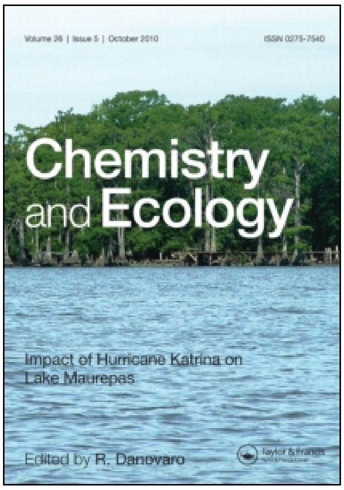

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Changing nutrient levels in Lake Maurepas following human population shifts in response to Hurricane Katrina

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Online publication date: 30 September 2010

Chemistry and Ecology
Vol. 26, No. 5, October 2010, 327–337

Changing nutrient levels in Lake Maurepas following human population shifts in response to Hurricane Katrina

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(*Received 21 January 2010; final version received 10 June 2010*)

Following Hurricane Katrina in August 2005, as many as 57% of residents in some parishes in the Lower Lake Pontchartrain Basin were displaced from their homes. Concurrently, the population in the Upper Lake Pontchartrain Basin, which drains into Lake Maurepas, increased by 62,000 residents, leading to increased residential and urban land use. These changes led to significant increases in phosphate and silicate concentrations in Lake Maurepas that are likely caused by non-point source pollution through erosion from new construction sites, fertilisation of new lawns and stress to existing wastewater treatment facilities. Average phosphate concentrations at three sites in Lake Maurepas increased by 76–205% and silicate levels increased by 60–83% compared with data collected in 2003 prior to the hurricane. Discharge-weighted averages increased even more dramatically, with phosphate and silicate concentrations increasing up to 161 and 394%, respectively. Discharge-weighted silicate and phosphate concentrations were 2.5 and 3.4 times greater than in 2003, respectively. Discharge-weighted silicate levels were 3.9 times greater than similar measurements from 1963. These large increases in nutrient and discharge-weighted nutrient concentrations are indicative of increased human population in the Upper Lake Pontchartrain Basin following Hurricane Katrina.

Keywords: phosphate; silicate; surface water; population shift

1. Introduction

Changing nutrient loads in lakes, rivers, estuaries and bays have become an increasingly important area of research. The contribution of enhanced nutrient loads from anthropogenic sources and their effect on natural water systems has been a focus of attention for many years and continues to be a subject of intense research worldwide. In 1947, Hasler reviewed early signs of eutrophication in nearly 40 lakes worldwide associated with increased levels of nutrients from anthropogenic sources with examples as early as 1897 [1]. Increased nutrient levels have been associated with increased levels of phytoplankton in saltwater systems such as the Adriatic Sea [2], the Atlantic Ocean near the coast of Spain [3], the Gulf of Mexico [4,5], Jinhae Bay in South Korea [6], the Mediterranean Sea near the coasts of Spain [7] and Egypt [8,9], and many others. Similar studies in brackish estuarine systems also demonstrate associations between nutrient levels and phytoplankton growth in areas such as the Liffey Estuary in Ireland [10], Piratininga Lagoon in

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ISSN 0275-7540 print/ISSN 1029-0370 online

DOI: 10.1080/02757540.2010.504670
http://www.informaworld.com

Brazil [11], the Targus Estuary in Portugal [12], and in estuaries in the USA, including Chesapeake Bay [13], estuaries in North Carolina [14] and the Lake Pontchartrain Basin in Louisiana [15–17]. Lake Maurepas is a freshwater lake in the Lake Pontchartrain Basin that drains into Lake Pontchartrain, a brackish lake. Freshwater systems are also affected by increased phytoplankton growth due to increased nutrient levels from anthropogenic sources. Example studies include Lake Albufera in Spain [18], Lake Lugano in Switzerland [19], Minichinda Stream in Nigeria [20], the Missouri River in the USA [21], the Nairobi [22] and Njoro [23] Rivers in Kenya, Salidito Reservoir in Cuba [24], and Silver and Casey Lakes in Iowa in the USA [25].

Anthropogenic pollution from agricultural and domestic run-off, and domestic and industrial wastewater are typical contributors to excess nutrient loads in surface water systems. This is particularly true for phosphates [26], which are typically at low levels in the absence of anthropogenic sources [27]. Ramesh reported that high levels of phosphorus in Indian rivers are due to anthropogenic sources, particularly agricultural run-off [28], while Dukes demonstrated that increased levels of nitrogen in North Carolina's Neuse River estuary are associated primarily with agricultural run-off [29]. Zhu determined that both nitrogen and phosphorus content of surface waters in China's Wujiang River Basin are caused by agricultural and domestic run-off [30], and Adedokun showed similar results in Nigerian rivers [31].

