Lake Madeline Bacteria Study
Final Report

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Acknowledgements

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Executive Summary

Lake Madeline is a man-made lake located on the western end of Galveston Island, Texas (Figure 1). 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. 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 survey of Lake Madeline and surrounding waters during June to October 2006. 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 of these indicator bacteria within the lake's watershed. Finally, EIH was asked to provide recommendations for further studies and potential solutions to any observed water quality violations.

Based on our monitoring data, Lake Madeline does not appear to be meeting State of Texas contact recreation water quality standards. Various bacteriological indicators are elevated throughout the lake during periods of increased rainfall, warmer temperatures and decreased salinity. The various storm sewers discharging into Lake Madeline appear to be the most significant sources of enterococci indicator bacteria during wet weather events. In addition, some of these sites contain elevated levels of enterococci even during dry weather. Our findings suggest that there appears to be a strong positive relationship between enterococci bacteria levels within storm sewers and precipitation. Similar trends were observed in the open waters of Lake Madeline. Computed FC/FS ratios support our hypothesis that most sources of bacteria are probably of human or mixed origin. Approximately 54%, 29% and 16% of the samples appeared to be composed of bacteria from human, animal and mixed origin respectively. However, some exceptions were noted including Offatts Bayou, Sydnor Bayou and some of the storm sewers located in the southeast end of Lake Madeline which drain the Greens Bayou/Wal-Mart area. Samples from these sites suggest that indicator bacteria are primarily of animal origin. However, the FC/FS ratio method is considered a very crude screening method and should not be used solely to definitively determine the origin of indicator bacteria

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, these elevated indicator bacteria probably originate from leaking wastewater collection systems (sanitary sewers). Sanitary sewer lines are usually located and buried adjacent to storm sewers. During high rainfall water can percolate from broken sanitary sewer lines and infiltrate storm sewers, ultimately discharging into Lake Madeline. We highly recommend that a more detailed investigation of the storm water and sanitary sewer collection systems be initiated to definitely determine the sources of contamination and remediate further discharges as needed. We understand the City of Galveston has already embarked on a sanitary sewer rehabilitation project to address some of these issues. 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. 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.

Historically water quality has been monitored in Lake Madeline by the Galveston County Health District (GCHD), Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and the Clean Rivers Program (CRP) administered locally by the Houston Galveston Area Council (HGAC) and the Environmental Institute of Houston (EIH). Routine monitoring has been primarily limited to a few locations within the watershed. Sampling has historically been conducted 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 GCHD, TPWD and TCEQ (R. Schultz – GCHD, Winston Denton – TPWD and TCEQ). Most recently during 2005 and 2006 the GCHD documented elevated enterococci bacteria levels in the Lake due to various potential sources including malfunctioning sanitary sewer outfalls and wastewater treatment facilities (R. Schultz pers. comm.). The primary water quality variables evaluated during these investigations have included bacteriological indicators and dissolved oxygen. These water quality indicators can effect human contact recreation and aquatic life respectively.

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. Two indicators that have been used routinely in Texas marine waters are fecal coliform and enterococci bacteria.

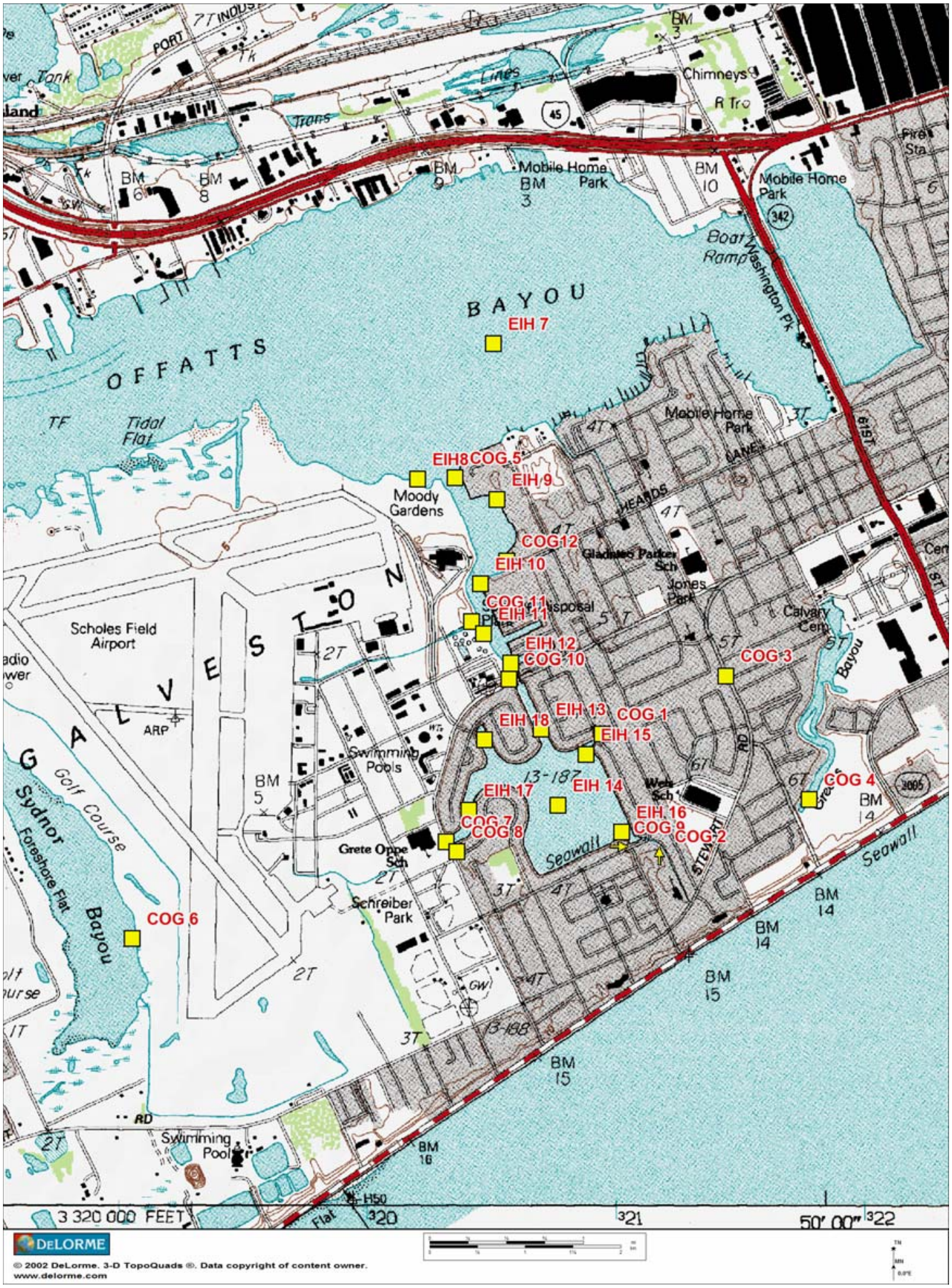

Figure 1. Location of Lake Madeline and sample sites.

Lake Madeline is part of the West Bay watershed. For regulatory purposes the state water quality standards for West Bay are also applicable to Lake Madeline. 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 enterococci 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. Historically, the less preferred indicator, fecal coliforms, was evaluated against a numerical water quality standard which included a geometric mean of 200 fecal coliform colonies per 100 ml. In addition, single samples should not exceed 400 colonies per 100 ml. As in the case of enterococci, similar sample size requirements and exceedance criteria apply to fecal coliform bacteria. 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. The *enterococci* and fecal coliform numerical criteria apply only to ambient surface water. TCEQ discharge permit limits apply to individual permitted wastewater systems.

One of the primary factors associated with fish kills in Lake Madeline in the past has been depressed dissolved oxygen. Although not a primary focus of our study we also included an analysis of dissolved oxygen levels within the lake. For regulatory purposes the state water quality standards for 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 contracted EIH to conduct a bacteriological survey of Lake Madeline and surrounding waters during June to October 2006. 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 of these indicator bacteria within the lake's watershed. Finally, EIH was asked to provide recommendations for further studies and potential solutions to any observed water quality problems.

Methods

Sites were 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. 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. Measurements collected during our study were also compared with historical data collected by various agencies 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 1 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 stormwater 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 June and ending in early October 2006. City of Galveston staff assisted in the collection of samples at sites accessible from land.

We attempted to sample during at least 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 enterococci as our primary indicator bacteria group. In addition, we conducted testing of fecal coliform bacteria primarily for comparison to historical data. Fecal coliforms and enterococci are the recommended indicators for assessment of human contact recreation uses in marine waters. Until recently fecal coliforms were used extensively to assess human health risks in ambient water. However, enterococci have 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). However this conclusion may be based on flawed analyses, suggesting enterococci are not necessarily better than fecal coliforms as an indicator (Fleisher 1991). McElyea (2003) found that enterococci levels were highly correlated with fecal coliforms concentrations and when used exceeded state water quality standards more frequently.

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. It should be noted that certain species of this group are known to be affiliated more with animal versus human feces (APHA 1998). Enterococci bacteria was monitored during both wet weather and dry weather sampling events. Fecal coliform bacteria were monitored at a limited subset of sites during some September and October sampling events.

