

Water Quality in the Near Coastal Waters of the Gulf of Mexico Affected by Hurricane Katrina: Before and After the Storm

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Received: 27 February 2008 / Accepted: 2 April 2009 / Published online: 30 May 2009
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Abstract Water quality was assessed following Hurricane Katrina in the affected waters of Alabama, Mississippi, and Louisiana. Post-landfall water quality was compared to pre-hurricane conditions using indicators assessed by EPA's National Coastal Assessment program and additional indicators of contaminants in water and pathogens. Water quality data collected after Hurricane Katrina suggest that the coastal waters affected by the storm exhibited higher salinity and concentrations of chlorophyll *a*, dissolved inorganic phosphorus, and total suspended solids following the storm compared to the previous 5-year averages. Higher bottom dissolved oxygen concentrations and light attenuation were also observed. Contaminant concentrations measured in the water column

were very low or undetectable, as were the presence of pathogens. Overall water quality did not significantly differ from water quality assessed in the five years preceding the storm. Statistical analyses indicate that use of a probabilistic survey design is appropriate for making pre-storm and post storm comparisons for water quality condition on an areal basis.

Keywords Alabama · Assessment · Coastal waters · Estuaries · Gulf of Mexico · Hurricane Katrina · Louisiana · Mississippi · Probabilistic survey · Water quality

The information in this article has been funded wholly (or in part) by the U.S. Environmental Protection Agency. It has been subjected to review by the National Health and Environmental Effects Research Laboratory and approved for publication. Approval does not signify that the contents reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. This is contribution number 1280 from the Gulf Ecology Division.

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Introduction

Hurricane Katrina battered parts of Florida, Louisiana, Mississippi and Alabama in August 2005, decimating many coastal communities in hardest hit Louisiana and Mississippi. A strong category three on the Saffir-Simpson scale, Katrina struck the northern Gulf of Mexico coast with sustained winds of 200 km h^{-1} and a central pressure of 920 mb (NOAA/NCDC 2005). Rainfall accumulations in the northern Gulf coast associated with Katrina were in excess of 20–25 cm and coastal storm surge reached 6–9 m above normal tide levels. The region suffered catastrophic losses of human life, homes and economic infrastructure as a result of Katrina, making the hurricane one of the costliest and deadliest natural disasters in U.S. history (NOAA 2006). The extent of damage caused by Katrina was evident in the populated areas of impacted states. Less apparent, however, was the effect the storm had on the water quality of the adjacent estuarine waters.

Hurricanes are normal disturbances for coastal ecosystems; however, these once resilient ecosystems have been

made vulnerable to natural disturbances due to extensive changes in land use within watersheds and altered coastal landscapes (Mallin and others 2002). Changes in land use and land cover along the Gulf of Mexico (GOM) coast are reflected in the rapid loss of coastal wetlands, particularly in Louisiana. Over the past several decades, coastal wetlands in Louisiana and other parts of the Gulf coast have been rapidly lost, taking with them their inherent storm protection services. An already rapid rate of wetland loss (approx. 0.86% year⁻¹) (Turner 1997) was accelerated by the landfall of Hurricane Katrina. Wetland loss east of the Mississippi River is attributed specifically to Hurricane Katrina's storm surge. Approximately 101 km² of marsh around the upper and central portions of Breton Sound were converted to open water. Throughout the Pontchartrain, Pearl River, Barataria, and Terrebonne basins, approximately 122 km² of marsh were lost. The area of the Mississippi River Delta incurred approximately 36 km² of loss (USGS Press Release 2005).

The incidence of hurricanes along the Gulf and Atlantic coasts has been increasing over the last ten years and with a continued increase in sea surface temperature, the frequency is expected to increase (Saunders and Lea 2008). Between 1985 and 2007, fourteen named storms have made landfall along the Louisiana and Mississippi coastal region, three which were category 3 or greater hurricanes—Elena, 1985; Andrew, 1992; Katrina, 2005 (<http://www.nhc.noaa.gov/pastall.shtml#annual>). It is essential to have baseline information for water quality in estuarine systems subjected to these storm events in order to understand how the ecological condition of coastal ecosystems are affected, how quickly they recover, if they do recover and to evaluate cumulative effects as a result of future storms (Greening and others 2006).

Research Objectives

To assess water quality in estuarine waters affected by Hurricane Katrina, the U.S. Environmental Protection Agency (EPA), in collaboration with the National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS) and US Food and Drug Administration (FDA) engaged in a comprehensive interagency effort to characterize the magnitude and extent of coastal contamination and associated human-health and ecological effects. The pre-Katrina component of this assessment included a subset of probabilistic survey data, from the National Coastal Assessment (NCA) Gulf of Mexico region (USEPA 2001a), which was analyzed to estimate the ecological condition of the near coastal waters of Louisiana, Mississippi, and Alabama, affected by the storm. The objective of our research is to provide a comprehensive and

scientifically sound assessment of water quality in the coastal waters affected by Hurricane Katrina and to establish a useful benchmark for determining how these conditions may change over subsequent years. We present probabilistic survey data characterizing water quality of the hurricane-impacted area before and after Hurricane Katrina and statistical analyses supporting the use of probabilistic survey designs for pre and post storm comparisons of water quality condition.

Methods

Survey Design

The sampling and analytical methods used for both pre- and post-Hurricane Katrina assessments used EPA's Environmental Monitoring and Assessment Program (EMAP) and NCA probabilistic monitoring approaches (<http://www.epa.gov/nheerl/arm>). A probability-based survey design is a scientifically rigorous method for sampling a subset of a target population to generate areally-based estimates using specific ecological indicators that may be used to infer condition or status, with a quantifiable measure of uncertainty, to the entire resource. The number of stations included in both the pre- and post-hurricane periods for both the Mississippi Sound-Lake Borgne (MS) and Lake Pontchartrain (LP) survey areas is summarized in Table 1. Specific information regarding the pre- and post-Katrina survey design follows.

Pre-Katrina

The assessment to characterize the ecological condition of the Hurricane impacted estuarine area prior to Hurricane Katrina landfall used data collected during the NCA surveys for sampling years 2000–2004. All sites were sampled once during July–September, a period in which ecological

Table 1 Summary of number of stations included in the pre- versus post-hurricane comparisons for Mississippi Sound (MS) and Lake Pontchartrain (LP) survey areas

Sampling period	MS	LP
Pre-hurricane		
2000	29	6
2001	36	10
2002	34	10
2003	37	13
2004	36	10
Total	172	49
Post-hurricane (Oct. 05)	30	30

responses to pollution exposure was expected to be severe (Summers and others 1995). The original NCA survey design covered all GOM estuarine area and included 35–50 sites per state, per year, selected using an areally-weighted, stratified, random selection method (<http://www.epa.gov/nheerl/arm>). Data used for the pre-Katrina assessment represented a post-stratified subset of these sites that included 221 locations sampled over the 5-year period in the open-water portion of the Mississippi Sound, Lake Borgne and Lake Pontchartrain estuaries (Table 1).

