Pulses: The Importance of Pulsed Physical Events for Louisiana Floodplains and Watershed Management

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Abstract

In the PULSES project, we studied the impacts of restored flood inputs from the Mississippi River into coastal marshes of the Breton Sound watershed, Louisiana. This diversion has multiple objectives including maintaining a desirable salinity gradient, restoring deteriorating wetlands and enhancing fisheries. Pulses ranged from 185 m^3 sec^{-1} for high flow, and 15 m^3 sec^{-1} for low flow. The high river pulse resulted in nearly 30 % of the discharge flowing over the marsh, while during the low pulse, most river water was confined to channels. Sedimentation on the marsh surface during the pulse was locally high in areas within 10 km of the diversion. In the upper estuary, estimated maximum removal rates of total nitrogen and nitrate during a two week pulse in March 2001 were 44 % and 57 % respectively, while phosphate and silicate were reduced by maximum values of 23 % and 38 % respectively. There was strong nitrate uptake by sediments and a major pathway of nitrogen removal was denitrification. Stable isotope analysis showed that nitrogen and carbon in river water were incorporated into estuarine organisms such as shrimp. Spatial models predicted that species composition in emergent marsh plant communities should shift in response to salinity gradients imposed by the diversion. Socio-economic surveys documented a wide diversity of opinions regarding the costs and benefits of the reintroduced river water. Overall, results showed several strong impacts in the low-salinity (<1 psu) region near the diversion structure, with some impacts such as salinity reduction extending further down-estuary.

Keywords: river diversion, Gulf of Mexico, habitat restoration, pulses

Introduction

Over the past century, there have been many changes in the Mississippi delta. These include massive loss of coastal wetlands, salt water intrusion, and deteriorating water quality. Partially in an effort to enhance fisheries production and to address the land loss problem, diversions of Mississippi River into coastal watersheds are being carried out. Over the last century, there have been a number of changes to the Mississippi River including increasing nutrient levels, especially nitrate, decreasing suspended sediment concentrations, and the introduction of exotic species such as zebra mussels and grass carp. These changes must be taken into consideration when designing diversions. Is the reintroduction of river water restoring a natural floodplain system, a result expected if the volume and timing of freshwater inputs are most important, or is this watershed management practice of reintroducing of river water driving the deltaic system in a new direction? This latter result may occur if the combination of much-lower-than-historical riverine sediment loads, and much-higher-than-historical nutrients, exotic species

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and anthropogenic chemicals proves more dominant than simple hydrologic restoration of a river-floodplain system. This article reports on initial results from the a multi-investigator 3 year project that set out to investigate these questions.

Study Area

In the PULSES project funded by EPA, USDA and NSF in the Water and Watershed program, we studied the multiple effects of different scales of river inputs into the Caernarvon watershed, just south of New Orleans (Figure 1). River inputs have been ongoing since the 1991 opening of a gated river diversion structure. Discharge levels ranged from 185 m^3 sec^{-1} for high flow, and 15 m^3 sec^{-1} for low flow (Figure 2).

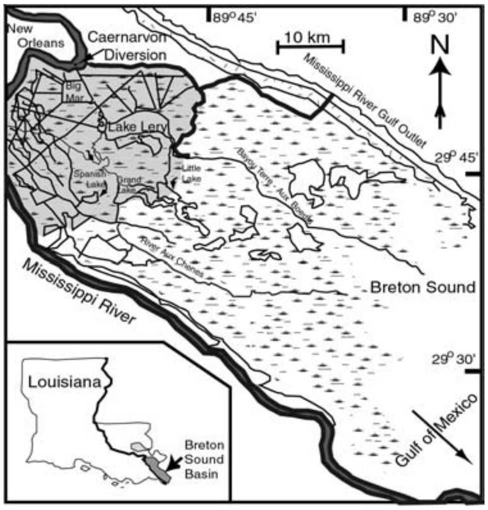

Figure 1. Breton Sound Basin with main region of estuary influenced by diversion highlighted in gray.

