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Modeling current and future freshwater inflow needs of a subtropical estuary to manage and maintain forested wetland ecological conditions

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ABSTRACT

Riverine input is essential for the sustainability of the estuaries, wetlands, and swamps into which they flow. An existing coastal ecosystem model was used with forested wetland and fish habitat indicators to evaluate current environmental conditions as well as future restoration projects via 50-year simulations of riverine flow with sea level rise and subsidence. The objective of this study was to utilize the Integrated Compartment Model developed for the Louisiana Coastal Protection and Restoration Authority's 2017 Coastal Master Plan to understand how alternations of riverine flow from existing rivers and future restoration projects may influence the spatial and temporal distribution of wetland habitats and suitability of fish habitats. The model was applied to the Lake Maurepas ecosystem where the Amite River flows into the lake and supports vital fisheries for surrounding communities, as well as a unique and valuable recreational resource. Additionally, the Amite River nourishes the marshes and swamps around Lake Maurepas that are essential for storm surge protection for the broader region. Modeling results suggest that the major contributing factor to the freshwater conditions to the Lake Maurepas area is the challenge of relative sea level rise − the combination of rising seas and subsidence. Fresh forested areas comprised of bald cypress (*Taxodium distichum*) and tupelo gum (*Nyssa aquatica*) in Maurepas Swamp decrease significantly under all future climate and relative sea level rise simulations except when future restoration projects are utilized. An estimated ~1000 km^2 of fresh forested wetland could be maintained over a 50-year period when considering certain restoration projects that increase freshwater flow and under climate change-related rainfall patterns, sea level rise and subsidence. However, modeled results indicate that more than 100% of the current riverine flows into the Maurepas Swamp region are still not sufficient to fully counteract the impacts of the assumed future sea level rise scenario and maintain the current forested wetlands surrounding Lake Maurepas. The higher salinities and more estuarine open water areas provide additional habitat in the future that will likely be more suitable for spotted seatrout (*Cynoscion nebulosus*), and adult bay anchovy (*Anchoa mitchilli*) than largemouth bass (*Micropterus salmoides*). Modeled future conditions of this ecosystem can inform restoration agencies and organizations by helping to prioritize and plan for future decades by incorporating critical factors such as sea level rise, subsidence and precipitation patterns, including the possible need to plan and prepare for changes in the fish communities and consider how that might influence the well-being of local communities.

1. Introduction

Freshwater bodies and estuaries worldwide are undergoing drastic change due to alteration of freshwater flow that impacts their ecology (Abrantes and Sheaves, 2010; Alber, 2002; Kimmerer, 2002; Sklar and Browder, 1998). Freshwater input serves many essential ecological functions, including the regulation of salinity and delivery of nutrients and sediments from the watershed (Alber, 2002; Baron et al., 2002). Without an adequate supply of fresh water, certain estuaries, wetlands, and swamps will be unable to provide key ecosystem services that support coastal communities, such as fisheries, flood protection, and recreation. In coastal communities around the world, demands on freshwater supply are increasing and future uncertainties (i.e., sea level rise and subsidence) threaten coastal communities (Doyle et al., 2007; Whitfield and Taylor, 2009). The determination of the freshwater inflow needs and the use of estuarine indicators is necessary to maintain

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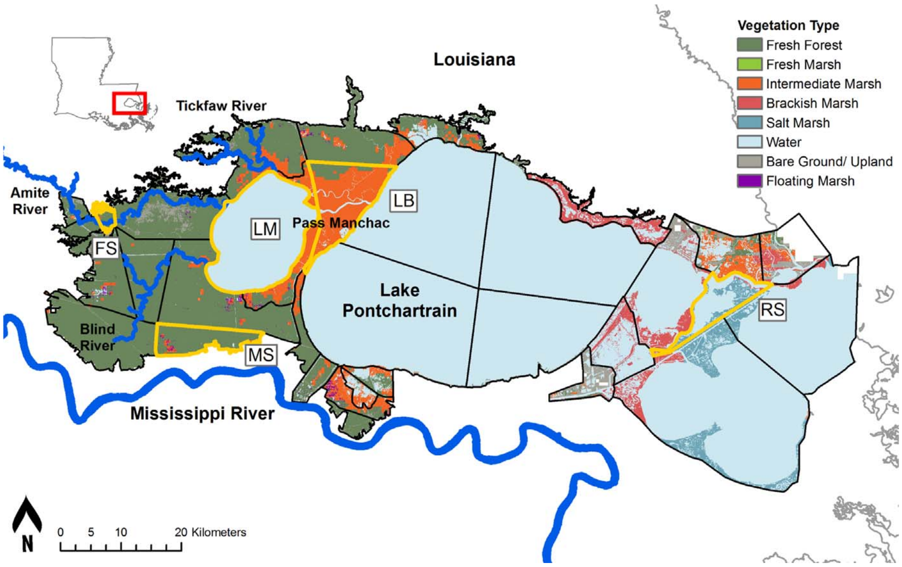

Fig. 1. Location of Lake Maurepas (LM) and Lake Pontchartrain in southern Louisiana, USA,. Current habitats and future restoration projects are labeled. Three rivers (Tickfaw, Amite, and Blind) that discharge into LM are labeled. Black lines indicate model compartment boundaries and gold lines highlight the compartments of interest, FS = French Settlement, LM, LB = land bridge, MS = Maurepas Swamp, RS = Rigolets.

the provision of these ecosystem services.

1.1. Study area background

In coastal Louisiana, USA, the Amite River flows into Lake Maurepas, and supports a vital fishery for surrounding communities such as Ponchatoula and Manchac, while providing a valuable recreational resource (Shaffer et al., 2016) (Fig. 1). Additionally, the inflow of the Amite River nourishes the marshes and swamps around Lake Maurepas that are essential for flood protection for the broader region (Shaffer et al., 2016, 2009). Lake Maurepas is located in the Mississippi River Delta complex (Flowers and Isphording, 1990), located between New Orleans and Baton Rouge, LA (Effler et al., 2007). It is 21 km wide, but no more than 3 m deep (Effler et al., 2007). Lake Maurepas is an oligohaline coastal lake with three rivers, Tickfaw, Blind, and Amite currently discharging roughly 144 $m^3 s^{-1}$ of freshwater into the western shore (Flowers and Isphording, 1990). Lake Maurepas then drains through Pass Manchac into eastern Lake Pontchartrain (Hoeppner et al., 2008). The Amite River discharges the most freshwater into this system and drains a watershed that is 3434 km^2 and about 58% forested (Wu and Xu, 2006). It is a warm water, low gradient coastal stream with upper reaches in Louisiana characterized by faster flows with sand or gravel substrata, while the lower reaches closer to Lake Maurepas are meandering, bayou-like rivers with slower flow, silt sediments overlaying sand, and extensive riparian wetlands (Felley, 1992). The wet season, with 69% of the annual discharge, occurs in winter and spring, and summer and fall are lower discharge periods, although urbanization of the watershed near Baton Rouge has increased discharges by 55% during the last 40 years (Wu and Xu, 2006).

The Maurepas Swamp surrounds Lake Maurepas and is in the Lake Pontchartrain Basin that includes 16 Louisiana parishes and spans approximately 12,000 km^2. This area is the second largest contiguous coastal forest in Louisiana (Effler et al., 2007). The swamp includes 776 km^2 of freshwater forested wetlands and 52 km^2 of fresh and oligohaline marshes (Shaffer et al., 2016). Historically, the Maurepas Swamp in the Mississippi River Delta complex (Flowers and Isphording, 1990) was dominated by vast forests of bald cypress (*Taxodium distichum* (L.) Rich., Order: Pinales, Family: Cupressaceae) and tupelo gum (*Nyssa aquatica* L., Order: Cornales Family: Cornaceae) (Effler et al., 2007; Keddy et al., 2007; Shaffer et al., 2003)(Fig. 1). Although bald cypress was traditionally used by Native Americans for building huts and canoes, notable anthropogenic changes did not occur until post European colonization. Subsequently, bald cypress became the dominant cash crop in Louisiana. Massive deforestation became possible with the invention of pullboats in the 1890′s. Pullboats, in conjunction with canal excavations, increased the accessibility to interior swamps, providing a mechanism for large-scale systematic clearcutting, depleting the timber resource by the late 1920′s (Effler et al., 2007; Keddy et al., 2007). Although much deforested land regenerated as bald cypress-tupelo second growth, by the 1960′s ecological changes in the region had already begun to foster a transition to marsh (Barras et al., 1994). One of the major stressors to the bald cypress and tupelo gum swamps is soil-water salinity (Shaffer et al., 2016) that inhibits natural regeneration (Allen et al., 1997) because of the relative inability to exclude ions (Na +, Cl-) from tree leaf tissue or compartmentalize the ions in cell vacuoles for osmotic adjustment (Allen et al., 1996). Thus, the accumulation of ions is likely disrupting photosynthesis (Allen et al., 1996) and causing leaf and eventually tree mortality (Pezeshki et al., 1987). Swamp areas that have already experienced salinity induced-stress include the areas near Lake Maurepas (Pezeshki et al., 1987; Shaffer et al., 2016).

Lake Maurepas and surrounding swamp and marshes provide valuable habitat to flora and fauna, which are likely to undergo additional change in spatial distribution under future environmental conditions. Distribution habitat models of fresh and estuarine fish species can help inform where habitat hot spots are located now and in the future (Hijuelos et al., 2016). For example, the freshwater largemouth bass (*Micropterus salmoides* Lacepede, Order: Perciformes, Family: Centrarchidae), tends to prefer estuarine open water habitat of low salinities (Glover et al., 2013) whereas spotted sea trout (*Cynoscion nebulosus* Cuvier in Cuvier and Valenciennes, Order: Perciformes, Family: Sciaenidae), a local recreational fisherman favorite, and bay anchovy (*Anchoa mitchilli*, Valenciennes in Cuvier and Valenciennes, Order: Clupeiformes, Family: Engraulidae) are more suitable for high salinities (Peebles et al., 2007). Hydrological models that are linked to habitat suitability indices of these fishes can help reveal how altering environmental conditions might influence the spatial distribution of habitats and indicator species.

Currently, the Maurepas Swamp is in critical condition and considered severely degraded (Shaffer et al., 2016). Within the last several decades, factors such as canal construction, sea level rise, subsidence, and regional drought have increased the frequent and intensity of saltwater intrusion from the Gulf of Mexico. Salt stress, in conjunction with reduced riverine input compared to historical conditions, nutrient poor water, low soil strength, nutria herbivory, prolonged flooding of certain areas due to alterations of drainage, and low bald cypress-tupelo recruitment are accelerating the conversion of swamp to marsh or open water (Shaffer et al., 2016, 2009). However, the foremost cause of the habitat conversion can be attributed to the lack of riverine input and the subsequent salt stress (Shaffer et al., 2009). Future management options include introducing more freshwater into the area to promote freshwater forested wetlands (CPRA, 2017), a restoration approach that has previously been deemed the indispensable and singular approach needed to achieve sustainability of this habitat (Shaffer et al., 2001). The freshwater restoration scenarios in the Maurepas Swamp region included in the 2017 Coastal Master Plan vary in magnitude of design capacity flowrates from 55 $m^3 s^{-1}$ to 710 $m^3 s^{-1}$. While the operation of these restoration flows varies as a function of freshwater availability in the Mississippi River, this is a substantial increase in flowrate reaching the Maurepas Swamp from the current average inflow of 144 $m^3 s^{-1}$ from the three tributaries.