Post-Katrina

Sampling was conducted in LP from October 11 to 14, 2005 and in MS from October 9 to 15, 2005. A major focus of these surveys was on the collection and analysis of water and sediment samples using standard protocols and core indicators incorporated in both EMAP and NCA (USEPA 1999, 2002a). By doing so, post-hurricane conditions measured one–two months after the hurricane could be compared to pre-hurricane conditions. As in prior NCA assessments, a probability-based sampling design consisting of 60 randomly selected sites, 30 in each of the two post-Hurricane survey areas (Fig. 1), was used to support statistical estimates of ecological condition, relative to the various water quality indicators measured.

Data Analysis

Water clarity, dissolved oxygen (DO), chlorophyll *a* (Chl_a), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) were evaluated using the guidance values in Table 2. For each station, indicators were assigned a rating of “good,” “fair,” or “poor” according to the guidance threshold values. An index for water quality, based on the ratings of the five equally weighted water quality parameters above, was determined by the frequency of condition at each station (Table 2). Water quality was assessed before and after the storm using the water quality index values. Post-hurricane contaminants and pathogens measured in water samples were compared to existing state or federal criteria, or guidance values found in the literature.

The areal extent of condition for the five water quality parameters and the water quality index was estimated using the cumulative distribution function (CDF). The CDF is the primary analytical tool for describing the condition of a resource using data from an areally-weighted, probability-based sampling design (Diaz-Ramos and others 1996). This approach has been applied throughout EPA’s related EMAP and NCA programs (USEPA 1999, 2002). Using the Horvitz-Thompson normal approximation method, the

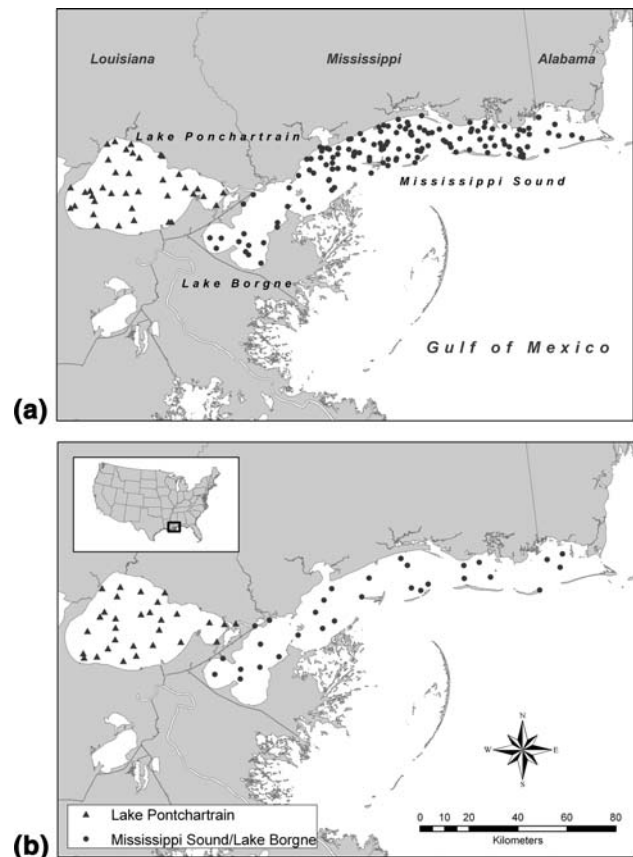


Fig. 1 Random probabilistic survey design with station locations for Lake Pontchartrain (LP) and Mississippi Sound-Lake Borgne (MS) study areas (a) sites for 2000–2004, pre-Hurricane Katrina (LP $n = 49$; MS $n = 172$); and (b) post-Hurricane Katrina (LP, $n = 30$; MS, $n = 30$)

CDF describes both the distribution and confidence intervals of indicator values across a resource. CDF analysis results were used to estimate the areal extent of an evaluated condition with respect to threshold or guidance values for each indicator collected. For pre- and post-Katrina, all water quality indicators were assessed in this manner. Similarly evaluated data, obtained prior to the hurricane, were available for the entire hurricane-impacted coastal area. These earlier assessments provided a solid pre-hurricane baseline to compare data collected post-Katrina.

Cluster analyses were performed on the results stemming from CDF outputs to investigate the potential impact of inter-annual variability on water quality ratings for MS and LP and to determine if the time period over which post-hurricane sampling occurred influenced interpretation of results pre- and post-Katrina (PRIMER-E software version 6; Clarke and Warwick 2001; Clarke and Gorley 2006). A Euclidian, rank dissimilarity matrix, based on arc-sine, square root transformed areal estimates, was used to generate cluster diagrams as described by Clarke and Warwick (2001) to discern any outliers.

Table 2 Threshold and guidance values for evaluating water quality

Parameter	Good	Fair	Poor
Bottom dissolved oxygen	>5.0 mg l ⁻¹	2.0–5.0 mg l ⁻¹	<2.0 mg l ⁻¹
Chlorophyll <i>a</i>	<5.0 µg l ⁻¹	5.0–20 µg l ⁻¹	>20 µg l ⁻¹
Dissolved inorganic nitrogen	<0.1 mg l ⁻¹	0.1–0.5 mg/l	>0.5 mg/l
Dissolved inorganic phosphorus	<0.01 mg l ⁻¹	0.01–0.05 mg l ⁻¹	>0.05 mg l ⁻¹
Water clarity (% light transmission @ 1 m)	>20%	10–20%	>10%
Water quality	≤1 indicator scored fair	≥2 indicators scored fair or 1 indicator scored poor	≥2 indicators scored poor

USEPA (2004)

To support the utility of probabilistically generated ratings and detect changes in areal extent of ecological conditions, a two-sample z test was performed to compare post-Katrina results to the pre-Katrina combined 2000–2004 assessment blocks for both survey areas. The two-sample z test was constructed using the percentage of condition and the standard deviation for each condition estimate for pre- and post-Katrina time periods in both LP and MS survey areas ($P = .05$).

Sample Collection and Analyses

Hydrographic parameters (DO, salinity, temperature, pH, depth, and water clarity) were measured, and water samples collected and analyzed DIN, DIP, Chla and total suspended solids (TSS) at the post-hurricane sites. Additional samples were collected at post-Katrina survey sites for inorganic and organic contaminants, oil and grease, and microbial pathogen indicators.