In addition to fecal coliform and enterococci we also monitored fecal streptococcus at selected sites and dates during late August, September and October. Although subject to fairly high error rates, fecal streptococci has been used in the past to assist in the differentiation of sources of bacteria (APHA 1985, 1998). It has been previously suggested that the ratio of fecal coliform to fecal streptococcus (FC/FS ratios) would provide information on possible sources of pollution. A ratio of greater than 4.1 was considered indicative of pollution derived from domestic wastes composed of human fecal material, whereas ratios less than 0.7 suggested pollution due to non-human warm blooded animal sources. Ratios between these two benchmark values would suggest a mixture of human and non-human sources. However, the value of this ratio has been questioned due the fact that the various species of fecal streptococci, including those that are more representative of animal wastes, tend to die off faster (APHA 1998). In addition, wastewater disinfection also seems to affect the ratio of these indicators. Also, the most common test for fecal streptococci tends to have high false positive rate. For these reasons APHA (1998) does not recommend the use of FC/FS ratios for differentiating human and animal sources of pollution. We however decided to use this ratio as a rough screening criteria taking into account the sources of error listed. We believe that the frequency of FC/FS ratios yielding a result that suggests human contamination will tend to be very conservative and probably underestimate the true frequency. Bacteriological testing was conducted using standard lab methods (TCEQ 2003b and APHA 1998).

We also measured additional variables that may influence bacteriological densities and survival. These included air temperature, water temperature, salinity, pH, transparency, dissolved oxygen at the surface, mid-depth and the bottom. 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 an influence on survival of indicator bacteria and pathogens. We used standard field and lab methods (TCEQ 2003b).

Information on wastewater treatment facilities within the Lake Madeline watershed was obtained from the TCEQ and EPA permit database. 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. Data from recent (October 2005-April 2006) investigations by GCHD was provided courtesy of Mr. Ronnie Schultz, Galveston County Health District. 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.

During this and past studies 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.

RESULTS

This report represents the final report for data collected during June 5 to October 8, 2006. Although additional water quality data was collected during these dates this condensed progress report focuses on the bacteriological, dissolved oxygen, salinity, and precipitation data collected during these events. All data collected during this project are available and can be provided in an electronic appendix upon request from guillen@uhcl.edu.

Historical Data

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 two sites contained the longest period of record for bacteriological data. They include the Offatts Bayou (EIH 7) and Lake Madeline (EIH 14) sites. 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 data suggests that Lake Madeline has been experiencing periodic elevated levels of fecal coliforms and enterococci bacteria since at least 1999 and 2002 respectively (Figures 2 and 3). Since most sampling is conducted during dry weather events it is likely that these values represent a negatively biased estimate of the true concentration of bacteria. Bacteria levels measured during our study were generally comparable to historical values. 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 enterococci levels (Figure 4 and 5). However, there does not appear to be a strong relationship between fecal coliform levels and salinity (Figure 6). Historical precipitation data was not available for the entire time series of fecal coliform measurements. Water temperature may also have an influence on bacteria levels. Bacteria levels were slightly elevated at higher temperatures (Figures 7 and 8). This is consistent with the general observation that these are thermophilic bacteria and experience optimum growth and survival at warmer temperatures.

Offatts Bayou exhibited lower Enterococci levels in comparison to Lake Madeline during 2001 through 2006 (Figures 2 and 9). Since most routine sampling is conducted during dry weather events, it is likely that these values represent a negatively biased estimate of the true concentration of bacteria. Bacteria levels measured during our study were generally higher than historical values. The slightly elevated levels during recent years suggest that incorporation of more wet weather events may have biased the values higher.

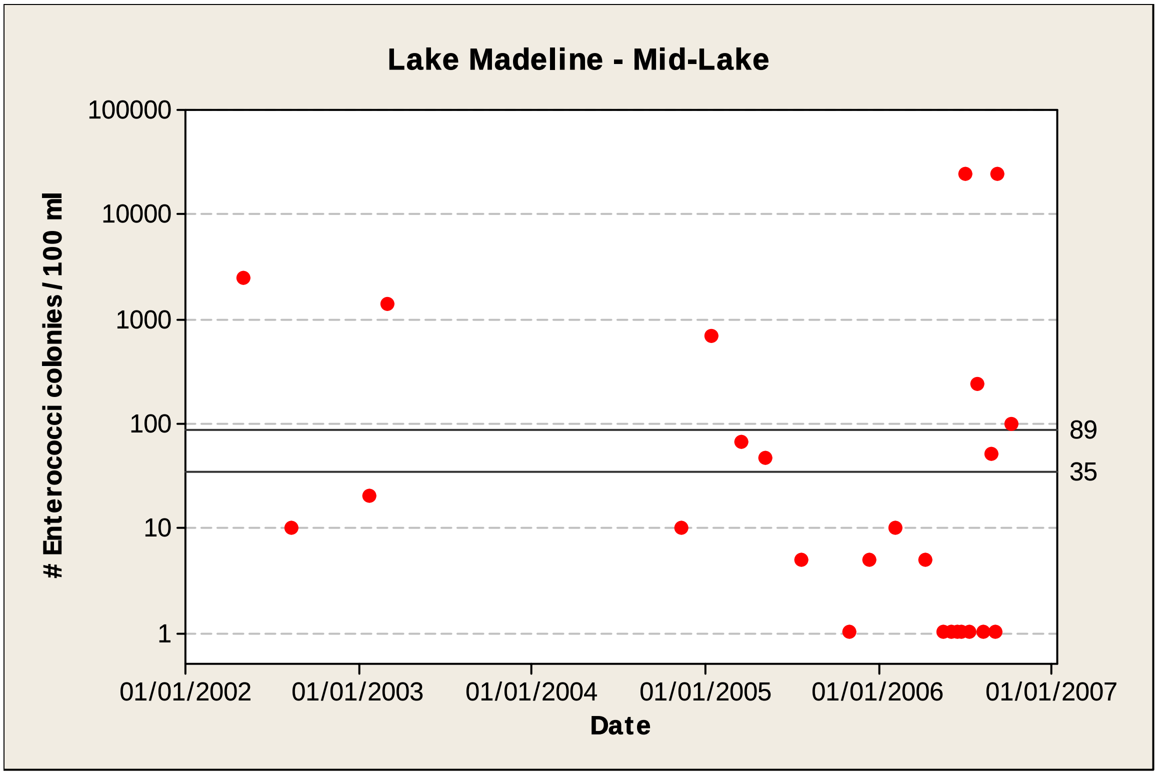

Figure 2. Historical trends in enterococci levels in Lake Madeline. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

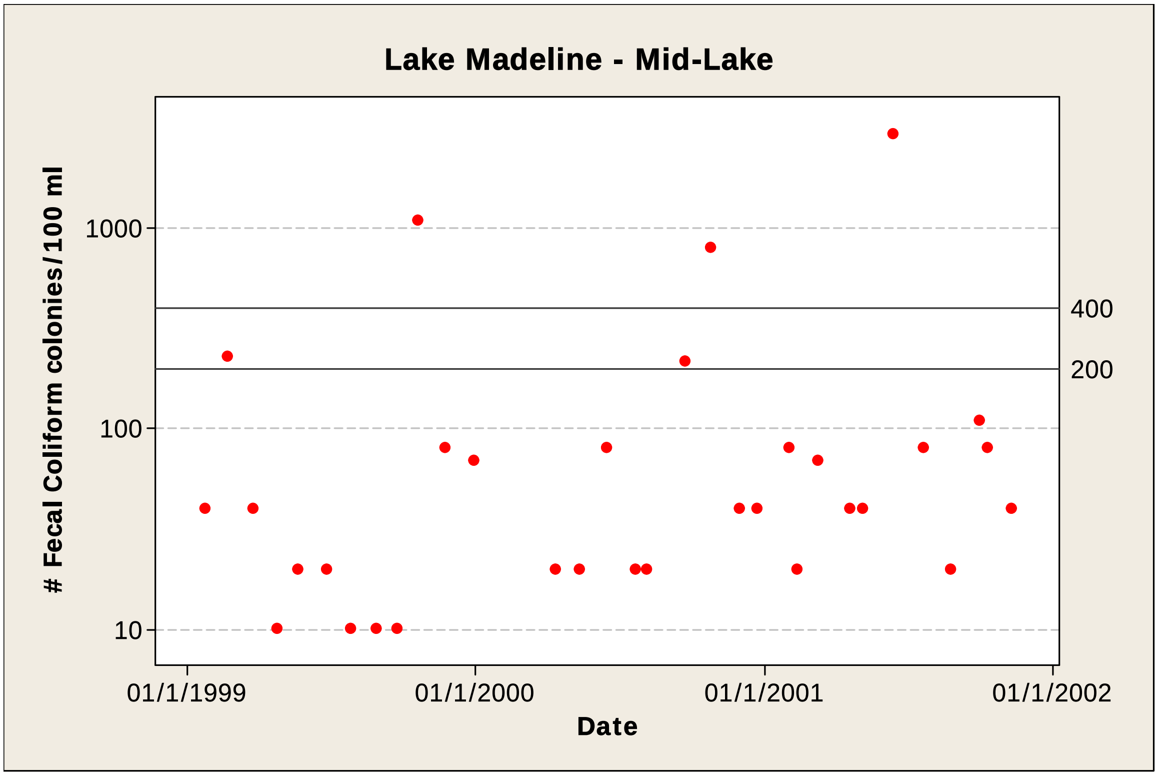

Figure 3. Historical trends in fecal coliform levels in Lake Madeline. The water quality standard is a geometric mean of 200 colonies per 100 ml and a single sample maximum of 400 colonies per 100 ml. Y-axis is log scale.

