Lake Madeline Bacteria Study
Final Summary Report

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Dr. George Guillen
University of Houston Clear Lake – Environmental Institute of Houston

Lake Madeline, Galveston

Environmental Institute of Houston

EIH Technical Report 2-10A

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Acknowledgements

I would like to thank the City of Galveston and the Ad Hoc Lake Madeline Committee for their financial and logistical support. In particular we would like to acknowledge the guidance and logistical support provided by the City of Galveston Public Works Department, including Eric Wilson who provided support in the form of data and also assisted us in sample collection at storm sewers. Finally I would like to thank all the students and staff who assisted in field work including Dianna Ramirez, Jenny Wrast, and Kelli Haskett who assisted in field collection and laboratory analysis of data. Thanks are also provided to Heather Biggs who provided GIS support during the evaluation of basin topography during the early stages of our proejct.

Table of Contents

List of Figures

List of Tables

Executive Summary

This final summary report represents an abbreviated report focusing on the issues of elevated indicator bacteria and hypoxia (low oxygen). A more comprehensive report that includes information on other variables accompanies this for the interested reader. Due to ongoing concerns about potential risks associated with exposure to sewage contaminated water and reoccurring fish kills, the City of Galveston contracted EIH to conduct a bacteriological surveys of Lake Madeline and surrounding waters during June to October 2006 and again in August through November 2010. The landfall of Hurricane Ike however disrupted monitoring during late September 2008. As a consequence we also conducted one intensive survey on April 2009. The primary objective of the study was to delineate the distribution of bacteriological indicators and potential violations of state water quality criteria or screening levels in the Lake Madeline watershed. The secondary objective was to identify the origin if possible of these indicator bacteria within the lake's watershed. A report was generated for the work conducted in 2006 which documented extensive violations of state of Texas water quality standards for both *Enterococcus* bacteria and the previous fecal coliform standards. In addition, there appeared to be very high levels of bacteria occurring in our several storm sewers suggesting cross contamination of storm water and sanitary sewer lines. The City of Galveston initiated repairs on sewer lines in the vicinity of Lake Madeline to address this problem. It was determined that a follow-up sampling and analysis two years later in 2008 was warranted to determine if indicator bacteria levels were still elevated.

Based on our intensive monitoring, Lake Madeline still does not appear to be meeting State of Texas contact recreation water quality standards during high rainfall events. For the purposed of the final report we focused our analysis on the currently approved State of Texas indicator bacteria, *Enterococcus* and the associated bacteriological standard. *Enterococcus* levels were elevated throughout the lake during periods of increased rainfall. The various storm sewers discharging into Lake Madeline appear to have the highest levels of indicator bacteria and are probably the most significant sources of *Enterococcus*. In addition, some of these sites contained elevated levels of even during dry weather. Our findings suggest that there appears to be a strong positive relationship between *Enterococcus* bacteria levels within storm sewers and precipitation.

In addition to elevated indicator bacteria, Lake Madeline continues to exhibit low oxygen levels in the deeper portions of the lake. These hypoxic levels will not support most forms of aquatic life. Many of these measurements are below the state minimum criteria. These low levels are reinforced by strong salinity induced stratification which reduces mixing, and apparent eutrophic (high nutrients and algae) conditions present in the upper portions of the water column. There does appear to be a slightly increasing trend in dissolved oxygen that may have been triggered by the introduction of solar mechanical circulation. However, additional years of monitoring will be necessary to evaluate the effectiveness of technological approaches to reduce bacteria loading.

The data collected during this study and past investigations supports the hypothesis that contaminated storm water runoff is a significant source of indicator bacteria within the watershed. Potential causes include faulty leaking wastewater collection systems (sanitary sewers) which can cause cross contamination of storm sewer discharges during high rainfall events and other sources such as runoff from facilities with domesticated animals, livestock and wild animals including colonial water birds. The ongoing investigations and repairs to the storm water and sanitary sewer collection systems being conducted by the City of Galveston will address some of these potential sources. Monitoring should be conducted as repairs are completed to document expected improvements in water quality.

Introduction

Lake Madeline is a man-made lake located on the western end of Galveston Island, Texas (Figure 1). The lake is irregular in shape and measures 1,506 feet wide at its longest axis. The calculated area is approximately 47.7 acres. There are two finger canals that extend from the lake along the northwestern and western end of the lake. Water depths near the middle of the lake extend to 25 feet in its deeper portions. Lake Madeline is connected to Offatts Bayou via a 3,925 ft long canal. The 26.21 acre canal is on average 30 ft wide and has an average depth of 13 feet. The total estimated drainage area into the lake is 953 acres (E. Wilson, City of Galveston, pers. comm.). Based on the observed tidal amplitude and the surface area of the lake, we estimated that the volume of water displaced within the lake during a tidal cycle is approximately 24.85 million gallons. An additional 13.66 million gallons is displaced in the connecting canal. The surrounding watershed including Offatts Bayou was highly modified prior to World War II by dredging to provide fill material for maintenance of the Galveston seawall (Gunter 1942). Since then the area has had numerous water quality problems including fish kills associated with resulting water stratification and poor circulation.

Water quality has been monitored in Lake Madeline by various agencies including Galveston County Health District (GCHD), Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and the Clean Rivers Program (CRP). Routine monitoring has been limited to a few locations within the watershed. Sampling usually occurs on a monthly or less frequent basis. Local citizens have observed and complained for many years about periodic fish kills, floating debris of sanitary sewer origin, and foul odors within the lake. Fish kills and poor water quality have also been documented within Lake Madeline by various agencies (R. Schultz – GCHD, Winston Denton – TPWD). During 2005 and 2006 the GCHD documented elevated Enterococcus bacteria levels in the Lake due to various potential sources including malfunctioning sanitary sewer outfalls and wastewater treatment facilities (R. Schultz pers. comm.). Offatts Bayou has exhibited impaired water quality and historical fish kills since the early 1930's due to poor circulation caused by the deep dredging and subsequent silting of the mouth (Gunter 1942, Cooper and Morse 1996) (Figure 2).

In Texas, water quality indicators are compared to state water quality standards, which include numeric criteria. These numerical criteria have been developed to protect various legally designated uses for each waterbody. Important uses included aquatic life protection and contact recreation. Human contact recreation can be detrimentally impaired when waters become contaminated with material that contains pathogens. However, due to their diversity and the complexity associated with culturing the organisms, it is very difficult to directly monitor the presence of pathogens. Instead, various indicators of human sewage contamination have been developed that can be used to assess the relative health risk of swimming in a waterbody. Their presence indicates that there is a higher probability of pathogens being found in the water. Currently only *Enterococcus* is approved as an indicator for evaluation of attainment of contact recreation standards in marine waters.

Figure 1. Location of Lake Madeline on Galveston Island, Texas.

Figure 2. Past shorelines in the vicinity of Lake Madeline illustrating the extensive modification of the shoreline.

