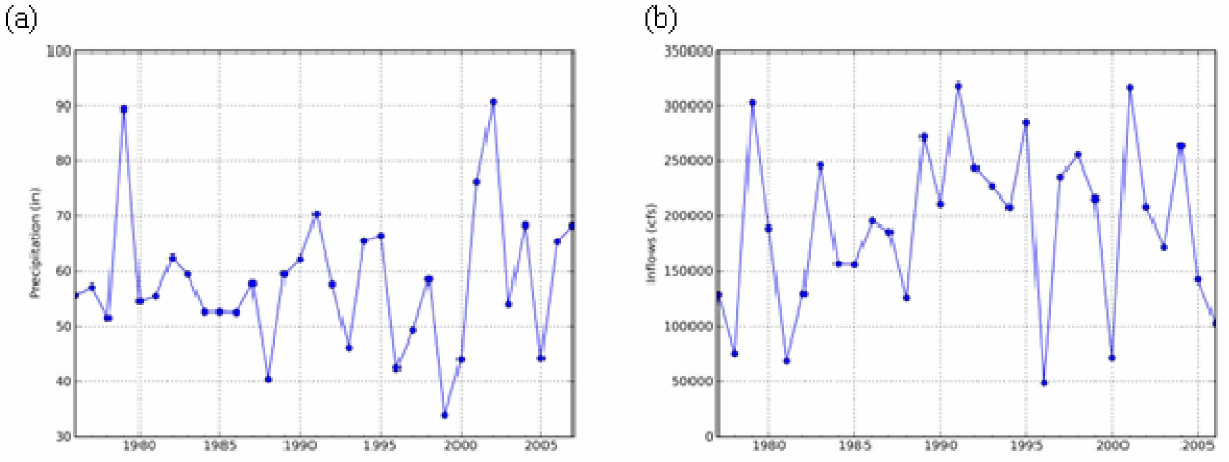

Figure 5.1 (a) Annual mean precipitation in the study region, as reported by City of Port Arthur rain gauge from 1977-2007 and (b) annual freshwater inflows from combined USGS stream gauge data for Sabine Lake (1977-2006).

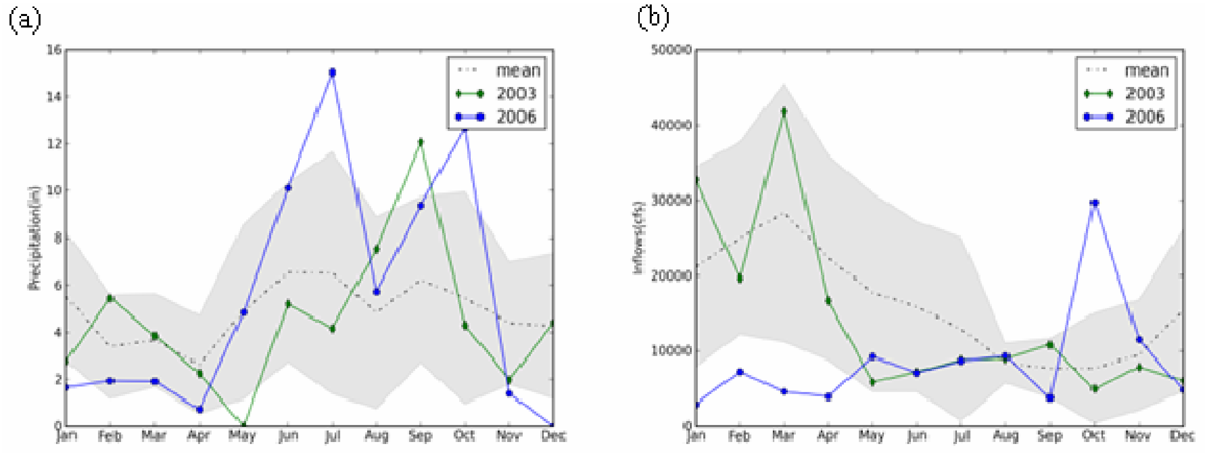

Figure 5.2 Comparison of average monthly precipitation and freshwater inflows during 2003 (green) and 2006 (blue) to the historical monthly average (dotted line with ±1sd as shaded area) for precipitation (1977-2007) and freshwater inflows (1977-2006); (a) precipitation as recorded at the City of Port Arthur rain gauge and (b) total freshwater inflow from combined USGS stream gauge data for Sabine Lake.

5.1.2 Recent Salinity Trends

Early studies reported average salinities ranging 4 to 6ppt in Keith Lake prior to September 1977 and the opening of the Fish Pass (USDA/SCS 1976). After opening the Fish Pass, salinities in Keith Lake rapidly increased to 12ppt (Bales *et al.* 1974, Stelly 1980) and today frequently remain at or above this level (Figure 5.3). Salinity data is limited or unavailable prior to 1988, so only recent, post-Fish Pass trends can be examined. Fortunately, semi-monthly salinity data is available for 15 sites in the J.D. Murphree WMA (see Figure 2.2 for site locations). Here, we present data for six of the sites; I, F, and C with a period of record from 1988-2007 and sites O, Q, and T with a shorter period of record, 1999-2007. Annual mean salinity varied spatially across the six sites, with sites closer to the Fish Pass having slightly higher salinities (Figure 5.3). Additionally, salinity varied among years with some years averaging a 5ppt increase. From 2001 to 2006, mean annual salinity at all sites increased by 5 to 10ppt. Although only two months of data were available for 2007 (not shown) at the time of analysis, records showed that salinities dropped dramatically at all sites in the first part of 2007. It is unclear if this trend continued in 2007 and 2008. Interestingly, salinity peaks occur in 1996, 2000, and 2006. These peaks correspond to years with unusually low volumes of freshwater inflow to Sabine Lake (Figure 5.1b). In addition, the 2006 salinity peak likely includes residual effects from Hurricane Rita in

2005. Similarly, residual effects from Tropical Storm Dean (August 1995) may have contributed to the salinity peak seen in 1996. There was no corresponding tropical storm event during or prior to the salinity peak in 2000.

Figure 5.4 compares recent trends in monthly salinity data collected by J.D. Murphree WMA at six semi-monthly monitoring sites (see Figure 2.2 for site locations). In addition to showing the long-term mean (±1sd) monthly salinity, data for 2003 and 2006 are plotted to allow for comparison to recent trends and to each other. For this dataset, the period of record depends on the sampling location. Mean monthly salinity changes throughout the year at all monitoring locations, with most locations ranging between 5 and 15ppt (dashed line, Figure 5.4). Although mean monthly salinities tend to be elevated if not increasing during the summer, all sites except the entrance to the Fish Pass (Site I) experience a decrease in salinities during July. This may be due to high precipitation combined with medium inflow events during this period (see Figure 5.2a,b). Data for 2003 does not follow this long-term trend (green line, Figure 5.4) perhaps due to lower levels of precipitation in July 2003 (green line, Figure 5.2a). The system also shows broad variation in salinity for any given month, regardless of location (grey area, Figure 5.4).

In spring 2003, salinities across the system were lower than normal, but became more typical of the long-term trend during the rest of the year. In contrast, 2006 began with high salinities at all sites. In fact, sites F and C were exceptionally high (>17ppt) and well above the normal range of variation (Figure 5.4c, e). These high salinity values can be attributed to both the effects of Hurricane Rita which brought saltwater into the system during September 2005 and very low freshwater inflow and rainfall during the first half of 2006. A large rainfall event in June and July 2006 (Figure 5.2) likely is the reason salinities decreased in the system during the summer of 2006.

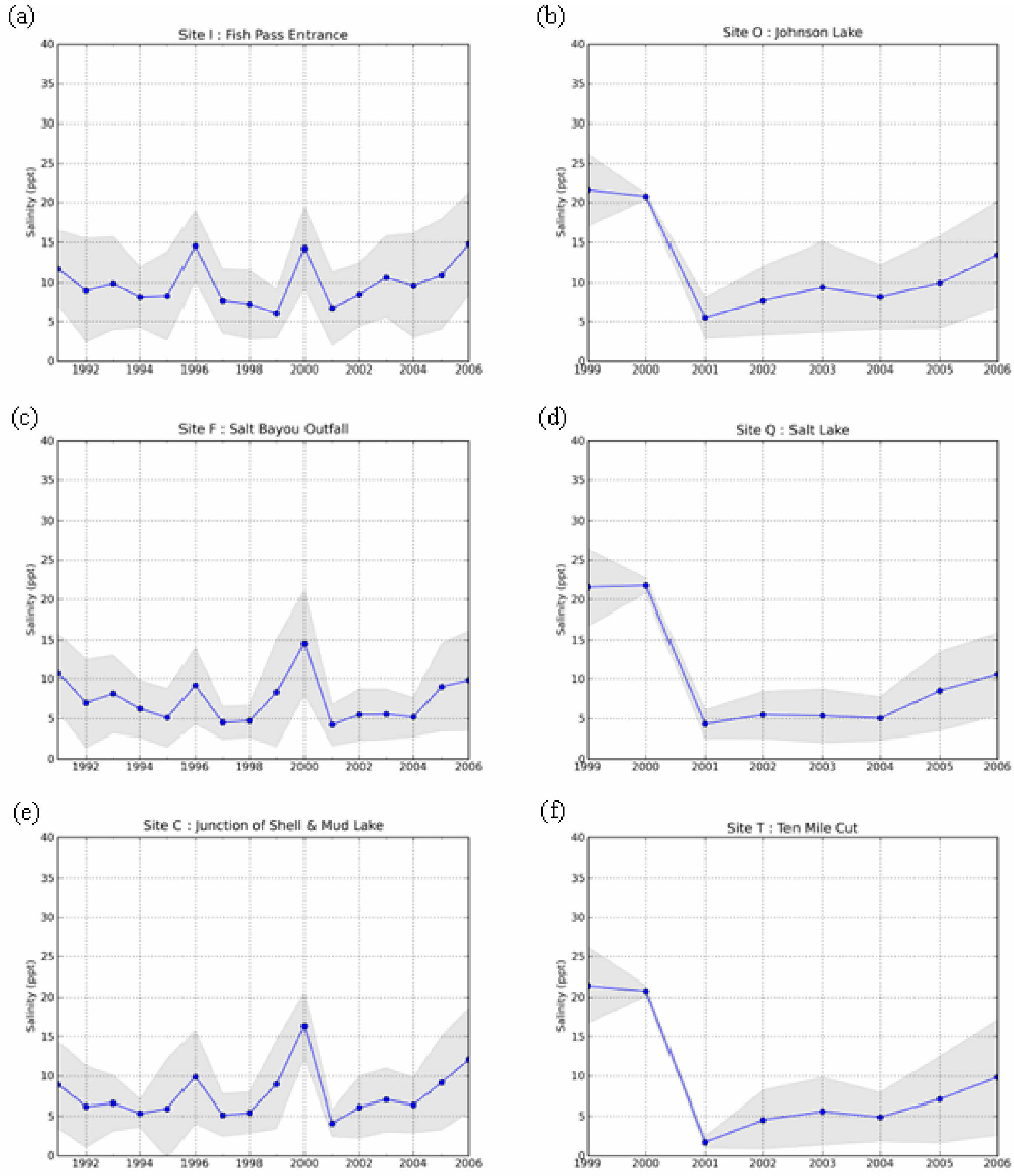

Figure 5.3 Annual mean salinity (based on TPWD's semi-monthly salinity data, ±1sd as shaded area) at six standard monitoring locations in the J.D. Murphree WMA; (a) Site I, (b) Site O, (c) Site F, (d) Site Q, (e) Site C, and (f) Site T. Sites I, F, and C were monitored from 1988–2007. Sites O, Q, and T were monitored from 1999–2006, except from November 2000 to May 2001.

