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# Estuarine, Coastal and Shelf Science

# Water quality of a coastal Louisiana swamp and how dredging is undermining restoration efforts

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## ARTICLE INFO

## ABSTRACT

The Bayou Boeuf Basin (BBB), a sub-basin of the Barataria Basin estuary in coastal Louisiana, consists of forested and floating wetlands receiving drainage from surrounding agricultural fields and urban watersheds. We characterized surface water quality in the BBB, and determined through hydrologic modeling if a series of levee breaks along major drainage channels would significantly improve water quality by allowing flow into surrounding wetlands. Surface water monitoring found surrounding sugarcane farm fields to be major sources of nutrient and sediment loading. Hydrological modeling indicated that levee breaks would increase N reduction from the current 21.4% to only 29.2%, which is much lower than the anticipated 90–100% removal rate. This was due to several factors, one them being dredging of main drainage channels to such a degree that water levels do not rise much above the surrounding wetland elevation even during severe storms, so only a very small fraction of the stormwater carried in the channel is exposed to wetlands. These unexpected results provide insight into an undoubtedly pervasive problem in human dominated wetland systems; that of decreased flooding during storm events due to channel deepening by dredging activities. Additional water quality management practices should be implemented at the farm field level, prior to water entering major drainage canals.

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## 1. Introduction

The Bayou Boeuf Basin (BBB) includes a network of bayous and streams that drain surrounding agricultural fields, as well as the northeast portion of the city of Thibodaux, Louisiana (Fig. 1). Stormwater runoff from agricultural and developed areas contains high levels of nutrients, sediments, and other pollutants, and is rapidly routed through the BBB with minimal retention or filtration. Prior to the construction of flood control levees, the BBB was an overflow swamp of Bayou Lafourche and the Mississippi River (Roberts, 1997), with spring flooding providing sediments, nutrients, and freshwater (Day et al., 2012). Today, flood control levees prevent this overflow, and water levels in the basin are controlled by rainfall and stormwater runoff from the surrounding uplands. Populated upland areas are confined to the perimeter of the basin,

accounting for 22.7% of the total basin area, of which 10.0% (711 ha) is urbanized and 90.0% (6386 ha) is in various forms of agriculture, mostly sugarcane farming (43.7%, 3100 ha; Braud et al., 2006). Stormwater runoff from sugarcane farm fields is a major source of sediment and nutrient pollution in the upper Barataria Basin (Southwick et al., 2002; LDEQ, 2007; Yu et al., 2008), and a majority of sediment and nutrient pollution in the BBB is from stormwater drainage of farm fields surrounding the perimeter of the basin (LDEQ, 2004).

One proposed way to improve water quality as well as wetland viability is to restore the hydrological connectivity of the basin so that upland runoff is directed through surrounding wetlands rather than past them. Numerous studies have shown that wetlands efficiently remove nutrients and sediments from overlying water (Nichols, 1983; Knight et al., 1987; Martin, 1988; Kantrowit and Woodham, 1995; Kadlec and Knight, 1996; Raisin et al., 1997; Day et al., 2004; Hunter et al., 2009). By allowing stormwater runoff to flow through wetlands rather than past them, water quality would be improved and forest productivity and reproductive success increased (Hopkinson and Day, 1980a,b). Water quality in the
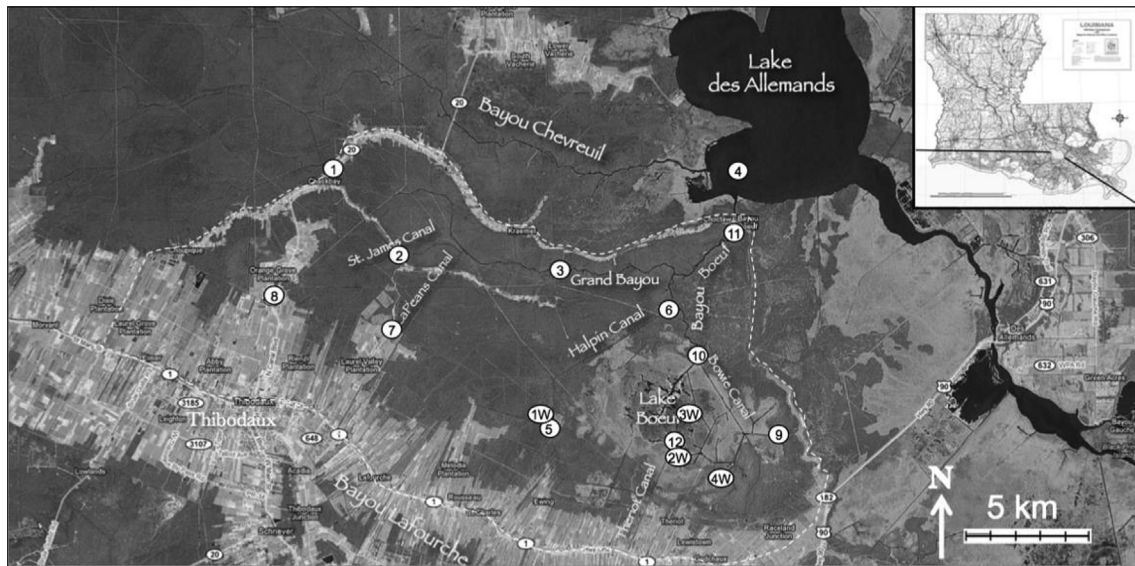
**Fig. 1.** Location of Bayou Boeuf Basin, a sub-basin within the larger Barataria Basin, Louisiana. Location of water quality sampling sites are indicated by numbers. 'W's refer to wetland sites, otherwise samples were collected in the channel. The dashed line indicates watershed boundary.

main channels of the basin is greatly influenced by non-point source agricultural runoff, and to a lesser extent by residential and commercial point sources (LDEQ, 2004, 2007). Water quality in the interior wetlands, however, is often quite different because of hydrological modifications, mainly low levee spoil banks formed from drainage canal and pipeline construction, which have isolated surrounding wetlands from the main drainage channels. Spoil banks have been found to decrease the net flux of materials to and from nearby wetlands, making these areas prone to excessive inundation (Swenson and Turner, 1987; Bryant and Chabreck, 1998). Not only do spoil banks decrease the quantity of sediments and nutrients available to maintain wetland elevation (Boumans and Day, 1994; Reed et al., 1997), but they also can increase flooding and lower soil Eh levels such that anoxic conditions and high sulfide concentrations cause dieback of vegetation (Mendelssohn et al., 1981; Cahoon and Turner, 1989; Mendelssohn and Morris, 2000).

