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Hydrology and water budget analysis of the East Joyce wetlands: Past history and prospects for the future

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ABSTRACT

The East Joyce Wetlands (EJW) bordering northwest Lake Pontchartrain have a long history of human induced changes, such as leveeing of the Mississippi River that eliminated almost all riverine input to the area and segmentation of the east and west Joyce wetlands by the construction of a railroad, U.S. highway 51, and Interstate 55. Dredged drainage canals and associated spoil banks channel upland runoff around the wetlands. The deep canal associated with I-55 causes both rapid short-circuiting of freshwater runoff to Lake Maurepas and saltwater intrusion from Lake Pontchartrain. Increasing soil salinity has caused wide-spread loss of forested wetlands in the areas. Recently, the discharge of secondarily treated municipal effluent into the northeastern EJW as part of the Hammond wetland assimilation project has focused attention on the area (i.e., Bodker et al., 2015). In response, we carried out a number of studies at the Hammond Assimilation Wetlands (HAW) detailed in Shaffer et al. (2015), as well as a series of hydrological measurements and modeling detailed here. These data show that drainage under the railroad was minimal and most flow through the wetlands was to the southeast. Water levels in the HAW were highly variable prior to the beginning of effluent discharge in 2006, with relatively high mean water levels that did not increase substantially from 2007 through summer 2009 despite the addition of municipal effluent. Following effluent addition, surface water levels lacked the variability of the pre-discharge period and mean water levels were about 20 cm higher from late 2009 until 2014 due to high rainfall in 2009, 2012, and 2013 and high effluent inflow due to significant infiltration into the city collection system. Historical net watershed inputs averaged 2.69 cm yr^{-1} if this volume of water were spread over the 4 km^2 area immediately south of the effluent distribution system, compared to 0.38 cm yr^{-1} for the effluent and 0.13 cm yr^{-1} for direct precipitation. Salinity records from five sites in the EJW showed a gradient of increasing salinity from north to south and strong seasonality, averaging 1.9–2.1 PSU near the lake to 0.4–0.6 PSU in the northwestern EJW. Peak salinities were 4.6–5.1 PSU near the lake and 1.8 PSU in northwestern EJW. There was also a significant decrease in salinity over time. Salinity was lower beginning in 2010 coinciding with the closure of the Mississippi River Gulf Outlet, high precipitation in the fall and winter of 2009, and in 2012 and 2013, and continuing operation of the assimilation system. Proposed plans to alternate effluent discharge between east and west Joyce wetlands should increase surface water depth variability as seen prior to effluent discharge and minimize salinity intrusion in both areas.

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1. Introduction

Wetland hydrology is characterized by very low relief, slow flow, high surface friction, and complicated flow patterns due to a complex mosaic of vegetation and shallow ponds and channels (Mitsch and Gosselink, 2007; Blahnik and Day, 2000). In coastal Louisiana, wetland hydrology is made even more complex by the effects of human activities such as channelization that short-circuits flow and/or allows saltwater intrusion, barriers to flow such as embankments and roads, and increasing urbanization of upland watersheds that affects volume, seasonality and quality of stormwater runoff (Cahoon et al., 2011; Conner et al., 2014; Richardson, 2005; Shaffer et al., 2009a; Wang et al., 2001). Here, we review the water budget and hydrological analyses carried out at the wetland assimilation system of the city of Hammond located in southeast Louisiana and we consider future management of the system to reverse impacts of hydrologic changes. We also consider the larger context of the history of changes in the western Pontchartrain Basin and their impact on regional and local hydrology. This paper is a continuation of work detailed in Shaffer et al. (2015), and specifically addresses the hydrology of the Hammond assimilation wetlands (HAW).

Wetland assimilation refers to the discharge of secondarily treated, disinfected municipal effluent from a wastewater treatment facility into wetlands rather than directly into a drainage canal, bayou, or stream, where water quality problems become evident (Kadlec and Knight, 1996; Day et al., 2004; Hunter et al., 2009a,b). The benefits of discharge of treated effluent into wetlands rather than into rivers and streams include improved water quality (Day et al., 2004), financial and energy savings (Ko et al., 2004), increased primary production (Hesse et al., 1998; Day et al., 2004; Brantley et al., 2008; Hunter et al., 2009a; Lundberg et al., 2011; Shaffer et al., 2015), and enhanced vertical accretion (Rybczyk et al., 2002; Brantley et al., 2008; Hunter et al., 2009b), as well as being more cost effective (Ko et al., 2004). The primary mechanisms by which wetlands remove nutrients from the water column are physical settling and filtration, chemical precipitation and adsorption reactions, and biological processes such as storage in vegetation and denitrification and volatization (Reddy and DeLaune, 2008). The ability of wetlands to remove nutrients from inflowing water is dependent on the nutrient species, residence time, and the area of receiving wetlands (Day et al., 2004; Dettmann, 2001; Kadlec and Knight, 1996). Nutrient uptake also is greatly influenced by the hydrology of the wetland. For example, when flow becomes overly channelized in a wetland it decreases the physical interface and time of interaction between the water and the surrounding landscape, resulting in lowered nutrient removal efficiency (e.g., Lane et al., 2015). It is therefore critical that the hydrology of wetlands receiving treated effluent is understood to prevent short-circuiting of water out of the wetland before adequate nutrient removal has occurred.

2. Objectives

The objectives of this study are to review the hydrology of the HAW and to consider future management. Specific objectives included: (1) document historical changes in the hydrology of the western Pontchartrain Basin due to human activities, (2) develop a water budget for the region, (3) present current hydrology data for the region, (4) identify major flow distribution patterns that predominate in the region, and (5) develop a hydrological model to the area.

3. Site description

The Joyce wetlands are located in the northwestern portion of the Pontchartrain Basin, extending from the Pleistocene uplands to the north near the city of Ponchatoula, south to North Pass, located north of Pass Manchac (Fig. 1). The Joyce wetlands are bordered

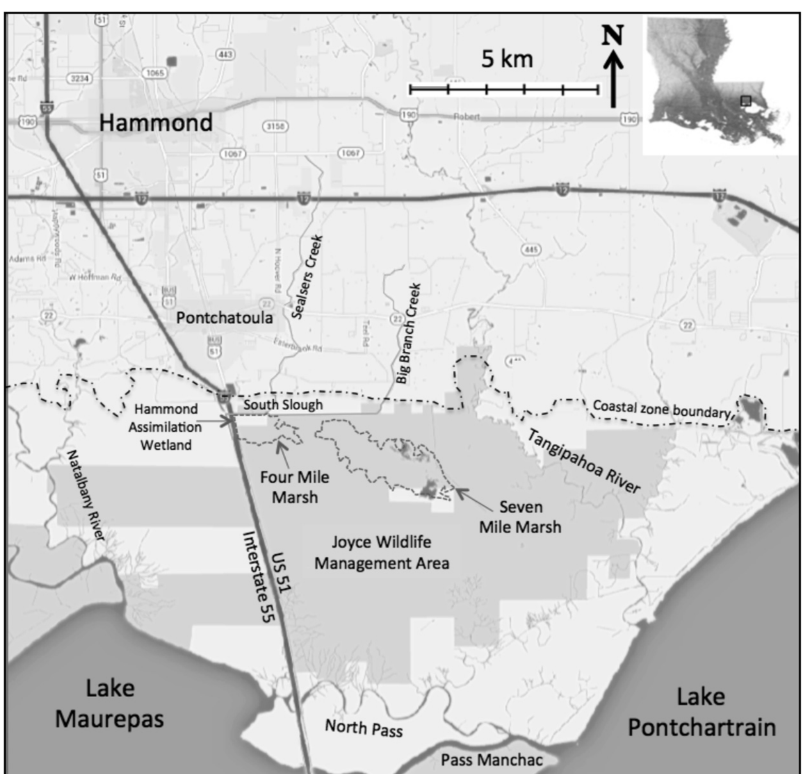

Fig. 1. The Joyce Wetlands, located south of Hammond and Ponchatoula, Louisiana. Shaded area is the Joyce Wildlife Management Area.