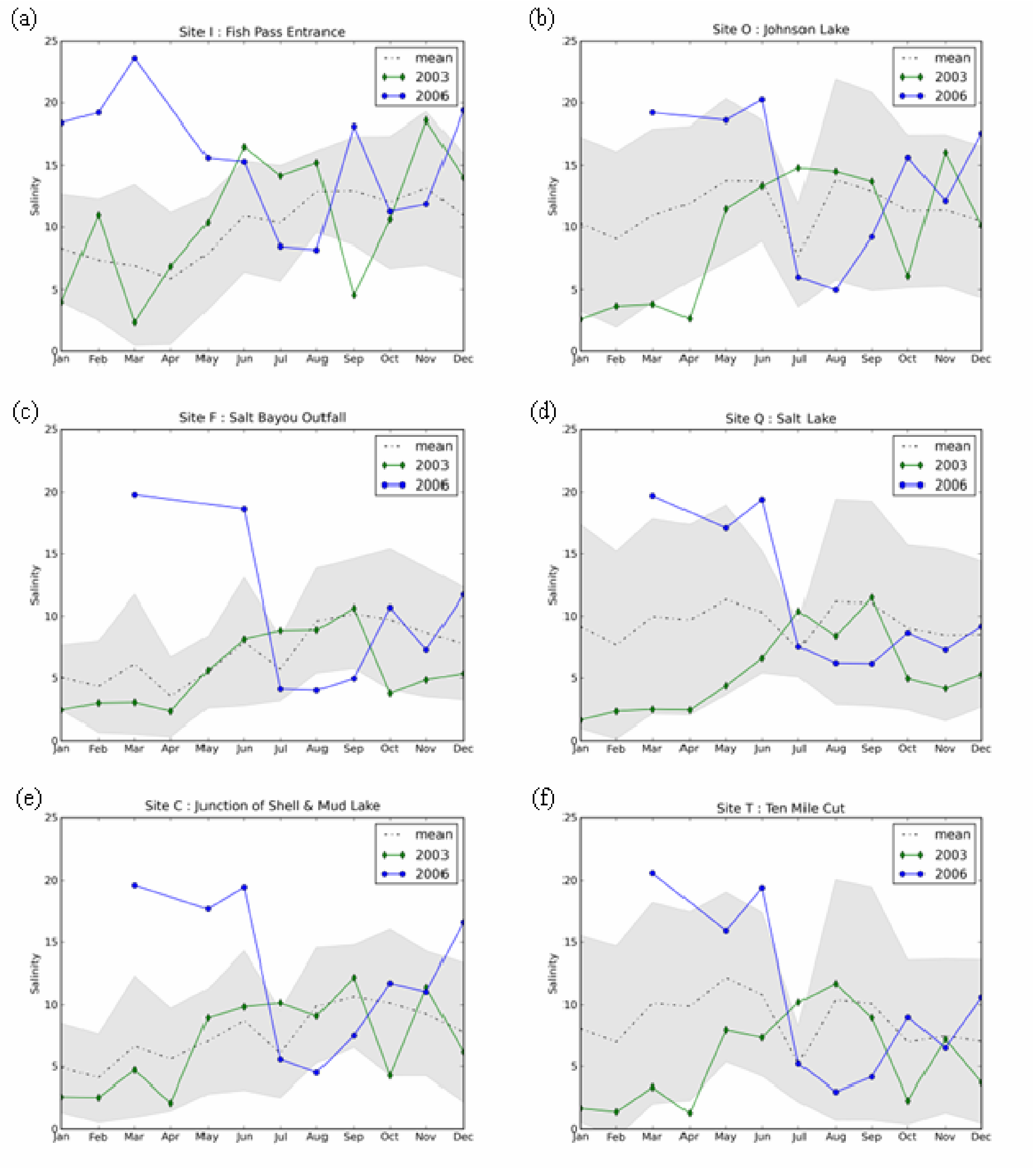

Figure 5.4 Comparison of TPWD semi-monthly salinity data in 2003 (green) and 2006 (blue) to the long-term mean (dotted line, ±1sd as shaded area) at six standard monitoring locations in the J.D. Murphree WMA; (a) Site I, (b) Site O, (c) Site F, (d) Site Q, (e) Site C, and (f) Site T. Sites I, F, and C were monitored from 1988–2007. Sites O, Q, and T were monitored from 1999–2006, except from November 2000 to May 2001.

5.2. 2003 Base Model Run

5.2.1. Description

Each siphon scenario model run was developed from a base run for the target year 2003. As noted above, 2003 was chosen with stakeholder input as the target year for scenario development and evaluation. This choice brought several challenges with regard to data availability. Certain datasets were not available, had missing data, or were available at lower spatial and temporal resolutions for 2003 compared to data availability in 2006. Attempts were made to fill in data gaps with additional sources or approximations where necessary. In particular, there were large data gaps along the GIWW tidal boundary condition and the Five-mile Cut salinity boundary condition, both of which emerged as important features in the 2006 model calibration runs. Another area of concern was the spatial resolution of NEXRAD precipitation data which is much lower at 16km x 16km in 2003 compared to 4km x 4km in 2006. This drop in resolution means that estimates of flow used to set the Five-mile Cut inflow boundary condition were less accurate in 2003 as compared to 2006. For the one-year simulation, initial conditions were constructed as outlined in *Section 3.4.5* for model calibration; temperature initial conditions were the same but salinity conditions reflected the target year 2003 (Figure 5.5). To initiate two-month scenario runs, the model was hot-started using model output for August 1 from the 2003 base run. This involves using modeled water surface elevation, velocity, salinity, and temperature from midnight October 30 in the 2003 base run to generate the initial conditions for the two-month scenario runs.

5.2.2. Comparison to Field Data

Although continuous field data is not available for 2003, semi-monthly point measurements were available, courtesy of TPWD/J.D. Murphree WMA, at fixed locations within the J.D. Murphree WMA portion of the system (see Figure 2.2). Figure 5.6 shows model-predicted salinities versus field measurements for six semi-monthly monitoring sites (JDM-I, O, F, Q, C, and T). Plots are arranged with the easternmost site in the upper left and the westernmost site in the lower right.

While the model was able to predict long-term salinity trends in the system, it was unable to capture shorter swings in salinity. In general, the model did a better job predicting salinity in the western half of the system. The model tended to underpredict salinities during the summer months in the eastern portion of the system..

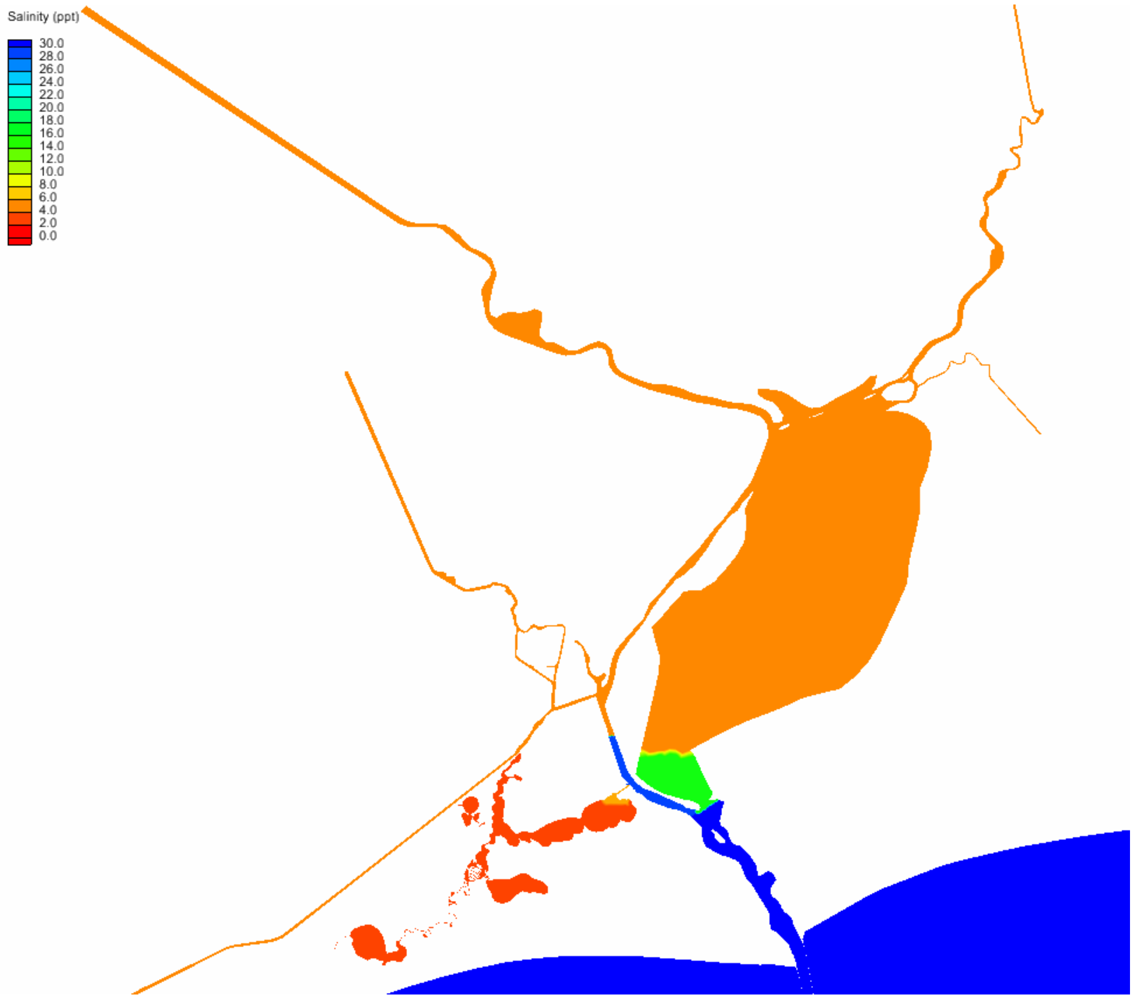

Figure 5.5 Schematic representing the initial salinity conditions in the 2003 model run.

It is presently unclear whether the underpredicted salinity values are due to data gaps, incorrect modeling assumptions, or salinity sources not included in the model domain. In comparing sites I, O, C, and T in Figure 5.7, salinity outside the Fish Pass (Site JDM-I, red line) is lower than salinities inside the system for much of the summer. This indicates that there may be an additional source of salinity, such as overtopping along the beach ridge due to high tides or tropical storms (*e.g.*, Grace or Claudette) that is not accounted for in the model. When the TWDB 2006 continuous salinity data is plotted with data from the nearest J.D. Murphree WMA semi-monthly sampling location (Figure 5.8), two important lessons are revealed: (1) the semi-monthly data does not capture the high-frequency variation in salinity which is characteristic of this system and (2) there are particular instances where the two datasets differ by more than 5ppt. This may be explained by sampling error, salinity stratification, or localized freshwater runoff contributing to spatial variation in salinity. Hence, the use of the semi-monthly salinity data to drive the 2003 model runs may be one source of error contributing to underpredicted salinity values.