The watershed of the Amite River and surrounding area sits in a low gradient coastal area that is prone to flooding from major precipitation events and coastal flooding from storm surge. From August 11–14, 2016, an unprecedented flood occurred in the Greater Baton Rouge area caused by a slow-moving system that delivered rainfall in excess of 31 inches (78 cm) in some places over a three-day period. Rivers swelled, including the Amite, resulting in at least 13 deaths and causing an estimated $10 billion in damages to homes and businesses (Watson et al., 2017). Major flooding occurred in the southern portions of Louisiana including areas surrounding Baton Rouge and Lafayette from rivers such as the Amite, Comite, Tangipahoa, Tickfaw, Vermilion, and Mermentau. Streamflow-gaging stations operated by the U.S. Geological Survey (USGS) recorded peak streamflows of record at 10 locations, and seven other locations experienced peak streamflows ranking in the top five for the duration of the period of record. In August 2016, USGS hydrographers made 50 discharge measurements at 21 locations on streams in Louisiana. Many of those discharge measurements were made for verifying the accuracy of stage-streamflow relations at gaging stations operated by the USGS. Following the storm event, USGS hydrographers recovered and documented 590 high-water marks, noting location and height of the water above land surface. Many of these high-water marks were used to create 12 flood-inundation maps for selected communities of Louisiana that experienced flooding during this event. Digital datasets of the inundation area, modeling boundary, water depth rasters, and final map products are available online (Watson et al., 2017). The event brought about reconsiderations of past riverine flood mitigation projects, such as the Comite River Diversion. Future climate conditions are likely to increase intense precipitation events and flooding (Melillo et al., 2014); therefore, ecosystem models can help managers understand how these riverine flow regimes and ecosystem responses may change in the future and help them prepare adaptive management strategies.

In addition to devastating flooding in the inland floodplain, there was a period immediately following the August 2016 flood in which there were substantially reduced salinities in the Pontchartrain estuary, as compared to the long-term median daily salinity (Fig. 2). Immediately following the heavy rainfall from August 10 through the 15, there was a period in which the hourly salinity signal at the Rigolets (the outlet of the Pontchartrain system) was essentially flat without any diurnal fluctuations in salinity that can be seen during periods of tidal exchange through the Rigolets. This indicates a substantial period of draining, in which fresh water from the inland flooding dominated any tidal dispersion or diffusion of salinity through the pass at the Rigolets. The sensitivity of salinity within the Pontchartrain system to the August 2016 flood was examined in this study.

1.2. Hydrology and environmental flow background

The objective of this study was to utilize the Integrated Compartment Model (ICM) developed for the Louisiana Coastal Protection and Restoration Authority (CPRA)'s 2017 Coastal Master Plan (White et al., 2017) to understand how alternations of riverine flow from existing rivers and future restoration projects may influence the spatial and temporal distribution of wetland habitats. The objective of the study was to explore how freshwater flow conditions alter the ecological condition of an estuary and to determine how future sea level rise and subsidence may influence the necessary riverine flow conditions, including flow regimes needed to maintain current conditions of salinity (~0.5 ppt, open water of lake) to support surrounding fresh forested wetlands. Specifically, the main research questions were:

- How do changing future freshwater inflows impact the area of fresh forested wetlands surrounding the Lake Maurepas ecosystem?
- How do changing future freshwater inflows impact freshwater conditions and estuarine fish habitat in the Lake Maurepas ecosystem?
- What future freshwater inflow is needed to adaptively manage the offset of relative sea level rise and maintain fresh forested wetlands?
- How will rainfall, affected by climate change, impact the freshwater and estuarine fish habitat and fresh forested wetland area surrounding the Lake Maurepas ecosystem?
- How does a 0.5% annual probability flood event impact the freshwater and estuarine fish habitat and fresh forested wetland area surrounding the Lake Maurepas ecosystem?
- How will the operation of the proposed Comite River Diversion impact the freshwater and estuarine fish habitat and fresh forested wetland area surrounding the Lake Maurepas ecosystem?

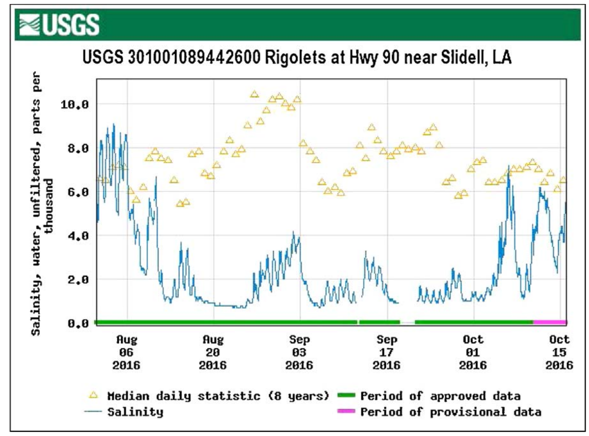

Fig. 2. Reduction in salinity concentration from the August 2016 Amite River flood at the outlet of Lake Pontchartrain; 2016 salinity (solid blue line) was consistent with long term median daily salinity (orange triangle) prior to extreme rainfall event from August 10 through August 15, 2016. Substantial freshening compared to the 8-year median daily salinity is evident throughout the months of August and September. Graph is from the USGS monitoring station located at The Rigolets, located between Lake Pontchartrain and Lake Borgne (USGS, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Integrated Compartment Model (ICM) framework

The ICM is a comprehensive and computationally efficient numerical model used to provide insights into coastal ecosystem dynamics and to evaluate restoration strategies. The ICM was developed for modeling the Louisiana 2017 Coastal Master Plan (White et al., 2017) and was built from several individual models that were previously used within coastal Louisiana (Couvillion et al., 2013; Meselhe et al., 2013; Visser and Duke-Sylvester, 2017; Visser et al., 2013).

The ICM consists of a link-node hydrologic model (ICM-Hydro) that simulates daily water surface elevations, flow rates, salinity, suspended sediment concentration, and water quality constituent concentrations. The simulated hydrologic conditions then drive a gridded vegetation dynamics model (ICM-LAVegMod) that simulates relative species coverage density of dozens of vegetation species that are common to the Louisiana coastal zone. Both hydrologic and vegetation conditions are passed into a wetland morphology relative elevation model (ICM-Morph) which models long-term landscape evolution as a function of pre-dominant vegetation types, sediment deposition rates, subsidence rates, and inundation and salinity stressors on the marsh surface. The ICM-Morph-updated landscape surface then results in an updated hydrologic and hydraulic network used during the next model time step in ICM-Hydro, as well as an updated land/water surface used during the next model time step in ICM-LAVegMod. Within the ICM framework, the original land/water surface is defined via satellite imagery (Couvillion, 2017) and updated annually via the ICM-Morph land collapse and gain functions. If a region defined as land is at an elevation that is persistently inundated by the annual mean water level by a depth greater than a threshold suitable for the predominant vegetation types present, the model will "collapse" the marsh and convert the area to water. Conversely, if a region is initially water and has an elevation that is persistently above the annual mean water level, the model will "gain" land and fill in the water region (Couvillion et al., 2013; White et al., 2017). This land/water classification is applied to each 30-m model grid cell in ICM-Morph, and throughout this paper the term "estuarine open water" will be used to reference the water portion of this land/water classification surface. The feedback between ICM subroutines occurs at an annual time step (White et al., 2017).

The vegetation model (ICM-LAVegMod) that is embedded in the ICM takes a niche-based approach to combine species characterizations and environmental conditions that allow establishment and persistence (Visser and Duke-Sylvester, 2017; Visser et al., 2013, 2017). Establishment and mortality tables based on the water level variability and average annual salinity drive the vegetation distribution with marsh types and swamps. The establishment of new tree growth is also controlled by wet-dry inundation cycles on the swamp surface (Visser and Duke-Sylvester, 2017; Visser et al., 2013). Fresh forested wetlands, intermediate marsh and estuarine open water are three main habitats that were utilized for this project. Bald cypress tends to dominate in percent cover of this study area.

For each model year, landscape and hydrologic conditions predicted within the ICM are used to assess the habitat suitability for a variety of fish, shellfish, wildlife, and bird species prevalent in coastal Louisiana. Habitat suitability index (HSI) values for different species were developed by combining species-specific suitability indices, vegetation coverage, salinity, and temperature conditions. The salinity-temperature suitability indices were developed via statistical analyses of fisheries-dependent catch data correlated to observed salinity and temperature measurements, and the vegetation coverage indices were developed from literature-based values (Hijuelos et al., 2016). For each species, the HSI values were normalized to vary between 0 and 1; a value of 0 indicates that no suitable habitat is present for a given species and a value of 1 indicates that optimal habitat pertaining to the salinity/temperature/vegetation characteristics present in the underlying data used to develop the indices. The HSI values are not a prediction of fish presence or absence, but are instead a snapshot in time and space of the model-predicted habitat conditions a given species was determined particularly sensitive to.

The HSIs developed for adult spotted seatrout (abbreviated as SPSTA for modeling consistency), adult bay anchovy (abbreviated as BAYAA for modeling consistency) and largemouth bass (abbreviated as LMBAS for modeling consistency) are included in this analysis (Hijuelos et al., 2017; Sable et al., 2017a, 2017b). These three species were chosen to assess the impact of changing salinity regimes within the Lake Maurepas region; spotted seatrout and bay anchovy are both salinity tolerant species that score relative low HSI values under current conditions in the Lake Maurepas ecosystem, whereas largemouth bass are a freshwater species that score relatively high HSI values in the region under current conditions.

A calibration and validation exercise was undertaken during the model development phase of the 2017 Coastal Master Plan; of which the final validated model was used for this study (Brown et al., 2017b). A variety of datasets were compiled for model calibration and validation; hydrologic data from the United States Geological Survey (USGS) and the Coastwide Reference Monitoring System (CRMS) (Folse et al., 2014) were the primary sources of observed data used to calibrate and validate the ICM predictions of daily mean water levels, flowrates, and salinity concentrations. The CRMS dataset contained the most comprehensive coverage from 2010 through the present, so the period from 2010 through 2013 was chosen as the model calibration period. A slightly smaller set of data was available from 2006 through 2010, and data from this time period was reserved for model validation (Brown et al., 2017b).

The previous long-term simulations conducted for the 2017 Coastal Master Plan frequently resulted in a conversion of forested wetlands to fresh herbaceous marsh within the Maurepas Swamp region (Alymov et al., 2017). Salinity tolerances between fresh forest and fresh marsh vegetation species within ICM-LAVegMod are very similar, indicating that the cause of this conversion was due to non-salinity hydrologic parameters. The only other parameter calculated dynamically within the ICM that may be controlling this long-term vegetation response was the water level variability (WLV), defined in ICM-LAVegMod as the standard deviation of the water surface elevation throughout a growing season. This parameter, WLV, was not included as a calibration parameter in the initial study, as described above, therefore a separate calibration effort was undertaken for this analysis in order to improve the ICM-predicted water level variability within the region of interest. A discussion of model calibration/validation results for the focus area of this analysis, as well as a discussion of the additional WLV calibration process is provided in the Supplementary Materials to this article.

2.2. Boundary conditions

All tributaries to the Louisiana Coastal Zone, other than the Mississippi and Amite Rivers, were assigned a representative year hydrograph for a model hindcast period from 2006 through 2016. Representative year hydrographs were determined by classifying years as wet/dry/average based upon observed average annual precipitation across the Louisiana Coastal Zone. The 25th percentile rainfall year was defined as dry, 75th percentile rainfall year was wet, and 50th percentile rainfall year was average. Observed wet/dry/average hydrographs for these respective years were used as representative wet/dry/average hydrographs for each respective tributary. The boundary condition inflow for the Amite River is the primary freshwater source for the Maurepas Swamp region, which was the focus of this analysis. Rather than using the representative year hydrographs developed for the tributaries outside of this region, a more detailed hydrographic analysis was conducted for the Amite River. The procedures used to develop synthetic hydrographs for the Amite River are detailed in a later section. Due to the vast drainage area of the Mississippi River upstream of the Louisiana Coastal Zone, the Mississippi River hydrograph downstream of Tarbert Landing (just downstream of the Old River Control Structure) is largely independent of the coastal rainfall patterns. Therefore, synthetic and/or representative hydrographs were not developed for the Mississippi River; the Mississippi River hydrograph was taken from the United States Army Corps of Engineers (USACE) gage at Tarbert Landing.

For simulations of the future 50 years (calendar years 2017–2066), the 50-year time series of observed flow at Tarbert Landing from 1964 through 2014 was used as the modeled Mississippi River hydrograph. For other tributaries to the model domain, excluding the Amite River, a 50-year pattern of representative dry/average/wet year hydrographs was developed from observed precipitation records from 1964 to 2014, following the procedure discussed above. The development of a synthetic hydrograph for the Amite River is discussed below.