to the east by the Tangipahoa River and to the west by the Natalbany River, but are bisected from north to south by I-55, US-51, and railroad tracks, essentially creating east- and west-Joyce wetland tracts. Most of the Joyce wetlands (both east and west) are part of the Joyce Wildlife Management Area (JWMA), a state natural area managed by the Louisiana Department of Wildlife & Fisheries. The HAW is located in the northwest corner of east-Joyce wetlands (EJW) tract, just north of the wildlife management area (Fig. 1). The total area of the EJW encompasses about 14,000 ha, while the HAW are about 121 ha (321 acres).

4. A history of the regional hydrology of the site

The Joyce wetlands were formed as part of the St. Bernard Delta after the Mississippi River abandoned the Teche Basin and switched to the Pontchartrain Basin 2000–4000 years ago (Saucier, 1963; Blum and Roberts, 2012). The Manchac land bridge, separating Lakes Pontchartrain and Maurepas, was formed during that time by a branch of the Mississippi River that flowed northward, carrying sediment and building a narrow span of land that severed modern Lake Maurepas from Lake Pontchartrain (Saucier, 1963; Keddy et al., 2007; Fig. 2). The Mississippi River supplied vast quantities of sediments to the Pontchartrain Basin, leading to the progradation of the shorelines in Lakes Pontchartrain and Maurepas. The Joyce wetlands were also nourished by rivers draining uplands to the north, such as the Tchefuncta, Tickfaw, Natalbany, and Amite Rivers. The present Pass Manchac occupies the eastern portion of what was the Amite River channel, and North Pass occupies the eastern portion of what was the Tickfaw–Natalbany River channel several thousand years ago (Saucier, 1963). The name 'Pass Manchac' signifies the influence of Bayou Manchac, which delivered large quantities of Mississippi River water to the Amite River during the last several hundred years before being cut off from the river by levees in 1814 (Manchac is a Choctaw word meaning 'rear entrance' referring to an alternative entrance to Lake Pontchartrain and New Orleans compared to the Mississippi; Kniffen, 1935; Keddy et al., 2007).

The hydrology of the east Joyce wetlands (EJW) prior to human modification was characterized by flow from Selsers and Big Branch creeks, which drain an 86 km^2 watershed that extends north of the Joyce wetlands, forming a one-way southerly flow into the wetlands. The watershed generates an average of about 385,000 m^3 day^{-1} or about 30 times the current discharge of treated effluent. Water flux into the region from the south was driven by daily micro-tides (<5 cm), but more so by periodic meteorological events with strong winds from the south causing much higher water level variations than astronomical tides. For example, the tide range at the Louisiana coast is about 30 cm, but frontal passages can lead to water level variations of >1 m in just a few days, and hurricanes can cause surges of >5 m (Moeller et al., 1993; Perez et al., 2000). In the study area, storms with high southerly winds raise water levels in Lake Pontchartrain, stacking up lake water onto the north shore by >1 m and leading to extensive flooding of the Joyce wetlands, including the HAW.

During the past century and a half, there have been a number of significant modifications of the landscape that substantially altered the hydrology of the region. From a broad perspective, the hydrology and ecology of the whole region have been dramatically changed due to the construction of flood control levees on the Mississippi River. Under natural conditions, the Pontchartrain Basin received regular large inputs of river water during spring floods. During high flow years of the Mississippi, crevasses delivered inputs as high as 5000–10,000 m^3/sec (Davis, 1993). This is equivalent to a major opening of the Bonnet Carré Spillway (Day