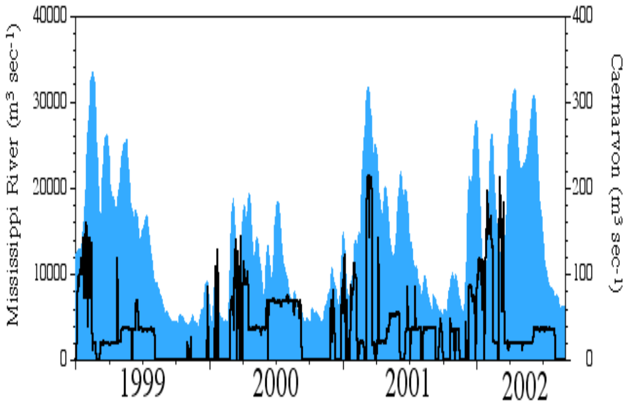

Figure 2. Mean daily Mississippi River (shaded) and Caernarvon structure (line) discharge from 1999 to 2002. Note the large pulses in 2001 and 2002 associated with this project.

Methods

Short-term sediment accumulation was measured by collecting sediment on 9 cm diameter pre-ashed, pre-weighed glass fiber filters (GF/F) with an underlying petri dish base (also 9 cm) (Reed 1989). Traps were pinned to the sediment at the level of the marsh surface, and a 0.5 inch mesh wire cage (0.3 m x 0.3 m) was anchored to the marsh around the filter pads as location markers and for protection from interference by fauna and large detritus. Filter pads were collected from the field sites at 1-4 week intervals and the filter number, location, and the date were recorded. This technique provides the net short-term deposition for individual locations, but cannot quantify deposition versus resuspension processes over the intervening sampling periods (Reed 1989).

In the laboratory, each pad was dried in an oven at 60 ºC to obtain dry weight and then ashed in a muffle furnace at 350 ºC (without preheating) for at least 16 hours to obtain estimates of ash weight and organic matter. Deposition of inorganic and organic sediments are reported as the mean (± 1 standard error) of 4 sediment traps at each location within a transect.

A 40-cm long x 10-cm diameter ^{210}Pb ($t_{1/2}$ = 22.3 y) core was collected on September 8, 2001 three km southwest of diversion in the marsh. The core was sectioned into 1-cm intervals immediately after collection, individually bagged and labeled, and returned to the LSU sediment laboratory. Each interval was dried overnight at 60 °C, homogenized with a mortar and pestle, packed into small volume vials, and sealed with epoxy. All core samples were set-aside for at least 30 days for the ^{210}Pb to reach equilibrium with its parent, ^{226}Ra ($t_{1/2}$ = 1620 y), prior to processing in an intrinsic germanium detector. Accumulation rates were calculated using the CIC model.

A total of 32 water quality transects were carried out in the Breton Sound estuary since September 2000 for water quality analysis. We used a flow-through system to continuously measure chlorophyll a, total suspended sediments (TSS), salinity, and temperature in major bayous and channels leading from the Caernarvon diversion to Breton Sound (Madden and Day 1992). Discrete water samples were taken at 20 locations in the estuary and later analyzed for nitrite+nitrate, ammonium, total nitrogen, total phosphorus, phosphate and silica (Standard Methods 1992).

Benthic nutrient exchange rates were estimated using a continuous flow system modified after Miller-Way and Twilley (1996) for the marsh metabolism studies. Sediment cores were taken seasonally at Big Mar (BM), Lake Leary East (LLE), Lake Leary West (LLW) and Grand Lake (GL). These stations are located with increasing distance from the diversion site. Cores were incubated with filtered water from their respective field site. Exchange rate calculations are based on concentration differences between the influent and effluent lines in steady state. Nutrient samples were measured using standard colorimetric techniques (Strickland and Parsons 1972) on a Lachat autoanalyzer.