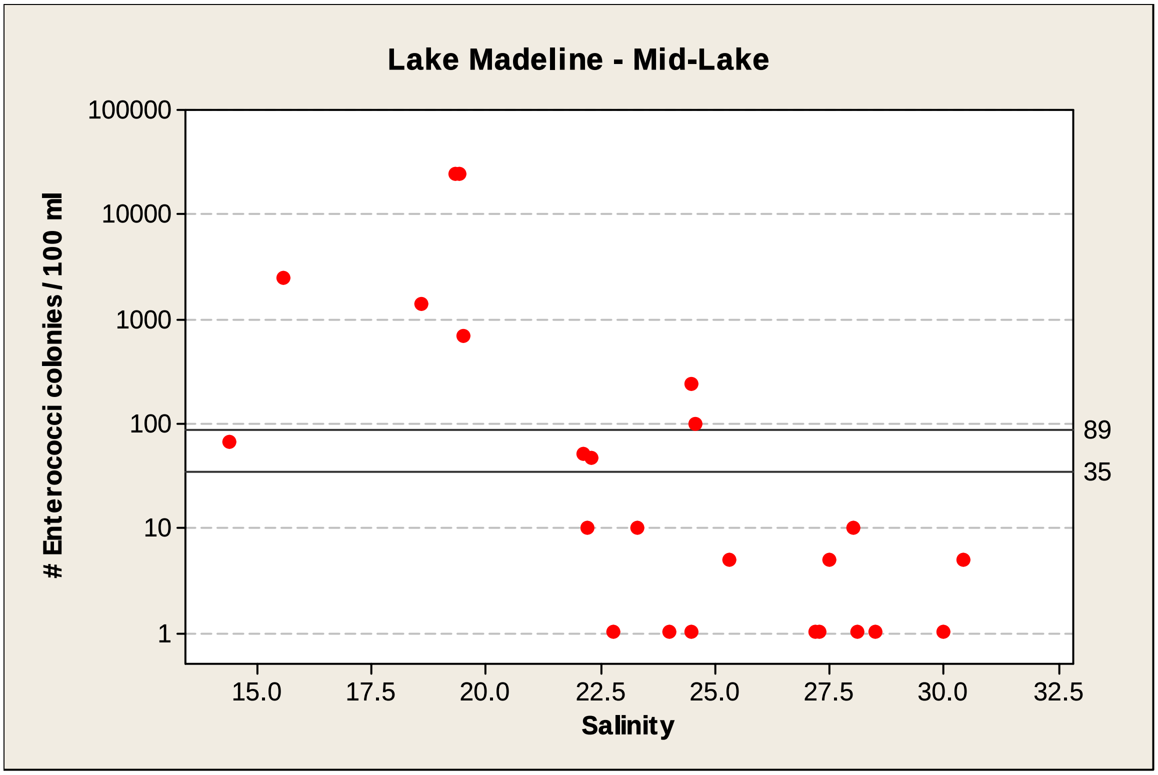

Figure 4. Relationship between enterococci levels and salinity in Lake Madeline between 2002 and 2006. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

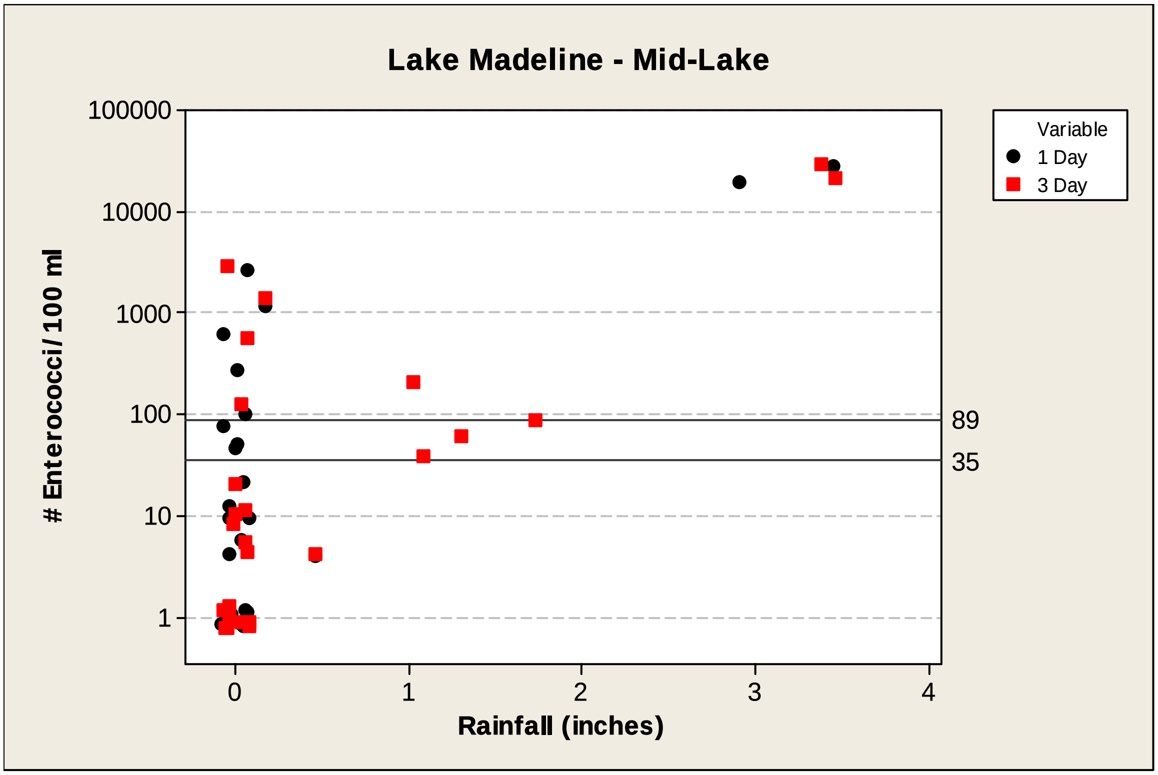

Figure 5. Relationship between enterococci levels and 1 and 3 day rainfall amounts in Lake Madeline between 2002 and 2006. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

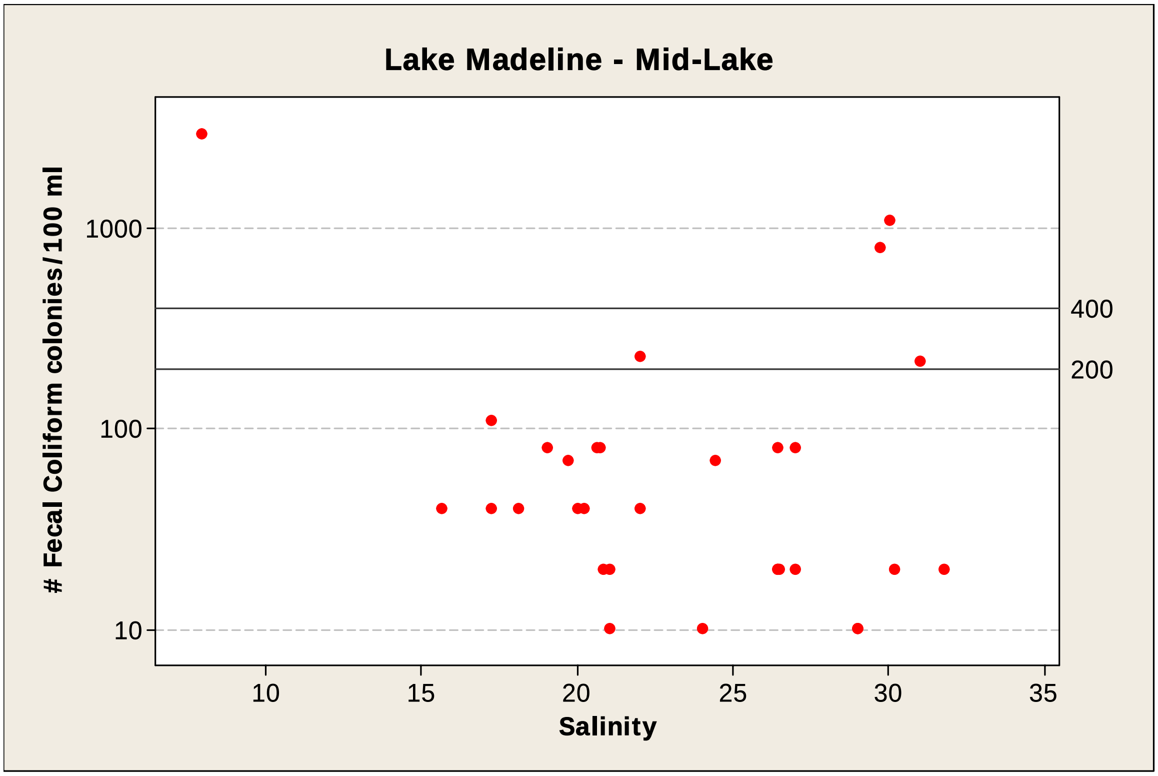

Figure 6. Relationship between fecal coliform levels and salinity in Lake Madeline between 1999 and 2006. The water quality standard is a geometric mean of 200 colonies per 100 ml and a single sample maximum of 400 colonies per 100 ml. Y-axis is log scale.