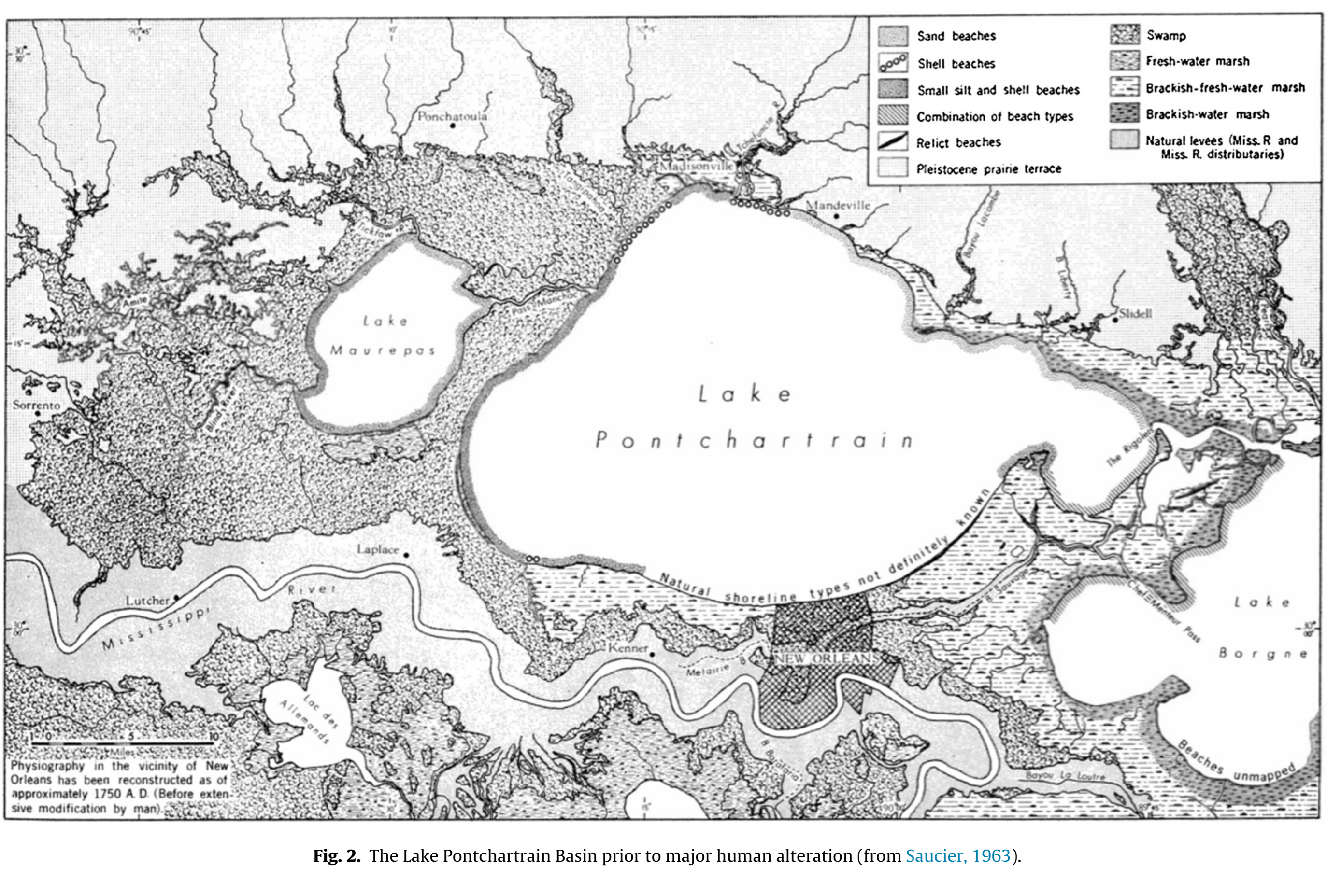

Fig. 2. The Lake Pontchartrain Basin prior to major human alteration (from Saucier, 1963).

et al., 2012). Davis (1993) documented hundreds of crevasses on the lower Mississippi after the arrival of Europeans. Saucier (1963) reported that the Bonnet Carré crevasse that functioned from about 1849 to 1890 deposited up to 2 m of sediments along the western shore of Lake Pontchartrain south of Pass Manchac. The elimination of river input has led to widespread deterioration of forested and emergent herbaceous wetlands surrounding Lake Maurepas (Shaffer et al., 2009a), with most of the remaining forested wetlands surrounding Lake Maurepas likely disappearing by mid century if current conditions persist (Shaffer et al., 2009a; Blum and Roberts, 2009).

Locally, the first major impact directly affecting the Joyce wetlands was the construction of railroad tracks during the mid 19th century, which were initially built on a bridge spanning the wetlands, but were rebuilt on the raised embankment that still stands today (Keddy et al., 2007). Although the embankment has a number of small openings for drainage, it severely restricts east–west water movement. US-51, constructed in 1926 parallel to the railroad, further reduced east–west flow. This was followed by the construction of I-55 in the 1960s, which left a large (>60 m wide) and deep (>5 m) canal running adjacent to the highway. This canal now serves as the major drainage channel for the region, shunting upland runoff from north directly into Lake Maurepas. The canal also is a conduit for salt water during drought and storm surges, and has been a major contributor to the demise of the baldcypress-water tupelo forest in the southern half of the Joyce wetlands (Keddy et al., 2007).

During the same period I-55 was being constructed, South Slough was dredged, which completed the hydrological isolation of the EJW by directing water from Selsers and Big Branch creeks, as well as diffuse runoff from the north, to the canal running parallel to I-55 into Lake Maurepas, bypassing the EJW (Fig. 1). The spoil generated from dredging South Slough was placed on the southern side of the canal, effectively blocking water from entering the EJW.

Since the construction of South Slough and the I-55 canal, saltwater intrusion has killed large areas of baldcypress-water tupelo forest in the Joyce wetlands. Short-term transient surface water salinity of 3.5 PSU was measured immediately south of South Slough during summer, 2006, just prior to effluent discharge (Lundberg, 2008). Had this salinity persisted, it would have led to mortality of the fresh vegetation. Practically all baldcypress and water tupelo trees on Jones Island and south of Pass Manchac have been killed primarily due to high salinities (Shaffer et al., 2009a). The lower third of the Joyce wetlands also have experienced a high rate of forest loss due to high salinities. Water tupelo has been eliminated from the lower two-thirds of the Joyce wetlands due to salinity stress because tupelo is a strictly freshwater species while baldcypress can tolerate salinities of 3-4 PSU and short-term salinity increases of >5 PSU (Allen et al., 1996; Campo, 1996; Conner et al., 1997; Shaffer et al., 2009a,b).

The construction of the Mississippi River Gulf Outlet (MRGO) in the early1960s led to dramatic increases in salinity in Lakes Borgne and Pontchartrain (Shaffer et al., 2009b). Salinity increases of about 3 PSU in Lake Pontchartrain led to salinity stress of surrounding freshwater wetlands. Over 6000 ha of freshwater forested wetlands were killed by high salinity after the opening of MRGO (Shaffer et al., 2009b). MRGO was closed in July 2009 and this led to a reduction of salinity in Lake Pontchartrain of about 3 PSU.

Periodic drought is a major threat to the freshwater forested and emergent wetlands bordering the western end of Lake Pontchartrain and surrounding Lake Maurepas. For example, salinity at the LaBranche wetlands during the drought of 1999–2000 was over three times normal levels, reaching 10–12 PSU (Shaffer et al. 2009a). These high salinities led to extensive baldcypress mortality, not only in the LaBranche wetlands, but over a large area of western Pontchartrain Basin (Keddy et al., 2007). Droughts, such as the 1999-2000 drought, occur periodically, with others recorded during 1953, 1963, and 1969. Such droughts, combined with the altered hydrology of the Joyce Wetlands, caused the widespread mortality of baldcypress that has been documented for the area (Shaffer et al., 2009a). It is clear that if a consistent and sustained freshwater source is not reintroduced to the area, loss of forested wetlands and freshwater marshes will continue.

5. Relative sea-level rise

One of the greatest threats to forested wetlands of coastal Louisiana is increasing sea level due to a combination of subsidence and eustatic sea-level rise (ESLR). Current ESLR is between 2 and 3 mm yr^{-1}, and there is a strong scientific consensus that the rate of ESLR will accelerate in association with global warming (FitzGerald et al., 2008; Meehl et al., 2009; McCarthy, 2009). The Intergovernmental Panel on Climate Change (IPCC, 2013) predicted sea-level rise of up to one meter by the end of the 21st century, with a range of uncertainty from 10 to 54 cm. Recent work based on semi-empirical methods suggests that ESLR may be more than one meter (Rahmstorf, 2007; Pfeffer et al., 2008; Mitrovica et al., 2009; Vermeer and Rahmstorf, 2009; Horton et al., 2014; Williams and Ismail, 2015). Increasing eustatic sea-level rise is especially critical in the Mississippi Delta, and other deltas, because it is augmented by high rates of subsidence. Relative sea level rise (RSLR), which is the combination of ESLR and subsidence, ranges from 3.6 to 4.5 mm y^{-1} in the Pontchartrain Basin (Penland and Ramsey, 1990). Due to the lack of sufficient accretion to compensate for RSLR, almost all of forested wetlands in the Maurepas Basin are semi-permanently flooded with little recruitment of seedlings that survive into adult trees (Shaffer et al., 2009a). About 3% of trees are disappearing each year, and if nothing is done, most of the forest will die out by mid century.