A source of concern in Louisiana's Upper Lake Pontchartrain Basin (Figure 1), and in Lake Maurepas in particular, is the potential for increasing nutrient levels in domestic run-off and wastewater due to a shift in human population following Hurricane Katrina. After Hurricane Katrina, many of the displaced residents from parishes surrounding New Orleans moved into parishes surrounding Baton Rouge. This shift in population from the Lower Lake Pontchartrain Basin to the Upper Lake Pontchartrain Basin was accompanied by increased land development

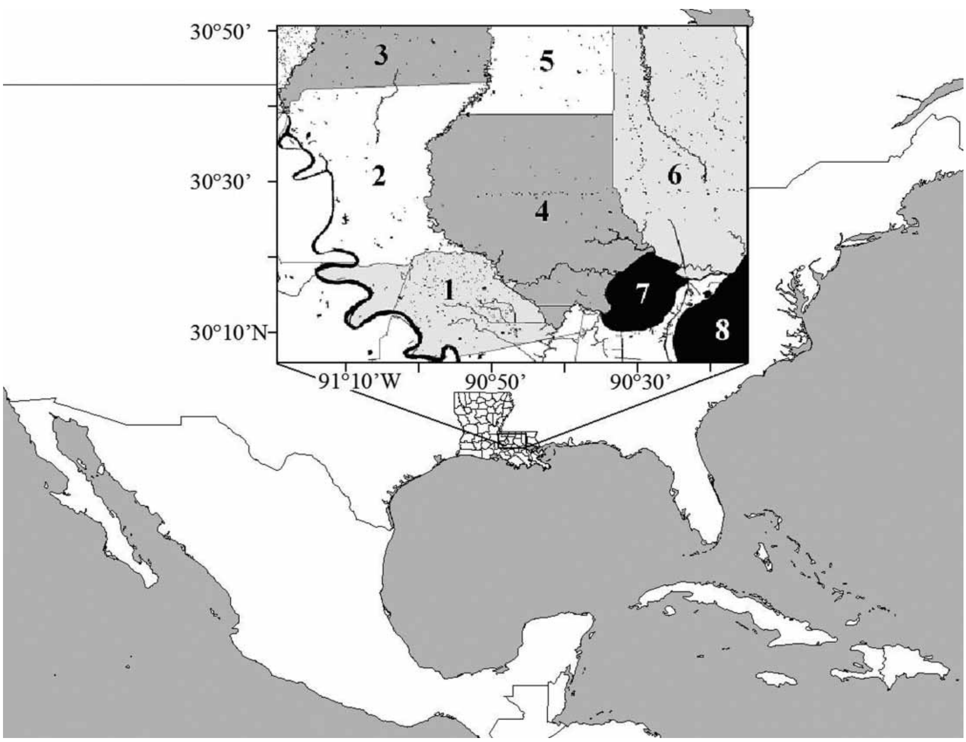

Figure 1. Louisiana's Upper Lake Pontchartrain Basin. (1) Ascension, (2) East Baton Rouge, (3) East Feliciana, (4) Livingston, (5) St. Helena, (6) Tangipohoa Parishes, (7) Lake Maurepas and (8) Lake Pontchartrain.

for housing and commercial usage. Non-point sources of pollution are typically associated with urban and developed land and are an important contributor to increasing nutrient concentrations in surface waters [32–34]. Total nitrogen, phosphorus and sediment discharges from lawns, golf courses and construction sites have been shown to increase as much as 250–300% compared with undisturbed vegetated areas [34]. Construction sites can have erosion rates 10–50 times greater than agricultural areas and as much as 500 times greater than undisturbed areas [33], and will likely contribute to increases in silicate levels in surface water. Because developed and urban land areas are known to be significant contributors to increased nutrients in surface waters, it is herein hypothesised that increases in human population in the Upper Lake Pontchartrain Basin following Hurricane Katrina will lead to increased nutrients in Lake Maurepas. Rabalais notes that nitrogen is typically the limiting nutrient for phytoplankton growth in marine water systems and phosphorus is typically the limiting nutrient for phytoplankton growth in freshwater systems; however, when transitioning from freshwater to saltwater in estuaries, complex multiple limitations to phytoplankton growth associated with nitrogen, phosphorus and silicon often occur [35]. The rivers and streams in the Upper Lake Pontchartrain Basin typically flow through wetland areas where much of the nitrate, as high as 88–97%, is assimilated into plant growth, whereas only 0–46% of the phosphate is assimilated [36], making potentially increasing levels of phosphate relatively more important than increases in nitrate concentrations. To determine whether nutrient levels in Lake Maurepas have increased following increases in the human population following Hurricane Katrina, this study focuses on the concentrations of phosphate, associated with the fertilisation of newly developed urban and residential areas, and silicate, associated with erosion from new construction sites. In addition, despite the importance of this lake in the Lake Pontchartrain Basin, relatively little water monitoring has been performed and the work presented here is an important baseline study in advance of potential freshwater diversion projects designed to prevent the loss of surrounding wetlands, particularly in the Maurepas Swamp area on the south side of the lake.