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 primarily dependent on the nutrient species, residence time, and the area of receiving wetlands (Kadlec and Knight, 1996; Dettmann, 2001; Day et al., 2004). Nutrient input into a wetland is normally expressed as a loading rate, which integrates nutrient concentration, inflow volume, and the area of the receiving wetland, and is generally expressed as the amount of nutrient introduced per unit area of wetland per unit time; normally as g N or P per $m^2$/yr. Richardson and Nichols (1985) found a clear relationship between loading rate and removal efficiency for N and P in a review of wetlands receiving regular inputs of municipal effluent, which have similar nutrient removal efficiencies as wetlands receiving stormwater runoff (Carleton et al., 2001). Comparable nutrient loading-uptake rates have also been reported for Louisiana coastal wetlands receiving water from the Mississippi River (Lane et al., 1999, 2004), from the Atchafalaya River (Smith et al., 1985; Lane et al., 2002), and for wetlands in the upper Mississippi River basin (Mitsch et al., 2001, 2005), as well as from other areas (Fisher and Acreman, 2004). Nutrient uptake is

also influenced by temperature and the hydrology of the specific wetland site. 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.

Intuitively, the most cost-effective way to restore the connection between wetlands and surrounding waterways would be a series of levee breaks along major drainage channels to allow water to flow into surrounding wetlands during storm events. We used FVCOM (Chen et al., 2003, 2006, 2007, 2008; Huang et al., 2008b) to simulate the hydrodynamics of strategic removal of spoil banks in the BBB (Huang et al., 2014).

## 2. Methods

### 2.1. Study area

Currently, the BBB is hydrologically bounded to the north and west by a natural levee between Grand Bayou and Bayou Chevreuil, to the south by the natural levee of Bayou Lafourche, and to the east by Louisiana Highway 307 (Fig. 1). Inflow from outside the basin occurs at the western end of Grand Bayou (a distributary of Bayou Citamon), and to some extent through Bayou Boeuf via Lac des Allemands during storms or wind induced high water in the greater Barataria Basin. Theriot Canal connects to Bayou Lafourche, but hydrological exchange is limited by a gated structure that is normally closed except to allow boats to pass (LDEQ, 2004).

The construction of roads, flood-control levees, access canals, and accompanying spoil banks have altered the natural hydrology of the BBB. Louisiana Highway 20 was completed in 1930, blocking flow from upper Barataria Basin except for a few culverts and bridges over major bayous, such as Grand Bayou (Conner et al., 1981, Fig. 1). Bayou Chevreuil was dredged in the 1950's, leaving spoil deposits along the sides, impeding exchange of water and materials between the forests and bayou (LDEQ, 2004).

Virgin stands of baldcypress forests were logged in the BBB between 1900 and 1920 (Mancil, 1972, 1980). After logging, water tupelo (*Nyssa aquatica*) and maple (*Acer rubrum* var. *drummondii*) increased in importance (Conner and Day, 1976). More recently, interruption of riverine inputs and permanent flooded conditions

has led to species intolerant to constant flooding, such as green ash (*Fraxinus pennsylvanica*), to die out while the recruitment of bald cypress (*Taxodium distichum*) and water tupelo has been prevented by constant inundation (Conner and Day, 1976; Conner and Toliver, 1990). As trees died, the canopy opened, and together with an abundance of decaying logs and stumps, shrubs such as buttonbush (*Cephalanthus occidentalis*) began to grow in the forest. Penetration of light through the thinning forest canopy has led to the growth of floating aquatic species such as water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna* sp.), and water fern (*Ceratopteris* sp.). Thus, the BBB wetlands consist mostly of non-recruiting bald cypress and water tupelo with floating aquatic vegetation underneath.

There have been significant land use changes in the upper Barataria Basin over the last several decades. From 1970 to 1992, urban land increased from 8% to 17% of the total upper basin area, primarily due to conversion from agricultural land, and to a lesser degree, bottomland forest (Nelson et al., 2002). Urban development continues to modify the natural landscape along the perimeter of the basin, with increased amounts of impervious surfaces accumulating greater amounts of pollutants and generating greater volumes of stormwater runoff than in pre-development times. This stormwater, along with drainage from farm fields, is shunted away from developed areas as rapidly as possible by canals and dredged natural channels, often bypassing wetlands to drain directly into Lake des Allemands where eutrophication is problematic.

## 2.2. Water quality

Discrete surface water samples were taken monthly for one year to characterize water quality entering the BBB from surrounding uplands, background conditions of the interior forested and emergent wetlands, and water quality in the main channels (Fig. 1). Water quality samples were collected from major channels as well as from two forested and two emergent wetlands (labeled with W in Fig. 1). These samples were analyzed for nitrate + nitrite ($NO_x$), ammonium ($NH_4$), total kjeldahl nitrogen (TKN), orthophosphate ($PO_4$), total phosphorus (TP), and salinity. The channel samples were also analyzed for total suspended sediments (TSS) and chlorophyll *a*. Total nitrogen (TN) was calculated as the sum of $NO_x$ and TKN values.

Discrete water samples were taken in acid-washed polyethylene bottles, stored on ice, and taken to the laboratory for processing. Within 24-h the water was subsampled into acid-washed bottles for TN and TP analysis. In addition, 60 ml from each water sample were filtered through pre-rinsed 25 mm 0.45 um Whatman GF/F glass fiber filters into acid-washed bottles and frozen. The total and filtered water samples, and the filters, were frozen for nutrient and chlorophyll *a* analysis, respectively. TSS and salinity were measured using methods as described by APHA (2005). $NO_x$ was determined using the automated cadmium reduction method with an Alpkem© autoanalyzer APHA (2005). $NH_4$ was determined by the automated phenate method, and $PO_4$ by the automated ascorbic acid reduction method APHA (2005). TN and TP were determined by methods described by Valderrama (1981). All nutrients parameters were measured with an Alpkem© autoanalyzer, with the accuracy checked every 20 samples with a known standard, and the samples redone if accuracy was off by 5%. Chlorophyll *a* concentrations were determined by a modified version of the technique described by Strickland and Parsons (1972). Salinity was measured in the lab using a Yellow Springs Instrument Co. YSI-85 m using the Practical Salinity Scale. Water quality analysis was carried out by Louisiana State University's Analytical Services Laboratory at the School of the Coast & Environment. All summary statistics were performed at an

$\alpha = 0.05$ level using JMP statistical software produced by SAS Institute, Inc. (Sall et al., 2012).