Grass shrimp were collected 11 times between December 2000 and July 2002 at 12 stations in upper Breton Sound for stable isotope analysis. Using dip nets, three replicate samples of at least 10 individuals were obtained at each station. For each replicate, composites of the tail muscles of ten average sized specimens were dried (60 ºC, overnight) and ground to a fine powder. For stable isotope analyses with a continuous flow system, we used a Carlo Erba 1500 elemental analyzer, coupled to a Finnigan Delta Plus mass spectrometer (Barrie and Prosser 1996). Our primary and secondary laboratory standards were glycine and bovine liver, respectively. The $\delta^{15}N$ values are reported relative to air N_2 that has a value of 0.0‰. The precision of our analyses was better than 0.2‰.

We have developed a general framework for the implementation of a 2-D finite-element hydrodynamic model in the Caernarvon diversion area. In a parallel effort, we have developed and calibrated an estuarine eutrophication model that includes multiple N, Si, and P uptake of the Monod type, and multiple algal assemblages, whose productivity is simultaneously dependent on nutrient concentrations, nutrient ratios, and ambient light intensity. The eutrophication model is designed to run either as a stand-alone module or as a component of a larger 2-dimensional hydrodynamic model. We also developed a landscape model to show impacts of pulsed freshwater input into the habitat (See Reyes et al. in this volume for detailed information).

We used a questionnaire-based survey for over 100 local stakeholders and face-to-face interviews with members of the Caernarvon Interagency Advisory Committee (CIAC), a legally constituted stakeholder groups of decision makers, responsible for providing inputs to the operation of the diversion facility. The CIAC includes federal, state, and local agency and government representatives, oyster, shrimp, and recreational fishers, and land-owners.

Results

The Caernarvon freshwater diversion structure discharges Mississippi River water into the Breton Sound estuary located east of the river and just SE of New Orleans. The estuary stretches SE for about 70-80 km from the diversion structure to the Gulf of Mexico (Figure 1). The upper 40 km of the estuary, encompassing an area of about 1,100 km^2, is composed of extensive marshes, small to medium size water bodies, and channels, while the lower estuary is open water in Breton Sound. Thus, the upper estuary is weakly to moderately coupled to the lower estuary due to shallow, sinuous channels and extensive marshlands. Tidal amplitudes at the Gulf of Mexico end are about 35 cm but are much less in the upper basin due to dampening effects of the marsh dominated area. In this upper estuary, winds and diversions cause much higher water level variations than do tides. Salinity is generally fresh (<1 psu) in the upper basin except during prevailing south winds or very low diversion flow.

Sediment deposition on marshes resulted from a complex set of conditions in which prevailing winds, water velocity, water levels or tides, river flow, and suspended solid loads all contribute to marsh surface delivery. Wind direction was a major controlling factor in providing both TSS and water levels high enough for marsh delivery. The Caernarvon diversion delivered sediment into the northernmost reach of the Breton Sound estuary, but strong or sustained south winds dampened diversion flow and sequestered diverted sediment in the northern estuary, thus preventing deposition in the lower reaches. Statistical analysis revealed that deposition in Breton Sound estuary varied by season, with distance from the diversion ("new" sediment source; see Figure 3), and with proximity to a major waterway.

Calculations based on results from the sediment pads indicated marsh vertical accretion could reach 2.25 cm yr^{-1}, while excess ^{210}Pb measurements recorded at the same site showed a much slower rate of 0.11 cm yr^{-1}. The ^{137}Cs sediment activities showed an annual accretion rate of 0.10 cm yr^{-1}, which agreed very well with ^{210}Pb measurements. These data illustrate an important point about marsh deposition. Short-term sediment trap measurements do not capture the effects of compaction and decomposition, and thus, represent a more ephemeral mode of deposition.

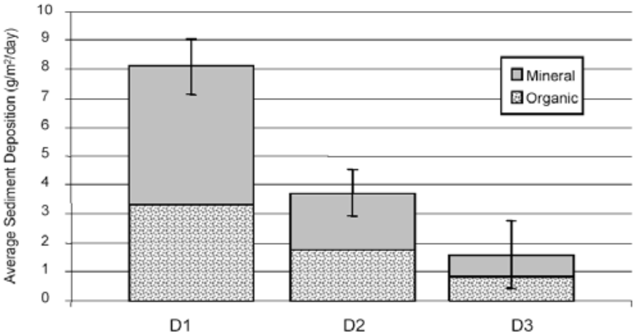

Figure 3. Average sediment deposition by sampling site distance, where D1 = < 6km (n = 5), D2 = 6 to 10 km (n = 6), and D3 = >10 km (n = 3). Background conditions at a reference station gave similar results to the D3 data. Overall deposition was highest within 10 km of the diversion.