2. Materials and methods

2.1. *Site selection and sample collection*

The Lake Pontchartrain Basin is located in the USA and its watershed encompasses $\sim 12,000\,\text{km}^2$ in 13 Louisiana parishes and 4 Mississippi counties with multiple rivers, streams and lakes. The largest lakes in this system include Lakes Maurepas (Figure 2), Pontchartrain, St. Catherine and Borgne. This study focuses on Lake Maurepas, in the Upper Lake Pontchartrain Basin. Lake Maurepas is a 236 km^2 freshwater lake with freshwater input primarily from the Amite, Blind and Tickfaw Rivers and the Reserve Canal. Lake Maurepas drains into Lake Pontchartrain primarily through North Pass and Pass Manchac in the eastern portion of the lake. The lake is surrounded primarily by undeveloped wetlands and marshes. Nine sites were selected for sample collection (Figure 2). Sampling sites at the mouths of the Amite, Blind and Tickfaw Rivers and the Reserve Canal were used to examine nutrient concentrations in water entering the lake. Three of the sites were located near the centre of the lake to observe changes in nutrient levels as water passes through the lake, and further sites were located at North Pass and Pass Manchac to determine the amount of nutrients remaining in the water as it moves into the passes into the Middle and Lower Lake Pontchartrain Basins. Sampling sites were reached by using 5.5–7.0 m boats provided by Southeastern Louisiana University's Turtle Cove Environmental Research Station and located using GPS. All water samples were collected using Van Dorn Alpha Horizontal water samplers (Wildlife Supply Company, Yulee, FL, USA), transferred to 1 L polystyrene bottles, transported

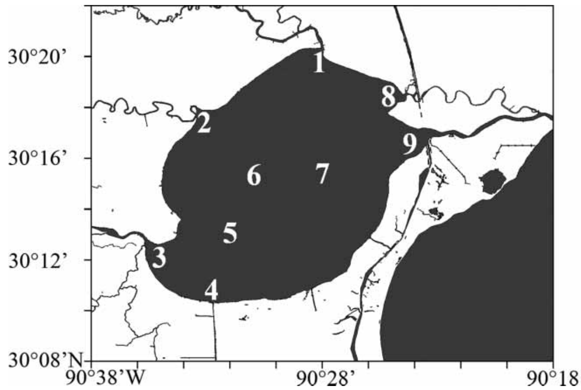

Figure 2. Lake Maurepas sampling sites: (1) Tickfaw River, (2) Amite River, (3) Blind River, (4) Reserve Canal, (5) Midlake 1, (6) Midlake 2, (7) Midlake 3, (8) North Pass and (9) Pass Manchac.

to the laboratory in coolers and stored in a refrigerator until analysed. Eight to twelve sets of samples were collected from the nine sampling sites from June 2007 to March 2008.

2.2. *Analytical methods*

The pH was measured directly in unfiltered samples using an Orion model 330 pH meter (Thermo Fisher Scientific, Waltham, MA, USA) that was calibrated using pH 4.0 and 7.0 buffers (VWR, West Chester, PA, USA). Samples were then vacuum filtered using Whatman GF/F filter paper (VWR). Spectroscopic analyses of phosphate (stannous chloride method) at 690 nm and silicate (heteropoly blue method) at 815 nm were completed on filtered water samples using standard methods [37] on a double beam Cary 1 UV–visible spectrometer (Varian Inc., Palo Alto, CA, USA). All samples were measured in triplicate to determine an average and 95% confidence limit. Statistical evaluation of the data was completed using Microsoft Excel, is based primarily on t-tests and differences were considered statistically significant at $p = 0.05$, the 95% confidence level. For some comparisons, sampling sites were grouped as inlet (Amite, Blind, Tickfaw and Reserve), midlake (Midlake 1–3) and outlet (North Pass and Pass Manchac) sites.