Hydrographic Profile Data

All sites were sampled in accordance with the standard procedures in the NCA Field Methods Manual (USEPA 2001b) and the NCA Quality Assurance Project Plan (USEPA 2001a, b) where applicable. Each station was located using Global Positioning System (GPS). A Hydrolab[®] H20 sonde was used to measure salinity, temperature, pH, and dissolved oxygen at 1 m intervals from surface to bottom at each station. Secchi depth was recorded as a measure of water clarity. Photosynthetically active radiation (PAR) was measured using a Licor[®] light meter equipped with a 2 pi cosine sensor at sites sampled pre-hurricane. Ambient PAR was recorded simultaneously with underwater PAR readings at 1 m intervals. Transmissivity, the percentage of ambient light reaching specific depth, was calculated from light meter readings. Only Secchi depth was recorded at post-Katrina sites. Where no light meter data were collected ($n = 4$; MS pre-Katrina),

Secchi depth was used to estimate transmissivity according to Smith and others (2006).

Nutrients, Chlorophyll, and Total Suspended Solids

Dissolved nutrients and Chla water samples were collected 0.5 m below the surface and 0.5 m above the bottom using a Beta Plus[®] sampler. Dissolved nutrients samples were filtered through a 25 mm GF/F glass-fiber filter into a 125 ml HDPE narrow-mouth Nalgene[®] bottle and stored at -70°C prior to analyses. Additional water from the sampler was filtered through the pre-combusted 25 mm GF/F glass-fiber filter to obtain the Chla sample. The filter was placed in a small plastic Petri dish, wrapped in aluminum foil, and stored at -70°C . Whole water samples were collected for both TSS and total nutrients. Water samples for TSS were collected into 1 l Nalgene bottles and filtered through pre-weighed 47 mm GF/F filters and frozen prior to analysis. Total nutrients samples were collected into 125 ml HDPE narrow-mouth Nalgene bottles and stored at -70°C . Dissolved and total nutrient samples were analyzed on a modified Technicon Autoanalyzer[®] using standard EPA methods and procedures (EPA method 349.0, EPA method 353.4 and EPA method 365.5). Chla samples were extracted using a modified Welshmeyer (buffered methanol) method and analyzed on a Turner[®] fluorometer (EPA method 445.0). TSS concentrations were obtained by gravimetric filtration followed by drying at $103\text{--}105^{\circ}\text{C}$ (EPA method 160.2).

Contaminants, Oil and Grease, and Atrazine

Inorganic and organic contaminant and oil and grease samples were collected into pre-cleaned and preserved bottles according to Battelle sampling protocol (SOP 5-200-02). Inorganic and organic contaminants in water were extracted and analyzed according to EPA approved methods (Battelle 2000). The inorganic and organic contaminants analyzed are presented in Table 3. Polycyclic

Table 3 List of chemicals/elements analyzed for water samples post-hurricane Katrina

Polynuclear aromatic hydrocarbons (PAHs)	Chlorinated pesticides other than DDT
Acenaphthene	Aldrin
Anthracene	Alpha-chlordane
Benz(a)anthracene	Dieldrin
Benzo(e)pyrene	Endosulfan I
Biphenyl	Endosulfan II
Chrysene	Endosulfan sulfate
Dibenz(a,h)anthracene	Endrin
Dibenzothiophene	Heptachlor
2,6-Dimethylnaphthalene	Heptachlor epoxide
Fluoranthene	Hexachlorobenzene
Fluorene	Mirex
2-Methylnaphthalene	Toxaphene
1-Methylnaphthalene	Trans-nonachlor
1-Methylphenanthrene	Specific herbicide
Naphthalene	Atrazine
Pyrene	Trace elements
Benzo(b)fluoranthene	Aluminum
Acenaphthylene	Antimony
Benzo(k)fluoranthene	Arsenic
Benzo(g,h,i)perylene	Cadmium
Ideno(1,2,3-c,d)pyrene	Chromium
2,3,5-Trimethylnaphthalene	Copper
Perylene	Iron
Phenanthrene	Lead
Oil and grease	Manganese
DDT and its metabolites	Mercury
2,4'-DDD	Nickel
4,4'-DDD	Selenium
2,4'-DDE	Silver
4,4'-DDE	Tin
2,4'-DDT	Zinc
4,4'-DDT	

aromatic hydrocarbons (PAHs) were analyzed by Gas Chromatograph(y)/Mass-Spectrometry. Trace metal concentrations were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) except for selenium and silver, which were analyzed by graphite furnace atomic absorption. Mercury was analyzed by cold-vapor atomic absorption. Pesticides and polychlorinated biphenyls (PCBs) were analyzed by Gas Chromatograph(y)—Electron Capture Detector (GC/ECD). Oil and grease concentrations were determined using standard methods for water and wastewater (American Public Health Association 1989; EPA method 1664). Samples for the analysis of atrazine in water were collected in 1 l amber bottles. Samples were extracted and analyzed by GC/MS (EPA method 4670).

Microbial Indicators

Separate surface water samples were collected into sterile 1 l bottles for measurement of microbial and pathogen indicators (enterococci, fecal coliforms, and *Clostridium perfringens* spores). According to USEPA standardized methods for fecal coliform enumeration (USEPA 1997), samples for fecal coliform were filtered on selective media, incubated for 24 h, and counted. Enterococci samples were enumerated using Enterolert[®] test kits which are based on USEPA standardized methods for enumeration of enterococci bacteria in marine waters (USEPA 2000a). *C. perfringens* spores were enumerated from water samples using membrane filtration onto a highly selective media (Duncan and Strong 1968; Handford 1974).

C. perfringens is a bacterium, found in the intestinal tract of humans and other animals. It enters the environment through feces. There are no EPA health-based ambient water quality criteria for *C. perfringens*. However, some scientists recommend using *C. perfringens* spores as a tracer of fecal pollution because their presence is a good indicator of recent or past fecal contamination in water and spores survive well beyond the typical life-span of other fecal bacteria.

Ambient Water Quality Criteria for Bacteria (USEPA 1986) recommends the use of enterococci, a group of bacteria found in the gastrointestinal tract of warm-blooded animals, as indicator organisms for measuring fecal contamination of marine waters for the designated use of swimming, as required by the Clean Water Act (Section 304). USEPA recommends that single sample maximums for bathing waters not exceed 104 colony forming units (cfu) per 100 ml.

Fecal coliform concentrations were compared to the 43 cfu 100 ml⁻¹ criteria (not to be exceeded by >10% of samples collected during a 30 day period) for shellfish harvesting waters (EPA 841-R-00-002). The criterion is identical to criteria developed under the National Shellfish Sanitation Program which is regulated by the U.S. Food and Drug Administration (USFDA 2007).

Results

CDFs, Cluster Analysis, and z Test

The results of the CDFs for all measured parameters and the water quality index are presented in Table 4. Areal estimates are shown for the combined pre-hurricane period from 2000 to 2004 for both the MS and LP and for post-Katrina.