Lake Madeline is part of the West Bay, Galveston Bay watershed. For regulatory purposes the state water quality standards for West Bay are also applicable to Lake Madeline. According to TCEQ (2002), Lake Madeline is considered an unclassified water body that has been assigned its own assessment unit 2424B. The primary monitoring site used to evaluate compliance with state water quality standards has been TCEQ monitoring site 16564 which is described as "Lake Madeline at corner of Beluche Drive and Dominique Drive in Galveston". TCEQ describes Lake Madeline as having a surface area of 0.1 square miles. The primary concerns for the waterbody included depressed dissolved oxygen and nutrient enrichment (e.g. ammonia). The current TCEQ designated uses of West Bay include high aquatic life use, oyster production, and contact recreation (TCEQ 2000). The associated numerical water quality standard for contact recreation in West Bay is a geometric mean of 35 *Enterococcus* colonies per 100 ml (TCEQ 2000 and 2003). In addition, single samples should not exceed 89 colonies per 100 ml. Normally the geometric mean criterion is evaluated based on a sample size of 10 or more. The single sample criterion is evaluated using a benchmark of no more than 25% of the samples being higher than this value. Both of these numerical criteria apply only to ambient surface water. The bacteriological criteria for oyster waters is defined as a median fecal coliform concentration, exclusive of buffer zones, that shall not exceed 14 colonies per 100 ml, with not more than 10% of all samples exceeding 43 colonies per 100 ml (TCEQ 2000). However, since most of Lake Madeline is within the 1000 ft shoreline buffer zone, these criteria do not apply. In addition, these waters are not classified as open to oyster harvest.

Another major water quality issue affecting Lake Madeline has been the occurrence of fish kills. Based on past data and the findings of Guillen and Moore (2006), the most likely immediate causative factor associated with fish kills in Lake Madeline in the past has been the occurrence of low (hypoxia) or no (anoxia) dissolved oxygen. This is turn is due to several ultimate causative mechanisms including deep topography, low tidal amplitude and loading from both contaminated storm water, runoff and wastewater effluent. Although not a primary focus of our study, an analysis of dissolved oxygen levels within the lake was presented and discussed by Guillen and Moore (2006). Therefore this report will only provide minimal additional supplementary analyses as needed to accommodate new data. For regulatory purposes the state water quality standards for dissolved oxygen and the protection of aquatic life in West Bay are also applicable to Lake Madeline. The associated numerical water quality standard for West Bay is a minimum 24 hour mean criteria of 5.0 mg/l dissolved oxygen and a daily minimum of 4.0 mg/l (TCEQ 2000). Daily minima are not to extend beyond 8 hours per 24-hour day.

Due to ongoing concerns about potential risks associated with exposure to sewage contaminated water and reoccurring fish kills, the City of Galveston originally contracted EIH to conduct a study of Lake Madeline during June to October 2006 to evaluate the distribution and causes of elevated indicator bacteria in Lake Madeline. Numerous recommendations were made based on the findings of that report which documented high levels of indicator bacteria and seasonally low dissolved oxygen levels. This included a need to continue and expand repairs of existing sanitary sewer collection lines to reduce ongoing loading to Lake Madeline. City of Galveston Public Works department had in fact embarked on a schedule of collection line inspections and repairs (E. Wilson pers. comm.) They indicated that by November 2007 the City of Galveston (COG) had completed extensive repairs of major sewer lines. The COG had also “slip lined” several smaller sewer lines in the Lake Madeline area. It was anticipated that the COG would conduct additional sewer line rehabilitation work during remainder of 2009. However, Hurricane Ike hit Galveston in September 2009. Since then the COG and other communities had to redirect much resources to repairing government infrastructure so this may have been delayed.

The local residents and/or COG installed a solar powered aeration system (i.e. Solar Bee) in Lake Madeline to increase vertical circulation and potentially reareation (Figures 3 and 4) . The solar pump was installed on June 25, 2007. The unit was installed at 21’ depth to reduce potential odors. To our knowledge the unit has been continuously in operation.

Another natural occurrence that affected Lake Madeline was the land-fall of Hurricane Ike on Galveston Island and bays. Hurricane Ike came ashore Galveston Island on September 13, 2008. A storm surge of over 10 feet inundated most of West Bay including Lake Madeline. Prior to this tide levels had been 3-4 feet above normal for several days.

The findings of the first portion of this project were published in Guillen and Moore (2006). The reader should consult with that report which provides extensive historical documentation of water quality conditions in Lake Madeline and conditions prior to implementation of collection line repairs and installation of the aerator. The primary objective of this final phase of the study was to delineate the distribution of bacteriological indicators and potential violations of state water quality criteria or screening levels in the Lake Madeline watershed. The secondary objective was to determine whether remedial actions taken by COG have had a measurable impact on the water quality as determined by targeted and routine ambient water quality monitoring. Finally we also briefly examine the response of dissolved oxygen to the solar aeration system.

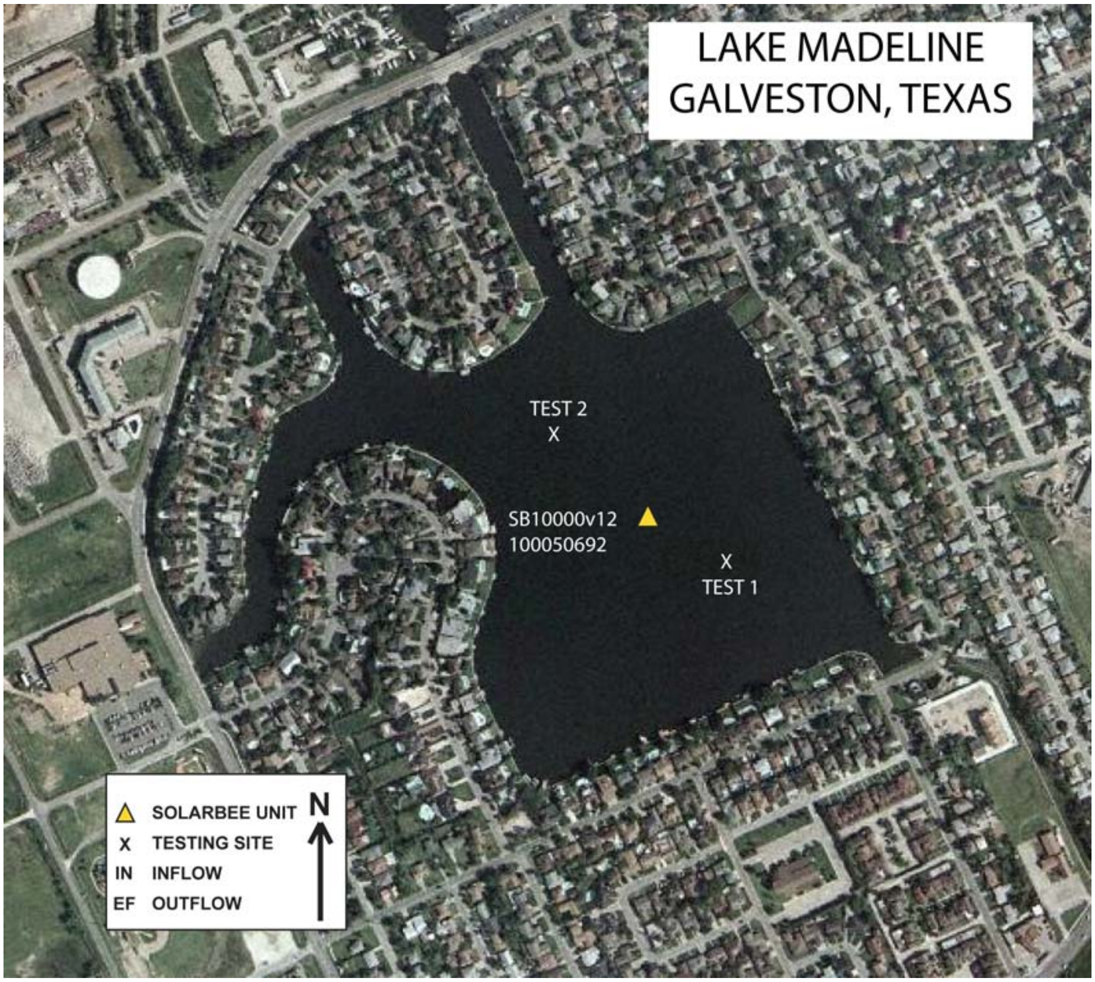

Figure 3. Location of subsurface aerator for Lake Madeline. Installed June 25, 2007.