## 2.3. Nutrient reduction

Nutrient reduction was calculated for St. James Canal and Halpin Canal using water quality sampling stations 8 and 2 as end member stations for St. James Canal, and stations 5 and 6 as end member stations for Halpin Canal. Percent reduction was calculated as $(Conc_{out}–Conc_{in})/Conc_{in} \times 100$, where $Conc_{in}$ is the concentration of parameter entering the canal and $Conc_{out}$ is the concentration of parameter exiting. Stations 8 and 5 were $Conc_{in}$ while stations 2 and 6 were $Conc_{out}$ for St. James Canal and Halpin Canal, respectively. Non-detectable values were assigned half the value of detection.

## 2.4. Nutrient loading

Based on the drainage channel distribution network of the BBB, we delineated six major upland drainage sub-basins (Fig. 2). Yu et al. (2008) quantified nonpoint source pollution from sugarcane farm fields located in northern Barataria Bay, less than 20 km from the BBB. Based on values given by Yu et al. (2008), we calculated yields from sugarcane fields to be 3.05 kg/ha/yr for TN, and 0.47 kg/ha/yr for TP. Using these values, yields from the six upland sub-basins range were estimated for TN and TP. The areas of wetlands likely to receive stormwater runoff from the sub-basins were also delineated (Fig. 2), and the resulting loading rates calculated.

## 2.5. Hydrologic modeling

The Finite Volume Coastal Ocean Model (FVCOM) was used to simulate the hydrodynamics of the BBB (Chen et al., 2003, 2006, 2007, 2008; Huang et al., 2008b, 2014). FVCOM is a collection of generalized computer programs and utility codes, designed for studying multi-dimensional hydrodynamics in oceans, coastal estuaries and bays, and rivers (Chen et al., 2003, 2006). FVCOM employs a non-overlapping triangular grid in the horizontal to resolve complex coastlines and geometries, and a sigma transformation in the vertical to convert irregular bottom topography into a regular computational domain (Blumberg and Mellor, 1987). FVCOM has been compared with analytic solutions to demonstrate model accuracy (Chen et al., 2007; Huang et al., 2008a), and has also been applied to a number of estuaries and coastal oceans with satisfactory results (Weisberg and Zheng, 2006; Frick et al., 2007; Chen et al., 2008; Huang et al., 2008b; Wang and Justic, 2009). The unstructured triangular grid makes FVCOM ideally suitable to accommodate the complex geomorphology found in Louisiana coastal areas. The flooding and drying capability in FVCOM make it suitable to simulate inundation over wetland regions.

An FVCOM model was set up for the St. James Canal watershed (Fig. 1, 'a' on Fig. 2). A fine mesh grid (horizontal resolution of 5 m) was located in the St. James Canal and other connected channels and bayous while a coarse grid (horizontal resolution of 60 m) was placed on surrounding wetlands. Wetland elevation and bathymetry data were interpolated from a 5 m × 5 m resolution digital elevation model (DEM) constructed from LIDAR observation, while water depth in the canal, channels, and bayous were from in-situ measurements and navigational charts. Most areas in this region were above the mean water level, indicating that these areas were dry when water level was low. The bathymetry in the canal and channels were very shallow (depth mostly less than 2.5 m).

Water level was recorded at five locations in the sub-watershed. A linear relationship was found between water level and channel velocity using regression analysis at two locations ($R^2 = 0.71$ and
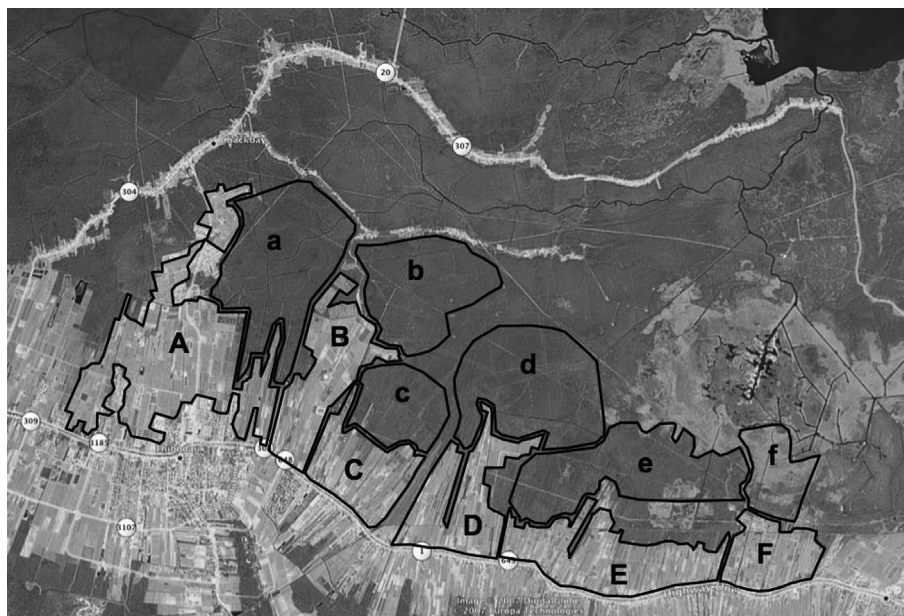
**Fig. 2.** Major upland drainage sub-basins (upper case letters) and corresponding receiving wetlands (lower case letters) in the Bayou Boeuf Basin.

0.87). Streamflow, that is the volume transport in the channel, was estimated based on the rating curve method suggested by United States Geological Survey (USGS) and was equal to the product of the channel velocity and cross-section area of the channel. We chose a modeling period of 1 February 2010 to 1 August 2010, a period of time where there were concurrent and continuous measurements of water level.

The numerical model was forced by three mechanisms. The first is freshwater inflow at the end point of the channel, which is equal to streamflow calculated above. The second is wind stress blowing at the water surface, which is based on wind speed and wind direction observations at New Orleans International Airport weather station located about 40 km away from the modeling domain. The third forcing is precipitation, also based on observations at New Orleans International Airport weather station. The water level boundary condition at downstream ends of the channels employed the radiation boundary condition with a frictional timescale proposed by Blumberg and Kantha (1985). No open boundary condition for velocity components is required since FVCOM uses a linear momentum approximation at the open boundary cells.