If any of the project simulations analyzed included a river diversion, the Mississippi River hydrograph was updated to account for the diverted flows; a discussion of the flood control and restoration projects analyzed is discussed below.

Initial landscape (land/water composition, elevation, and vegetation coverage) for this analysis was based on the landscape developed for the 2017 Coastal Master Plan analysis (Couvillion, 2017) and represents the present day landscape as used for model calibration and validation (Brown et al., 2017b). Observed precipitation, evapotranspiration, wind, air and water temperature, tidal conditions, water quality inflow, and tributary river inflow were used for model year 2006–2016 following the 2017 Coastal Master Plan analysis (Brown, 2017).

2.3. Scenario development

For the future 50-year simulations, boundary condition data for precipitation, evapotranspiration, eustatic sea level rise rates, and subsidence rate assumptions were chosen to match the Medium Environmental Scenario developed for the 2017 Coastal Master Plan (Meselhe et al., 2017a). This scenario assumed a rate of subsidence equal to approximately the lowest quintile of observed subsidence measurements within the Louisiana Coastal Zone (Reed and Yuill, 2017). The eustatic sea level rise rate for this scenario was set equal to 0.63 m over the 50-year simulation period; this corresponds with a 1.0 m rise by the end of the 21 st century (Pahl, 2017). Current guidance from NOAA indicates that an “Intermediate” global sea level rise scenario with a projected 1.0 m rise in global mean sea level by 2100 has a 17% likelihood of being exceeded under a business-as-usual-case greenhouse gas emissions scenario represented by RCP8.5 (Sweet et al., 2017).

2.3.1. Amite River boundary conditions

Several steps were taken to generate representative hydrographs needed for the 50-year simulations. First, daily flow data for the USGS 07378500 Amite River near Denham Springs, LA station were retrieved using the download function of the United States Environmental Protection Agency (USEPA) Better Assessment Science Integrating Point & Non-point Sources Modeling Framework (BASINS 4.1) software (US EPA, 2015) for the period of record 1/1/1939 to 12/31/2015. The daily discharge data were then input into The Nature Conservancy Indicators of Hydrologic Alteration (IHA) software package (Richter et al., 1996) to perform a hydrographic separation to summarize long periods of daily hydrologic data into a series of ecologically relevant hydrologic parameters. These parameters, Environmental Flow Components (EFCs), classified each daily flow as extreme low flow, base flow, high flow pulse, and flood flows. This hydrographic classification is a preprocessing step to the application of the Hydrology-Based Environmental Flow Regime (HEFR) Methodology, developed to assess environmental flows for the state of Texas (Opdyke et al., 2014). HEFR produced a statistical array of EFCs for each month of the year, including subsistence flows, base flows, and high flow pulses, as shown in Table S1 in the Supplementary Material. Peak streamflow for the August 2016 flood at the USGS 07378500 Amite River at Denham Springs gage, of 5,801.5 $m^3 s^{-1}$ on 8/14/2016, was sourced from Watson et al. (2017).

Using these EFCs, synthetic hydrographs with representative daily flows were created for a hypothetical dry, wet, and average years based on matching the timing and magnitude of peak and low flows in the historic hydrograph. Years were determined to be dry, average, or wet based on quartiles of the historical record − the lowest quartile were considered dry, and the highest quartile were considered wet years. Synthetic hydrographs for representative dry, wet, and average years are shown in Fig. 3.

If considering only standard instream flow requirements to support riverine and riparian ecosystems, the study would account for no peak flows and only approximately 15% of the total observed mean annual

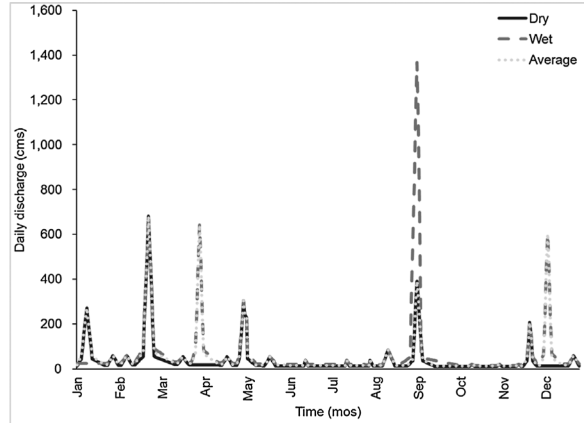

Fig. 3. Synthetic hydrographs for the Amite River at Denham Springs for dry, wet, and average years.

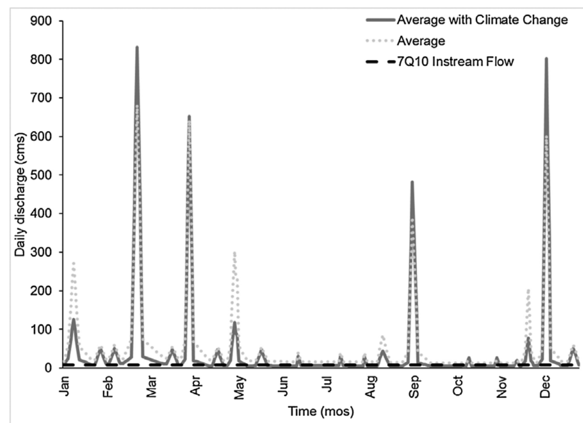

Fig. 4. Comparison of environmental and adjusted hydrographs for the Amite River at Denham Springs (i.e., minimum environmental flow to overall average and climate-change adjusted synthetic hydrographs).

flow of water entering the estuary. An instream flow requirement such as the lowest seven-day average flow that occurs on average once every 10 years (7Q10), was calculated to be 8.4 $m^{-3} s^{-1}$ using USEPA DFLOW, part of the BASINS 4.1 suite (Fig. 4).

2.3.2. Amite River hydrograph adjusted for climate change scenario

Although there is uncertainty regarding future seasonal precipitation trends, climate change models do indicate some consistency, in particular under higher greenhouse gas emission scenarios. In the latest U.S. National Climate Assessment, Melillo et al. (2014) conclude that while changes to long-term precipitation trends are relatively uncertain, the southern United States may experience drier precipitation conditions compared to present day. Seasonal precipitation volumes vary largely by the emissions scenario being assumed. High emissions scenarios A2 and RCP8.5 (from CMIP3 and CMIP5 analyses, respectively) consistently show drier seasonal precipitation in coastal Louisiana. However, under an assumed rapid-reduction of emissions, scenario RCP 2.6 (from CMIP5), coastal Louisiana shows little to no significant change in seasonal rainfall volumes (Table 1).

The changes in future long-term precipitation and seasonal trends may be relatively uncertain, however there is indication that the largest precipitation events experienced during a given year may substantially increase in volume throughout the 21 st century. Over the past several decades, the southeastern United States has seen, on average, a 27% increase in volume of the largest precipitation event in each year. Climate modeling efforts consistently indicate that this trend will continue throughout the 21 st century, even in regions where the overall

Table 1
Potential change in seasonal precipitation volumes in coastal Louisiana at the end of 21 st century, compared to 20th century values. Values are estimated from the U.S. National Climate Assessment and relative confidence in model conclusions are not included in this table (Melillo et al., 2014).

Season	A2 Scenario[a]	RCP 2.6 Scenario[b]	RCP 8.5 Scenario[a]
Winter	0 – 20% Reduction	no significant change	0 – 10% Reduction
Spring	10 – 20% Reduction	no significant change	0 – 10% Reduction
Summer	10 – 20% Reduction	no significant change	10 – 20% Reduction
Fall	0 – 20% Reduction	0 – 10% Increase	0 – 10% Increase

[a] A2 & RCP8.5 are roughly equivalent and are "continued emissions" scenarios.
[b] RCP2.6 is an emissions scenario representing a rapid reduction in greenhouse gas emissions.

precipitation volumes are predicted to decrease (Melillo et al., 2014).

With respect to ecologically important flow regimes, a likely significant hydrologic regime shift would be a reduction in overall precipitation volumes, with a simultaneous increase in volume of the largest precipitation events. This increase in watershed "flashiness" would result in increased peak flowrates with a simultaneous decrease in baseflows, and conforms to the possible trends projected to occur in coastal Louisiana. This projected increase in watershed flashiness was used to develop a new synthetic hydrograph for the Amite River, representing a potential future hydrologic regime as a result of projected climate change.

From the hydrologic regime analysis described above, the average year synthetic hydrograph for the Amite River has a total annual flow volume 2.2 km^3 of water, which is a depth of 630 mm over the entire 3435 km^2 watershed upstream of the Denham Springs USGS station. All subsequent runoff and rainfall volumes discussed in this analysis will be presented as a depth over the 3435 km^2 watershed area. Of this 630 mm total annual runoff volume: the four largest events of the year contain 404 mm of runoff – 31% of the non-peak flow is contained in the hydrograph as baseflow (70 mm) and 69% of remaining non-peak flow (156 mm) is contained in 14 non-peak flow events. Assuming the annual precipitation-runoff volume relationship (Equation A) developed by Xu and Wu (2006), the total annual precipitation volume that would result in the average synthetic hydrograph for the Amite River is 1707 mm.

$$Q_{annualvolume} = 0.704*Precip_{annualvolume} - 572 \tag{A}$$

Based upon the projected reductions in annual rainfall in coastal Louisiana (Table 2), this analysis assumed that the Amite River watershed would experience a 5% reduction in annual rainfall, which results in a total annual precipitation volume of 1621 mm, with a corresponding annual runoff volume of 570 mm. It was then assumed that a change in volume contained in the largest precipitation events would result in a directly proportional increase in runoff volumes. The Amite River watershed runoff volume increases exponentially with increases in precipitation volume (Xu and Wu, 2006); therefore, the assumption of direct proportionality made here is likely conservative. As discussed earlier, historical trends indicate a 27% increase in precipitation volume contained in the largest 1% of events in a given year. It was assumed for this analysis, that the top four events would see an increase in precipitation volume of 20%, resulting in an 20% increase to 484 mm of annual runoff contained in the top four events of the synthetic hydrograph. This results in 85 mm of flow remaining to be partitioned between baseflow and non-peak events. Assuming no change in the number of precipitation events in a given year and no change in the proportionality of baseflow-to-non-peak event flow, the climate change synthetic hydrograph contained 26 mm of baseflow volume and 59 mm of flow for the 14 non-peak flow events. Annual volumes for each component of the hydrograph are provided in Table 2, and Fig. 5 shows the event volumes and monthly baseflow volumes for the average synthetic hydrograph in addition to the assumed climate change hydrograph (Fig. 6).

Table 2
Components for average synthetic and assumed climate change hydrograph (in mm).

Hydrograph Components	Present-day Average	Assumed Climate Change
Annual precipitation volume	1707	1621
Annual runoff volume	630	570
Volume in top 4 peak events	404	484
Volume in 14 non-peak events	156	59
Volume in baseflow	70	26

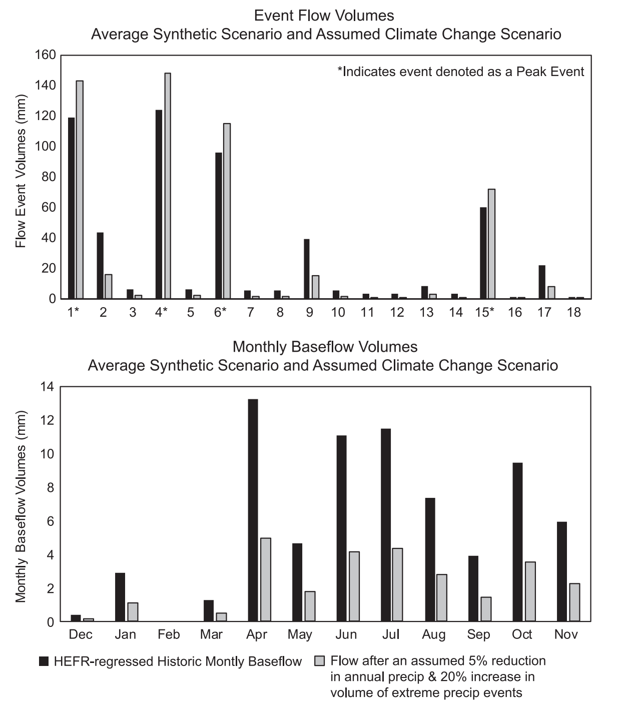

Fig. 5. Hydrograph flow event volumes (top) and monthly baseflow volumes (bottom) for the average synthetic hydrograph (black) and the climate change hydrograph (gray).