Figure 4. Solar powered aerator assembly floating in middle of Lake Madeline.

Methods

Sites were previously selected in consultation with City of Galveston officials and the Ad Hoc Lake Madeline Committee in order to better determine potential sources of indicator bacteria. Potential sources that were examined included wildlife, livestock, domesticated animals, point source and non-point source discharges (Guillen and Moore 2006). This was be done by comparing sample results from potential sources (e.g. storm sewer lines, wastewater discharge points) with open water sites and "control" sites minimally influenced by storm sewer systems and other human use. We continued this approach during the final phase of the project to determine if temporal trends exist.

Samples were collected at 24 sample sites within the Lake Madeline watershed and adjacent areas throughout the survey (Figure 5 and Table 1). During dry weather conditions a total of 18 sites were generally monitored. During wet weather events we monitored an additional 6 sites which included various storm water sewers and ditches. Three sites were located outside the Lake Madeline drainage. They include the middle of Offatts Bayou (EIH 7), Sydnor Bayou (COG 6) and a drainage ditch located within the Moody Gardens complex which drains into Offatts Bayou (EIH 8). Sydnor Bayou served as a negative control to Lake Madeline, since it is outside the immediate watershed and not subject to the same amount of urban development. Samples were collected approximately every 2 weeks for a period of 4 months starting in the summer (June 06 and August 08) and ending in October 2006 or November 2008 respectively. We also collected once during April 2009. City of Galveston staff assisted in the collection of samples at sites accessible from land.

We attempted to sample during at least 2-3 wet weather events that yielded significant rainfall. A significant rainfall event was defined as a one inch of rain recorded within a 4 hours period, following an interval of at least 72 hours of no precipitation. This definition is consistent with past studies which have focused on bacteriological loading. However, due to logistics we adjusted this definition and instead tried to sample immediately after any rainfall event that yielded at least 1 inch of rain within a 24 hour period. Precipitation data was obtained from the Scholes Field Airport National Weather Service Station. Samples were not collected when sea conditions were hazardous (e.g. lightning and/or NOAA marine warnings).

We utilized *Enterococcus* as our primary indicator bacteria group. In addition, we conducted testing of fecal coliform bacteria primarily for comparison to historical data. Fecal coliform monitoring was not conducted during the second phase (2008-2009) of the project so there will not be any extensive additional discussion of the fecal coliform data previously evaluated in Guillen and Moore (2006). Until recently fecal coliforms were used extensively to assess human health risks in ambient water. However, *Enterococcus* has been recommended over fecal coliforms due to the fact that is has been judged to be a better indicator of exposure to human waste and associated pathogens (EPA 1986). McElyea (2003) found that *Enterococcus* levels were highly correlated with fecal coliform concentrations and when used exceeded state water quality standards more frequently.

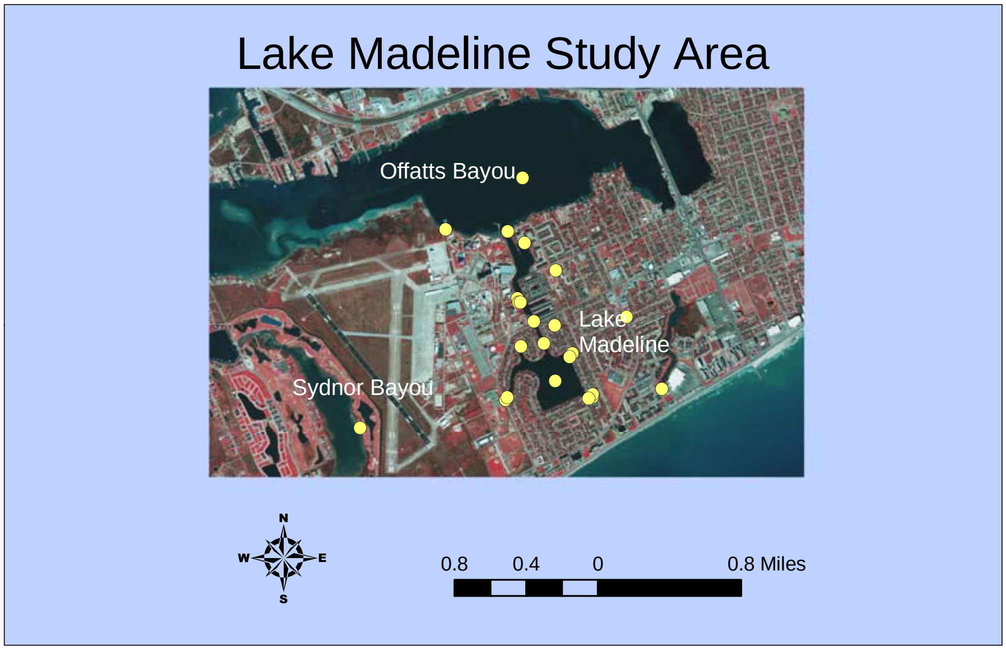

Figure 5. Location of Lake Madeline sample sites in yellow. See table 1 for description of each site.

Table 1. Description of sample sites monitored during the study.