Discharge from the diversion structure controls salinity through much of the estuary, especially during large 'pulses' when almost the entire estuary freshens. Temperature of incoming Mississippi River water ranged from 6-32 ºC and generally equilibrated to the rest of the estuary within 10 km, but there were several times when cooler water from the diversion propagated through the entire estuary. During most transects, there were substantial reductions in most nutrient forms, especially nitrate, as water flowed through the estuary. Incoming Mississippi River nitrate concentrations ranged from 41-285 µmol L^{-1}, and concentrations at mid-estuary ranged from 1-75 µmol L^{-1}. Possible mechanisms for this reduction are dilution with Gulf water, rain, or ground water, and uptake by phytoplankton, bacteria, and marsh plants, denitrification, or burial. In the upper estuary, maximum estimated removal rates of total nitrogen and nitrate during a two-week pulse in May 2001 were 44% and 57 % respectively, and phosphate and silicate were reduced by 23 % and 38 % respectively. During this period, the upper estuary was almost entirely fresh, rainfall was low and we assumed that ground water was negligible. On the other hand, overland flow across marshes mixed river water with low nutrient marsh water, diluting river nutrient concentrations, and actual removal rates may be lower than the calculated maximum rates to the extent that such dilution occurred. N burial and denitrification are other sinks for N in these coastal watersheds.

These changes in nutrient concentrations during the May 2001 river pulse also led to downestuary changes in stoichiometric nutrient ratios, with an overall increase in the dissolved DSi:DIN ratio and a decrease in the DIN:DIP ratio (Figure 4, Table 1, Lane et al. in review). At this time and during other spring discharge pulses, chlorophyll concentrations near the diversion were low, but increased after suspended sediments decreased below 80 mg L^{-1} several km from the diversion structure. Overall, chlorophyll levels generally peaked at mid-estuary, and gradually decreased to low levels in Breton Sound (Lane et al. in preparation).

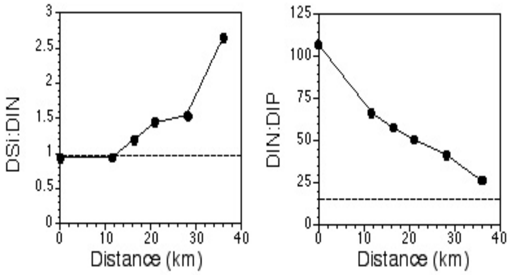

Figure 4. Molar ratios of DSi:DIN, and DIN:DIP with distance from the Caernarvon structure during the spring pulse of 2001. Horizontal dashed lines indicate the Redfield ratio. Distance was determined as a straight-line from the structure to the respective sampling stations.

Table 1. Concentrations of dissolved inorganic silicon (DSi), total nitrogen (TN), dissolved inorganic nitrogen (DIN), total phosphorus (TP), dissolved inorganic phosphorus (DIP) and salinity with distance from the Caernarvon structure during the spring pulse of 2001 (most data are from March 22, 2001).

Distance (km)	DSi (µM)	TN (µM)	DIN (µM)	TP (µM)	DIP (µM)	Salinity (PSU)
0	117.8	138.9	128.3	5.1	1.2	0
11.8	108.3	108.8	112.9	3.4	1.7	0
16.4	96.6	99.3	86.8	2.6	1.4	0
21.2	76.8	72.9	50.6	2.0	1.0	0
28.3	62.1	60.3	35.5	2.2	0.9	1.5
36.0	47.9	49.9	16.9	2.0	0.8	4.5