All assumed climate change impacts were calculated from projected changes in annual precipitation volumes, and adjusted flow volumes were calculated via the methods described. The model boundary conditions, however, require time series of flowrates, not event volumes. The hydrograph analysis conducted upon the Amite River historical flow observations was used to develop correlations between event peak flowrates and total event volume. Wu and Xu (2006) determined seasonal patterns in observed precipitation-runoff behavior; following their approach, separate flowrate-to-volume correlations were developed for the wet season (winter and spring) and the dry season (summer and fall). The correlations are shown in Fig. 7. They were used to convert the event volumes into an annual time series of daily flowrates for the climate change scenario assumed for this analysis (Fig. 7).

2.3.3. Project scenarios

In addition to the environmental and climate change scenarios described in the previous sections, a variety of projects currently proposed for construction in the Amite watershed were assessed with the ICM model. The projects analyzed here included the Comite River Diversion flood control project and the suite of environmental restoration and flood protection projects included in the draft 2017 Coastal Master Plan.

The Comite River Diversion is a proposed flood control project in the Amite watershed which proposes to divert flow from the Comite River (a tributary of the Amite) west into the Mississippi River upstream

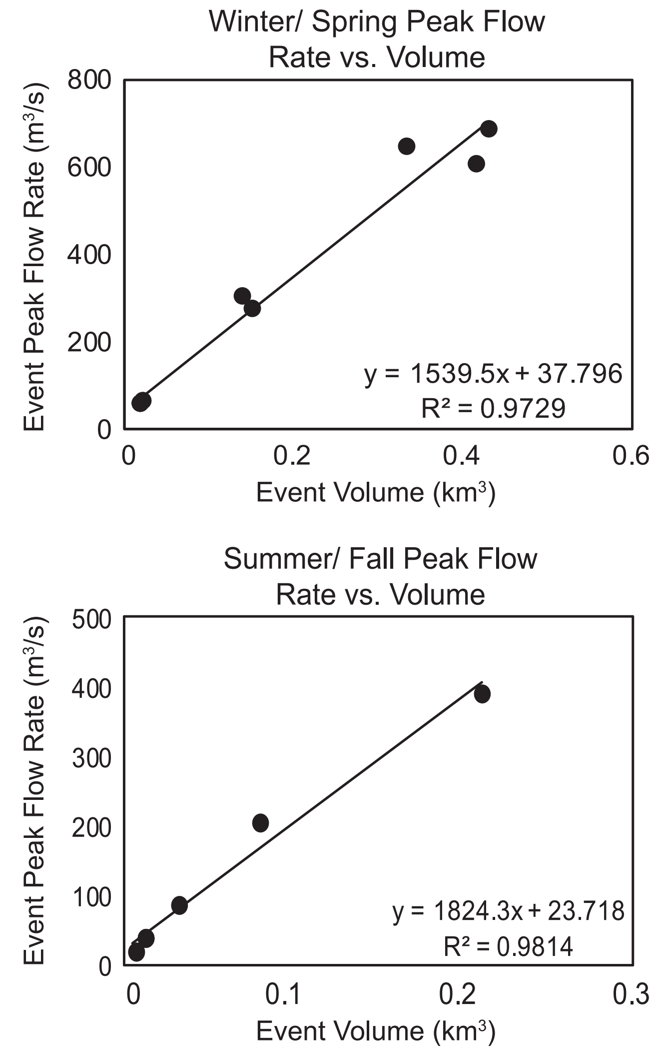

Fig. 6. Event peak flowrate to event flow volume correlations used to develop annual hydrograph for climate change scenario.

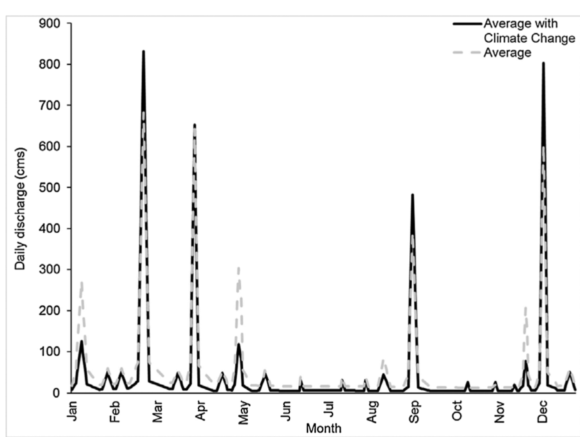

Fig. 7. Daily discharge synthetic hydrographs for the Amite River at Denham Springs, showing increased flashiness with decreased baseflow and minor flow pulses in climate change scenario versus average year.

of Baton Rouge. To incorporate the project in the model simulations, the Amite River synthetic hydrographs were adjusted by reducing peak flowrates by an amount equal to the peak flows diverted from the Comite into the Mississippi River. A synthetic hydrograph for the

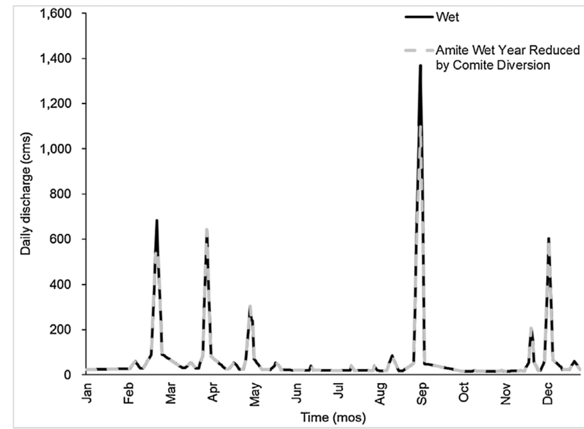

Fig. 8. Amite River discharge hydrograph for the Amite River at Denham Springs, reduced by operation of the Comite River Diversion.

Comite River was developed following the same protocol discussed above for the Amite, using the USGS 07377500 Comite at Olive station. This synthetic Comite hydrograph was then reduced based on the design operational regime criteria contained in the Comite River Diversion Hydraulic Model Investigation (Hite, 1994). The total daily discharge of the Amite River ICM boundary condition was then subsequently reduced by the amount of Comite River discharge that was conveyed out of the diversion structure. The modified hydrograph is shown in Fig. 8.

The draft list of projects included in the 2017 Coastal Master Plan included several projects with potential impacts upon the hydrology of the Maurepas Swamp region: the Union Freshwater Diversion, the East Maurepas Diversion and the Manchac Landbridge Diversion. Additional hydrologic impacts upon this region may occur under high relative sea level rise scenarios with the presence of the Lake Pontchartrain Barrier, a storm surge protection structure on the outlet of Lake Pontchartrain (CPRA, 2017). The final version of the 2017 Master Plan included the addition of a few projects that were not included in the draft plan analyzed here; however, these projects were not located in the vicinity of the Maurepas Swamp study area.

Specific simulations were designed to evaluate whether restoration projects can substantially influence the ecological condition of Lake Maurepas and the surrounding wetlands under a variety of future climate scenarios. Additionally, in order to assess the sensitivity of Lake Pontchartrain salinity to the August 2016 flood, a scenario was developed in which the 2016 flood was reduced in magnitude to a 1% event, to determine how much of the observed freshening in August 2016 at the Rigolets could be attributed to the extreme rainfall that occurred. A summary of all simulations analyzed is presented in Table 3.

2.4. Model limitations

The ICM framework was developed for multi-decadal, planning-level simulations of coastal zone dynamics. The model subroutines were developed to capture the ecosystem processes important to coastal restoration planners and engineers, while at the same time maintaining a computational efficiency suitable for completing hundreds of 50-year simulations. Therefore, it is important to understand the limitations of the modeling framework. The ICM-Hydro subroutine is the only model subroutine that operates on a continuous timestep; all other subroutines use either monthly or annual timesteps. The primary limitation of the ICM-Hydro subroutine is the spatial resolution required to maintain this continuous timestep, which subsequently limits the spatial representation of hydrologic parameters that are utilized by other ICM subroutines.

The ICM-LAVegMod and ICM-Morph subroutines are limited by the empirical nature of their underlying equations. The vegetation model

Table 3
Model simulation numbers, names, years, and descriptions that represent hydrological modifications of the coastal Amite River that include future climate conditions of rainfall, sea level rise and subsidence as well as restoration projects. Simulations include medium RSLR, as detailed in the Scenario Development section above.

Sim. #	Name	Start Year	Sim. Years	Description
G005	2016_NF	2006	11	11-year + normal wet 2016 (flood reduced)
G006	2016_FL	2006	11	11-year + 2016 flood
G007	BASE	2017	50	50-year + normal rainfall
G008	BASE_CC	2017	50	50-year + climate change rainfall
G009	BASE + CD	2017	50	50-year + normal rainfall + Comite River Diversion
G010	BASE_CC +MP	2017	50	50-year + climate change rainfall + All Draft MP2017 Projects
G011	BASE + MP	2017	50	50-year + normal rainfall + All Draft MP2017 Projects
G013	BASE_CC +MP + AD	2017	50	50-year + climate change rainfall + All Draft MP2017 Projects + Additional Diversion Input at year 30

predicts the percent coverage of each included species for each model grid, but it is inherently sensitive to the accuracy of the starting land cover data and the coarse resolution of the salinity and water level variability predictions. The species-level coverages are then classified into predominant marsh type (e.g. fresh, intermediate, etc.) for determining marsh collapse stressors in ICM-Morph. The inundation and salinity stress collapse thresholds are Boolean, whereas the underlying data used to develop the thresholds indicate a less discrete continuum of marsh prevalence/collapse (Couvillion and Beck, 2013).

An additional limitation to the ICM-Morph subroutine is the lack of a dynamic process to incorporate organic matter accumulation in wetland soils. Inorganic sediment deposition on the marsh surface is dynamically calculated via the linkages between ICM-Hydro and ICM-Morph; however organic matter accumulation is applied annually based on historic data. This organic matter loading varies by marsh type and regionally across the coastal zone, however it does not change over time nor does it respond to hydrologic forcings. A brief overview of the general modeling assumptions are provided in Brown et al. (2017a), and a discussion of model limitations and shortcomings are provided in Cobell et al. (2017).

As with any numerical model, a wide variety of factors (e.g. error in the initial conditions, assumed forcings/boundary conditions, parametric uncertainty, numerical representation of physical processes and other simplifying assumptions) will result in model uncertainties, errors, and limitations. The overall model performance and errors are discussed Brown et al. (2017b); and a rigorous uncertainty and sensitivity analysis has also been conducted on the ICM as it was used for developing the 2017 Coastal Master Plan (Meselhe et al., 2017b).

3. Results

3.1. Hydrologic response to synthetic hydrographs of tributary inflow

Synthetic hydrographs were created to represent future conditions of the Amite River and included wet, dry, and average conditions (Fig. 3). The observed Amite River hydrograph was compared to these synthetic hydrographs and shows good correlation with respect to overall range in stage. Time series of daily mean water level within the Maurepas Swamp model compartment (MS) and at the Lake Pontchartrain outlet at the Rigolets (RS) show the impact of using a synthetic hydrograph to represent Amite River inflow to the model domain as compared to using the observed record (Fig. 9). The synthetic hydrograph resulted in a slightly less variable stage in MS (bottom left) than when observed inflow was used (top left). The overall range in stage was consistently bounded by approximately −0.2 to +0.7 m NAVD88. The peak water level of 2011 occurred during Tropical Storm Lee in early September. Regardless of the hydrographs used for tributary inflow, the extreme events appear to coincide with the downstream Gulf boundary conditions.