Station	Description	Type	Sampling Period
EIH 7	CENTER OF OFFATTS BAYOU	Ambient	Both
EIH 8	EFFLUENT CHANNEL INTO OFFATTS FROM MOODY GARDEN TO THE RIGHT OF THE CAPITANS DOCK	Source	Both
COG 5	THE MOUTH OF LAKE MADELINE CANAL @ OFFATTS BAYOU	Ambient	Both
EIH 9	INSIDE LM CANAL MARINA AT MOST NORTHERN POINT	Ambient	Both
COG 12	HEARDS LANE STORM SEWER TO LAKE MADELINE CHANNEL	Source	Wet weather
EIH 10	IN CANAL IMMEDIATELY UPSTREAM OF MARINA	Ambient	Both
COG 11	DRAINAGE DITCH FROM AIRPORT TO LAKE MADALINE CHANNEL	Source	Wet weather
EIH 11	Airport Wastewater Plant discharge into Lake Madeline Channel	Source	Both
EIH 12	LM Channel, just downstream of Jones Road bridge	Ambient	Both
COG 10	48 " STORM SEWER ALONG JONES ROAD IN LAKE MADELINE CHANNEL DIRECTLY BELOW BRIDGE	Source	Wet weather
EIH 13	LM Channel, just upstream of Jones Road bridge at entrance into LM	Ambient	Both
EIH 15	NE CORNER OF LAKE MADELINE	Ambient	Both
COG 1	60 INCH STORM SEWER @ BELUCHE NEAR GEROL	Source	Both
COG 3	STEWART RD SEWER IN VICINITY OF FAIRWAY LN - 7402 STEWART (BAPTIST CHURCH)	Source	Both
EIH 16	SE CORNER of LM	Ambient	Both
COG 9	STORM SEWER @ BELUCHE SOUTH OF LAKE MADELINE: BETWEEN THE BOAT LAUNCH AND BLACK	Source	Wet weather
COG 2	CONCRETE CHANNEL @ SE CORNER OF LAKE MADELINE AT GRATED STORM DRAIN	Source	Both
COG 4	GREENS BAYOU @ OVERFLOW TO LAKE MADELINE BEHIND WALMART	Source	Both
EIH 14	MIDDLE OF LAKE MADELINE	Ambient	Both
EIH 18	N CORNER of LM	Ambient	Both
EIH 17	NW CORNER of LM	Ambient	Both
COG 7	STORM SEWER CROSSING JONES DRIVE ACROSS FROM OPIE SCHOOL	Source	Wet weather
COG 8	STORM SEWER ALONG EAST SIDE OF JONES RD ACROSS FROM OPIE SCHOOL	Source	Wet weather
COG 6	SYDNOR BAYOU NEAR GOLF COURSE	Ambient	Both

The *Enterococcus* group is a subgroup of the fecal streptococci. Some species of bacteria within this group are known to be affiliated more with animal versus human feces (APHA 1998). *Enterococcus* bacteria were monitored during both wet weather and dry weather sampling events. In addition to *Enterococcus* we also monitored fecal coliform and fecal streptococcus at selected sites and dates during 2006. These data were discussed in depth during our first report and not presented again. Fecal coliform and streptococci monitoring was not repeated in 2008 due to the complete transition of water quality standards to *Enterococcus* and the accumulation of sufficient historical *Enterococcus* data to evaluate temporal trends. *Enterococcus* was tested using the IDEXX® defined substrate method. During our study we encountered samples with high concentrations of bacteria, which saturated the culture media, yielding "greater than values". In contrast, we also encountered samples that contained very dilute concentrations of bacteria which yielded "less than values". For our graphical and numerical analyses we used the actual value associated with these measurements and dropped the less than or greater than symbol. .

We also measured additional variables that may influence ambient bacteria densities and survival. These included water temperature, salinity, pH, transparency, dissolved oxygen at the surface, mid-depth and the bottom, nitrate + nitrite nitrogen, orthophosphate and total phosphorus, and total suspended solids. These water quality variables have been shown to be correlated with and/or affect the survival of indicator bacteria. In particular water temperature and salinity can have a substantial influence on survival of indicator bacteria, pathogens and dissolved oxygen saturation (Maier et al. 2009). We used standard field and lab methods (TCEQ 2003b). Briefly, a YSI® multiparameter probe and data display unit was used to collect data on water temperature, salinity, dissolved oxygen, pH and depth. The instrument was calibrated prior to use each day and then checked at the end of each run. A secchi disk tube was used to estimate water transparency. Observations on weather, tides and water color were recorded as well.

Information on wastewater treatment facilities within the Lake Madeline watershed was obtained from the TCEQ and EPA permit database and used during the preparation of our report. In addition, past water quality data available electronically from HGAC, EIH, and GCHD, was obtained and compiled for comparison to our data set and to examine past trends in bacteriological indicators. We obtained precipitation data for the period prior to each sampling event during our study and some historical monitoring events, from the National Weather Service meteorological station at Scholes Field, which is located within 2 miles from the site.

Results

This report represents the final report for data collected during June 5 to October 8, 2006 and again from 8/20/08 to 4/28/09. Most of the results pertaining to comparison of bacteriological methods and historical evaluation of water quality problems were documented in Guillen and Moore (2006) and will not be discussed again in this report unless needed. All data collected during this project for both reports are available and can be provided in an electronic appendix upon request from guillen@uhcl.edu.

In evaluating the historical data our objective was to select sites that were representative of Lake Madeline and a nearby "control site". Based on a review of agency data we found that several sites contained sufficient periods of record for bacteriological data. They include the Offatts Bayou (EIH 7) and Lake Madeline (EIH 14) sites and Offatts at CM 18 and English Bayou. Although Offatts Bayou is connected to Lake Madeline, it is also subject to more flushing and dilution. To better evaluate the time series we included the results of our study in the analysis.

Historical baseline monitoring data suggests that Lake Madeline had experienced periodic elevated levels of *Enterococcus* bacteria since from 2002 through 2005 but since then levels had declined substantially (Figure 6). Most routine sampling is conducted during dry weather events which would bias observations of indicator bacteria on the low. However, this trend even if based on dry weather conditions only suggests that chronic loading of indicator bacteria into the watershed may have slowed after implementation of some of the sewer line repairs.

In contrast bacteria levels measured during our study were generally higher due to the inclusion of rainfall events. The slightly elevated levels during recent years suggest that incorporation of more wet weather events may have biased the values higher. This is supported by the observed relationships between salinity, rainfall and *Enterococcus* levels reported by Guillen and Moore (2006). Our study was limited to the warmer months of the year to reduce the influence of differential survival caused by fluctuating temperatures. In general Offatts Bayou and the COG WWTP exhibited lower *Enterococcus* levels in comparison to Lake Madeline ambient waters during intense survey sampling in 2006 through 2009 (Figures 7). There appears to be an overall decline in indicator bacteria levels between 2006 and 2008-09 for all categories except storm sewer dischargers. Storm sewer levels increased substantially although there was considerable variability around the average concentration of indicator bacteria. Specific storm sewer sites that experienced increased levels of indicator bacteria between 2006 and 2008-09 were sites COG 1, 3, 4, 8, and 12 (Figures 7, 8, and Table 1). These differences were not however statistically significant when all sites were pooled and tested between time periods (years). This suggests that there has not been an observable improvement in storm sewer indicator bacteria levels between 2006 and 2009. However, this does not infer increased loading since very little flow data was collected. We are taking this limited flow data and will attempt to compute loading rates.