Nitrate fluxes in winter/spring 2002 indicated very low uptake or even efflux of nitrate from the sediment. Denitrification rates (see Kana et al. 1998) increased with increasing distance to the diversion and increasing water temperatures in the field, with maximum rates of up to 325 µmol N_2-N flux m^{-2} h^{-1} at Grand Lake (GL). In summer 2002 high nitrate fluxes into the sediments of more than 350 µmol NO_3 m^{-2} h^{-1} were estimated for cores from Big Mar (BM). Nitrate uptake rates decreased regionally from that maximum down to zero with increasing distance from the diversion. This drop is consistent with a reduction of ambient dissolved inorganic nitrate in the water to non-detectable levels (Figure 5). Denitrification rates at Big Mar were higher than 300 µmol N_2-N flux m^{-2} h^{-1} in summer and even though no nitrate uptake was detected for Grand Lake with our method, denitrification rates of up to 100 N_2-N flux m^{-2} h^{-1} were measured.

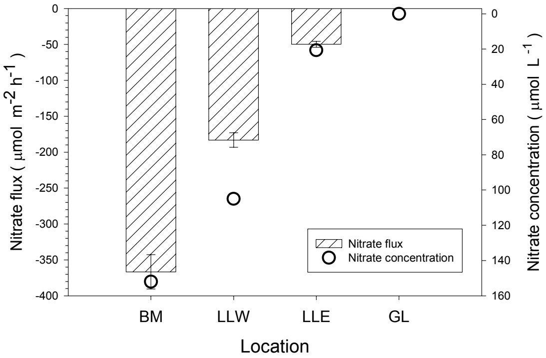

Figure 5. Nitrate flux averaged from 3 replicate cores per location (summer 2002). Bars show nitrate flux, with flux into the sediment as negative value. Circles give the ambient nitrate concentration in the water column.

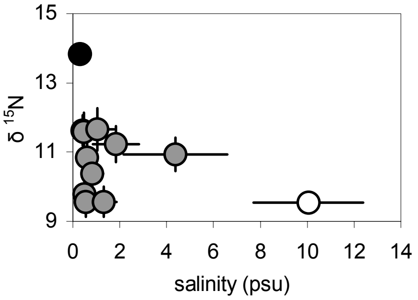

Figure 6. Average $\delta^{15}N$ (‰) values of grass shrimp muscle tissue vs. average salinity for the 12 sampling stations. Samples were collected 11 times between Dec. 2000 and July 2002. Error bars represent 95% confidence levels. The black and white symbols stand for the stations closest to the diversion and marine station, respectively.

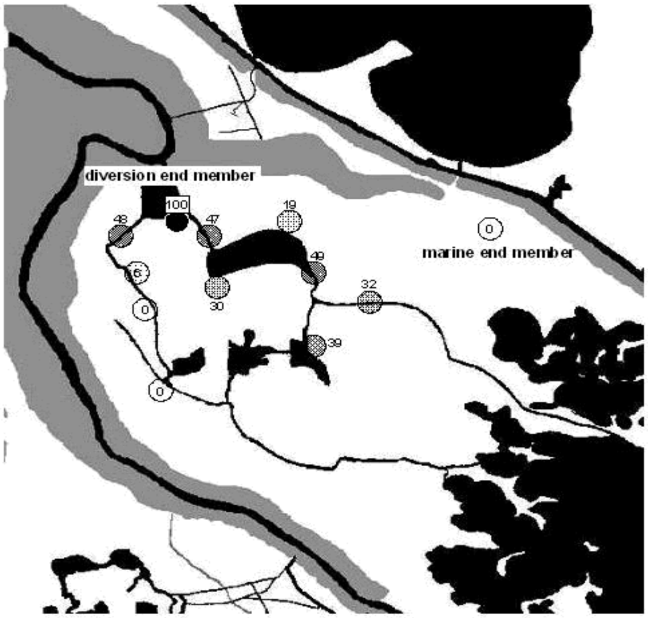

Figure 7. Average contribution (%, black = 100%, and white = 0%) of Mississippi River nitrogen to shrimp muscle tissue for the 12 sampling stations. Calculations area based on figure 3 and the assumption that the $\delta^{15}N$ values at the station closest to the diversion completely derive from Mississippi River nitrogen and that the $\delta^{15}N$ values at the most marine station are not influenced by the Mississippi River nitrogen.