3.2. Model simulations

Throughout the simulations analyzed, the most consistent hydrologic response seen was a persistent increase in mean water levels of approximately 0.4 m throughout the 50-year simulation (Fig. 10). Each compartment experienced this increase in water level due to the assumed eustatic sea level rise scenario of 0.43 m that was imposed upon the downstream tidal boundary conditions in the Gulf of Mexico. One compartment, MS, displayed a different behavior with respect to mean water level under the scenarios with restoration projects implemented. The MS compartment was the receiving compartment for a large freshwater diversion project in the 2017 Coastal Master Plan that was implemented in year nine. As seen in Fig. 10, when the diversion is implemented in the two restoration scenarios (G010 BASE_CC +MP vs G011 BASE + MP in Fig. 10), the large influx of freshwater (several times the total current inflow into the basin) results in a clear and persistent increase in mean water level for the remainder of the simulation. A response can also be seen in the water level variability (WLV) of this compartment when the diversion is first implemented. This large spike in WLV is an artifact of the calibration/correction factor applied. The correction factors were developed based on the calibration period, which did not have a large restoration project implemented. The operational regime of freshwater diversions (CPRA, 2017), results in the flowrate being constantly varied and potentially deactivated. During the first year of operation, the combination of the abrupt shift in mean water level with the newly fluctuating diversion flowrate resulted in a high WLV value that was then multiplied by the correction factor, resulting in this exaggerated response signal.

A more realistic water level variability response is seen in the French Settlement (FS) compartment (Fig. 10). The WLV starts relatively high; however, as the downstream tidal boundary increases in elevation due to the assumed eustatic sea level rise scenario, this tailwater dampens the WLV signal. In the last few years of the model, there are several extreme events in the Mississippi River hydrograph (sustained droughts as well as peak flows that resulted in opening of the Bonnet Carre Spillway), resulting in highly fluctuating operational flows in the diversion projects, increasing the WLV. Further compounding this response is the presence of additional projects included in the 2017 Coastal Master Plan that impact this region; a flood protection system across the Lake Pontchartrain outlet included active flood gates in the model that are shut once water levels on the Gulfward side are above a given threshold elevation. This threshold water surface elevation trigger is met more often in the later years after several decades of sea level rise, resulting in the increase in WLV in the last simulation decade.

Salinity patterns throughout the future at these four locations are consistent with the behavior of the mean water levels due to rising sea levels. At all locations, under a future with no restoration, salinity increases substantially during the last model decade. Regardless of location within this region, the restoration projects included in the 2017

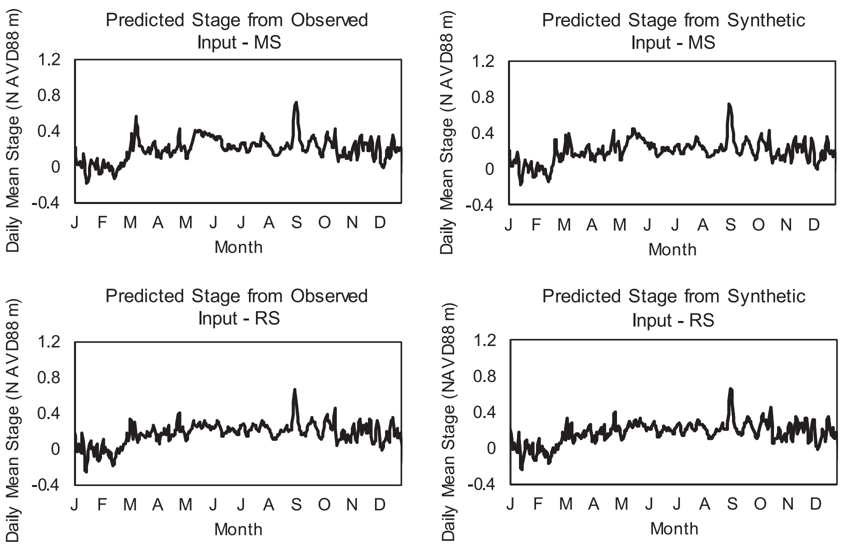

Fig. 9. Daily mean water level for 2011 in Maurepas Swamp (MS) (top) and Rigolets (RS) (bottom) for the simulation with observed tributary inflows (left panels) and for the representative and synthetic tributary hydrographs developed for this study (right panels).

Coastal Master Plan had a large impact and resulted in salinities remaining consistently low throughout the entire 50-year simulation (Fig. 10).

The impact of climate change precipitation patterns did not have a discernible effect on salinity patterns, which is likely due to the long-term mean salinity concentrations being analyzed. Any impact of a "flashier" future hydrograph would likely be upon short term salinity behavior, which is not a significant driver for ecological response within the ICM framework. Minor impacts could be seen upon annual mean water level values due to assumed climate change rainfall (G010 BASE_CC +MP vs G011 BASE + MP in Fig. 10). However, the magnitude of these changes is negligible and do not appear to have an impact upon the ecological response of the region to these climate change rainfall assumptions.

3.2.1. Modeled habitat responses

The area of estuarine habitats for the simulations that represent future with (G010 BASE_CC + MP and G011 BASE + MP) and without restoration projects (G007 BASE and G008 BASE_CC) changed over the 50-year period (Fig. 11). After the eighth year, output from the two groups of simulations diverged in terms of fresh forested wetland, intermediate marsh, and estuarine open water areas. For example, simulations G010 BASE_CC +MP and G011 BASE + MP with restoration measures tend have more vegetated area than simulation G007 BASE and G008 BASE_CC (without restoration).

After year 40, the intermediate marsh area tended to increase and the fresh forested wetland area decreased when no restoration projects were included. The estuarine open water conditions in this ecosystem tended to exponentially increase over time for the simulations with (G010 BASE_CC +MP and G011 BASE + MP) and without (G007 BASE and G008 BASE_CC) restoration projects.

By year 50, output from the baseline simulations (G007 BASE and G008 BASE_CC) with no future restoration projects indicate that the area of fresh forested wetlands will lose about 0.2×10^9 m^2 (Fig. 11). Intermediate marsh will likely replace some of the fresh forested wetlands and increase the area of habitat by about 0.75×10^8 m^2 at year 50 with no future restoration projects. Adding restoration projects over a 50-year period appears to help maintain the area of fresh forested wetlands and intermediate marshes present at year 0 (Fig. 11). The estuarine open water habitat area continues to increase over time and is higher for simulations with no future restoration projects (Fig. 11). Bald cypress trees are an important species in the ecosystem and is represented in the vegetation modeling. The percent cover of bald cypress trees in the study area with no future restoration projects (G008 BASE_CC) from year 0 to year 50 decreased in areas that were primarily found southwest of Lake Maurepas and areas along the north and south shoreline of Lake Pontchartrain (Fig. 12). Compared to the simulation G008 BASE_CC without restoration projects, the future with no restoration resulted in a substantial decrease of bald cypress percent coverage mainly in an area along the southern shoreline of Lake Pontchartrain (Fig. 12).

Comparison of the habitat responses for three simulations (G007 BASE, G010 BASE_CC +MP and G011 BASE + MP) indicates that implementing coastal restoration projects can decrease salinity levels (especially after year 30) and maintain coverage of forested wetlands in the FS, LB and MS model compartments of the study area (Fig. 1). For some of the model components, like MS, the mean water level can increase and be variable with restoration projects in place (G010 BASE_CC +MP and G011 BASE + MP) compared to simulations with no restoration projects (G007 BASE).

The Comite River Diversion is a suggested flood control structure that could also impact the salinity of the downstream basin, but construction on the structure was never finished. Long-term simulations of the Amite River and the Maurepas Swamp (G009 BASE + CD) when compared to a simulation with no restoration scenario (G007 BASE) indicated that diverting freshwater (on an annual basis depending on flow conditions) from the Amite River will not alter the salinity or the area of fresh forested wetland in the FS and LM compartment of the study area (Figs. 1 and 13), nor other habitats (Figure 14).

A comparison of simulations was conducted to determine the freshwater inflows needed to maintain the approximate current spatial extent of forested wetlands. (G010 BASE_CC +MP to G013 BASE_CC +MP + AD). To hypothetically counteract the decreasing extent of forested wetlands projected to occur even under a future with restoration measures, the flow of an additional hypothetical diversion was added from the Mississippi River to the Amite River; the operating regime of the Union Freshwater Diversion included in the 2017 Coastal Master Plan was repeated and added to the model as additional freshwater flow in the Amite River immediately upstream of the model domain. The operation regime assumed that the diversion would not be active during very low or very high flow conditions in the Mississippi River (below 5600 $m^{-3}\,s^{-1}$ and above 17,000 $m^{-3}\,s^{-1}$, respectively). Once the Mississippi River flow was above 5600 $m^{-3}\,s^{-1}$, the diverted flowrate would increase linearly to a maximum design flow of 710 $m^{-3}\,s^{-1}$ when the Mississippi River is at 11,200 $m^{-3}\,s^{-1}$. The diversion would remain at this design flowrate until the Mississippi River exceeded the 17,000 $m^{-3}\,s^{-1}$ threshold, at which point the diversion would be deactivated. The response in terms of fresh forested area is shown in Fig. 15.

Simulating the August 2016 Amite River flood (G006 2016_FL)

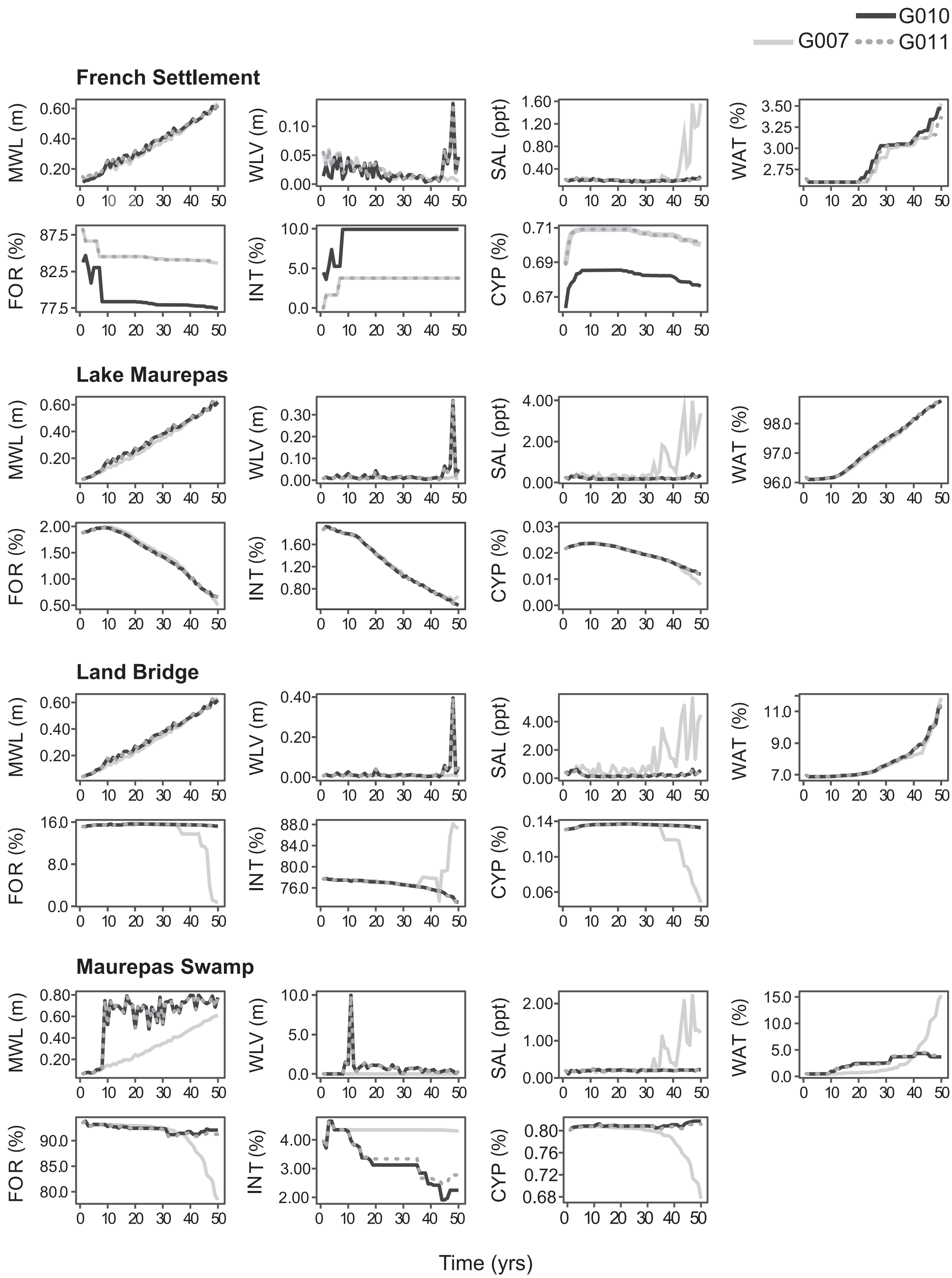

Fig. 10. Estimated ecological variables for French Settlement, Lake Maurepas, Land Bridge, and Maurepas Swamp compartments. Variables included mean water level (MWL), water level variability (WLV), salinity (SAL), percent area of water (WAT (%)), percent area of fresh forest (FOR (%)), percent area of intermediate marsh (INT (%)), and percent area of cypress (CYP (%)) for simulations G007 BASE, G010 BASE_CC + MP, and G011 BASE + MP.