When the two sample periods, pre-Katrina (2000–2004) and post-Katrina (2005), were compared using a two-

Table 4 Results of cumulative distribution function (CDF) analysis for measured parameters and the water quality index for the Mississippi Sound-Lake Borgne (MS) and Lake Pontchartrain (LP) survey areas

	MS		LP	
	Pre-Katrina	Post-Katrina	Pre-Katrina	Post-Katrina
Dissolved oxygen				
Missing	11.5	0.0	0.0	0.0
Poor	2.3	0.0	14.3	0.0
Fair	32.9	3.3	30.6	3.3
Good	53.3	96.7	55.1	96.7
Chlorophyll <i>a</i>				
Missing	0.3	0.0	2.0	0.0
Poor	0.0	13.3	0.0	0.0
Fair	39.5	76.7	46.9	90.0
Good	60.2	10.0	51.0	10.0
Dissolved inorganic nitrogen				
Missing	0.0	0.0	0.0	0.0
Poor	0.0	0.0	0.0	0.0
Fair	5.1	0.0	12.2	3.3
Good	94.9	100.0	87.8	96.7
Dissolved inorganic phosphorus				
Missing	0.0	0.0	0.0	0.0
Poor	21.4	0.0	22.4	0.0
Fair	57.4	90.0	59.2	93.3
Good	21.2	10.0	18.4	6.7
Water clarity				
Missing	6.7	10.0	14.3	16.7
Poor	32.2	10.0	0.0	3.3
Fair	11.9	46.7	6.1	36.7
Good	49.3	33.3	79.6	43.3
Water quality index				
Missing	0.0	0.0	0.0	0.0
Poor	6.1	0.0	4.1	0.0
Fair	68.2	90.0	77.6	86.7
Good	25.8	10.0	18.4	13.3
Total suspended solids				
Missing	0.0	0.0	0.0	0.0
<10 mg l ⁻¹	54.1	13.3	8.2	13.3
10–20 mg l ⁻¹	33.1	40.0	51.0	20.0
>20 mg l ⁻¹	12.8	46.7	40.8	66.7
Salinity				
Oligohaline	2.9	0.0	71.4	3.3
Mesohaline	38.0	50.0	22.4	96.7
Polyhaline	55.9	50.0	6.1	0.0
Euhaline	3.3	0.0	0.0	0.0
Oil and grease				
<5 mg l ⁻¹		63.3		6.7
5–10 mg l ⁻¹		36.7		90.0
>10 mg l ⁻¹		0.0		3.3

Values represent the condition of each resource as an areal percentage and across the pre-Katrina period (2000–2004) and post-Katrina (2005)

sample *z* test, the areal percentage of “good” condition was significantly different for all parameters except DIP in MS and for the water quality index, DIN and DIP in LP; however, the changes in “fair” condition was significant for these parameters, excluding DIN (Table 5). Significant differences were detected in the areal percentage of “poor” condition in LP for DO and DIP, which decreased post-Katrina and for TSS which increased. In MS the percentage of area exhibiting “poor” conditions was significantly lower for DIP and water clarity and higher for DIP, TSS, and Chla post-storm.

The results of the cluster analyses support the use of the CDF output for estimating and comparing condition from probabilistic survey data across temporal scales. Water quality index variability had little impact on the interpretation of CDF results across the years for both survey areas (Fig. 2). Groupings of condition by year show no significant differences in the interpretation of CDF output based on the areal percentages for each condition for five water quality parameters collectively. The only exception in these results was in LP for 2002 and 2003 where areas classified as fair in 2002 grouped closer to areas with poor ratings. The proximity to fair–poor threshold values resulted in the fair condition clustering with poor. The differences between the post Katrina and the previous five years in the each category (poor, fair and good) indicates that the indicators contributing to that condition were different, i.e., low water clarity as opposed to low DO., but interpretation of water quality was not affected. Although sampled outside of the summer index period, the post-Katrina interpretation of condition was comparable across index periods. Our comparisons evaluate water quality in periods with the potential of highest ecological stress as demonstrated in the summer months and following catastrophic events.

Dissolved Oxygen

Following the storm, the area of MS with bottom DO concentrations >5 mg l⁻¹ was estimated at 97% and approximately 3% of the area had bottom DO concentrations ranging from 2 to 5 mg l⁻¹. No bottom DO concentrations <2 mg l⁻¹ were observed after Hurricane Katrina. Bottom DO concentrations >5 mg l⁻¹ were observed for 53% of the survey area from 2000 to 2004. Two percent of the area was considered hypoxic (<2 mg l⁻¹) and 33% had DO measurements between 2 and 5 mg l⁻¹ (Table 4). The areal distribution of DO concentrations >5.0 mg l⁻¹ was significantly higher than the previous five years (Table 5).

In the survey post-Katrina, an estimated 97% of the area of LP had bottom DO concentrations >5 mg l⁻¹, an areal increase of approximately 42% compared to the 2000–2004 pre-storm estimates. Approximately 14% of the area

Table 5 Two-sample z test results comparing pre-Katrina and post-Katrina areas constructed using the percentages for good, fair and poor condition and the mean standard deviation (Mean SD) for each condition estimate for both Lake Pontchartrain (LP) and Lake Borgne-Mississippi Sound (MS) survey areas ($P \leq 0.05$; 1 SD)

Parameter	Pre-Katrina			Post-Katrina			LP			MS			Significant at 0.05?			
	Estimate (% Good)	Mean SD	MS	Estimate (% Good)	Mean SD	MS	Estimate (% Good)	Mean SD	MS	p	s	z				
WQ Index	18.37	0.04	25.76	0.03	13.33	0.06	10.00	0.06	0.0759447	0.0503401	0.1576118	0.6628526	N	0.0627576	2.5114383	Y
Bottom DO	55.10	0.06	53.31	0.04	96.67	0.03	96.67	0.03	0.0696449	-0.4156463	-0.4335510	5.9680768	Y	0.0501888	8.6384073	Y
Mean DIN	87.76	0.05	94.89	0.02	96.67	0.03	100.00	0.00	0.0578771	-0.0891156	-0.0510632	1.5397386	N	0.0221811	2.3021042	Y
Mean DJP	18.37	0.06	21.22	0.03	6.67	0.05	10.00	0.06	0.0742713	0.1170068	0.1121793	1.5753971	Y	0.0647967	1.7312484	N
Mean CHL	51.02	0.05	60.18	0.02	10.00	0.06	10.00	0.06	0.0724250	0.4102041	0.5018053	5.6638493	Y	0.0638759	7.8559367	Y
Mean TSS*	8.16	0.06	54.14	0.04	13.33	0.08	13.33	0.08	0.0934086	-0.0517007	0.4080821	0.5534893	N	0.0868420	4.6991333	Y
Water Clarity	79.59	0.05	49.26	0.03	43.33	0.08	33.33	0.07	0.0954733	0.3625850	0.1592173	3.7977643	Y	0.0770784	2.0656547	Y