We used FVCOM to simulate the hydrodynamics of strategic removal of spoil banks in the BBB using several scenarios (Table 1). The most intensive scenario would be complete removal of the spoil bank levees. A less intensive option would be gapping the levees at specific intervals. For this analysis, we choose three gap intervals (1 km, 0.5 km, and 0.1 km) with two gap widths (5 m and

20 m), providing eight scenarios for this study (Table 1). Scenario 1 is the current condition at the BBB, scenarios 2–7 are various gap interval and width combinations, and Scenario 8 is the removal of all levees. In addition, when analyzing and discussing various scenarios we also considered the different rate of rainfall. For example, during July 1st and 2nd the average daily precipitation rate is 7–10 cm/day, we refer to as a small rain event, while during July 9th the precipitation rate is about 18–20 cm/day, which we refer to as a large rain event.

Model results of flow field and wetland inundation among different scenarios were difficult to quantify by inspecting the instantaneous flow vectors and wet/dry area data imagery. Therefore, we calculated percent wetland contact time, which represents the proportion of water that flowed through wetlands, similated by 600 Lagrangian particles in FVCOM simulations. Total residence time, which is a measure of the average time water parcels spend in the sub-basin, was also calculated. Nutrient reduction was predicted by calculating the loading rate of the proportion of water passing over wetlands using the highest TN concentration found at station 8 (4.83 ml/L) and half of the wetland area in the basin (~8 km²), then applying that loading rate to the relationship developed by Richardson and Nichols (1985) to estimate nutrient reduction for that proportion of water flowing over wetlands, which was then deducted from the total amount of water exiting the sub-basin. By using the largest TN concentration and only half of the available wetland area, our estimates of nutrient reduction are conservative.

## 3. Results

### 3.1. Water quality

$NO_x$ concentrations in the BBB ranged from the detection limit (0.01 mg/L) to 2.90 mg/L, with a mean of $0.06 \pm 0.02$ mg/L (Fig. 3). The highest concentration (2.9 mg/L) was found at station 8, which is located at the southern end of St. James Canal and receives drainage for a large area of sugarcane farm fields, including Orange Grove and Abby sugarcane plantations. Station 2, located down channel from station 8, had elevated but consistently lower

**Table 1**
Modeling scenarios for spoil bank modifications.

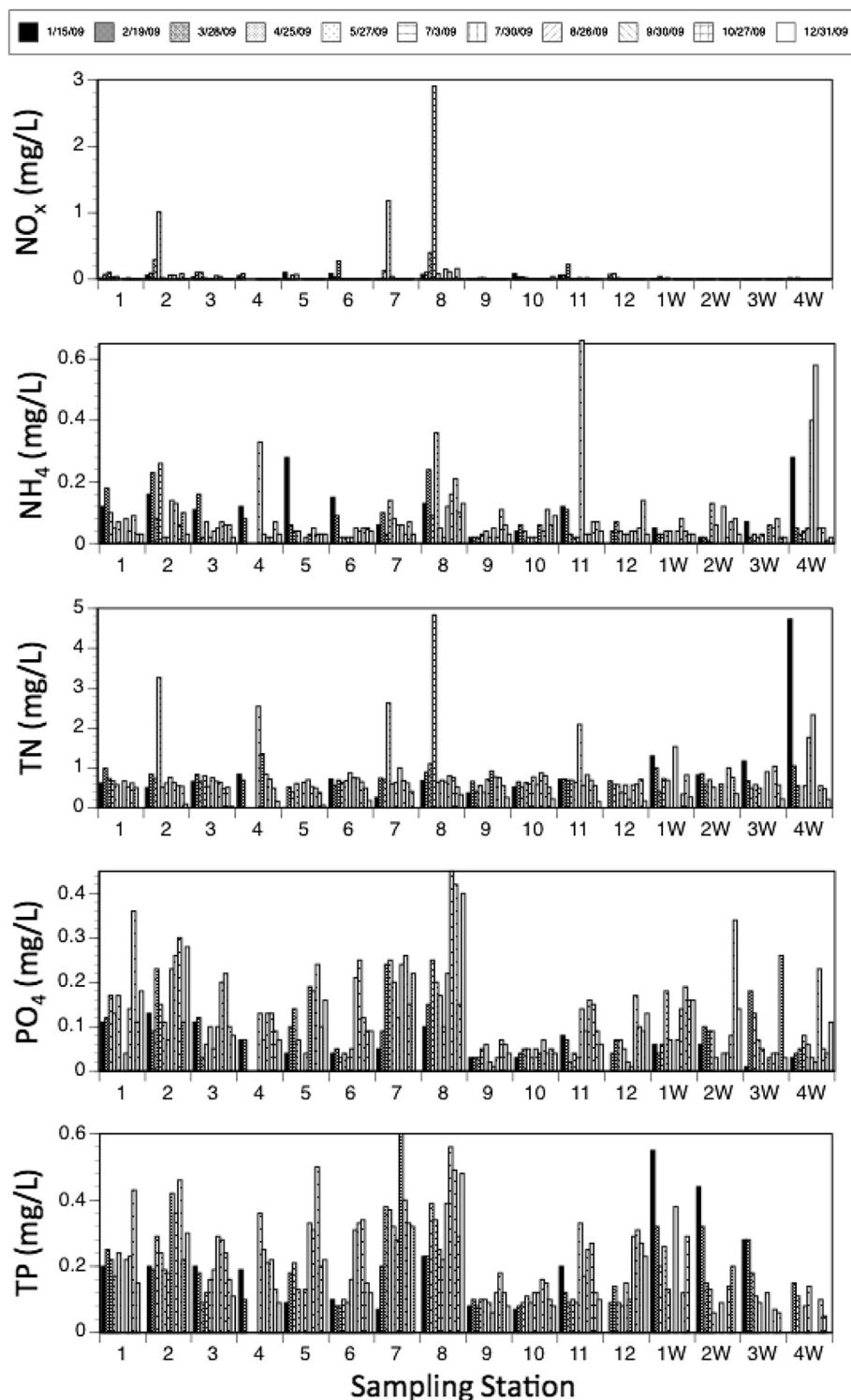| Scenario | Gap interval | Gap width |
|---|---|---|
| 1 | No change | |
| 2 | 1 km | 5 m |
| 3 | 1 km | 20 m |
| 4 | 0.5 km | 5 m |
| 5 | 0.5 km | 20 m |
| 6 | 0.1 km | 5 m |
| 7 | 0.1 km | 20 m |
| 8 | All levees removed | |

**Fig. 3.** Nitrate + nitrite (NO$_x$), ammonium (NH$_4$), total nitrogen (TN), orthophosphate (PO$_4$), and total phosphorus (TP) concentrations of surface water samples taken from the Bayou Boeuf Basin.

concentrations than station 8, suggesting uptake by the intervening wetland. Station 7 also had high NO$_x$ concentrations, presumably from runoff from the Laurel Valley and Rienzi sugarcane plantations. Ammonium concentrations ranged from the detection limit (0.01 mg/L) to 0.66 mg/L, with a mean of 0.07 ± 0.01 mg/L. The highest NH$_4$ concentration (0.66 mg/L) was found at station 11 on July 3, 2009, but concentrations were much lower during the other

sampling dates. Stations 8 and 2, which receive drainage from major sugarcane farm fields, had consistently elevated NH$_4$ concentrations. Station 4 W, a forested wetland site, had higher NH$_4$ concentrations than the other wetland sites. TN concentrations ranged from below the detection limit (0.01 mg/L) to 4.83 mg/L, with a mean of 0.74 ± 0.05 mg/L, and reflected the trends found for NO$_x$ and NH$_4$.