6. Precipitation/evaporation fluxes

Precipitation and temperature data were obtained from the National Climate Data Center for the meteorological station at the New Orleans International Airport from 2004 to 2014. Using these data, evapotranspiration (PET) was calculated using the Thornthwaite equation (Thornthwaite, 1948). Monthly precipitation was highly variable over the 11-year time span from 2004 to 2014 (Fig. 3, left panel). The majority of rain occurred during the spring and late summer. On average, the greatest amount of precipitation occurred in August (19.4 cm) and the least in November (6.2 cm, Fig. 3, right panel, blue). Average annual precipitation was 153.1 cm.

Potential evapotranspiration (PET) showed a typical trend of higher values during the warmer months and lower values during the winter months (Fig. 3, right panel, red). PET ranged from 2.1 to 16.6 cm mo^{-1}, with an average of 107.4 cm yr^{-1}. Average precipitation exceeded average PET during all months except June, August, and September, resulting in a surplus of precipitation in comparison with PET during the majority of the year (Fig. 3, right panel, line). Average net annual water surplus is 45.0 cm yr^{-1}. The water deficit during the summer months combined with dominant southerly winds leads to conditions favoring saltwater intrusion during major storm events. Discharge of treated effluent from the Hammond wastewater treatment plant creates a freshwater buffer that reduces the potential for salinity intrusion, especially during times of water deficit.

7. Municipal effluent discharge

In November 2006, the city of Hammond began discharging secondarily treated, disinfected municipal effluent to 121 ha (321 acres) of the HAW in the northwest corner of the EJW (Fig. 1). A

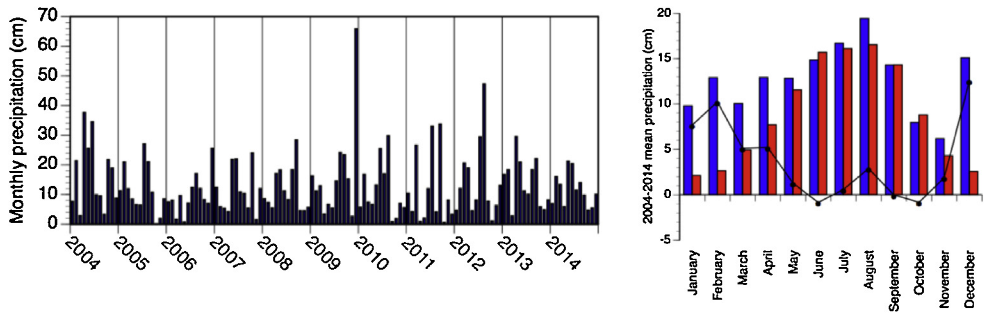

Fig. 3. Monthly precipitation (left panel. Average rainfall (right panel, blue), potential evapotranspiration (right panel, red) and net surplus/deficit (right panel, line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

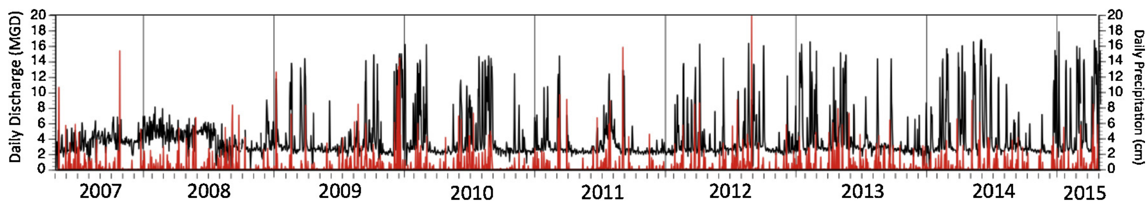

Fig. 4. Daily effluent discharge (black) and precipitation (red) at the HAW. Precipitation data from National Climate Data Center New Orleans International airport station. Daily discharge from the Hammond Water and Sewage Department. Peaks in effluent discharge are related to high inflow and infiltration into the Hammond collection system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.2 km effluent distribution system was constructed on the spoil levee running east–west on the south side of South Slough canal to disperse to the HAW to the south. The effluent is discharged via nine hundred 7.6-cm diameter outlets emanating from the main pipe. However, only 100–200 outlets are operational at any given time (each outlet is controlled with a hand operated spigot). Thus, the location of the discharged effluent can be moved east or west depending on environmental conditions.

Influent wastewater is collected and passed through the South WWTP three-cell oxidation lagoon, then disinfected by chlorination, and piped to the city of Ponchatoula's wastewater treatment plant for dechlorination prior to discharge to the HAW. Hammond's wastewater treatment facility has a design capacity of approximately 8 million gallons day^{-1} (MGD; ~30,000 m^3 d^{-1}). However, discharge can be much higher during wet weather due to high levels of inflow and infiltration into the collection system. For example, base discharge is about 2.7 MGD (Settoon, personal communication), but during storms discharge as high as 17.9 MGD has been recorded (Fig. 4), and the mean discharge since input began is 4.1 ± 0.05 MGD. The city of Hammond is currently carrying out a major repair and upgrade of its collection system so that effluent discharge rates should decrease in the near future. In addition, there is interest in a secondary outfall system to be constructed on the west side of I-55 creating two independent assimilation wetlands. This would enable pulsing of effluent for several months to one assimilation wetland, allowing complete drawdown of the other wetland, which would alleviate any water level stress to vegetation and promote greater nutrient assimilation. More details of the HAW are given in Shaffer et al. (2015).

Table 1
Mean annual water level, total precipitation, and total discharge at the HAW. Water level is relative to the wetland surface. Higher water levels after 2010 reflect higher precipitation and high inflow and infiltration into the Hammond collection system.

Year	Water Level (cm ± s.e.)	Precipitation (cm)	Discharge (m^3)
2004	17.1 ± 1.1	201.4	0
2007	9.2 ± 0.3	135.5	3,340,853.1
2008	17.7 ± 0.6	137.3	5,523,521.5
2009	16.2 ± 0.7	201.5	5,693,865.0
2010	18.1 ± 0.4	137.0	5,833,773.9
2011	20.0 ± 0.5	138.8	4,592,158.8
2012	23.2 ± 0.4	173.5	5,227,275.2
2013	29.8 ± 0.3	168.6	5,784,866.3
2014	31.2 ± 0.5	139.1	6,287,606.9

8. Water level at the assimilation wetlands

Water level at the assimilation wetlands generally followed effluent discharge and regional precipitation patterns, with a trend of slightly increasing water levels at the assimilation wetlands over time; with water levels before 2011 being 20 cm lower than after 2011 (Table 1). Major spikes in water level at the HAW wetlands

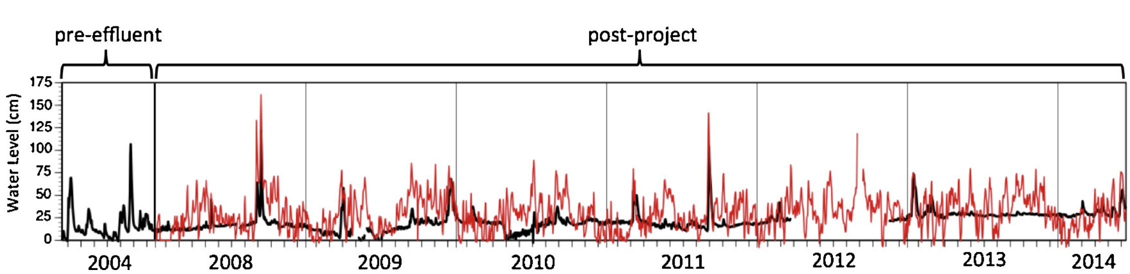

Fig. 5. Water level at the HAW (black) and at North Pass (red; CRMS0034). Data calibrated with zero at the wetland surface for the HAW and NAVD for North Pass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Hydrologic inputs to the HAW of effluent, rainfall, and historically from the watershed, expressed as cm per day over a 4 km^2 area south of the effluent discharge pipe.