3. Results and discussion

3.1. *Changes in human population in the upper Lake Pontchartrain Basin*

On August 29, 2005, Hurricane Katrina made US landfall along the Louisiana and Mississippi Gulf Coasts. It is estimated that >600,000 people in Louisiana were displaced from their homes, particularly in Orleans and St. Bernard Parishes in the Middle and Lower Lake Pontchartrain Basins [38]. Table 1 summarises the average estimated population of the 13 parishes in the Lake Pontchartrain Basin from 2003 to 2005 prior to the hurricane and from 2006 to 2008 after the displacement of residents from the southern portion of the Lake Pontchartrain Basin [39]. The greatest impact of Hurricane Katrina, in terms of population displacement, occurred in Orleans Parish. In June 2005, Orleans Parish had an estimated 458,000 residents. By June of the following year, its population had decreased to an estimated 201,000 residents. Although the population has steadily increased to an estimated 306,000 residents in June of 2008, the average population in Orleans Parish in the three years following Hurricane Katrina remains 46% below the average for the three years before the hurricane. The population of Jefferson Parish in the three years following

Table 1. Three-year average populations before and after Hurricane Katrina in parishes located in the Lake Pontchartrain Basin.

Parish	Average population 2003–2005	Average population 2006–2008	Lakes receiving freshwater input
Ascension	86,000	99,000	Maurepas
East Baton Rouge	417,000	434,000	Maurepas
East Feleciana	21,000	21,000	Maurepas
Livingston	101,000	116,000	Maurepas
St. Helena	10,000	10,000	Maurepas
St. Charles	48,000	51,000	Maurepas and Pontchartrain
St. John The Baptist	44,000	47,000	Maurepas and Pontchartrain
Tangipohoa	103,000	114,000	Maurepas and Pontchartrain
Jefferson	457,000	435,000	Pontchartrain
Orleans	464,000	249,000	Pontchartrain
St. Tammany	209,000	229,000	Pontchartrain
Washington	44,000	45,000	Pontchartrain
St. Bernard	66,000	28,000	Pontchartrain and Borgne

the hurricane also decreased; however, the change in population was only 5%. Most dramatically affected in terms of relative population was St. Bernard Parish, where the population in the three years following Hurricane Katrina was 57% lower than in the three years before the hurricane. The remaining parishes in watersheds draining into the Middle and Lower Lake Pontchartrain Basins, St. Charles and St. John the Baptist Parishes to the southwest of Lake Pontchartrain and St. Tammany and Washington Parishes to the north of Lake Pontchartrain, experienced 2–10% increases in population over 2006–2008 compared with 2003–2005.

Of greatest interest in this study are the estimated population changes occurring in the parishes in the Upper Lake Pontchartrain Basin. East Baton Rouge Parish increased in population by ∼17, 000 residents for the three years following the hurricane compared with the previous three years. However, because of the already large population of this parish, the relative increase was only 4%. The number of residents in Ascension, Livingston and Tangipohoa Parishes increased by 11,000–15,000 persons. Although similar in magnitude to the population increase in East Baton Rouge Parish, the smaller initial populations led to relative population increases of 11–16%. The potential effects of population increases in Tangipohoa Parish on the water quality in Lake Maurepas will be somewhat mitigated because some rivers and streams flow into Lake Maurepas, while others drain into Lake Pontchartrain. The overall population in parishes draining at least in part into Lake Maurepas increased by nearly 62,000 residents (7%) following Hurricane Katrina.

3.2. *Analysis of current pH and comparison to historical data*

Water samples for pH analysis were collected eleven times between June 8, 2007 and January 29, 2008 at each of the nine sampling sites with average pH values for any collected sample ranging from 6.25 ± 0.11 ($n = 3$) to 8.28 ± 0.01 ($n = 3$). The average pH throughout the lake during this study was 7.19 ± 0.06 ($n = 99$). Based on monthly samples obtained by the Louisiana Department of Environmental Quality (LDEQ) between January and December 2001, average pH values at sites near Pass Manchac, the Tickfaw River and the Blind River were 7.13 ± 0.16 ($n = 12$), 6.9 ± 0.3 ($n = 12$) and 7.0 ± 0.2 ($n = 12$), respectively [40]. The average pH obtained in this study at similar locations were 7.24 ± 0.12 ($n = 11$), 6.84 ± 0.19 ($n = 11$) and 7.03 ± 0.15 ($n = 11$) and were not statistically different (p ranged from 0.22 to 0.98). Thus the pH in Lake Maurepas had not changed in response to human population shifts associated with Hurricane Katrina.