PO$_4$ concentrations ranged from below the detection limit (0.01 mg/L) to 0.45 mg/L, with a mean of 0.11 ± 0.01 mg/L (Fig. 3). As with NO$_x$ and NH$_4$, high discrete sample PO$_4$ concentrations were found at stations 8, 7, and 2. High PO$_4$ concentrations were also measured at stations 5 and 6, which are located along Halpin Canal and receive stormwater runoff from the Melodia Plantation (Fig. 1). Station 1, which receives water from upper Barataria Basin, also had elevated PO$_4$ concentrations. TP concentrations ranged from the 0.05 mg/L to 1.19 mg/L, with a mean of 0.24 ± 0.04 mg/L and had similar trends as PO$_4$ at all stations except the wetland sites, which had generally higher TP concentrations earlier in the study and higher PO$_4$ levels during the later months.

TSS concentrations ranged from below the detection limit (0.1 mg/L) to 173.0 mg/L, with a mean of 12.8 ± 2.3 mg/L (Fig. 4). The highest concentrations were found at Station 7, presumably from runoff from the Laurel Valley and Rienzi Plantations, as well as stations 8 and 2, due to runoff from the Abby and Orange Grove Plantations, respectively (Fig. 1). Chlorophyll $a$ concentrations ranged from below the detection limit (0.02 ug/L) to 137.2 ug/L, with a mean of 10.7 ± 1.4 ug/L (Fig. 4). The Lake des Allemands station (4) had the highest chlorophyll concentration found during the study (137.2 ug/L, mean 28.9 ± 16.4 ug/L). Stations 9, 10 and 11 also had elevated chlorophyll $a$ concentrations with means of 19.3 ± 16.4, 14.0 ± 0.54, and 13.9 ± 0.89 ug/L, respectively. Salinity concentrations ranged from below the detection limit (0.1 PSU) to 0.5 PSU, with a mean of 0.1 ± 0.006 PSU.

### 3.2. Nutrient reduction

In St. James Canal, there were substantial reductions of nutrients and sediments, and overall increases in chlorophyll $a$ as water passed through the channel (Table 2a). NO$_x$ concentrations decreased on average by 39%, NH$_4$ by 21%, TN by 21%, PO$_4$ by 21%, TP by 20%, and TSS by 25% (Table 2a). Chlorophyll $a$ concentrations fluctuated over time, but overall increased by 70%.

Water quality trends were not as consistent in Halpin Canal, which had unexpected increases in nutrient and sediment

**Table 2a**
Percent change in water quality parameters in St. James Canal (na = not available).

| Date | NO$_x$ (mg/L) | NH$_x$ (mg/L) | TN (mg/L) | PO$_4$ (mg/L) | TP (mg/L) | TSS (mg/L) | CHL (ug/L) |
|---|---|---|---|---|---|---|---|
| 1/15/09 | −14% | 23% | −26% | 30% | −13% | 40% | −13% |
| 2/19/09 | −10% | −4% | −6% | −40% | −17% | −50% | 256% |
| 3/28/09 | −28% | −11% | −34% | −8% | −26% | −14% | 82% |
| 4/25/09 | −65% | −28% | −33% | −25% | −29% | −35% | 100% |
| 5/27/09 | −75% | −60% | −20% | −35% | −24% | 1% | −13% |
| 7/3/09 | na | 0% | −10% | −30% | −18% | −64% | −55% |
| 7/30/09 | −60% | 17% | 17% | 5% | 8% | na | 55% |
| 8/26/09 | −45% | −19% | −21% | −42% | −36% | 13% | 282% |
| 9/30/09 | 0% | −71% | −27% | −29% | −6% | −63% | −38% |
| 10/27/09 | −50% | 0% | 4% | −27% | −24% | −44% | 14% |
| 12/31/09 | na | −77% | −73% | −30% | −38% | −30% | 100% |
| Mean | −39% | −21% | −21% | −21% | −20% | −25% | 70% |

**Table 2b**
Percent change in water quality parameters in Halpin Canal (na = not available).

| Date | NO$_x$ (mg/L) | NH$_x$ (mg/L) | TN (mg/L) | PO$_4$ (mg/L) | TP (mg/L) | TSS (mg/L) | CHL (ug/L) |
|---|---|---|---|---|---|---|---|
| 1/15/09 | −20% | −46% | 100% | 0% | 11% | −15% | 36% |
| 2/19/09 | 100% | 50% | 8% | −50% | −56% | 150% | 517% |
| 3/28/09 | 100% | −50% | 77% | −79% | −62% | −72% | 1239% |
| 4/25/09 | −86% | −50% | 3% | −43% | −23% | −52% | 98% |
| 5/27/09 | na | na | na | na | na | na | na |
| 7/3/09 | na | 0% | 26% | 20% | 19% | 23% | −86% |
| 7/30/09 | −50% | 67% | 7% | 11% | −6% | −62% | −36% |
| 8/26/09 | −50% | −20% | 40% | 39% | 6% | −47% | 280% |
| 9/30/09 | na | 67% | 33% | −50% | −32% | −32% | −53% |
| 10/27/09 | −50% | 67% | 29% | −10% | −25% | −79% | 71% |
| 12/31/09 | na | 33% | 200% | −44% | −45% | −38% | 50% |
| Mean | −1% | 12% | 47% | −21% | −21% | −22% | 212% |