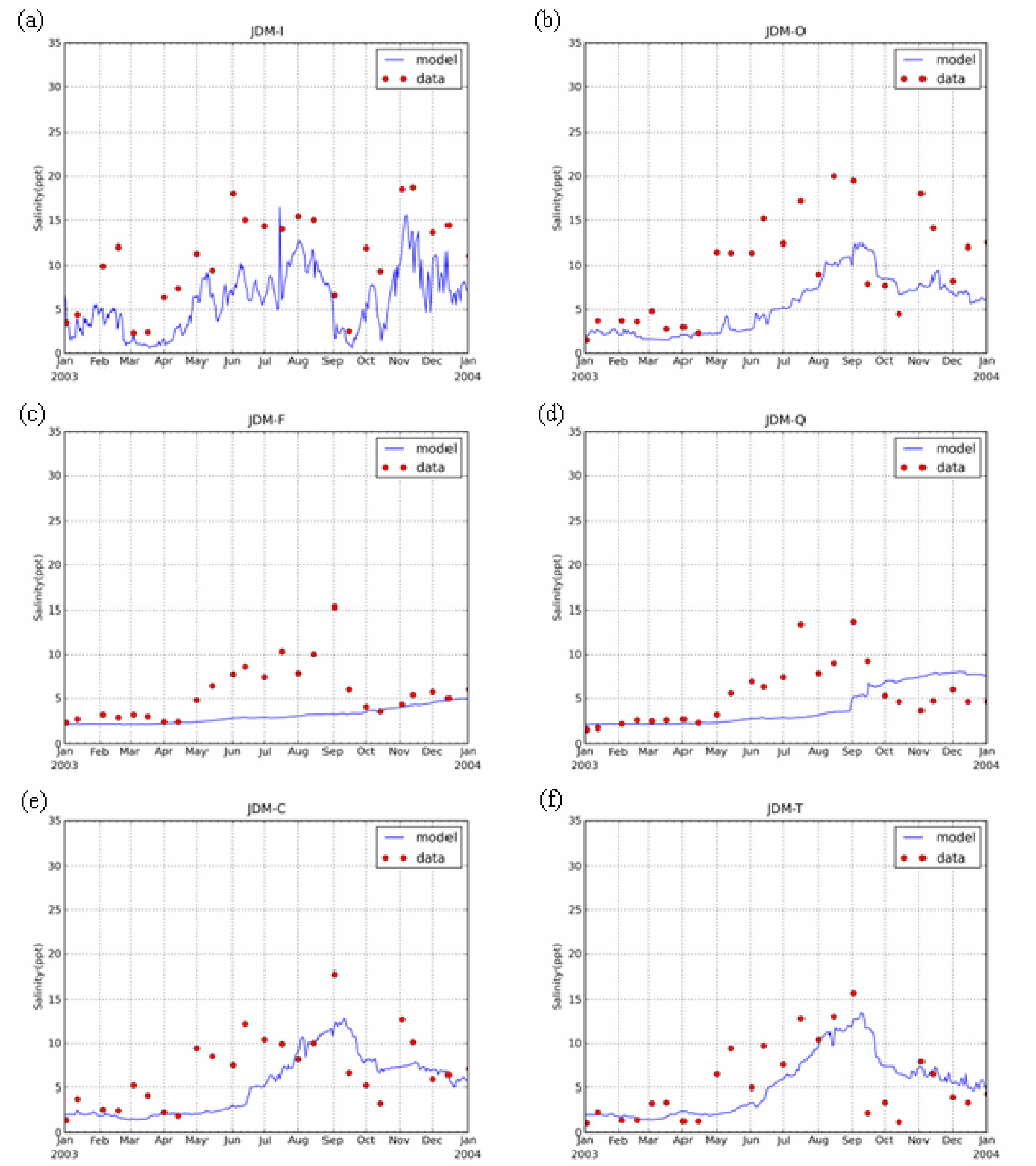

Figure 5.6 2003 model-predicted salinities versus TPWD semi-monthly point measurements of salinity at six standard monitoring locations in the J.D. Murphree WMA; (a) JDM-I, (b) JDM-O, (c) JDM-F, (d) JDM-Q, (e) JDM-C, (f) JDM-T.

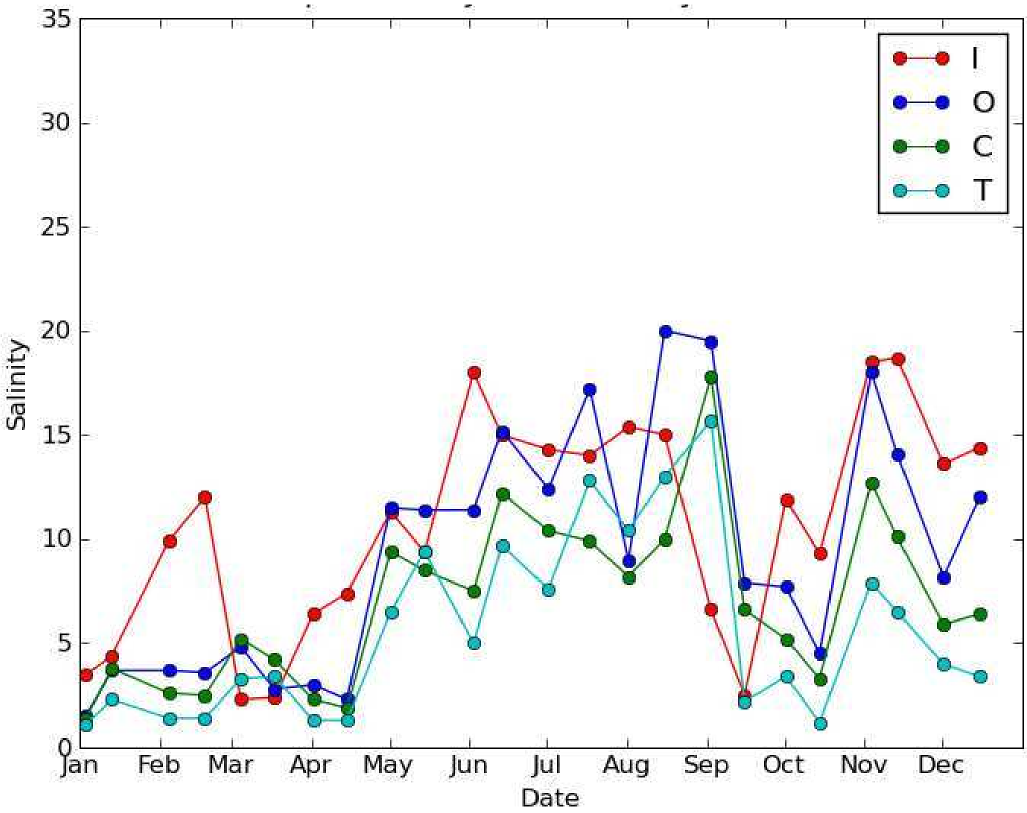

Figure 5.7 TPWD semi-monthly salinity data in 2003 at four standard monitoring locations in the J.D. Murphree WMA; JDM-I (red), JDM-O (blue), JDM-C (green), JDM-T (aqua). (See Figure 2.2 for station locations.)

5.2.3. Applicability

In its present state of development, the model is not ideal for absolute predictions of salinity at all locations in the system, but is suitable for evaluating the relative change in salinity following the introduction of freshwater into the system via siphons. Despite particular instances of incongruence, the model captures the major salinity trends occurring in the system for the target year 2003. One exception is in the highly dynamic region near the Fish Pass that previously was found to be an issue during model calibration. *Section 3.5.6* discusses this and other issues related to model development, and *Section 6.4 Future Research* in the *Discussion* provides suggestions to improve model performance.

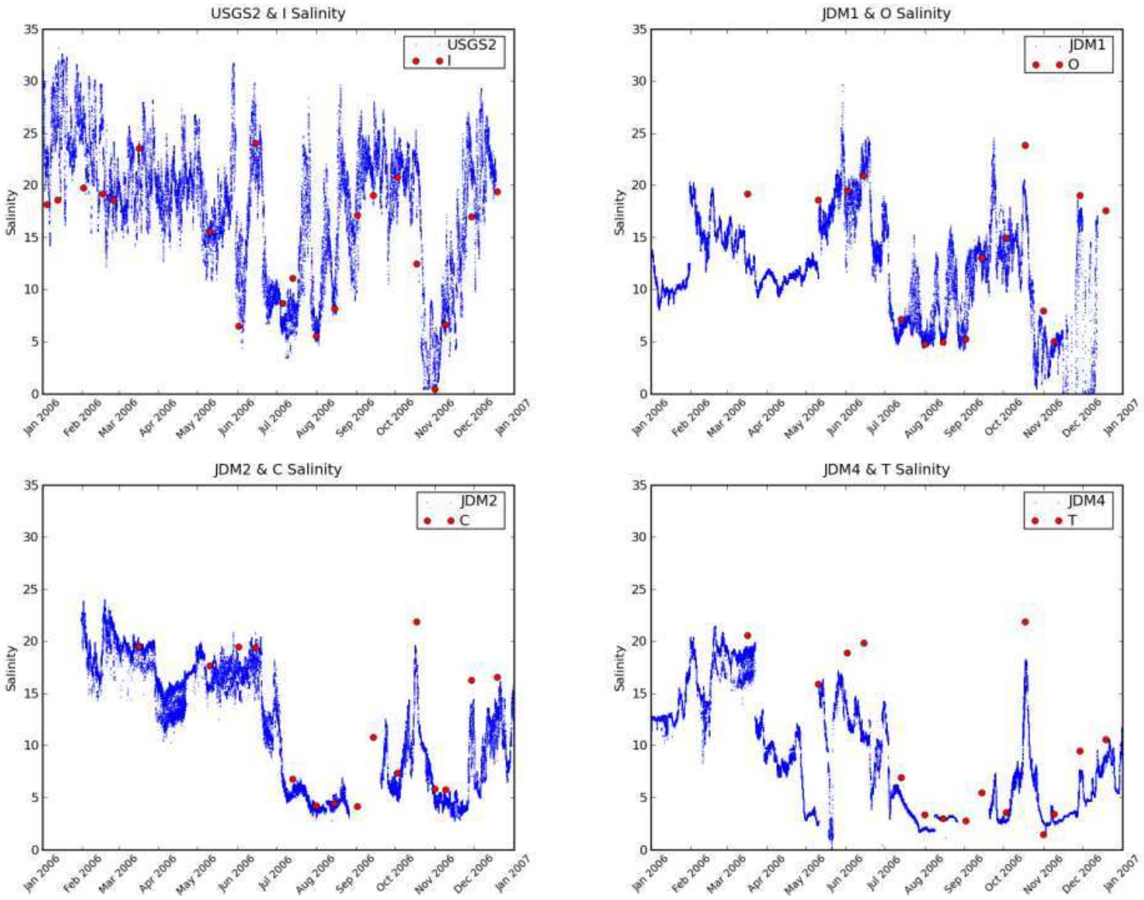

Figure 5.8 Comparison of TWDB continuous salinity measurements with TWPD semi-monthly salinity measurements collected in 2006 at four areas in the J.D. Murphree WMA, (a) USGS2 and JDM-I, near the Fish Pass, (b) JDM1 and JDM-O near the western edge of Keith Lake, (c) JDM2 and JDM-C near the western edge of Shell Lake, and (d) JDM4 and JDM-T in Ten-mile Cut.

5.3. Scenario Results

Results for a total of 12 scenario runs are presented in this section, including: (1) full one-year scenario runs for each of the three siphon locations (Star Lake, Willow Lake, and Salt Bayou Outfall) and (2) shortened two-month seasonal runs for each of the three siphon locations. Three, full one-year runs were used to evaluate salinity mitigation for each siphon location. These scenarios were based on having a constant siphon flow of 1.42m^3/s (50cfs) throughout the target year 2003. Additionally, a series of nine, two-month runs were used to evaluate the performance of each siphon under differing rates of flow, a constant siphon flow of 1.42m^3/s (50cfs), a doubled rate at 2.84m^3/s (100cfs) and a linearly decreasing siphon flow starting at 1.42m^3/s (50cfs) and decreasing to 0m^3/s (0cfs) over the two-month period. Results are presented for each of the six locations.

5.3.1. One-year Scenario Runs

Results from the 2003 one-year model runs show that regardless of location, the addition of freshwater flow through a siphon reduces salinity in the system (Table 5.1). However, the degree and extent of salinity mitigation is based on siphon location and time of year, regardless of consistency in siphon flow. Figure 5.9 provides a visualization of modeled salinity values across the system for the base run (no siphon) and three siphon-location scenarios (Star Lake, Willow Lake, and Salt Bayou Outfall siphons) for two selected dates, September 1, 2003 and November 15, 2003. These graphics clearly display the broad effect of having a siphon located in the upper watershed (*e.g.,* Star Lake, Figures 5.9b). Although the Willow Lake and Salt Bayou Outfall siphons are effective at reducing salinities, the effect is usually localized (Figures 5.9c, d).

The Star Lake siphon is the most effective at reducing salinity, with a decrease of more than 6ppt at certain locations and times of the year (Figures 5.10 and 5.11). Moreover, the Star Lake siphon is able to consistently reduce salinities throughout the system during the model year. The exception is Site 3 near the Salt Lake Outfall where the Star Lake siphon has little effect on salinities.

The Willow Lake and Salt Bayou Outfall siphons behave similarly, reducing salinities between 0 and 4ppt, but only for certain times of the year and at sites in the nearby vicinity (*i.e.*, Sites 2, 3 and 4, Figures 5.10 and 5.11). Unlike the Star Lake siphon which mimics the natural west-to-east pattern of flow through the watershed, a siphon located midway in Willow Lake or at the Salt Bayou Outfall changes the pattern of circulation in the system. This results in a slight increase in salinity for the western portion of the system (*e.g.,* Site 6, Figures 5.10f and 5.11f) during certain times of the year.