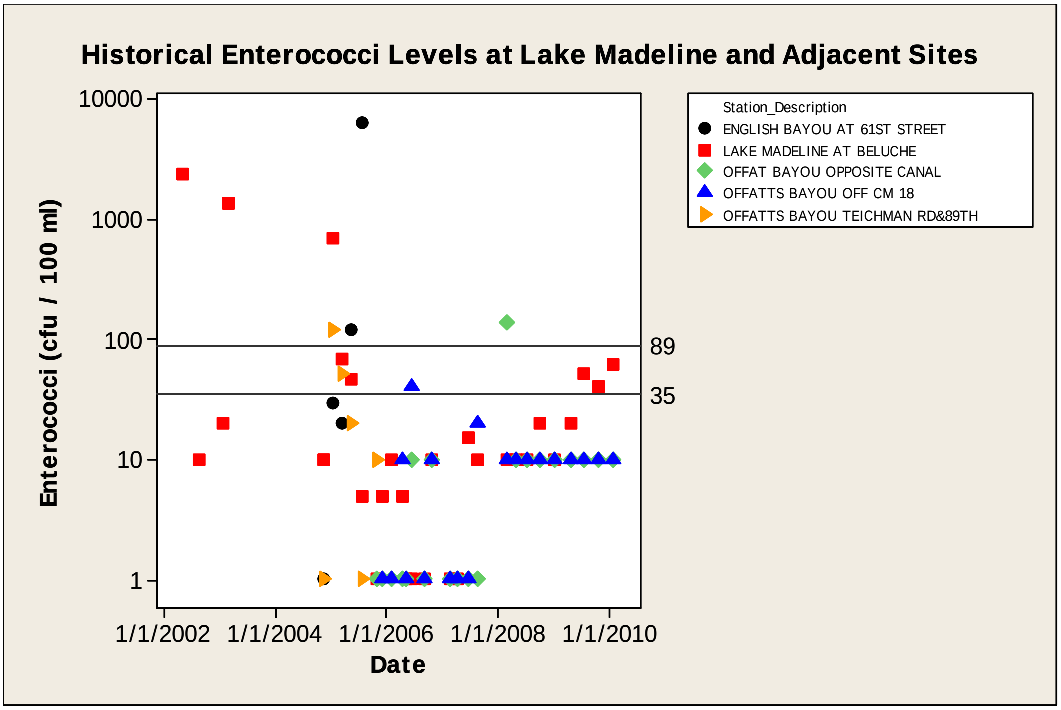

Figure 6. Historical trends in *Enterococcus* levels in Lake Madeline and adjacent areas. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale. We included 2002-2005 Lake Madeline levels previously evaluated by Guillen and Moore (2006) to evaluate longer trends.

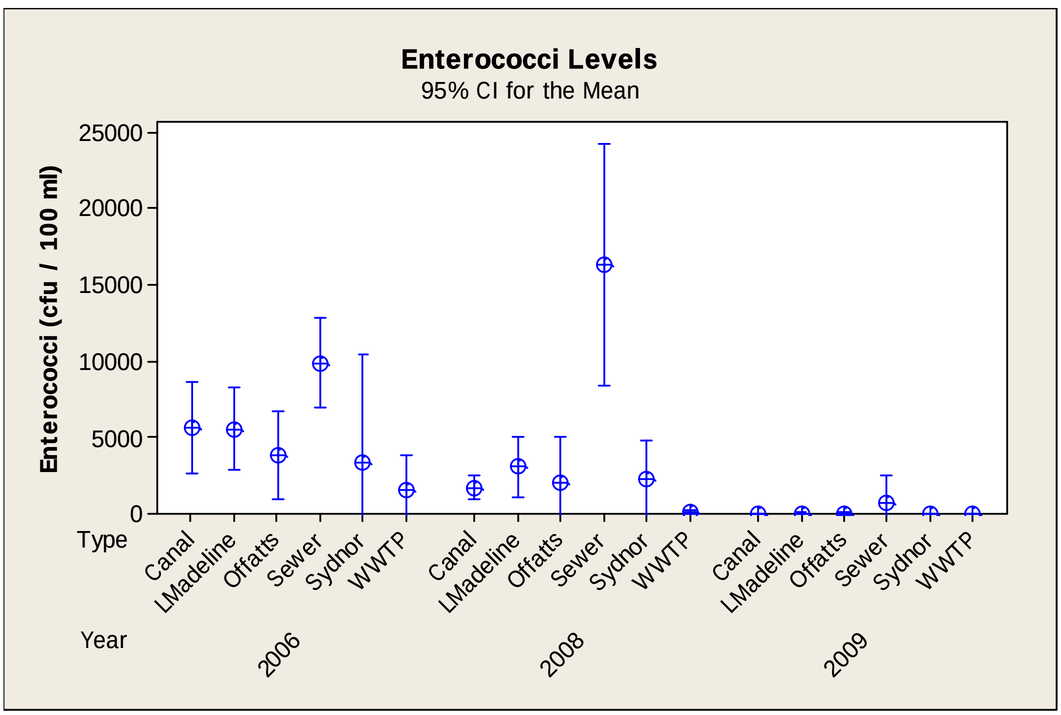

Figure 7. Comparison of *Enterococcus* levels by sampling site type and year. Data based on *Enterococcus* samples collected during targeted sampling during 2006, 2008 and 2009.

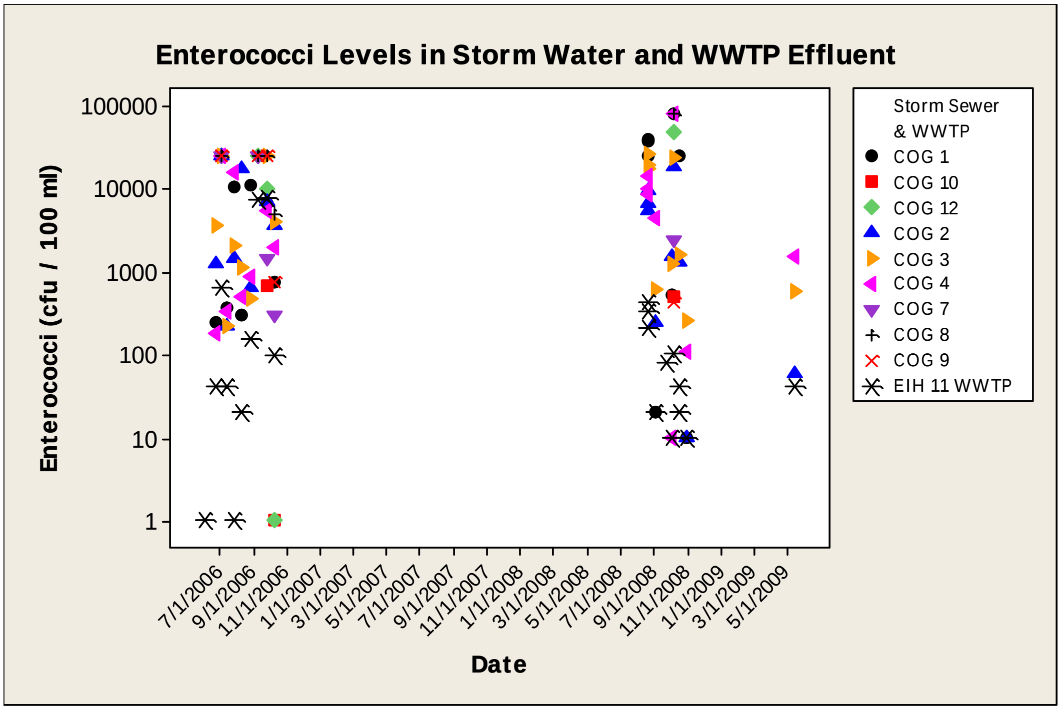

Figure 8. Enterococcus levels measured during targeted sampling during 2006, 2008 and 2009 at the City of Galveston WWTP discharge and selected storm sewers (see Table 1 for description of sites). Y-axis is log scale.