	Depth over 4 km^2 (cm d^{-1})
Effluent	0.36
Rainfall	0.42
Historical watershed	2.69

were often correlated with similar water level spikes at North Pass (Fig. 5; data from Coastwide Reference Monitoring System (CRMS) site 0034), due to lake water flowing up the I-55 canal and entering the EJW through the railroad culverts as well as overland flow from North Pass. As noted earlier, the Hammond wastewater collection system has high levels of inflow and infiltration so heavy rains lead to much higher flows from the treatment plant and higher water levels in the HAW.

Assuming an average of 45.7 cm y^{-1} (0.13 cm day^{-1}) of precipitation after accounting for evapotranspiration, the 86-km^2 watershed feeding Selsers and Big Branch creeks generates on average 111,600 m^3 d^{-1} of stormwater runoff. If this volume of water was spread over the 4 km^2 area immediately south of the effluent distribution system, it would be 2.69 cm day^{-1}. By comparison, if the volume of effluent currently being discharged were spread over the same 4 km^2 area, it would be 0.36 cm deep (Table 2). Thus, the current volume of effluent being discharged into the assimilation wetlands by the city of Hammond is approximately 7 times less than the volume of stormwater runoff that flowed into the wetlands before hydrological alteration, and slightly less than the volume of average rainfall (0.42 cm day^{-1}) over the 4 km^2 area.

Multiple regression analysis was carried out with the HAW water level as the dependent variable and Discharge, Precipitation and North Pass water level as independent variables using JMP statistical software produced by SAS Institute, Inc. (Sall et al., 2012). North Pass water level and Discharge were the only significant variables, accounting for 21.5% of the variation in water level. However, when regressed alone, North Pass water level accounted for 18.0% of the observed variation, and Discharge accounted for only 7.4%. In general, the highest water levels in the HAW were correlated with high water levels at North Pass and to a lesser degree Discharge, but at lower water levels other variables such as discharge were dominant.

9. Salinity at the East Joyce wetlands

Scientists from the Louisiana Department of Wildlife & Fisheries have collected monthly salinity measurements at several locations in the EJW since 2006 (Fig. 6). The PM, MB and Pr stations in the south had the highest peak salinities at 4.9, 5.1 and 4.6 PSU, respectively, while the northerly SW and I-55 stations both had peak salinities of 1.8 PSU. If drought conditions were to continue for a prolonged period, the peak salinities at the SW and I-55 stations would be toxic to freshwater vegetation. The PM and MB stations had significantly higher mean salinities (2.1 ± 0.1 and 1.9 ± 0.1 PSU ± s.e., respectively) than the Pr station (1.4 ± 0.1 PSU ± s.e., $p < 0.0127$), and all three stations had significantly higher mean salinities than the SW and I-55 stations (0.4 ± 0.04 and 0.6 ± 0.1 PSU ± s.e., respectively, $p < 0.0001$). These data clearly show the strong salinity gradient running north–south from the assimilation wetlands to North Pass. There were also decreasing salinities at all of the stations over time (linear regression, $p < 0.001$), with an apparent decrease in salinity occurring at the beginning of 2010, with mean salinities after this time being significantly lower at all stations (one way ANOVA, $p = 0.0196$). This decrease coincides with the closure of MRGO, which occurred during the summer of 2009, high precipitation in the fall and winter of 2009, 2012, and 2013, and continuing operation of the assimilation system.

10. Water flux through the railroad culverts

During the initial feasibility study for the assimilation wetland, an issue of concern was whether water flows out of EJW

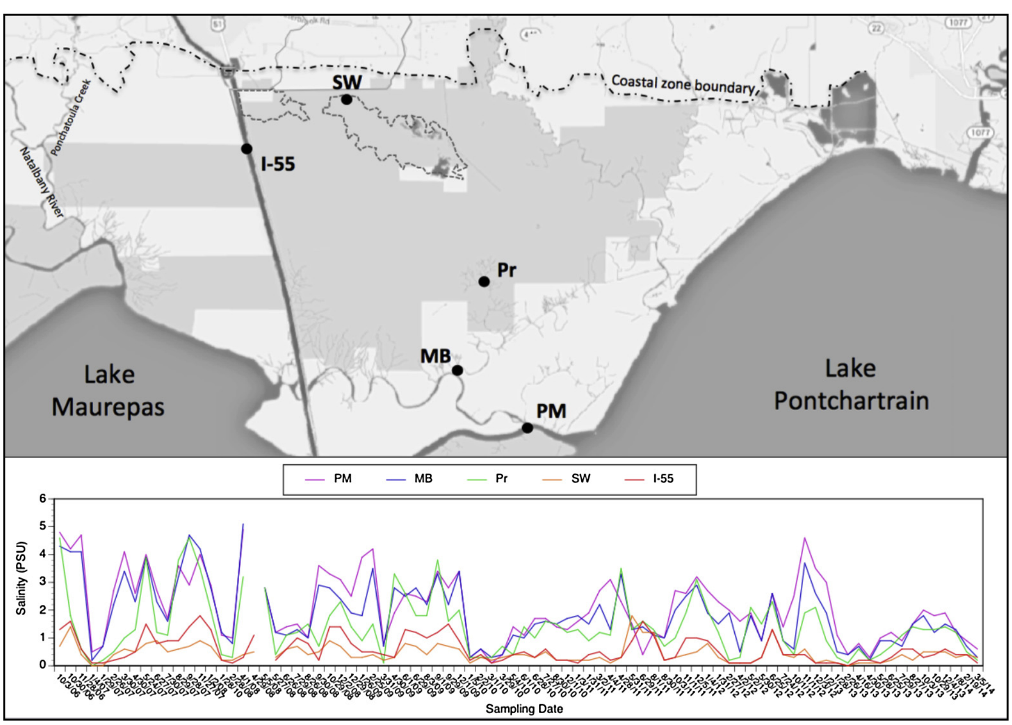

Fig. 6. Salinity at the East Joyce wetlands from 2006–2014.

Table 3
Water flux through culverts and bridges on the western edge of the EJW (+: flow into the EJW and −: flow out of the EJW (cm s^{-1})). Bridge #1 is located near North Pass, and #16 is located at South Slough. The Wildlife and Fisheries boardwalk (Mid Site) is located between #14 and #15. No data is given for bridges 2, 3, 6, 7, 14, and 15 because flow was zero for all measurements.

