MISSISSIPPI RIVER AND TRIBUTARIES SYSTEM

2011 POST-FLOOD REPORT

APPENDIX F
ENVIRONMENTAL AND CULTURAL RESOURCES

SECTION IV

Water-Quality and Phytoplankton Communities in Lake Pontchartrain before, during, and after the Bonnet Carré Spillway openings in 2008 and 2011, Louisiana. by Scott V. Mize, Dennis, K. Demcheck, and Brett W. Rivers

ABSTRACT

The periodic release of Mississippi River water into Lake Pontchartrain during exceptionally high flood years has the potential to affect the chemistry and ecology of the lake. The U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers monitored the chemical and ecological response of the 2008 and 2011 Mississippi river freshwater diversions into the normally brackish oligotrophic lake. Constituents monitored included major ions, nutrients, chlorophyll, phytoplankton, selected algal toxins, and triazine herbicides. Both events were similar in that the initial water-quality response was characterized by shifts in inorganic constituents such as chloride and inorganic nitrate. Emphasis shifted to biological effects as the lake system responded to the influx of freshwater and nutrients. The phytoplankton community in 2008 showed an extended response of bloom species within the lake to the influx of river water that was evident even after the water-chemistry indicated that the lake had returned to pre-diversion conditions. In contrast, in 2011 the community response of bloom species occurred much farther eastward in Mississippi Sound and in the lake outlet following Tropical Storm Lee.

The Bonnet Carré spillway delivered a maximum of about 169,000 cubic feet per second (cfs) from April 11-May 8, 2008 and a maximum of 314,000 cfs from May 9- June 20, 2010, nearly 3 times more volume than the amount discharged in 2008. Total suspended sediment concentration and the percentage of fines (silt and clay) in release water was higher in 2008 than in 2011. Estimated nutrient and sediment loads were determined from measured discharge and water-quality sample results collected from the spillway from 2008 and 2011. Nutrient and sediment load estimates for 2011, where 2 – 4 times larger than for 2008.

Spatial and temporal water-quality differences in spillway and lake samples from 2008 and 2011 were examined using Principal Components Analysis (PCA). Bonnet Carré Spillway inputs from the river into the lake differed temporally and were related to annual differences in the river water quality. Time-series trajectories were overlain on the PCA biplots to examine changes in lake water-quality characteristics between the 2008 and 2010 sampling periods (1-4). Lake samples at all locations (north, south, and outlets) in 2008 and 2011 were most similar during periods 1, time prior to arrival of river water at the Causeway and period 4, after river water had departed the lake. Water quality changes related to the river inputs were most evident in period 2, once river had reached the Causeway, and period 3, after river water departed the Causeway but before the diverted water had departed from the lake. The larger differences among 2008 and 2011 lake samples occurred during period 3. Period 3 samples in 2008 were high in calcium, chloride, magnesium, and sulfate, and chlorophyll a, and organic nitrogen and carbon. In 2011, samples in period 3 were more similar to river water and were high in nitrate, ammonia, atrazine, silica, phosphorous, and orthophosphate. Time-series trajectories in period 4 indicated a gradual return to lake conditions prior to river water influence.

Phytoplankton communities were used as indicators of water quality. Changes in phytoplankton composition corresponded to changing water-quality conditions in periods 1 through 4 in 2008 and 2011. Phytoplankton community similarities were illustrated with non-metric multi-dimensional scaling two-dimensional ordinations. Both cell densities and biovolume measures of phytoplankton communities indicate community differences among sampling periods. The initial lake phytoplankton community response in 2008 to nutrient increases was related to accumulations of diatoms and green algae. During periods of low nutrient concentrations, bloom accumulations (> 90% biomass) of blue-greens occurred by July and August. Water-quality data indicated a gradual reversion to pre-diversion lake conditions by June to July, but shifts in the phytoplankton composition were still evident through September 2008. During 2011 phytoplankton communities in the lake were mostly composed of diatoms and cryptophytes. By July and August 2011, river water still influenced lake water quality and phytoplankton communities showed little variation in composition at mid-lake locations, yet Mississippi Sound phytoplankton samples were dominated (about 80% biomass) with bloom levels of blue-greens. By September 2011, post Tropical Storm Lee, the phytoplankton composition of the outlet and the Mississippi sound locations were composed mainly of saltwater species of dinoflagellates, green algae, and crytophytes. Although the lake exhibited a visual response to the freshwater influx, with dissolved oxygen exceeding 120% saturation, an obvious or prolonged algal bloom was not observed. A possible reason is that the massive and sustained diversion flow produced bloom conditions, but in Mississippi Sound rather than in Lake Pontchartrain in 2011.

INTRODUCTION

The Bonnet Carré Spillway (Fig. 1), located 28 miles northwest of New Orleans, was constructed in the early 1930's as part of an integrated flood-control system for the lower Mississippi River system. The spillway control structure consists of 350 individual bays or openings that can be opened to divert water from the Mississippi River to Lake Pontchartrain to relieve pressure on levees downstream. Heavy rains in the Mississippi and Ohio River valleys in early spring 2008 and in 2011 resulted in increased pressure on levees along the lower Mississippi River in Louisiana, threatening the City of New Orleans. In response, the U.S. Army Corps of Engineers opened the Spillway in April 2008 for the first time in 11 years (U.S. Army Corps of Engineers, 2009) and again three years later in May 2011. In 2008, up to 160 of the 350 bays were opened and in 2011 up to 330 of the 350 bays were opened and Mississippi River water flood waters were diverted into the 629-square mile Lake Pontchartrain. Lake Pontchartrain which is hydraulically connected to the Gulf of Mexico is more accurately characterized as an estuarine embayment. Peak flows through the spillway were about 169,000 cubic feet per second on April 22, 2008 and 316,000 cubic feet per second from May 15- 20, 2011.

Carefully managed freshwater diversions can provide positive water-quality effects in addition to flood control, but also for lake resources such as fisheries, sea grass production, and wetland restoration. An understanding of nitrogen, particularly nitrate, concentrations in the Lower Mississippi River and Lake Pontchartrain basins during hydrologic events such as high water is critical to understanding the flux of nutrients into Lake Pontchartrain and ultimately into the Gulf of Mexico. Nutrients from the Mississippi River basin could pose an environmental threat to the Gulf of Mexico, which is experiencing hypoxic areas and degradation of aquatic resources (Rabalais et al., 1996). After further analyses of the Pontchartain Estuary, ortch and Hird (2010) showed a need for further study of chlorophyll and algal data in Lake Pontchartrain and surrounding Mississippi Sound during spillway openings. In 2008 and again in 2011, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers (USACE), began a study to assess the influence of river water from the

Mississippi River on water quality and phytoplankton (algae) communities in Lake Pontchartrain during and after the opening of the Bonnet Carré spillway.

Figure 1. Sample locations at the Bonnet Carré Spillway and within Lake Pontchartrain before, during, and after 2008 and 2011 spillway openings.

Purpose and Scope. This report characterizes surface-water quality and phytoplankton communities as indicators of surface-water quality for selected sites in Lake Pontchartrain before and after the Bonnet Carré Spillway opening in 2008 and 2011. A comparison of surface water quality conditions and algal communities is used to help refine the understanding of lake conditions both before and after flood events in which river water inputs have entered the lake. This report (1) compares 2008 and 2011 surface-water discharge, suspended sediment, and nutrient concentrations and loadings into the Lake Pontchartrain through the Bonnet Carré spillway; and (2) characterizes 2008 and 2011 surface-water quality and phytoplankton community conditions spatially and temporally in the lake.