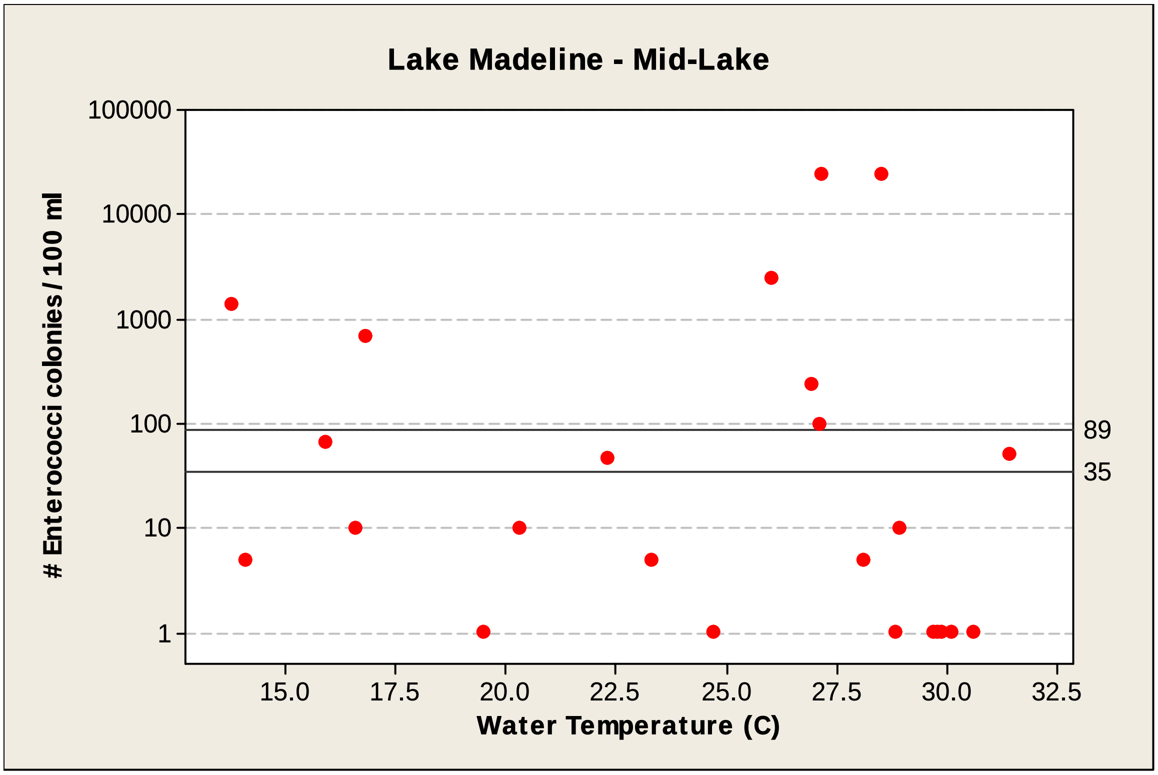

Figure 7. Relationship between enterococci levels and water temperature in Lake Madeline between 2002 and 2006. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

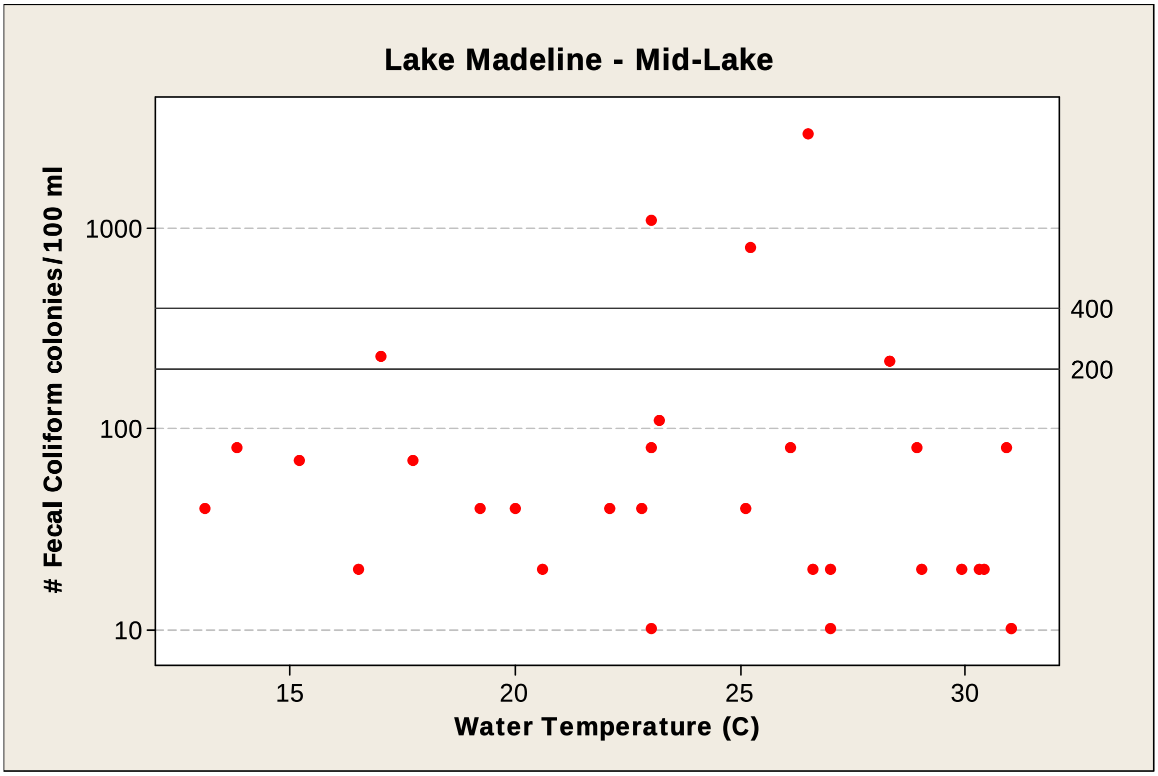

Figure 8. Relationship between fecal coliform levels and water temperature in Lake Madeline between 2002 and 2006. The water quality standard is a geometric mean of 200 colonies per 100 ml and a single sample maximum of 400 colonies per 100 ml. Y-axis is log scale.

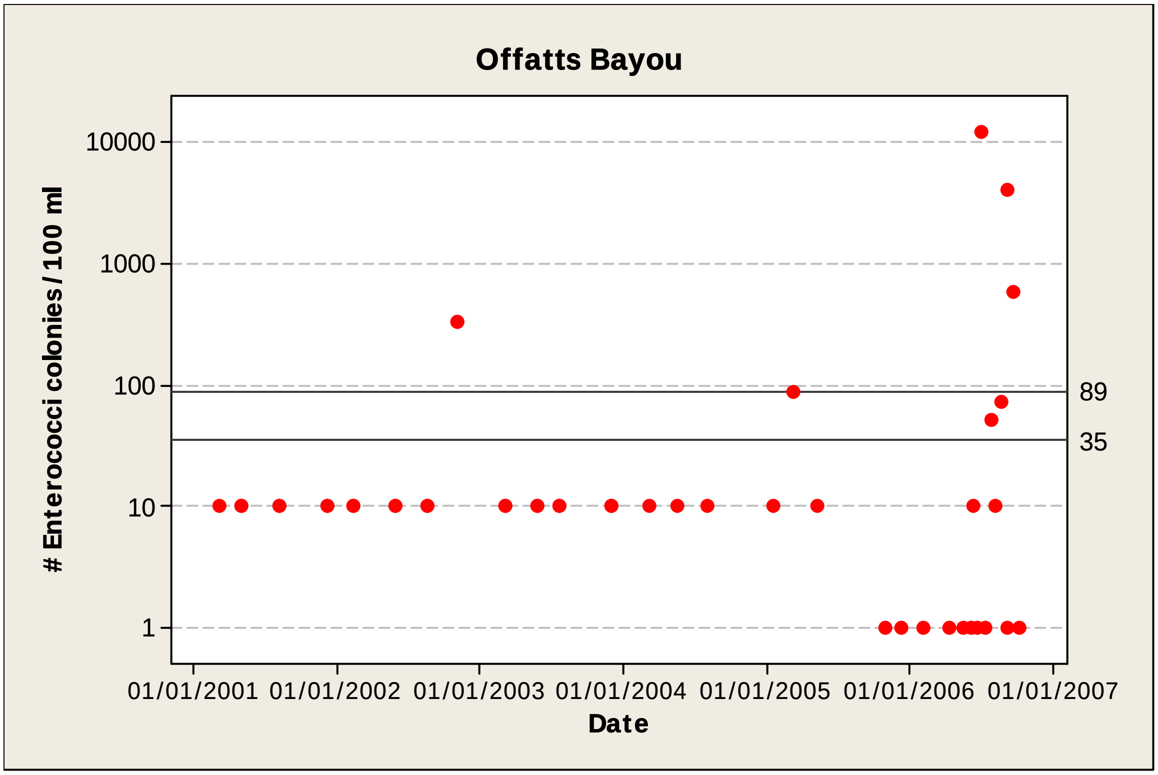

Figure 9. Historical trends in enterococci levels in Offatts Bayou. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

This is supported by the observed relationships between rainfall and enterococci levels in Offatts Bayou (Figure 10). We did not have a complete extensive time series for fecal coliform bacteria and salinity data, so we were not able to conduct those analyses.