concentrations (Table 2b), perhaps due to mixing with water from Bayou Boeuf, a short distance from end-member Station 6. Overall, there was a negligible decrease in NO$_x$ concentrations, a 21% decrease in PO$_4$ and TP, a 22% decrease in TSS, and a 212% increase in chlorophyll $a$ levels (Table 2b).
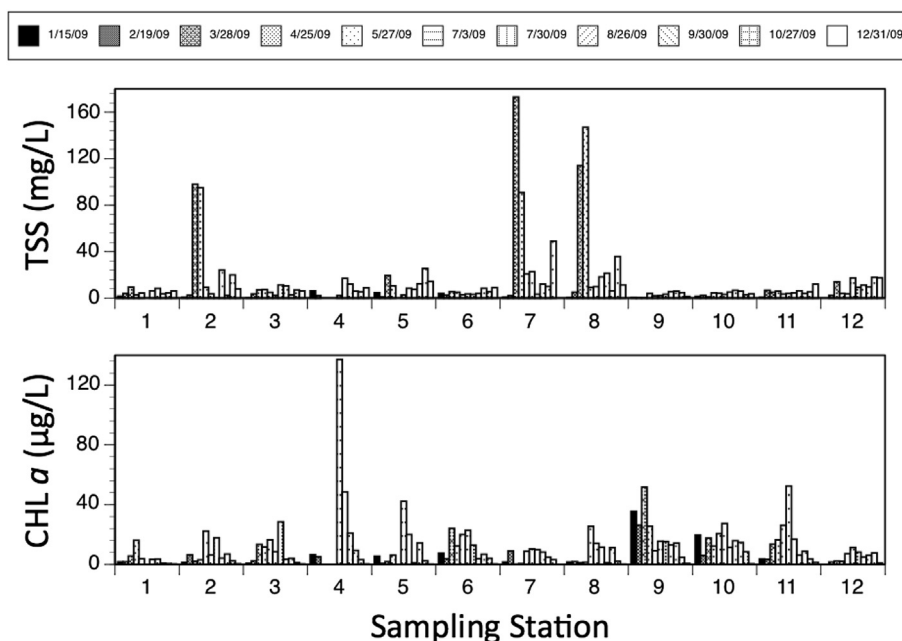


**Fig. 4.** Total suspended sediments (TSS) and chlorophyll $a$ (CHL $a$) concentrations of surface water samples taken from the Bayou Boeuf Basin.

**Table 3**
Nutrient yields for various sub-basins, and loadings for receiving wetlands.

| Site | Basin area (ha) | Yield TN (kg/yr) | Yield TP (kg/yr) | Wetland area (ha) | TN loading (g/m$^2$/yr) | TP loading (g/m$^2$/yr) |
|------|-----------------|------------------|------------------|-------------------|-------------------------|-------------------------|
| A | 1731 | 5281 | 812 | 1290 | 0.41 | 0.06 |
| B | 769 | 2347 | 361 | 977 | 0.24 | 0.04 |
| C | 642 | 1960 | 301 | 529 | 0.37 | 0.06 |
| D | 980 | 2989 | 460 | 1226 | 0.24 | 0.04 |
| E | 1063 | 3244 | 499 | 1124 | 0.29 | 0.04 |
| F | 239 | 731 | 112 | 432 | 0.17 | 0.03 |

### 3.3. Nutrient loading

Based on values given by Yu et al. (2008), N and P yields from the six upland sub-basins range from 731 to 5281 kg/yr for TN, and from 112 to 812 kg/yr for TP (Table 3). The loading rates to areas of wetlands likely to receive stormwater runoff from the sub-basins range from 0.17 to 0.41 g/m$^2$/yr for TN, and from 0.03 to 0.06 g/m$^2$/yr for TP (Table 3).

### 3.4. Hydrologic modeling

Comparisons between FVCOM simulation results and observations are made for the purposes of establishing some degree of model veracity to justify the model analyses used later. Hourly time series of water level from observations (thick lines) and model output (thin lines) are shown in Fig. 5 for three water level stations. Visual inspection shows that good agreement for both amplitude and pattern exists at these stations. Quantitative comparisons based on regression analyses and Index of Agreement (Willmott, 1981; Warner et al., 2005) are also greater than 0.8 for all stations. Therefore, a degree of model veracity is established.

The FVCOM simulation results for the St. James Canal watershed are shown in Fig. 6. Inspection of the flow field in the main channels and the wetlands indicates that rainfall was the largest factor contributing to the variation of water level and flow velocity in the region. When there was no rain, most of the wetlands were dry. Waters from the upstream sugarcane field were mainly confined in the narrow, relatively deep channels (Fig. 6a). The velocity magnitude was very small in the St. James Canal, normally on the order of several centimeters per second. Just after a small rain event (precipitation rate 7—10 cm/day), most of the wetlands in the computational domain were covered by water (Fig. 6b). Since there are no spoil banks on the south bank of the St. James Canal, there was free connection between waters in the canal and the wetlands south of the canal. However, the height of the northern spoil bank levee is over 1 m with only a few small gaps (<10 m), forming a barrier between the water in the St. James Canal and the wetlands north of it, limiting hydrological exchange. The average water depth was less than 20 cm in the wetlands, and water velocity was less than 10 cm/s in most regions except in the upper stream of the St. James Canal (close to Station 8) where it could reach about 12—15 cm/s. Just after a large rain event (precipitation rate 18—20 cm/day), almost all wetlands were flooded with water (Fig. 6c). There were waters flowing from the St. James Canal to the northern wetlands through the existing gaps in the northern spoil bank. Depending on the width of the gap, the velocity at some gaps could reach as high as 20 cm/s. In addition, the high flows in the channels also increased compared to the small rain case, reaching 15—20 cm/s in the relatively shallow channels (i.e., the channel that extends to the north).