The $\delta^{15}N$ values for grass shrimp showed a strong gradient throughout the sampling area, with highest values close to the diversion and decreasing values further away from it (Figures 6 and 7). River-derived nitrogen was strongly incorporated into the food web leading to grass shrimp with elevated $\delta^{15}N$ values through much of the estuary. However, at marsh-influenced sites, this effect was much diminished. The simplest interpretation of these results is that there is another nitrogen source present in marsh-influenced sites, with the source having low $\delta^{15}N$ values. Nitrogen fixation that is active in Louisiana marshes (Nixon 1980, DeLaune and Patrick 1990) could provide this source, with low $\delta^{15}N$ values near 0‰ typically associated with N from nitrogen fixation (Shearer and Kohl 1989). Use of marsh nitrogen derived from this fixation, or also possible use of dissolved organic nitrogen that may have low $\delta^{15}N$ values in river water (Fry and Allen 2003) possibly could lead to the lower $\delta^{15}N$ values in food webs at these stations.

The habitat model was used to test the effects of different management scenarios. Modeled riverine inputs had strong effects on watershed dynamics, as detailed by Reyes et al. in a separate paper in this volume.

We incorporated information from Caernarvon in an analysis of the relations among natural capital, pollution, and social welfare. Results showed that sustainable functioning of natural systems should contribute substantially to development of societal wealth in Louisiana. Preliminary results of the stakeholder analysis revealed that although there is high level agreement that coastal land loss is a significant problem, diversions are not always viewed as an appropriate solution to this problem. This is due to a combination of factors, especially that 1) local people tend to make judgments based on heuristics (e.g., personal experience for generalization), 2) there are significantly different responses among decision makers, experts, and local people, 3) channels to accommodate public opinions are available, but not actively used, therefore, 4) diverse opinions and conflicts exist and persist.

Conclusions

The ecological studies revealed very dynamic behavior of salinity, suspended sediments, chlorophyll a, and nutrients. In this system that is relatively well-flushed by riverine pulses and other weather events, year-round algal blooms were not observed. However, nutrients from the Caernarvon diversion supported high chlorophyll a concentrations in the mid estuary, especially during summer. During high discharge, chlorophyll a concentrations close to the diversion structure were low, likely due to high light attenuation caused by high suspended sediment concentrations, but chlorophyll often increased in mid estuary after suspended sediment concentrations decreased below 80 mg L^{-1}. During periods of low discharge, this mid estuary production was sustained, and was most likely supported by the regeneration of nutrients supplied in the year during high discharge. These results indicated moderate eutrophication at some sites, but added nutrients may also have beneficial effects, especially stimulating marsh productivity.

There are also active sinks for added nutrients, especially denitrification. The availability of dissolved inorganic nitrate in the water column has a major impact on observed denitrification fluxes, and especially in summer competition between plankton and sediment for potentially limiting nitrogen supplies, must be taken into account for estimations of nitrogen removal from the system.

The importance for river-derived nitrogen for the aquatic food web can be relatively high, especially close to the diversion. The overall geographic pattern of $\delta^{15}N$ values reflects the general hydrology of the Breton sound watershed, with some distinction between open water and marsh-influenced stations.

Landscape modeling and socio-economic analyses showed positive effects of the diversion, with little indications of negative impacts. This is consistent with previous analyses that emphasize the value of natural systems for a sustainable biosphere (Templet 1999, 2000). The stakeholder analysis revealed significant perception gaps among diverse stakeholders on the diversion, partially due to heuristics-based judgments, resulting in the increasing need of systematic information processing.

The results of the study suggest that there are benefits as well as potential detrimental impacts of diversions. The diversion results in nutrient uptake, some marsh accretion, lower salinities and incorporation of riverine materials into local food webs. There is concern, however, over the potential of high nutrient levels leading to eutrophication, and that long-duration pulses of one month or more can depress fisheries yields of shrimp and oysters. These costs and benefits need to be carefully considered in the management of diversions.

Acknowledgments

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