Table 5.1 Salinity mitigation results at six representative locations following a one-year simulation for each siphon under a constant 1.42m^3/s flow. Mean and maximum reduction in salinity (ppt) are compared to the no-siphon base run. Results also are shown in Figures 5.10 and 5.11.

	1-Year Run, Constant Siphon Flow of 1.42m^3/s					
Sites	**Star Lake Siphon**		**Willow Lake Siphon**		**Control Structure Siphon**	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Site 1	-0.60	-6.23	-0.15	-3.25	-0.17	-3.56
Site 2	-2.04	-6.54	-0.66	-3.60	-0.71	-3.92
Site 3	-0.63	-2.17	-0.46	-1.14	-2.98	-5.06
Site 4	-2.70	-6.97	-0.83	-5.37	-0.59	-4.31
Site 5	-2.14	-4.97	-0.29	-1.60	-0.19	-1.23
Site 6	-2.85	-7.93	+0.08	-0.43	0	-0.29

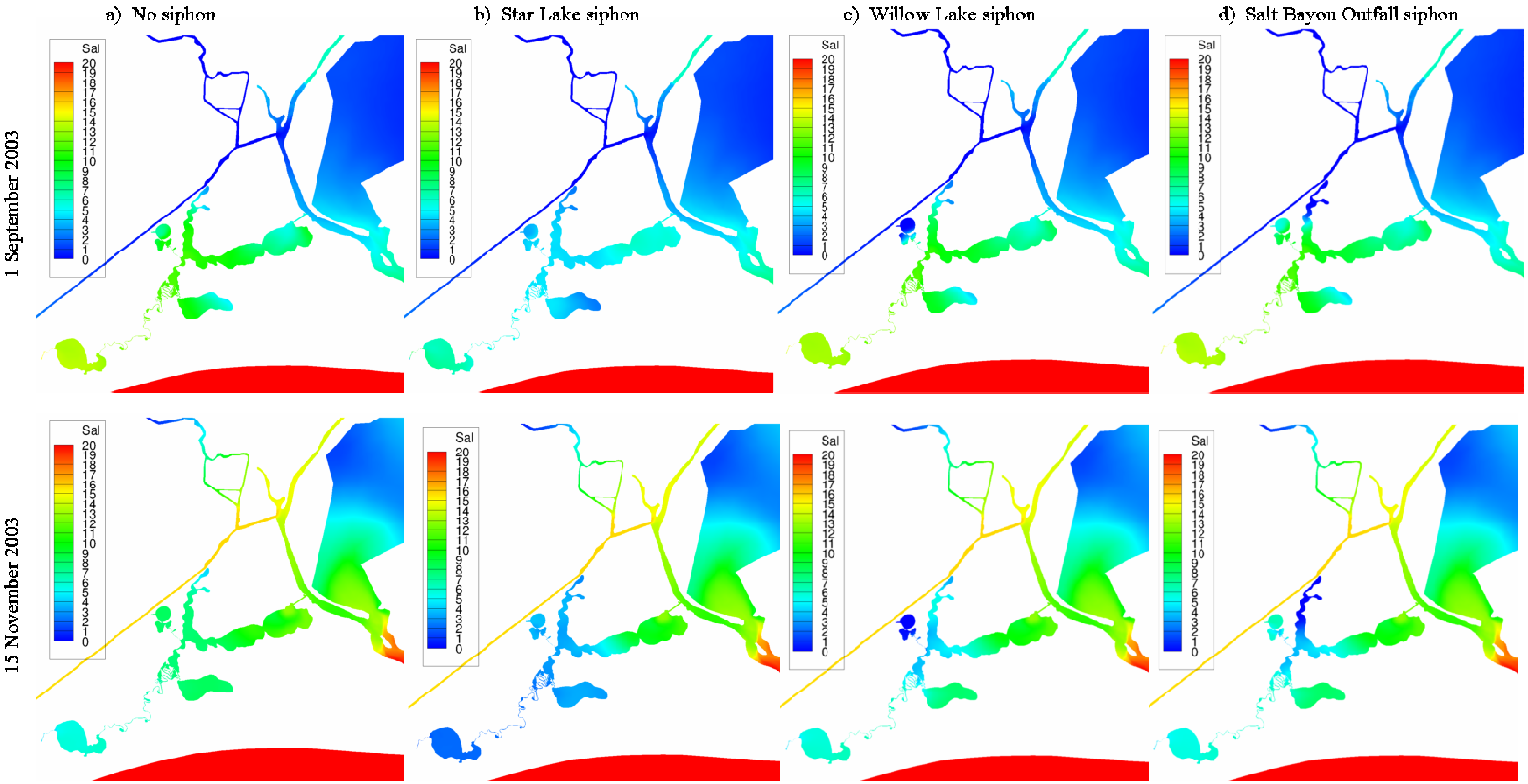

Figure 5.9 Model simulated salinity on September 1 (top row) and November 15, 2003 (bottom row) for Salt Bayou under four siphon-location scenarios; (a) no siphon, (b) Star Lake siphon, (c) Willow Lake siphon, and (d) Salt Bayou Outfall siphon. Siphon flow rates were held constant at 1.42m^3/s.

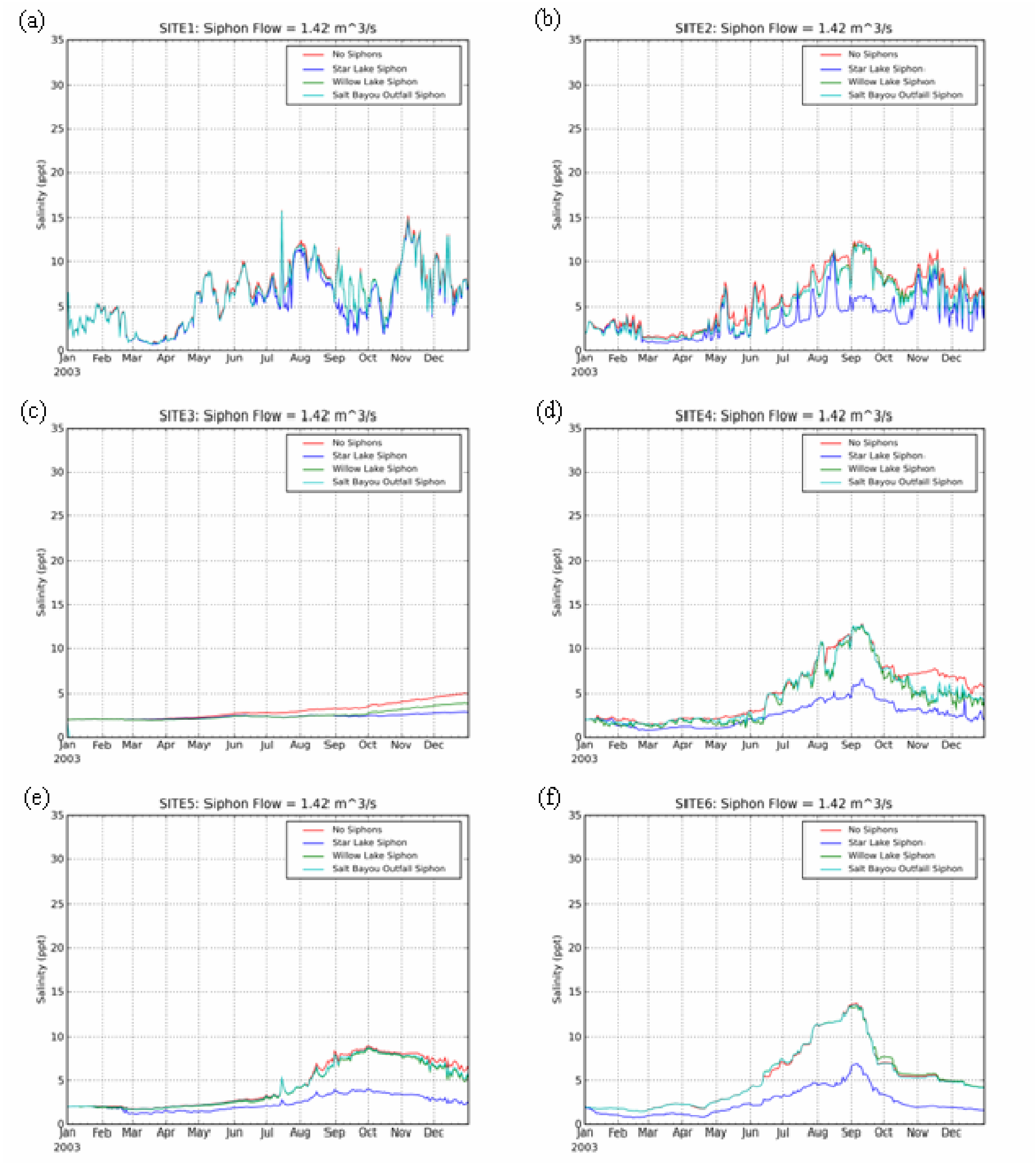

Figure 5.10 One-year simulated salinities for four siphon-location scenarios, no siphon (red), Star Lake siphon (blue), Willow Lake siphon (green), Salt Bayou siphon (aqua), for the target year 2003 at six representative sites in the Salt Bayou watershed, (a) Site 1, (b) Site 2, (c) Site 3, (d) Site 4, (e) Site 5, and (f) Site 6. Reported values correspond to estimated salinities under a constant siphon flow of 1.42m^3/s.

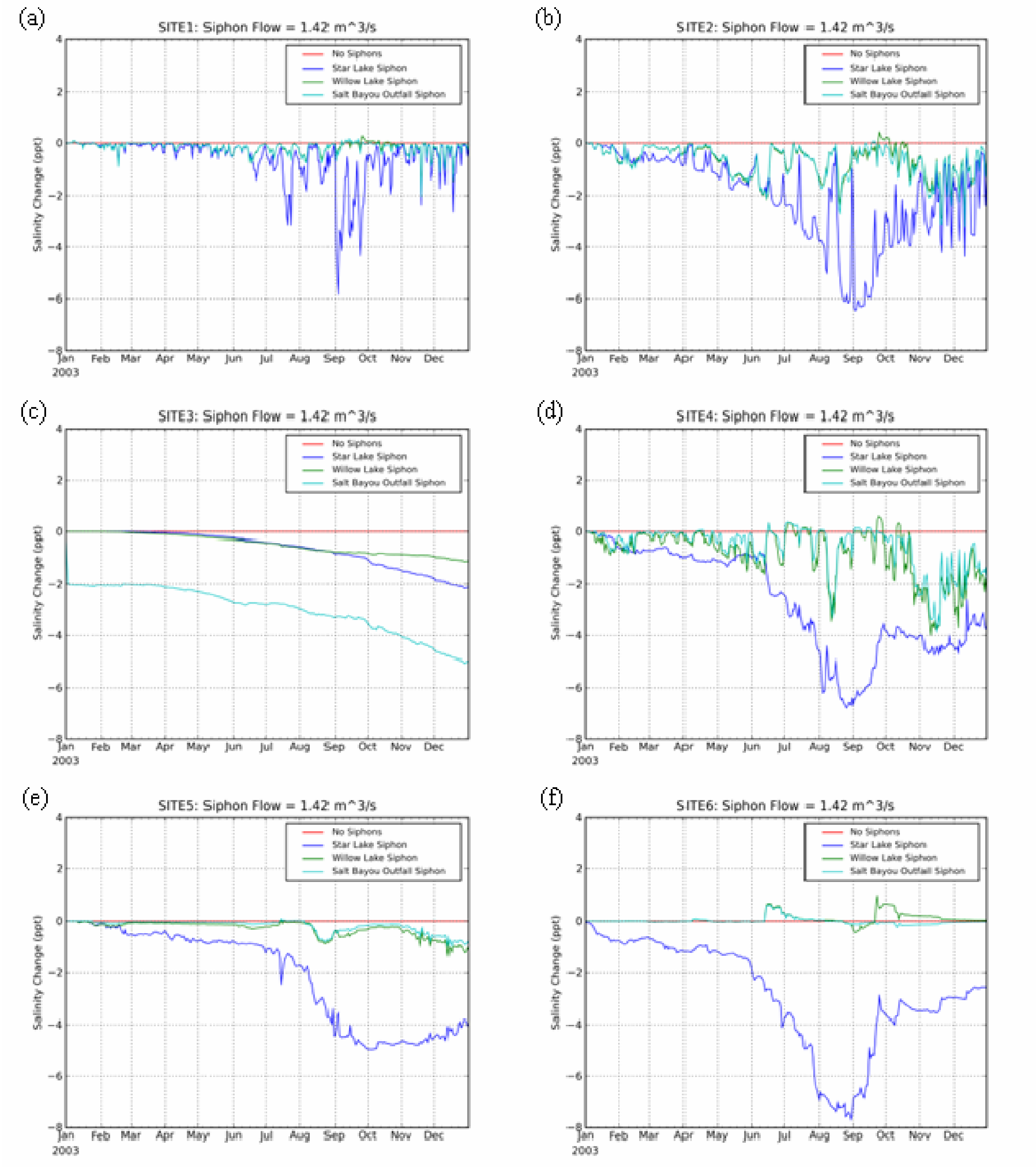

Figure 5.11 One-year simulated decrease in salinity for four siphon-location scenarios, no siphon (red), Star Lake siphon (blue), Willow Lake siphon (green), Salt Bayou siphon (aqua), for the target year 2003 at six representative sites in the Salt Bayou watershed, (a) Site 1, (b) Site 2, (c) Site 3, (d) Site 4, (e) Site 5, (f) Site 6. Values correspond to the relative change in salinity when a siphon with a constant flow of 1.42m^3/s is present versus compared to the base run with no siphon.