Modeling results predicted 22.6% N reduction given the current levee case (scenario 1), which is validated by our observed N reduction for 21% for St. James Canal (Table 2a). As anticipated, the
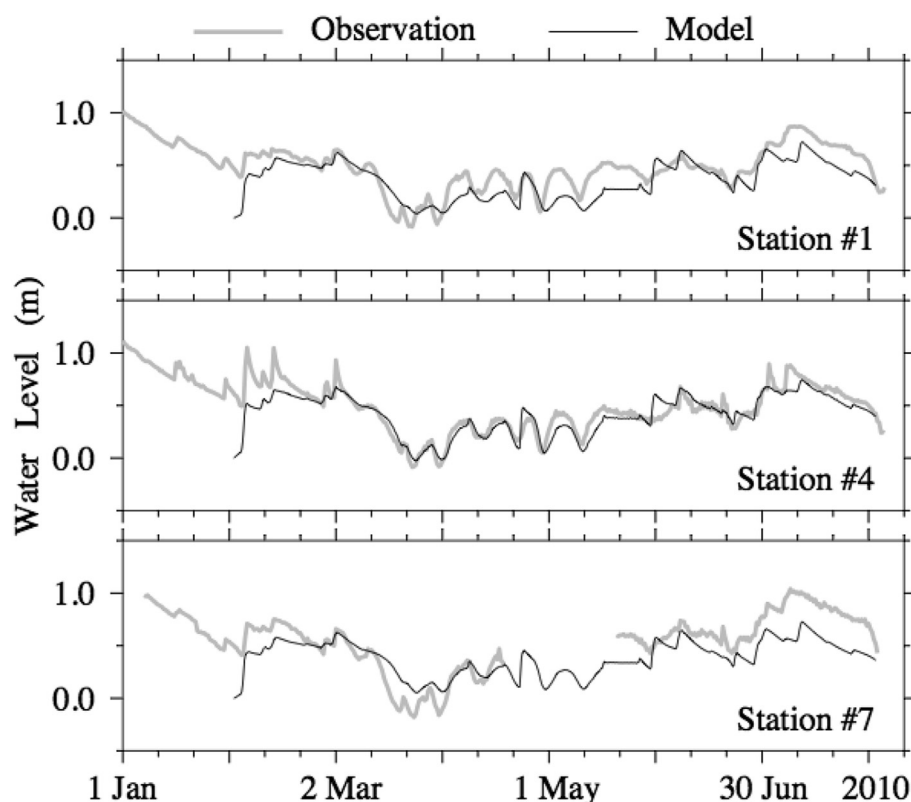


**Fig. 5.** Time-series comparison for hourly water level observed (gray thick line) and FVCOM simulated (black thin line) at water level stations 1, 4, 7.
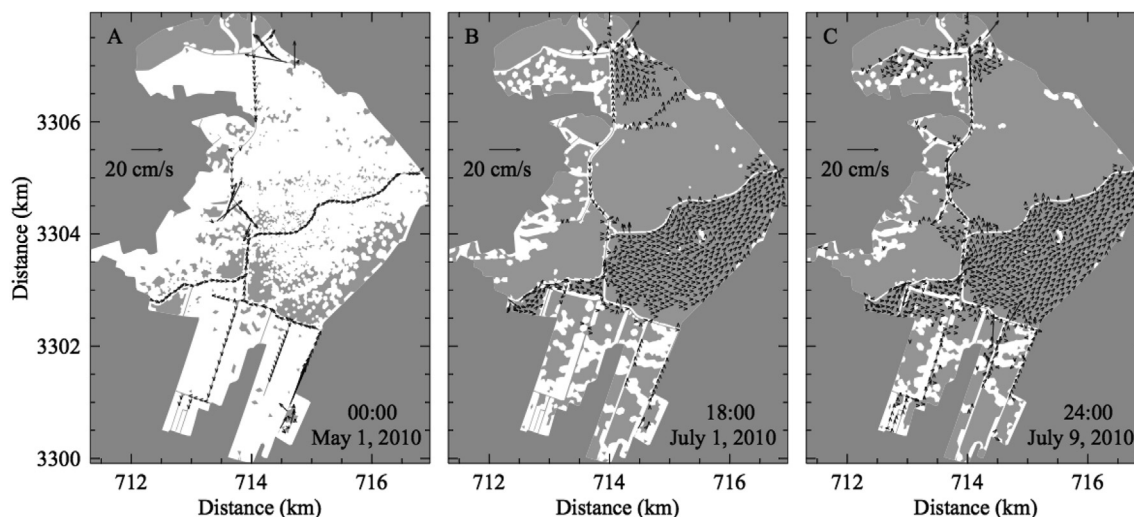
**Fig. 6.** FVCOM modeled velocity vectors and wetland inundation at various times for current spoil bank configuration. Light gray color indicates area covered by water, while white color indicates no water.

gapping scenarios increased the storm water residence time on wetlands compared to the current levee case (Table 4). These results represent the time period from May 23 to June 13, 2010, which included several large and small rain events. Residence time initially increased as the gap:interval ratio decreased, but then decreased with a continued decrease in the gap:interval ratio. The gap:interval ratio with the highest percent wetland contact time was 500m:5m (scenario 4; 41.8%) closely followed by 1000m:20m (scenario 3; 40.8%). The spoil bank interval:gap ratio of 500m:5m (scenario 4; Table 4) had the highest N reduction of 29.2%. The 500m:20m ratio (scenario 5) had the highest total residence time, however, less water had contact with surrounding wetlands (33.1% vs. 41.8%) and therefore less N reduction was predicted. Counter-intuitively, the scenario with the lowest wetland contact time was when all of levees were removed (scenario 8), which had a percent wetland contact time of 9.1% and an N reduction of only 16.7% (Table 4). The most likely reason for this is that (1) the channel has been severely deepened by dredging and that (2) the surrounding spoil bank levees channel and raise water levels, facilitating wetland contact. To test the dredging hypothesis, we ran the model at 1/3, 1/2, and 2/3's of current mean depth using scenario 8 (no levees). Results indicate rapidly increasing percent wetland contact and total N reduction with decreasing channel depth, with a 31.3% N reduction rate at 1/3 depth (Table 5).

## 4. Discussion

The BBB has undergone numerous anthropogenic alterations over the past century, including logging and clearing of the uplands for agriculture along with the construction of roads, flood-control levees, drainage canals, and spoil bank levees. These hydrological alterations effectively impounded the basin, with rainfall and stormwater runoff from the surrounding uplands controlling water levels in the basin. The surrounding uplands, especially along the southern border of the basin, have been highly modified for sugarcane farming by the construction of a massive network of drainage channels. These channels funnel stormwater from the fields into large drainage canals such as St. James and Halpin, often bypassing wetlands to drain directly into Lakes Boeuf and des Allemands. The modeling results indicate only a 16.7% N reduction if all of the levees were removed because the main drainage channels have been deepened by dredging to such an extent that even during severe storms water levels do not rise much above the surrounding wetland elevation. The presence of levees alters hydrology by raising water levels, allowing more water to come in contact with wetlands and increasing N reduction to the observed 21% (Tables 2b and 4).