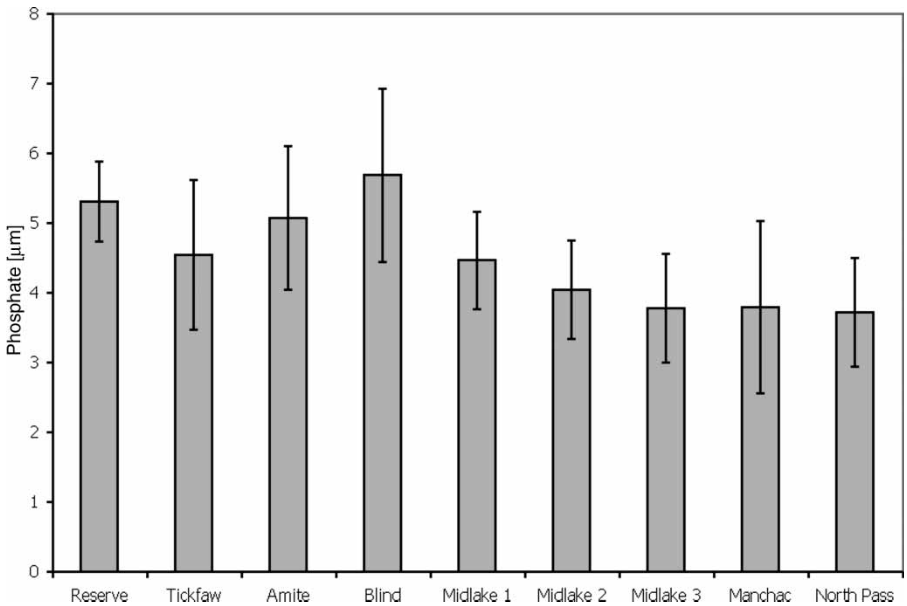

Figure 3. Phosphate concentrations in Lake Maurepas. Inlet sites: Reserve Canal, Tickfaw River, Amite River and Blind River; midlake sites: Midlake 1–3; and outlet sites: Pass Manchac and North Pass. Error bars represent 95% confidence limits for 12 sampling trips.

Table 2. Phosphate concentrations at inlet, midlake and outlet sampling sites.

	Phosphate (μM)	Minimum (μM)	Maximum (μM)
Inlet sites ($n = 47$)	5.2 ± 0.3	2.3	8.5
Midlake sites ($n = 36$)	4.2 ± 0.3	1.7	7.1
Outlet sites ($n = 24$)	3.9 ± 0.6	1.2	8.4

3.3. *Analysis of current phosphate concentrations and comparison to historical data*

Water samples for phosphate analysis were collected 12 times from June 2007 to March 2008 at each of the nine sampling sites and were filtered prior to analysis (Figure 3). The average phosphate concentration in Lake Maurepas was 4.5 ± 0.3 μM ($n = 107$) and ranged from 1.2 ± 0.3 μM ($n = 3$) at Pass Manchac on June 22, 2007 to 8.5 ± 0.7 μM ($n = 3$) at the Blind River site on June 8, 2007. The data was grouped into inlet, midlake and outlet sites for comparison and the results are shown in Table 2. In general, the concentration of phosphate decreased as water moved from the freshwater inlet sites to the middle of the lake. Based on analysis using the t-test, the average phosphate concentration at inlet sites (5.2 ± 0.6 μM, $n = 48$) is statistically different from both the midlake (4.1 ± 0.4 μM, $n = 36$) and outlet (3.6 ± 0.7 μM, $n = 24$) sites, with $p = 0.0008$ and 0.001, respectively. The average phosphate concentrations at the midlake and outlets sites, based on the t-test, were not significantly different ($p = 0.37$). It is expected that the decrease in phosphate concentration as the water moves across the lake is due to assimilation by growing phytoplankton; however, phytoplankton concentrations were not determined during this study, and thus this hypothesis cannot be tested at this time.

Phosphate results for this study can be compared with two distinct historical data sets. Average phosphate concentrations were calculated for three sites from 12 monthly samples taken analysed by LDEQ in 2001, the most recent data available for sites in Lake Maurepas prior to Hurricane Katrina. Phosphate concentrations in 2001 were 4.5 ± 1.3 μM ($n = 12$) near the mouth of the

Blind River, 4.2 ± 1.0 μM ($n = 12$) at the mouth of the Tickfaw River and 3.9 ± 1.2 μM ($n = 12$) at Pass Manchac [40]. The change in phosphate concentrations at these three sites from 2001 to 2007/2008 was 22, 10 and −3% respectively. However, at all three sites, the average phosphate concentrations were not statistically different: $p = 0.23$, 0.53 and 0.77 for the Blind River, the Tickfaw River and Pass Manchac, respectively.