5.3.2. Two-month Scenario Runs

Results from the two-month model runs for a constant siphon flow of $1.42m^3/s$ (Tables 5.2 to 5.4, Figures 5.12 to 5.14) are similar to those seen in the one-year model runs for the same level of flow (Figures 5.10 and 5.11). Again, the Star Lake siphon was most effective in reducing salinities at all sites except near Site 3 (Shell Lake near Salt Bayou Outfall; Table 5.2, Figure 5.12c). Under a constant siphon flow scenario, Star Lake siphon flows take 18 days before beneficial effects propagate to the middle of the system (Site 4) and nearly a month before reductions in salinity are observed at the Fish Pass (Site 1; Figure 5.12a,d,f). This time lag is based on the runs conducted so far and should not be generalized to other years due to the highly dynamic nature of the flow in this system.

Tables 5.2 to 5.4 and Figures 5.12 to 5.14 compare the effect of different siphon flow rates on net salinity reduction effect (salinity mitigation) for each siphon location. The overall trend suggests that as expected, greater rates of siphon flow enhance the ability of a siphon to reduce salinities. However, this increased effectiveness is variable over time, ranging from less than 1ppt to over 6ppt.

In the model results, a linearly decreasing siphon flow rate has only limited impact on the ability of that siphon to reduce salinity. This is likely an artifact of the model and due in part to the long lag time for water to move through the system, as noted above, and the short, two-month duration of the model run.

The Star Lake siphon is the least affected by changing the rate of freshwater flow through the siphon (Figure 5.12). Among the three flow-rate cases, the differences in salinity at each site were less than 1ppt (Table 5.2).

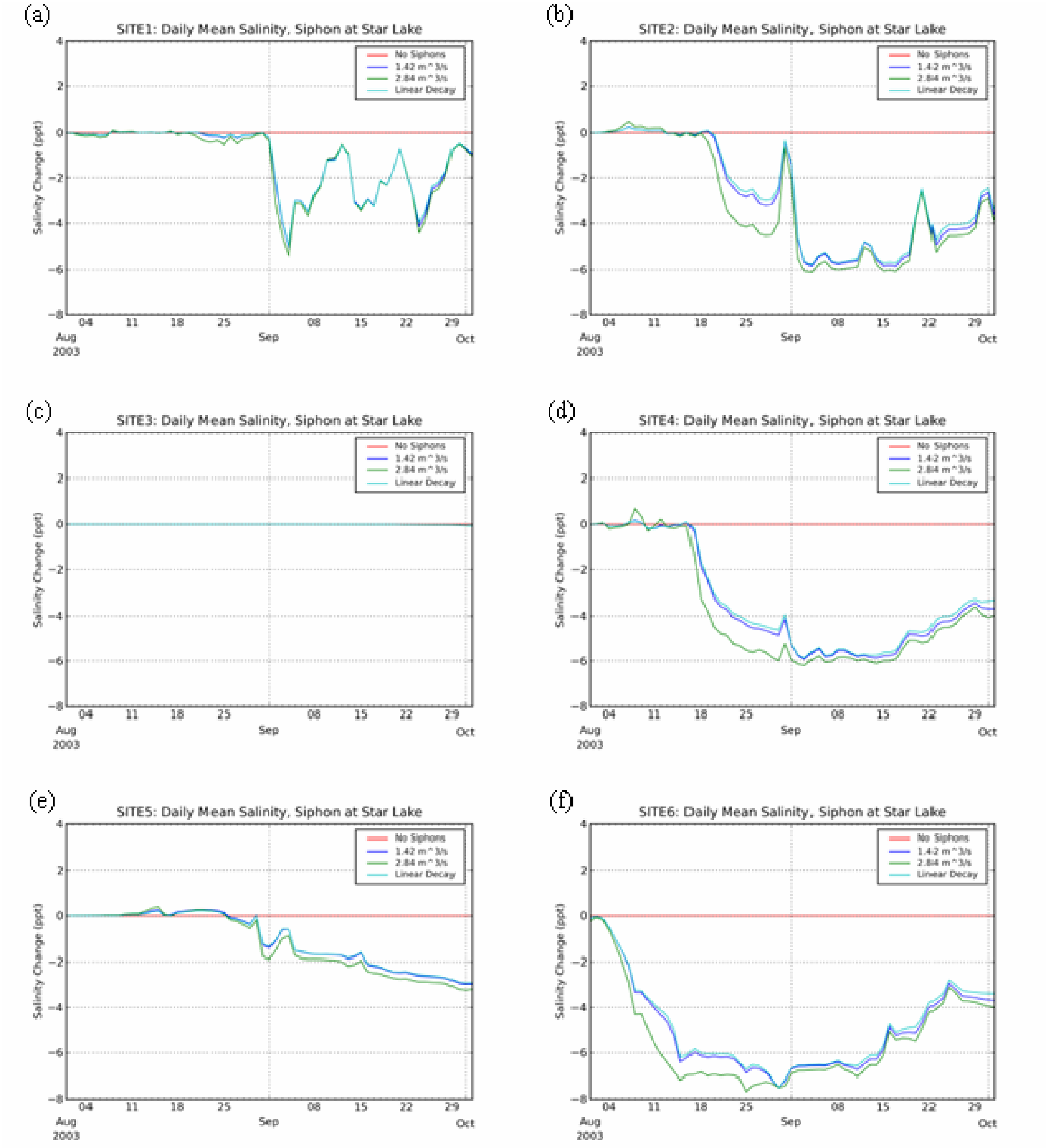

Figure 5.12 Simulated change in salinity for three flow-rate scenarios at the Star Lake siphon, a constant flow of 1.42m^3/s (blue), a constant flow of 2.84m^3/s (green), and a linear decrease in flow from 1.42m^3/s to 0m^3/s (aqua) for a two month time period from August to September 2003 at six representative sites in the Salt Bayou watershed, (a) Site 1, (b) Site 2, (c) Site 3, (d) Site 4, (e) Site 5, (f) Site 6. Values correspond to the relative change in salinity, as compared to the base run with no siphons (red).

Table 5.2 Salinity mitigation results at six representative locations following a two-month simulation for three siphon flow-rate scenarios conducted at the Star Lake siphon. Mean and maximum reduction in salinity at six locations, as compared to the no-siphon base run for 2003 are reported. Results also are shown in Figure 5.12.

	2-Month Run, Star Lake Siphon					
Sites	**Siphon Inflow 1.42m^3/s**		**Siphon Inflow 2.84m^3/s**		**Siphon Inflow linearly decreasing from 1.42m^3/s**	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Site 1	-1.15	-5.74	-1.25	-5.97	-1.14	-5.62
Site 2	-2.79	-5.87	-3.16	-6.15	-2.70	-5.82
Site 3	-0.01	-0.08	-0.01	-0.08	-0.01	-0.07
Site 4	-3.44	-6.39	-3.85	-6.56	-3.33	-6.35
Site 5	-1.03	-2.99	-1.18	-3.27	-1.02	-2.95
Site 6	-4.99	-7.85	-5.46	-7.88	-4.87	-7.87

The Willow Lake (Table 5.3, Figure 5.13) and Salt Bayou Outfall (Table 5.4, Figure 5.14) siphons behave similarly for the most part, further reducing salinities by 1-2ppt under the 2.84m^3/s siphon flow case. Although they do not reduce salinities to the same levels throughout the system as the Star Lake siphon, they *periodically* dramatically reduce local salinities. For example, following a doubling of the siphon flow rate at both locations (2.84m^3/s), local salinities (at sites 2 and 4) dropped by 4-6ppt (Figures 5.13a, d and 5.14a, d, respectively).

For all siphons, the effect of doubling the siphon flow rate varied during the two-month period. At times, a salinity reduction is difficult to discern (*e.g.,* Star Lake Site 1) and at other times was more than 5ppt (*e.g.,* Willow Lake Site 4). Results for the two-month simulation with a linear decrease in siphon flow were not informative as the simulation time was not enough to capture the full effect of this decreasing flow throughout the system.

Table 5.3 Salinity mitigation results following a two-month simulation for three siphon flow-rate scenarios conducted at the Willow Lake siphon. Mean and maximum reduction in salinity at six locations, as compared to the no-siphon base run for 2003 are reported. Results also are shown in Figure 5.13.

Sites	2-Month Run, Willow Lake Siphon					
	Siphon Inflow 1.42m^3/s		Siphon Inflow 2.84m^3/s		Siphon Inflow linearly decreasing from 1.42m^3/s	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Site 1	-0.04	-1.51	-0.22	-3.59	-0.05	-1.16
Site 2	-0.35	-1.89	-0.97	-4.23	-0.24	-1.48
Site 3	-0.01	-0.07	-0.02	-0.12	-0.01	-0.06
Site 4	-0.48	-4.75	-1.29	-7.85	-0.34	-4.24
Site 5	-0.37	-0.89	-0.57	-1.54	-0.28	-0.73
Site 6	+0.04	-0.18	-0.07	-0.20	-0.07	-0.20

Table 5.4 Salinity mitigation results following a two-month simulation for three siphon flow-rate scenarios conducted at the Salt Bayou Outfall siphon. Mean and maximum reduction in salinity at six locations, as compared to the no-siphon base run for 2003 are reported. Results also are shown in Figure 5.14.