Description of Study Area. The Lake Pontchartrain basin is a 629-square mile lake located in south-eastern Louisiana just north of New Orleans and is hydraulically connected to the Gulf of Mexico through two major passes (Rigolets and Chef Menteur Pass). The lake is more accurately characterized as an estuarine embayment in which a gradient of freshwater in the eastern portion of the lake changes to brackish water in the western portion of the lake near the lake outlets. Most natural freshwater inputs into Lake Pontchartrain include drainage from Lake Maurepas in the west and from north shore drainages such as the Tangipahoa and Tchefuncte rivers as well as a few other bayous on the northeastern shore. During Bonnet Carré Spillway openings, Mississippi River water is diverted into Lake Pontchartrain via a 5-mile spillway located on the southwestern end of the lake.

Acknowledgments. The authors would like to thank the Greater New Orleans Expressway Commission for allowing access to crossovers on the Causeway Bridge. The authors would also thank Rodney Mach, and Eric Glisch, U.S. Army Corp of Engineers, New Orleans District, and Dr. Barb Kleiss, U.S. Army Corps of Engineers, Mississippi Valley Division for project development, and assistance and financial support with the study and report. Appreciation is extended to the following (USGS) employee Alexis Smith for assistance with sampling.

METHODS OF DATA COLLECTION AND ANALYSIS

Continuous and discrete sampling methods were used in 2008 and 2011. Continuous sampling using water quality monitor and a nitrate monitor located on the causeway in the southern part of the lake. A water-quality monitor and a nitrate monitor were suspended from the Lake Pontchartrain Causeway bridge about 10 feet below the water surface at crossover 7 – Mile 9 turnaround (about 15 miles east of the diversion and 3.5 miles from the south shore of the lake from April to July, 2008 and again from May to October, 2011 (Fig. 1). The lake depth at the site is about 16 feet. The monitors were equipped with internal loggers and recorded hourly measurements of nitrite + nitrate (presented as nitrate), water temperature, dissolved oxygen, specific conductance, salinity, and pH. Water-quality-monitor data were reviewed and, if where needed, corrected for instrument drift and biofouling following methods described in Wagner et al. (2006) prior to data analysis. Discrete surface-water samples were collected in the Bonnet Carrré Spillway and three other areas of the lake (north, south, and lake outlet) before, during, and after both 2008 and 2011 openings.

Sample Locations. Discrete water-quality samples were collected and analyzed for major inorganic ions, nutrients, chlorophyll *a*, atrazine, and phytoplankton. Samples were collected from one site within the Bonnet Carré Spillway about 2 miles downstream from the control structure, from three sites on the Lake Pontchartrain Causeway bridge, and from two sites, Rigolets at Hwy 90 near Slidell, LA (Rigolets), and Chef Menteur Pass at Chef Menteur, LA (Chef Menteur Pass) in 2008, and one site Highway 11 near Slidell, LA (Hwy 11) in 2011 on lake outflows into the Gulf of Mexico (Fig. 1). Samples at Lake Pontchartrain outflows were collected (to the extent possible) during outgoing tides to minimize the collection of estuarine waters from Lake Borgne and the Gulf of Mexico. Samples were collected weekly while the spillway was open and bimonthly after the spillway closure until October of each year, 2008 and 2011(Table 1).

Table 1. Surface-Water Quality Phytoplankton Data-Collection Sites in the Lake Pontchartrain Basin in Southeastern Louisiana, 2008 and 2011

			Sampling Period	
U.S. Geological Survey Station Number	**U.S. Geological Survey Station Name**	**Descriptive Location in Lake**	**April 2008 too Oct. 2008**	**May 2011 to Oct. 2011**
300115090245000	Bonnet Carre Spillway at U S Hwy 61 near Norco, LA	lake input	x	x
300412090084300	Lake Pontchartrain at Causeway Bridge nr Metairie, LA	midlake (south)	x	x
300904090075200	Lake Pontchartrain at Causeway mile 9, near Metairie, LA	midlake (south)	x	x
301528090064600	Lake Pontchartrain at Causeway near Mandeville, LA	midlake (north)	x	x
301001089442600	Rigolets at Hwy 90 near Slidell, LA	lake pass (outlet)	x	
300403089481300	Chef Menteur Pass at Chef Menteur, LA	lake pass (outlet)	x	
301050089511600	Lake Pontchartrain at Hwy 11 Causeway nr Slidell, LA	lake pass (outlet)		x
300722089150100	Mississippi Sound near Grand Pass, LA	Mississippi Sound[1]		x[2]

[1] This sample is not located in Lake Pontchartrain but is located within the lake discharge into Mississippi Sound
[2] This site was only sampled twice for phytoplankton in the summer.

Data Analysis. Procedures used to collect and process water samples followed standard USGS guidelines (U.S. Geological Survey, 2001). Water samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colo. using methods described by Fishman et al. (1989), Patton et al. (2000), Britton et al. (1987), Wershaw et al. (1987), and Sandstrom et al. (1992). Chlorophyll samples were collected using two different techniques. In 2008, chlorophyll samples were collected from the whole water column (equal depth integrated) and in 2011 sample were sampled just within the photic zone (approximately to top 1 meter of water). Chlorophyll samples were not adjusted for differences before data analysis, but 2008 sample are suspected to be underestimating the actual values. Phytoplankton samples were collected using National Water Quality Assessment Program protocols (Porter et al. 1993; Moulton et al. 2002). Phytoplankton samples were preserved with a 1 percent Lugol's solution and sent to the Academy of Natural Sciences in Philadelphia, Pa. for taxonomic analysis. Phytoplankton were identified and enumerated to practical taxonomic levels (normally species or genus level), following processing and analysis protocols according to Charles et al. (2002).

Determinations of total discharge and loadings were based on measured discharge and chemical analysis results, yet in cases where daily discharge and or chemical analysis results were not available estimates were used in order to calculate loads. In 2008, daily discharge estimates were interpolated between measured discharge values. USACE calculated discharge values were used for 2011 missing daily discharge values. Chemical concentration results were not collected daily; therefore, chemical concentrations were interpolated between measured concentration values. Because discharge measurements within the Bonnet Carré Spillway can only be collected during diversion openings, too few discharge and concentration datasets exists to use load estimation methods based on long-term comprehensive or annual data. So, two methods commonly used for short-term events, such as storm events, were used to estimate solute loads at the Bonnet Carré Spillway at US highway 61, the average method and the period-weighted approach (Aulenbach, 2006). Each method uses daily discharge and concentration values to determine an instantaneous load for the day. Using the average method all daily discharge and sample concentrations collected during the spillway openings in 2008 and 2011 were averaged respectively and multiplied to determine the loads for each opening by year. The period-weighted approach involved determining a daily discharge and daily sample concentration for each day of the opening for each year and calculating the instantaneous load for each day. The summation of all of the instantaneous loads for each opening was the final load estimate for each year.

Four critical sampling periods were selected for 2008 and 2011 water quality and phytoplankton samples based on continuous monitoring data, satellite imagery, and field observations to help describe physical, chemical, and biological changes in relation to the arrival and departure of river water into Lake Pontchartrain. These sampling periods were used to examine differences among sampling periods and years.

Water quality and biological data sets were analyzed using a Plymouth Routines In Multivariate Ecological Research (PRIMER, version 6.0; Clark and Gorley, 2006). Water quality data were log transformed and normalized prior to entry in the principal components analysis (PCA). Trajectory plots were generated based on chronological order of sample collection by year and were overlain onto PCA biplots illustrating the chemical time- series patterns. Phytoplankton density data was fourth -root transformed to down weigh high abundance species prior to the generation of Bray-Curtis similarity resemblance matrices. Phytoplankton resemblance matrices were then represented as non-metric multidimensional (NMDS) ordination plots. Samples within a NMDS that plot that are closer to one another have more similar composition; whereas, samples that plot further away from one another are less similar. The effectiveness of the NMDS plots in accurately representing the temporal relation at a given site was assessed with a two-dimensional stress value.