Bridges	3/30/04	4/1/04	4/5/04	4/7/04	4/12/04	4/13/04	4/25/04	4/26/04	4/26/04	5/12/04	5/22/04
16	0	−8.0	0	0	−8.3	−22.0	0	−16.6	−12.5	−33.3	−119.0
13	−3.0	0	0	0	0	0	0	3.0	0	4.3	−31.3
12	0	0	0	0	0	0	0	4.1	−4.7	4.3	−19.0
11	0	0	0	0	0	0	0	3.7	−12.5	3.2	−32.5
10	0	0	0	0	0	0	−3.2	5.0	0	16.0	−28.8
9	0	0	0	0	0	0	0	3.3	0	3.7	−19.8
8	−1.0	0	0	0	0	0	0	0	0	0	−37.0
5	0	0	0	3.5	−5.5	0	0	4.0	−5.7	0	−136.3
4	0	−2.4	0	0	−5.8	0	0	1.6	−10.0	0	−15.3
1	0	0	0	0	−1.0	0	−2.7	0	0	0	−41.6

by way of the railroad culverts along the western border, thereby bypassing much of the available wetlands. To determine the importance of this potential short circuit, a number of measurements of flow through the culverts and bridges under the service road on the east side of I-55 were made.

Between North Pass and South Slough, there are 15 culverts or bridges under the road and railroad. We measured water level and current direction and velocity 11 times from March 30 to May 22, 2004 (Table 3). During the study period, there were no strong flows measured either into or out of the EJW, even when there had been heavy rains. The only exception was the final flow measurement when lake levels were low. For example, the measurements on May 12 occurred after heavy rains of between 13 and 25 cm the prior two days and the flow at South Slough was strong toward the west at 33 cm s^{-1}. However, at the same time as water flowed west through South Slough, there was no flow through the bridges and culverts under the road, or where there was flow (openings 9, 10, 11, 12, and 13), the flow was east into the marsh. On May 22, following additional heavy rains and low lake levels, there was strong flow westward out of the EJW. These data indicate that the most important factor controlling flow along the western boundary of the assimilation wetland is the water level in Lakes Maurepas and Pontchartrain. The high range of water levels in these lakes exerts primary control over water levels in the EJW.

It is likely that water flow out of the EJW to the west occurs mainly in the winter when lake levels are generally lowest, although measurements show that this can occur at times of year other than winter. High Tangipahoa River levels with east winds could also contribute to a westerly flow of water through the area. We conclude that water flow through the western boundary of the EJW is not a dominant pathway of water movement.

11. Water flow in the assimilation wetlands

A dye study was carried out to measure water flow characteristics at the HAW. Water flow direction and speed were measured in July and November 2009, and March, May and August 2010, by tracking multiple dye drops over a period of several hours at 31 locations in and around the HAW. Observations were made at four boardwalks in the immediate effluent discharge area, referred to as 'Treatment Boardwalks 1-4', as well as at forested wetlands to the east and southeast of the discharge pipe, referred to as the 'Swamp sites', at the Railroad Culvert under the railroad south of South Slough, and at the Joyce Wildlife Management Area Boardwalk, referred to as the 'Joyce Boardwalk' (Fig. 7). At the Treatment Boardwalks, measurements were made at approximately 10, 50, 100, 150, and 200 m from the discharge pipe. At the Joyce Boardwalk, measurements were made at five locations spaced evenly over the length of the boardwalk, with the western-most site in the borrow canal immediately east of the railroad, and the eastern-most site at the eastern end of the boardwalk.

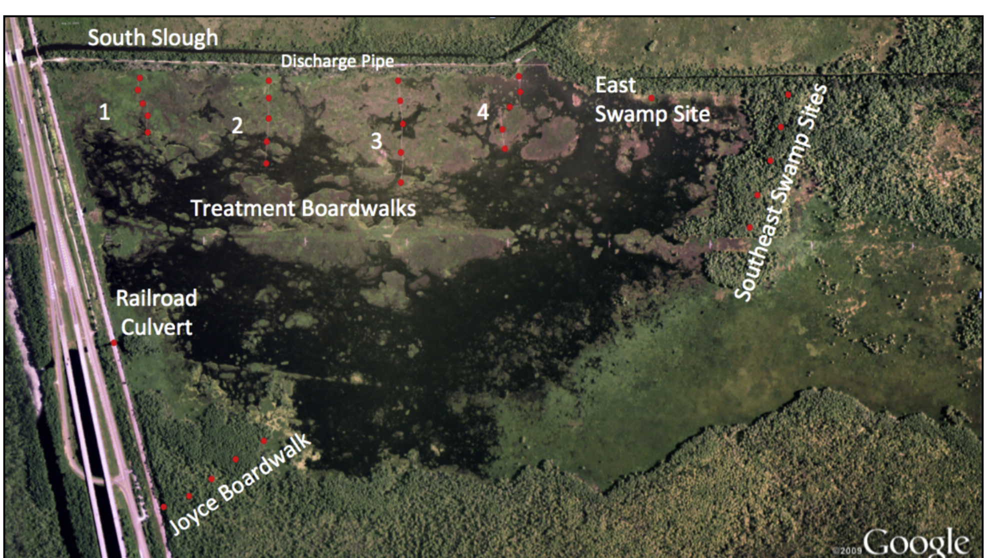

Fig. 7. Locations of water flow measurements (indicated by red dots) in and around the HAW (2010 Google Earth imagery). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Water flow was measured by dropping several ml of red rhodamine dye into the water, and then measuring the movement of the resulting dye patch. Observations also were made for up to 15 min until the dye patch was either no longer visible or inaccessible. Time, distance, and direction traveled were recorded. When there were significant winds during measurements, care was taken to measure subsurface water flow rather than the surface flow, which was often strongly influenced by winds. On several occasions, we observed the surface film moving in the opposite direction to that of the subsurface water flow but the water column movement was clearly visible from the moving dye patch. Water level data of Lake Pontchartrain and several locations in the Joyce wetlands were obtained for analysis of regional hydrological forcings.

11.1. July 2, 2009

During the July 2nd sampling effort, effluent was being discharged from the eastern end of the discharge pipe at 2.13 MGD, with effluent flowing southeast, feeding the only area of standing water present in the assimilation wetlands due to a recent drought (Fig. 8a). There was no surface standing water at Treatment Boardwalks 1 and 2, or at the Joyce Boardwalk, and there was no flow at the Railroad Culvert. Water depths at Treatment Boardwalk 4 were 8–10 cm with velocities of 3–4 cm s^{-1}. At the edge of the cypress seedling exclosure, about 30 m from the discharge pipe at Treatment Boardwalk 4, flow was 10 cm s^{-1}. Water depths were deeper at the Swamp sites, ranging 16–30 cm with velocities of 2.1–3.3 cm s^{-1} at the east Swamp sites and 0.5–1.7 cm s^{-1} at the southeastern Swamp sites. These results indicate that as effluent flowed away from the discharge pipe it spread out and velocity slowed. These measurements represent water flow movement under relatively dry conditions.