Sites	2-Month Run, Salt Bayou Outfall Siphon					
	Siphon Inflow 1.42m^3/s		Siphon Inflow 2.84m^3/s		Siphon Inflow linearly decreasing from 1.42m^3/s	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Site 1	-0.06	-1.61	-0.19	-3.61	-0.04	-1.19
Site 2	-0.37	-2.13	-0.85	-4.23	-0.18	-1.66
Site 3	-3.22	-3.58	-3.23	-3.58	-3.21	-3.49
Site 4	-0.22	-3.36	-0.65	-5.88	-0.11	-2.90
Site 5	-0.19	-0.52	-0.38	-1.05	-0.19	-0.49
Site 6	-0.02	-1.02	+0.06	-0.17	+0.03	-0.33

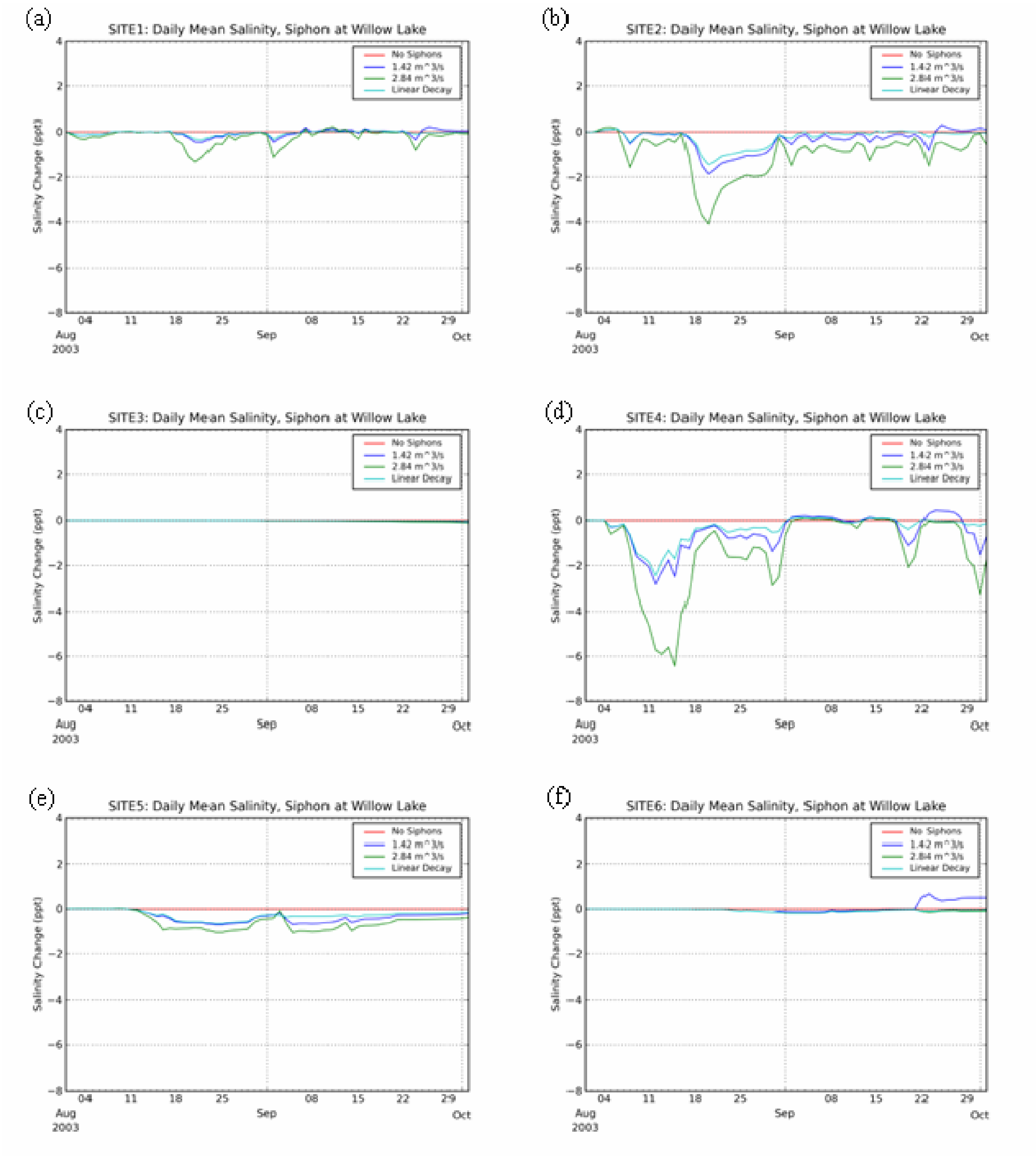

Figure 5.13 Simulated change in salinity for three flow-rate scenarios at the Willow Lake siphon, a constant flow of 1.42m^3/s (blue), a constant flow of 2.84m^3/s (green), and a linear decrease in flow from 1.42m^3/s to 0m^3/s (aqua) for a two month time period from August to September 2003 at six representative sites in the Salt Bayou watershed, (a) Site 1, (b) Site 2, (c) Site 3, (d) Site 4, (e) Site 5, (f) Site 6. Values correspond to the relative change in salinity, as compared to the base run with no siphons (red).

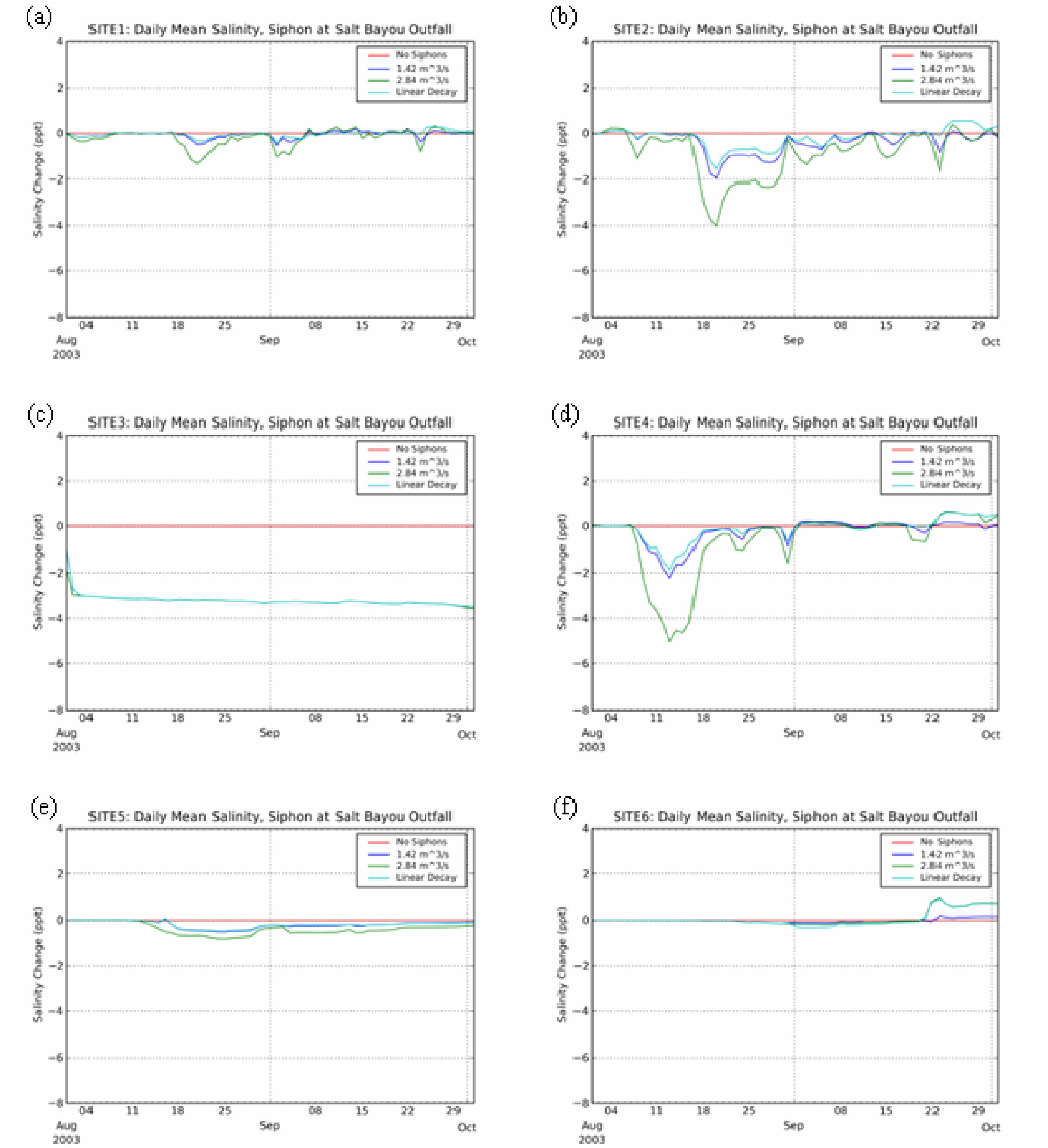

Figure 5.14 Simulated change in salinity for three flow-rate scenarios at the Salt Bayou Outfall siphon, a constant flow of 1.42m^3/s (blue), a constant flow of 2.84m^3/s (green), and a linear decrease in flow from 1.42m^3/s to 0m^3/s (aqua) for a two month time period from August to September 2003 at six representative sites in the Salt Bayou watershed, (a) Site 1, (b) Site 2, (c) Site 3, (d) Site 4, (e) Site 5, (f) Site 6. Values correspond to the relative change in salinity, as compared to the base run with no siphons (red).

6. Discussion

6.1. Hydrology and Salinity

Sabine Lake and the surrounding coastal wetlands, particularly those within Salt Bayou have a long history of modification which has altered local hydrology, patterns of circulation, and the influx of salinity. However, aside from earlier studies which document persistent freshwater conditions throughout the wetland (Bales *et al.* 1974) followed by rapid salinization upon re-opening the Fish Pass (Wern 1979, Stelly 1980), historical datasets do not exist. Instead, this study compared data from the study period (2003 and 2006) to a contemporary data record consisting of 30 years of precipitation and freshwater inflow data for the region and nearly 20 years of salinity data for the wetland system. Recent records of local annual precipitation and freshwater inflows to Sabine Lake show no particular trends, but records of monthly precipitation and inflow show differences in the timing of peak events. Precipitation over the region (as measured by the City of Port Arthur rain gauge) peaks in late summer to fall, whereas total freshwater inflows to Sabine Lake peak in early spring. Precipitation is the single direct source of freshwater to Salt Bayou and an important factor in reducing salinity across the wetland. However, salinity within the wetland, particularly the eastern portion, is determined more by the volume of freshwater inflows entering Sabine Lake, because these inflows affect the level of salinity in water entering the system via the Fish Pass.

Area land managers are familiar with the varying levels and sources of salinity and the lack of freshwater as factors which affect conditions within the Keith Lake/Salt Bayou system. *From this modeling exercise, however, fluctuating zones of salinity were identified and attributed to a complex balance between four sources of water: (1) freshwater inflows from the Sabine and Neches rivers, (2) saline water tidally forced into the system from the Gulf of Mexico, (3) saline water coming from the GIWW, and (4) water (fresh or saline) flowing from Star Lake on the western side of the system.* The three external sources of water determine the salinity of water entering the system through the Fish Pass; whereas, the volume and salinity of water flowing from Star Lake determines the extent of salinity intrusion caused by the other sources of water. Under ideal conditions, Star Lake would supply a large enough volume of freshwater to maintain the historic west-to-east pattern of flow which could displace and dilute salinities lower in the system, *e.g.*, Keith Lake. Presently though, the truncated watershed (a result of the placement of the GIWW) is unable to supply sufficient freshwater flows. Moreover, an additional source of saline water (due to overtopping along the beach ridge) increases salinity levels in the water that flows from Star Lake, further limiting the ability of the system to *push-back* against the external sources causing salinity intrusion through the Fish Pass.

6.2. Model Calibration and Caveats

A hydrodynamic and salinity transport model was constructed to provide a tool for evaluating the use of freshwater siphons as a strategy to maintain reduced levels of surface water salinity in the Keith Lake/Salt Bayou system. The model does well at capturing water surface elevation and velocities, except at the westernmost sites which are strongly influenced by estimated inflows applied at the Salt Bayou Watershed boundary condition. The model does better at capturing long-term trends in salinity than short-term fluctuations. As noted in *Section 5.2*, for the target year 2003, the model underpredicts salinity at various locations within the system. While the model underpredicted 2003 salinities and while 2003 was not an ideal year for modeling purposes, the relative reduction in salinity observed in the model results is indicative of each siphon's potential to reduce salinity levels in the system.

Another point for consideration is that the model presently does not extend beyond open water to include the marsh areas of the system. Moreover, not all open water areas were included, *e.g.*, Star Lake, Wild Cow Bayou, etc. We expect that if marshes were included, some portion of freshwater from the siphons would permeate into the marshes, reducing the volume entering the main channels, and possibly reducing the spatial extent of salinity mitigation. Even so, a reduction of salinity in the marsh could enhance salinity reduction in the open water, thus still providing a benefit.

Finally, freshwater flow through each siphon is assumed to be constant throughout the year (except in the two-month scenario examining a linear decrease over time). The actual flow provided by each siphon however will depend on the relative difference in water level on either side of the GIWW. Given that the effectiveness of the siphons varies throughout the year, this suggests that siphons may not be able to supply the necessary flows during times when they would be most effective at reducing salinities.