indicated that the daily average surface water salinity in the Rigolets (RS) model compartment decreased compared to conditions if there was no flood (G005 2016_NF). The surface water salinity in the Lake Maurepas (LM) compartment showed little effect from the flood and the long-term impact upon the HSI for largemouth bass indicated no response to the inclusion of the 2016 flood in Lake Maurepas, whereas there was an impact further downstream at the Rigolets (Fig. 16). The response of the fresh forested wetland area at the end of the simulation (August 31) in the FS compartment did not differ (7,389,000 m^2) between the two simulations, with (G006 2016_FL) and without a flood (G005 2016_NF). Nor for other compartments (LB: 18,816,300 m^2 G006 2016_FL vs. 18,766,800 m^2 for G005 2016_NF and LM: 4,804,200 m^2

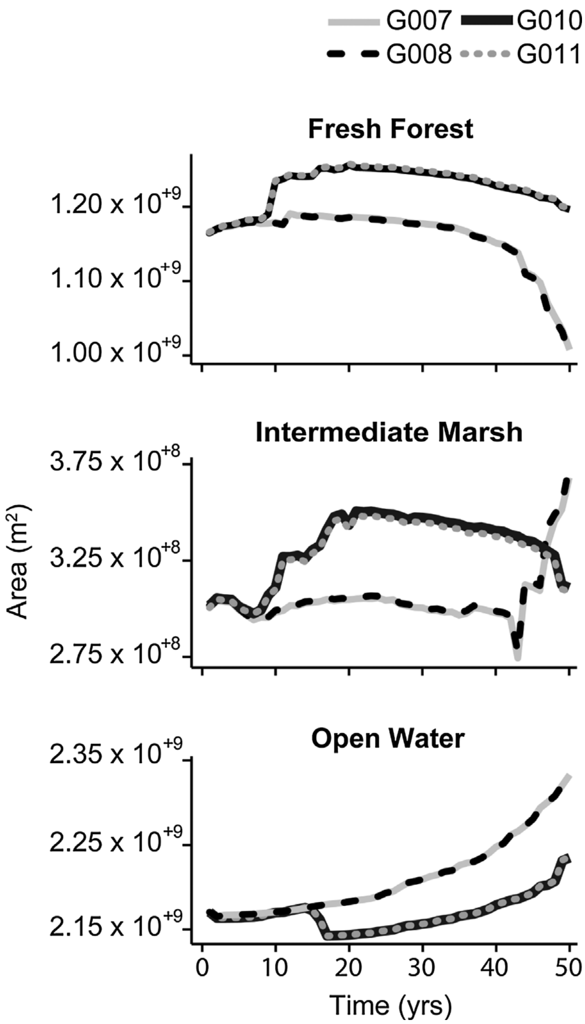

Fig. 11. Estimated total area of fresh forested wetlands, intermediate marsh, and estuarine open water for each simulation over 50 years that represent future with (G010 BASE_CC +MP and G011 BASE + MP) and without restoration simulations (G007 BASE and G008 BASE_CC). See Table 3 for a description of simulation numbers.

G006 2016_FL vs. 4,806,000 m^2 for G005 2016_NF).

Fig. 17 shows salinity at the Rigolets (RS) for the period of 2016 in which the salinity reduction was most prevalent in the USGS observed data (Fig. 2) during the August 2016 flood. The ICM-predicted salinity during and after the flood event compares well to the observed data, with a minimum salinity of less than 1 ppt being reached in mid-August. Salinity values remain depressed throughout September and only reach 4 ppt and above during the last four days of September in the ICM simulation. The observed salinity remained depressed through this entire time and this 4 ppt threshold was not exceeded until the end of the first week of October (Fig. 2).

3.2.2. *Modeled fish habitat suitability responses*

Habitat suitability in various regions of the study area for the indicator fish is likely to change in the long-term due to climate change and restoration projects (Fig. 18). Overall, the Lake Maurepas (LM) compartment had some of the highest HSI scores (maximum of ~ 0.5) for the largemouth bass, spotted seatrout, and adult bay anchovy. The other compartments, including French Settlement (FS) tended to have similar HSI scores (< 0.16) for the four simulations that included with (G010 BASE_CC +MP and G011 BASE + MP) and without (G007 BASE and G008 BASE_CC) restoration projects. In addition, the HSI scores all increased after year 20 in the FS compartment indicating overlapping suitable habitat conditions of these fish species in this compartment. The HSI scores for all the fauna in the compartments of the Land Bridge (LB), and Maurepas Swamp (MS) indicated a divergence of habitat suitability with simulations of no restoration projects (G007 BASE and G008 BASE_CC) resulting in higher HSI scores over time compared to simulations with restoration projects (G010 BASE_CC +MP and G011 BASE + MP) (Fig. 18). The HSI scores in simulations 10 and 11 in the MS compartment tended not to change over 50 years.

Some of the simulations were designed to incorporate predicted future changes in local precipitation patterns that included G008 BASE_CC and G011 BASE + MP compared to G007 BASE and G010 BASE_CC +MP without them to determine how local rainfall and river hydrology as well as future restoration scenarios (G010 BASE_CC +MP and G011 BASE + MP) could influence the habitat suitability of fish and the vegetated habitat of the Lake Maurepas ecosystem (Fig. 19). The largemouth bass HSI scores in model component FS and LM showed opposite patterns (Fig. 19) over 50 years. The LM component had higher HSI scores only when the future restoration projects were included. HSI scores were similar and the lowest at 50 years for both simulations of G007 BASE and G008 BASE_CC that included no future restoration projects, even when including precipitation patterns affected by climate change (Fig. 19).

Habitat suitability responses of largemouth bass during the 2016 flood of the Amite River was modeled (Fig. 16). HSI scores of largemouth bass were about 0.26 for both LM and RS compartments with no simulated flood. The RS compartment experienced higher HSI scores, up to 0.40 by the end of summer 2016 with the simulated flood but the compartment LM did not (Fig. 16). The operation of the Comite River Diversion (G009 BASE + CD) was also evaluated (Fig. 13) for compartments FS and LM. The modeled HSI scores for the three fish species did not change due to the operation of the Comite River Diversion (compare G007 BASE to G009 BASE + CD) (Fig. 14).

4. Discussion

Ecological restoration projects that involve increasing freshwater inflow into estuarine ecosystems can have substantial effects on coastal habitats over a 50-year period. The modeled results incorporating climate-change related rainfall patterns indicate that restoration projects (starting in year 10) that increase freshwater inflow can maintain an area (~ 1×10^9 m^2) of fresh forested wetland over 50 years and prevent some of the vegetated habitat from converting to estuarine open water. These results are not only contingent upon the specific restoration projects modeled during this analysis, but also rely heavily upon the assumed scenario(s) of future environmental conditions. For example, Alymov et al. (2017) show substantial differences in vegetation cover and land/water composition within the Maurepas Swamp region depending when different rates of subsidence and eustatic sea level rise are assumed. The acceleration of eustatic sea level rise rates in the latter decades of these 50-year simulations are also an important factor for the temporal trends of land change. The impact of the acceleration during the last model decade can clearly be seen in Fig. 11.

Coastal vegetation, including those that are herbaceous in freshwater marshes and trees in freshwater swamps will be directly affected by the increase in salinity caused by sea level rise. For example, community composition of fresh marshes are expected to transition to more saline marsh types (Herbert et al., 2015) that will likely influence their productivity (Stagg et al., 2016), decomposition and degradation (Stagg et al., In review; Williams and Rosenheim, 2015), and short-term carbon accumulation rates (Baustian et al., 2017; Craft, 2007; Neubauer, 2008). In addition, biogeochemical pathways are altered with increases in salinity as seawater sulfate regulates decomposition via sulfate reduction that generates sulfides, which are also toxic to plants (Neubauer and Craft, 2009).

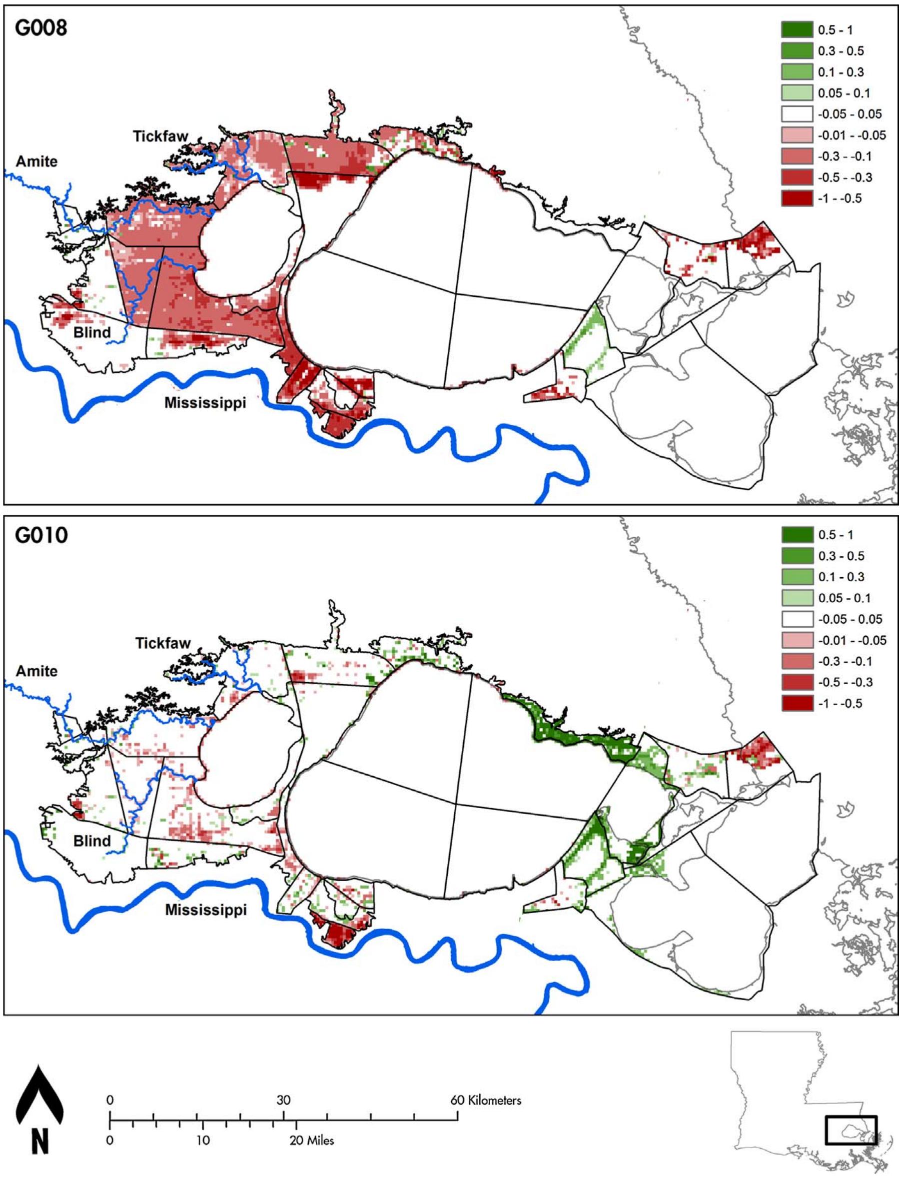

Fig. 12. Difference map between year 0 and year 50 in percent coverage (-1 to +1) of bald cypress (green is higher and red is lower) for simulations without future restoration projects (G008 BASE_CC – top panel) and simulations with future restoration projects (G010 BASE_CC + MP – bottom panel). See Table 3 for a description of the simulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