Historical data suggests that Lake Madeline and Offatts Bayou have been experiencing periodic hypoxia since 2005 and 2001 respectively (Figures 11 and 12). Dissolved oxygen levels were generally lowest near the bottom. The incidence of hypoxia was more frequent at Lake Madeline, which also exhibited a wider 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.

Galveston County Health District Investigations

We examined data collected by the GCHD during surveys conducted in Lake Madeline in October 2005 through April 2006 (Table 2). Their data suggests several potential sources of enterococci bacteria including storm drains. Highest ambient levels were generally encountered during periods of higher rainfall with some exceptions. During these periods elevated enterococci were observed throughout Lake Madeline. During April 26, 2006 enterococci levels were elevated in the canal adjacent to the WWTP (COG 12), but were low in the WWTP effluent. Photos provided by Mr. Ronnie Schultz document the presence of visual signs of raw sewage during December 14-15, 2006, near the vicinity of the WWTP and Jones Road Bridge (EIH 11 and 12) and the stormwater outfall near Oppe Elementary (COG 7). GCHD also provided us with photos documenting a sanitary sewer overflow in the vicinity of 81st street near Lake Madeline on October 16, 2006. One day and 3 day rainfall amounts during this date were 3.91 and 5.07 inches respectively.

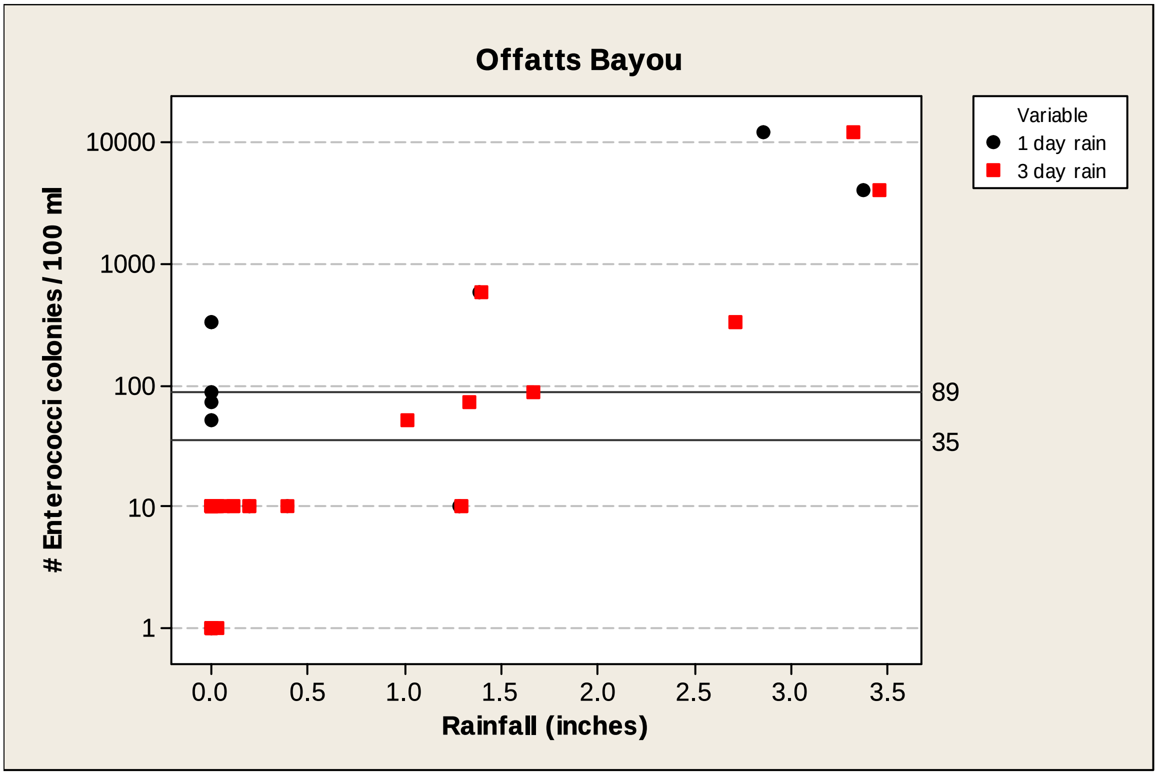

Figure 10. Relationship between enterococci levels and 1 and 3 day rainfall amounts rainfall in Offatts Bayou between 2001 and 2006. The water quality standard is a geometric mean of 35 colonies per 100 ml and a single sample maximum of 89 colonies per 100 ml. Y-axis is log scale.

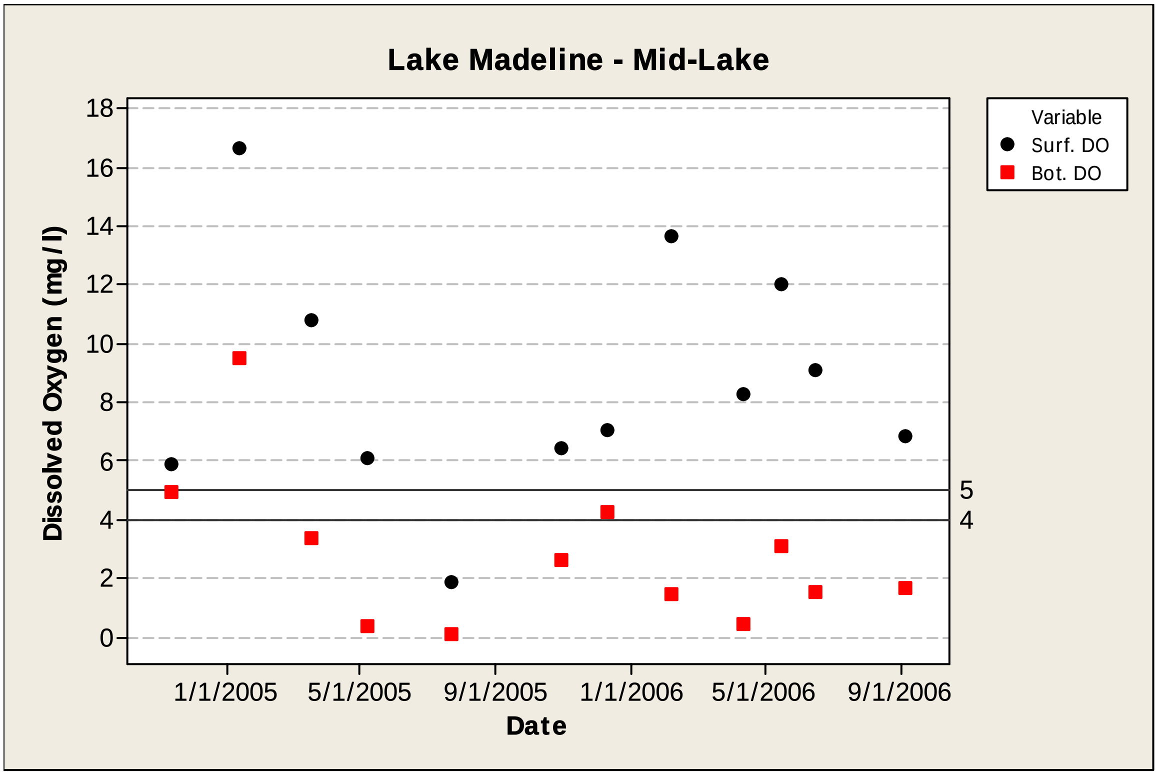

Figure 11. Dissolved oxygen levels measured at the surface (1 ft) and 1 ft above the bottom at Lake Madeline. The water quality standard is a 24 hour minimum average of 5 mg/l and an 8 hour minimum of 4 mg/l.

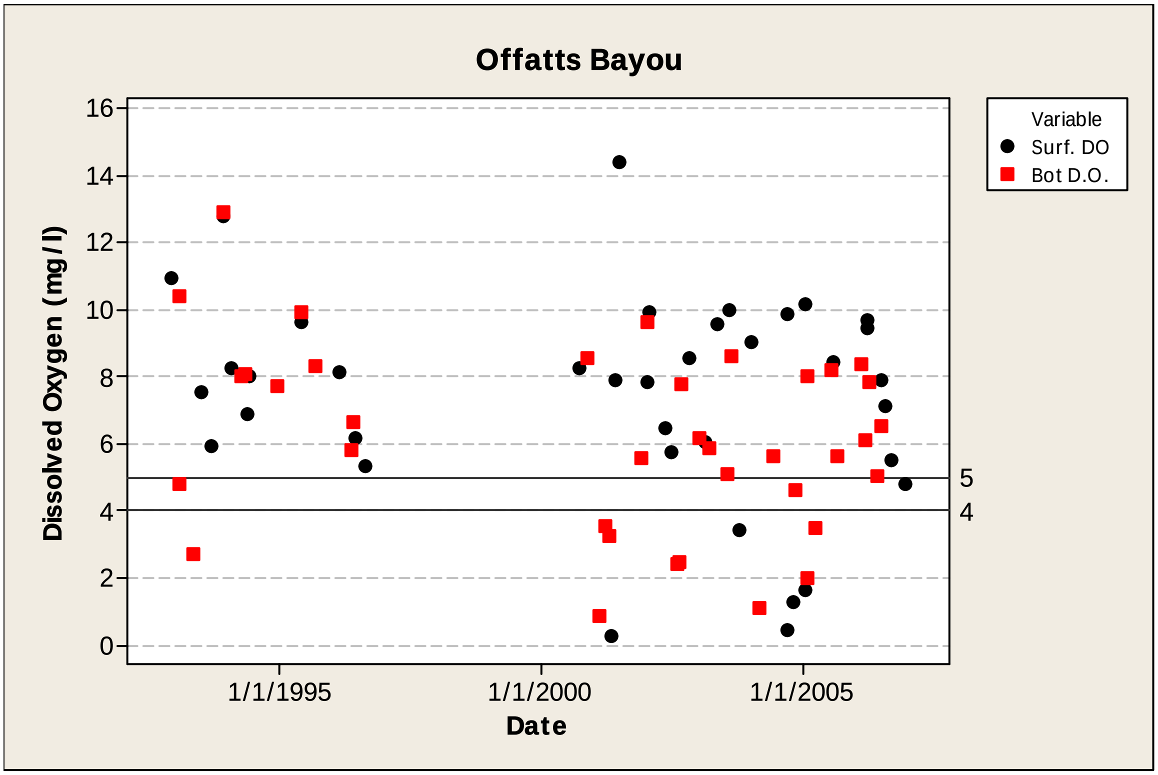

Figure 12. Dissolved oxygen levels measured at the surface (1 ft) and 1 ft above the bottom at Offatts Bayou. The water quality standard is a 24 hour minimum average of 5 mg/l and an 8 hour minimum of 4 mg/l.