COMPARISON WATER QUALITY CHARACTERISTICS 2008 AND 2011

The amount and duration of spillway inputs varied between 2008 than 2011. Yearly spillway inputs from the river into the lake differed temporally and were related to annual differences in the river water quality and the quantity of diverted water. Generally, water quality samples from the lake showed little variation spatially, but larger differences were detected among temporal samples associated with the lake conditions prior to, during, and after the spillway openings. Comparisons between years and among time periods relieved some surface-water quality characteristics differed between the 2008 and 2010 samples from the Bonnet Carré Spillway and in lake samples.

Bonnet Carré Spillway Inputs into Lake Pontchartrain. Discharge of Mississippi river water diverted through the Bonnet Carrré Spillway in 2008 and 2011 varied greatly in magnitude and duration (Fig. 2). Total volume of river water discharged in Lake Pontchartrain through the spillway in 2008 was about 281 billion cubic feet or about 145% of the estimated lake volume (J. Lovelace, USGS, written communication 2008). The total volume discharged into the lake in 2011 was about 780 billion cubic feet over 400% of the estimated lake volume and nearly 3 times more volume than the amount discharged in 2008. Peak discharge in 2008 (169,000 ft^3/s) was almost half that of 2011 (314,000 ft^3/s). Also, the timing of the river diversion was different in 2008 compared to 2011. In 2008, the river diversion open in April 2008 and lasted approximately 4 weeks (28 days), whereas the diversion in 2011 did not open until May 2011 and lasted approximately 6 weeks (44 days).

Discharge and Suspended Sediment. Discharge and corresponding suspended sediment concentrations varied among 2008 and 2011 releases (Fig. 3). Total suspended sediment concentration and the percentage of fines (silt and clay) in release water was higher in 2008 than in 2011. The differences in rates of discharge flowing in the spillway in 2008 which was much lower than 2011 may account for the differences in 2008 and 2011 suspended sediment samples. Samples in 2011 contained lower percentages of fines which are more indicative of higher flow conditions that existed in 2011 and would be able to suspend more sand-sized particles.

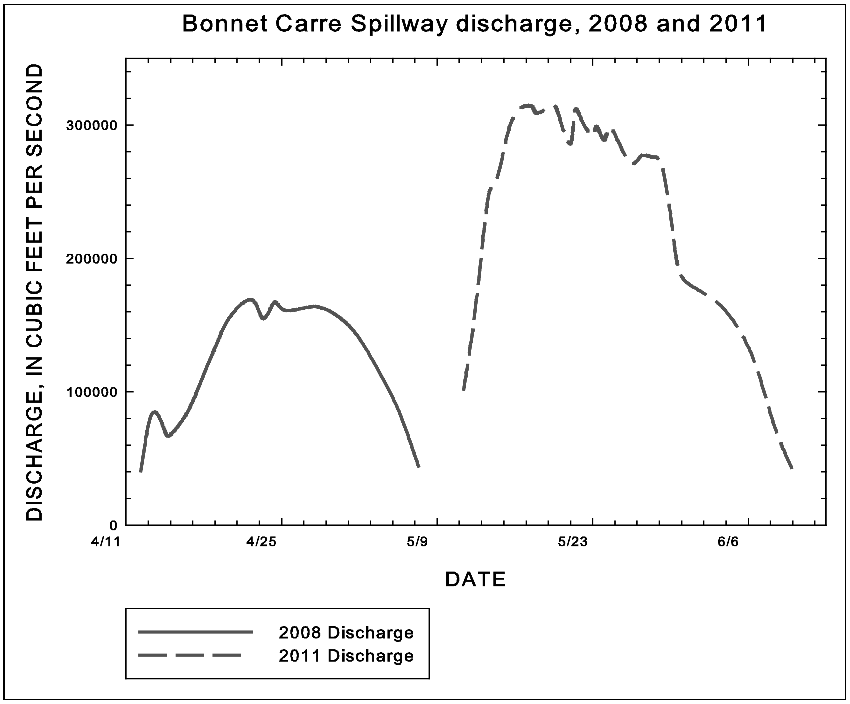


Figure 2

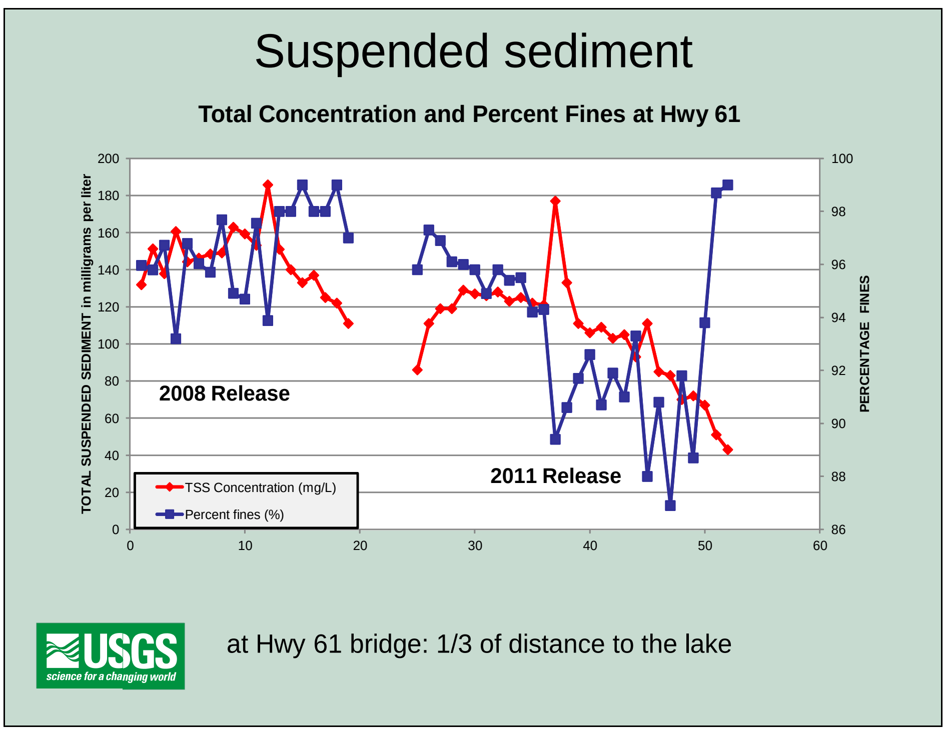


Figure 3. Total Suspended Sediment and Percent Fines in 2008 and 2011 from Highway 61 Bridge within the Bonnet Carré Spillway

Nutrient Concentrations and Loadings. Estimated nutrient and sediment loads were determined using the average method and period-weighted approach (Aulenbach, 2006) from measured discharge and water-quality sample results collected at the Bonnet Carré Spillway from 2008 and 2011. Total load estimates were determined for dissolved nitrite plus nitrate, total nitrogen, dissolved orthophosphate, total phosphorus, dissolved silica, and total suspended sediment (Table 2A). As expected, load estimates for 2011, where 2 – 4 times larger than for 2008. With the exception of dissolved orthophosphate and total suspended sediment, both the average and the period-weighted estimates produced loads with relative percent differences (RPD) of less than 10% among estimates (Table 2B). Higher RPDs up to 25 % were associated with dissolved orthophosphate and total suspended sediment. When comparing dissolved nitrite and nitrate and total nitrogen results in 2011 from this study using the average and period-weighted approach estimates to the 2011 LOADEST estimations reported from Hypoxia in the Gulf of Mexico website estimates varied especially with total nitrogen loads which had RPDs over 130% (Table 2B).

The large RPDs between load estimates in this study and LOADEST estimates may be related to computational differences in the load estimation calculations and/or that the loads were based on different measurements of the Mississippi River flow. Load estimates in this study were based on actual discharge and chemical results measured within the Bonnet Carré Spillway and not based on a percentage of flow diverted through the spillway. RPD of load estimates of the dissolved nitrite plus nitrate were only 50% or less, yet the total nitrogen estimates were much more variable (with RPDs up to133%) and may have been associated with the physical mechanics of spillway itself. Diverted Mississippi river water flowing into the pre-bay prior to entry into the spillway is capturing river water only from the upper portion of the water column which probably carries a lower suspended load than the middle and lower sections of the water column. Also, diverted river water once in the pre-bay has decreased in velocity and lost a portion of its suspended load prior to entering the spillway structure. This may account for the larger differences in load estimates in the total nitrogen fraction than the dissolved nitrogen fraction.