6.3. Effectiveness of Siphons as a Mitigation Strategy

For this wetland system, the installation of a freshwater siphon can be an effective means for managing open water salinities if sufficient water is available on the upstream side. Using survey data from Pothina *et al.* (2007), the area of open water included in the hydrodynamic model is estimated to be approximately 6,100 acres. Assuming an average depth of 3ft, the volume of water represented in the hydrodynamic model is equal to 18,300 acre-ft. The siphon flow estimate of 50cfs (1.42 m^3/s), given in *Section 4.4* and which is comparable to the rate of flow recorded in 2006 in Five-mile Cut (TWDB data), provides 2,980 acre-ft of water in 30 days – a volume equal to approximately 16% of the modeled system's volume. If we assume an initial salinity of 15ppt, no other source of fresh or saline water entering the system, and that siphon flows flush an equivalent amount of saline water out of the system, then at this rate of flow salinity should decrease approximately 2.4ppt in 30 days or 4.8ppt in 60 days. In a two-month simulation, where other sources of salinity and water are present, the Star Lake siphon provided a mean reduction of 2.28ppt for the six representative sites evaluated.

An in-depth comparison of three candidate locations revealed that (1) the ability of a particular siphon to reduce salinity levels varies throughout the year and (2) the extent of a siphon's effect on salinity reduction depends on location. The model indicated that a siphon installed in the upper reaches of the system (*i.e.,* the Star Lake siphon) will yield a broader reduction in salinity, particularly in the western end of the system. Whereas, siphons installed mid-way through the system (*i.e.,* Willow Lake or at the Salt Bayou Outfall) will have primarily a localized effect on salinity reduction. The Star Lake siphon seemed to be the most effective at reducing salinity intrusion. This is most likely because it enhances the natural downstream pattern of flow in the system. Siphons at Willow Lake and the Salt Bayou Outfall are working against the natural flow patterns in the system and also may be rendered less effective by prevailing winds driving flow to the north and east of the Salt Bayou (Fisher 1988).

Prior to this modeling study, the J.D. Murphree WMA established a desired salinity maintenance target of 0 to10ppt at the intersection of Keith Lake and Johnson Lake (Site 2). Although the analysis of siphon effectiveness considered salinity mitigation at six locations within the Salt

Bayou system, Site 2 is an important site for further discussion. The most effective siphon-scenario case, for meeting this management goal, is that which assists in maintaining the salinity target at Site 2. Following a one-year simulation, the Star Lake siphon appears to be the most effective choice, reducing salinity levels on average by 2ppt and at times by over 6ppt (Table 5.1, Site 2 and Figures 5.10b, 5.11b). The Willow Lake and Salt Bayou Outfall siphons are less effective, but are still able to reduce salinities on average by 0.5 to 1ppt and at times over 3ppt (Table 5.1). In the 2003 one-year base run with no siphons, modeled daily mean salinity exceeded the target value on 47 days. Under a scenario of constant flow through the Star Lake siphon, daily mean salinity exceeded the target for only two days. This same inflow scenario applied to the Willow Lake and Salt Bayou Outfall siphons resulted in the target salinity value being exceeded on 24 and 23 days, respectively. Overall, this suggests that a siphon bringing an additional source of freshwater to the system can serve as an effective management tool to mitigate salinity impacts throughout the watershed. These results must be tempered by the need to collect better information on the system to allow for a more adequate model calibration.

6.4. Future Research and Feasibility Studies

6.4.1. Improvements to the Hydrodynamic Model

Two hydrodynamic and salinity transport models were presented here, a model consisting only of open water (*base grid*) and a model which included marsh areas along with open water (*marsh grid*). As previously stated, the base grid was selected for use in this study due to computational limitations, though future modeling studies of this system would benefit by using a marsh model to better capture patterns of salinity distribution and dilution. Additional issues with the current model include its tendency to underpredict absolute salinities and the errors in the phase and magnitude of water velocities at certain locations. Based on the knowledge gained from this study, any future model should incorporate the following features:

- Star Lake and Wild Cow Bayou sections of the wetland along with estimated or measured salinities for Star Lake
- Operations of the Perkin’s Levee control structure

- Salinity inputs to the interior marsh due to overtopping events along the beach ridge
- Improved estimation of rainfall-runoff over the Salt Bayou watershed
- Improved application of the freshwater boundary conditions within Salt Bayou by applying disaggregated estimates of rainfall-runoff at multiple points within the watershed
- Improved model calibration focused on modeling water velocities more accurately

The ability of the model to predict absolute salinity values may be improved as the elements mentioned above are added. In terms of model calibration, the frequency and extent of salinity stratification in the Sabine-Neches Waterway and the location of the salinity front in the waterway and in Sabine Lake are of concern. These phenomena are not well studied in this region and may require additional data collection to properly capture in a hydrodynamic model. Further model calibration aimed at properly capturing these features would improve the overall ability of the model to simulate salinity and water velocities in the Keith Lake/Salt Bayou system.

At this stage, it is a challenge to accurately model marshes, particularly ones as complex as in the Salt Bayou complex, and extremely difficult if not impossible to accurately represent salinity intrusion via the beach ridge. Presently, the interaction between surface water salinity and soil pore water salinity is poorly understood. Further, estimating salinity intrusion from the beach ridge will require a separate overland flow model that includes high spatial resolution marsh elevation and foliage data and takes into account the interactions between the saline sheet flow and the marsh. This overland flow model then will need to be integrated with the hydrodynamic model to properly represent the effects of salinity intrusion via overtopping along the beach ridge.

In contrast, it would be fairly easy to include disaggregated estimates of rainfall-runoff or to incorporate marshes. Additional information that would greatly enhance the ability of a simulation model to capture system dynamics include: (1) detailed records for the operation of control structures within the wetland and (2) additional water quality and flow data throughout the system at frequent (weekly or less) intervals. In this study, model inconsistencies could not be properly resolved due to the lack of adequate salinity data and information on water flow within certain parts of the system. With additional data, salinity sources could have been identified along with the effect of flow in Five-mile Cut on the eastern part of the system. This would have led to a better estimate of the model's western boundary conditions. TWDB recommends that future data collection efforts focus on obtaining continuous water quality data. While the J.D. Murphree WMA semi-monthly data was essential to conducting this study and in itself is an excellent data set, it is unable to capture the frequent fluctuations in salinity that are a common feature of this system.

While the improvements described here would enable the model to better represent the Keith Lake/Salt Bayou system and would make it an even more valuable tool for evaluating proposed management scenarios, this does not suggest that the absence of these enhancements significantly affects our overall conclusions about the viability and effectiveness of siphons to reduce salinities within the system. Moreover, the existing model complements the current study by the USACE on modifications to the Fish Pass by providing the most recent model of existing conditions within the Keith Lake/Salt Bayou system.

6.4.2. Feasibility of Siphons as a Mitigation Strategy

The study presented herein should not be taken as a comprehensive feasibility study, but rather as an exploratory analysis of using freshwater siphons as a salinity mitigation strategy. While this analysis has shown the beneficial effect of providing freshwater inputs at three locations in the Salt Bayou system, the analysis does so in only a very preliminary way. For a proper comprehensive feasibility study, two additional studies are required. First, a water availability study which analyzes the timing and volume of water available in the marshes north of the GIWW will be required at each potential siphon location. This analysis is necessary to determine whether the required head and volume of water is available to provide sustained freshwater flow. This study may be possible using the existing water level data collect by Jefferson County DD6, though additional data may be required. Second, an engineering feasibility study is necessary to consider all aspects related to constructing an effective siphon system across the GIWW. These include, but are not limited to, intake and outtake design, prevention of sediment deposition, and maintenance procedures. One passive technique for preventing sediment deposition that may be worth exploring is using multiple, smaller diameter pipes bundled together rather than a single large diameter pipe. Higher flows through the smaller pipes should enable the inverted siphon system to be self-cleaning (Butler and Davies 2004, p.184).

7. CONCLUSIONS

The Keith Lake/Salt Bayou wetland complex is a dynamic system presently exhibiting signs of stress related to salinity intrusion caused by several external forces. For decades, this system has been assimilating changes to the local hydrology and surrounding wetlands, but now requires management and mitigation strategies to offset increased rates of salinity intrusion and to restore the historic biodiversity and functioning of the wetland. In recent years, local land managers have been working together to devise management strategies to mitigate and stabilize salinity within the system. This key goal, held by both the J.D. Murphree WMA and McFaddin NWR, is essential for ensuring conservation of this unique wetland system. The study presented here provides an exploratory analysis for one of the proposed management strategies aimed at achieving this goal. From this study, area land managers now can factor in basic knowledge that the installation of a passive, inverted freshwater siphon can serve to mitigate salinity within Salt Bayou. In addition, it appears that the most effective location for siphon installation is in the headwaters of the system near Star Lake. This location enhances the natural downstream flow of water, pushing against saline waters entering through the Fish Pass, thus propagating the beneficial effects over greater distances than a similarly installed siphon in the middle of the system (*e.g.*, Willow Lake or Salt Bayou Outfall).

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LITERATURE CITED

Alperin, L.M. 1977. Chapter 3. Transformation of the Sabine. In: *Custodians of the Coast: History of the United States Army Engineers at Galveston.* Galveston District, United States Army Corps of Engineers, Galveston, Texas.

Bales, D.P., B.A. Burnett, G. Chambers, B.F. Henningsen, J.O. Jones, J.L. Parlsey, R.R. Roden, and R.L. Savino. 1974. *Biological, Geological, and Physical-Chemical Parameters of a Southeast Texas Estuary.* National Science Foundation SOS Grant # GY-11509, Lamar University, Beaumont, Texas.

Berg, R. 2009. *Tropical Cyclone Report, Hurricane Ike (ALO92008).* National Hurricane Center, 23 January 2009.

Butler, D. and J.W. Davies. 2004. *Urban Drainage*, 2nd edition. Taylor and Francis, New York, New York.

Dias, J.M., M.C. Sousa, X. Bertin, A.B. Fortunato, and A. Oliveira. 2009. Numerical modeling of the impact of the Ancão Inlet relocation (Ria Formosa, Portugal). *Environmental Modelling & Software*, 24: 711-725

Ditty, Jim. National Marine Fisheries Service. Email communication to N. Kuhn at TPWD, Jim.ditty@noaa.gov.

Fisher, J.C. 1988. *Hydrologic Data for the Salt Bayou Estuary Near Sabine Pass, Texas, October 1984 to March 1986*. U.S. Geological Survey Open-file Report 88-499. 128p.

Foreman, M.G.G., D. Stucchi, Y.-L. Zhang, and A.M. Baptista. 2005. Estuarine and tidal currents in the Broughton Archipelago. *Atmospherie-Ocean*, 44:47-63.

Furnans, J.F. 2006. *HydroEdit User's Manual*. Texas Water Development Board. Austin, Texas. 33p.

Galperin, B., L.H. Kantha, S. Hassid, A. Rosati. 1988. A quasi-equilibrium turbulent energy model for geophysical flows. *Journal of Atmospheric Science* 45:55–62.

Gillham, R. 1898. Letter of Mr. Robert Gillham, Chief Engineer, Kansas City, Missouri, March 19, 1898. Pages 26-33, In: *Ship Canal at Sabine Pass, Texas—Letter from the Secretary of War, transmitting a letter from the Chief of Engineers in response to the joint resolution of Congress approved May 28, 1898, relating to a ship canal at Sabine Pass*. Texas, 55th United States Congress, 2nd Session: House of Representatives, Document No. 549. Washington, DC. 42p.

Kuhn, N. Texas Parks and Wildlife Department. Email communication August 15, 2007, nathan.kuhn@tpwd.state.tx.us.

Lay, D.W., and T. O'Neil. 1942. Muskrats on the Texas Coast. *The Journal of Wildlife Management* 6:301-311.

Longley, W.L. 1994. *Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs.* Prepared by Texas Water Development Board and Texas Parks and Wildlife Department. Texas Parks and Wildlife Press, Austin, Texas. 386p.