The modeling results indicate a 27.5–31.3% N reduction if all of the levees were removed and the channel depth was a half to a third of its current depth (Table 5). Approximately the same reduction (29.2%) can be attained using a spoil bank interval:gap ratio of 500m:5m due to the interaction of levees constricting flow and raising water levels to overcome increased channel depth, allowing water to pass into wetlands. The potential N and P loading rates calculated for this study, 0.17–0.41 g/m$^2$/yr for TN, and from 0.03 to 0.06 g/m$^2$/yr for TP, are very low (Table 3). Comparison of these loading rates to the loading-uptake relationships found in the literature (e.g., Richardson and Nichols, 1985; Hunter et al., 2009) indicates more than sufficient capacity for wetlands to fully assimilate the nutrient load generated by the upland sub-

**Table 4**
FVCOM modeling results for various scenarios.

| Scenario | Gap interval:width (m) | Total residence time (d) | Wetland contact (%) | Q wetland (L) | N Loading (g/m$^2$/y) | Wetland N Reduction (%) | Total N Reduction (%) |
|---|---|---|---|---|---|---|---|
| 1 | No Change | 13.2 | 22.6 | 4.27E+08 | 4.70 | 82.5 | 21.4 |
| 2 | 1000:5 | 13.2 | 35.1 | 6.64E+08 | 7.32 | 80.5 | 26.4 |
| 3 | 1000:20 | 13.3 | 40.8 | 7.70E+08 | 8.49 | 79.6 | 28.7 |
| 4 | 500:5 | 14.4 | 41.8 | 7.91E+08 | 8.71 | 79.4 | 29.2 |
| 5 | 500:20 | 17.3 | 33.1 | 6.26E+08 | 6.89 | 80.8 | 25.5 |
| 6 | 100:5 | 14.9 | 33.0 | 6.24E+08 | 6.88 | 80.8 | 25.5 |
| 7 | 100:20 | 14.9 | 31.3 | 5.92E+08 | 6.52 | 81.1 | 24.8 |
| 8 | No levees | 8.4 | 9.1 | 1.73E+08 | 1.90 | 84.7 | 16.7 |

**Table 5**
FVCOM modeling results for various channel depths using the no levees scenario.

| Fraction of current depth | Mean depth (m) | Total residence time (d) | Wetland contact (%) | Q wetland (L) | N Loading (g/m$^2$/y) | Wetland N reduction (%) | Total N reduction (%) |
|---|---|---|---|---|---|---|---|
| 1 | 2.5 | 8.4 | 9.1 | 1.73E+08 | 1.90 | 84.7 | 16.7 |
| 2/3 | 1.65 | 12.4 | 31.3 | 5.92E+08 | 6.52 | 81.1 | 24.8 |
| 1/2 | 1.25 | 12.7 | 37.8 | 7.14E+08 | 7.87 | 80.1 | 27.5 |
| 1/3 | 0.83 | 13.4 | 46.6 | 8.80E+08 | 9.70 | 78.7 | 31.3 |

watersheds, with 90–100% reduction. The reason for the discrepancy between our results and those of others can be explained by the fact that there must be physical contact between water and wetlands for nutrient reduction to take place (Blahnik and Day, 2000), and for the BBB case, most water stays in the channel bypassing surrounding wetlands (Fig. 7). Given the most efficient spoil bank interval-gap ratio (500m:5m), water from upstream sugarcane fields drained out of the watershed in 14.4 days with 41.8% flowing through wetlands (Table 4). The remaining proportion of water (62.2%) remained in the deep channel, and thus had no direct contact with wetlands. There is thus a potential for increased nutrient reduction if more water had contact with wetlands.

During the course of this study, it was proposed that weirs be constructed in the main drainage canals to force water onto the wetland surface. This idea was abandoned, however, once it was realized that the North Lafourche Conservation Levee and Drainage District, the local government body responsible for dredging of drainage canals in the BBB, would oppose any obstruction to drainage or boat navigation. Given the current depth of the drainage canals, it is virtually impossible to spread stormwater

runoff through wetlands via the canals without impeding drainage. A possible solution might be to pump stormwater into wetlands rather than into canals using some sort of conveyance and manifold system, however, cost constraints and the sociopolitical factors surrounding drainage in southern Louisiana would have to be overcome. Thus, after implementing gaps at a 500m:5m ratio, additional water quality improvements should be implemented at the farm field level, prior to water entering major drainage canals, using methods such as edge of field vegetation filter strips, ditch management, and other best management practices that would reduce the amount of sediment and nutrient entering surrounding waterways.

## 5. Conclusions

Sugarcane farm fields to the south of the BBB were found to be the major sources of nutrients and total suspended sediments to surrounding waterways. A cost-effective mechanism to reduce these pollutants would be a series of breaks in the existing spoil banks along major drainage channels to allow water to flow into surrounding wetlands. Modeling results indicate implementation of a spoil bank interval:gap ratio of 500m:5m would increase N reduction from 21.4% to 29.2%, which is much lower than the theoretical 90–100% removal rate. One reason for this discrepancy is that dredging has deepened the main drainage canals to such a degree that even during severe storm events, water levels do not rise much above the surrounding wetland elevation, so only a very small fraction of the stormwater carried by channels is exposed to wetlands. Additional water quality management practices should be implemented at the farm field level, prior to water entering major drainage canals.

**Fig. 7.** The FVCOM simulated trajectories of 600 water particles initially released in the southwest corner of the wetland. In this simulation, the ratio of spoil bank interval to gap width is 500m:5m. Note that most of the particles stay in the channels and that there are large areas of wetlands, such as south and northwest of the St. James Canal, where water particles never pass through.

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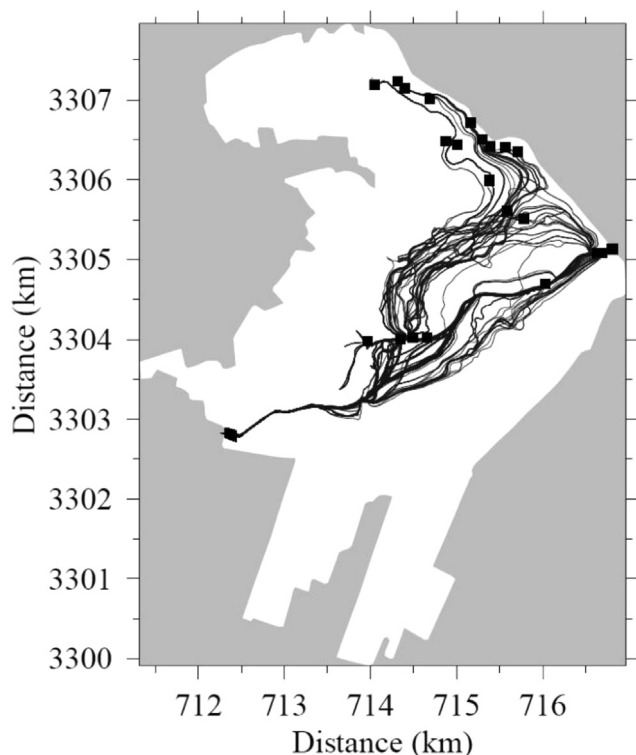
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