Table 2A. Estimated nutrient and sediment loads in metric tons determined from measured discharge and water-quality sample results collected at Bonnet Carre Spillway at U.S. Highway 61 near Norco, LA 2008 and 2011 [d, days]

			Estimated Loads in Metric Tons					
Estimation Method	**Year Sampled**	**Cumulative Sampling Period**	**Dissolved Nitrite Plus Nitrate**	**Total Nitrogen**	**Dissolved Orthophosphate**	**Total Phosphorus**	**Dissolved Silica**	**Total Suspended Sediment**
Period-weighted approach[1]	2008	April (20d)	6,967	10,354	305	1,099	36,964	900,169
		May (8d)	2,501	3,457	103	309	11,533	220,683
		Total	9,468	13,810	408	1,408	48,497	1,120,852
	2011	May (23d)	16,944	24,413	805	2,338	98,924	1,716,352
		June (21d)	8,960	12,247	926	1,180	46,631	590,942
		Total	25,904	36,659	1,731	3,518	145,555	2,307,294
Average method[2]	2008	Total	9,707	14,005	431	1,283	48,815	1,098,072
	2011	Total	25,615	36,182	1,407	3,342	142,594	1,792,552
Reported LOADEST estimates[3]	2011	Total	15,500	180,000	--	--	--	--

Table 2B. Relative Percent Difference Among Total Load Estimates Determined For The Bonnet Carre Spillway, LA in 2008 and 2011

			Relative Percent Difference of Total Loads					
Estimation Method	**Year Sampled**	**Cumulative Sampling Period**	**Dissolved Nitrite Plus Nitrate**	**Total Nitrogen**	**Dissolved Orthophosphate**	**Total Phosphorus**	**Dissolved Silica**	**Total Suspended Sediment**
Period-weighted approach[1]	2008	Total	2.49	1.40	5.54	9.3	0.65	2.05
Average method[2]	2011	Total	1.12	1.31	20.6	5.13	2.05	25.1
Period-weighted approach[1]	2011	Total	50.3	132	--	--	--	--
Reported LOADEST estimates[3]								
Average method[2]	2011	Total	49.2	133	--	--	--	--
Reported LOADEST estimates[3]								

[1] Period-weighted approach as described by Aulenbach (2006); summation of instantaneous loads (daily discharge*daily parameter concentration*conversion factor) for cumulative sampling period
[2] Average method as described by Aulenbach (2006); average load (average discharge*average parameter concentration*conversion factor) for cumulative sampling period
[3] LOADEST estimations from Preliminary Spring 2011 discussions reported from Hypoxia in the Gulf of Mexico website<http://toxics.usgs.gov/hypoxia/mississippi/oct_jun/graphics.html >

Spatial and Temporal Spillway and Lake Conditions in 2008 and 2011. Spatial and temporal water-quality differences in spillway and lake samples from 2008 and 2011 were examined using Principal Components Analysis (PCA). Bonnet Carré Spillway inputs from the river into the lake differed temporally and were related to annual differences in the river water quality. Time-series trajectories were overlain on the PCA biplots to examine changes in lake water-quality characteristics between the 2008 and 2010 sampling periods (1-4).

Water Quality Characteristics. Generally, 2008 spillway samples had slightly higher concentrations of nitrate and ammonia than concentrations in 2011yet, chlorophyll a and atrazine was slightly higher in 2011 release water. Figure 4 shows results of PCA of water quality differences in monthly spillway samples. April 2008 and June 2011 samples varied from May samples in 2008 and 2011. April samples from 2008 were high in ammonia and were associated with an ammonia peak in the Mississippi river in 2008. The 2008 ammonia peak in the Mississippi river ranged from 0 .77mg/L at St. Francisville to 0.137mg/L at Baton Rouge in March 2008 and were above the average peak level concentration of about 0.040 mg/L for recent (2009-2011) spring Mississippi samples. April 2008 spillway samples concentrations only reached the average Mississippi river peak levels of around 0.035mg/L and were nearly twice the concentrations of all other 2008 and 2011 spillway samples. May samples from 2008 and 2011 were most similar between years and slightly varied in nutrient concentrations and were either high in dissolved organic nitrogen or in phosphorous and silica. June 2011 spillway samples contained higher concentrations of sulfate, calcium, magnesium, and orthophosphate than April 2008 samples or May 2008 and 2011 samples.

Overall lake conditions differed in 2008 and 2011. Generally, water quality in period 1, 2 and 4 were similar in 2008 and 2011, yet the largest differences occurred in sampling period 3 samples.

Period 3 samples in 2008 were high in calcium, chloride, magnesium, and sulfate, and chlorophyll a, and organic nitrogen and carbon. In 2011, samples in period 3 were more similar to river water and were high in nitrate, ammonia, atrazine, silica, phosphorous, and orthophosphate. Silica concentrations in 2008 lake samples were significantly reduced in early June compared to silica concentrations at mid-lake locations in 2011 which remained high. Chlorophyll a concentrations in 2008 were much higher and tended to have a large broad peak whereas chlorophyll a concentrations in 2011 had a distinct bimodal distribution at mid-lake locations. Atrazine concentrations in lake samples also were different in 2008 being much lower than in 2011 samples at mid-lake and at the lake outlet.

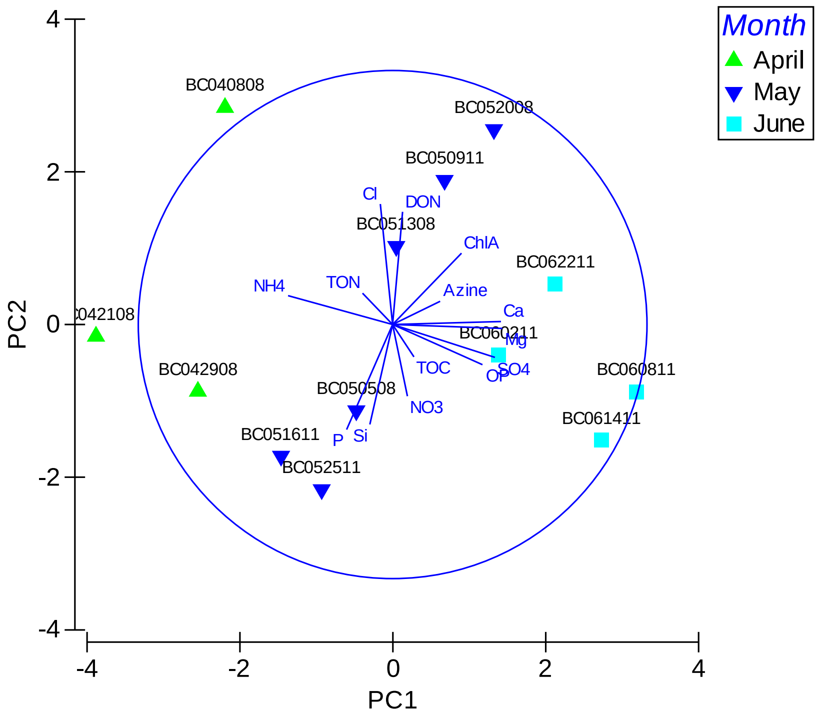


Figure 4. Principal Components Analysis ordination biplots showing monthly differences in Bonnet Carre Spillway samples from 2008 and 2011. Sample coordinates in relation to chemical species indicate monthly differences in chemical concentrations; vectors indicate direction of higher concentration.