Matsumoto, J. 1991. *Simulation Analysis of Changes in Flow Exchange in the Upper Laguna Madre with Removal of Portions of the John F. Kennedy Causeway*. Texas Water Development Board staff report. 46p.

Matsumoto, J. 2005. *Effects of Structures and Practices on the Circulation and Salinity Patterns of Galveston Bay, Texas.* Texas Water Development Board staff report. 131p.

Moffatt and Nichol Engineers. 2001. *Hydraulic Modeling for the Keith Lake Cut Shoreline Protection Project #1033*. Prepared for the Texas General Land Office, September 2001.

Morton, R.A., N.A. Purcell, and R.L. Peterson. 2001. Shallow stratigraphic evidence of subsidence and faulting induced by hydrocarbon production in coastal Southeast Texas. USGS Open File Report 01-274. (*http://pubs.usgs.gov/of/2001/of01-274/index.html*)

Mukai A. Y., J. J. Westerink, R. A. Luettich Jr., and D. Mark. 2002. *Eastcoast 2001: A tidal constituent database for the western North Atlantic, Gulf of Mexico and Caribbean Sea.* Technical Report ERDC/CHL TR-02-24. U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. 201p.

Pothina., D., J.F. Furnans, and T. Connell. 2007. *Hydrographic Survey of the Keith Lake-Salt Bayou System*. Prepared by Texas Water Development Board for the Texas Parks and Wildlife Department. 12p.

O'Connell, J. 2006. *Coastal Marsh Restoration Using Terraces: Effects on Waterbird Habitat in Louisiana's Chenier Plain*. A Master's Thesis submitted to Louisiana State University. 110p.

Oliveira, A., A.B. Fortunato, and L. Pinto. 2006. Modeling the Hydrodynamics and the Fate of Passive and Active Tracers in the Guadiana Estuary. *Estuarine, Coastal and Shelf Science* 70:76-84.

Rezsutek, Michael. Texas Parks and Wildlife Department. Email communication March 15, 2005, michael.rezsutek@tpwd.state.tx.us.

SELFE. 2007. *SELFE 2.0d User Manual*. Oregon Health and Science University, Portland, Oregon.

SMS. 2008. *Surface Modeling System (SMS) 10.0 Users Manual*. Environmental Modeling Systems Inc., South Jordan, Utah.

Stelly, T. D. 1980. *Currents and biota at the Salt Bayou Weir and the Keith Lake Water Exchange Pass of Sea Rim State Park.* Masters Thesis submitted to Department of Biology, Lamar University, Beaumont.

Stokes, Janelle S. U.S. Army Corps of Engineers. Email communication March 27, 2009. janelle.s.stokes@usace.army.mil.

Sutherlin, Jim. Texas Parks and Wildlife Department, J.D. Murphree Wildlife Management Area, jim.sutherlin@tpwd.state.tx.us.

Joint Water Management Concept Plan. 1990. *Salt Bayou Project Joint Water Management Concept Plan for Sea Rim State Park, McFaddin National Wildlife Refuge, and Murphree Wildlife Management Area.* Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service. 34p.

Texas Department of Water Resources. 1981. *Sabine-Neches Estuary: A Study of the Influence of Freshwater Inflows*. LP-116. Texas Department of Water Resources, Austin, Texas.

Tolan, Jim. Texas Parks and Wildlife Department. Email communication to N. Kuhn at TPWD, james.tolan@tpwd.state.tx.us.

Trimm, Bryan. Golden Pass LNG Terminal c/o ExxonMobil Development Company. Email communication February 21, 2007, bryan.a.trimm@exxonmobil.com.

Umlauf, L., Burchard, H., 2003. A generic length-scale equation for geophysical turbulence models. *Journal of Marine Research* 6:235–265.

U.S. Department of Agriculture and Soil Conservation Service. 1976. *Keith Lake Water Exchange Pass: Fish and Wildlife Development Resource Conservation & Development Measure Plan.* Prepared for the Texas Parks and Wildlife Department and Coastal Soil and Water Conservation District.

Walther, Patrick. U.S. Fish and Wildlife Service, McFaddin National Wildlife Refuge. Email communication December 9, 2008, patrick_walther@fws.gov.

Wang, C.F., H.V. Wang, and A.Y. Kuo 2008. Mass Conservative Transport Scheme for the Application of the ELCIRC Model to Water Quality Computation. *Journal of Hydraulic Engineering*, 134:1166-1171.

Weiner, R.F., and R.A. Matthews. 2003. *Environmental Engineering,* 4th edition. Butterworth-Heinemann, Amsterdam.

Wern, J.L. 1979. *Preliminary Report on the Macrobenthic Study at Sea Rim State Park and Adjacent Keith Lake*. Prepared for the Texas Parks and Wildlife Department. 23p.

White, C.J., and W.S. Perret. 1974. Short term effects of the Toledo Bend project on Sabine Lake, Louisiana. pp. 710-721 *In* A.L. Mitchell (ed.), *Proceedings of the 27th Annual Conference, Southeast Association Game and Fish Committees, Hot Springs, Arkansas, 1973*.

Zhang, Y.-L. 2006. *Adaptation of the ELCIRC model to Texas bays and estuaries.* Report submitted under contract #0504830543 to Texas Water Development Board, Austin, Texas. 12p.

Zhang, Y.-L. 2008. *Hydrodynamic Model Adaptation.* Report submitted under contract #0704830669 to Texas Water Development Board, Austin, Texas. 16p.

Zhang, Y.-L., and A.M. Baptista. 2008. SELFE: A semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation. *Ocean Modelling* 21: 71-96.

APPENDIX A: Bathymetry

Complete details of the generation of model bathymetry are found in Pothina *et al.* (2007); however, selected portions are repeated in this appendix.

Table A.1 Description of Processed Survey Data

Description	Datum	Vertical Datum	Processed Data File Name
Merged survey data	NAD83 State Plane Texas South Central Zone (feet)	NAVD88	KeithLake_Merged_StatePlaneTXSouthCentralUSft_NAVD88.csv
Interpolated Bathymetry for Keith Lake/Salt Bayou	NAD83 State Plane Texas South Central Zone (feet)	NAVD88	KeithLake_Interpolated_StatePlaneTXSouthCentraUSft_NAVD88.csv
Hydrodynamic Model Bathymetry for Entire Domain	NAD83 UTM15 (m)	Mean Sea Level	KL-Sabine_Model_NAD83UTM15_MSL.csv

Generation of Model Bathymetry

To generate bathymetry for the TWDB hydrodynamic model the merged and extrapolated bathymetry dataset was converted from NAVD88 to Mean Sea Level (MSL). Since there exists no established datum conversion from the NAVD88 vertical datum to tidal MSL datum, we chose to approximate a conversion by subtracting 2.32 feet. This 2.32 feet value is the average correction that was used in converting sounding depths to bathymetric elevations based on field level measurements in the TWDB survey. Shallow pools of water that the survey boats were unable to traverse were set to be 1.3 feet NAVD (or approximately -1 foot MSL).

Another model bathymetric dataset developed for a modeling project of the Sabine-Neches Waterway was obtained from the U.S. Army Corps of Engineers (USACE). This data was referenced to the Mean Low Tide (MLT) tidal datum. The USACE dataset was clipped to exclude areas covered by the merged bathymetric dataset described in this report. The USACE data was then referenced to the same MSL data of the TWDB hydrodynamic model bathymetry by subtracting 1 foot. This shift was calculated from a comparison of an overlapping region in the Sabine-Neches Ship Channel.

Table A.2 Description of Individual Bathymetric Surveys

Survey	Year	Horizontal Datum	Vertical Datum	Vertical Datum Adjustment (ft)	Raw Data File Name
TWDB	2007	NAD83 State Plane Texas South Central Zone (feet).	NAVD88	0.0000	KL_TWDB_Bathymetry_GeoNAD83_Feet.csv
Exxon-Mobil Pipeline	2006	NAD83 State Plane Texas Central Zone (feet).	Not Referenced	+1.6530	KL_Exxon_PipeLine_StatePlaneTxCentralUSFt.csv
Exxon-Mobil Fish Pass	2006	NAD83 State Plane Texas South Central Zone (feet).	Not Referenced	+0.5128	KL_Exxon_FishPass_StatePlaneTxSouthCentralUSft.csv
Exxon-Mobil Pintail Flats	2006	NAD83 State Plane Texas South Central Zone (feet).	NAVD88	+0.0000	KL_Exxon_Pintail_STatePlaneTxSouthCentralUSft.csv
J.D. Murphree WMA	2002	Geographic NAD83	Not Referenced	+2.5922	KL_JDM_Bathymetry_GeoNAD83_Feet.csv
McFaddin NWR	2002	Geographic NAD83	Not Referenced	+1.6185	MCF_Bathymetry_GeoNAD83_Feet.csv
USACE SNWW (model grid)	-	NAD83 UTM15 (m)	Mean Low Tide	-1.0000	USACE_SNWW_NAD83UTM15_MLT.csv

APPENDIX B: Calibrated Model Parameters

SELFE v2.0d parameter input file (param.in) for 2006 Final Calibrated Model Run

```
KLGrid_20080421 SabPassTides Jan06-Dec06
01/01/2006 00:00:00 CST
0 ipre
0 ntracers
0 iwrite
0 imm
0 ihot
1  ics
-124 46.25  slam0 sfea0
0 ihorcon
0.6   implicitness
0 1   baroclinic/barotropic
1 1.0     coldstart
365.        rnday
1 2.      ramp
45.   dt
!
1 nadv
15. 15. dtb_max
0.01  h0
0 nchi (0: Cd; 1: roughness)
1  ncor (0: f-plane; 1: variable)
2 45.  nws
1 1 ! Windramp
0 !iwindoff
1 1 heat salt budget evap
3   turbulence closure (0 const.; 1 step function; 2 P P; 3 MYG)
KL KC
1  i.c.
0 40. ntip
0  nbfr
8 nope
36 1 0 0 1  !Ocean
2 0 1 0 2  !Bayou
0.0
2 0 1 0 2  !Sabine
0.0
2 0 1 0 2  !Neches
0.0
2 0 1 0 2  !Taylor
0.0
3 1 0 0 1  !ICWW
4 0 2 0 0  !Siphon @ Willow Lake
0
5 0 1 0 1  !5 MileCut
80 1920 ! 1hr output, new file each day
0   elevation: iof,touts,toutf,spool
0   pressure
```

```
0  airt
0  humidity
0  solar
0  short wave rad
0  long wave rad
0  upwelling flux
0  downwelling flux
0  total flux
0  evap rate
0  precip rate
0   Wind speed
0   Wind stress
1   dahv
0   Vertical velocity
1   Temperature in C
1   Salinity in psu
0   Density in kg/m^3
0   eddy diffusivity
0   eddy viscosity
0   Turbulent kinetic energy
0   Turbulent mixing length
1   zcor
1   Horizontal velocity
0   Test output
1 NHSTAR
50 1000 1.e-12
0  iflux ihcheck
1 0 lq int_mom
1.e6  h_bcc1
0 islip
0 86400. 400. 0. 401. 0.  inu_st, step_nu,
!
0 mmm
2 idrag
!
1 ihhat
1 1 upwind
0. 0.
0.5 ! Shapiro Filter
5 1 50.
10 !maxvel
0 inunfl
1 indvel
0.5 5. s[12]_mxnbt
```

APPENDIX C: Description of Accompanying DVD

This report is accompanied by a DVD that contains all field data collected as part of this project, calibrated model and scenario run input files, the SELFE version 2.0d source code, analysis scripts, figures, animations and a copy of this report. This DVD is available from TWDB upon request.

Table C.1 Folder Layout on Accompanying DVD

Folder	**Description**
Analysis Scripts	Python, Shell and Fortran programs written to analyze data and model results
Animations	Video clip animations of model and scenario runs
Bathymetry	Raw and processed bathymetry data, including TWDB bathymetric survey final report.
Field Data	Field data collected by TWDB and USGS December 2005 – April 2007
Figures	High resolution maps and figures from analysis of data and model results
Model	SELFE v2.0d Source Code, SMS format base and marsh model grids, Input files for calibrated model and scenario runs