In a separate study, Day collected 12 sets of water samples from near the Blind River, the Reserve Canal and Pass Manchac from April 2002 to May 2003. Day reported average phosphate concentrations of 1.9 ± 1.0 μM ($n = 12$) at the Blind River, 1.9 ± 1.0 μM ($n = 12$) at the Reserve Canal and 2.3 ± 1.0 μM ($n = 12$) at Pass Manchac [41]. The phosphate concentrations determined in this study represent increases of 76, 205 and 184%, respectively, at the Blind River, Reserve Canal and Pass Manchac sampling sites compared to those reported by Day. Statistical analysis of the two data sets reveals that in all three cases, the increasing phosphate concentrations are significant with $p = 0.03$ for the Pass Manchac data and $p < 0.0001$ for the remaining sites.

When concentrations of phosphate in 2002/2003 from Day's work are compared with the current study, there is a clear increase in the level of phosphate in the surface water of Lake Maurepas.

At first glance, there appears to be no increase in phosphate levels after the shift in human population following Hurricane Katrina when the LDEQ data from 2001 is compared with the findings in this study. However, the concentration of nutrients in surface water is generally found to increase with increasing levels of rainfall in a watershed, and differences in the data become more apparent when the amount of water discharged into the lake is considered. The average discharges into Lake Maurepas during the three study periods were $41 \pm 14\,\mathrm{kL \cdot s^{-1}}$ during the current study, $81 \pm 22\,\mathrm{kL \cdot s^{-1}}$ during the collection of samples by LDEQ and $95 \pm 16\,\mathrm{kL \cdot s^{-1}}$ during the study by Day [41]. To account for differences in water discharge rates between the three studies, discharge-weighted concentrations were calculated by dividing the phosphate concentration by the average discharges for the three days leading up to each sample collection. The discharge-weighted phosphate concentration was greater in the current study than in either of the previous studies. The discharge-weighted phosphate concentrations are summarised in Table 3 for sampling locations that are directly comparable. After accounting for disparate discharge rates, phosphate concentrations are 56–86% larger during the current study compared with the LDEQ data from 2001 and 146–394% larger than those observed by Day in 2002/2003. After statistical analysis, all sites showed statically relevant increases, with p ranging from 0.001 when comparing data from the Blind River location with discharge-weighted phosphate concentrations observed by Day to 0.05 when comparing discharge-weighted phosphate concentrations at the Tickfaw River with those observed by LDEQ. The only site where a statistically relevant increase in discharge-weighted phosphate concentration was not observed ($p = 0.19$), despite a relative increase of 72%, was at Pass Manchac, when comparing values observed in this study with those reported by LDEQ. Overall, increased levels of phosphate and discharge-weighted phosphate have been observed in Lake Maurepas after Hurricane Katrina compared with historical data from the years preceding the hurricane. These increased levels are most likely due to the fertilisation of lawns associated with the construction of the new housing needed to accommodate the influx of people into the Upper Lake Pontchartrain Basin after the hurricane and to the increase in the relative amount of urban/residential land use at the expense of forested/undisturbed land that is generally a lesser contributor to non-point source phosphate pollution.

3.4. *Analysis of current silicate concentrations and comparison to historical data*

Because silicate can be an important nutrient for diatoms and there is potential for increasing concentration of silicate in run-off due to erosion from new construction sites, eight water

Table 3. Comparison of discharge weighted phosphate concentrations with historic data.

	Reserve Canal phosphate ($nmol \cdot s^{-1} \cdot L^{-2}$)	Blind River phosphate ($nmol \cdot s^{-1} \cdot L^{-2}$)	Pass Manchac phosphate ($nmol \cdot s^{-1} \cdot L^{-2}$)	Tickfaw River phosphate ($nmol \cdot s^{-1} \cdot L^{-2}$)
This study ($n = 12$)	0.36 ± 0.12	0.36 ± 0.11	0.26 ± 0.14	0.27 ± 0.07
Day ($n = 11$)	0.10 ± 0.06	0.07 ± 0.05	0.09 ± 0.06	
LDEQ ($n = 12$)		0.19 ± 0.08	0.15 ± 0.11	0.17 ± 0.08