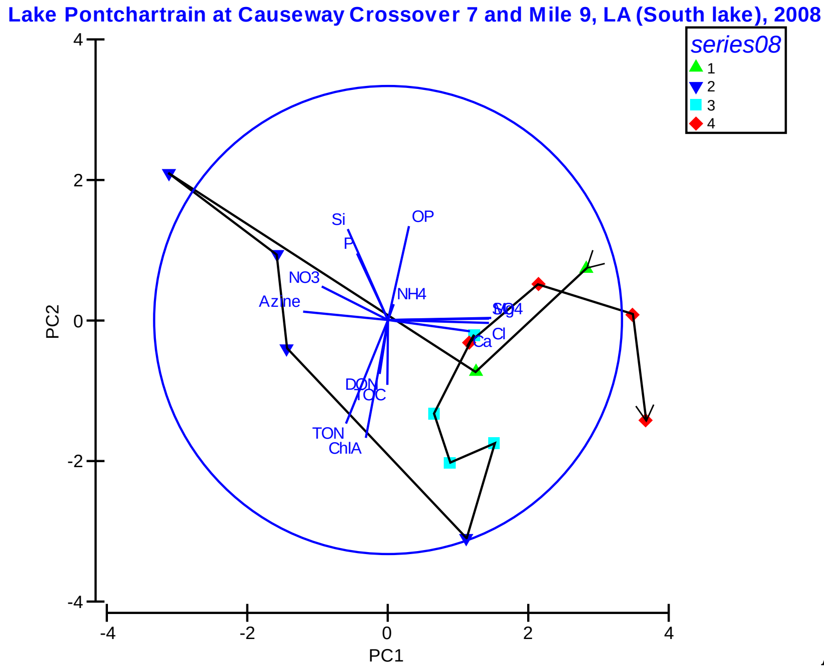
Figure 5 (south lake sites), 6 (north lake site), and 7 (lake outlet sites) show water chemistry results of lake samples from 2008 and 2011 on PCA biplots with time-series trajectories correlating to the sampling periods. The time-series arrows indicate the chronological sampling order and the show the temporal changes in water chemistry samples and the pathway in relation to the PCA vectors (chemical species). The evolution of chemical conditions is shown by following the arrow through the model. Each sample plots on the PCA biplot based on the chemical composition of the sample at the point in time the sample was collected. Sampling periods represent time periods of lake sampling related to the arrival and departure of river water into the lake and help to distinguish between pre and post diversion lake conditions.

Lake samples at all locations (north, south, and outlets) in 2008 and 2011 were most similar during periods 1, time prior to arrival of river water at the Causeway and period 4, after river water had departed the lake. Water quality changes related to the river inputs were most evident in period 2, once river had reached the Causeway, and period 3, after river water departed the Causeway but before the diverted water had departed from the lake. The larger differences among 2008 and 2011 lake samples occurred during period 3. Time-series trajectories in period 4 indicated a gradual return to lake conditions prior to river water influence.

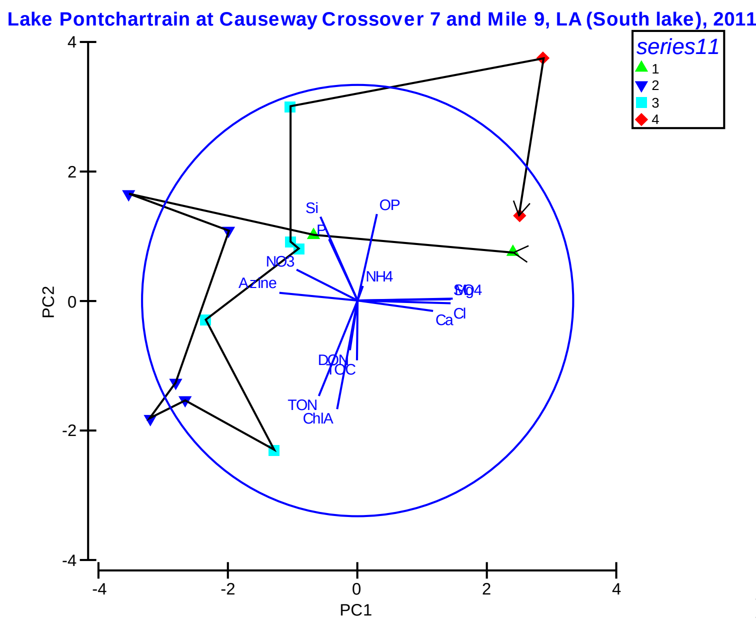
In both 2008 and 2011, at Causeway Crossover 7 and Mile 9 (south lake) was the first lake location to receive diverted river water after the spillway had opened. Dramatic decreases in water temperature and specific conductance were evident in 2008 and 2011 and showed a rapid decrease as river water begin to dominate the water quality conditions along the south lake shoreline. Figure 5 shows the initial lake response and corresponding changes in water chemistry in period 2 were similar in 2008 and 2011, yet during sampling period 3, 2008 and 2011 sample chemistries differed and 2008 samples were higher in calcium, chloride, magnesium, and sulfate, chlorophyll a, organic nitrogen and carbon whereas 2011 samples were higher in nitrate, ammonia, atrazine, silica, and orthophosphate.

Similar to the south lake, the north lake site at Causeway crossover 2 (Figure 6) showed similar patterns in water quality concentrations in periods 1,2 and 4 but period 3 differed. Nutrients including phosphorous, orthophosphate, nitrate, ammonia, and silica and atrazine concentrations were much higher in period 3 in 2011 than 2008. The presence of the high amount s of nutrients and atrazine indicate that river water dominated the north lake site in 2011 even during period 3 when river water influence in 2008 was minimal. The dominates of river water at the north lake site in 2011 may be due larger amount of river water discharged in 2011 and the river replaced much of the lake water until period 4 when tropical storm Lee helped flush the lake of river water. North lake 2008 samples in period 3 were dominated by higher concentrations of calcium, chloride, magnesium, and sulfate, chlorophyll a, and organic nitrogen and carbon.

Figure 7, shows the lake outlet time-series trajectories of water quality for one lake outlet site Rigolets at Highway 90 near Slidell in 2008 and the 2011 lake outlet site at Highway 11 Causeway near Slidell. Nearly identical to patterns observed at the mid-lake (north and south) sites, water quality in period 1 and 4 showed that pre- and post- diversion conditions were similar although sample chemical compositions varied among outlet sites in 2008 and 2011. Outlet site chemical conditions in period 1 and 4 in 2008 were different from 2011 partially because the location of the sites had changed between 2008 and 2011. In 2008, the site was located in the lake pass where flow is constricted and velocities are faster as lake water exits into Lake Borgne and the site is heavily influenced by tidal fluctuations and higher salinity waters. While in 2011, the outlet site was relocated further inland to help decrease chemical variability associated with the tidal fluctuations and constricted flow. Sampling period 3, like at the mid-lake sites, outlet sites showed the greatest differences among 2008 and 2011 samples. Outlet samples in 2008, from period 3, had higher concentrations of calcium, chloride, magnesium, and sulfate, chlorophyll a, total organic carbon, and total organic nitrogen than 2011 outlet sample which were high in nitrate, ammonia, atrazine, silica, phosphorous, orthophosphate, and dissolved organic nitrogen.