Parameter	Pre-Katrina			Post-Katrina			LP			MS			Significant at 0.05?			
	Estimate (% Fair)	Mean SD	MS	Estimate (% Fair)	Mean SD	MS	Estimate (% Fair)	Mean SD	MS	p	s	z				
WQ Index	77.55	0.04	68.18	0.03	86.67	0.06	0.00	0.06	0.0759447	-0.0911565	0.6817563	1.2003006	N	0.0627576	10.8633290	Y
Bottom DO	30.61	0.06	32.92	0.04	3.33	0.03	0.00	0.03	0.0696449	0.2727891	0.3291891	3.9168556	Y	0.0501888	6.590193	Y
Mean DIN	12.24	0.05	5.11	0.02	3.33	0.03	0.00	0.00	0.0578771	0.0891156	0.0510632	1.5397386	N	0.0221811	2.3021042	Y
Mean DJP	59.18	0.06	57.37	0.03	93.33	0.05	0.00	0.06	0.0742713	-0.3414966	0.5737043	4.5979612	Y	0.0647967	8.8539062	Y
Mean CHL	46.94	0.05	39.48	0.02	90.00	0.06	13.33	0.06	0.0724250	-0.4306122	0.2614603	5.9456329	Y	0.0638759	4.0932514	Y
Mean TSS*	51.02	0.06	33.05	0.04	20.00	0.08	46.67	0.08	0.0934086	0.3102041	-0.1361246	3.3209358	Y	0.0868420	1.5674968	N
Water Clarity	6.12	0.05	11.90	0.03	36.67	0.08	10.00	0.07	0.0954733	-0.3054422	0.0189502	3.1992424	Y	0.0770784	0.2458560	N

Parameter	Pre-Katrina			Post-Katrina			LP			MS			Significant at 0.05?			
	Estimate (% Poor)	Mean SD	MS	Estimate (% Poor)	Mean SD	MS	Estimate (% Poor)	Mean SD	MS	p	s	z				
WQ Index	4.08	0.04	6.06	0.03	0.00	0.06	0.00	0.06	0.0759447	0.0408163	0.0606319	0.5374480	N	0.0627576	0.9661291	N
Bottom DO	14.29	0.06	2.31	0.04	0.00	0.03	0.00	0.03	0.0696449	0.1428571	0.0231125	2.0512211	Y	0.0501888	0.4605114	N
Mean DIN	0.00	0.05	0.00	0.02	0.00	0.03	0.00	0.00	0.0578771	0.0000000	0.0000000	0.0000000	N	0.0221811	0.0000000	N
Mean DJP	22.45	0.06	21.41	0.03	0.00	0.05	0.00	0.06	0.0742713	0.2244898	0.2141164	3.0225642	Y	0.0647967	3.3044322	Y
Mean CHL	0.00	0.05	0.00	0.02	0.00	0.06	13.33	0.06	0.0724250	0.0000000	-0.1333333	0.0000000	N	0.0638759	2.0873796	Y
Mean TSS*	40.82	0.06	12.80	0.04	66.67	0.08	46.67	0.08	0.0934086	-0.2585034	-0.3386242	2.7674465	Y	0.0868420	3.8993142	Y
Water Clarity	0.00	0.05	32.17	0.03	3.33	0.08	10.00	0.07	0.0954733	-0.0333333	0.2217232	0.3491378	N	0.0770784	2.8765935	Y

*TSS < 10 mg L⁻¹

a TSS < 10 mg l⁻¹

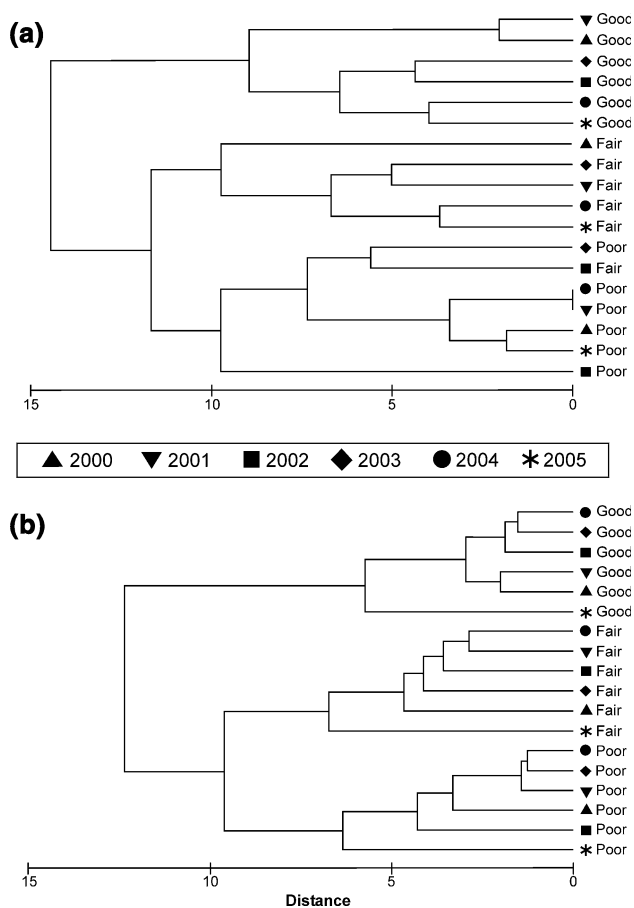


Fig. 2 Results of cluster analyses generated from areal percentages comparing the CDF results for the five core indicators (DIN, DIP, water clarity, DO and Chla). Groupings of condition across the years show no significant influence of inter-annual variability on the interpretation of CDF output (a) Lake Pontchartrain ($n = 79$) and (b) Lake Borgne-Mississippi Sound ($n = 192$)

of LP had bottom DO concentrations $<2 \text{ mg l}^{-1}$ in the period before the storm. Bottom DO concentrations $<2 \text{ mg l}^{-1}$ were not observed during the post-Katrina survey in LP (Table 4).

Salinity

Salinity measurements post-Katrina in MS were significantly higher than values measured in the years prior (Table 4). Salinity data from 2000 to 2004 estimate the average areal distribution of salinity for the survey area as $<3\%$ oligohaline, 38% mesohaline, 56% polyhaline and 3% euhaline, based on NOAA's salinity zone designations (NOAA 1999). Following the Hurricane, the salinity measured characterized approximately 50% of the area being mesohaline and 50% polyhaline (Table 4).

In the 5-year period prior to Hurricane Katrina, approximately 71% of the area of LP was oligohaline and 23% mesohaline and 6% polyhaline. Higher salinities were

observed after the storm, with only 3% of the surveyed area characterized as oligohaline and 97% of the area as mesohaline (Table 4).