Table 2. Summary of selected data collected by GCHD during October 2005 through April 2006.

GCHD ID	EIH Station #	Type	Site	Date	Temp (C)	Salinity (psu)	dl	# Enterococci/ 100 ml	NH3 mg/l	1 day rain inches	3 day rain inches
4	EIH 12	Ambient	RV Dock	10/17/2005				4	0.39	0	0
2	EIH 15	Ambient	2702 Beluche	10/17/2005			<	2	0.06	0	0
4	EIH 12	Ambient	RV Dock	12/14/2005	16.4	13.3		2520	1.44	2.1	2.1
3	EIH 12	Ambient	RV Ramp	12/15/2005	16.5	12.4		3460	1.54	0	2.1
5A	EIH 16	Ambient	Beluche Ramp	12/15/2005	16.1	8.2		2480	0.77	0	2.1
2	EIH 15	Ambient	2702 Beluche	12/15/2005	14.7	16.7		2351	0.28	0	2.1
2	EIH 15	Ambient	2702 Beluche	12/15/2005	14.7	16.7		1904	0.28	0	2.1
6	COG 7	Discharge	Oppe Bridge Outfall	12/15/2005	15.8	2.4		5160	0.25	0	2.1
6A	EIH 17	Ambient	Oppe at 46 Lakeview	12/22/2005	9.1	8.8		2987	0.32	0	0
6B	COG 7	Discharge	Oppe Bridge Outfall	12/22/2005	12.3	4.5		9804	0.48	0	0
6C	COG 8	Discharge	Oppe - outfall on right side	12/22/2005	8.8	10.1		8664	0.34	0	0
4	EIH 12	Ambient	RV Dock	3/24/2006	15.3	23.9		128	0.38	0	0
2	EIH 15	Ambient	2702 Beluche	3/24/2006	18.2	21.6		112	0.48	0	0
5A	EIH 16	Ambient	Beluche Ramp	3/24/2006	14	22.8		560	0.14	0	0
5B	EIH 16	Ambient	Beluche Corner by Ramp	3/24/2006	14	22.8		182	0.21	0	0
6	COG 7	Discharge	Oppe Bridge Outfall	3/21/2006	19.3	25.6		560	0.24	0	0.11
6	COG 7	Discharge	Oppe Bridge Outfall	3/21/2006	19	23.7		106	0.4	0	0.11
6C	COG 8	Discharge	Oppe - outfall on right side	3/24/2006	11.9	22.5		108	0.19	0	0
6	COG 7	Discharge	Oppe Bridge Outfall	4/5/2006	22.3	20.4		72	1.15	0	0
6E	COG 7	Discharge	Manhole across from Oppe	4/5/2006	23	18.5		100	1.39	0	0
4	EIH 12	Ambient	RV Dock	4/21/2006	22.5	23.4		6000	0.11	0.51	0.51
2	EIH 15	Ambient	2702 Beluche	4/21/2006	22.4	3.6		39600	0.48	0.51	0.51
2	EIH 15	Ambient	2702 Beluche	4/21/2006	22.4	3.6		45000	0.46	0.51	0.51
5A	EIH 16	Ambient	Beluche Ramp	4/21/2006	24.6	14.9		14400	0.14	0.51	0.51
6C	COG 8	Discharge	Oppe - outfall on right side	4/21/2006	23.6	14.4		14400	0.22	0.51	0.51
12A	COG 12	Discharge	3/4 way down inlet from Skymaster	4/26/2006	23.7	24.2		138	0.13	0	0
13A	COG 12	Discharge	Half way down inlet from Skymaster	4/26/2006	23.5	24.9		532	0.15	0	0
14A	COG 12	Discharge	Inlet beside WWTP at Skymaster	4/26/2006	23.4	21.7		228	0.29	0	0
11A	COG 7	Discharge	WWTP outfall	4/26/2006	25.5	1.7		24	0.9	0	0
11A	COG 7	Discharge	WWTP outfall	4/26/2006	25.5	1.7		24	0.9	0	0
11B	COG 7	Discharge	WWTP outfall	4/26/2006	25.5	1.7		80		0	0
11B	COG 7	Discharge	WWTP outfall	4/26/2006	25.5	1.7		140		0	0

Current Study

Based on our monitoring data, Lake Madeline does not appear to be meeting contact recreation water quality standards (Table 3 and Figure 1). The geometric mean level of enterococci at open water sites within Lake Madeline for the survey period was 212 colonies/100 ml. Approximately 75% of the samples exhibited enterococci levels exceeding 35 colonies/100 ml. On July 13, 2006 we also sampled the bottom water at the center of Lake Madeline and found elevated enterococci levels even though surface levels were low. This suggests an interaction between bacteria levels and salinity or sediment.

Storm sewers and open channels within Lake Madeline exhibited elevated enterococci levels (Table 3). When all sampling events (storm sewers and open channel sites) were analyzed the geometric means concentration was 2,087 colonies/100 ml. The geometric mean for wet weather events (July 3, September 9 and 24, 2006) for discharge sites was 13,759 colonies/100 ml. Considering only dry weather events and a smaller number of storm sewers and discharge points, the geometric mean was still elevated at 478 colonies/100 ml. The various storm sewers discharging into Lake Madeline appear to be significant sources of enterococci bacteria. These sites contain elevated levels of enterococci even during most dry weather events. During the wet weather events on July 3, September 9 and 24, 2006, bacteria levels were highly elevated throughout the watershed including the various storm sewers. Although not as high, the Offatts Bayou and Sydnor Bayou sites also had elevated levels on these dates as well.

These findings suggest that there appears to be a positive relationship between enterococci levels at storm sewer sites monitored during dry and wet weather events (COG 1-4), and precipitation (Table 3; Figures 1, 13 and 14). This is especially evident when evaluating the influence of 3 day accumulated rainfall as measured at the Scholes Field NWS Station. Similar trends were observed in the open waters of Lake Madeline (Table 3; Figures 1, 13 and 15). These observed relationships further support our hypothesis that malfunctioning wastewater collection systems may be a significant source of indicator bacteria within the watershed.

We also monitored fecal coliform and fecal streptococci indicator bacteria levels at selected sites on August 9 and 25 and September 9 and 24. Although not strongly correlated, those data show similar trends with enterococci levels (Figure 16). In order to estimate the possible source of the observed bacteriological indicator levels we also conducted fecal streptococcus tests and constructed FC/FS ratios for a subsample of dates and sites (Table 4). Our data and analyses suggest that most of the bacteria are probably of human or mixed origin. Approximately 54%, 29% and 16% of the samples appeared to be composed of bacteria from human, animal and mixed origin respectively. Some notable exceptions included Offatts Bayou, Sydnor Bayou and some of the storm sewers located in the southeast end of Lake Madeline which drain the Wal-Mart area. Samples from these sites indicate bacteria of animal origin. Again the reader is reminded that the FC/FC ratio method is considered a very rough screening method and should not be used to definitively determine the origin of these bacteria.

Table 3. Summary of enterococci data collected during June 5 to October 8, 2006. The July 3, September 9 and 24, are considered wet weather sampling events.