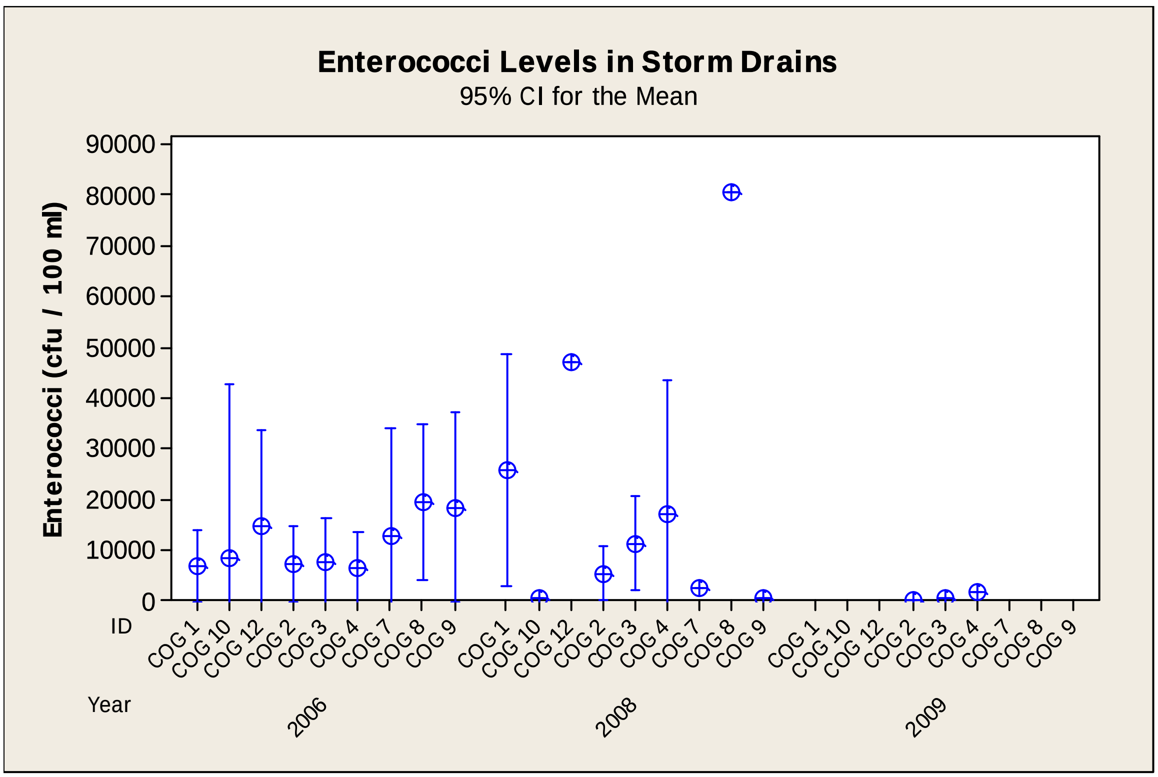

Figure 9. *Enterococcus* levels in storm drains surrounding Lake Madeline during 2006, 2008 and 2009. .

Table 2. Results of Kruskal-Wallis Test on Enterococcus levels for all storm drain samples during each yearly period. Based on the results of the non-parametric test there was no significant difference between years. Individual sites would not be tested due to the presence of unbalanced experimental data and low number of replicates for some time periods.

Year	N	Median	Ave Rank	Z
2006	51	3930.0	45.5	0.01
2008	36	5963.0	47.4	0.55
2009	3	583.0	22.7	-1.54
Overall	90		45.5	

H = 2.47 DF = 2 P = 0.290
H = 2.49 DF = 2 P = 0.287 (adjusted for ties)

* NOTE * One or more small samples

Based on our wet and dry weather targeted monitoring data, and historical trend data it appears that Lake Madeline indicator bacteria levels do appear to be dropping during dry weather conditions, but continue to be elevated in storm sewer outfalls during rainy periods. The influence of this contaminated runoff on the ambient water within Lake Madeline is however uncertain, since there is a general trend of declining bacteria levels. Furthermore storm water appears to continue to have elevated indicator bacteria, which most likely originated from several sources including humans and animals (Guillen and Moore 2006). The discrepancy between observed trends in storm water and ambient open water indicator bacteria levels may be due to the inability to obtain precise flow measurements in tidal waters. The reason is although the concentration of bacteria in storm water may have been higher during 2008, discharge flows may have been lower, which translates into lower loading into the Lake Madeline basin. The overall influence of Hurricane Ike during September 2008 is also difficult to evaluate. The storm may have flushed out much of the accumulated organic detritus on the bottom of Lake Madeline which would have resulted in lower biochemical oxygen demand and consequently higher ambient dissolved oxygen.

Historical data suggests that Lake Madeline and Offatts Bayou have been experiencing infrequent depressed dissolved oxygen in surface waters since 2005 and 1995 respectively (Figures 10). However, when bottom dissolved oxygen readings are included the incidence of hypoxia increase (Figures 11 and 12). Dissolved oxygen levels do appear to be increasing slightly in recent years in both bottom and surface waters in Lake Madeline (Figures 13 and 14). Artificial aeration at Lake Madeline may have contributed to this trend but it is difficult to conclude anything definitively since the trend is very weak and similar increases were observed in other waterbodies (Figure 11). The incidence of hypoxia was more frequent at Lake Madeline, which also exhibits a wide variation between surface and bottom readings. This suggests that Lake Madeline is more stratified and less mixed than Offatts Bayou. As previously mentioned fish kills have been recorded in Offatts Bayou by Texas Parks and Wildlife Department (Winston Denton – TPWD pers. comm.). Fish kills in Offatts Bayou are rare and have not reported in recent years although they have been documented from the late 1930's onward (Gunter 1946).

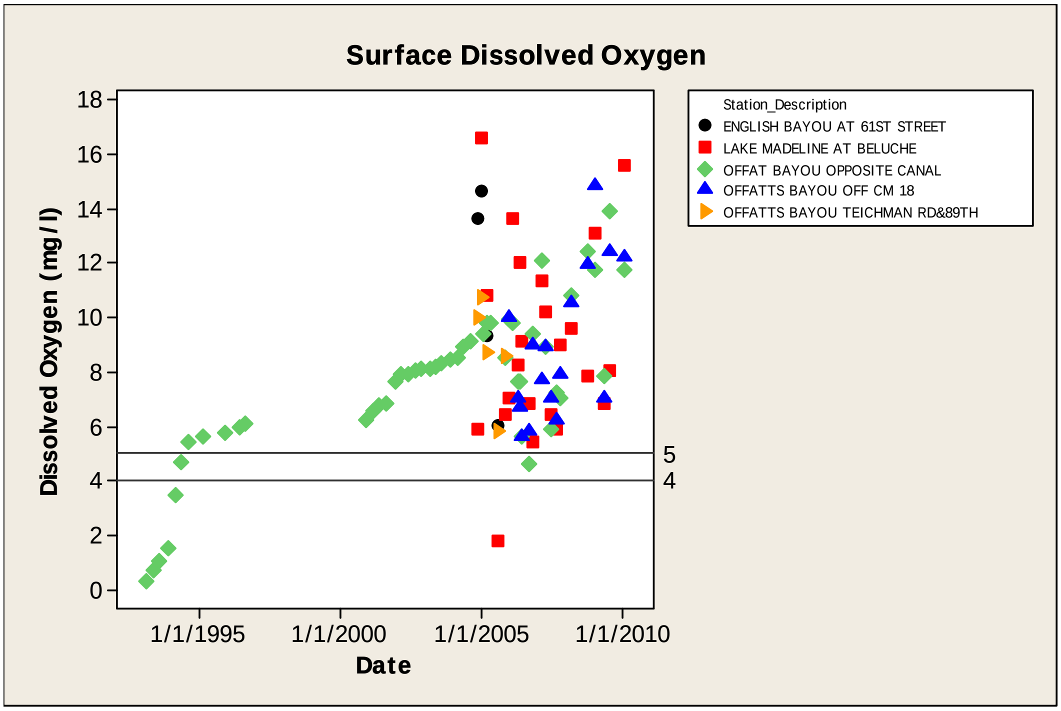

Figure 10. Historic surface dissolved oxygen levels measured at the surface (1 ft) at Lake Madeline and Offatts Bayou. The water quality standard is a 24 hour minimum average of 5 mg/l and an 8 hour minimum of 4 mg/l.