Water Clarity

The areal extent of good water clarity significantly decreased post-Katrina in MS and LP. Good water clarity decreased approximately 16% and 36% in MS and LP, respectively. Poor water clarity was not observed in LP prior to Katrina. A significant shift from good to fair was detected in water clarity for LP. The area with poor water clarity in MS significantly decreased from 32% to 10% . (Table 4).

Dissolved Inorganic Nutrients

Following Hurricane Katrina, all of MS and 97% of LP had DIN concentrations $<0.1 \text{ mg/l}$. DIN concentrations were significantly lower in MS post-Katrina. The percent area of the MS with DIP concentrations between 0.01 and 0.05 mg/l increased after the storm compared to 2000–2004; however, the percentage of area with DIP concentrations $>0.05 \text{ mg/l}$ decreased 22% (Table 4). No DIP concentrations $>0.05 \text{ mg/l}$ were observed in LP following the storm, but the areal percentage of DIP scored as fair increased approximately 34% (Table 4). The increase in fair was significant, showing a decrease in the area rated as good and a decrease in poor for DIP.

Chlorophyll *a*

Chla concentrations measured in the water column in the MS in the month following Katrina were higher than the previous 5-year average. The biggest differences between pre and post-Katrina were the areal extent of Chla concentrations $<5 \text{ ug l}^{-1}$ and $5\text{--}20 \text{ ug l}^{-1}$ (Table 4). The areal distribution decreased 50% and 26% for concentrations $<5 \text{ ug l}^{-1}$ and $5\text{--}20 \text{ ug l}^{-1}$, respectively compared to values from the previous 5-year period. Approximately 13% of the area of MS had Chla concentrations $>20 \text{ ug l}^{-1}$ after the storm, compared to no area prior, a significant increase in poor.

In LP, the cumulative distribution results for Chla showed an increase in fair and a decrease in good by 43% and 41% , respectively. In contrast to MS, no concentrations of Chla $>20 \text{ ug l}^{-1}$ were observed in LP following the storm (Table 4); however there were significant decreases in concentrations $<5 \text{ ug l}^{-1}$ and increases in concentrations $5\text{--}20 \text{ ug l}^{-1}$.

Total Suspended Solids

TSS concentrations significantly increased in MS and LP post-Katrina resulting in an increase in the areal percentage

of both areas with concentrations $\geq 20 \text{ mg l}^{-1}$. The area of MS exhibiting $\geq 10 \text{ mg l}^{-1}$ TSS increased approximately 41% and the area with concentrations $< 10 \text{ mg l}^{-1}$ significantly decreased (Table 4). A lower percentage of TSS concentration ranging between 10 and 20 mg l^{-1} occurred in LP, indicating a shift towards higher concentration of TSS post-Katrina.

Water Quality Index

A shift toward fair was detected in the CDF for water quality in MS after the storm with a significant decrease in good water quality following the storm. A similar, but smaller change was seen for LP which showed a significant increase in fair water quality ($P = 0.05$). No poor water quality was observed in either survey area post Katrina in contrast to 2000–2004 (Table 4).

Contaminants

No oil and grease concentrations for MS samples exceeded the 10 mg l^{-1} concentration listed for effluent of permitted outfalls in Mississippi surface waters. The majority (63%) of the area had oil and grease concentrations $\leq 5 \text{ mg l}^{-1}$. Concentrations > 5 and $\leq 10 \text{ mg l}^{-1}$ were measured for 37% of the surveyed area. Approximately 90% of the area surveyed in LP had concentrations of oil and grease between 5 and 10 mg l^{-1} . Oil and grease concentrations exceeded 10 mg l^{-1} for 3% of LP and 7% of the area had oil and grease concentrations $\leq 5 \text{ mg l}^{-1}$.

Concentrations of metals detected in water samples collected from MS and LP are presented in Table 5. No metals concentrations exceeded EPA's acute criteria for the protection of aquatic life in marine waters; however, chronic exposure criteria were exceeded for copper at one

station, lead at a second station and for both at a third station in MS (USEPA 2002b) (Table 6).

All concentrations measured in water samples collected from LP and MS were below detection limits for both pesticides and PAHs. Atrazine was detected in water samples from five of the 28 MS sampling stations. Concentrations ranged from 0.10 to 0.18 ug l^{-1} . Concentrations at all sites were well below the currently proposed saltwater water quality criterion of 17 ug l^{-1} .

Microbial Indicators

Results from the post-Katrina survey in MS show that concentrations of *C. perfringens* spores in the water column were undetectable or low. Microbial samples are not routinely collected under the NCA Program; therefore, no pre-storm data were available to make pre- and post-Katrina comparisons. None of the samples from either LP or MS exceeded criteria for fecal coliform. The highest concentrations measured were $12 \text{ cfu } 100 \text{ ml}^{-1}$ and $3 \text{ cfu } 100 \text{ ml}^{-1}$ in LP and MS, respectively. Bacterial enumeration for enterococci for both LP and MS indicate that the number of cfu observed did not exceed the $104 \text{ cfu } 100 \text{ ml}^{-1}$ guidance criteria. The maximum number of cfu 100 ml^{-1} observed was 2 in LP and 10 in MS.

Discussion

Water quality can be severely degraded following the passage of a hurricane. Although water quality is highly variable in Gulf of Mexico estuaries, as noted by Pennock and others (1999), long term monitoring data can be useful in examining the short-term effects of these climatic events. Our assessments in the weeks post-Katrina indicate

Table 6 Concentrations of metals in water samples collected from Lake Pontchartrain and Lake Borgne-Mississippi Sound stations post-Hurricane Katrina compared to EPA criteria protective of aquatic life in salt water

Analyte (ppm)	Lake Pontchartrain	Lake Borgne-MS Sound	Acute	Chronic
Aluminum	40.06–2106.4	85.06–1776.8	–	–
Arsenic	0.345–0.777	0.49–1.11	149	78
Cadmium	0.018–0.042	0.016–0.213	45.4	10
Chromium	0.142–0.763	0.212–0.75	–	–
Copper	0.954–2.15	0.808–5.43	13.5	3.6
Lead	0.049–0.724	0.109–10.6	133	5.3
Mercury	0.001–0.003	0.001–0.273	2.1	1.1
Nickel	0.878–5.55	0.618–3.18	118	13.1
Selenium	0.121–0.237	0.076–0.297	564	136
Silver	0–0.041	0.006–0.022	2	–
Zinc	0.804–39.5	0.781–13.7	92.7	84.2

USEPA (2002b); National Recommended Water Quality Criteria table EPA-822-R-02-047

that negative impacts on water quality in the affected areas surveyed were short-lived or had not yet developed. This short-term impact on particular water quality measures is supported by more frequent monitoring programs conducted by the Louisiana Department of Environmental Quality (LDEQ) in the days immediately following the storm and throughout the following months. The tributaries associated with the estuarine areas in our survey sampled by LDEQ and stream sites sampled by USGS, exhibited some evidence of short-term water quality degradation (LDEQ 2006; Rebich and Coupe 2005). These conditions are not uncommon in the upper reaches of these systems during the course of the year and are commonly expected following hurricane landfall, as these areas exposed to and receive immediate runoff from adjacent land uses. In addition to the direct hit by Katrina, the area was also subjected to heavy rainfall from Hurricane Rita which made landfall along the Texas-Louisiana border on September 24, 2005. However, results summaries from the USGS sampling efforts report “nearly all of the results from the water-quality samples were below available criteria, with the exceptions of a few dissolved oxygen, total phosphorus, aluminum, and copper concentrations” and there were no indications of “systematic contamination in the aftermath of Hurricane Katrina at the streams sampled during this study” (Rebich and Coupe 2005).