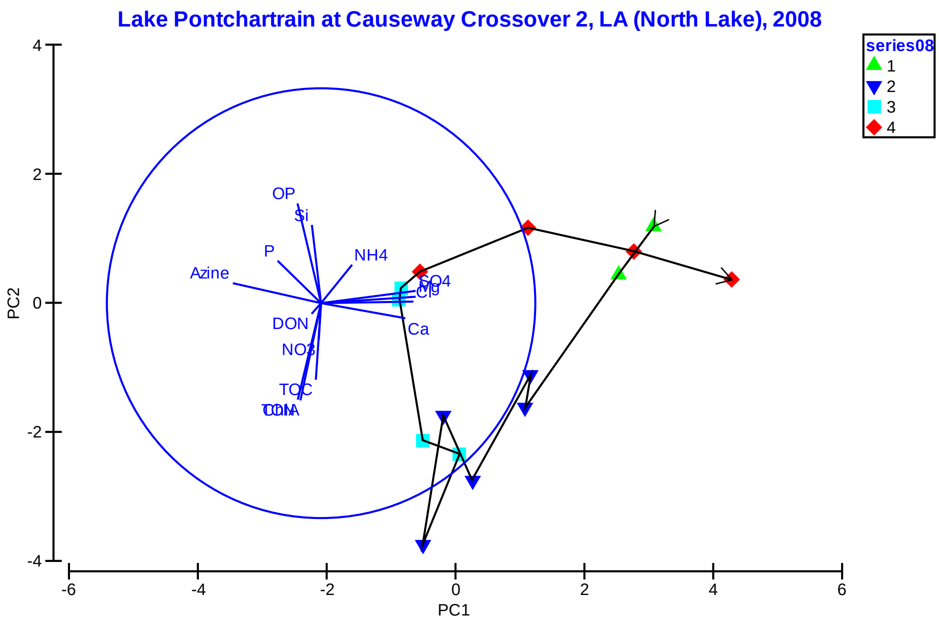


A

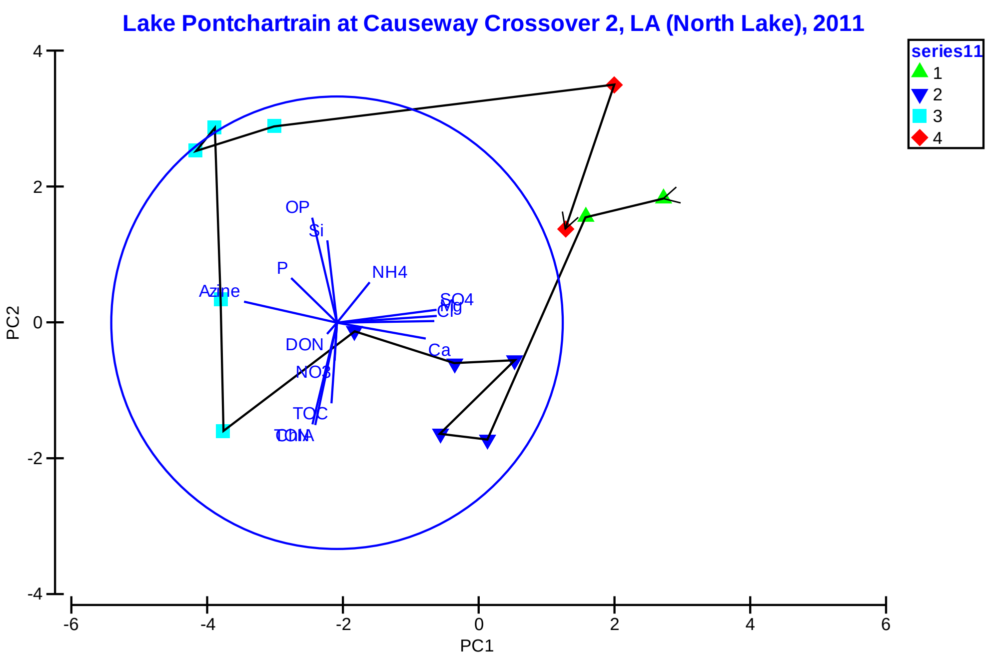


B

Figure 5. Principal Components Analysis ordination biplots showing time series trajectories from 2008 (A) and 2011 (B) sample coordinates in relation to chemical species from Causeway Crossover 7 and Mile 9, south lake, Lake Pontchartrain before, during, and after 2008 and 2011 Flood spillway openings. Numbers indicate sampling period (1, prior to arrival of river water at the Causeway; 2, once river water had reached the Causeway; 3, after river water departed the Causeway; 4, after river had departed the lake).



A



B

Figure 6. Principal Components Analysis ordination biplots showing time series trajectories from 2008 (A) and 2011 (B) sample coordinates in relation to chemical species from Causeway Crossover 2, north lake, Lake Pontchartrain before, during, and after 2008 and 2011 Flood spillway openings. Numbers indicate sampling period (1, prior to arrival of river water at the Causeway; 2, once river water had reached the Causeway; 3, after river water departed the Causeway; 4, after river had departed the lake).

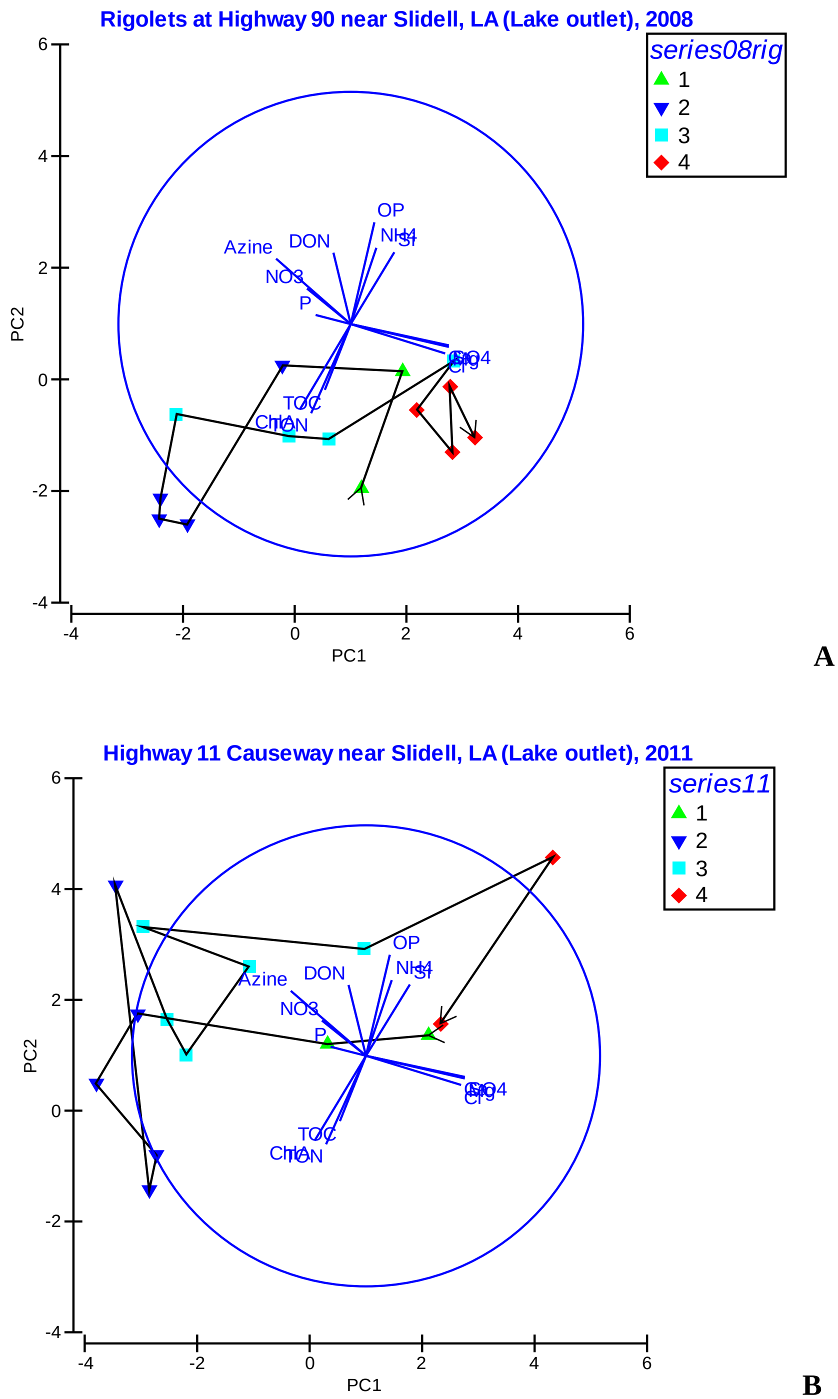
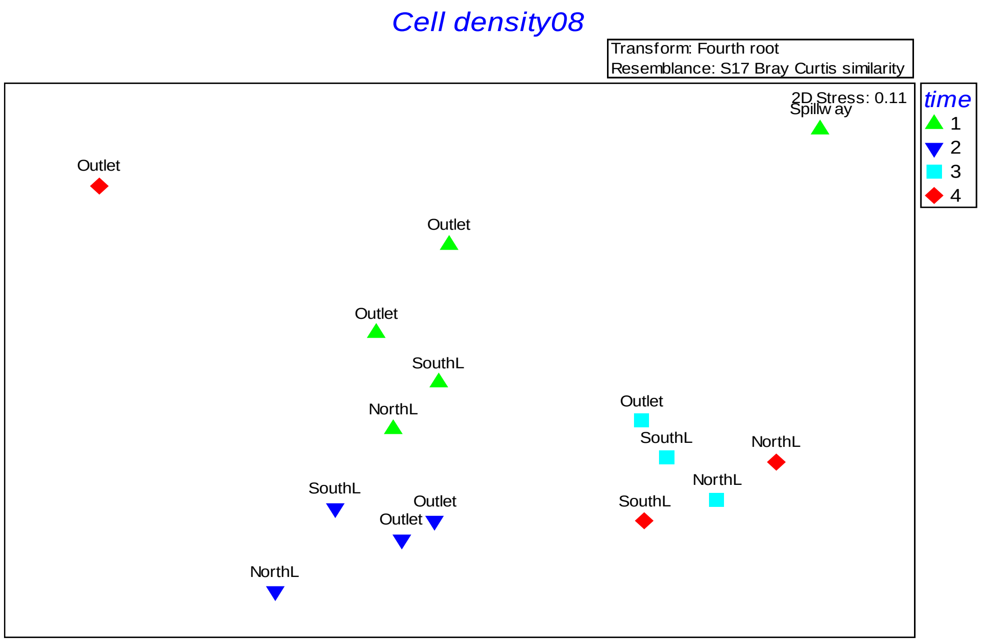