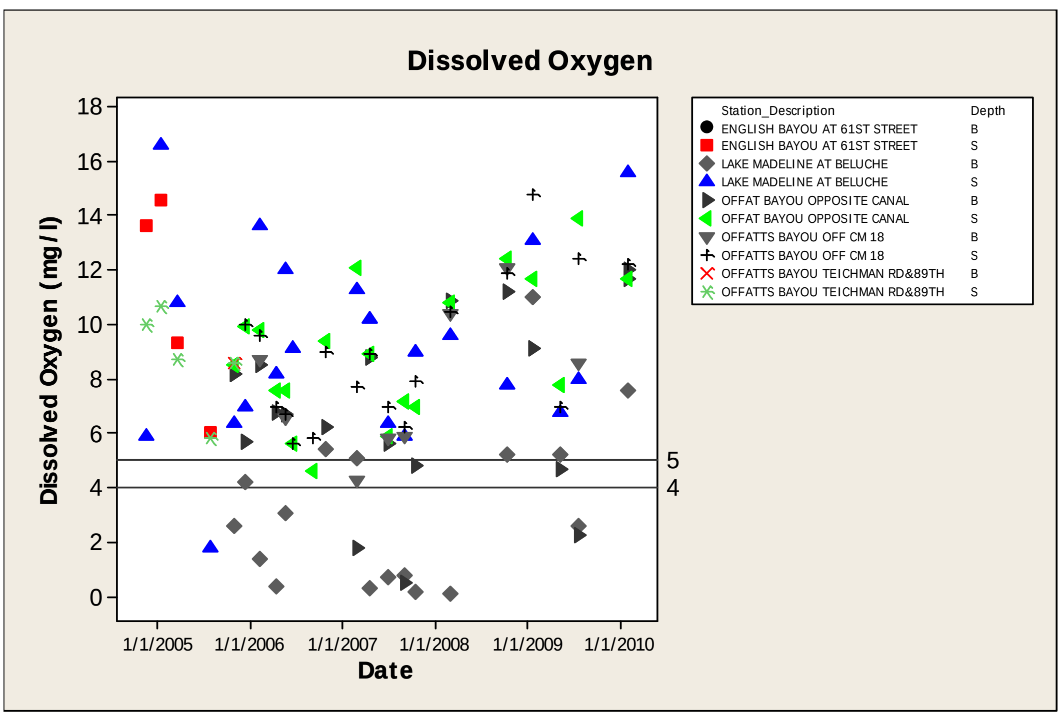

Figure 11. Historical dissolved oxygen levels measured at 1 ft above the bottom at Lake Madeline and Offatts Bayou. The water quality standard is a 24 hour minimum average of 5 mg/l and an 8 hour minimum of 4 mg/l.

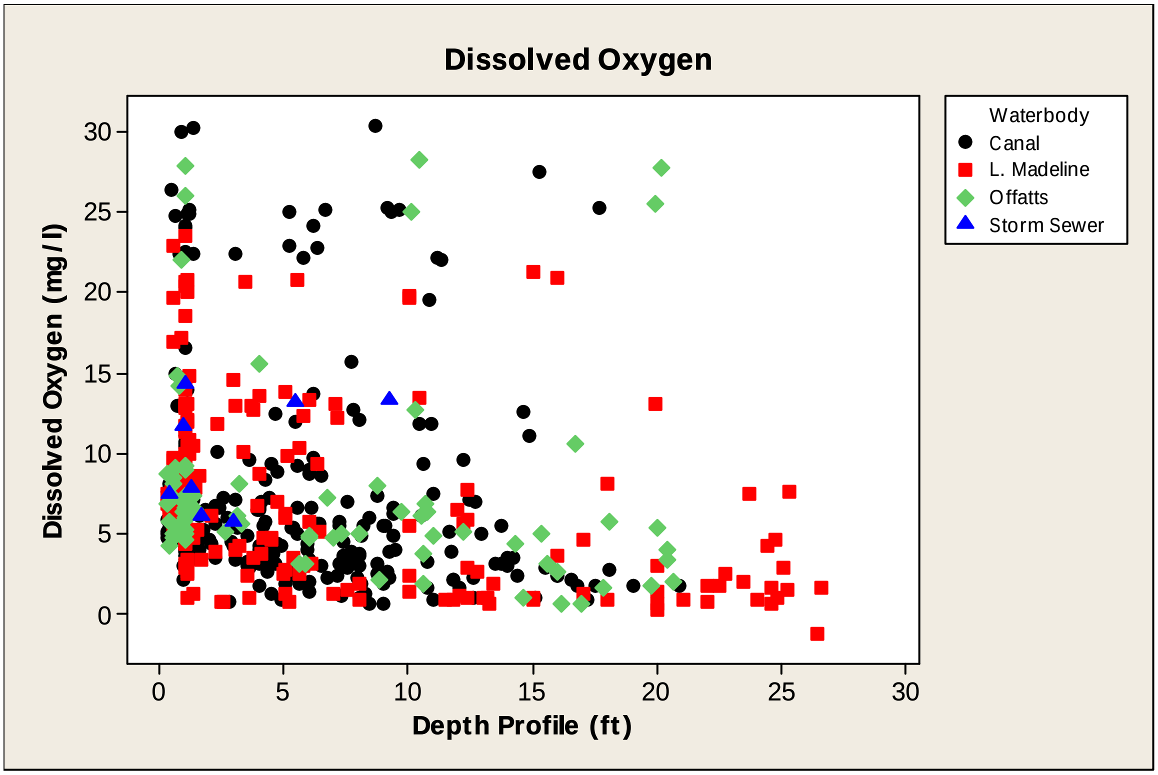

Figure 12. Dissolved oxygen measurements at Lake Madeline, Offatts Bayou, boat canal and selected storm sewers during 2006, 2008 and 2009.