Hurricanes making landfall in coastal areas dominated by human development have apparent effects on water quality (Mallin and others 2002; Bales 2003; Ko and Day 2004; Hagy and others 2006). Coastal landscapes comprised primarily of urban, industrial and agricultural land uses can compound the effects of hurricanes on water quality with contributions from concentrated animal feed operations and waste water treatment plants damaged during the passage of hurricanes and account for the majority of nutrient and pathogen loading (Mallin and Corbett 2006). The Lake Borgne-Mississippi Sound and Lake Pontchartrain estuarine drainage areas are predominantly forested and emergent wetlands (NOAA 1999). Approximately 13% of these estuarine drainage areas is classified as agricultural, and less than 3% is developed (suburban and industrial land uses combined). The concentration of the population in large urban areas below sea level in Louisiana, destroyed by Katrina, were identified as the major sources of pollution to adjacent waters (Mallin and Corbett 2006). Despite the pumping of flood waters into Lake Pontchartrain and the widespread destruction of infrastructure in these coastal areas, water quality as assessed using the probabilistic survey data compared to pre-storm conditions shifted slightly from good to fair on an areal basis; however, poor water quality was not observed as evaluated using NCA threshold values. LDEQ and USGS sampling during our survey period also reflect

only minor, localized and short-lived water quality degradation (LDEQ 2006; Rebich and Coupe 2005).

Slow moving storms dumping tremendous amounts of rain can cause flood conditions and increase runoff and river flow, resulting in excessive amounts of nutrients and contaminants bound to sediments being delivered to estuarine waters (Rabalais and others 1998). The turn of Katrina to the east after landfall prevented excessive river flow into the Gulf coastal waters thereby reducing the water quality impact from riverine input. Open exchange with the Gulf of Mexico and the shallow characteristics of many GOM estuaries, including Mississippi Sound, result in bottom waters being mixed during the passage of coastal storms due to sustained winds and tidal action. In the five years period prior to the storm, strong stratification was not measured in LP; however, salinity differences greater than 10 psu and 5–10 psu were observed for 3% and 12% of the MS survey area respectively. Post-hurricane, only 7% of the survey area had bottom-surface salinity differences 5–10 psu and 93% showed salinity differences less than 5 psu. The reduction in salinity stratification suggests water column mixing. Hagy and others (2006) report that stretches of the Pensacola Bay system seasonally affected by hypoxia, were well oxygenated due to mixing by strong winds and flushing by tidal surge in the days immediately following the passage of Hurricane Ivan. In Charlotte Harbor DO values dropped to near hypoxia concentrations in response to Hurricanes Charley, Frances and Jeanne during the 2005 season, however, within a month, DO concentrations recovered to pre-storm conditions. Recovery was attributed to attributed to Charlotte Harbor’s flushing rate due to proximity to the Gulf of Mexico (Tomasko and others 2006). Elimination of the hypoxic or “dead zone” in the near shelf waters of the GOM following Katrina’s landfall (Swarzenski 2006) also provides strong evidence as to the degree of mixing in these impacted waters surveyed.

Increased primary production, reflected by increased Chl_a concentrations, may also support the higher DO concentrations measured post-Katrina. This increase in primary production could be due to the perturbation of bottom sediments and the reintroduction of nitrogen and phosphorus into the water column fueling algal production as observed in Mobile Bay, Alabama following the passage of Hurricane Ivan (Park and others 2007). The areal percentage of the MS with concentrations of dissolved inorganic nitrogen (DIN) $>0.1 \text{ mg l}^{-1}$ decreased following the storm, while the area with dissolved inorganic phosphorus (DIP) concentrations $>0.01 \text{ mg l}^{-1}$ increased compared to the previous 5-year period. In MS, nutrient concentrations post-Katrina were lower than the previous 5-year average, resulting in waters previously classified poor becoming fair. Dissolved nutrient concentrations measured in

Pensacola Bay after Hurricane Ivan were within normal range; however, in areas where hypoxia developed in the months following, ammonium levels greatly increased (Hagy and others 2006). This increase in bottom ammonium was assumed to be related to the decomposition of organic debris. Similarly, reductions in DO in the streams north of Lake Pontchartrain during the weeks following hurricane landfall were attributed to accumulation of massive amounts of woody, vegetative and structural debris (LDEQ 2006). Sampling 6 weeks after the storm may have been too late to detect spikes in nutrient input and too early to see increased ammonium due to increased decomposition; however, the increase in Chla in MS in the presence of elevated DIP concentrations post-Katrina may be indicative of an increased input of nutrients into the system following the passage of the hurricane.

As expected, increased light attenuation was observed in the post-Katrina survey areas. Elevated Chla and TSS concentrations decreased water clarity and contributed to lower water quality index values. Increased suspended solids concentrations, an order of magnitude, have been observed in the coastal areas of Louisiana during the passage of even remote storms (Walker 2001). Increased runoff due to rainfall in the immediate area may have also contributed to the increased TSS concentrations and decreased water clarity. The upper reaches of coastal systems and those with limited exchange with ocean waters tend to exhibit higher light attenuation coefficients, i.e., decreased water clarity (Mallin and others 2002; Dix and others 2008). The significant decrease in “good” and increase in “fair” water clarity observed in LP may be related to the combination of the limited exchange with the GOM, runoff and re-suspension, and the pumping of flood waters into the estuary. Although “fair” water clarity significantly increased in the MS survey area, the area exhibiting “poor” water clarity decreased. These observations reflect the open exchange between the GOM and MS proper, which represents most of the survey area.