11.2. November 11, 2009

A tropical storm made landfall near Mobile, AL, a few days prior to the November 11th monitoring event that brought in high southerly winds resulting in elevated water levels in Lake Pontchartrain as well as in the assimilation wetland (Fig. 8b). Water was observed moving into the assimilation wetlands from the south at the Joyce Boardwalk at 1.0–3.8 cm s^{-1}. Flow at the Railroad Culvert was to the east (into the wetlands) at 13.0 cm s^{-1}, which is considerably higher than any other flow velocity measured in this study. These measurements show the effect of elevated lake levels pushing water into the area. Flows at the Treatment Boardwalks were erratic but generally to the east and north at <2.2 cm s^{-1} with depths ranging from 13 to 35 cm. Water flowed to the east at the Swamp sites with depths ranging from 23 to 48 cm. Effluent discharge was at 2.14 MGD.

By November 16, water levels in Lake Pontchartrain had fallen and water was flowing out of the assimilation wetland. Discharge was at 2.47 MGD. Flow at the Railroad Culvert was to the west at 5.6 cm s^{-1}, and flow was southerly at the Joyce Boardwalk. By November 19, water was still flowing to the west at the Railroad Culvert, but velocity had fallen to 2.4 cm s^{-1}. Effluent was being discharged at 2.26 MGD, and water movement at the Treatment Boardwalks was to the west, south, and east as the effluent spread out from the discharge pipe into the assimilation wetland and the greater EJW complex.

These results indicate that elevated water levels in Lake Pontchartrain moved water into the Joyce wetlands from the south, as well as through the I-55 canal and through the Railroad Culvert. Water then generally moved to the east and south at low velocities. When water levels in Lake Pontchartrain fell, water flowed out of the assimilation wetlands for several days. Water was measured flowing to the south at the Joyce Boardwalk and to the west at the Railroad Culvert. When outside forcings were minimal, as on November 19, some water was measured flowing to the southwest, however, most water tended to spread out to the southeast.

11.3. March 17, 2010

The winter of 2010 was one of the wettest winters on record, with 53 cm of rainfall from December 2009 to March 2010. Effluent was being discharged at 2.54 MGD in the vicinity of Treatment

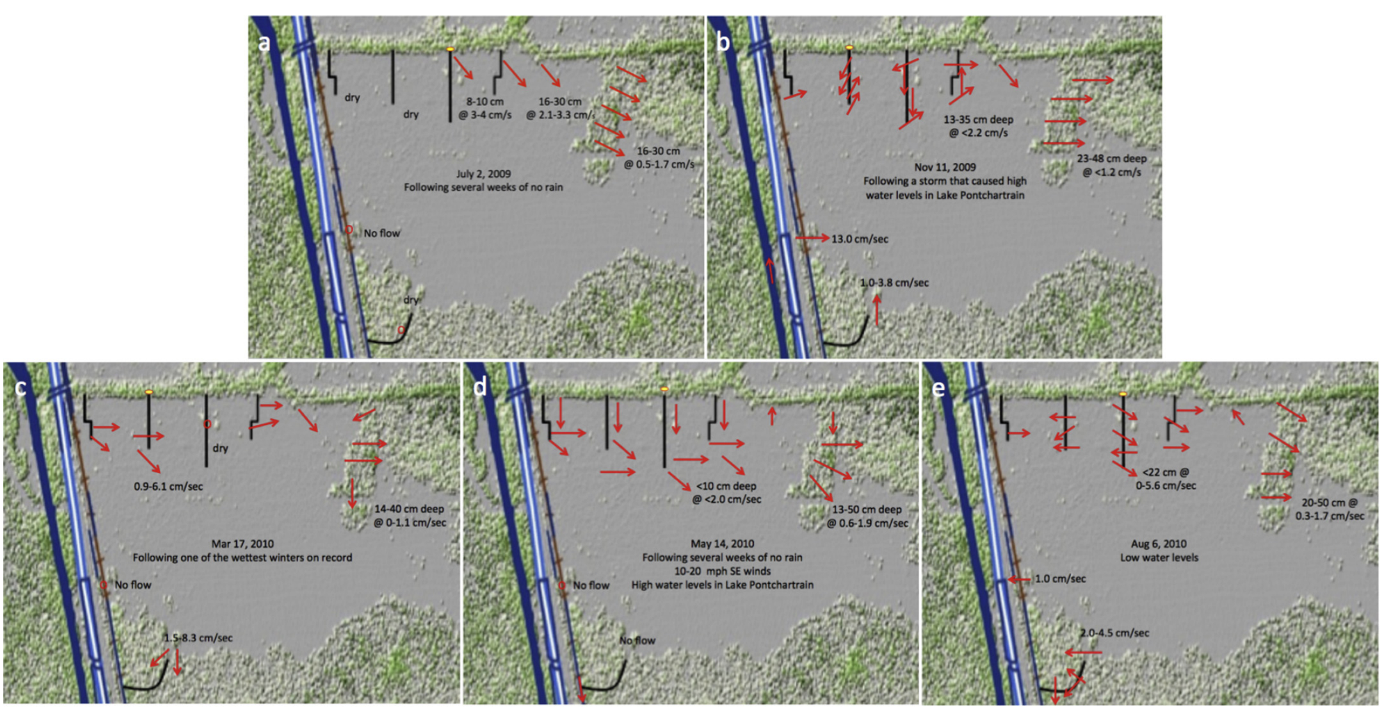

Fig. 8. Hydrology in the HAW on July 2 (a) and November 11, 2009 (b), March 17 (c), May 14 (d), and August 6, 2010 (e).

Boardwalk 2, and flowed to the east and southeast at 0.9–6.1 cm s^{-1}, averaging 2.9 cm s^{-1} (Fig. 8c). There was no surface water at Treatment Boardwalk 3. Water flowed <1.1 cm s^{-1} generally to the east and south at the Swamp sites, with depths ranging from 14 to 40 cm. Flow was southwesterly along the Joyce Boardwalk at 1.5–8.3 cm s^{-1}. There was no flow at the Railroad Culvert.

11.4. May 14, 2010

The measurements on May 14 were taken after several weeks of no rainfall. Effluent was being discharged at 2.48 MGD near Treatment Boardwalk 3, and there was a brisk southeast wind of 16–32 km h^{-1}. Water levels in Lake Pontchartrain were elevated as indicated by higher than average water levels at the Joyce Boardwalk. Flow was to the south in the old borrow canal east of the railroad, but there was little flow at the Joyce Boardwalk and no flow at the Railroad Culvert (Fig. 8d).

Flows at the Treatment Boardwalks were mostly <2 cm s^{-1} and were generally to the south and east. In small open ponds, the southeast wind caused dye at the surface to move in the direction of the wind, however, deeper water moved in the opposite direction. Only in shallow (~5 cm) ponds did most of the water column move in the same direction as the wind, but at much lower velocities. Water depth was <10 cm at all the Treatment Boardwalk sites, and much of the assimilation wetland did not have any standing water.

At the Swamp sites, water flowed 0.6–1.9 cm s^{-1} with 13–50 cm of depth. Flows were southerly to easterly, with the exception of a measurement in a ditch at the eastern Swamp site where flow was to the north. This is consistent with all previous measurements where water depth at the Swamp sites was deeper than at the Treatment Boardwalk sites and velocities were less.