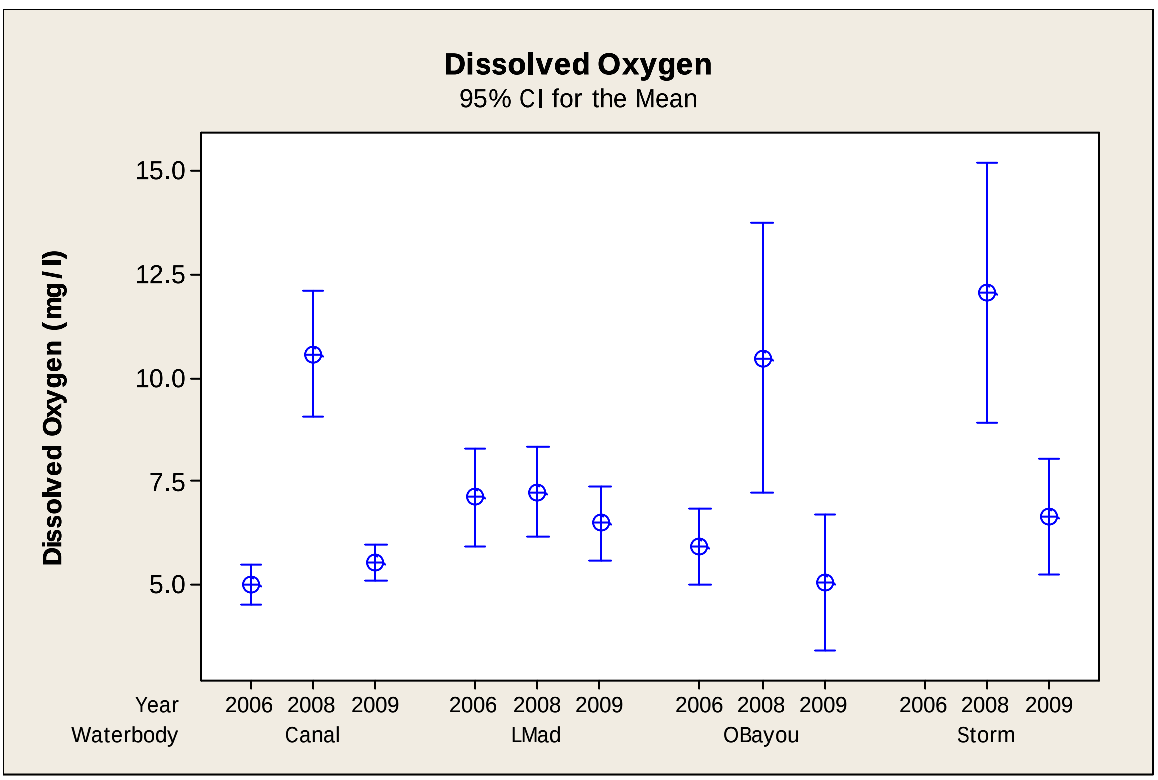

Figure 13. Mean and 95% confidence intervals for dissolved oxygen at each waterbody type and year.

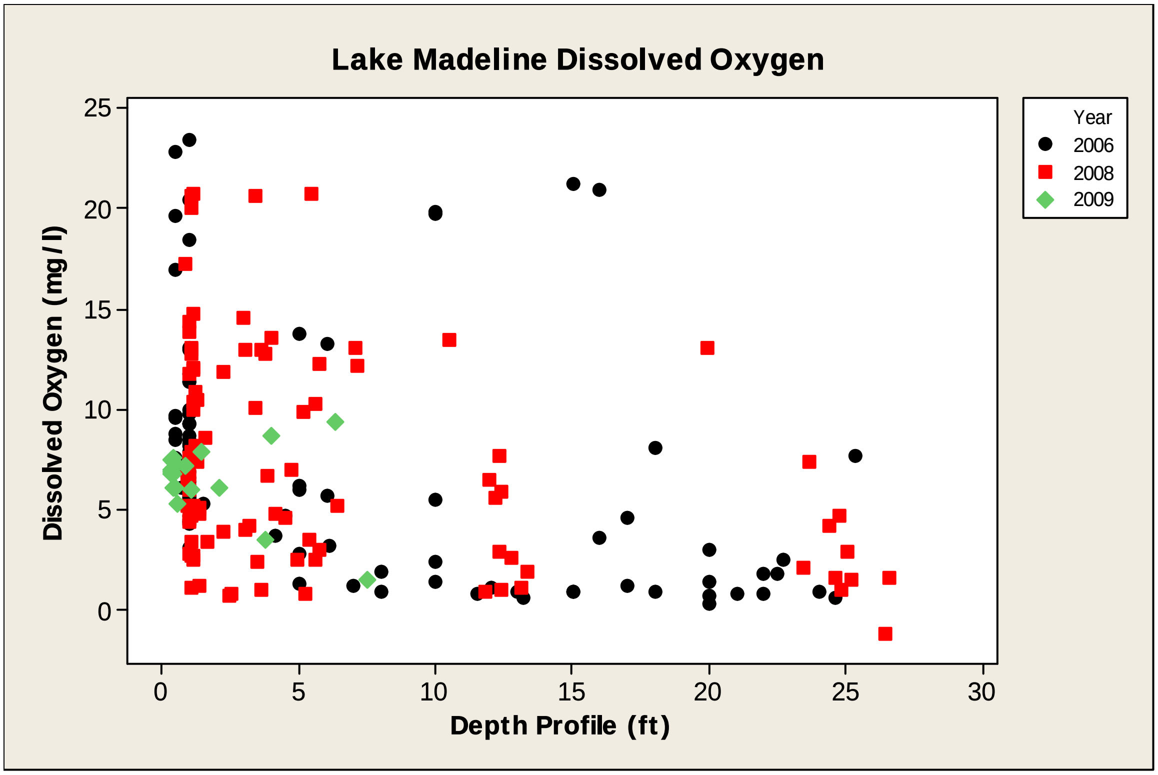

Figure 14. Dissolved oxygen profile composed from various sites during 2006, 2008-2009.

Discussion

Based on our monitoring data, Lake Madeline does not appear to be meeting contact recreation water quality standards during wet weather events. *Enterococcus* bacteria are generally elevated throughout the lake during periods of increased rainfall. The various storm sewers discharging into Lake Madeline are continuing to be significant sources of *Enterococcus* bacteria. Also, these storm sewers contain elevated levels of Enterococcus even during most dry weather events. Our previous findings (Guillen 2006) further suggest that there appears to be a strong positive relationship between Enterococcus levels at storm sewer sites monitored during dry and wet weather events, and precipitation. Similar trends were observed in the open waters of Lake Madeline.

In addition to continuing bacteriological problems Lake Madeline is exhibiting ongoing hypoxic or anoxic conditions in the deeper portions of the Lake. These conditions are reinforced by strong salinity induced stratification which reduces mixing, and increases apparent eutrophic (high nutrients and algae) conditions present in the upper portions of the water column. These conditions occur less frequently in the adjacent canal and Offatts Bayou.

The data collected during this study and past investigations supports the hypothesis that contaminated storm water runoff is a significant source of indicator bacteria within the watershed. However, the origin of these elevated indicator bacteria are probably varied and include cross contamination from leaking wastewater collection systems (sanitary sewers), waterfowl, domesticated animals and livestock. Due to the fact that the watershed lies within the coastal zone and includes rural portions of Galveston Island watershed it is very likely that all these sources contribute to elevated indicator bacteria in Lake Madeline. We highly recommend that a routine monitoring program that supplements the ongoing state monitoring programs be implemented to continue to track progress toward reducing indicator bacteria levels and increasing dissolved oxygen levels. This can also be coordinated with citizens interested in Citizen Monitoring Programs.

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