Station	Description	5-Jun	24-Jun	3-Jul	13-Jul	27-Jul	9-Aug	25-Aug	9-Sep	24-Sep	8-Oct
EIH 7	CENTER OF OFFATTS BAYOU	< 1	< 1	12,033	< 1	52	10	73	3,968	576	< 1
EIH 7	CENTER OF OFFATTS BAYOU (bottom)				10	31					
EIH 8	EFFLUENT CHANNEL INTO OFFATTS FROM MOODY GARDEN TO THE RIGHT OF THE CAPITANS DOCK	158	1,171	> 24,196	116	624	75	1,201	9,234	> 24,196	200
COG 5	THE MOUTH OF LAKE MADELINE CANAL @ OFFATTS BAYOU	20	< 1	> 24,196	< 1	202	31	41	17,329		< 1
EIH 9	Inside LM Canal marina at most northern point	106	75	> 24,196	< 1	272	20	97	15,531	441	100
COG 12	HEARDS LANE STORM SEWER TO LAKE MADELINE CHANNEL			> 24,196					> 24,196	9,804	< 1
EIH 10	IN CANAL IMMEDIATELY UPSTREAM OF MARINA	20	41	> 24,196	20	160	63	122	17,329	> 24,196	< 1
COG 11	DRAINAGE DITCH FROM AIRPORT TO LAKE MADALINE CHANNEL	13	41	> 24,196					> 24,196	1,565	< 1
EIH 11	Airport Wastewater Plant discharge into Lake Madeline Channel	< 1	41	644	41	< 1	20	158	7,270	7,701	100
EIH 12	LM Channel, just downstream of Jones Road bridge	10	20	> 24,196	< 1	272	75	20	9,804		840
COG 10	48 " STORM SEWER ALONG JONES ROAD IN LAKE MADELINE CHANNEL DIRECTLY BELOW BRIDGE STRUCTURE			> 24,196						670	< 1
EIH 13	LM Channel, just upstream of Jones Road bridge at entrance into LM	51	10	> 24,196	< 1	269	30	10	> 24,196		< 1
EIH 15	NE CORNER OF LAKE MADELINE	216	86	> 24,196	31	2,187	41	231	> 24,196	857	100
COG 1	60 INCH STORM SEWER @ BELUCHE NEAR GEROL		239	> 24,196	364	10,462	295	11,199		6,488	740
COG 3	Stewart Rd Sewer in vicinity of Fairway Ln - 7402 Stewart (Baptist Church)		3,654	> 24,196	226	2,014	1,145	471		> 24,196	3930
EIH 16	SE CORNER of LM	110	581	> 24,196	41	97	10	52	> 24,196	> 24,196	2380
COG 9	STORM SEWER @ BELUCHE SOUTH OF LAKE MADELINE: BETWEEN THE BOAT LAUNCH AND BLACK PLASTIC DRAIN			> 24,196					> 24,196	> 24,196	740
COG 2	CONCRETE CHANNEL @ SE CORNER OF LAKE MADELINE AT GRATED STORM DRAIN		1,259	> 24,196	226	1,421	17,329	631		6,867	3550
COG 4	GREENS BAYOU @ OVERFLOW TO LAKE MADELINE BEHIND WALMART		178	> 24,196	336	15,531	504	884		5,475	1990
EIH 14	MIDDLE OF LAKE MADELINE	< 1	< 1	> 24,196	< 1	238	< 1	52	> 24,196		100
EIH 14	MIDDLE OF LAKE MADELINE (bottom)				120						
EIH 18	N CORNER of LM	1,059	3,873	> 24,196	10	414	52	84	> 24,196	487	< 1
EIH 17	NW CORNER of LM	431	41	> 24,196	20	189	41	52	> 24,196	19,863	< 1
COG 7	STORM SEWER CROSSING JONES DRIVE ACROSS FROM OPIE SCHOOL			> 24,196					> 24,196	1,467	300
COG 8	STORM SEWER ALONG EAST SIDE OF JONES RD ACROSS FROM OPIE SCHOOL			> 24,196					> 24,196	> 24,196	4800
COG 6	SYDNOR BAYOU NEAR GOLF COURSE		411	> 24,196	1,956	187	10	20		121	< 1

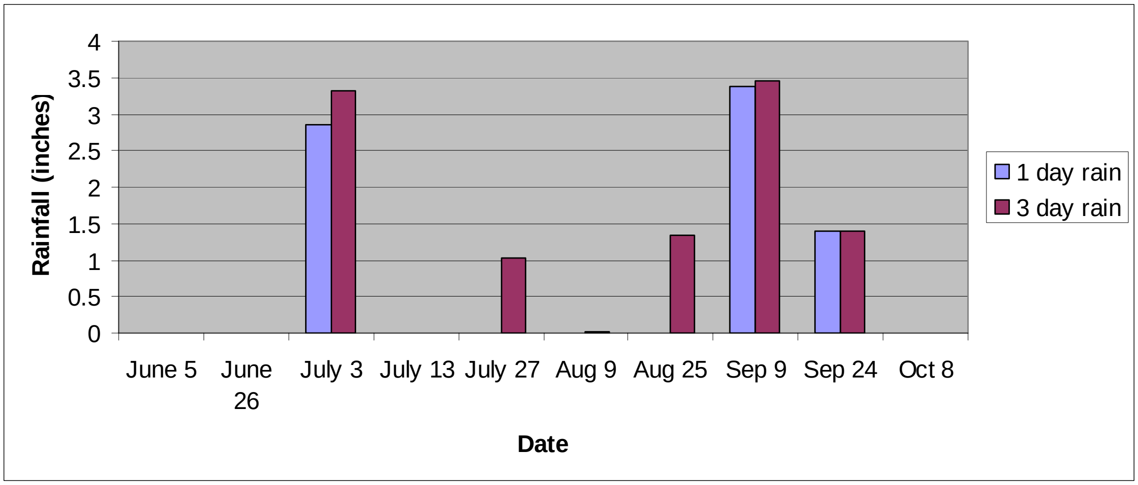

Figure 13. Rainfall accumulation during each sample date and the previous 2 days.

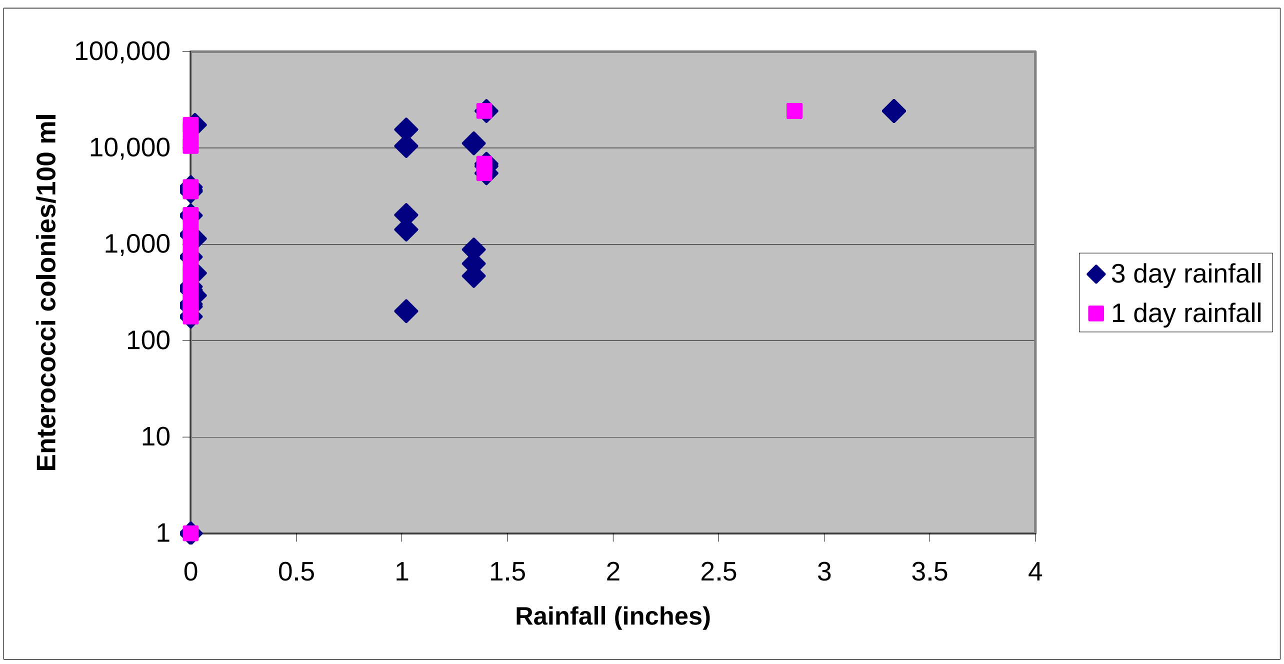

Figure 14. Comparison of enterococci levels and 1 and 3 day rainfall amounts at selected storm sewers (COG 1-4) monitored during dry and wet periods. The data point for the 2.86 and 3.33 inches of rainfall amount represents 5 sites, i.e. 5 observations. Y-axis is log scale.