Figure 7. Principal Components Analysis ordination biplots showing time series trajectories from 2008 (A) and 2011 (B) sample coordinates in relation to chemical species from Rigolets and Highway 11 Causeway, lake outlet, Lake Pontchartrain before, during, and after 2008 and 2011 Flood spillway openings. Numbers indicate sampling period (1, prior to arrival of river water at the Causeway; 2, once river water had reached the Causeway; 3, after river water departed the Causeway; 4, after river had departed the lake).

Phytoplankton as Indicators of Water Quality. Phytoplankton communities were used as indicators of water quality. Changes in phytoplankton composition corresponded to changing water-quality conditions in periods 1 through 4 in 2008 and 2011. Phytoplankton community similarities were illustrated with non-metric multi-dimensional scaling (NMDS) two-dimensional ordinations. Both cell densities and biovolume measures of phytoplankton communities indicate community differences among sampling periods related to the arrival and departure of Mississippi river flood water into Lake Pontchartrain 2008 (Figure 9) and 2011 (**Figure 10 in process**).

The 2008 NMDS plot of phytoplankton community composition shows the spatially similarities among lake sites, yet compositions differed temporally corresponded with sampling periods in the lake (Figure 9). An NMDS ordination with a stress level of 0.11 indicates a good representation of community compositions among samples according to Clark & Warwick (2001). As expected, the composition of phytoplankton at the Spillway (river water) in 2008 during period 1 differed from all other period 1 lake samples. One outlier, the 2008 Chef Menteur Pass outlet site had a different community structure than other period 3 and 4 lake sites that grouped together in the NMDS. The grouping of the period 3 and 4 samples indicates that during these sampling periods the composition of phytoplankton were similar and were dominated by blue-green algae as shown in Figure 11.
The initial lake phytoplankton community response in 2008 to nutrient increases was related to accumulations of diatoms (Fig. 11). During periods of low nutrient concentrations, bloom accumulations (> 90% biomass) of blue-greens occurred by July and August. As blue-green algae cell densities and biovolumes increased in the summer so did the species richness of blue-green algae, particularly the harmful algae bloom taxa. Cell densities and biovolume of the phytoplankton lake indicator taxa *Skeletonema costatum*, Anabaena sp. and *Cylindrospermopsis raciborskii* were highest and dominated the diatom and blue-green algae communities during the period of most river water influence on the lake and immediately following the freshwater inflows. The dominance and recession of these indictor taxa reflect the dramatic changes that occurred in the phytoplankton community in response to an increase in nutrient-rich freshwater from the diversion into the lake and not normal seasonal phytoplankton compositional differences. Water-quality data indicated a gradual reversion to pre-diversion lake conditions by June to July, but shifts in the phytoplankton composition were still evident through September 2008.



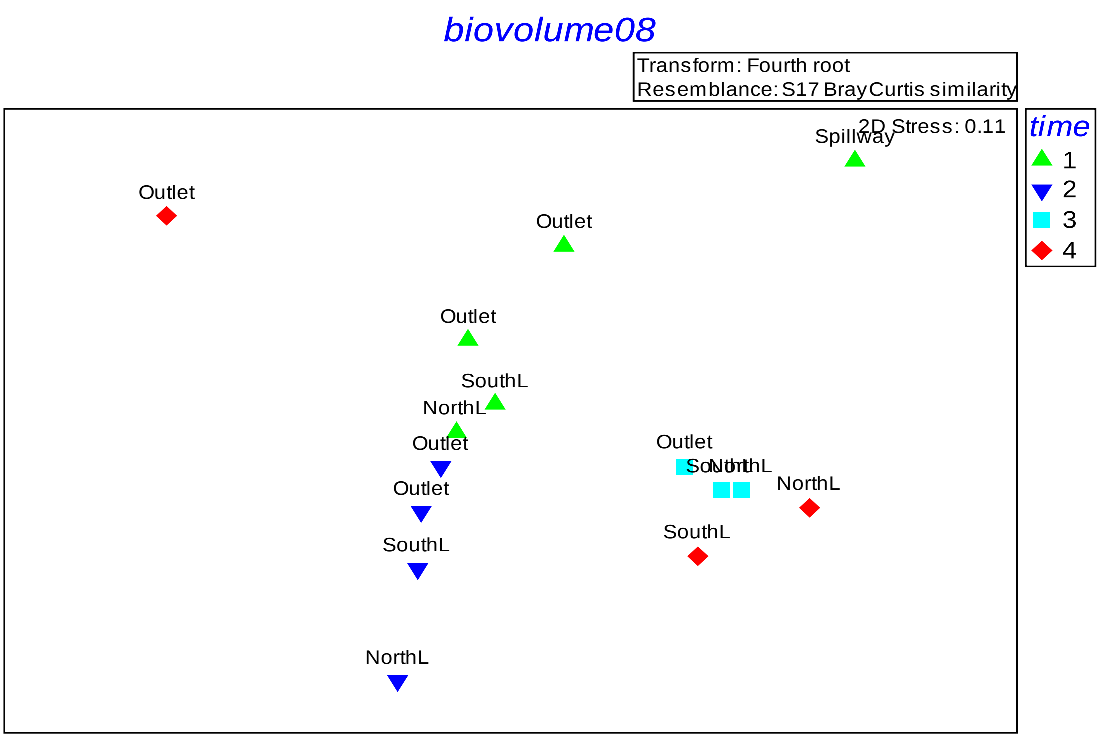


Figure 9 Phytoplankton community similarities illustrated with non-metric multi-dimensional scaling (MDS) two-dimensional ordinations. Both cell densities and biovolume measures of phytoplankton communities indicate community differences among time periods related to the arrival and departure of Mississippi River flood water into Lake Pontchartrain, 2008.