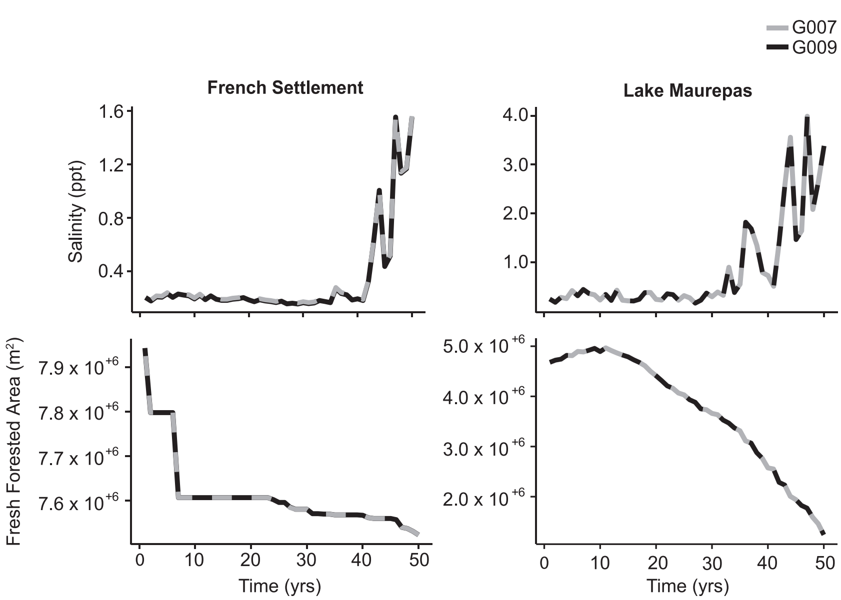

Fig. 13. Estimated salinity and fresh forested wetland area from year 0–50 of the French Settlement (FS) and Lake Maurepas (LM) model compartments for simulations with (G009 BASE + CD) and without (G007 BASE) the proposed Comite River Diversion. See Table 3 for a description of simulations.

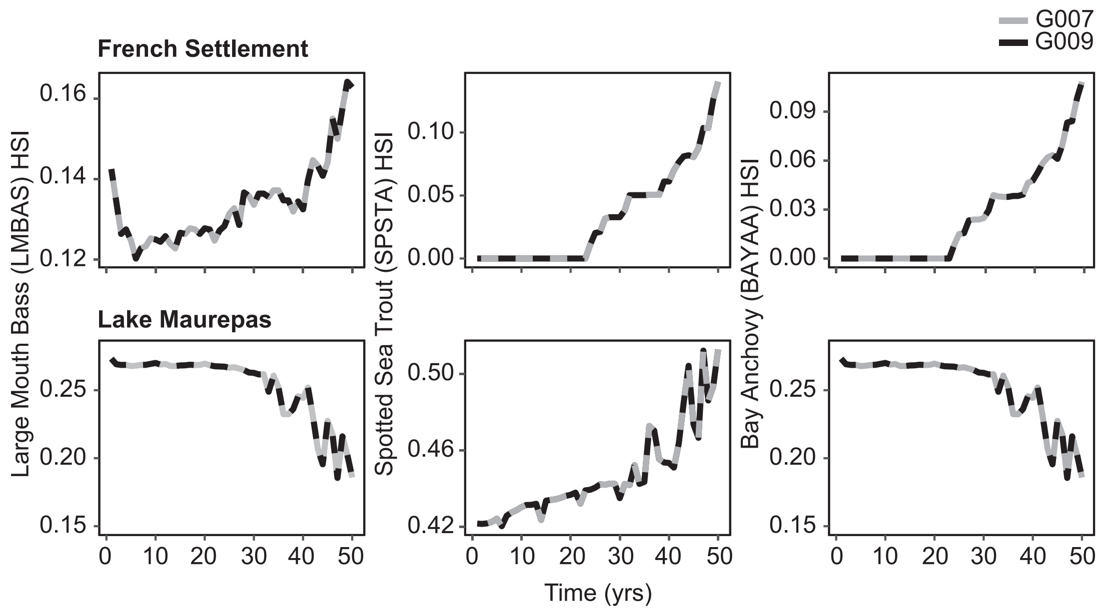

Fig. 14. Habitat suitability index (HSI) scores for three fish, largemouth bass (LMBASS), adult spotted seatrout (SPSTA), and adult bay anchovy (BAYAA) for simulations with (G009 BASE + CD) and without (G007 BASE) the operation of the proposed Comite River Diversion for 50 years.

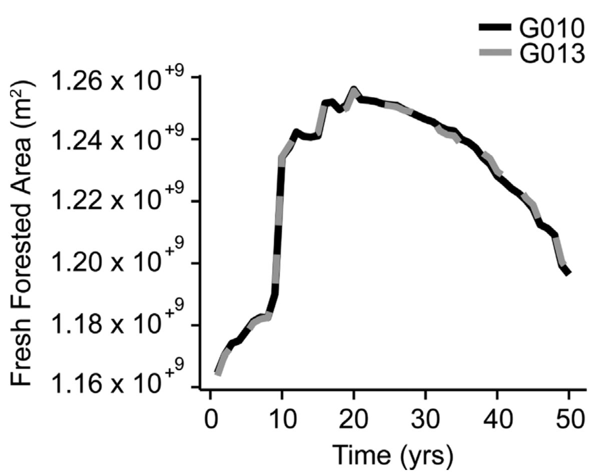

Fig. 15. Fresh forested area in the study region, over 50 years, with respect to the effects of climate change rainfall (G010 BASE_CC +MP) and the input of additional water diverted (G013 BASE_CC +MP + AD) from the Mississippi River.

4.1. Impact of changing future freshwater inflows on the area of freshwater forested wetlands

Previous studies have stressed the need for an increase of freshwater inflow to the Maurepas Swamp to maintain habitats and their ecosystem services (Keddy et al., 2007; Shaffer et al., 2001, 2016, 2009). One study suggested that an ecosystem restoration target of the total vegetated habitat (162,000 ha = 1.6×10^9 m^2) should be set and would require information about the "probable trajectories of future stresses such as rising sea levels and changing climate" (Keddy et al., 2007). These model simulations take into account their suggestions and the model output of the area of fresh forested wetlands (~1×10^9 m^2) at year 50 with the future restoration projects is near their suggested goal of 90% of that total vegetated habitat to be bald cypress-tupelo swamp (1.4×10^9 m^2) (Keddy et al., 2007). Using models to help predict changes in environmental indicators can be helpful to coastal restoration planners and managers when deciding about future freshwater inflow needs.

Introducing freshwater into estuaries and observing the vegetated habitat indicator responses and secondary benefits has been conducted elsewhere. For example, a modeling study found that with increasing freshwater inflow into the Everglades, seagrass communities could be restored to historic species compositions (Herbert et al., 2011). In the Nueces Delta, Texas, reintroducing freshwater inflow via an overflow diversion canal increased marsh productivity as indicated by increases in abundance and biomass (Montagna et al., 2002; Riera et al., 2000). This Nueces Delta study also found that the reintroduction of freshwater inflow increased benthic fauna biomass, an important indicator of brown shrimp nursery habitat, through generating ideal feeding and growth conditions (Montagna et al., 2002; Riera et al., 2000). Besides utilizing vegetated habitat as an indicator of environmental response, net ecosystem metabolism has previously been suggested as an alternative ecological indicator in areas where environmental conditions are predominately influenced by freshwater inflows (Russell et al., 2006). These indicators suggest that freshwater inflow is needed for estuaries to maintain ecological conditions and functions. This type of information yields important insight for managers.

4.2. Impact of changing future freshwater inflow on freshwater and estuarine fish habitat

It is estimated that with the assumed subsidence and sea level rise rates (Meselhe et al., 2017a) for this region, that estuarine open water habitat will increase without future restoration projects. These estuarine open water areas, such as LM and the overlying water in some of the vegetated habitats will also likely experience higher salinities in 50 years if no future restoration projects are implemented. With higher salinities and more estuarine open water habitat, the estuarine open water habitat is likely more suitable for spotted seatrout and adult bay anchovy compared to largemouth bass. This means that coastal managers may need to plan and prepare for changes in the fish habitats of the area and how that might influence the well-being of local fishing communities that may depend on them. Reductions in freshwater inflow can decrease estuarine resident and dependent fish and shrimp abundances resulted in State of Florida implementing management approaches that limit the percent withdrawal of streamflow (Flannery et al., 2002). Other studies have used a comparative ecosystem ecology and a network analysis approach to determine the effects of freshwater inflow reduction (Baird and Heymans, 1996).

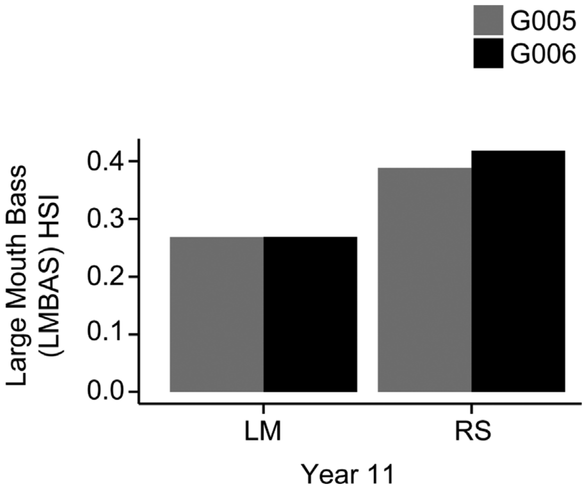

Fig. 16. HSI scores of LMBASS in the Lake Maurepas (LM) and Rigolets (RS) model compartments.and the area of fresh forested wetlands for simulations with (G006) and without (G005) the Amite River flood of August 2016. See Table 3 for a description of simulations.

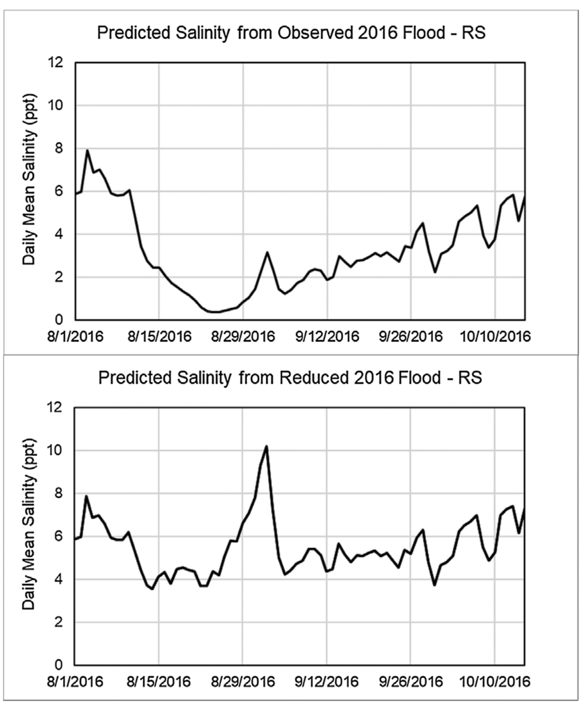

Fig. 17. Model-predicted mean daily salinity for August through October 2016 demonstrating freshening of the Lake Pontchartrain outlet at the Rigolets (RS) during the simulated August 2016 flood (top) and with the August flood reduced to a 1% annual event (bottom).