11.5. August 6, 2010

Effluent was being discharged at 13.9 MGD near Treatment Boardwalk 3 on August 6, 2010, after several days of heavy rain. Water flowed away from Treatment Boardwalk 3, flowing west and southwest at Boardwalk 2 and east and southeast at Boardwalk 3 (Fig. 8e). Velocity ranged from 0 to 5.6 cm s^{-1} with depths <22 cm. Flow at the Swamps sites was to the east and southeast at 0.3–1.7 cm s^{-1} with 20–50 cm depth. Water flowed west through the Railroad Culvert at approximately 1 cm s^{-1}.

We draw the following conclusions from the dye study and the flow measurements described above. In the immediate discharge area, measurements at the boardwalks and in the swamp to the east of the discharge pipe showed that the flow was generally to the south and east. In the marsh, water depths were generally less than 10 cm and often there was no standing or moving water. Current velocities were generally less than 5 cm s^{-1}. In the swamp water depths were deeper but current velocities were lower. At the Joyce boardwalk, current speed and direction depended mostly on recent rainfall and lake water levels. During periods of low rainfall, hydrology did not seem to be strongly linked to the effluent discharge. The general pattern of water movement was to the south and east, and the volume of water flowing through the Railroad Culvert was much less than flow south and east through the wetlands. Part of the reason for this is that the cross section area of water flow in the wetlands is much larger than that of the Railroad. For example, the HAW is about 2 km wide; a 10 cm deep water column would have a cross section area of about 160 m^2 compared to 2.5 m^2 for the railroad opening.

12. Hydrological modeling

Hydrologic inputs to the wetland study area include precipitation, daily tides, upland runoff, and discharge from the Tangipahoa River during high river stage. To understand the hydrologic behavior of the wetland system a TABS-MD computer hydrologic model was developed. The TABS-MD is an engineering model that has been used extensively in the university research environment (Barrett, 1996; Freeman, 1992; Roig, 1994). Barrett (1996) used the TABS-MD model for wetland design. Freeman (1992) conducted a review of the model behavior in shallow water, and Roig (1994) used this tool for marsh and wetland modeling.

Two modules (GFGEN and RMA2) of the TABS-MD were used in this study. The module GFGEN was used to create the finite element mesh of the study area (Fig. 9, left), and the module RMA2 simulated hydrodynamic conditions of the study area. The RMA2 program is a two-dimensional depth-averaged finite element hydrodynamic model that assumes the fluid is vertically well mixed with a hydrostatic pressure distribution, and vertical acceleration is assumed negligible.

A 6.5 MGD discharge run of one-month duration was made to examine the change of water surface elevation and velocity profile compared to a no discharge scenario. Based on surveyed and observed data, the topography of the receiving wetland was created and the ranges in elevation were found to be roughly 30 cm. A constant tide elevation of 30 cm was used as the boundary condition.

Model results suggested that water levels would be raised by less than 2 cm under the designed discharge scenario and that flows were at steady state in less than one month. The modeling did not

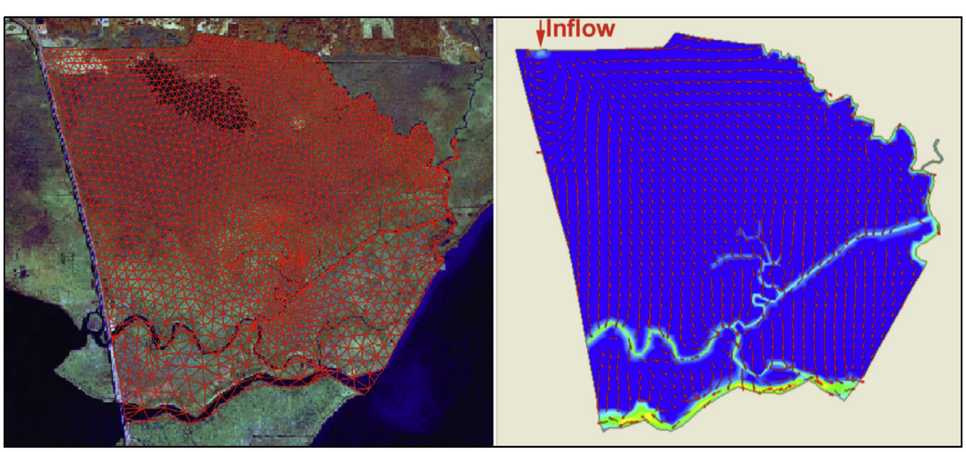

Fig. 9. The finite element mesh of the EJW used in the TABS-MD hydrologic model (left panel) and water flow vectors at steady state resulting from TABS-MD hydrologic model (right panel). See text for discussion.

take into consideration friction of the wetland vegetation. Change in flow velocity due to the discharge was found to be 0.2 cm s^{-1}. Flow directions are mostly southeastern while some circulation toward the west also occurred in the northwestern part of the area. This was consistent with field measurements made during high water periods (Fig. 9, right). Because the person who was running the model moved, no further runs were carried out. We are currently implementing the Delft 3D model for the area to develop a more detailed understanding of the hydrology of the area. This modeling effort will more accurately reflect vegetation and open water conditions and include estimates of friction in herbaceous and forested vegetation.

13. Summary and conclusions

From these results, the following conclusions can be drawn. Over the past century and a half, there have been dramatic changes in the hydrology of the Joyce wetlands and more generally in western Lake Pontchartrain and Lake Maurepas and in surrounding wetlands. Leveeing of the river led to loss of riverine input and the construction of the railroad and U.S. 51 effectively separated east and west Joyce wetlands. A deep canal associated with the construction of I-55 allows rapid runoff of fresh water from the north and rapid saltwater intrusion from the south. Saltwater intrusion has led to widespread death of forested wetlands. There is a strong north-south salinity gradient in the EJW. Closure of MRGO and the effluent input reduced salinity, especially in the northwest EJW. The construction of South Slough and resulting spoil placement eliminated practically all input of upland runoff into the EJW. This upland runoff was about seven times greater than the present effluent discharge. Hydrologic measurements in 2009 at the site indicate that practically all flow in the wetlands is to the south and east with very little flow eastward. In the immediate discharge area, measurements at the Treatment Boardwalks and at the Swamp sites showed that water flow was almost always to the south and east. At the Treatment Boardwalks, water depths were generally <10 cm with velocities of <5 cm s^{-1}. At the Swamp sites, water depths were deeper and velocities were lower than at the Treatment Boardwalks. At the Joyce Boardwalk, water direction and velocity depended mostly on rainfall and water levels in Lake Pontchartrain. During periods of normal or high rainfall, hydrology did not seem to be strongly linked to the effluent discharge. Peak water levels in the northwest EJW were primarily driven by high lake water levels, with effluent discharge having little impact. Proposed plans to alternate effluent discharge between east and west Joyce wetlands would allow complete drawdown periods to alleviate any water level stress to vegetation and promote greater nutrient assimilation while minimizing salinity intrusion at both areas.

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