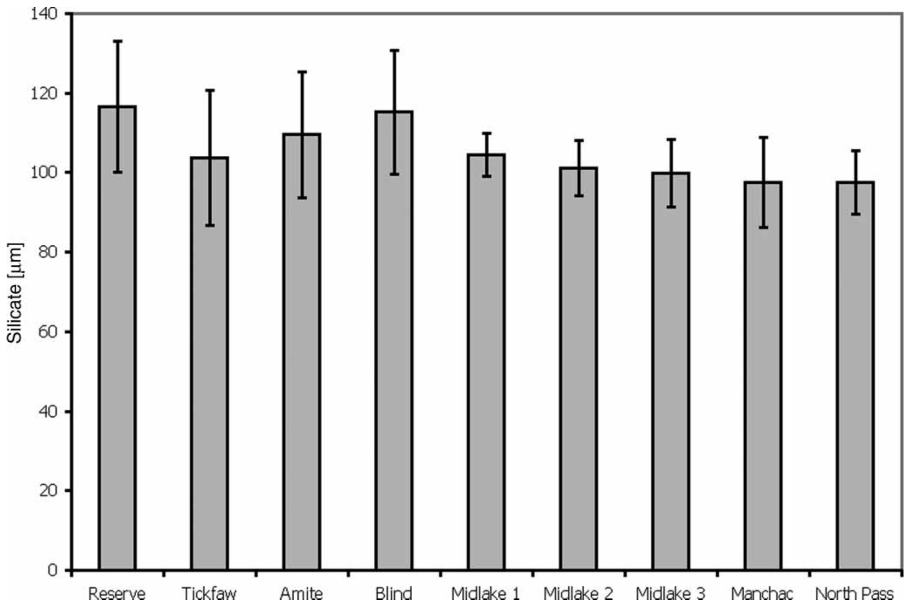

Figure 4. Silicate concentrations in Lake Maurepas. Inlet sites: Reserve Canal, Tickfaw River, Amite River and Blind River; midlake sites: Midlake 1–3; and outlet sites: Pass Manchac and North Pass. Error bars represent 95% confidence limits for eight sampling trips.

samples were collected from each of the sampling sites between September 2007 and March 2008 (Figure 4). The silicate concentrations ranged from $66.7 \pm 0.1\,\mu M$ ($n = 3$) on September 10, 2007 at Pass Manchac to $159.3 \pm 0.7\,\mu M$ ($n = 3$) on January 14, 2008 at the Reserve Canal. The samples were grouped into inlet, midlake and outlet sites for comparison (Table 4). The average silicate concentration in Lake Maurepas over the course of this study was $105 \pm 4\,\mu M$ ($n = 72$). In general, silicate concentration decreased as the water moved from inlet sites toward the centre of the lake and into the passes leading downstream into Lake Pontchartrain. As observed with phosphate, silicate concentrations at the inlet sites were statistically different from those observed at the midlake and outlet sites with $p = 0.016$ and 0.003, respectively based on t-test comparison of the means. While continuing to decrease in concentration when compared with the midlake samples, the average silicate concentration at the outlet sites is not statistically different ($p = 0.20$). A decrease in silicate concentration as water moves from the inlet sites across the lake is not unexpected and can be attributed to settling of silicate containing particles and incorporation in phytoplankton as a nutrient, both of which would increase with longer residence time in the lake.

The United States Geological Survey (USGS) measured silicate concentrations at Pass Manchac on a regular basis from December 1962 to September 1963 and reported four measurements in 1970, 1998 and 1999. Because of the limited number of samples after 1963 and the significant

Table 4. Silicate concentrations at inlet, midlake, and outlet sampling sites.

	Silicate (μM Si)	Minimum (μM Si)	Maximum (μM Si)
Inlet sites ($n = 32$)	110 ± 7	77	159
Midlake sites ($n = 24$)	103 ± 4	75	113
Outlet sites ($n = 16$)	93 ± 7	67	110

Table 5. Comparison of discharge weighted silicate concentrations to historic data.

	Reserve Canal silicate ($\text{nmol} \cdot \text{s}^{-1} \cdot \text{L}^{-2}$)	Blind River silicate ($\text{nmol} \cdot \text{s}^{-1} \cdot \text{L}^{-2}$)	Pass Manchac silicate ($\text{nmol} \cdot \text{s}^{-1} \cdot \text{L}^{-2}$)
This study ($n = 8$)	20 ± 9	19 ± 9	16 ± 8
Day ($n = 11$)	8 ± 4	8 ± 3	7 ± 4
USGS ($n = 8$)			4 ± 2