4.3. Impact of rainfall affected by climate change on freshwater and estuarine fish habitat and forested freshwater wetlands

Future restoration projects to increase freshwater flow, with or without climate-change related rainfall patterns, suggest that some areas of the Lake Maurepas ecosystem may provide more suitable habitat of largemouth bass. For example, LM and LB seem to be more suitable (higher HSI scores) over 50 years with these future restoration projects compared to MS and FS. Also, FS tended not to change over time in terms of HSI scores among the various model simulations. Therefore, planners and managers need to be aware of the spatial variability in long-term ecosystem responses when making decisions about restoration projects. Higher variability in riverine freshwater input (e.g., flashier hydrographs) under a climate-change related rainfall scenario could potentially alter the wet-dry cycles of the forested wetlands, impacting the tree establishment criteria for seedling growth. However, while these dynamics are included in the vegetation model, any response to the altered wet-dry cycles was outweighed by either rising water levels and salinities under a future without restoration projects, or by the large increase in freshwater under a future with restoration projects which managed to largely counteract the impact from rising sea levels. The relatively low levels of suspended sediment that would be delivered to the Maurepas Swamp under these assumed restoration scenarios did not serve to provide enough elevation gain in the forested wetland to further magnify any increase in tree establishment due to changes to wet-dry cycles and tree establishment.

4.4. Impact of an 0.5% annual probability flood on freshwater and estuarine fish habitat and forested freshwater wetlands

In the summer of 2016 a record flood occurred in the basin of the Amite River. Modeled results from the summer 2016 flood indicated that the salinity of the LM compartment did not change, likely because lake salinities were already low (< 0.5 ppt). However, modeled output from the more saline component RS (typically > 1 ppt), indicated that peak salinity (approximately 10 ppt) would decrease to 7.5 ppt with the flood in August 2016. Even with episodic freshwater floods, temporary fresher habitat could be more suitable to other fish species like largemouth bass, and the model output suggested a slight change in habitat suitability with the 2016 flood. However, it is important to note that these HSI scores are simplifications of the habitat needs of nekton and do not consider other important factors, such as prey resources or predation risk (Meador and Kelso, 1990).

4.5. Impact of the proposed Comite River Diversion and freshwater and estuarine fish habitat and forested freshwater wetlands

Since the flood displaced thousands of local citizens, disrupted schools and businesses, it received the immediate attention of state and federal planners and coastal managers about how to manage water resources in the region. One of the local and urban flood protection projects that has been considered in the past, but has not yet been implemented, is the Comite River Diversion near Baton Rouge, LA. The intention of the project is to alleviate flooding from the Comite River and divert it into the Mississippi River to prevent downstream flooding of the other rivers, including the Amite River. Model simulation comparisons (G007 BASE vs. G009 BASE + CD) indicate that operating the Comite River Diversion for 50 years by preventing flood waters from entering the Amite will have no discernible change in long-term salinity concentrations, area of fresh forested wetlands, or HSI scores of fresh and estuarine fish for the FS and LM compartments, which are located near the mouth of the Amite River. Therefore, the potential construction and operation of the Comite River Diversion will likely not substantially influence the downstream ecosystem condition, based on model simulations.

4.6. Future freshwater inflow needed to adaptively manage the offset of sea level rise and maintain forested freshwater wetlands

Although an additional freshwater diversion into the Amite River provides a marginal improvement in forested area in the last decade of the 50-year simulation (Fig. 15), a decreasing trend of fresh forested wetland area is still apparent. This indicates that flows greater than the proposed restoration projects included in the 2017 Coastal Master Plan (which are already more than 100% of the current riverine flows into the Maurepas Swamp region) are not sufficient to fully counteract the impacts of the assumed sea level rise scenario and maintain the forested wetlands surrounding Lake Maurepas. This has important management

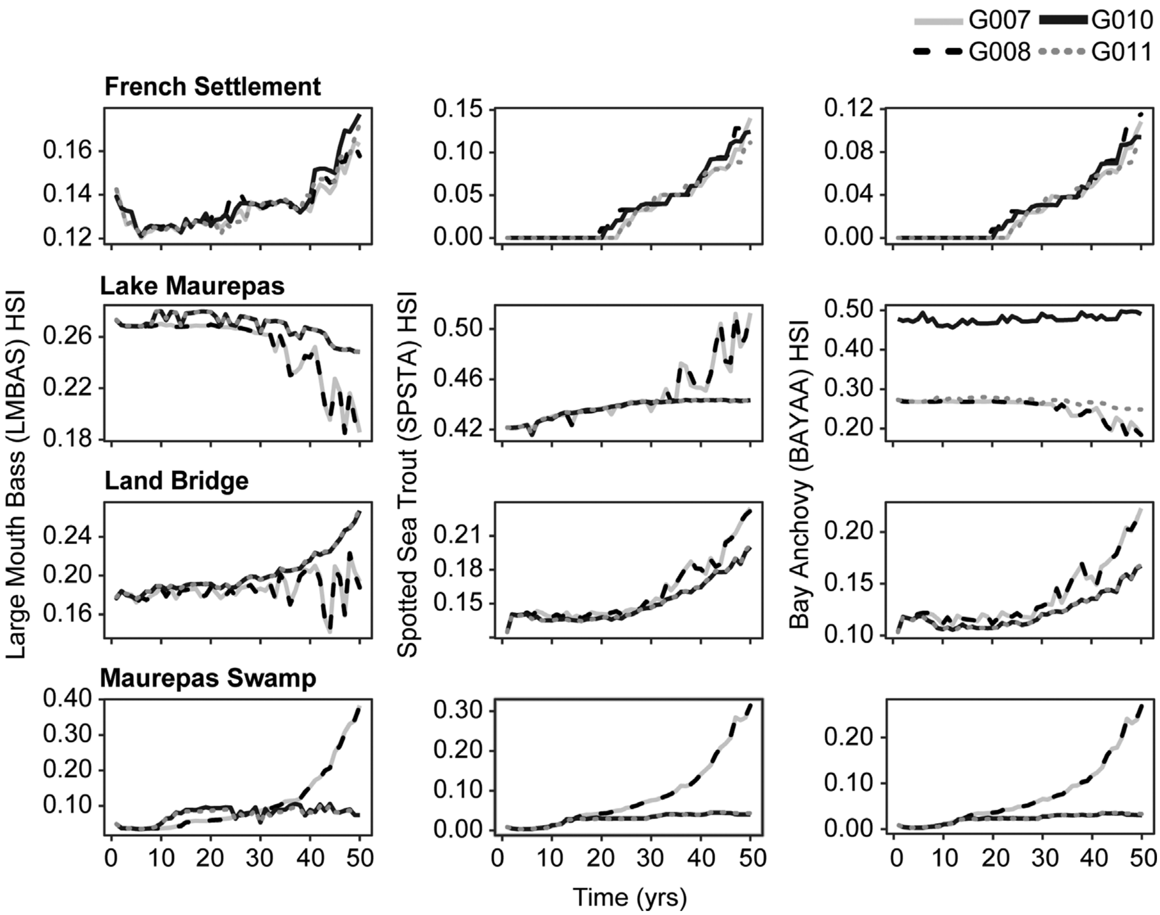

Fig. 18. HSI scores for largemouth bass (LMBASS), adult spotted seatrout (SPSTA), and bay anchovy (BAYAA) for four simulations with (G010 BASE_CC + MP and G011 BASE + MP) and without (G007 BASE and G008 BASE_CC) restoration projectsover a 50-year time period. See Table 3 for a description of simulations.

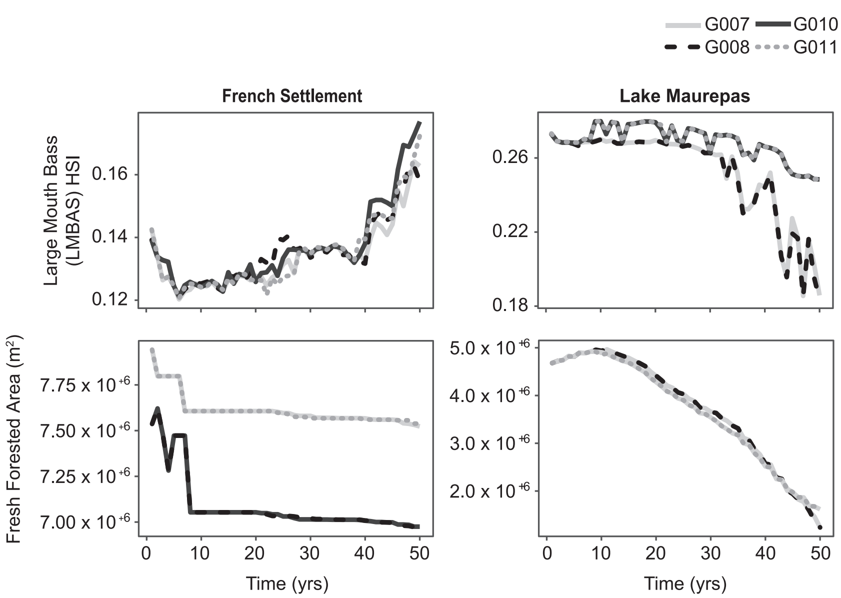

Fig. 19. HSI scores for largemouth bass (LMBASS) and the area of fresh forested wetlands to contrast simulations (G007 BASE vs. G008 BASE_CC and G010 BASE_CC + MP vs. G011 BASE + MP) that have climate change rainfall conditions. See Table 3 for a description of simulations.

implications for future use of surface water in the Amite River basin, as well as the planning and success of forested wetland conservation and restoration efforts.

The model output of future conditions of the Lake Maurepas ecosystem could be directly used by local, state and federal stakeholders that are charged with restoration planning. For example, local organizations such as the Lake Pontchartrain Basin Foundation, have already invested in restoring this ecosystem by planting bald cypress trees in the land bridge area because of the ecosystem services they provide (e.g., critical line of defense in reducing risk from storm surge (Henkel et al., 2017). Besides maintaining the planted trees, freshwater is important for the regeneration of buried seeds for germination and establishment (Keddy et al., 2007) in fresh forested wetlands (Henkel et al., 2017). As the state moves forward with implementation of the restoration program, management decisions will be continuously and adaptively adjusted to account for the latest environmental, climate change, and financing projections. The ICM was developed primarily for use in informing the long-term planning and adaptive management activities. The model can provide insights at both the coast-wide scale and the more fine-tuned, in-depth regional analysis, such as that conducted in this study. Results of the modeled future conditions of this ecosystem may help local restoration efforts by helping to prioritize and plan for the next 50 years through incorporating critical factors such as sea level rise, subsidence, and precipitation patterns. However, the ICM does not consider other important ecological processes, such as herbivory and eutrophication that could result from diverting nutrient-rich Mississippi River water into the basins (Morris et al., 2013; Turner and Rabalais, 1991). Nevertheless, these modeled environmental indicators provide managers and other end-users important long-term information about potential future conditions when freshwater inflow alterations are expected.

5. Conclusions

This modeling study suggests that a major driver to the change in long-term freshwater conditions of the Lake Maurepas area is relative sea level rise − the combination of rising seas and sinking land. Fresh forested areas in Maurepas Swamp decrease significantly under all future climate and relative sea level rise simulations except when there are restoration projects. In this study, those restoration projects are outlined in Louisiana's 2017 Coastal Master Plan. Future restoration projects that involve increasing freshwater flows into an estuary ecosystem, can have substantial effects on habitats over a 50-year period. The modeled results indicate that by using certain restoration projects that increase freshwater flow and by considering climate change-related rainfall patterns, an estimated $\sim 1 \times 10^9\,m^2$ of fresh forested wetland could be maintained over a 50-year period. Without restoration action, higher salinities and more estuarine open water will likely produce habitats more suitable for spotted seatrout and adult bay anchovy compared to largemouth bass. Model results also indicate that the August 2016 flood event along the Amite River had little impact on these habitats. In addition, removing additional fresh water from the Amite River as a flood protection measure via a diversion does not appear to affect modeled salinities or the amount of fresh forested wetland in French Settlement or Lake Maurepas areas. These modeled results greatly depend on the specific restoration projects included and on the assumed future predictions of environmental conditions but provide valuable insight to coastal managers and decision makers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.10.005.

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