Post-Katrina, the areal distribution of saline waters within the survey areas drastically differed from previous 5-year period. According to Solis and Powell (1999) the volume weighted average salinities of Lake Pontchartrain, Mississippi Sound and Mobile Bay are 12, 15 and 12, respectively. The change in salinity within these estuarine systems is related to the extreme tidal surge associated with the passage of the storm. Dramatic shifts in salinity are expected after hurricane landfall (Van Dolah and Anderson 1991; Hagy and others 2006; Park and others 2007). Since estuaries are transitional waters, salinity shifts are primarily climatically driven. The microtidal, shallow estuaries of the GOM are particularly susceptible to wind driven processes during storms. In addition to altering benthic and phytoplankton communities, increases in salinity can result in

salinity-related marsh kills, especially in regions deprived of fresh water inflow. As noted by Walker (2001), more information is needed to advance our knowledge of the relative importance of salinity stress on the biological condition of estuarine systems following disturbance.

No concentrations of contaminants were found in the water column exceeding marine criterion when we sampled approximately six weeks following landfall of Hurricane Katrina. Additional bedded sediment samples taken during this survey indicated no detectable change in contaminant concentrations from previous survey years. Since concentrations of contaminants in both the water and the sediments were low, it is unlikely that the waters sampled following Hurricane Katrina were subjected to persistent sources of elevated levels of contaminants. Continued monitoring by LDEQ supports these conclusions, showing no detectable levels of contaminants in the surface waters and no biotoxicity in the months following Katrina (LDEQ 2006).

Criteria for fecal coliform in estuarine waters were not exceeded in any of samples collected. Concentrations of *C. perfringens* in the water column were not detectable in most cases, with a few stations showing a very low presence. These data support a very low concentration of feces from warm blooded mammals in the surface waters of LP and MS 6 weeks following Hurricane Katrina. Since pathogen indicator data were not collected during previous sample years, and most data collected regularly are site specific for shellfish harvest regulation, changes in bacterial counts could not be compared. Following heavy rain events, increases in fecal contamination concentrations are not uncommon. Subsequent to Katrina, any discharges from flooded or compromised municipal treatment systems were of brief duration or rapidly diluted. Results of sampling conducted by LDEQ regularly before and after the storm indicate short-lived increases in fecal contamination in some canal systems with return to non-exceedence levels in the month following. Similar results were reported in the stream sites monitored by USGS (Rebich and Coupe 2005) Environmental conditions were reported as unchanged in LP as result of the hurricane and subsequent pumping of New Orleans flood waters into the water body (LDEQ 2006).

Following Hurricane Katrina, water quality assessed using the five core water quality parameters (DO, Chla, DIN, DIP and water clarity) did not differ from previous years. Compared to five years of probabilistic survey data, water quality was not negatively altered and in some instances environmental measures positively increased. The estuaries affected by Katrina, like many southeastern U.S Atlantic and Mexico estuaries frequently disturbed by hurricanes, demonstrate rapid (with months) recovery in water quality (Dix and others 2008; Park and others 2007;

Hagy and others 2006; Mallin and Corbett 2006; Tomasko and others 2006; Van Dolah and Anderson 1991; Mallin and others 2002). From an ecological perspective, these shallow near coastal systems may even “benefit from the scouring activity of these storms” (Burkholder and others 2004). The water quality index was driven by changes in water clarity, Chla and DIP in the post-storm survey. While we cannot determine causation of these changes from snapshot data, we can infer from the literature as to the most likely influences on these conditions. More important is the concept of having data and statistically valid methodologies in place to enable us to make pre-and post storm comparisons (Urquhart and others 1998; Faustini and Kaufmann 2007).

Ideally, post-storm sampling of the Hurricane Katrina impacted area would have begun immediately following landfall and continued for a period of time, but with the catastrophic damage to infrastructure and deference to Katrina victims, such activity was inappropriate from a logistics and humane perspective. The post-storm sampling was developed to capture conditions that might show the potential for persistent storm-related ecological stress and to establish a baseline related to a catastrophic natural disaster. In Gulf of Mexico estuaries, summer (July–September) is a period when ecological response to toxicological (Summers and others 1995) and physical (Summers 2001) stressors is most likely to be severe. The post-Katrina survey methodology differed from previous surveys in that it was conducted a few weeks outside the index period. However, the comparison between the pre- and post-hurricane results seems most relevant since all the assessments are based on time-periods where ecological stress is expected.

Cluster analyses show very little influence of the inter-annual variability on the interpretation of CDF results; deeming the utility of the probabilistic survey for comparing conditions across temporal scales appropriate; although our post-storm sampling occurred outside of established index period. RF Van Dolah and others (unpublished data) evaluated summer versus year round sampling for six water quality measures: total nitrogen (TN), total phosphorus (TP), Chla, DO, pH, and fecal coliform in South Carolina’s open water and tidal creek resources. When compared using the same threshold values, the summer sampling identified a higher percentage of good versus fair and poor condition than the year round sampling. The difference was primarily due to differences observed in the TN, TP, and Chla. In a second analysis using DO, pH, and fecal coliform, the summer versus year round outputs were much closer with respect to the percentage of good, fair poor (RF Van Dolah and others unpublished data). For open water estuarine resources in South Carolina, Hayes and others’s assessment using monthly DIN, DIP, and Chla was consistent with the NCA

condition assessments (KC Hayes and others unpublished data). The two-sample z test indicates significant differences in condition before and after the storm and allows us to make statistically valid comparisons between changes in ecological condition using indicator data collected. More intensive monitoring programs in the days immediately after and weeks following Katrina strengthen our post-storm condition assessment as does the literature pertaining to the influence of hurricanes on Gulf of Mexico estuarine systems.

Ecological resilience can be measured by the “magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior” (Holling and others 1995). Following Hurricane Katrina, assessments for water quality indicate that such natural disasters may allow for a natural turnover and purging thereby maintaining and improving the ecological condition analogous to the manner in which fires influence forest ecology (Bales 2003; Hagy and others 2006). We were fortunate to have comparable data for pre-storm and post-storm water quality to evaluate condition. These assessments emphasize the need for consistent, comparable data collection and analyses for making statistically valid estimates of condition over both temporal and spatial scales. Understanding the effects of natural disasters on coastal waters under current watershed management practices is vital for improving water quality and evaluating ecological resilience in these aquatic ecosystems.

Acknowledgments This article expands upon water quality information that has been included in a report entitled “Environmental Conditions in Northern Gulf of Mexico Coastal Waters Following Hurricane Katrina” which was prepared by the U.S. Environmental Protection Agency (EPA), Office of Water (OW), Office of Research and Development (ORD). The content of this report was contributed by EPA, the National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS). Special recognition is due to the field crews of the EPA Gulf Ecology Division, NOAA National Centers for Coastal Ocean Science, USGS National Wetlands Research Center and USGS Water Resources Division-Louisiana Water Science Center for completing this survey under extreme conditions. We thank all staff of state and federal agencies who provided technical reviews and recommendations for this effort.

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