length of time between them, only the samples from the early 1960s are compared with the current work. The average concentration of silicate at Pass Manchac based on the USGS data was $61 \pm 11\,\mu\text{M}$ ($n = 8$) [42]. The average concentration of silicate at Pass Manchac in the current study was $96 \pm 11\,\mu\text{M}$ ($n = 8$). The concentration of silicate in the current study after Hurricane Katrina increased by 57% compared with the pre-Katrina data from the USGS and is statistically different ($p < 0.0001$). A second pre-Katrina study was completed by Day between April 2002 and May 2003. Day reported the concentration of silicate at Pass Manchac to be $60 \pm 20\,\mu\text{M}$ ($n = 12$) [41]. Statistical analysis of the silicate concentrations in the USGS and Day studies shows no statistical difference ($p = 0.60$). Compared with the study completed by Day, the concentration of silicate in this work at Pass Manchac is statistically different ($p < 0.001$) and represents a 169% higher silicate concentration. Similar results were obtained when comparing silicate concentration from this work at the Blind River and the Reserve Canal, where the concentrations increased from $71 \pm 18\,\mu\text{M}$ ($n = 12$) and $64 \pm 21\,\mu\text{M}$ ($n = 12$), respectively, to $114 \pm 14\,\mu\text{M}$ ($n = 8$) and $117 \pm 11\,\mu\text{M}$ ($n = 8$). The concentrations of silicate in this study were significantly different from those observed by Day at both the Blind River and Reserve Canal sampling sites ($p < 0.001$ in both cases). Clearly, the concentration of silicate in Lake Maurepas has increased compared with earlier studies conducted prior to Hurricane Katrina. Discharge-weighted average concentrations were also examined for silicate and are summarised in Table 5. According to US Census records, the population in the six parishes comprising the Upper Lake Pontchartrain Basin was 374,000 in 1960 [43] and increased to an estimated 731,000 by 2003 and 791,000 in 2007 [37]. Over these timeframes, discharge-weighted silicate concentrations increased as well. In this study, discharge-weighted silicate concentrations were larger than those observed by Day prior to Hurricane Katrina by 139, 161 and 137%, respectively, at the Blind River, Reserve Canal and Pass Manchac. Each of these increased silicate levels were statistically, relevant, with p-values ranging from 0.02 to 0.03. The increase in discharge-weighted silicate in the Upper Lake Pontchartrain Basin between the USGS study in 1962/1963 and the current study was even larger at 367% ($p = 0.006$). The increase in discharge-weighted silicate concentrations at Pass Manchac between 1962 and 2003 was only 64%, but was followed by a 137% increase between 2003 and 2007. The drastic increase in discharge-weighted silicate clearly cannot be a consequence of population increase alone, since the population increased by 96% from 1960 to 2003, whereas it increased only 8% from 2003 to 2007. However, rapid growth following Hurricane Katrina necessitated rapid increases in construction on a much larger scale than needed to provide housing over the slower growth rate associated with the earlier timeframe. Thus the rapid infusion of human population into the Upper Lake Pontchartrain Basin and the concurrent growth in construction has led to increased urban and residential run-off and increased levels of silicate in the surface waters of Lake Maurepas.

4. Conclusions

Following Hurricane Katrina in August 2005, many displaced residents settled in the parishes situated in the Upper Lake Pontchartrain Basin. These parishes, which drain into Lake Maurepas, experienced an $\sim 62{,}000$ resident increase in population. Direct comparison of phosphate concentrations between the current study and two historical data sets did not provide a conclusive answer regarding increases in phosphate levels following increasing human populations in the Upper Lake Pontchartrain Basin following Hurricane Katrina. Although discharge-weighted phosphate concentrations at Pass Manchac did not show a statistically relevant increase between LDEQ data recorded in 2001 and the current study, increases in discharge-weighted phosphate concentrations ranging from 57 to 394% at all other directly comparable sampling locations were statistically relevant between both LDEQ records from 2001 and a more recent study conducted by Day. In all cases, statistically relevant increases were observed between the current study and historical data for both direct measurement of silicate concentrations (57–83%) and discharge-weighted silicate levels (137–367%). Increasing levels of the non-point source pollutants silicate and phosphate were observed in this study, are known to be associated with run-off from urban and residential land use, and are likely to have been caused by the documented rapid increase in human population in the Upper Lake Pontchartrain Basin.

Acknowledgements

We gratefully acknowledge the financial support of the Southeastern Louisiana University's Lake Pontchartrain Basin Research Program and its funding by the United States Environmental Protection Agency. We thank Robert Moreau and Hayden Reno at Southeastern Louisiana University's Turtle Cove Environmental Research Station for their help and guidance in training in the operation of boats and Mr Reno's guidance and experience in navigating Lake Maurepas' waters. Finally, we thank Ms Caroline Leung at the Louisiana Technical University's College of Business for providing the population data described in this work.

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