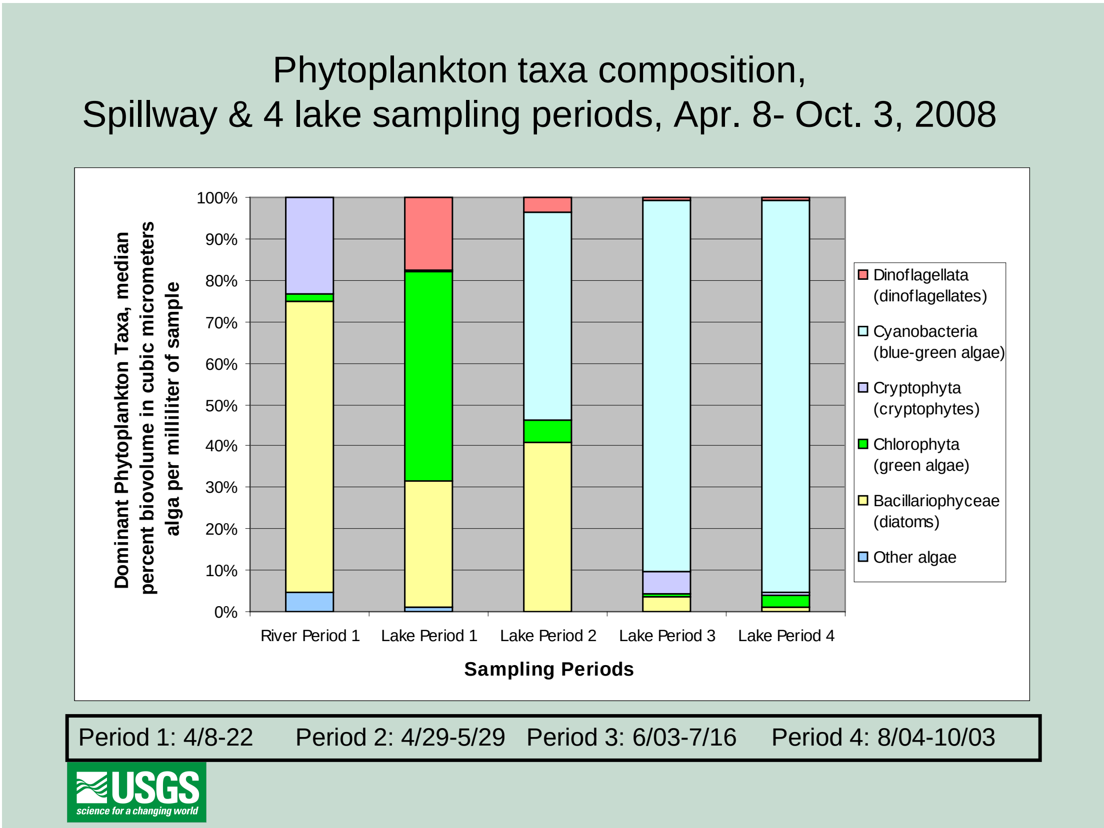


Figure 11. Composition of dominant phytoplankton taxa for the Bonnet Carre Spillway, and four sampling periods at five sites in Lake Pontchartrain, April to October 2008.

During 2011 phytoplankton communities in the lake were mostly composed of diatoms and cryptophytes. By July and August 2011, river water still influenced lake water quality and phytoplankton communities showed little variation in composition at mid-lake locations, yet Mississippi Sound phytoplankton samples were dominated (about 80% biomass) with bloom levels of blue-greens. By September 2011, post Tropical Storm Lee, the phytoplankton composition of the outlet and the Mississippi sound locations were composed mainly of saltwater species of dinoflagellates, green algae, and crytophytes. Although the lake exhibited a visual response to the freshwater influx, with dissolved oxygen exceeding 120% saturation, an obvious or prolonged algal bloom was not observed. A possible reason is that the massive and sustained diversion flow produced bloom conditions, but in Mississippi Sound rather than in Lake Pontchartrain in 2011.

A combination of factors influenced the water quality and phytoplankton communities in 2008 and 2011. The nature and characteristics of the spillway openings themselves were different in magnitude and duration in 2008 and 2011. In addition to the increase in freshwater from the spillway in 2011, the closure of the Inter Harbor Navigation Canal (IHNC) in New Orleans along the south shore of the lake prior to the 2011 spillway opening has helped to decrease the salinity in the lake especially in the vicinity of canal. All of these factors that have contributed to the reduction of salinity in the lake and push the freshwater-saltwater interface from within the lake in 2008 to outside of the lake into the Mississippi Sound in 2011.

REFERENCES

Aulenbach, BT, and Hooper, RP, 2006, The composite method: an improved method for stream-water solute load estimation, *Hydrol. Process.* 20, 3029-3047.

Britton LJ, and Greeson PE, 1987, Methods for collection and analysis of aquatic biological and microbiological samples. U.S. Geological Survey Techniques of Water-ResourcesInvestigations, p139-140

Charles DF, Knowles C,and Davis RS, 2002, Protocols for the analysis of algal samples collected as partof the U.S.Geological Survey National Water-Quality Assessment Program. Patrick Center for Environmental Research, Academy of Natural Sciences, Philadelphia, p 1-124

Clark, KR, and Gorley, RN, 2006, PRIMER v6: User Manual/Tutorial. Plymouth, England.

Clark, KR, and Warwick RM, 2001, Change in marine communities: an approach to statistical analysis and interpretation. 2nd ed. Plymouth, England.

Dortch, M, and Hird, J, 2010, Review and Analysis of Pontchartrain Estuary Water Quality as Impacted by Opening of the Bonnet Carre Spillway, report from Moffatt and Nichol.

Fishman MJ, and Friedman LC (1989) Methods for Determination of Inorganic Substances in Water and Fluvial Sediments: Techniques of Water-Resources Investigations of the U.S. Geological Survey. p 1-545

LOADEST estimations from Preliminary Spring 2011 discussions reported from Hypoxia in the Gulf of Mexico website, Available via DIALOG. *http://toxics.usgs.gov/hypoxia/mississippi/oct_jun/graphics.html*

Mize, SV, and Demcheck DK., 2009, Water quality and phytoplankton communities in Lake Pontchartrain during and after the Bonnet Carré Spillway opening, April to October 2008, in Louisiana, USA, *Geo-Marine Letters* 29:431-440

Moulton SR II, Kennen JG, Goldstein RM, and Hambrook JA (2002) Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment Program, U.S. Geological Survey Open-File Report 02-150, p 1-75

Patton CJ, and Truitt EP (2000) Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory-- Determination of ammonium plus organic nitrogen by a Kjeldahl digestion method and an automated photometric finish that includes digest cleanup by gas diffusion, U.S. Geological Survey Open-File Report 00-170, p 1-31

Porter SD, Cuffney TF, Gurtz ME, and Meador MR (1993) Methods for collecting algal samples as part of the National Water-Quality Assessment Program, U.S. Geological Survey Open-File Report 93-409, p 1-39

Sandstrom MW, Wydoski DS, Schroeder MP, Zamboni JL, and Foreman WT (1992) Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory--Determination of organonitrogen herbicides in water by solid-phase extraction and capillary-column gas chromatography/mass spectrometry with selected-ion monitoring, U.S. Geological Survey Open-File Report 91-519, p 1-26

U.S. Geological Survey (2001) National field manual for the collection of water-quality data, U.S.Geological Survey Techniques of Water-Resources investigations, book 9, chaps. A1-A9, Available via DIALOG. *http://pubs.water.usgs.gov/twri9A. Accessed 12 Dec 2008*

Wagner RJ, Boulger RW Jr, Oblinger CJ, and Smith BA (2006) Guidelines and standard procedures for continuous water-quality monitors—Station operation, recomputation, and data reporting: U.S. Geological Survey Techniques and Methods, p 1-51, Available via DIALOG. http://pubs.water.usgs.gov/tm1d3. Accessed 11 Apr 2008

Wershaw RL, Fishman MJ, Grabbe RR, and Lowe LE (eds) (1987) Methods for the determination of organic substances in water and fluvial sediments, U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A3, p 1-80