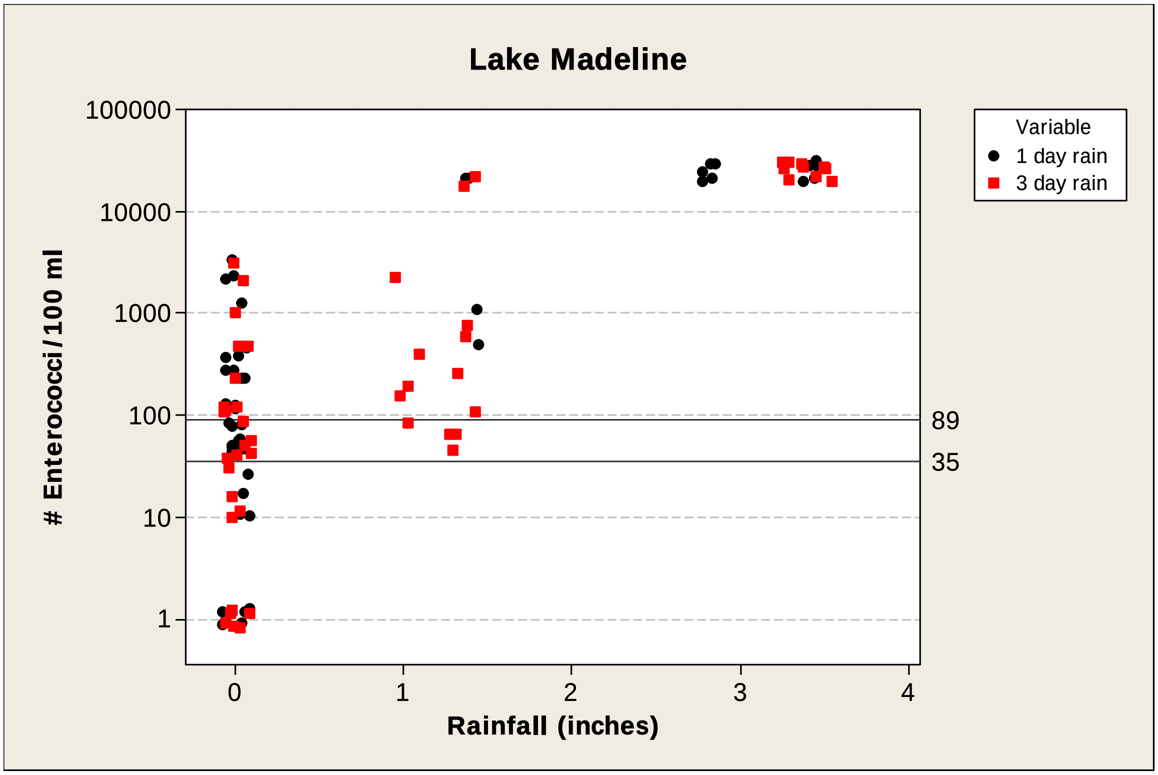

Figure 15. Comparison of enterococci levels and 1 and 3 day rainfall amounts at open water sites within Lake Madeline monitored during dry and wet periods. The data points for the 3.3 and 3.46 inch rainfall amounts represent all 5 sites, i.e. 5 observations. Y-axis is log scale.

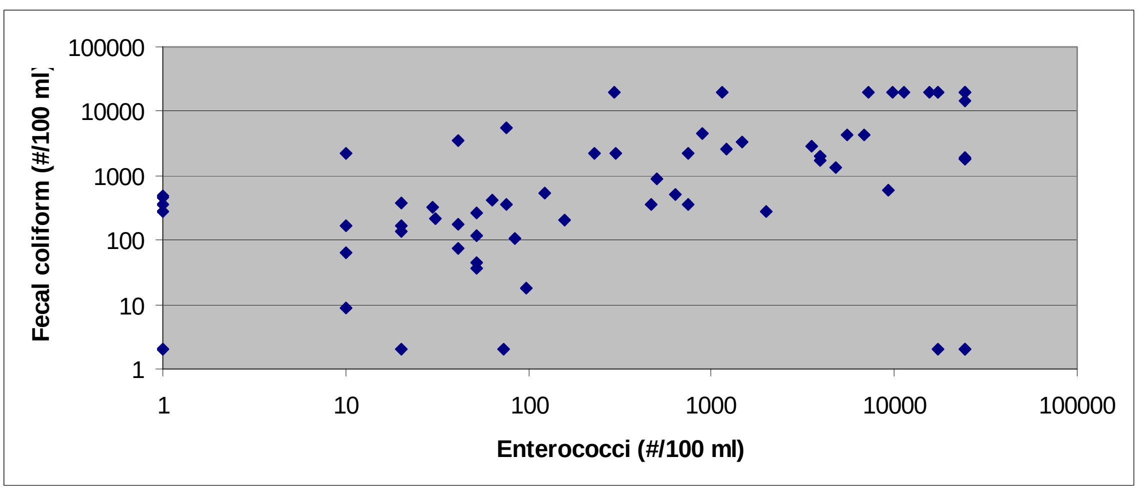

Figure 16. Comparison of enterococci and fecal coliform levels monitored on selected dates of the study period. Y and X-axis is log scale.

Table 4. Comparison of enterococci, fecal coliform, fecal streptococcus and FC/FS ratios at selected dates and sites.

ID	DESCRIPTION	Date	Rainfall (inches)	dlEnt	Enterococci (#/100ml)	dlFC	Fecal Coliform (#/100ml)	dlFS	Fecal Streptococci (#/ 100 ml)	FC/FS	Primary Potential Source (4.1; 0.7)
EIH 7	Center of Offatts Bayou	8/25/2006	1.34		73	<	2		9	0.2	**Animal**
EIH 14	Middle of Lake Madeline	8/25/2006	1.34		52		36	<	2	18.0	Human
EIH 18	N corner of Lake Madeline	8/25/2006	1.34		84		109		9	12.1	Human
COG 1	Storm sewer @ Beluche near Gerol	8/25/2006	1.34		11199	>	20000		1155	17.3	Human
COG 2	Storm drain SE corner Lake Madeline	8/25/2006	1.34		631		500		560	0.9	Mixed
COG 3	Stewart Road sewer near Fairway Ln	8/25/2006	1.34		471		360		782	0.5	Mixed
COG 4	Greens bayou @ overflow to L. Mad. Behind Walmart	8/25/2006	1.34		884		4564		850	5.4	Human
COG 6	Sydnor Bayou near golf course	8/25/2006	1.34		20	<	2		6945	0.0	**Animal**
COG 2	Storm drain SE corner Lake Madeline	9/24/2006	1.40		6867		4400	>	20000	0.2	**Animal**
COG 3	Stewart Road sewer near Fairway Ln	9/24/2006	1.40	>	24196		19300		618	31.2	Human
COG 4	Greens bayou @ overflow to L. Mad. Behind Walmart	9/24/2006	1.40		5475		4300		17200	0.3	**Animal**
COG 7	Storm sewer @ Jones Dr. across from school	9/24/2006	1.40		1467		3300		582	5.7	Human
COG 1	Storm sewer @ Beluche near Gerol	10/8/2006	0.00		740		364	<	2	182.0	Human
COG 2	Storm drain SE corner Lake Madeline	10/8/2006	0.00		3550		2800		455	6.2	Human
COG 3	Stewart Road sewer near Fairway Ln	10/8/2006	0.00		3930		1727		273	6.3	Human
COG 4	Greens bayou @ overflow to L. Mad. Behind Walmart	10/8/2006	0.00		1990		273		545	0.5	**Animal**
COG 5	Offatts @ mouth of Lake Madeline Canal	10/8/2006	0.00		1	<	2	<	2	1.0	Mixed
COG 6	Sydnor Bayou near golf course	10/8/2006	0.00		1		364	<	2	182.0	Human
COG 7	Storm sewer @ Jones Dr. across from school	10/8/2006	0.00		300		2200		909	2.4	Mixed
COG 8	Storm sewer along east side of Jones Rd across from school	10/8/2006	0.00		4800		1364		6909	0.2	**Animal**
COG 9	Storm sewer @ Beluche	10/8/2006	0.00		740		2182		636	3.4	Human
COG 10	Lake Madeline Canal @ 61st street bridge	10/8/2006	0.00		1		273	<	2	136.5	Human
COG 11	Drainage ditch from airport to L. Mad. Channel	10/8/2006	0.00		1		455	<	2	227.5	Human
COG 12	Heards Lane storm sewer to L. Mad. Channel	10/8/2006	0.00		1	<	2		182	0.0	**Animal**

Although in some cases the FC/FS ratio suggests that the origin of bacteria may be mainly animal origin, the reader should also be aware that various pathogens can be transmitted from animals to humans via fecal matter in surface waters. This information should only be used to assist the reader on determining the source of elevated indicator bacteria and not the relative risk to humans.

Discussion

Based on our monitoring data, Lake Madeline does not appear to be meeting contact recreation water quality standards. Various bacteriological indicators are elevated throughout the lake during periods of increased rainfall, warmer temperatures and decreased salinity. The various storm sewers discharging into Lake Madeline appear to be significant sources of enterococci bacteria. Also, these storm sewers contain elevated levels of enterococci even during most dry weather events. Our findings further suggest that there appears to be a strong positive relationship between enterococci 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. Computed FC/FS ratios support our hypothesis that most of the sources of bacteria are probably of human or mixed origin. Approximately 54%, 29% and 16% of the samples appeared to be composed of bacteria from human, animal and mixed origin respectively. However, some exceptions were noted including Offatts Bayou, Sydnor Bayou and some of the storm sewers located in the southeast end of Lake Madeline which drain the Greens Bayou/Wal-Mart area. Samples from these sites suggest that indicator bacteria are primarily of animal origin. However, the FC/FC ratio method is considered a very crude screening method and should not be used to definitively determine the origin of these bacteria.

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, these elevated indicator bacteria probably originate from leaking wastewater collection systems (sanitary sewers). Sanitary sewer lines are usually located and buried adjacent to storm sewers. During high rainfall water can percolate from broken sanitary sewer lines and infiltrate storm sewers, ultimately discharging into Lake Madeline. This problem is fairly common in older cities possessing aging storm water and sanitary sewer systems.

We highly recommend that a more detailed investigation of the storm water and sanitary sewer collection systems be initiated to definitely determine the sources of contamination and remediate further discharges as needed. We understand the City of Galveston has already embarked on a sanitary sewer rehabilitation project to address some of these issues. Monitoring should be conducted as repairs are completed to document expected improvements in water quality.

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